Detrital Zircon Geochronology of Cordilleran Retroarc Foreland Basin Strata, western North America

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Abstract

We present a compilation of 8,702 U-Pb analyses from 96 detrital zircon samples of Jurassic-Eocene North American Cordillera foreland basin system strata. Of these samples, 31 are new and unpublished. Variation in detrital zircon age spectra between samples records erosion or recycling of basement and cover rocks within the Cordilleran orogenic wedge. Each sample can be classified into one of six major provenance groups, whose age spectra suggest derivation from 1) Mesozoic eolianites of the western United States, 2) Paleozoic passive margin strata of the western United States, 3) Paleozoic passive margin strata of western Canada, 4) the Mogollon Highlands, 5) the Cordilleran magmatic arc, or 6) Yavapai-Mazatzal Province crystalline basement rocks. Referencing these provenance interpretations to their location and stratigraphic deposition age produces a detailed spatial and temporal record of sediment dispersal within the foreland basin system. Late Jurassic provenance is dominated by recycling of Mesozoic eolianites, predominately from sources in the Sevier thrust belt. Cretaceous-Eocene provenance is dominated by recycling of the passive margin, with increasing complexity upsection. A composite age-probability plot of 1,539 arc-derived detrital zircons reveals a decrease in high flux event recurrence interval that is correlated with an increase in convergence rate. We interpret this relationship as evidence that corroborates some predictions of the Cordilleran orogenic cyclicity model of DeCelles et al., [2009].

Section 1: Introduction

Siliciclastic strata deposited in continental basins contain detrital zircons with U-Pb age spectra that vary systematically throughout geologic time. Within sufficiently
populated datasets, the relative abundance of specific ages can be used to identify the timing of first-order magmatic and accretionary processes [e.g., Condie and Aster, 2009]. This approach is particularly salient in understanding ancient supercontinent cycles, as detrital zircons have higher preservation potential than prima facie bedrock exposures. Detrital zircon geochronology is also applicable at the continent scale. For example, numerous studies show that variations in detrital zircon age spectra track the long-term distribution of orogenic belts, Andean-type magmatic arcs, and sediment dispersal systems [e.g. Dickinson and Gehrels, 2003; 2009; LaMaskin, 2012; Leier and Gehrels, 2011; Rainbird, et al., 1992]. Moreover, detrital zircons can resolve crustal recycling within individual orogenic systems. Provenance analysis conducted in the North American Cordillera is particularly successful at linking synorogenic strata to specific orogenic wedge structures [e.g. Dickinson and Gehrels, 2008; Fuentes et al., 2009; Lawton and Bradford, 2011; Lawton et al., 2010; Leier and Gehrels, 2011].

In this paper, we present a large detrital zircon database (8,702 U-Pb ages) that samples Jurassic-Eocene synorogenic strata deposited within the Cordilleran foreland basin system of North America (Figure 1). The objectives of this study are to 1) define a framework for interpreting detrital zircon provenance in the foreland basin system, 2) utilize provenance interpretations and paleocurrent data to map sediment dispersal pathways during Cordilleran orogenesis, and 3) track exhumation of specific tectonostratigraphic sequences in the Cordilleran orogenic wedge. All of the samples included in this study can be categorized into one of six provenance groupings, which are genetically tied to recycling of sedimentary sequences or erosion of primary Laurentian igneous and metamorphic rocks. Whenever possible, provenance interpretations were
guided by the use of Kolmogorov–Smirnov (K-S) statistics, which test whether age spectra could have been derived from the same parent population. The 27 samples that could not be grouped using K-S statistics were qualitatively interpreted based on comparison of age peaks with published references. In general, samples that could not be classified statistically displayed mixed provenance.

Section 2: Samples

Of the 96 detrital zircon samples considered in this study, 31 have not been reported previously. Here we summarize the sampled stratigraphy (Figure 2) at the regional scale, beginning with new samples from southwestern Montana. All of the new samples were collected from fresh surfaces on roadcuts or outcrops. Samples consisted of ~10 kg of rock fragments. In each case, care was taken to avoid contamination during collection, transport, and storage processes. Detrital zircon sample metadata (Table DR1), analytical data (Table DR2), and representative cathodoluminescence (CL) images (Figure DR1) are available in the data repository.

Section 2.1: New Samples

Seven Cretaceous and Paleogene foreland basin samples were collected in southwestern Montana. Sample 10DM25 was collected from a fluvial sandstone in the Aptian (125-112 Ma) Kootenai Formation [DeCelles, 1986] in a canyon ~9 km west of Dell, Montana, in the Tendoy Mountains. The Kootenai Formation unconformably overlies the Upper Jurassic Morrison Formation. Sample 10DM17 was collected from a ledge of fluvial and littoral Frontier Formation sandstone located along a drainage on the northeastern flank of Mt. Cohen, in the Beartooth Range. Dyman et al. [2008] reported palynological data indicating a Coniacian (89.3-85.8 Ma) depositional age for the middle
to upper Frontier Formation in the nearby Centennial Range. These data correlate well with existing geochronological and palynological data from the Frontier Formation in the extreme southwestern Lima Peaks region, which encompasses the bulk of the Montana samples.

Five samples from various members of the synorogenic, Upper Cretaceous to Paleogene Beaverhead Group were collected from the Lima Peaks region. Depositional age ranges for the Beaverhead Group samples presented here were determined using the nomenclature of Haley and Perry (1981). All Beaverhead Group samples were collected from fluvial sandstones and alluvial fan conglomerates (Haley and Perry, 1981). In the McKnight Canyon area, located 10 km northwest of Dell, Montana, samples 10DM22 and 10DM23 were collected from the Campanian (83.5-70.6 Ma) and lower Maastrichtian (70.6-65.5 Ma) intervals of the Beaverhead Group, respectively. These two samples are age equivalent with samples of the lower limestone conglomerate (10DM09) and upper quartzite conglomerate (10DM20) collected near Bannack, Montana ~50 km along the range front to the north. Sample 10DM11 was collected from the Red Butte Conglomerate of the Beaverhead Group in the Ashbough Canyon area, which is thought to be the only Paleocene (65.5-55.8 Ma) interval in the Group.

Eight detrital zircon samples were collected from the foreland basin sequence in southwestern Wyoming and northeastern Utah, in the region surrounding the Uinta Mountains (“Uinta” region, Figure 2). The only Jurassic sample in the set was collected from the Upper Jurassic Salt Wash Member of the Morrison Formation (sample 7.19.06.2), located ~85 m above the base of the Morrison Formation in section 1RF of Currie [1998], near Redfleet reservoir, Utah. Currie [1998] interpreted this interval as
recording a sandy braided river system.

The remainder of the Uinta region samples were deposited during the Cretaceous. Of these samples, three are fluvial sandstones and four are synorogenic conglomerates. Sample K2 was collected from the Lower Cretaceous Kelvin Formation located 29 m stratigraphically above a 10 m thick massive gray calcrete zone in the lower part of the formation. This calcrete marks the contact between the Kelvin Formation and the underlying Morrison Formation. Upward-fining fluvial channel sandstones with prominent chert pebble conglomerates in their lower parts are exposed in roadcuts along Utah State Highway 32, on the western shore of Rockport Reservoir. Sample EM6 was collected from an outcrop of fluvial-deltaic channel sandstone of the Chimney Rock Member of the Rock Springs Formation along the eastern side of Wyoming State Highway 430. Sample EM4 was collected from distributary mouth bar sandstone of the fluvial-deltaic basal Blair Formation, located just east of County Road 48, ~830 m north of its junction with Wyoming State Highway 430. Devlin et al. [1993] reported likely Campanian depositional ages for the Chimney Rock Member and the basal Blair Formation of ~81 Ma and ~82-83 Ma, respectively.

Detrital zircon samples collected from synorogenic conglomerates in the Uinta region offer insight into provenance relationships within the Sevier belt during the Late Cretaceous. Sample ECH1 was collected from the upper part of the lower member of the Echo Canyon Conglomerate, ~860 m northeast of the Echo Junction exit on Interstate Highway 80. The sampled interval is fluvial sandstone that is interbedded with cobble to pebble conglomerates representing shallow braided streams on a stream-dominated alluvial fan. Nichols and Bryant [1990] and DeCelles [1994] reported palynological data
for these strata that indicate a Coniacian-Santonian (89.3-83.5 Ma) depositional age.

Sample CR7 was collected from the type locality of the Canyon Range Conglomerate, in Wildhorse Canyon in the northern Canyon Mountains of central Utah. This coarse-grained sandstone was interbedded with cobble to boulder conglomerate beds, and has a poorly constrained Cenomanian-Turonian (99.6-89.3 Ma) depositional age [DeCelles et al., 1995; DeCelles and Coogan, 2006; Lawton et al., 2007]. Sample HF2 of the Campanian-Maastrichtian Hams Fork Conglomerate member of the Evanston Formation [DeCelles, 1994; DeCelles and Cavazza, 1999] was collected from coarse-grained sandstone exposed in outcrop along the north side of the frontage road, ~4.3 km southwest from the Emory exit on Interstate Highway 80. This locality is in the upper reaches of Echo Canyon, where a natural bridge is present in the sandstone just below the sample site. Samples EM2 and LM73 were collected from a coarse-grained upper shoreface sandstone in the upper part of the Little Muddy Creek Conglomerate, in a canyon ~8 km west of the intersection of Interstate Highway 189 and Utah State Highway 412. The Little Muddy Creek Conglomerate was likely deposited during the Santonian [Pivnik, 1990].

