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Research Article

Detrital Zircon U-Pb Geochronology of Upper Devonian and Lower Carboniferous Strata of Western Laurentia (North America): A Record of Transition from Passive to Convergent Margin

Makram Hedhli,[1,2] William A. Matthews,[2] Thomas Hadlari,[1] Daniel Alonso-Torres,[2] Stephen Edward Grasby,[1,2] and Benoit Beauchamp[2]

[1]*Geological Survey of Canada, 3303-33rd St NW, Calgary, AB, Canada T2L 2A7*
[2]*University of Calgary, 2500 University Drive NW, Calgary, AB, Canada T2N 1N4*

Correspondence should be addressed to Makram Hedhli; makram.hedhli@nrcan-rncan.gc.ca

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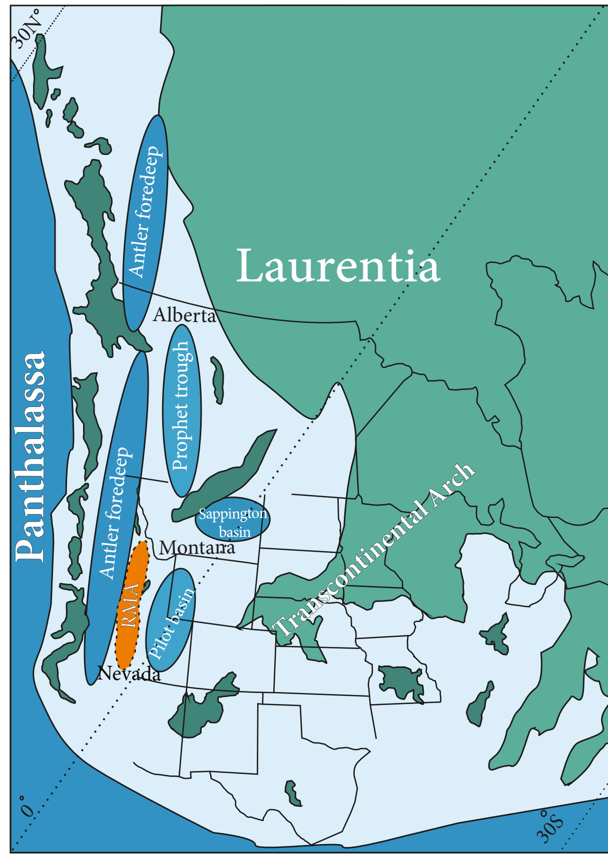
The Late Devonian-Early Carboniferous (DC) Antler orogeny in southwestern Laurentia is contemporaneous with influx of clastic sediments, unconformities, and volcanism across much of western Laurentia (WL), suggesting the demise of the Paleozoic passive margin. However beyond the type Antler orogeny in southwestern Laurentia, the DC tectonic setting is still unclear. Westerly sediment provenance has been suggested as evidence of a convergent margin setting in a foreland basin. However, there is a gap in our understanding in central WL (Alberta and Montana) despite the fact that paleogeographic reconstructions place this area at the centre of WL. We provide detrital zircon (DZ) U-Pb geochronological data from strata in Alberta, Montana, and Nevada that are synchronous with the Antler orogeny to constrain sediment dispersal patterns and test the westerly sediment sourcing hypothesis. We show three DZ facies specific to particular geographic locations: DZ facies 1 in southern Nevada has a prominent subpopulation of early to mid-Mesoproterozoic (mode at 1430 Ma), DZ facies 2 in northeastern Nevada has a late Paleoproterozoic population (mode at 1823 Ma), and DZ facies 3 in Alberta and Montana displays Mesoproterozoic to Neoproterozoic (mode at 1036 Ma), mid-Paleozoic (mode at 411 Ma), and depositional (ca. 360-340 Ma) ages. North-south variation in DZ facies indicates that WL basins were locally sourced from various tectonic fragments having different signatures. Comparing our data with published data, we show that WL is dominated by DZ recycled from uplifted older strata with input from mid-Paleozoic arc terrane (s) to the west. Westerly sourcing is evidenced by the presence of near-depositional ages and affinities of this study's DZ facies with strata located to the west. Our results and geological evidence from other studies suggest that the Antler orogeny triggered a depositional shift and controlled sediments dispersal in WL, signaling the demise of the Paleozoic passive margin.

1. Introduction

It is well accepted that the western margin of the North American continent has an accretionary history whereby several terranes have collided since the Mesozoic [1]. However, the onset of terrane accretion could have started as early as the Silurian to Early Devonian based on scattered evidence that is largely masked by the Mesozoic Cordilleran orogenies [2–8]. This transition from a passive to convergent margin in western Laurentia (WL) is poorly understood. Eastward convergence, possibly involving western terranes in southwestern Laurentia (ancestral North America) that culminated with the Antler orogeny and emplacement of the Roberts Mountain allochthon over carbonate platform strata, is only documented in present-day Idaho and Nevada [2, 8, 9]. However, Upper Devonian ash beds, Late Devonian plutons and metamorphism, occurrences of unconformities in Upper Devonian strata, influx of conglomerates and siliciclastic, and carbonate factory shutdown in western Canada and western United States are consistent with the transition from passive to convergent margin along the entire extent of Western Laurentia around this time [5–7, 10].

Geographically scattered geochronological studies have attempted to unravel the history of the Devonian to Carboniferous (DC) tectonic evolution of western Laurentia and investigate sedimentary provenance and the origin of terranes that bounded western Laurentia [10–14]. These studies used geochronology of detrital zircon grains as an indirect tool to investigate tectonics, by attempting to understand how sediment moved through sedimentary basins. Geochronological studies from southwestern Laurentia [11, 14, 15] and northern-western Laurentia [7, 8, 10, 12, 13, 16, 17] have focused on the DC tectonic evolution of WL and the origins of terranes that bounded it. Detrital zircon provenance data from the Devonian to Carboniferous sedimentary succession of central western Laurentia, present-day southern Alberta and Montana (Figure 1), should be fundamental in understanding late Paleozoic sediment dispersal and paleogeography of the North American Cordillera. However, there is still a major gap in our understanding in central western Laurentia: present-day southern Alberta and Montana. In this study, we provide the new detrital zircon U-Pb geochronological data from samples collected from strata in the Canadian segment of the cordillera that are coeval with the Antler orogeny, along with data from Antler orogeny syntectonic strata in southern Montana and northern and southern Nevada in the United States. We combined our data with previously published results from Proterozoic and lower Paleozoic strata to characterize sediment source areas and better constrain sediment dispersal patterns along western Laurentia. This allowed us to test whether sediments were shed from suspect terranes and associated uplifted Laurentian strata to the west and discuss the tectonic scenarios proposed for the Antler orogeny.



RMA: Robert mountain allochton

Figure 1: Paleogeographic reconstruction of western Laurentia and main depositional areas during the latest Devonian to earliest Carboniferous, after Blakey and Ranney (2017) [79].

2. Geological Background

The Paleozoic passive margin of western North America developed along Panthalassa, the ancestor of the present Pacific Ocean basin that formed following the breakup of the Neoproterozoic supercontinent Rodinia in the late Neoproterozoic to Cambrian [18–20]. In western North America, passive margin deposits consisting of Cambrian to Devonian siliciclastic and carbonate strata are organized into [21] supersequences bounded by continent-wide unconformities. These sedimentary sequences overlie thick Precambrian (730-570 Ma) continental rift to drift suite deposits (i.e., Windermere Supergroup) (e.g., [19, 20]). It is suggested that the demise of the passive Laurentia margin occurred as early as middle Paleozoic, synchronous with the Antler orogenic pulses (e.g., [5, 10]). Occurrence of ash beds in DC strata of western Canada and western USA and detrital zircon grains with Silurian to Devonian depositional ages [6, 22] suggest the existence of a volcanic arc to the west. Nevertheless, the efforts to constrain the timing of the passive to convergent margin transition are hindered by the overprint of Mesozoic and Cenozoic magmatic, metamorphic, and deformational events that led to the emergence of the North American Cordillera [1, 7].

