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Research Article

Provenance of Paleogene Strata at Slim Buttes, South Dakota: Implications for post-Laramide Evolution of Western Laurentia

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Slim Buttes is a 30 km long by 10 km wide set of buttes containing Paleogene strata in northwest South Dakota. At Reva Gap in northern Slim Buttes, Eocene-Oligocene terrestrial strata of Chadron and Brule Formations of the White River Group unconformably overlie the Paleocene Fort Union Formation. An angular unconformity separates the White River Group from overlying Oligocene and Miocene strata of the Arikaree Group. Using detrital zircon U-Pb ages, we determine the provenance of these rocks as part of a broader synthesis of post-Laramide sedimentation in the Rocky Mountains and western Great Plains.

The Chadron Formation age spectrum is dominated by Cretaceous and Proterozoic grains that are interpreted to be locally recycled from the underlying Cretaceous and Paleocene strata. The Brule Formation has a maximum depositional age of ~34 Ma; Paleogene zircons dominate the age spectrum, and a wide variety of older zircons are also present. The Oligocene zircons are interpreted to have been sourced from volcanic systems in the Great Basin to the southwest, while the subsequent proportions of the zircons were derived from a variety of source areas in the Nevadaplano and Rocky Mountain areas to the southwest. Sparse amounts of Archean zircons are thought to represent the burial of Laramide uplifts throughout Wyoming at the time of Brule deposition, making for a regional paleotopography with little relief across the western interior of the United States. The Miocene-age Arikaree Group sand has a maximum depositional age of ~26 Ma and a multimodal detrital zircon age spectrum. The Arikaree Group provenance likely represents continued sourcing in the Great Basin volcanic systems and Nevadaplano, the beginnings of the re-exhumation of Laramide basement uplifts, and subsequent sediment evacuation out of the western interior and into the Gulf of Mexico to the southeast. Our findings indicate that the transport process and detrital zircon provenance signatures of these strata are decoupled, and each have their own independent evolution. The volcanic signature is primarily transported via aeolian processes (i.e. volcanic ash), and the recycled detrital zircon signature is primarily transported via fluvial processes.

INTRODUCTION

The Rocky Mountains of North America are characterized by the Laramide province: rugged, high-elevation mountain ranges bounded by flat basins making for a high-relief landscape from the basin floors to the mountain peaks. During Cretaceous to Eocene time, the foreland of the Cordilleran thrust belt (Sevier highlands) was structurally partitioned into many small basins bounded by Precambrian crystalline rocks. These rocks were uplifted by high-angle reverse faults in response to Sevier-Laramide crustal thickening related to subduction of the oceanic Farallon plate beneath the North American continent (Fig. 1A) (e.g. Craddock et al., 2022; Craddock & Malone, 2022; Dickinson & Snyder, 1978).

Deposits of the White River Group and correlative strata are preserved within the post-Laramide lowlands in the Great Plains in Nebraska, South Dakota, and North Dakota, as well as intermontane regions of the Rocky Mountains in Colorado, Wyoming, and Montana (Corradino et al., 2021; Rowley & Fan, 2016; T. M. Schwartz & Schwartz, 2013; Sears & Beranek, 2022; Thomson et al., 2022; Fig. 1B). White River strata are also present in paleovalleys atop Laramide ranges such as the Bighorn Mountains, Black Hills, and Washakie Range (Caylor et al., 2023; J. R. Malone et al., 2022; McKenna & Love, 1972). Miocene strata are widespread across the Great Plains of North America, mainly in badlands-type localities like Badlands National Park or Slim Buttes, SD, based on their association with