Collaboration with ExxonMobil drilling projects in the La Barge and Piceance basins of southwestern Wyoming and northwestern Colorado yielded 15 core and cutting samples from the Cordilleran retroarc foreland basin system. Samples from the Piceance basin were collected at a drill site located ~50 km northwest of the town of Rifle, Colorado, on the western slope of the Rocky Mountains. These samples include the Upper Jurassic Entrada Formation (T52X-17935), the Upper Cretaceous Mancos (T67-14419) and Corcoran (PCU12120) Formations, the Upper Cretaceous to Paleocene
Williams Fork Formation (T67-7420, T67-8024, PCU7620, PCU7980, PCU-9470) and the Paleocene to Eocene Ohio Creek (T67-7084), Wasatch (T26-2673, PCU4020), and Uinta Formations (09CA01). Samples from the La Barge basin were collected at a drill site located ~20 km northwest of La Barge, Wyoming along State Highway 235. These include the Adaville Formation (LBRG-3500) and the Almond Formation of the Mesaverde Group (LBRG-2700, LBRG2900). All of the La Barge samples were deposited during the Campanian (~84-71 Ma).

**Section 2.2: Published Samples**

65 samples were compiled from literature for analysis alongside the new data presented here. These samples are distributed along the frontal Sevier belt in southern Canada and the United States and span a >1500 km segment of the Cordilleran orogenic system (Figure 1). Although stratigraphic range and sample density vary along strike (Figure 2), most regions are sufficiently populated throughout the Late Jurassic-Paleocene phase of Cordilleran orogenesis. The following is a summary of the compiled data, organized by region and author.

Samples from the southwestern United States cluster around the shared border between the states of Colorado, Utah, Arizona, and New Mexico. These data from the Four Corners region (Figure 2) include 21 samples from Dickinson and Gehrels [2008], 11 samples from Lawton & Bradford [2011], and seven samples from Lawton et al. [2010]. When combined, these data provide good coverage of the Upper Jurassic to Upper Cretaceous foreland basin throughout the region. The initial stages of Cordilleran orogenesis are well resolved here, as 11 of the samples are from the Upper Jurassic Morrison Formation.
Samples from localities that trace the central Sevier belt in Utah, Colorado, Wyoming, and Idaho compose the Uinta region grouping. Of the 24 Uinta samples (Figure 2), only one was compiled from literature—the Campanian Kaiparowits Formation [Lawton & Bradford, 2011]. Therefore, our new data are critical in bridging the gap in published data between the Four Corners region and Montana.

The Montana region data consist of a combination of seven new and 11 compiled samples. New samples, along with two samples from Leier and Gehrels [2011] are located along the frontal Cordilleran thrust belt, south of the Helena Thrust Salient [Schmidt and O'Neill, 1982]. Samples north of the Salient include an additional sample from Leier and Gehrels [2011] and eight samples from Fuentes et al. [2011].

Most samples from Canada are distributed along the frontal Cordilleran thrust belt in southwest Alberta and central British Columbia. An additional group of samples are from the distal foreland basin in central Alberta. These samples consist of seven samples from Leier and Gehrels [2011] and seven samples from Raines et al. [submitted].

Section 3: Methods

Section 3.1: Detrital Zircon Uranium-Lead Geochronology

All detrital zircon samples included in this study—whether newly generated or compiled from the literature—were prepared and analyzed using consistent protocols at the Arizona Laserchron Center (http://www.laserchron.org).

Zircon grains were extracted from samples in the traditional crushing and grinding manner. Additional separation was accomplished using a Wilfley table, heavy liquids, and a Frantz magnetic separator. A large aliquot (~1000-2000) of zircon grains was mounted alongside fragments of the Sri Lanka standard on a 1-inch round epoxy
“puck”. Prior to isotopic analysis, samples were sanded to a depth of ~20 microns, polished, and cleaned.

U-Pb analyses were conducted using laser ablation multicollector inductively coupled plasma mass spectrometry (LA-MC-ICPMS) [Gehrels et al., 2006, 2008]. Zircons were ablated using a Photon Machines Analyte G2 excimer laser with a 30-micron beam diameter. The net effect of the ablation process produces pits on the zircon crystals that are ~15 microns deep. The ablated material is transported in helium to the plasma source of the Nu HR ICPMS, which measures U, Th, and Pb isotopes simultaneously. Measurements were conducted in static mode using Faraday detectors with $3 \times 10^{11}$ ohm resistors for $^{238}\text{U}$, $^{232}\text{Th}$, $^{208}\text{Pb}$-$^{206}\text{Pb}$, and discrete dynode ion counters for $^{204}(\text{Pb+Hg})$ and $^{202}\text{Hg}$. Each analysis consists of one 15 second integration on peaks with the laser off, 15 one second integrations with the laser firing, and a 30 second delay to purge for the next analysis. The ablation process produces ion yields of ~0.8 mv per ppm.

Individual analyses carry analytical uncertainties of ~1-2% (at the 2-sigma level) for $^{206}\text{Pb}/^{238}\text{U}$ ages that result from uncertainty in determining $^{206}\text{Pb}/^{238}\text{U}$ and $^{206}\text{Pb}/^{204}\text{Pb}$. Errors in measurement of $^{206}\text{Pb}/^{207}\text{Pb}$ and $^{206}\text{Pb}/^{204}\text{Pb}$ produce similar ~1-2% (at the 2-sigma level) uncertainties for > 1.0 Ga $^{206}\text{Pb}/^{207}\text{Pb}$ ages. However, analytical error in determining $^{206}\text{Pb}/^{207}\text{Pb}$ ages substantially increases for zircon grains with ages <1.0 Ga. The cutoff for reporting $^{206}\text{Pb}/^{238}\text{U}$ versus $^{206}\text{Pb}/^{207}\text{Pb}$ ages averages ~1.0 Ga, but is adjusted for each sample to avoid dividing clusters of ~1.0 Ga analyses.

Inter-element fractionation of Pb/U (~5%) and Pb isotopes (<0.2%) was corrected using in-run analyses of fragments of the Sri Lanka zircon standard. This large zircon
crystal has an age of 563.5 ± 3.2 Ma at 2-sigma uncertainty. Concentrations of U and Th were also determined relative to known quantities in the Sri Lanka zircon, which are ~518 ppm of U and 68 ppm of Th. \(^{204}\text{Hg}\) interference with \(^{204}\text{Pb}\) was accounted for by measuring \(^{202}\text{Hg}\) during laser ablation and subtracting \(^{204}\text{Hg}\) according to the natural \(^{202}\text{Hg}/^{204}\text{Hg}\) of 4.35. Hg-corrected \(^{204}\text{Pb}\) and an assumed initial Pb composition [Stacey and Kramers, 1975] were used to correct for common Pb. Uncertainties of 1.5% for \(^{206}\text{Pb}/^{204}\text{Pb}\) and 0.3% for \(^{207}\text{Pb}/^{204}\text{Pb}\) were applied to the compositional values based on observed variation in Pb isotopic composition in modern crustal rocks.

U-Pb analytical data are reported in Table DR2. Uncertainties are at the 1-sigma level and include only measurement errors. U-Pb analyses in excess of 20% discordance (determined by comparison of \(^{206}\text{Pb}/^{238}\text{U}\) and \(^{206}\text{Pb}/^{207}\text{Pb}\) ages) or >5% reverse discordance were not considered. Interpreted U-Pb ages based on the above corrections are plotted in Figure 5a-h using the routines of Isoplot [Ludwig, 2008]. In this procedure, the distribution of ages and their measurement uncertainties are normalized into single curves to create age-probability diagrams.

**Section 3.2: K-S Provenance Analysis**

To simplify the process of statistical provenance analysis, samples were initially sorted into qualitative provenance groupings based on visual examination of their probability distribution functions (PDFs), which display the presence and relative abundance of age peaks (e.g. Figure 4). Qualitative groups were then tested for internal consistency, which is a measure of the percentage of statistically indistinguishable spectra in a given grouping, using an in-house K-S statistical program developed at the Arizona Laserchron Center (available at [http://www.laserchron.org](http://www.laserchron.org)). The K-S test compares
detrital zircon age spectra to evaluate the null hypothesis that the two distributions are the same. Specifically, the K-S test compares the maximum probability difference between two cumulative distribution function (CDF) representations of the age spectra. Dependence on the CDF, which sums probabilities with increasing age, results in heightened sensitivity to the relative abundance of age peaks rather than their presence or absence. This characteristic caused samples with fewer grains or skewed peak abundances to be rejected. Nevertheless, 69 samples were deemed statistically indistinguishable from >50% of other samples in one of the six qualitative provenance groupings, which were defined based on published datasets (see detrital zircon signatures in Section 5, below). The 27 samples that could not be grouped statistically (distinguishable from >50% of grouped samples) were qualitatively interpreted within the context of published datasets (see Section 5) and Laurentian basement age domains (Figure 3). These groupings include all samples that were interpreted to document first-cycle erosion of primary igneous and metamorphic sources, as well as mixed provenance signals. Possible explanations for why qualitatively grouped samples failed the statistical test are discussed in the provenance results sections, below (6.1.1-6.1.7).

