Detrital zircon facies of Cordilleran terranes in western North America

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ABSTRACT

Paleozoic–Mesozoic basins in Cordilleran terranes of western North America contain detrital zircon U-Pb age distributions that vary over 10–100 Ma in a systematic and predictable manner. A minimum of four detrital zircon age distributions, here termed "detrital zircon facies," are present: (1) Paleoproterozoic and Archean facies, chiefly found in Paleozoic and early Mesozoic accretionary complexes, is defined by late Archean–early Proterozoic (ca. 2.7–2.3 Ga) and late Proterozoic ages (ca. 2.0–1.6 Ga) with variable quantities of Paleozoic and early Mesozoic ages. (2) Mixed Proterozoic and Phanerozoic facies is found in Early–Late Jurassic basins and is defined by grains spanning ca. 2.0 Ga–160 Ma, derived from eastern-southwestern Laurentian transcontinental sources and enriched by western U.S. and eastern Mexican early Mesozoic plate-margin magmatism. (3) Triassic and Jurassic facies, found in Late Jurassic–Early Cretaceous basins, is defined by Late Jurassic ages (peak ca. 155 Ma) with a subordinate proportion of Triassic ages (peak ca. 230 Ma). (4) Jurassic and Early Cretaceous facies is found in late Early–early Late Cretaceous marginal basins and is defined by Jurassic and Early Cretaceous ages (ca. 200–130 and ca. 130–100 Ma). Detrital zircon U-Pb ages from terranes of western North America record stages of basin formation during phases of the supercontinent cycle and reflect second-order variability in the tectonic setting of an active continental plate margin. At this temporal and spatial scale, the integrated evolution of orogenic, erosion, and sediment-transport systems controls sediment provenance.

INTRODUCTION

On a global time-integrated scale, detrital zircon U-Pb age distributions reflect episodic magmatic accretion of continental crust (i.e., first-order scale, 100–1000 Ma, e.g., Condie and Aster, 2009). At an order of magnitude finer scale (i.e., second-order, 10–100 Ma, 100,000 km^2 of rock), detrital zircon U-Pb age distributions in continental-margin basins should reflect the long-term distribution of orogenic belts, long-lived Andean-type magmatic arcs, and continental sediment-dispersal systems (e.g., Leeder, 1988; Patchett et al., 1999). Supporting evidence for this scale of tectonic control on sedimentary provenance in the ancient rock record exists, but is generally sparse and typically does not document transitional stages of paleotectonics (e.g., Rainbird et al., 1992; Riggs et al., 1996; Dickinson and Gehrels, 2003; Tyrrell et al., 2007; Druschke et al., 2011).

In this paper, my objectives are to use detrital zircon U-Pb data in terranes of western North America to (1) assess long-term provenance links to the Laurentian craton, (2) identify multi-stage sediment sources through time, and (3) emphasize second-order scale observation in detrital zircon U-Pb age studies. I suggest that this observational scale is critical for understanding changes in tectonic setting along active plate margins, as has been shown for neodymium isotopic values in continental sedimentary rocks (Patchett et al., 1999). In western North America, analysis of the detrital zircon record at this scale elucidates the transition from a marginal-basin regime (i.e., Karig, 1974; Tarney et al., 1981) during most of Paleozoic and early Mesozoic time, to an Andean-type integrated margin by Late Mesozoic time (i.e., McClelland et al., 1992; Saleeby and Busby-Spera, 1992; Dickinson et al., 1996; DeCelles, 2004) and argues against models invoking exotic ribbon continents (e.g., Johnston, 2008; Hildebrand, 2009).

DETRITAL ZIRCON AGE DISTRIBUTIONS IN WESTERN NORTH AMERICA

Over the past ~20 years, the application of U-Pb geochronology to detrital zircon grains has yielded significant insight concerning sediment sources to western North American basins. In particular, terranes of western North America have been extensively studied using detrital zircon U-Pb ages with numerous contrasting interpretations (e.g., Ross and Bowring, 1990; Miller and Saleeby, 1995; Gehrels and Kapp, 1998; Gehrels et al., 2000; Brown and Gehrels, 2007; Wright and Wyld, 2007; Grove et al., 2008; Scherer and Ernst, 2008; Snow and Ernst, 2008; Piercey and Colpron, 2009; LaMaskin et al., 2011).

