A Late Jurassic to Early Cretaceous record of orogenic wedge evolution in the Western Interior basin, USA and Canada

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ABSTRACT

The Late Jurassic to Early Cretaceous fill of the Western Interior foreland basin is characterized using geochronological data in order to assess the stratigraphic expression of wedge-top geomorphology, as controlled by sediment cover and denudation. In northern Montana, USA, and Alberta, Canada, wedge-top deposits are poorly preserved; however, their former presence may be inferred from the detrital record in the foreland basin. We present new U/Pb detrital zircon data from nine samples collected near Great Falls, Montana, augmented with field data. The stratigraphy at Great Falls is characterized by Late Jurassic marine and nonmarine deposits, which are truncated by a basin-wide sub-Cretaceous unconformity. Aaptian and lower Albian strata overlying the unconformity are dominated by nonmarine deposits, which transition up-section into a predominantly marine succession related to a major transgression of the Boreal Seaway in the Albanian.

Detrital zircon grains from Great Falls strata yield age spectra that can be subdivided into three groups using multidimensional scaling. Group 1 is characterized by diverse zircon populations, which are interpreted to record recycling of pre-Cordilleran sedimentary strata transported via foreland basin-axial river systems with headwaters in the southwestern United States. Group 2 is characterized by the dominance of Mesozoic detrital zircon grains, which are interpreted to record sediment dispersal by fluvial systems with headwaters in the Cordillera. Group 3 is intermediate between groups 1 and 2, based on its proportion of Mesozoic zircon grains. This group records a diversification of the provenance from one dominated by Cordilleran igneous rocks to include recycled sedimentary strata.

New data are integrated with three other data sets from Montana and Alberta such that stratigraphic thicknesses (a proxy for accommodation development) and provenance evolution can be compared across the basin. The detrital record in each area, which transitions from diverse provenance to predominantly Cordilleran through the entire stratigraphic section, can be linked to the burial of the pre-foreland strata in the wedge-top depoise. This record elucidates a period of evolution of the western margin of North America to a more Andean-type system with primary input to the basin from an active magmatic arc.

INTRODUCTION

Aggradation and denudation of proximal foreland basin deposits in the wedge-top depozone are first-order controls on sediment flux to more-distal parts of foreland basin systems (Ben-Avraham and Emery, 1973; DeCelles, 1994; DeCelles and Giles, 1996; Roddaz et al., 2005; Ross et al., 2005; Horton, 2018). Burial of the frontal toe of the orogen can heal complex topography and enhance direct sediment transfer from the orogenic hinterland to a basin. Conversely, denudation of these wedge-top sediments can lead to structural control of river pathways; the process also can expose older stratigraphy in the orogenic wedge, which can be reflected by provenance changes in the adjacent foreland basin (Ross et al., 2005; Lawton et al., 2010).

Sediments in the wedge-top depozone accumulate on top of orogenic structures and are part of the frontal toe of the orogenic wedge (DeCelles and Giles, 1996). These synorogenic strata accumulate near the erosional/depositional surface and are characterized by low preservation potential such that the history of sedimentation in this zone is difficult to discern (e.g., Coogan, 1992; Frisch et al., 2001; McMechan et al., 2018). More distal parts of the foreland basin contain well-established records of orogenic processes (e.g., Heller and Paola, 1989; Ross et al., 2005; Quinn et al., 2016). Therefore, we hypothesize that the history of the wedge-top depozone can be elucidated by investigating strata in more-distal parts of the foreland basin. This is particularly relevant to understanding topographic evolution in fold-thrust belts that have been deeply incised during subsequent orogenesis and glaciation (Osborn et al., 2006).

We present a detrital zircon data set from Western Interior basin strata exposed near Great Falls, Montana, USA. The units provide a unique window into the Late Jurassic–Early Cretaceous evolution of the foreland basin because outcrops of these strata are rare except within the fold-thrust belt, which is ~100 km west of the study area. New data are integrated with previously presented data sets from across the basin in order to consider the history of burial and exhumation of the frontal toe of the orogenic wedge (Figs. 1) (Puentes et al., 2011; Leier and Gehrels, 2011; Raines et al., 2013; Benyon et al., 2014; Blum and Pecha, 2014; Quinn et al., 2016). This study emphasizes the potential impact of wedge-top dynamics on sediment dispersal across foreland basins and the structural evolution of the orogen.
Figure 1. (A) Modified geological map of Montana, USA, which highlights the Great Falls outcrop belt (after Garrity and Soller, 2009). The inset shows the setting of the Great Falls and other areas with detrital zircon data sets relative to the major bedrock provinces of North America (modified after Dickinson and Gehrels, 2009b). Inset: A—Appalachian Orogen; AC—Archean Craton; AFB—Appalachian Foreland Basin; C—Cordilleran magmatic arc and accreted terranes; CL—Cold Lake; EM—East Mexico Arc; G—Grenville Orogen; GC—Grande Cache; GF—Great Falls; GR—Gibson Reservoir; GRP—Granite–Rhyolite Province; JE—Jurassic eolianites; TH—Trans-Hudson Orogen; YC—Yucatan–Campeche Terrane; W—Wopmay Orogen; WHR—Wyoming–Hearne–Rae cratons. (B) Balanced cross section showing a reconstruction of the Early Cretaceous orogen–foreland basin system of the southern Canadian Cordillera (after Price, 1994). Line of section is shown in the inset of Figure 1A.
STUDY AREA AND STRATIGRAPHY

The outcrops of interest to this study are within 30 km of Great Falls, Montana (Fig. 1). This location is ideal for the study of basin evolution in the Late Jurassic to Early Cretaceous because of the unique access to outcropping undeformed strata of this age exposed in the distal foreland plains. Because the stratigraphy can be correlated into western Montana and the Alberta foreland basin to the north, the Great Falls area is key for integrating data across the region.

The stratigraphic nomenclature for this study (Figs. 2, 3) is mostly based on the convention defined by Walker (1974); however, we refer to the basal sandstone of the Kootenai Formation as the Cut Bank Member (Glaister, 1959; Hopkins, 1985) and the Quartzose Sandstone unit as the Sunburst Member (Glaister, 1959; Hopkins, 1985; Hayes, 1990). The Upper Jurassic–Lower Cretaceous stratigraphy is more than 200 m thick in the study area (Figs. 2 and 3). Sedimentological characteristics and the interpreted depositional environments for individual units are summarized in Table 1.