Section 4: Tectonic Setting

The North American Cordilleran thrust belt and retroarc foreland basin system (Figure 1) initiated in Late Jurassic time in response to North Atlantic spreading and coeval subduction of oceanic plates along the western margin of Laurentia [DeCelles, 2004]. At this time, the Cordilleran forearc region transformed from a zone of fringing arcs and interarc oceanic basins to a coherent, east dipping arc-trench system [Harper and Wright, 1984; Wright and Fahan, 1988; Saleeby et al., 1992; Dickinson et al., 1996].
the retroarc region, Late Jurassic topographic highs and magmatic centers formed and began to shed volcanoclastic and siliciclastic sediments into marginal marine basins of the western United States—marking the initiation of a composite orogenic wedge [Jordan, 1985; Meyers and Schwartz, 1994]. Sedimentation in the foreland basin system remained intimately linked with Cordilleran shortening in the retroarc thrust belt for the next >100 My.

The modern expression of Mesozoic oceanic subduction along the western margin of North America is the Cordilleran magmatic arc, a >5000 km long belt of Late Triassic to Late Cretaceous calc-alkaline granitoid batholiths and related volcanic rocks [Saleeby et al., 1992]. These rocks crop out in a nearly continuous belt from the Coast Ranges Batholith in southeastern Alaska and western Canada to the Peninsular Ranges batholith in Baja California (Figure 1). The orogen-scale history of magmatism in the Cordilleran arc is complex, as locations and magmatic addition rates vary through time for individual arc segments [Gaschnig et al., 2010; Paterson et al., 2011]. Of these segments, the Sierra Nevada batholith of central and southern California is perhaps the best understood. Radiometric ages of plutonic rocks in the Sierra Nevada reveal major pulses in magmatic activity between 160-150 Ma and 100-85 Ma [Barton, 1990; Ducea, 2001].

Nearly orthogonal convergence between the rapidly westward moving North American plate and the oceanic Farallon plate drove shortening in the Cordilleran retroarc thrust belt [Engebretson, 1984]. This complex zone of eastward verging faulting and folding can be divided into five tectonostratigraphic zones. From west to east, these zones include the Luning-Fencemaker thrust belt; the central Nevada thrust belt; a high-elevation plateau referred to as the Nevadaplano; the Sevier fold-thrust belt; and the
Laramide intraforeland basement uplifts [DeCelles, 2004]. Each of these tectonomorphic zones experienced shortening, crustal thickening, metamorphism, and/or magmatic activity during the Late Jurassic to Eocene and are generally considered to be the product of a coherent orogenic wedge with an eastward-migrating thrust front and foreland basin system. The easternmost expression of thin-skinned thrust faulting and related folding in the Cordilleran retroarc region is referred to by a variety of terms, including the Sevier belt in Utah, Wyoming and Idaho; the Montana disturbed belt; and the Canadian Rocky Mountains thrust belt [Allmendinger, 1992]. Frontal thrusts in this belt locally override the Cordilleran foreland basin system that developed within North America’s >5,000,000 km² Western Interior Basin.

The Sevier thrust belt is dominated by low angle thrust faults that transported Neoproterozoic-upper Mesozoic sedimentary rocks in their hanging walls. Although Armstrong [1968] defined the Sevier belt as exclusively thin-skinned, later work has shown that significant slices of Precambrian metamorphic basement rocks were incorporated into some thrusts [e.g. Burchfiel and Davis, 1972; Royse et al., 1975; Skipp, 1987; Schirmer, 1988; Yonkee, 1992; DeCelles, 1994]. Low angle thrust faults of the Sevier belt merge with ductile shear zones at depth in eastern Nevada and western Utah [Camilleri et al., 1997; DeCelles and Coogan, 2006]. Therefore, the Sevier thrust belt spans a north-south distance of >1500 km and restores to ~200 km in maximum width following restoration for Cenozoic extension [Gans and Miller, 1983; Long, 2012]. Along-strike variations in structural style, lithofacies, and paleogeography in the Sevier belt can be invoked to explain differing detrital zircon affinities in the Cordilleran retroarc foreland basin system.
Section 5: Detrital Zircon Signatures

Successful application of detrital zircon provenance analysis hinges upon sufficient understanding of the distribution of primary igneous sources for the grains, as well as the signature of potentially recycled sediments. Fortunately, the igneous history of North American basement and the detrital zircon characteristics of overlying sedimentary rocks are relatively well understood. Here we present relevant geochronological data that enable provenance interpretation using detrital zircon geochronology in the Cordilleran retroarc foreland basin system. Detrital zircon age spectra of potentially recycled tectonostratigraphic sequences are plotted in Figure 4. Also plotted on this Figure, and mapped on Figure 3, are characteristic age ranges for major North American crustal provinces.

Section 5.1: Laurentian Basement Rocks

The Laurentian craton, which is dominantly composed of reworked Archean (>1.8 Ga) continents and continental fragments, came together during the Paleoproterozoic (2.0-1.8 Ga) Trans-Hudson orogeny [Hoffman, 1989]. Today, these rocks are exposed in basement uplifts of the northern United States and in the Canadian Shield region of central Canada and Greenland. During the Proterozoic, multiple collisional events (1.71-1.30 Ga) accreted juvenile terranes to the cratonal core [Whitmeyer and Karlstrom, 2007]. Yavapai (1.8-1.7 Ga), Mazatzal (1.7-1.65 Ga), and Grenville (1.2-1.0 Ga) rocks compose the bulk of this more juvenile crust. Following their accretion, the Yavapai and Mazatzal provinces were intruded by plutons associated with an A-type magmatic event (1.48-1.34 Ga) [Van Schmus et al., 1996]. The net effect of these processes was to create a stable Laurentian craton and platform composed of distinct crustal provinces.
(Figure 3) whose age signatures recur throughout North America’s sedimentary record.

In Montana, southern Alberta, and southern British Columbia, Laurentian embayments provided the accommodation space for a thick accumulation of Mesoproterozoic-Neoproterozoic siliciclastic strata. These strata, which have since been metamorphosed up to middle greenschist grade, contain detrital zircon ages that plot within the North American Magmatic Gap (NAMG)—a time period for which no known Laurentian sources are preserved. The presence of these zircons requires an exotic terrane outboard of western Laurentia. Stewart et al. [2010] argued on the basis of crustal ages and Hf isotopic signatures that these zircons were likely derived from eastern Antarctica and Australia when they were connected to southwestern Laurentia within a proto-Rodinian supercontinent. Alternatively, these zircons may have been eroded from an undocumented 1.6-1.5 Ga African source that was exposed during the Grenvillian orogeny. Whatever the case, sediments that filled these basins came to dominate trailing thrust sheets of the Montana disturbed belt and the Canadian Rocky Mountains thrust belt (Figure 1) [Price, 1981; Fuentes et al., 2012].

Section 5.2: North American Passive Margin

Thrust sheets of the Sevier belt are principally constructed from an elongated prism of thick sediments that were deposited on the passive western margin of Laurentia following the breakup of Rodinia. Basal, Neoproterozoic strata of this sequence accumulated in embayments west of the Wasatch hinge line, which demarcates the eastern extent of significant rifting of Laurentian crystalline basement rocks [Hintze, 1988]. These strata are dominated by siliciclastic rocks that reached maximum thicknesses of >10 km [Link et al., 1993]. During the early Paleozoic, passive margin
sedimentation overlapped Precambrian crystalline basement rocks east of the hinge line, reaching maximum thicknesses of ~12 km in western Utah.

Gehrels et al., [1995] systematically sampled five transects of the North American passive margin for detrital zircon provenance analysis between Sonora, Mexico and southeastern Alaska. Their dataset was updated by Gehrels and Pecha [in prep], who present high-age-density detrital zircon data from the same stratigraphy (n~200). Their results, which reveal a dominance of local Laurentian sources, enable K-S test fingerprinting of northerly or southerly provenance for Cordilleran retroarc foreland basin strata. The authors identified three major trends relevant to this objective: 1) Ordovician strata are dominated by Trans-Hudson (1.8-2.0 Ga) and Wopmay (2.0-2.3) ages along the entirety of the Laurentian margin; 2) non-Ordovician strata generally mimic the age spectra of nearby Laurentian basement provinces; and 3) Grenville-aged (1.2-1.0 Ga) grains are ubiquitous throughout.

