Local-to-distant provenance cyclicity of the southern Front Range, central Colorado: Insights from detrital zircon geochronology

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ABSTRACT

Analysis of detrital zircon U-Pb ages from the Phanerozoic sedimentary record of central Colorado reveals variability in sediment transport pathways across the middle of the North American continent during the last 500 m.y. that reflects the tectonic and paleogeographic evolution of the region. In total, we present 2222 detrital zircon U-Pb ages from 18 samples collected from a vertical transect in the vicinity of Colorado’s southern Front Range. Of these, 1792 analyses from 13 samples are published herein for the first time. Detrital zircon U-Pb age distributions display a considerable degree of variability that we interpret to reflect derivation from (1) local sediment sources along the southern Front Range or other areas within the Yavapai-Mazatzal Provinces, or (2) distant sediment sources (hundreds to thousands of kilometers), including northern, eastern, or southwestern Laurentia. Local sediment sources dominated during the Cambrian marine transgression onto the North American craton and during local mountain building associated with the formation of the Ancestral and modern Rocky Mountains. Distant sediment sources characterize the remaining ~75% of geologic time and reflect transcontinental sediment transport from the Appalachian or western Cordilleran orogenies. Sediment transport mechanisms to central Colorado are variable and include alluvial, fluvial, marine, and eolian processes, including windblown volcanic ash from the distant mid-Cretaceous Cordilleran arc. Our results
highlight the importance of active mountain building and developing topography in controlling sediment dispersal patterns. For example, locally derived sediment is predominantly associated with generation of topography during uplift of the Ancestral and modern Rocky Mountains, whereas sediment derived from distant sources reflects the migrating locus of orogenesis from the Appalachian orogen in the east to western Cordilleran orogenic belts in the west. Alternating episodes of local and distant sediment sources are suggestive of local-to-distant provenance cyclicity, with cycle boundaries occurring at fundamental transitions in sediment transport patterns. Thus, identifying provenance cycles in sedimentary successions can provide insight into variability in drainage networks, which in turn reflects tectonic or other exogenic forcing mechanisms in sediment routing systems.

INTRODUCTION

The technological breakthrough of efficient collection of detrital zircon geochronologic data using laser ablation–inductively coupled plasma–mass spectrometry (LA-ICP-MS) has led to a step change in our ability to track sediment dispersal patterns and refine paleogeographic models (Gehrels, 2012; Lawton, 2014; Fildani et al., 2016; Sharman et al., 2017). William R. Dickinson, in collaboration with George Gehrels at the University of Arizona, was at the forefront of this “detrital zircon revolution” (Gehrels, 2012), particularly as applied to the Phanerozoic stratigraphic record of the western United States (e.g., Dickinson and Gehrels, 2003, 2008a, 2008b, 2009a, 2009b, 2010; Dickinson et al., 2009, 2012). Although W.R. Dickinson’s research using detrital zircon geochronology focused primarily on Colorado Plateau sandstones, his interests also extended elsewhere in the Rocky Mountain region of the western United States. In particular, Dickinson et al. (1988) established the timing of Laramide deformation and basin formation, with implications for the paleogeographic development of the Rocky Mountains during the Laramide orogeny. Although many of these interpretations have stood the test of time, more recent studies have built upon this early work to further refine the timing and controls of the paleogeographic evolution of this region (Galloway et al., 2011; Blum and Pecha, 2014; Sharman et al., 2017).

In documenting the provenance evolution of sedimentary basins, past workers have noted that some systems exhibit drainage basin expansion and contraction over time (e.g., Blum and Pecha, 2014). This pattern can be recognized in basin fill as the transition from local sediment sources to those more distant from the sedimentary basin, or vice versa. The transition from local-to-distant sediment sources has been identified as a key marker of important geologic events in some sedimentary systems. For instance, the Cretaceous–Paleogene Gulf of Mexico sedimentary basin underwent drainage expansion during Paleocene time, possibly in response to active tectonism in the hinterland (Blum and Pecha, 2014; Sharman et al., 2017).

This manuscript provides the first comprehensive analysis of detrital zircon U-Pb ages from the Phanerozoic sedimentary record of central Colorado, complementing the work of W.R. Dickinson and others that focused on stratigraphic sections to the west (e.g., Gehrels et al., 2011; May et al., 2013). Specifically, we examined sedimentary units within the southern Front Range, between the cities of Denver and Colorado Springs, and within the adjacent Denver Basin (Fig. 1). As demonstrated by Gehrels et al. (2011) for the Grand Canyon of the Colorado River, detrital zircon age distributions within a vertical sedimentary succession can provide insight into sediment transport patterns and the paleogeographic evolution of a region over geologic time scales. We demonstrate that the sedimentary record of central Colorado exhibits a number of local-to-distant sediment source area episodes, providing insight into changing sediment transport pathways across the middle of the North American continent during the last 500 m.y.

GEOLOGIC BACKGROUND

As many as ~5000 m of Phanerozoic strata overlie Proterozoic crystalline rocks in the vicinity of the southern Front Range in central Colorado (see composite stratigraphic section; Fig. 2). The crystalline basement and overlying sedimentary rocks record series of major geologic episodes that reflect the tectonic and stratigraphic development of this region over ~1.8 b.y. (Raynolds and Hagadorn, 2015, 2016).

Assembly of Continental Crust (Ca. 1.8–1.1 Ga)

The crystalline basement in central Colorado is part of a geographically extensive realm of Paleoproterozoic rocks that were accreted onto Archean basement during the Yavapai (ca. 1.7–1.8) and Mazatzal (ca. 1.6–1.7 Ga) orogenies (Fig. 3; Tweto, 1987; Karlstrom and Williams, 2005). Mesoproterozoic intrusions (ca. 1.4 Ga) are widespread along the Front Range and elsewhere within the southwestern United States (Figs. 3 and 4; Nyman et al., 1994; Mahan et al., 2013). The southern Front Range also hosts the ca. 1.1 Ga Pikes Peak batholith, an anomalous intrusion of Grenville age that is >800 km from the dominant Grenville orogenic belt found to the southeast, east, and northeast (Figs. 3 and 4; Smith et al., 1999).
Passive Margin and Epicontinental Seaway  
(Ca. 500–340 Ma)

Outcrops of Upper Cambrian–Mississippian strata comprise a relatively thin (~250 m) succession deposited on the craton and within a passive margin found along the western, southern, and eastern sides (present-day coordinates) of Laurentia following rifting of the supercontinent Rodinia (Johnson, 1945; Grose, 1972; Stewart and Poole, 1974; Blakey, 2011). A shallow basin formed in central Colorado, in which predominantly marine sediments were deposited; this basin was part of a larger epicontinental seaway that extended across much of southern Laurentia (Myrow et al., 2003; Blakey, 2011). Major stratigraphic packages were deposited in transgressive and regressive cycles of the Sauk, Tippecanoe, and Kasaskia sequences (Sloss, 1963; Raynolds and Hagadorn, 2016). These cycles typically consist of mature quartz arenite deposited in coastal settings overlain by marine shale, limestone, or dolostone (Grose, 1972). Siddoway and Gehrels (2014) examined four detrital zircon samples from sandstone beds within the basal portion of three of these sequences, including the Upper Cambrian Sawatch Formation, Middle Ordovician Harding Sandstone, and the Upper Devonian

