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DETRITAL SANIDINE AGES FROM THE UPPER JURASSIC BRUSHY BASIN MEMBER OF THE MORRISON FORMATION AND OVERLYING STRATA, SANDOVAL COUNTY, NEW MEXICO

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Abstract—The Morrison Formation, a world-famous Jurassic stratigraphic unit in the western United States, consists of three members in New Mexico (ascending): the Salt Wash, Brushy Basin, and Jackpile Members. This study focuses on $^{40}Ar/^{39}Ar$ ages of detrital sanidines (DS) from the Brushy Basin and Jackpile Members in New Mexico, near the San Ysidro area in Sandoval County. The formation's stratigraphy is characterized by sandstone-dominated and mudrock-dominated units. The research used six DS samples, two from the uppermost Brushy Basin Member, three from the Jackpile Member, and one from the basal Oak Canyon Member of the Dakota Sandstone, to determine the maximum depositional age (MDA) and to characterize provenance. Maximum depositional age results for the Brushy Basin Member are Late Jurassic, at ≤150.39 ± 0.41 and ≤148.86 ± 0.31 Ma, for two samples that are a combination of integrated dates from low-resolution age spectrum and total fusion analyses; this is similar to prior $^{40}Ar/^{39}Ar$ dates of 147–155 Ma from Utah. These are also analytically indistinguishable from U-Pb zircon dates (149–150 Ma) from Colorado. The youngest MDA of the Jackpile Member samples comes from the stratigraphically highest sample and is ≤151.39 ± 0.15 Ma, which does not resolve whether the Jackpile is Late Jurassic or Early Cretaceous. The lowest Dakota Sandstone had a single youngest grain at 213.4 ± 0.2 Ma, much older than the $^{40}Ar/^{39}Ar$ ash age of 98.1 ± 2.4 Ma from this unit elsewhere. Provenance changes markedly upsection based on the distribution of DS dates: The Brushy Basin Member contains dominantly 160–190 Ma Jurassic grains whereas the Jackpile Member and Dakota Sandstone contain dominantly 250–300 Ma Permian–Triassic grains. This is consistent with a disconformity between the Brushy Basin and Jackpile Members and northerly fluvial transport of Jackpile Member sands across a regional sub-Cretaceous unconformity in southern Arizona and New Mexico. Furthermore, the overall correspondence of DS dates between the Jackpile Member and the Dakota Sandstone versus less correspondence with the Brushy Basin could support a Cretaceous age for the Jackpile Member. These findings demonstrate the power of DS dating, especially age spectrum analysis, for refining Mesozoic chronostratigraphy.

INTRODUCTION

The Morrison Formation is a well-known Jurassic stratigraphic unit that crops out in the western United States from northern Montana to central New Mexico and from central Utah to western Oklahoma. Deposition was primarily by fluvial processes in the vast Morrison foreland basin with north-directed fluvial transport from uplifted areas of the Mogollon highlands and Bisbee basin rift flank to the south and west (e.g., Lawton, 1994; Dickinson, 2018; Chapman and DeCelles, 2021). Age constraints on the Morrison Formation come from diverse biostratigraphic data, magnetostratigraphy, and radioisotopic ages that indicate that Morrison Formation deposition took place over about 8 My during the Late Jurassic, from 147 to 155 Ma (e.g., Trujillo and Kowallis, 2015; Chapman and DeCelles, 2021).

In New Mexico, the Morrison Formation crops out across much of the northern part of the state, north of approximately the latitude of Socorro (Lucas and Anderson, 1998; NMGMR, 2003). Here, it is a tripartite unit: (1) a lower, sandstone-dominated unit called the Salt Wash Member or Westwater Canyon Member; (2) a medial, mudrock-dominated unit called the Brushy Basin Member; and (3) an upper, sandstone-dominated unit, the Jackpile Member, a unit apparently present only in New Mexico. The formation thickens from 0 m to about 300 m towards the Four Corners area (Chapman and DeCelles, 2021).

Direct age constraints on the Morrison Formation strata in New Mexico are relatively few. Limited magnetostratigraphy has been undertaken (Steiner et al., 1994), and what few radioisotopic ages have been published are based on old analyses (e.g., K/Ar). Biostratigraphy of the New Mexico Morrison Formation identifies characteristic Late Jurassic dinosaurs such as *Allosaurus*, *Apatosaurus*, *Camarasaurus* and *Diplodocus* from the Brushy Basin Member (Lucas and Heckert, 2015). Most of the radioisotopic ages published for the Morrison Formation are $^{40}Ar/^{39}Ar$ and U-Pb ages of ash beds in Utah and Colorado (Kowallis et al., 1991; Trujillo and Kowallis, 2015; Galli et al., 2018).

Here, we report $^{40}Ar/^{39}Ar$ ages of DS in the Brushy Basin and Jackpile Members of the Morrison Formation near San Ysidro in Sandoval County (Figs. 1–4). Our study was largely motivated by a desire to determine the age of the Jackpile Member, but unfortunately, it did not resolve that age other than to demonstrate that the Jackpile Member is no older than Late Jurassic. Nevertheless, this study demonstrates well the value and accuracy of detrital sanidine (DS) geochronology for Jurassic chronostratigraphic research.

STRATIGRAPHIC CONTEXT

Morrison Formation strata are extensively exposed in the southeastern San Juan Basin (e.g., Woodward, 1987; Anderson and Lucas, 1996; Lucas, 2021). We sampled a stratigraphic section of the uppermost Brushy Basin Member and the entire overlying Jackpile Member of the Morrison Formation, and the basal strata of the overlying Oak Canyon Member of the Dakota Sandstone (Fig. 1). The section we sampled (Figs. 1 and 2) is located off the flank of Bernalillito Mesa along the Cabezon

