ABSTRACT

Late Neoproterozoic to Cambrian sandstone units are common in western Laurentia and record initial transgression of the craton after the formation of the western passive margin during the latest Neoproterozoic to earliest Cambrian. Detrital zircon measurements from 42 latest Neoproterozoic to Cambrian basal Sauk sequences and five older Neoproterozoic sandstone samples from a region extending from the Mexico–United States border to central British Columbia, Canada, are combined with previous results to characterize sediment source areas and dispersal systems. Detrital zircon populations in Neoproterozoic and Cambrian sedimentary rocks are divided into six facies based on a statistical comparison using multidimensional scaling. Detrital zircon facies are found in unique geographical regions reflecting proximity to the major tectonic provinces of Laurentia. Samples from northern regions are dominated by Archean and Paleoproterozoic zircons derived from Archean tectonic provinces and the orogenetic belts that record the assembly of the Laurentian craton. More southerly sample locations show an increase in detrital zircons derived from younger Paleoproterozoic orogenic belts and early Mesoproterozoic intrusive suites. Detrital zircons from Grenville-aged sources are common in the south. The Transcontinental Arch, a feature interpreted to have controlled large-scale sediment dispersal patterns in the mid- to late Cambrian, likely played a major role in isolating the southern and northern signatures. Our data set can be used to test tectonic models for the Cordilleran orogen that invoke Jurassic or Cretaceous collision of a ribbon continent as the driving mechanism for orogenesis. Cambrian rocks of the Cassiar-Antler platform juxtaposed with North America during the hypothetical ribbon continent collision show the same geographic distribution of detrital zircon facies as similar-aged rocks from autochthonous and paraautochthonous locations on the Laurentian margin. The concordance of detrital zircon facies across the proposed suture is a negative result for models that predict large dextral displacements, on the order of 2000 km, across the suture.

INTRODUCTION

Laterally persistent latest Neoproterozoic to Cambrian sandstone units mark the base of the western Laurentian passive margin succession (Sloss, 1963; Bond and Kominz, 1984; Lickorish and Simony, 1995; Fedo and Cooper, 2001), and are exposed along the length of the Cordillera from Mexico to the Northwest Territories of northern Canada (Stewart et al., 2001; Hadlari et al., 2012). These strata record the initial transgression of the Laurentian craton following the onset of thermal subsidence (Bond and Kominz, 1984; Bond et al., 1984, 1985; Levy and Christie-Blick, 1991; Yonkee et al., 2014) and cover an important period in the evolution of complex life (Marshall, 2006).

The widespread occurrence of sandstone facies suitable for detrital zircon geochronology, and the relatively limited time span of their deposition, make them ideally suited for understanding variations in provenance of Laurentia-derived detritus along the mobile Cordilleran margin. These variations provide useful constraints on the paleogeographic position of displaced crustal fragments in the Cordillera and contribute to a fuller understanding of large-scale early Paleozoic sediment dispersal patterns in Laurentia.

Previous studies of Neoproterozoic to Cambrian deposits in western Laurentia have been sub-regional in extent (e.g., Stewart et al., 2001; Amato and Mack, 2012) or incorporated only a small number of widely spaced samples (Gehrels et al., 1995; Gehrels and Pecha, 2014). These studies reveal that latest Neoproterozoic to Cambrian rocks exhibit significant geographic variation in detrital zircon populations, reflecting proximity to the major tectonic provinces of Laurentia. However, the wide sample spacing in previous studies and a lack of samples along the Canadian segment of the Cordillera and from the thin cratonic successions exposed in Laramide structures to the east has limited the usefulness of these variations in continent-scale paleogeographic reconstructions.

Here we report new detrital zircon results from Neoproterozoic and Cambrian sandstones in a ~1×10⁶ km² region extending from the southern United States to central British Columbia, Canada (Fig. 1). These data are integrated with previous studies to investigate large-scale provenance patterns in western Laurentia during the Cambrian. These results provide a baseline with which to compare Laurentia-derived detrital zircon populations in displaced terranes. As a first application of this new data set, we evaluate tectonic models for the Cordillera that involve the Cretaceous collision of composite ribbon continents as the driving force for Cretaceous orogenesis (SAYBIA of Johnston (2008), and Rubia of Hildebrand (2009)). To do this, we compare detrital zircon populations of samples from autochthonous and paraautochthonous locations known to be deposited on the western margin of Laurentia with those interpreted by some to have been deposited on the ribbon continent.
Neoproterozoic to Cambrian strata are common along the western margin of Laurentia, and include latest Neoproterozoic to Cambrian sandstones that form the base of the Sauk sequence (Sloss, 1963). These sandstones are referred to as basal Sauk sandstones in this paper. Forty-two samples of basal Sauk sandstones were collected at 26 locations (Figs. 1 and 2). See Table 1 for details of the sampled units, ages, and locations. Detailed descriptions of the sampled formations and locations are included in the Supplemental Information. The western units, which are latest Neoproterozoic to middle Cambrian in age and were deposited on Mesoproterozoic to Neoproterozoic sedimentary successions, were sampled from allochthonous thrust sheets within the Rocky Mountains and Sevier fold-and-thrust belts or from structures associated with Basin and Range extension. To the east, basal Sauk sandstones, which are middle to late Cambrian in age and rest unconformably above ca. 1.1 Ga to ca. 2.7 Ga crystalline rocks of the Laurentian craton, were collected from autochthonous to parautochthonous units involved in Laramide, Rocky Mountains, and Sevier deformation. These new data were integrated with published data from 36 basal Sauk sandstones (Table 1).

For consistency with the ribbon continent models for the Cordillera being tested here, basal Sauk sequence sandstones are divided into two major groups. Western samples deposited on thick Mesoproterozoic and Neoproterozoic sedimentary successions are part of the Cassiar (Canada and northern United States) or Antler platforms (United States). Eastern samples deposited on thin Neoproterozoic deposits or directly on crystalline rocks of Laurentia are part of the North American platform. Classifications for each sample are given in Table 1, and the significance of the platform interpretation is discussed below. To facilitate provenance interpretations, five sandstone samples were collected from older Neoproterozoic formations that underlie basal Sauk sequence sandstones in some of the western locations. These samples were collected to ascertain the importance of local recycling of detrital zircon populations from older sedimentary successions during Sauk transgression. Sample locations for older Neoproterozoic samples are given in Table 1 and their relationship to the overlying basal Sauk sequence sandstones are outlined in the Supplemental Information.

## METHODS

Zircon was extracted by the standard mineral separation procedures of crushing, water table, heavy liquids, and magnetic separation. A representative fraction of the zircon-rich separate was then dump-mounted into a round 25.4 mm plastic form and cast in epoxy. To avoid biasing the detrital zircon populations, no selection of zircons by physical characteristics was undertaken. Mounts were ground using 5 and 3 µm silicon carbide abrasive films and then polished using 1 µm diamond film. Grinding and polishing were done by hand using low-pile polyester films mounted on glass to ensure a very flat finish on the final mount. This preparation procedure ensures consistent laser focus between grains.

