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THE CAMPANIAN-MAASTRICHTIAN BACULITE ZONAL SEQUENCE IN THE PIERRE SHALE, BERWIND CANYON, LAS ANIMAS COUNTY, COLORADO

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Abstract — At Berwind Canyon, northeast of Trinidad, Colorado, the upper 100 m of the Pierre Shale yield the most extensive upper Campanian-lower Maastrichtian record of fossil mollusks (primarily bivalves and ammonites) in the Colorado portion of the Raton Basin. This record includes the zonal baculitid ammonites (from oldest to youngest) *Baculites compressus* (Say, 1820), *B. cuneatus* Cobban, 1962, *B. reesidei* Elias, 1933, *B. jenseni* Cobban, 1962, *B. eliasi* Cobban, 1958, *B. baculus* Meek and Hayden, 1861, *B. grandis* Hall and Meek, 1855 and *B. clinolobatus* Elias, 1933, as well as other index mollusks (e.g., scaphitid ammonites, gastropods, and inoceramids). Thus, we identify eight ammonite zones in the condensed section of the Pierre Shale in Berwind Canyon, which record an important phase in the tectonic evolution of the basin.

INTRODUCTION

Lee (1917, p. 132, pl. 12) first mentioned the Pierre Shale at Berwind, Colorado and presented a measured section from the Pierre Shale up to the Raton Formation. However, Lee's focus in Berwind Canyon was on the coal-bearing Vermejo Formation, so he presented very little information on the Pierre Shale in the canyon. Berry (2010, 2016, 2017, 2018a) has published studies of some of the ammonites and associated fossils in the Pierre Shale in Berwind Canyon. Here, we describe, illustrate and place in a measured stratigraphic section, this important ammonite zonal sequence.

STRATIGRAPHY AND AMMONITE ZONES

On the southern edge of Berwind Canyon near its mouth, about 100 m of the upper part of the Pierre Shale is well exposed (Fig. 1). The lower ~60 m of this section are gray to dark gray beds of shale with numerous limestone concretions, often concentrated in horizons or thin intervals. These are commonly characteristic of offshore marine strata of the Pierre Shale, and most of the macrofossils are found in the limestone concretions. The upper ~40 m of the Pierre Shale is a lower shoreface facies of siltstone and thin sandstone beds. This facies is much less fossiliferous than the underlying shale interval, and grades upward into the Upper Cretaceous Trinidad Sandstone. We place the base of the Trinidad Sandstone in the Berwind Canyon section at the stratigraphic level where there is much more sandstone than siltstone (Fig. 1).

In the Raton Basin, the Pierre Shale is about 700 m thick (Johnson and Wood, 1956). Thus, the Pierre Shale section at Berwind Canyon is only the upper 14% of the formation. Nevertheless, the section encompasses eight ammonite zones of the upper Campanian and lower Maastrichtian. At Red Bird, Wyoming, in a very thick and basinal section of the Pierre Shale, the *Baculites reesidei* through *B. clinolobatus* zones are present through ~350 m of section (Gill and Cobban, 1966). However, at Berwind Canyon, these same zones are present over ~70 m of section, which indicates that Berwind Canyon exposes a condensed section of the upper part of the Pierre Shale, presumably because of a local reduction in the amount of accommodation space resulting from the early Laramide reactivation of the northeastern flank of the Raton Basin (Las Animas Arch) as an anticlinal uplift (Berry and Flores, 2018).

We recognize eight ammonite zones in the upper part of the Pierre Shale at Berwind Canyon (in descending order): the Maastrichtian *Baculites clinolobatus* (localities 10783, 12057, 12243), *B. grandis* (localities 10784, 12242), *B. baculus* (locality 10780) zones and the Campanian *B. eliasi* (locality 12241), *B. jenseni* (localities 12049, 12240), *B. reesidei* (locality 12239), *B. cuneatus* (locality 12238), and *B. compressus* (localities 10782, 12058) zones.

These ammonite zones contain other index mollusks, including other baculites, scaphitid ammonites, nautiloids, gastropods and inoceramids (Table 1).

ABBREVIATIONS AND CONVENTIONS

NMMNH = New Mexico Museum of Natural History and Science, Albuquerque. All dimensions are in millimeters. Rib index refers to the number of ribs in a distance equal to the whorl height.

