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# U-Pb Detrital Geochronology and Provenance Comparisons from the Nonmarine Strata of the Dakota Group, Lytle Sandstone, and Morrison Formation in Northeastern New Mexico

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# U-PB DETRITAL GEOCHRONOLOGY AND PROVENANCE COMPARISONS FROM NONMARINE STRATA OF THE DAKOTA GROUP, LYTLE SANDSTONE, AND MORRISON FORMATION IN NORTHEASTERN NEW MEXICO

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ABSTRACT — U-Pb detrital zircon ages from sedimentary rocks of the Early-Late Cretaceous (Albian-Cenomanian) Dakota Group, Late Jurassic-Early Cretaceous(?) Lytle Sandstone, and Late Jurassic (Tithonian) Morrison Formation in northeastern New Mexico provide new geochronologic and provenance constraints on the age range and sources of detritus delivered to the Cordilleran foreland basin during Jurassic-Cretaceous time. Presented here are four U-Pb age spectra (n=978 analyses) from detrital zircons extracted from nonmarine stratigraphic horizons from these units where they crop out in the western Dry Cimarron Valley and near the Creston anticline just west of Las Vegas, New Mexico. All four stratigraphic units share strong similarities in the distribution of Paleo-Mesoproterozoic zircon ages with the majority falling between 1800-1600 (Yavapai-Mazatzal provinces), 1450-1350 (A-type granitoids), and 1300-1000 Ma (Grenville province). Neoproteozoic–Jurassic peak ages are also similar across all units with primary peaks occurring between 625-595, 430-415, 190-150 Ma. Neoproteozoic and early Paleozoic ages overlap ages of recycled Mesozoic eolionites of the Colorado plateau, whereas Jurassic ages overlap ages of magmatic sources of the Cordilleran arc. Although the Dakota Group contains elevated occurrences of Early-Late Cretaceous-age zircons with peak ages between 105-95 and 125-120 Ma, there are no occurrences of zircons younger than Late Jurassic in either the Morrison Formation or Lytle Sandstone. The nine youngest ages from the Morrison Formation fall between Early-Late Jurassic (between ~190–150 Ma), whereas the nine youngest ages from the Lytle are between Middle–Late Jurassic (~172–150 Ma). The nine youngest ages from overlying strata of the Mesa Rica Sandstone and Pajarito Formation are all Late Cretaceous (Cenomanian-earliest Turonian) and occur between ~100-92 Ma. The youngest detrital zircon ages from the Morrison Formation and Lytle Sandstone support a Late Jurassic (Tithonian) age for these units, whereas the youngest ages from both members of the Dakota Group indicate an age of earliest Late Cretaceous (Cenomanian). However, it is certainly possible that the youngest Cretaceous zircons in the Dakota Group originated from reworked, air-fall tuffs (rather than fluvial, water-laid deposits), thus the absence of these Cretaceous grains in the Lytle Sandstone could have resulted from a temporary hiatus in deposition of air-fall material to the Lytle Sandstone during the Early Cretaceous.

## INTRODUCTION

The Mesozoic Cordilleran foreland basin is located in the western part of North America and is one of the best exposed and more widely studied foreland systems in the Western Hemisphere (e.g., Heller et al., 1986; Coney and Evenchick, 1994; DeCelles and Currie, 1996; DeCelles, 2004; Dickinson, 2004; Fuentes et al., 2011; Lawton and Bradford, 2011; Laskowski et al., 2013; Lawton et al., 2014; Leary et al., 2015; Yonkee and Weil, 2015). The stratigraphic response to normal subduction of the Farallon plate beneath North America during the Jurassic-Early Cretaceous and the subsequent Late Cretaceous transition from flexural to dynamic subsidence across the foreland has been well studied (e.g., Cross and Pilger, 1978; Mitrovica et al., 1989; Pang and Nummedal, 1995; DeCelles and Currie, 1996; Currie, 1998; DeCelles, 2004; Painter and Carrapa, 2013; Leary et al., 2015) and is preserved in Late Jurassic-Late Cretaceous foreland basin strata throughout parts of the western U.S. Late Jurassic-Cretaceous strata crop out throughout much of central and northern New Mexico and are thought to record the initial phase of sedimentation in the distal foreland associated with normal subduction and accompanying deformation within the Sevier fold-thrust belt and magmatism and volcanism in the

Cordilleran arc. However, there has been very little focus on determining the provenance and further constraining the age of these strata (e.g., Lytle Sandstone) in northeastern New Mexico.

The focus of this study is on provenance and formation-age relationships between nonmarine synorogenic strata of the Early-Late Cretaceous (Albian-Cenomanian) Dakota Group, the Late Jurassic-Early Cretaceous(?) Lytle Sandstone, and latest Jurassic (Tithonian) Morrison Formation in northeastern New Mexico (Figs. 1, 2). Presented here are four U-Pb detrital zircon age spectra from nonmarine portions of the Dakota Group, Lytle Sandstone, and uppermost Morrison Formation that crop out in the western Great Plains near the western Dry Cimarron Valley and Laramide-age Crestone anticline just west of Las Vegas, New Mexico (Fig. 1). New ages from these strata help constrain upsection provenance trends in the distal parts of the Cordilleran foreland and allow for determining some of the youngest detritus sourced to the basin during latest Jurassic-Cretaceous time. Results from this study are presented and discussed in the context of provenance and age relationships across nonmarine units in the study area with the specific goal of determining the youngest zircon ages in the Lytle Sandstone and comparing them to the underlying Morrison Formation and overlying Dakota Group.

