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New Mexico Geology, v. 29, n. 3 pp. 75-99, Print ISSN: 0196-948X, Online ISSN: 2837-6420.
https://doi.org/10.58799/NMG-v29n3.75

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# A condensed middle Cenomanian succession in the Dakota Sandstone (Upper Cretaceous), Sevilleta National Wildlife Refuge, Socorro County, New Mexico

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## Abstract

The upper part of the Dakota Sandstone exposed on the Sevilleta National Wildlife Refuge, northern Socorro County, New Mexico, is a condensed, Upper Cretaceous, marine succession spanning the first five middle Cenomanian ammonite zones of the U.S. Western Interior. Farther north in New Mexico these five ammonite zones occur over a stratigraphic interval more than an order of magnitude thicker. The basal part of this marine sequence was deposited in Seboyeta Bay, an elongate east-west embayment into New Mexico that marked the initial transgression of the western shoreline of the Late Cretaceous seaway into New Mexico.

The primary mechanism for condensing this section was nearshore, submarine erosion, although nondeposition played a minor role. The ammonite fossils from each zone are generally fragments of internal molds that are corroded on one side, indicating submarine burial, erosion of the prefossilized steinkern, and corrosion on the sea floor. In addition, the base of the condensed succession is marked by a thin bed that contains abundant, white-weathering, spherical to cylindrical phosphate nodules, many of which contain a cylindrical axial cavity of unknown origin.

The nodules lie on the bedding surface of the highly burrowed, ridge-forming sandstone near the top of the Dakota and occur in the overlying breccia. The breccia consists of rip-up clasts of sandstone and eroded internal molds of the ammonite *Conlinoceras tarrantense*, the zonal index for the basal middle Cenomanian. The nodules below the breccia imply a time of erosion followed by nondeposition or sediment bypass during which the phosphatization occurred. The breccia implies a time of submarine erosion, probably storm-related.

Remarkably, this condensed succession and the basal part of the overlying Mancos Shale tongue contain one of the most complete middle Cenomanian ammonite sequences in the U.S. Western Interior. Five of the six ammonite zones that characterize the middle Cenomanian of the Western Interior are found on Sevilleta National Wildlife Refuge. Only representatives of the second oldest zone are missing, although stratigraphically there is room for this zone. Fossils from each zone occur in stratigraphically separated beds; no zone overlaps with or is superimposed on another.

Maps of the western shoreline of the seaway at the beginning and end of the time represented by the condensed succession show the progression of the Late Cretaceous seaway from embayment to ocean covering most of New Mexico. These maps, combined with the resolving power of the middle Cenomanian biostratigraphic framework, indicate that the southern shoreline of Seboyeta Bay, which was only a few miles south of Sevilleta National Wildlife Refuge, was virtually stationary for most of this time. This ensured

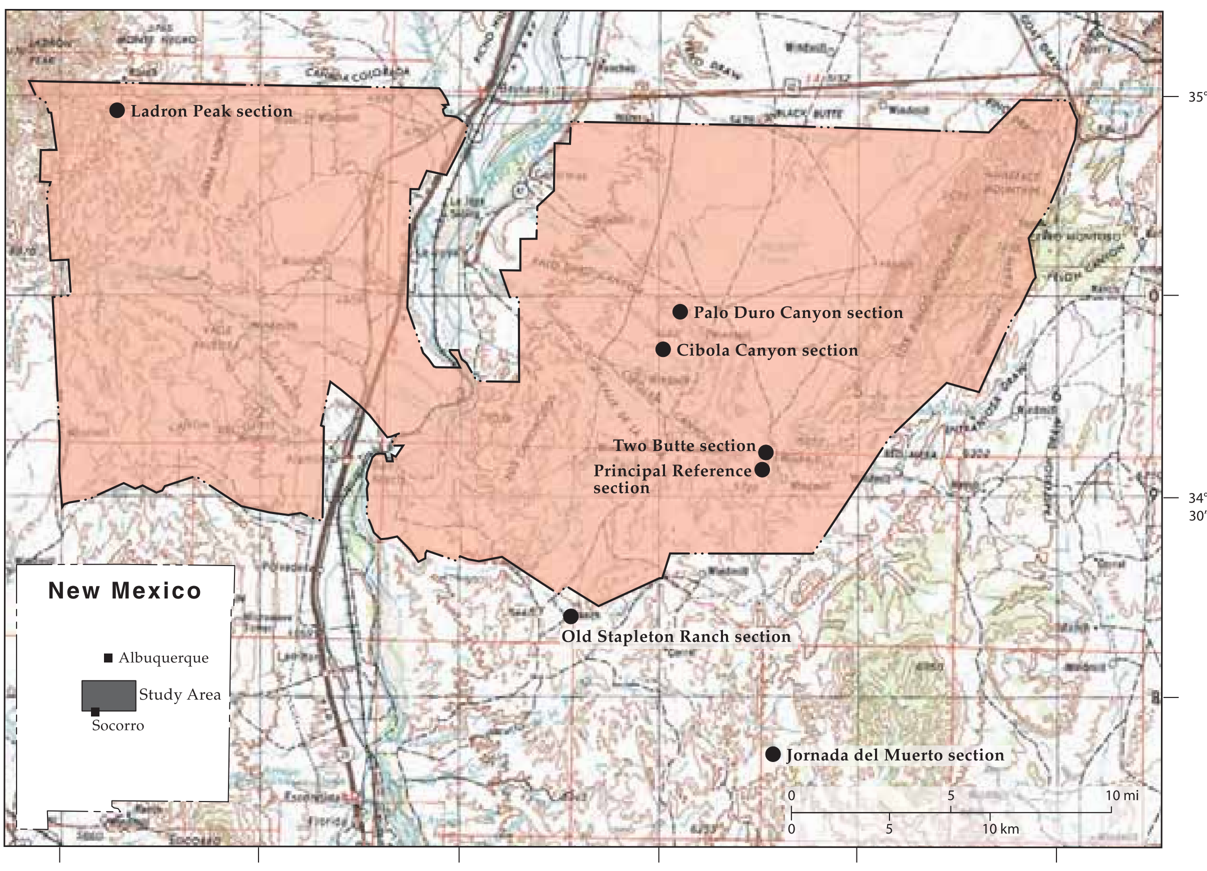



FIGURE 1— Map showing the locations of sections mentioned in the text that are on or near the Sevilleta National Wildlife Refuge, northern Socorro County, New Mexico. Refuge area shown in pink.

## Sevilleta National Wildlife Refuge

Vertical digital orthophotograph from summer 2005 of the northern border between Sevilleta National Wildlife Refuge to the south and private land to the north. At an altitude of about 35,000 ft this image includes, from the top, NM–60 east of Bernardo, basalt-capped Black Butte (Turututu) at the far right, and the abrupt change to ungrazed vegetation south of the refuge boundary. Image prepared by Mark Mansell.

The 9,227 ha (228,000 acres = 624 $mi^2$) Sevilleta National Wildlife Refuge is located in the Chihuahuan Desert approximately 32 km (20 mi) north of Socorro, New Mexico (Fig. 1). It was established in 1973 by the U.S. Fish and Wildlife Service to maintain natural ecological processes and to preserve and enhance native wildlife habitat.

The refuge is approximately 32 km (20 mi) from north to south by 48 km (30 mi) from east to west. This vast area spans the width of the Rio Grande rift in central New Mexico. It is bounded on the east by the 2,100-m (7,000-ft)-high Los Pinos and Manzano Mountains and on the west by the 2,700-m (9,000-ft)-high Sierra Ladrones. The Rio Grande valley splits the area into two parts with about a third of the refuge on the west and about two-thirds on the east. Sevilleta's northern boundary, which is a fairly linear east-west line, lies at about the latitude of Bernardo, New Mexico. It's southern boundary, which is irregular, lies just north of Polvadera, New Mexico (Fig. 1).

On recent high-altitude and satellite images, the refuge's northern boundary is a distinct east-west-trending line, 26 km (16 mi) long between the Rio Grande on the west and the Manzano Mountains on the east. The area north of this line is light brown, whereas the area south of the boundary, which has not been grazed for more than 30 yrs, is dark brown. This color contrast can also be seen extending westward from the Rio Grande to the Sierra Ladrones, but it is not as distinct or as linear as the eastern segment.

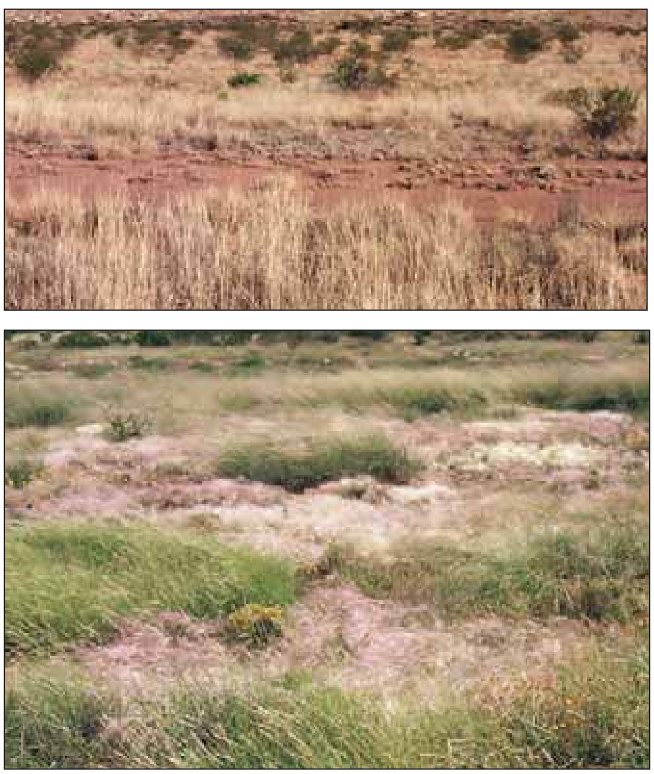
The refuge is a major portion of the La Joya de Sevilleta Land Grant, which was bequeathed to Spanish settlers by the King of Spain in 1819. The area apparently reminded the earliest settlers of Seville, Spain. Don Juan Oñate's expedition of 1598 applied the name Nueva Sevilleta to a Piro Indian pueblo on the Rio Grande near present-day La Joya (Julyan 1998, p. 190).

After the Mexican–American War, President Roosevelt issued a patent on the land to the residents of the land grant. When New Mexico became a state in 1912, the community became responsible for taxes on the land grant. These taxes were not paid, and Socorro County bought the land in a public sale in 1928.

General Thomas Campbell purchased the land from Socorro County in 1936. The Campbell family worked the land and operated a cattle ranch on it for more than 30 yrs. The Campbell Family Foundation with the assistance of The Nature Conservancy donated 220,000 acres of the Sevilleta Land Grant to the citizens of the United States in 1973 to be used as a natural area and wildlife sanctuary. The land is to be held forever in its natural state and is dedicated to ecological and wildlife research in a natural environment. On December 28, 1973, the Sevilleta National Wildlife Refuge was established.

The goals of the refuge are to protect and manage endangered species and to preserve, restore, and maintain its original biological diversity. Portions of the refuge are set aside for scientific research that is compatible with its goals, and the refuge is designated as a long-term ecological research site in partnership with the University of New Mexico. Since its creation in 1973 the Sevilleta National Wildlife Refuge has been returning slowly to the natural conditions that might have existed around the turn of the twentieth century. Amigos de la Sevilleta National Wildlife Refuge, Inc., is a volunteer, nonprofit group dedicated to supporting the refuge in the conservation of wildlife and their habitats through environmental education and research.

This text is loosely paraphrased from two sources: the Sevilleta National Wildlife Refuge Web site (http:// www.fws.gov/southwest/refuges/newmex/sevilleta/index.html) and a state of New Mexico information sign at mileage marker 166 at the rest area on the east side of I–25.



The ungrazed refuge responds to summer monsoon rains with a variety of grasses and wild flowers. The upper photo was taken June 30, 2006, and the lower on September 20, 2006. Both are the same area, but not the same view.

that the refuge was under shallow, well-oxygenated, marine waters for much of middle Cenomanian time. It also ensured that deposited sediments would be subjected periodically to erosion by nearshore waves and currents.

This report marks the first recorded occurrence in New Mexico of the following ammonite species: *Acanthoceras muldoonense* (zonal index), *A. bellense* (zonal index), *Turrilites (Euturrilites) scheuchzerianus*, *Cunningtoniceras* cf. *C. cunningtoni*, and *Paraconlinoceras leonense*. The occurrences of the zonal indices in the Dakota Sandstone on and to the south of the refuge increase not only their geographic distributions, but also the biostratigraphic resolution in the middle Cenomanian of New Mexico.

## Introduction

The upper part of the Dakota Sandstone and the basal part of the overlying Mancos Shale tongue exposed on the Sevilleta National Wildlife Refuge (Sevilleta or the refuge), northern Socorro County, New Mexico (Fig. 1), contain one of the most complete middle Cenomanian (Upper Cretaceous) ammonite sequences in the Western Interior of the United States. Of the six recognized ammonite zones for the middle Cenomanian of the Western Interior, only the second oldest is not represented on the refuge, although stratigraphically there is space for this zone in the section.

This biostratigraphic record is all the more remarkable because ammonites from four of the initial five zones occur in stratigraphically separated beds in the upper 11 ft (3.4 m) of the Dakota Sandstone. Elsewhere in the region, time-equivalent beds are as much as 13 times thicker. There is room stratigraphically in the sequence for all five middle Cenomanian faunal zones, and no faunal zone is superimposed on another. There is no evidence for subaerial exposure of any of these beds.

The base of this condensed succession on Sevilleta is marked by abundant white-weathering, irregularly spherical to cylindrical, phosphate nodules as much as 8 cm in diameter and 10 cm long that have weathered free of the matrix and now litter the outcrop. These nodules are interpreted to indicate a period of erosion followed by very slow deposition.

A thin bed of gray breccia at this same level is composed of rip-up clasts of gray sandstone that contains internal molds and impressions of ammonites and local, dark-gray phosphate nodules, similar in size and shape to the white nodules. Body fossils of ammonites from throughout the succession are internal molds that are generally incomplete (broken) and show effects of submarine erosion with at least one side corroded. The breccia and corroded internal molds reveal several episodes of submarine erosion.

