Provenance of the upper Eocene Castle Rock Conglomerate, south Denver Basin, Colorado, U.S.A.

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ABSTRACT

The Castle Rock Conglomerate contains distinctive clasts from the Colorado Front Range, and when combined with detrital zircon ages, the unit can be subdivided into two lithofacies. Precambrian quartzites and stretched-pebble conglomerates from Coal Creek Canyon (to the northwest of the Castle Rock Conglomerate outcrop belt) and detrital zircons from Precambrian and Tertiary igneous rocks identify a northern provenance with detritus derived from tens of kilometers northwest of Denver, Colorado. A second source, composed of mainly granite from the Pikes Peak batholith, lies in the southern Front Range west of the Castle Rock Conglomerate outcrop belt. Both the north and west lithofacies can be mapped in the Castle Rock Conglomerate outcrop belt by using the presence (north) and absence (west) of Coal Creek Canyon quartzite clasts. This distinction is confirmed by detrital zircon ages. The north lithofacies dominates the present-day, northernmost outcrops, but dilution and interbedding with west lithofacies increase as the southeast-flowing basin axial paleodrainage meets piedmont tributaries that carried Pikes Peak batholith detritus from the west and southwest. The basin axial drainage transported coarse conglomerate southward about 120 km during Castle Rock Conglomerate deposition (36.7–34.0 Ma). The Precambrian quartzite exposed in Coal Creek Canyon is interpreted to be an important point source that can be useful in provenance studies of sediments shed from the Colorado Front Range. Additionally, detrital zircons from Laramide-age igneous rocks show potential for improved stratigraphic resolution in Paleogene strata of the Denver Basin.

KEY WORDS: Castle Rock Conglomerate, Colorado, Denver Basin, detrital zircon geochronology, late Eocene, provenance, upper Eocene.

INTRODUCTION

The Castle Rock Conglomerate (**Tcr**) forms a southeast-trending belt of outcrops that cap many mesas and fill paleovalley lows from the northern part of Douglas County into Elbert and El Paso counties, Colorado (Fig. 1). The formation has been of interest beginning with early gold exploration (Gabriel, 1933), and it is found as far south as Calhan, Colorado, in exposures near Paint Mines Interpretive Park (Fig. 1). Although geologists have examined the conglomerate since before Richardson (1915) named it, the detailed provenance has been elusive. All authors agree that the uplifted Front Range is the source area (Richardson, 1915; Morse, 1979, 1985; Keller and Morgan, 2016). Without examining and identifying the composition of the clasts over the whole deposit, however, it is difficult to determine which part of the Front Range contributed the coarse detritus. Additionally, missing eroded strata north of the preserved outcrops of the **Tcr** and a Neogene reversal of basin axial drainage from southward to northward flow (Cole and Braddock, 2009) have complicated interpretations of the provenance. Using new stratigraphic information, detailed petrographic interpretation, and zircon laser-ablation geochronology, we reevaluate the provenance of the **Tcr** and provide new understanding of the late Eocene evolution of the Denver Basin.

GEOLOGIC SETTING

Richardson (1915) named the Castle Rock Conglomerate (**Tcr**) after a prominent butte named Castle Rock (now Rock Park) in the city of Castle Rock, Colorado (Fig. 2). The formation is characterized by its coarse grain size, arkosic composition, large-scale cross-stratification (commonly meters in width and up to tens of meters in length, referred to hereafter as megatrough cross-strata), and angular clasts of rhyolite interpreted to be derived from the 36.7-Ma Wall Mountain Tuff (Morse, 1985; Keller and Morgan, 2017). Occurrence of clasts of the Wall Mountain Tuff and late Eocene *Brontothere* remains (extinct after 34.0 Ma; Prothero, 2017) bracket deposition of the **Tcr** between 36.7 and 34.0 Ma. Beneath the Wall Mountain Tuff is the middle to upper Eocene Larkspur conglomerate after Thorson (2011), which does not contain clasts of Wall Mountain Tuff (Fig. 1).

Understanding of the provenance of the **Tcr** has been based on the occurrence of distinctive blue-gray quartzite clasts in some outcrops. Gabriel (1933), who was looking for the source of placer

Rocky Mountain Geology, June 2018, v. 53, no. 1, p. 29–43, doi:10.24872/rmgjournal.53.1.29, 8 figs., 1 table, 1 appendix supplemental file
Received 19 January 2018 • Revised Submitted 2 April 2018 • Accepted 3 April 2018 • Published online June 2018

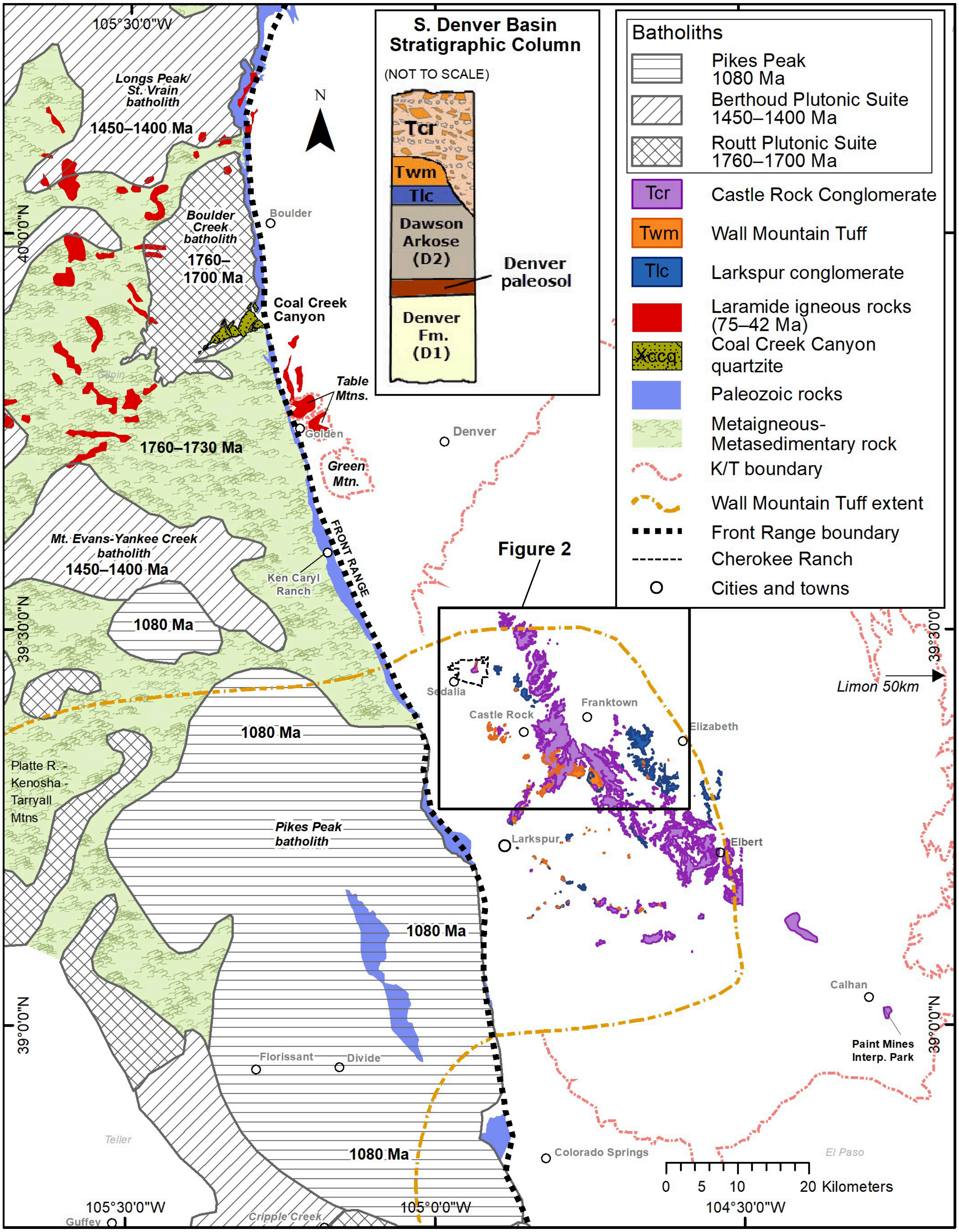

Figure 1. Map of the **Tcr**, Wall Mountain Tuff, and Larkspur conglomerate outcrops in the south Denver Basin (Thorson, 2011) and key plutonic rocks of their Front Range provenance (Sims et al., 2001). Laramide igneous rocks are from Larson, 2004. Note the location of Coal Creek Canyon and Calhan, at opposite ends of the Castle Rock Conglomerate outcrop belt.

gold discovered in Douglas County, examined the rock type and petrography of clasts within the **Tcr.** He favored a provenance "north and west of Denver" mainly on the basis of the presence of the quartzite that he described as "identical" to Precambrian quartzite exposed in Coal Creek Canyon. Morse (1979, 1985) did not note the quartzite clasts, but described the paleogeography of the Wall Mountain Tuff and **Tcr**, concluding that the conglomerate was derived from the west and northwest, transported by an ancestral Platte River that drained a terrain dominated by the Pikes Peak Granite. Evanoff (2007) supported a northern provenance based on the quartzite and stretched-pebble quartzite metaconglomerate, both from Coal Creek Canyon, 50 km to the northwest. In recognition of both the quartzite and Wall Mountain Tuff clasts, Abbott and Cook (2012) believed that the main provenance was to the west with sediment transported by the paleo-Platte River, with a tributary from the north to explain the blue-gray quartzite. Morgan et al. (2013) proposed multiple sources for the quartzite clasts and hypothesized that there was a southwestern source for these rock types, but did not specifically identify the location of that source. Most recently, Keller and Morgan (2016, 2017) identified north- and northeast-draining tributaries to the southeast-trending main paleochannel and reported: "There is no evidence as yet linking this quartzite (blue-gray quartzite in the **Tcr**) to sources other than Coal Creek Canyon."

