

Evolution of the Jura-Cretaceous North American Cordilleran margin: Insights from detrital-zircon U-Pb and Hf isotopes of sedimentary units of the North Cascades Range, Washington

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ABSTRACT

The U-Pb age and Hf-isotope composition of detrital zircons from Jurassic to Upper Cretaceous sedimentary rocks adjacent to the southern North Cascades–Coast Plutonic Complex continental magmatic arc document shifting provenance, the tectonic evolution of the arc system, and translation along the continental margin. Systematic changes in the detrital-zircon data provide insight that the western margin of North America evolved from: marginal basins adjacent to continent-fringing oceanic arcs (ca. 160–140 Ma); forearc basins adjacent to mid-Cretaceous (ca. 120–90 Ma) Andean-type continental arcs; and addition of a cratonic source to forearc and accretionary wedge units to Cordilleran arc systems in the mid-Late Cretaceous (ca. 85 Ma). Jurassic Methow terrane, Nooksack Formation, and western mélangé belt units dominantly contain detrital zircons derived from accreted oceanic terranes, whereas Lower Cretaceous strata from the same units have age peaks that correspond to known pulses of magmatism in Cordilleran continental magmatic arc systems. The age peaks and Hf-isotope signature of the Jurassic and Lower Cretaceous strata are comparable to multiple sources exposed along the margin. In contrast, the Upper Cretaceous western mélangé belt has distinct Precambrian zircon populations and unradiogenic Late Cretaceous zircons that are more similar to southwestern than northwestern Laurentian sources. Statistical comparisons confirm provenance similarities between rocks of the North Cascades and those 700–2000 km to the south and, thus, support margin-parallel translation from as far as the latitude of southern California.

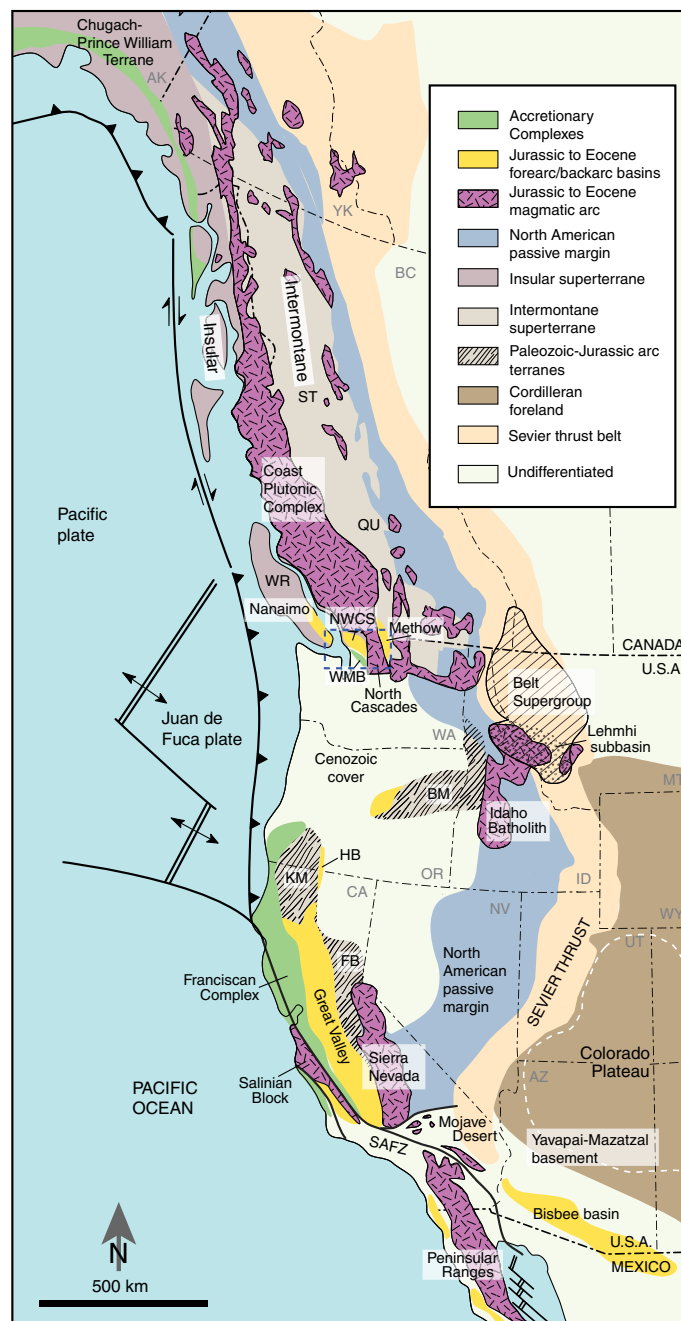
INTRODUCTION

Sedimentary basins associated with ancient arc systems arguably yield a more detailed history of arc evolution compared to arc volcanic components, which are typically not preserved, or the plutonic rocks, which are variably eroded and exposed (Gehrels, 2014). Jurassic to Eocene convergence along the western margin of the North American continent resulted in the accretion of multiple oceanic-arc terranes, intrusion of arc plutons, and formation of large

sedimentary basins (e.g., Saleeby and Busby-Spera, 1992; Dickinson, 2004). The U-Pb age spectra of detrital zircons from western North American Cordilleran sedimentary rocks have been used to help understand episodic high-flux magmatism (Paterson and Ducea, 2015), the timing at which sediment sources were uplifted and when basins subsided (e.g., DeGraaff-Surpless et al., 2003; Laskowski et al., 2013; Surpless et al., 2014), paleogeography, and terrane mobility (e.g., Gehrels et al., 1995; Housen and Beck, 1999; Barbeau et al., 2005). Hafnium-isotope analyses of detrital zircons are used as an additional fingerprint of sedimentary provenance (e.g., Gehrels and Pecha, 2014; Surpless et al., 2014; Holland et al., 2015) by comparing to zircon Hf-isotope compositions of potential source rocks (e.g., Goodge and Vervoort, 2006; Gaschnig et al., 2011; Lackey et al., 2012; Shaw et al., 2014).

Controversy surrounds the Late Cretaceous tectonic history of northwestern North America, with many studies suggesting significant terrane translation for parts of the Insular and Intermontane superterranes and the plutonic rocks of the Coast Plutonic Complex–North Cascades range that separate the two superterranes (e.g., Monger et al., 1982; Cowan et al., 1997) (Fig. 1). Early paleomagnetic studies of the Cretaceous plutonic and sedimentary rocks suggested that the Insular superterrane and Coast Plutonic Complex–North Cascades formed ~2500–3000 km to the south relative to the North American craton and were translated to the north between ca. 90–55 Ma (the “Baja-BC” hypothesis; Beck et al., 1981; Umhoefer, 1987; Ague and Brandon, 1996; Enkin et al., 2001). More recent paleomagnetic studies interpret moderate (~1600–2000 km) translation of these same rocks from reconstructions based on a combination of corrections to the paleomagnetic data and known fault offsets (Kim and Kodama, 2004; Krijgsman and Tauxe, 2006; Umhoefer and Blakey, 2006; Rusmore et al., 2013). Conversely, evidence from measured lateral offsets on faults as well as stratigraphic correlations between similar packages of rocks indicate significantly less (<1000 km) northward translation (Price and Carmichael, 1986; Monger, 1997; Wyld et al., 2006). In comparison, paleomagnetic signatures of rocks in the Intermontane superterrane, located to the east of the Coast Plutonic Complex–North Cascades arc, suggest they originated ~1100 km to the south of their current position relative to the North American craton (Irving et al., 1995; Symons et al., 2005).

Figure 1. Generalized geologic map of western North America highlighting the major tectonic elements of the Cordilleran arc system and the sedimentary units adjacent to the different arc belts (modified from Yankee and Weil, 2015). BM—Blue Mountains; FB—Foothills Belt; HB—Hornbrook Basin; KM—Klamath Mountains; QU—Quesnellia; NWCS—Northwest Cascades thrust system; SAFZ—San Andreas fault zone; ST—Stikine terrane; WMB—western mélangé belt; WR—Wrangellia.



The North Cascades range is located at the southern end of the “Baja-BC” block and the Jurassic to Eocene Coast Plutonic Complex–North Cascades continental magmatic arc, which stretches from Alaska to Washington (Fig. 1). The crystalline core of the North Cascades arc system is juxtaposed with coeval sedimentary units and Paleozoic and Mesozoic tectonostratigraphic terranes by major dextral strike-slip structures, the Ross Lake fault zone to the east and the Straight Creek fault to the west (Misch, 1966; Monger, 1986; Miller and Bowring, 1990; Umhoefer and Miller, 1996; Gordon et al., 2010). The sedimentary units and terranes, from west to east, are grouped into: (1) the western mélangé belt (WMB), representative of accretionary-wedge material that is outboard of the arc; (2) the northwest Cascades thrust system (NWCS) and its footwall sedimentary rocks, presently in a forearc position to the arc; and (3) the Methow terrane, which was formed as a forearc basin but was juxtaposed with the eastern, inboard boundary of the North Cascades core by the Late Cretaceous (Miller, 1994) (Fig. 2). These packages of rocks are fault-bounded, and all include sediment that was deposited before and during the interval when proposed terrane translation was occurring (ca. 90–55 Ma) (e.g., Misch, 1966; Brandon et al., 1988; Hurlow, 1993; Tabor, 1994; Umhoefer, 2003; Brown and Gehrels, 2007; Brown, 2012). Thus, the sedimentary rocks surrounding the North Cascades core likely contain valuable information about their provenance, which may provide insight into terrane-translation hypotheses.

This study uses U-Pb and Hf-isotope analyses of detrital zircons from accretionary-wedge and forearc-basin deposits inboard and outboard of the North Cascades crystalline core to interpret the Jurassic–Late Cretaceous tectonic history surrounding the arc (Fig. 2). The new zircon analyses presented here are used to evaluate potential source terranes for these sediments and are compared to previous detrital-zircon and Hf-isotope studies of the western Cordillera to evaluate terrane translation.

■ GEOLOGIC SETTING

The western margin of the North American continent experienced multiple episodes of accretion of oceanic-arc terranes, batholith emplacement, and sedimentation in large basins during Jurassic to Eocene convergence (e.g., Saleeby and Busby-Spera, 1992; Dickinson, 2008). Voluminous magmatism is represented by the Peninsular Ranges batholith (e.g., Silver and Chappell, 1988; Busby, 2004; Morton et al., 2014), Sierra Nevada batholith (e.g., Bateman, 1992; Coleman and Glazner, 1997; Cecil et al., 2012), Idaho batholith (e.g., Hyndman, 1983; Gaschnig et al., 2009), and plutons that form the Coast Plutonic Complex–North Cascades range (e.g., Barker and Arth, 1984; Gehrels et al., 2009; Miller et al., 2009) (Fig. 1). Coeval Jurassic–Eocene sedimentary units deposited during arc activity are preserved along the present-day North American margin. Accretionary complexes, such as the Franciscan Complex (Hamilton, 1969; Blake et al., 1988; Ernst, 2011), western mélangé belt (Jett and Heller, 1988; Tabor et al., 1993, 2003), and Chugach–Prince William terrane (Plafker et al., 1994; Kusky et al., 1997; Cowan, 2003) were assembled near the sub-

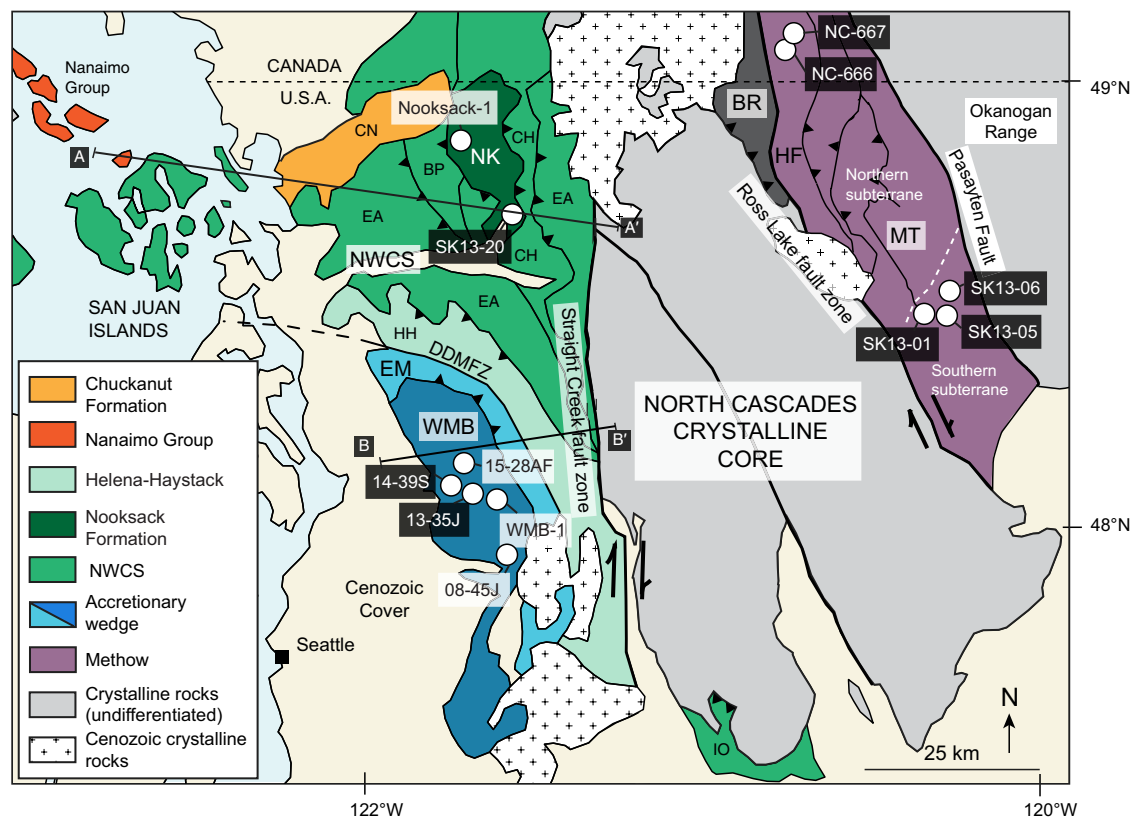


Figure 2. Simplified geologic map of northwestern Washington and southern British Columbia showing Jurassic to Paleocene sedimentary basins adjacent to the North Cascades continental magmatic arc and where samples were collected (black boxes for this study; white boxes from previous work [see text]). Lines A–A' and B–B' represent the location of cross sections shown in Figure 4. BR—Bridge River Hozameen; BP—Bell Pass mélangé; CH—Chilliwack Group; CN—Chuckanut Formation; DDMFZ—Darrington–Devil’s Mountain fault zone; EA—Easton Suite; EM—eastern mélangé belt; HF—Hozameen fault; HH—Helena Haystack mélangé; IO—Ingalls Ophiolite; WMB—western mélangé belt; MT—Methow terrane; NK—Nooksack Formation; NWCS—Northwest Cascades thrust system. Compiled from Brown and Gehrels (2007), Miller et al. (2009), and DeGraaff-Surplus et al. (2003).