Erosive episodes within condensed successions are highly unusual. Accordingly, we define the condensed succession on Sevilleta as a relatively thin, but apparently faunally complete, stratigraphic succession of middle Cenomanian age that is represented elsewhere in the region by time-equivalent sections that are more than an order of magnitude thicker.

| Stephenson and Reeside (1938) | Cobban and Reeside (1952) | Cobban and Scott (1973) | Cobban (1988) |
|---|---|---|---|
| Zone 1 (Graneros Shale) | *Acanthoceras*? sp. A. | *Plesiacanthoceras wyomingense* | *Plesiacanthoceras wyomingense* |
| | *Acanthoceras*? *amphibolum* | *Acanthoceras amphibolum* | *Acanthoceras amphibolum* (94.96 m.y. B.P.) |
| *Acanthoceras* spp. | | | *Acanthoceras bellense* |
| | | *Acanthoceras muldoonense* | *Acanthoceras muldoonense* |
| | | *Acanthoceras granerosense* | *Acanthoceras granerosense* |
| *Exogyra columbella* | *Calycoceras* sp. | *Calycoceras (Conlinoceras) gilberti* | *Conlinoceras tarrantense* (95.73 m.y. B.P.) |

FIGURE 2— Chart showing the evolution of the middle Cenomanian ammonite zonation in the Western Interior of the United States from 1938 to 1988. The two radiometric ages, in millions of years before the present (m.y. B.P.), shown below *Conlinoceras tarrantense* and *Acanthoceras amphibolum*, are derived from bentonites within the zones (Cobban et al. 2006).

Four middle Cenomanian ammonite species, including two zonal indices for the Western Interior of North America, are reported from New Mexico for the first time. Subsequently, the two index species have been found at other localities in Socorro County, indicating that they may be common middle Cenomanian faunal elements in New Mexico that have been overlooked in the past.

In the sections of the paper that follow we will discuss: (1) the evolution of the high-resolution biostratigraphic and geochronologic framework that allowed us to recognize this condensed succession; (2) the regional and local Upper Cretaceous stratigraphic framework of Sevilleta National Wildlife Refuge; (3) the detailed stratigraphy and biostratigraphy of the upper part of the Dakota Sandstone on Sevilleta that contains the condensed succession; and (4) the time-equivalent but much thicker sections at Laguna, New Mexico, and Pueblo, Colorado.

Two maps showing the approximate position of the western shoreline of the Late Cretaceous seaway at the beginning and end of the time represented by this condensed succession show that the seaway went from an embayment in central New Mexico to a full ocean that covered most of the state. We conclude the paper with illustrations and brief descriptions of the four middle Cenomanian zonal ammonite species that occur in the upper part of the Dakota Sandstone on the refuge.

Information about Sevilleta National Wildlife Refuge, where the condensed succession was first recognized, can be found on page 76. Speculation on the origin of the phosphate nodules, which are unusual but not unique in the Upper Cretaceous of the Western Interior, appears as Appendix 1. Appendix 2 is a list of all the numbered collections mentioned in the text or shown on the figures. Each species from a collection number is listed separately and identified as to kind of fossil (e.g., ammonite). The stratigraphic range of each species is also shown.

## High-resolution biostratigraphy

In this portion of the paper we describe the evolution of the faunal zonation of the middle Cenomanian using primarily four key papers covering the years 1938 to 1988 (Fig. 2). There are many more papers that could have been included on Figure 2, but these four tell the essential story in graphical form without overwhelming detail. We discuss a few other supplemental papers as well. For a discussion of the evolution of the faunal zonation for the entire Upper Cretaceous of the Western Interior, the interested reader is referred to Cobban et al. (2006).

The resolving power of this middle Cenomanian biostratigraphic framework increased three fold during the half century of research profiled in Figure 2, from two zones in 1938 to six zones in 1988 and at present. The average geochronological resolving power of each zone increased from approximately 450 k.y./zone to 150 k.y./zone. Within New Mexico, middle Cenomanian resolution has increased almost two fold. Before this study, which recognizes five zones, only three of these six zones (and only two of the initial five zones) had been identified in New Mexico.

Formal faunal zonation of the Upper Cretaceous of the Western Interior began with Stephenson and Reeside's 1938 comparison of the Upper Cretaceous of the Western Interior and the Gulf Coast regions. Stephenson and Reeside (1938) subdivided the

Western Interior Upper Cretaceous into 10 fossil zones and listed important molluscan species for each zone. Zone 1, their lowest zone, corresponds to the middle Cenomanian of today's usage. Important species in this zone included the oyster *Exogyra columbella* Meek at the base and various species of the ammonite *Acanthoceras* in the rest of the Graneros Shale (Fig. 2, left column).

Cobban (1951) established a sequence of 20 ammonite zones for the Cenomanian through Santonian strata of the Colorado Group in Montana and the Black Hills of South Dakota. Cobban and Reeside (1952) applied this zonation to the entire Western Interior. The middle Cenomanian portion of their GSA correlation chart, which consists of three ammonite zones, is shown in the second column from the left on Figure 2. The three ammonite species they recognized are, from oldest to youngest, *Calycoceras* sp., *Acanthoceras*? *amphibolum*, and *Acanthoceras*? sp. A. The major refinements offered by Cobban and Reeside (1952) were the addition of *Calycoceras* sp. at the base of the middle Cenomanian and identification the *Acanthoceras* spp. of Stephenson and Reeside (1938) as *Acanthoceras*? *amphibolum* and an undetermined, but distinct *Acanthoceras*? sp. A. Note that there is still an unfilled gap between *Calycoceras* sp. and *Acanthoceras*? *amphibolum*.

After further study, Cobban (1961, p. 738, table 1) suggested using the ammonite *Borissiakoceras compressum* Cobban for the basal zone of the middle Cenomanian because it was more definitive than *Calycoceras* sp., a genus that ranged into the early Turonian in the Western Interior. He also identified the undetermined *Acanthoceras*? sp. A. as *Acanthoceras*? *wyomingense* Reagan.

The detailed stratigraphic and biostratigraphic work of Cobban and Scott (1973) on the Graneros Shale and Greenhorn Limestone in the Pueblo, Colorado, region resulted in the addition of two more zones and the choice of *Calycoceras (Conlinoceras) gilberti* as the index species for the basal middle Cenomanian zone (Fig. 2, third column). It appears suddenly, along with all the other macrofauna, in the middle of the Graneros Shale in the Thatcher Limestone Member. Two newly named species, *A. granerosense* and its descendant *A. muldoonense*, filled most of the stratigraphic interval between *C. gilberti* and *A. amphibolum*. The stratigraphic interval between *A. muldoonense* and *A. amphibolum*, which can be as much as 30 ft (10 m) in the Pueblo area, was poorly fossiliferous, and contained only one bed of unidentifiable gypsiferous casts of large acanthoceratid ammonites. Cobban and Scott (1973, p. 33) believed that "…this gap probably marks the time of *A. alvaradoensis* Moreman." *Plesiacanthoceras wyomingense* (Reagan), which Cobban and Scott (1973, table 4) recognized as a zonal index for the uppermost middle Cenomanian in the Western Interior, does not occur in the Pueblo area.

Cobban (1984a, fig. 2) excluded both *A. granerosense* and *A. muldoonense* from the middle Cenomanian zonation of the Western Interior because of their (then) limited geographic distribution and the possibility that they could both lie within the broad zone of *A. amphibolum*. Our present collections from Sevilleta not only extend the geographic range of the *A. muldoonense*, but also show that it does not overlap with *A. amphibolum*. *Acanthoceras granerosense* has not yet been found in New Mexico.

The middle Cenomanian ammonite zonation reached its present state of detail with the work of Cobban (1987a, 1988) on the acanthoceratid ammonites from the Western Interior (Fig. 2, right column). Cobban (1988) assigned the species *amphibolum* to the genus *Cunningtoniceras*; subsequently, Kennedy and Cobban (1990) have reassigned *amphibolum* to *Acanthoceras*. We update Cobban's original generic assignment on Figure 2.

The biggest change from Cobban and Scott (1973) was that the zone between *A. muldoonense* and *A. amphibolum* was filled by *A. bellense*, a species described originally from central Texas. Also note that the subgenus *Conlinoceras* was raised to full generic rank and that the species *gilberti* was replaced by *tarrantense*, a closely related, but more widely distributed species.

In regard to the addition of *A. bellense* to the zonation, Cobban (1987a, p. 24) states that "*Acanthoceras bellense* has not been previously considered in the ammonite zonation of the Western Interior. This species is known from a very limited area near Osage, Wyoming, on the west flank of the Black Hills. …The position of this fossil in the middle Cenomanian acanthoceratid sequence is not clear. …It seems likely that *Acanthoceras bellense* lies some place between the zones of *Acanthoceras muldoonense* and [*Acanthoceras*] *amphibolum*." The Dakota Sandstone localities on Sevilleta National Wildlife Refuge, which we will discuss in later sections of this paper, show unequivocally that *A. bellense* does lie between *A. muldoonense* and *A. amphibolum*. At one of these localities, *A. bellense* is associated with the ammonite *Paraconlinoceras leonense*, just as it is in the Belle Fourche Shale in Wyoming and the Eagle Ford Formation of Texas.

The two absolute ages shown on Figure 2 (right column) are $^{40}Ar/^{39}Ar$ ages updated by Cobban et al. (2006, fig. 1) from Obradovich (1994). The 95.73 m.y. B.P. age is from the bentonite bed in the Graneros Shale that is 20 cm below the Thatcher Limestone Member of the Graneros Shale, Pueblo County, Colorado (Obradovich 1994, table II, loc. 25, p. 385).

The 94.96 m.y. B.P. age, which is from the *A. amphibolum* Zone, came from the Soap Creek Bentonite Bed in the Frontier Formation, Natrona County, Wyoming (Obradovich 1994, table II, loc. 24, p. 385). The Soap Creek Bentonite is equivalent to the marker bentonite of the Lincoln Member of the Greenhorn Limestone of Pueblo, Colorado, area (Cobban and Scott 1973) and to the informal "x-bentonite" of petroleum usage. At Pueblo, the marker bentonite lies about two-thirds of the way through the *A. amphibolum* Zone (Cobban and Scott 1973, plate 40).

These two ages, one slightly below the lowest zone and the other about two-thirds of the way through the penultimate zone of the middle Cenomanian, span 770 k.y. We will use these ages as given to calculate durations and rates for several events within the middle Cenomanian.

The average duration of each of the first five ammonite range zones of the middle Cenomanian is 154 k.y. Assuming that this average holds for the last zone, the *P. wyomingense* Zone, we calculate a duration of 924 k.y. for the entire middle Cenomanian substage and an age of 94.81 m.y. B.P. for the upper boundary of the middle Cenomanian substage. This figure compares quite favorably with the 94.71 m.y. B.P. age from the *Dunveganoceras pondi* Zone, the basal zone of the upper Cenomanian (Cobban et al. 2006, fig. 1). This age was derived from a bentonite about midway through the *D. pondi* Zone in the Frontier Formation, Carbon County, Wyoming (Obradovich 1994, table II, loc. 23).

The close agreement between the calculated and determined radiometric ages of the substage boundary indicates that rate calculations can be made with a fairly high degree of time-confidence. Although thickness can be measured fairly accurately (probably to within 15%), shoreline positions are poorly constrained because of isolated exposures of Upper Cretaceous strata in southern New Mexico. We regard the calculated rates not as absolute numbers, but as order-of-magnitude estimates.

## The Upper Cretaceous of Sevilleta National Wildlife Refuge

In this section of the paper we place the Upper Cretaceous on Sevilleta National Wildlife Refuge into its regional context, discuss the geologic history of this middle Cenomanian through lower Coniacian sequence, and describe in detail the middle Cenomanian condensed succession in the Dakota Sandstone on the refuge.

### Regional lithostratigraphy

The composite Upper Cretaceous stratigraphic section on Sevilleta National Wildlife Refuge (Fig. 3) serves not only to place the middle Cenomanian condensed succession in context, but also to illustrate the regional Upper Cretaceous framework (Fig. 3). In Socorro County, New Mexico, marine rocks are confined to the lower 1,200–1,500 ft (400–500 m) of the Upper Cretaceous section. These cyclically interbedded marine and nonmarine strata were deposited dur-

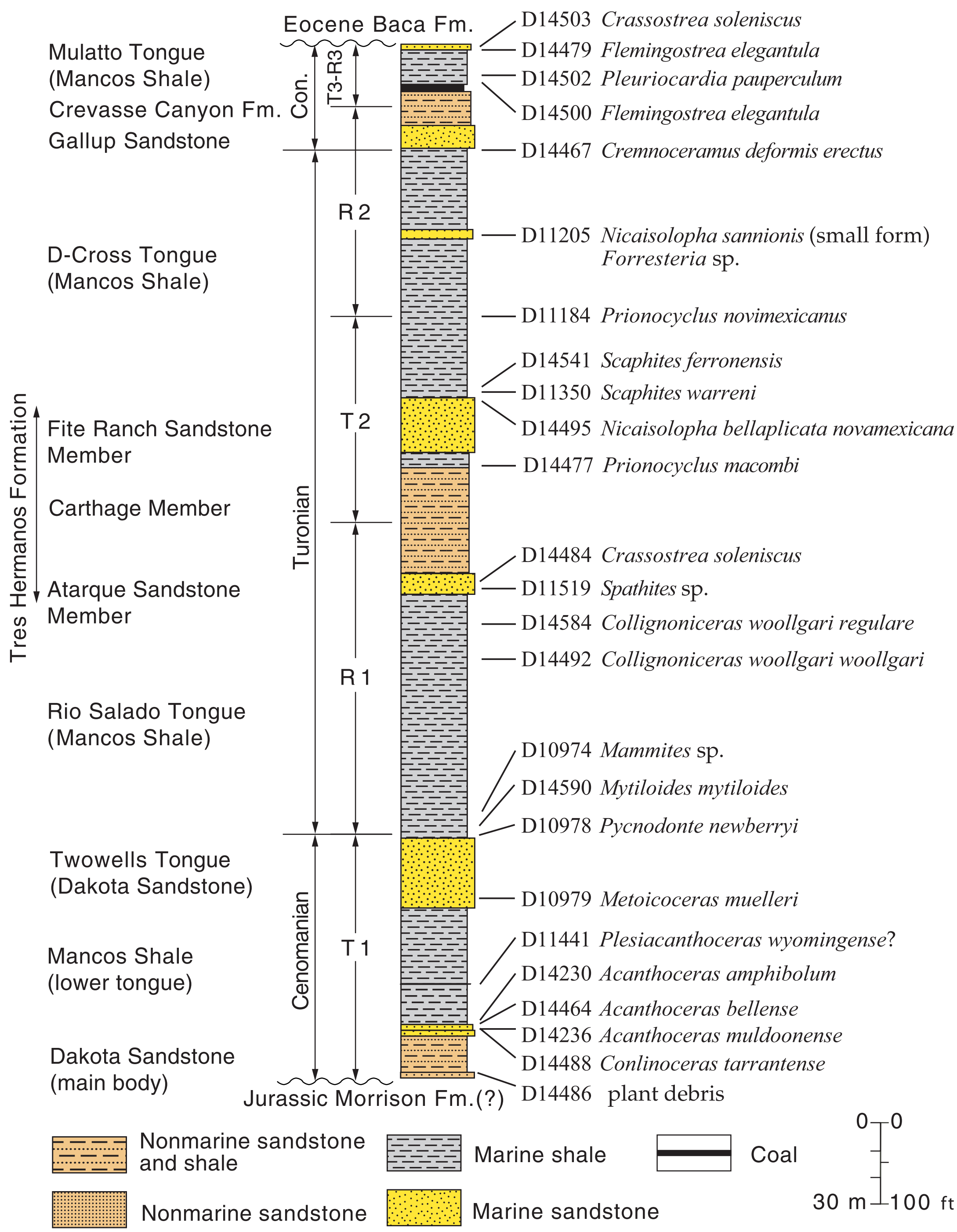



FIGURE 3— Composite Upper Cretaceous stratigraphic section exposed on the Sevilleta National Wildlife Refuge, Socorro County, New Mexico (modified from Wolberg 1985).

ing the first three (of at least five) major transgressive-regressive (T-R) cycles of the Late Cretaceous seaway in New Mexico. The three earliest cycles range in age from middle Cenomanian to early Coniacian. Using Molenaar's (1983) terminology, we designate these three cycles by the numbers one through three (e.g., T1-R1), with one, the earliest, and three, the latest cycle.