Figure 1. (A) Uplifts (dark gray) and basins (stippled light gray) of the Rocky Mountain region (modified from Dickinson et al., 1988; Lawton, 2008; Davis et al., 2009; Heller and Liu, 2016). Eastern limit of Sevier thrust belt is from Galloway et al. (2011). White circles indicate detrital zircon sample locations (Table 1). (B) Cross section across the southern Front Range (after Raynolds, 2002). Abbreviations: CS—Colorado Springs; D—Denver.
**Figure 2.** Composite stratigraphic section of the southern Front Range and adjacent Denver Basin (adapted from Grose, 1972; Milito, 2008; Dechesne et al., 2011; Siddoway and Gehrels, 2014). Units with detrital zircon data are shown in red, italicized text (Table 1). Samples from Siddoway and Gehrels (2014) are indicated by asterisks. See main text for an explanation of interpreted sediment source(s). Color of stratigraphic units corresponds to basin history episodes (Raynolds and Hagadorn, 2015). Tectonostratigraphic assemblages are from May et al. (2013), with depositional environment interpretations modified to reflect units in the study area. Abbreviations: C—Cambrian; Cyn—Canyon; E—Eastern; Fm.—Formation; Jr—Jurassic; K—Cretaceous; L—Lower; Ls—Limestone; M—Mississippian; Mbr—Member; Pc—Paleocene; Prot—Proterozoic; N—Northern; Ss—Sandstone; Tr—Triassic; U—Upper; W—Western.
Williams Canyon Formation (Fig. 2; Table 1; Myrow, 1998; Allulee and Holland, 2005).

**Ancestral Rocky Mountain Orogeny (Ca. 320–280 Ma)**

A thick succession (~1200 m) of Pennsylvanian–Lower Permian conglomerate, arkosic sandstone, siltstone, and mudstone (Fountain Formation and related units; Fig. 2) was deposited across central Colorado during the Ancestral Rocky Mountain orogeny (De Voto, 1980; Kluth and Coney, 1981; Sweet and Soreghan, 2010). The lower Fountain Formation has been interpreted as a fan-delta complex containing both marine and subaerial depositional environments, whereas the middle and upper parts of the Fountain Formation are interpreted as deposits of fluvial braid plains and alluvial fans (Maples and Suttner, 1990; Sweet and Soreghan, 2010). In the study area, paleocurrent orientations suggest radial sediment dispersal toward the east, away from the ancestral Front Range (Howard, 1966). Siddoway and Gehrels (2014) examined one detrital zircon sample from the basal Fountain Formation (Glen Eyrie Member), and we collected one sample from the overlying main arkosic body of the Fountain Formation (Fig. 2).

Figure 3. Basement age domains of North America, in Ga (modified from Dickinson and Gehrels, 2009b; Fildani et al., 2016).

Figure 4. Geologic map of the Front Range showing Proterozoic–Archean basement and Cretaceous–Lower Paleogene volcanics of the Colorado Mineral Belt, modified from Reed et al. (2005), Karlstrom and Williams (2005), and Mahan et al. (2013). Abbreviations: CP—Castle Pines; WY—Wyoming; NB—Nebraska; CO—Colorado; NM—New Mexico.

Archean (Wyoming province)  
- ≥ 2.5 Ga Late Archean

Paleoproterozoic (Yavapai-Mazatzal province)  
- ~1.8-1.6 Ga schists and gneisses  
- ~1.7 Ga granitic rocks

Mesoproterozoic (anorogenic)  
- ~1.4 Ga granitic rocks  
- ~1.1 Ga granitoid (Pikes Peak batholith)

Phanerozoic  
- Cretaceous-Paleogene igneous rocks (Colorado Mineral Belt)
Tectonic Quiescence and Healing of Ancestral Rocky Mountain Topography (Ca. 280–145 Ma)

Lower Permian to Jurassic units in the southern Front Range record a period of relative tectonic quiescence, despite the margins of the North American continent undergoing both convergent and divergent tectonism (Blakey, 2011; Raynolds and Hagadorn, 2015). These series of stratigraphic units record the erosional leveling and healing of Ancestral Rocky Mountain topography, including the Permian–Triassic Lyons, Lykins, and Jelm Formations, and the Jurassic Sundance and Morrison Formations (Fig. 2; Turner and Peterson, 2004; Raynolds and Hagadorn, 2015). We collected detrital zircon samples from the eolian-fluvial Middle Permian Lyons Sandstone and the fluvial Upper Jurassic Morrison Formation (Fig. 2).

Western Interior Seaway (Ca. 105–68 Ma)

Incursion of the Western Interior Seaway into central Colorado during Early Cretaceous time is recorded in the deltaic South Platte Formation of the Dakota Group (Weimer and Land, 1972; Kauffman and Caldwell, 1993; Raynolds and Hagadorn, 2015). Continued marine deposition throughout much of Late Cretaceous time is recorded by predominantly fine-grained units, including the Pierre Shale, which is ~1500 m thick, and lesser sandstone (including the Codell Sandstone Member of the Carliile Shale; Fig. 2; Roberts and Kirschbaum, 1995). The Fox Hills Sandstone marks the final regression of the Western Interior Seaway in latest Cretaceous time, and this unit is overlain by coastal plain facies of the Laramie Formation (Dechesne et al., 2011). We sampled three units from this interval: the South Platte Formation (Dakota Group), the Codell Sandstone, and the Fox Hills Sandstone (Fig. 2).

TABLE 1. DETRITAL ZIRCON U-Pb SAMPLES

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<th>Longitude (°W)</th>
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Note: Age information from Suttner et al. (1984), Raynolds (2002), Maples and Suttner (1990), and Raynolds and Hagadorn (2016). Fm.—Formation; Mbr.—Member; Ss.—Sandstone.

Laramide Orogeny, Denver Foreland Basin (Ca. 68–54 Ma)

Deposition of coarse-grained arkosic sandstone and conglomerate of the D1 Sequence during latest Cretaceous time marked a major shift in sedimentation style in central Colorado coincident with the onset of the Laramide orogeny (Fig. 2; Dickinson and Snyder, 1978; Raynolds, 2002; Raynolds and Hagadorn, 2015). Uplift of the southern Front Range was accompanied by foreland basin development in the adjacent Denver Basin (Raynolds, 2002; Kelley, 2002; Dechesne et al., 2011). Following a hiatus during late Paleocene time, synorogenic deposition resumed with deposition of the Lower Eocene D2 Sequence (Raynolds, 2002). Igneous intrusions and volcanism of the Colorado Mineral Belt also developed within and southwest of the southern Front Range during this time (Chapin, 2012). Five detrital zircon samples were collected for this study from the synorogenic D1 and D2 Sequences exposed in core from the Castle Pines borehole within the proximal Denver Basin foreland (Fig. 2; Robson and Banta, 1993).
Tectonic Quiescence, Topographic Healing, and Exhumation (Ca. 45–Present)

Central Colorado experienced a second period of relative tectonic quiescence and topographic healing following uplift of the southern Front Range during the Laramide orogeny. Topographic relief of the southern Front Range and surrounding Rocky Mountain highlands was reduced to a number of isolated peaks that extended above a low-relief plain, the Rocky Mountain erosion surface (Epis and Chapin, 1975; Scott and Taylor, 1986; Chapin and Kelley, 1997). Few deposits of this phase are preserved in the vicinity of the study area, with the exception of the Wall Mountain tuff and the overlying Castle Rock Conglomerate (latest Eocene age; Raynolds, 2002; Evanoff, 2007). Progressive erosion exhumed the buried Laramide landscape, ultimately resulting in the modern topography of the southern Front Range. We collected a detrital zircon sample from the modern South Platte River, which drains much of the central and southern Front Range (Fig. 4).