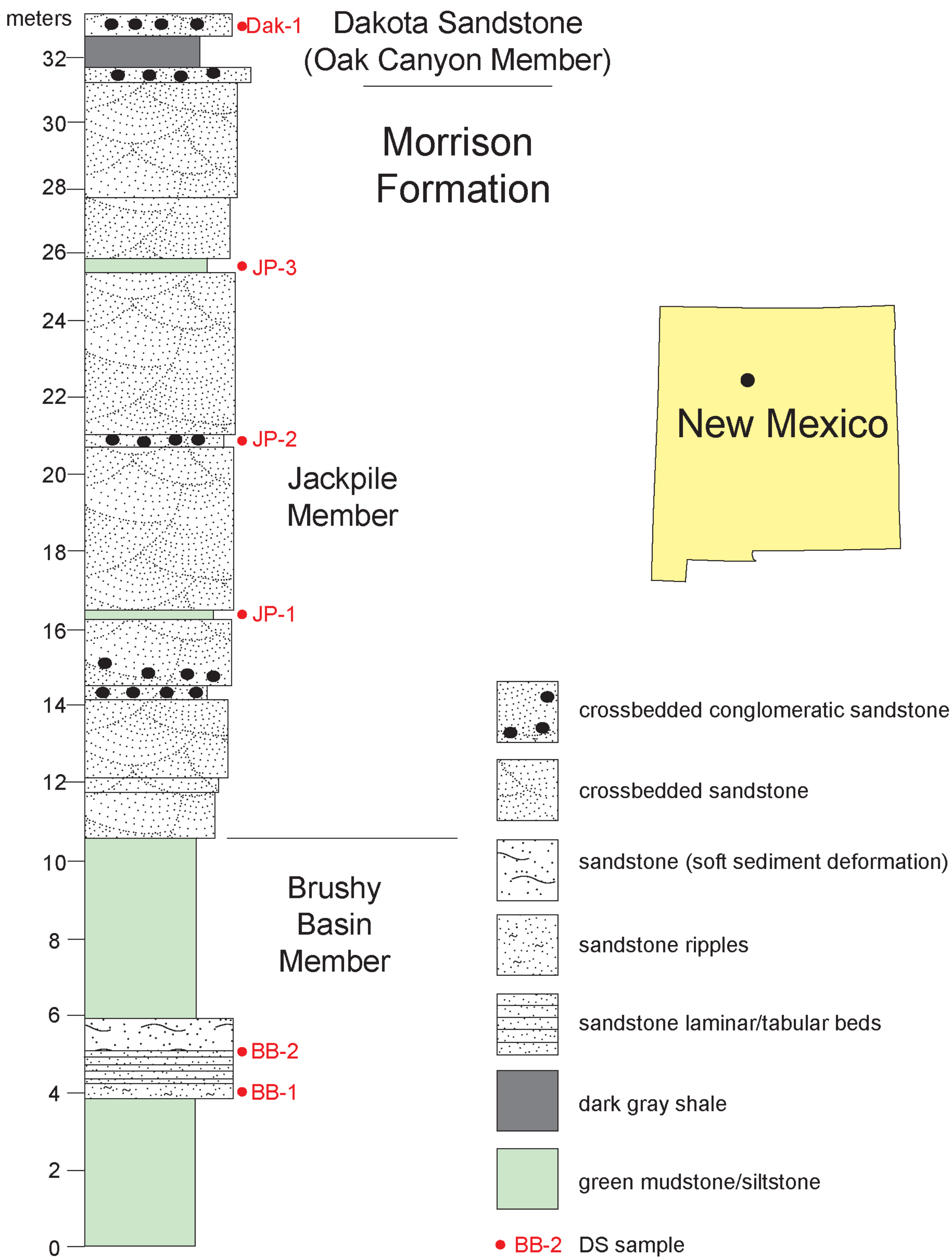

Figure 1. Stratigraphic column of the upper Brushy Basin Member, Jackpile Member, and lower Dakota Sandstone near San Ysidro, New Mexico, sampled for DS analysis. Note that the field abbreviations for sample identifiers have been simplified in the figure and text.

Road at approximately 35.495979º, −106.924422º. At this stratigraphic section, the upper ~10–11 m of the Brushy Basin Member are exposed and are mostly pale green mudrock intercalated with one interval of sandstone. The lower part of this sandstone interval, about 7.6 m beneath the overlying Jackpile Member, was sampled in two places for DS (Fig. 3). This sandstone bed is an isolated channel element of ripple, laminar, and tabular bedded sandstone overlain by an interval with soft-sediment deformation structures. The soft-sediment deformation structures consist of modified fine- to medium-grained sandstone that developed up to ~5-m-long cylinder-like structures with near circular to dome-shaped cross sections. External surfaces of the soft-sediment deformation structures have parting lineations that are parallel to the orientation of the cylinders, which is approximately east-west. Internally, the core of each cylinder is composed of massive, structureless sandstone or bent layered sandstone that parallels the external morphology of the cylinder.

The Jackpile Member of the Morrison Formation overlies the Brushy Basin Member at a sharp contact between cross-bedded sandstone and underlying pale green mudrock. The Jackpile Member is about 22 m thick and mostly cross-bedded kaolinitic sandstone and conglomeratic sandstone with a couple of pale green sandy mudstone interbeds (Fig. 4). The sands are deeply weathered so that most feldspars have been kaolinized. Therefore, we sampled from green sandy mudstones (Fig. 1) in hopes of finding preserved and pristine sanidine.

The basal part of the Cenomanian (cf. Sealey and Lucas, 2018), the Oak Canyon Member of the Dakota Sandstone, disconformably overlies the Jackpile Member and contains beds of silica-pebble conglomerate and dark gray shale. We sampled from a sandstone lens above gray mudstone within a meter of the basal Dakota Sandstone unconformity (Figs. 1 and 5).