A colleague once characterized the Upper Cretaceous of northwestern Socorro County as "a sea of shale on top of the Dakota Sandstone." This seems an apt analogy. In simplest terms, the Upper Cretaceous of Socorro County consists of a thin basal sandstone followed by a thick sequence of marine shale that is subdivided into three unequal parts by two sequences of nearshore marine sandstones and nonmarine strata. Rock names that are applied to these generalized units are, from base to top, Dakota Sandstone, lower tongue of the Mancos Shale, Tres Hermanos Formation, D-Cross Tongue of the Mancos Shale, Gallup Sandstone, Crevasse Canyon Formation, and Mulatto Tongue of the Mancos Shale. Where the Twowells Tongue of the Dakota

Sandstone is present, the upper part of the lower tongue of the Mancos Shale is called the Rio Salado Tongue (Fig. 3). Most of the net deposition appears to have taken place during the regressions, when the western shoreline of the Late Cretaceous seaway was retreating in a generally northeasterly direction across Socorro County.

The western shoreline of the Late Cretaceous seaway entered New Mexico from the east during middle Cenomanian time and continued to advance (transgress) across the state until the end of Cenomanian time. At the end of this initial transgression (T1), the Late Cretaceous seaway covered most if not all of New Mexico and the northeastern third of Arizona (Hook and Cobban 1977, fig. 1). Rock units associated with T1 in Socorro County include the intertongued Dakota Sandstone and Mancos Shale sequence through the basal part of the Rio Salado Tongue (Fig. 3). During R1, the western shoreline retreated (regressed) northeasterly beginning in southwest New Mexico. By middle Turonian time, the shoreline had retreated well to the northeast of Sevilleta, so that nonmarine strata in the Carthage Member of the Tres Hermanos Formation were deposited on the refuge. Rock units associated with R1 include the upper part of the Rio Salado Tongue of the Mancos Shale, as well as the Atarque Sandstone Member and lower part of the Carthage Member of the Tres Hermanos Formation (Fig. 3).

During T2, marine waters again covered Sevilleta as the shoreline moved southwestward across west-central New Mexico. By the middle of late Turonian time, the seaway covered the northern two-thirds of New Mexico and a small portion of northeastern Arizona (Hook and Cobban 1979, fig. 4). Rock units associated with T2 include the upper part of the Carthage Member and the Fite Ranch Sandstone Member of the Tres Hermanos Formation and the basal part of the D-Cross Tongue of the Mancos Shale. During R2, the shoreline retreated northeastward until early Coniacian time, leaving a terrestrial record on the refuge in the form of economic coals in the basal Crevasse Canyon Formation. Rock units associated with R2 include the upper part of the D-Cross Tongue, the Gallup Sandstone, and the basal part of the Crevasse Canyon Formation (Fig. 3). R2, also called the Gallup regression, appears to be unique to New Mexico and Arizona (Molenaar 1983, p. 218).

Until recently, there were only two recognized cycles of transgression-regression recorded in the Upper Cretaceous rocks of Socorro County. Our work on Sevilleta revealed a thin sequence of fossiliferous, marine sandstones and shales just above the coal in the Crevasse Canyon and just below the Tertiary unconformity. These lower Coniacian beds represent T3-R3 and are at least equivalent to the Mulatto Tongue of the Mancos Shale. This thin sequence of marine beds, which is capped by a coquina of brackish water oysters (Fig. 3, D14503 level), indicates that the seaway had not advanced too far to the southwest of the refuge (T3) before retreating to the northeast (R3). We have not found any evidence of younger marine rocks in the county. However, structural complications, along with subsequent Late Cretaceous and early Tertiary erosion that has removed much of the post-early Coniacian strata from Socorro County, make it difficult to know for certain if there are any younger T-R cycles in the area. Molenaar (1983, fig. 10), who was unaware of the presence of the Mulatto Tongue on the refuge, shows the maximum extent of the T4 shoreline to be approximately 50 mi (80 km) northeast of Sevilleta.

This relatively simple stratigraphic picture becomes slightly more complicated in northwest Socorro County and on northern Sevilleta National Wildlife Refuge by the incursion of (1) the Twowells Tongue of the Dakota Sandstone into the lower tongue of Mancos Shale at the end of T1 (Fig. 3), and (2) an additional tongue of Gallup Sandstone in the D-Cross Tongue of the Mancos Shale (Hook et al. 1983, sheet 1B). A thin remnant of that Gallup Sandstone tongue is present in the D-Cross Tongue of the Mancos Shale on Sevilleta (Fig. 3, D11205 level).

## Local lithostratigraphy

The Upper Cretaceous is exposed on Sevilleta in isolated exposures and consists of at least 1,260 ft (384 m) of mainly marine clastic rocks from the base of the main body of the Dakota Sandstone to the last known marine sandstone (D14479 level), 100 ft (30 m) above the base of the Crevasse Canyon Formation (Fig. 3). In addition there is an unknown, but substantial, thickness of nonmarine rocks in the Crevasse Canyon Formation elsewhere on the refuge above that marine sandstone and below the erosional contact with the overlying Eocene Baca Formation. This erosional contact is generally high in the Crevasse Canyon Formation, but cuts as deeply as the top of the Dakota Sandstone just north of the Two Butte section (Fig. 1).

Baker (1981) assembled the composite stratigraphic section for Sevilleta (Fig. 3) from measured sections at the Principal Reference section and the Cibola Canyon section (Fig. 1). Wolberg (1985) published the section to illustrate the stratigraphic position of an important vertebrate fauna. We have added stratigraphic detail to the Dakota Sandstone and the Crevasse Canyon Formation/Mulatto Tongue of the Mancos Shale portions of the column. Most of the detailed biostratigraphy on Figure 3 is new.

The composite section consists of the following rock units in ascending order: main body of the Dakota Sandstone, 66 ft (20 m) thick; lower tongue of the Mancos Shale, 140 ft (43 m) thick; Twowells Tongue of the Dakota Sandstone, 85 ft (26 m) thick; Rio Salado Tongue of the Mancos Shale, 295 ft (90 m) thick; Tres Hermanos Formation, 241 ft (73 m) thick; D-Cross Tongue of the Mancos Shale, 303 ft (92 m) thick; Gallup Sandstone, 30 ft (10 m) thick; Crevasse Canyon Formation, 50 ft (15 m) thick, and Mulatto Tongue of the Mancos Shale, 50 ft (15 m) thick. The total, but incomplete, thickness of the Upper Cretaceous composite section is 1,260 ft (384 m; Fig. 3).

There is, however, no one section on the refuge that contains the entire stratigraphic sequence. The Principal Reference section (PRS) for the Upper Cretaceous on Sevilleta (Fig. 1) contains the most complete exposure of Upper Cretaceous rocks on the refuge. Approximately 2 mi$^2$ (5 km$^2$) of Upper Cretaceous rocks crop out in a continuous band, approximately 2 mi (3.2 km) long and 1 mi (1.6 km) wide.

The only rock unit shown on Figure 3 that does not crop out in the PRS area is the Twowells Tongue of the Dakota Sandstone, which was not deposited this far south on the refuge. A continuous shale section 360–380 ft (110–116 m) above the Dakota Sandstone at the PRS is the time equivalent of the Twowells Tongue. It contains *Pycnodonte newberryi* (Stanton) (D14485) at the top and *P.* aff. *P. kellumi* (Jones) (D14294) at the base. These fossils indicate that clays were being deposited at the PRS while time-equivalent sands that would become the Twowells were being deposited farther north in the Palo Duro Canyon and Cibola Canyon areas (Fig. 1). Mellere (1994) documents subaerial erosion within the Twowells in west-central New Mexico in the Acoma Basin, northwest of Sevilleta. We saw no evidence for subaerial exposure or erosion of the Twowells on the refuge.

The Twowells Tongue is confined depositionally to the northeast quarter of Sevilleta, necessitating a nomenclatural change to the south, where the Twowells Tongue is absent. At the Principal Reference and the Two Butte sections, the entire shale package between the Dakota Sandstone and the Tres Hermanos Formation is referred (informally) to the lower tongue of the Mancos Shale. See Hook et al. (1983, sheet 1B) for usage in Socorro County.

The 1,260-ft (384-m)-thick stratigraphic sequence on Sevilleta shown on Figure 3 was deposited during 7.18 m.y., based on radiometric ages from Cobban et al. (2006). The net (compacted) depositional rate for this composite section is 175.5 ft/m.y. (53.5 m/m.y.). We will refer to this rate as the long-term depositional rate at Sevilleta in the sections that follow; see Table 1.

## Biostratigraphy

Biostratigraphically, the Upper Cretaceous rocks on Sevilleta National Wildlife Refuge are one of the best-documented middle Cenomanian to Coniacian sections in New Mexico. The fossil collections shown

TABLE 1— Comparison of the net (compacted) depositional rate for the upper portion of the Dakota Sandstone at the Principal Reference section on Sevilleta National Wildlife Refuge to: (1) the Upper Cretaceous as a whole on Sevilleta National Wildlife Refuge; (2) the Upper Cretaceous minus the Dakota Sandstone on Sevilleta National Wildlife Refuge; (3) the time-equivalent portion of the intertongued Dakota Sandstone–Mancos Shale at Laguna, New Mexico; and (4) the time-equivalent portion of the Graneros Shale at Muldoon Hill, Colorado.

| Stratigraphic section | Start date (m.y. B.P.) | End date (m.y. B.P.) | Duration (m.y.) | Thickness ft (m) | Depositional rate ft/m.y. (m/m.y.) | Ratio (to Principal Reference section) |
|---|---|---|---|---|---|---|
| Upper Dakota Sandstone: Sevilleta National Wildlife Refuge, Principal Reference section | 95.73 | 94.96 | 0.77 | 11 (3.4) | 14.3 (4.4) | 1 |
| (1) Upper Cretaceous: Sevilleta National Wildlife Refuge (long-term depositional rate) | 95.73 | 88.55 | 7.18 | 1,260 (384) | 175.5 (53.5) | 12.3 |
| (2) Upper Cretaceous minus Dakota: Sevilleta National Wildlife Refuge | 94.96 | 88.55 | 6.41 | 1,194 (364) | 186.3 (56.8) | 13.0 |
| (3) Dakota–Mancos: Laguna section | 95.73 | 94.96 | 0.77 | 147 (44.8) | 190.9 (58.2) | 13.3 |
| (4) Graneros Shale: Muldoon Hill section | 95.73 | 94.96 | 0.77 | 57 (17.4) | 74.0 (22.6) | 5.2 |

on Figure 3 were collected over a 28-yr-interval. The higher the number following the letter "D," the more recent the collection. The earliest collections (D10974 and D10979) were made in September 1979; the latest collection (D14584) was made in April 2007. There is a gap in the collecting from 1982 to 2003.

Upper Cretaceous rocks on Sevilleta are fossiliferous from bottom to top and range in age from middle Cenomanian (D14488 *Conlinoceras tarrantense* level) to early Coniacian (D14467 *Cremnoceramus deformis erectus* level). This broad interval spanning 7.18 m.y. contains 30 ammonite range zones in the Western Interior (Cobban et al. 2006, fig. 1). The average duration for each of these ammonite zones is about 239 k.y./zone, more than 50% longer than the average duration of the first five middle Cenomanian ammonite zones, which averaged about 154 k.y./zone.

Nine of the 30 index species that give their names to these range zones have been found on or near Sevilleta. These include the five middle Cenomanian ammonites that have been collected from the Dakota Sandstone and overlying Mancos Shale on the refuge: *Conlinoceras tarrantense* (D14488), *Acanthoceras muldoonense* (D14236), *A. bellense* (D14464), *A. amphibolum* (D14230), and *Plesiacanthoceras wyomingense* (D11441) along with the middle Turonian ammonites *Collignoniceras woollgari* (two subspecies, D14492 and D14584), *Prionocyclus macombi* (D14477), *Scaphites warreni* (D11350), and *Scaphites ferronensis* (D14541).

Most of the fossil collections shown on Figure 3 came from the Principal Reference section and the Cibola Canyon section (Fig. 1). However, three other localities contributed significantly to our understanding of the Upper Cretaceous on the refuge. The Ladron Peak section in northwestern Sevilleta contributed the *Collignoniceras woollgari* faunas (D14492 and D14584) that allowed us to date the upper part of the Rio Salado Tongue of the Mancos Shale. The Old Stapleton Ranch section, just south of the refuge, contains the only fossiliferous concretions in the upper part of the Carthage Member of the Tres Hermanos Formation (D14477) and showed unequivocally that the upper Carthage Member is marine and lies in the *P. macombi* Zone. The Jornada del Muerto section, 10 mi (17 km) southeast of the refuge, confirmed that the phosphate nodules in the Dakota Sandstone lie within the *Conlinoceras tarrantense* Zone.

Older accounts of fossil collections from Sevilleta are primarily of historical value and include Darton (1928) and Wilpolt et al. (1946). Darton (1928, p. 75) lists a marine fauna (identified by T. W. Stanton) from above the coal in the Crevasse Canyon Formation at the Garcia y Goebel mine northeast of Socorro. We think that the Garcia y Goebel mine was located on Sevilleta at the Cibola Canyon section (Fig. 1). We worked with Baker (1981) on the initial understanding of the stratigraphy and paleontology of Sevilleta. Wolberg (1985) used Baker's (1981) stratigraphy to provide a framework for an important collection of vertebrates from the refuge. He lists and illustrates 19 taxa of selachians (sharks and rays) from a 1-ft (0.3-m)-thick bed of sandstone near the base of the Atarque Sandstone Member of the Tres Hermanos Formation (Fig. 3, D14484 level) from the Palo Duro Canyon section (Fig. 1).