Jurassic deposits transition from the marine Swift Formation to the non-marine Morrison Formation (Table 1) (Cobban, 1945; Harris, 1966; Fox and Groff, 1966; Suttner, 1969; Brenner and Davies, 1974; Walker, 1974; Hayes, 1983). Jurassic strata are truncated by the basin-wide sub-Cretaceous unconformity (Fig. 2). The overlying Kootenai Formation is dominated by fluvial deposits, with marine influence interpreted by some workers (Glaister, 1959; Oakes, 1966; Shelton, 1967; Walker, 1974; Mudge and Rice, 1982; Hopkins, 1985; Hayes, 1986; Farshori and Hopkins, 1989; Hayes, 1990). Two major flooding events are evident in Lower Cretaceous strata, recorded by (1) the lacustrine or restricted marine Ostracod Member of the Kootenai Formation, and (2) the marine shale and shoreface deposits of the Flood Member of the Blackleaf Formation, which overlies the Kootenai Formation (Cannon, 1966; Fox and Groff, 1966; Finger, 1983).

METHODS

Measured stratigraphic sections totaling ~290 m were used to compile sedimentological data. Paleocurrent measurements were acquired from dune foresets, ripple foresets, and bed scours (n = 630).
Rock samples weighing 3–4 kg were collected in the field for detrital zircon measurements. Two samples were collected from Upper Jurassic strata of the Swift Formation (Ellis Group) and of the overlying Morrison Formation (Fig. 2). Five samples were selected from the Early Cretaceous Kootenai Formation (two from the Cut Bank Member and one each from the overlying Sunburst, Red Sandstone, and Upper Kootenai Members) (Fig. 2). Two samples were collected from the Alban–Cenomanian Blackleaf Formation. Both these samples are from regionally mappable sandstone units within the Flood Member, the lowermost unit within the Blackleaf Formation (Cannon, 1966).

Sandstone samples were pulverized, and initial separation of heavy minerals was performed on an MD Gemini Goldharvester™ shaking table (a water table). Zircon was further concentrated using heavy liquids and magnetic separation. A representative fraction of the zircon-rich separate was mounted into a 25.44-mm form and cast in epoxy. Mounts were then ground to expose the cores of the zircons and polished. U–Pb isotopic data were collected using laser ablation–inductively coupled plasma mass spectrometry (LA-ICPMS) at the University of Calgary by the methods of Matthews and Guest (2017). Zircon grains were ablated using a 33-μm beam diameter, which was chosen to minimize grain-size bias. In each session, four reference materials were ablated: (1) Temora-2 (Black et al., 2004), (2) 91500 (Wiedenbeck et al., 1995), (3) FC-1 (Paces and Miller, 1993), and (4) 1242 (Mortensen and Card, 1993).

This was done to correct for laser-induced elemental fractionation, to account for instrumental mass fractionation and drift, to calibrate the measured isotopic ratios, and to validate the measurement method. For data reduction, we used lotile™ v. 2.5 (Paton et al., 2010) and the custom Microsoft Excel™ macro ARS4.0 (Matthews and Guest, 2017). We performed data visualization using the Excel plug-in Isoplot (Ludwig, 2012) and plotted normalized probability density data using an Excel macro from the Arizona LaserChron Center. Full isotopic data and sample locations can be found in the Supplemental Data Table.

The maximum depositional age (MDA) of the samples was calculated as the weighted average of the youngest dates (minimum of n = 3) that overlap within uncertainty at the 2-sigma level (Dickinson and Gehrels, 2009a). To standardize error propagation between the Great Falls and other data sets used in this study, analytical and systematic errors were added in quadrature to the errors reported in previous studies following recommendations by Horstwood et al. (2016).

To compare the detrital zircon populations objectively, multidimensional scaling (MDS) plots were constructed using a MATLAB script (MuDisc) provided by Vermeesch (2013). MDS analysis is based on D-values, which are produced as part of the Kolmogorov–Smirnov test and represent “distance” between two samples (Vermeesch, 2013; Spencer and Kirkland, 2015). D-values are arranged in a matrix and plotted on a Euclidian plane while attempting to honor the “distances” in the matrix. Normal-distribution, synthetic age populations were created in Excel and added to the MDS plot to show important age inputs (Spencer and Kirkland, 2015).

| UK058 | UK058_253 | NA | 84 | 1840 | 2.00 | 0.05111 | 2.3N |
|-------|-----------|----|----|------|------|----------|------|
| UK058U | UK058_204 | NA | 1082 | 1935 | 0.1 | N | A6 | 1.5006 | 2.20 | 0.05351 | 2.3N |
| UK058U | UK058_174 | NA | 2976 | 5008 | 0.0 | N | A6 | 2.4610 | 2.10 | 0.04979 | 0.1 | NA | NA |
| UK058U | UK058_101 | NA | 6591 | 4420 | 34 | 0.0 | N | A6 | 2.6174 | 2.00 | 0.04967 | 0.8 | NA | NA |
| UK058U | UK058_141 | NA | 3127 | 2806 | 0.1 | N | A5 | 4.1126 | 2.10 | 0.04779 | 0.2 | NA | NA |
| UK058U | UK058_21N | NA | 2182 | 6300 | 70 | 1. | NA | NA | 56.6893 | 2.00 | 0.05067 | 0.3 | NA | NA |
| UK058U | UK058_70N | NA | 36 | 2920 | 50 | 1. | NA | NA | 55.1876 | 2.50 | 0.04941 | 1.1N |
| UK058U | UK058_102 | NA | 1493 | 1804 | 0.1 | N | A5 | 7.6369 | 2.30 | 0.05051 | 1.4N |