Complicating the interpretations of provenance of the **Tcr**, during the late Eocene the axial drainage of the Denver Basin flowed southeasterly rather than northeast as it does today (Keller and Morgan, 2013). Paleocurrent directions measured in the **Tcr** by Keller and Morgan (2013, 2016, 2017) reveal a main paleochannel with south–southeast flow and tributary channels that flowed northeast. Today, after probable middle Miocene uplift of the southern Denver Basin and the Front Range (Cole and Braddock, 2009; Cather et al., 2012), the main **Tcr** paleochannel parallels Cherry Creek (flowing north; Fig. 2). Outcrops within the main channel are about 260 m higher 64 km to the southeast in El Paso County than they are in the northernmost outcrops in Douglas County (this mea-

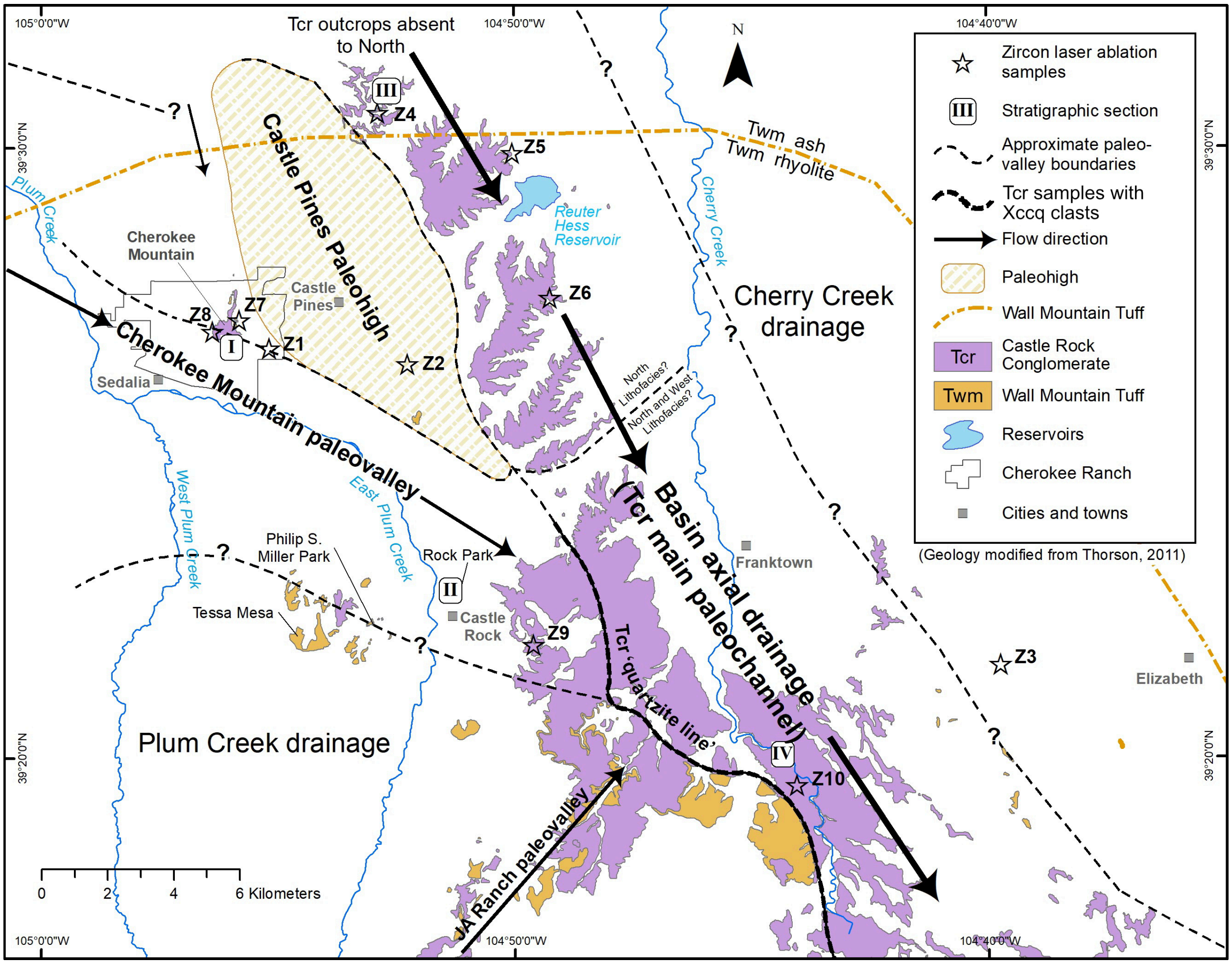

Figure 2. Map of **Tcr** and Wall Mountain Tuff showing location of the inferred **Tcr** main paleochannel, Cherokee Mountain paleovalley, JA Ranch paleovalley, and Castle Pines paleohigh. Stars show locations of geochronology samples Z1–Z10. Roman numerals I–IV show stratigraphic section locations.

surement agrees closely with Keller and Morgan, 2016, 2017), reflecting the post-**Tcr** rotation of the southern Denver Basin.

POTENTIAL SOURCES OF CLASTS AND ZIRCONS IN THE CASTLE ROCK CONGLOMERATE

In order to clarify provenance of the **Tcr**, we outline petrographic and age characteristics of the likely (and previously identified) sources. Figure 3 shows pictures of **Tcr** and quartzite of Coal Creek Canyon (**Xccq**) outcrops and clasts, which are discussed in detail below.

Precambrian Quartzite of Coal Creek Canyon

Quartzite of Coal Creek Canyon (**Xccq**) is exposed as part of a complex of Precambrian (1760–1730 Ma) metamorphic rocks that crop out south of the Boulder Creek batholith in the Front Range (Fig. 1, Fig. 3*A*). Between 1,370 m and 2,560 m of Precambrian quartzite within Coal Creek Canyon are mapped over about 72 km^2 (Wells et al., 1964; Wells, 1967; Fig. 1 this paper), in four stratigraphic quartzite units (lowermost "A" through uppermost "D") separated by layers of schist. Although the quartzite has multiple colors, the C unit is largely gray quartzite (Fig. 3*B*), as much as 1,000 m thick. **Xccq** was originally proposed as a source for the **Tcr** quartzite by Gabriel (1933). The term "bluish-gray" in reference to this quartzite was first used by Evanoff (2007).

Xccq contains upper amphibolite facies metamorphic minerals: andalusite, sillimanite, garnet, muscovite, and biotite with andalusite particularly common in the gray (blue-gray) quartzite of the C unit (Wells, 1967). Wells et al. (1964) describe the quartzite as generally well foliated, fine to coarse-grained, and interlayered with lenses of conglomerate. Although Wells (1967) described some surfaces of cataclastic shear, most of the quartzites sampled in the main channel of the **Tcr** in this study (Fig. 4) are recrystallized quartz with irregular (sutured) boundaries, highly foliated, with grain-size reduced fabrics, probably a result of crystal-plastic deformation.

Pebble conglomerate is interlayered within the thick (600 m) quartzites of the D unit (Wells et al., 1964). The conglomerate contains clasts of quartzite that are rounded and equidimensional to oval, some flat. Most pebbles lie parallel to bedding, but sparse groups are inclined 20 degrees suggesting imbricate structure (Wells et al., 1964). Evanoff (2007) later interpreted this rock as a stretched-pebble metaconglomerate. The distinctive stretched fabric, quartzite pebbles, and matrix of the conglomerate (Fig. 3*C*) are not described anywhere along the Front Range except within Coal Creek Canyon.