**Section 5.3: Mesozoic Eolianites**

Vast ergs (sand seas) developed in southwest Laurentia during the Permian-Jurassic. Today, these ergs are preserved in the form of eolianites in the Four Corners region of the southwestern United States. Provenance analysis of zircons from these sandstones reveals a dominance of Grenvillian (1315-1000 Ma), Pan-African (750-500 Ma), and Paleozoic (500-310 Ma) grains throughout the section [Dickinson & Gehrels, 2003]. In addition, each sample contains younger zircons whose ages overlap with those of Appalachian plutons that trace the Laurentian-Gondwana suture. These populations are interpreted to record a transcontinental drainage system with headwaters in eastern Laurentia [Dickinson & Gehrels, 2003, 2009]. During Cordilleran contractional
deformation, leading thrusts of the Sevier belt deformed these strata. Therefore, it is likely that Appalachian-derived sediments experienced second-cycle deposition within the Cordilleran retroarc foreland basin system.

**Section 5.4: Cordilleran Magmatic Arc**

Arc magmatism in western North America dates back to the initiation of subduction along the western margin of Laurentia during the Permian [Dickinson and Lawton, 2001]. The oldest arc rocks are preserved in the Permian-Triassic (284-232 Ma) magmatic arc of eastern Mexico, which intruded Gondwanan crust above a subduction zone located in present-day central Mexico. This segment was bound to the north by a transform fault, which truncated the continental margin prior to the breakup of Pangea. The oldest *de facto* Cordilleran magmatism initiated with subduction beneath this truncated margin during mid-Early Triassic time [Dickinson, 2000]. Most Cordilleran magmatism intruded an elongate zone located 100-250 km inboard of the arc-trench system (Figure 1). Today, a discontinuous belt of deeply exhumed granitic batholiths characterizes this zone. These exposures have been studied in detail to reconstruct changing magmatic addition rates and paleogeography of the North American margin [Tobisch et al., 1986; Busby-Spera, 1988; Barth et al., 1997; Dunne et al., 1998; Ducea, 2001; Paterson et al., 2004, Saleeby et al., 2008; Gehrels et al., 2009; Miller et al., 2009].

Detrital zircon provenance analysis of retroarc region strata indicates that the magmatic arc and retroarc thrust belt formed a topographically-integrated, Andean-type margin by Late Jurassic-Early Cretaceous time [Fuentes et al., 2009]. These results are supported by geological investigation of Early to Middle Jurassic, intra-arc grabens that contain marine sediments [Saleeby and Busby-Spera, 1992] followed by accumulation of
substantial Late Jurassic arc-derived detritus in the retroarc region, indicating significant elevation gain [Christiansen et al., 1994]. This evidence suggests that 1) detrital zircons of retroarc foreland basin strata record the magmatic history of the post-Late Jurassic arc and 2) that the Cordilleran magmatic arc formed a drainage divide beginning by Late Jurassic time that blocked eastward transport of Cordilleran terrane-derived sediments.

Section 6: Results

Comparison of foreland basin age spectra (Figures 5a-h) to those of potential provenance candidates (Figure 4) through K-S and qualitative provenance analysis produced six major provenance groupings and two mixed provenance subgroupings that describe variations in age spectra within the Cordilleran retroarc foreland basin system. In this section, we describe the individual groupings, quantify their internal consistency using K-S testing, then use stratigraphic depositional ages (see references, table DR1) to reconstruct sediment dispersal pathways in the foreland basin system during the Late Jurassic, Cretaceous, and early Paleogene (Figures 6a-e).

Section 6.1: Comparison with Potential Source Regions

All samples included in this study can be categorized into one of six provenance interpretation groups that are genetically linked to tectonostratigraphic sequences that were exhumed during Cordilleran orogenesis. Samples with unimodal age distributions were generally interpreted to represent deposition of grains derived from primary igneous or metamorphic sources. The remaining samples, which are characterized by multiple age-probability peaks, were interpreted to represent recycling of Mesozoic eolianites or the Laurentian passive margin. This type of interpretation, which favors secondary sedimentary sources over primary igneous sources, is appropriate in this setting because
the sedimentary rocks of interest dominate the North American Cordilleran thrust belt. This interpretation is also consistent with abundant conventional light-mineral sedimentary petrological data from Cretaceous and lower Cenozoic sandstones from throughout the Cordilleran foreland basin, which indicate predominantly recycled orogenic provenance [e.g., Suttner et al., 1981; Dickinson et al., 1986; DeCelles, 1986; DeCelles and Burden, 1992; Goldstrand, 1992; Currie, 1997; Lawton et al., 2003].

**Section 6.1.1: Cordilleran Magmatic Arc**

A relatively small proportion of foreland basin samples display a dominance of Cordilleran magmatic arc-derived (<250 Ma) detrital zircons. Where present, however, this signature overwhelmed all other age-probability peaks. The eight samples whose PDF’s are plotted in Figure 5a each contain at least 50% arc-derived detrital zircons. The group as a whole averages 75% arc-derived zircons. Despite these unimodal provenance characteristics, none of the samples pass the K-S test for internal consistency. We attribute this finding to the tendency of young age-probability peaks to cluster near the stratigraphic depositional age of each sample, which ranges in age from the Early Cretaceous to the Eocene (125-48 Ma; Table DR1). Maximum depositional ages (Figure 5a)—which were determined by averaging the age of the youngest coherent group of three detrital zircons—fall within the stratigraphic depositional age brackets of all arc-derived samples. Unfortunately, stratigraphic depositional ages for some of the samples are relatively poorly constrained (+/- 12 My maximum). Therefore, we did not calculate detrital zircon lag times.

Peak ages can be compared to magmatic flux curves for segments of the Cordilleran magmatic arc (Figure 7) to guide provenance interpretations. The Sierra
Nevada and Coast Mountains segments of the arc (Figure 1) were dominant between
~180-90 Ma [Paterson et al., 2011]. In addition, the Idaho batholith preserves plutons as
old as ~125 Ma, although abundant magmatism likely did not begin until ~100 Ma
[Gaschnig et al., 2010]. The Blackleaf and Kootenai Formations in northern Montana
(ISR80, 1FG70), which contain peak ages of ~97 and ~109 Ma, were likely derived from
some combination of these sources. The Coast Mountains, Cascades, and Idaho-Montana
segments became the most productive after ~90 Ma [Gaschnig et al., 2010; Paterson et
al., 2011]. This transition is likely related to propagation of the Laramide flat slab under
the southwestern United States, which displaced the melting zone of the Sierra Nevada
arc [Coney and Reynolds, 1977; Dickinson and Snyder, 1978]. The remainder of the arc-
dominated samples contain peak ages that are younger than ~90 Ma. Therefore, they
were likely derived from some combination of sources that excludes the Sierra Nevada
arc.

Arc-derived detrital zircons in all samples can be examined to reveal a basin-
averaged, relative magmatic flux curve. All grains younger than 200 Ma were plotted as
a composite PDF in Figure 7 for comparison with 1) velocity and age data for the
Farallon plate [Engebretson, 1984], 2) periods of arc magmatism in the Idaho-Montana
arc [Gaschnig et al., 2010], and 3) relative flux curves for other segments of the
Cordilleran arc [Paterson et al., 2011]. This analysis reveals a apparent increase in the
frequency of high relative flux events after ~100 Ma, from a recurrence interval of ~50
My to ~25 My. Possible explanations for what drove this increase are discussed in
section 7, below. The apparent similarity between the igneous and basin-averaged
detrital proxies suggests that detrital zircon geochronology is a valid tool for studying arc
magmatism.

Section 6.1.2: Yavapai-Mazatzal

Samples characterized by a unimodal, 1800-1600 Ma relative abundance peak and <50% arc-derived detrital zircons compose the Yavapai-Mazatzal provenance group (Figure 5b). We interpret that these 11 samples record first cycle deposition of zircons eroded from the Yavapai-Mazatzal basement province in the western United States, as there are no known sedimentary sequences that correlate can contribute Paleoproterozoic ages in such high abundance. Initially, grains younger than ~250 My were included in K-S statistical comparison of grouped samples. However, the tendency of young age probability peaks to correlate with stratigraphic deposition age introduced cumulative relative abundance curve (CDF) variation powerful enough to prevent consistent statistical matching. This is the same phenomenon that prevented statistical grouping of the Cordilleran Magmatic Arc samples, described above. A second K-S test, this time excluding arc-derived (<250 Ma) grains, was far more successful. The test revealed 98% internal consistency within this grouping, meaning that each sample was deemed statistically indistinguishable from other samples in the group 98% of the time.