^{40}AR/^{39}AR AGES

Methods

Detrital sanidine was concentrated by standard methods from six Mesozoic sandstone samples and dated by the

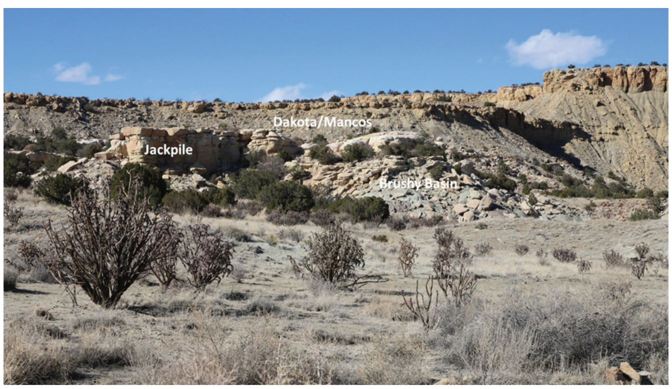

Figure 2. Outcrop photograph of the upper Brushy Basin Member, Jackpile Member, and lower Dakota Sandstone sampled for DS analysis. Jackpile Member cliff is at 35.495979°, −106.924422°. *Photo by Karl Kalstrom*

Figure 3. Uppermost Brushy Basin Member of Morrison Formation. BB-1 is 7.4 m below base of Jackpile Member; BB-2 is from cemented medium-grained sandstone just below a gutter cast that shows parting lineation at edge of an alluvial channel. Location: 35.496225°, −106.923430°, ~1,769 m elevation. Spencer Lucas taking notes, John Rogers with Jacob staff. *Photo by Karl Kalstrom*

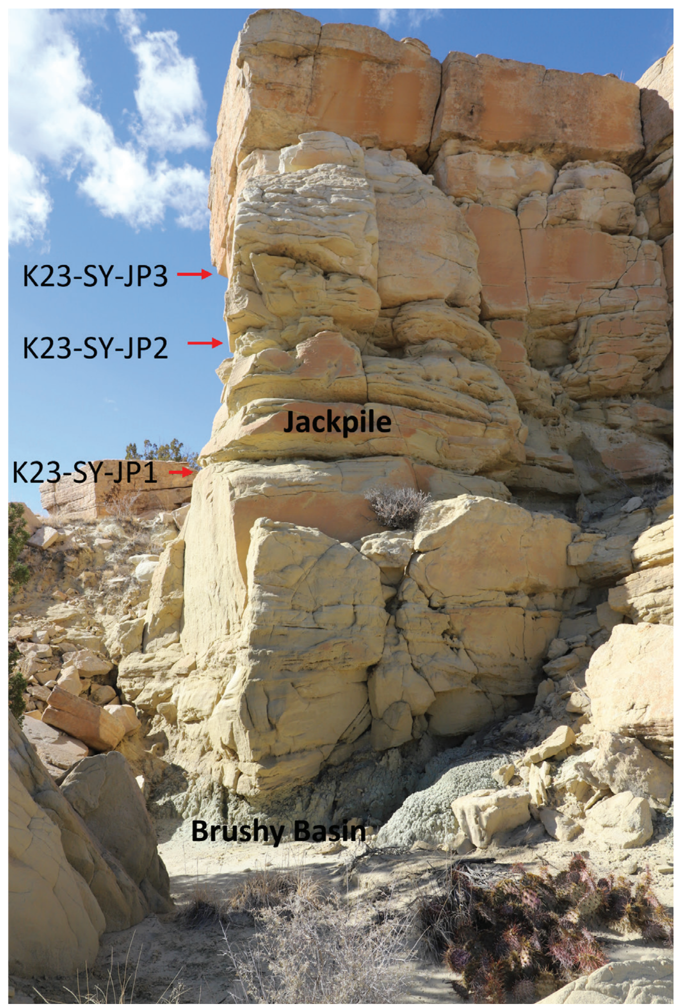

Figure 4. Overview of lower part of Jackpile Member with basal contact on green mudrock of uppermost Brushy Basin Member. JP-1 is from a 10-cm-thick green siltstone parting 8.7 m above base (35.495979°, −106.924422°), JP-2 is from a pocket of mudstone between large cross-bedded sandstones (35.495702°, −106.924720°), JP-3 is from a green siltstone 4.6 m below top (17.6 m in section; 35.496500°, −106.925677°).

Figure 5. Dak-1, 0.8 m above basal Dakota Sandstone unconformity, calcite-cemented sandstone encased in black shales (35.495787°, −106.926840°). Expected age was 98 Ma based on ash beds found in this interval elsewhere.

$^{40}Ar/^{39}Ar$ method. Detailed analytical methods are provided in the Appendix data and briefly described here. Detrital sanidine was irradiated in two packages: NM-335 was irradiated for 21 hours and contained the three Jackpile samples, and NM-345 was irradiated for 30 hours and housed the Dakota Sandstone and Brushy Basin Member samples. Both irradiations were in the CLICIT position at the Oregon State University research reactor. Fish Canyon sanidine was included to monitor neutron fluence (J-factor) and is assigned an age of 28.201 Ma (Kuiper et al., 2008). Crystals were fused and/or step-heated (2-steps, A and B) with a CO_2 laser, and extracted argon isotopes were measured on an ARGUS VI mass spectrometer. The maximum depositional age (MDA) is calculated based on the inverse variance weighted mean of the youngest population of dates. Four of the samples have a MDA defined by the date of a single analysis. Age calculation uses a total decay constant for ^{40}K of 5.463e-10 /a (Min et al., 2000). Age uncertainty is reported at ± 1σ and includes the error of the J-factor and neutron interferences.

Results

Six DS-bearing samples were dated by the $^{40}Ar/^{39}Ar$ method: two samples (BB-1, BB-2) from the Brushy Basin Member, three samples (JP-1, JP-2, JP-3) from the Jackpile Member, and one sample (Dak-1) from the Oak Canyon Member of the Dakota Sandstone, which is the stratigraphically highest. A combination of 2-step age spectrum and total fusion analyses were conducted; Dak-1 analyses were dominated by total fusion, and the other samples mostly used the age spectrum method (Table 1; Appendix data). A total of 1,023 crystal dates are reported. However, 1,104 grains were analyzed, and 83 grains were omitted because they were likely Precambrian microcline or orthoclase, and their high concentration of ^{40}Ar saturated the mass spectrometer detector and provided meaningless dates. A total of 1,988 argon isotopic analyses were conducted for this study. For the step-heating results, the preferred age is given by the integrated age. For total fusion results, the reported date is the preferred date.