duction trench of the active Mesozoic arcs (Fig. 1). Sediment also accumulated in forearc basins, including the Great Valley sequence (Dickinson, 1995), the Hornbrook Formation (Nilsen, 1984), the Methow terrane (Tennyson and Cole, 1978), and the Nanaimo Group (Mustard et al., 1995), and in backarc basins, such as the McCoy-Bisbee basin (Barth et al., 2004) and the Gravina belt (Crawford et al., 1987) (Fig. 1). Detrital zircons from these sediments reveal distinct “detrital-zircon facies,” which relate changes in detrital-zircon age characteristics to evolving tectonic setting (LaMaskin, 2012). For example, pre-Middle Jurassic rocks have Precambrian detrital zircons with a transcontinental (Appalachian orogeny) age signature, whereas younger (Jurassic to Cretaceous) rocks have dominantly Mesozoic detrital zircons that reflect the development of an Andean-type continental margin (LaMaskin, 2012).

Plutonic and metamorphic rocks of the Coast Plutonic Complex–North Cascades Range stretch ~1800 km from northern Washington to Alaska and are the result of subduction-related plutonism and the development of an Andean-type arc from ca. 160–48 Ma (Gehrels et al., 2009). Plutons of this arc intruded

the suture zone between the allochthonous Paleozoic and Mesozoic rocks that make up the Wrangellia and Alexander terranes of the Insular superterrane and the Quesnel, Cache Creek, and Stikinia terranes within the Intermontane superterrane (Fig. 1; e.g., Monger et al., 1982, 1994).

Sedimentary Units Adjacent to the North Cascades

The Methow terrane (Barksdale, 1975), the northwest Cascades thrust system (Misch, 1966; Brandon et al., 1988; Brown and Gehrels, 2007), the western mélangé belt (Frizzell et al., 1987; Tabor et al., 1993), and the Nanaimo Group mainly contain volcanic and plutonic sedimentary detritus (Jett and Heller, 1988; Mustard, 1994; DeGraaff-Surplus et al., 2003; Brown and Gehrels, 2007; Brown, 2012; Surplus et al., 2014). The NWCS and WMB were amalgamated with the Insular superterrane by the Late Cretaceous (Misch, 1966; Brown, 1987; Brandon et al., 1988), whereas the Methow terrane lies between the plutonic rocks of the Coast Plutonic Complex–North Cascades and Intermontane

superterrane (Monger et al., 1982). All of these units are separated from the exhumed crystalline core of the arc by major dextral strike-slip faults—the Straight Creek fault to the west and the Ross Lake fault zone to the east (Fig. 2; Misch, 1966; Miller and Bowring, 1990; Miller, 1994; Umhoefer and Miller, 1996; Baldwin et al., 1997; Gordon et al., 2010). Each unit is discussed in detail below and summarized in Table 1.

Methow Terrane

The Methow terrane contains a thick sequence of Jurassic to Cretaceous sedimentary and lesser volcanic rocks deposited on Triassic oceanic basalts. The terrane is located to the east of the crystalline core and is bounded by the Ross Lake and Hozameen fault zones to the west and the Pasayten fault to

TABLE 1. SEDIMENTARY UNITS ADJACENT TO THE NORTH CASCADES

Unit nomenclature	Description
Methow terrane	
<i>Northern subterrane</i>	
Spider Peak Formation*	Early Triassic ophiolitic greenstone and chert.
Ladner Group†	
Boston Bar Formation	Early to Middle Jurassic marine argillite, siltstone, lithic sandstone, minor conglomerate.
Dewdney Creek Formation	Middle to Late Jurassic marine coarse grained sandstone, conglomerate, siltstone, pyroclastic rocks, volcanic flows.
<i>Southern subterrane</i> [§]	
Newby Group	Middle Jurassic(?)–Early Cretaceous (base not exposed) marine sedimentary rocks including black argillite, volcanic sandstone, tuff, and breccia.
<i>Cretaceous overlap assemblage</i> [#]	
Jackass Mountain Group	Early Cretaceous proximal marine and deltaic medium- to coarse-grained arkosic and volcanoclastic sandstone.
Pasayten Group	Mid- to Late Cretaceous shallow marine and fluvial chert, lithic, and arkosic sandstones, conglomerates, and lesser andesitic volcanic flows.
Goat Wall Unit	Late Cretaceous non-marine volcanics and volcanoclastic sandstones
Footwall and nappes of the northwest Cascades thrust system	
<i>Footwall (autochthon)</i>	
Wrangellia**	Paleozoic and Triassic composite terrane consisting of oceanic flood basalts and marine sedimentary rocks.
Wells Creek volcanic member††	Early Jurassic dacite, volcanic breccia, and tuff with small amounts of interbedded argillite; oceanic-arc provenance.
Nooksack Formation††	Late Jurassic–Early Cretaceous marine island-arc deposits of volcanoclastic sandstone and argillite.
<i>Components of the NWCS</i> ^{§§}	
Yellow Aster Complex	Early to mid-Paleozoic allochthonous terrane composed of gneisses and plutonic rocks.
Bell Pass mélange	Late Jurassic to Early Cretaceous heterogeneous assemblage of rocks including metagabbro, metatonalite, silicic gneiss, amphibolite gneiss, quartzite, schist, and ultramafic rocks.
Easton metamorphic suite	Late Jurassic to Early Cretaceous greenschist, amphibolite, ultramafics, and phyllite (i.e., Darrington Phyllite)
Lummi Formation	Late Jurassic ocean floor and trench deposits consisting of volcanic- and chert-rich graywacke turbidites.
Constitution Formation	Late Jurassic trench deposits of volcanic-rich sandstone and siltstone with interlayered chert and oceanic basalt.
Fidalgo Complex	Late Jurassic arc-related ophiolitic rocks with volcanic-lithic graywacke deposited on top.
<i>Overlap between Wrangellia and NWCS</i> ^{##}	
Nanaimo Group	Cretaceous to Paleogene marine and non-marine foreland basin sandstone and conglomerate.
Accretionary wedge: western mélange belt	
Western mélange belt***	Cretaceous(?)–Paleogene accretionary wedge containing blocks of sandstone, Jurassic gabbro-tonalite, and lesser limestone and chert in an argillite matrix.
<p><i>Note:</i> Only describes units mentioned in the text. NWCS—Northwest Cascades thrust system. *Ray (1990). †Mahoney (1993). ‡Mahoney et al. (2002). §Tennyson and Cole (1978); DeGraaff-Surpless et al. (2003); Haugerud et al. (1996). **Monger and Journeay (1994). ††Misch (1966), Tabor et al. (2003). ‡‡Tabor et al. (2002); Brown and Gehrels (2007). ##Mustard et al. (1995). ***Tabor et al. (2002); Brown (2012).</p>	

the east (Fig. 2). The Methow terrane is interpreted to have been deposited in a forearc basin (Coates, 1974; Barksdale, 1975), but it reached its current inboard position with respect to the North Cascades by ca. 92 Ma, when it was intruded by the Black Peak pluton (Miller, 1994; Shea et al., 2016). The Triassic–Jurassic base of the Methow terrane is divided into northern and southern subterrane (Fig. 3; McGroder, 1988). Oceanic basalt of the Lower Triassic Spider Peak Formation is the basement in the northern subterrane (Ray, 1986, 1990). The Lower to Middle Jurassic Ladner Group is unconformable on the Spider Peak Formation and includes the Boston Bar Formation and overlying Dewdney Creek

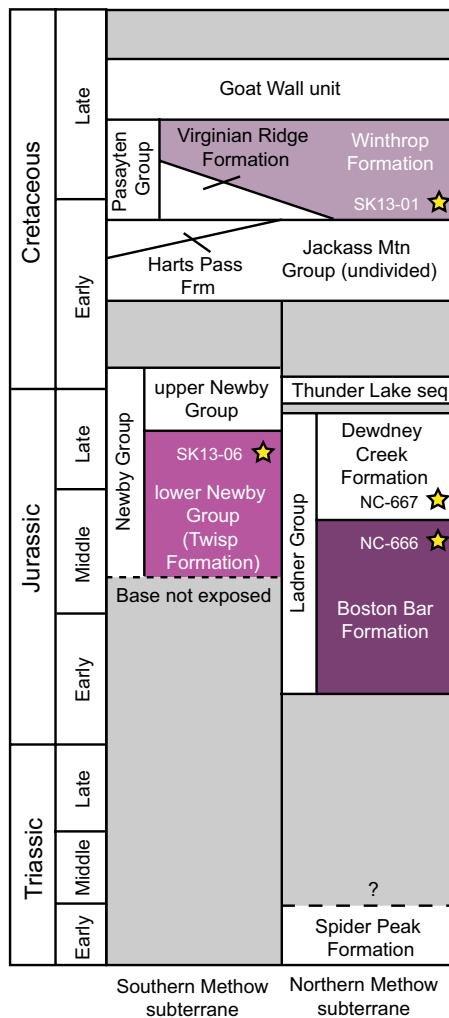
Formation (Coates, 1974; Mahoney, 1993). The lowest unit of the southern subterrane is the Jurassic Newby Group, which includes the lower Newby Group (Twisp Formation) and the upper Newby Group (Barksdale, 1975; McGroder et al., 1990). The base of the Newby Group is not exposed. The Newby and Ladner Groups consist of volcanic-lithic, marine sandstones and black shales, and lesser volcanic rocks (Coates, 1974; Barksdale, 1975; O'Brien, 1986; Tabor et al., 1989). The Thunder Lake sequence contains sandstone and shale that were disconformably deposited on the Ladner Group in the northern subterrane (Coates, 1974).

The Hauterivian to Albian Jackass Mountain Group overlaps both subterrane, and the correlative early to middle Albian Harts Pass Formation is present in the southern subterrane (Coates, 1974; McGroder et al., 1990). The Jackass Mountain Group is dominantly composed of marine and marine-marginal feldspathic sandstone (Barksdale, 1975; DeGraaff-Surpless et al., 2003). The Harts Pass Formation is composed of east-derived sandstone and siltstone (Tennyson and Cole, 1978). The Middle to Upper Cretaceous Pasayten Group lies above the Jackass Mountain Group and Harts Pass Formation and includes the westerly-derived, marginal-marine, Cenomanian(?) to Turonian Virginian Ridge Formation (black shale and chert-pebble conglomerate) that interfingers with the easterly-derived, non-marine Albian to Turonian Winthrop Formation (arkosic sandstone) (Tennyson and Cole, 1978; Kiessling and Mahoney, 1997; DeGraaff-Surpless et al., 2003). The Turonian to Coniacian Goat Wall unit is stratigraphically above the Pasayten Group and includes volcanoclastic sedimentary rocks and andesites (Haugerud et al., 1996; Enkin et al., 2002).

A number of studies have focused on the Cretaceous Winthrop and Harts Pass Formations, including paleocurrent, sandstone petrography, paleomagnetic, detrital zircon, and paleofloral investigations (Fig. 3; Coates, 1974; Garver, 1992; Garver and Brandon, 1994; Kiessling and Mahoney, 1997; DeGraaff-Surpless et al., 2003; Miller et al., 2006; Surpless et al., 2014). DeGraaff-Surpless et al. (2003) and Surpless et al. (2014) interpret that the Jackass Mountain and Pasayten Groups were derived from proximal sources located to the east of the basin based on detrital-zircon peaks of ca. 160–150 and 120–110 Ma with very minimal (<1%) input from inboard cratonic or recycled sedimentary sources. Possible sources of these zircons include the eastern belt of the Coast Plutonic Complex and/or the Okanogan Range, a ca. 120–110 Ma plutonic complex located to the east (Surpless et al., 2014).

In comparison to the Cretaceous strata, there have been no detrital-zircon analyses of the Jurassic Methow strata. Fossil evidence suggests Lower to Middle Jurassic ages for the Ladner Group (Coates, 1974; Mahoney, 1993). Moreover, a plutonic clast from the Dewdney Creek Formation yields a U-Pb multi-grain isotope dilution-thermal ionization mass spectrometry (ID-TIMS) zircon age of ca. 235 Ma; the clast is interpreted to be derived from the Quesnel terrane to the east of the Methow terrane (O'Brien et al., 1992). From the southern Methow subterrane, the Twisp Formation is intruded by the ca. 142 Ma Alder Creek stock, indicating that the Formation is older than earliest Cretaceous (U-Pb isotope dilution-thermal ionization mass spectrometry zircon; Mahoney et al., 2002).