Isotopic data were acquired on an Agilent 7700 quadrupole inductively coupled plasma—mass spectrometer (ICP-MS) coupled to a Resonetics RESOchron 193 nm excimer laser ablation system. Ablation occurred within a Lurin Technic M-50 dual volume ablation cell. For details of the ablation cell performance and the laser ablation system, see Müller et al. (2008). All laser settings, dwell times for each measured mass, gas flow rates, and ICP-MS settings can be
Figure 2. Stratigraphic charts for select sample locations. Sampled basal Sauk sequence units are highlighted in yellow; older Neoproterozoic units sampled in this study are highlighted in orange. Black thrust symbol within the stratigraphic sections indicates that the section is carried in a thrust sheet. Bold red thrust symbol marks the approximate location of the boundary between samples from the Cassiar-Antler platform (west) and North American platform (east); see text for discussion. References are given in Roman numerals and are listed in the Supplemental Information (footnote 1). Sample numbers, formations, and province and state abbreviations for symbols are the same as in Figure 1.
<table>
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<th>Reference</th>
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<th>n</th>
<th>Platform</th>
<th>Latitude (°N)</th>
<th>Longitude (°W)</th>
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TABLE 1. DETAILS OF DETRITAL ZIRCON SAMPLE LOCATIONS AND FORMATIONS, WESTERN NORTH AMERICA (continued)

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Note: Platform refers to the sampled unit belonging to either the North American or Cassiar-Antler Platform (see text for discussion). Province, state and country abbreviations: AB—Alberta; AZ—Arizona; BC—British Columbia; CA—California; CO—Colorado; ID—Idaho; MT—Montana; MX—Mexico; NM—New Mexico; NV—Nevada; SO—Sonora; UT—Utah; WY—Wyoming.
found in the Supplemental Information (footnote 1). A laser energy of 1.5 J/cm² and beam diameters of 30 μm and 40 μm were employed.

The measurement method employed a sample-bracketing strategy with measurements of the calibration reference material, Temora 2 (Black et al., 2004), run every 10 unknowns, or roughly every 10 min. Temora 2 is relatively young (417 Ma), and as such, contains little ²⁰⁷Pb. Low ²⁰⁷Pb beam intensity can lead to greater uncertainty in correction for instrumental mass fractionation of lead isotopes due to the low precision of the measured ²⁰⁶Pb/²⁰⁴Pb ratio of the calibration reference. To avoid this, two sequential calibrations of the calibration reference were employed between each set of 10 unknowns. Three validation reference materials with ages between 1065.4 Ma and 2679.8 Ma were measured in each measurement session to validate the results and to assess random and systematic uncertainties. Each measurement began with a 15 s gas blank acquired with the laser off. This was followed by a 30 s ablation and a 5 s delay to record washout back to background. For each sample, 120–140 unknowns were measured.

Data reduction was handled in the commercially available lolite software package (version 2.5) (Paton et al., 2010) and a custom Microsoft Excel Visual Basic for Applications (VBA) macro (ARS4.0; operation of macro outlined in Matthews and Guest, 2016). Background subtraction and correction of raw isotopic ratios for laser-induced elemental fractionation, instrumental mass fractionation, and drift in the sensitivity of the ICP-MS was performed in lolite. Final isotopic ratios and their associated standard deviations of the mean and error correlations were exported from lolite to Excel where the final uncertainty propagation was performed and ages were calculated. No common lead correction was attempted. Instead, interrogation of the time-resolved ²⁰⁴Pb signal intensity and calculated ²⁰⁷Pb/²⁰⁴Pb ages was used to eliminate measurements, or portions of measurements, contaminated by common lead as per practices reported in Horstwood et al. (2016). Standard deviation of the mean absolute offset and mean offset of ²⁰⁸Pb/²³⁵U for dates <1500 Ma, and ²⁰⁷Pb/²⁰⁶Pb for dates >1500 Ma. Dates were filtered for outliers using the probability of concordance calculated by the concordia age function in Isoplot software (version 4.15) (Ludwig, 1998, 2012). Measurements with <1% probability of concordance were eliminated from the data set. Final data are presented as normalized probability density functions calculated using a VBA macro.

Multidimensional scaling (MDS) is used to aid in visualizing the statistical differences between the large number of samples included in this study and to more objectively group samples exhibiting similar detrital zircon populations into facies (see discussion below; Vermeesch, 2013; Spencer and Kirkland, 2016). In this study, the maximum difference between the cumulative probability density functions for each pair of samples—the D statistic of the Kolmogorov-Smirnov test—is used to quantify the dissimilarity of the samples. The D statistic is measured between each pair of samples to create a matrix of dissimilarity. The MDS approach then plots the samples on a Euclidean plane while attempting to honor the differences between samples in the dissimilarity matrix. As such, the distance between samples in the MDS plot is roughly equal to the dissimilarity between the samples based on the D statistic, and samples containing similar detrital zircon populations will plot in the same region.

The addition of normally distributed unimodal synthetic populations has been shown to aid in visualizing the differences between samples on an MDS plot (Spencer and Kirkland, 2016). Here, five synthetic populations with ages drawn from the major populations found in Cambrian rocks of western Laurentia (2700, 1780, 1650, 1430, and 1100 Ma) were plotted with the Cambrian and Neoproterozoic samples on a single non-metric MDS “map” using the IsoplotR software from Vermeesch (2013).

The grouping of samples into detrital zircon facies assumes that the relative proportions of detrital zircon populations measured in a sample are representative of the parent rock. Pullen et al. (2014) demonstrated that low-n (where n
is the number of single-grain measurements conducted per sample) subsets of a large detrital zircon data set poorly reproduce the relative proportions of components of the zircon population. To reduce the likelihood of drawing spurious correlations between samples, we limit our comparison to data sets with an average of 100 measurements per sample. While this strategy precludes the integration of some commonly cited detrital zircon data sets (e.g., Stewart et al., 2001; average 22 measurements per sample), it minimizes the effect of sampling variability on our analysis.

In this study, we combine our new data with previously published data for Cambrian and Neoproterozoic samples (Table 1). All previously measured samples were acquired by LA-ICP-MS. Results from previous work are reported here using the same concordance filtering criteria applied to our new data and the same 1500 Ma cutoff between 206Pb/238U and 207Pb/206Pb dates. The level of reported uncertainties varies between the different data sets integrated in this study. In some cases, only random uncertainties associated with the standard deviation of the mean for the individual data points were reported (“analytical uncertainties”). In other studies, random and systematic components of uncertainty were reported, although it was not always clear what systematic components were included. We used all the reported components of uncertainty, random and systematic, to plot these data in our figures.

## RESULTS

Uranium-lead measurements of detrital zircons from basal Sauk and older Neoproterozoic sandstones yielded 4743 dates that passed our concordance filter. Complete isotopic data for measurements reported here can be found in the Supplemental Information (footnote 1). A single probability density function incorporating all of the new samples reveals five major populations of detrital zircon: (1) Archean to early Neoproterozoic (3.5–2.4 Ga; mode 2.7 Ga); (2) Paleoproterozoic (2.0–1.6 Ga; mode 1.8 Ga); (3) early Mesoproterozoic (1.5–1.3 Ga; mode 1.4 Ga); (4) late Mesoproterozoic (1.3–1.0 Ga; modes 1.2 and 1.1 Ga); and (5) Neoproterozoic to Cambrian (0.8–0.5 Ga; various modes between 0.8 and 0.5 Ga) (Fig. 3). Important geographical variations in the presence, absence, and relative proportions of these five major populations are discussed below and used to understand Cambrian provenance patterns and to test tectonic models for the Cordillera.

### CRYSTALLINE PROVENANCE OF DETRITAL ZIRCON

The physical and chemical durability of zircon enables it to survive multiple weathering, transport, deposition, and burial cycles. As such, provenance interpretations must consider derivation from not only the crystalline rocks from which the zircons ultimately derive, but also potential recycling from older sedimentary successions (Dickinson et al., 2009; Hadlari et al., 2015).