Here, I compile published and new detrital zircon U-Pb ages from pre-Devonian–early Late Cretaceous, arc-related basins in terranes of western North America. The compilation includes terranes with sufficient available data from west of the $^{87/86}Sr_i$ = 0.706 line (Armstrong et al., 1977), from the southern California Coast Range to the Yukon-Tanana terrane in the north. My compilation, observations, and interpretations are specific to the time frame in this geographic range only; they are not intended to be a comprehensive review of Cordilleran provenance and tectonics, but rather, to serve as a starting point for continued investigation at this scale.

The overwhelming fundamental observation from the data is that regardless of interpreted terrane association, at a stratigraphic scale of 10–100 Ma, distinct age distributions are present in the same stratigraphic order along strike of the western North American margin. I recognize a minimum of four distinct detrital zircon age distributions in pre-Devonian–early Late Cretaceous clastic sedimentary successions in western North America. These age distributions vary systematically

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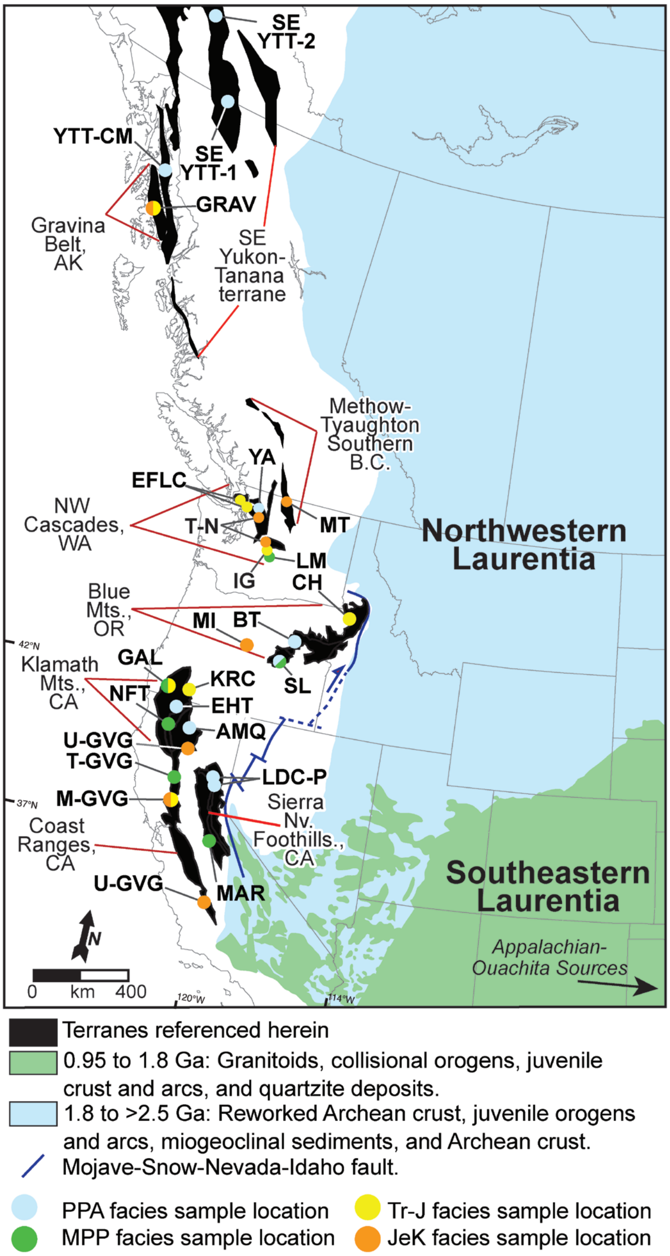