Figure 3. Schematic diagram of the stratigraphy exposed in the northern and southern Methow subterrane. Gray fill indicates an unconformity, and yellow stars designate the approximate location of analyzed samples. Modified after Haugerud et al. (1996) and Surpless et al. (2014).



Northwest Cascades Thrust System

The NWCS is a fault-bounded nappe stack located to the northeast of the Darrington–Devil’s Mountain fault zone and to the west of the Straight Creek fault (Fig. 2). The nappes of the NWCS consist of Paleozoic to Mesozoic oceanic and island-arc assemblages, with a large component of Jurassic–Early Cretaceous immature, oceanic clastic strata that have experienced multiple episodes of accretion and subduction-zone metamorphism (Brandon et al., 1988; Brown and Gehrels, 2007).

Sedimentary components of the nappes, including the Lummi Formation, Constitution Formation, Easton Metamorphic Suite, and the Fidalgo Complex dominantly have unimodal detrital-zircon populations between ca. 160–140 Ma that are interpreted to be arc-derived and close to their depositional ages (ca. 150–135 Ma; Brown and Gehrels, 2007). The Bell Pass mélangé consists of an oceanic chert, basalt, argillite, and graywacke matrix with blocks of the same lithologies as well as large tectonic blocks of the Twin Sisters Dunite, Baker Lake Blueschist, and Yellow Aster Complex (Brown, 1987; Tabor et al., 2003). The latter complex is also found as tectonic lenses within the Bell Pass mélangé and includes Paleozoic and Neoproterozoic feldspathic and calc-silicate gneisses with lesser ultramafite (Misch, 1966). A sandstone of the Bell Pass mélangé contains both arc-related Mesozoic detrital zircons and Precambrian zircons that may have been derived from the Yellow Aster Complex or North American passive margin rocks (Brown and Gehrels, 2007). In comparison, Yellow Aster Complex paragneisses are characterized by Paleozoic and Precambrian detrital zircons and were likely derived from the passive margin or outboard terranes of the North American Cordillera (Brown and Gehrels, 2007) or northeastern Laurentian sources (Schermer et al., 2015).

The Nooksack Formation is exposed in the footwall of the nappe stack (Fig. 4) and is a thick sequence of slaty to phyllitic, marine sandstones and argillites (Misch, 1966; Tabor et al., 2003). The ca. 180–175 Ma (J.M. Mattinson reported in Franklin, 1985) Wells Creek Volcanic Member is found at the base of the unit (Misch, 1966; Tabor et al., 2003). The Nooksack Formation is

thought to be autochthonous, and the clastic rocks are potentially fan deposits of a volcanic arc associated with Wrangellia (Sondergaard, 1979; Brown and Gehrels, 2007). The Nooksack Formation was deposited by ca. 114 Ma based on the youngest population of detrital zircons in a sandstone near the top of the section (Brown and Gehrels, 2007). Fossil ages are mostly between ca. 155–130 Ma (Tabor et al., 2003).

The emplacement of the NWCS nappes on the Nooksack Formation occurred after deposition of the sandstone within the Bell Pass mélangé and, thus, has been loosely bracketed to ca. 114–59 Ma (Tabor, 1994; Brown and Gehrels, 2007). However, the majority of thrusting is generally interpreted to have occurred by the beginning of the Late Cretaceous (Misch, 1966; Brandon et al., 1988; McGroder, 1991).

Nanaimo Group

The Nanaimo Group is an Upper Cretaceous overlap sequence consisting of dominantly marine and non-marine clastic sediments that were deposited unconformably on Wrangellia to the west and the Coast Plutonic Complex to the east, and the sequence is in fault contact with the NWCS (Mustard, 1994) (Figs. 1 and 2). Portions of the NWCS and Nanaimo Group share a similar provenance based on the presence of similar quartz arenite clasts in both units (Garver, 1988) and cobbles probably derived from the Yellow Aster Complex in the Nanaimo Group (Brown, 2012). The Nanaimo Group sediments deposited before the early Campanian (ca. 80–72 Ma) are characterized by a Mesozoic detrital-zircon signature, whereas younger Nanaimo units have a mix of Jurassic to Cretaceous arc-related ages as well as Proterozoic dates (Mustard et al., 2006; Mahoney et al., 2014; Matthews et al., 2017). The appearance of Proterozoic zircons in the latest Cretaceous strata has been linked to uplift and erosion of potential sources in the Belt Supergroup region to the east (Mustard et al., 2006; Mahoney et al., 2014) or in the Mojave terrane in southwestern Laurentia (Matthews et al., 2017).

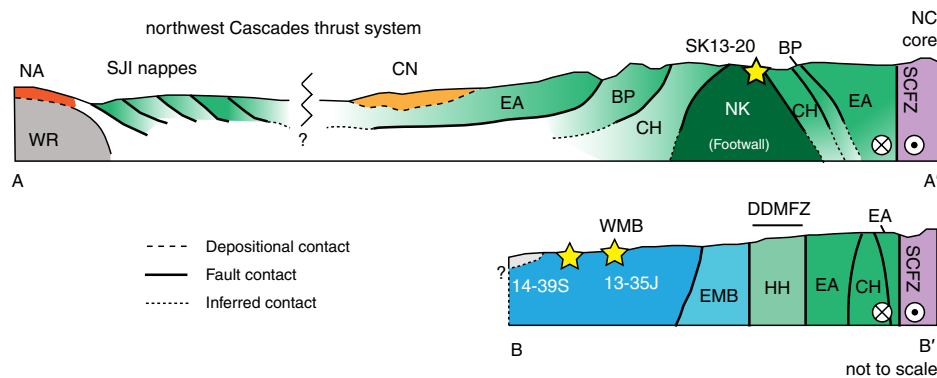


Figure 4. Schematic cross section of the Northwest Cascades (NC) thrust system (simplified from Brandon et al. [1988] and Brown and Gehrels [2007]) and western mélangé belt (simplified from Tabor et al. [2003]) showing the units that are contained within individual nappes. Approximate sample locations are designated by the yellow stars. BP—Bell Pass mélangé; CH—Chilliwack Group; CN—Chuckanut Formation; DDMFZ—Darrington–Devil’s Mountain fault zone; EA—Easton Metamorphic Suite; EMB—eastern mélangé belt; HH—Helena Haystack mélangé; NA—Nanaimo Group; NK—Nooksack Formation; SCFZ—Straight Creek fault zone; SJI—San Juan Islands; WMB—western mélangé belt; WR—Wrangellia.

Western Mélange Belt

The WMB is an accretionary complex separated from the NWCS by the Darrington-Devil's Mountain fault zone (Fig. 2). The accretionary wedge was assembled by ca. 59 Ma, when the nonmarine Chuckanut Formation was deposited on top of the WMB (Eddy et al., 2015). The WMB is dominantly composed of a weakly metamorphosed argillite and graywacke matrix that hosts blocks of marble, metagabbro, sandstone, metadiabase, and chert (Tabor et al., 1989, 1993). The sandstones of the WMB are divided into three petrofacies: arkosic, lithic, and chert-rich (Jett and Heller, 1988). Based on lithologic similarities, the WMB has been compared to the Franciscan Complex (Jett and Heller, 1988) and the Methow terrane (Garver, 1988). Detrital zircons have been analyzed from three arkosic sandstones and two lithic sandstones of the WMB; our U-Pb results from two WMB samples were previously reported in Dragovich et al. (2014) and Dragovich et al. (2015). Maximum depositional ages (MDA) are recalculated here for the detrital-zircon data reported in Dragovich et al. (2014), Dragovich et al. (2015), and Dragovich et al. (2016) using the youngest three analyses that overlap at 2-sigma uncertainty to be consistent with this and other studies. The arkoses have dates from and MDAs of: (1) ca. 230 to 87 Ma and ca. 89 Ma (08-45J; Dragovich et al., 2009); (2) ca. 2.3 Ga to 84 Ma and ca. 87 Ma (WMB-1; Brown, 2012); and (3) ca. 2.1 Ga to 69 Ma and ca. 72 Ma (13-35J; our data reported in Dragovich et al., 2014), respectively. One lithic sample has a unimodal age population centered at ca. 167 Ma and an MDA of ca. 152 Ma (15-28AF; Dragovich et al., 2016). The second lithic sandstone yields dates between ca. 2.1 Ga and 107 Ma with an MDA of ca. 109 Ma (14-39S; our data reported in Dragovich et al., 2015). The Jurassic to Cretaceous detrital zircons from all samples are interpreted to be derived from arc-related sources, whereas Precambrian zircons in the arkoses with Late Cretaceous MDAs indicate a combination of arc and inboard sources (Dragovich et al., 2009; Dragovich et al., 2016; Brown, 2012).

Paleogeographic Reconstructions

Previous investigations of the Methow terrane, NWCS, and accretionary wedge units that border the North Cascades range have resulted in differing ideas of where these rocks originated. Paleomagnetic and faunal data from the Methow terrane and Nanaimo Group suggest that these sediments may have undergone large-scale translation (~2500–3000 km), i.e., the “Baja-BC hypothesis,” between ca. 90–50 Ma (Beck, 1976; Irving et al., 1985; Umhoefer, 1987; Ward et al., 1997; Miller et al., 2006). Paleomagnetic (Enkin et al., 2002), paleofloral (Miller et al., 2006), and zircon fission-track (Garver and Brandon, 1994) results suggest that the Methow terrane formed at least 2000 km to the south, potentially as a forearc basin to the Peninsular Ranges batholith of southern California and Mexico, and reached its current latitude between 48°N and 52°N by ca. 55 Ma (Garver and Brandon, 1994; Enkin et al., 2002). More recent paleomagnetic data from the Nanaimo basin that have been corrected for depositional flattening of magnetic inclinations suggest the strata origi-

nated significant distances (~1600–2000 km) to the south and were adjacent to the southern Sierra Nevada in the Late Cretaceous (Kim and Kodama, 2004; Krijgsman and Tauxe, 2006). Furthermore, the presence of Archean detrital zircons (older than ca. 2.5 Ga) in the Nanaimo Group has been used to argue for (Housen and Beck, 1999) and against (Mahoney et al., 1999) translation.

In contrast, others emphasize that the known displacements on large strike-slip faults in the region are much too small for the necessary translation indicated by the paleomagnetic data (e.g., Monger and Price, 1996). Reconstructions that rely on known fault offsets can account for ~700 km of displacement for rocks of the Insular superterrane in northwestern Washington (e.g., Wyld et al., 2006). The reconstructions of Wyld et al. (2006) place the WMB and Nanaimo Basin at the latitude of the Klamath Mountains and northern Sierra Nevada and the Methow terrane to the north of the Hornbrook-Ochoco basins at ca. 100 Ma. This more moderate ~700 km displacement is consistent with lithologic and detrital-zircon data that suggest various components of the NWCS nappes formed at the latitude of the Klamath Mountains (Brown, 1987; Brandon et al., 1988; Brown and Gehrels, 2007; MacDonald et al., 2008). These hypotheses of paleogeography and magnitude of terrane translation can be further evaluated, and potentially refined, with U-Pb and Hf-isotope investigations of detrital zircon from samples from the Methow terrane, NWCS, and WMB. These data are the first Hf-isotope characterization of the WMB, NWCS, and the Jurassic strata of the Methow terrane. Comparison of the Cascades U-Pb and Hf data are used to assess possible sedimentary sources, and the relationship of these sedimentary units to each other, and to basins located at different latitudes in the present-day North American Cordillera.

METHODS

Samples were collected for detrital-zircon U-Pb and Hf-isotope analyses from: (1) arkosic sandstones from the Winthrop Formation (SK13-01), Twisp Formation (SK13-06), and the Virginian Ridge Formation (SK13-05) and volcanoclastic sandstones from the Boston Bar Formation (NC-666), and Dewdney Creek Formation (NC-667) of the Ladner Group, all of which are from the Methow terrane; (2) a fine-grained, arkosic sandstone (SK13-20) from the Nooksack Formation of the NWCS; and (3) an arkosic sandstone (13-35J) and a fine-grained lithic sandstone (14-39S) from the WMB (Fig. 2 and Table 2).

Zircon separation was performed at the University of Nevada, Reno, using standard crushing, magnetic, and heavy liquid (methylene iodide) density-separation procedures. Grains were mounted in 1-inch epoxy rounds, which were polished to expose the approximate center of the zircon crystals. Cathodoluminescence (CL) images of zircons were acquired using either a FEI Quanta 400f scanning electron microscope (SEM) at the University of California–Santa Barbara or a JEOL JSM-7100FT SEM at the University of Nevada, Reno. These images were used to guide the U-Pb and Hf-isotope analyses, ensuring that spots were placed within discrete growth zones whenever possible (Fig. 5H).

Both U-Pb and Hf isotopes were measured by laser-ablation, multi-collector, inductively coupled plasma mass spectrometry (LA-MC-ICPMS).