The vast majority of detrital zircon in basal Sauk sequence sandstones ultimately derive from crystalline sources within the Laurentian craton (Fig. 3). A broad distribution of Archean to Paleoproterozoic (>2.4 Ga) dates are consistent with ultimate sources in cratonic cores that form the oldest rocks of the Laurentian craton (Hoffman, 1988). The broad high in the probability density function in the late Paleoproterozoic (mode 1.78 Ga), which includes grains between 2.0 and 1.6 Ga, derive from a collage of Proterozoic orogenic provinces and their associated accreted terranes that record the assembly of the Laurentian craton. Zircon grains yielding dates between 2.4 Ga and 1.8 Ga derive from Proterozoic orogenic belts and the associated accreted terranes.
Figure 4. Nonmetric multidimensional scaling plot of the detrital zircon age spectra of select Cambrian samples from southwestern Laurentia and of five unimodal synthetic populations. Plot is based on the D statistic of the Kolmogorov-Smirnov test, and this is the value of the axes; see text for discussion. Samples that plot close to one another contain similar detrital zircon populations. Detrital zircon data are divided into six facies (A, B, C, D, E, F) based on this plot, geological information, and visual inspection of the samples’ probability density functions. Samples from this study are shown with red text. Dashed black line indicates the boundary between samples that contain >3% Archean grains and those that contain <3% Archean grains. Dashed grey line indicates the boundary between samples that exhibit A1 and A2 detrital zircon facies. White squares containing letters in the MDS map are used to identify the following samples: Y—Yanks Peak; Q—Quartzite Range; T—Three Sisters; G—Gold Creek. Black arrow at sample 59 indicates its reassignment to facies E; see text for discussion. See Figure 1 for province and state abbreviations appearing in the symbol explanation.
that stitch together the Archean cratonic cores. Grains yielding dates between 1.8 Ga to 1.68 Ga may derive from the Yavapai province of southern Laurentia or post-orogenic magmatic bodies (e.g., the Swift Current anorogenic province). Grains yielding dates between 1.7 Ga and 1.6 Ga may derive from the Mazatzal province immediately south of the Yavapai. A prominent Mesoproterozoic mode at 1.43 Ga indicates derivation from extensive A-type plutons that intrude the Yavapai and Mazatzal provinces throughout southern and southeastern Laurentia (Anderson and Bender, 1989). Zircon grains yielding dates between 1.3 Ga and 1.0 Ga ultimately derive from the Grenville province, which records the final assembly of the supercontinent Rodinia and is found in Texas (southern United States) and along the southeastern margin of Laurentia. Neoproterozoic and early Cambrian detrital zircons derive from magmatism associated with crustal thinning during deposition of the Windermere Supergroup and the formation of the western Laurentian passive margin in the latest Neoproterozoic to Cambrian.

**IDENTIFICATION OF DETRITAL ZIRCON FACIES**

Large bodies of genetically related rock commonly exhibit reproducible detrital zircon distributions due to similarities in the rock’s source regions and mixing and homogenization of sediments in the depositional system. These reproducible patterns have been referred to as “barcodes” (e.g., Link et al., 2005), “signatures” (e.g., Hadlari et al., 2012; Benyon et al., 2014), “types” (e.g., Dumitru et al., 2015, 2016), or “facies” (e.g., LaMaskin, 2012). Here we refer to these patterns as detrital zircon facies, as we feel this terminology is a natural complement to the concept of depositional facies used by sedimentologists.

To provide a framework for the discussion of provenance patterns in western Laurentia, samples are divided into detrital zircon facies based on similarities in the age and relative proportions of their major zircon populations. Rather than relying solely on the visual comparison of detrital zircon populations, a statistical approach involving MDS was employed. All 42 Cambrian and five Neoproterozoic samples reported here were combined with previously published results from 36 Cambrian and seven Neoproterozoic samples to create a single MDS plot (Figs. 4 and 5). Probability density functions for all samples, grouped according to the MDS plot, are provided (Figs. 6 and 7).

Detrital zircon populations were divided into six detrital zircon facies based mainly on groupings of the samples in the MDS plot, but also incorporating the known geographic distribution of the samples and formations studied (Fig. 4). Visual inspection of probability density functions was used in some cases to draw boundaries between samples with subtle but significant differences in their detrital zircon population (e.g., samples 38 and 15). Facies A was divided into two subfacies, A1 and A2, based on the presence of Mesoproterozoic, Neoproterozoic, and Cambrian zircon populations in the latter. Removing these components from facies A2 samples would result in A1 signatures.

Detrital zircon facies are not restricted to single formations, with each facies found in samples from at least three to as many as six formations. In general, detrital zircon facies correspond to discrete geographical regions of western Laurentia, with some overlap. Samples containing Archean grains plot on the left of the MDS map nearer the 2700 Ma synthetic population; a dashed line demarcating the boundary between samples that contain greater than and less than 3% Archean detritus is provided as a reference (Fig. 4). Samples with increasing proportions of Grenvillian detritus plot toward the bottom right of the map near the 1100 Ma synthetic population. Samples that plot in the top right of the map contain variable mixtures of late Paleoproterozoic and Mesoproterozoic grains as evidenced by their proximity to the 1650 Ma and 1430 Ma synthetic populations. Samples that plot in the top left of the map contain prominent Paleoproterozoic populations and cluster near the 1780 Ma synthetic population. Samples that plot in the middle of the diagram represent mixtures of these five major components.

Detrital zircon facies A1 and A2 are found in formations in the central and northern portions of the study area, including the Yanks Peak, McNaughton, Gog, Hamill, Quartzite Range, Three Sisters, Gold Creek, Flathead, Geertsen Canyon, and Horsethief Creek formations (Fig. 8). A1 and A2 detrital zircon facies are characterized by Archean to early Paleoproterozoic (3.0–2.4 Ga) populations and a dominant late Paleoproterozoic population between 1.9 and 1.7 Ga, with a mode of ca. 1.8 Ga (Fig. 6, groups A1 and A2; Fig. 7, group...
Figure 6. Normalized probability density functions for select Cambrian samples of southwestern Laurentia. Samples with numbers in red are from this study. Dates are $^{206}\text{Pb}/^{238}\text{U}$ for dates $<1500$ Ma, and $^{207}\text{Pb}/^{206}\text{Pb}$ for dates $>1500$ Ma. Samples with $<1\%$ probability of concordance were filtered from the data set. Curve fill color corresponds to the sampled unit (Pk.—Peak; R.—Range; Cr.—Creek; S.—Sisters). Probability density functions are normalized for each detrital zircon facies (A1, A2, B, C, D, E, F). Outliers are samples that did not fall within a facies defined using the multidimensional scaling plot (see Fig. 4). A line at 1.8 Ga is provided as a visual reference for the age of the Paleoproterozoic population discussed in the text. Data sources and details of the sample locations are provided in Table 1. Geologic time scale abbreviations: MC—Mesozoic–Cenozoic; Pal.—Paleozoic; Neopr.—Neoproterozoic; Mesopr.—Mesoproterozoic; Paleoprot.—Paleoproterozoic; NA—Neoarchean; MA—Mesoarchean; PA—Paleoarchean.
Figure 7. Normalized probability density functions for select Neoproterozoic samples of western Laurentia. Samples with numbers in red are from this study. Dates are 206Pb/238U for dates <1500 Ma, and 207Pb/206Pb for dates >1500 Ma. Samples with <1% probability of concordance were filtered from the data set. Curve fill color corresponds to the sampled unit. Probability density functions are normalized for each detrital zircon facies (A1, B, C). A line at 1.8 Ga provided is provided as a visual reference for the age of the Paleoproterozoic population discussed in the text. Data sources and details of the sample locations are provided in Table 1. Geologic time scale abbreviations: MC—Mesozoic–Cenozoic; Pal.—Paleozoic; Neopr.—Neoproterozoic; Mesopr.—Mesoproterozoic; Paleoprot.—Paleoproterozoic; NA—Neoarchean; MA—Mesoarchean; PA—Paleoarchean.