2.1. Roberts Mountain Allochthon and Antler Orogeny. The Roberts Mountain allochthon (RMA) consists of an imbricated sequence of Cambrian to Upper Devonian basinal sedimentary rocks with minor mafic volcanic rocks emplaced eastward onto a lower Paleozoic platform carbonate above the Roberts Mountain thrust fault [9, 23–25]. The RMA was emplaced from southern Idaho to central Nevada during the Late Devonian and Early Mississippian phase of the Antler orogeny [9]. It was initially suggested that the RMA strata originated in western Laurentia [6, 25] as a part of a contractional foreland basin. More recent models for the Antler orogeny are at odds with this idea. Speed and Sleep and Speed et al. hypothesized that an arc-continent collision occurred and that the Roberts Mountain allochthon was transported and emplaced as an accretionary prism [26, 27]. However, lack of remnants of a collided arc and occurrence of a subsided broad extensional region behind the thrust belt (Havallah basin in western Nevada) led different scientists to propose new ideas. These include the following: (I) a Mediterranean-style thrust-belt system [24], whereby thrusting occurred behind a zone of trench retreat, while a region of extension developed in the hanging

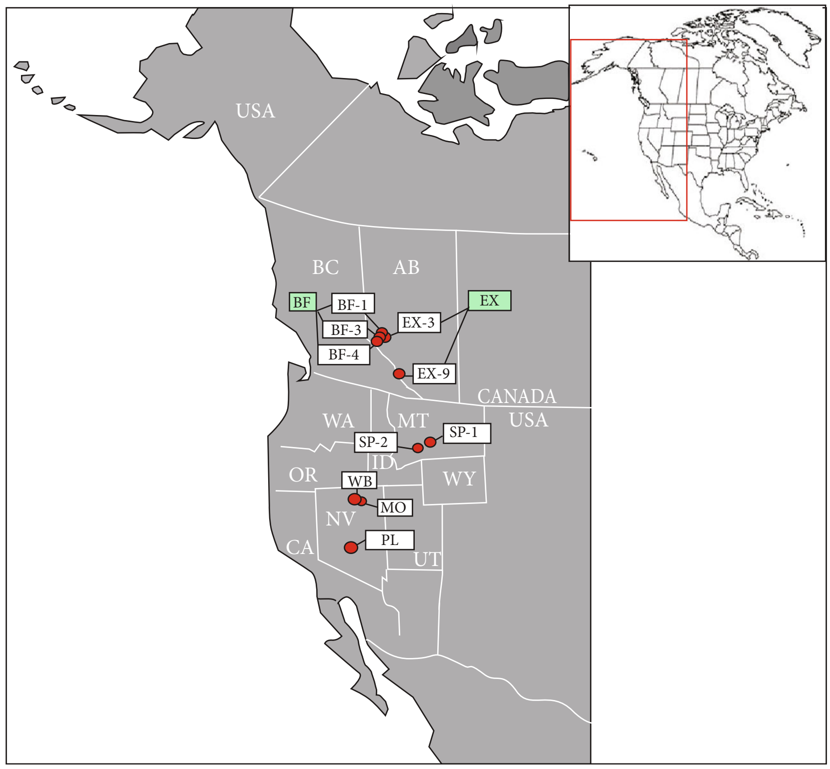


Figure 2: Map showing the approximate geographic location of collected DZ samples in this study (only western provinces and states are shown in the grey outline).

wall of the subduction systems without any arc collision; (II) dextral-oblique convergence along the western margin whereby terranes were transported from the peri-Gondwanan realm, around the southern margin of Laurentia to the paleo-Pacific Ocean leading to juxtaposition of arc fragments and Roberts Mountain allochthon against the Laurentian margin [28]; or (III) sinistral-oblique plate convergence and microplate accretion (e.g., [5, 7, 11, 29]) that invoke the north to south juxtaposition of Baltican, Caledonian, or Peace River Arch-affinity terranes along the western Laurentian margin. Alternative, but more controversial, models suggest that the overall history of western Laurentia was marked by westward subduction of the North American plate and Mesozoic collision with a composite interoceanic arc terrane [30] or "ribbon continent" [31] and thus refute the occurrence of the Antler orogeny. However, these models are precluded by stratigraphic continuity across the southeastern Canadian Cordillera [32] and contiguous Proterozoic and Cambrian geology across the theoretical Mesozoic suture, including remarkable east-west continuity of Cambrian detrital zircon facies combined with north-south variation [33, 34].

2.2. Antler Orogeny Spatial Extent and Control on Sedimentation. A potential continuation of the Antler belt to the north of Idaho and south of central Nevada has been obscured by younger tectonic and magmatic events that reworked the continental crust [35]. Nevertheless, it has been suggested that the northwestern and central western margin of Laurentia (Alberta and Montana) recorded an Antler-related compression and uplift [3]. A discontinuous orogenic belt, known as the Cariboo orogen and a possible extension of Antler orogen, existed to the west of Canada [36, 37]. Westerly derived sandstone and conglomerate interpreted as remnants of an easterly prograding clastic wedge, and contemporaneous granitic plutonism and volcanism in today's British Columbia and Yukon are inferred as a record of this orogenic activity [10, 38, 39]. Several authors have proposed that the Antler orogeny affected the morphology of western Laurentian basins throughout the Famennian time (e.g., [5, 13]). Deposition of Late Devonian to Early Carboniferous sediments (e.g., the Exshaw and Banff formations in western Alberta and Sappington Formation in southwestern Montana) along the western margin of Laurentia may have recorded a shift in the depositional style and sediment provenance (e.g., [4, 6]). Shallowing, unconformities, and influx of clastic sediments in the latest Devonian followed by rapid subsidence and deposition of thick carbonate succession in the early Mississippian are consistent with deposition of DC strata in an Antler foreland basin that likely extended from western Alberta to southern Nevada (e.g., [5, 25, 40]) (Figure 1).

3. Methods

3.1. Samples. Samples were collected executed along a north-south transect representing the Late Devonian to Early Mississippian western margin of Laurentia (Figures 2 and 3). Samples were collected from four distinct sample locations: (1) two siltstones from the lower Tournaisian upper member

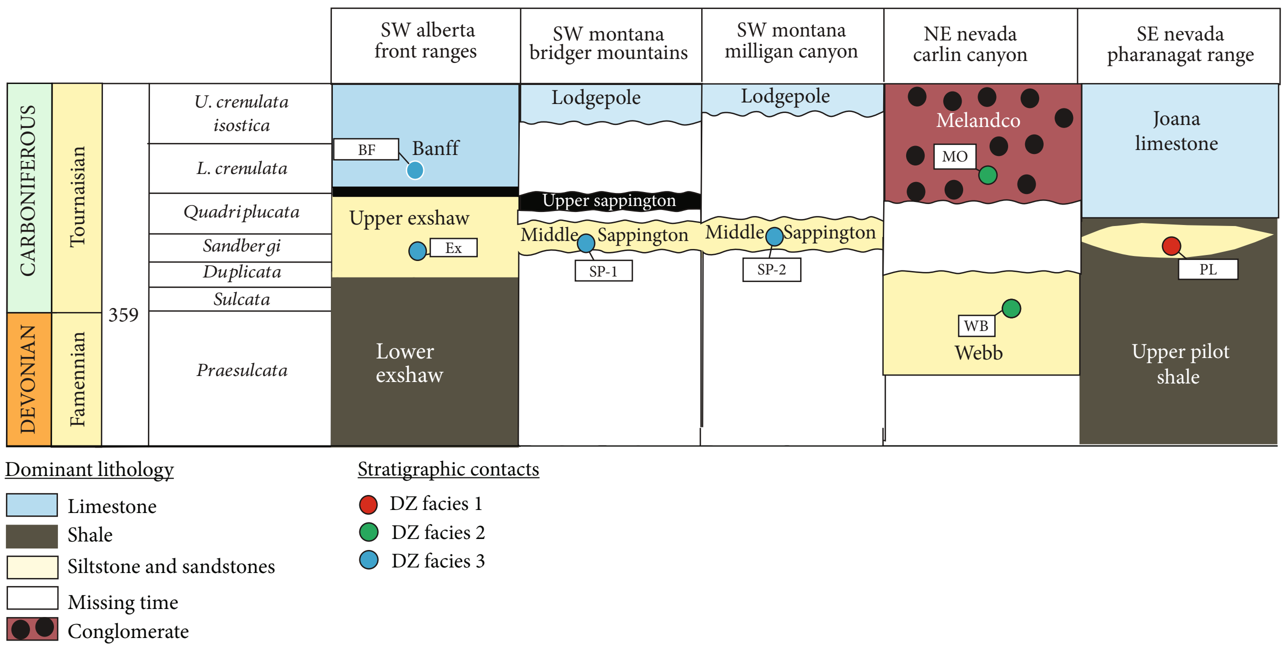


Figure 3: Ages, biostratigraphic zones, lithostratigraphic units, and stratigraphic locations of detrital zircon samples in this study.

of the Exshaw Formation (EX-3 and Ex-9) in southern Alberta that were combined into a composite sample EX and three silty-limestones from the lower to middle Tournaisian Banff Formation (BF-1, BF-3, and BF-4) that were combined into one composite sample BF; (2) two sandstones from the lower Tournaisian Middle Member of the Sappington Formation (SP-1 and SP-2) in the Bridger Mountains of southern Montana; (3) one sandstone from the upper Famennian Webb Formation (WB) and one chert conglomerate from the lower to middle Tournaisian Melandco Formation (MO) in Carlin Canyon near Elko in northeastern Nevada; and (4) one sandstone sample from upper Famennian Pilot Shale (PL) in the Pahranagat Range, near Alamo in southern Nevada (Table 1). Multiple thin sections were cut and used to conduct petrographic study on the sampled intervals (see supplementary file stratigraphy and petrography, Figure S1).