56 Bartnik, Hampton, and Mack

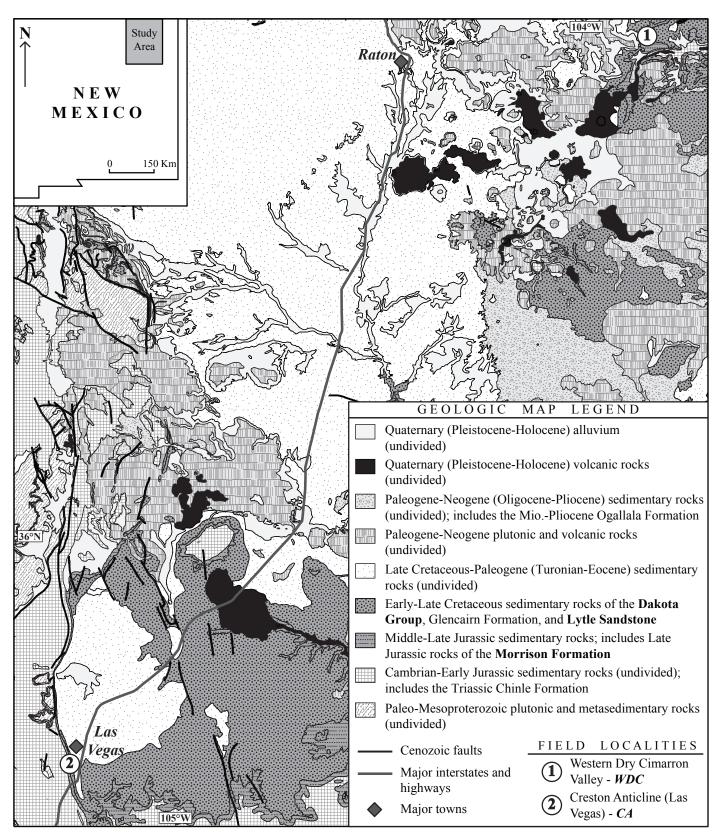


FIGURE 1. Generalized geologic map showing parts of northeastern New Mexico with emphasis on Late Jurassic–Late Cretaceous sedimentary rocks of the Dakota Group, Lytle Sandstone, and Morrison Formation. Geologic and geographic data from New Mexico Bureau of Geology MR, 2003 data base NMBGMR, 2003.

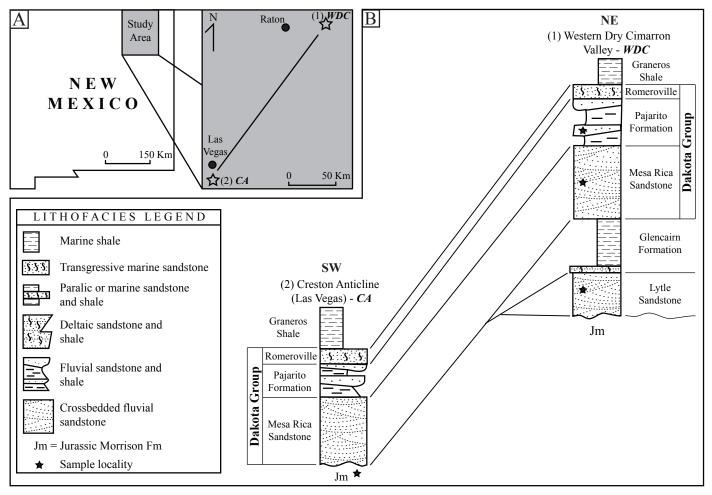


FIGURE 2. Field localities and generalized stratigraphic overview showing uppermost Jurassic-upper Cretaceous rocks in the western Dry Cimarron Valley and Creston anticline in northeastern New Mexico. A) Map showing field localities in northeastern New Mexico. B) Stratigraphy of interest in this study includes nonmarine rocks of the Morrison Formation (Jm) and Lytle Sandstone, as well as nonmarine portions of the Dakota Group (Mesa Rica Sandstone and Pajarito Formation). Stars depict stratigraphic horizon where U-Pb detrital zircon samples were collected from each field locality. Stratigraphic nomenclature from the Dry Cimarron Valley is from Kues and Lucas (1987).

# STRATIGRAPHIC OVERVIEW

The latest Jurassic-earliest Late Cretaceous depositional history of the Cordilleran foreland basin in northeastern New Mexico is recorded by a continuous to discontinuous stratigraphic succession that includes from-base-to-top (1) Late Jurassic (Tithonian) nonmarine strata of the Morrison Formation, (2) Late Jurassic–Early Cretaceous(?) nonmarine strata of the Lytle sandstone and Early Cretaceous (Albian) marine strata of the Glencairn Formation, and (3) Early-Late Cretaceous (Albian-Cenomanian) marine and nonmarine strata of the Dakota Group (Fig. 2). We adopt the stratigraphic nomenclature of Kues and Lucas (1987), which calls for separating the Lytle Sandstone and Glencairn Formation from the previously referenced "Purgatoire Formation" (Rothrock, 1925; De Ford, 1927; Bullard, 1928; Darton, 1928 Stovall, 1943; Baldwin and Muehlberger, 1959; Long, 1966; Scott, 1970). In addition, we also apply the usage of Kues and Lucas (1987) when referencing the three discrete members of the Dakota Group, which include (1) basal Early Cretaceous (Albian) nonmarine strata of the Mesa Rica Sandstone, (2) overlying Early (Albian) nonmarine strata of the Pajarito Formation, and (3) uppermost Late Cretaceous (Cenomanian) marine strata of the Romeroville Sandstone.