Figure 8. Map showing the geographic extent of detrital zircon facies defined by multidimensional scaling; also shown are the major tectonic provinces of North America (modified after Whitmeyer and Karlstrom, 2007; Grouse Creek Block based on Gaschnig et al., 2013). Abbreviations: SCA—Swift Current anorogenic province; ECG—Elves Creek gneiss. Bold red line depicts the approximate location of the geological features that constitute the Transcontinental Arch (TCA; modified after Carlson, 1999). Also shown are summary probability density functions for each of the six facies, highlighting prominent modes in their detrital zircon populations; curve fills correspond to the major tectonic provinces of North America depicted in the map. Dates are 206Pb/238U for dates <1500 Ma, and 207Pb/206Pb for dates >1500 Ma. Samples with <1% probability of concordance were filtered from the data set. N is the number of samples; n is the number of measurements. A reference line at 1.8 Ga is provided as a visual reference. Geologic time scale abbreviations: MC—Mesozoic–Cenozoic; Pal.—Paleozoic; Neopr.—Neoproterozoic; Mesopr.—Mesoproterozoic; Paleoprot.—Paleoproterozoic; NA—Neoarchean; MA—Mesoarchean; PA—Paleoarchean.

A1). Minor early Mesoproterozoic 1.5–1.3 Ga populations are found in the southernmost A1 samples and the majority of A2 samples. Facies A2 is differentiated from A1 based on the occurrence of significant populations of ca. 1.4 Ga and Neoproterozoic to Cambrian zircons. Geographically, A2 samples are found in the west and generally overlie A1 samples.

Facies B is found in samples from the Tintic, Osgood Mountain, and Stirling formations of northern Utah, southern California, and Nevada (United States) (Figs. 5, 8). This facies is characterized by an Archean to early Paleoproterozoic (mainly 3.0–2.5 Ga) population, subequal late Paleoproterozoic 1.9–1.7 Ga (mode ca. 1.8 Ga) and early Mesoproterozoic 1.5–1.3 Ga (mode ca. 1.4 Ga) populations, and a small late Mesoproterozoic 1.3–1.0 Ga (mode ca. 1.1 Ga) population (Figs. 6 and 7, group B).

Facies C is found in samples from the Osgood Mountain, Tintic, Prospect Mountain, Proveedora, and Mutual formations of Utah, southern Idaho, and Nevada (United States) and northern Mexico (Figs. 5, 8). These samples are characterized by an Archean (mainly 3.0–2.5 Ga) population, subequal late Paleoproterozoic 1.9–1.6 Ga (mode ca. 1.8 Ga) and early Mesoproterozoic 1.5–1.3 Ga (modes at 1.42 and 1.36 Ga) populations, and a dominant late Mesoproterozoic ca. 1.2 to ca. 1.0 Ga (modes at 1.2 and 1.1 Ga) population (Figs. 6 and 7, group C).

Facies D is found in samples from the Flathead, Sawatch, Prospect Mountain, Ignacio, and Tapeats formations of Wyoming, Utah, Colorado, and Arizona (United States) (Fig. 8). These samples are characterized by nearly bimodal detrital zircon populations dominated by late Paleoproterozoic 1.8–1.6 Ga (mode ca. 1.7 Ga) and narrow early Mesoproterozoic (mode ca. 1.4 Ga)
show two modes at 1.84 and 1.78 Ga (Fig. 8, group A2). Our data suggest that a younger peak at 1.78 Ga. Paleoproterozoic populations in facies A2 also 6, group A1, samples 7, 8, 16, 22, 27 and 35), an older peak at ca. 1.84 Ga and A1 samples show two modes in their Paleoproterozoic populations (e.g., Fig. 6, group E).

Facies E is found in one sample from the Flathead Sandstone of southernmost Wyoming and the Tapeats, Wood Canyon, and Bliss formations of Nevada, Arizona, California, and New Mexico (United States) (Fig. 8). These samples are characterized by late Paleoproterozoic 1.8–1.6 Ga (mode <1.7 Ga), early Mesoproterozoic 1.5–1.3 Ga (mode 1.4 Ga), and prominent late Mesoproterozoic 1.3–1.0 Ga (mode 1.2 Ga) populations (Fig. 6, group E).

Facies F is found in samples from the Wood Canyon and Campito Formations of California and Nevada and two samples from the Bliss Sandstone of southern New Mexico (Fig. 8). These samples are dominated by a single narrow mode at ca. 1.1 Ga. Scattered dates between 1.5 and 1.2 Ga are present in most samples (Fig. 6, group F). Two samples (76 and 77) of the Bliss Sandstone contain abundant zircons that yield dates near 0.5 Ga.

### PROVENANCE INTERPRETATION OF DETRITAL ZIRCON FACIES

The provenance of Cambrian and Neoproterozoic the detrital zircon facies described above can be used to constrain large-scale sediment source areas and dispersal systems active during the Cambrian throughout western Laurentia. Here we focus on large-scale patterns of sediment dispersal, and as such, important small-scale variations in the provenance of individual samples may not be addressed.

**Facies A1 and A2**

Provenance interpretations for Archean components of the northern facies, A1 and A2, are relatively straightforward. Archean components in these samples likely derive ultimately from Laurentian Archean provinces, such as the Hearne, Superior, Wyoming, and Medicine Hat blocks that were exposed to the east prior to Cambrian transgression (Fig. 8) (Hoffman, 1988; Whitmeyer and Karlstrom, 2007).

The provenance of Paleoproterozoic zircon populations is more complicated. Overall, Paleoproterozoic grains from A1 and A2 samples yield a mode of 1.78 Ga (Fig. 8, groups A1 and A2). However, the asymmetry of the peak in many A1 and A2 probability density functions suggests that a smaller population of older zircons is present and is not well resolved in our data set. Inspection of the individual probability density functions reveals that several A1 samples show two modes in their Paleoproterozoic populations (e.g., Fig. 6, group A1, samples 7, 8, 16, 22, 27 and 35), an older peak at ca. 1.84 Ga and a younger peak at 1.78 Ga. Paleoproterozoic populations in facies A2 also show two modes at 1.84 and 1.78 Ga (Fig. 8, group A2). Our data suggest that the occurrence of two distinct Paleoproterozoic detrital zircon populations is widespread, and their origin is discussed below.

The provenance of zircons that compose the older >1.8 Ga population is straightforward. Zircons with ages >1.8 Ga could derive from relatively proximal Paleoproterozoic arcs and orogenic belts, such as the Taltson or Rimby arcs which record the assembly of the Laurentian craton and are interpreted in the subsurface of Alberta (Canada) based on borehole penetrations and geophysical measurements (Fig. 8; Ross et al., 1991). Alternatively, these grains could derive from the Trans-Hudson province to the east where these ages are common (Ross et al., 1991; Hoffman, 1988).

The origin of the younger <1.8 Ga Paleoproterozoic zircons is more difficult to determine. The younger components could derive from the 1.8–1.7 Ga Yavapai province to the south (Fig. 8), which was exposed until at least the middle Cambrian (May et al., 2013). Magmatism in the Yavapai province was continuous between 1.78 and 1.71 Ga with a magmatic peak at 1.74 Ga (Bickford et al., 2008). As such, the timing of magmatism in the Yavapai province is a poor fit to the northern Cambrian rocks. Grains younger than 1.75 Ga are not common in facies A1 and A2 samples, and the mode of the <1.8 Ga zircon population from Cambrian rocks is older (1.78 Ga). Furthermore, the Yavapai province was extensively intruded by ca. 1.4 Ga A-type granites (Anderson and Bender, 1989) that provide abundant zircons to Cambrian sedimentary rocks in that region (e.g., samples from facies D). If the <1.8 Ga population of Paleoproterozoic zircons was derived from the Yavapai province, then a commensurate population of Mesoproterozoic zircons would be expected. Minor Mesoproterozoic populations are found in some samples (e.g., Fig. 6, group A1, samples 1, 2, 17, 28, 29, 31, 35), but are largely absent in most. Also, paleoflow directions in the Cambrian are dominantly west directed (Mountjoy and Aitken, 1963; Young, 1979; Devlin and Bond, 1988), inconsistent with derivation from the Yavapai province. For these reasons we find it unlikely that ca. 1.78 Ga zircons in Cambrian rocks were sourced from the Yavapai province.