Table 1 summarizes the distribution of analyses and the calculated MDA for each sample. Many of the two-step spectra yielded plateau ages (Table 1, Appendix data) where both steps are analytically indistinguishable, and these plateau spectra are consistent with sanidine that cools rapidly during eruption. Representative age spectra of the youngest DS grains are given for the Brushy Basin and Jackpile Members samples (Fig. 6). Figures 6l and 6m show two grains with plateau spectra, whereas Figures 6e, 6h, 6j, 6n, and 6o reveal minor age discordance between the A and B steps. This minor discordance is not suggestive of radiogenic argon loss, but likely results from slight isotope fractionation during step-heating. The lighter isotope ^{39}Ar is preferentially degassed compared with the heavier ^{40}Ar, thus resulting in a slightly younger date for the A step compared with the B step (cf. Phillips et al., 2022). Both the plateau spectra and slightly discordant spectra provided accurate integrated ages.

Age spectra with significant discordance between the A and B steps are less likely to yield perfectly robust integrated ages (Figs. 6b–6d, 6f, and 6j). Here, the A step is substantially younger than the B step and indicative of post-depositional argon loss. With only a resolution of two heating steps, it is not possible to evaluate fully the level of argon loss, but we suggest that it is minor because the B-step dates are only slightly (typically ~1 My) older than the integrated ages (Fig. 6). Although we report the integrated (total gas) ages as the preferred age, it is important to note that none of the MDAs include grains with highly discordant spectra. Total fusion data cannot be fully evaluated for argon loss as their age spectrum is defined by a single heating step (Figs. 6a and 6k). The vast majority of DS dating, and sanidine dating in general, is done with total fusion analyses. This is because sanidine has a simple thermal history. Optical inspection during final grain selection can greatly eliminate grains with obvious alteration that can lead to argon loss. The age spectra for grains younger than 300 Ma show minor discordance overall. This demonstrates that older sanidine can also yield robust total fusion ages, so total fusion dates are included in the determination of some MDAs.

The MDAs for each sample together with the number of dates used for calculation are summarized in Table 1. Both of the Brushy Basin Member samples yield Late Jurassic MDAs with BB-1 at 148.86 ± 0.31 Ma and the overlying BB-2 at

150.39 ± 0.41 Ma (Table 1, Appendix data). The youngest MDA of the Jackpile Member samples comes from the stratigraphically highest sample and is 151.39 ± 0.20 Ma based on a total fusion date (Table 1). The Jackpile Member samples, JP-1 and JP-2, have MDAs of 166.5 ± 1.1 Ma and 193.79 ± 0.11 Ma, respectively. The Dakota Sandstone sample, Dak-1, has a single youngest grain at 213.4 ± 0.2 Ma.

Figure 7 shows age probability and cumulative n (number or grains dated) diagrams where the latter plots dates arranged from youngest to oldest. Total fusion and integrated dates younger than 300 Ma are plotted. BB-1 and BB-2 are dominated by DS younger than 300 Ma with strong age modes between 160 and 170 Ma and between 180 and 190 Ma (Figs. 7e, 7f, 7k, and 7l). The three Jackpile samples have similar distributions to each other (Figs. 7b–7d, and 7h–7j), but contrast with the Brushy Basin Member samples that have only minor Jurassic grains and a dominance of Permian–Triassic grains. The Dakota Sandstone sample had a poor yield of sanidine grains, and many microcline or orthoclase (based on Precambrian dates) were inadvertently selected for dating. Of the grains younger than 300 Ma, all are Triassic (Figs. 7a and 7g). There are a significant number of dates between 300 and 400 Ma, and these are likely a combination of DS, detrital microcline, and detrital orthoclase crystals (Appendix data). Precambrian grains are very likely not sanidine, but rather microcline or orthoclase.

AGE AND CORRELATION

The latest numerical calibration of the Jurassic chronostratigraphic scale places the Kimmeridgian–Tithonian boundary at ~149.2 Ma and the Jurassic–Cretaceous boundary at ~143.1 Ma (Hesselbo et al., 2020). Thus, our Brushy Basin ages straddle the Kimmeridgian–Tithonian boundary and are clearly Late Jurassic ages.

Previously published numerical ages for the Brushy Basin

TABLE 1. Summary of DS results and previously published data.

$^{40}Ar/^{39}Ar$ detrital sanidine (DS) - this study

Sample	Unit	Location (lat long)	n SH	n p	n tf	n MDA	MDA (Ma)	±1ωρ
Dak-1	Dakota	35.495787° −106.926840°	9	1	87	1	213.42	0.20
JP-3	Jackpile	35.495979° −106.924422°	58	4	3	1	151.39	0.15
JP-2	Jackpile	35.495979° −106.924422°	259	4	3	1	193.79	0.11
JP-1	Jackpile	35.495979° −106.924422°	227	22	23	1	166.5	1.1
BB-2	Brushy Basin	35.496225° −106.923430°	145	59	10	2	150.39	0.41
BB-1	Brushy Basin	35.496225° −106.923430°	184	46	15	3	148.86	0.31
							n-total =	1023

Published data for Brushy Basin

Sample	Location	Age (Ma)	±1χρ
Kowallis et al. (1991)*: $^{40}Ar/^{39}Ar$ plagioclase in ash deposits			
MC-JMB-57	MC, UT	149.5	0.8
MC-JMB-53.5	MC, UT	148.9	0.6
MC-JMB-48	MC, UT	147.1	1.2
MC-JMB-43	MC, UT	149.7	0.6
MC-JMB-17.75	MC, UT	151.3	0.7
Dino-3	DNM, UT	154.9	1.2
Galli et al. (2018): U/Pb zircon in ash deposits			
FP218.8	FP, CO	149.43	0.059
JMB-39	FP, CO	150.208	0.094

Notes:
n SH - number of DS grains analyzed by step-heating
n P - number of DS grains yielding plateau spectra from the step-heating analyses n tf - number of DS grains analyzed by total fusion
n total - total number of DS dates reported (step-heat plus total fusion) n MDA - number of DS dates defining maximum depositional age
MDA - maximum depositional age. Based on single youngest grain (n=1) or weighted mean of n >1 dates
MC, UT. Montezuma Creek section, Utah
DNM, UT - Dinosaur National Monument, Utah FP, CO - Fruita Paleontological Research Natural Area, Colorado
* Dates recalculated to Fish Canyon sanidine age of 28.201 Ma and total ^{40}K decay constant of 5.463e-10 /a