Figure 1. Map illustrating present-day location of terranes discussed in this paper, age distribution of Laurentian Precambrian crust, and detrital zircon sample locations: SEYTT—Southeastern Yukon-Tanana terrane; YTT-CM—Yukon-Tanana terrane in Coast Mountains; GRAV—Gravina Belt; MT—Methow-Tyaughton; EFLC—Easton-Fidalgo-Lummi-Constitution; YA—Yellow Aster; IG—Ingalls Graywacke; T-N—Tonga-Nooksack; LM—Lookout Mountain; CH—Coon Hollow; BT—Baker terrane; MI—Mitchell Inlier; SL—Snowshoe and Lonesome fms.; KRC—Klamath River Conglomerate; GAL—Galice; AMQ—Antelope Mountain Quartzite; EHT—Eastern Hayfork terrane; NFT—North Fork terrane; U-GVG—Upper Great Valley Group; T-GVG—"Tithonian" Great Valley Group; LDC-P—Lang-Duncan-Culberton allochthons and Picayune Valley Fm.; M-GVG—Middle Great Valley Group; MAR—Mariposa; JEK—Jurassic–Early Cretaceous; MPP—Mixed Proterozoic and Phanerozoic; and PPA—Paleoproterozoic and Archean. See Table DR1 for specific data sources[1]. Adapted from Gehrels (2001); Wyld and Wright (2001); DeGraaff-Surpless et al. (2002); Wyld et al. (2006); Brown and Gehrels (2007); Nelson and Gehrels (2007); base modified from Whitmeyer and Karlstrom (2007).

based on the depositional age and tectonic setting of the basin (cf. Gehrels, 2003).

1. Paleoproterozoic and Archean distribution (PPA; Figs. 1 and 2A) is defined by an age distribution of late Archean–early Proterozoic (ca. 2.7–2.3 Ga) and late Proterozoic ages (ca. 2.0–1.6 Ga), with variable quantities of Paleozoic and Early Mesozoic ages dependent on depositional age of the rocks. The majority of samples do not include Mesoproterozoic ages (ca. 1.5–1.0 Ga). PPA is dominant in Paleozoic rocks from California to Alaska, in terranes typically defined as subduction-accretionary complexes or subduction mélange.

2. Mixed Proterozoic and Phanerozoic distribution (MPP; Figs. 1 and 2B) is defined by a multimodal age distribution spanning 2.0–0.16 Ga, including distinct age ranges of (1) late Paleoproterozoic (ca. 2.0–1.6 Ga); (2) Mesoproterozoic (ca. 1.5–1.0 Ga); (3) Neoproterozoic (ca. 0.8–0.6 Ga); (4) early Paleozoic (ca. 0.5–0.35); (5) late Paleozoic (ca. 350–250 Ma); and (6) early Mesozoic (ca. 250–160 Ma). MPP is present in Early–Late Jurassic samples, typically in forearc/intra-arc basins in terranes defined as island-arc complexes.

3. Triassic and Jurassic distribution (TrJ; Figs. 1 and 3A) is defined by a dominant Middle–Late Jurassic (ca. 175–145 Ma) age distribution, with variable quantities of Triassic ages (ca. 250–220 Ma), and a general lack of Precambrian ages. (Note that Fig. 3A is truncated at 300 Ma.) TrJ is present in samples from an extensive belt of Late Jurassic–Early Cretaceous basins that has long been recognized as correlative but of unclear tectonic setting (i.e., Cowan and Brandon, 1981; Garver, 1988; McClelland et al., 1992; Miller and Saleeby, 1995).

4. Jurassic and Early Cretaceous distribution (JeK; Figs. 1 and 3B) is defined by an approximately bimodal age distribution of Jurassic–Early Cretaceous (ca. 200–130 Ma) and Early Cretaceous ages (ca. 130–100 Ma). JeK is found in samples from late Early–early Late Cretaceous basins, generally recognized as the forearc of the western North American Andean-style margin (i.e., Great Valley forearc) (Ingersoll, 1979; Degraaff-Surpless et al., 2002; Brown and Gehrels, 2007; Jacobson et al., 2011).