At ca. 15–10 Ma, central Colorado transitioned from an aggradational to an erosional regime that may have been triggered by regional uplift (Epis and Chapin, 1975; Trimbel, 1980; Eaton, 1987; Leonard, 2002; McMillan et al., 2006) and/or climatic change (Molnar and England, 1990). Progressive erosion exhumed the buried Laramide landscape, ultimately resulting in the modern topography of the southern Front Range. We collected a detrital zircon sample from the modern South Platte River, which drains much of the central and southern Front Range (Fig. 4).

METHODS

Samples

Twelve samples (Pennsylvanian to Eocene) of fine- to coarse-grained sandstone were collected from (1) outcrops within or adjacent to the southern Front Range and (2) subsurface drill core in the proximal Denver Basin (Table 1). A sample of sand from the modern South Platte River was also collected (Table 1). These samples are supplemented by data from five previously published samples (Siddoway and Gehrels, 2014) to provide a vertical transect through the major sand-bearing units in the stratigraphic succession of the southern Front Range (Fig. 2).

U-Pb Geochronology

Detrital zircons were extracted following standard mineral separation procedures at the University of Texas at Austin (e.g., Hart et al., 2016). Concentrated zircon separates were attached to 1 in. (2.5 cm) round acrylic mounts using sticky tape. Approximately 140 zircon grains per sample were analyzed at random, provided that each grain was of sufficient size to focus a 30-µm-diameter laser spot and sufficiently free of inclusions and grain surface imperfections. Zircon grains were analyzed using LA-ICP-MS at the University of Texas at Austin Geo-Thermochronometry Laboratory (e.g., Chang et al., 2006). Ablation of the zircon grain from the surface inward during analysis allows depth profiling of individual zircons (e.g., Kelly et al., 2014). Thirty-nine grains showed distinct rim versus core relationships that could be identified by the transition from a young to old U-Pb age during the progression of the analysis (Table DR1).

Data were reduced using Iolite and the VisualAge data reduction scheme (Paton et al., 2010). An 850 Ma 206Pb/238U age cutoff was used to select either the 206Pb/238U age or 207Pb/206Pb age for plotting and analysis. Analyses younger than 850 Ma were filtered from the data set if the 2ε internal error of the 206Pb/238U age exceeded 10% or if discordance between the 206Pb/238U and 207Pb/206Pb ratios exceeded 15%. Analyses with 206Pb/238U ages older than 850 Ma were filtered if discordance between the 206Pb/238U and 207Pb/206Pb ratios exceeded 30% or were >15% reverse discordant. In total, 52 analyses (<3% of the total data set) were discarded (Table DR1 [see footnote 1]). Zircon U-Pb analyses were calibrated using GJ-1 (ca. 600 Ma) as a primary standard (Jackson et al., 2004; Liu et al., 2010). Plesovice (337 Ma; Sláma et al., 2008) and 91500 (1065 Ma; Wiedenbeck et al., 2004) standards were used as secondary standards. Samples were analyzed during seven different analytical sessions, and the weighted mean average of the Plesovice and 91500 standards for each session was within 4% and 3% of the expected age, respectively (Table DR2 [see footnote 1]).

Maximum Depositional Age Calculations

The youngest detrital zircon analyses provide an estimate of a sample’s maximum depositional age (MDA; Fedo et al., 2003). The difference between the MDA and an independent estimate of the depositional age is the lag time (Δt; e.g., Gehrels et al., 2011). Low lag times indicate that young zircon grains were present at the time of deposition, a circumstance typically associated with volcanic and/or rapidly exhumed plutonic or metamorphic source areas.

We considered three methods of calculating MDA, following the recommendations of Dickinson and Gehrels (2009a). The youngest single age (YSG) metric assigns the MDA as the age and uncertainty of the youngest detrital analysis. We assigned the YSG as the detrital analysis with the lowest age plus 1σ uncertainty. Although the YSG is often compatible with the depositional age, it lacks statistical robustness as a consequence of relying on a single analytical measurement that may be affected by Pb loss or other analytical complications (Dickinson and Gehrels, 2009a).

To improve statistical robustness, two additional metrics have been proposed for calculating MDAs that rely on a number detrital analyses that overlap within analytical uncertainty: (1) the weighted mean age of the youngest two or more grains

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1GSA Data Repository Item 2018353, Detrital zircon U-Pb ages (Table DR1), secondary zircon standard results (Table DR2), and a list of samples and data sources used in Figure 8 (Table DR3), is available at www.geosociety.org/datarepository/2018/, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA.
**Table 2. Maximum depositional age and lag time (Δt) calculations**

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**Note:** Min—minimum; Max—maximum; Avg—average; YSG—youngest single age; YC1σ(2+)—weighted mean age of the youngest two or more grains that overlap at 1σ uncertainty; YC2σ(3+)—weighted mean age of the youngest three or more grains that overlap at 2σ uncertainty. Lag time uncertainty is reported as the 2σ uncertainty of either YC1σ(2+) or YC2σ(3+) (Dickinson and Gehrels, 2009a). We calculated these metrics by sorting the detrital analyses by age plus 1σ uncertainty, selecting the first occurrence of 2 or 3 detrital analyses overlapping at the specified uncertainty level, and calculating a weighted mean average. These metrics have the advantage of providing a more statistically robust MDA estimate (Dickinson and Gehrels, 2009a). However, YC1σ(2+) and YC2σ(3+) typically yielded older MDA estimates than YSG, resulting in larger calculated lag times (Table 2).

We calculated lag time by subtracting the average of the depositional age range for each sample from the MDA (Table 2). Lag time uncertainty is reported as the 2σ uncertainty of either the individual detrital analysis (YSG) or the weighted mean age of the youngest cluster (YC1σ[2+]) or YC2σ[3+] plus the uncertainty in the depositional age range (Table 2). A lag time is considered to be within error of the depositional age if the uncertainty is greater than the lag time itself (Table 2).

**DETRITAL ZIRCON U-Pb AGES AND PROVENANCE INTERPRETATION**

We present 2222 zircon U-Pb age analyses from 18 sandstone or sand samples that range in age from Late Cambrian to modern (Table 1). Of these, 1792 analyses from 13 samples are published herein for the first time (Table DR1 [see footnote 1]), with the remainder published by Siddoway and Gehrels (2014). Normalized detrital age distributions and major age peaks are presented in Figure 5 and discussed in the following sections.

**Potential Sediment Source Areas**

Provenance interpretations based on detrital zircon U-Pb analyses can be guided by comparison with the geologic age of North American basement (Fig. 3; Hoffman, 1989; Dickinson and Gehrels, 2009b). In general, we divided North American basement provinces into five major categories that reflect the progressive addition of continental crust since Archean time. These are, in order of decreasing age, (1) northern Laurentia (>1.8 Ga), including the Archean Wyoming and Superior Provinces, (2) southeastern Laurentia (1.3–1.8 Ga), including the Yavapai, Mazatzal, and midcontinent provinces, (3) southeastern Laurentia, Grenville orogeny (ca. 1.3–1.0), (4) southeastern Laurentia, Appalachian orogeny, and associated peri-Gondwanan terranes (ca. 0.76–0.36 Ga), and (5) the western Cordilleran arc (<0.3 Ga) (Fig. 3).