Member in Colorado and Utah range in age from about 147 to 156 Ma (Trujillo and Kowallis, 2015; Galli et al., 2018; Chapman and DeCelles, 2021). The MDAs of the Brushy Basin Member reported here are consistent with those ages. Uppermost Brushy Basin Formation strata may vary in age across the region as the top of the member is beveled by an unconformity. The youngest DS-derived MDA from the Brushy Basin Member (BB-1) of 148.86 ± 0.31 Ma is within 2σ of a zircon age of 149.43 ± 0.059 Ma (Galli et al., 2018) from the uppermost Brushy Basin Member in Colorado suggesting that these two horizons may be temporally equivalent. Additionally, since Galli et al. (2018) argue that the age of 149.43 Ma represents the latest deposition of the Brushy Basin Member, the

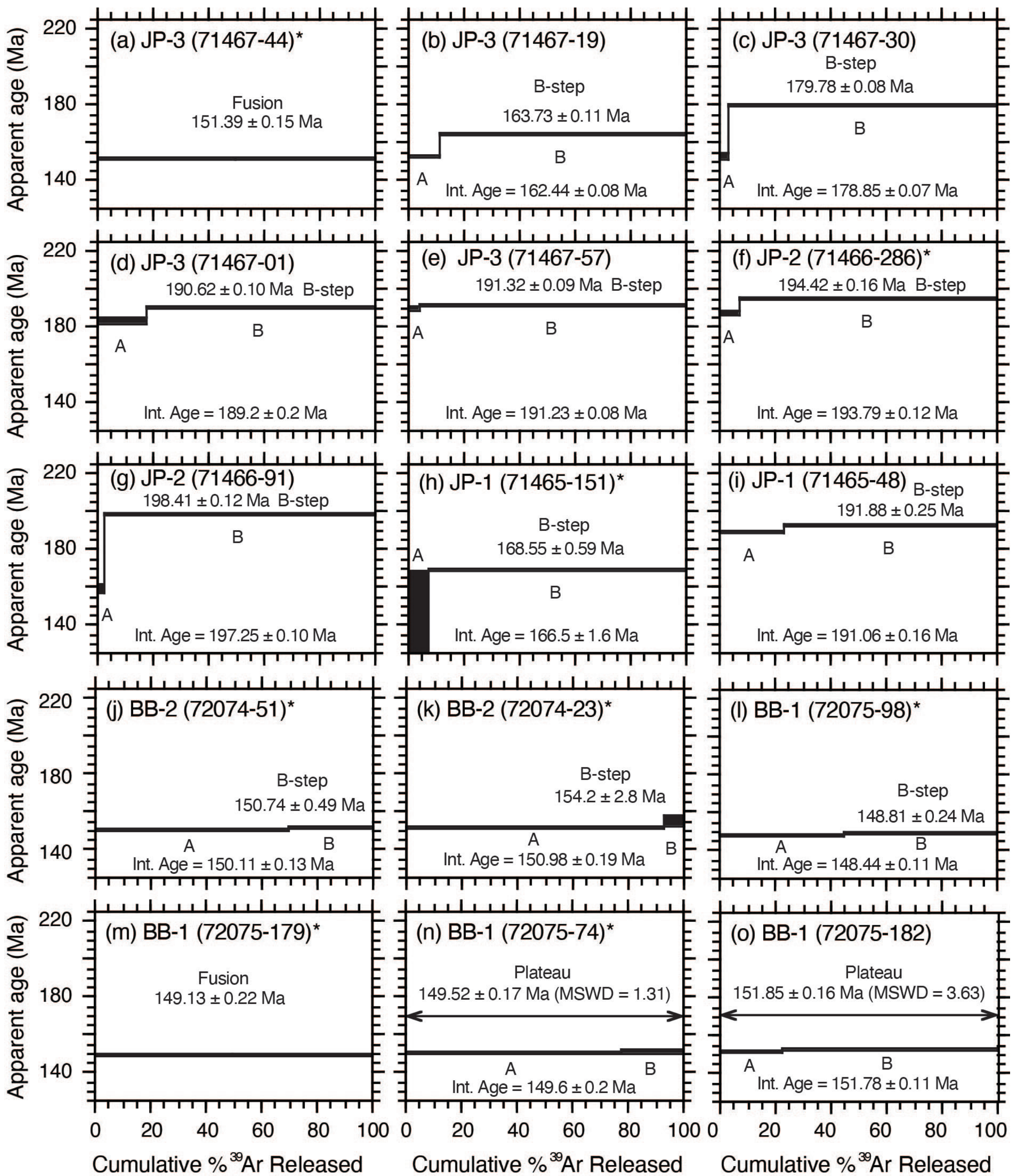

Figure 6. $^{40}Ar/^{39}Ar$ age spectra of selected youngest dates from the Brushy Basin and Jackpile Members samples. Here, there are examples of spectra that are "flat" and define a plateau spectrum where both heating steps yield analytically indistinguishable dates (n, o). Most spectra show very minor discordance (e.g., j, k, l) and yield robust integrated ages. Some spectra show significant discordance between the A and B steps (e.g., b, c, g), but still do not appear to lead to strongly inaccurate integrated ages. Single-step (total fusion) data for two DS results are represented as age spectra and are interpreted to yield robust dates (a, m). Sample names indicated with an * are dates used to calculate MDAs. Only 10 crystals from the Dakota Sandstone were analyzed by step-heating, and most were Precambrian (Appendix data) and are thus not shown here.

concordant DS MDA is likely near the true depositional age for our BB-1 sample.

Maximum depositional ages of the Jackpile Member only indicate a depositional age younger than 151.39 ± 0.15 Ma (Table 1). Despite this DS result being based on a total fusion result, it is considered accurate due to only minor argon loss observed in some age spectrum results. Thus, the DS data do not fully resolve the age of the Jackpile Member other than to confirm it is no older than Late Jurassic. However, as discussed below, the significant difference in DS age distributions between the Brushy Basin and Jackpile Members samples (Fig. 6) could imply a significant depositional hiatus between the units.