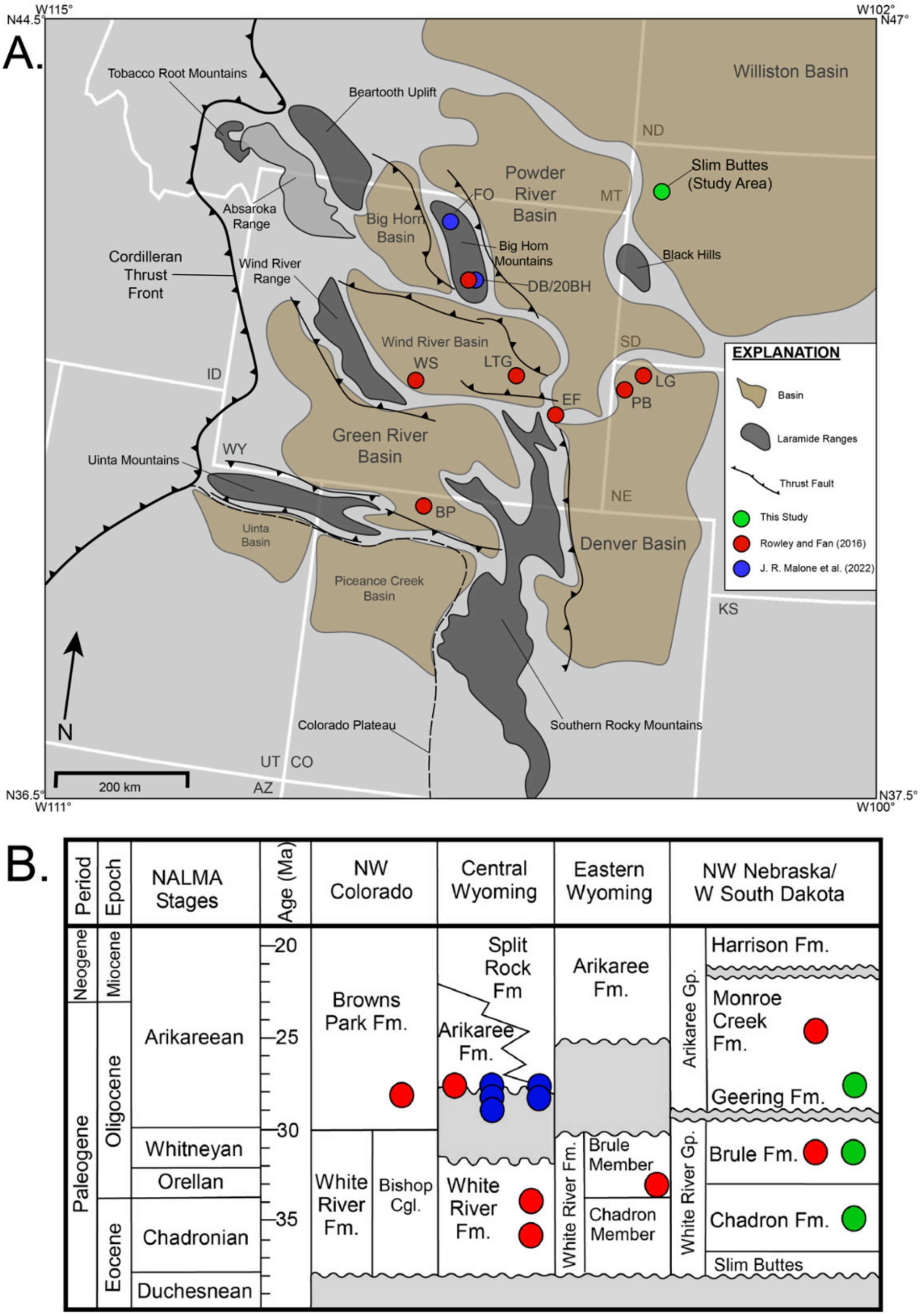

Figure 1. (A) Regional physiographic map, featuring an overview of the different sedimentary basins, thrust systems, and mountain belts throughout the western U.S. interior. (B) Stratigraphic correlation of Eocene-Miocene strata in various parts of the western interior. Sample locations are labeled in green (this study), blue (J. R. Malone et al., 2022), and red (Rowley & Fan, 2016). Modified from J.R. Malone et al. (2022).

White River Group exposures, or in bluffs such as Pine Bluffs, NE (Rowley & Fan, 2016).

The evolution and extent of post-Laramide basin-fill sediment and subsequent sediment evacuation remains in question. Previous work suggests that Laramide basins and adjacent uplifts were buried by late Eocene-Miocene volcaniclastic sediment up to elevations of ~2700–3000 m above sea level (Anderson et al., 2019; Caylor et al., 2023; Konstantinou, 2022; McKenna & Love, 1972; Pecha et al., 2022; Steidtmann & Middleton, 1991) making for subdued relief from the Sevier highlands east into the Great Plains. The provenance of Paleocene-Eocene synorogenic basin sediments proximal to the Sevier belt are interpreted by Malone and other (2016) to be derived from recycling of the Neoproterozoic Brigham Formation uplifted in the Sevier Paris thrust sheet, as evidenced by the strong presence of a Yavapai (~1750 Ma) age component in the detrital zircon U-Pb age distributions, however, it is unknown if this signal of Sevier Belt-derived Yavapai-aged recycled zircons is present in younger and more distal sediments like the Oligocene-Miocene White River Group strata preserved in South Dakota. In this study, we present new detrital zircon geochronology results on three units of Oligocene-Miocene strata sampled from Slim Buttes, South Dakota, as part of an ongoing effort to constrain the timing and pace of sediment fill and evacuation across the Rocky Mountains and the western Great Plains.

BACKGROUND

Slim Buttes is an outlier of Paleogene strata in northwestern South Dakota, distant from other areas where equivalent-age strata are well-exposed. Slim Buttes is surrounded at lower elevations by an unconformable contact with the Paleocene Fort Union Formation (Sawyer & Fahrenbach, 2011). The White River Group (Chadron and Brule Formations) at Slim Buttes consists of a variety of facies, including tuffaceous sandstone, limestone, gypsum, and conglomerate deposited in fluvial channels, fluvial floodplains, lacustrine, eolian, and local alluvial fan environments (Larson & Evanoff, 1998; McKenna & Love, 1972; Singler & Picard, 1979). The lower section of the Chadron Formation consists of a distinct, coarse-grained, and massive quartz-rich white sandstone (Lillegraven, 1970; Maher & Persinger, 2023) with thickness of as much as 20 meters. The top of the Chadron Formation consists of dark brown, smectite-rich mudstone up to six meters thick. In the southern area of Slim Buttes, the brown mudstone is missing locally, likely due to erosion associated with the channel complex making up the overlying Brule Formation (Maher & Persinger, 2023). The Brule Formation has a basal conglomerate that is composed of intraclasts and is overlain by medium to fine white tuffaceous sandstones with thin brown mudstone layers.

The Arikaree Group at Slim Buttes consists of brown-green resistant sandstone greater than 35 meters in thickness. Pink feldspar grains and small granitoid lithics are consistent with a basement source. In southern Slim Buttes, finer-grained sandstones similar in appearance to the underlying Brule Formation are intercalated with the coarser sandstones (Fig. 2).