Figure 3. Composite stratigraphic section of the Great Falls, Montana, USA, area. The section was produced with field measurements and published measured sections from Ballard (1966), Cannon (1966), Fox and Groff (1966), Harris (1966), and Walker (1974). c—coarse-grained; cl/coal—clay/coal; f-fine-grained; Fm.—Formation; m—medium-grained; Mb.—Member; sl—silt; vf—very fine-grained. Yellow—sandstone; gray—shale, siltstone; blue—limestone.
Detrital zircon results are presented as probability density plots and maximum depositional ages are reported in Figure 4. The oldest zircon populations in the Swift and Morrison Formations are Archean in age (2700–2640 Ma) (Fig. 4). Both samples contain (1) prominent Mesoproterozoic to earliest Neoproterozoic populations (at 1470–1400 Ma and 1200–950 Ma), (2) Neoproterozoic populations (at 950 Ma and 615–590 Ma), and (3) a prominent Carboniferous population (at 310 Ma). The zircon populations of the Swift and Morrison Formations are composed of 20% Mesozoic detrital zircons with age modes in the Triassic (235 Ma) and Jurassic (160–150 Ma). In the Swift Formation, the Jurassic mode dominates, whereas the Triassic and Jurassic modes are almost equal in the Morrison Formation. Both these units exhibit average paleocurrent directions to the north (Fig. 4B).
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Appalachian Orogen (850–285 Ma)  Cordilleran Orogen (<245 Ma)
East Mexico Arc (284–232 Ma)  Grenville Orogen (1300–900 Ma)
Granite-Rhyolite Province/A-Type Plutons (1500–1300 Ma)
Taupun-Mauputal (1800–1600 Ma)
Trans-Hudson Orogen (1900–1800 Ma)

Figure 4. (A) Normalized probability density plots (errors incorporated at the 1-sigma level) and maximum depositional ages (MDA) for nine detrital zircon samples. (B) Paleoflow rose diagrams for seven stratigraphic units. North is to the top of each rose diagram. (C) Probability density plots (errors incorporated at the 2-sigma level) for each of the stratigraphic units sampled with a scale change at 350 Ma to highlight young detrital zircon populations. The two Cut Bank Member samples are grouped because of their similarity. Colors indicate the major magmatic provinces of North America. Fm—Formation; Mb—Member; MDA—maximum depositional age. N—number of samples; n—number of individual measurements (ages and flow directions).
The Cut Bank and Sunburst Member samples share many populations with the underlying strata. The Cut Bank and Sunburst Members have more prominent populations in the Archean to Paleoproterozoic (2800–2600 Ma and 2150–2000 Ma) and the Silurian–Devonian (430–410 Ma) than do the Swift and Morrison strata. The Cut Bank Member samples also have a prominent mode in the Paleoproterozoic at 1840–1780 Ma, and the Sunburst Member has a prominent mode at 1620 Ma. Both have populations in the Permian–Triassic (260–230 Ma). The zircon populations of the Cut Bank and Sunburst Members are composed of 10%–11% and 8% Mesozoic detrital zircons, respectively, including a Jurassic population (160–155 Ma). Like the Jurassic strata, measurements from the Cut Bank Member indicate an average paleoﬂow to the north. Measurements from the Sunburst Member display a large spread but average paleoﬂow direction is to the west (Fig. 4B).

The zircon populations of the Red Sandstone Member, Upper Kootenai Member and the lower sandstone of the Flood Member are distinct from the older samples in that they are composed mainly of Mesozoic detrital zircon grains (84%–95%) (Fig. 4C). There are three major Late Triassic to Cretaceous populations in the probability density plots. The most prominent is Jurassic in age (160 Ma), and the two subordinate populations are Late Triassic–Early Jurassic (220–190 Ma) and Cretaceous (115–110 Ma) in age. The Red Sandstone Member is characterized by north-directed paleoﬂow measurements. Paleoﬂow indicators in the Upper Kootenai Member are characterized by mean paleoﬂow direction to the east. Paleoﬂow measurements collected from the lower sandstone of the Flood Member at one outcrop location are characterized by paleoﬂow to the north (Fig. 4B).

The zircon population of the upper sandstone of the Flood Member is composed of 51% Mesozoic detrital zircon grains (Fig. 4). The Mesozoic zircon populations are the same as underlying strata (160 and 110 Ma). There are Proterozoic populations, most notably at 1830 and 1030 Ma, and minor populations at 650, 450, and 360 Ma.

## ANALYSIS AND INTERPRETATION

The ultimate sources of detrital zircon grains are interpreted on the basis of correlation with published ages of North American magmatic assemblages (Figs. 1 and 4C). Archean detrital zircons (>2500 Ma) ultimately derive from the cratonic cores of North America (Hoffman, 1988; Card, 1990). Paleoproterozoic detrital zircon grains are associated with the Trans-Hudson Orogen (1900–1800 Ma), similar orogens that stitch together the Archean cores, and the Yavapai–Mazatzal Province (1790–1610 Ma) (Hoffman, 1988; Van Schmus et al., 1993; Van Kranendonk et al., 1993; Zhao et al., 2002; Whitmeyer and Karlstrom, 2007). Mesoproterozoic detrital zircon sources include the Granite–Rhyolite Province in the southern and eastern United States (1550–1300 Ma) (Whitmeyer and Karlstrom, 2007), A-type plutons found throughout the United States (1480–1340 Ma) and the Grenville Orogen of the eastern and southern United States and eastern Canada (1300–900 Ma) (Easton, 1986; Windley, 1988; Anderson and Bender, 1989; Whitmeyer and Karlstrom, 2007; Dickinson, 2008). Neoproterozoic detrital zircon grains (850–550 Ma) are derived from peri-Gondwanan terranes that collided with North America during the Appalachian Orogen (Eriksson et al., 2004; Becker et al., 2005; Park et al., 2010). Plutons associated with the Appalachian Orogen and precursor rift assemblages span the Neoproterozoic to the Paleozoic and supply a portion of the 760–285 Ma grains (Dickinson and Gehrels, 2009b; Park et al., 2010).

Magmatic assemblages younger than the middle Permian are associated with the East Mexico Arc (284–232 Ma) (Torres et al., 1999), the Cordilleran magmatic arc (<245 Ma), and accreted terranes of the Cordilleran Orogen (Fig. 5). Triassic and later Mesozoic igneous rocks and detrital zircon are present on the Willowa and Olds Ferry Terranes of Washington, Idaho, and Oregon (LaMaskin et al., 2011; LaMaskin, 2012; LaMaskin et al., 2015; Gaschnig et al., 2017a). Triassic to Early Jurassic magmatic assemblages are reported from the Mojave Desert and the Eastern Coast Plutonic Complex (Barth and Wooden, 2006; Gehrels et al., 2009). Jurassic plutons are present in the Western Coast Plutonic Complex, Sierra Nevada Batholith, and the Omineca Belt of interior British Columbia (Fig. 5) (Archibald et al., 1983; Hyndman, 1983; Armstrong, 1988; Ducea, 2001; Gaschnig et al., 2009; Gehrels et al., 2009; Paterson et al., 2011). Similar segments of the Cordillera were active in the Early Cretaceous. An additional episode of Early Cretaceous magmatism is evident in the Suture Zone Suite of the western margin of the Idaho Batholith (Manduca et al., 1993; Gaschnig et al., 2017b).