TABLE 2. SAMPLE LOCATIONS AND DESCRIPTIONS

Sample number	Unit	Rock type	Location		No. of zircons	Major U-Pb zircon date peaks (Ma)	Maximum depositional age (Ma)
			UTM E	UTM N			
Backarc (Methow terrane)							
SK13-01	Pasayten Group (Winthrop Formation)	Arkosic sandstone	701854	5361821	162	115, 160	105 ± 2
SK13-06	Newby Group (Twisp Formation)	Arkosic sandstone	709572	5370305	27	155	152 ± 3
NC-666	Ladner Group (Boston Bar Formation)	Volcaniclastic sandstone	641480	5454576	100	170	165 ± 4
Forearc (northwest Cascades thrust system)							
SK13-20	Nooksack Formation	Fine-grained sandstone	595062	5389431	114	155	145 ± 3
Accretionary wedge (western mélangé belt)							
13-35J	Arkosic petrofacies	Arkosic sandstone	59159	5304985	129	74, 90, 165, 190, 1400, 1700	72 ± 2
14-39S	Lithic petrofacies	Lithic sandstone	582117	5308085	145	110, 160, 180	109 ± 3

The zircon U-Th-Pb isotopes were measured first at the University of California–Santa Barbara using a Nu Instruments Plasma HR MC-ICP-MS coupled with a 193 nm Photon Machines excimer laser. A spot size of ~15–24 μm was used with a laser fluence of 3–4 J/cm², producing an ablation pit depth of ~6–10 μm (60–100 shots/analysis). Samples were bracketed every 6–8 analyses with the standards 91500 (1062.4 ± 0.4 Ma, primary standard; Wiedenbeck et al., 1995) and GJ1 (608.5 ± 0.4 Ma, secondary standard; Jackson et al., 2004). The average measured value for secondary standard GJ1 was 599 ± 11 (n = 105). Data were reduced using Lolite v. 2.3 (Paton et al., 2010). Errors were calculated using the reproducibility of the standards during each run but were a minimum of 2% based on the long-term reproducibility of in-house standards. For dates greater than 1.0 Ga, the ²⁰⁷Pb/²⁰⁶Pb age is reported, whereas the ²⁰⁶Pb/²³⁸U age is used for younger grains (cf. Gehrels et al., 2008). Data were filtered using a 90% concordance filter for grains >ca. 400 Ma to eliminate dates that were highly affected by lead loss (cf. Gehrels, 2012). Maximum depositional ages were estimated based on the youngest detrital-zircon age population that included at least five concordant, overlapping analyses (Dickinson and Gehrels, 2009). The U-Pb results are shown in kernel density estimate plots (Figs. 5A–5H; Vermeesch, 2012) and in Supplemental Table S1¹.

Based on the U-Pb dates, representative zircons from significant age populations were subsequently analyzed for Hf isotopes at the Radiogenic Isotope and Geochronology Laboratory (RIGL) at Washington State University. Hafnium-isotope ratios were measured using a New Wave UP 213 Nd-YAG (213 nm) laser ablation system paired with a ThermoFinnigan Neptune MC-ICPMS. A 40-μm spot was used for the Hf analyses and was placed directly on the smaller U-Pb ablation pit. The laser fluence was ~7 J/cm² with a repetition rate of 10 Hz, ablating a 30–40 μm deep pit. The mass spectrometer gas-flow

rates and Faraday-cup configurations for the mass spectrometer followed the parameters described in Fisher et al. (2014b). Plesovice (¹⁷⁶Hf/¹⁷⁷Hf = 0.282482 ± 12, Sláma et al., 2008) was used as the primary standard, and FC-1 (¹⁷⁶Hf/¹⁷⁷Hf = 0.282183 ± 12, Fisher et al., 2014a) and GJ-1 (¹⁷⁶Hf/¹⁷⁷Hf = 0.282000 ± 23, Morel et al., 2008) were used as the secondary standards. Measured ¹⁷⁶Hf/¹⁷⁷Hf values for the secondary standards were 0.282180 ± 65 (n = 29) and 0.282010 ± 35 (n = 32), respectively. Hafnium-isotope ratios were normalized relative to ¹⁷⁶Hf/¹⁷⁷Hf = 0.282482 for Plesovice (Sláma et al., 2008). Data reduction and interference corrections followed the methods outlined in Fisher et al. (2011) and Fisher et al. (2014b). For the calculation of ε_{Hf} values and initial ¹⁷⁶Hf/¹⁷⁷Hf ratios, we used the chondritic uniform reservoir (CHUR) Lu-Hf values of Bouvier et al. (2008) and the ¹⁷⁶Lu decay constant determination of Söderlund et al. (2004). The results are shown in Figure 6 and Supplemental Table S2 (see footnote 1).

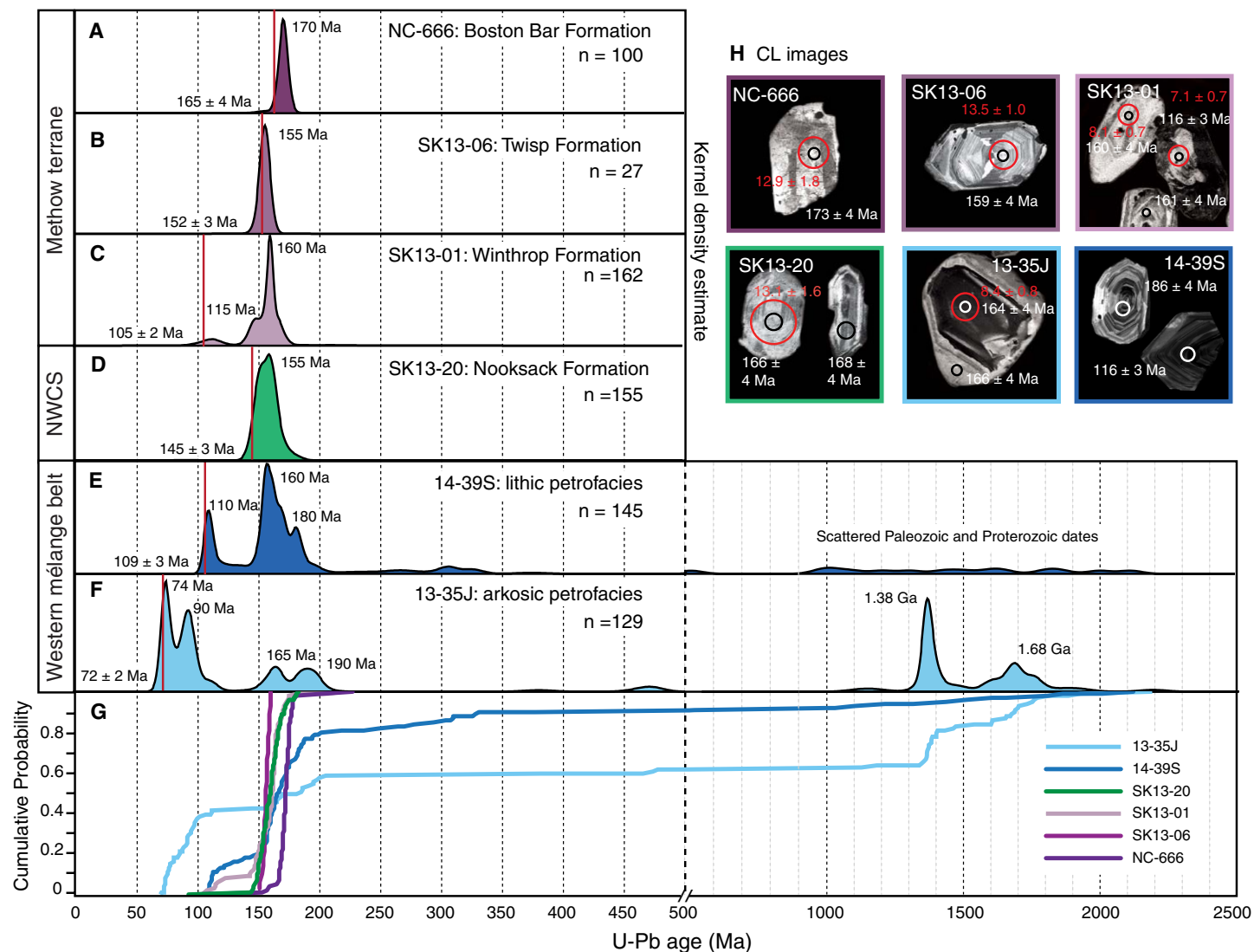
U-Pb AND Hf-ISOTOPE RESULTS

Methow Terrane

Detrital zircons from Jurassic to Lower Cretaceous rocks near the base of the northern and southern subterrane of the Methow terrane have not been previously characterized. Two volcaniclastic sandstones were collected from the basal clastic units of the northern subterrane (Ladner Group): one from the Dewdney Creek Formation and the other from the Boston Bar Formation (Fig. 3). The Dewdney Creek sample (NC-667) did not yield any zircon. Zircons from the Boston Bar Formation sandstone (NC-666) are dominantly prismatic to subrounded with oscillatory zoning (Fig. 5H). One zircon yields a ca. 97 Ma date, whereas the rest range between ca. 226–152 Ma (n = 99), with a maxi-

¹Supplemental Tables. Table S1: Detrital-zircon U-Pb data and Table S2: Detrital-zircon Lu-Hf data. Please visit <http://doi.org/10.1130/GES01501.S1> or the full-text article on www.gsapubs.org to view the Supplemental Tables.

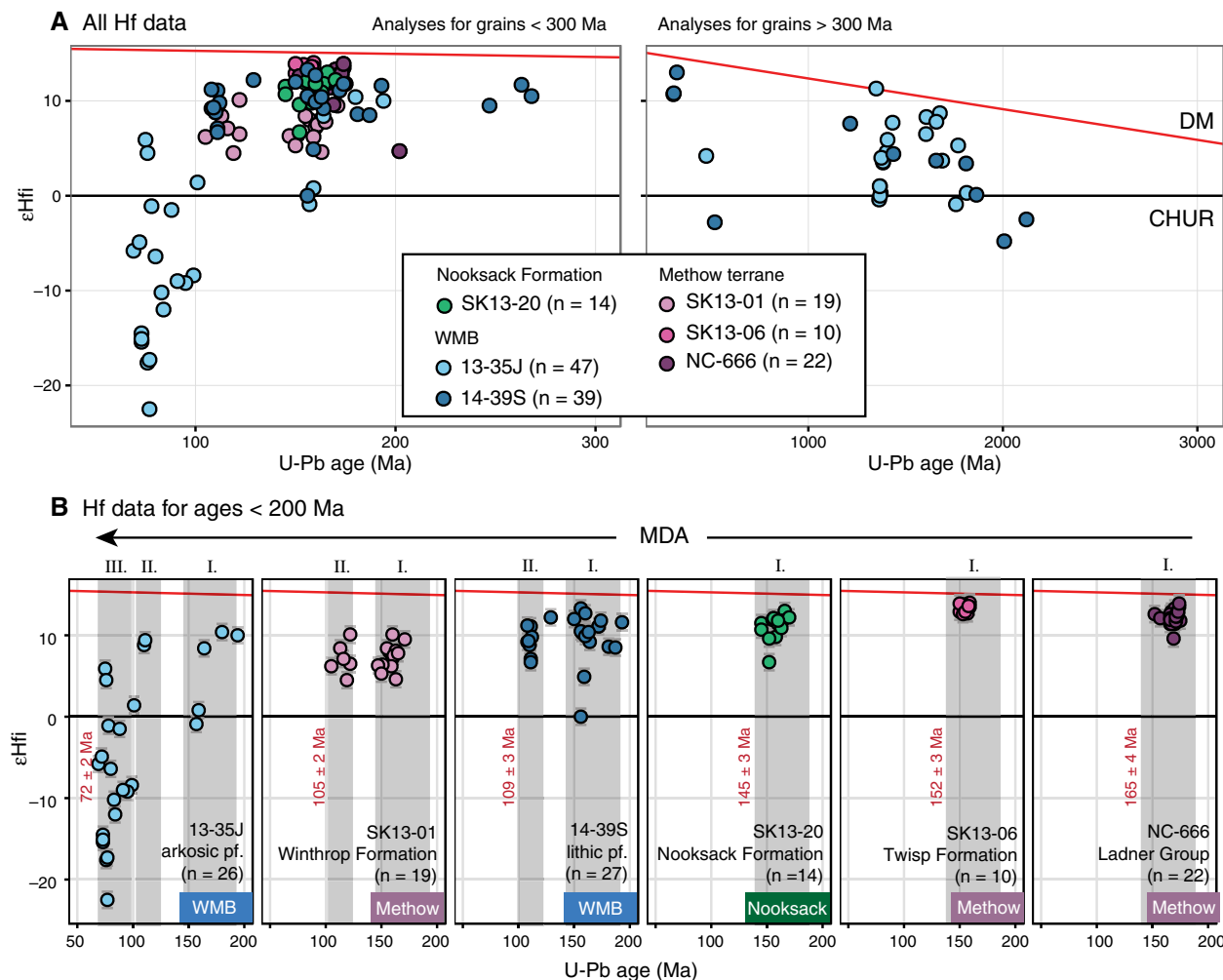
Figure 5. Kernel density estimate plots for this study's detrital-zircon data (note the change in scale for the x-axis at 500 Ma), with the ages of the peaks and maximum depositional age and associated 2-sigma error labeled for samples: (A) Boston Bar Formation NC-666; (B) Twisp Formation SK13-06; (C) Winthrop Formation SK13-01; (D) Nooksack Formation SK13-20; (E) lithic petrofacies of the WMB 14-39S; (F) arkosic petrofacies of the WMB 13-35J. The red line indicates the maximum depositional age. (G) Cumulative-probability plot for all samples. (H) Representative cathodoluminescence images from each sample showing zircon texture, the laser ablation-inductively coupled plasma mass spectrometry (LA-ICPMS) age, and the LA-ICPMS Hf-isotope composition. The Hf spot (red) is 40 μm across and the U-Pb spot is 15 μm across. NWCS—Northwest Cascades thrust system.



maximum depositional age (MDA) of 165 ± 4 Ma. The majority of the grains form a peak at ca. 170 Ma (n = 93) (Fig. 5A). Hafnium-isotope results from this ca. 170 Ma population have a small range of compositions, from those characteristic of the depleted mantle with ϵ_{Hf} of +13.9 to slightly less radiogenic ϵ_{Hf} of values of +9.6 (n = 22) (Fig. 6). One ca. 202 Ma grain has a lower ϵ_{Hf} of +4.6; the ca. 97 Ma zircon was too small to analyze (<40 μm).