3.2. U-Pb Geochronology. Samples were processed and measured using the method outlined in Mathews and Guest [41]. We measured up to 300 grains per sample. Isotopic ratios were calibrated using FC-1 [42], and four reference materials with ages ranging from Neoarchean to Paleogene were used to validate the results. Data reduction was performed in iolite (V2.5; [43]) using the VisualAge data reduction scheme [44]. Data were filtered using a probability of concordance algorithm [41, 45, 46]. Grains yielding a probability of concordance < 1% were removed from the dataset. The $^{206}Pb/^{238}U$ ratio was used for grains yielding dates < 1500 Ma, and the $^{207}Pb/^{206}Pb$ isotopic ratio was used for grains yielding dates > 1500 Ma because numerous authors have noted that $^{206}Pb/^{238}U$ dates yield lower uncertainties for younger dates on average, whereas $^{207}Pb/^{206}Pb$ dates yield lower uncertainties for older dates (e.g., [41, 46, 47]). Moreover, for a large number of measurements, Spencer and Kirkland (2016) noted that the optimum cutoff between the $^{206}Pb/^{238}U$ and $^{207}Pb/^{206}Pb$ isotopic systems was 1500 Ma (see supplementary file method setup).

4. Results

To provide a framework for the interpretation and discussion of the DC provenance patterns in western Laurentia, samples were grouped into detrital zircon facies (DZ facies) based on similarities in the relative proportions of their major zircon subpopulations. A DZ facies is defined as large bodies of genetically related rocks that exhibit reproducible detrital zircon age distributions due to similarities in the rock's source regions, mixing, and homogenization of sediments in the depositional system [48]. Detrital zircon facies are not restricted to single formations, and each facies can be found in samples from several formations [34]. Visual inspection of normalized probability density plots was used to divide the detrital zircon populations into three DZ facies. This was done based on grouping of samples and integration of their known geographic distribution and studied formations (Figure 4). A summary of results is found in Table 2.

DZ facies 1 occurs in southern Nevada. It comprises samples from the Upper Devonian Pilot Formation (PL-1, $n = 144$; mode 1430 Ma). This DZ facies displays a dominant DZ subpopulation of 1460-1320 Ma with subordinate subpopulations of 1900-1600 Ma and 1000-1020 Ma and minor 440 to 348 Ma. The youngest grain in this population is 348 ± 12.1 Ma and is close to the depositional age of the sample.

DZ facies 2 is found in northeastern Nevada. It comprises samples of the Upper Devonian Webb Formation (WB: $n = 166$; mode 1030 Ma) and Lower Carboniferous Melandco Formation (MO: $n = 218$; mode 1822 Ma) (Figure 4). This DZ facies is marked by one main population

TABLE 1: Geographic location and GPS coordinates of the collected DZ samples in this study from Alberta (AB), Montana (MT), and Nevada (NV). Datum: WGS 84. NTS: National Topographic System grid in Canada.

Sample ID	Location	Formation	Age	NTS	Latitude	Longitude	Number of measurements	Number of accepted dates
BF-1	AB-Jura Creek	Banff	Early Mississippian	82 O/3	51 05′29″N	115 09′29″W	49	21
BF-3	AB-Lafarge quarry	Banff	Early Mississippian	82 O/3	51 03′51″N	115 10′58″W	33	5
BF-4	AB-Gap Lake	Banff	Early Mississippian	82 O/3	51 03′02″N	115 14′34″W	44	21
EX-3	AB-Lafarge quarry	Exshaw	Devonian-Mississippian	82 O/3	51 03′51″N	115 10′58″W	162	93
EX-9	AB-Crowsnest Pass	Exshaw	Devonian-Mississippian	82 G/10	49 37′31″N	114 38′50″W	21	12
SP-1	MT-Bridger Range	Sappington	Devonian-Mississippian	NA	45 54′10″N	110 58′23″W	300	193
SP-2	MT-Milligan Canyon	Sappington	Devonian-Mississippian	NA	45 25′51″N	111 40′18″W	199	134
MO	NV-Carlin Canyon	Melandco	Early Mississippian	NA	40 52′26″N	116 12′22″W	296	218
WB	NV-Carlin Canyon	Webb	Devonian-Mississippian	NA	40 52′26″N	116 12′22″W	300	166
PL	NV-Pahranagat Range	Pilot	Devonian-Mississippian	NA	37 14′3.7″N	115 19′43″W	218	144

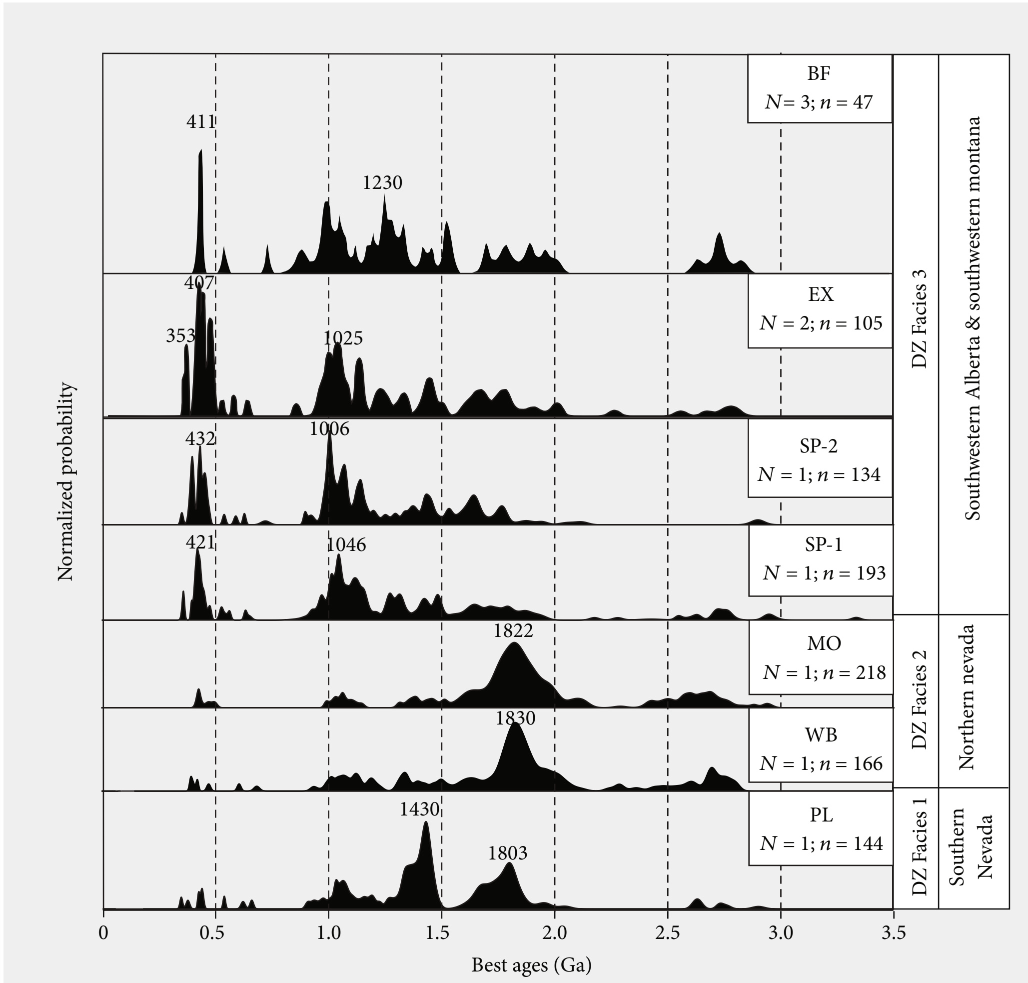


Figure 4: Normalized probability density plots of detrital zircon data from Devonian-Carboniferous strata of western Alberta, southwestern Montana, and northern and southern Nevada with geographic location and DZ facies. Sample labels, number of rock samples (N), and DZ number per sample (n) are shown in boxes on the upper right corner of density plots.

of 2000-1740 Ma with minor 1250-1000 Ma, 490 to 392 Ma, and 3000-2500 Ma populations. The youngest grain, at 392 ± 11.6 Ma, is older than the depositional age.