### Provenance Interpretation and Evolution

Samples are subdivided into two endmember groups and one intermediate group based on the MDS plot and visual inspection of their detrital zircon populations (Fig. 6). The first endmember is characterized by diverse detrital zircon spectra with populations spanning the Mesozoic to Archean. The other endmember is characterized by detrital zircon spectra dominated by Mesozoic populations derived from Cordilleran magmatic rocks. The intermediate group appears to be transitional with both Mesozoic populations and Paleozoic–Precambrian zircon populations.

#### Group 1—Diverse Detrital Zircon Spectra

Group 1 consists of the basal units in this study (i.e., Swift, Morrison, Cut Bank and Sunburst strata) and is characterized by detrital zircon populations derived from all the major magmatic provinces of North America (Fig. 6). The distribution of zircon populations is consistent with recycling of sedimentary strata uplifted along the Mogollon highlands and incipient Cordilleran fold-thrust belt in the southwestern United States (Fig. 7; Dickinson and Gehrels, 2008a, 2009b; Leier and Gehrels, 2011; Laskowski et al., 2013; May et al., 2013). Group 1 samples are also characterized by a Jurassic detrital zircon population from primary igneous sources in the Cordillera (Fig. 4).
Mesozoic eolianites in the southwestern United States (Fig. 7) are characterized by broad detrital zircon populations derived from the Appalachian orogeny (populations at 615 and 420 Ma) and the Grenville orogeny (populations at 1160 and 1055 Ma) (Dickinson and Gehrels, 2008a; 2009b; Laskowski et al., 2013). Paleozoic and Proterozoic detrital zircon populations in Group 1 samples are similar to the Mesozoic eolianites (Fig. 7). Additionally, the eolianite strata contain Late Permian–Triassic populations (260–235 Ma) (Fig. 4), which constitute a major population in each Group 1 sample and are also common in Triassic strata (e.g., Chinle Group, Moenkopi Formation) of the southwestern United States (Dickinson and Gehrels, 2008b). Group 1 samples have Jurassic populations (165–150 Ma) that are too young to be a significant component of the eolianite strata and must be attributed to the Cordilleran magmatic arc. Plutonic and volcanic strata of this age are widespread along the strike of the western continental margin, limiting their usefulness in provenance interpretation (Fig. 5).

Local sources of detrital zircon grains could also account for specific modes in these samples. Sedimentary strata of Cordilleran terranes and North American passive-margin units west of the study area have zircon populations similar to the southwestern eolianites (LaMaskin et al., 2011; LaMaskin, 2012; Gehrels and Pecha, 2014). The Belt Supergroup, which outcrops in northwestern Montana, contains abundant Proterozoic and Archean detrital zircons (Ross and Villeneuve, 2003). The Yavapai–Mazatzal-age Big Sky Orogen in southwestern Montana is an alternative source for Mesoproterozoic detrital zircon (Harms et al., 2004). Three distinct chert varieties—black, red, and phosphatic—and sponge spicules are reported from petrographic study of the Morrison and Kootenai Formations and give the sandstones a “salt-and-pepper” appearance in the field (Suttner, 1969). Suttner (1969) ascribes provenance of these components to the Permian–Pennsylvanian Phosphoria, Wood River, and Quadrant Formations of western North America and notes that because the Permian–Pennsylvanian section is relatively intact in Montana, these diagnostic components are derived from west or south of the Montana–Idaho border. Texturally, framework grains of the Swift, Morrison, and Kootenai Formations have been reported as round to subround, which supports the hypothesis of second-cycle deposition of these units (Ballard, 1968). Given the limitations of this data set, it is difficult to rule out these local sources; however, north-directed paleoflow for the Swift, Morrison, and Cut Bank units, and the continuity of similar Morrison Formation (Dickinson and Gehrels, 2008a; May et al., 2013) and Early Cretaceous (Leier and Gehrels, 2011) detrital zircon spectra with samples south of the Great Falls area support southern provenance as most likely.

**Figure 6.** Multidimensional scaling plot of the nine detrital zircon samples from Great Falls, Montana, USA, showing two endmember groups of zircon spectra and one intermediate group. Solid lines indicate nearest neighbors, and dashed lines indicate second nearest neighbors. Mb.—Member; Fm.—Formation.

**Figure 7.** Composite probability density plot of all the detrital zircon ages from Group 1 samples from Great Falls, Montana, USA, compared to a composite probability density plot of detrital zircon ages from the southwestern United States eolianites (Dickinson and Gehrels, 2008a). Error incorporated into both probability density functions are at the 2-sigma level.
The Sunburst Member is unique in that it is characterized by an average paleoflow direction to the west, which is difficult to reconcile with detrital zircon spectra that suggest a source area to the south (Fig. 4). The population at 260 Ma in the Sunburst Member overlaps in age with plutonism in the East Mexico Arc, reinforcing a southern component of the provenance. Of note, the Sunburst Member is also distinct petrographically, with higher proportions of quartz and less chert than the underlying units (Walker, 1974; Hayes, 1990). We speculate that the drainage system deviated east of Great Falls, perhaps deflecting away from uplifted highlands (cf. Christopher, 2003) and eventually diverting westward through the study area. As such, the ultimate sources of zircon remain unchanged from underlying units; the deviation of the sediment routing system away from the fold-thrust belt led to reduced enrichment of chert and lithic grains in the unit.