Although basement domains provide a first-order framework for interpreting sediment source areas based on detrital zircon age distributions, a number of factors can complicate such a straightforward interpretation. For instance, sediment may not originate directly from crystalline basement, and it may be recycled from older stratigraphic units (e.g., Dickinson et al., 2009). Zircon is readily recycled because it can withstand multiple cycles of erosion, transport, and deposition over geologic time.
Figure 5. Kernel density estimates, histograms, and pie plots of detrital zircon U-Pb ages from the southern Front Range and adjacent Denver Basin (plots generated using detritalPy; Sharman et al., 2018). Samples are arranged in ascending stratigraphic order; lowermost five samples are from Siddoway and Gehrels (2014). Only ages younger than 300 Ma are shown on left (number of ages younger than 300 Ma and total number of ages are shown in parentheses). Prominent age peaks are labeled (Ma). Abbreviations: L—Lower; U—Upper.
Rim versus Core Age Relationships

Zircon grains with distinct rim and core U-Pb ages reflect a composite magmatic and/or metamorphic history (e.g., Kelly et al., 2014) that can provide greater resolution in identifying the specific sediment source area(s). In total, 39 grains from 10 samples yielded distinct rim and core U-Pb ages, with the number of rim versus core relationships per sample varying from 0 to 9 (Fig. 6). All but three grains had core ages ranging from 2.1 to 0.8 Ga and rim ages younger than 1.7 Ga (Fig. 6).

We interpreted four rim-core age clusters that included all but four grains (Fig. 6). Cluster A is characterized by young (younger than 0.25 Ga) rims on 1.8–1.3 Ga cores. These ages are strongly suggestive of Cordilleran arc rims on older Yavapai-Mazatzal cores, suggesting a sediment source in the western United States (Fig. 3). These grains are only found in samples from the Sevier retroarc foreland and Laramide intracontinental foreland basins.

Cluster B shows a wide range of core ages (2.1–0.8 Ga) with Neoproterozoic–Paleozoic rims (0.7–0.3 Ga). These grains are dominantly found in samples that contain large Grenville, Appalachian, and peri-Gondwanan age populations (Fig. 5). We interpret these data to represent Appalachian and/or peri-Gondwanan rims on midcontinent, Grenville, or older cores. These grains are consistent with an origin in southeastern Laurentia (Fig. 3).

Cluster C contains 1.2–0.8 Ga rims on 1.7–1.3 Ga cores. Grains in this category are only found in Upper Jurassic Morrison Formation, Lower Cretaceous Dakota Group, and the uppermost Cretaceous–Paleogene synorogenic samples. These grains could represent either (1) Pikes Peak batholith rims on ca. 1.45 Ga Mesoproterozoic units found locally in the southern Front Range, or (2) Grenville-aged rims on midcontinent cores. These grains could be originally derived from either eastern Laurentia or locally from the southern Front Range.

Cluster D contains a small number of 1.7–1.35 Ga rims on slightly older 1.85–1.65 Ga cores (Fig. 6). Such ages are widespread in the Yavapai-Mazatzal Provinces, and therefore these grains are interpreted to have originated in southwestern Laurentia (Fig. 3). This interpretation is consistent with this cluster being present in the western-derived Fox Hills Sandstone and locally derived synorogenic samples.

Detrital Zircon Samples

Sawatch Formation (Upper Cambrian)

Two samples from the Upper Cambrian Sawatch Formation (CSGU and CSWC) showed entirely Paleoproterozoic to Mesoproterozoic zircon that ranged in age from ca. 1.83–1.32 Ga, with major age peaks at 1.44 Ga and 1.71–1.70 Ga (Fig. 5; Siddoway and Gehrels, 2014). The youngest detrital zircons are much older than the depositional age of both samples, resulting in long lag times (>846 m.y.; Fig. 7; Table 2).

The dominance of age peaks at 1.44 Ga and ca. 1.70 Ga suggests that the Sawatch Formation was derived broadly from the local Yavapai-Mazatzal basement framework of the southwestern United States (ca. 1.8–1.6 Ga) and from associated 1.45 Ga Mesoproterozoic intrusions (Figs. 3 and 4; Nyman et al., 1994; Karlstrom and Williams, 2005). Similar age peaks are found in the Lower-Middle Cambrian Tapeats Sandstone and Bright Angel Shale in the Grand Canyon (Fig. 8), units that are also interpreted as derived from the Yavapai-Mazatzal Provinces (Gehrels et al., 2011). Although the Sawatch Formation was deposited unconformably on the Pikes Peak batholith (Siddoway and Gehrels, 2014), both samples lack any zircon of the same age as the batholith (ca. 1.08 Ga; Fig. 4; Smith et al., 1999). Thus, we infer that the dominance of Yavapai-Mazatzal ages indicates local derivation from the southwestern United States, but likely not from the immediate vicinity of the present-day southern Front Range.

Harding Sandstone (Middle Ordovician)

A single sample from the Middle Ordovician Harding Sandstone (HARD-13) is dominated by Archean and Paleoproterozoic
detrital zircon (92%) with major age peaks at 2.72 Ga and 1.85 Ga (Fig. 5; Siddoway and Gehrels, 2014). A less abundant population of 1.48–1.38 Ga zircon (7%) and a single grain age of 1.14 ± 0.055 Ga are also present. The lag time based on the YSG is 679 m.y. and increases to 921 or 960 m.y. if the YC1σ(2+) or YC2σ(3+) metrics are used, respectively (Fig. 7; Table 2).

The abundance of Archean and Paleoproterozoic zircon in the Harding Sandstone is unique relative to all other samples from central Colorado (Figs. 5 and 9), but it is similar to other Ordovician samples from the western North America passive margin, which tend to have unique detrital zircon age distributions relative to underlying and overlying units (Gehrels and Pecha, 2014; Siddoway and Gehrels, 2014). For example, HARD-13 contains similar age peaks and age population proportions to the age-equivalent Eureka Springs Quartzite (Middle–Upper Ordovician) deposited in southern Nevada (Fig. 8; Workman, 2012). The dominant age peak of 1.85 Ga is older than the Yavapai orogeny, but it could have been derived from sediment sources farther to the north (e.g., the Peace River arch region, 2.3–1.8 Ga, and Trans-Hudson Province, 1.9–1.8 Ga) or northeast (Penokean Province, ca. 1.85 Ga; Fig. 3; Dickinson and Gehrels, 2009b; Gehrels and Pecha, 2014). A northern or northeastern sediment source is also suggested by abundant late Archean zircon (ca. 2.8–2.6 Ga; Fig. 5), which could have been supplied from the Superior and/or Wyoming Provinces (Fig. 3). Paleogeographic reconstructions of Blakey (2011) depict distant, nonmarine highlands to the northwest (Peace River arch) and northeast (Penokean and Superior Provinces), supporting the interpretation that sediment was supplied from one or both of these regions (Gehrels and Pecha, 2014).

**Williams Canyon Formation (Upper Devonian)**

A sample from the Upper Devonian Williams Canyon Formation (BLACY-13) displays a much broader age spectrum than older samples, and it is the stratigraphically lowest sample in central Colorado to contain abundant Grenville (40%) and Paleozoic (15%) zircon (Fig. 5; Siddoway and Gehrels, 2014). Major age peaks occur at 1.36, 1.08, and 0.44 Ga (Fig. 5). Calculated lag times for this sample range from 22.9 m.y. (YSG) to 62.1 m.y. (YC1σ[2+] or YC2σ[3+]; Fig. 7; Table 2), which are much lower durations than underlying samples.

