Detrital zircon record of mid-Paleozoic convergent margin activity in the northern U.S. Rocky Mountains: Implications for the Antler orogeny and early evolution of the North American Cordillera

Luke P. Beranek¹, Paul K. Link², and C. Mark Fanning³
¹DEPARTMENT OF EARTH SCIENCES, MEMORIAL UNIVERSITY OF NEWFOUNDLAND, 9 ARCTIC AVENUE, ST. JOHN’S, NEWFOUNDLAND AND LABRADOR A1B 3X5, CANADA
²DEPARTMENT OF GEO SCIENCES, IDAHO STATE UNIVERSITY, 921 SOUTH 8TH AVENUE, POCATELLO, IDAHO 83209, USA
³RESEARCH SCHOOL OF EARTH SCIENCES, AUSTRALIAN NATIONAL UNIVERSITY, 142 MILLS ROAD, CANBERRA, ACT 0200, AUSTRALIA

ABSTRACT

The passive to convergent margin transition along western Laurentia drove early development of the North American Cordillera and culminated years (e.g., Cawood et al., 2009). Field evidence for the oldest tectonic feature the north to south, time-transgressive juxtaposition of Baltican- and Caledonian-affinity terranes along the Cordilleran margin.

INTRODUCTION

Accretionary orogenic systems are built by repeated tectonothermal events that construct mountain belts over tens of hundreds of millions of years (e.g., Cawood et al., 2009). Field evidence for the oldest tectonic events in such long-lived orogens can therefore be obscured by later phases of deformation, metamorphism, and magmatism that effectively rework the continental crust. However, it is widely accepted that ancient siliciclastic strata are important archives of early orogen processes and capable of retaining the precise age, spatial extent, and exhumation histories of old mountain belts (Allen et al., 1991; Ross et al., 2005; Weislogel et al., 2006; Cawood et al., 2007; Anfinson et al., 2013; Gehrels, 2014; Colpron et al., 2015; McClelland et al., 2016). Detrital mineral provenance studies of syntectonic strata have proven to be especially useful for identifying the geological elements that supply clastic detritus to sedimentary basins during convergent margin activity, such as passive margin sequences, cratonal blocks, and volcanic arcs (Clift et al., 2009; Hampton et al., 2010; Park et al., 2010; LaMaskin, 2012; Beranek et al., 2013a, 2015; Bradley and O’Sullivan, 2016; Zhang et al., 2016).

The Cordilleran orogen of western North America (Fig. 1) is the type example of an accretionary system and has a documented history of mid-Paleozoic to Cenozoic tectonothermal events (e.g., Dickinson, 2004, 2006; Nelson et al., 2013). Studies of mid-Paleozoic plate convergence have mostly focused on components of the Late Devonian–Mississippian Antler orogeny in the Great Basin of Nevada, which culminated in lower Paleozoic deep-water rocks of the Roberts Mountain allochthon (Fig. 1) (western assemblage of Roberts et al., 1958; siliceous assemblage of Burchfiel and Davis, 1975) being thrust over carbonate platform strata (eastern or carbonate assemblage) of the Laurentian margin (Nilsen and Stewart, 1980; Johnson and Pendergast, 1981; Poole et al., 1992). Outside of the Great Basin, a protracted history of plate convergence is further evidenced by Middle to Late Devonian arc magmatism, metamorphism, and deformation (e.g., Mortensen, 1992; Root, 2001; Dusel-Bacon et al., 2006) and Late Devonian–Early Mississippian backarc extension, syntenic sulfide mineralization, and syntectonic sedimentation (e.g., Eibacher, 1983; Gordey et al., 1987; Miller et al., 1992; Turner and Otto, 1995; Nelson et al., 2006; Diehl et al., 2010) in parts of the Alaskan, Canadian, and United States Cordillera.

Mid-Paleozoic backarc extension ultimately led to the rifing of continental arc fragments and opening of a marginal ocean basin along western North America (Creaser et al., 1997; Piercey et al., 2004; Colpron et al., 2007). Three plate tectonic scenarios are typically proposed to explain the Antler orogeny: (1) the collision of an east-facing arc system of Laurentian or
Terranes of Siberian, Baltican, & Caledonian affinities
- Alexander (AX)
- Arctic Alaska, Ruby (RB)
- Farewell (FW), Kilbuck (KB)
- Okanagan (OK), Trinity-Yeke (TY)
- Sierra City-Shoo Fly (SC)
Terranes of northern Panthalassic affinity
- Angayucham (AG), Tozitna
- Wrangellia (WR)
Terranes of Tethyan affinity
- Cache Creek (CC), Bridge River Baker, Rattlesnake Creek

Figure 1. Paleozoic to early Mesozoic terranes of the North American Cordillera modified from Colpron and Nelson (2009). Terranes are grouped according to crustal affinity and interpreted positions in early Paleozoic time. Outlined box shows the geographic location of Pioneer Mountains region in Figure 2A. BC—British Columbia, CA—California, ID—Idaho, NV—Nevada, OR—Oregon, UT—Utah, WA—Washington.

PALEOZOIC STRATIGRAPHY OF THE PIONEER MOUNTAINS, IDAHO

Paleozoic rocks in the Cordilleran thrust belt of east-central Idaho crop out within three structural-stratigraphic zones that from west to east comprise the Pioneer, Copper Basin, and Hawley Creek thrust plates (e.g., Link and Janecke, 1999). Cambrian to Devonian strata to the east of the Pioneer thrust (Fig. 2A) consist mostly of shallow-water, platformal strata.
Mid-Paleozoic convergent margin activity in the northern U.S. Rocky Mountains | RESEARCH

Figure 2. (A) Simplified bedrock map of the Pioneer Mountains region, east-central Idaho, modified from Lewis et al. (2012). White circles show the location of detrital zircon samples reported in this study. Penn.—Pennsylvanian. (B) Cambrian to Permian correlation chart for the Hawley Creek, Copper Basin, and Pioneer thrust plates. Detrital zircon samples are shown by white circles and sample numbers. Dol.—Dolomite, Fm.—Formation, Gp.—Group, Mt.—Mount, Rob.—Roberts.

rocks of the Cordilleran passive margin (eastern assemblage of the North American parautochthon) that are assigned to the Sauk, Tippecanoe, and Kaskaskia sequences of the North American craton. The Ordovician Kinnikinic Quartzite (Fig. 2B) is a prominent siliciclastic unit in east-central Idaho and broadly correlative with the Eureka Quartzite of eastern Nevada that is beneath the Roberts Mountain allochthon. Ketner (1968) concluded that quartz-rich Ordovician sand sheets in the western United States were sourced from the Peace River Arch, a long-lived positive feature in northwestern Alberta and northeastern British Columbia (e.g., O’Connell et al., 1990; Cecile et al., 1997), and transported southward along the Cordilleran shelf by longshore processes. This hypothesis is supported by the increased textural maturity of Ordovician shelf sandstones from western Canada to the southwestern United States (e.g., Ketner, 1968) and Precambrian detrital zircon signatures that are consistent with northwestern Laurentian provenance (e.g., Gehrels and Ross, 1998; Baar, 2009; Wulf, 2011; Gehrels and Pecha, 2014). Shallow-water quartz sandstone units also occur throughout the carbonate-dominated Devonian Jefferson Formation within the Copper Basin and Hawley Creek thrust plates (Fig. 2B), including Famennian strata in the Lost River Range near Borah Peak (Grader and Dehler, 1999).