## Condensed Dakota Sandstone successions on the refuge

In this section of the paper we will describe in detail the Dakota Sandstone from three areas on Sevilleta National Wildlife Refuge that contain condensed successions. We define condensed succession on Sevilleta as a relatively thin, but apparently faunally complete, stratigraphic succession of middle Cenomanian age that is represented elsewhere in the region by time-equivalent sections that are more than an order of magnitude thicker. This definition emphasizes the faunal completeness of a regionally thin succession of strata without specifying the mechanism that condensed the section. This allows for both slow deposition and erosion within a thin but apparently faunally complete section. In using the faunal modifier "apparently," we recognize that unfossiliferous strata can represent some zones.

### Principal Reference section

The main body of the Dakota Sandstone at the Principal Reference section (PRS) is 66 ft (20.1 m) thick and dips 30° toward the northwest. It is disconformable with the underlying Upper Jurassic Morrison Formation(?), which is in erosional contact with the Triassic Chinle Group (Cather et al. 2004). Figure 4 shows the distribution of middle Cenomanian fossils in the uppermost 18 ft of the Dakota Sandstone and the lower part of the overlying Mancos Shale at the PRS.

The Dakota Sandstone consists of four major units: (1) a lower, nonmarine, ridge-forming quartzite that is 6 ft (1.8 m) thick; (2) a middle, nonmarine, valley-forming, sandstone and carbonaceous shale unit, 43 ft (13.1 m) thick; (3) an upper, marine, ridge-forming, extensively burrowed and bioturbated sandstone, 6 ft (1.8 m) thick; and (4) an upper, marine unit of interbedded, thin, resistant and non-resistant sandstones, 11 ft (3.4 m) thick (Fig. 5A).

Impressions of plant debris and seeds (Fig. 5B) and carbonaceous shale are common in units 1 and 2. *Thalassinoides* burrows (Fig. 5D), which indicate marine deposition, are common on the upper surface of unit 3, which forms a prominent dip slope at the PRS (Fig. 5C). Phosphate nodules occur in place along with the burrows and weather

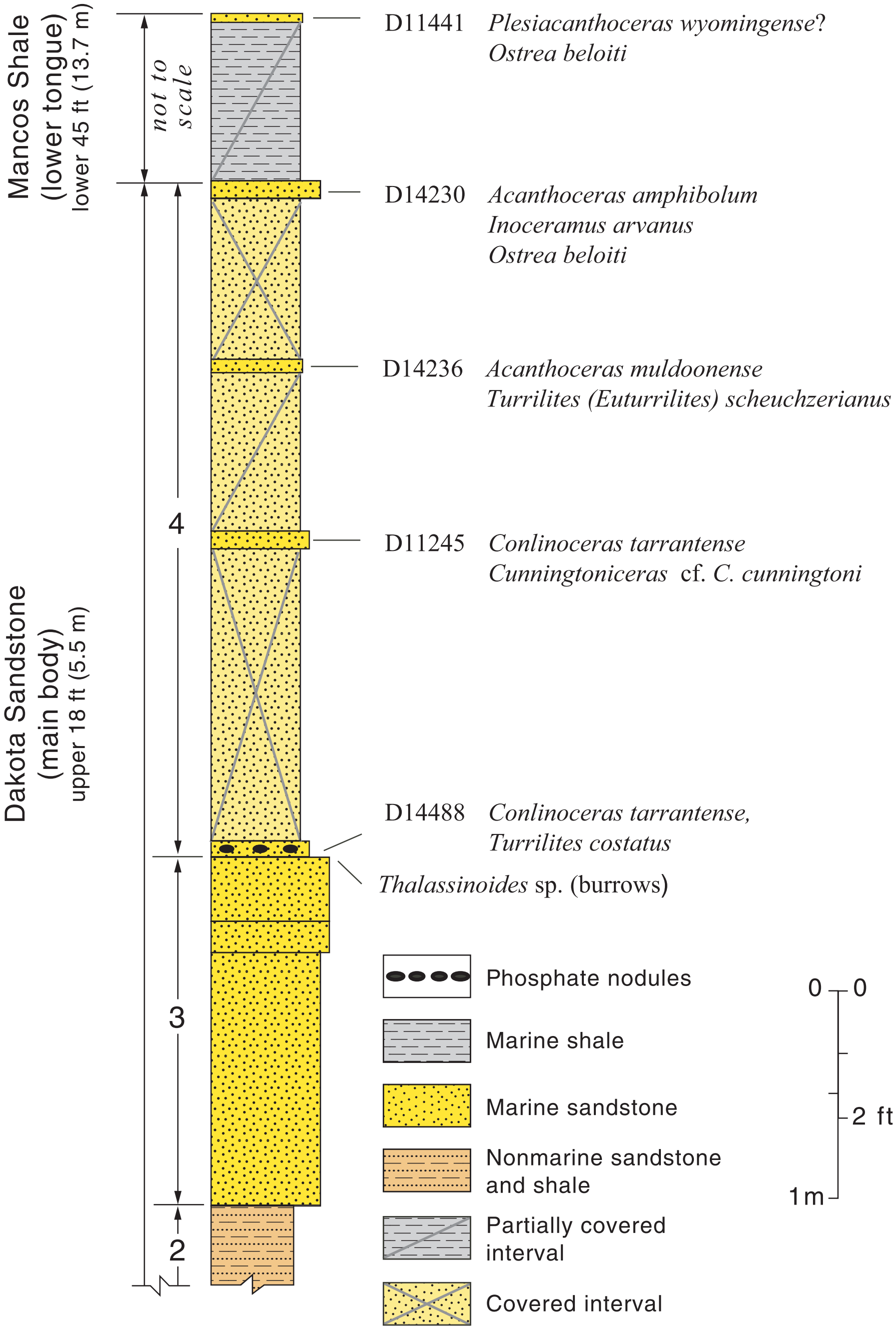



FIGURE 4— Stratigraphic section of the upper part of the Dakota Sandstone and the base of the lower tongue of Mancos Shale exposed at the Principal Reference section on Sevilleta National Wildlife Refuge. See Figure 1 for its location.

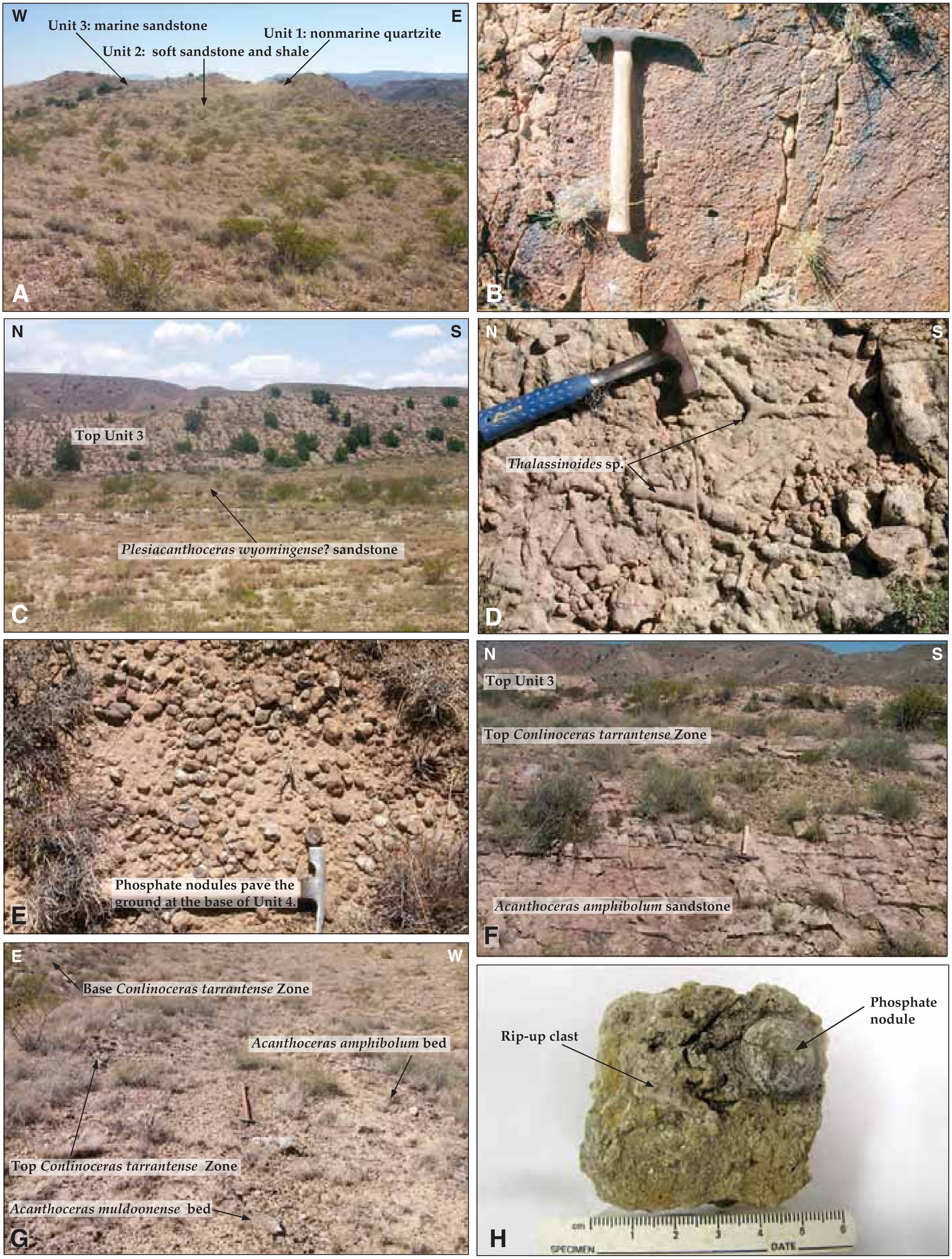
out of the base of unit 4, commonly paving the ground (Fig. 5E). Body fossils occur first at the base of unit 4 (Fig. 5F,G).

*Conlinoceras tarrantense* is found in two thin, resistant sandstones in the basal 5 ft (1.5 m) of the unit 4 (Fig. 5G). The lower occurrence (D14488 level) is a 2–3-inch (5–8-cm)-thick, gray-weathering sandstone and sandstone breccia. The breccia is a fine-grained sandstone that contains rip-up clasts of similar sandstone as much as 4 inches (10 cm) across and reworked phosphate nodules (Fig. 5G). Reworked internal molds and impressions of *C. tarrantense* are common in the breccia and commonly cut across bedding. White- to dark-gray-weathering, irregularly spherical to cylindrical phosphate nodules as much as an inch (2.5 cm) in diameter and 2 inches (5 cm) long are abundant in the bed and litter the ground where they have weathered free of the matrix (Fig. 5E). The body chamber of one internal mold of *C. tarrantense* contains one of these nodules. The upper bed containing *C. tarrantense* is a 3-inch (8-cm)-thick, brown-weathering, fine-grained, resistant sandstone that crops out more-or-less continuously along the Dakota outcrop (Fig. 5G). The preservation of the ammonites from this bed (D11245) is much better than in the lower bed, although only incomplete internal molds have been found.

*Acanthoceras muldoonense* occurs in a 2–3-inch (5–8-cm)-thick sandstone that is 2.5 ft (0.8 m) higher in the section (Fig. 5G). *Acanthoceras amphibolum* appears in some abundance in a 6-inch (15-cm)-thick, dark-brown-weathering, limy sandstone with ironstone concretions that marks the top of the Dakota Sandstone (Fig. 5F,G). A thin sandstone, 45 ft (13.7 m) above the base of the Mancos Shale (Fig. 3, D11441 level and Fig. 5C) contains an ammonite questionably identified as *P. wyomingense.* The stratigraphic intervals at the PRS that could contain *A. granerosense* and *A. bellense* are covered (Fig. 5G), but are relatively thick, approximately 2.5 ft (0.8 m) each.

The body fossils of ammonites from all beds in the Dakota Sandstone in the PRS consist of incomplete, internal molds of outer whorls that often show effects of ero-

FIGURE 5—Representative outcrop and hand-specimen photographs of the Dakota Sandstone and basal part of the overlying lower tongue of Mancos Shale at the Principal Reference section. **A**—View looking along strike to the north showing the lower three units of the Dakota Sandstone. **B**—Impressions of plant debris (D14486) are common on the tops of beds in the upper few inches of unit 1. **C**—View looking updip to the east from the Mancos Shale showing the prominent Dakota dip slope formed by the extensively burrowed sandstone, unit 3, and part of the overlying tongue of Mancos Shale. The thin ledge-forming sandstone in the Mancos in the middle ground contains the *Plesiacanthoceras wyomingense*? fauna (D11441). **D**—This extensively burrowed, marine sandstone forms the top of unit 3, the prominent dip slope shown in C. **E**—Phosphate nodules weather out of the top of unit 3 and the overlying few inches of unit 4 and commonly pave the ground. Note the axial cavity in the nodule above the hammer head. **F**—Thin, resistant, fossiliferous sandstones in unit 4, the uppermost, marine unit of the Dakota, form noncontinuous, minor ridges. This view, looking updip to the east, shows the resistant 6-inch (15-cm)-thick sandstone that forms the top of the Dakota Sandstone and contains the *Acanthoceras amphibolum* fauna (14230). A resistant sandstone about midway between it and the prominent ridge formed by the burrowed sandstone at the top of unit 3, contains *Conlinoceras tarrantense* and marks the top of the *C. tarrantense* Zone (D11245). **G**—View looking along strike to the south in unit 4 shows that most of unit is covered. The sandstones containing *C. tarrantense* (D11245) and *A. amphibolum* (D14230) crop out fairly continuously; the sandstone containing *A. muldoonense* (D14236) crops out intermittently along the trace marked by the Jacob's staff. **H**—Hand specimen (x 0.85) of the breccia from the base of unit 4 (D14488 level). The breccia contains reworked phosphate nodules along with rip-up clasts of a gray sandstone that commonly contain impressions of *Conlinoceras tarrantense*.