The presence of Paleozoic- and Grenville-age peaks suggests a provenance shift toward source regions in southeastern Laurentia, where Grenville and Appalachian provinces are present (Fig. 3). The age range of the dominant Paleozoic population (ca. 463–405 Ma) overlaps specifically with the Taconic orogeny of the Appalachian Mountain region and is notably narrower than that found in overlying samples, which tend to have a broad Neoproterozoic–Paleozoic age population (ca. 725–300 Ma; Fig. 5). The 1.36 Ga peak is younger than the 1.45 Ga Mesoproterozoic peak typical of intrusions within the Yavapai-Mazatzal Provinces (Fig. 5). Instead, we suspect that the Mesoproterozoic zircon within sample BLACY-13 may be derived from the 1.5–1.35 Ga midcontinent region (Fig. 3; Dickinson and Gehrels, 2009b), which is more consistent with an eastern sediment source that also accounts for Appalachian and Grenville age populations (Fig. 3).
Figure 8. Comparison of detrital zircon U-Pb ages from central Colorado with those from Colorado Plateau and adjacent areas (see Table DR3 for a complete list of samples and data sources [text footnote 1]). Distributions are shown as normalized kernel density estimates (bandwidth of 10 m.y.; Sharman et al., 2018). (A) Uinta–Piceance Creek basin (Davis et al., 2009, 2010; Dickinson et al., 2012; Foreman et al., 2012); (B) Straight Cliffs Formation of the Kaiparowits Plateau (Szwarc et al., 2015); (C) Morrison Formation (Dickinson and Gehrels, 2008a); (D) Permian of the Grand Canyon (Gehrels et al., 2011); (E) Pennsylvanian to Lower Permian of the Grand Canyon (Gehrels et al., 2011); (F) Devonian of the Grand Canyon (Gehrels et al., 2011); (G) the Ordovician Eureka Quartzite of southern Nevada (Workman, 2012); and (H) the Lower-Middle Cambrian of the Grand Canyon (Gehrels et al., 2011). Pie diagrams show the proportions of age populations within each sample (see Fig. 5 for color key). Number of samples and number of analyses are shown in parentheses.

Figure 9. Multidimensional scaling plots of detrital zircon samples from central Colorado. (A) All samples shown in Figure 5. (B) Subset of samples (see dashed rectangle in A). Dark black arrows indicate stratigraphic-up section for the synorogenic Cretaceous–Paleogene samples. Pie diagrams show the proportions of age populations within each sample (see Fig. 5 for color key). Gray shading indicates interpreted source area regions. Plots generated using detritalPy (Sharman et al., 2018).
The major provenance transition observed in the Upper Devonian Williams Canyon Formation is also observed in the Grand Canyon, but not until Mississippian time (Surprise Canyon Formation; Gehrels et al., 2011). In contrast to central Colorado, Middle–Upper Devonian units in the Grand Canyon (Temple Butte Formation) display age spectra that are more consistent with a dominant source from the local Yavapai-Mazatzal Provinces (Fig. 8; Gehrels et al., 2011).

**Fountain Formation (Pennsylvanian–Lower Permian)**

A sample from the basal portion of the Lower Pennsylvanian Fountain Formation (Glen Eyrie Member; MSGE313) is dominated by 1.8–1.3 Ga zircon (70%) with major age peaks at 1.71 Ga and 1.45 Ga (Fig. 5; Siddoway and Gehrels, 2014). Lesser abundances of 1.22–1.03 Ga zircon (~20%) are also present. A second sample (DB-FF-03) from the coarse-grained, arkosic portion of the formation displays a unimodal age peak of 1.45 Ga with 84% of all analyses falling between 1.55 and 1.4 Ga (Fig. 5). The single youngest analyses within DB-FF-03 and MSGE313 display lag times of 22.9 and 243.7 m.y., respectively. However, lag time calculations based on YC1σ(2+) or YC2σ(3+) metrics are of longer duration (737–1126 m.y.; Fig. 7; Table 2).

As with the Upper Cambrian Sawatch Formation, both Fountain Formation samples are dominated by peak ages (ca. 1.70–1.72 and Ga 1.44 Ga) typically associated with the Yavapai-Mazatzal Provinces (Figs. 3 and 9). The dominance of the 1.45 Ga peak in sample DB-FF-03 may reflect local derivation from a Mesoproterozoic intrusion that is in close proximity to the sample site (Fig. 4; Howard, 1966). Sample MSGE313 (Glen Eyrie Member) displays a much more pronounced 1.71 Ga peak and a subdued 1.45 Ga peak relative to DB-FF-03. These age peaks are also consistent with derivation from local exposures of Yavapai-Mazatzal basement. It is not clear whether the Grenville age population (ca. 1.22–1.03) in the Glen Eyrie Member represents recycled Grenville sources or first-cycle erosion of the local Pikes Peak batholith (ca. 1.08 Ga; Smith et al., 1999). The latter interpretation is supported by the observation that zircon derived from the main Grenville orogenic belt to the southeast is typically associated with Appalachian zircon, which is scarce in sample MSGE313 (Figs. 3 and 5). The Fountain Formation samples thus are consistent with previous interpretations of a local sediment source (e.g., Howard, 1966), associated with the uplift of the Ancestral Rocky Mountains (Fig. 9; Kluth and Coney, 1981).

**Lyons Sandstone (Middle Permian)**

A sample from the eolian Lyons Sandstone of Middle Permian age (DB-LS-02) contains a wide range of age peaks and populations, including major groupings at 2.85–2.65 Ga (11%), 1.95–1.50 Ga (27%), 1.4–1.26 (8%), 1.20–0.94 Ga (25%), and 675–335 Ma (24%). The calculated lag time based on the YSG is 39.9 m.y., but this increases to 61.4–70.1 m.y. if YC1σ(2+) or YC2σ(3+) metrics are used, respectively (Fig. 7; Table 2).

The Lyons Sandstone sample displays a similar detrital zircon age spectrum to Permian units within the Grand Canyon that are interpreted to be derived primarily from distant sources to the east, including the Appalachian and/or Ouachita orogenies (Fig. 8; Gehrels et al., 2011). Archean grains (ca. 2.85–2.65 Ga) are more abundant in the Lyons Sandstone than in either the Grand Canyon or the Permian Appalachian basin (Gehrels et al., 2011), suggesting additional sediment contribution from Archean basement to the north or northeast (Fig. 3). The Lyons Sandstone thus records a major provenance shift from the local Yavapai-Mazatzal Provinces, which are the dominant sediment sources for the underlying Fountain Formation, to distant sources in the east and north. A similar provenance change is observed in the Paradox Basin during Early Permian time, where locally sourced, fluvial units of the Cutler Group are overlain by distantly sourced eolianites (Lawton et al., 2015).

**Morrison Formation (Upper Jurassic)**

A sample from the Upper Jurassic Morrison Formation (DB-MF-03) displays broadly similar detrital zircon ages to the underlying Lyons Sandstone sample, with the exception of fewer Archean grains and a small population (6%) of ca. 169–150 Ma zircon (peak age of 155 Ma; Fig. 5). The Morrison Formation sample is the stratigraphically lowest in the sample transect to contain lag times that overlap within error of the depositional age range, regardless of which MDA metric is employed (Fig. 7; Table 2).

The similarity of the Morrison Formation age distribution patterns to those from the underlying Lyons Sandstone and older Jurassic eolianites of the Colorado Plateau region suggests a source in southeastern Laurentia, including the Appalachian Mountains (Dickinson and Gehrels, 2009b). However, regional paleocurrents within the Morrison Formation in the Colorado Plateau region show that sediment transport was toward the northeast, with sediment likely recycled from older sedimentary units within the Sevier thrust belt and/or Mogollon Highlands (e.g., Dickinson and Gehrels, 2008a). Our sample is similar to other Morrison Formation samples from the Colorado Plateau (Fig. 6), exclusive of the Westwater Canyon Member, supporting the connection of the Morrison Formation in central Colorado with age-equivalent units to the south and/or southwest (Dickinson and Gehrels, 2008a). The short lag time likely reflects Cordilleran arc activity that supplied contemporaneous zircon to the Morrison fluvial system.