The source of zircons in the White River Group at the Slim Buttes locality may have been first-cycle, eroding from crystalline basement rocks uplifted during the Laramide Orogeny or recycling of zircon eroding from uplifted sedimentary rocks to the west. Additionally zircon in the White River group at the Slim Buttes locality may have been derived from syndepositional active volcanism. The Archean Wyoming Province consists of 3.2-2.8 Ga gneissic rocks that are intruded by abundant 2.7-2.5 Ga granites along the margin of the province (Mogk et al., 2022). The most proximal Archean crust exposed during White River deposition occurs in the Bighorn Mountains of northern Wyoming. Here, Archean granite and gneiss range in age from 2960-2850 Ma (J. E. Malone et al., 2019) and were exposed by early middle Eocene time (Anderson et al., 2018). Archean zircons may have been recycled from various Neoproterozoic-Phanerozoic strata that occur throughout the region (Craddock et al., 2015; Foreman et al., 2022; May et al., 2013; Welch et al., 2022; Yonkee et al., 2014). Proterozoic zircons may have been derived from exposed Yavapai Terrane (1.8-1.7) Ga rocks in Colorado (Whitmeyer & Karlstrom, 2007) Other Proterozoic and Paleozoic zircons may have been recycled from Neoproterozoic metasedimentary strata in southeast Idaho (Laskowski et al., 2013; D. H. Malone et al., 2016; J. R. Malone et al., 2022; Yonkee et al., 2014) in the Sevier-Laramide foreland to the west and their associated synorogenic strata (May et al., 2013; Malone et al., 2022).

Mesozoic zircons were likely derived from batholiths in the Sevier hinterland or southwest Montana (Gaschnig et al., 2010; Gottlieb et al., 2022; T. Schwartz et al., 2021; Malone et al., 2022; Thomson et al., 2022). Cenozoic magmatism in western North America peaked between 37-22 Ma, with intermittent rhyolitic eruptions between 458 Ma, both before and after the mid-Cenozoic ignimbrite flareup (Henry & John, 2013). Calderas associated with the ignimbrite flareup have been found in the Great Basin (Best et al., 2016; Henry & John, 2013).

The Great Basin in eastern Nevada and western Utah was an active volcanic source from ~36 to 29 Ma producing ~30 calderas (Henry & John, 2013). Great Basin volcanism consisted mostly of felsic pyroclastic eruptions and was initially rhyolitic in composition from 36 to 31 Ma but evolved into dacitic compositions after 31 Ma (Larson & Evanoff, 1998). Peak volcanism in the Great Basin occurs at ~28 Ma (Best et al., 2016).

Calderas in southwestern Montana and northwestern Wyoming (Feeley & Cosca, 2003; D. H. Malone, Craddock, Schmitz, et al., 2017), and southern Colorado (Lipman & McIntosh, 2008) constitute a larger ignimbrite province throughout western North America during the Paleogene. Volcanism occurred in northeastern Idaho and southwestern Montana. Eocene-Oligocene volcanic fields included the Hog Heaven field, Helena field, Bear Paw Mountains field, Virginia City Field, Gravelly Range, and more (Fritz et al., 2007).

METHODOLOGY

U-Pb geochronologic analyses were conducted by laser ablation inductively coupled plasma mass spectrometry (LA-ICPMS) at the Arizona LaserChron Center. Please refer to the Element2 methodology at www.laserchron.org for the details of our analytical techniques. These U-Pb geochronology methods also have been described by Gehrels et al. (2008), Gehrels and Pecha (2014), and Sundell et al. (2021). The details of detrital zircon U-Pb age data are provided in the supplementary data.