We refer to latest Jurassic-Early Cretaceous strata in northeastern New Mexico as a "continuous to discontinuous" stratigraphic succession in the sense that very little to no strata was exhumed, removed, or deformed until well after sedimentation during latest Cretaceous-Paleocene time. However, there are several unconformities observed throughout these strata. The largest gap in sedimentation is observed across the Morrison-Lytle-Glencairn stratigraphic interval where a disconformity of nearly 30 million years occurs between the top of the Late Jurassic (Tithonian) Morrison Formation and base of the Early Cretaceous (Albian) Glencairn Formation (Kues and Lucas, 1987). Note that strata of the Lytle and Glencairn crop out throughout the Dry Cimarron Valley, but both pinch out to the south in the Creston anticline region (Fig. 2). The Morrison-Lytle-Glencairn stratigraphic interval is also perhaps the least understood unconformity in the succession due to very poor age constraint on the Lytle Sandstone. It has not as yet

been determined whether the Lytle Sandstone represents a latest Jurassic-earliest Cretaceous stratigraphic horizon more closely linked with the Morrison Formation or an Early Cretaceous unit more closely associated with the late Albian Glencairn Formation and overlying Dakota Group. An Early Cretaceous (middle-late Albian) age has been assigned to the Lytle Sandstone based on regional stratigraphic relationships and correlation of the Lytle Sandstone to the late Albian Cheyenne Sandstone, which occupies the same stratigraphic horizon just above the Morrison Formation in south-central Kansas (e.g., Ward, 1986). However, no fossils or other age constraints have been reported from the Lytle Sandstone in the Dry Cimarron region. Thus to date, the age of the Lytle Sandstone could be anywhere from latest Jurassic-Early Cretaceous (mid-late Albian; Kues and Lucas, 1987). The top Morrison-base Lytle contact appears to be largely transitional with no significant evidence of a disconformity, whereas the top Lytle-base Glencairn contact is thought to be an erosional, disconformable contact (Kues and Lucas, 1987).

The contact between the top Glencairn-base Dakota Group (i.e., Mesa Rica Sandstone) has been characterized as a sharp, erosional disconformity (with very little time missing between units), whereas the top Mesa Rica-base Pajarito contact is thought to be transitional with evidence for interbedding where the contact has been documented in east-central New Mexico (Kues and Giles, 1987). The contact between the top Pajarito and base Romeroville Sandstone is likely gradational and is marked by a clear lithologic transition from fine-grained strata of the Pajarito to clean quartz sandstone at the base of the Romeroville (Kues and Lucas, 1987). The following text provides a brief stratigraphic overview of nonmarine portions of the Dakota Group (i.e., Mesa Rica Sandstone and Pajarito Formation), Lytle Sandstone, and uppermost Morrison Formation in northeastern New Mexico. Kues and Lucas (1997) provide a more comprehensive stratigraphic and paleontologic summary of all Late Jurassic-Cretaceous units exposed throughout the Dry Cimarron Valley.

# DAKOTA GROUP Pajarito Formation

The Pajarito Formation overlies the Mesa Rica Sandstone and is the youngest and finest-grained nonmarine member of the Dakota Group. It consists of poorly exposed outcrops of interbedded sandstone, siltstone, and shale throughout the western Dry Cimarron and Creston localities (Figs. 2, 3A, 3B). In the Dry Cimarron Valley, the Pajarito consists of ~20 m of massive, bioturbated, orange-yellow, quartz sandstone and gray, organic-rich siltstone and shale that is interpreted to represent nonmarine sedimentation in a delta plain environment (Kues and Lucas, 1987). The age of the Pajarito Formation is thought to be latest Early Cretaceous (late Albian) based on reported occurrences of nine taxa of marine molluses (Stoval, 1943). Footprints of the Cretaceous Amblydactylus (ichnogenus of ornithopod dinosaurs) have also been reported from parts of the Pajarito in northeastern New Mexico (Gillette and Thomas, 1985; Lucas et al., 1986; Lucas et al., 1987).

#### Mesa Rica Sandstone

The Mesa Rica Sandstone directly overlies the Glencairn Shale in the western Dry Cimarron Valley (Figs. 2, 3C) and represents the basal part of the Dakota Group in northeastern New Mexico. The Mesa Rica consists largely of medium- to coarse-grained sandstone with isolated occurrences of pebble-conglomerate and organic material (Figs. 2, 3C). A total thickness of 33 m is reported for the Mesa Rica Sandstone in the Dry Cimarron Valley (Kues and Lucas, 1987), and the unit is interpreted to represent a sheetflow-dominated, fluvial depositional environment (Gilbert and Asquith, 1976; Kisucky, 1987; Kues and Lucas, 1987; Holbrook, 1996). An Early Cretaceous (Albian) age is assigned to the Mesa Rica Sandstone due primarily to occurrences of Cretaceous plant species (Rothrock, 1925; Nöe, 1925; Stoval, 1943).