**Dakota Group (Lower Cretaceous)**

A sample from the Lower Cretaceous (Upper Albian) South Platte Formation of the Dakota Group (DB-DF-03) shares many similar age populations to the underlying Morrison Formation and Lyons Sandstone, with major age peaks occurring at 1.62 Ga, 1.09 Ga, 433 Ma, and 109 Ma (Fig. 5). As with the Morrison Formation sample, the calculated lag time of DB-DF-03 is within error of the depositional age of the formation (Fig. 7; Table 2).

Past work on Dakota Group provenance has shown distinct eastern and western sources of sediment deposited around the periphery of the Western Interior Seaway (MacKenzie and
Detrital zircon ages within the Dakota Group of central Colorado are consistent with a western source, with sediment deposited within a deltaic complex along the western margin of the seaway (Weimer and Land, 1972). Sample DB-DF-03 is distinct from four other samples of the Dakota Formation deposited along the eastern margin of the Western Interior Seaway in Nebraska and Kansas that display higher proportions of Grenville- and Appalachian-aged zircon, and that have lower abundances of Cordilleran arc and Yavapai-Mazatzal ages (Fig. 10; Finzel, 2014).

**Codell Sandstone (Upper Cretaceous)**

A sample from the Upper Cretaceous (Turonian) Codell Sandstone Member of the Carlile Formation (DB-CS-01) is dominated by a unimodal 98 Ma age peak with 83% of zircon grains yielding ages between 111 and 94 Ma (Fig. 5). This sample contains abundant euhedral zircon and apatite grains. Calculated lag times (2–2.4 m.y.) are slightly older than, but within 2σ analytical error of, the expected depositional age range of the sample (Fig. 7; Table 2).

The abundance of a single age mode in the Codell Sandstone and the euhedral zircon morphology suggest that this sample is dominated by wind-transported, volcanic ash–derived zircon. Our results mirror those of Holm-Denoma et al. (2016), who identified a similar, unimodal 96 Ma peak in a sample of the Codell Sandstone Member. The abundance of ash-derived zircon over fluvial-derived zircon may be related to: (1) the depositional age of the Codell Sandstone Member, which overlaps with a period of high rates of magmatic flux in the Sierra Nevada and Peninsular Ranges volcanic arcs that would have produced numerous volcanic eruptions and provided an abundant source of volcanic ash to the retroarc foreland (Ducea, 2001), and (2) the Codell Sandstone Member accumulating in a relatively distal, marine shelfal setting that may have been starved of fluvial clastic input along the shoreline of the Western Interior Seaway (Weimer and Sonnenberg, 1983; Milito, 2008).

**Fox Hills Sandstone (Upper Cretaceous)**

A sample from the Upper Cretaceous (Maastrichtian) Fox Hills Sandstone (CP-2824) displays several prominent age peaks, including 1.72 Ga, 1.45 Ga, 168–164 Ma, 101 Ma, and 77 Ma (Fig. 5). Zircon grains from 1.81 to 1.62 Ga are particularly abundant (45%), with an additional significant component of zircon younger than 300 Ma (21%). Detrital zircon grains from 1.3 to 0.3 Ga are present in lower abundances (20%) than underlying Cretaceous–Permian units (52%–62%; Fig. 5). A lag time of 4 ± 4.4 m.y. from the YSG is within error of the depositional age of the sample. Lag time calculations based on YC1σ(2+) and YC2σ(3+) are slightly older than the depositional age at 6.8 ± 4.0 m.y. and 7.6 ± 3.8 m.y., respectively (Fig. 7; Table 2).

Detrital zircon ages from the Fox Hills Sandstone sample are broadly consistent with derivation from southwestern Laurentia (Yavapai-Mazatzal and Cordilleran arc provinces). Lesser abundances of Appalachian, peri-Gondwanan, and Grenville ages likely reflect diminished sedimentary recycling of older stratigraphic units relative to the underlying Morrison Formation and Dakota Group. Age peaks and proportions in the Fox Hills Sandstone are similar to the older (Turonian–Santonian) Straight Cliffs Formation, which was deposited in a more proximal position within the Cordilleran retroarc foreland basin (Fig. 6; Szwarc et al., 2015), supporting the interpretation of sediment delivery to the Fox Hills Sandstone from the western United States.

**D1 Sequence (Upper Cretaceous–Lower Paleocene)**

Three samples from the lower, middle, and upper part of the uppermost Cretaceous–Lower Paleocene D1 Sequence (CP-2349, CP-1522, and CP-607) display a number of prominent age peaks, including 1.69 Ga, 1.45–144 Ga, 1.14–1.03 Ga, 419–407 Ma,
108–107 Ma, and 69 Ma (Fig. 5). Sample CP-2349 displays a smaller percentage of 1.3–0.8 Ga zircon (27%) versus the overlying two samples (49%–52%). The opposite trend is observed in 0.8–0.3 Ga zircon, where the abundance decreases upward from 20% to 5%. The lower two samples (CP-2349 and CP-1522) contain major mid-Cretaceous and Jurassic age populations, whereas sample CP-607 contains a prominent latest Cretaceous age peak (69 Ma; Fig. 5). Lag times calculated from the YSG are within error of the depositional age, with the exception of sample CP-1522, which has a single zircon (60.3 ± 1.0 Ma) that is anomalously young for this sample’s latest Cretaceous age assignment. This young grain is slightly discordant (5.5%), perhaps suggesting the occurrence of minor Pb loss (Table DR1 [see footnote 1]). Lag times based on YC1t(2+) and YC2σ(3+) range from 5 to 39 m.y. and are compatible with the expected depositional age of this sample (Fig. 7; Table 2).

All three D1 Sequence samples were deposited within an intracratonic foreland basin associated with uplift of the southern Front Range during the Laramide orogeny (Raynolds, 2002; Dechesne et al., 2011). Previous studies have largely interpreted the synorogenic fill of the Denver Basin to have been derived locally from the vicinity of the southern Front Range (Dickinson et al., 1988; Kelley, 2002; Wilson, 2002; Dechesne et al., 2011), and detrital zircon results from the proximal portion of the basin are consistent with this interpretation (Figs. 9 and 11).

We interpret vertical trends in detrital age distributions from the D1 Sequence to reflect unroofing, a process where sediment input from overlying sedimentary cover is gradually reduced relative to sediment input from the underlying crystalline core. The stratigraphic pattern of the Castle Rock Conglomerate (Upper Eocene) strongly suggests that this unit was primarily derived from the local Pikes Peak batholith (Figs. 4 and 9). Although such ages are also widespread along the southeastern margin of Laurentia where the main Grenville orogenic belt developed (Fig. 4), sediment supplied from these regions is typically accompanied by Paleozoic–Neoproterozoic zircon from Appalachian and peri-Gondwanan belts (e.g., Dickinson and Gehrels, 2009b). Small quantities of Paleocene–Eocene and ca. 1.45 Ga zircon in the D2 Sequence samples could also have been supplied locally from Mesoproterozoic intrusive units and from Colorado Mineral Belt volcanic units (Fig. 4). The lack of Yavapai–Mazatzal ages (1.8–1.6 Ga) is somewhat surprising considering the abundance of these units in the southern Front Range (Fig. 4). However, our results are consistent with both interpreted northeast-flowing paleocurrents (Dechesne et al., 2011) and petrographic analysis that indicates primary derivation from plutonic materials and a lack of metamorphic lithic grains (Wilson, 2002), observations that are compatible with primary derivation from the Pikes Peak batholith. Furthermore, the lack of Yavapai–Mazatzal ages may be partly explained by greater zircon fertility of the Pikes Peak batholith relative to surrounding basement units, as suggested by a single sample from the modern South Platte River (see below).