Precambrian Plutons

Three Precambrian plutonic suites cut the metamorphic rocks exposed along the eastern Front Range (Kellogg et al., 2008; Fig. 1 this paper). The oldest is the Routt plutonic suite (1760–1700 Ma), which crops out north of Coal Creek Canyon as the Boulder Creek batholith, and farther south, to the west of the Pikes Peak batholith in the Platte River, Kenosha, and Tarryall mountains. The Berthoud plutonic suite, including the Longs Peak-Saint Vrain, Silver Plume, and Mount Evans-Yankee Creek batholiths (1450–1400 Ma), is exposed north of the Boulder Creek batholith and between the Boulder Creek and Pikes Peak batholiths to the south (Kellogg et al., 2008). Some intrusive rocks of the Berthoud plutonic suite are present southwest of the Pikes Peak pluton. The youngest and southernmost Precambrian plutonic unit is the 1080-Ma Pikes Peak Granite, which dominates the eastern part of the Front Range southwest of Denver (Kellogg et al., 2008).

Tertiary Igneous Rocks

Tertiary intrusive and volcanic rocks in the Front Range are also potential sources for **Tcr** zircons. Laramide-age (75–42 Ma; Larson, 2004) intrusive rocks are located in the central to northern part of the Front Range, west and northwest of Denver, surrounding the Boulder Creek batholith (Fig. 1). Late Paleogene igneous rocks (40–26 Ma; Larson, 2004) of the Southern Rocky Mountain volcanic field (Lipman, 2007) are exposed in the southern part of the Front Range, mainly west of the Pikes Peak batholith. Occurrence of Wall Mountain Tuff (36.7 Ma) detritus is one of the defining characteristics of the **Tcr**. This tuff is thought to have erupted from the Mount Princeton area of the Colorado Front Range, flowed to the northeast, spilled onto the piedmont, and came to rest in the Castle Rock area (McIntosh and Chapin, 2004). Large (up to 3 m) blocks of the tuff were subsequently incorporated into the **Tcr** (Fig. 3*D–E*). The Larkspur conglomerate that underlies the Wall Mountain Tuff does not contain clasts of the tuff (Thorson, 2011).

METHODS

Field Studies

Documentation of field relations for this study began in 2009 at Cherokee Ranch, near Sedalia (Fig. 2). These **Tcr** exposures are the most westerly and thickest reported in the outcrop belt. Measured sections through the **Tcr** were made at Cherokee Ranch (Section I), Rock Park (Section II), and McArthur Drive (Section III) using a tape measure, a Global Positioning System, and existing maps. A previously measured section (Morse, 1985; Fig. 3*F* this paper) at Castlewood Canyon and Highway 83 was reexamined and modified (Section IV) in Figure 5. Particular attention was paid to the presence or absence of **Xccq** (Coal Creek Canyon quartzite) clasts. Where present, the quartzite was sampled and thin sections made. Sites were carefully selected within the **Tcr** outcrop belt and basin area for detrital zircon sampling.

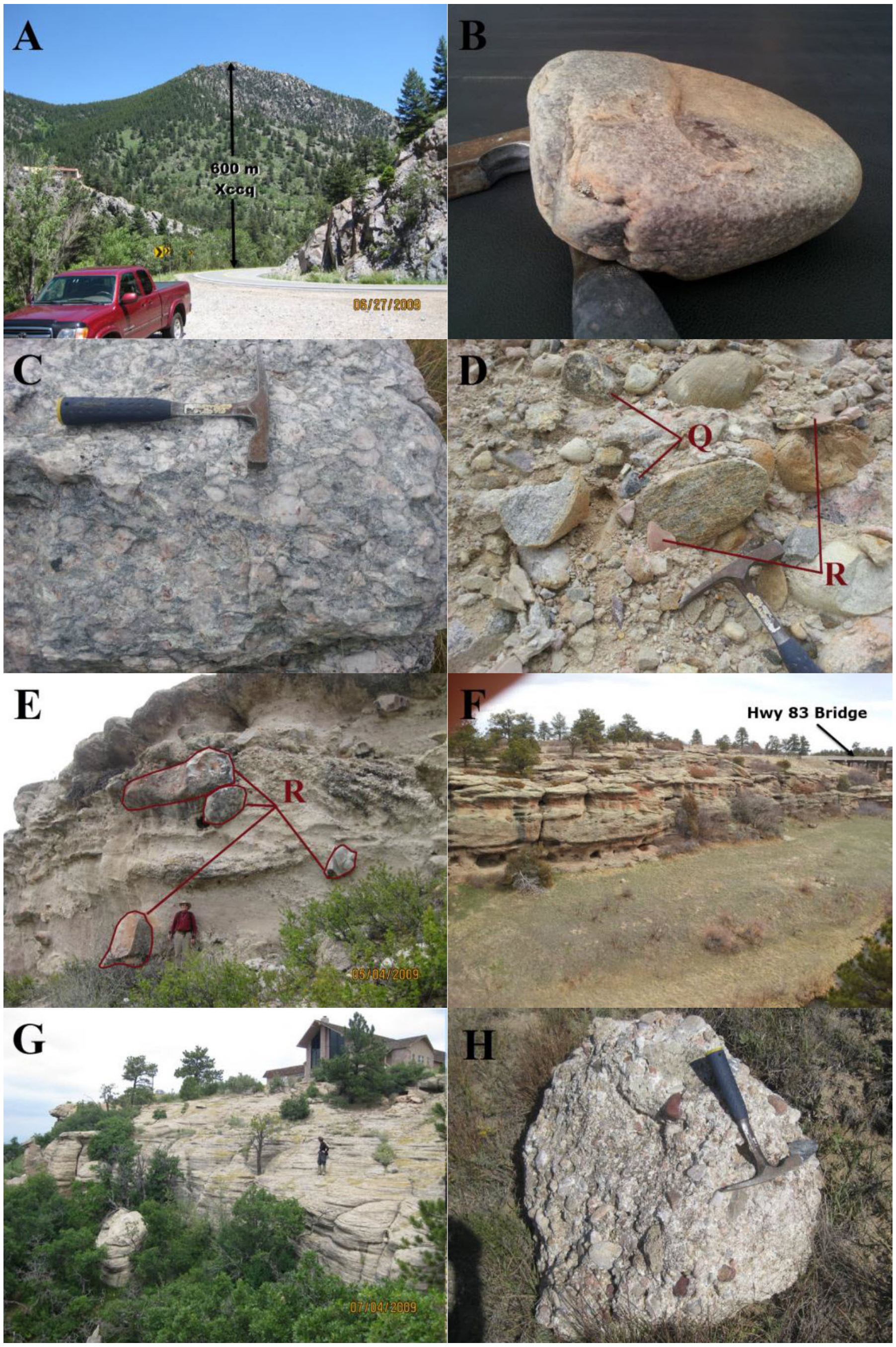

Figure 3. Selected pictures of **Tcr** clasts and outcrops. ***A*,** Outcrops of Proterozoic quartzite (**Xccq**) exposed in Coal Creek Canyon. View is to the north from Highway 72 showing a vertical thickness of 600 m of quartzite. The entire view of Crescent Mountain and the Highway 72 outcrop is of Precambrian quartzite. ***B*,** A typical rounded 160 mm clast of gray (bluish-gray) quartzite from the main channel of the **Tcr**. Note top and base of hammer beneath the clast. ***C*,** Stretched-pebble metaconglomerate at the mouth of Coal Creek Canyon. This distinctive rock type is believed to be unique to Coal Creek Canyon quartzite exposures. ***D*, Tcr** boulder conglomerate exposed on Hess Road near Reuter-Hess Reservoir. Q = **Xccq** (Coal Creek Canyon quartzite) clasts, R = Wall Mountain Tuff rhyolite clasts. Near site of Sample Z5. ***E*,** Outcrop of the **Tcr** rhyolite boulder bed member on the south side of Cherokee Mountain on Cherokee Ranch, viewable from Highway 85 near Sedalia. The largest rhyolite boulder is 1.5 × 3 m. ***F*,** Exposures of **Tcr** at the crossing of Highway 83 and Cherry Creek. Morse (1985) measured 30 m of **Tcr** at this location. North lithofacies containing clasts of **Xccq** are interbedded here with west lithofacies. ***G*, Tcr** horizontally laminated member (9 m thick) exposed south of Highway 86. ***H*,** Boulder of **Tcr** in Paint Mines Interpretive Park, southeast of Calhan. **Tcr** here contains clasts of andalusite-bearing **Xccq**, 120 km from Coal Creek Canyon.