# Lytle Sandstone

The Lytle Sandstone underlies the basal Long Canyon Sandstone Bed of the Glencairn Shale in the Dry Cimarron Valley (Figs. 2, 3C, 3D) and is thought to be the oldest Early Cretaceous strata exposed in this region. The unit consists largely of planar and cross-stratified sandstone and siltstone with isolated occurrences of conglomeratic sandstone (Figs. 2, 3E) that contain primarily chert clasts with isolated occurrences of quartz and quartzite clasts. The Lytle throughout the Dry Cimarron region ranges from 10–20 m thick (e.g., Stoval, 1943; Cooley, 1955; Baldwin and Muehlberger, 1959; Kues and Lucas, 1987) and likely records sedimentation in a fluvial-dominated system. Poor age constraint from this unit precludes a consensus on whether the Lytle is closer in age to the overlying Albian Glencairn Formation and basal Dakota Group or to the underlying Tithonian parts of the Morrison Formation. However, there are strong lithologic similarities with the Lytle Sandstone and known Albian units across parts of Kansas (e.g., Cheyenne Sandstone), Colorado (e.g., Burrow Canyon Formation), Utah (e.g., Cedar Mountain Formation), and further north in parts of Montana and Wyoming (e.g., Cloverly Formation). Each of these discrete units occupies the same stratigraphic horizon at the top of the Morrison Formation and base of late Albian strata (i.e., Glencairn-equivalents). At present, the best age constraints for the Lytle Sandstone are occurrences of Late Jurassic dinosaur fossils (e.g., Apatosaurs, Allosaurus, Camarasaurus, and Stegosaurus) reported from the top of the Morrison Formation (collected as high as 6 m below the base of the Lytle; Stovall, 1938; 1943; West, 1978) and occurrences of Albian marine invertebrate mollusks (e.g., Texigryphaea) in the basal part of the overlying Glencairn Formation (Cooley, 1955; Kues and Lucas, 1987).

## **Morrison Formation**

The uppermost part of the Morrison Formation was observed and sampled just west of Las Vegas, New Mexico in the east limb of the Creston anticline (Figs. 2, 3F). At this location (and throughout northeastern New Mexico), the uppermost part

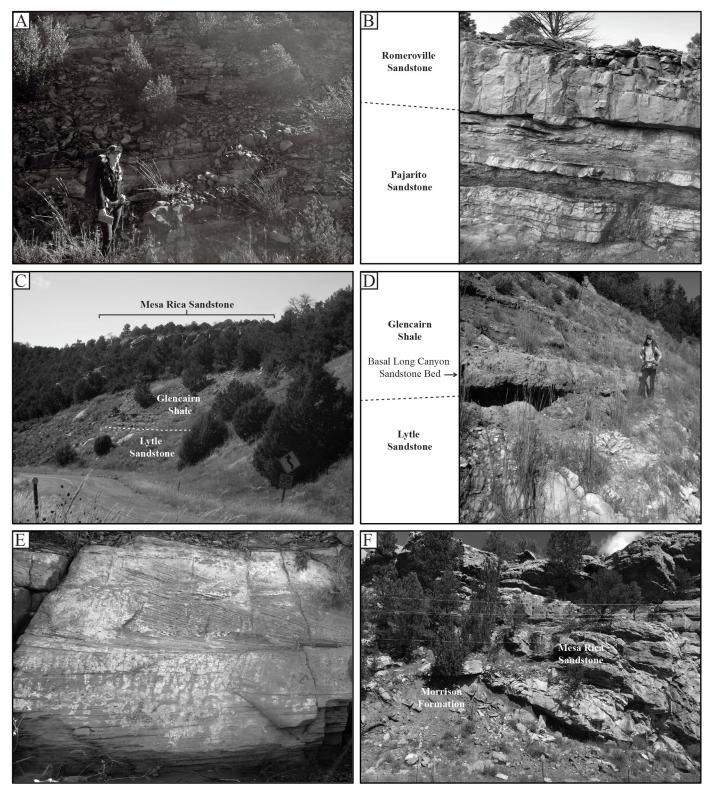


FIGURE 3. Field photos showing Late Jurassic—Cretaceous strata from the western Dry Cimarron Valley and Creston anticline northeastern New Mexico. A) Thin, tabular to lenticular, nonmarine sandstone beds of the Pajarito Formation of the Dakota Group exposed in the western Dry Cimarron Valley (geologist for scale).

B) Interbedded nonmarine sandstone and siltstone beds of the upper part of the Pajarito Formation and overlying marginal marine sandstone of the Romeroville Sandstone (top Dakota Group) exposed near the Creston anticline. For scale, the Romeroville Sandstone in this photo is ~1 m thick. C) View to the south showing the western Dry Cimarron Valley of the nonmarine Lytle Sandstone (base), overlying marine Glencairn Shale, and Mesa Rica Sandstone of the Dakota Group (top). Road and road sign for scale. D) Photo showing contact between the top of the Lytle Sandstone and basal Long Canyon Sandstone Bed of the Glencairn Shale in the western Dry Cimarron Valley (geologist for scale). E) Tangential foresets (upper) and plane bed-parallel laminations (lower) in the Lytle Sandstone of the western Dry Cimarron Valley (rock hammer for scale). F) View to the north showing tilted beds of the Morrison Formation and overlying Mesa Rica Sandstone along the eastern limb of the Creston anticline. Note that both the Lytle Sandstone and Glencairn Shale are absent from the stratigraphic interval between the Morrison and Mesa Rica Sandstone. For scale, the Morrison Formation in the field of view in this photo is ~5.5 m thick.