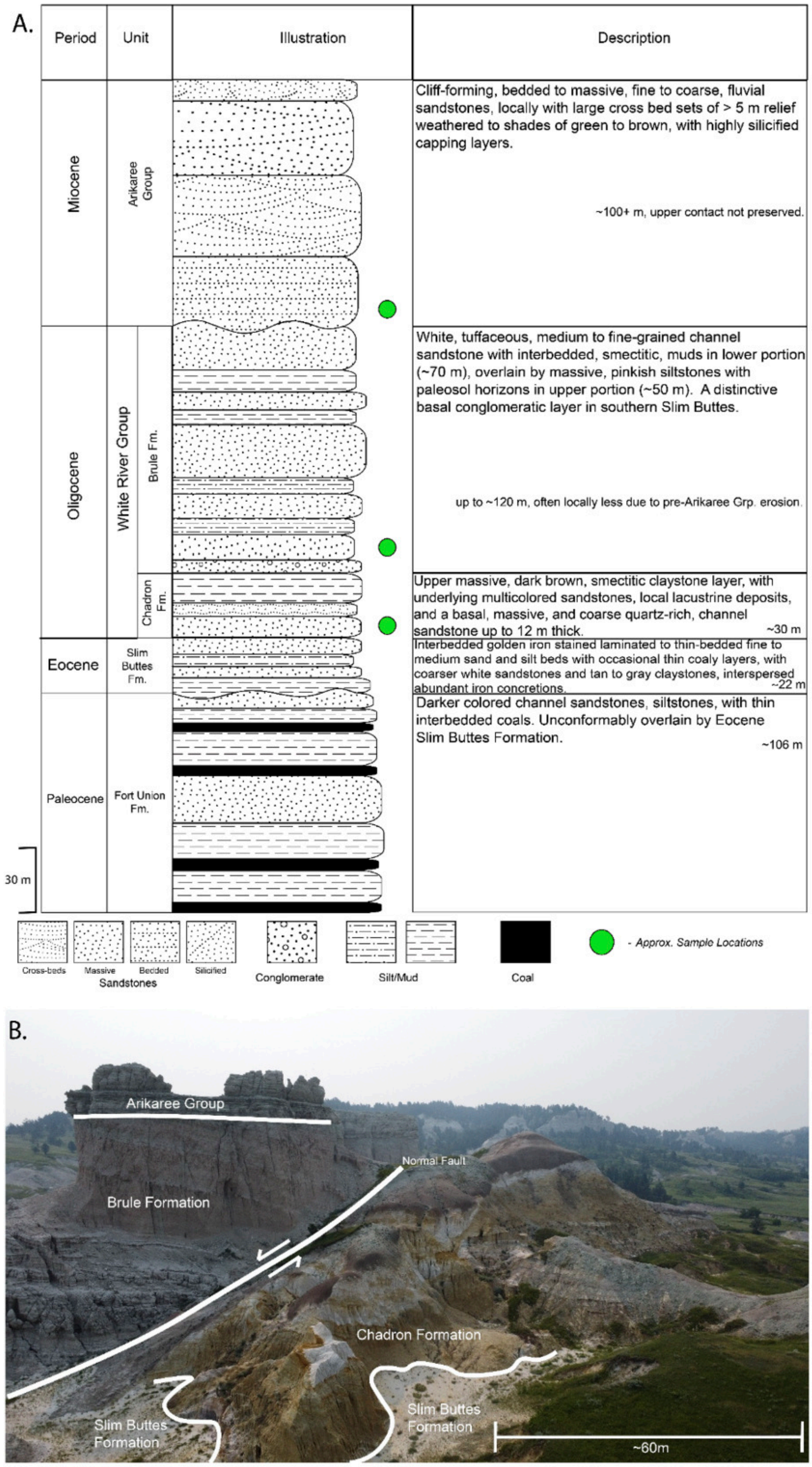

Figure 2. (A) Localized stratigraphic column of geologic units within the study area. Lithologic descriptions are modified from field observations, Lillegraven (1970), and Maher and Persinger (2023). (B) Drone photo, taken near Reva Gap, pointing south. Illustration denotes units and contacts; dipping Brule Fm. in fault-contact with Chadron Fm. and Slim Buttes Fm., overlain by angular discordance by flat-lying Arikaree Group.

Figure 3. Field photos, (A) Close-up of the Chadron Formation displaying its variety of facies, including the coarse-grained white sandstones. The gold and pink layers below may belong to the Slim Buttes Fm. (B) Drone photo of the top of the butte featured in Fig. 2B, displaying dipping Brule Fm. Overlain with angular discordance by flat-lying Arikaree Group.

The zircon ages from this study, as well as the samples from J.R. Malone et al. (2022) and Rowley and Fan (2016) are shown on kernel density estimate plots using DetritalPy (Fig. 4, Sharman et al., 2018) to compare age populations from across the extent of the White River Group. The bin widths are 50 m.y. A multidimensional scaling (MDS) plots was constructed with DZmds (Fig. 5A; Saylor et al., 2019). The maximum depositional ages for the Brule Formation and the Arikaree Group were calculated by taking the weighted mean average of the youngest zircon populations (Fig. 5B-C; Dickinson & Gehrels, 2009; Sharman & Malkowski, 2020).

RESULTS

We report U-Pb geochronological results with measured age uncertainties of 1-2% (1-σ error). Age peaks were visually selected. The detrital zircon age distribution for the Chadron Formation shows age peaks at 78 Ma and 1735 Ma with minor age peaks at ~1200 Ma and ~1500 Ma. Detrital zircon grains with Archean, Paleozoic, and Mesozoic ages are present in lower quantities. The youngest zircon analyzed has an age of 70.47±0.65 Ma. Age distributions for Chadron-equivalent samples in Rowley and Fan (2016) have fewer Archean and Proterozoic zircons and younger age peaks at ~36 Ma (Figs. 4, 5). The distributions of older zircon populations are similar across the Chadron samples (Fig. 4).

The Brule Formation shows an age prominent peak at 35 Ma with a minimal distribution of older-age zircon grains, in distinct contrast to the Chadron Formation. The youngest grain analyzed reveals an age peak at 32.98±0.51 Ma and the MDA using the youngest population of zircon grains with overlapping error estimates presents an age of