**Castle Rock Conglomerate (Upper Eocene)**

A sample from the uppermost Eocene Castle Rock Conglomerate (DB-CR-01) displays prominent age peaks at 1.76–1.68 Ga, 1.46 Ga, 1.09 Ga, and 37 Ma (Fig. 5). Mesozoic, Paleozoic, Neoproterozoic, and Archaean zircon are conspicuously absent. Zircon grains from 1.2 to 1.0 Ga comprise 43% of the sample, with lesser abundances of 1.56–1.32 Ga (32%) and 1.82–1.65 Ga (9%) zircon. The youngest zircon analyses yield maximum depositional ages of ca. 34.7 ± 0.4 Ma, which are consistent with the stratigraphic position of the Castle Rock Conglomerate overlying the Wall Mountain Tuff (36.7 Ma; Fig. 7; Table 2) and the presence of bones of *Chadronian brontothere*, which went extinct at ca. 35.5 Ma (Evanoff, 2007).

Detrital zircon ages within the Castle Rock Conglomerate support previous interpretations of a source area within the local southern Front Ranges (e.g., Steven et al., 1997). Age populations within the Castle Rock Conglomerate sample suggest that 1.45 Ga Mesoproterozoic intrusions, the 1.08 Ga Pikes Peak batholith, and the volcanic units of the Paleogene Colorado Mineral Belt were within the source area (Figs. 4, 5, and 9). The similarity of this sample with the modern South Platte River sample also supports the interpretation of a local sediment source area (Figs. 5 and 9).

**South Platte River (Modern)**

A sand sample from the modern South Platte River (DB-SPR-01) displays major age peaks at 1.75 Ga, 1.43 Ga, 1.085 Ga,
Figure 11. Paleogeographic reconstructions of southern North America showing generalized, schematic sediment transport pathways to central Colorado (red circle). Other sediment transport pathways are not depicted. Figure is modified from Lochman-Balk (1972), Mallory (1972), Dickinson and Gehrels (2003), Blakey (2011), and May et al. (2013).
and 67 Ma (Fig. 5). Small numbers of Paleozoic and Upper Neoproterozoic grains are also present (3%). Calculated lag times are >59 m.y. (Fig. 7; Table 2).

The catchment area upstream of sample DB-SPR-01 extends throughout much of the Front Range from Cheyenne, Wyoming, to just north of Colorado Springs (Fig. 4). Major age populations in the South Platte River largely reflect the expected sources in the Front Range, including the Yavapai Province, Mesoproterozoic intrusions, the Pikes Peak batholith, and the uppermost Cretaceous–Paleogene Colorado Mineral Belt (Fig. 4; Reed et al., 2005; Karlstrom and Williams, 2005). The few grains of Paleozoic, late Neoproterozoic, and early Paleoproterozoic age lack a local source, but they could have been recycled from sedimentary units in the foothills of the Front Range (Fig. 5). Although the Pikes Peak batholith only accounts for 18% of the exposed Front Range within the South Platte River catchment (Reed et al., 2005), it comprises ~54% of the detrital zircon analyses (Figs. 4 and 5). This may be driven by higher denudation and/or higher zircon yield within the Pikes Peak batholith relative to surrounding units.

**SUMMARY: SEDIMENT TRANSPORT TO CENTRAL COLORADO**

Detrital zircon U-Pb ages within stratigraphic units of central Colorado reveal evolving sediment transport mechanisms and pathways over the past ~500 m.y. that reflect the tectonic and stratigraphic history of North America (Fig. 11). Central Colorado has been located near the center of southern Laurentia, a distance of at least 1100 km from the boundary of the North American plate, since Cambrian time (Fig. 11). Given the intracontinental position of central Colorado, this region provides a valuable cratonal perspective of sediment transport within and across North America that complements other stratigraphic records from more marginal regions of the continent (e.g., Gehrels et al., 2011; Park et al., 2010; May et al., 2013).

In particular, the stratigraphic record of central Colorado exhibits varying provenance patterns that alternate between sediment derived from local and distant sources. Although the definition of local versus distant sediment sources is subjective, and the boundary between them is gradational, we define local source areas as being within the immediate vicinity of central Colorado, typically within tens to a few hundreds of kilometers from the deposit. We consider distant sediment sources to be regions that are hundreds to thousands of kilometers distant from the deposit, comprising geologic units not present in the immediate vicinity of central Colorado.

Using these criteria, local sediment sources are dominant during three time periods in central Colorado: (1) Late Cambrian time during marine transgression onto a denuded, peneploplane Precambrian landscape, (2) Pennsylvanian–Early Permian time during the Ancestral Rocky Mountain orogeny, and (3) latest Cretaceous–Cenozoic time during and after the Laramide orogeny and formation of the Denver Basin. During these time periods, sediment was predominantly transported by alluvial, fluvial, and marine processes from local sources within the Yavapai-Mazatzal Provinces (Fig. 11). Although these episodes of locally sourced sediment deposition only account for 25% or less of the total span of geologic time since the late Cambrian, they constitute ~42% of the stratigraphic thickness in the region. This disproportionate representation of locally derived sediment is likely a function of increased accommodation during foreland basin development that promoted sediment production from local basement uplifts (i.e., Ancestral and modern Rocky Mountain uplifts).

Distant sediment sources were dominant during two time periods in central Colorado: (1) Ordovician–Mississippian time, when sediment was transported from distant sources in the north and east (Figs. 11B–11C), and (2) Permian–Late Cretaceous time, when sediment was transported from sources far to the east, southwest, and/or west (Figs. 11E–11G). Sediment transport mechanisms during this time were varied and included fluvial, marine, and eolian processes, including windblown volcanic ash produced from distant volcanic eruptions of the mid-Cretaceous Cordilleran arc.

During all time periods, the source of sediment supplied to central Colorado corresponds to the locus of active mountain building and the creation of topography, highlighting the importance of high-relief, tectonically active sediment sources that dominate sediment dispersal patterns. With the exception of the initial Cambrian transgressive deposits, locally derived sediment is associated with local mountain-building events of the Ancestral and modern Rocky Mountains. Distant sediment sources correspond with mountain building in either the Appalachian (predominantly Paleozoic) or western Cordillera orogenic belts (predominantly Mesozoic; Fig. 11). Rivers and wind would have carried large volumes of sediment away from these mountain belts, some of which was transported through and deposited within central Colorado (Fig. 11).

The shift from transcontinental sediment transport from Appalachian to western Cordilleran sources occurred between Permian and Jurassic time (Fig. 11). Despite the fundamental importance of this change, variations in detrital zircon U-Pb age distributions across this transition are subtle. For example, the western-derived Upper Jurassic Morrison Formation contains many of the same age populations as the underlying Appalachian-derived Lyons Sandstone (Figs. 5 and 9). The lack of a pronounced change likely reflects a significant component of sediment recycling of older units that were sourced from southeastern Laurentia and subsequently uplifted and eroded within the western Cordillera (Dickinson and Gehrels, 2008a).