The Jackpile Member is a bit of an anomaly in the Morrison

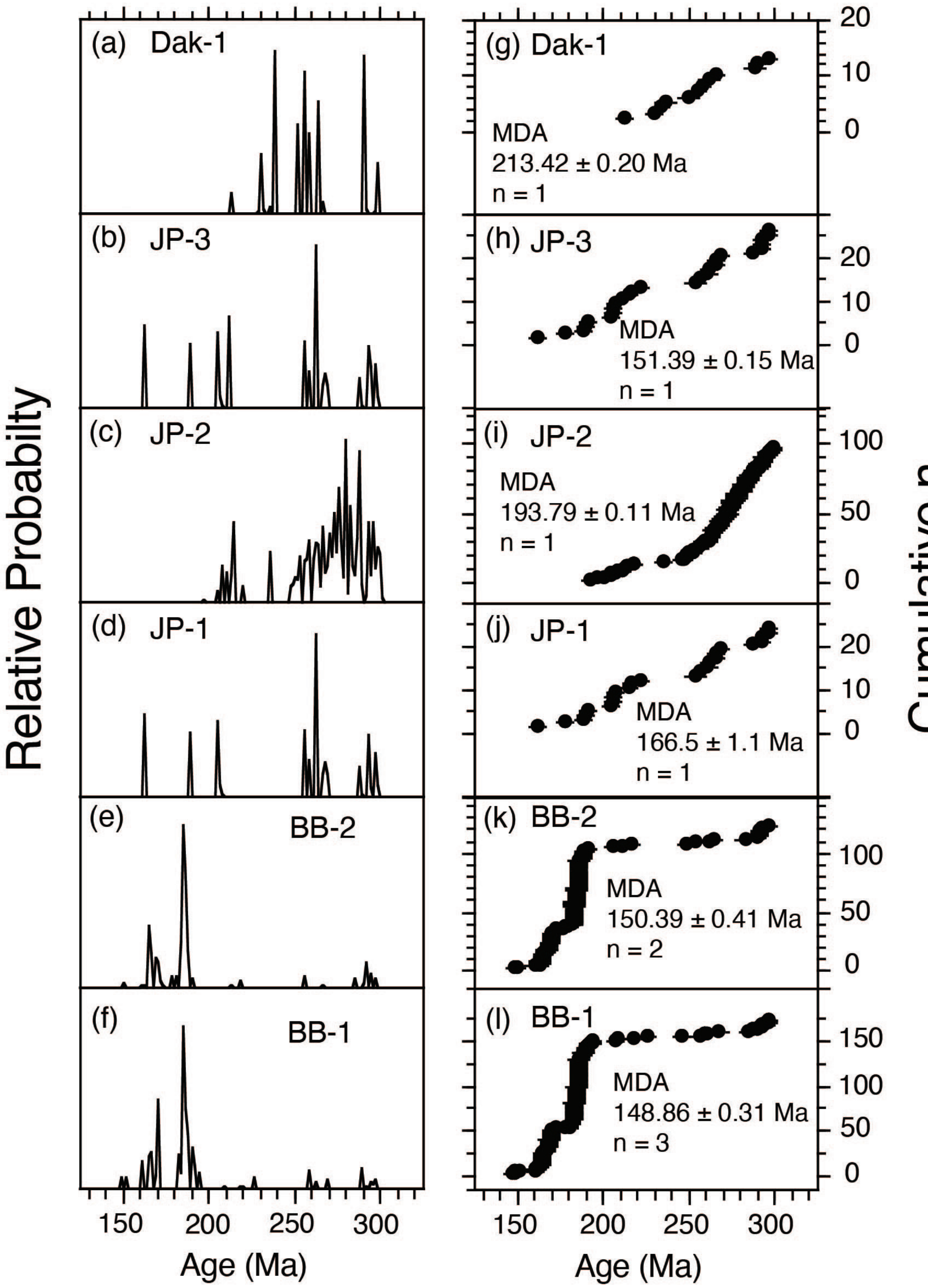

Figure 7. Relative probability (a–f) and cumulative n (g–l) diagrams of DS dates that are less than 300 Ma. Both integrated and total fusion dates are plotted. MDAs are calculated from the youngest single grain (g–j) or the youngest population of dates (k and l). There is a distinct change in the distribution of DS dates between the Brushy Basin Member, which are mostly Jurassic, and the Jackpile Member, which are mostly Permian and Triassic.

Formation section as no Upper Jurassic strata similar to it are present outside of the New Mexico portion of the Morrison depositional basin. Thus, as noted by Lucas (2021) and Cather (2021), several workers have drawn attention to the possibility that the Jackpile Member is a Lower Cretaceous unit equivalent to the Burro Canyon Formation to the north, which it resembles in its sandstone-dominated lithology and stratigraphic position (cf. Aubrey, 1986). Detrital zircon (DZ) data support that correlation (Dickinson and Gehrels, 2010; Dickinson, 2018).

Jackpile Member DS age distributions differ from the Bushy Basin spectra (Fig. 6). Dickinson and Gehrels (2008, 2009), employing U-Pb DZ analysis, also documented differences in the spectra of the Salt Wash and Jackpile Members. Dickinson and Gehrels (2009) employed a variety of statistical techniques on the DZ of the Jackpile Member, producing a wide range of dates from a maximum age of 212 ± 2 Ma (youngest 2σ grain cluster) to a minimum of 187 ± 2 Ma (youngest single grain). Based on DZ spectral characteristics, Dickinson and Gehrels (2008, 2009) correlated the Jackpile Member with the Early Cretaceous Burro Canyon Formation that displays a similar DZ spectra. Our $^{40}Ar/^{39}Ar$ ages permit this correlation but do not resolve the age of the Jackpile Member, so more study is planned.

Based on ammonite biostratigraphy, the Oak Canyon Member of the Dakota Sandstone is middle Cenomanian (Sealey and Lucas, 2018). Head and Owen (2005) reported an $^{40}Ar/^{39}Ar$ age of 98.1 ± 2.4 Ma (middle Cenomanian) for their "A bentonite" bed, which is stratigraphically low in the Oak Canyon Member.