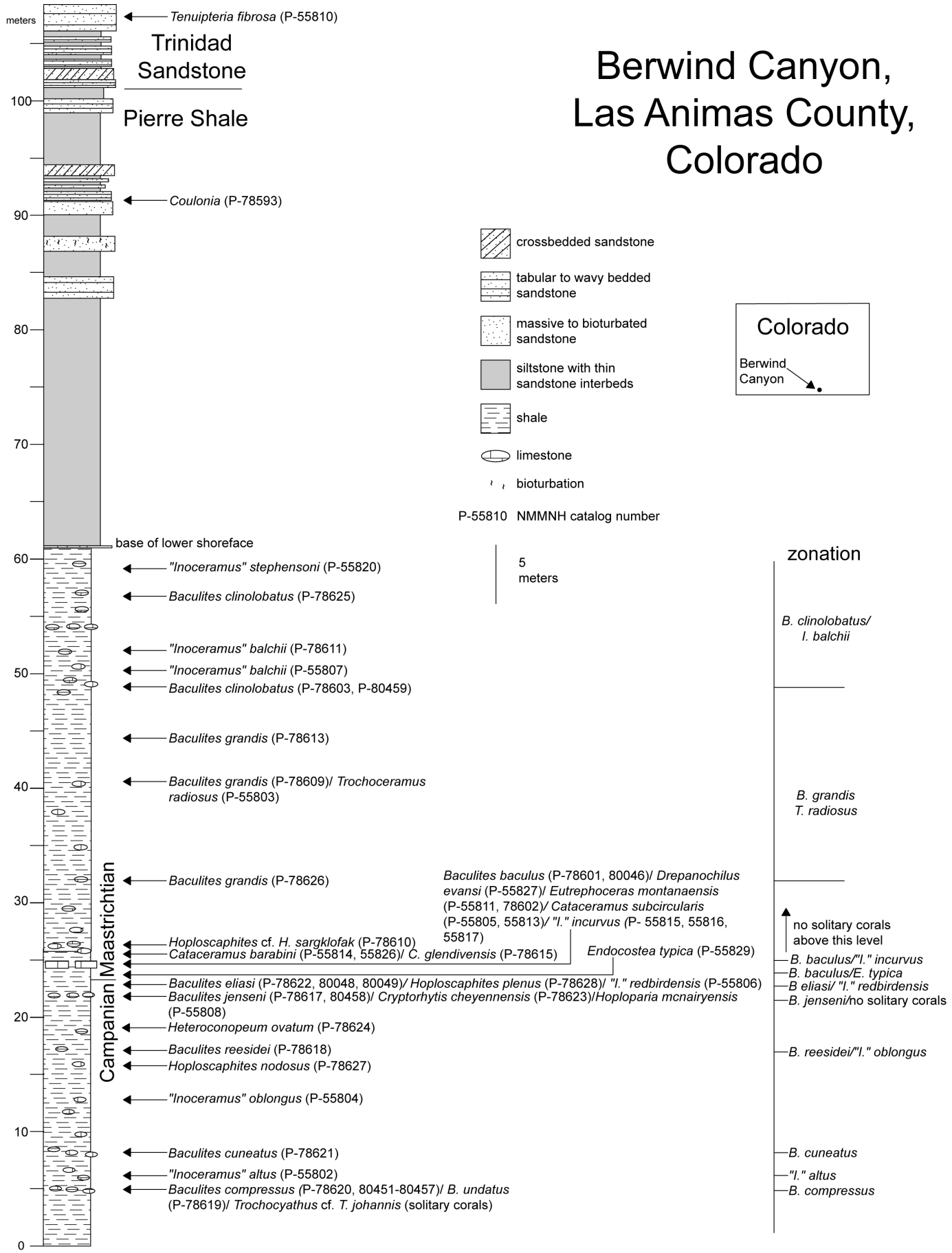
Berwind Canyon, Las Animas County, Colorado
meters
Trinidad Sandstone
Pierre Shale
Tenuipteria fibrosa (P-55810)
Coulonia (P-78593)
base of lower shoreface
"Inoceramus" stephensoni (P-55820)
Baculites clinolobatus (P-78625)
"Inoceramus" balchii (P-78611)
"Inoceramus" balchii (P-55807)
Baculites clinolobatus (P-78603, P-80459)
Baculites grandis (P-78613)
Baculites grandis (P-78609)/ Trochoceramus radiosus (P-55803)
Baculites grandis (P-78626)
Hoploscaphites cf. H. sargklofak (P-78610)
Cataceramus barabini (P-55814, 55826)/ C. glendivensis (P-78615)
Baculites baculus (P-78601, 80046)/ Drepanochilus evansi (P-55827)/ Eutrephoceras montanaensis (P-55811, 78602)/ Cataceramus subcircularis (P-55805, 55813)/ "I." incurvus (P- 55815, 55816, 55817)
Endocostea typica (P-55829)
Baculites eliasi (P-78622, 80048, 80049)/ Hoploscaphites plenus (P-78628)/ "I." redbirdensis (P-55806)
Baculites jenseni (P-78617, 80458)/ Cryptorhytis cheyennensis (P-78623)/Hoploparia mcnairyensis (P-55808)
Heteroconopeum ovatum (P-78624)
Baculites reesidei (P-78618)
Hoploscaphites nodosus (P-78627)
"Inoceramus" oblongus (P-55804)
Baculites cuneatus (P-78621)
"Inoceramus" altus (P-55802)
Baculites compressus (P-78620, 80451-80457)/ B. undatus (P-78619)/ Trochocyathus cf. T. johannis (solitary corals)
Campanian
Maastrichtian
0
10
20
30
40
50
60
70
80
90
100
crossbedded sandstone
tabular to wavy bedded sandstone
massive to bioturbated sandstone
siltstone with thin sandstone interbeds
shale
limestone
bioturbation
P-55810 NMMNH catalog number
5 meters
Colorado
Berwind Canyon
zonation
B. clinolobatus/ I. balchii
B. grandis
T. radiosus
no solitary corals above this level
B. baculus/"I." incurvus
B. baculus/E. typica
B eliasi/ "I." redbirdensis
B. jenseni/no solitary corals
B. reesidei/"I." oblongus
B. cuneatus
"I." altus
B. compressus