Ordovician to Silurian siliciclastic rocks of the Phi Kappa and Trail Creek Formations comprise continental slope and rise facies of the Cordilleran passive margin (western assemblage of the Roberts Mountain allochthon) that crop out to the west of the Pioneer thrust fault (Figs. 2A, 2B). The Phi Kappa Formation, and in particular its basal Basin Gulch Quartzite Member, is correlative with the shallow-water Kinnikinic Quartzite of east-central Idaho and the deep-water Valmy and upper Vinini Formations of the Roberts Mountain allochthon in Nevada. For example, the basal Phi Kappa Formation contains Ordovician hexactinellid sponges that are similar to those in the Vinini Formation (Rigby et al., 1981; Rigby, 1995) and likely diagnostic of the warm water paleo-Pacific realm (Carrera and Rigby, 1999). Although it is generally agreed that Roberts Mountain allochthon strata have Laurentian provenance, there has been considerable debate about the origins of some deep-water Ordovician rocks in the Great Basin (see Gehrels et al., 2000a). In one popular scenario, texturally immature sandstones of the upper Vinini and Valmy Formations have provenance tie the Peace River Arch region of northwestern Laurentia and were deposited in offshelf environments near their present locations; lower Vinini Formation strata in this scenario were derived from nearby source regions in southwestern Laurentia (e.g., Smith and
Gehrels, 1994; Gehrels et al., 1995, 2000a). Linde et al. (2016) modified this hypothesis and proposed that upper Vinini and Valmy strata were deposited offshore of the Peace River Arch, near the latitude of the present-day U.S.-Canadian border, and subsequently transported ~1000 km south by a sinistral strike-slip fault system prior to the Antler orogeny. DeVonian Milligen Formation strata are limited to the Pioneer thrust plate (Figs. 2A, 2B) and comprise >1000 m of variably deformed black shale, chert, sandstone, conglomerate, mafic sills, and tuff. The Milligen depocenter was a restricted marine basin that received clastic input from unknown sources to west and the Cordilleran shelf to the east (Turner and Otto, 1988). As outlined by Link et al. (1995), a general sequence of events for the Milligen Formation includes (1) Early Devonian (Emsian) deposition of the east-derived Cai quartzite member; (2) Middle to Late Devonian (Eliefian to Frasnian) deposition of the Triumph argillite member during localized extensional faulting and exhalative mineralization; and (3) Late Devonian (Frasnian) deposition of the west-derived Independence sandstone member. The Milligen Formation locally contains an Antler age penetrative cleavage that is not observed in younger strata of the Pioneer Mountains region (Sandberg et al., 1975; Turner and Otto, 1988, 1995). Although the Milligen Formation likely composed part of the Roberts Mountain allochthon in east-central Idaho, the Pioneer thrust is a Cretaceous structure and does not mark the trace of a Late Devonian–Mississippian fault system (Dover, 1980; Rodgers et al., 1995).

Mississippian Copper Basin Group and equivalent rocks of the Copper Basin thrust plate (Figs. 2A, 2B) represent the Antler foreland basin sequence in east-central Idaho. Lower Mississippian flysch strata in the Pioneer Mountains comprise >4200 m of east- and north-prograding fan delta to submarine fan deposits that were rapidly buried (Wilson et al., 1994; Link et al., 1996). Flexural loading tied to the emplacement of the Roberts Mountain allochthon and synsedimentary normal faulting within the foreland drove early subsidence within the narrow (~70 km wide) Copper Basin depocenter (Wilson et al., 1994). Decompacted sedimentation rates for lower Tournaisian strata are ~950–1400 m/m.y. (Link et al., 1996), but most textural troughs, but consistent with hybrid, flexural- and fault-controlled basins (e.g., Houseknecht, 1986). Middie to Upper Mississippian molasse strata consist of deltaic and shallow-marine siliciclastic rocks that are >1700 m thick and record waning sediment supply and accommodation space after a period of late Tournaisian uplift and tilting (Link et al., 1996).

Wilson et al. (1994) and Link et al. (1996) concluded that a transcurrent plate setting best fit the evidence for both rapid subsidence and synsedimentary normal faulting in the Copper Basin depocenter. Following a model for Devonian–Mississippian transcurrent faulting from Arctic Canada to the southwestern United States proposed by Eisbacher (1983) that included field evidence for left-lateral shearing along the cratonic margin of the northern Canadian Cordillera, it was predicted (Wilson et al., 1994; Link et al., 1996) that the Copper Basin depocenter formed within a sinistral fault system. In this model, the Copper Basin Group accumulated within a releasing bend basin that was bordered on its south side by an uplifted restraining bend of Kinnikinic Quartzite near the Snake River Plain. For example, the conglomeratic Scorpion Mountain Member of the Argosy Creek Formation, making up a submarine fan with northward paleocurcvents in the middle of the Copper Basin Group, contains white clasts of Kinnikinic Quartzite that coarsen to boulder sized toward the south. Detrital zircon data reported here show that zircons in a quartzite cobbles (sample 40JMP94) are identical to those in the Copper Basin Group quartz sandstone matrix (sample 10JMP94). Preacher et al. (1995) recognized that these Tournaisian strata contained detrital zircons older than 1800 Ma that were identical to those of the Valmy Formation in Nevada. Elsewhere in the Copper Basin Group, Mississippian conglomerates contain cherty argillite rock fragments that suggest provenance from western assemblage Phi Kappa and Milligen strata of the Roberts Mountain allochthon (Link et al., 1996). East of the Pioneer Mountains, distal turbidite (McGowan Creek Formation) and carbonate (White Knob Limestone) successions of the Hawley Creek thrust plate (Figs. 2A, 2B) were deposited at the boundary between the eastern margin of the Antler foreland basin and the western edge of the cratonal platform.

Middle Pennsylvanian to lower Permian siliciclastic-carbonate marine rocks of the Sun Valley Group and Snaky Canyon Formation (Fig. 2B) compose the Antler overlap succession in east-central Idaho (e.g., Mahoney et al., 1991; Geslin, 1998). In the Pioneer thrust plate, Sun Valley Group rocks unconformably overlie deformed Milligen Formation strata. Link et al. (2014) reported that Sun Valley Group strata yield Archean to Paleozoic detrital zircons with key age groupings ca. 1840, 1750, 1650, 1450, 1150, 1040, 650, 565, and 440–415 Ma. Although these provenance signatures are similar to other Pennsylvanian–Permian strata in the northern U.S. and southern Canadian Rocky Mountains (e.g., Gehrels and Pecha, 2014), it is uncertain if certain detrital zircons, including ca. 440–415 Ma zircons, were recycled through underlying rocks of the Pioneer thrust plate or if they were ultimately sourced from the convergent margins of northern or eastern North America (Link et al., 2014).

METHODS AND MATERIALS

Twelve rock samples from the Pioneer, Copper Basin, and Hawley Creek thrust plates were collected for detrital zircon U-Pb geochronology (see locations in Fig. 2A). The suite includes three samples of the Kinnikinic Quartzite (09LR01, 05STA09, 09TD10), one sample of the Basin Gulch Quartzite Member of the Phi Kappa Formation (06PL13), two samples of the Milligen Formation (11LB04, 02TD10), one sample of the Jefferson Formation (05PL13), and five samples of the Copper Basin Group (09LB04, 05PL15, 40JMP94, 10JMP94) and equivalent Salmon River assemblage (24PL09). Detrital zircons were separated using conventional rock crushing, grinding, wet shaking table, and heavy liquid and magnetic separation techniques. Three of the samples (09LR01, 40JMP94, 10JMP94) were analyzed by secondary ion mass spectrometry using a SHRIMP (sensitive high-resolution ion microprobe) instrument at the Australian National University following the methods of Williams (1998) and Link et al. (2005). The remaining nine samples were analyzed by laser ablation–inductively coupled plasma–mass spectrometry (LA-ICP-MS) at the Arizona LaserChron Center, University of Arizona, using the methods described by Gehrels et al. (2008). Analytical results, sample locations, and notes about data treatment are provided in Tables DR1 and DR2 in the GSA Data Repository.

Deposited offshore of the Peace River Arch, near the latitude of the present-day U.S.-Canadian border, and subsequently transported ~1000 km south by a sinistral strike-slip fault system prior to the Antler orogeny.

GSA Data Repository Item 2016277, Table DR1: SIMS detrital zircon U-Pb isotopic data and age results; Table DR2: LA-ICP-MS detrital zircon U-Pb isotopic data and age results; Table DR3: LA-ICP-MS detrital zircon Hf isotope data, is available at www.geosociety.org/pubs/ft2016.htm, or on request from editing@geosociety.org.
Figure 3. Probability density distribution stacked histogram plots of Ordovician detrital zircon samples from the Pioneer Mountains region, east-central Idaho. LA-ICP-MS—laser ablation–inductively coupled plasma–mass spectrometry; SIMS—secondary ion mass spectrometry. (A) Kinnikinic Quartzite quartz arenite (sample 5TA09; East Fork of Salmon River). (B) Kinnikinic Quartzite quartz arenite (sample 09TD10; head of East Fork of Wood River). (C) Kinnikinic Quartzite quartz arenite (sample 09LR01; west of Borah Peak, Lost River Range). (D) Phi Kappa Formation, Basin Gulch Quartzite Member quartz arenite (sample 06PL13; Little Fall Creek).