The Little Belt arc is another possible source area for these grains (Fig. 8). Magmatism in the Little Belt arc is interpreted to record Paleoproterozoic convergence between the Hearne and Wyoming cratons (Mueller et al., 2002). Harms et al. (2004) used evidence of deformation and metamorphism in basement inliers in western Montana and Idaho (United States) to suggest that convergence between the cratons culminated in the 1.78–1.72 Ga Big Sky orogen. If arc magmatism was continuous until collision at 1.78 Ga, then parts of the Little Belt arc may be young enough to provide the <1.8 Ga components observed in Cambrian detrital zircon populations. However, the only exposed portions of the Little Belt arc yield zircon crystallization ages of ca. 1.86 Ga (Mueller et al., 2002), and no evidence of major magmatism <1.8 Ga has been found. As such, the importance of the Little Belt arc as a source area in the Cambrian remains unclear.

The <1.8 Ga zircons could derive from the ca. 1.77 Ga Swift Current anorogenic province (Collerson et al., 1988). The Swift Current anorogenic province was originally described based on borehole intersections in the subsurface near Swift Current, Saskatchewan (Canada) (Fig. 8) and may be related to more
widespread Paleoproterozoic magmatism in the Hearne province (Peterson et al., 2015). Zircon crystallization ages of 1779 ± 3 Ma and 1820 ± 1 Ma for grains in the otherwise Archean Loveina block of the Hearne craton in southeastern Alberta, and interpretations of aeromagnetic data, suggest that the Swift Current anorogenic province may be widespread in southeastern Alberta (Ross et al., 1991).

Farther east in Minnesota and Wisconsin (United States), post-orogenic granitoids that intrude the Penokean terrane yield ages between 1.80 Ga and 1.75 Ga (mode at 1.77 Ga) that overlap with <1.8 Ga zircon populations in facies A1 and A2 basal Sauk sequence sandstones (Holm et al., 2005). Derivation of basal Sauk sequence Paleoproterozoic zircon populations from this region would require transport of <1.8 Ga zircon populations across the predominately >1.8 Ga Trans-Hudson orogen. The absence of prominent >1.8 Ga populations in some samples (e.g., samples 22, 25, 27 and 35) and the dominance of <1.8 Ga populations in most A1 and A2 samples favors derivation from a source area west of the Trans-Hudson, but we cannot rule out derivation from the mid-continent region.

We interpret that <1.8 Ga Paleoproterozoic zircons in facies A1 and A2 Cambrian samples most likely derive from the Swift Current anorogenic province to the east. The widespread occurrence of these grains in Cambrian samples suggests that the Swift Current anorogenic province may be more extensive than originally mapped by Collerson et al. (1988). Hafnium isotopic evidence could further constrain the provenance of <1.8 Ga zircons. Source areas in the Little Belt arc, Rimby arc, parts of the Trans-Hudson orogen, or post-orogenic plutons in the Penokean terrane would likely exhibit juvenile signatures, whereas Nd isotopic data requires that the Swift Current anorogenic province formed by melting of older Archean crust (Collerson et al., 1988).

Neoproterozoic to Cambrian detrital zircon populations in facies A2 samples are related to rifting of western Laurentia to form the Neoproterozoic Windermere basin and ultimately the western Laurentian passive margin in the Cambrian. Evidence of Neoproterozoic to Cambrian magmatism of various ages has been described along the length of the orogen (Colpron et al., 2002, and references therein). Proterozoic populations were likely eroded from older sedimentary and volcanic sequences, whereas Cambrian magmatism may have been syndepositional (e.g., Colpron et al., 2002).

In summary, detrital zircon populations from groups A1 and A2 derive mainly from Laurentian crystalline sources to the east (Fig. 9, A1/A2), consistent with paleoflow measurements that are dominantly west directed (Mountjoy and Atkin, 1963; Young, 1979; Devlin and Bond, 1988). The predominance of <1.8 Ga grains in Cambrian rocks suggests that the Swift Current anorogenic province may be more widespread than previously mapped, and was likely a significant source of sediment in the Cambrian. The similarity between Cambrian A1 and A2 signatures and those of the underlying Neoproterozoic samples (Fig. 7, group A1) suggests little change in provenance during much of the late Neoproterozoic and into the early Cambrian. Furthermore, the similarity between Neoproterozoic and Cambrian rocks makes evaluating the importance of local recycling of Neoproterozoic sedimentary rocks in the Cambrian difficult. Neoproterozoic to Cambrian zircon populations were likely recycled from older Windermere deposits, with the exception of Cambrian grains, some of which may have been syndepositional.

Facies B

Samples exhibiting facies B detrital zircon populations are found in Utah, southern Idaho, and northern Nevada (Fig. 8). Geographic overlap exists between facies B samples and those of facies A, C, and D, likely reflecting the complexity of source areas and abundant recycling of older sedimentary successions in this area.

Archean zircons are found in all facies B samples (Fig. 6, group B). Crystal-line sources for Archean zircons include the Grouse Creek block of northeastern Nevada and southern Idaho, and the Wyoming province to the east (Fig. 8) (Whitmeyer and Karlstrom, 2007). Alternatively, Archean zircons could be recycled from older Neoproterozoic successions, such as the Mutual Formation which underlies many of the Cambrian facies B sample locations and contains Archean grains (Fig. 7, group C; see discussion below).

Facies B detrital zircon populations are characterized by prominent Paleoproterozoic zircon populations with a mode ca. 1.8 Ga (Fig. 8). As in facies A1 and A2, zircons with ages >1.8 Ga could derive from juvenile arcs and orogenic belts associated with assembly of the Laurentian craton. Proximal sources for these grains would include orogenic belts associated with the amalgamation of Mojavia and the Grouse Creek block (Fig. 8). Unlike our interpretation for facies A1 and A2, younger Paleoproterozoic zircons (<1.8 Ga) in facies B likely derive from the Yavapai province to the east. This interpretation is supported by an abundance of early Mesoproterozoic grains, consistent with derivation from A-type granites that intrude the Yavapai province (Anderson and Bender, 1989).

Late Mesoproterozoic populations are found in all facies B samples and are composed of a wide range of ages between 1.25 and 1.0 Ga with a mode ca. 1.11 Ga (Fig. 8). This broad distribution of ages is distinct from that of facies E samples, which are dominated by ca. 1.2 Ga zircons derived from local plutonic sources in southern New Mexico (Amato and Mack, 2012), and from that of facies F samples, which are nearly unimodal at ca. 1.1 Ga (Fig. 8, group B versus E and F). The range of late Mesoproterozoic ages in facies B samples is similar to that found in the Neoproterozoic Uinta Mountain Group of northeastern Utah (Mueller et al., 2007; Dehler et al., 2010; Kingsbury-Stewart et al., 2013) and to late Mesoproterozoic zircon populations in the Mutual Formation (Fig. 7, group C) that underlies many of the facies B samples. Much of the sediment in the Uinta Mountain Group is interpreted to derive from Grenville-age (1.3–1.0 Ga) plutonic rocks exposed in the southern Grenville orogen. The Uinta basin is one of a number of Neoproterozoic basins that received detritus from the eroding Grenville orogen in the Neoproterozoic, an event referred to as the “Grenville flood” (Rainbird et al., 1997; Mueller et al., 2007). The similarity between Mesoproterozoic detrital zircon populations of the Mutual Formation
and the Uinta Mountains Group suggests that they shared a similar source, and that both ultimately derive from the Grenville orogen (Yonkee et al., 2014).