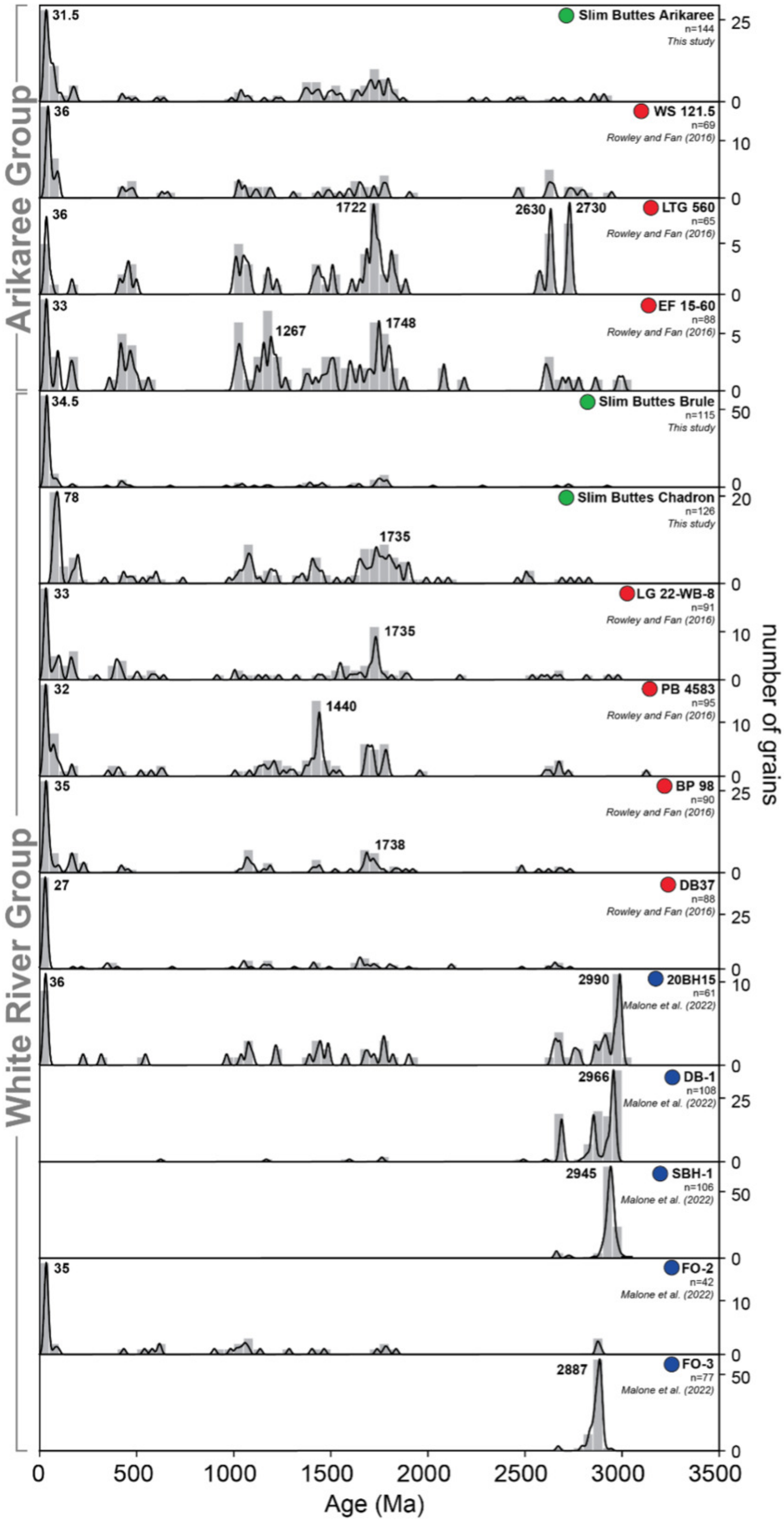

Figure 4. Kernal density estimate (KDE) and of Paleogene strata at Slim Buttes (green, this study), the Bighorn Mountains (blue, J. R. Malone et al., 2022) and elsewhere in Wyoming, Bin width is 50 m.y. Nebraska, and Colorado (red, Rowley & Fan, 2016). Labeled numbers indicate peak ages. X-axis is box height, which differ based on zircon yield per sample.