The Twisp Formation represents the oldest clastic unit in the Newby Group of the southern Methow subterrane (Fig. 3). An arkosic sandstone (SK13-06) from this formation was relatively zircon poor, and only 27 zircons were analyzed. The zircons are euhedral and have variable internal textures, from no zoning to sector zoning and oscillatory zoning (Fig. 5H). The zircons have a narrow range of dates from ca. 159–150 Ma, defining a ca. 155 Ma peak and

Figure 6. Hafnium results for (A) all zircons from this study (note change in scale for the x-axis at 300 Ma) and (B) zircons with ages <200 Ma from this study (n = number of analyses for zircons <200 Ma), with colors for each sample corresponding to Figure 5 and in order of older inferred maximum depositional age (MDA) (red text) from left to right. In both figures, depleted mantle (DM) and chondritic uniform reservoir (CHUR) values are shown for reference (Vervoort and Blichert-Toft, 1999). In (A), typical 2-sigma errors are smaller than each analysis point and are typically ± 1.0 epsilon unit, and in (B), the gray bars indicate the 2-sigma errors. In (B), the gray boxes correspond to key age populations described in the text (I. Jurassic [190–180 Ma and 170–150 Ma], II. Mid-Cretaceous [120–100 Ma], and III. Late Cretaceous [100–70 Ma]) and for the western mélangé belt [WMB] samples. pf.—petrofacies.



a 152 ± 3 Ma MDA (Fig. 5B). Initial ϵ_{Hf} values form a tight cluster around near-depleted mantle values, from +14.0 to +12.6 (n = 10) (Fig. 6).

An arkosic sandstone was collected from the Upper Winthrop Formation within the mid to Upper Cretaceous Pasayten Group located stratigraphically above the Twisp Formation to complement the extensive detrital-zircon data set of DeGraaff-Surpless et al. (2003) and Surpless et al. (2014) (Fig. 3). This sandstone (SK13-01) has subhedral zircons with variable internal textures, ranging from oscillatory-zoned grains to unzoned grains (Fig. 5H). The zircons record dates from ca. 217–103 Ma (n = 162), with an MDA of 105 ± 2 Ma. Zircon

dates show a small peak at ca. 115 Ma (n = 8) and a much larger peak at ca. 160 Ma (n = 101) (Fig. 5C). Zircons from both age peaks have a similar distribution of ϵ_{Hf} values from +10.1 to +4.5 (n = 19) (Fig. 6).

Nooksack Formation

A fine-grained arkosic sandstone from the Nooksack Formation (SK13-20) (Fig. 4) was collected stratigraphically below the sample from Brown and Gehrels (2007) following their structural interpretation. The zircons from the

sandstone are euhedral and dominantly display oscillatory zoning (Fig. 5). Dates range from ca. 182–143 Ma ($n = 114$), with one outlier at ca. 92 Ma. The majority of the dates cluster at ca. 155 Ma ($n = 84$) and yield a MDA of 145 ± 3 Ma (Fig. 5D). Initial ϵ_{Hf} values of zircons from the ca. 155 Ma age population cluster between +13.0 and +6.7 ($n = 14$) (Fig. 6).

Western Mélange Belt

Two samples of the western mélange belt were collected from two of the three petrofacies of Jett and Heller (1988) to characterize the clastic components of the accretionary wedge: a lithic sandstone of the lithic petrofacies (14-39S) and an arkosic sandstone of the arkosic petrofacies (13-35J). Our U-Pb results from these samples were previously reported in Dragovich et al. (2014) and Dragovich et al. (2015), respectively, and are summarized here with the CL images and new Hf-isotope results. Sample 14-39S is a lithic sandstone composed of subangular to subrounded quartz, plagioclase, and volcanic-lithic fragments (Dragovich et al., 2015). Zircons from the lithic sandstone (14-39S) are dominantly rounded and have a mix of unzoned-, sector-, and oscillatory-internal textures (Fig. 5). The zircons range in age from ca. 2.12 Ga to 108 Ma ($n = 145$), with age peaks at ca. 110 Ma ($n = 20$), ca. 160 Ma ($n = 63$), and ca. 180 Ma ($n = 15$). The rest of the dates are scattered between ca. 2.12 Ga–217 Ma with minor peaks centered at ca. 305 Ma ($n = 4$) and 325 Ma ($n = 3$) (Fig. 5E), with a resulting MDA of 109 ± 3 Ma MDA. The ca. 110 Ma peak has ϵ_{Hf} values between +11.2 and +6.7 ($n = 8$), whereas the dominant ca. 160 Ma peak has slightly higher ϵ_{Hf} values from +13.7 to +9.2, with outliers at +0.0 and +4.5 ($n = 10$). The ca. 180 Ma peak has ϵ_{Hf} values from +11.8 to +8.5 ($n = 6$), and late Paleozoic zircons (ca. 325–250 Ma) have ϵ_{Hf} between +9.5 and +13.0 ($n = 6$) (Fig. 6A). The zircons with dates at ca. 2.1 and 0.5 Ga are less radiogenic (ϵ_{Hf} of -2.5 to -4.8 , $n = 3$), whereas zircons with dates between 1.8 and 1.1 Ga have more radiogenic ϵ_{Hf} values that range from +7.6 to +0.1 ($n = 5$) (Fig. 6B).

In comparison, the arkosic sandstone contains abundant detrital potassium feldspar and lesser muscovite and biotite (Dragovich et al., 2014). Zircons from the sandstone are slightly rounded, range from stubby to elongate, and are oscillatory zoned to unzoned (Fig. 5). The zircons have dates that range from ca. 2190–67 Ma ($n = 129$; MDA of 72 ± 2 Ma), with prominent Late Cretaceous peaks at ca. 74 ($n = 18$) and 90 Ma ($n = 17$), Proterozoic peaks at ca. 1.37 ($n = 23$) and 1.68 Ga ($n = 13$), and minor peaks at ca. 165 ($n = 6$) and 190 Ma ($n = 8$) (Fig. 5F). The initial ϵ_{Hf} values of Late Cretaceous zircons range from +5.9 to -22.5 ($n = 19$) and are dominantly negative ($n = 16$). The ϵ_{Hf} for Jurassic to Early Cretaceous zircons are clustered between +10.4 and +8.4 ($n = 3$) and +0.9 and -0.8 ($n = 2$). For the Proterozoic peaks, zircons typically plot above or near CHUR with +11.3 to -0.4 ($n = 12$) values for the 1.37 Ga peak and +8.4 to -0.7 ($n = 8$) for the 1.68 Ga peak, with a trend toward more positive values for younger grains (Fig. 6B).

DISCUSSION

Detrital-Zircon Provenance

The U-Pb age data from the Methow, Nooksack Formation, and WMB samples form peaks centered in four main periods: pre-Triassic (>250 Ma), Jurassic (ca. 190–180 and ca. 170–150 Ma), mid-Cretaceous (ca. 120–100 Ma), and Late Cretaceous (ca. 100–70 Ma). The sources for these ages have been documented throughout the North American Cordillera, and their characteristic ages and Hf-isotope signatures are summarized in Table 3. The provenance for the major age peaks in each sample is discussed below.

Jurassic Units

All Jurassic (ca. 165–145 Ma) samples from the Methow terrane (NC-666, MDA = ca. 165 Ma; SK13-06, MDA = ca. 152 Ma) and Nooksack Formation (SK13-20, MDA = ca. 145 Ma) of this study are characterized by unimodal detrital-zircon age peaks (ca. 170–150 Ma). Hafnium isotopes from these zircons yield near-depleted mantle compositions (ϵ_{Hf} of +14 to +9) (Fig. 6). The lithologies of these rocks also indicate marine environments with dominantly volcanic sediment sources. These combined characteristics suggest that the zircons were likely associated with an accreted Jurassic oceanic arc. Potential sources are common throughout the Cordillera as Late Jurassic arc assemblages and ophiolites were accreted along the entire North American continental margin; however, no Hf-isotope data are available from these sources for comparison (Table 3).

Mid-Cretaceous Units

Jurassic zircons in mid-Cretaceous units from the Methow (SK13-01, MDA = ca. 105 Ma) and WMB (14-39S, MDA = ca. 109 Ma) of this study have distinctly less radiogenic Hf-isotope compositions (ϵ_{Hf} = +10.1 to +4.6 and ϵ_{Hf} = +13.3 to +0.0, respectively) than the Jurassic zircons from the basal Methow and Nooksack strata described above (Fig. 6). These strata also contain Early Cretaceous (ca. 120–100 Ma) zircons that plot between depleted-mantle and CHUR values (Fig. 6). The less radiogenic Hf-isotope signature for ca. 120–100 Ma and 160–140 Ma zircons likely resulted from interaction of juvenile melts with more evolved crustal materials, as observed in continental arc systems such as the Peninsular Ranges batholith, Sierra Nevada batholith, and Coast Plutonic Complex (e.g., Cecil et al., 2011; Lackey et al., 2012; Shaw et al., 2014) (Fig. 7A and Table 3). Thus, the sediment provenance for the Methow terrane must have switched from primarily an oceanic arc to a continental arc that incorporated crustal material source during the Jurassic to the Cretaceous, respectively. The Jurassic and Cretaceous zircons from the WMB cover a larger range of ϵ_{Hf} values and include ca. 190–180 Ma and scattered Paleozoic and Proterozoic

TABLE 3. SUMMARY OF DETRITAL-ZIRCON SOURCES FOR MAIN AGE POPULATIONS

Age population	Potential sources	Age range (Ma)	Hf-isotope composition (ϵ_{Hf}) [*]	References
Late Cretaceous–Paleocene (100–70 Ma)				
	Coast Plutonic Complex	100–50	+12 to +5	Gehrels et al. (2009); Cecil et al. (2011)
	Idaho batholith	100–85	–9 to –23	Gaschnig et al. (2009, 2011)
		80–67		
	North Cascades	96–88	—	Miller et al. (2009)
		78–71		
	Sierra Nevada batholith	100–85	—	Irwin and Wooden (2001)
	Transverse Ranges	85–65	–2 to –25	Barth et al. (2016)
	Mojave terrane (Laramide plutons)	85–65	–15 (avg.)	Needy et al. (2009); Fisher et al. (2017)
	Peninsular Ranges batholith	100–75	+12 to –3	Morton et al. (2014); Shaw et al. (2014)
Early Cretaceous (120–100 Ma)				
	Coast Plutonic Complex	118–100	+8 to +5	Gehrels et al. (2009); Cecil et al. (2011)
	Okanogan Complex	120–110	—	Hurlow and Nelson (1993)
	Sierra Nevada batholith	124–105	+12 to –5	Lackey et al. (2012)
	Peninsular Ranges batholith	126–100	+12 to +1	Shaw et al. (2014)
Jurassic (190–180 Ma and 170–150 Ma)				
	Coast Plutonic Complex	177–162	+12 to +3	Gehrels et al. (2009); Cecil et al. (2011)
		157–142		
	Ingalls (Washington), Fidalgo (Washington), and Josephine (Oregon and California) ophiolite	170–160	—	Harper (1984); Harper et al. (2003); Whetten et al. (1980)
	Blue Mountains	170–150	—	LaMaskin et al. (2015)
	Klamath Mountains	180–140	—	Harper and Wright (1984)
	Sierra Nevada batholith	180–150	—	Chapman et al. (2012)
	Transverse Ranges	180–140	—	Needy et al. (2009)
	Peninsular Ranges batholith	170–160	+3 to –3	Morton et al. (2014); Shaw et al. (2014)
Pre-Mesozoic (>250 Ma)				
	Appalachian orogen	700–300	–2 to –30	Dickinson et al. (2012); Gehrels and Pecha (2014)
	Grenville province	1300–900	+10 to 0	Dickinson et al. (2012); Gehrels and Pecha (2014)
Southwestern Laurentia				
	Mojave terrane	1790–1640	+11 to –10	Bryant et al. (2001); Wooden et al. (2012)
	Yavapai-Mazatzal province	1800–1600	—	Bowring and Karlstrom (1990); Van Schmus et al. (1993)
	Anorogenic granites	1400–1300	+8 to –1	Bryant et al. (2001); Goodge and Vervoort (2006); Wooden et al. (2012)
Northwestern Laurentia				
	Archean terrane fragments	2700–2400	—	Foster et al. (2006)
	Belt Supergroup	1470–1400	+4 to –8	Link et al. (2007); Stewart et al. (2010)
		1820–1680	+10 to –12	
		2700–2400	—	
	Lemhi subbasin	1380	+10 to –2	Doughty and Chamberlain (1996); Lewis et al. (2010)

*The ‘—’ indicates there is no published Hf-isotope data for comparison.

populations that are not observed in the Winthrop Formation (Figs. 5 and 6). This suggests that these units were part of separate depositional systems and likely sourced from different segments of the Cordilleran arc. The age peaks observed in both samples have many sources in the North American Cordillera (i.e., Fig. 8 and Table 3); thus, neither the Hf-isotope signature nor the age peaks in the mid-Cretaceous Methow and WMB samples are distinctive of a unique provenance.