If Grenville detritus in the Mutual Formation was derived from the southern Grenville orogen, was this also true for Grenville detritus in Cambrian rocks? Yonkee et al. (2014) interpreted lower Cambrian strata in western Utah to derive from the region of the Transcontinental Arch, a northeast-southwest–aligned basement high that runs roughly down the middle of the Laurentian craton that was onlapped during Sauk transgression (Sloss, 1963, 1988; see Carlson [1999] for an excellent discussion; Fig. 8). However, late Mesoproterozoic plutons in Colorado, such as the ca. 1.09 Ga Pikes Peak Granite (Schärer and Allègre, 1982), are younger than the mode of the late Mesoproterozoic population in facies B samples (ca. 1.11 Ga), and could not have supplied the broad range of late Mesoproterozoic ages found in them. Furthermore, the lack of late Mesoproterozoic grains in facies D samples, some of which were deposited directly atop the Pikes Peak Granite (Fig. 6, group D, samples 48 and 49), suggests that the Pikes Peak Granite was not a significant sediment source at this time. We speculate that Grenville detritus in facies B samples was derived from local recycling of older sedimentary successions rich in these components.

The geographic and temporal distribution of Cambrian samples containing Grenville detritus supports this interpretation. In north-central Utah, facies A, B, C, and D rocks are found in close proximity, commonly occurring at the same locality (Fig. 8). Evidence for crustal thinning in the lower Cambrian in
western Utah (Yonkee et al., 2014) could explain rapid changes in detrital zircon facies. Extensional faulting would have allowed the Cambrian sedimentary system to remain accessible to older Neoproterozoic rocks rich in Mesoproterozoic zircons. Furthermore, rapid changes in paleodrainage patterns in an evolving rift landscape could explain similarly rapid temporal and geographic variability in detrital zircon facies in this region (Cawood et al., 2012). Facies B detrital zircon populations likely derive from mixing of detritus from Archean and Paleoproterozoic crystalline source areas to the east, such as the Wyoming and Yavapai provinces, with late Mesoproterozoic grains recycled from older sedimentary successions (Fig. 9B).

**Facies C**

Facies C detrital zircon populations are similar to those of facies B, except that the proportions of Paleoproterozoic and Mesoproterozoic zircon populations differ and the age of the Paleoproterozoic mode is more variable (Fig. 6, group B versus C; Fig. 8). Facies B detrital zircon populations are dominated by late Paleoproterozoic zircons (1.9–1.6 Ga; 42% of dates) with lesser proportions of early (1.6–1.3 Ga; 26%) and late (1.3–1.0 Ga; 13%) Mesoproterozoic zircons. In contrast, facies C detrital zircon populations are dominated by late Mesoproterozoic zircons (47%) with lesser proportions of late Paleoproterozoic (20%) and early Mesoproterozoic grains (22%).

We interpret facies C zircon populations to derive from the same source areas as facies B (described above). Of the eleven samples that exhibit facies C detrital zircon populations, seven are from the Neoproterozoic Mutual Formation of Utah and southern Idaho (Fig. 7, group C). As discussed previously, sediment of the Mutual Formation was likely derived from the Grenville orogen, while Cambrian facies C samples in Utah likely derive from local recycling of the Mutual Formation or from the Uinta Mountain Group, which contain similar detrital zircon populations (Fig. 7, group C). Variability in the age of the Paleoproterozoic mode in facies C samples may reflect variable contributions from the Yavapai province to the east and older 1.8–1.9 Ga arcs in western Utah and Nevada.

The Proveedora Formation of northern Mexico also exhibits a facies C detrital zircon population. Overall, detrital zircon populations in the Proveedora are similar to facies E samples from the Bliss Sandstone in southern New Mexico except that the mode of the late Mesoproterozoic population in the Proveedora (ca. 1.1 Ga) is younger than that in the Bliss to the north (ca. 1.2 Ga). We interpret the Proveedora sandstone to derive from the same source regions as facies E samples (discussed below), with local input of ca. 1.1 Ga grains from intrusions of this age found in northern Mexico (Iriondo et al., 2004) (Fig. 9C).

**Facies D**

Facies D detrital zircon populations are characterized by bimodal Paleoproterozoic and Mesoproterozoic zircon populations and mainly derive from proximal sources within the Yavapai and Mazatzal provinces (Fig. 8). The Paleoproterozoic zircon population has a peak age of ca. 1.7 Ga and likely includes contributions from both the underlying Yavapai province and the Mazatzal province to the south. The near absence of >1.8 Ga and Archean grains indicates that little detritus was derived from the Wyoming craton to the north or Paleoproterozoic arcs and orogens to the northeast and west.

Mesoproterozoic populations likely derive from A-type plutons that extensively intrude the Yavapai and Mazatzal provinces (Fig. 8; Anderson and Bender, 1989). The peak age (1.43 Ga) is similar to the mode in the distribution of ages for early Mesoproterozoic plutons in Laurentia (Goode and Vervoort, 2006). Small variations in the mode of the Mesoproterozoic population likely reflect subtle differences in the ages of early Mesoproterozoic plutons in the sediment source areas of the samples (Fig. 6, group D).

Minor late Mesoproterozoic populations yield a mode of ca. 1.06 Ga and overlap in age with the Grenville orogen in the south and east of Laurentia (1.3–1.0 Ga; Fig. 8). Alternatively, these grains could derive from the Pikes Peak Granite, upon which samples 48 and 49 were deposited. The similarity between the mode of the late Mesoproterozoic population (ca. 1.06 Ga) and that of the Pikes Peak Granite (ca. 1.09 Ga) suggests that local sourcing of these minor components is likely.

We interpret that Cambrian detrital zircons of facies D were derived from relatively local sources within the Yavapai and Mazatzal provinces (Fig. 9D). The lack of Archean and >1.8 Ga zircon populations suggests that little detritus was derived from the Wyoming craton to the north in the middle to late Cambrian, consistent with paleoflow measurements that suggest transport dominantly to the west (Stewart et al., 2001, and references therein). The origin of late Mesoproterozoic populations is difficult to determine due to their relative scarcity, but they could derive from local sources such as the Pikes Peak Granite within the Yavapai province.

**Facies E**

Facies E detrital zircon populations are found in two geographically isolated regions. The majority of facies E samples are found at the south end of the studied area, mainly in samples of the late Cambrian Bliss Sandstone of southwestern New Mexico (Amato and Mack, 2012), our Tapeats Sandstone samples from southern Nevada and central Arizona, and one sample of the Wood Canyon Formation in southern California (Fig. 8). Sample 59 from the Tapeats Sandstone in southern Nevada was grouped with facies D samples based on the MDS plot (Fig. 4). We have chosen to group it with facies E samples for our provenance interpretation due to the similarity in the age of its Paleoproterozoic mode to other facies E samples and the occurrence of a large population of Phanerozoic grains in sample 59 that are uncommon in facies D samples (Fig. 6, group D). One sample of the Flathead Sandstone collected in southern Wyoming also exhibits facies E detrital zircon populations (Fig. 6, group E, sample 33). Provenance interpretations for these two distinct regions
will be discussed separately due to subtle but important differences in their detrital zircon populations.

Detrital zircon populations in the southern geographic occurrence of facies E show significant variability, reflecting the importance of local source areas (Fig. 6, group E) (Amato and Mack, 2012). Facies E is dominated by a younger Paleoproterozoic zircon population (mode <1.7 Ga), reflecting increased input of detritus from the Mazatzal province relative to facies D. Mesoproterozoic zircons derive from A-type anorogenic granites that are common in New Mexico (Fig. 8; Amato and Mack, 2012; Amato et al., 2011).