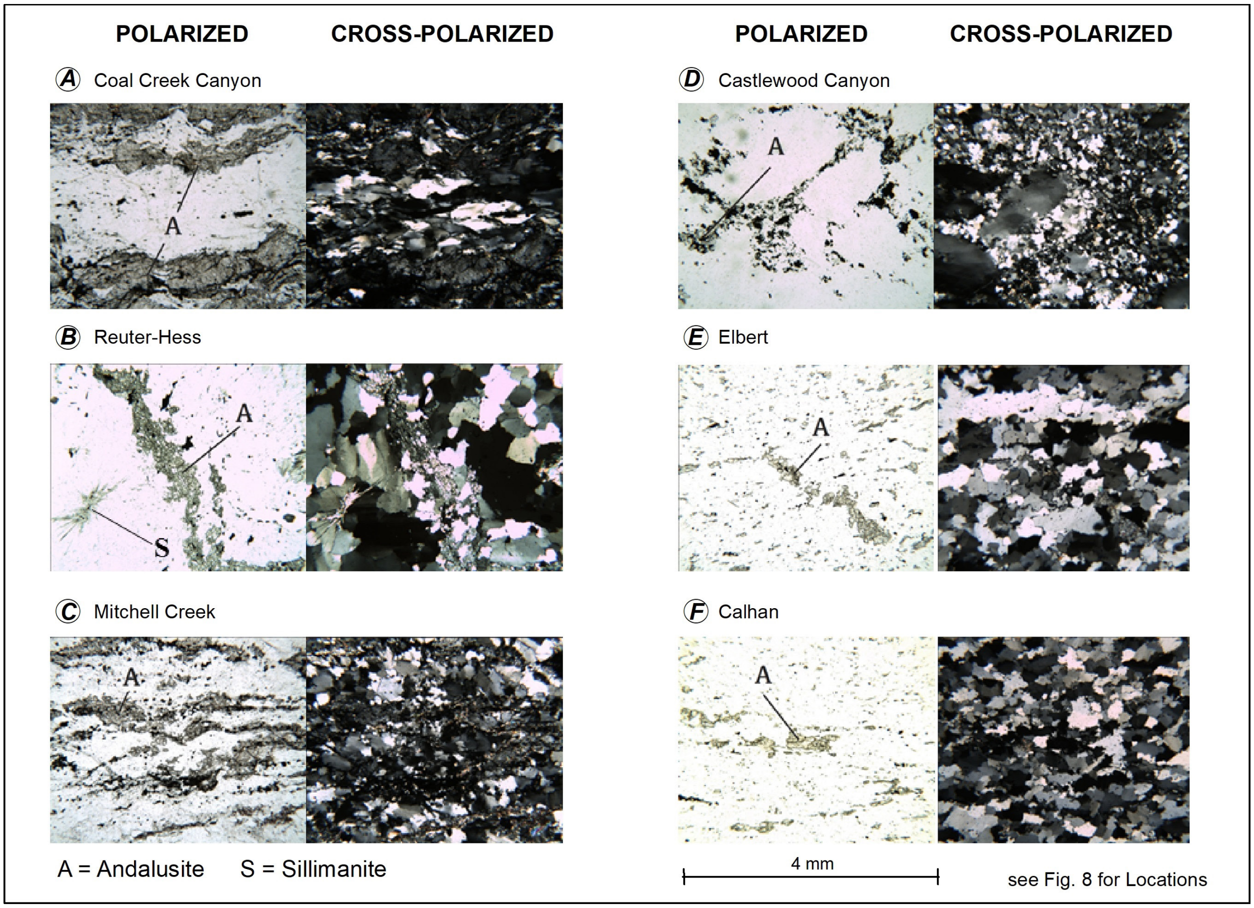

Figure 4. Photomicrographs (***A***–***F***) of quartzite in Coal Creek Canyon and from clasts of quartzite from the main channel, and near Calhan. A = andalusite, S = sillimanite. Locations ***A***–***F*** are shown in Figure 8. Quartzite textures show foliation and recrystallization from crystal-plastic deformation.

Petrography

Thin sections of **Tcr** quartzite clasts were made for comparison with **Xccq** samples collected from Coal Creek Canyon. There are other reported locations of Precambrian quartzite including Ken Caryl Ranch and Cañon City (Blue Ridge), and Paleocene conglomerates of Green Mountain in Jefferson County (Fig. 1). Thin sections of quartzite clasts from these localities were made and examined for mineralogy, metamorphic mineral assemblage, and tectonic fabric using a standard petrographic microscope.

Geochronology

Twelve samples (Fig. 2; Table 1; Appendix 1) were selected for zircon U-Pb geochronology by laser–ablation, inductively coupled plasma–mass spectrometry (LA–ICP–MS). We collected seven samples (Z4–Z10) from the **Tcr**. Five additional samples (Z1–Z3, and Z11–Z12) were taken from older and younger strata. Sample Z1 was taken from the top of the Paleocene Denver Formation (D1; Dechesne et al., 2011) a few feet below the Denver paleosol on Cherokee Ranch. Two samples (Z2 and Z3) were taken from the Larkspur conglomerate. A single sample was taken from the Ogallala Formation near Limon, Colorado (Z11), and a Miocene(?) sandstone at Divide, Colorado (Z12).

Samples were crushed using a jaw crusher and a disc mill. Isolation of zircons was done using standard density (water table and heavy liquids) and magnetic techniques. Nearly pure zircon separates were mounted in epoxy, polished using standard polishing techniques, and mapped by backscattered electron and monochromatic cathodoluminescence imaging on a scanning electron microscope. Analysis by LA–ICP–MS followed protocol outlined in Kylander-Clark et al. (2013). Data were obtained at 4 Hz for 15 to 20 seconds on spot sizes ranging from 15 to 24 μm in diameter and 6 to 8 μm deep. Measurement of isotopic concentrations were completed on a Nu Instruments plasma multi-collector ICP–MS with ^{238}U and ^{232}Th on Faraday detectors and ^{208}Pb, ^{207}Pb, ^{206}Pb, and ^{204}Pb using ion counters. Standard corrections and final isotopic ratios were calculated using Iolite software (Paton et al., 2010) with the 91500 zircon (1065 Ma; Wiedenbeck et al., 2004) as the primary reference material; Plešovice (337 Ma; Sláma et al., 2008) was