Upper Cretaceous Units

Detrital zircons from the Upper Cretaceous WMB arkose sample (13-35J, MDA = ca. 72 Ma) reveal distinctive Late Cretaceous and Proterozoic peaks in addition to smaller ca. 120–100 Ma and ca. 190–150 Ma populations that, as discussed above, have many potential sources. The Late Cretaceous populations form peaks at ca. 90 and 74 Ma, which correspond to multiple potential

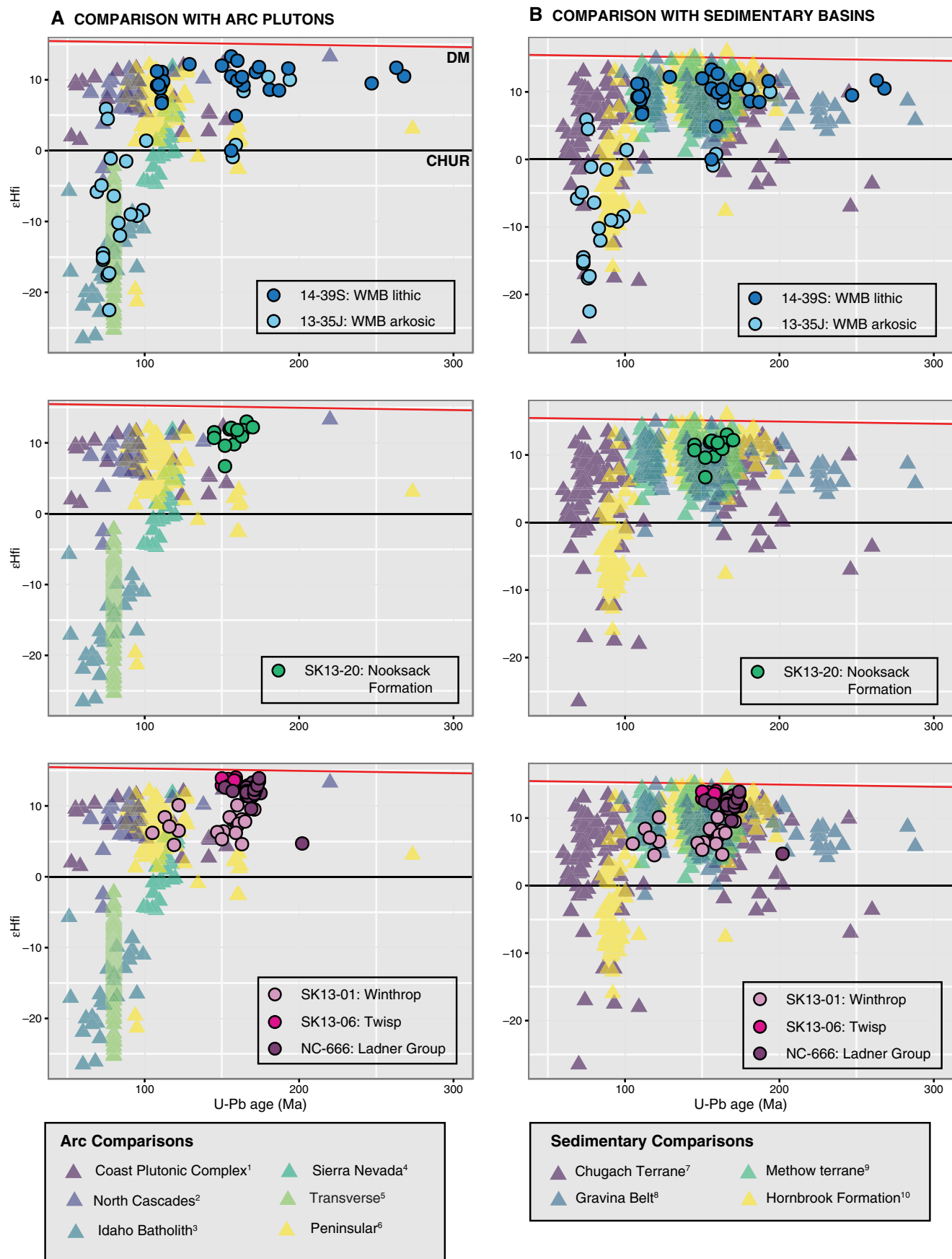


Figure 7. Comparison of Hf-isotope data from this study to (A) North American Cordilleran arc plutons and to (B) other sedimentary basins exposed adjacent to the arc belts. The data are grouped by the position relative to the arc (western mélangé belt [WMB], Northwest Cascades thrust system, and Methow terrane). Data sources footnoted as follows: 1—Cecil et al. (2011); 2—Matzel et al. (2008)*; 3—Gaschnig et al. (2011); 4—Lackey et al. (2012); 5—Barth et al. (2016); 6—Shaw et al. (2014); 7—Garver and Davidson (2015); 8—Yokelson et al. (2015); 9—Surpless et al. (2014); 10—Surpless and Beverly (2013), Surpless (2015). *Calculated from whole-rock Nd data using the formula $\epsilon_{\text{Hf}} = 1.36 * \epsilon_{\text{Nd}} + 2.95$. CHUR—chondritic uniform reservoir; DM—depleted mantle.

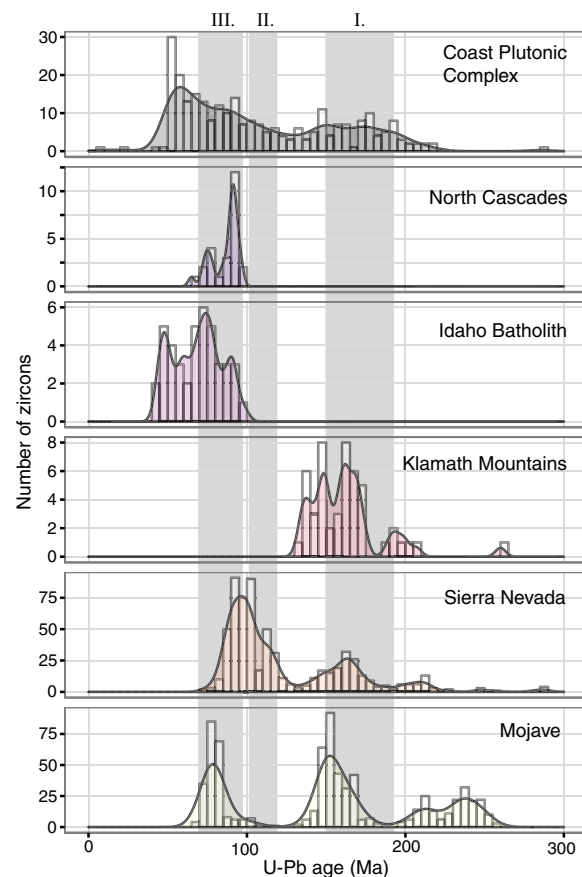


Figure 8. Compilation of age data from plutonic rocks of western North America, generally oriented from north to south. Gray boxes correlate with main age ranges discussed in the text (I. Jurassic [190–180 Ma and 170–150 Ma], II. Mid-Cretaceous [120–100 Ma], and III. Late Cretaceous [100–70 Ma]). Data sources: Coast Plutonic Complex, Gehrels et al. (2009); North Cascades, Miller et al. (2009); Idaho Batholith, Gaschnig et al. (2009); Klamath Mountains, Irwin and Wooden (1999); Sierra Nevada, Chapman et al. (2012); Mojave, Needy et al. (2009).

sources as pluton emplacement occurred along the entire North American continental margin at this time (Fig. 8 and Table 3). However, the zircons from sample 13-35J have a wide spread of Hf-isotope compositions for both the ca. 90 Ma ($\epsilon_{\text{Hf}} = -1.5$ to -12.0) and ca. 74 Ma ($\epsilon_{\text{Hf}} = +5.9$ to -22.5) peaks (Fig. 6). The unradiogenic compositions of most zircons indicate assimilation of older crustal material into the arc magma; the Hf-isotope compositions are between depleted mantle and the expected ϵ_{Hf} values of Proterozoic crust at $t = 100$ –

70 Ma. Zircon-Hf and whole-rock Nd-isotope data from 100 to 70 Ma plutons in the Coast Plutonic Complex and North Cascades all yield more radiogenic compositions (Cui and Russell, 1995; Matzel et al., 2008; Cecil et al., 2011) (Fig. 7A and Table 3) and thus are not likely the source of the Late Cretaceous zircons in the WMB. Unradiogenic Hf-isotope compositions are observed in ca. 100–70 Ma Idaho Batholith zircons (Toth and Stacey, 1992; Lund et al., 2003; Gaschnig et al., 2009, 2011, 2013) (Fig. 7A and Table 3); however, WMB zircons also include more radiogenic grains and require an additional source.

In the southwest, there are also multiple potential sources of this age and range of Hf-isotope compositions. Plutons (ca. 100–85 Ma) of the southern Sierra Nevada intrude east of the $^{87}\text{Sr}/^{86}\text{Sr} = 0.706$ line, which may result in the assimilation of Proterozoic material and the required spread of Hf-isotope compositions (Kistler, 1990). Furthermore, Transverse Ranges plutons have zircons with a range of unradiogenic Hf-isotope signatures, contain inherited Proterozoic (ca. 1.8–1.7 Ga) zircons, and are interpreted to intrude the edge of the Mojave province (Barth et al., 2016) (Fig. 7 and Table 3). Whole-rock Nd-isotope analyses and zircon ϵ_{Hf} values from Late Cretaceous Laramide plutons within the Mojave province also indicate variable assimilation of Proterozoic basement rocks (Lang and Titley, 1998; Fisher et al., 2017) (Table 3).

Overall, the available Hf-isotope data from a single source do not fully describe the observed $+6$ to -23 ϵ_{Hf} values for the ca. 100–70 Ma WMB zircons. In addition, a combination of northern sources, such as the Coast Plutonic Complex–North Cascades with the Idaho Batholith, does not match the observed range in the WMB sample. However, a combination of Cretaceous plutons in the Mojave province and Transverse Ranges and a southern Sierran source (yet to be documented by Hf-isotope analyses) may explain the range of ϵ_{Hf} values for Late Cretaceous zircons in the WMB.

The WMB arkose also includes dates between ca. 1.8–1.6 Ga and ca. 1.40–1.34 Ga with a distinct peak at 1.38 Ga (Fig. 5F). This combination of zircon ages has been observed in other accretionary wedge and forearc units along the continental margin (Fig. 9) and has been interpreted to represent either derivation from southwestern (Mojave terrane and Yavapai-Mazatzal Province; Dickinson et al., 2012; Sharman et al., 2014; Garver and Davidson, 2015; Matthews et al., 2017) or northwestern Laurentia (Belt Supergroup, Mustard et al., 2006; Lemhi Subbasin of the Belt Supergroup, Dumitru et al., 2016). Both the Mojave and Yavapai-Mazatzal terranes contain potential sources of ca. 1.8–1.6 Ga zircons and were intruded by anorogenic granites between 1.4 and 1.3 Ga (Bowring and Karlstrom, 1990; Van Schmus et al., 1993; Bryant et al., 2001; Goodge and Vervoort, 2006; Wooden et al., 2012) (Table 3). Thus, sediment sourced from southwestern Laurentia is likely to dominantly contain zircon with ages between 1.8 and 1.6 Ga and 1.4–1.3 Ga.

In comparison, potential sources of Precambrian zircons in northwestern Laurentia include the Belt Supergroup and fragments of 2.7–2.4 Ga Archean terranes, all of which have been largely obscured by the Idaho Batholith and younger cover rocks (Foster et al., 2006; Gaschnig et al., 2013, Vervoort et al., 2016). The detrital zircons of Mesoproterozoic Belt Supergroup have ages that are dominantly between 1.82 and 1.68 Ga and form a ca. 1.75 Ga peak with