Group 3—Intermediate Detrital Zircon Spectra

The upper sandstone of the Flood Member, the stratigraphically youngest sample in this study, is composed of 51% Mesozoic detrital zircon grains, making it intermediate between the two endmembers, Group 1 and Group 2 (Fig. 6). This suggests that the sediment source areas diversified upwards through the stratigraphic section. The Mesozoic populations in Group 3 overlap with Group 2 samples, indicating that similar Cordilleran arc sediment sources contributed detritus to this unit. Proterozoic detrital zircon populations are dominated by a Grenville-age population (1030 Ma) and a subordinate Trans-Hudson-age population (1830 Ma). Neoproterozoic to Paleozoic (670–370 Ma) zircon ages also occur in composite signature of the Mesozoic eolianites of the southwestern United States and in populations of Group 1 (Fig. 4) (Dickinson and Gehrels, 2009b). The upper sandstone of the Flood Member could record either the recycling of Jurassic–Lower Cretaceous foreland basin strata or the reincorporation of pre-foreland sedimentary strata into the drainage system.
SPATIAL–TEMPORAL BASIN EVOLUTION

By comparing new data from Great Falls with data from Gibson Reservoir, Grande Cache, and Cold Lake, the evolution of sediment sources, sediment dispersal, and basin partitioning can be assessed over a period of orogen evolution and basin filling that lasted for ~50 m.y. (Fig. 11). The interpretation of sediment routing systems from the Cordillera and other areas of North America to the foreland basin illustrate large-scale trends in the evolution of drainage in the region.

Late Jurassic

Jurassic deposits record marine to nonmarine basin filling, which is typical of foreland basin clastic wedges (Table 1) (Cant and Stockmal, 1989; Fuentes et al., 2011; Miles et al., 2012; Kukulski et al., 2013; Raines et al., 2013). Overall, the thickness of these units is controlled by variations in accommodation and differential erosion of pre-Cretaceous units during incision of the sub-Cretaceous unconformity (Fig. 9) (Leckie and Smith, 1992; Hayes et al., 1994; Gillespie and Heller, 1995; Miles et al., 2012). That continental deposits at Grande Cache, Alberta (e.g., Monteith Formation), are stratigraphically younger than continental deposits in Montana (e.g., Morrison Formation) is interpreted to record south-to-north, basin-axial filling of foreland accommodation space (Fig. 2) (Poulton et al., 1990; Kukulski et al., 2013).

MDAs for the Swift and Morrison Formations from Great Falls (152 ± 2.4 Ma and 151 ± 2.2 Ma respectively) and Gibson Reservoir (168 ± 5.5 Ma and 162 ± 4.5 Ma support Late Jurassic deposition of these units; these ages indicate that deposition may have been diachronous, or that different sources of Jurassic zircon were available to the different areas.

Detrital zircon data, including the close association of Jurassic units at Great Falls and Grande Cache (Fig. 10), support the interpretation that Late Jurassic sediment dispersal was characterized by basin-axial fluvial systems with headwaters in the southwestern United States (Fig. 11) (Hamblin and Walker, 1979; Miles et al., 2012). While this interpretation apparently best fits this data set, transverse sediment routing during this time period has also been reported. For example, the upper part of the Monteith Formation (Monteith A member) records local recycling of pre-foreland sediments in Montana (e.g., Monteith Formation), are stratigraphically younger than continental deposits at Grande Cache, Alberta (e.g., Monteith Formation). That continental deposits at Grande Cache, Alberta (e.g., Monteith Formation), are stratigraphically younger than continental deposits in Montana (e.g., Morrison Formation) is interpreted to record south-to-north, basin-axial filling of foreland accommodation space (Fig. 2) (Poulton et al., 1990; Kukulski et al., 2013).

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MDAs for the Swift and Morrison Formations from Great Falls (152 ± 2.4 Ma and 151 ± 2.2 Ma respectively) and Gibson Reservoir (168 ± 5.5 Ma and 162 ± 4.5 Ma support Late Jurassic deposition of these units; these ages indicate that deposition may have been diachronous, or that different sources of Jurassic zircon were available to the different areas.

Detrital zircon data, including the close association of Jurassic units at Great Falls and Grande Cache (Fig. 10), support the interpretation that Late Jurassic sediment dispersal was characterized by basin-axial fluvial systems with headwaters in the southwestern United States (Fig. 11) (Hamblin and Walker, 1979; Miles et al., 2012). While this interpretation apparently best fits this data set, transverse sediment routing during this time period has also been reported. For example, the upper part of the Monteith Formation (Monteith A member) records local recycling of pre-foreland sedimentary strata of the Canadian passive margin (Figs. 10 and 11). Raines et al. (2013) attributed this to the propagation of transverse drainage systems across the foredeep. Additionally, the Morrison Formation in Utah has been shown to include the record of transverse sediment dispersal by distributive fluvial systems (Hartley et al., 2015; Owen et al., 2015). Previously, Upper Jurassic strata in Montana have been assigned to a backbulge setting with passage of the forebulge interpreted to have created the sub-Cretaceous unconformity (DeCelles, 2004; Fuentes et al., 2009; 2011). The detrital zircon spectra are statistically similar at Great Falls, Gibson Reservoir, and Grande Cache, and all the samples contain Jurassic populations, which derive from the west though they may have been delivered to the basin aerially as ash fall (Fig. 8).
Figure 9. Cross section correlating composite stratigraphic sections from each area using the top of the Kootenai Formation (and equivalent surfaces) as the datum. Vertical scale is in meters. Units with detrital zircon data are indicated by the black diamonds with numbers in parentheses indicating the number of zircon samples for each unit. Location map is inset. (A) Stratigraphic section from the foothills of western Montana, USA, at Gibson Reservoir (Fuentes et al., 2011). (B) Stratigraphic section from Great Falls, Montana, USA, from field measurements and Ballard (1966), Cannon (1966), Harris (1966), and Walker (1974). (C) Stratigraphic section from the northwest Alberta foothills, Grande Cache, Alberta, Canada (Miles et al., 2012; Kukulski et al., 2013; and Quinn et al., 2016). (D) Stratigraphic section from the subsurface at Cold Lake, Alberta, Canada (Hutcheon et al., 1989; Feldman et al., 2008). Fm.—Formation; Mb.—Member; cl/coal—clay/coal, vf—very fine sandstone; m—medium sandstone; Ss.—sandstone; yellow—sandstone; gray—shale; blue—limestone.
Figure 10. Multidimensional scaling (MDS) plot of data from areas in Montana, USA, and Alberta, Canada. Solid lines indicate nearest neighbors, and dashed lines indicate second nearest neighbors. (A) MDS plot of all the detrital zircon data from each of the four study areas. Synthetic age populations are shown with stars to highlight important inputs to the samples. Annotations indicate the interpretation of the provenance signals. The dashed box indicates the expanded area in Figure 10B. (B) Scale expansion to show the statistical differences between samples that are too similar to observe at the scale of Figure 10A. L—Lower; M—Middle; U—Upper.
Upper Jurassic strata of the Monteith Formation in the Grande Cache area have been assigned to the foredeep on the basis of thickness, sandstone provenance, and composition (Price and Mountjoy, 1970; Monger et al., 1982; Cant and Stockmal, 1988; Leckie and Smith; 1992, Miles et al., 2012). The similarity between the detrital zircon spectra in the Late Jurassic system and the occurrence of Cordilleran magmatic-arc grains in these deposits do not support the hypothesis that a forebulge significantly influenced sediment dispersal in the basin during the Late Jurassic. The basin configuration is potentially analogous to the modern foreland east of the central Andes, where the forebulge is buried and does not influence sediment routing patterns (Chase et al., 2009).