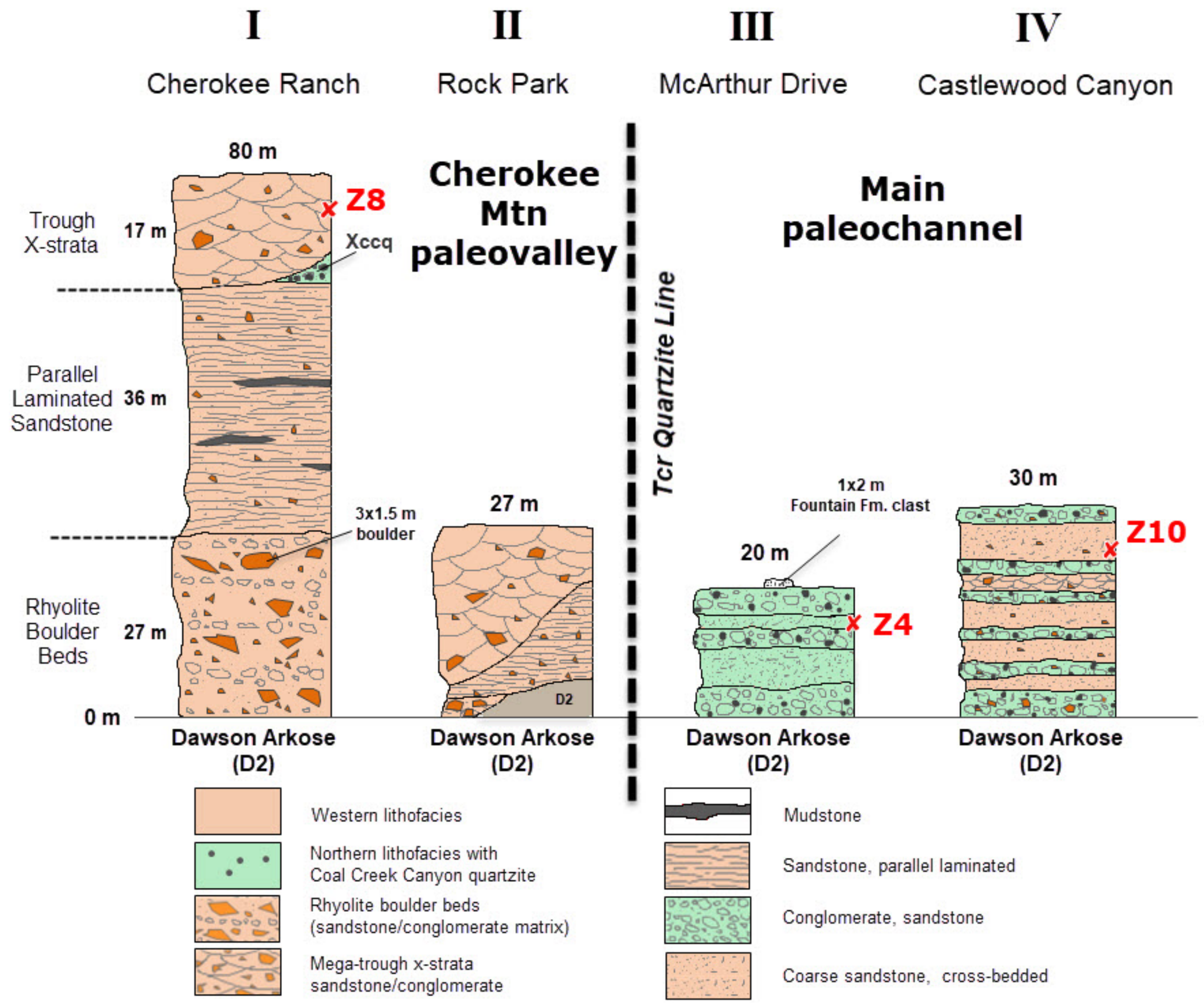

Figure 5. Stratigraphic sections I–IV. Locations shown on Figure 2. I–III are from this study, IV is modified from Morse (1985), with depositional features removed to show conceptual interbedded nature of the north and west lithofacies. Stratigraphic location of Z4, Z8, and Z10 are shown. Section III does not contain rhyolite. A large block of Fountain Formation sits on top of column III.

also measured for quality control. We consistently obtained weighted mean ^{206}Pb/^{238}U ages within 1% of the reference value for Plešovice (339.6 ± 3.5 Ma; n = 60) and GJ-1 (606.1 ± 5.4 Ma; n = 73), and, thus, we conservatively add 1% uncertainty in quadrature to the final age of each sample. All errors are 2σ unless expressed otherwise. Histograms and probability density plots of the geochronologic data were made using DensityPlotter (Vermeesch, 2012).

RESULTS

New Stratigraphic Observations from the Castle Rock Conglomerate

Previously unmapped exposures of **Tcr** found on Cherokee Mountain on Cherokee Ranch are 80 m thick. At this location, the formation can be divided into three informal members (Fig. 5): (1) a basal "rhyolite boulder bed" unit, 27 m thick, containing large angular blocks (the largest measured ~1.5 × 3 m) of rhyolite floating in a matrix of coarse, fluvial sandstone and conglomerate (Fig. 3*E*); (2) the middle member consists of ~36 m of mostly horizontally laminated sandstone with interspersed lenses of mudstone (Fig. 3*G*) (rhyolite is sparse in the middle member); and (3) a topmost cliff-forming member, ~17 m thick, which is cemented by opal and composed of arkosic conglomerate cap rock with well-developed trough cross-stratification. This uppermost member has an overall channel geometry with numerous internal cut-and-fill structures, and has eroded at least 5 m into the underlying parallel-laminated sandstone (Fig. 5). Paleocurrent directions taken from megatrough cross-strata in the upper member trend east–southeast.

Table 1. Detrital Zircon geochronology samples.

#	Name	Location[*]	Formation	Age	Comments[†]	Q[§]	W[‡]
Z12	Divide Miocene	486192, 4365469	Miocene sandstone	Miocene(?)	crs ss/grus, in city of Divide		
Z11	Ogallala	601933, 4358075	Ogallala Formation	Miocene–Pliocene	ss, congl, Cedar Point, near Limon	x	x
Z10	Castlewood Canyon	522894, 4353028	Castle Rock Conglomerate	late Eocene	congl, Castlewood Canyon State Park	(tr)	x
Z9	Plum Creek Parkway	515566, 4357157	Castle Rock Conglomerate	late Eocene	congl, Ridge Road roundabout		x
Z8	Westridge Shelter	504251, 4366634	Castle Rock Conglomerate	late Eocene	congl. near Rattlesnake Road		x
Z7	Raccoon Knob	505913, 4367024	Castle Rock Conglomerate	late Eocene	ss matrix of congl, Cherokee Ranch	x	x
Z6	Lemon Gulch	515243, 4367802	Castle Rock Conglomerate	late Eocene	crs ss	x	x
Z5	Reuter-Hess	414100, 4372046	Castle Rock Conglomerate	late Eocene	crs ss in congl w/ rip-up D2 clasts	x	x
Z4	McArthur Drive	509099, 4373677	Castle Rock Conglomerate	late Eocene	crs ss in congl	x	
Z3	Aggregate Quarry	530396, 4356866	Larkspur conglomerate	middle to late Eocene	crs ss w/bldr congl	x	
Z2	Happy Canyon	511145, 4365469	Larkspur conglomerate	middle to late Eocene	congl/ss		
Z1	Denver Fm. (D1)	506645, 4366061	Denver Fm. (D1 Sequence)	Paleocene	ss, 2m below Denver paleosol on Cherokee Ranch	x	

[*] Location as UTM WGS 84, zone 13N

[†] crs = coarse, ss = sandstone, congl = conglomerate, bldr = boulder

[§] Q = Coal Creek Canyon quartzite clasts in sample. "x" indicates present; "(tr) indicates trace

[‡] W = Wall Mountain Tuff clasts in sample. "x" indicates present

Our mapping in the northern part of the **Tcr** outcrop belt shows that blue-gray quartzite clasts are largely absent in the **Tcr** west of the interfluve that separates the present-day Cherry Creek and Plum Creek drainage basins (Fig. 2). Only a small amount of **Xccq** is found in the upper 10 m of the **Tcr** in the northernmost Plum Creek drainage. Conversely, **Tcr** exposures in the Cherry Creek drainage contain clasts of **Xccq** intermittently throughout its entire thickness (Fig. 5).

Petrography of Front Range Quartzite

Thin sections of **Xccq** clasts taken in the **Tcr** main channel outcrop belt contain andalusite and the distinctive foliation and penetrative deformation fabrics described from Coal Creek Canyon by Wells et al. (1964; Fig. 4 this paper). At many of the sampling sites along the **Tcr** main channel, we also found clasts of stretched-pebble metaconglomerate, although less frequently than clasts of quartzite. The upper amphibolite metamorphic facies and highly foliated, grain-size reduced fabrics of Coal Creek Canyon that characterize the main channel of the **Tcr** were not found in Blue Ridge, north of Cañon City, nor Ken Caryl Ranch. Both localities also lack andalusite.

Light gray quartzite clasts on Green Mountain are thought to be derived from Coal Creek Canyon (Drewes and Townrow, 2005). The quartzite clasts we collected at the base, middle, and top of Green Mountain did not have highly foliated, grain-size reduced fabrics, and they lacked andalusite. The Green Mountain quartzite clasts may be derived from Coal Creek Canyon but lack the distinctive characteristics of Wells' "unit C", and no quartzite conglomerate was found. **Xccq** clasts comprise less than 1% of the Green Mountain conglomerates.

Detrital Zircon Geochronology

Five generalized zircon age groupings are clear in the new detrital zircon data from the **Tcr** (Z4–Z10): ~1700 Ma, ~1400 Ma, ~1100 Ma, 70–42 Ma, and ~37 Ma. These five groupings are shown in Figs. 6–7, denoted as colored vertical lines or areas. No ages younger than 36.7 Ma (the age of the Wall Mountain Tuff) are present in the **Tcr**. Only a few Mesozoic and pre-1700-Ma zircon ages were obtained from the **Tcr**. Northernmost samples (Z4–Z6) in the **Tcr** have the most ~1700-Ma grains.

Zircon from samples that lie stratigraphically below the **Tcr** have many of the same age peaks; however, two (Z2 and Z3) taken from the Larkspur conglomerate show contrasting distributions. Z2 has mostly ~1100-Ma zircons. Z3 has mostly ~1700- and ~1400-Ma peaks. The oldest sample (Z1), moreover, shows a significant abundance of Paleocene zircon that is sparse or absent in all other samples. The sample from the Ogallala Formation (Z11, stratigraphically above the **Tcr**) includes the youngest zircons analyzed at ~28 Ma. Most samples collected from locations with obvious rhyolite clasts derived from Wall Mountain Tuff include zircon grains of that age (~36.7 Ma), whereas the sample from Reuter-Hess (Z5) and the Ogallala Formation (Z11) both include tuff clasts, but no 36.7-Ma zircon.