Figure 4. Probability density distribution stacked histogram plots of Devonian detrital zircon samples from the Pioneer Mountains region, east-central Idaho. LA-ICP-MS—laser ablation–inductively coupled plasma–mass spectrometry. (A) Emsian Cait quartzite quartz arenite of the lower Milligen Formation (sample 02TD10; East Fork of Wood River). (B) Frasnian Independence sandstone sublithic arenite of the upper Milligen Formation (sample 11LB04; east of Picabo). (C) Famennian Jefferson Formation sandstone (sample 05PL13; west of Borah Peak, head of Rock Creek, Lost River Range).
Initial $^{176}\text{Hf}/^{177}\text{Hf}$ ratios are reported as $e_{\text{Hf}(t)}$ and represent the isotopic composition at the time of crystallization relative to the chondritic uniform reservoir (Fig. 6).

**RESULTS**

**Ordovician Kinnikinic Quartzite**

Three samples of medium- to coarse-grained quartz arenite from the Lost River Range (09LR01), Pioneer Mountains (09TD10), and along the Salmon River near Bayhorse (05TA09) contain clear to pink to red detrital zircons that range in size from 50 to 100 µm. The samples are dominantly composed of Paleoproterozoic (76%–88%) detrital zircons with probability age peaks that range from 1862 to 1828, 1959 to 1918, and 2099 to 2072 Ma (Figs. 3A–3C). Archean detrital zircons are found in all rock samples (9%–19%), whereas late Mesoproterozoic (1072–1043 Ma) detrital zircons are only recognized in sample 09TD10.

**Ordovician Phi Kappa Formation**

A sample of fine-grained quartz arenite near the formation base (Basin Gulch Quartzite Member) in the Pioneer Mountains (06PL13) contains clear to pink to red detrital zircons that range in size from 25 to 50 µm. The sample mostly yields Paleoproterozoic (81%) detrital zircons with probability age peaks of 1846, 1924, and 2079 Ma (Fig. 3D). Archean detrital zircons are found in all rock samples (9%–19%), whereas late Mesoproterozoic (1072–1043 Ma) detrital zircons are only recognized in sample 09TD10.

**Devonian Milligen Formation**

A sample of coarse-grained quartz arenite from the Lower Devonian (Emsian) Cait quartzite (02TD10) has well-rounded, clear to pink detrital zircons that appear similar to those within Ordovician strata of the Pioneer Mountains area. The sample is mostly composed of Paleoproterozoic (81%) detrital zircons with probability age peaks of 1839, 1922, and 2082 Ma (Fig. 4A). Archean detrital zircons compose 19% of the sample.

A sample of medium-grained sublithic arenite from the Upper Devonian (Frasnian) Independence sandstone (11LB04) contains equant to elongate detrital zircons that are 30–100 µm. The sample is mainly composed of Mesoproterozoic to latest Paleoproterozoic detrital zircons (71%) with probability age peaks of 1662 Ma and 1745 Ma (Fig. 4B). Smaller age groupings of early Paleozoic (450–428 Ma), early Neoproterozoic (954–928 Ma), and Archean (2754–2508 Ma) detrital zircons are also present. Three Silurian detrital zircons in the Independence sandstone sample were analyzed for Hf isotope geochemistry. Detrital zircons with ages of 428, 432, and 434 Ma yielded $e_{\text{Hf}(t)}$ values of $-27.3$, $-5.6$, and $-10.7$, respectively (Fig. 6).
Devonian Jefferson Formation

A sample of Upper Devonian (Famennian) sandstone from the Jefferson Formation in the Lost River Range (05PL13) contains detrital zircons that are 50–100 μm. The sample has an abundance of Mesoproterozoic to late Paleoproterozoic detrital zircons (82%) that give probability age peaks of 1652 Ma and 1848 Ma (Fig. 4C). Subsidiary probability age peaks occur ca. 505, 1145, 1304, 1386, 1568, and 2089 Ma.

Mississippian Copper Basin Group and Salmon River Assemblage

Four samples of the Copper Basin Group (09LB04, 05PL15, 40JMP94, 10JMP94) and one sample of the correlative Salmon River assemblage (24PL09) in the Pioneer Mountains region contain clear to pink, sub-rounded to rounded detrital zircons that are 20–100 μm. Sedimentary lithic sandstones from the basal Copper Basin Group (09LB04, Little Copper Formation) and overlying strata (05PL15, Argosy Creek Formation) have significant amounts of Paleoproterozoic (77%–82%) and Archean (18%–23%) detrital zircons and yield probability age peaks that range from 1783 to 1768, 1845 to 1808, 1978 to 1920, and 2055 to 2018 Ma (Figs. 5A, 5B). Sample 40JMP94 is a cobbable-sized clast of quartz arenite in the Copper Basin Group (Scorpion Mountain Member, Argosy Creek Formation) and sample 10JMP94 represents quartz sandstone matrix stratigraphically near the clast. Both samples are dominated by Paleoproterozoic detrital zircons (92%) with most ages around 1868–1830 Ma and 2093 Ma (Figs. 5C, 5D). The Salmon River assemblage sample (20PL09) contains abundant Paleoproterozoic detrital zircons (80%) and displays probability age peaks of 1843 Ma and 2079 Ma (Fig. 5E).

Pennsylvanian–Permian Sun Valley Group

Link et al. (2014) reported the detrital zircon U-Pb signatures of Sun Valley Group strata in the Pioneer Mountains. We analyzed 35 zircons from 3 samples studied by Link et al. (2014) for Hf isotope geochemistry (see locations in Fig. 2; results in Fig. 6). A sample of Middle Pennsylvanian shallow-marine sandstone (01PL12, Hailey Member, Wood River Formation, n = 15) has Devonian (393 and 379 Ma), Silurian (431 and 426 Ma) and Ediacaran (564–588 Ma) detrital zircons that yield positive εHf values of +4 to +14, whereas some other Ordovician to Silurian to grains (470, 444, 436 Ma) are characterized by negative εHf values of −16 to −4.5. A sample of Upper Pennsylvanian to lower Permian turbiditic sandstone (04TD10, Eagle Creek Member, Wood River Formation, n = 8) contains Devonian (396 Ma), Silurian (434–421 Ma), and Ordovician (448 Ma) detrital zircons with εHf values of −32 to −5.5. A sample of lower Permian turbiditic sandstone (03PL12, Wilson Creek Member, Wood River Formation, n = 12) is mostly composed of Early Devonian (419–413 Ma), Silurian (429 Ma), Ordovician (465 Ma), Cambrian (501, 495 Ma) and Ediacaran (585, 557 Ma) detrital zircons with negative εHf values of −14 to −1; this sample also contains Pennsylvanian grains of 321 Ma and 308 Ma that yield εHf values of −5.4 and +4.6, respectively.

DISCUSSION

Early Paleozoic Passive Margin System of Western Laurentia

Modern and ancient passive margin systems are characterized by well-mixed siliciclastic strata (Ingersoll, 1990; Ingersoll et al., 1993) with detrital zircon ages that are much older than the time of sediment accumulation (e.g., Cawood and Nemchin, 2001; Cawood et al., 2012). In western North America, such relationships are best preserved by lower Paleozoic sandstone units that crop out along the length of the Rocky Mountains and equivalent ranges from northern Canada to the southwestern United States (e.g., Gehrels and Ross, 1998; Gehrels et al., 2000a; Gehrels and Pecha, 2014). New sediment provenance results of Ordovician to Lower Devonian rocks in east-central Idaho strengthen this hypothesis and demonstrate that the youngest detrital zircons in the Kinnikinnic Quartzite, Phi Kappa Formation, and lower Milligen Formation (Cait quartzite) are ~500–1300 m.y. older than the inferred depositional ages of their host rocks. The abundance ofPaleoproterozoic and Archean detrital zircons in Ordovician to Lower Devonian strata of east-central Idaho (Fig. 7A; this study), Great Basin of Nevada (Fig. 7B), and southern British Columbia (Fig. 7C) therefore supports the presence of an established Cordilleran passive margin system that was the site of long-term sediment recycling (e.g., Ketner, 1968; Cawood et al., 2012). Despite the evidence for episodic rifting and magmatism in western Canada and United States (e.g., Cecile et al., 1997; Lund et al., 2010), early Paleozoic zircons are only locally preserved in the Cambrian–Devonian sedimentary record (e.g., Todt and Link, 2013; Gehrels and Pecha, 2014). The detrital zircon signatures of Ordovician to Lower Devonian passive margin strata in east-central Idaho instead...
reflect provenance from Precambrian (ca. 1850, 1920, 2080, and 2700 Ma) crystalline basement units and their supracrustal derivatives. The new U-Pb results from the Pioneer Mountains are most consistent with Precambrian sources of the northwestern Canadian shield (e.g., Slave, Hottah, Great Bear, Fort Simpson, and Trans-Hudson basement domains; Hoffman, 1988; Hanmer et al., 2004), including unique-aged Paleoproterozoic (2100–2000 Ma) rocks of the Buffalo Head and Chinchaga terranes in the Peace River Arch region that are diagnostic of northwest Laurentian provenance (e.g., Gehrels and Ross, 1998; Gehrels and Pecha, 2014).