TABLE 1. Associated fauna by ammonite zone and locality in the measured section at Berwind Canyon, Colorado.

Ammonite Zone	Locality nos.	Specimens
Baculites compressus	10782, 12058	*Baculites compressus* (Say), *Baculites undatus* Stephenson
Baculites cuneatus	12238	*Baculites cuneatus* Cobban
Baculites reesidei	12239	"*Inoceramus*" *oblongus* Meek, *Baculites reesidei* Elias
Baculites jenseni	12049, 12240	*Cryptorhytis cheyennensis* (Meek and Hayden), *Baculites jenseni* Cobban
Baculites eliasi	12241	"*Inoceramus*" *redbirdensis* Walaszczyk, Cobban and Harries, *Baculites eliasi* Cobban, *Hoploscaphites plenus* (Meek and Hayden)
Baculites baculus	10780	*Cataceramus*? *barabini* (Morton), *Cataceramus*? *subcircularis* (Meek), *Cataceramus*? *glendivensis* Walaszczyk, Cobban and Harries, *Endocostea typica* Whitfield, "*Inoceramus*" *incurvus* Meek and Hayden, *Eutrephoceras montanaensis* (Meek), *Baculites baculus* Meek and Hayden
Baculites grandis	10784, 12242	*Trochoceramus radiosus* (Quaas), *Baculites grandis* Hall and Meek
Baculites clinolobatus	10783, 12057, 12243	"*Inoceramus*" *balchii* Meek and Hayden, "*Inoceramus*" *stephensoni* Walaszczyk, Cobban and Harries, *Baculites clinolobatus* Elias

SYSTEMATIC PALEONTOLOGY

Phylum MOLLUSCA
Class CEPHALOPODA Cuvier, 1797
Order AMMONOIDEA Zittel, 1884
Suborder AMMONITINA Hyatt, 1889
Family BACULITIDAE Gill, 1871
Genus *BACULITES* Lamarck, 1799
***Baculites compressus* (Say, 1820)**
Figure 2A-B

Referred Material: NMMNH locality 12058: P-80451-P-80457, 8 small to moderate sized fragments; NMMNH locality 10782: P-78620, 2 fragments.