DZ facies 3 is found in southwestern Alberta and southwestern Montana. It contains samples from the Exshaw, Sappington, and Banff formations: EX ($n = 105$; modes 407 Ma and 1025 Ma), SP-1 ($n = 193$; modes 421 Ma and 1006 Ma), SP-2 ($n = 134$; modes 432 Ma and 1046 Ma), and BF ($n = 47$; mode 411 Ma and 1230 Ma) (Figure 4). This DZ facies is marked by three main populations of 480-370 Ma, 1250-940 Ma, and 1500-1400 Ma with scattered 3000-2500 Ma grains. See supplementary material Table DR1 for the full dataset.

5. Interpretation

5.1. Detrital Zircon Facies Distribution. Comparison of the DZ facies from the DC strata of western Laurentia reveals five major detrital zircon subpopulations that vary in prominence based on their geographic location along a north-south transect (Figure 5): (1) the Archean subpopulation (3000-2500 Ma) is found in all the DZ facies in all samples in variable but low (<10%) proportions; (2) Paleoproterozoic (ca. 2000-1.600 Ma; mode at 1823 Ma) is found in northern Nevada and as a secondary peak in southern Nevada; (3) Early Mesoproterozoic (ca. 1500-1300 Ma; mode at 1430 Ma) is found in southern Nevada; and then (4) Mesoproterozoic to Early Neoproterozoic (ca. 1250-950 Ma; mode at 1036 Ma) and (5) Ordovician-Silurian to Devonian (ca. 440-351 Ma, mode at 392 Ma) are both found mainly in central western Laurentia (Alberta and Montana). Those two subpopulations also can be found in south and northern Nevada. Relative proportions of these major populations are discussed below and are used to interpret Devonian to Carboniferous provenance patterns (Table 2).

5.2. Geological Provinces of Laurentia. Proterozoic and Archean aged geological provinces of Laurentia provide distinguishable crustal fragments with distinctive DZ ages (e.g., [49]). Most DZ in the mid-Devonian to mid-Mississippian Kaskaskia sequence ultimately derive from these two crystalline sources (Figure 6). Grains older than 2500 Ma in all the

Table 2: Summary of results with DZ facies.

DZ facies	Geographic location	Paleogeographic location	Samples	Prominent subpopulations in order of prominence (Ma)	DZ facies age peaks in order of prominence (Ma)	Number of best ages	Youngest grain (Ma)
DZ facies 1	Southern Nevada	Southern Laurentia (southern region)	PL	1460-1320, 1900-1600, 1100-1020	1430, 1800, 1033, 443	139	348 ± 12.1
DZ facies 2	Northern Nevada	Southern Laurentia (northern region)	MO and WB	2000-1700, 2750-2600, 1250-1000, 420-392	1823, 2702, 1120, 423	383	392 ± 11.6
DZ facies 3	Southwestern Alberta and southwestern Montana	Central Laurentia	EX, BF, SP-1, SP-2	480-370, 1250-940, 1500-1400	411, 1036, 1153, 1463	489	340.9 ± 6.6

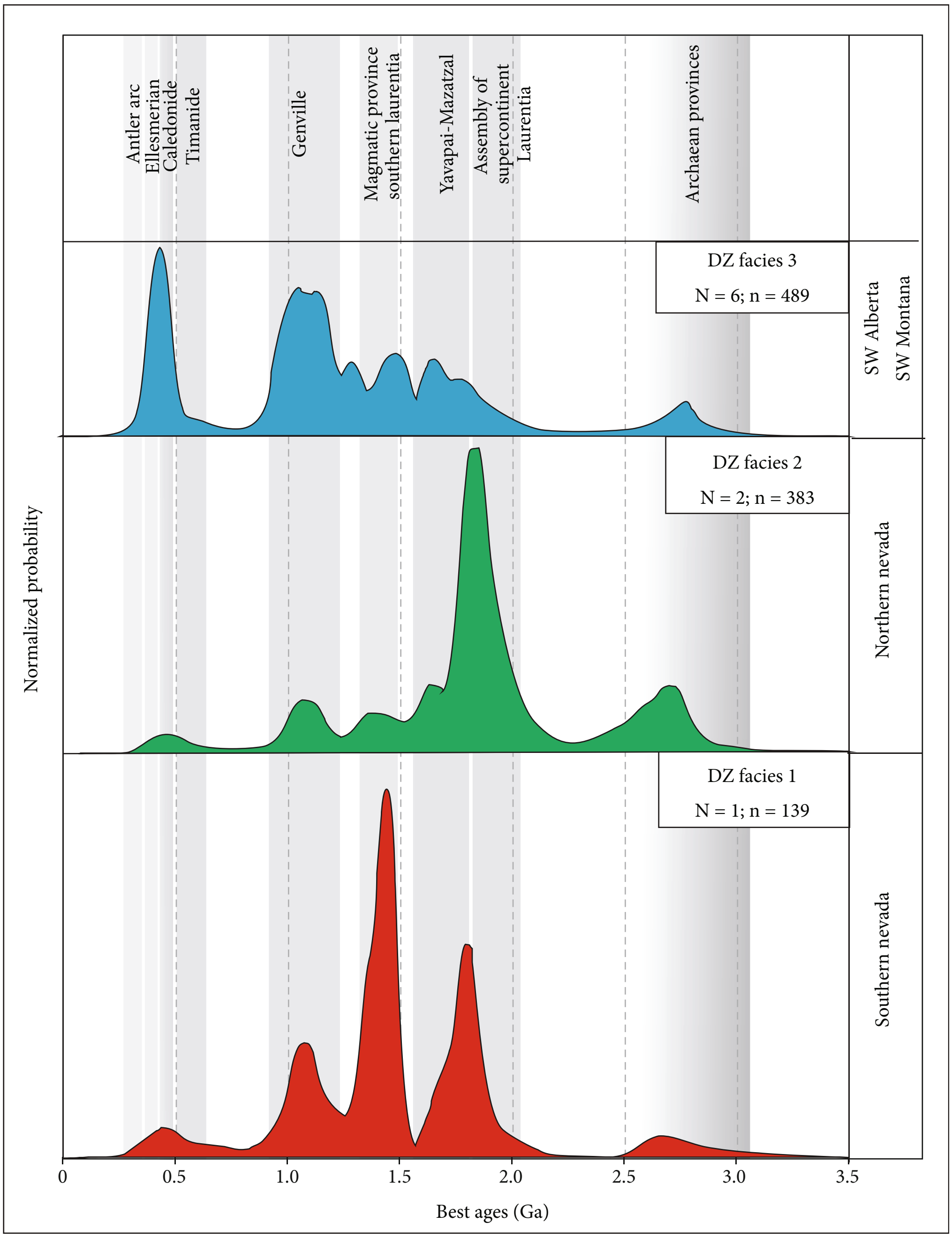


FIGURE 5: Normalized probability density plots of detrital zircon facies from DC strata of western Laurentia.