DISCUSSION

The compilation presented here shows sequential regularity in distinct detrital zircon U-Pb ages at a scale of 10–100 Ma. The detrital zircon age distributions represent a definable aspect of large bodies of rock, are observation based, and allow for distinction between adjacent units. As such, they are here designated "detrital zircon facies." The age ranges present in a given detrital zircon facies (i.e., their recognition criteria) relate directly to known regional source areas of both primary *and* recycled grains. In the following sections, I review each detrital zircon facies and implications for development of the western Laurentian margin (Fig. 4).

Paleozoic–Early Mesozoic Time

The provenance of PPA facies is either (1) crystalline sources in northwestern Laurentia (Gehrels et al., 1995, 2000), (2) rifted and translated crustal fragments of the Precambrian–Paleozoic

[1]GSA supplemental data item 2012079, Table DR1: Data sources, is available online at www.geosociety.org/pubs/ft2012.htm. You can also request a copy from *GSA Today*, P.O. Box 9140, Boulder, CO 80301-9140, USA; gsatoday@geosociety.org.

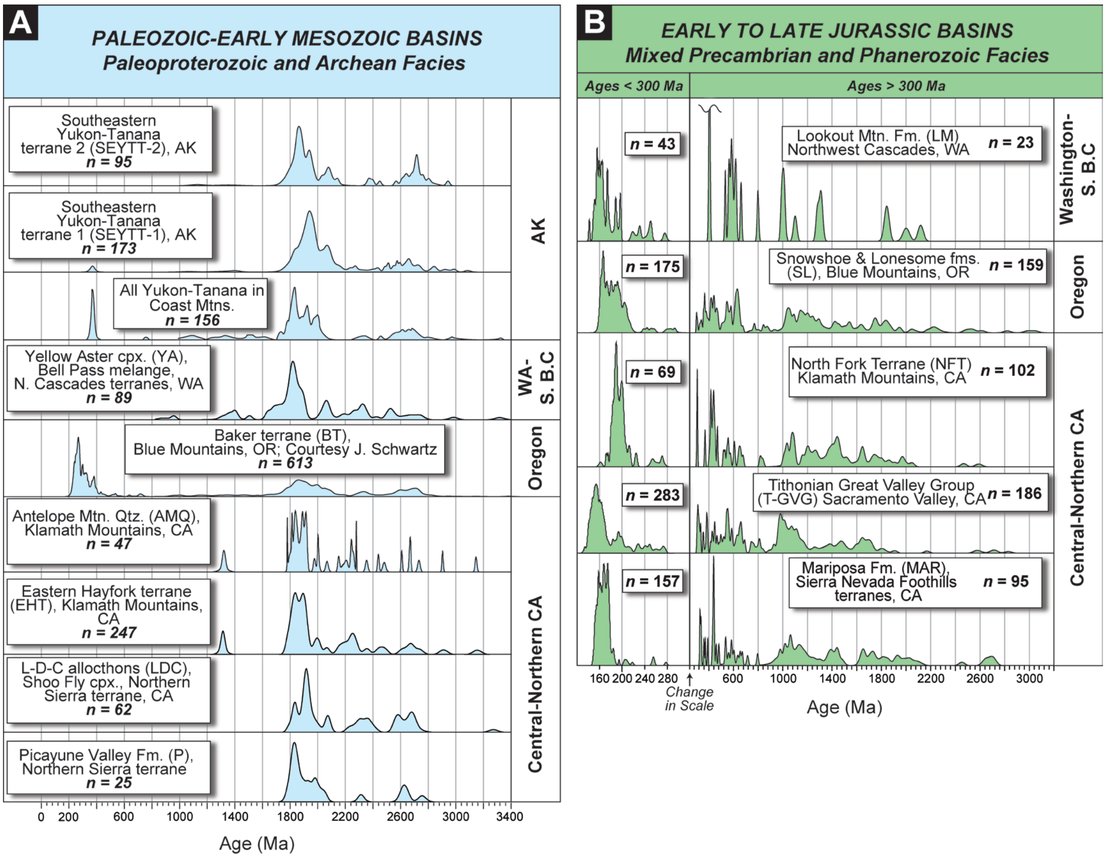

Figure 2. Detrital zircon U-Pb age data from (A) Paleozoic–Mesozoic subduction-accretionary complexes and (B) Early to Late Jurassic basins in island-arc complexes. Specific data sources are shown in Table DR1 (see footnote 1).