of the formation consists of interbedded shale, siltstone, and isolated lenticular and tabular beds of massive sandstone (e.g., Stanton, 1905; Rothrock, 1925; DeFord, 1927; Mankin, 1972). Overall, thickness of the Morrison Formation in this region is variable and ranges from ~30-150 m with average thicknesses falling between ~90–125 m (Mankin, 1972). The Late Jurassic age of the Morrison Formation is well established by numerous occurrences of fossils (e.g., dinosaurs, plants, amphibians) and dated ash beds. The top of the Morrison in the Dry Cimarron Valley is thought to be Late Jurassic (likely Tithonian) based on occurrences of the dinosaur fossils *Apatosaurs*, *Allosaurus*, Camarasaurus, and Stegosaurus found in the uppermost part of the unit (Stovall, 1938, 1943; West, 1978). Kues and Lucas (1987) point out that it is possible that the top of the Morrison in the Dry Cimarron Valley could be as young as earliest Early Cretaceous given that Early Cretaceous ages have been reported from the upper parts of the unit in other localities (e.g., Douglass and Johnson, 1984; Bowman et al., 1986).

# **METHODS**

Three detrital zircon samples were collected from nonmarine stratigraphic horizons in the Pajarito Formation (n=291 analyses), Mesa Rica Sandstone (n=300 analyses), and Lytle Formation (n=293 analyses) in the western Dry Cimarron Valley. In addition, one detrital zircon sample was collected from the uppermost Morrison Formation (n=94 analyses) in the Las Vegas/Creston anticline region (Figs. 1, 2). Given the somewhat poor exposure of the Morrison Formation throughout the Dry Cimarron Valley, we opted to collect and analyze the Morrison where it crops out just west of Las Vegas, New Mexico. Table 1 provides a summary of all sample localities. Zircon crystals were extracted from samples at New Mexico State University using standard heavy-mineral separation techniques (i.e., utilizing a Chipmunk jaw crusher, Bico pulverizer, 30-micron mesh sieve, Gemini table, Frantz separator, sodium polytungstate, and methylene iodide). Zircons were then placed into a one-inch epoxy mount with zircon standards R33, Sri Lanka (SL), and FC at the Arizona Laserchron Center in Tucson, Arizona. Zircon mounts were sanded to a depth of ~20 microns, polished, imaged, and cleaned prior to analysis. Cathodoluminescence images were acquired to assist in identifying locations for ablation pits at the cores of zircons.

All U-Pb analyses of detrital zircons were conducted by laser ablation inductively coupled mass spectrometry (LA-ICPMS) at the Arizona LaserChron Center. Data produced from zircon analyses were imported into an Excel spreadsheet ("agecalc"), which corrects data, calculates ages, uncertainties, and errors (Gehrels et al., 2008). In "agecalc", raw data is first corrected for background intensities and excess  $^{204}\mathrm{Hg}$  that is indicated by above-background  $^{202}\mathrm{Hg}$ . Next, for each analysis, the errors in determining  $^{206}\mathrm{Pb}/^{238}\mathrm{U}$  and  $^{206}\mathrm{Pb}/^{204}\mathrm{Pb}$  result in the application of a measurement error of ~1-2% (at  $2\sigma$ ) in the  $^{206}\mathrm{Pb}/^{238}\mathrm{U}$  age. Errors in  $^{206}\mathrm{Pb}/^{207}\mathrm{Pb}$  and  $^{206}\mathrm{Pb}/^{204}\mathrm{Pb}$  measurements also result in ~1-2% (at  $2\sigma$ ) uncertainty in age for grains that are >1.0 Ga, but are substantially larger for younger grains due to low intensities of  $^{207}\mathrm{Pb}$  signals. For most analyses, the

cross-over in precision of  $^{206}\text{Pb}/^{238}\text{U}$  and  $^{206}\text{Pb}/^{207}\text{Pb}$  ages occurs at  $\sim 1.2$  Ga. Correction of common lead is done by using Hg-corrected  $^{204}\text{Pb}$  and assuming an initial Pb ratio from Stacey and Kramers, (1975). Uncertainties of 1.5 for  $^{206}\text{Pb}/^{204}\text{Pb}$  and 0.3 for  $^{207}\text{Pb}/^{204}\text{Pb}$  are applied to these model ratios based on variations of Pb ratios in modern crystalline rocks. Inter-element fractionation of Pb/U is generally  $\sim 5\%$ , whereas apparent fractionation of Pb isotopes is generally < 0.2%. Analyses of standards are used to correct for these fractionations. The uncertainty resulting from the calibration correction is generally 1-2% ( $2\sigma$ ) for both  $^{206}\text{Pb}/^{207}\text{Pb}$  and  $^{206}\text{Pb}/^{238}\text{U}$  ages.