TECTONIC IMPLICATIONS

Figure 8 summarizes the regional context for Late Jurassic deposition by showing a paleogeographic subcrop map for units that underlie Cretaceous rocks of the region (modified from Chapman and DeCelles, 2021). The Sevier thrust belt was active to the west so that Morrison rivers north of the latitude of the Four Corners flowed east. To the south, rivers flowed northeast off of the Mogollon highlands uplift in Arizona that formed by a combination of a back-arc foreland bulge and/or the uplifted rift flank of the Bisbee basin. This tectono-sedimentary system formed a low-angle regional unconformity where Cretaceous strata rest on progressively older units

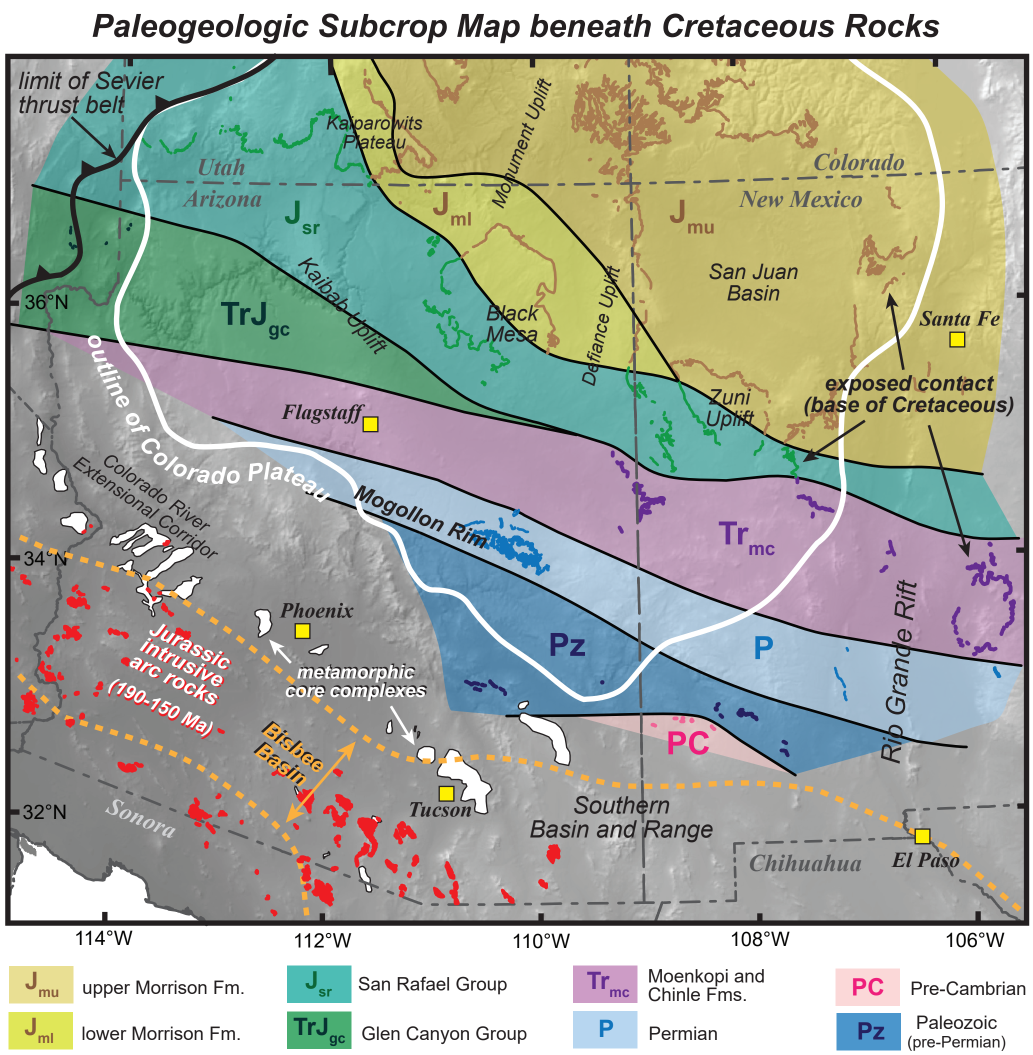

Figure 8. Subcrop map beneath Cretaceous strata in much of the Four Corners region (modified from Chapman and DeCelles, 2021).

towards the highlands (Chapman and DeCelles, 2021). Near San Ysidro, New Mexico, the basal Dakota Sandstone is ~98 Ma and rests unconformably on the unconformity-bounded Jackpile Member.

As already stated, the initial motivation for this study was to date the Jackpile Member and thereby resolve the duration of the lacunas above and below it. This remains unresolved. Using ≤148 Ma for the uppermost Brushy Basin Member, our data suggest a total sub-Dakota Sandstone lacuna of 50 My. If the Jackpile is Late Jurassic, most of that time is missing at the sub-Dakota Sandstone contact. If the Jackpile Member correlates more closely with ~125 Ma Lower Cretaceous Burro Canyon Formation in Colorado, about half of the "missing time" (e.g., half of the Early Cretaceous series) is at the sub-Jackpile Member unconformity. The provenance data from the DS analyses (Fig. 7) show that the Jackpile Member has detritus that is more similar to the Dakota in containing a dominance of 200–300 Ma grains derived from Triassic and Permian strata. This may be most compatible with northeast-flowing rivers sourced from the beveled pre-Cretaceous subcrop shown in Figure 8. It may also be suggestive of a Cretaceous age of the Jackpile Member, though it is not conclusive evidence of geologic age.

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REFERENCES

Anderson, O.J. and Lucas, S.G., 1996, Stratigraphy and depositional environments of Middle and Upper Jurassic rocks, southeastern San Juan Basin, New Mexico: New Mexico Geological Society, Guidebook 47, p. 205–210. https://doi.org/10.56577/ffc-47.205

Aubrey, W.M., 1986, The nature of the Dakota-Morrison boundary, southeastern San Juan Basin: American Association of Petroleum Geologists Studies in Geology, no. 22, p. 93–104. https://doi.org/10.1306/st22455c7

Cather, S.M., 2021, Jurassic stratigraphic nomenclature for northwestern New Mexico: New Mexico Geological Society, Guidebook 71, p. 251–258. https://doi.org/10.56577/ffc-71.251

Chapman, J.B., and DeCelles, P.G., 2021, Beveling the Colorado Plateau: Early Mesozoic rift-related flexure explains erosion and anomalous deposition in the southern Cordilleran foreland basin: Tectonics, v. 40, no. 6. https://doi.org/10.1029/2020tc006517

Dickinson, W.R., 2018, Tectonosedimentary relations of Pennsylvanian to Jurassic strata on the Colorado Plateau: Geological Society of America Special Paper 533, 184 p. https://doi.org/10.1130/spe533

Dickinson, W.R., and Gehrels, G.E., 2008, Sediment delivery to the Cordilleran foreland basin: insights from U-Pb ages of detrital zircons in Upper Jurassic and Cretaceous strata of the Colorado Plateau: American Journal of Science, v. 308, p. 1041–1082.