**Early Cretaceous–Aptian**

Overall, the thickness of Early Cretaceous strata (e.g., Lower Mannville Group in Alberta) is fairly consistent across the region (Hayes et al., 1994), indicating that foreland subsidence associated with a crustal load to the west had limited impact on accommodation development (Gillespie and Heller, 1995). The thickness variations that do exist in Lower Cretaceous deposits are significantly influenced by differential erosion on the angular sub-Cretaceous unconformity, with thicker sediment accumulations occupying paleovalley systems incised into Jurassic and pre-foreland sedimentary rocks (Jackson, 1984; Hayes, 1986; Ranger and Pemberton, 1988; Wightman and Pemberton, 1997; Ardies et al., 2002; Zaitlin et al., 2002).

Fluvial sandstones of the Cut Bank Member and the McMurray Formation overlie the sub-Cretaceous unconformity in the Great Falls and Cold Lake areas, respectively (Table 1; Figs. 2 and 9). At Gibson Reservoir and Grande Cache, the sub-Cretaceous unconformity is overlain by fluvial conglomerate (the basal conglomerate of the Kootenai Formation and the Cadomin Formation, respectively (Figs. 2 and 9) (McLean, 1977; Heller and Paola, 1989; Leier and Gehrels, 2011).

MDAs for the McMurray Formation (117 ± 4.7 Ma) (Benyon et al., 2014, 2016) and the Cadomin Formation (117 ± 2.4 Ma) are consistent with Aptian deposition and validate the stratigraphic correlation of these units. Syndepositionally formed zircon grains are not abundant in basal Cretaceous strata of the southern areas, so robust MDAs could not be calculated; however, biostratigraphic and lithostratigraphic correlation indicate the lower Kootenai Formation strata are likely time equivalent to the northern units (Burden, 1984) (Fig. 2).

After the incision of the sub-Cretaceous unconformity, basin-axial river systems routed sediment northwards from the United States to Alberta and Saskatchewan (Leier and Gehrels, 2011; Benyon et al., 2014, 2016, Blum and Pecha, 2014). Diverse detrital zircon spectra for eastern-area samples from Great Falls (Cut Bank Member) and Cold Lake (McMurray Formation) are consistent with interpretations of broad drainage basins in the southwest and/or southeast United States (Figs. 10 and 11). Detrital zircon populations in the western areas (Cadomin Formation and basal conglomerate of the Kootenai Formation) con-
tain abundant detrital zircons that ultimately derive from the Trans-Hudson Orogen but are attributed to recycling of uplifted pre-foreland basin strata in the Canadian segment of the fold-thrust belt (Leier and Gehrels, 2011). The differences in the detrital zircon spectra between the western areas and the eastern areas confirm that the basin was segregated into multiple paleodrainages, presumably controlled by topography on the unconformity surface (Jackson, 1984; Leckie and Smith; 1992; Leckie and Cheek, 1997; Wightman and Pemberton, 1997; Benyon et al., 2014, 2016; Blum and Pecha, 2014).

Early Cretaceous–Aptian-Albian

Strata deposited near the Aptian–Albian boundary are less strongly controlled by accommodation development in major valley systems as topography across much of the basin was infilled by this time (Jackson, 1984; Leckie and Smith, 1992). A transgression of the basin at this time is consistent with the onset of increased tectonic subsidence, possibly associated with dynamic mantle subsidence and eustatic sea-level rise (Fig. 9) (Jackson, 1984; Mitrovica et al., 1988; Leckie and Smith, 1992; Hayes et al., 1994), which is reflected in subsidence models from western Montana (Fuentes et al., 2009).

Flooding of the foreland basin by the Boreal Sea is variably expressed in the stratigraphic record (McLean and Wall, 1981; Jackson, 1984; Leckie and Smith, 1992). At Great Falls, fluvial deposits with possible marine influence in the Red Sandstone Member underlie the lacustrine to restricted marine limestone of the Ostracod Member (Table 1). In Alberta, the Bluesky Formation records deposition in a marine to estuarine setting (Jackson 1984; Smith et al., 1984; Hubbard et al., 2004; MacKay and Dalrymple, 2011). The Cold Lake area is characterized by a thick succession of deltaic and estuarine valley-fill facies in the Clearwater Formation (Putnam, 1982; Putnam and Pedskalny, 1983; Hutcheon et al., 1989, Feldman et al., 2008; Maynard et al., 2010). The high proportion of sandstone at Cold Lake was linked to the persistence of a major continental river system by Blum and Pecha (2014) on the basis of pre-Mesozoic detrital zircon populations.

The Red Sandstone is stratigraphically older than the other units considered for this time period because of its position below the Ostracod Member, which is generally considered to be time-equivalent to the Wabiskaw Member and Bluesky Formation (Figs. 2 and 9). However, the MDA calculated for the Red Sandstone Member (108 ± 1.6 Ma) is younger than the Clearwater Formation (115 ± 3.4 Ma) and the Bluesky Formation (114 ± 2.2 Ma). While these data are conflicting, they generally support deposition of these units near the Aptian–Albian boundary. This analysis suggests that either the propagation of uncertainty in these data sets or fine-scale correlations of this time period should be revisited (i.e., correlation of the Ostracod Member from Montana to Alberta could be problematic).