Devonian Provenance Trends: A Record of the Passive to Active-Margin Transition?

Convergent margins typically have first- or second-cycle detrital zircons that closely approximate the age of deposition (e.g., Cawood et al., 2012). The geology of the upper Milligen Formation is broadly suggestive of such an active plate setting, including evidence for mafic volcanism and localized faulting, and therefore provides a unique opportunity to investigate mid-Paleozoic tectonism in the northern U.S. Rocky Mountains.

Frasnian strata of the Independence sandstone are part of a regional submarine fan succession that presumably sampled rocks to the west of Mil- ligen depocenter (Link et al., 1995). Despite its provenance signature being significantly different from that of the lower Milligen Formation (Cait quartzite), the youngest detrital zircons in the Independence sandstone sample are mid-Silurian (ca. 430 Ma) and predate the depositional age of the unit by ~50 m.y. This sample consists of well-mixed turbidite sandstone and therefore suggests that an adjacent Devonian magmatic arc complex, if present, did not generate abundant zircon, or that such arc-type rocks were not sampled by this part of the submarine fan system. Three potential source regions are considered in the following (western, northern, and eastern Laurentian margins) to evaluate mid-Paleozoic provenance ties with Upper Devonian strata (Fig. 8A) of east-central Idaho.

**Potential Sources from the Western Laurentian Margin**

The North American Cordillera contains linear belts of subduction-related rocks, syntectonic strata, and volcanic- and sediment-hosted sulfide occurrences that provide compelling evidence for a west-facing, mid-Paleozoic convergent margin system to have existed along western Laur- entia (e.g., Albers and Bain, 1985; Richards, 1989; Rubin et al., 1990; Mortensen, 1992; Erdmer et al., 1998; Nelson et al., 2002, 2006; Piercey et al., 2004, 2006; Devine et al., 2006; Dusel-Bacon et al., 2006; Paradis et al., 2006; Ruk et al., 2006). Field-based studies in western Canada have further recognized mid-Paleozoic deformation and metamorphism within continental margin rocks of known or inferred Laurentian crustal affinity (e.g., Klepacki and Wheeler, 1985; Root, 2001; Colpron et al., 2006; Berman et al., 2007; Kraft, 2013). In the northern U.S. Rocky Mountains, the record of Devonian convergent margin activity is typically obscured by Mesozoic tectonism and arc magmatism. For example, Paleozoic rocks in the Pioneer thrust plate, including deformed Milligen Formation strata, were telescoped during the Sevier orogeny, intruded by the regionally extensive Idaho batholith, and overlain by Eocene volcanic units (Rodgers et al., 1995; Gaschig et al., 2010, 2011, 2013).

The Eastern Klamath and Northern Sierra terranes are largely underlain by early to mid-Paleozoic convergent margin rocks and have long been considered potential candidates for the so-called Antler arc in the western United States (e.g., Nilsen and Stewart, 1980; Swickeurt and Snyder, 1981; Poole et al., 1992; Gehrels et al., 2000b). Lindsley-Griffin et al. (2006, 2008) provided the most recent overview of these terranes. Grove et al. (2008) reported that Lower to Middle Devonian strata of the Eastern Klamath terrane in northern California yield unimodal 480–380 Ma or 490–410 Ma detrital zircon populations (Sissel Gulch Graywacke and Gazelle Formation) or mixed 480–410 Ma and 2000–1000 Ma age signatures (Duzel Phyllite and Moffett Creek Formation) with probability peaks of ca. 1000, 1450, and 1650 Ma (Figs. 8B, 8C). These detrital zircon ages support local provenance from rock units in the Klamath Mountains (Yreka and Trinity subterrane), including 435–400 Ma plutonic rocks, Devonian volcanic and volcaniclastic rocks, and cratonal strata that were metamorphosed to blueschist facies (e.g., Wallin et al., 1995; Wallin and Metclaf, 1998; Grove et al., 2008; Lindsley-Griffin et al., 2008). Metasedimentary rocks and cratonal strata of the Northern Sierra terrane in northern California (Sierra City mélange, Shoo Fly Complex) that are intruded by the 372 ± 6 Ma Bowman Lake batholith (Cecil et al., 2012) have detrital zircon age distributions similar to those of Eastern Klamath terrane strata (Figs. 8D, 8E; Grove et al., 2008) and likely have provenance from mid-Silurian and Ediacaran igneous rocks (Saleeby et al., 1987; Saleeby, 1990) and variably deformed cratonal strata (Harding et al., 2000).

Devonian strata of the Chase formation compose part of the enigmatic basement to southern Quesnellia (Okanagan subterrane) in the Okanagan-Kootenay region of southeastern British Columbia (Fig. 1; Monger et
Although Silurian–Early Devonian magmatic rocks are not yet recognized, 431 Ma granitoid boulders (Roback et al., 1994) with an inferred western source from an uplifted block called the Okanagan high (e.g., Thompson et al., 2006; Colpron and Nelson, 2009). In the southern Canadian Rockies near the British Columbia–Alberta border, Late Devonian ties with an outboard source are further demonstrated by west-derived continental margin strata of the Sassenach Formation (Savoy et al., 2000; Stevenson et al., 2000) that yield Archean to early Paleozoic detrital zircons (Gehrels and Pecha, 2014) with age peaks of ca. 440, 1220, 1430, 1630, and 1720 Ma (Fig. 8G). In combination with evidence for Middle Devonian deformation in the adjacent Purcell Mountains of southeastern British Columbia (Fig. 1; Root, 2001), it seems likely that the Okanagan subterrane was juxtaposed with the distal Cordilleran margin by Late Devonian time (Colpron and Nelson, 2009; Kraft, 2013).

Detrital zircon U-Pb and Hf isotope results of the present study support the hypothesis that some Upper Devonian strata of the Pioneer Mountains were derived from the erosion of a Paleozoic arc built on Proterozoic crust. We propose that convergent margin rocks of the Eastern Klamath, Northern Sierra, and Quesnellia terranes were western source areas for the Independence sandstone and Jefferson Formation of east-central Idaho, and more broadly, the Sassenach Formation in the southern Canadian Rocky Mountains. Future studies are therefore predicted to identify evolved zircon Hf isotope signatures for Eastern Klamath, Northern Sierra, and Quesnellia arc-type rocks and arc-proximal strata. For example, the Independence sandstone contains 434–428 Ma detrital zircons (Fig. 6) with evolved Hf isotopic compositions [εHf(t) = −27.3 to −5.6; X = −14.5] and Archean to Proterozoic model ages (2700–1530 Ma). Most similar-aged (444–426 Ma; n = 57, 71%) detrital zircons in the basal Sun Valley Group (01PL12; Middle Pennsylvanian Hailey Member, Wood River Formation), a unit that Link et al. (2014) suggested may have recycled parts of the underlying Milligen Formation, yield εHf(t) < 0 and Paleoproterozoic to Mesoproterozoic model ages that are comparable with the Independence sandstone results. Upper Pennsylvanian to lower Permian strata of the Eagle Creek (04TD10) and Wilson Creek (03PL12) Members are similarly dominated by 448–413 Ma zircons with evolved εHf(t) values of −32 to −1 (n = 11/11, 100%), but Link et al. (2014) concluded that these Sun Valley Group strata have eastern or northern provenance from arc rocks of the Ellesmerian, Appalachian, or Caledonian orogenic belts. Pennsylvanian (Spray Lakes Group) and Triassic (Whitehorse Formation) marine strata in the British Columbia Cordillera show detrital zircon U-Pb age and Hf isotope signatures that compare favorably with those of the Independence sandstone and Sun Valley Group (Fig. 6; Gehrels and Pecha, 2014), which suggests that Paleozoic orogenic activity, regardless of its location around the edges of Laurentia, led to fundamental changes in the isotopic composition of the post-Devonian Cordilleran margin (e.g., Boghossian et al., 1996).