Description: NMMNH P-80451-P-80457 from locality 12058 are eight poorly preserved, small to moderate-sized fragments of *Baculites compressus*. All specimens have a very compressed, elliptical cross section, as in *B. compressus* (Hall and Meek, 1855, p. 400; Larson et al., 1997, p. 29). The shells have smooth flanks and dorsums and mostly weakly ribbed venters (P-80451, Fig. 2A-B). *B. reesidei* Elias, 1933 differs from *B. compressus* mostly in its stronger ventral ribbing (Cobban, 1962, p. 131). The weathered suture on one specimen (P-80452), and a better preserved one on a smaller fragment (P-80453), are similar to an illustration of the suture of *B. compressus* by Meek (1876, pl. 20, fig. 3c). The description of the suture matches Meek's (1876, p. 401), with an external lobe nearly twice as wide as long with two widely separated branches; first lateral saddle symmetrically bifid and about as long as the external lobe but about half as wide; first lateral lobe longer than the external lobe and about half as wide; first lateral lobe narrow stemmed with two small, parallel, terminal branches and two opposite lateral branches; second lateral saddle very similar to the first; second lateral lobe bifid and shorter and a little broader than the first; third lateral saddle much narrower than the others; dorsal lobe shorter than second lateral and much narrower.

Occurrence: Upper Campanian *Baculites compressus* Zone.

***Baculites cuneatus* Cobban, 1962**
Figure 2C-D

Referred Material: NMMNH locality 12238: P-78621, fragment.

Description: NMMNH P-78621 (Fig. 2C-D) from locality 12238 is a moderately preserved, moderate-sized fragment that is mostly body chamber. It has a compressed trigonal (cuneiform) cross section with a broad dorsum and a narrow venter. The cross section is similar to an illustration of *Baculites cuneatus* by Cobban (1962, pl. 25, fig. 5). The venter bears faint to weak, evenly spaced ribs. The flanks are smooth except where the outer shell layer is present, where they and the dorsum have weak striations. Suture is not adequately preserved.

Occurrence: Upper Campanian *Baculites cuneatus* Zone.

***Baculites reesidei* Elias, 1933**
Fig. 2E-F

Referred Material: NMMNH locality 12239: P-78618, body chamber fragment.

FIGURE 1. Measured stratigraphic section of the upper part of the Pierre Shale and lower part of the Trinidad Sandstone at Berwind Canyon, Colorado, showing fossil catalog numbers and ammonite zonation.