According to stratigraphic position, the Red Sandstone Member is the oldest unit in this study that is dominated by detrital zircon grains from Mesozoic sources in the Cordillera (Figs. 9 and 10). The Clearwater Formation is also dominated by Mesozoic detrital zircon grains, sharing the two populations at 160 and 110 Ma with the Red Sandstone Member (Fig. 8B; samples AOS6, AOS16, AOS18). The zircon data are consistent with petrographic studies that reported large proportions of volcanic and plutonic detritus preserved by early hydrocarbon charge at Cold Lake (Putnam and Pedskalny, 1983; Hutcheon et al., 1989). The Clearwater Formation sandstone in the Cold Lake area contains angular to subangular grains, including abundant intact feldspar grains, and volcanic rock fragments, which support first-cycle deposition (Putnam and Pedskalny, 1983).

The detrital zircon spectra from the Bluesky Formation at Grande Cache have a significant proportion of Jurassic detrital zircon grains; however, the population at ca. 1800 Ma and the diversity of other ages in the sample indicate the continued importance of uplifted pre-foreland basin sedimentary sources (Fig. 10). Distinction between zircon spectra from the west (i.e., Bluesky Formation) and east (i.e., Clearwater Formation) could be attributed to basin partitioning associated with the initial incursion of the Boreal Sea into the basin, which may have segregated sediment sinks adjacent to the fold-thrust belt from those hundreds of kilometers to the east (cf. Somme et al., 2009; Blum et al., 2013; Bhattacharya et al., 2016). This mode of basin partitioning could be analogous to the documented effect of post-glacial sea-level rise on drainage basins in the southern United States and Europe (Blum and Womack, 2009; Maselli et al., 2011).

Early Cretaceous–Middle Albian

Middle Albian strata thicken westward owing to asymmetric accommodation development associated with flexural subsidence of the foreland basin (Fig. 9) (Hayes et al., 1994). The Upper Kootenai Formation is nearly twice as thick at Gibson Reservoir relative to Great Falls. The Spirit River Formation at Grande Cache was deposited in a foredeep setting and is hundreds of meters thick (Smith et al., 1984), whereas the equivalent units at Cold Lake are less than 100 m thick.

The Upper Kootenai Member is largely nonmarine at Great Falls and Gibson Reservoir (Table 1) (Fuentes et al., 2011). The Spirit River Formation at Grande Cache consists of marine shoreline units at its base, which transition upward into nonmarine deposits of the Falher and Notikewin Members (Quinn et al., 2016). The stratigraphy at Cold Lake is characterized by shoreface and fluvial valley deposits of the Grand Rapids Formation (Maynard et al., 2010).

MDAs calculated for strata are consistent with deposition from the Aptian boundary to the middle Albian (104 ± 1.8 Ma, Upper Kootenai Member, Great Falls; 110 ± 2.0 Ma, Notikewin Member, Grande Cache; 113 ± 2.4 Ma, Upper Kootenai Member, Gibson Reservoir; 115 ± 1.0 Ma, Middle Grand Rapids, AOS12, Cold Lake). Within the uncertainty of the method, the diachronity of the strata cannot be ascertained. However, physical correlation in the subsurface of Alberta has demonstrated an overall northward progradation of fluvial-deltaic depositional systems during this time interval (Smith et al., 1984).
Mesozoic zircons derived from the Cordillera were the dominant component of age spectra from Great Falls (Upper Kootenai Formation), Gibson Reservoir (Upper Kootenai, 1FG70), and Grande Cache (Notikewin Member) areas by this time (Figs. 10 and 11). In southwestern Alberta, there are orogen-derived gold-bearing igneous-clast conglomerates, consistent with the dominance of Cordilleran-derived detritus (Leckie and Craw, 1995). In the Cold Lake area, the detrital zircon record in the Grand Rapids Formation exhibits an upward transition from dominance by Cordilleran magmatic arc zircon (Lower Grand Rapids, AOS20) to more-diverse age spectra (Upper Grand Rapids, AOS9). It is plausible that for these units the Cordilleran signature was diluted by an influx of sediment from the south and east at this time (cf. Blum and Pecha, 2014).

**DISCUSSION**

The detrital zircon data from each of the four areas featured in this study show a transition from diverse spectra (i.e., Group 1) to spectra dominated by Cordilleran magmatic rocks (i.e., Group 2). When the data are considered as a whole, Cordilleran magmatic sources of sediment dominate sediment supply for a period of several million years from the Aptian boundary to the middle Albian (Figs. 4, 8, and 10). Because changes in the detrital zircon record on the order of 10–100 Ma logically are linked to changes in the tectonic setting of the basin (LaMaskin, 2012), we suggest that the change in zircon spectra observed in the data from the Western Interior foreland basin reflects the change from a margin dominated by uplifted pre-foreland sedimentary strata and basin-axial sediment routing to a margin with extensive sediment aggradation on top of the orogenic wedge, similar to what is observed in the modern foreland basin of the central Andes (Horton, 1998).

The wedge-top depozone overlies the front of the orogenic wedge and is both an important sink for sediments derived from the adjacent orogen and a potential source of sediments as it undergoes deformation and denudation (DeCelles and Giles, 1996). Deformation in the underlying orogenic wedge controls the pattern of sedimentation in this zone. It has been suggested that shortening in the wedge is associated with sediment bypass of the wedge-top zone because thickening the wedge leads to uplift and the destruction of accommodation (DeCelles, 1994; DeCelles and Giles, 1996; Horton, 1998). In active orogenic belts, the frontal thrusts of the orogen are blind and wedge-top sediments commonly blanket the deforming orogenic wedge (Ben Avraham and Emery, 1973; Vann et al., 1986; Horton and DeCelles; 1997; Horton, 1998). These deposits can be kilometers thick and extend from tens to hundreds of kilometers from the orogen (Burbank et al., 1997; Horton, 1998). Wedge-top deposits have rarely been described from the northern Cordilleran foreland basin (e.g., McMechan et al., 2018). Presumably, the paucity of these strata has to do with their preservation potential. This naturally raises the question of whether their former presence can be inferred from the detrital record in the basin.