**Potential Sources from the Northern Laurentian Margin**

Upper Devonian strata of the Milligen and Jefferson Formations together record an influx of ca. 450–430 Ma and 1650–930 Ma detrital zircons into the Cordilleran margin system, with only minor evidence for the 2700–1800 Ma age populations that were dominant in Lower Devonian and older passive margin strata (Fig. 8A). An analogous provenance change is revealed by Silurian and Devonian–Mississippian rocks that document the incursion of 450–430 Ma, 1650–930 Ma, and other detrital zircons along the northern Laurentian or Franklinian margin (e.g., Gehrels et al., 1999; Beranek et al., 2010, 2015; Lemieux et al., 2011). These early Paleozoic and Proterozoic detrital zircons were shed from the south-vergent, Ellesmerian orogenic belt in Late Devonian–Mississippian time, carried southwest by terrestrial and marine transport systems, and eventually deposited into the Cordilleran shallow-water shelf (Ross et al., 1997; Beranek et al., 2010). It has been proposed that Ellesmerian foreland basin detrital zircons mark the erosion of accreted arcs with Baltic or northern Caledonian crustal affinities along northern North America (Beranek et al., 2010, 2015; Lemieux et al., 2011; Anfinson et al., 2012a, 2012b; Link et al., 2014; Link and Gehrels, 2015).
2012b, 2013, 2016). An Ellesmerian provenance for Frasnian–Famennian strata in east-central Idaho is therefore permissable, but it calls for detrital zircons to be transported >3000 km from their sites of origin during the Late Devonian. The Independence sandstone sample, however, yields 434–428 Ma detrital zircons with evolved Hf isotopic compositions (εHf(t) = −27.3 to −5.6, X = −14.5) and Hf model ages (2700–1530 Ma) that are not typical of such Ellesmerian strata (Fig. 6). For example, 470–400 Ma detrital zircons in Upper Devonian strata of eastern Alaska (Nation River Formation) and the Canadian Arctic Islands (Blackley and Parry Islands Formations) yield more juvenile εHf(t) values that range from −2 to +8 (X = 43.5; Anfinson et al., 2012b) and +1 to +15 (X = 8.2; Gehrels and Pecha, 2014), respectively.

**Potential Sources from the Eastern Laurentian Margin**

Some studies have argued for the incursion of Paleozoic and Mesoproterozoic detrital zircons into Cordilleran basins to indicate provenance from the Appalachian orogen of eastern Laurentia (e.g., Dickinson and Gehrels, 2003; Gehrels et al., 2011; Link et al., 2014; Lawton et al., 2015). For example, a central Appalachian provenance is interpreted for upper Paleozoic sandstones of the Grand Canyon that are dominantly composed of ca. 475–270 Ma and 1200–1000 Ma detrital zircons (Gehrels et al., 2011). Scenarios for eastern Laurentian provenance generally invoke pan-continental river systems to transport Appalachian detritus to Cordilleran basins. Most of the early Paleozoic arc terranes in the Appalachians formed along the margins of Gondwana by the recycling of Mesoproterozoic and older crust (e.g., Nance et al., 2008). Early Paleozoic detrital zircons that are derived from Gondwanan source rocks therefore yield moderate to evolved εHf(t) values of +5 to −15 (e.g., Mueller et al., 2008; Bahlburg et al., 2010, 2011; Reimann et al., 2010).

Although the available Hf isotope data for Gondwanan-affinity zircons in the Appalachians (Mueller et al., 2008) broadly overlap with our Independence sandstone results (Fig. 6), an eastern Laurentian source for Upper Devonian strata is likely inconsistent with the western derivation of upper Milligen Formation turbidites. However, Eagle Creek and Wilson Creek strata of the Sun Valley Group, along with the correlative Tensleep and Weber Sandstones in Wyoming, contain detrital zircon age populations that suggest that big rivers from the Appalachians supplied sediment to the northern U.S. Rocky Mountains by Late Pennsylvanian time (Link et al., 2014). As discussed here, the evolved εHf(t) values of Eagle Creek (04TD10) and Wilson Creek (03PL12) detrital zircons mostly agree with the southern Appalachian reference frame (Fig. 6). These and other data imply that the Transcontinental Arch, a long-lived positive feature of the central United States, prevented eastern Laurentian zircons from entering Late Devonian basins of the northern U.S. Rocky Mountains (Link et al., 2014).

**Mississippian Sediment Recycling in the Antler Foreland Basin**

Foreland basins are filled with deep-water flysch or shallow-water molasse deposits that generally have a recycled orogen provenance from uplifted continental margin rocks (e.g., Dickinson et al., 1983b; Garzanti et al., 2007). Peripheral and retroarc foreland basins, such as those in the Himalayan and Cordilleran orogens, respectively, are subsequently dominated by detrital zircons that are older than the age of sediment accumulation, with only minor evidence for syndepositional magmatic activity (e.g., Cawood et al., 2012). For example, Mesozoic foreland basin deposits to the east of the Rocky Mountains fold and thrust belt were primarily sourced from uplifted passive margin strata and contain recycled Proterozoic and Archean detrital zircons of Laurentian affinity (e.g., Fuentes et al., 2009; Hadlari et al., 2014, 2015; Lawton et al., 2014).

Several models have been proposed to explain the driving forces responsible for Mississippian subsidence and syntectonic sedimentation adjacent to the Roberts Mountain allochthon (e.g., Speed and Sleep, 1982; Trexler and Pitcher, 1990; Dorobek et al., 1991; Miller et al., 1992; Trexler et al., 2003). Because one can identify in syntectonic strata the geological elements that supply clastic detritus to foreland basins, the provenance signatures of Mississippian flysch deposits in east-central Idaho give new insights into the Antler orogenic system. In the Pioneer Mountains, Lower Mississippian syntectonic strata were south and west derived (Wilson et al., 1994) and mostly contain recycled Archean to Paleoproterozoic detrital zircons and lithic fragments that imply provenance from Roberts Mountain allochthon units in the Antler highlands (Phil Kappa and Milligen Formations) and underlying Ordovician passive margin rocks of the Copper Basin and Hawley Creek thrust plates (Fig. 9A). These data are consistent with Antler flysch in the Pioneer Mountains being partially derived from intraforeland blocks of Kinnikini Quartzite that were uplifted during regional tectonism (Wilson et al., 1994; Link et al., 1996). At a broader scale, recycled Archean to Proterozoic detrital zircons of Laurentian affinity also dominate Middle to Upper Mississippian foredeep strata (Tonka Formation) in the Great Basin of Nevada (Fig. 9B); however, rare syndepositional (340 ± 8 Ma, 346 ± 4 Ma) contributions to this unit (Gehrels and Pecha, 2014) imply proximity to an outboard arc system. Lower Mississippian strata of the Antler backbulge basin in the Great Basin of southwestern Utah (Joana Limestone) have provenance connections with both east-central Idaho and Nevada flysch successions and are characterized by recycled Archean and Paleoproterozoic detrital zircons (Fig. 9C) with only minor evidence of Ediacaran to early Paleozoic components (Cole et al., 2015).