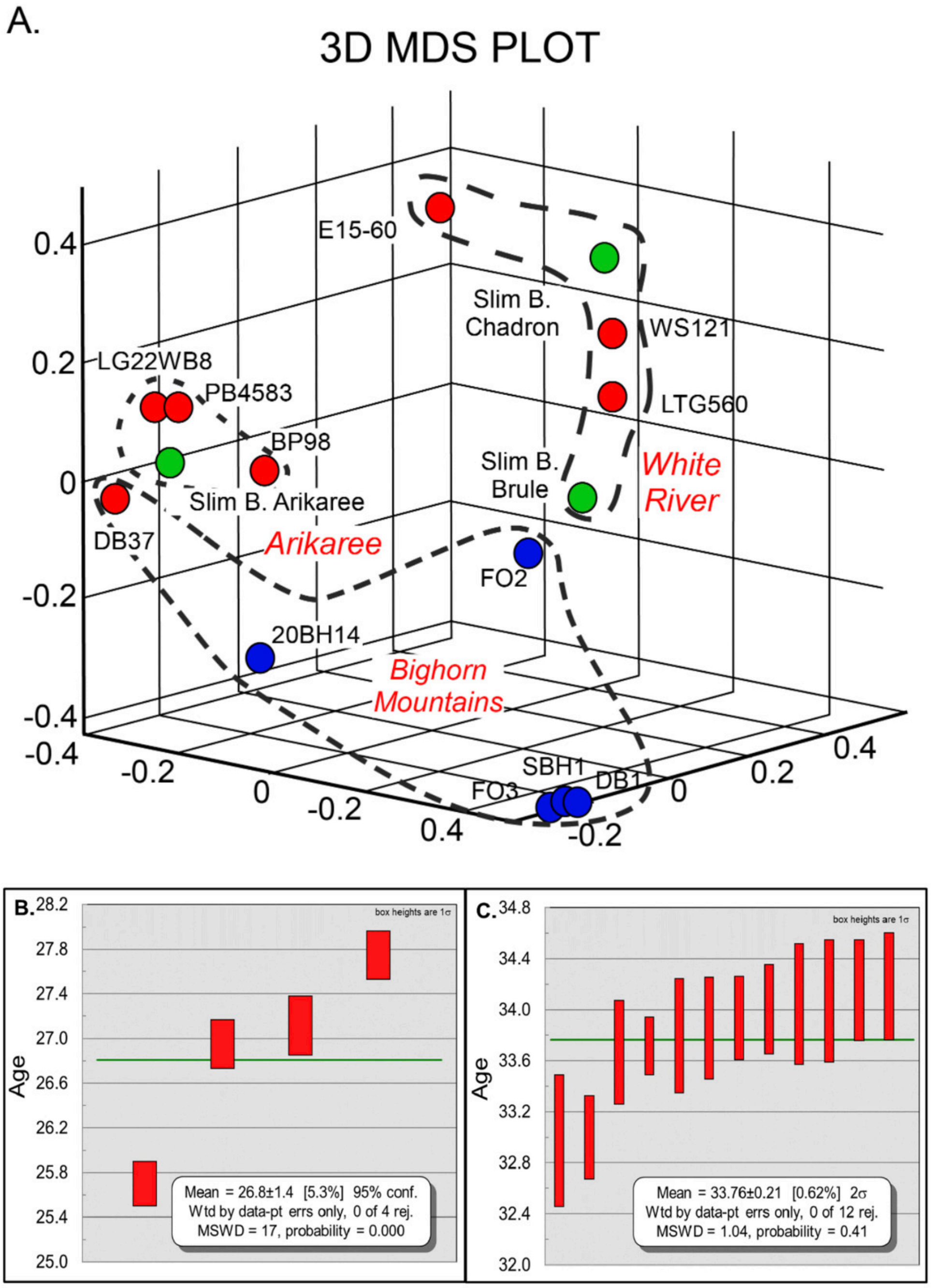

Figure 5. (A) MDS comparison of detrital zircon U–Pb age spectra of samples at Slim Buttes (green, this study), the Bighorn Mountains (blue; J. R. Malone et al., 2022) and elsewhere in Wyoming, Nebraska, and Colorado (red; Rowley & Fan, 2016). Dashed circles denote chronofacies, which are labeled in red text. (B, C) Maximum depositional ages (MDAs) of (B) Arikaree Group and (C) Brule Formation Vertical boxes denote analysis 1-σ error.

33.76±0.21 Ma (Fig. 5C). The Brule sample at Slim Buttes closely matches J.R. Malone et al. (2022) samples taken from White River sandstone successions filling paleovalleys in the Big Horn Mountains (Figs. 4, 5A).

In the Arikaree Group, the zircon age distribution plots display a prominent age peak at 33 Ma, with fewer middle Proterozoic zircons. The youngest grain analyzed has an age of 25.72±0.20 Ma and the MDA is 26.80±1.4 Ma (Fig. 5B). The three Arikaree-equivalent samples from Rowley and Fan (2016) present similar zircon age distributions (Figs. 4, 5A).

DISCUSSION

Sediment Provenance

The Chadron Formation contains no Paleogene zircons, which is anomalous for White River or Arikaree strata that occur throughout the region (Fig. 4; J. R. Malone et al., 2022; Rowley & Fan, 2016). The Formation overlies Paleogene and Cretaceous units (Fig. 2A; Lillegraven, 1970; Terry, 1998), which may indicate that these zircons are locally recycled from these rocks. Alternatively, these zircons may have been recycled from distal Paleogene-Cretaceous strata in the Sevier highlands, or perhaps the Sevier highlands continuously supplied sediment from the Cretaceous through the late Paleogene. We prefer the former interpretation because it is likely that distal source areas were buried by younger strata and that Laramide ranges would have been topographic barriers to sediment routing. Moreover, the paucity of younger grains, which must have been distally derived further supports the local source interpretation. That, or there was no volcanic activity at the time of the deposition of this sandstone that would have supplied the younger zircon population.

MDS reveals a tight cluster of White River Group samples (Fig. 5A; Rowley & Fan, 2016). The occurrence of a variety of Cretaceous zircon ages (i.e. no well-defined age peak) indicates possible sources in the Idaho batholith. Chadron zircons younger than 90 Ma may have been derived from the more proximal Boulder, Tobacco Root, or Pioneer batholiths in southwest Montana (Gaschnig et al., 2010), or recycled from the underlying Fort Union Formation (Welch et al., 2022).

The Brule Formation and Arikaree Group ages are consistent with other data included in this study (Figs. 4, 5; J. R. Malone et al., 2022; Rowley & Fan, 2016). The Brule sample plots closely to sample FO2 from J.R. Malone et al. (2022) on multidimensional scaling (Fig. 5A) indicating statistical similarity to valley-fill White River Formation atop the Bighorn Range. There is a significant lack of Archean age zircons, or anything much older than the Cenozoic in the Brule Formation, though a slight increase in the population of Precambrian zircons is seen in the Arikaree Group (Fig. 4). The Oligocene zircons are distally transported by pyroclastic plumes from Utah and Nevada (Fig. 6B; Larson & Evanoff, 1998). Other potential Oligocene sources include the Hog Heaven Volcanic Field (30.8–36 Ma; Lange et al., 1994), the San Juan province (35–20 Ma; Roy et al., 2004), the Dillion volcanic field (49–17 Ma; Fritz et al., 2007) and many of the active calderas in the Great Basin (~37–26 Ma; Henry et al., 2012; Henry & John, 2013). Potential calderas within the Great Basin contributing volcaniclastic sediment to the White River Group could have been, but are not limited to, the Thomas Range (~37–32 Ma), Indian Peak (~32–27 Ma), Marysvale Volcanic Province (~27–19 Ma; Maybeck et al., 2022; Holliday et al., 2023), and the Central Nevada Volcanic Field (~36–18.4 Ma) (Best et al., 2016; Henry et al., 2012; Henry & John, 2013). Zircons grains with ages between ~51–43 Ma are sourced from either the Challis or Absaroka volcanic fields in Wyoming, Montana, and Idaho (Feeley & Cosca, 2003; D. H. Malone, Craddock, Schmitz, et al., 2017). All samples except for SBH1 and FO3 from J.R. Malone et al. (2022) have a Yavapai-age (~1750 Ma) component. The 1750-1600 Ma zircons in more westerly samples may have been recycled from the Neoproterozoic Brigham Group in Idaho (D. H. Malone et al., 2016) or the Sevier-Laramide synorogenic rocks shed from Brigham Group strata in the upper plate of Paris thrust sheet (D. H. Malone et al., 2022; T. Schwartz et al., 2021; T. M. Schwartz et al., 2019; Thomson et al., 2022; Fig. 6C). MDS indicates samples with a high Archean age population are statistically distinct from Slim Buttes samples (Fig. 5A).