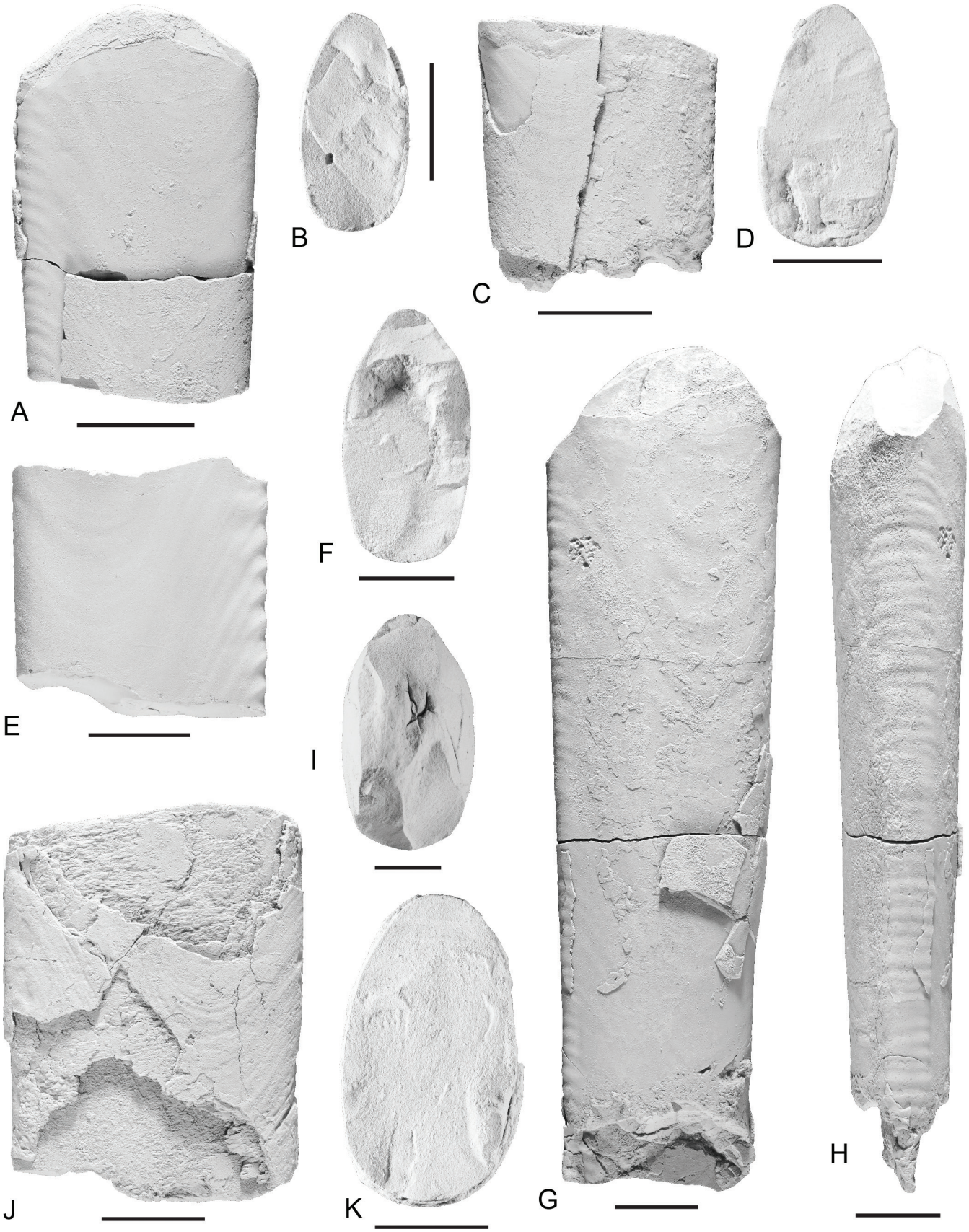

FIGURE 2. **A-B**) *Baculites compressus* (Say, 1820), **A**) lateral and **B**) cross sectional views, NMMNH P-80451 from locality 12058; **C-D**) *Baculites cuneatus* Cobban, 1962, **C**) lateral and **D**) cross sectional views, NMMNH P-78621 from locality 12238; **E-F**) *Baculites reesidei* Elias, 1933, **E**) lateral and **F**) cross sectional views, NMMNH P-78618 from locality 12239; **G-I**) *Baculites jenseni* Cobban, 1962, **G**) lateral, **H**) ventral and **I**) cross sectional views, NMMNH P-80458 from locality 12049; **J-K**) *Baculites eliasi* Cobban, 1958, **J**) lateral and **K**) cross sectional views, NMMNH P-78622 from locality 12241. Scales equal 2 cm.

Description: NMMNH P-78618 (Fig. 2E-F) from locality 12239 is a moderately preserved fragment of a body chamber. The cross section is compressed, with the venter much narrower than the dorsum. The venter bears strong, evenly-spaced ribs that give it an almost corrugated appearance. The rib index is approximately 8. *Baculites reesidei* has an average ventral rib index of 7-8 (Larson et al., 1997, p. 39). The flanks and dorsum have faint striations. The flank striations project sharply forward on the upper flank and connect to the ventral ribs. The striations on the dorsum are convex.

Occurrence: Upper Campanian *Baculites reesidei* Zone.

Baculites jenseni Cobban, 1962
Figure 2G-I

Referred Material: NMMNH locality 12049: P-80458, large, partial shell; NMMNH locality 12240: P-78617, partial phragmocone.

Description: NMMNH P-80458 (Fig. 2G-I) from locality 12049 is a moderately large shell of *Baculites jenseni* that is almost all body chamber. The cross section is compressed ovate on the adapical end of the shell and more broadly ovate on the adoral end. The shell has smooth flanks and a weak ventrolateral depression (Cobban, 1962, p. 129). The venter bears 12 to 14 weak, evenly spaced ribs per shell diameter. The ventral rib index of *B. jenseni* ranges from 5 to 14, with an average of 9 (Cobban, 1962, p. 130). The degree of taper is fairly low. Only fragments of the complex suture are preserved.

NMMNH P-78617 from locality 12240 is a moderately-preserved, partial phragmocone of *Baculites jenseni*. The cross section is fairly broadly ovate. The flanks are smooth and bear a ventrolateral depression. The dorsum is also smooth. The venter is weakly and moderately densely ribbed. A count was difficult to obtain, but the rib index appears to be greater than 10. The suture is complex, with bifid saddles and a long lateral lobe. It is similar to an illustration by Cobban (1962, text fig. 1a).

Occurrence: Upper Campanian *Baculites jenseni* Zone.

Baculites eliasi Cobban, 1958
Figure 2J-K

Referred Material: NMMNH locality 12241: P-78622, mostly body chamber; P-80048, phragmocone fragment; P-80049, fragment.