# **RESULTS**

This study provides four new U-Pb detrital zircon age spectra (n=978 analyses) from nonmarine portions of the Dakota Group (Pajarito Formation and Mesa Rica Sandstone), Lytle Sandstone, and the Morrison Formation (Figs. 4A, 4B). Ages are presented for each sample (at 2 $\sigma$  error) in the context of (1) peak occurrences of Paleoproterozoic–Phanerozoic age zircons, (2) percent occurrence of Phanerozoic-age zircons, and (3) cluster and occurrence of the youngest Mesozoic zircons (i.e., nine youngest grains) in each sample. Note that Archean age grains occur but are isolated and rare in all four samples (Fig. 4A). A summary of all geochronologic data collected from this study can be found in the online Data Repository (http://nmgs.nmt.edu/repository).

Sample DCV-PAR-01 (Dakota Group – Pajarito Formation) contains a range of Paleo-Neoproterozoic zircons (n=158 total) that fall primarily between 1700-1600 Ma (peak age at 1659 Ma), 1450-1350 Ma (peak age at 1421 Ma), 1300-1000 Ma (peak ages at 1256 and 1066 Ma) and 670-595 Ma (peak age 624 Ma; Fig. 4A). The remaining Cambrian-Cretaceous zircons (n=133 total) fall largely between 475–360 Ma (peak ages at 467, 413 and 376 Ma), 190-150 Ma (peak age at 168 Ma), 125-120 Ma (peak age at 123 Ma) and 105-95 Ma (peak age at 99 Ma; Fig. 4B). A total of ~43% of Phanerozoic zircons are Cambrian-Pennsylvanian, whereas just ~1% and ~2% are Permian and Triassic in age, respectively (Fig. 4B). Approximately 18% of grains are Jurassic, ~22% are Early Cretaceous, and the remaining ~14% are Late Cretaceous age (Fig. 4B). The nine youngest ages from the Pajarito Formation are Late Cretaceous in age and fall between 98±1 and 93±2 Ma (Fig. 4B).

Sample DCV-MR-01 (Dakota Group – Mesa Rica Sandstone) contains Paleo-Neoproterozoic zircons (n=190 total) that fall primarily between 1800–1600 Ma (peak ages at 1876,1739, and 1636 Ma), 1450–1350 Ma (peak age at 1463 Ma), 1300–1000 Ma (peak ages at 1146 and 1062 Ma) and 670–595 Ma (peak age 616 Ma; Fig. 4A). Cambrian–Cretaceous zircons (n=110 total) fall largely between 475–360 Ma (peak ages at 453, 418, and 378 Ma), 190–150 Ma (peak age at 166 Ma), and 105–95 Ma (peak age at 100 Ma; Fig. 4B). Approximately 45% of Phanerozoic age zircons are Cambrian–Pennsylvanian and just 2% and 3% are Permian and Triassic in age, respectively (Fig. 4B). Remaining Mesozoic age grains compose ~50% of all Phanerozoic grains with ~19% of ages being Jurassic, ~18% Early Cretaceous, and ~13% being

TABLE 1. Summary of GPS locations for all U-Pb detrital zircon samples from this study.

Samp. Name (n=analyses)	Field Locality	Formation	Lat./Long.	Formation Age
DCV-PAR-01 (n=291)	W. Dry Cimarron	Pajarito Fm.	36.9408/-103.8736	Early-Late Cretaceous. (Albian)
DCV-MR-01 (n=300)	W. Dry Cimarron	Mesa Rica Ss.	36.9372/-103.8706	Early Cretaceous (Albian)
DCV-LYT-01 (n=293)	W. Dry Cimarron	Lytle Ss.	36.9339/-103.8686	Late Jurassic-Early Cretaceous?
CR-MOR-01 (n=94)	Crestone Anticline	Morrison Fm.	35.5594/-105.2428	Late Jurassic (Tithonian)

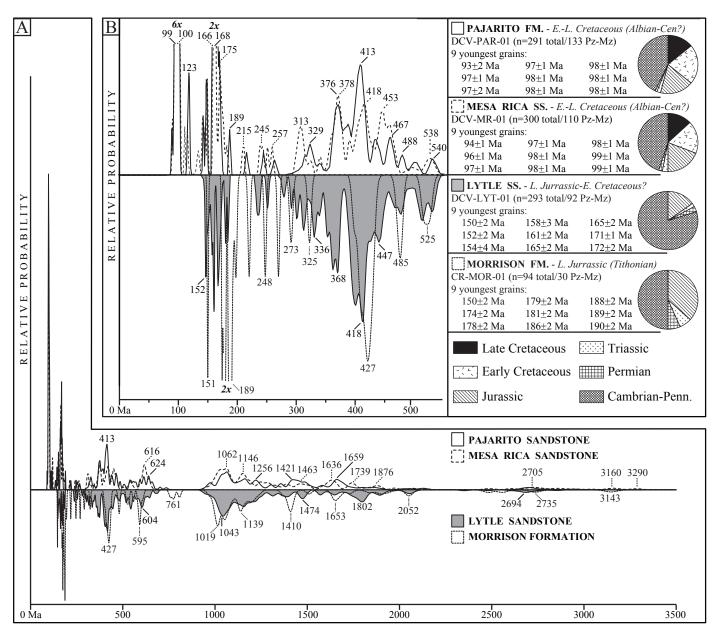


FIGURE 4. Diagrams showing relative age probability density plots, pie diagrams, and summaries of youngest U-Pb detrital zircon ages from the Pajarito Formation, Mesa Rica Sandstone, Lytle Sandstone, and Morrison Formation of northeastern New Mexico. A) Summaries showing Precambrian—Phanerozoic detrital zircon ages for each unit (n=978 analyses). Specific ages represent primary and secondary peak age occurrences. Note strong similarities in occurrences of Precambrian detrital zircons from all four stratigraphic intervals. B) Diagrams showing Phanerozoic detrital zircon ages (n=365 analyses), pie diagrams, and youngest nine ages from each unit. Pie diagrams depict relative detrital zircon contributions from Permian—Late Cretaceous Cordilleran magmatic arc sources and magmatic and recycled Cambrian—Pennsylvanian sources. Note that all four samples have similar Paleozoic—Jurassic zircon occurrences and peak ages. The Dakota Group contains elevated percentages of Early—Late Cretaceous zircons whereas the Morrison Formation and Lytle Sandstone contain only Jurassic and older zircon grains.