Section 6.1.3: Mesozoic Eolianite

Samples that display similarities to a composite PDF representation of 10 samples from Jurassic eolian and associated marine and fluvial sandstones [Dickinson & Gehrels, 2003; 2009] of the southwestern United States (Figure 3) were included in the Mesozoic Eolianite provenance group (Figure 5c). Twenty three samples match our criteria, which include mirroring of the presence and relative abundance of age-probability peaks at 420 Ma, 615 Ma, 1055 Ma, and 1160 Ma (Figure 5c). We interpret that these samples were
recycled from Mesozoic eolianites in the western United States rather than from a combination of primary Appalachian and Grenville sources in eastern North America (Figure 3) so as to favor the simplest possible sediment dispersal system that is consistent with regional paleocurrent data. K-S testing of the grouped samples reveals 92.5% internal consistency when arc-derived detrital zircons are excluded.

Section 6.1.4: Mogollon Highlands

Nine samples of Upper Cretaceous foreland basin system strata of the Four Corners region (Figure 2) are characterized by Laurentian age-probability peaks centered around 1700 Ma, 1450 Ma, and 1100 Ma (Figure 5d). In addition, these samples contain abundant arc-derived detrital zircons. K-S testing of these data against samples from the other provenance groups yielded no statistically indistinguishable results. It is likely that the high variability of peak relative abundance within this sample set precluded the possibility of quantitative provenance analysis using K-S statistics. Despite their mathematical dissimilarity, all of the samples were deposited within a relatively restricted zone of the foreland basin system, in close proximity to the Mogollon Highlands of the southwestern United States (Figure 1). This ancient rift shoulder is a reasonable provenance candidate, as it exposed all of the required tectonostratigraphic elements—including Yavapai-Mazatzal basement, Paleozoic cover, and Cordilleran magmatic arc rocks—during Jurassic-Cretaceous time [Dickinson and Gehrels, 2008]. Our interpretation of these samples is consistent with those of the Dickinson and Gehrels, [2008] and Lawton & Bradford [2011], from whom these data were compiled.

Section 6.1.5: Laurentian Passive Margin

One third of the foreland basin samples presented in this study contain detrital
zircon age-probability peaks that match the distribution of local Laurentian cratonal and platformal tectonostratigraphic elements. Rather than attributing their detrital zircon spectra to a combination of primary sources, we infer that these samples were recycled from Laurentian passive margin strata that dominate the Cordilleran thrust belts in the western United States and Canada. Gehrels and Pecha’s [in prep] detrital zircon data from passive margin strata exposed in the Cordilleran thrust belt in the western United States (Utah, Nevada) and southern Canada (British Columbia) form the basis for two provenance groupings that encompass 34 foreland basin samples.

The United States passive margin group (Figure 5e) contains 24 samples that display three dominant age-probability peaks of equal relative probability centered at 1700 Ma, 1450 Ma, and 1100 Ma. The samples in this group mirror age-probability peaks from the Utah-Nevada passive margin and are 78% internally consistent. The Canada passive margin group (Figure 5f) contains 10 samples with a dominant age-probability peak centered at 1900 Ma and three subordinate age-probability peaks at 2700 Ma, 2100 Ma, and 1100 Ma. These samples mirror British Columbia passive margin age spectra and are 64% internally consistent. Two of the samples in the Canada passive margin group, BTC and SKR, were poor statistical matches. The fact that they are statistically distinguishable from >50% of the other samples would normally warrant rejection under our statistical provenance analysis criteria (see Section 3.2). However, Leier and Gehrels [2011] interpret these samples to have been recycled from the Canada passive margin, alongside five other samples (ODR, SHC, CDM, EBK, and GCH) from the Cadomin Formation. These samples, which were also independently categorized into this group, are much better statistical matches. Therefore, we chose to retain samples
BTC and SKR.

Section 6.1.6: Mixed Passive Margin and Laurentian Basement

Archean, Proterozoic, Paleozoic, and Mesozoic age-probability peaks of similar magnitudes characterize four samples from southwest Montana. The distributed nature of the peaks, as well as our inability to correlate all of the peaks to one source, implies that these strata were derived from at least two distinct tectonostratigraphic sequences. We infer that the Yavapai-Mazatzal (1800-1600 Ma), Laurentian anorogenic plutonic (1480-1340 Ma), Grenville (1200-1000 Ma), and Peri-Laurentian (750-300 Ma) peaks reflect recycling of United States passive margin detrital zircons (Figure 5e) into the southwestern Montana foreland. However, the presence of an additional, Archean (~2750) age-probability peak in these strata requires at least one additional source, which is likely the Archean basement of the north-central United States (Figure 3). K-S testing of the four samples confirms that they were all derived from statistically indistinguishable parent populations, i.e., this group is 100% internally consistent.

Section 6.1.7: Ordovician Passive Margin

The remaining nine samples are difficult to group using K-S or qualitative provenance analysis due to the high variability in age-probability peak relative abundance. Some of these samples qualitatively resemble United States passive margin group spectra (GCMONTEITH, UT06-8B, MB1007, and SKR), while others appear more similar to the Canada passive margin group (BTC, 1SFSR1, 1GR100, UT0715, AND UT06-4). The sole characteristic that these samples share is the presence of a well to poorly defined, two-tiered age-probability peak that straddles the age boundary between the Trans-Hudson (2000-1800 Ma) and Wopmay (2300-2000 Ma) provinces.
Gehrels and Pecha (in prep) identified a similar age-probability peak in Ordovician passive margin strata of the western United States and Canada (Figure 4). Therefore, we propose that these anomalous samples record mixing of passive margin strata with anomalously abundant Ordovician passive margin strata. It is plausible that this signature is indicative of erosion and recycling of passive margin strata in an Ordovician-dominated thrust system, such as the Roberts Mountain allochthon in central Nevada [e.g. Gehrels et al., 2000]. In this model, the tendency of samples to qualitatively represent United States or Canadian passive margin strata likely depends on the location of the thrust sheet along the Cordilleran orogenic front.

Section 6.2: Depositional Age-Referenced Provenance

Detrital zircon samples were mapped on one of five paleogeographic reconstructions (R. Blakey, “Paleogeography and Geologic Evolution of North America”) and symbolized according to their provenance interpretation group (coded by symbol shape and color). Paleogeographic reconstructions and a list of data sources are available at http://cpgeosystems.com/nam.html. Knowledge of the extent of interpreted sediment sources (Figure 3) and age-appropriate generalized paleocurrent directions [DeCelles, 2004] was used to map likely sediment dispersal pathways within the foreland basin system (Figures 6a-e). Timing of the emergence of provenance groups was used to construct a record of Late Jurassic to Eocene exhumation within the Cordilleran orogenic wedge.

Section 6.2.1: Late Jurassic Provenance

PLACEHOLDER FOR Figure 6A

Most Late Jurassic detrital zircon samples are from the Morrison Formation,
which formed a 50-200 m thick blanket of fluvial deposits that covered ~150,000 km² of the Cordilleran foreland between the Sevier thrust front and the Rio Grande rift [Furer, 1970; Currie, 1998; DeCelles and Burden, 1992; Turner and Peterson, 2004]. Morrison Formation provenance in the Four Corners region is dominated by recycling of Mesozoic eolianites. This interpretation is consistent with DeCelles and Burden’s [1992] inference that K-feldspar in the Morrison Formation is indicative of Mesozoic eolianite recycling from the thrust belt to the west. Samples that show this correlation are from the Jackpile (CP53), Recapture (CP25), Salt Wash (CP49, CP36, CP35, CP29, CP19), Fiftymile (CP52), and Tidwell (CP41) Members. However, two contemporaneous samples from the Westwater Canyon Member (CP21, CP13) display Mogollon Highlands provenance. The close spatial association of samples from both groups (Figure 6a) implies that samples in this region were derived from a combination of thrust belt and Mogollon Highlands sources. Although a compilation of sediment dispersal directions [DeCelles, 2004] indicates a dominance of east-directed transport, we propose that a northeast-directed fluvial system may have also existed (Figure 6a) in the southern Four Corners region. Our interpretation of Morrison Formation samples is consistent with that of Dickinson and Gehrels [2008], from whom these data were compiled.

Two new samples were collected from the Upper Jurassic Entrada (T52X-17935) and Morrison (719062) Formations in the Uinta region. These samples match the criteria of the Mesozoic Eolianite interpretation group, suggesting either that Mesozoic eolianites were exposed in the Sevier belt to the west, or that they were recycled northwards from the flanks of the Mogollon Highlands. Sedimentological data does not preclude either interpretation, as both northeast and southeast-directed dispersal was documented in the
region (Figure 6a). However, petrographic data from the Morrison Formations in Wyoming records an unroofing sequence, which is consistent with the bulk of Upper Jurassic strata in this region being recycled from westerly, thrust belt sources [DeCelletes and Burden, 1992; Currie, 1998].