DZ facies are consistent with ultimate sources in the Hearne, Wyoming, and Superior provinces and Mojavia that form the oldest rocks of the Laurentian craton [49, 50]. Zircon grains yielding dates between 2400 Ma and 1800 Ma derive from Proterozoic orogenic belts and the associated accreted terranes that stitch together the Archean cratonic provinces. Late Paleoproterozoic grains between 2000 and 1600 Ma (mode 1800 Ma) derive from a collage of Proterozoic orogenic provinces and their associated accreted terranes. In DZ facies 1 and DZ facies 2, grains yielding dates between 1800 Ma and 1600 Ma associated with grains yielding 1480–1340 Ma with a prominent Mesoproterozoic mode at 1430 Ma mode indicate provenance from the Yavapai and Mazatzal provinces to the south and the extensive A-type plutons that intrude them [51]. In DZ facies 1, zircon grains yielding dates between 1250 Ma and 1000 Ma are indicative of Grenville terranes that bounded Laurentia to the east and south as a record of the assembly of the supercontinent Rodinia. The Grenville orogen and associated foreland deposits and arcs of southern and eastern North America (Figure 6) were only a significant easterly sediment source for WL throughout the Neoproterozoic [14, 51, 52] prior to the uplift of the Transcontinental Arch (TCA) [53]. Neoproterozoic to early Paleozoic detrital zircons (600-500 Ma) are found and derive from rifting and magmatism. The latter grains are associated with crustal thinning during deposition

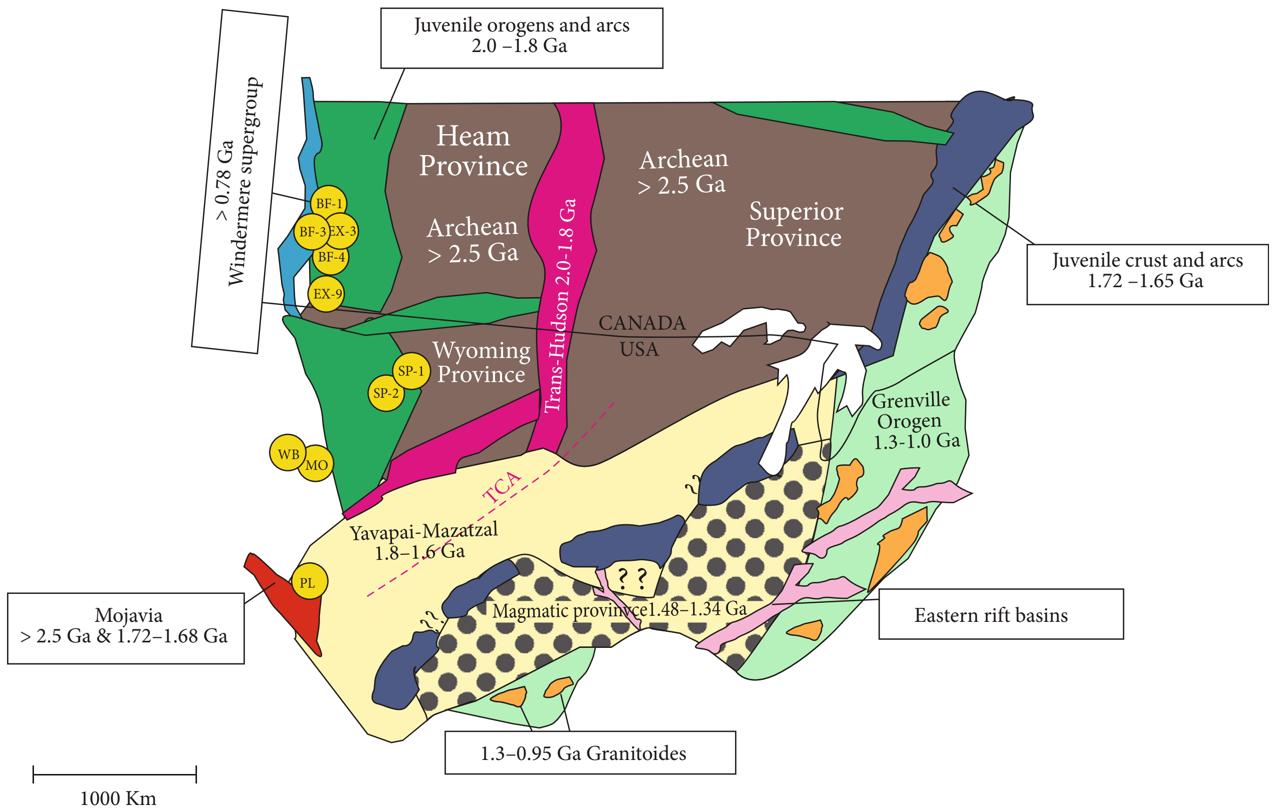


Figure 6: Simplified map locations of the main Archean through Neoproterozoic basement features of Precambrian North America (Laurentia). Figure modified after Whitmeyer and Karlstrom [49] and references therein. The pink dashed line is showing the location of the Transcontinental Arch (TCA). Yellow circles show the approximate location of collected samples in this study.

of the Windermere Supergroup and the development of the western Laurentian passive margin in the latest Neoproterozoic to Cambrian. Mid-Paleozoic grains (380-340 Ma) are close to depositional ages and indicate derivation from volcanic arcs in or near Laurentia.

5.3. Role of Recycling. Owing to the refractory nature of sand-sized detrital zircon grains and their ability to survive multiple cycles within sedimentary systems while retaining U-Pb crystallization ages as a record of their ultimate sources, recycling of detrital zircon through sedimentary systems should be considered the primary sourcing mechanism for Paleozoic strata (e.g., [54–56]). In western Laurentia, Proterozoic and lower Paleozoic siliciclastic successions are major detrital zircon reservoirs and are marked by detrital zircon facies that are found in unique geographical regions reflecting proximity to the major tectonic provinces of Laurentia [57]. Overall, the western margin of Laurentia is marked by detrital zircons derived from older successions with a north-south variation in detrital zircon facies—yet east-west continuity [34]. Below we examine the south to north detrital zircon distribution and their sources.

5.4. Southern Nevada: DZ Facies 1. The overall DZ age signature (dominant age peak of 1430 Ma with subordinate ca. 1050 Ma and 1800 Ma) of the Pilot Formation suggests mixed but local sourcing into the Pilot Basin during the Late Devonian and Early Carboniferous. Proximal sourcing is further indicated by the textural and mineralogical immaturity (poorly sorted lithic arenite) of the Pilot Formation sandstones (Figure 7) (see supplementary file stratigraphy and petrography, Figures S1A and S1B). Recycling of lower Paleozoic strata of southwestern Laurentia and possible sourcing from Pikes Peak batholith [58] and/or other as-yet unidentified similar age plutons in the region seem to be the dominant processes of sediment delivery into the Pilot Basin. Except for the mid-Paleozoic grains, the Pilot sandstone has similar detrital zircon spectra to Cambrian strata to the east and northeast: the Flathead Sandstone of southernmost Wyoming, the Tapeats Formation of Nevada [34], the Pikes Peak batholith in Colorado, and the Prospect Mountain Formation in western Utah [19] (Figure 7). Recycling of Cambrian strata also explains the occurrence of grains with Grenvillian ages (1250-1000 Ma) in the Upper Devonian and Lower Carboniferous strata. Throughout the early to mid-Paleozoic, Cambrian strata were a considerable reservoir for these ages along with the Yavapai-Mazatzal (1600-1800 Ma) provinces and midcontinent granite (1400 Ma) ages after the uplift of the TCA that blocked the direct transport of Grenvillian grains to WL [52, 59]. The 440 to 348 Ma grains are consistent with ages found to the west in eastern Klamath rocks in Northern California and are suggested to be derived from a mid-Paleozoic to Late Devonian volcanic arc to the west [22].