Basin Evolution and Paleogeography

The provenance evolution of late Paleogene strata at Slim Buttes reveal major changes to drainage organization and sediment routing. The detrital zircon age spectra include both first cycle volcanically-derived zircons from distal sources transported by eolian processes and primary and recycled zircons derived from more proximal sources and transported via fluvial processes. Erosion rates and basin fill kept pace or caught up with uplift of Laramide structures, such that there was little relief between Laramide ranges and the adjacent basins (J. R. Malone et al., 2022; Rowley & Fan, 2016; Steidtmann & Middleton, 1991). The presence of White River and Arikaree Group strata atop the Bighorn Mountains and Wind River Ranges suggests the Laramide basins were filled up to ~2700-3000 meters above present-day sea level during the Oligocene, fed by east-flowing fluvial systems from the Sevier highlands to the west, making for a regional paleogeography containing little relief (Caylor et al., 2023; Pecha et al., 2022; Steidtmann & Middleton, 1991; Zhu & Fan, 2018). To the southwest was the Nevadaplano, a high plateau reaching elevations up to 3500 m in the late Oligocene, which would eventually form the Basin and Range province during crustal extension in the later Cenozoic (Henry et al., 2012). Thermochronological data from Caylor et al. (2023) suggests burial of Laramide ranges and basins was maintained between ~40 Ma through ~10 Ma.

During the Paleocene and Eocene, paleodrainage systems routed sediment to the north into Montana until ~50 Ma, when the local provenance shifted to proximal volcanics such as Absaroka and Challis Volcanic Fields, and with the Idaho river system becoming the dominant drainage vector (Pecha et al., 2022; Welch et al., 2022). During the Oligocene, east-flowing fluvial systems carried sediment from the Sevier highlands at least as far as the Bighorn Basin and atop the Bighorn Range (D. H. Malone et al., 2016). By the Miocene, paleodrainage systems routed sediment from the southern Rocky Mountains into the Gulf of Mexico, with the Bell River system moving northeastward (Blum et al., 2017; Pecha et al., 2022; Zhu & Fan, 2018; Corradino et al., 2022; Fig. 6A). The divide between these two systems was north of Slim Buttes near the present-day U.S.-Canada border.

Chadron Formation deposition was earlier in the lifespan of the ignimbrite flare-up, and extensive Eocene sediment with a significant direct or air-transport volcanic input may have been absent in this drainage basin. The east-flowing paleodrainage system reported by Malone et al. (2016) may be contributing sediment off the Paris thrust sheet of the Sevier belt until the drainage shifted north and east as in Welch et al. (2022).

The Brule Formation has a high concentration of Oligocene zircons and almost complete absence of Precambrian through Mesozoic age zircons despite multiple nearby Laramide uplifts that would otherwise serve as source areas. The almost complete absence of Precambrian through

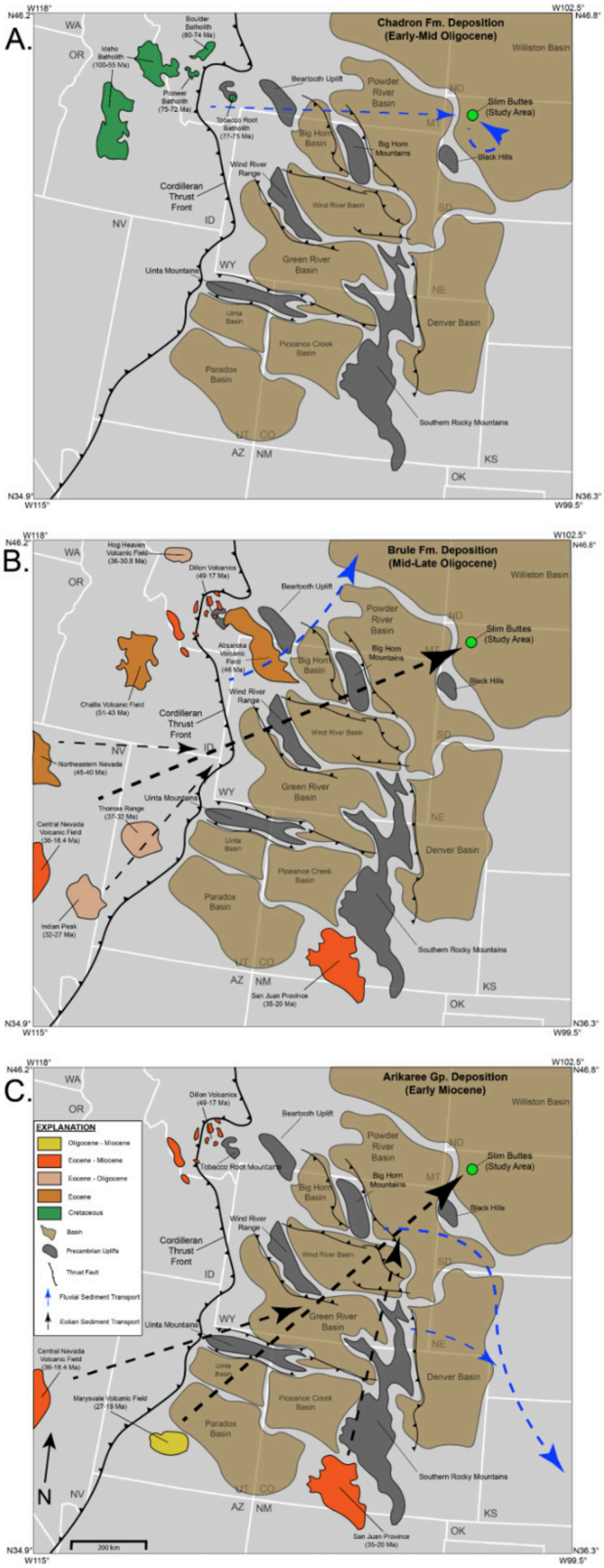

Figure 6. Source characterization of each unit in map view, showing sedimentary basins, thrust systems, mountain belts, and matching magmatic source areas for A: Chadron Fm.; B: Brule Fm.; C: Arikaree Group Dashed lines and arrows indicate sediment transport direction.