Late Mesoproterozoic zircon populations are a major component of many facies E samples. The mode of the late Mesoproterozoic population (ca. 1.2 Ga) is similar to the age of plutons in western Texas and southern New Mexico (Bickford et al., 2000; Rämö et al., 2003; Amato and Mack, 2012; Howard et al., 2015), but also overlaps with widespread Grenville plutonism in the east and southeast of the United States. Sources of late Mesoproterozoic grains to the north, such as the Pikes Peak Granite, are younger (ca. 1.09 Ga) and unlikely to have contributed to facies E samples.

Middle Cambrian zircons are abundant in a number of western facies E samples (Fig. 6, group E, samples 59 and 65). Amato and Mack (2012) used paleocurrent measurements and the geographic extent of Bliss Sandstone samples containing Cambrian zircons to demonstrate that these zircons derived from the 510 ± 5 Ma Florida Mountains granite. Our samples of the Tapeats Sandstone from central Arizona and southern Nevada (Fig. 4, group E, samples 59 and 65) also contain abundant middle Cambrian detrital zircons that overlap in age with the Florida Mountains granite. Eight measurements from our sample in central Arizona and seven measurements from southern Nevada yield concordant ages of 502.8 ± 8.1 Ma and 504.8 ± 8.2 Ma [206Pb/238U] dates; 2σ including all sources of random and systematic uncertainty), respectively (Figs. 8, 10). These ages are the same, within uncertainty, as the age of Florida Mountains granite and could indicate that Florida Mountains granite-derived detritus reached as far west as southern Nevada in the late Cambrian. This finding is consistent with paleocurrent data that indicate generally east-to-west transport at this time (Stewart et al., 2001; Amato and Mack, 2012).

Other components of the detrital zircon signature support a connection between the Tapeats Sandstone of central Arizona and southern Nevada with the Bliss Sandstone of southwestern New Mexico. The modes of the Paleoproterozoic zircon populations in our samples (1.67 Ga) are consistent with derivation predominantly from the Mazatzal province, and are similar to that of the bliss Sandstone (1.68 Ga; Amato and Mack, 2012). While similar Paleoproterozoic populations are present in Tapeats Sandstone samples of the Grand Canyon, Arizona (Fig. 6, group D, samples 60 and 61; Gehrels et al., 2011), the mode of the distribution is older (1.71–1.73 Ga), suggesting greater input from the older Yavapai province. Likewise, Mesoproterozoic populations in the Grand Canyon samples are younger (ca. 1.1 Ga) and less abundant than those found in the Bliss and Tapeats from Arizona and Nevada (Amato and Mack, 2012).

Our results support the interpretation of Amato and Mack (2012) that the Transcontinental Arch formed a significant drainage divide in the middle to late Cambrian. Significant differences in the provenance of the Tapeats in the Grand Canyon and the Tapeats in central Arizona and southern Nevada are consistent with the presence of the arch during the middle to late Cambrian.

Facies E detrital zircon populations were derived from a mixture of sources in the Mazatzal and southern Yavapai provinces combined with locally derived detritus from Mesoproterozoic and Paleozone intrusive rocks in southwestern New Mexico (Fig. 9E). The importance of farther-traveled detritus from Grenville sources to the east cannot be ruled out. We suggest that a late Cambrian sediment delivery pathway skirted the southern limit of the Transcontinental Arch, delivering sediment as far as southern Nevada and California (Fig. 9E).

The northern geographic occurrence of facies E is enigmatic. To the north, Cambrian sandstones exhibit facies A1 and A2 zircon populations, characterized by abundant Archean and Paleoproterozoic (mode ca. 1.8 Ga) and minimal Mesoproterozoic zircons (e.g., Fig. 6, group A1, samples 25, 27, and 28). This contrasts strongly with the southern Wyoming facies E sample, which exhibits younger Paleoproterozoic populations (mode <1.7 Ga), prominent populations of Mesoproterozoic grains, and abundant late Mesoproterozoic ca. 1.1 Ga zircons (Fig. 6, group E, sample 33). However, the facies E sample from the northern geographic region is not dissimilar to facies D samples of central Colorado (Fig. 6, group D, samples 45, 46, 48 and 49). Facies D samples are characterized by a similar Paleoproterozoic zircon population (mode ca. 1.7 Ga) and prominent Mesoproterozoic population, but lack significant Mesoproterozoic grains. The occurrence of late Mesoproterozoic ages and the relatively young mode of the dominant Mesoproterozoic zircon population in this sample (mode of 1.38 Ga versus ca. 1.43 Ga in facies D) likely resulted in its inclusion in facies E rather than facies D in the MDS plot (Fig. 4). We interpret the northern occurrence of facies E sample to result from local sourcing of younger Mesoproterozoic A-type granites and detritus from the Pikes Peak Granite (Fig. 9E).

Facies F

Facies F samples are distinct amongst Cambrian detrital zircon populations of western Laurentia. Facies F detrital zircon populations are characterized by a unimodal age distribution with a mode ca. 1.1 Ga (Fig. 8) and are found in samples of the Wood Canyon Formation of California and Nevada, the Campito Formation of California, and two samples from the Bliss Sandstone of southwestern New Mexico. The provenance of the two Bliss Sandstones with facies F detrital zircon populations was interpreted by Amato and Mack (2012) to result from local sourcing of ca. 1.1 Ga grains from proximal plutons in New Mexico.

The origin of the ca. 1.1 Ga grains in the Wood Canyon and Campito Formations was investigated by Howard et al. (2015) using zircon Hf and whole-rock Nd isotopic data. Based mainly on Hf isotopic data, they concluded that 1.1 Ga zircons most likely derive from plutons exposed in the Llano uplift of Texas, rather than more proximal sources such as the Pikes Peak Granite or similar-age plutons in southern New Mexico and Sonora (Mexico). However,
this raises an interesting problem because it requires that sediments transporting major 1.1 Ga zircon populations bypassed the area of Tapeats deposition, where these ages are not common (Fig. 8; Howard et al., 2015). Maximum depositional ages from our data set resolve this issue. The occurrence of significant numbers of ca. 505 Ma grains in the Tapeats Sandstone of central Arizona and Nevada requires that these units be at least 30 m.y. younger than the Wood Canyon, which is thought to have been deposited in the latest Neoproterozoic to earliest Cambrian (starting at 548 Ma) (Corsetti and Hagadom, 2000). As such, the distinct detrital zircon signature of the Wood Canyon Formation likely represents an earlier phase of sediment delivery that predated the deposition of the facies E Tapeats and Bliss Sandstones. Furthermore, the Neoproterozoic Stirling Formation, which underlies the Wood Canyon in southern Nevada and parts of California, is characterized by a facies B detrital zircon population (Fig. 7, group B; Fig. 8), with diverse Paleoproterozoic and Mesoproterozoic ages. This suggests that the source area and sediment dispersal systems that supplied detritus to facies E rocks were not active in the latest Neoproterozoic. As such, the sedimentary system that supplied facies F detrital zircon populations was likely short lived and, based on the limited distribution of facies F deposits, aerially restricted (Fig. 9F).

**SUMMARY OF PROVENANCE INTERPRETATION**

With the possible exception of facies F, detrital zircon populations in basal Sauk sequence sandstones are derived from proximal crystalline and sedimentary source areas with little evidence of long-distance transport. Where basal Sauk sequence sandstones are deposited over older sedimentary successions, they may have inherited major components of their detrital zircon populations or be entirely derived from recycling of the older units. The importance of local recycling is well demonstrated in western Utah, where facies B, C, and D are found in close geographic proximity and are interpreted to represent mixing of zircon derived from ultimate crystalline and recycled sedimentary sources.