northwestern Laurentian miogeocline (Nelson and Gehrels, 2007; cf. Bradley et al., 2007; Beranek et al., 2010a), or (3) originally peri-Gondwanan/Avalonian crust that was tectonically emplaced along the southern Laurentian margin in early–mid-Paleozoic time and subsequently translated along the plate margin in mid–late Paleozoic time (Wright and Wyld, 2006; Grove et al., 2008). Thus, rocks bearing PPA facies may reflect sediment derivation from northwestern Laurentian sources enhanced by plate-margin magmatism or multicycle sediment reworking and tectonic translation of crustal fragments allochthonous to western North America.

Regardless of the ultimate source of age-characteristic zircon grains, PPA facies sand was present in arc-basin complexes on the western North American plate margin by mid-Paleozoic time (Harding et al., 2000; Spurlin et al., 2000; cf. Lindsley-Griffin et al., 2006), and was subsequently recycled along the margin (Fig. 4) (e.g., Scherer et al., 2010; LaMaskin et al., 2011). Noteworthy, non-PPA age distributions in Paleozoic accretionary-subduction complexes of the Klamath Mountains and Sierra Nevada may represent exotic crust, structurally intercalated with PPA-bearing rocks, or may suggest other explanations (e.g., Harding et al., 2000; Wright and Wyld, 2007; Grove et al., 2008).

Early–Late Jurassic Time

The age distribution in MPP facies represents transcontinental sand shed from the greater Ouachita-Appalachian orogeny and enriched by southwestern Laurentian sources, as well as early Mesozoic, plate-margin magmatism in the western U.S. and eastern Mexico (Fig. 4; cf. Dickinson and Gehrels, 2003, 2009; Rahl et al., 2003). The presence of a transcontinental signature in each of these Early–Late Jurassic basins (Fig. 2B; cf. Izsak et al., 2007; Dickinson and Gehrels, 2008a, 2009; LaMaskin et al., 2011) suggests proximity to North America and the modern southwestern U.S. in early Mesozoic time, and that active orogenic structures and the plate-margin arc itself were not barriers to sediment transfer from the craton to the arc.

Existing data suggest that these transcontinental sediments were not incorporated into western North American peripheral-arc systems until Early Jurassic time (Fig. 4; ca. 190–185 Ma, Klamath Mountains, North Fork terrane) (Scherer and Ernst, 2008). It is not clear why transcontinental sediment was not delivered to arc-basin systems of the western U.S. during late Paleozoic time coincident with onset of the Alleghanian orogeny in eastern Laurentia (Hatcher, 2010). Additional data is needed from rocks of Late Paleozoic–Early Jurassic age to assess the timing of delivery of transcontinental sands to plate-margin basins and the transition from PPA to MPP facies.

Despite interpretations of a forearc setting for most Early–Late Jurassic basins (e.g., Dickinson, 1979; MacDonald, 2006; Scherer and Ernst, 2008; Snow and Ernst, 2008), MPP facies may also represent deposition (1) in a flexural basin adjacent to the uplifted western Nevadan back-arc basin (i.e., Jurassic Luning-fencemaker fold-thrust belt) (Wyld, 2002; Dorsey and LaMaskin, 2007; LaMaskin et al., 2011); (2) in extensional basins along the northward-deepening plate-margin arc (e.g., Busby-Spera, 1988; Barth et al., 2004; Dickinson and Gehrels, 2009; LaMaskin et al., 2011); or (3) in suprasubduction zone basins during arc extension and subsequent closure (e.g., Snoke, 1977; Harper, 1980; Hacker et al., 1995). Along-strike variability in modern southeast Pacific active margins suggests that these alternatives are not mutually