Late Cretaceous in age (Fig. 4B). The nine youngest ages from the Mesa Rica Sandstone are Late Cretaceous in age and fall between 99±1 and 94±1 Ma (Fig. 4B).

Sample DCV-LYT-01 (Lytle Sandstone) contains numerous Paleo-Neoproterozoic zircons (n=201 total) that fall primarily between 1800–1600 Ma (peak age at 1802 Ma), 1500–1350 Ma (peak age at 1474 Ma), 1300–1000 Ma (peak age 1043 Ma) and 670–550 Ma (peak age 604 Ma; Fig. 4A). The remaining Cambrian–Cretaceous zircons (n=92 total) fall largely between 460–320 Ma (peak ages at 447, 418, 368, and 336 Ma), and 190–145 Ma (peak age at 152 Ma; Fig. 4B). A majority (~79%) of Phanerozoic zircons are Cambrian–Pennsylvanian whereas Permian and Triassic grains compose just 3% and 2%, respectively (Fig. 4B). Approximately 16% of Phanerozoic grains are Jurassic in age (Fig. 4B). There are no occurrences of Cretaceous zircons in this sample. The nine youngest ages from the Lytle Sandstone are Middle–Late Jurassic in age and fall between 172±2 and 150±2 Ma (Fig. 4B).

Sample CR-MOR-01 (Morrison Formation) contains Paleo-Neoproterozoic zircons (n=64 total) that fall primarily between 1700–1600 Ma (peak age at 1653 Ma), 1450–1350 Ma (peak age at 1410 Ma), 1300–1000 Ma (peak ages at 1139 and 1019 Ma) and 800–550 Ma (peak ages 761 and 595 Ma; Fig. 4A). The remaining Cambrian–Cretaceous zircons (n=30 total) fall largely between 540–315 Ma (peak ages at 525, 485, 427 and 325 Ma), 280–215 Ma (peak ages at 276 and 248 Ma), and 200–145 Ma (peak ages at 189 and 151 Ma; Fig. 4B). A total of ~50% of Phanerozoic zircons are Cambrian–Pennsylvanian, ~7% are Permian, ~7% are Triassic, and ~36% are Jurassic in age (Fig. 4B). The nine youngest ages from the Morrison Formation are Early–Late Jurassic in age and fall between 190±2 and 150±2 Ma (Fig. 4B).

#### DISCUSSION

New U-Pb detrital zircon ages from nonmarine sedimentary rocks of the Dakota Group (Mesa Rica Sandstone and Pajarito Formation), Lytle Sandstone, and Morrison Formation in northeastern New Mexico constrain magmatic and recycled source areas that supplied sediment to the distal margins of the Cordilleran foreland during the Late Jurassic-Cretaceous. In addition, the youngest zircon grains in these strata provide some insight on the maximum depositional ages of each unit (Fig. 4B). All four stratigraphic units share strong similarities in occurrences of Jurassic and older zircon ages with the majority falling between 1800–1600, 1450–1350, 1300–1000, 625–595, 430-415, and 190-150 Ma. Paleo-Mesoproterozoic zircon ages overlap ages of the Yavapai (1800-1700 Ma) and Mazatzal (1700–1600 Ma) provinces, A-type granitoids (1450–1350 Ma), as well as the Grenville (1300–1000 Ma) province (Figs. 4, 5). Neoproterozoic and early Paleozoic zircons were likely originally derived from peri-Gondwanan, Appalachian source areas and transported west to southwestern Laurentia during the Pennsylvanian (e.g., Dickinson and Gehrels, 2009a; Garber et al., 2018; Kissock et al., 2018). Neoproterozoic-early Paleozoic magmatic provinces are sparse throughout the southwestern U.S., although recycled zircons of this age range have been documented from Jurassic eolionite strata from the Colorado Plateau (Dickinson and Gehrels, 2008, 2009b) as well as other locations throughout the U.S. Midcontinent (e.g., Garber et al., 2018; Kissock et al., 2018; Potter-McIntire et al., 2018).

Permian—Triassic zircons do not compose large percentage of ages, but they are consistently present in all samples and were likely derived from parts of the Cordilleran arc of northern and eastern Mexico, western Arizona, and eastern California (e.g., Busby-Spera, 1988; Lawton and McMillan, 1999; Torres et al., 1999; Dickinson and Lawton, 2001; Barth and Wooden, 2006; Haxel et al., 2008; Arvizu et al., 2009). Jurassic zircon ages from this study overlap in part with magmatic provinces in the Sierra Nevada (e.g., Ducea, 2001). Both the Mesa Rica Sandstone and Pajarito Formation of the Dakota Group contain Early—Late Cretaceous zircons, which were likely derived from magmatic provinces in the Cordilleran arc of California, Baja, and Sonora as well as the oldest parts of the Sierra Nevada arc (e.g., Ducea, 2001).