DISCUSSION

Petrography of the Coal Creek Quartzite and Quartzite Clasts in the Castle Rock Conglomerate

In order to evaluate the hypothesis that Coal Creek Canyon was the source of the quartzite clasts in the **Tcr** (Gabriel, 1933; Evanoff, 2007), we compared the petrography of the quartzite in the canyon with other occurrences of Precambrian quartzite and the clasts collected from the **Tcr**. Samples from Coal Creek Canyon layer C (Wells, 1967) are characterized by upper amphibolite facies mineral assemblage (most importantly including andalusite), and deformational fabrics that are not present in the quartzites exposed near Cañon City (Jones et al., 2009) and at Ken Caryl Ranch (Figs. 1 and 5). Many, but not all, quartzite clasts in the **Tcr** main channel have abundant andalusite and penetrative deformation fabrics like those at Coal Creek Canyon. Similarly, the stretched-pebble quartzite metaconglomerates that are restricted to Coal Creek Canyon occur with the quartzite in many **Tcr** sections we examined. Taken together, we suggest that this is strong evidence that the source of the quartzite clasts in the **Tcr** was the Coal Creek Canyon area and not other exposures of quartzite exposed along the Front Range. Green Mountain quartzites lack the deformation features and andalusite of the C layer (Wells, 1967), but may have come from other quartzite layers within the Coal Creek Canyon or were not derived from Coal Creek Canyon.

Coal Creek Canyon contains enough quartzite and is well positioned at the eastern margin of the Front Range to have supplied all Precambrian quartzite observed in the **Tcr**. We suggest that the Coal Creek exposure of quartzite may be considered a point-source of the andalusite-bearing quartzite and stretched-pebble conglomerate for the Denver Basin. Before contributing to the **Tcr** during the late Eocene, the **Xccq** quartzite clasts also contributed to the Paleozoic Fountain Formation and Paleocene Green Mountain Conglomerate (Abbott and Cook, 2012).

Areal Distribution of Xccq Clasts in the Castle Rock Conglomerate

Clasts of blue-gray quartzite identified as likely derived from Coal Creek Canyon occur in the northernmost outcrops of **Tcr** (Z4–Z6 from northern Douglas County). They also occur in Castlewood Canyon (Z10) and outcrops near Elbert and Calhan, Colorado (Figs. 1 and 3*H*). These sections all occur along the eastern side of the exposures of **Tcr**. To the west, quartzite clasts are largely absent. The only exceptions to this are rare occurrences of the clasts at Raccoon Knob (Z7) and some buttes at Philip S. Miller Park (Fig. 2, although, at this last location, no andalusite has been identified in the clasts).

Assuming that the source of the **Xccq** clasts is restricted to Coal Creek Canyon, they had to have been derived from the northwest and distributed 130 km southeast to Calhan (Fig. 1). Transport would have occurred in what was identified as the main paleochannel of the **Tcr** by Keller and Morgan (2016, 2017). These authors also note the occurrence of **Xccq** at a few locations in **Tcr** horizons that are associated with the northeast-flowing JA Ranch and Bucks Mountain tributaries. They interpret these locations as confluences of tributaries with the main southeast-flowing paleochannel, where southeast horizons overlie northeast horizons. In these tributaries, blue-gray quartzite was not found upstream (southwest) away from the confluences. These authors conclude that blue-gray quartzite in horizons of northeast flow was likely derived originally from Coal Creek Canyon and may have been reworked from main paleochannel sediments by younger northeast-directed flow.

Larkspur conglomerate samples (Z2–Z3), like the **Tcr**, show two distinct lithofacies, one north (containing **Xccq**) and one west (no **Xccq**). It is suggested that the **Tcr** lithofacies architecture was already in place by 41 Ma during Larkspur conglomerate deposition, with slightly different depocenters, when the Wall Mountain Tuff erupted.

Sources of the Zircons

Zircons from all three recognized Precambrian intrusive suites (Routt plutonic suite [~1700 Ma], Berthoud plutonic suite [~1400 Ma], and Pikes Peak batholith [~1100 Ma]) are

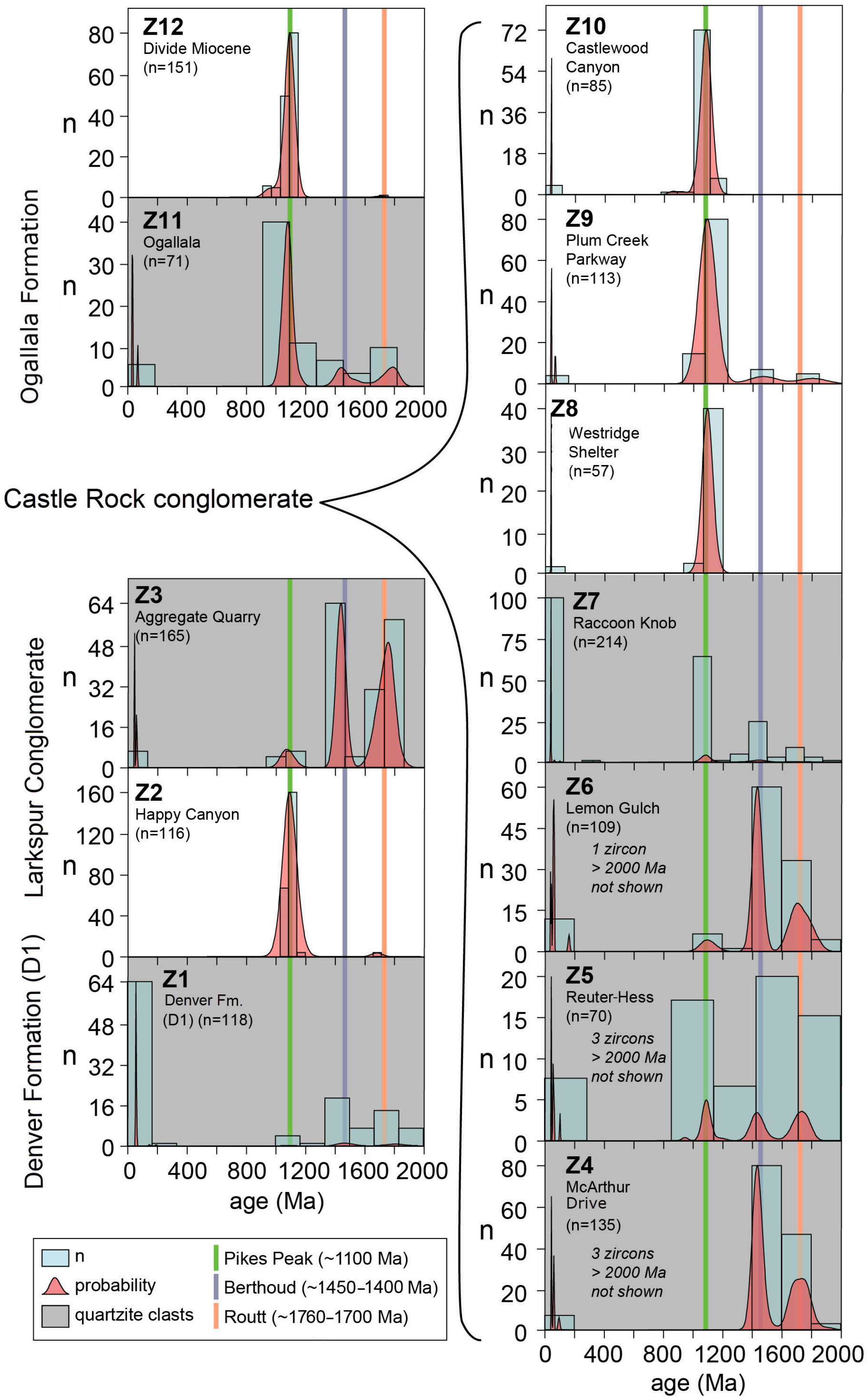

Figure 6. Probability density plots of 0–2000 Ma detrital zircon data for samples Z1–Z12. Overall, samples are in stratigraphic order, Z1 (oldest) to Z12 (youngest); however, internal stratigraphy of the **Tcr** was not determined in this study and samples are arranged from north (bottom) to south (top).