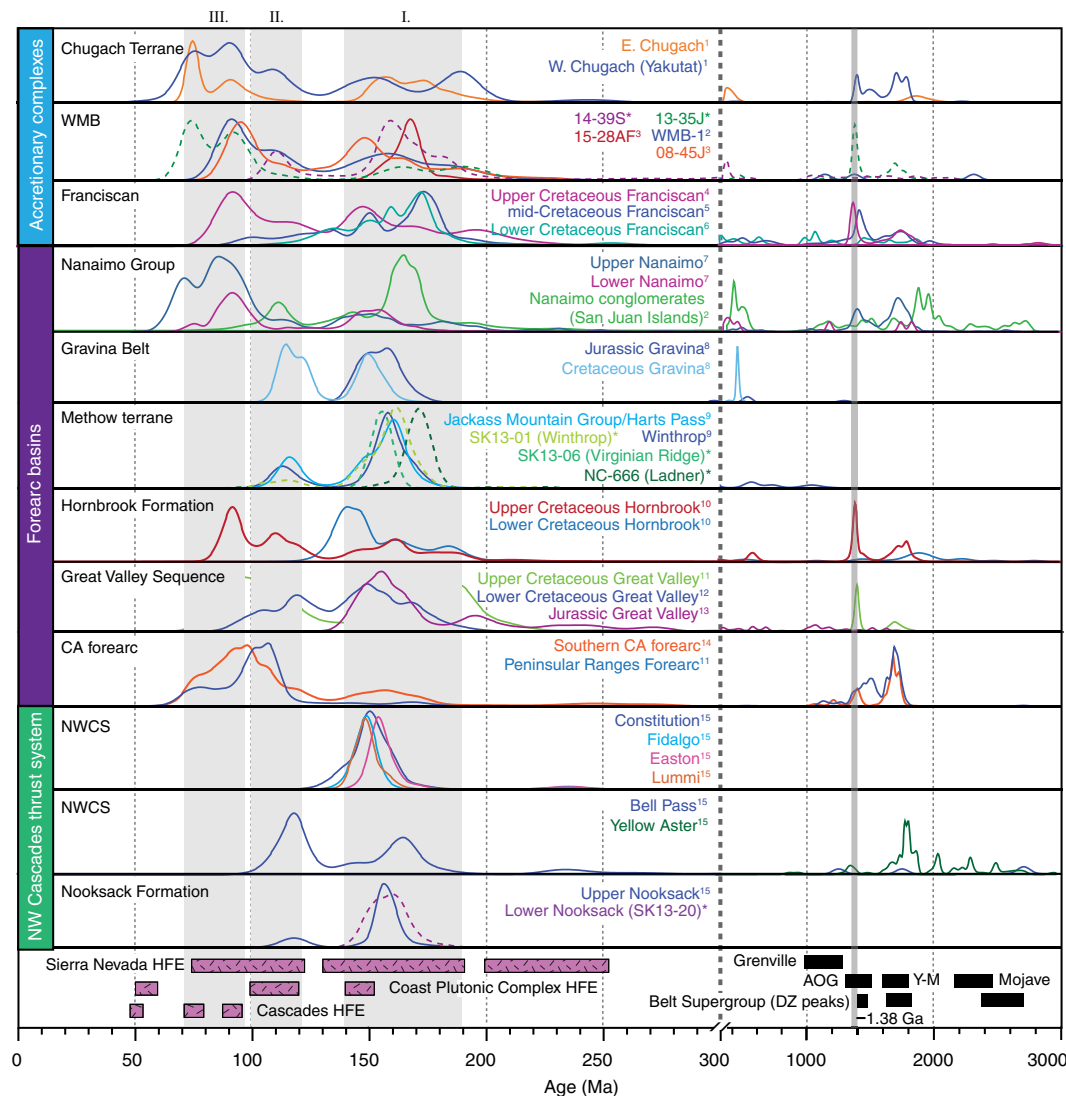


Figure 9. Kernel density estimate plots for detrital-zircon (DZ) age spectra from Jurassic to Paleocene sedimentary units along the North American continental margin (note change in scale for the x-axis at 300 Ma). High-flux events in segments of the Cordilleran arc, magmatism in the SW United States, and Belt Supergroup detrital-zircon peaks are plotted for comparison at the bottom. Gray boxes correlate with main age ranges discussed in the text (I. Jurassic [190–180 Ma and 170–150 Ma], II. Mid-Cretaceous [120–100 Ma], and III. Late Cretaceous [100–70 Ma]). Sources footnoted as follows: *—this study (dashed lines); 1—Garver and Davidson (2015); 2—Brown (2012); 3—Dragovich et al. (2009) and Dragovich et al. (2016); 4—Dumitru et al. (2015); 5—Snow et al. (2010); 6—Dumitru et al. (2010); 7—Mustard et al. (1995), Mahoney et al. (1999), Matthews et al. (2017); 8—Yokelson et al. (2015) and Kapp and Gehrels (1998); 9—DeGraaff-Surpless et al. (2003) and Surpless et al. (2014); 10—Surpless and Beverly (2013) and Surpless (2015); 11—Sharman et al. (2014); 12—Surpless et al. (2006); 13—DeGraaff-Surpless et al. (2002); 14—Jacobson et al. (2011); 15—Brown and Gehrels (2007). Comparisons: Sierra Nevada high-flux event (HFE); Paterson and Ducea (2015); Coast Plutonic Complex HFE, Gehrels et al. (2009); North Cascades HFE, Miller et al. (2009); anorogenic granites (AOG), Yavapai-Mazatzal (Y-M), Mojave, Whitmeyer and Karlstrom (2007); Belt Supergroup detrital-zircon peaks, Ross and Parrish (1991); Stewart et al. (2010); Grenville, Whitmeyer and Karlstrom (2007). CA—California; NWCS—Northwest Cascades thrust system; WMB—western mélange belt.

smaller age populations between 1.47 and 1.40 Ga and 2.70–2.40 Ga (Link et al., 2007; Stewart et al., 2010). The southern end of the Belt Supergroup (Lemhi Subbasin) was intruded by 1.38 Ga bimodal rift plutons (Doughty and Chamberlain, 1996; Lewis et al., 2010). Dumitru et al. (2016) argue that the Lemhi Subbasin may have been a major source of ca. 1.38 Ga detrital zircons to the Cordilleran forearc and accretionary wedge, but has since been obscured by younger ig-

neous intrusions and volcanic cover. Other sediment sources in northwestern Laurentia likely also include ca. 2.55 Ga and 670 Ma crust (Gaschnig et al., 2013). Thus, sediment derived from the northwestern Laurentian would likely include a Belt Supergroup sediment source resulting in a strong ca. 1.75 Ga peak and 2.70–2.40 Ga and 1.47–1.38 Ga zircons, potentially derived from Archean basement or anorogenic intrusions in the Lemhi Subbasin, respectively.

The Hf-isotope data from the potential sediment sources in southwestern and northwestern Laurentia cover a similar range of values for both Proterozoic populations and do not distinguish between the two sources (Fig. 10 and Table 3). Moreover, these data overlap with the observed Hf-isotope signature of the two Proterozoic WMB zircons ($\epsilon_{\text{Hf}} = +11.3$ to -0.4 and $+8.7$ and -0.9) (Fig. 10).

However, the combination of age peaks observed in the WMB is more indicative of a southwestern Laurentian source. A Belt Supergroup provenance would likely be characterized by a dominant 1.75 Ga peak and include an Archean component, whereas the two main Proterozoic populations (1.8–1.6 Ga and 1.4–1.3 Ga) in the WMB sample 13-35J have similar amounts of grains ($n = 18$ versus $n = 25$), and there are no grains between 2.7 and 2.4 Ga (Fig. 5). Thus, the overall age pattern in 13-35J more closely matches available data from southwestern Laurentia sources.

Sediment Source Pathways

Comparison of detrital-zircon age patterns for sedimentary units of northwestern Washington and southern British Columbia with coeval MDAs highlight similarities in provenance (Fig. 11). The unimodal peaks of the ca. 170–140 Ma units of northwestern Washington and southern British Columbia suggest deposition in a basin that received input from only local sediment sources. The lithologies and near-depleted mantle Hf-isotope compositions

suggest that the sources were dominated by volcanic detritus and were likely oceanic-arc terranes. These oceanic arcs were likely continent fringing based on the narrow age range (Fig. 11A).

Early Mesozoic oceanic-arc terranes were accreted to the continental margin sometime in the Late Jurassic to earliest Cretaceous, and active east-dipping subduction resulted in a high-standing Andean-type arc and the development of large forearc basins (Saleeby and Busby-Spera, 1992; Dickinson, 2008). The Hf-isotope compositions of detrital zircons deposited in the Methow terrane between ca. 120–100 Ma (this study; Surpless et al., 2014) generally have ϵ_{Hf} compositions that range from approximately $+13-0$ (i.e., between the depleted mantle and CHUR), indicating assimilation of crustal material into a juvenile arc magma and the switch from oceanic- to continental-arc sediments (Fig. 7B). Development of the high-standing arc (e.g., Saleeby and Busby-Spera, 1992; House et al., 2001) and potentially an orogenic plateau (Whitney et al., 2004; Miller et al., 2016) likely acted as a topographic barrier that blocked significant material with an inboard signature from reaching large forearc basins at this time (Fig. 11B). Minor amounts of pre-arc detrital zircons (i.e., $>ca.$ 300 Ma) were recycled from the host rocks of the arc.

Detrital zircons in the western mélange belt and Nanaimo Group deposited after ca. 80–72 Ma record the addition of a large component of cratonic sediment (Fig. 11C). During the mid-Late Cretaceous, major tectonic reorganization occurred along the continental margin, including the beginning of flat slab subduction, which resulted in the cessation of magmatism in the Sierra Nevada batholith. Collapse and exhumation of the southern

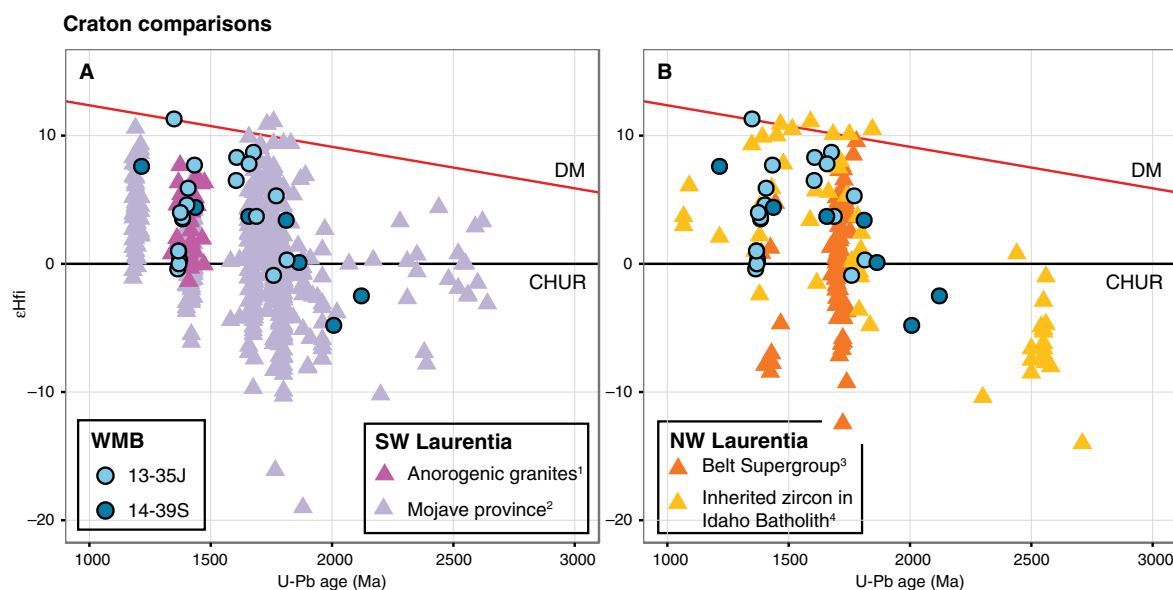
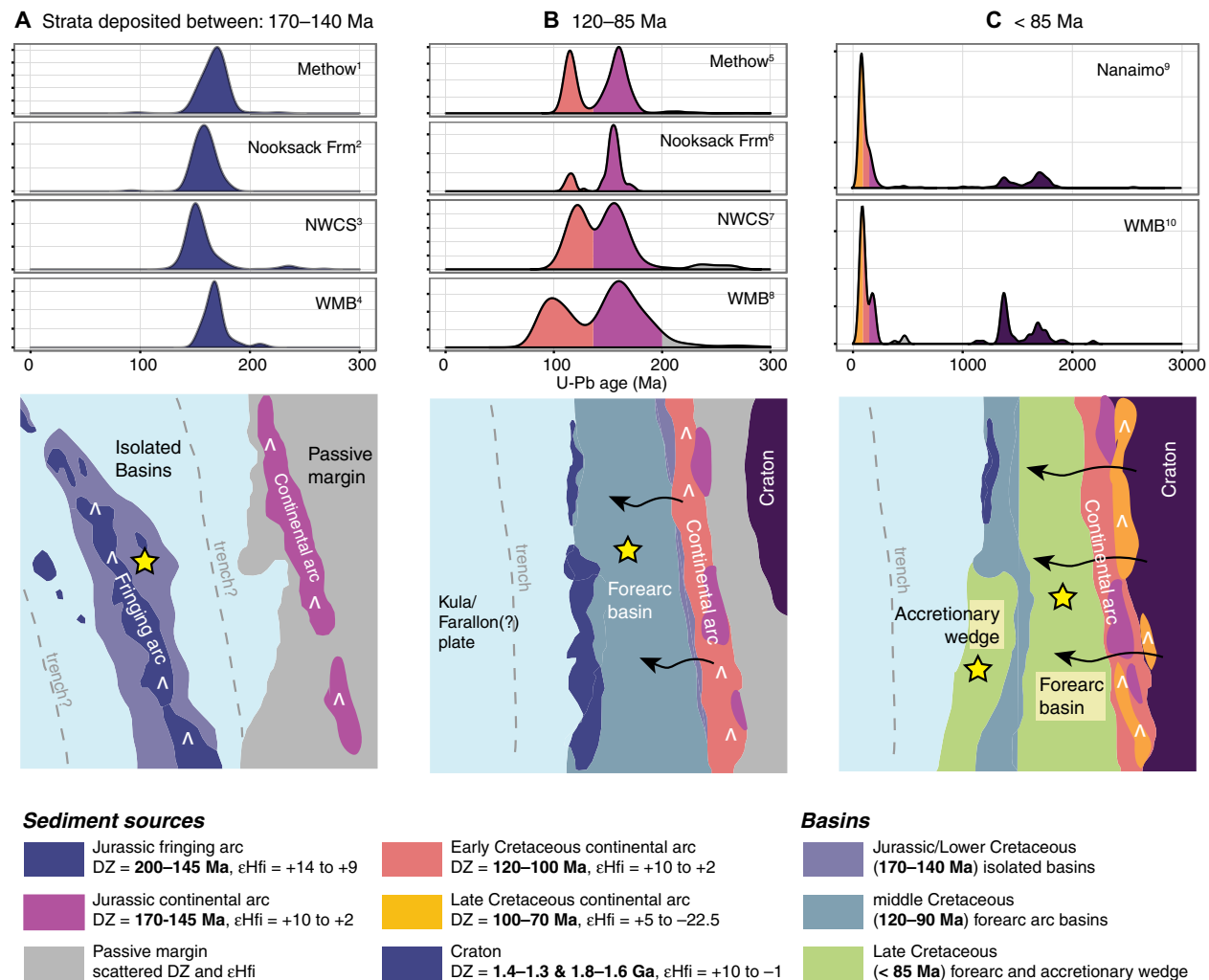


Figure 10. Comparison between the Hf-isotope data from western mélange belt Precambrian zircons and potential sources in (A) southwestern (Mojave province basement and anorogenic granites) and (B) northwestern (Belt Supergroup and inherited zircons in the Idaho Batholith) Laurentia. Data sources are footnoted as follows: 1—Goodge and Vervoort (2006); 2—Wooden et al. (2012); 3—Stewart et al. (2010); 4—Gasching et al. (2013). DM—depleted mantle; CHUR—chondritic uniform reservoir; WMB—western mélange belt.