Mesozoic grains may be attributed to dilution from a high zircon fertility source. These sources may be contributing sediment, but the signal is just not as detectable at the number of grains analyzed for that sample. Age spectra of the samples of valley-filling White River Formation from J.R. Malone et al. (2022) plot closely to the Brule Formation ages (Fig. 5A). This statistical similarity suggests that both the White River Formation atop the Bighorn Range as well as the Brule Formation at Slim Buttes were a part of the same basin-filling sediment and show relief reduction between Laramide basins and ranges, with a steady, gradual decline in regional elevation from west to east.

The dominance of zircons sourced from volcanic provinces in the Great Basin (Fig. 6B; Larson & Evanoff, 1998) suggests consideration of two transport mechanisms. It is possible that northeastward-flowing fluvial systems carried sediment from Utah and Nevada to South Dakota and Wyoming. A large-scale regionally integrated fluvial system would be a complicated process and would require a system on the scale of something such as the modern Mississippi River drainage system routing from southwest to northeast.

The alternative is primarily eolian deposition into the Great Plains in general, and the Slim Buttes locality in particular, from sources in Nevada and Utah as ash fall. Decoupling of fluvial and eolian detrital zircon signatures was revealed Holocene strata in Argentina (Capaldi et al., 2019). Long distance (>1000 km) eolian transport of detrital zircons is documented in the Ordovician Bighorn Dolomite in Wyoming (D. H. Malone, Craddock, McLaughlin, et al., 2017). This is more plausible, given their explosivity, and given the pervasive tuffaceous lithologies present in the Brule Formation and other equivalent White River Group Members (Lillegraven, 1970; Maher & Persinger, 2023). Zhu and Fan (2018) found that intense late Eocene-Oligocene regional volcanism supplied abundant air fall zircons into the latest Eocene-Oligocene sedimentary systems in Colorado. Larson and Evanoff (1998) interpreted the source of ashes in the Douglass and Flagstaff Rim areas of Wyoming as originating from volcanism in Utah and Nevada; this sourcing characteristic may be the case across a wide extent of the White River Group and other correlative units in the region. The consistency of Brule Formation sandstones and facies with their significant volcanic content on a scale that spans states, along with their lack of older zircons, indicates a landscape buried in reworked ignimbrite ash fall. Sediment source areas shifted from west, to west-southwest, to southwest over the course of deposition of the three units (Fig. 6). We suggest a depositional mechanism with ash carried from the southwest by eolian processes and then fed into and recycled by a semi-regional fluvial system in northwest South Dakota. Given the areal extent and intensity of volcanism in each respective region through the middle Cenozoic, an eolian transport mechanism would not require constant and rearrangement of fluvial drainage with time. Windswept sediment off the Colorado Rockies could contribute to the minor Proterozoic signature. In any case, the transition from the Chadron to Brule Formation sediment provenance indicates a major turning point in paleogrography and drainage basin evolution. This is consistent with the development of the northeast-flowing Bell River system and immense southern expansion of the headwaters of the White River drainage system to the south due to the development of high-standing volcanic topography (Mayback et al., 2022)

The Arikaree Group presents a resurgence in older zircon populations that are absent in the underlying Brule Formation, including the presence of Archean and Proterozoic grains. Following the same logic used in consideration of the Brule Formation, this implies the Eocene and Oligocene burial of the Laramide ranges were beginning to be incised by ~20 Ma. This is about 10 m.y. earlier than determined by Caylor et al. (2023) in their study of the more distal Bighorn and Wind River uplifts. One scenario is that the paleodrainage system established during Brule Formation deposition began eroding the proximal Black Hills Laramide uplift. This would account for the distinctly coarser grain size and presence of feldspar grains, and the presence of larger fluvial bedforms in the Arikaree Group sandstones of Slim Buttes. If these interpretations of the Arikaree Group provenance are correct, Neogene re-incision may have begun earlier in the eastern Laramide province and migrated west during the Miocene (Caylor et al., 2023). Alternatively, sediment may also have been contributed from the highest areas of the Wyoming Laramide uplifts which were never buried during the Eocene-Oligocene, negating the need for an earlier, eastern incision.

CONCLUSIONS

The provenance of strata at Slim Buttes records a dynamic depositional setting and paleogeographic evolution through the middle Cenozoic. Considering the composition, structure, and geochronology of the Paleogene strata at the Slim Buttes, we conclude the source of sediment for the Northern Great Plain was primarily controlled by the aeolian input of volcanic-derived sediment from explosive volcanic centers located in the southwest with a subordinate contribution of sediment from fluvial systems eroding the high topography to the west in the Cordilleran thrust belt. Early in the Oligocene, local sourcing of zircons occurred. Later in the Oligocene, large volumes of ash were transported into the Slim Buttes locality, over the top of buried Laramide ranges, into a local fluvial system, depositing tuffaceous sandstones and related interbedded fluvial lithologies. Arikaree Group deposition occurred during the early Neogene re-exhumation of the Laramide uplifts and their environs. These sediments were transported to and deposited in continental margin depositional systems to the north and south.

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Supplementary Materials

Supplemental File, U-Pb Data

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Supplemental File: U-Pb Methodology

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