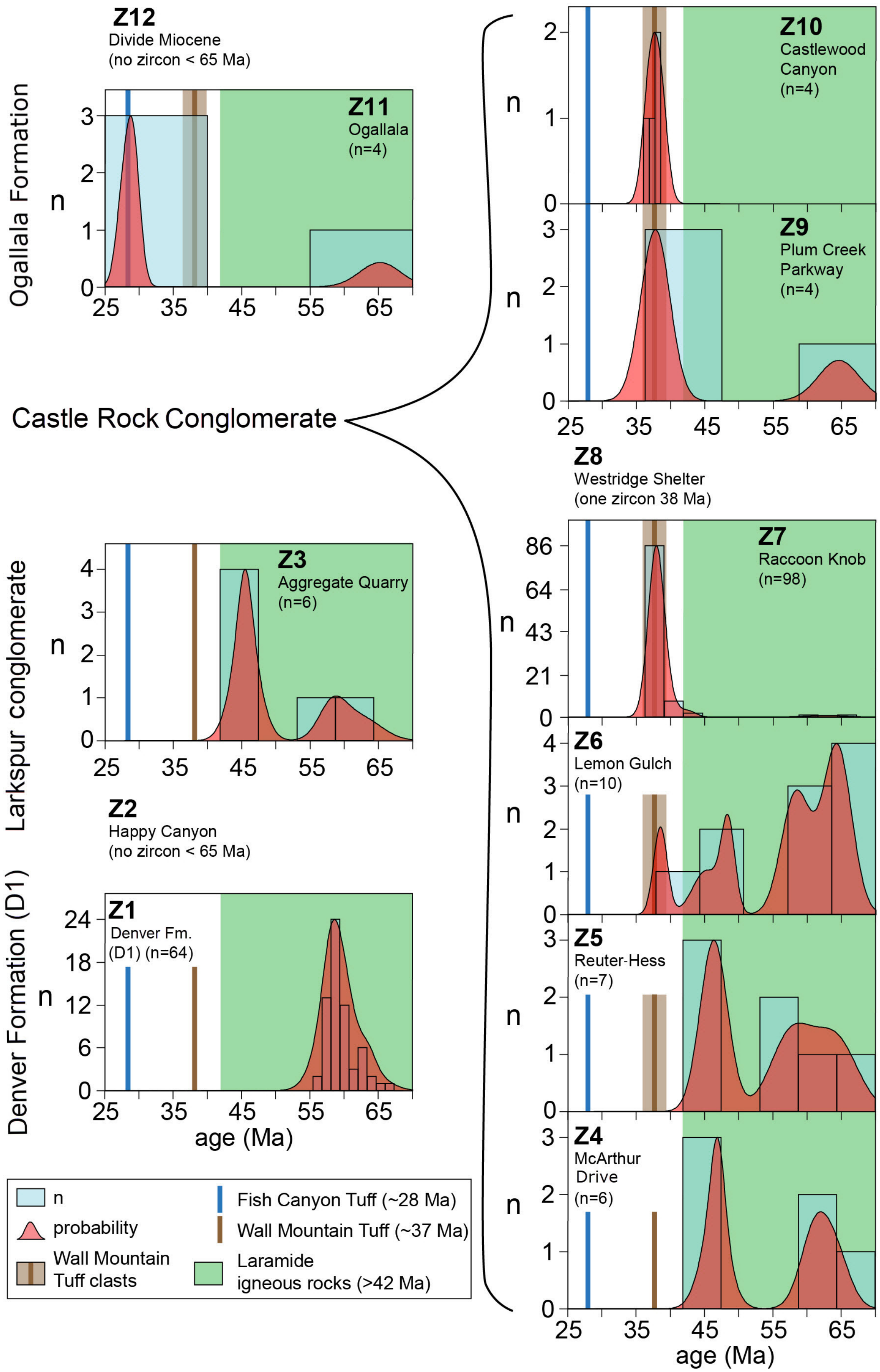

Figure 7. Probability density plots of 25–70 Ma detrital zircon data for samples Z1–Z12. Sequence of samples is the same as in Figure 6. Green-shaded age range represents Laramide igneous intrusive rocks (75–42 Ma).

represented in the populations (Fig. 6). In general, samples are characterized by either a dominance of zircons from the Routt and Berthoud plutonic suites, or the Pikes Peak batholith. Exceptions to this generalization are the samples from Reuter-Hess and Raccoon Knob (Z5 and Z7, respectively), which have a mixture of all Precambrian zircon populations.

Most samples also include Tertiary zircons. The sample from the Denver Formation (Z1/Cherokee Ranch) is the only sample with Tertiary zircons dominated by sources in the Laramide plutons. Other samples with more than a single Tertiary zircon older than the Wall Mountain Tuff (~36.7 Ma) include Z3 (Larkspur conglomerate) and Z4–Z6 (**Tcr**). Samples with significant zircon grains derived from Laramide plutons are the same as those that are characterized by zircons from the Routt and Berthoud plutonic suites (Figs. 6–7). The sample from the Ogallala Formation (Z11) is distinct from the others in that it contains grains younger than the Wall Mountain Tuff. The approximately 28-Ma zircons in this sample are likely derived from the voluminous Fish Canyon Tuff that erupted from the San Juan volcanic field to the west (~28.5 Ma; Schmitz and Bowring, 2001; Lipman, 2007). That the samples of **Tcr** do not contain Fish Canyon Tuff zircons is entirely consistent with fossil evidence that the conglomerate is older than 34 Ma (Prothero, 2017).

With the exception of the Wall Mountain Tuff, the **Tcr** is missing detrital zircon ages from the late Paleogene igneous rocks (40–26 Ma). We see no significant andesitic volcanic clasts within the west lithofacies of the **Tcr**. Apparently, the late Paleogene igneous rocks of the Southern Rocky Mountain volcanic field that erupted during deposition of the **Tcr** (36.7–34 Ma) did not duplicate the mobility of the Wall Mountain Tuff and were not carried into the late Eocene west lithofacies of the deposit.

Paleogeography of the Castle Rock Conglomerate Landscape

Taken together, the new data for the distribution of **Xccq** clasts derived from Coal Creek Canyon and the detrital zircon geochronology provide a strong basis for distinguishing different portions of the **Tcr** paleogeographic setting (Fig. 8). Samples with quartzite clasts derived from the north have detrital zircon populations that are consistent with derivation from northern sources in the Routt and Berthoud plutonic suites, as well as Laramide-age plutonic rocks. Samples that lack the quartzite clasts are dominated by Precambrian zircons derived from the west in the Pikes Peak batholith. The **Tcr** samples from Reuter-Hess (Z5) and Raccoon Knob (Z7) have ambiguous (likely both northern and western) sources.

Samples dominated by sources from the north span nearly the entire stratigraphy sampled in this study including the Denver Formation (Z1/Cherokee Ranch), Larkspur conglomerate (Z3), **Tcr** (Z4–Z6, Z10), and Ogallala Formation (Z11). With the exception of the Denver Formation sample (Z1), these all lie in the far east of the study area. Samples from the Larkspur conglomerate (Z2) and **Tcr** (Z8–Z9) to the west are dominated by western sources. Considering the distribution of **Xccq** clasts and northern provenance zircons, a boundary can be defined between **Tcr** samples with and without **Xccq** clasts, and detrital zircons, which we informally call the "quartzite line." The quartzite line can be traced for at least 17 km (Fig. 2). Because quartzite clasts and northern-provenance zircon occur in the single Denver Formation (D1) sample from the western part of the study area, and because there is **Xccq** quartzite in the Larkspur conglomerate that lies west of the quartzite line, we restrict usage of the quartzite line in this discussion to a feature of **Tcr** deposition.

We suggest that the quartzite line delineates a boundary between two paleodrainages (Fig. 2). To the east, the main paleovalley is the same as that identified by Keller and Morgan (2016, 2017) as the **Tcr** main paleochannel. This main channel likely represents the axial flow of the Denver Basin during the late Eocene. To the west, a second drainage, filled with 80 m of **Tcr** exposed on Cherokee Mountain, is now recognized. We refer to this informally as the Cherokee Mountain paleovalley (Fig. 2). The **Tcr** cap rock of Cherokee Mountain (Fig. 5) probably correlates with the **Tcr** cap rock of Rock Park (Fig. 2). Paleocurrent measurements at both sites indicate an east–southeast paleotransport (Fig. 8). Keller and Morgan (2017) suggested a possible tributary to the main **Tcr** main paleochannel in this area. The depocenter for the **Tcr** in the Cherokee Mountain paleovalley appears to align with ancient Front Range drainage (shown as the North Fork paleovalley, Fig. 8) recognized by Scott and Taylor (1986).

The **Tcr** main channel and Cherokee Mountain paleovalley are separated in the north by an area informally called the Castle Pines paleohigh (Fig. 2). In addition to suggested separation of the two **Tcr** paleovalleys by this high, the lack of Wall Mountain Tuff and **Tcr** in the same area supports the inference that this was a topographic high at 37 Ma. In the southern part of the study area, the **Tcr** main channel and the Cherokee Mountain paleovalley converge (about 3 km east–southeast of the city of Castle Rock). Additionally, the JA Ranch paleovalley and Bucks Mountain trend (both from Keller and Morgan, 2017) enter the main channel to the south (Fig. 8). Support for the convergence of the Cherokee Mountain paleovalley with the **Tcr** main channel includes both northern- and western-derived detrital zircon at the Plum Creek Parkway site (Z9) and a mixture of western-derived zircons and quartzite clasts at the Castlewood Canyon site (Z10).