W
E
Unit 3: marine sandstone
Unit 1: nonmarine quartzite
Unit 2: soft sandstone and shale
A
B
N
S
Top Unit 3
*Plesiacanthoceras wyomingense*? sandstone
C
N
S
*Thalassinoides* sp.
D
Phosphate nodules pave the
ground at the base of Unit 4.
E
N
S
Top Unit 3
Top *Conlinoceras tarrantense* Zone
*Acanthoceras amphibolum* sandstone
F
E
W
Base *Conlinoceras tarrantense* Zone
*Acanthoceras amphibolum* bed
Top *Conlinoceras tarrantense* Zone
*Acanthoceras muldoonense* bed
G
Phosphate
nodule
Rip-up clast
H

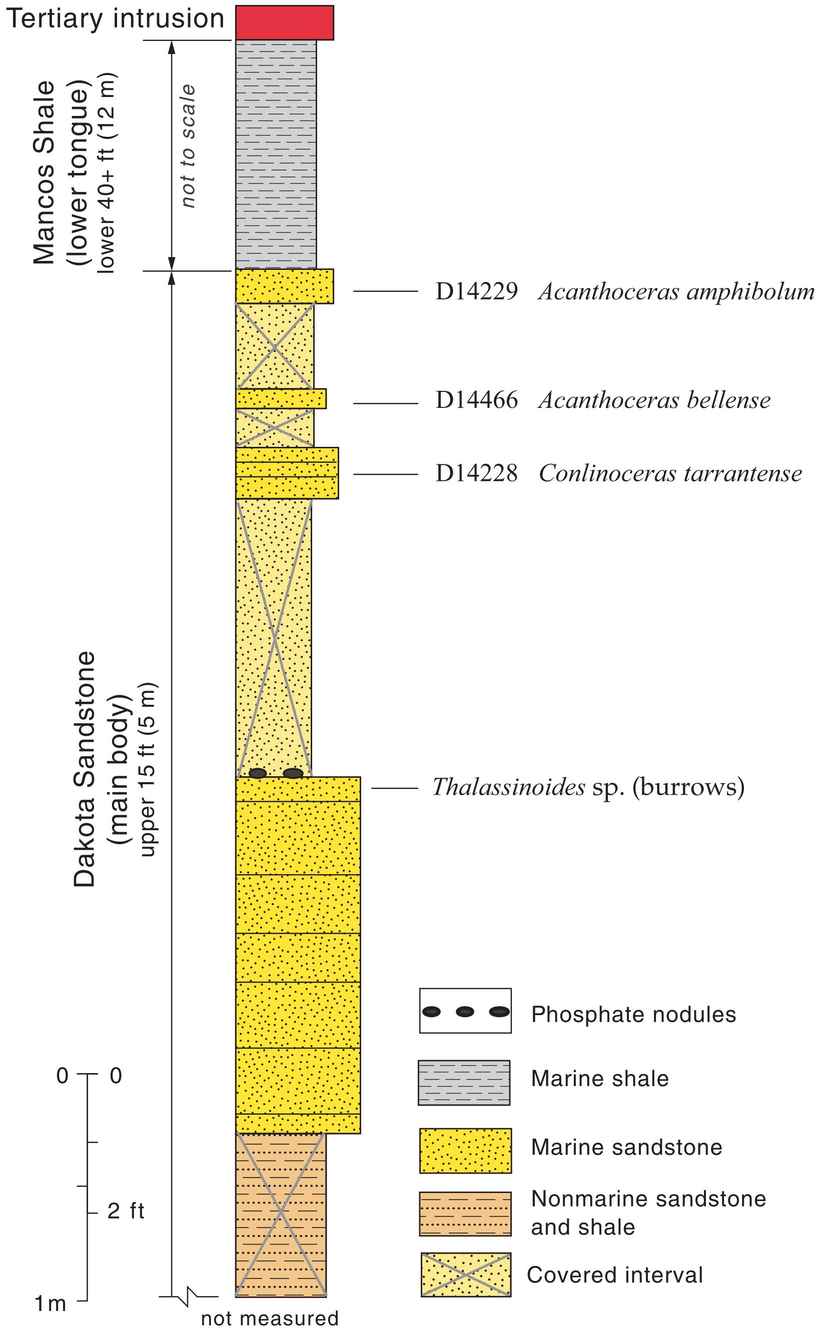



FIGURE 6—Stratigraphic section of the upper part of the Dakota Sandstone and the base of the lower tongue of Mancos Shale exposed at the Two Butte section, 1 mi (1.6 km) northeast of the Principal Reference section. See Figure 1 for its location.

sion. Usually at least one side is corroded. Unlike other well-studied Cretaceous condensed sequences (e.g., Hook and Cobban 1981 and Kennedy et al. 1977), these internal molds have not been colonized by oysters or other encrusting organisms.

Ammonites dominate the invertebrate faunas from the Dakota Sandstone at the PRS (as well as everywhere else on the refuge). An undescribed oyster along with one specimen of *Turrilites costatus* Lamarck, two specimens of *Cunningtoniceras* cf. C. *cunningtoni*, and a few gastropods occur with abundant *C. tarrantense* (D11245 and D14488 levels). *Turrilites costatus* and the gastropods occur in phosphate nodules as do a crab claw and a piece of wood containing many shipworm tubes.

The phosphate nodules that occur in and weather out of the breccia and sandstone at the base of unit 4 (D14488) are of considerable interest and importance in the interpretation of the uppermost part of the Dakota Sandstone on Sevilleta (Fig. 5E). We speculate on their origin in Appendix 1. For the present, their importance lies in marking the base of the *C. tarrantense* Zone at both Sevilleta and the Jornada del Muerto.

The 11 ft (3.4 m) of section between the phosphate nodules and the top of the Dakota Sandstone were deposited over 770 k.y., yielding a net (compacted) depositional rate of 14.3 ft/m.y. (4.4 m/m.y.). This rate is more than an order of magnitude less than the rate of 175.5 ft/m.y. (53.5 m/m.y.) calculated for the entire composite section at Sevilleta, which includes the Dakota! See Table 1.

#### Two Butte section

The Dakota Sandstone of the Two Butte section (TBS) is similar to that of the PRS, probably because it is only a mile to the northeast (Fig. 6). The two sections are not connected by continuous outcrop, and there may be a fault separating them. The upper part of the Dakota dips 5° southwest and forms a minor bench at the base of the two small buttes held up by a thin cap of Tertiary intrusive rock (Fig. 7A,B). The lower part of the Dakota is disconformable on red beds of the Triassic Chinle Group. Most of the marine part of the Dakota is covered (Fig. 7B), just as it is at the PRS. The resistant sandstones that do crop out are generally discontinuous. The condensed succession is thinner here than at the PRS and is a little more than 7 ft (2.1 m) thick. Most of the thinning takes place above the top of the *C. tarrantense* Zone, suggesting that more erosion has occurred here in post-*C. tarrantense* time than at the PRS.

Loose phosphate nodules (D14489; Fig. 7C) were collected at the top of the *Thalassinoides*-burrowed, upper bench-forming sandstone. The breccia seen at the PRS, if present here, does not crop out. *Conlinoceras tarrantense* (D14228) was collected from an 8-inch (19-cm)-thick bed of fine-grained sandstone that is approximately 4 ft (1.2 m) above the upper bench-forming sandstone. *Acanthoceras amphibolum* (D14229) was collected from a resistant, dark-brown, 6-inch (15-cm)-thick, fine-grained sandstone with small ironstone concretions that marks the top of the Dakota Sandstone in the southern part of Sevilleta (Fig. 7D).

Biostratigraphically the importance of the TBS lies in the *A. bellense* collection (D14466) that occurs stratigraphically between *C. tarrantense* (D14228) and *A. amphibolum* (D14229). The internal mold of *A. bellense* was collected in-place along a thin, steep drainage channel separating the two buttes (Fig. 7A). The relative order of the three zones is certain. There is only approximately 7 inches (18 cm) of section to accommodate the missing *A. granerosense* and *A. muldoonense* Zones.

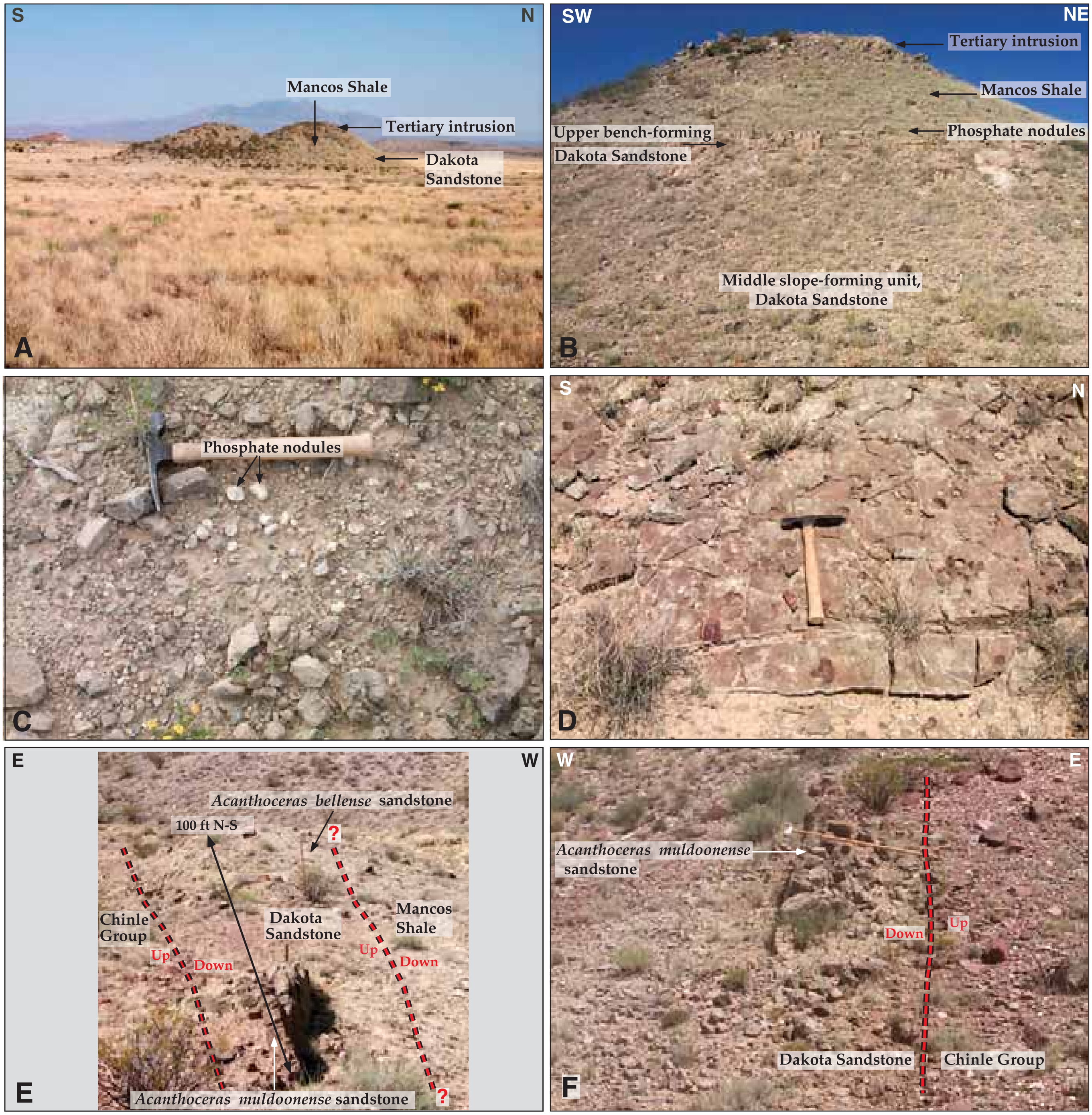



FIGURE 7—Representative outcrop photographs of the Dakota Sandstone and basal part of the overlying tongue of Mancos Shale at the Two Butte section (**A–D**) and the Palo Duro Canyon section (**E** and **F**). **A**—View looking west toward Two Butte hill during the dry season; Sierra Ladrones in the background. A resistant Tertiary intrusion near the base of the Mancos Shale preserves this important section of the Dakota Sandstone. **B**—Close-up view of the north end of Two Butte hill, after the monsoon season rains. The upper ridge-forming sandstone of the Dakota forms a prominent bench around the hill. **C**—White-weathering phosphate nodules are common on top of the burrowed, upper ridge-forming sandstone of the Dakota. **D**—Exposure of the top of Dakota Sandstone approximately 1 mi (1.6 km) north of Two Butte hill, looking down on the bedding surface. This resistant, brown-weathering sandstone contains *A. amphibolum* and many "ironstone" concretions that weather out leaving a depression in the bed stained dark brown by iron oxides. **E**—The extremely small, 100-ft (30-m)-long, fault-bounded outcrop at the Palo Duro Canyon section. Only 11 ft (3.4 m) of Dakota is present here. Broken internal molds of *Acanthoceras muldoonense* occur only in the dark-brown, resistant sandstone in the foreground (D14249 level); many impressions of *A. bellense* occur only in the thin-bedded sandstone in the right middle ground (D14225). View is to the south. **F**—The same outcrop viewed to the north showing the *A. muldoonense* sandstone (D14249). The 5-ft Jacob's staff puts this very thin but completely marine section in perspective.

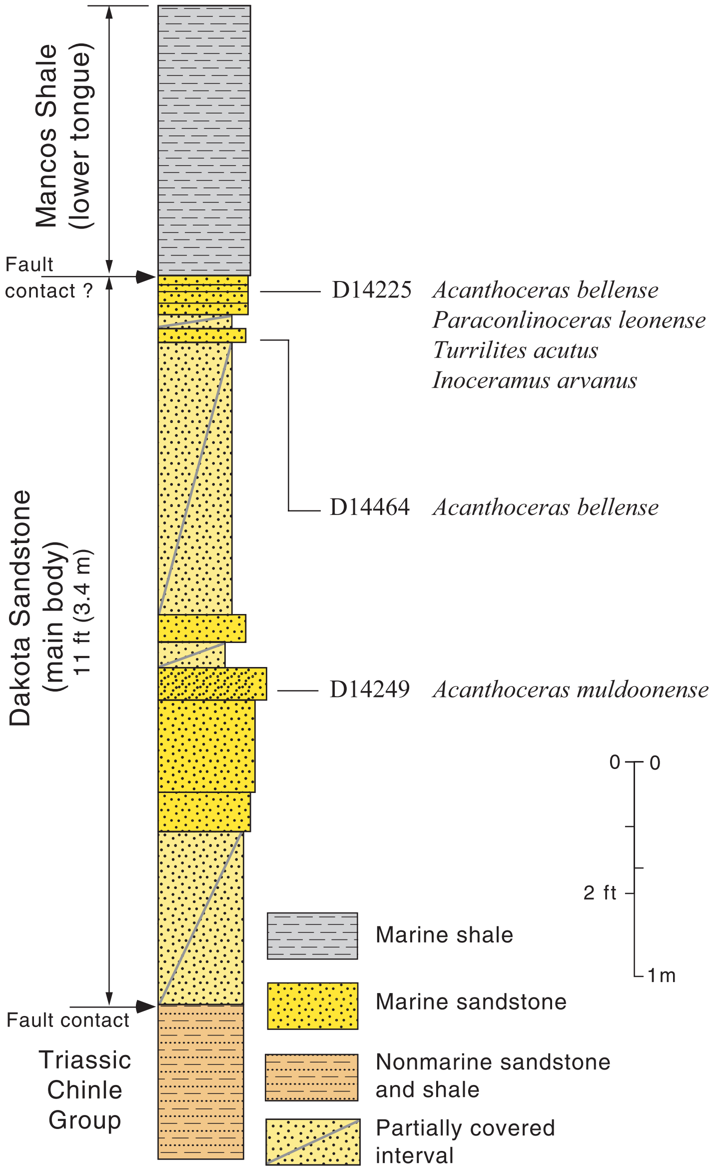



FIGURE 8—Stratigraphic section of the Dakota Sandstone and lower tongue of the Mancos Shale exposed at Palo Duro Canyon section. See Figure 1 for its location.