Two additional Morrison Formation samples were collected in northern Montana (1GRX, 1GRZ). These samples have indistinguishable age spectra from Mesozoic Eolianite group samples of the southwestern United States. The two samples are accompanied by one Kootenai Formation sample (TFI) that displays United States Passive Margin provenance in southwest Montana. Therefore, we interpret that these samples were recycled from exposures of Mesozoic eolianites in the Sevier belt (Figure 6a). Fuentes et al. [2009] interpreted that Late Paleozoic and Triassic detrital zircons (~330-180 Ma) in these samples (1GRX, 1GRZ) were derived from igneous rocks in the eastern part of the Intermontane Belt. In addition, those authors concluded that Late Proterozoic to Cambrian detrital zircons in these samples must have originated in uplifted Mesozoic eolianite strata of the Sevier belt. However, both of these age populations are present in Dickinson and Gehrels’ [2009] Mesozoic Eolianite data. Therefore, we prefer the interpretation that Morrison Formation throughout the United States was derived mostly from Mesozoic Eolianites, rather than from multiple sources that span a broad geographic range.

Upper Jurassic strata of the northern foreland basin system in Canada do not contain abundant Late Mesozoic-Triassic detrital zircons. This observation was previously used to argue for the presence of a drainage divide north of the Omenica Belt, near the international border [Mack and Jerzykiewicz, 1989; Ross et al., 2005, Leier &
Gehrels, 2011] that prevented northward transport of Intermontane Belt sediments. This inference is also valid for our provenance model, which links the Late Mesozoic-Triassic grains to Mesozoic eolianites rather than the Intermontane Belt. All of the Late Jurassic samples from Canada presented in this study were derived from passive margin strata, which were likely exposed in thrust sheets of the Sevier and the Canadian Rocky Mountains thrust belts. Kootenay (BASALKOOTENAY), Nikanassin (PROSPECTCREEK), and Monach Formation (GCMONACH) samples were predominately derived from the passive margin of the United States while the three northernmost samples were derived from the local thrust belt. These interpretations imply northward transport of United States passive margin strata, perhaps via longshore transport along the western shoreline of the interior seaway represented in the 145 Ma paleogeographic reconstruction (Figure 6a).

Section 6.2.2: Early Cretaceous Provenance

PLACEHOLDER FOR Figure 6B

During the Early Cretaceous, the Cordilleran foreland transitioned from a Mesozoic Eolianite to Passive Margin-dominated provenance regime. Eighteen of the 27 samples from this period display either Canada passive margin or United States passive margin provenance (Figure 6b). However, the architecture of sediment dispersal systems remained largely the same. For example, we interpret that chert-rich, Monteith Formation (UPPERMONTEITH) in Canada was recycled from passive margin strata exposed in the Sevier belt. This interpretation requires northwards transport, perhaps along the same pathway that we inferred for Upper Jurassic samples (Figures 6a, 6b). In addition, two samples (CP14, CP27) of Burro Canyon Formation and one sample (UT06-
8B) of Buckhorn Formation evidence continued northeast-directed recycling of Mesozoic eolianites in the Four Corner’s region. Mesozoic Eolianite provenance was also determined for the Kelvin (K2) and Kootenai (10DM25) Formations in the Uinta and Montana regions.

Kootenai and Blackleaf Formation samples (1FG70, ISR80) in northern Montana are the earliest record of Cordilleran magmatic arc dominated provenance in the foreland basin system. These samples imply that there was not a regional topographic barrier between the magmatic arc and foreland basin system during the Early Cretaceous. Detrital zircons in these samples could have been derived from four segments of the magmatic arc that preserve age-appropriate igneous rocks. These include the Sierra Nevada arc, the Coast Mountains arc, the Cascades arc and the Suture Zone Suite in the Idaho-Montana arc [Gaschnig et al., 2010] (Figures 1, 6a-e). Our provenance model favors derivation from the Idaho-Montana arc, as it is the most proximal (Figure 6b).

Section 6.2.3: Cenomanian–Santonian Provenance

PLACEHODER FOR Figure 6C

Cenomanian-Santonian detrital zircon samples (Figure 6c) record complex, mixed provenance in the western United States. Nevertheless, a simple provenance model involving east-directed dispersal in the Montana and Uinta regions, and continued northeast-directed dispersal in the Four Corners region can explain all of the samples. Generalized sediment dispersal data [DeCelles, 2004] from this period, which indicate east-directed dispersal in the Montana region and a mix of east and north-directed dispersal in the Uinta and Four Corners regions, are consistent with this interpretation.

Samples of the Mancos (CP33, CP23) and Toreva (CP9) Formations record the
reemergence of Mogollon Highlands provenance in the Uinta and Four Corners regions. These samples were deposited outboard of contemporaneous samples from the Canyon Range and Sanpete Formations (CR7 and UT06-3), which record recycling of the United States passive margin. These interpretations suggest that proximal samples were derived from local sources to the west, whereas distal samples were transported axially. This pattern is consistent with the Santonian paleogeographic reconstruction, which places the Cretaceous Interior Seaway shoreline precisely at the divide between the two provenance groupings. This boundary might demarcate the transition between fluvial and longshore transport regimes.

Two new samples from the Mancos (T67-14419) and Blair (EM4) Formations in the Uinta region signal the emergence of Yavapai-Mazatzal provenance in the retroarc region. These samples are difficult to interpret, as there is no petrographic or structural evidence for exhumation of Yavapai-Mazatzal basement thrust sheets in the Sevier belt or Laramide intraforeland province during this period. These samples might have been derived from basement exposures on the flanks of the Mogollon Highlands. This interpretation requires ~1700 km of northeast-directed axial transport, presumably via longshore transport along the shoreline of the Cretaceous Interior Seaway.

Detrital zircons from the Frontier Formation (10DM17) reveal continued erosion of Cordilleran magmatic arc rocks during the Coniacian (~89-86 Ma) in the Montana region. However, very few arc-derived detrital zircons were identified in the synorogenic, lower member of the Beaverhead Group (10DM09) in nearby southwest Montana, suggesting the existence of a local drainage divide. Instead, Beaverhead Group detrital zircon age spectra are dominated by Archean, Proterozoic, and Paleozoic ages.
that indicate mixed passive margin and Archean basement provenance. These characteristics suggest that basement-involved thrust sheets of the Cabin Culmination had been exhumed by Santonian time (~86-84 Ma). A study of paleovalleys in southwest Montana [Janecke et al., 2000] confirms that Beaverhead Group deposits were located along drainages whose headwaters tapped exposures of Archean Wyoming Province basement rocks.

**Section 6.2.4: Campanian-Paleocene Provenance**

PLACEHOLDER FOR Figure 6D

Thirty-one Campanian-Maastrichtian (~84-66 Ma) detrital zircon samples indicate complex, mixed provenance for foreland basin strata of the United States (Figure 6d). During this time, Idaho-Montana arc provenance continued to dominate in northern Montana, as shown by samples of the St. Mary’s River (1BB44) and Two Medicine (2SR240) Formations. In southern Montana, arc-derived grains remained subordinate, as three more samples from the Beaverhead Group (10DM20, 10DM22, 10DM23) indicate mixed United States passive margin, Archean basement, and Yavapai-Mazatzal basement provenance. The Yavapai-Mazatzal group sample (10DM20) was deposited north of the northernmost extent of Yavapai-Mazatzal basement (Figure 3). Therefore, we interpret that these ages were recycled from Paleoproterozoic Belt Supergroup strata, which are exposed in trailing thrust sheets of the northernmost Sevier belt [DeCelles, 2004]. Further support for this hypothesis is provided by abundant quartzite clasts in sample 10DM20, which is described as a quartzite conglomerate by Haley and Perry [1991].

Late Cretaceous Uinta and Four Corners region samples indicate mixed United States passive margin, Mogollon Highlands, Cordilleran magmatic arc, and Yavapai-
Mazatzal provenance (Figure 6d). We infer that all of these tectonostratigraphic sequences were exposed locally in the Sevier belt and newly formed (~85 Ma) Laramide intraforeland province [DeCelles, 2004; Fuentes et al., 2012]. Mesozoic Eolianite affinity also reappeared at this time, in the Wahweap (CP39) and Almond (LBRG-2700) Formations. These data indicate that either Mesozoic eolianites continued to be exposed in the Sevier belt, or that younger foreland basin strata that inherited the Mesozoic eolianite signature began to be exhumed. The latter model requires third-cycle deposition of Mesozoic eolianite sediments that were eroded from older foreland basin strata such as the Morrison Formation. However, clast count data from coeval Campanian-Maastrichtian conglomerates in the proximal foreland basin indicate widespread exposure of Mesozoic eolianites in the frontal thrust belt at this time [DeCelles, 1994; Lawton et al., 2007].

PLACEHOLDER FOR Figure 6E

The mixed provenance character of the Cordilleran retroarc foreland basin system continued into the Paleocene-Eocene in the Uinta region (Figure 6e). Seven samples of this age indicate United States Passive Margin, Yavapai-Mazatzal, and Cordilleran Magmatic Arc provenance. The youngest sample from the Beaverhead Group in southwest Montana (10DM11) displays United States passive margin provenance, implying that significant quantities of Idaho-Montana arc-derived sediments remained isolated from Beaverhead Conglomerate drainages until at least ~65 Ma. However, sample 09CA01 from the Uinta Formation records magmatic arc provenance with a dominant age peak at ~46 Ma (Figures 5a, 6e. These data suggest that the Idaho-Montana arc was shedding sediment into the foreland basin, despite the absence of
characteristic ages in the most proximal samples.