Description: NMMNH P-78622, P-80048 and P-80049 from locality 12241 are three moderately preserved shell fragments of *Baculites eliasi*. The cross section is elliptical to subelliptical. The cross sections of the NMMNH specimens are not as stout as illustrations of their cross sections by Cobban (1958, text fig. 1f-g, pl. 91, figs. 5, 9), but are closer to figure 4 of the same plate. The largest specimen (P-78622, Fig. 2J-K), which is mostly body chamber, has a maximum length of 68 mm. The degree of taper is 1.5. The shells are smooth except for faintly ribbed venters on two specimens. The largest fragment has a ventral rib index of about 14 or 15. The ventral rib index of *B. eliasi* ranges from 12 to 15 (Cobban, 1958, p. 664). Only fragments of suture are preserved.

Occurrence: Uppermost Campanian *Baculites eliasi* Zone.

Baculites baculus Meek and Hayden, 1861
Figure 3A-C

Referred Material: NMMNH locality 10780: P-55828, partial phragmocone; P-80046, partial body chamber; P-80047, small phragmocone fragment; P-78601, large phragmocone fragment.

Description: NMMNH P-78601 and P-80046 from locality 10780 are a moderately preserved fragment of a phragmocone and a partial body chamber. P-78601 (Fig. 3A-C) is a fairly large fragment of a phragmocone. The stout cross section is broadly elliptical, with slightly rounded flanks and venter and a flattened dorsum. The venter and dorsum are smooth. The flanks bear low, broad, arcuate undulations that extend from the dorsolateral edge to below the ventrolateral shoulder (Meek and Hayden, 1861, p. 445). The moderately preserved suture has simple, broad, rectilinear elements. P-80046 is a partial body chamber with a stout, ovate cross section with a flattened dorsum, slightly round flanks and a broadly rounded venter. Some shell material bears concave striations on the flanks and convex ones on the venter. The flanks have low, broad, crescentic undulations that extend from the dorsolateral shoulder to below the ventrolateral shoulder.

Occurrence: Earliest Maastrichtian *Baculites baculus* Zone.

Baculites grandis Hall and Meek, 1855
Figure 3D-E

Referred Material: NMMNH locality 12242: P-78613, large, partial shell; P-78609, large fragment; NMMNH locality 10784: P-78626, 1 septum.

Description: NMMNH P-78613 (Fig. 3D) from locality 12242 is a moderately preserved, large, partial shell of *Baculites grandis* that is mostly body chamber. The shell is 141.5 mm long with a maximum whorl height of 83.6 mm. The cross section is ovate. Ornamentation consists of strong, very broad, arcuate undulations that extend across the entire flank (Elias, 1933, p. 307). There are three flank undulations for the shell diameter. These undulations form faint arcs over the dorsum and also project forward over the ventrolateral shoulder but are not preserved on the venter. The degree of taper for this fragment is low. Only fragments of suture are preserved, but the elements appear to be simple and rectilinear. The first lateral saddle is broad and bifid.

NMMNH P-78609 (Fig. 3E) from locality 12242 is a moderately preserved, large fragment, about 89 mm long, of a body chamber of *Baculites grandis*. The cross section is ovate with a whorl height of 91 mm at the adoral end. The only indication of flank undulations is where the flanks elevate at both ends of the fragment with a depressed area in between. The dorsum appears to have one very faint arc. The rest of the fragment is smooth.

NMMNH P-78626 from locality10784 is one septum of a phragmocone, with an almost trigonal cross section, identified as *Baculites* cf. *B. grandis*.

Occurrence: Early Maastrichtian *Baculites grandis* Zone.