Figure 11. Detrital-zircon signatures and cartoon figures depicting tectonic setting for rocks deposited between ca. 170–140 Ma, ca. 120–90 Ma, and less than ca. 85 Ma. Data sources are footnoted as follows: 1—Twisp Formation and Ladner Group, this study; 2—Nooksack Formation, this study; 3—Constitution Formation, Easton Metamorphic Suite, Fidalgo Complex, and Lummi Formation; Brown and Gehrels (2007); 4—lithic petrofacies, western mélangé belt; Dragovich et al. (2016); 5—Harts Pass Formation; Jackass Mountain Group and Winthrop Formation; DeGraaff-Surpless et al. (2003), Surpless et al. (2014), and this study; 6—Nooksack Formation; Brown and Gehrels (2007); 7—Tonga Formation and Bell Pass mélangé; Brown and Gehrels (2007); 8—arkosic and lithic petrofacies; Dragovich et al. (2009), Brown (2012), and this study; 9—Upper Nanaimo Group; Mahoney et al. (1999), Mustard et al. (1995), and Matthews et al. (2017); 10—arkosic petrofacies; this study.



part of the Sierra Nevada batholith (Chapman et al., 2012) led to a breach in the arc at ~34°N latitude and allowed a flood of sediment from the Mojave terrane to be released to the forearc and trench (Jacobson et al., 2011; Sherman et al., 2014). Uplift associated with the Sevier orogeny and erosion of rocks in the Belt Supergroup or Lemhi Subbasin in northwestern Laurentia during this time may also have fed sedimentary material to the forearc and accretionary wedge units along the Cordilleran margin (Mahoney et al., 2014; Dumitru et al., 2016).

Paleogeographic Implications

The Jurassic to Cretaceous paleogeography of the western North American paleomargin has been heavily debated (e.g., Beck, 1980; Monger and Price, 1996; Housen and Beck, 1999; Enkin et al., 2002). A combination of data from known offsets on identified faults, lithologies, and reconstructions based on paleomagnetic data has been used to argue that the rocks of the North Cascades were translated from more southerly latitudes to their present position.

However, the various models suggest a wide range of points of origin and thus amounts of translation: (1) ~700 km from the latitude of the Klamath Mountains and northern Sierra Nevada (Brandon et al., 1988; Garver, 1988; Wyld et al., 2006); (2) ~1600 km from the latitude of the southern end of the Sierra Nevada batholith (Umhoefer, 2003; Kim and Kodama, 2004; Umhoefer and Blakey, 2006); or (3) ~2300–2500 km at the latitude of northern Mexico during the mid-Cretaceous (“Model B” of Cowan et al., 1997; “Baja-BC” hypothesis; Beck and Noson, 1972; Enkin et al., 2001).

To evaluate these three contrasting hypotheses, detrital-zircon data from the sedimentary units juxtaposed against the North Cascades magmatic arc are compared via multidimensional scaling (MDS) to data from coeval basins to examine potential links and trends along the continental margin (Vermeesch et al., 2016) (Fig. 12). The MDS results are plotted on a dimensionless Shepard plot that graphically ranks the Kolgrov-Smirnov dissimilarities between the age distributions of each sample to all other samples (Fig. 12; Kruskal and Wish, 1978; Borg and Groenen, 2005; Vermeesch, 2013). The distances between samples on the plot are proportional to dissimilarities in their detrital-zircon age spectra; thus, clusters indicate similar age patterns. Comparison of published detrital-zircon data from California to Alaska show that detrital-zircon spectra vary systematically with depositional age and latitude (Fig. 12). For example, samples of similar stratigraphic age plot together and shift as a group with age toward the center of the diagram (Fig. 12). Samples from Alaska to southern California with Upper Cretaceous MDAs cluster in the center of the plot (Fig. 12).

Statistical comparisons show that the basal parts of the Methow terrane in northern Washington and southern British Columbia are the most similar to rocks of the NWCS and to ca. 160–140 Ma rocks in Oregon and northern and central California (Fig. 12). Cretaceous strata in the Methow terrane have a distinct bimodal detrital-zircon signature of ca. 170–150 Ma and ca. 120–100 Ma and contain more sediment derived from less radiogenic plutonic sources than the older strata (Figs. 9 and 11). The bimodal signature is present in coeval strata in the Great Valley sequence of central California (DeGraaff-Surpless et al., 2002; Sharman et al., 2014), the Hornbrook Basin of northern California and southern Oregon (Surpless and Beverly, 2013; Surpless, 2015), and the Mitchell Inlier of the Blue Mountains in central-eastern Oregon (B. Housen in LaMaskin, 2012). Methow strata in Washington are more similar to rocks currently in Oregon and northern California than Methow units in southern British Columbia, which have a larger proportion of ca. 120–100 Ma grains and are more similar to southern California forearc units (Fig. 12). Overall, the Methow detrital zircons are dominated by ages that are common along the continental margin, lack Proterozoic peaks that provide links to a particular latitude, and do not help to determine the amount of terrane translation.

Detrital-zircon results from the NWCS and its footwall (Nooksack Formation) reveal similar age characteristics as the Methow terrane, including a switch from a unimodal detrital-zircon age signature in the Lower Cretaceous strata to a bimodal distribution in younger strata (Fig. 11). Detrital zircons from the NWCS cluster with samples from the Hornbrook Basin and northern and

central Californian units (Fig. 12). Statistical comparisons show that quartzite cobbles in conglomerates in the NWCS, Nanaimo, and Hornbrook Basin may have the same sources (Fig. 12). Previous studies have suggested that the components that make up the nappes of the NWCS are linked to the Klamath Mountains and northern Californian sources (i.e., Garver, 1988; Brandon et al., 1988; MacDonald et al., 2008). New data from the Nooksack Formation presented here yield a unimodal Jurassic age peak, which could have originated from multiple sources along the continental margin.

The Jurassic to Upper Cretaceous clastic components of the WMB have similar detrital-zircon age patterns and MDAs as other units in northwestern Washington, southwestern British Columbia, northern California, and Oregon (Fig. 12). These similarities support the Jett and Heller (1988) sediment petrofacies correlation between the WMB and the Californian Franciscan Complex and the minimum fault-offset reconstruction of Wyld et al. (2006). In terms of the origin of the youngest WMB components, Dumitru et al. (2016) suggest that a southwest-flowing paleoriver originating in the Lemhi Subbasin may have delivered sediment containing the 1.8–1.6 Ga, 1.38 Ga, and 100–70 Ma detrital zircons to the vicinity of the Hornbrook Basin, Franciscan Complex, and Great Valley sequence between southern Oregon and central California at ca. 85–65 Ma. Given this hypothesis, the proposed paleoriver system may have sourced the WMB sediment deposited at ca. 72 Ma. However, we interpret that the ca. 72 Ma arkosic sandstone of the WMB was likely derived from the Mojave terrane based on the relative abundances of zircon populations, combination of detrital-zircon age peaks, and the Hf-isotope composition of the 100–70 Ma zircons. Original deposition of the sediment probably occurred around the breach in the southern California arc followed by subsequent northward translation and incorporation into the western mélange belt. This interpretation requires that some components of the WMB originated along the continental margin between southern California and Oregon ca. 72 Ma and were assembled in Washington by the early Tertiary. Strata with similar detrital-zircon signatures currently located at northern latitudes (e.g., the Nanaimo Group and Yakutat Group of the Chugach terrane) are also interpreted to have been deposited at the latitude of the southern Sierra Nevada based on paleomagnetic data and detrital zircons, respectively (i.e., Kim and Kodama, 2004; Garver and Davidson, 2015; Matthews et al., 2017). These results support moderate translation (~1600–2000 km) and place these units at the breach in the southern Sierra Nevada ca. 72 Ma. The systematic change to multiple Mesozoic peaks and influx of extra-regional sediment in Late Cretaceous strata may also suggest similar tectonic settings in multiple locations along strike of the continental margin (Figs. 9 and 12).

CONCLUSIONS

New U-Pb and Hf-isotope data from detrital zircon in the Jurassic to Cretaceous sedimentary rocks presently adjacent to the North Cascades magmatic arc correlate with coeval units of similar tectonic affinities along the North

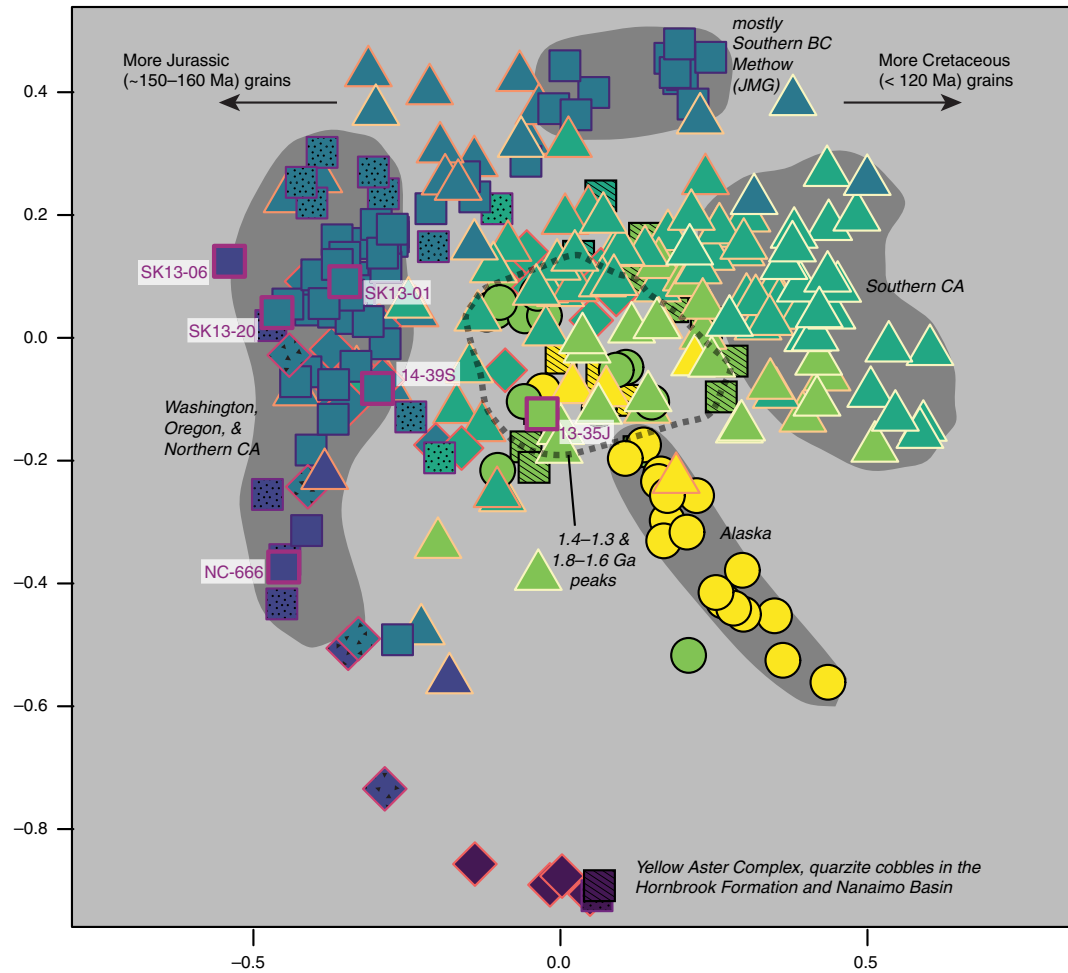
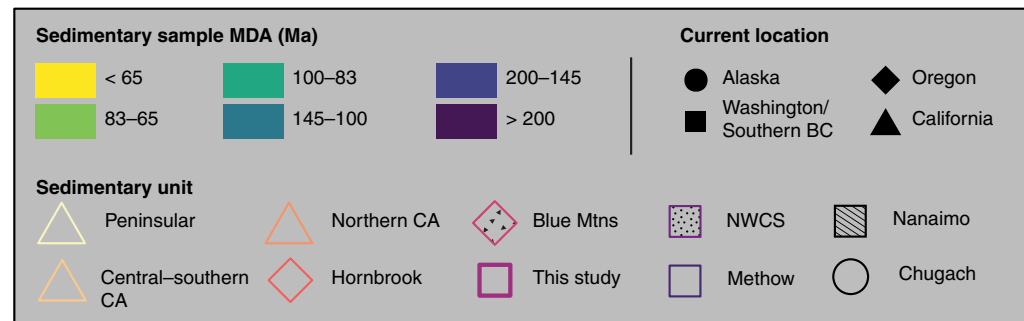


Figure 12. Multidimensional scaling plot color coded by inferred maximum depositional age (MDA) (shape fill color) and sedimentary unit (outline color) for samples from northern Baja California to Alaska. Data sources: Peninsular Ranges forearc—Sharman et al. (2014); Southern California forearc—Sharman et al. (2014); Franciscan Complex—Ernst et al. (2009); Snow et al. (2010); Sharman et al. (2014); Chapman et al. (2016); Dumitru et al. (2016); Great Valley sequence—DeGraaff-Surpless et al. (2002); Surpless et al. (2006); Hornbrook Basin: Surpless and Beverly (2013); Surpless (2015); Blue Mountains, LaMaskin et al. (2015); Methow—DeGraaff-Surpless et al. (2003); Surpless et al. (2014); NWCS—Brown and Gehrels (2007); western mélange belt—Brown (2012); Nanaimo Group—Mustard et al. (1995); Mahoney et al. (1999); Matthews et al. (2017); Chugach terrane—Garver and Davidson (2015). BC—British Columbia; JMG—Jackass Mountain Group; NWCS—Northwest Cascades thrust system.



American margin from northern Mexico to Alaska. New detrital-zircon data from the Methow terrane and NWCS characterize their sedimentary sources but are not diagnostic of paleolatitude. In comparison, the Proterozoic age populations along with the Hf-isotope compositions of the youngest grains in the Upper Cretaceous western mélange belt (WMB) share similarities with potential sources in southwestern Laurentia. This suggests a more southerly origin, at least for the arkosic petrofacies of the WMB. Furthermore, these new data extend the age of rocks in the western mélange belt to the latest Cretaceous and provide estimates for the timing and source of Jurassic sedimentation in the Methow subterranean. Understanding the provenance of these units relates them to the overall evolution of North America Cordillera, from the accretion of oceanic arcs, to the development of a continental-magmatic arc similar to the modern-day Andes, and finally to long-distance, margin-parallel translation.

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