Section 7: Discussion

Comparison of detrital zircon age spectra to those of potential provenance candidates revealed six major provenance groupings in the Cordilleran retroarc foreland basin system. Each of the groupings corresponds to a specific sequence of igneous, metamorphic, or sedimentary rocks that were deformed in or exposed near the Cordilleran orogenic wedge. Referencing provenance interpretations to stratigraphic depositional ages revealed the chronology of exhumation and transport within the retroarc region. Arc-derived detrital zircons, which were extracted from the composite spectrum of foreland basin detrital zircons, were used to construct a basin-averaged proxy for Cordilleran arc flux. Integration of these datasets affirms the utility of detrital zircon geochronology in studying orogenic systems on continents.

In the United States, Late Jurassic foreland basin sedimentation was dominated by recycling of Mesozoic eolianites (Figure 6a). Paleocurrent measurements from these strata indicate westerly to southwesterly provenance [Suttner et al., 1981; DeCelles and Burden, 1992; Currie, 1998], which is consistent with the requirements of our detrital zircon provenance analysis. These observations led us to conclude that most recycled Mesozoic eolianite sediment was derived from the Sevier belt (Figure 1), implying that Mesozoic eolianites dominated leading thrust sheets during this time. However, some Late Jurassic strata of the Four Corners region may have been recycled from the flanks of the Mogollon Highlands. In contrast, provenance analysis of Upper Jurassic foreland basin strata in Canada reveals a dominance of Canada passive margin recycling. Yet some samples are more similar to the United States passive margin, which implies that
Sediments may have experienced axial, northward transport along the shoreline of the Late Jurassic interior seaway (Figure 6a).

Sedimentation above the basal Cretaceous unconformity was dominated by complex, mixed provenance in the foreland basin system. Variations during this period can be explained by the changing tectonostratigraphic composition of the Cordilleran orogenic wedge as it propagated and progressively shortened over a period of ~100 Ma. The first appearance of particular provenance groups was used to determine the timing of source exhumation. Deposition of mixed passive margin and Laurentian basement provenance foreland basin strata in the western United States reveals that basement-involved structural culminations were exposed by Campanian to Maastrichtian time (~86-66 Ma). In addition, deposition of Mogollon Highlands group sediments in the Four Corners region reveals that basement, cover, and arc rocks were exposed on the Mogollon flanks during the Late Jurassic and Late Cretaceous.

Arc-derived detrital zircons with ages younger than 200 Ma were combined to create a basin-averaged proxy for Cordilleran magmatic arc flux (Figure 7). Visual inspection of this curve reveals high flux events (HFEs) at ~160 Ma, ~100 Ma, ~75 Ma, and ~45 Ma. Before ~100 Ma, the interval between HFEs appears to have been ~60 My. After ~100 Ma, this interval decreased to ~25 My. The cyclical nature of these HFEs suggests that coupled upper-plate processes were likely interacting with subduction zone processes to control the evolution of the North American Cordillera. Interpretation of the detrital record of magmatic arc flux within the framework of the Cordilleran orogenic cyclicity model of DeCelles [2009] explains the increase in high flux event frequency at ~100 Ma.
In Cordilleran orogenic systems, convergence is accommodated by subduction of an oceanic plate and shortening of a continental plate. Typically, upper continental crust shortens across a retroarc thrust belt while the lowermost continental crust is shoved beneath the arc—fueling episodic high flux magmatism [Ducea and Barton, 2007; DeCelles et al., 2009]. The recurrence interval of high flux magmatism should therefore vary according to changes in the convergence rate. In the North American Cordillera, relatively slow convergence between the Farallon and North America plates produced two HFEs with a recurrence interval of ~60 My between 160-100 Ma (Figure 7).

Convergence rates increased after ~100 Ma, as indicated by an increase in Farallon plate velocity of ~100 km/my [Engebretson, 1984]. This increase coincided with a >50% reduction in HFE recurrence interval between ~100 Ma and 50 Ma, from ~60 My to ~25 My. We propose that the increase in plate convergence velocity caused the decrease in HFE recurrence interval.

Detrital zircon geochronology is commonly used to investigate first-order magmatic and accretionary processes. In addition, many workers have used detrital zircon geochronology to resolve recycling and erosion of tectonostratigraphic sequences within orogenic systems. This technique has proven particularly effective in North American Cordillera. However, detrital zircons from the retroarc region of Cordilleran orogenic systems should also be used to examine orogen-scale arc magmatic processes. For instance, the detrital record of Cordilleran arc magmatism is much less difficult to interpret at the orogen scale than the compilation of igneous flux curves presented in Figure 7. These curves, despite their detail, do not reveal any clear trends in recurrence interval of HFEs or relative flux between HFEs. The clarity of the detrital zircon curve is
undoubtedly related to the averaging that is characteristic of detrital proxies. However, this characteristic should not be considered a limitation, especially when examining orogen-scale tectonic processes.

Section 8: Conclusions

Foreland basin strata in the Cordilleran retroarc region contain age spectra with varying proportions of 1) 2.5 Ga cratonic, 2) 2.3–1.6 Ga Wopmay, Trans-Hudson, and Yavapai-Mazatzal, 3) 1.48-1.34 Ga intracratonic magmatic, 4) 1.2-1.0 Ga Grenville, 5) 750-250 Ma peri-Laurentian, and 6) <250 Ma Cordilleran magmatic arc detrital zircons. Variations in the presence, absence, and relative abundance of age peaks within these ranges defined six provenance groupings that describe variations within the foreland basin system. Recycled groups include samples that display Mesozoic Eolianite, Canada passive margin, and United States passive margin provenance. Groups whose age spectra suggest a component of first-cycle erosion include the Yavapai-Mazatzal, Cordilleran Magmatic Arc, Mogollon Highlands, Mixed Passive Margin and Ordovician Passive Margin, and mixed Passive Margin + Yavapai-Mazatzal interpretation groups. Characteristic age spectra for each grouping were defined in Section 6. Whenever possible, K-S statistics were used to quantify the internal consistency of provenance groups. These tests successfully categorized 69 of the 96 total samples.

Late Jurassic provenance was dominated by recycling of Mesozoic eolianites in the United States and passive margin strata in Canada. Most recycling was linked to exhumation Cordilleran thrust belt. However, some samples from this period suggest a component of axial transport, especially in the Four Corners region and in southern Canada (Figure 1, 6a). Foreland basin provenance became increasingly complex during
the Cretaceous-Eocene. Progressive shortening and propagation in the Cordilleran orogenic wedge during this period exhumed all of the crustal elements required to explain the provenance interpretation groups. Emergence of Yavapai-Mazatzal provenance in the Uinta and Montana regions during the Campanian-Maastrichtian signaled the exhumation of basement-involved thrust sheets between ~86-66 Ma.

The detrital record of arc magmatism from the Cordilleran foreland basin system reveals a correlation between increasing convergence rates and a decrease in high flux event recurrence interval at ~100 Ma. These data corroborate predictions of the Cordilleran orogenic cyclicity model of DeCelles et al. [2009], which links coupled upper-plate processes to subduction zone processes. The apparent utility of detrital zircon data as a proxy for arc magmatism in this study suggests that it is a useful tool for evaluating arc magmatism at the continent scale in retroarc settings.
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Nichols, D. J., and B. Bryant (1990), Palynologic data from Cretaceous and lower Tertiary rocks in the Salt Lake City 30“ x 60” Quadrangle, in Geologic map of the Salt Lake City 30” x 60” Quadrangle, north-central Utah, and Uinta County,