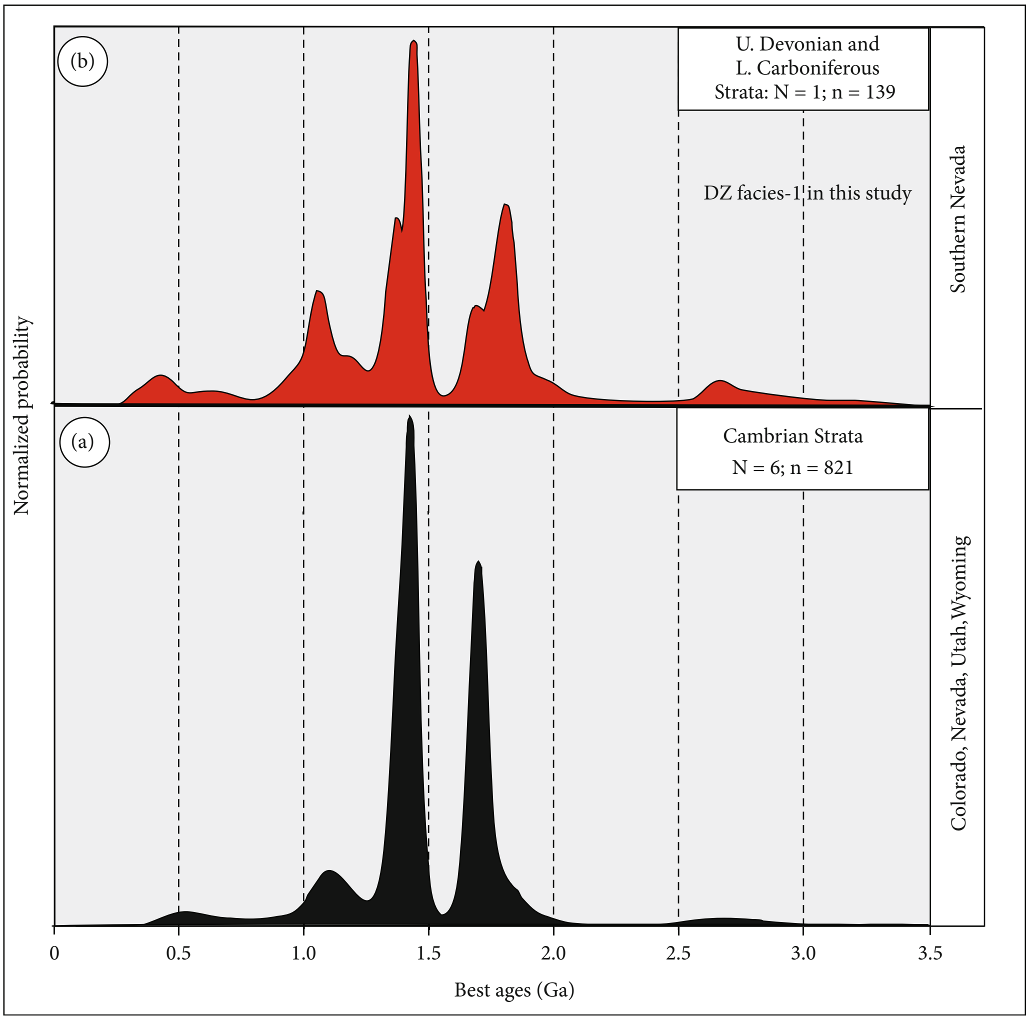


FIGURE 7: Detrital zircon reference frames for Devonian to Mississippian strata in southern Nevada: (a) Cambrian strata in Colorado, Nevada, and Wyoming from Matthews et al. [34] and Cambrian strata in Utah from Yonkee et al. [19]; (b) Devonian to Mississippian strata in southwestern Nevada from this study (DZ facies 1).

5.5. Northern Nevada: DZ Facies 2. The youngest ages in DZ facies 2 are Silurian (419.8 ± 18.4 Ma) and Early Devonian (392 ± 11.6 Ma) (Figure 5). These ages predate the depositional ages of the Webb and Melandco formations by ~40 to 60 Myr. DZ facies 2 is strikingly similar to results from lower Ordovician Valmy and Eureka formations in Northern Nevada [60, 61], Carboniferous deposits from northern Nevada (Battle and Tonka formations [60]), and southern Idaho (Copper Basin Group and Salmon River Formation in the Pioneer Mountains of Idaho [11]) (Figure 8). This suggests that DZ signatures of the Webb and Melanco formations (DZ facies 2) likely reflect recycling of lower Paleozoic strata since the latest Devonian and lasted throughout the Carboniferous. Recycling of Paleozoic strata from the south and to the east is less likely because of lack of ca. 1430 Ma ages characteristic of the Cambrian strata in the area (e.g., [19, 34, 61]) (Figure 8). Uplifted pre-Cambrian and Cambrian strata on the western flank of the Transcontinental Arch are expected to supply the basins to the west with ca. 1400 Ma grains, a characteristic signature of the midcontinent magmatic province (1340-1480 Ma) [51]. Sourcing from the north would imply that northern Nevada and southern Idaho strata should have similar DZ signatures to DZ facies 3 in Alberta and Montana which is not the case (Figure 5). In the vicinity of our study area, Upper Devonian sediments of the Pioneer Mountains in Idaho are characterized by DZ spectra similar to DZ facies 2 and are marked by evolved Hf isotopes [11]. It has been suggested that sediments in the area were derived from the erosion of a Paleozoic arc built on Proterozoic crust [10]. Paleoproterozoic (2000-1800 Ma) and Ordovician to Devonian ages (380-480 Ma) are found to have Yreka and Trinity subterranes of the eastern Klamath terrane's assemblage (Gazelle, Duzel, and Sissel Gultch formations) to the west of our study area [22] suggesting that these could be source terranes for Silurian to Devonian grains in DZ facies 2. Conglomerate and arenite samples in this study consist of poorly sorted sandstone indicating proximal sourcing. A plausible source of DZ facies 2 grains is uplifted Paleozoic strata to the west of the basin, implying westerly sourcing. Yet the lack of syndepositional zircons in DZ facies 2 is enigmatic. This suggests that the basin was far from the arc or on the opposite side of

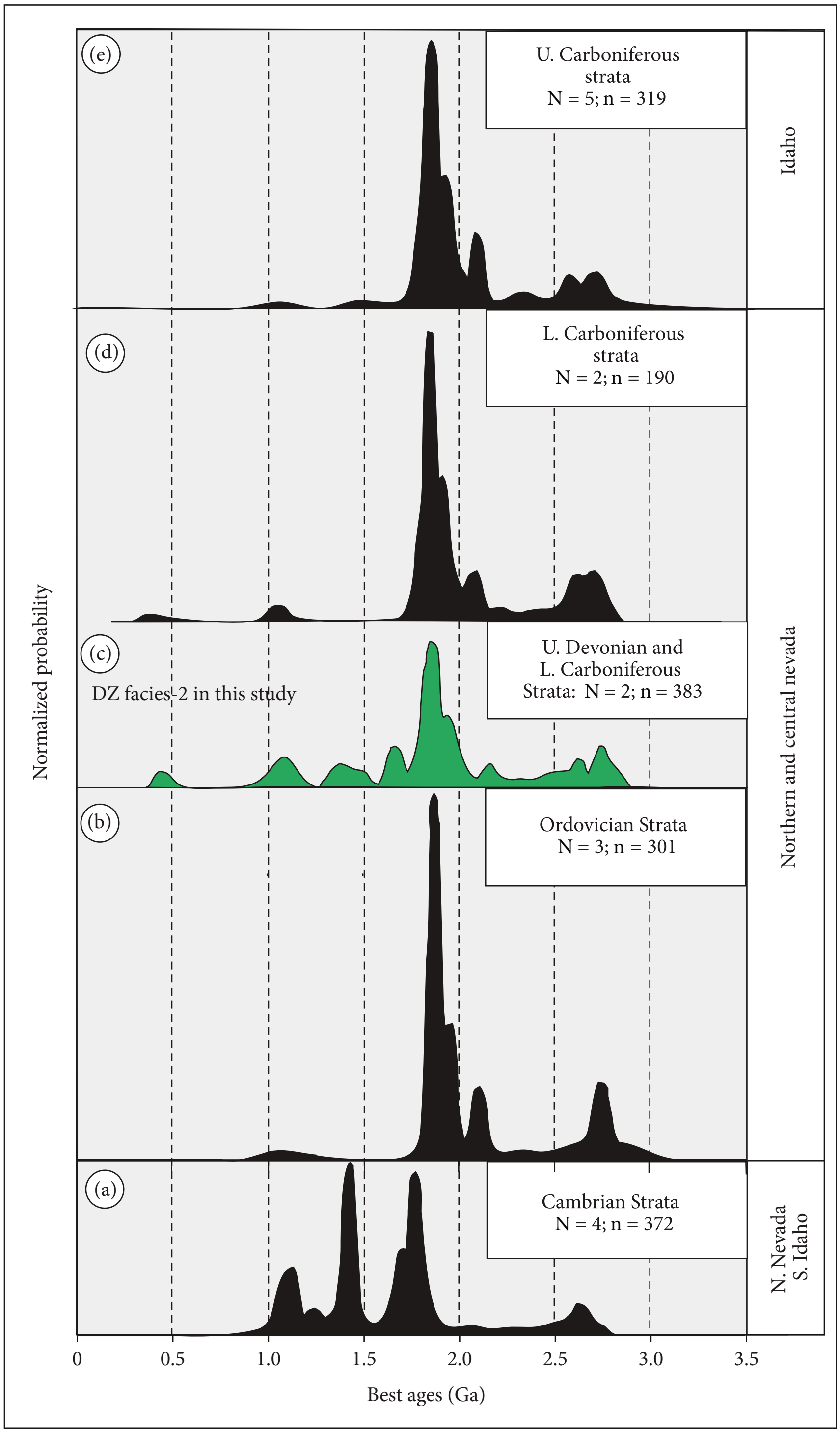


Figure 8: Detrital zircon reference frames for Devonian to Mississippian strata in northern Nevada: (a) Cambrian strata: Osgood Mountain Formation, Osgood Mountain Nevada [60, 61]; lower Cambrian Camelback Mountain Formation in Pocatello, Idaho [19]; (b) Ordovician strata: Valmy and Eureka formations in northern Nevada [60]; (c) Devonian to Mississippian strata in northern Nevada from this study (DZ facies 2); (d) Carboniferous strata: Battle and Tonka formations [60]; (e) Upper Carboniferous strata: Copper Basin Group and Salmon River Formations in the pioneer mountains of Idaho [11].

the basin from the arc (e.g., [11]). However, ash transport of zircon from the arc could have supplied the basin with near-depositional age grains. This processes have been suggested to bring abundant near-depositional age grains to the Upper Cretaceous in the Alberta basin from the Coast Mountains Batholith 500 km to the west [62]. It is possible that ash was not preserved or in the Late Devonian, wind patterns diverted ash clouds away from the Pilot basin.