Sediment recycling in the northern Cordillera took place within restricted marine basins that were located behind a west-facing continental margin.
implications for models of the Antler orogeny

The Late Devonian–Mississippian Antler orogeny is arguably the most significant plate tectonic event in the early history of the North American Cordillera and culminated with the east-directed emplacement of the Roberts Mountain allochthon onto the adjacent continental margin (e.g., Roberts et al., 1965; Burchfiel and Davis, 1975; Nilsen and Stewart, 1980). Although the framework geology of this orogenic belt in the Great Basin of Nevada has been studied for decades, there is still no consensus on the driving forces responsible for Antler tectonism. New detrital zircon results from the Pioneer Mountains of east-central Idaho, in combination with constraints from published studies, allow us to examine three plate tectonic scenarios proposed for the Antler orogeny.

arc-continent collision models

Arc-continent collision models for the Antler orogeny propose that Late Devonian–Mississippian deformation resulted from the west-facing Cordilleran passive margin clogging the subduction zone of an east-facing arc system (Burchfiel and Davis, 1972; Schweikert and Snyder, 1981; Speed and Sleep, 1982; Dickinson, 2006). Roberts Mountain allochthon strata in these scenarios compose accretionary prism or subduction complex rocks that were thrust eastward onto the Cordilleran platform as the arc approached the continent (Speed and Sleep, 1982; Dickinson et al., 1983a). The Northern Sierra and Eastern Klamath terranes may have composed part of the converging Antler arc; however, it is uncertain if the timing of Early to Middle Devonian deformation and metamorphism therein (e.g., Cashman, 1980; Saleebey et al., 1987; Wallin et al., 2000) is consistent with that required by models for Late Devonian–Mississippian arc-continent collision and foreland basin sedimentation. Because accretionary prism and subduction complex rocks typically show evidence of syntectonic magmatic activity (e.g., Amato et al., 2013; Chapman et al., 2016), Roberts Mountain allochthon strata in this model are expected to contain Paleozoic detrital zircons from the adjacent Sierra-Klamath arc. The Precambrian-dominated detrital zircon signatures of most Roberts Mountain allochthon units appear to be inconsistent with Paleozoic arc provenance; however, Upper Devonian Milligen Formation strata in the Pioneer Mountains yield Silurian detrital zircons that broadly support ties with known rock assemblages of the Northern Sierra, Eastern Klamath, and Queensellia terranes (e.g., Saleebey et al., 1987; Roback et al., 1994; Wallin and Metcalf, 1998; Grove et al., 2008). Antler foreland basin rocks in the western United States, which in part were derived by the recycling of Roberts Mountain allochthon units, are similarly endowed in Paleoproterozoic and Archean detrital zircons with only minor contributions from an inferred Mississippian arc (ca. 340 Ma; Gehrels and Pecha, 2014). Despite the lack of robust evidence for the Roberts Mountain allochthon being part of an accretionary prism or subduction zone complex (see review by Miller et al., 1992), detrital zircon provenance data may provide a nonunique test of the arc-continent collisional model (Gehrels et al., 2000b).

noncollisional models

Most noncollisional models for the Antler orogeny feature craton-directed retroarc deformation in the region behind a west-facing continental arc (e.g., Burchfiel and Davis, 1972; Miller et al., 1984, 1992). The Roberts Mountain allochthon in these scenarios consists of outer continental margin strata that accumulated in extensional or transtensional basins prior to Devonian subduction initiation along western North America. For example, lower Paleozoic alkaline volcanic rocks and syn-genetic sulfide mineralization in the Roberts Mountain allochthon and outer North American parautochthon are consistent with an extensional or transtensional tectonic setting (e.g., Turner and Otto, 1988; Miller et al., 1992; Otto and Zieg, 2003). Broadly analogous basinal environments are also suggested for the continental margin of western Canada (e.g., Goodfellow et al., 1995; Cecile et al., 1997; Goodfellow and Lydon, 2007). Roberts Mountain allochthon strata yield detrital zircon signatures that are compatible with western Laurentian provenance (Figs. 7A, 7B) and therefore support the paleogeographic assumptions of the noncollisional model. Mississippian syntectonic strata of the Antler foreland in east-central Idaho and Nevada contain recycled Precambrian detrital zircons that were sourced from uplifted passive margin rocks (Figs. 9A, 9B) and show only minor inputs from the adjacent arc, similar to Mesozoic foreland basin systems of western North America (Fuentes et al., 2009; Raines et al., 2013).

Burchfiel and Royden (1991) proposed a noncollisional model in which a generally west-facing arc system is subjected to an episode of subduction along its inboard eastern side. This model was based on modern Apennine-type orogenic belts in the Mediterranean that display the foreland-directed migration of such retrograde subduction zones, likely driven by slab rollback, and extension in the overriding plate (Royden and Burchfiel, 1989). The Roberts Mountain allochthon in this model would comprise accretionary prism rocks that were tectonically emplaced on the Cordilleran shelf as a result of the migrating arc system approaching the continental margin. Burchfiel and Royden (1991) argued that such arcs do not truly collide, and that this type of passive accretion could explain the absence of a collided arc to the west of the Antler belt. As discussed herein for the arc-continent collision model, the Precambrian-dominant detrital zircon signatures of most western assemblage units may be inconsistent with the Roberts Mountain allochthon composing part of an accretionary prism.

oblique convergence models

Recent models for the Antler orogeny predict that mid-Paleozoic Cordilleran orogenesis was linked to oblique convergence along western North America. Wright and Wyld (2006) proposed that a migrating subduction system, analogous to that of the modern Scotia and Caribbean arcs, transported the Alexander, Eastern Klamath, and Northern Sierra terranes from the peri-Gondwanan realm around the southern margin of Laurentia to the paleo–Pacific Ocean (eastern Panthalassa) during the early Paleozoic. In their model, subsequent mid-Paleozoic Antler tectonism in
the Great Basin was the result of north-propagating, dextral-oblique convergence and juxtaposition of these arc fragments against the Cordilleran margin. Wright and Wyld (2006) considered rock units of the Roberts Mountain allochthon, except the Ordovician Vinini Formation, to have non–western Laurentian origins.

Colpron and Nelson (2009, 2011) modified this migrating subduction system hypothesis and proposed that the basement domains of the Eastern Klamath, Northern Sierra, and Quesnellia terranes evolved near northeastern Baltic and the northern Caledonian orogen prior to westward transport around the northern margin of Laurentia. According to Colpron and Nelson (2009), subsequent Middle to Late Devonian subduction initiation along western North America was broadly linked to a sinistral transient fault system that nucleated near northwestern Canada and propagated southward to the southwestern United States. Sinistral transient faulting in this model led to the north to south, time-transgressive juxtaposition of the Baltic-Caledonian-affinity terranes against the Cordilleran margin, which is in part evidenced by Middle Devonian deformation in the Purcell Mountains of southeastern British Columbia and Late Devonian–Mississippian Antler tectonism in Idaho and Nevada. Colpron and Nelson (2011) concluded that an average velocity of ~5 cm/yr is required to accommodate the translation of exotic terranes from northwestern Canada to the southwestern United States during the Devonian. The accreted exotic blocks, along with existing parts of the Laurentian continental margin (e.g., Yukon-Tanana; Colpron et al., 2007), formed the substrate to a west-facing continental arc system that subsequently underwent backarc rifting to generate a marginal ocean basin that we refer to as the Slide Mountain Ocean (e.g., Miller et al., 1984, 1992; Mortensen, 1992; Creaser et al., 1997; Piercey et al., 2004; Nelson et al., 2006; Colpron et al., 2007).

Paleozoic Paleogeography

Paleogeographic scenarios for three time slices (Middle to Late Ordovician, Middle to Late Devonian, and Late Devonian to Early Mississippian) are discussed next and shown in Figure 10.

Middle to Late Ordovician

The detrital zircon signatures of shallow-water shelf (e.g., Kinnikinic Quartzite, Eureka Quartzite, Mount Wilson Formation) and deep-water slope and rise (e.g., Phi Kappa Formation, Valmy Formation) strata indicate shared provenance from ca. 1850, 1920, 2080, and 2700 Ma rocks in northwestern Laurentia and argue for the Cordilleran margin to be the site of extensive sediment recycling during the Middle to Late Ordovician. The north-facing Cordilleran margin straddled the paleoequator at this time, with longshore currents (Ketner, 1968), perhaps driven by southwest-directed trade winds (northeasterlies), accommodating the transport of quartz-rich sediment from the Peace River Arch to the southwestern United States (Fig. 10A). Middle to Late Ordovician sea-level fluctuations may have also influenced sediment provenance signatures on a regional scale. For example, the maximum exposure of cratonic rocks in the U.S. Rocky Mountains occurred during an Ordovician lowstand, which in some cases resulted in provenance signatures being dominated by proximal sources instead of the Peace River Arch (Pope et al., 2008; Baar, 2009; Wulf, 2011).

Proterozoic to lower Paleozoic strata that characterize the Franklinian and Appalachian passive margins of Laurentia (Fig. 10A) are similarly endowed in Precambrian detrital zircons that are much older than the time of sediment deposition; this supports the large-scale recycling of cratonic rocks after the breakup of supercontinent Rodinia (e.g., Hadlari et al., 2012; Beranek et al., 2013b). Detrital zircons from Ellesmere Island and northern Greenland (Fig. 7D) and western Newfoundland (Fig. 7E) yield Archean to Paleoproterozoic age peaks that compare favorably with Cordilleran margin samples. Passive margin rocks in areas such as western Newfoundland (Fig. 7E), however, are more proximal to the Grenville orogen of eastern North America and therefore yield greater amounts late Mesoproterozoic detrital zircons while lacking 2100–2000 Ma grains that are typical of Peace River Arch provenance.