### Palo Duro Canyon section

The Palo Duro Canyon section (PDCS) is the most unusual Dakota section on the refuge. Here, the entire Dakota Sandstone section is only 11 ft (3.4 m) thick and is entirely marine (Figs. 7E,F and 8). The top of the Dakota is a 7-inch (18-cm)-thick, fine to very fine grained, very thin bedded, yellow-weathering sandstone (without ironstone or limonitic concretions) that lies not in the *A. amphibolum* Zone, but in the lower *A. bellense* Zone (Figs. 7E and 8, D14225 level). The basal 4.5 ft (1.4 m) of the section is poorly fossiliferous, with only scraps of oyster shells observed near the bottom. No phosphate nodules were found in these basal beds.

Both the thinness of the Dakota Sandstone and the older age for its top suggest strongly that the outcrop is bounded by faults on both bottom and top (Fig. 7E). The area around this very small outcrop, which is 100 ft (30 m) long and 50 ft (16m) wide, is structurally complex. The Dakota dips 60° to the west (Fig. 7E,F). Unfortunately, there is little chance for physical evidence for the postulated faults, e.g., slickensided beds. The lower contact of the Dakota with the Chinle Group is sandstone against shale, and the upper contact with the Mancos Shale is sandstone against shale. The absence of the 50 ft (16 m) of nonmarine beds at the base of the Dakota is compelling evidence for a fault at the base of the Dakota. The older than expected age for the top of the Dakota (*A. bellense* instead of the younger *A. amphibolum*) could be the result of deposition at a more seaward site than the PRS or TBS. Consequently, we have queried the upper fault contact on Figures 7E and 8.

The importance of the PDCS lies in (1) its contained faunas and (2) evidence for high-energy conditions during *A. muldoonense* time. Palo Duro Canyon was the first section on Sevilleta where we collected both *A. muldoonense* and *A. bellense* in stratigraphically separated beds (Fig. 8, levels D14249, D14225, and D14464). These collections led to an intensive effort to find evidence for these two zones at PRS and the TBS. Subsequently, we found *A. muldoonense* at the Jornada del Muerto section and *A. bellense* at Carthage, 24 mi (38 km) south of the refuge.

Fragments of internal molds of *A. muldoonense*, primarily portions of body chambers, occur in and have weathered out of a dark-brown, 6-inch (15-cm)-thick, highly resistant, upper fine-grained sandstone that supports a small ridge (Fig. 7E,F). This sandstone contains the coarsest quartz grains in the section (upper fine versus very fine grained); the internal molds of *A. muldoonense* are commonly filled with even coarser clastic particles. One of the coarsely filled specimens is illustrated in the Systematic paleontology section (see Fig. 13 C,D). We interpret this coarse sandstone to represent deposition in a nearshore, high-energy environment; the coarser clastic particles filling the shells could represent a storm event or a minor regression of the shoreline.

The basal 4.5 ft (1.4 m) of section could represent deposits of both the *C. tarrantense* and *A. granerosense* Zones. The phosphate nodule bed is absent. Given the widespread nature of this phosphate nodule bed in the area, it appears that the fault at the base of the section has cut it out.

The PDCS is also the only section on the refuge where *Paraconlinoceras leonense* occurs, here in association with *A. bellense*.

## Discussion

### Thatcher fauna

Earlier in this report we mentioned the "sudden" occurrence of invertebrate macrofauna in middle Cenomanian strata at the level of the Thatcher Limestone Member of the Graneros Shale. This sudden appearance of macrofauna in the Western Interior is always at the same level in middle Cenomanian marine strata and commonly above a substantial thickness of strata containing marine microfaunas. Cobban (1961, p. 738) was the first to notice that "The oldest unquestioned Cenomanian megafossil zone in the Western Interior region is the level of the Thatcher limestone member of the Graneros shale of southeastern Colorado."

The Graneros Shale of southeastern Colorado is a marine unit that is approximately 114 ft (34.7 m) thick at Rock Canyon anticline, its principal reference section west of Pueblo, Colorado (Cobban and Scott 1973, pp. 7–14 and pl. 40). There it consists of a lower barren unit of noncalcareous shale, 69 ft (21 m) thick; the Thatcher Limestone Member, 1 ft (0.3 m) thick; and an upper fossiliferous unit of noncalcareous shale, 44 ft (13.4 m) thick. The terms "barren" and "fossiliferous" pertain only to invertebrate macrofossils; the lower barren unit contains arenaceous foraminifera, most of which are benthonic (Eicher 1965). The only other fossils observed in the lower barren unit by Cobban and Scott (1973, p. 10) were fish scales, bones, and wood.

By contrast, they list three ammonite species, one gastropod species, and five bivalve species from the Thatcher Member; and 10 ammonite species, one gastropod species, and three bivalve species from the upper fossiliferous unit (Cobban and Scott 1973, pp. 7–8). This sudden appearance of marine invertebrates at the level of the Thatcher Member is apparently the result of a change in salinity of the early Graneros seaway from brackish below the Thatcher level to normal marine at and above it. Foraminiferal evidence indicates that at the time of deposition of Thatcher limy muds, the Graneros interior seaway had joined both the boreal sea to the north and the Gulf coastal sea to the south (Eicher 1965). Characteristic molluscan species of this "Thatcher" fauna include *Conlinoceras tarrantense* (Adkins), *Exogyra columbella* Meek, and *Plicatula arenaria* Meek.

Once normal-marine salinity was established during the lower middle Cenomanian *C. tarrantense* Zone, an abundance of invertebrate marine life filled the newly opened niches. Cobban and Hook (1989, p. 248) list 37 bivalve species, 11 gastropod species, and five ammonite species from the Thatcher fauna in west-central New Mexico.

#### Time-equivalent sections

In previous sections of this paper we established that the net (compacted) depositional rate for the upper 11 ft (3.4 m) of the Dakota Sandstone on Sevilleta National Wildlife Refuge is an order of magnitude less than that for the entire 1,260 ft (384 m) of Upper Cretaceous from the base of the Dakota to the top of the last marine bed (Mancos Shale) in the sequence (Table 1). The net (compacted) depositional rate for the upper Dakota is 14.3 ft/m.y. (4.4 m/m.y.), whereas the long-term rate for the composite section is 175.5 ft/m.y. (53.5 m/m.y.). This huge discrepancy indicates that the net depositional rate for the Dakota was extremely slow compared to the rate for the entire section and suggests strongly that the uppermost Dakota is a condensed succession. The corroded, but un-encrusted ammonite molds from four ammonite zones and the breccia at the base of the succession suggest that the condensed succession resulted from several cycles of deposition and submarine erosion. The phosphate nodules at the base of the sequence indicate that nondeposition (sediment bypass) also played a role, at least early in the history.

To demonstrate conclusively that the uppermost Dakota Sandstone on Sevilleta is indeed a condensed succession, it must be shown that it is thin when compared to time-equivalent sections in the region or basin. The criterion for time-equivalent sections is the thickness between the first occurrence of the Thatcher fauna to the last occurrence of *A. amphibolum*.

Comparison with two key reference sections of time-equivalent rocks in the region confirms that the upper Dakota Sandstone on Sevilleta is 13 times thinner than time-equivalent rocks at Laguna, New Mexico, and five times thinner than time-equivalent rocks at Pueblo, Colorado (Fig. 9). The net (compacted) depositional rate at Sevilleta is comparably lower as well (Table 1). The depositional rate at Laguna, New Mexico, in a comparable paleoenvironmental setting is 13 times greater than at Sevilleta; the rate at Pueblo, Colorado, for the Graneros Shale, which was deposited in a more seaward setting, is five times greater.

Time-equivalent rocks near Laguna, New Mexico, 70 mi (113 km) northwest of Sevilleta, are in the classic intertongued Dakota–Mancos sequence (Landis et al. 1973). They consist of (in ascending order) the upper part of the Oak Canyon Member of the Dakota Sandstone, the Cubero Tongue of the Dakota Sandstone, the Clay Mesa Tongue of the Mancos Shale, and the lower part of the Paguate Tongue of the Dakota Sandstone (Fig. 9). The entire sequence from the base of the Oak Canyon to the top of the Paguate is approximately 260 ft (79.2 m) thick.

A silty limestone bed, 16 ft (4.9 m) below the top of the Oak Canyon (D7080 level) is lithologically similar to and faunally identical to the Thatcher Limestone Member of the Graneros Shale in southeastern Colorado. At the Laguna section, the most diagnostic Thatcher fossil is the oyster *Exogyra columbella* Meek, which was Stephenson and Reeside's (1938) guide fossil to the Graneros and middle Cenomanian (Fig. 2). Elsewhere in west-central New Mexico this limestone and equivalent beds of calcareous, ferruginous concretions have yielded *C. tarrantense* (Landis et al. 1973; Cobban 1977a). A 3-ft (0.9-m)-thick sandstone bed, 25 ft (7.6 m) above the base of the Paguate contains *A. amphibolum* (D7084 level).

This sequence near Laguna, New Mexico, of intertongued Dakota–Mancos, from the first occurrence of the Thatcher fauna (D7080 level) to the first and only occurrence of *A. amphibolum* (D7084), is 147 ft (44.8 m) thick (Fig. 7). In contrast, the age-equivalent strata at the PRS are 11 ft (3.4 m) thick. Age-equivalent rocks at Laguna are 13.3 times thicker than at Sevilleta. The net (compacted) depositional rates are 190.9 ft/m.y. (58.2 m/m.y.) at Laguna versus 14.3 ft/m.y. (4.4 m/m.y.) at Sevilleta (Table 1). Note that the long-term depositional rate at Sevilleta is very close to the Laguna time-equivalent rate.

In the Pueblo, Colorado, area the Thatcher fauna's stratigraphic range in the Graneros Shale is two to three times greater than its 5-ft (1.5-m) range in the Dakota Sandstone at Sevilleta. At the principal reference section of the Graneros Shale a few miles east of Pueblo, the Thatcher fauna ranges through approximately 14 ft (4.3 m) of section. At the Muldoon Hill section southwest of Pueblo, it ranges through approximately 9 ft (2.7 m) of section (Fig. 9).

At Muldoon Hill, the type locality of *A. muldoonense*, the stratigraphic sequence from first appearance of the Thatcher fauna to the last appearance of *A. amphibolum* is 57 ft (17.4 m) thick (Fig. 9), more than five times thicker than at PRS. Even without factoring in the greater compaction rate for muds versus sands, this range difference indicates that the section at Sevilleta is condensed.

#### Relative positions and preservation of ammonites in the Dakota Sandstone

In previous sections of the paper we have shown that the marine portion of the Dakota Sandstone on Sevilleta National Wildlife Refuge represents a condensed succession. A rather unusual one in that submarine erosion appears to be the major process that created the thinned section, but preserved the middle Cenomanian faunal record almost intact. Given this erosive geologic history, it is surprising, if not fortuitous, that four of the first five middle Cenomanian ammonite zones are preserved in the Dakota Sandstone on Sevilleta, and that stratigraphic space is left for the missing zone. In this section of the paper, we examine the distribution of these zones in the measured stratigraphic sections (Fig. 10) on Sevilleta and the distribution of fossils within a zone. The assumption that we make is that ammonite species on Sevilleta occur in the order predicted for the Western Interior (Fig. 2). We test this assumption by examining the relative position of *A. bellense*, the newest member of the zonation, in the sequence.

The two more shoreward condensed successions, the Principal Reference section (PRS) and the Two Butte section (TBS), are approximately 1 mi (1.6 km) apart and are physically quite similar. The PRS succession is approximately 4 ft (1.2 m) thicker than the 7-ft (2.1-m)-thick TBS. Both begin at the top of the burrowed, upper ridge-forming sandstone, where loose phosphate nodules cover the ground, and they end with the dark-brown, resistant sandstone that contains *A. amphibolum*. The *C. tarrantense* Zone is approximately 5 ft (1.5 m) thick in each section. The stratigraphic separation between the *C. tarrantense* Zone and the *A. amphibolum* Zone is approximately 5 ft (1.5 m) at PRS and approximately 1.6 ft (0.5 m) at TBS. This thickness difference is probably the result of different episodes and rates of erosion at the two sections. The thinner interval at TBS contains the younger *A. bellense* fauna, and the thicker interval at PRS contains the older *A. muldoonense* fauna. At the PRS there is approximately