**IMPLICATIONS FOR COLLISIONAL MODELS OF THE CORDILLERAN OROGEN**

For over 40 yr, most tectonic models for the North American Cordillera have invoked accretion of terranes onto North America to explain Paleozoic to Cenozoic orogenesis (Dewey and Bird, 1970; Dercourt, 1972; Monger et al., 1972; Monger, 1997; DeCelles, 2004; Yonkee and Weil, 2015). In these broadly accepted models, the Cordilleran orogen is the product of mainly orogen-parallel shortening caused by eastward obduction of terranes from the subducting plate (e.g., Monger, 1997; Dickinson, 2004; Nelson et al., 2013). Deformation of the Cambrian to Triassic platform succession of western Laurentia occurred above an east-dipping subduction zone during the Cretaceous to Cenozoic Sevier and Laramide orogenies. This model will be referred to herein as the “general accretionary model.”

Despite its broad acceptance, some authors have observed that a number of geological and geophysical observations are difficult to reconcile with the general accretionary model for the Cordillera. Most importantly for this discussion:

1. The presence of two west-facing Paleozoic platform successions along much of the length of the Cordillera, the Rocky Mountain and Cassiar platforms in Canada and the Antler and North American platforms in the United States, that have different geological histories and faunal assemblages (Johnston and Borel, 2007; Johnston, 2008; Hildebrand, 2009) indicates that they were separated by a broad ocean basin during the Paleozoic (Johnston and Borel, 2007; Johnston, 2008).

2. Paleomagnetic constraints on the latitude of many of the terranes that compose the orogen suggest that they were thousands of kilometers to

![Figure 10. Weighted average $^{206}$Pb/$^{238}$U ages for Cambrian grains from samples 59 and 65 of the Tapeats Sandstone (NV—Nevada; AZ—Arizona); uncertainties are 2σ and include all random and systematic components of uncertainty. Measurement shown in gray was not included in the weighted average. MSWD—mean square of weighted deviates.](image-url)
the south of their current positions during the Late Cretaceous (e.g., Irving et al., 1996).

These and other perceived shortcomings have led some (Johnston and Borel, 2007; Johnston 2008; Hildebrand, 2009) to propose alternative models for the orogen. In these models, westward subduction of the North American plate leads to Jurassic (Johnston, 2008) or Cretaceous (Hildebrand, 2009) collision of North America with a composite intra-oceanic arc terrane or “ribbon continent.” Models involving westward subduction reconcile the presence of two Paleozoic platforms in the western Cordillera. The western platform succession, with its distinct geological history, including the presence of thick Neoproterozoic and Neoproterozoic sedimentary successions, and exotic fauna, is part of the ribbon continent, far traveled, and was juxtaposed with the North American margin during the Mesozoic. Northward translation of the ribbon continent during final accretion to North America is invoked to reconcile the paleomagnetic data. These models will be referred to as the “ribbon continent model,” as orogeny in the eastern parts of the Cordillera occurred due to collision of the North American plate with a composite ribbon continent.

The general accretionary and ribbon continent models for the Cordillera make different predictions for the provenance of Cambrian sandstones deposited on the North American and Cassiar-Antler platforms. In the general accretionary model, western Neoproterozoic to Cambrian units (McNaughton, Hamill, Three Sisters, Quartzite Range, Geertsen Canyon, Prospect Mountain, and Wood Canyon formations), which comprise the base of the Paleozoic succession of the Cassiar-Antler platform, represent distal equivalents of easterly units (Gog, Flathead, Tintic, Sawatch, Ignacio, Bliss, and Tapeats formations) deposited as part of the North American platform. Although the western units are somewhat older (latest Neoproterozoic to Early Cambrian) than eastern units (middle to upper Cambrian), the general accretionary model predicts that rocks of the Cassiar-Antler platform were proximal to Laurentia in the Cambrian and, as such, may have had access to similar provenance areas in Laurentia and therefore may contain similar detrital zircon facies. In contrast, the ribbon continent model predicts that deposition of the western units occurred on an isolated landmass (Johnston, 2008; Hildebrand, 2009) and would not necessarily share similar source areas in the Cambrian. Furthermore, the ribbon continent model stipulates that significant late Cretaceous to Cenozoic dextral translation of western Cassiar-Antler platform relative to North America occurred prior to final docking in the early Cenozoic (e.g., Hildebrand, 2015; Sigloch and Mihalynuk, 2013). As such, Cambrian detrital zircon facies in western units would likely be different from those of the North American platform to their east.

Of the six detrital zircon facies identified in basal Sauk sandstones, five (A, B, D, E, and F) are found in samples from both the Cassiar-Antler and North American platforms, while only one (facies C; Fig. 11) is unique to basal Sauk sequence rocks of the Antler platform, with no North American platform equivalent. As discussed previously, basal Sauk sandstones with facies C detrital zircon populations likely derive from recycling of the older Neoproterozoic successions on which they were deposited. As such, the lack of facies C detrital zircon populations in samples from the North American platform is readily explained by a lack of proximal Neoproterozoic rocks with facies C detrital zircon populations to recycle.

The geographic distribution of detrital zircon facies in rocks of the Cassiar-Antler platform is similar to that of the North American platform, suggesting that they shared similar source areas and limiting the north-south offset that has occurred between them (Fig. 11). For example, in the north, samples exhibiting A1 and A2 detrital zircon facies are found in both platforms along >1500 km of strike length (Fig. 11, sections U and X). Farther south, samples of the Antler platform that exhibit facies D detrital zircon populations are found in west-central Utah at roughly the same latitude as facies D samples from the North American platform in Colorado and northern Arizona (Fig. 11, section Y). Likewise, facies F samples are found in positions interpreted to be part of the North American platform and to the west in the Antler platform, all within southern California and southernmost Nevada (Fig. 11, section Z).

Could this arrangement be produced by collision of a ribbon continent? The origin of the ribbon continent is not well constrained. If the crust of the ribbon continent were a sliver rifted away from Laurentia in the Cambrian (Johnston, 2001), rocks of the Cassiar-Antler platform and the North American platform could have had access to similar-aged source areas and could, therefore, exhibit a similar geographic distribution of detrital zircon facies. However, this scenario would require that the ribbon continent had drifted far enough relative to the Laurentian craton to satisfy the paleomagnetic and faunal data sets before being juxtaposed and translated in the Mesozoic to approximately the same latitude from where it was derived in the Cambrian. The geographic continuity of detrital zircon facies between rocks of the Cassiar-Antler and North American platforms is consistent with the general accretionary model for the orogen and argues against major orogen-parallel offset between them.

CONCLUSIONS

Detrital zircons populations from Cambrian sandstones of the basal Sauk sequence are divided into six major facies groups based on statistical comparison. The geographic extents of the major facies groups are consistent with local derivation of sediments from crystalline source areas in western Laurentia, with important local recycling where older sedimentary successions were made available for erosion by rifting. Northern rock units are characterized by bimodal detrital zircon populations dominated by Archean and Paleoproterozoic ages. To the south, Archean zircons become scarce and populations are dominated by younger Paleoproterozoic zircons derived from the Yavapai and Mazatzal provinces and early Mesoproterozoic zircons derived from the A-type granites that intrude those provinces. Farther south, Grenville-aged detritus becomes more prominent, with local Cambrian plutonism providing...
Figure 11. Comparison of detrital zircon populations along four roughly east-west transects from the Cassiar-Antler platform into the North American platform; locations of the sections are shown in the map. The red thrust symbol marks the approximate location of the hypothesized suture (modified after Hildebrand, 2009). Black lines are basal Sauk sequence sandstones; grey lines are older sandstones. Details for all sample locations are given in Table 1. n is the number of measurements in each curve. Sample numbers and formations are given using symbols from Figure 1. Prominent modes are given in Ma; a line at 1.8 Ga is provided as a visual reference for the age of the Paleoproterozoic population.
useful constraints on sediment delivery pathways around the southern limit of the Transcontinental Arch. The east-west continuity of detrital zircon facies between rocks of the Cassier-Antler and North American platforms at similar latitudes suggests that no major orogen-parallel offset has occurred between them. This observation supports general accretionary models for the North American cordillera and argues against the ribbon continent.

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