Middle to Late Devonian

Our preferred model for Middle to Late Devonian paleogeography generally follows the conclusions of Colpron and Nelson (2009) and features a migrating subduction system near northwestern Canada (Fig. 10B). In the Colpron and Nelson (2009) model, this migrating subduction system transported exotic crustal fragments from the northern end of the Caledonides westward into Panthalassa. A sinistral transient fault along the Cordilleran margin spawned from this migrating subduction system and accommodated the southward displacement of some exotic crustal fragments, such as the basement units of the Eastern Klamath, Northern Sierra, and Quesnellia terranes. Eifelian folding and thrusting in the Purcell Mountains of British Columbia (Root, 2001) likely records part of the oblique convergence associated with this fault system in southeastern British Columbia (Fig. 10B) and is broadly consistent with the sinistral transient hypothesis of Eisbacher (1983) for the Canadian Cordillera. Linde et al. (2016) proposed that some Ordovician rock units of the Roberts Mountain allochthon in Nevada originally formed near the U.S.-Canadian border, north of the Great Basin, and were subsequently translated southward by a Devonian sinistral fault.

A transient plate setting is consistent with the geology of Middle to Upper Devonian strata in the Pioneer Mountains. For example, the Milligen Formation records Middle to Late Devonian extension or transtension that was associated with mafic volcanism, localized extensional faulting, and exhalative base-metal mineralization (e.g., Turner and Otto, 1988; Link et al., 1995). The 450–430 Ma and 1650–930 Ma detrital zircons observed in the Late Devonian Independence sandstone and Jefferson Formation (Fig. 8A) and Late Devonian Sassenach Formation in the southern Canadian Rockies (Fig. 8G) imply proximity to exotic rocks of the Eastern Klamath, Northern Sierra, and Quesnellia terranes after their oblique juxtaposition along the Cordilleran margin. Middle to Late Devonian provenance ties between the exotic terranes and the Cordilleran margin broadly agree with average displacement rates of ~5 cm/yr from northwestern Canada to the southwestern United States (Colpron and Nelson, 2011).

Late Devonian to Early Mississippian

A west-facing continental arc system was present along the Cordilleran margin in Late Devonian to Early Mississippian time (Fig. 10C). East-dipping subduction probably initiated during the Middle to Late Devonian and propagated southward from northwestern Canada to the southwestern United States (Colpron and Nelson, 2009). Backarc extension and opening of a marginal ocean basin in the region behind the arc was subsequently ongoing in the northern Cordillera by the Early Mississippian (e.g., Piercey et al., 2004) and also likely propagated from north to south (Fig. 10C).

Mississippian Copper Basin Group strata document rapid subsidence, syndepositional faulting, and reworking of lower Paleozoic passive margin strata in the Antler foreland basin of east-central Idaho. We favor a sinistral-oblique tectonic setting for the Copper Basin depocenter based on the results of previous field (e.g., Wilson et al., 1994; Link et al., 1996) and tectonic analysis (Eisbacher, 1983; Reid and Dorobek, 1991; Colpron and Nelson, 2009, 2011) studies. Following these regional constraints,
Mid-Paleozoic convergent margin activity in the northern U.S. Rocky Mountains

Figure 10. Paleozoic paleogeography for Laurentia with focus on Cordilleran margin development. See text for explanation. 

(A) Middle to Late Ordovician time slice modified from plate reconstruction of van Staal and Hatcher (2010). Longshore currents along Cordilleran margin transport northwest Laurentian-affinity sediment from Peace River Arch (PRA) of northwestern Canada to the southwestern United States. B.C.—British Columbia; Is.—Island. 

(B) Middle to Late Devonian time slice modified from base map of Colpron and Nelson (2009). The northern margin of Laurentia is the site of a west-migrating subduction system. Sinistral fault system develops along Cordilleran margin and accommodates the southward displacement of some Baltican- and/or Caledonian-affinity terranes. Eifelian deformation in Purcell Mountains of southeastern British Columbia results from the interaction of Baltican- and/or Caledonian-affinity terranes and Cordilleran margin. Cal.—Caledonides. 

(C) Late Devonian to Early Mississippian time slice modified from base map of Colpron and Nelson (2009). Tectonic development of the Antler orogeny is linked to sinistral transcurrent system along western Laurentia. AA—Arctic Alaska; CH—Chukotka; EK—Eastern Klamath terrane; NS—Northern Sierra terrane; PE—Pearya terrane; QN—Quesnellia; YT—Yukon-Tanana terrane. 

(D) Speculative plate tectonic setting for the Pioneer Mountains region modified from Eisbacher (1983), Wilson et al. (1994), Link et al. (1996), and Lund (2008). Copper Basin depocenter is a releasing-bend basin bounded on the south by an uplifted restraining-bend of lower Paleozoic passive margin rocks and to the west by western Laurentian strata of the Roberts Mountain allochthon. Gp.—group.
especially the stratigraphic framework of Wilson et al. (1994), we conclude that Mississippian flysch successions of east-central Idaho were deposited in a releasing bend basin that was bounded on the south by an uplifted restraining bend (Fig. 10D).

The releasing bend basin in the Pioneer Mountains was located immediately north of the Snake River transfer zone (Fig. 10D), a northeast-trending structural feature of the Laurentian craton in the Snake River Plain region of southern Idaho and northern Nevada (Lund, 2008). North of the Pioneer Mountains, we speculate that the northeast-trending St. Mary–Mojave transform zone (Fig. 10D) similarly controlled Devonian–Mississippian faulting and sedimentation in the Okanagan–Kootenay region of southeastern British Columbia. For example, Middle Devonian deformation, mafic volcanism, and sedimentation in the Purcell Mountains (Fig. 10D) described by Root (2001) may have been influenced by structures associated with the St. Mary–Mojave transform zone. It is therefore likely that future studies of Devonian–Mississippian strata in the northern U.S. and southern Canadian Rocky Mountains will discover new evidence for mid-Paleozoic tectonism near long-lived basement structures.