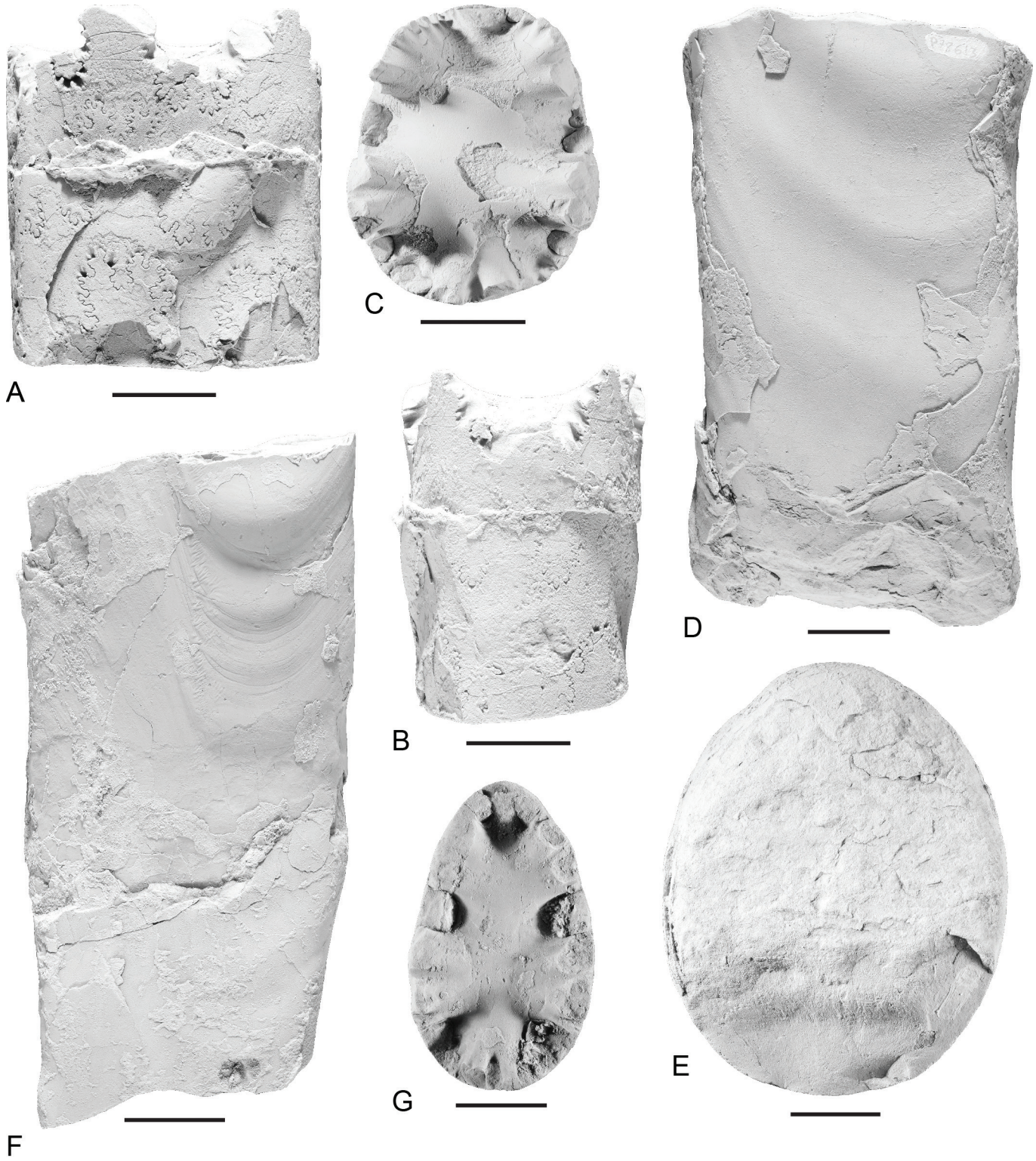

FIGURE 3. **A-C**) *Baculites baculus* Meek and Hayden, 1861, **A**) lateral, **B**) ventral and **C**) cross sectional views, NMMNH P-78601 from locality 10780; **D**) *Baculites grandis* Hall and Meek, 1855, lateral view, NMMNH P-78613 from locality 12242; **E**) *Baculites grandis*, cross sectional view of NMMNH P-78609 from locality 12242; **F**) *Baculites clinolobatus* Elias, 1933, lateral view, NMMNH P-80459 from locality 12057; **G**) *Baculites clinolobatus*, cross sectional view, NMMNH P-78603 from locality 12243. Scales equal 2 cm.

Baculites clinolobatus Elias, 1933
Fig. 3F-G

Referred Material: NMMNH locality 12057: P-80459, partial body chamber; NMMNH locality 10783: P-78625, fragment; NMMNH locality 12243: P-78603, 2 septa.

Description: NMMNH P-80459 (Fig. 3F) from locality 12057 is a moderately large, slightly distorted, partial body chamber of *Baculites clinolobatus*. It has a compressed ovate cross section (Elias, 1933, p. 310). There are low, broad, arcuate undulations on the dorsal half of the flank. The venter has a few faint ribs on the adapical end of the shell. Weak striations arc across the dorsum with a broad convexity continuing across the upper half of the flanks following the course of the undulations, then projecting forward on the ventral side.

NMMNH P-78603 from locality 12243 is two moderately preserved septa of *Baculites clinolobatus*. The cross section is compressed ovate (Fig. 3G).