Dickinson, W.R., and Gehrels, G.E., 2009, Use of U-Pb ages of detrital zircons to infer maximum depositional ages of strata—A test against a Colorado Plateau Mesozoic database: Earth and Planetary Science Letters, v. 288, p. 115–125. https://doi.org/10.1016/j.epsl.2009.09.013

Dickinson, W.R., and Gehrels, G.E., 2010, Implications of U-Pb ages of detrital zircons in Mesozoic strata of the Four Corners region for provenance relations in space and time: New Mexico Geological Society, Guidebook 61, p. 135–146. https://doi.org/10.56577/ffc-61.135

Galli, K.G., Buchwaldt, R., Lucas, S.G. and Tanner, L., 2018, New chemical abrasion thermal ionization mass spectrometry dates from the Brushy Basin Member, Morrison Formation, western Colorado—Implications for dinosaur evolution: Journal of Geology, v. 126, p. 473–486. https://doi.org/10.1086/699208

Head, C.F. and Owen, D.E., 2005, Insights into the petroleum geology and stratigraphy of the Dakota interval (Cretaceous) in the San Juan Basin, northwestern New Mexico and southwestern Colorado: New Mexico Geological Society, Guidebook 56, p. 434–444. https://doi.org/10.56577/ffc-56.434

Hesselbo, S.P., Ogg, J.G., Ruhl, M., Hinnov, L.A. and Huang, C.J., 2020, The Jurassic Period, *in* Gradstein, F.M., Ogg, J.G., Schmitz, M.D. and Ogg, G.M., eds., Geologic Time Scale 2020. Amsterdam, Elsevier, p. 955–1021. https://doi.org/10.1016/b978-0-12-824360-2.00026-7

Kowallis, B J., Christiansen, E.H. and Deino, A.L., 1991, Age of the Brushy Basin Member of the Morrison Formation, Colorado Plateau, western USA: Cretaceous Research, v. 12, p. 483–493. https://doi.org/10.1016/0195-6671(91)90003-u

Kuiper, K.F., Deino A., Hilgen, F.J., Krijgsman, W., Renne, P.R., and Wijbrans, J.R., 2008, Synchronizing the rock clocks of Earth history: Science, v. 320, p. 500–504.

Lawton, T.F., 1994, Tectonic setting of Mesozoic sedimentary basins, Rocky Mountain region, United States, *in* Caputo, M.V., Peterson, J.A. and Franczyk, K., eds., Mesozoic systems of the Rocky Mountain region, USA: Denver, Rocky Mountain Section, Society for Sedimentary Geology, p. 1–25.

Lucas, S.G., 2021, Jurassic stratigraphy of the southeastern Colorado Plateau, west-central New Mexico—2020 synthesis: New Mexico Geological Society, Guidebook 71, p. 241–250.

Lucas, S.G. and Anderson, O.J., 1998, Jurassic stratigraphy and correlation in New Mexico: New Mexico Geology, v. 20, p. 97–104. https://doi.org/10.58799/nmg-v20n4.97

Lucas, S.G. and Heckert, A.B., 2015, New Mexico's record of Jurassic fossil vertebrates: New Mexico Museum of Natural History and Science Bulletin, v. 68, p. 97–104.

Min, K., Mundil, R., Renne, P.R. and Ludwig, K.R., 2000, A test for systematic errors in $^{40}Ar/^{39}Ar$ geochronology through comparison with U-Pb analysis of a 1.1 Ga rhyolite: Geochimica Cosmochimica Acta, v. 64, p. 73–98. https://doi.org/10.1016/s0016-7037(99)00204-5

New Mexico Bureau of Geology and Mineral Resources, 2003, Geologic map of New Mexico: New Mexico Bureau of Geology and Mineral Resources, 2 sheets, scale 1:500,000. https://doi.org/10.58799/116894

Phillips, D., Matchan, E.L., Dalton, H., and Kuiper, K.F., 2022, Revised astronomically calibrated $^{40}Ar/^{39}Ar$ ages for the Fish Canyon Tuff sanidine—Closing the interlaboratory gap: Chemical Geology, v. 597, p. 1–8. https://doi.org/10.1016/j.chemgeo.2022.120815

Sealey, P.L. and Lucas, S.G., 2018, Late Cretaceous (Cenomanian-Campanian) ammonite systematic paleontology and biostratigraphy, southeastern San Juan Basin, Sandoval County, New Mexico: New Mexico Museum of Natural History and Science Bulletin 80, 245 p.

Steiner, M.B., Lucas, S.G. and Shoemaker, E.M., 1994, Correlation and age of the Upper Jurassic Morrison Formation from magnetostratigraphic analysis, *in* Caputo, M.V., Peterson, J.A. and Franczyk, K.J., eds., Mesozoic systems of the Rocky Mountain region, USA: Denver: Rocky Mountain Section, Society for Sedimentary Geology, p. 315–330.

Trujillo, K.C. and Kowallis, B.J. 2015, Recalibrated legacy $^{40}Ar/^{39}Ar$ ages for the Upper Jurassic Morrison Formation, Western Interior, U.S.A.: Geology of the Intermountain West, v. 2, p. 1–8. https://doi.org/10.31711/giw.v2.pp1-8

Woodward, L.A., 1987, Geology and mineral resources of Sierra Nacimiento and vicinity, New Mexico: New Mexico Bureau of Mines and Mineral Resources Memoir 42, 84 p. https://doi.org/10.58799/m-42

Appendix can be found at
https://nmgs.nmt.edu/repository/index.cfml?rid=2025004

Common collared lizard (*Crotaphytus collaris*) on the Ojo Alamo Sandstone in Cuba, New Mexico.