CONCLUSIONS

Paleozoic continental margin strata of the Pioneer Mountains, east-central Idaho, have detrital zircon U-Pb age and Hf isotope signatures that provide new constraints on the early growth and evolution of the North American Cordillera. Quartz-rich lower Paleozoic strata of the Cordilleran passive margin mostly contain Precambrian detrital zircons that are ~500–1300 m.y. older than the depositional ages of their host rocks. These results are consistent with widespread early Paleozoic sediment recycling along the western margin of Laurentia, analogous to the passive margin histories of northern and eastern North America after the break-up of supercontinent Rodinia. The passive to convergent margin transition in the northern U.S. Rocky Mountains occurred by Middle to Late Devonian time, and is in part documented by west-derived Frasnian turbidite successions that shed Protoreozoic and early Paleozoic detrital zircons into the Cordilleran margin system. The available detrital zircon Hf isotope data suggest that the western source for these Pioneer Mountains strata was an early Paleozoic arc built on Protoreozoic crust, with potential provenance regions in outboard basement complexes of the Eastern Klamath, Northern Sierra, and Quensnellia terranes. Mid-Paleozoic convergent margin activity in east-central Idaho was related to the enigmatic Antler orogeny and primarily preserved by a penetrative cleavage in Middle to Late Devonian time, as inferred from the preservation of early Paleozoic detrital zircons into the Cordilleran margin system. The available detrital zircon Hf isotope data suggest that the western source for these Pioneer Mountains strata was an early Paleozoic arc built on Protoreozoic crust, with potential provenance regions in outboard basement complexes of the Eastern Klamath, Northern Sierra, and Quensnellia terranes. Mid-Paleozoic convergent margin activity in east-central Idaho was related to the enigmatic Antler orogeny and primarily preserved by a penetrative cleavage in Middle to Late Devonian time, as inferred from the preservation of early Paleozoic detrital zircons into the Cordilleran margin system. The available detrital zircon Hf isotope data suggest that the western source for these Pioneer Mountains strata was an early Paleozoic arc built on Protoreozoic crust, with potential provenance regions in outboard basement complexes of the Eastern Klamath, Northern Sierra, and Quensnellia terranes. Mid-Paleozoic convergent margin activity in east-central Idaho was related to the enigmatic Antler orogeny and primarily preserved by a penetrative cleavage in Middle to Late Devonian time, as inferred from the preservation of early Paleozoic detrital zircons into the Cordilleran margin system. The available detrital zircon Hf isotope data suggest that the western source for these Pioneer Mountains strata was an early Paleozoic arc built on Protoreozoic crust, with potential provenance regions in outboard basement complexes of the Eastern Klamath, Northern Sierra, and Quensnellia terranes. Mid-Paleozoic convergent margin activity in east-central Idaho was related to the enigmatic Antler orogeny and primarily preserved by a penetrative cleavage in Middle to Late Devonian time, as inferred from the preservation of early Paleozoic detrital zircons into the Cordilleran margin system. The available detrital zircon Hf isotope data suggest that the western source for these Pioneer Mountains strata was an early Paleozoic arc built on Protoreozoic crust, with potential provenance regions in outboard basement complexes of the Eastern Klamath, Northern Sierra, and Quensnellia terranes. Mid-Paleozoic convergent margin activity in east-central Idaho was related to the enigmatic Antler orogeny and primarily preserved by a penetrative cleavage in Middle to Late Devonian time, as inferred from the preservation of early Paleozoic detrital zircons into the Cordilleran margin system. The available detrital zircon Hf isotope data suggest that the western source for these Pioneer Mountains strata was an early Paleozoic arc built on Protoreozoic crust, with potential provenance regions in outboard basement complexes of the Eastern Klamath, Northern Sierra, and Quensnellia terranes. Mid-Paleozoic convergent margin activity in east-central Idaho was related to the enigmatic Antler orogeny and primarily preserved by a penetrative cleavage in Middle to Late Devonian time, as inferred from the preservation of early Paleozoic detrital zircons into the Cordilleran margin system. The available detrital zircon Hf isotope data suggest that the western source for these Pioneer Mountains strata was an early Paleozoic arc built on Protoreozoic crust, with potential provenance regions in outboard basement complexes of the Eastern Klamath, Northern Sierra, and Quensnellia terranes. Mid-Paleozoic convergent margin activity in east-central Idaho was related to the enigmatic Antler orogeny and primarily preserved by a penetrative cleavage in Middle to Late Devonian time, as inferred from the preservation of early Paleozoic detrital zircons into the Cordilleran margin system. The available detrital zircon Hf isotope data suggest that the western source for these Pioneer Mountains strata was an early Paleozoic arc built on Protoreozoic crust, with potential provenance regions in outboard basement complexes of the Eastern Klamath, Northern Sierra, and Quensnellia terranes. Mid-Paleozoic convergent margin activity in east-central Idaho was related to the enigmatic Antler orogeny and primarily preserved by a penetrative cleavage in Middle to Late Devonian time, as inferred from the preservation of early Paleozoic detrital zircons into the Cordilleran margin system. The available detrital zircon Hf isotope data suggest that the western source for these Pioneer Mountains strata was an early Paleozoic arc built on Protoreozoic crust, with potential provenance regions in outboard basement complexes of the Eastern Klamath, Northern Sierra, and Quensnellia terranes. Mid-Paleozoic convergent margin activity in east-central Idaho was related to the enigmatic Antler orogeny and primarily preserved by a penetrative cleavage in Middle to Late Devonian time, as inferred from the preservation of early Paleozoic detrital zircons into the Cordilleran margin system. The available detrital zircon Hf isotope data suggest that the western source for these Pioneer Mountains strata was an early Paleozoic arc built on Protoreozoic crust, with potential provenance regions in outboard basement complexes of the Eastern Klamath, Northern Sierra, and Quensnellia terranes. Mid-Paleozoic convergent margin activity in east-central Idaho was related to the enigmatic Antler orogeny and primarily preserved by a penetrative cleavage in Middle to Late Devonian time, as inferred from the preservation of early Paleozoic detrital zircons into the Cordilleran margin system. The available detrital zircon Hf isotope data suggest that the western source for these Pioneer Mountains strata was an early Paleozoic arc built on Protoreozoic crust, with potential provenance regions in outboard basement complexes of the Eastern Klamath, Northern Sierra, and Quensnellia terranes. Mid-Paleozoic convergent margin activity in east-central Idaho was related to the enigmatic Antler orogeny and primarily preserved by a penetrative cleavage in Middle to Late Devonian time, as inferred from the preservation of early Paleozoic detrital zircons into the Cordilleran margin system. The available detrital zircon Hf isotope data suggest that the western source for these Pioneer Mountains strata was an early Paleozoic arc built on Protoreozoic crust, with potential provenance regions in outboard basement complexes of the Eastern Klamath, Northern Sierra, and Quensnellia terranes. Mid-Paleozoic convergent margin activity in east-central Idaho was related to the enigmatic Antler orogeny and primarily preserved by a penetrative cleavage in Middle to Late Devonian time, as inferred from the preservation of early Paleozoic detrital zircons into the Cordilleran margin system. The available detrital zircon Hf isotope data suggest that the western source for these Pioneer Mountains strata was an early Paleozoic arc built on Protoreozoic crust, with potential provenance regions in outboard basement complexes of the Eastern Klamath, Northern Sierra, and Quensnellia terranes. Mid-Paleozoic convergent margin activity in east-central Idaho was related to the enigmatic Antler orogeny and primarily preserved by a penetrative cleavage in Middle to Late Devonian time, as inferred from the preservation of early Paleozoic detrital zircons into the Cordilleran margin system. The available detrital zircon Hf isotope data suggest that the western source for these Pioneer Mountains strata was an early Paleozoic arc built on Protoreozoic crust, with potential provenance regions in outboard basement complexes of the Eastern Klamath, Northern Sierra, and Quensnellia terranes. Mid-Paleozoic convergent margin activity in east-central Idaho was related to the enigmatic Antler orogeny and primarily preserved by a penetrative cleavage in Middle to Late Devonian time, as inferred from the preservation of early Paleozoic detrital zircons into the Cordilleran margin system. The available detrital zircon Hf isotope data suggest that the western source for these Pioneer Mountains strata was an early Paleozoic arc built on Protoreozoic crust, with potential provenance regions in outboard basement complexes of the Eastern Klamath, Northern Sierra, and Quensnellia terranes. Mid-Paleozoic convergent margin activity in east-central Idaho was related to the enigmatic Antler orogeny and primarily preserved by a penetrative cleavage in Middle to Late Devonian time, as inferred from the preservation of early Paleozoic detrital zircons into the Cordilleran margin system. The available detrital zircon Hf isotope data suggest that the western source for these Pioneer Mountains strata was an early Paleozoic arc built on Protoreozoic crust, with potential provenance regions in outboard basement complexes of the Eastern Klamath, Northern Sierra, and Quensnellia terranes. Mid-Paleozoic convergent margin activity in east-central Idaho was related to the enigmatic Antler orogeny and primarily preserved by a penetrative cleavage in Middle to Late Devonian time, as inferred from the preservation of early Paleozoic detrital zircons into the Cordilleran margin system. The available detrital zircon Hf isotope data suggest that the western source for these Pioneer Mountains strata was an early Paleozoic arc built on Protoreozoic crust, with potential provenance regions in outboard basement complexes of the Eastern Klamath, Northern Sierra, and Quensnellia terranes. Mid-Paleozoic convergent margin activity in east-central Idaho was related to the enigmatic Antler orogeny and primarily preserved by a penetrative cleavage in Middle to Late Devonian time, as inferred from the preservation of early Paleozoic detrital zircons into the Cordilleran margin system. The available detrital zircon Hf isotope data suggest that the western source for these Pioneer Mountains strata was an early Paleozoic arc built on Protoreozoic crust, with potential provenance regions in outboard basement complexes of the Eastern Klamath, Northern Sierra, and Quensnellia terranes. Mid-Paleozoic convergent margin activity in east-central Idaho was related to the enigmatic Antler orogeny and primarily preserved by a penetrative cleavage in Middle to Late Devonian time, as inferred from the preservation of early Paleozoic detrital zircons into the Cordilleran margin system. The available detrital zircon Hf isotope data suggest that the western source for these Pioneer Mountains strata was an early Paleozoic arc built on Protorezo...