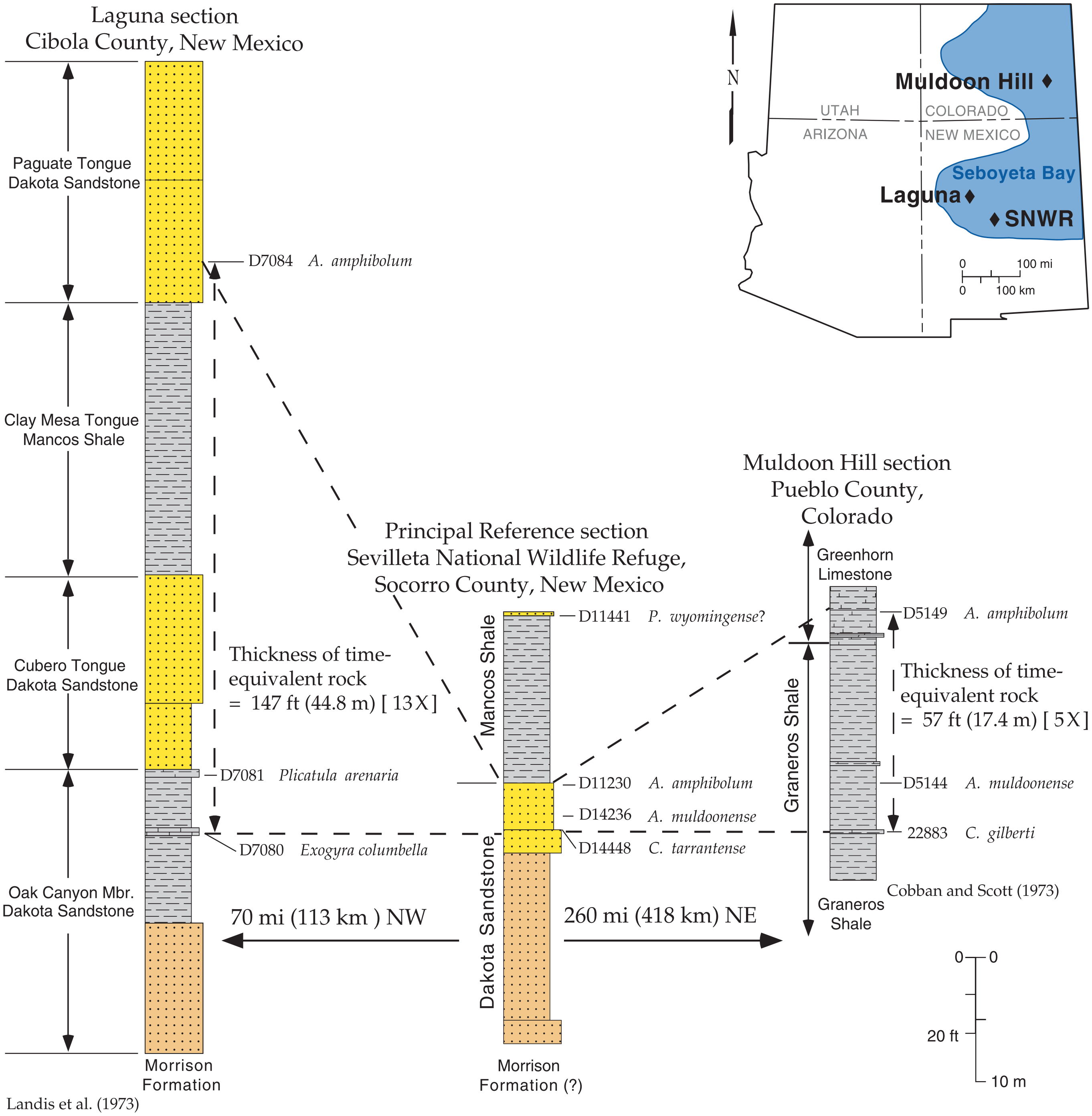



FIGURE 9—A comparison of time-equivalent sections in the region reveals that the middle Cenomanian Dakota Sandstone succession on Sevilleta National Wildlife Refuge is condensed. Age-equivalent rocks in the region are as much as 13 times thicker than those at the Principal Reference section. The three sections are hung on the base of the *C. tarrantense* Zone. Rock symbols and colors are the same as those used in Figs. 3, 4, 6, and 8. Thin limestones are shown with a brick pattern.

2.5 ft (0.8 m) stratigraphically on either side of the *A. muldoonense* bed for the *A. granerosense* and *A. bellense* faunas. At TBS, there is only approximately 7 inches (18 cm) of stratigraphic space to represent both the *A. granerosense* and *A. muldoonense* Zones.

The stratigraphic sections for the PRS and TBS are hung on the top of the burrowed, upper ridge-forming marine sandstone to facilitate comparison; we regard this horizon and the base of the overlying phosphate nodules as a synchronous event in the region (Fig. 10).

The Palo Duro Canyon section (PDCS) is the most seaward of the three sections and is strikingly different from the two more landward sections. It is bounded by a fault at the base, where it is in contact with the Triassic, and is probably bounded by a fault at the top, which lies in the *A. bellense* Zone, not the younger *A. amphibolum* Zone of the shoreward sections. The PDCS also contains the thickest post-*A. muldoonense* section on the refuge, approximately 6 ft (1.8 m). We interpret this increased thickness to deposition in deeper water than the shoreward sections, where current and storm-generated erosion would be less likely. This is especially true during *A. bellense* time, when the shoreline had transgressed south

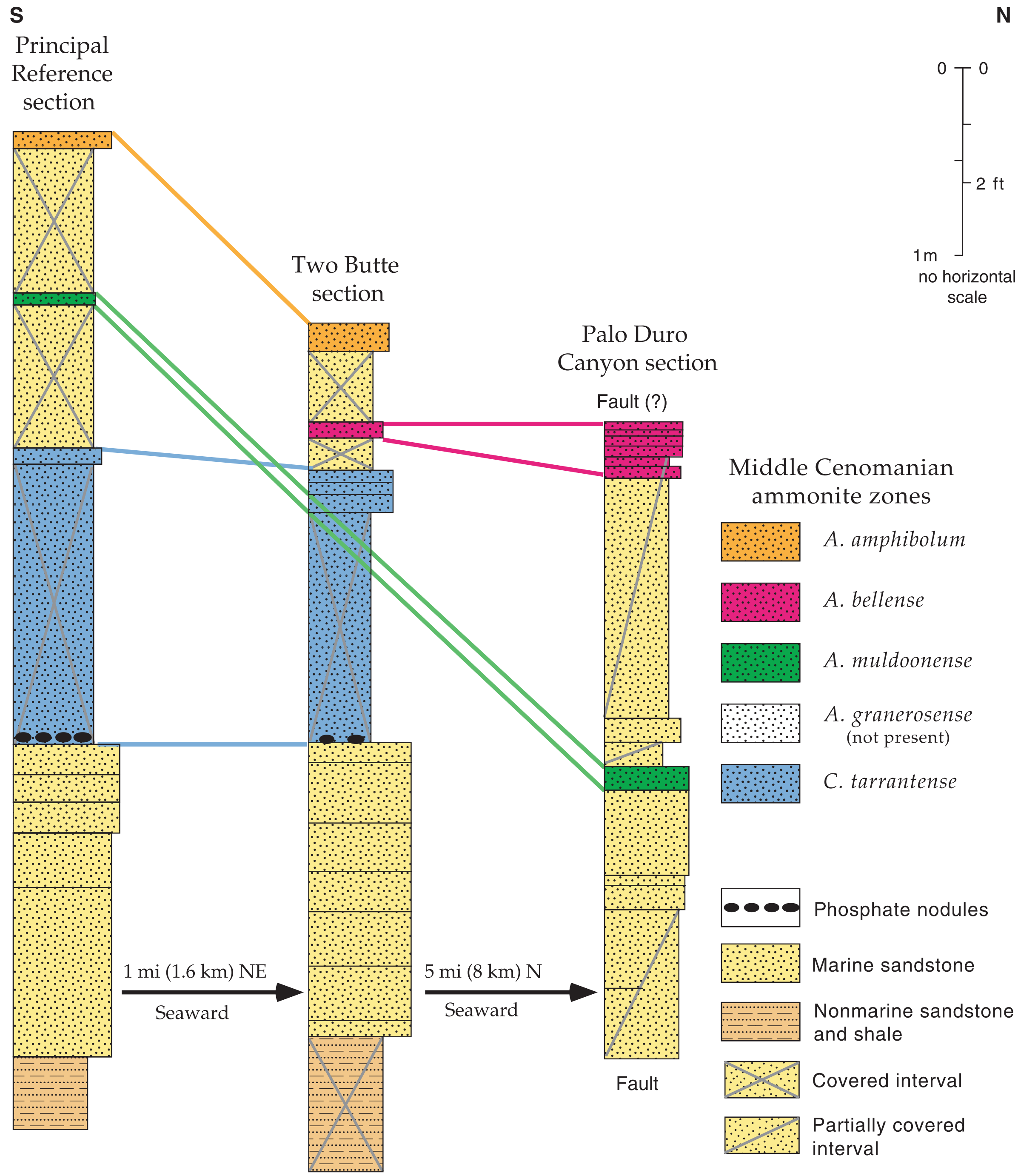



FIGURE 10—Cross section through the three condensed successions in the upper part of the Dakota Sandstone on Sevilleta National Wildlife Refuge. The sections are arranged from south to north, proceeding in a seaward direction. Correlation is by color-coded ammonite zones. See Figure 1 for section locations. Note that there is a vertical scale, but no horizontal scale.

of the Carthage coal field, 24 mi (38 km) south of the refuge. The PDCS is hung on the top of the *A. bellense* bed with respect to the TBS. This is not necessarily a timeline, but it is the only horizon that is correlative to one in the TBS. It also displays graphically the age relationship difference at the top of the Dakota between the two sections. The green line shows the correlation of the *A. muldoonense* Zone with the PRS.

There is no one section on Sevilleta that contains all four of these preserved ammonite zones (Fig. 10). Two of the sections, PRS and TBS, contain representatives from three zones, but have only two in common. The third section, the fault-bounded PDCS, contains representatives from two zones, but has only one zone in common with each of the other two sections.

The relatively thick *C. tarrantense* Zone at the PRS offers some insight into the complex preservational process of the ammonite zones. It is the only zone to contain evidence of an alternation of a very low energy, nondepositional environment that produced phosphate nodules with a very high energy, erosive environment that produced a rip-up clast breccia. The phosphatization of internal molds of an ammonite and gastropods suggests erosion before phosphatization. The *C. tarrantense* Zone is also the only zone on Sevilleta that is not confined to a single bed, but spans 5 ft (1.5

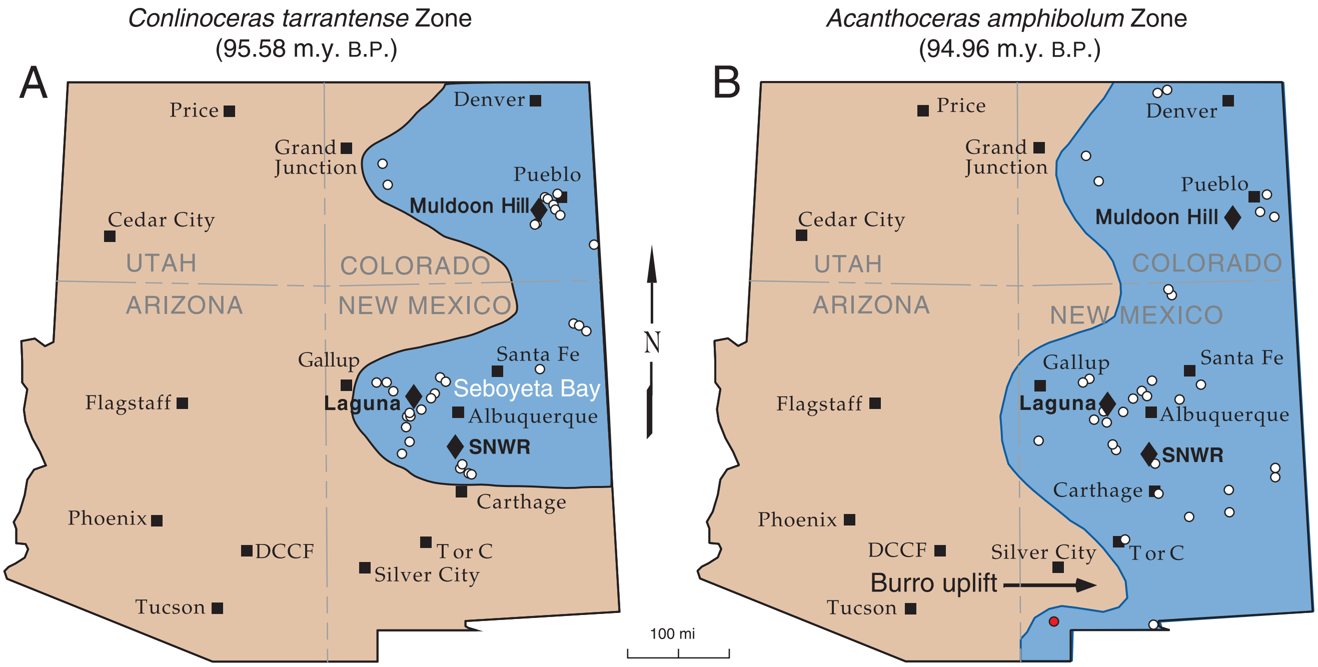



FIGURE 11—Two maps of the Four Corners states showing the approximate positions of the western shoreline of the Late Cretaceous seaway at the end of the time represented by the *Conlinoceras tarrantense* Zone (A) and the *Acanthoceras amphibolum* Zone (B). The geographic locations of the key, time-equivalent sections from Figure 9 are shown by black diamonds; USGS localities containing fossils indicative of the respective zone are shown by white-filled circles. The red-filled circle on (B) is a locality from the literature (Lucas and Lawton 2005). Abbreviations used on the maps are for Truth or Consequences (T or C) and Deer Creek coal field (DCCF).

m) of section in two beds. This suggests that a relatively thick section was deposited during *C. tarrantense* time and that only part of this section, probably the middle portion, was eroded. There is no evidence of subaerial erosion on Sevilleta during *C. tarrantense* time, suggesting that all the erosive episodes occurred in nearshore, submarine environments.

The Palo Duro Canyon section (Fig. 8) illustrates another important point—the vagaries of fossilization in a single bed. The Dakota caps two small hills over the 100 ft (30 m) of north-south outcrop (Fig. 7E,F). There is more-or-less continuous exposure of the resistant beds from one hill to the other. Fossils of *A. muldoonense* (D14249 level) are abundant on the north hill and absent to the south. The thin beds of sandstone that contain many impressions of *A. bellense* (D14225 level) in the south, are unfossiliferous in the north. So, it is as difficult to explain the preservation of so many zones in this erosively condensed succession on Sevilleta as it is to explain the preservation of fossils within these two beds at the PDCS. In fact, it took four trips to the Palo Duro Canyon outcrops before we found the *A. muldoonense* fauna.

The lesson learned from the PDCS is to walk each bed several times looking for fossiliferous "sweet spots," for example, concentrations of broken oyster shells. It took several trips to the PRS to work out the zonation there, as well. After discovering the *A. bellense* fauna at Palo Duro Canyon, we searched unsuccessfully for it at the PRS. If it were not for the outcrop along the 2-ft (0.6-m)-wide, steep drainage channel at the TBS, the *A. bellense* fauna would be known only from PDCS and its relative zonal position would simply be above the *A. muldoonense* Zone.

It takes all three Dakota sections on Sevilleta to work out the relative position of the *A. bellense* fauna, the newest zonal index. Based on the PDCS alone, its position in the sequence is simply that it occurs above *A. muldoonense* (Fig. 10). The TBS indicates that the *A. bellense* fauna occurs between *C. tarrantense* and *A. amphibolum*, but gives no information on the position of *A. muldoonense*. The PRS shows that the *A. muldoonense* fauna occurs between *C. tarrantense* and *A. amphibolum*; therefore, *A. bellense* occupies the zone between *A. muldoonense*, below, and *A. amphibolum*, above, just as Cobban (1987a) predicted; thus, validating our assumption.