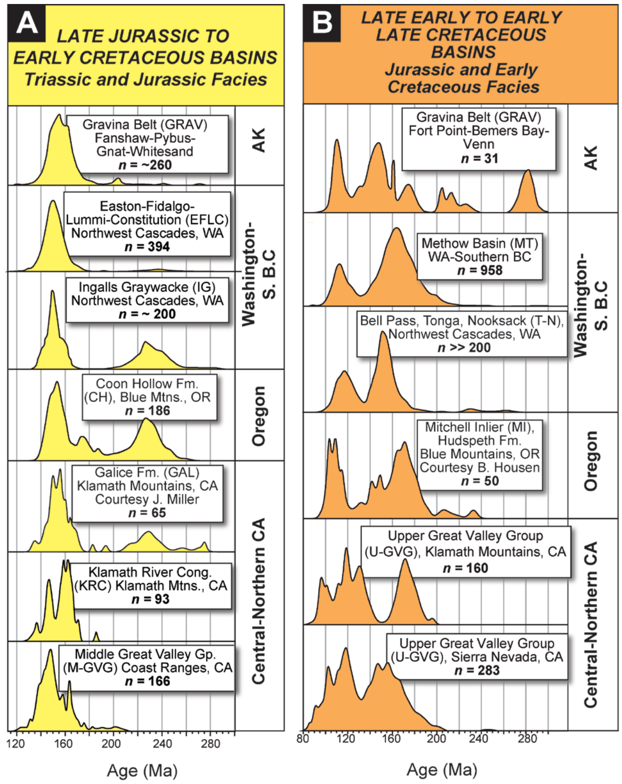

Figure 3. Detrital zircon U-Pb age data from (A) Late Jurassic–Early Cretaceous basins and (B) late Early to early Late Cretaceous basins. Specific data sources are shown in Table DR1 (see footnote 1).

exclusive. Proposed Cretaceous dextral-transpressive shear along the Mojave-Snow-Nevada-Idaho shear zone would have resulted in northern displacement of these originally southwestern U.S. basins (Wyld and Wright, 2001).

Late Jurassic–Early Cretaceous Time

In Late Jurassic–Early Cretaceous basins bearing TrJ facies, the paucity, or complete absence, of Precambrian zircon grains, in conjunction with a voluminous record of Middle–Late Jurassic magmatism, is interpreted to represent initial isolation of basins from the Laurentian craton due to nascent construction of the Andean-type margin (Figs. 3A and 4). Where Precambrian ages *are* present, age distributions mimic underlying MPP facies. A decrease in the relative abundance of Precambrian grains as compared to older samples discussed here may also simply represent an overwhelming *increase* in Mesozoic grains; however, for large sample sizes (e.g., Methow basin), Precambrian grains are not represented, suggesting that the decrease is not due to simple dilution.

The stratigraphic transition from MPP to TrJ facies is interpreted to record stepwise growth of orogenic highlands, as sediment pathways that were connected to the craton were cut off and new ones established along the rising plate margin. I propose that the transition from MPP to TrJ facies illustrates that, despite retro-arc thrusting and associated elevation gain during Middle Jurassic time (Wyld, 2002; Fuentes et al., 2009), there was not a contiguous mountain belt (i.e., topographically integrated) along the Pacific margin until Late Jurassic–Early Cretaceous time. According to this model, continental-scale drainage patterns in the western U.S. were reversed between Late Jurassic–Early Cretaceous time and transcontinental sands no longer entered western U.S. marginal basins. Instead, sediment sources to marginal basins became restricted to active arc and older igneous basement rocks in the now high-standing continental-margin, Andean-type arc.