Occurrence: Uppermost lower Maastrichtian *Baculites clinolobatus* Zone.

BIOSTRATIGRAPHY

Baculites compressus has been found in the Pierre Shale in Colorado, Kansas and South Dakota and in the Bearpaw Shale of Montana, Alberta and Saskatchewan (Elias, 1933, Warren, 1934; Landes, 1940; Larson et al., 1997; Kennedy et al., 2000; Sava, 2007). *B. cuneatus* has been reported from the Pierre Shale in Colorado and South Dakota, the Bearpaw Shale in Montana and from Canada (Cobban, 1962; Larson et al., 1997; Sava, 2007; Kennedy et al., 2000). *B. reesidei* has been found in the Pierre Shale in Colorado and Wyoming, the Bearpaw Shale in Montana and from Kansas, South Dakota, Alberta and Saskatchewan (Cobban, 1962; Gill and Cobban, 1966; Larson et al., 1997; Kennedy et al., 2000). *B. jenseni* has been reported from the Pierre Shale in Colorado, South Dakota and Wyoming, the Bearpaw Shale in Montana and Canada and the Lewis Shale in Wyoming (Cobban, 1962; Gill and Cobban, 1966; Larson et al., 1997). *B. eliasi* has been collected from the Pierre Shale in Colorado, Wyoming, Kansas, Nebraska, North Dakota, South Dakota and Montana and from the Bearpaw Shale in Montana (Cobban, 1958; Gill and Cobban, 1966; Larson et al., 1997; Berry, 2016, 2018a), as well as from Alberta and Saskatchewan (Larson et al., 1997). *B. baculus* occurs in the Pierre Shale in New Mexico, Colorado and Wyoming and in the Craie phosphatée de Ciply of Cuesmes, Belgium (Gill and Cobban, 1966; Kennedy, 1993; Berry, 2016, 2018a; Sealey and Lucas, 2018). Larson et al. (1997) reported *B. baculus* from Colorado to eastern Montana and farther north in Alberta and Saskatchewan. *B. grandis* has been found in the Pierre Shale in Colorado, Wyoming and Kansas, and in Montana (Elias, 1933; Gill and Cobban, 1966; Larson et al., 1997). *B. clinolobatus* has been reported from the Pierre Shale in Colorado, Wyoming, Kansas and South Dakota (Gill and Cobban, 1966; Landman and Waage, 1993; Larson et al., 1997; Berry, 2016, 2018a).

Correlation between the Western Interior Basin and the Global Standard Stratotype Section and Point for the Campanian-Maastrichtian stage boundary near Tercis, France, places this boundary at the first appearance datum of *Endocostea typica* (Whitfield, 1880) or at the base of the *Baculites baculus* ammonite zone (Fig. 1; Walaszczyk et al., 2001). At Berwind Canyon, the upper 100 m of the Pierre Shale yield the most extensive upper Campanian-lower Maastrichtian record of fossil mollusks in the Colorado portion of the Raton Basin. This section is thus an important reference section in southeastern Colorado of the upper Campanian-lower Maastrichtian interval of the upper Pierre Shale.

TECTONIC IMPLICATIONS

Deposition of the Pierre Shale in the Raton Basin signaled dynamic subsidence associated with flat-slab subduction of the Farallon Plate beneath northeastern New Mexico and south-central Colorado (Berry, 2018a). Tectonically driven subsidence caused by uplift of either the rejuvenated San Luis Highlands or the incipient Sangre de Cristo Mountains to the west was coupled with the anticlinal uplift of the northeastern flank of the Raton Basin and a pattern of differential stratal accumulation across the basin (Berry, 2018a). For the last 30 years, episodes of stratal condensation in this region have been attributed to reactivation of the Las Animas arch, a structural remnant of the Late Paleozoic uplift of the Ancestral Rocky Mountains (reviewed by Berry and Flores, 2018). During such episodes, decreased sedimentation rates along the flank of this arch led to the local proliferation of otherwise exceptionally rare environmental indicators, which thrived in this sediment-starved setting (Berry, 2016, 2018b), whereas stratal accumulation rates remained comparatively high in other regions of this basin (Berry and Flores, 2018; Sealey and Lucas, *this volume*). Therefore, reactivation of the Las Animas arch in the late Campanian and early Maastrichtian marks an important phase in the tectonic evolution of the Raton Basin, as this structure appears to have been among the first to delimit the modern basin.

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