Figure 1 - Tectonic overview map of the North American Cordillera showing the location of foreland basin system samples, their interpreted provenance (coded by symbol), their stratigraphic age (coded by color), and aerial extent of major exposures of igneous and metamorphic rocks (references in Table DR1; bedrock geology from USGS National Map, http://www.nationalmap.gov). Chronostratigraphic relationships between samples from the four sampling regions (1- Four Corners 2- Uinta 3- Montana 4- Canada) are discussed in the text and plotted in Figure 2. Overlapping sample icons of the same stratigraphic age and provenance interpretation were reduced to one symbol. Satellite imagery is from ESRI EarthSat.
Figure 2 - A. Location of detrital zircon samples and boundaries of the four sampling regions charted in Figure 2b and discussed in the text. B. Formation names and generalized stratigraphic relationships for detrital zircon samples. Where present, numbers in parentheses indicate the number of samples from individual units within a given sample region. See table DR1 for depositional age references. Time scale simplified from Walker and Geissman [2009].
Figure 3 - Location of North American crustal provinces that may have supplied detrital zircons to the Cordilleran retroarc foreland basin system. Age domains are color-coded to match those of the age-probability diagrams in Figures 4 and 6a-h. Adapted from Gehrels et al. (2011) and references therein.
**Figure 4** - Composite normalized probability curves for potentially recycled tectonostratigraphic sequences of the western United States and Canada. Shaded age domains are color coded to match corresponding Laurentian crustal provinces that are mapped in Figure 3. Normalized probability curves for Ordovician passive margin samples (gray and unfilled) are plotted atop the rest of Gehrels & Pecha’s [in prep] data to illustrate their pronounced differences. These curves are reflected horizontally in Figures 6c, 6e, and 6f to facilitate visual comparison of the interpreted provenance matches.
**Figure 5a** - Individual normalized probability curves for detrital zircon samples of the Cordilleran Magmatic Arc provenance interpretation group. Samples are plotted atop a graph of major crustal age domains that correspond to those mapped in Figure 3. Normalized probability curves are arranged so that the northernmost samples are at the top of the figure. Maximum depositional ages were calculated for each sample by averaging the youngest group of three zircons with overlapping ages.
**Figure 5b** - Composite normalized probability curve for the Yavapai-Mazatzal provenance interpretation group. Data are plotted against the age ranges of the Laurentian basement rocks mapped in Figure 3. Highlighted crustal age domain columns correspond to the age of the dominant probability peak that defines the interpretation group. Internal consistency of the grouped samples was quantified using K-S statistical analysis of all grains older than 250 Ma, so as to avoid sampling bias. Detrital zircon ages not included in the comparisons are symbolized as a hollow curve. The chart at right displays P values for each K-S comparison. P values >0.05 indicate that two detrital zircon populations are statistically indistinguishable, and are highlighted in yellow.
K-S P-values using error in the CDF

**Figure 5c** - Composite normalized probability curve for the Mesozoic Eolianites provenance interpretation group. Data are plotted against the age ranges of the Laurentian basement rocks mapped in Figure 3 and a reflected composite normalized probability curve of the interpreted source tectonostratigraphy. Highlighted crustal age domain columns correspond to the age of the dominant probability peak that defines the interpretation group. Internal consistency of the grouped samples was quantified using K-S statistical analysis of all grains older than 250 Ma, so as to avoid sampling bias. Detrital zircon ages not included in the comparisons are symbolized as a hollow curve. The chart above displays P-values for each K-S comparison. P values >0.05 indicate that two detrital zircon populations are statistically indistinguishable, and are highlighted in yellow.

**Mesozoic Eolianites (Dickinson & Gehrels, 2009)**

- **23 Samples**

- **10 Samples**
Figure 5d - Individual normalized probability curves for detrital zircon samples of the Mogollon Highlands provenance interpretation group. Samples are plotted atop a graph of major crustal age domains that corresponded those mapped in Figure 3. Shaded domains correspond to the age-probability peak ranges that define this qualitative provenance classification. Normalized probability curves are arranged so that the northernmost samples are at the top of the figure.
that two detrital zircon populations are statistically indistinguishable, and are highlighted in yellow.

The chart above displays P values for each K-S comparison. P values >0.05 indicate using K-S statistical analysis of all grains older than 250 Ma, so as to avoid sampling bias. Detrital zircon ages not included in the dominant probability peak that defines the interpretation group. Internal consistency of the grouped samples was quantified probability curve of the interpreted source tectonostratigraphy. Highlighted crustal age domain columns correspond to the age of the 1.34-1.48 anorogenic magmatism

Figure 5e - Composite normalized probability curve for the United States Passive Margin provenance interpretation group. Data are plotted against the age ranges of the Laurentian basement rocks mapped in Figure 3 and a reflected composite normalized probability curve for the United States Passive Margin provenance interpretation group. Data

Internal Consistency: 78%

K-S P-values using error in the CDF

Figure 5e - Composite normalized probability curve for the United States Passive Margin provenance interpretation group. Data are plotted against the age ranges of the Laurentian basement rocks mapped in Figure 3 and a reflected composite normalized probability curve of the interpreted source tectonostratigraphy. Highlighted crustal age domain columns correspond to the age of the dominant probability peak that defines the interpretation group. Internal consistency of the grouped samples was quantified using K-S statistical analysis of all grains older than 250 Ma, so as to avoid sampling bias. Detrital zircon ages not included in the comparisons are symbolized as a hollow curve. The chart above displays P values for each K-S comparison. P values >0.05 indicate that two detrital zircon populations are statistically indistinguishable, and are highlighted in yellow.
Figure 5f - Composite normalized probability curve for the Canada Passive Margin provenance interpretation group. Data are plotted against the age ranges of the Laurentian basement rocks mapped in Figure 3 and a reflected composite normalized probability curve of the interpreted source tectonostratigraphy. Highlighted crustal age domain columns correspond to the age of the dominant probability peak that defines the interpretation group. Internal consistency of the grouped samples was quantified using K-S statistical analysis of all grains older than 250 Ma, so as to avoid sampling bias. Detrital zircon ages not included in the comparisons are symbolized as a hollow curve. The chart above displays P values for each K-S comparison. P values >0.05 indicate that two detrital zircon populations are statistically indistinguishable, and are highlighted in yellow.
Figure 5g - Composite normalized probability curve for the mixed United States Passive Margin and Yavapai-Mazatzal provenance interpretation group. Data are plotted against the age ranges of the Laurentian basement rocks mapped in Figure 3. Highlighted crustal age domain columns correspond to the age of the dominant probability peak that defines the interpretation group. Internal consistency of the grouped samples was quantified using K-S statistical analysis of all grains older than 250 Ma, so as to avoid sampling bias. Detrital zircon ages not included in the comparisons are symbolized as a hollow curve. The chart above displays P values for each K-S comparison. P values >0.05 indicate that two detrital zircon populations are statistically indistinguishable, and are highlighted in yellow.
Figure 5h - Individual normalized probability curves for detrital zircon samples of the mixed passive margin and Ordovician passive margin provenance interpretation group. Samples are plotted atop a graph of major crustal age domains that corresponded those mapped in Figure 3. Shaded domains correspond to the age-probability peak ranges that define this qualitative provenance classification. Normalized probability curves are arranged so that the northernmost samples are at the top of the figure.
Figure 6a: Upper Jurassic detrital zircon sample locations, sample names, and interpreted provenance plotted on a late Late Jurassic (145 Ma) paleogeographic reconstruction (R. Blakey, http://cpgeosystems.com/nam.html). Black arrows indicate generalized sediment dispersal directions after DeCelles (2004). Dashed arrows indicate interpreted sediment dispersal pathways based on provenance.
Figure 6b: Lower Cretaceous detrital zircon sample locations, sample names, and interpreted provenance plotted on a late Early Cretaceous (100 Ma) paleogeographic reconstruction (R. Blakey, http://cpgeosystems.com/nam.html). Black arrows indicate generalized sediment dispersal directions after DeCelles (2004). Dashed arrows indicate interpreted sediment dispersal pathways based on provenance.
Figure 6c: Cenomanian-Santonian (~100-84 Ma) detrital zircon sample locations, sample names, and interpreted provenance plotted on a Santonian (85 Ma) paleogeographic reconstruction (R. Blakey, http://cpgeosystems.com/nam.html). Black arrows indicate generalized Cenomanian sediment dispersal directions after DeCelles (2004). Dashed arrows indicate interpreted sediment dispersal pathways based on provenance.
Figure 6d: Campanian-Maastrichtian (~84-66 Ma) detrital zircon sample locations, sample names, and interpreted provenance plotted on a latest Maastrichtian (65 Ma) paleogeographic reconstruction (R. Blakey, http://cpgeosystems.com/nam.html). Black arrows indicate generalized Maastrichtian sediment dispersal directions after DeCelles (2004). Dashed arrows indicate interpreted sediment dispersal pathways based on provenance.
Paleocene-Eocene (~66-47 Ma) Detrital Zircon Provenance
50 Ma Paleogeography

Provenance Interpretation
- Canada Passive Margin
- United States Passive Margin
- Mesozoic Eolianite
- Mogollon
- Cordilleran Magmatic Arc
- Yavapai-Mazatzal

Figure 6e: Paleocene-Eocene (~66-47 Ma) detrital zircon sample locations, sample names, and interpreted provenance plotted on an Eocene (50 Ma) paleogeographic reconstruction (R, Blakey, http://cpgeosystems.com/nam.html). Dashed arrows indicate interpreted sediment dispersal pathways based on provenance.
Figure 7: a. Probability distribution function of arc-derived detrital zircons in the foreland basin system [this study]. b. Farallon plate velocity and age at the subduction interface from Engebretson [1984]. c. Relative flux curves interpreted from exposures of igneous rocks along three segments of the Cordilleran magmatic arc after Paterson et al. [2011], and references therein. No flux data are available for the Idaho and Montana batholiths. To facilitate comparison, we plot age ranges of major igneous suites in this region [Gaschnig et al., 2010] above the relative flux curves.