In North America, magmatic rocks generated during formation of the Cordillera are generally preserved to the west of the fold-thrust belt, which is largely composed of pre-foreland sedimentary strata (Figs. 1 and 11). Therefore, to preserve Mesozoic-dominated detrital zircon spectra in the foreland, rivers that supplied sediment to the Western Interior basin from the magmatic hinterland would need to have traversed the fold-thrust belt without incorporating detrital zircon grains from pre-foreland sedimentary strata, which in aggregate yield diverse detrital zircon spectra (Fig. 7) (Ross and Villeneuve, 2003; Dickinson and Gehrels, 2009b; May et al., 2013; Gehrels and Pecha, 2014; Golding et al., 2015). Aerial delivery of Early Cretaceous zircon to the basin is possible or even probable; however, most of the zircon in these samples is Jurassic in age, supporting an interpretation that fluvial sediment routing was an important process (Figs. 4 and 8). We suggest that these fluvial systems and/or volcanic rocks aggraded a significant thickness of sediment on top of the orogenic wedge, thereby shielding pre-foreland rocks from erosion (Fig. 12).
The deposition and removal of wedge-top strata have been shown to significantly impact landscape evolution and sediment dispersal. Osborn et al. (2006) hypothesized that the Canadian Rocky Mountains as a landscape in its present form did not emerge until ~30 m.y. after the end of orogenesis because a thick sequence (~2–20 km) of Mesozoic wedge-top strata covered pre-Mesozoic sedimentary rocks. Ross et al. (2005) presented detrital zircon data from southern Alberta that first demonstrated the transition from Mesozoic-dominated detrital zircon spectra to more-diverse spectra in the Paleocene, attributing this pattern to uncovering of the orogenic wedge. The new data, presented herein, establish that this transition was synchronous across the basin to within a few millions of years and likely tectonically controlled.

Mesozoic-dominated zircon spectra from the Western Interior basin do contain pre-Mesozoic zircon populations, which are characteristic of pre-Cordilleran foreland strata of North America (Fig. 12). Blum and Pecha (2014) use the pre-Mesozoic zircon populations of the Clearwater and Grand Rapids Formations to argue for the longevity of a proposed continental river system. However, it is unclear whether across the Western Interior basin these pre-Mesozoic grains represent input via recycling from early foreland basin strata (Late Jurassic–Aptian) in the wedge-top; pre-foreland basin strata uplifted in the orogenic wedge; sedimentary strata from Appalachia, the southwestern United States, or the accreted terranes; or some combination of these sources.

Detrital zircon spectra from Great Falls, Cold Lake, and Grande Cache diversify up stratigraphic section after a long period of being dominated by Mesozoic Cordilleran sources (Fig. 8). The reincorporation of many detrital components that were characteristic of earlier Mesozoic strata suggests that the wedge-top may have become an important sediment source in the middle to late Albian (cf. Ross et al., 2005); however, contributions from the other potential sources previously discussed cannot be ruled out by these data. Nevertheless, we speculate that the record of burial and exhumation of the wedge-top depozone should be more widespread in the detrital record of foreland basins than has been reported to date.

Numerical and physical modeling studies have demonstrated that sedimentation is a key variable in the structural evolution of a mountain belt because surficial processes are an important control on the taper angle of the orogen (Storti and McClay, 1995; Lageson et al., 2001; Simpson, 2010; Buter, 2012). The rate of sediment generation in an orogen is controlled by elevation and climate, which are to some degree tectonically controlled and linked (e.g., rain-shadow effects, glaciation). It also has been hypothesized that the addition of volcanic rocks to the wedge can alter the taper state of the orogenic wedge (Lageson et al., 2001). Therefore, deciphering the record of aggradation in the wedge-top in ancient orogen-basin systems allows for conjecture about tectonic and structural evolution of the orogen as well as inferences concerning episodes of increased tectonic activity or tectonic quiescence. Some attempts to decipher this record exist for the Cordilleran Orogen of North America; however, these studies focus on time periods after the Early Cretaceous (DeCelles, 1994; DeCelles and Mitra, 1995; Lageson et al., 2001).

The orogenic influence on foreland basin strata is well established (e.g., Heller and Paola, 1989; Ross et al., 2005; DeCelles et al., 2009; Horton, 2018). Recent research has hypothesized that the rheology of foreland basin deposits can control the structural evolution of the fold-thrust belt (Chapman and DeCelles, 2015) and that changes in sediment yield may be linked to deformation in the interior of the orogen (Wipple, 2009). Therefore, the recognition of sediment aggradation on top of orogenic structures is essential to testing hypotheses of orogen–foreland basin interaction. In the case explored here, an episode of substantial sedimentation on the orogenic wedge during the Albian hypothetically would correspond to thrust movements in the orogen. In combination with late Albian–early Cenomanian cooling ages from thrust faults in the Canadian Rockies reported by Pana and Van der Pluijm (2015), the connection between wedge-top dynamics and foreland basin strata warrants further investigation. In this study, we provide key indirect evidence for significant Jurassic–Early Cretaceous wedge-top deposits in the Northern Cordillera foreland basin system.

**CONCLUSIONS**

Detrital zircon data from Upper Jurassic–Lower Cretaceous strata of Great Falls, Montana, can be segregated into three groups using multidimensional scaling. Upper Jurassic–Aptian strata exhibit diverse detrital zircon spectra (Group 1) interpreted to record sediment recycling from pre-foreland strata of the southwest United States and the Cordilleran margin of North America. Near the Aptian–Albian boundary, the detrital zircon provenance shifts to spectra dominated by Mesozoic grains originating from magmatic rocks of the Cordillera (Group 2). In the Albian, the uppermost unit of this study is characterized by zircon spectra less dominated by Cordilleran magmatic sources (Group 3), recording a diversification of the provenance area to include recycling of sedimentary strata.

Data from Great Falls are compared to data from Gibson Reservoir in western Montana, Grande Cache in west-central Alberta, and Cold Lake in east-central Alberta in order to evaluate the evolution of sediment routing systems to the foreland basin. This comparison shows that Late Jurassic sediment routing was dominated by basin-axial transport systems. Detrital zircon data confirm that in the Aptian, sediment-dispersal patterns were strongly controlled by basin partitioning linked to topography created during formation of the sub-Cretaceous unconformity. Near the Aptian–Albian boundary, Boreal Sea transgression potentially led to the east-west segregation of the basin.

The data from each of the areas show an evolution from diverse spectra to Cordilleran magmatic-dominated spectra. The dominance of Cordilleran magmatic sources plausibly records covering of the orogenic wedge by the aggradation of sediments and volcanic strata on top of the orogenic wedge, insulating pre-foreland strata with diverse detrital zircon spectra from being reworked into the basin. The recognition of this episode of Cordilleran–foreland basin evolution has implications for the application of orogenic models to the geological record.
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