Although the Dakota Group contains elevated occurrences of young Cretaceous-age zircons with peak ages between 105-95 and 125-120 Ma, there are no occurrences of zircons younger than Late Jurassic in either the Morrison Formation or Lytle Sandstone. The nine youngest ages from the Mesa Rica Sandstone and Pajarito Formation are all Late Cretaceous (Cenomanian-earliest Turonian) and occur between ~100-92 Ma. The nine youngest ages from the Morrison Formation all fall between Early-Late Jurassic (between ~190-150 Ma), whereas the nine youngest ages from the Lytle Sandstone are between Middle-Late Jurassic (~172-150 Ma). This trend in youngest age of detrital zircons from the Lytle Sandstone supports a Late Jurassic age for this previously undated unit. However, we caution that although U-Pb maximum depositional ages have been used to provide much needed age constraints on poorly dated stratigraphic successions, this approach alone may not always reflect the true age of a unit (e.g., Dickinson and Gehrels, 2009b). In the case of the Lytle Sandstone, it is certainly possible that the youngest zircons in this unit (as well as the overlying Dakota Group; e.g., Amato et al., 2018) originated from reworked, air-fall tuffs rather than fluvial, water-laid deposits. In this scenario, the absence of Cretaceous grains in the Lytle Sandstone could be interpreted as a temporary hiatus in air-fall material being deposited/delivered to the Lytle Sandstone during the Early Cretaceous. If this were the case, the similarity in zircon ages and provenance between the Morrison Formation and Lytle Sandstone could be explained by later reworking and recycling of Morrison Formation detritus into the Lytle Sandstone during the Early Cretaceous. This could be tested by much more regional detrital geochronologic studies on the Lytle Sandstone and equivalent units throughout Oklahoma, Colorado, Utah, and Kansas (e.g., Cheyenne Sandstone, Burrow Canyon Formation, Cedar Mountain Formation).

# **CONCLUSIONS**

U-Pb detrital zircon geochronologic trends from the nonmarine parts of the Dakota Group, Lytle Sandstone, and Morrison Formation in northeastern New Mexico are similar, with

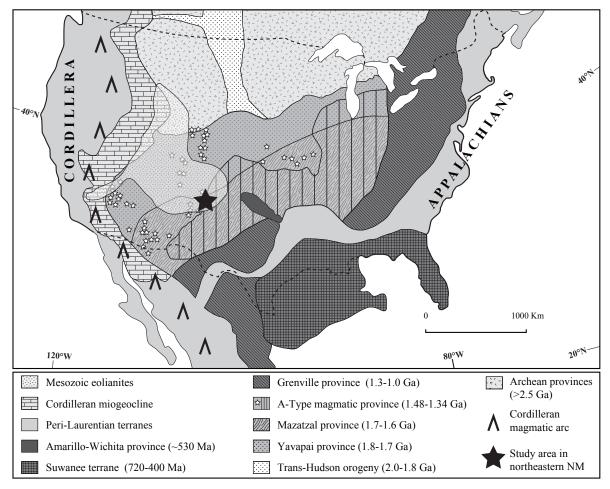


FIGURE 5. Precambrian—Phanerozoic province map showing crustal boundaries of North America (modified from Laskowski et al., 2013 and Gehrels et al., 2011). Original crustal boundaries are from Hoffman (1988). Distribution of Mesozoic eolionites are from Leier and Gehrels (2011).

the exception of Early-Late Cretaceous-age zircons that only occur in the Mesa Rica Sandstone and Pajarito Formation of the Dakota Group. Paleo-Mesoproterozoic zircon ages in all samples overlap ages of basement provinces of the Yavapi (1800-1700 Ma) and Mazatzal (1700-1600 Ma) provinces, A-type granitoids of the central and southwestern U.S. (1450– 1350 Ma), and the Grenville province (1300–1000 Ma). Neoproterozoic-early Paleozoic grains from all samples represent second- to possibly third-order recycling of zircons that were derived most recently from Jurassic eolionite strata from the Colorado Plateau (Dickinson and Gehrels, 2009b). Permian-Late Cretaceous zircons overlap in age with Cordilleran magmatic arc source areas in parts of northern and eastern Mexico, eastern California, Baja, Sonora, and western Arizona (e.g., Busby-Spera, 1988; Lawton and McMillan, 1999; Torres et al., 1999; Dickinson and Lawton, 2001; Ducea, 2001; Barth and Wooden, 2006; Haxel et al., 2008; Arvizu et al., 2009). The voungest detrital zircons in each unit are consistent with a Late Jurassic age for the top of the Morrison Formation and support a Early-Late Cretaceous age (Albian-earliest Cenomanian) for the Mesa Rica Sandstone and Pajarito Formations of the Dakota Group. The youngest group of zircons from the Lytle Sandstone supports an age of Late Jurassic. However, future

geochronologic work is needed to determine whether the lack of Cretaceous-age zircons in the Lytle indicates a Late Jurassic age or simply represents a temporary hiatus in air-fall detritus (rather than fluvial, water-laid sediment) to the distal margins of the Cordilleran foreland during the Early Cretaceous.

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