A comparison of lag time versus depositional age reveals that samples as old as Devonian contain at least a single grain that overlaps within error of the depositional age range of the sample, whereas Cambrian and Ordovician samples have lag times of many hundreds of millions of years (Fig. 7; Table 2). A similar pattern was observed in samples from the Grand Canyon, where shortened lag times in Devonian–Permian strata were interpreted to reflect increased rates of source area exhumation during the
Appalachian orogeny (Gehrels et al., 2011). The short lag times found in Jurassic–Eocene samples (average of 1.4 m.y. based on the YSG; Fig. 7) are likely related to contemporaneous Cordilleran arc magmatism during deposition of these samples. The YSG is compatible with depositional age estimates for all samples, with the exception of CP-1522, in which the youngest analysis may have been influenced by Pb loss. The youngest sample analyzed (the modern South Platte River) shows an increase in lag time relative to underlying samples (Fig. 7), likely reflecting a lack of igneous activity younger than the Colorado Mineral Belt in the vicinity of the southern Front Range (Fig. 4).

LOCAL-TO-DISTANT PROVENANCE CYCLES

The alternation between local and distant sediment sources to central Colorado is suggestive of cyclic variations between local and distant provenance episodes. We speculate that two complete local-to-distant provenance cycles and one partial cycle are preserved in the sedimentary record of the southern Front Range (Fig. 2). The first cycle is stratigraphically thin (~250 m thick), yet it accounts for approximately a third of all geologic time since sedimentation began in late Cambrian time (Figs. 2 and 11A). The local provenance of the Upper Cambrian Sawatch Formation, as with other basal Cambrian sandstones that directly overlie the Great Unconformity, likely reflects reworking of local sources of deeply weathered Precambrian basement (Fig. 11A; e.g., Gehrels et al., 2011; May et al., 2013; Siddoway and Gehrels, 2014). However, following initial marine transgression, detrital zircon age distributions suggest sediment transport from sources that lay far to the northeast and east (Figs. 11B–11C).

The second provenance cycle initiated with locally supplied sediment derived from erosion of the Ancestral Rocky Mountains that transitioned to sediment derived from distant sources in both eastern and western North America (Figs. 2 and 11D–11G). Unlike the first provenance cycle, which appears to have been initiated in response to regional marine transgression, the second provenance cycle initiated due to far-field convergent tectonism likely related to the assembly of Pangea (Kluth and Coney, 1981). This cycle accounts for ~50% of the geologic time and 78% of the stratigraphic thickness within the entire composite stratigraphic section of the southern Front Range (Fig. 5).

The third and final provenance cycle initiated with locally supplied sediment from the uplifted southern Front Range during the Laramide orogeny and continued during postorogenic uplift and exhumation of the region (Figs. 2 and 11H). The initiation of this provenance cycle had a similar underlying cause to the preceding cycle, i.e., far-field tectonism associated with the convergent margin of North America (Saleeby, 2003). Presumably, eventual erosion and leveling of the central Rocky Mountains will result in a more extensive drainage network that will again deliver sediment from distant sources to central Colorado. This may have already occurred during and after late Eocene time with the development of the Rocky Mountain erosion surface that accompanied healing of Laramide topography (Epis and Chapin, 1975). However, the depositional record of this episode is missing near the southern Front Range and adjacent Denver Basin, obscuring the history of Oligocene–Miocene sediment transport to this region (Fig. 5).

May et al. (2013) defined four major tectonostratigraphic assemblages (TSA) that characterize the Phanerozoic sedimentary succession of the Bighorn Basin in northwest Wyoming (Figs. 1 and 2), each characterized by a distinctive, first-order detrital zircon U-Pb age pattern. Although the southern Front Range is located some 700 km from the Bighorn Basin, the same general tectonostratigraphic assemblages are broadly applicable to the stratigraphic record of central Colorado (Fig. 2). One notable exception is that the Bighorn Basin lacks synorogenic sediments associated with the Ancestral Rocky Mountain orogeny that are present in central Colorado (i.e., Fountain Formation; Fig. 2).

Figure 12 presents a comparison of detrital zircon U-Pb ages from each of the four tectonostratigraphic assemblages defined by May et al. (2013). Tectonostratigraphic assemblages interpreted to be characterized by distant sediment sources show a remarkable, first-order similarity (Fig. 12). This includes TSA1 (excluding locally derived Cambrian and synorogenic sandstone) and TSA2–TSA3, which are characterized by passive-margin and transitional/retroarc foreland basin settings, respectively (Fig. 12). The correspondence of detrital age distributions between the Bighorn Basin and central Colorado during these episodes is consistent with regionally extensive sediment transport patterns across much of the central North American craton (Fig. 11).

Episodes of local provenance, including the Cambrian deposits of TSA1 and synorogenic sediments associated with the Ancestral and modern Rocky Mountains (a portion of TSA1 and all of TSA4) show a remarkable dissimilarity between the Bighorn Basin and central Colorado (Fig. 12). Locally derived sandstone of TSA1 reflects the age of underlying basement, which is older in the vicinity of the Bighorn Basin (Archean Wyoming Province) than in the vicinity of the southern Front Range (Yavapai Province; Figs. 3 and 4). Locally derived units of TSA4 are interpreted to reflect recycling of older sedimentary units in the vicinity of the Bighorn Basin (May et al., 2013), whereas TSA4 units in central Colorado show a prominent Pikes Peak batholith signature, reflecting first-cycle erosion of local basement (Fig. 12). Unsurprisingly, comparison of the Bighorn Basin with central Colorado suggests that episodes characterized by local sediment sources produce detrital age distributions that may not be correlated over long distances.

We propose that provenance cyclicity between local-to-distant sediment source episodes may be a pattern that can be recognized globally in other sedimentary successions, yielding insight into changing drainage boundaries that reflect the tectonic and paleogeographic evolution of a region. The change from local to distant sediment sources has been documented as an important signal of changing boundary conditions in a number of systems, including: (1) the Cretaceous–Paleogene forearc of southern California, which records provenance changes associated with
Figure 12. Comparison of detrital zircon U-Pb ages from central (C.) Colorado with those from Bighorn Basin, grouped by the tectonostratigraphic assemblages (TSA) defined by May et al. (2013). Bighorn Basin data are from May et al. (2013). Pie diagrams show proportions of age populations within each sample (see Fig. 5 for color key). Number of samples and number of analyses are shown in parentheses.
subduction of an oceanic plateau (Jacobson et al., 2011; Sharman et al., 2015), (2) Miocene–Pliocene sediments of the Salton Trough of southern California, which record the integration of the Colorado River drainage (Dorsey et al., 2011; Cloos, 2014; Kimbrough et al., 2015), and (3) Upper Cretaceous units within the retroarc foreland Austral Basin of Patagonia, which record a source area shift from the local arc to distant cratonic sources to the north (Malkowski et al., 2017). Although the transition between local and distant sediment sources may signify a tectonic driver (e.g., the initiation of the third provenance cycle during the initiation of the Laramide orogeny; Fig. 2), other mechanisms that influence sediment transport (e.g., eustasy, climate) may also be important factors in controlling provenance cyclicity in sedimentary successions.

Identification of local-to-distant source area cycles has implications for predicting changes in the size of the source area drainage, fluctuating sediment supply and sediment composition, and variable stratal architecture within the system. For instance, source-to-sink systems with long-distance sourced sediment are more likely to have large fluvial catchments, large sediment loads, and large trunk fluvial systems (Somme et al., 2009), particularly if the source area headwaters extend into high-relief mountain belts (Sharman et al., 2017). Such integrated systems are more likely to produce large, offshore submarine canyon-fan systems, some of which host significant petroleum reserves (Carvajal et al., 2009). Ultimately, identifying provenance cyclicity in the geologic record is important for understanding both the tectonic and paleogeographic evolution of a region and for predicting down-system and up-system sedimentary systems and depositional architectures.

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Local-to-distant provenance cyclicity of the southern Front Range