The presence of TrJ facies in rocks as old as ca. 153–150 Ma (Fig. 4; Galice Formation, Klamath Mountains Province; Miller et al., 2003; Saleeby et al., 1982) suggests that plate reorganization from a complex, marginal-basin regime to an Andean-style margin may have initiated in middle Late Jurassic time (cf. Miller and Saleeby, 1995; Dumitru et al., 2010). A continuous basinal record of this Late Jurassic tectonic reorganization may be found in the western Klamath Mountains, where the Galice Formation includes both a transcontinental MPP facies (i.e., Izsak, et al., 2007) and a TrJ facies (i.e., Miller et al., 2003). Syndepositional, suprasubduction compression of the Galice basin in the western Klamath Mountains (Snoke, 1977; Wyld and Wright, 1988; Harper et al., 1994) may represent the earliest manifestation of plate reorganization. This compilation of detrital zircon U-Pb age data supports the idea of a "common origin for coeval strata on differing basement terranes" (Miller and Saleeby, 1995, p. 18,057), suggesting along-strike integration of disparate substrate crust by Late Jurassic time.

Late Early–Early Late Cretaceous Time

In late Early–early Late Cretaceous basins containing JeK facies, the general lack of Precambrian zircon grains represents continued isolation of marginal basins from the craton by the high-standing Andean-style margin (Figs. 3B and 4). Considering the analytical precision of SHRIMP (sensitive high-resolution ion microprobe) and LA-ICPMS (laser-ablation–inductively coupled plasma mass spectroscopy) methods, the nearly bimodal age distribution is a clear record of the two main magmatic phases of the Mesozoic Andean-type arc (i.e., Late Jurassic and Late Cretaceous; Ducea, 2001; Irwin and Wooden, 2001; Irwin, 2003). Any true differences in age modes and variance represent expected variability in the timing of arc magmatism along the Andean-type arc.

CONCLUSIONS AND IMPLICATIONS

In western North America, detrital zircon U-Pb age distributions vary in a systematic and predictable manner and are interpreted to reflect second-order variability in the tectonic setting of an active plate margin. I suggest that at a second-order, 10–100 Ma scale, detrital zircon ages are governed by plate-tectonic setting, in a similar manner to controls on neodymium isotopic values from continental sedimentary rocks (Patchett et al., 1999). At the second-order scale, the integrated evolution of orogenic, erosion, and sediment-transport systems controls detrital zircon U-Pb age distributions and, accordingly, sediment provenance.

Critical evaluation of the model presented here, and integration with rapidly emerging data sets from the miogeocline and interior of the western U.S. and Canada (e.g., Dickinson and Gehrels, 2008a, 2008b, 2009; Scherer et al., 2008; Dickinson et al., 2010; Beranek et al., 2010b; Druschke et al., 2011; Fuentes et al., 2010; Leier and Gehrels, 2011) from tectonically enigmatic thin-skinned sheets such as the Roberts Mountain and Golconda allochthons (e.g., Riley et al.,