Data from two samples do not fit neatly into this inferred paleogeographic reconstruction. Although the sample from Reuter-Hess (Z5) was taken from the **Tcr** main paleochan-

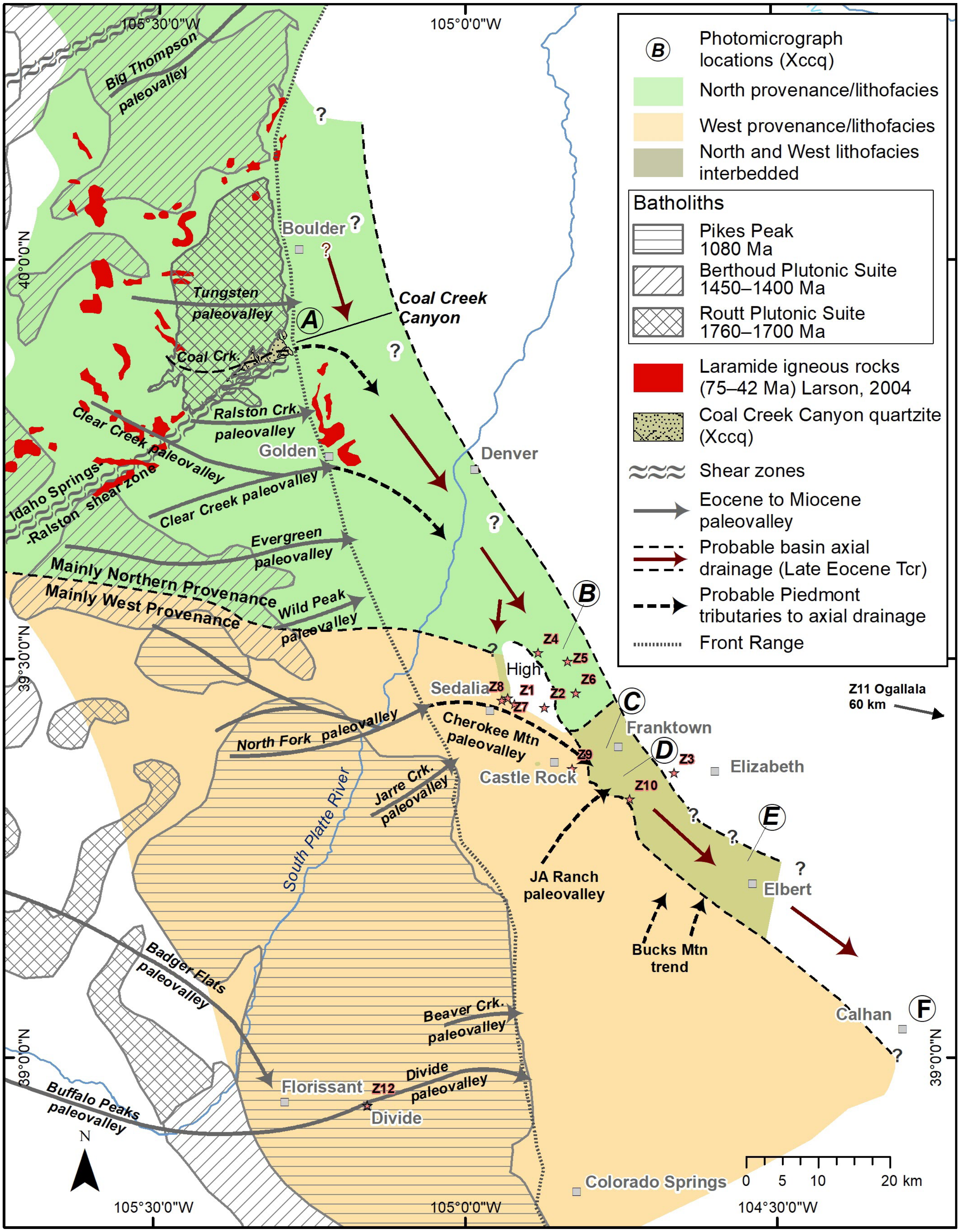

Figure 8. Summary map showing the suggested drainage system in the late Eocene for the **Tcr**. Location of geochronology samples (red stars) and photomicrographs of quartzite (Fig. 5). Front Range Eocene to Miocene paleovalleys are from Scott and Taylor (1986).

nel (Fig. 3*F*) and has both quartzite and northern-derived Precambrian zircons, it also includes a significant abundance of zircon from the Pikes Peak batholith (Fig. 7). This sample locality has a dearth of Pikes Peak Granite clasts in outcrop, and also has abundant rip-up clasts of the underlying Dawson Arkose (D2). The Dawson includes alluvial fan deposits known to have been derived from Pikes Peak terrain to the west (Dechesne et al., 2011); therefore, we suggest that the source of the Pikes Peak zircons in this sample may be the underlying Dawson Arkose (D2).

The sample from Raccoon Knob (Z7) was collected adjacent to the Cherokee Mountain paleovalley and contains abundant clasts of Pikes Peak Granite, but it has both quartzite clasts and a well-mixed population of northern- and western-derived zircons (Fig. 7). We suggest that there was a minor drainage from the north around the Castle Pines paleohigh that flowed into the Cherokee Mountain paleovalley intermittently (Fig. 8). We infer that it was small and intermittent because the deposits are thinner conglomerate channel lenses interbedded with more massive west lithofacies. Additionally, another **Tcr** sample collected nearby (Z8/Westridge Shelter) is more characteristic of outcrops on Cherokee Mountain, and it includes neither **Xccq** clasts nor northern-derived zircons.

CONCLUSIONS

Combining stratigraphy, mapping, and paleocurrent data with clast petrography and detrital zircon geochronology permits new insights into the **Tcr** depositional system, which can assist the study of other Paleogene strata. We suggest that the northern part of the **Tcr** depocenter was divided into two channels. The **Tcr** main channel contains detritus derived from northern sources characterized by clasts of andalusite-bearing quartzite and stretched-pebble conglomerate, and zircons derived from the Routt and Berthoud plutonic suites. The Cherokee Mountain paleovalley derived sediment mainly from the west, characterized by zircons derived from the Pikes Peak batholith. The two valleys were separated by a paleohigh (drainage divide) that we call the Castle Pines, which formed from deeper valley erosion after Larkspur conglomerate deposition and before the eruption of the Wall Mountain Tuff. The rhyolite is present on fringes of the high, but the ash-flow followed the valley lows and was unable to surmount much of the Castle Pines paleohigh. South of the Castle Pines paleohigh, the lithofacies become interbedded within the main channel and other drainages join from the west and southwest.

We suggest that Coal Creek Canyon was a source of quartzite and stretched-pebble conglomerate clasts that can be used as a point-source provenance tool for other studies in the Denver Basin. Furthermore, the distribution of Precambrian and Tertiary igneous rocks of variable age, which provided abundant zircon to sediments, allows good control for understanding sediment sources in sedimentary rocks deposited east of the Front Range since the Cretaceous.

ACKNOWLEDGMENTS

The authors have had a great deal of help over the years of mapping, data collection, and writing. The Cherokee Ranch & Castle Foundation supported initial mapping of Cherokee Ranch. Their financial assistance and support started in motion the discovery phase of the complexity of the **Tcr**. The hospitality and generous sharing of Douglas County landowners (too numerous to mention here) allowed further expansion of ideas. Their help is greatly appreciated. Supportive geologic discussions with Bob Raynolds, Scott Knight, Ian Miller, Emmett Evanoff, Mike Dempsey, David Morse, Steve Cather, Chuck Chapin, Steve Keller, Donna Anderson, and fellow Cherokee Ranch Science Institute members were essential in bringing the final paper to a conclusion. Douglas Kirkland improved the text. Magdalena Kascak is much appreciated for her creative Geographic Information Systems' and computer skills in preparing figures. Heather Koch patiently listened to and contributed to endless geology discussions, ably assisted in fieldwork, and helped review the manuscript. Amanda Sutter was supported through a generous gift to the Department of Geological Sciences, The University of North Carolina at Chapel Hill, by Jesse Davis. Andrew Kylander-Clark is thanked for his hospitality and support in collecting the geochronologic data. Journal reviews by Stephen Keller, David Morse, Bob Raynolds, and Arthur Snoke significantly improved and clarified the manuscript. Arthur Snoke, Robert Waggener, and Brendon Orr with *Rocky Mountain Geology* are thanked for their efficient editorial handling of the manuscript.

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SCIENTIFIC EDITOR: ARTHUR W. SNOKE