5.6. Alberta and Montana: DZ Facies 3. Occurrences of bentonite (altered volcanic ash) beds in the Exshaw, Banff, Sappington, and Lodgepole formations [63] and reported ultramafic intrusions from northeastern British Columbia dated to 365.9 ± 2.1 Ma, 359.4 ± 3.4 Ma, and 353.3 ± 3.6 Ma [64] suggest a convergent margin setting in northwest Laurentia (e.g., [5, 6, 64]) during this time. DZ facies 3 found in the Exshaw, lower Banff, and Sappington formations displays dominant ages between ca. 440 and 360 Ma with a subordinate population of ca. 1250-1000 Ma and some grains that overlap with depositional ages at ca. 360-340 Ma. Occurrence of Grenville orogen ages (ca. 1250–1000 Ma) in DZ facies 3 spectra suggests that these deposits were not recycled from local Laurentia passive margin sequences such as upper Neoproterozoic and Cambrian strata to the east which prominently exhibit 1800 Ma age peak [20, 34] (Figure 9). Limited amount of 1800–1600 Ma (Yavapai-Mazatzal) and 1480–1340 Ma (midcontinent granite-rhyolite) grains suggests the unlikelihood of sourcing from the south, where Grenvillian ages are found in Cambrian and Precambrian strata (e.g., [14, 61, 65]). Sourcing from the north is a possibility but unlikely. Workers have suggested that during the latest Devonian and throughout the Carboniferous, sediments were shed from the Arctic southward and westward by marine and pan-continental terrestrial transport systems [17, 66] based on occurrence of Grenvillian ages in the Carboniferous strata such as the Mattson delta complex of Yukon, northwestern Canada. Ellesmerian foreland strata in the Canadian Arctic Islands recorded the erosion of terranes and accreted arcs along northern Laurentia with northern Caledonian crustal affinities [16] (Figure 9) and therefore contain Silurian to Devonian ages (ca. 440 to 386 ± 13 Ma) and Genvilian ages [67]. We argue against the provenance from the Arctic because of the paucity of the 700-500 Ma population in DZ facies 3. With modes at ca. 1036 Ma and 418 Ma, DZ facies 3 contrasts with ages obtained from Upper Devonian Ellesmerian strata, which exhibit a strong ca. 536 Ma mode and a dominant 500-700 Ma population in the western part of the Canadian Arctic Islands and Northwest Territories of Canada [12] (Figure 9). Additionally, northerly sourcing calls for detrital zircon transport from the Canadian Arctic down to southern Alberta and Montana over 2000-3000 km. Such transport distance would have thoroughly reworked the sediments of the Exshaw, Sappington, and Banff formations. Yet the detrital material of these formations is moderately immature mineralogically and texturally (see supplementary file stratigraphy and petrography, Figures S1C and S1D) with considerable amount of feldspar and lithic fragments suggesting more proximal sourcing.

Westerly sourcing is a plausible hypothesis because the Mesoproterozoic detrital zircon grains hosted by older strata occur in the west and do not require transport from a long distance source. There are abundant potential recycled sources of detrital zircon with Grenvillian ages (1250-1000 Ma) in the cordillera that extend from Washington through southern to northern British Columbia (BC) such as Neoproterozoic rift deposits of the Toby Conglomerate in eastern BC [20] and the lower Neoproterozoic Buffalo Hump sandstone of Washington [68] (Figure 9). 1300–1000 Ma ages were reported from Yukon, located to the northwest of our study, as record of late Mesoproterozoic metamorphism and magmatism in the crust beneath northern Yukon [69]. Moreover, Grenvillian ages also occur in the older Devonian strata such as the Sassenach Formation of the Jasper Basin in the Alberta Rocky Mountain fold-and-thrust belt [8]. Detrital zircon close to depositional ages between ca. 359 ± 10 Ma and 340 ± 6.6 Ma in DZ facies 3 (this study) is interpreted to reflect a provenance from a Devonian to Carboniferous active nearby volcanic arc to the west. A suspect source terrane with a Mesoproterozoic basement and a Paleozoic arc might have been present along the outboard edge of the Canadian Cordilleran margin (e.g., [11, 62, 70]). The younger ages of DZ facies 3 match ages found in the mid-Paleozoic Chilliwack arc terrane in northwestern Washington or the Devonian plutons of the Yukon-Tanana terrane. Both the Chilliwack and Yukon-Tanana terranes display Paleozoic arc ages with a strong signature of Paleoproterozoic basement (ca. 1800 Ma mode) [71, 72]. However, the Chilliwack composite terrane displays 1250-1000 Ma ages found in DZ facies 3 (absent in Yukon-Tanana terrane) and 500-400 Ma, with a pre-Devonian high-grade metamorphism and plutonism [71]. This suggests that the Chilliwack terrane or a terrane of similar geology might have been the suspect source of these westerly derived sediments.

6. Discussion

6.1. Paleogeography and Existing Models for the Antler Orogeny. The history of Western Laurentia seems to be marked by alternation of tectonic pulses and quiescence since the middle Paleozoic [5]. Beyond the limit of the Robert Mountain allochthon, the geological setting of the Devonian to Carboniferous interval of western Laurentia is still unclear. However, geological evidence suggests that the margin had evolved into a convergent setting by the Devonian (e.g., [73]). Overall, occurrence of syn-depositional age peaks around ca. 360-340 Ma, ash beds in the Exshaw, Banff, and Lodgepole formations, plutons in northeastern BC (e.g., [6]), recognized mid-Paleozoic deformation and metamorphism, sediment-hosted sulfide deposits (e.g., [2, 74, 75]), and regional unconformities support the evidence of syn-depositional volcanism connected to a subduction complex and tectonism to the west. Our sediment provenance study results are consistent with a convergent plate setting along western Laurentia, whereby a sediment source shifted from easterly during the Neoproterozoic to mid-Paleozoic [20, 34], to westerly during the Late Devonian to Early Carboniferous. These source areas might have been part of the so-called Antler hinterland. Combined with uplifted Laurentian strata, these westerly positioned source areas supplied an Antler foreland basin with sediments derived from erosion of older strata (e.g., [8, 57, 60, 61, 71, 76]). Evidence for westerly derived sedimentation is less prominent in southwestern Laurentia (southern Nevada) with dominant source areas located to the east relatively to central