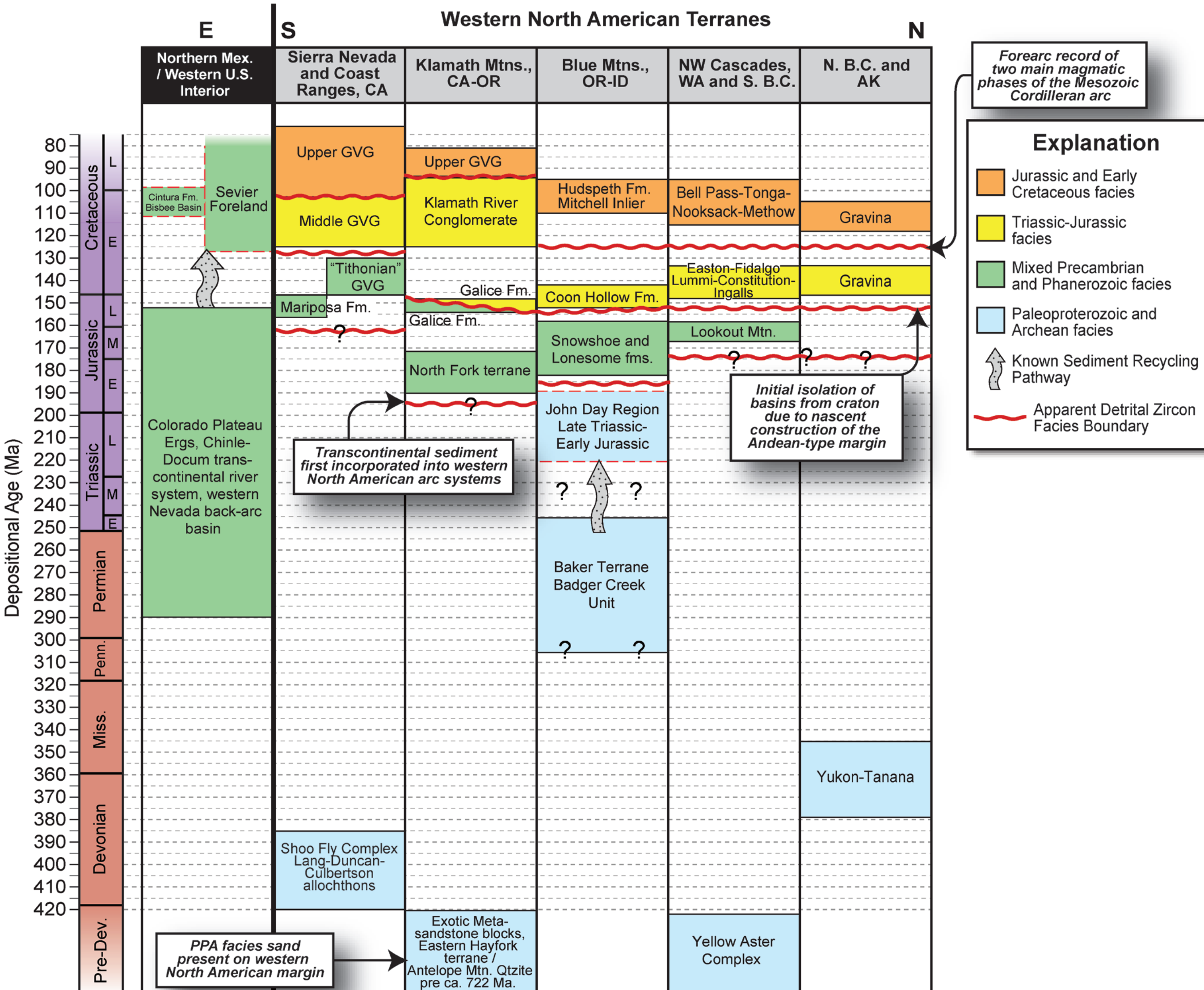

Figure 4. Chronostratigraphic distribution of detrital zircon facies in western North American terranes, as well as referenced samples from the western U.S. interior. GVG—Great Valley Group; PPA—Paleoproterozoic and Archean. Specific data sources are shown in Table DR1 (see footnote 1).

2000; Gehrels et al., 2000; Wright and Wyld, 2006), and roof pendants within the Sierra Nevada batholith (e.g., Memeti et al., 2010), may help resolve the affinity of numerous western Laurentian basins through time. Continued integration of data sets will lead to a better understanding of the pace, areal extent, and along-strike variability of North American plate-margin tectonics with inference for global plate-tectonic processes.

The model proposed here unifies a large data set collected over thousands of kilometers and representing hundreds of millions of years of sedimentation, sets forth predictions for new data collection, and is inherently testable both regionally and on other continents. Identification of age distributions that *do not* fit the model presented here is critical and may point to a truly allochthonous origin for rocks within western North America (e.g., Harding et al., 2000; Wright and Wyld, 2007; Grove et al., 2008). A global evaluation of detrital zircon U-Pb age distributions at this scale may provide important information for understanding the pace and spatial scale of crustal growth via arc and terrane accretion.

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