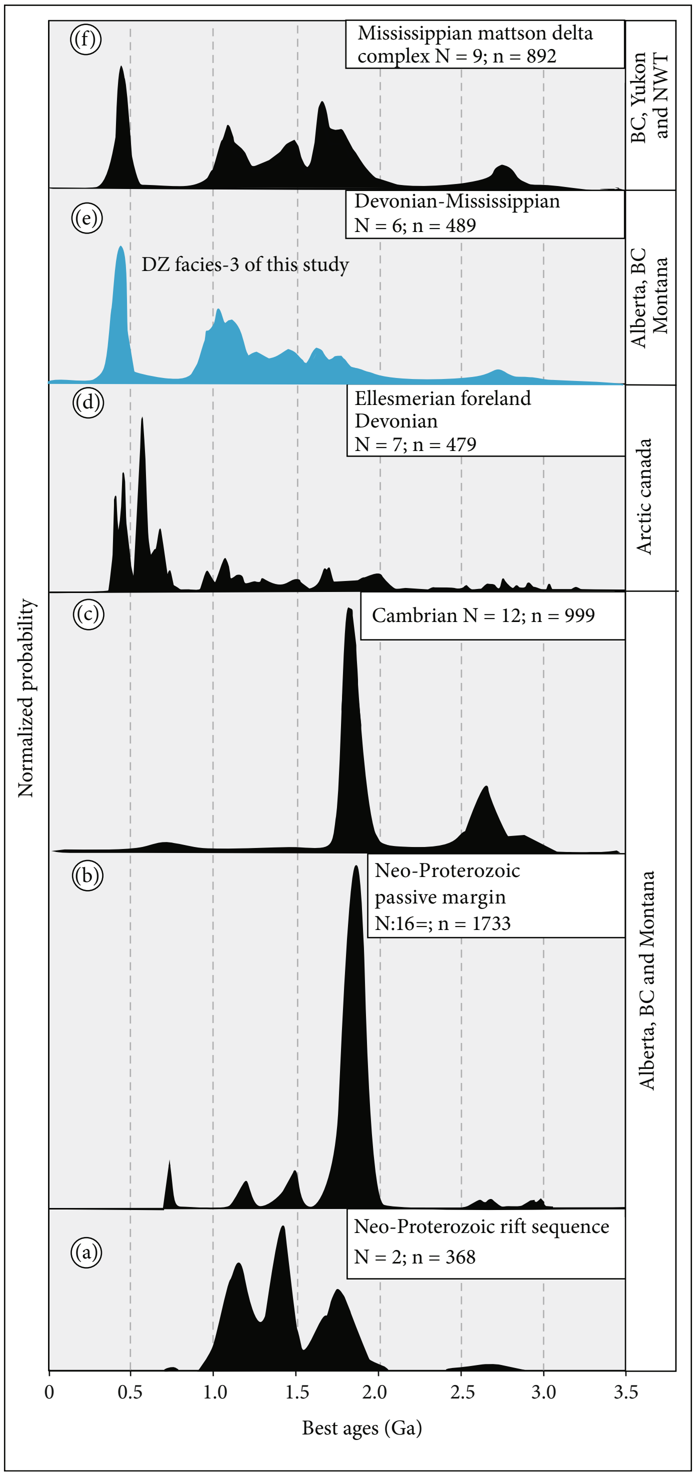


FIGURE 9: Detrital zircon reference frames for Devonian to Mississippian strata in Alberta and Montana: (a) Neoproterozoic passive margin sequence in western Canada [20]; (b) Neoproterozoic Toby Formation, eastern British Columbia (BC) [20]; (c) Cambrian strata in Alberta, BC, and Montana [34]; (d) Devonian arctic clastic wedge [16]; (e) Devonian to Carboniferous strata in Alberta and Montana (DZ facies 3); (f) Mississippian Mattson delta complex in Yukon [17].

WL (Alberta and Montana and northern Nevada) where most source areas are located to the west (Figure 6). However, Silurian to Devonian detrital zircon ages (ca. 400-390 Ma) are present in southern Nevada. This might indicate that the Pilot basin of southern Nevada was located near the eastern edge of the foreland basin or beyond the extent of the Antler orogen.

6.2. Origin of the Antler Terranes. While the mid Paleozoic tectonic setting and dislocation history of terranes and

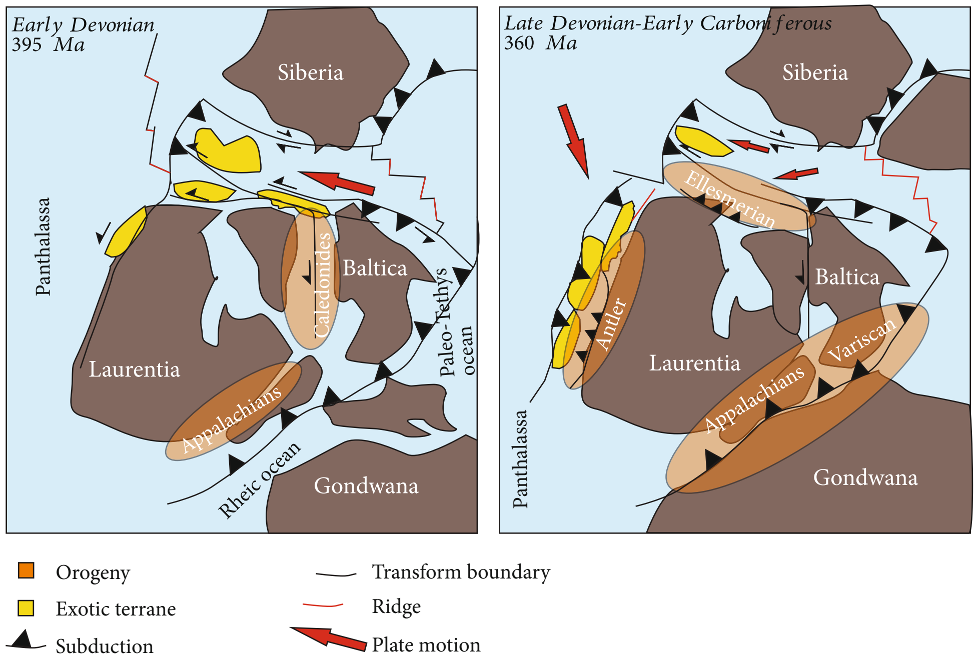


FIGURE 10: Paleogeographic reconstruction after Colpron and Nelson [13]. "Northwest Passage" model showing Early to Late Devonian plate configuration and exotic terrane motion around northern and western Laurentia leading to the Antler orogeny in the latest Devonian to earliest Carboniferous.

associated orogenies including the Antler orogeny fits within the context of this work, the origin of terranes involved in the Antler orogeny is beyond the scope of this study. Based on our demonstration of westerly sourcing of sediments to western Laurentian basins during the DC, we support a late Paleozoic convergent setting for western Laurentia. We only examined existing models in a conservative manner (e.g., [13, 22, 28]) (Figure 10). In the south, the RMA might be a mix of cratonic western Laurentian and exotic arc provenance [9, 22]. In central Laurentia, early generally accepted models hypothesized that the terranes consisted of pericratonic extensive magmatic arcs and associated fringing basins (e.g., [77]). However, recent studies suggest that early Paleozoic arc terranes that are found in today's California, Washington, British Columbia, and Alaska might have originated in the Arctic region of Laurentia, Baltica, or the Caledonides (e.g., [7, 11, 13, 29, 78]). Some of these terranes (e.g., YTT and Chilliwack) have detrital zircon populations with mid-Paleozoic ages partially similar to our DZ facies, and ostensibly they might be contributing source areas. Thus, we agree with workers favoring the Baltican origin for terranes bounding North America such as the Northwest Passage of Colpron and Nelson (2009) (e.g., [11, 61, 78]) (Figure 10).

7. Conclusion

(i) We show that the distribution of detrital zircon facies in the Devonian to Carboniferous strata of western Laurentia indicates north-south differences in detrital zircon facies, yet these facies have consistent character along east-west transects. This indicates that during the Late Devonian to Carboniferous, western Laurentia basins were locally sourced from various tectonic fragments with different signatures

(ii) In southern Nevada (southwestern Laurentia), striking similarities between the results of this study and detrital zircon data from Neoproterozoic and Cambrian strata in Nevada suggest that lower Paleozoic strata were recycled from the east with an input from an Ordovician-Devonian arc to the west

(iii) In northern Nevada (southcentral western Laurentia), comparison of our data with detrital zircon data from lower Paleozoic strata in Idaho and northern Nevada suggests that Devonian-Carboniferous (DC) strata were recycled from uplifted lower Paleozoic strata to the west with an input from an Silurian-Devonian arc to the west

(iv) In Alberta and Montana (central western Laurentia), Devonian to Carboniferous strata display dominant 440-360 Ma zircon age populations with Grenvillian ages between 1250 and 1000 Ma and some near depositional ages around ca. 360-340 Ma. These ages support the model of westerly sourcing of recycled uplifted Neoproterozoic strata yielding Mesoproterozoic and older detrital zircon with contribution of an active Antler volcanic arc to the west

(v) Coupled with other geological evidence such as occurrences of ash beds and lithological character of DC strata, DC plutonic and volcanic activity, Devonian high-grade metamorphism and deformation, and paleomagnetic data from various studies in the Cordillera, the findings of this study suggest that the Antler orogeny triggered a depositional shift to clastic sedimentation and controlled the sediment dispersal in western Laurentia during the Late Devonian and Early Carboniferous

Data Availability

Detrital zircon data can be found in a PDF file submitted with the manuscript as a supplemental material. Field data is included in the manuscript. Stratigraphic and petrographic data is attached as a supplemental material file.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this article.

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Supplementary Materials

Three (3) supplementary material files are included. A detrital zircon data table (DR1) file and a supplementary U-Pb geochronology method setup file. The additional file stratigraphy and petrography include stratigraphic and petrographic information of the studied lithostratigraphic units with Figure S1 (selected picture showing outcrops of sampled sections in Alberta, Montana, and Nevada) and Figure S2 (photomicrographs of immature sandstone and siltstone of the studied formations). *(Supplementary Materials)*

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