## Middle Cenomanian shorelines

In order to understand the geologic history of the Upper Cretaceous in the Western Interior, we have found it useful to construct shoreline maps using well-defined, stratigraphically constrained faunas. We construct these maps by plotting the positions of our collecting localities for a key biostratigraphic zone on a base map, adding paleogeographic information such as the positions of nearshore sandstones and offshore shales that contain that fauna, then making an educated guess as to the position of a smoothed shoreline. Often we know that a particular shoreline has to lie between two localities because of the biostratigraphic age difference at the bases of transgressive or regressive marine sections. The primary assumption we make in constructing these maps is that the rocks that contain the fossils are essentially in place; i.e., they have not been moved large distances on thrust faults. In New Mexico this is a reasonable assumption. In Montana, it is not reasonable, and positions of fossil localities need to be adjusted to reflect movement on thrust faults.

Cobban's (1984b, fig. 2) upper Cenomanian *Mytiloides mytiloides* shoreline map is an excellent example of this process. It shows the approximate position of the western shoreline at the time that the calcarenites at the top of the Bridge Creek Limestone Beds of the Rio Salado Tongue of the Mancos Shale were deposited on Sevilleta (Fig. 3, D14590 level). These calcarenites are discussed in more detail in the section of the paper on high-energy offshore deposits.

Of the six ammonite species used to zone the middle Cenomanian, only *C. tarrantense* and *A. amphibolum* are abundant and widespread enough to be used in reconstructing the early Late Cretaceous shorelines in New Mexico and adjacent states. *Acanthoceras granerosense* has not yet been found in New Mexico; *A. muldoonense* and *A. bellense* are known from only a few localities on or just south of Sevilleta; and *P. wyomingense* is a boreal species that has a much wider distribution in Wyoming. Fortunately, bentonites from the range zones of both *C. tar-*

*rantense* and *A. amphibolum* have been dated (Fig. 2). These radiometric ages will allow us to calculate net transgression rates based on reconstructions of the positions of the shoreline during the middle Cenomanian.

Hook et al. (1980, p. 44) showed that the marine rocks that contain the Thatcher fauna form an arcuate pattern on the map of New Mexico that opens to the east and is centered on Mount Taylor, just west of Laguna, New Mexico, and is roughly 75 mi (120 km) across in both east-west and north-south directions. They interpreted this pattern to be the result of deposition of marine sediments into an embayment of the Late Cretaceous seaway that transgressed westward into New Mexico. They named this embayment Seboyeta Bay. The basal, marine Upper Cretaceous rocks to the north, west, and south of Seboyeta Bay in New Mexico contain faunas that are younger than the Thatcher fauna. A similar, but unnamed embayment is interpreted for Colorado (Cobban et al. 1994, fig. 4).

Figure 11A is an updated version of the southern portion of the map of Cobban et al. (1994) showing the approximate position of the western shoreline at the end of *C. tarrantense* time and the locations of collections containing the Thatcher fauna. The only change to the earlier map is to the position of the southern shoreline in New Mexico, which has moved approximately 15 mi (24 km) farther south to reflect the position of a *C. tarrantense* collection from the north end of the Jornada del Muerto coal field. This southern shoreline has to lie between the Jornada del Muerto coal field and the Carthage coal field, another 15 mi (24 km) farther to the southwest, where the oldest fauna we have collected is from 4 ft (1.2 m) above the base of the Dakota Sandstone and contains the much younger *A. bellense* (D14490). There is no evidence of the phosphate nodules in the Dakota Sandstone below the *A. bellense* bed at Carthage.

We assume that the *C. tarrantense* shoreline was in place at 95.58 m.y. B.P., at the end of the *C. tarrantense* Zone. Obradovich's (1994) revised age of 95.73 m.y. B.P. is at the beginning of the zone. The five middle Cenomanian zones average about 0.15 m.y. each, yielding an estimated age of 95.58 m.y. for the end of the zone.

Figure 11B is an updated version of a map we (Cobban and Hook 1980, fig. 3) published showing the general position of the western shoreline at the end of the time represented by the zone of *A. amphibolum*. The Late Cretaceous seaway covered most of New Mexico, with the exception of the Burro uplift in extreme southwestern New Mexico. The major change from our earlier map is the addition of a locality in the bootheel of New Mexico that contains *Turrilites acutus americanus* Cobban and Scott, an ammonite confined to the *A. amphibolum* Zone. That find, reported by Lucas and Lawton (2005, p. 67) as *T. acutus acutus* Cobban and Scott [*sic*], indicates to us that the Burro uplift was a positive area as late as *A. amphibolum* time. The oldest faunas in the Late Cretaceous rocks north and east of the Burro uplift are younger than *A. amphibolum* (Cobban et al. 1989).

For the calculations that follow, we assume that the *A. amphibolum* shoreline was in place at the end of the *A. amphibolum* time. Obradovich's (1994) revised age of 94.96 m.y. B.P. is from a bentonite, approximately two-thirds of the way through the zone, but we use the published revised age of 94.96 m.y. B.P. for consistency in our calculations.

Thus, the *A. amphibolum* map (Fig. 11B) shows the approximate position of the western shoreline about 620 k.y. later than the *C. tarrantense* map (Fig. 11A). During that 620 k.y., Seboyeta Bay expanded (transgressed) approximately 88 mi (142 km) to the west along the New Mexico–Colorado border, approximately 44 mi (71 km) to the northwest of Gallup, and approximately 75 mi (120 km) to the southwest from near Carthage to the foothills of the Burro uplift. These distances, especially the one to the southwest, are approximate because of sparse control.

Assuming that Seboyeta Bay continued to expand (transgress) uniformly during this time, these transgression distances provide an upper limit on the net transgression of 142 mi/m.y. (227 km/m.y.) and a lower limit of 71 mi/m.y. (106 km/m.y.). The southern shoreline of Seboyeta Bay transgressed at a net rate of 121 mi/m.y. (194 km/m.y.). Put into human perspective, the upper limit translates into 0.75 ft/yr (0.23 m/yr), less than a foot of net transgression per year.

However, the high-resolution biostratigraphy suggests that the southern shoreline of Seboyeta Bay was virtually stationary during the time represented by the *C. tarrantense* through *A. bellense* Zones. The base of the marine section at the Carthage coal field, 24 mi (38 km) south of the PRS, lies in the *A. bellense* Zone, suggesting that Carthage was not under marine water until 300 k.y. after Sevilleta.

There were undoubtedly minor oscillations of this shoreline between minor transgression and minor regression many times during that 300 k.y. The PRS was located offshore during this time, but just a few miles from the shoreline. The water was probably shallow and well oxygenated; the nearshore sediments would have been subjected to wave, current, and tidal effects, including erosion. We found no evidence of subaerial exposure in the rocks in the upper part of the Dakota Sandstone on Sevilleta. The erosion that preceded the phosphate-nodule formation could have been caused by currents; the breccia, by a major storm.

As the shoreline oscillated back and forth, some deposits that were laid down could have been eroded and probably were. Although there is no physical evidence for the *A. granerosense* fauna at the PRS (Fig. 4), there is room for it stratigraphically. The *A. muldoonense* fauna is preserved, but normal marine or storm currents could have eroded many beds deposited during the time of that zone. High-energy conditions were necessary to fill the body chambers of *A. muldoonense* with extremely coarse sediment at the PDCS (see Fig. 13 C,D). As the shoreline transgressed southwestward during *A. bellense* time, finer sediments were deposited on Sevilleta at both the Two Butte and Palo Duro Canyon sections and preserved this fauna (Fig. 9).

The net transgression rate of the southern shoreline of Seboyeta Bay from the end of *C. tarrantense* time to the beginning of *A. bellense* time was probably close to zero. After reaching Carthage during *A. bellense* time, the southern shoreline had to accelerate greatly to reach the bootheel of New Mexico by the end of *A. amphibolum* time. Most of the 75 mi of transgression to the southwest probably occurred during the 308 k.y. presented by these two zones. If so, the net southwestward transgression rate would have doubled from the previous estimate to almost 250 mi/m.y. or 1.3 ft/yr. Sevilleta National Wildlife Refuge would have been several tens of miles from the shoreline in deeper water during *A. amphibolum* time. Storm-generated currents would probably have caused erosion of beds of *A. amphibolum* age.

This interpretation of shoreline movement suggests that the southern shoreline of Seboyeta Bay was almost stationary during much of middle Cenomanian time. Sevilleta was located just a few miles offshore and could have had a plentiful supply of nearshore, sandy sediments, before erosive episodes. Given that each of the middle Cenomanian zones had an average duration of about 150 k.y., the total deposited section could have been substantial, before periodic erosive episodes. In a later section of the paper we will estimate how much sediment could have been deposited, based on regional and long-term, net depositional rates (Table 1.)

### Phosphate nodules

Phosphate nodules and pebbles occur at two levels in the Upper Cretaceous on the Sevilleta National Wildlife Refuge: one near the top of the middle Cenomanian Dakota Sandstone and the other at the base of the middle Turonian D-Cross Tongue of the Mancos Shale (Fig. 3, D14488 and D14495 levels). The pebbles from the D-Cross Tongue are smaller than the nodules from the Dakota Sandstone and consist almost entirely of phosphatized internal molds of small bivalves with a rare phosphatized chamber filling from an ammonite. Baker (1981) determined that these pebbles were composed of carbonate apatite. By contrast, less than 1% of the Dakota nodules are recognizable as fossils. Hook et al. (1983,


FIGURE 12—This representative selection of phosphate nodules (x 0.56) is from the D14488 level at the Principal Reference section (Fig. 4).

p. 22) discuss the phosphate pebbles and disconformity at the base of the D-Cross in Socorro County, New Mexico; in the remainder of this section we will discuss the older phosphate nodules in the Dakota Sandstone.

The top of the upper ridge-forming unit of the Dakota Sandstone and basal few inches of the overlying sandstone are marked by abundant white-weathering, phosphate nodules that litter the outcrop at the PRS (Figs. 5E, 12). Similar phosphate nodules have been found in a 3-inch (7.5-cm)-thick sandstone near the top of the Dakota Sandstone in the Jornada del Muerto coal field, 10 mi (16 km) southeast of Sevilleta (Fig. 1).

These nodules at the PRS lie on the bedding surface of the upper ridge-forming sandstone and are in a 2-inch (5-cm)-thick breccia of rip-up clasts of sandstone and corroded internal molds of *C. tarrantense* that is directly above that sandstone (Fig. 5E,H). They range in shape from almost perfect spheres and cylinders to highly irregular variants of these end members. Most are 1–2 cm in diameter and as long as 5 cm, although the cylindrical ones occur as fragments.

Most elongate nodules contain a cylindrical cavity oriented along the nodule's long axis. These longitudinal cavities are usually circular in cross section and usually 5 mm in diameter, although the axial cavities of the longer nodules taper slightly. These axial cavities are lined with either one or two layers of well-sorted, fine quartz grains. The nodule's outer surface is typically rough and knobby, coated with fine detrital quartz grains, but is not encrusted by organisms or scratched. A few nodules are recognizable as phosphatized internal molds of fossils or have nucleated around fossils. The fossils include gastropods, arthropods, bored wood, and a single ammonite. One nodule had a shark tooth attached to it.

Our original interpretation of these nodules was that they represented marine coprolites that had been burrowed by elongate animals. These organisms deposited the quartz grains on the burrow wall to support it.

As we observed more of the field characteristics of the nodules, we realized that this burrowed-coprolite hypothesis was unsupportable because: (1) the nodules contained no recognizable, undigested organic material (e.g., bones); (2) the central cavity was always aligned with the long axis of the cylindrical nodules and was missing from the spherical nodules; and (3) the now phosphatized internal molds of fossils could not have passed intact through the guts of large animals such as sharks.

Although these Sevilleta nodules are interesting and unusual, they are by no means unique in the Upper Cretaceous record. Similar phosphate nodules with axial cavities (but no quartz grains) have been reported from the Virgin Creek Member of the Pierre Shale in South Dakota by Searight (1937, p. 37), who thought they might be serpulid tubes. Gries (1940, pp. 32–33) called them "Indian beads," but thought they were more likely to be some type of plant.

Several investigations of phosphatized internal molds in Upper Cretaceous rocks (e.g., Kennedy and Garrison 1975) suggest a two-stage process for phosphate-nodule formation: (1) gradual lithification of the carbonate sediment that fills the shells along with dissolution of the aragonitic shells during burial and (2) exhumation of the pre-fossilized internal molds that are subsequently phosphatized on the sea floor. Tourtelot in (Tourtelot and Cobban 1968, p. 18) interpreted phosphate nodules at the base of the Niobrara Formation in South Dakota to be the result of phosphate replacement of fine-grained calcite at a shallow but indeterminate depth before erosion. Both scenarios require carbonate sediments. This process accounts for the phosphatized internal molds at Sevilleta but does not account for the majority of nodules that are not recognizable as fossils.

Whatever the origin of these Dakota Sandstone nodules, they are abundant over a wide area at the same biostratigraphic position. They provide a valuable correlation aid and signify that the environmental conditions that produced them were fairly widespread in Socorro County during early middle Cenomanian time along the southern shoreline of Seboyeta Bay.

In Appendix 1 we speculate on the origin of these nodules based on their observable field characteristics. Petrological and geochemical analyses of these nodules are beyond our capabilities. We hope that someone with those abilities will want to do this kind of detailed analysis.

#### Estimated magnitude of the disconformity (missing section)

In this section we use two methods to estimate the amount of section that was eroded to produce the disconformity associated with the nodule bed in the basal part of the marine Dakota Sandstone at the PRS. First, we must establish the magnitude of the unconformity based on the ages of the fossils on either side of the unconformity. Then, we use the long-term, net depositional rate at Sevilleta (Table 1) to calculate an expected average thickness for the middle Cenomanian ammonite zones. We assume that the limy beds at Laguna that are lithologically and faunally equivalent to the Thatcher Limestone Member of the Graneros Shale were deposited at Sevilleta and later were eroded. The Laguna section provides an outcrop thickness of these beds for the estimate.

At the PRS phosphate nodules lie on a burrowed but otherwise unfossiliferous sandstone and are found in the overlying breccia in association with sandstone with impressions of *C. tarrantense* (Fig. 5H). The only datable fossil in the phosphate nodules is *T. costatus*; it has a known range in the Western Interior of upper lower Cenomanian through upper middle Cenomanian in New Mexico. The previous occurrences, both from New Mexico, are from (1) the upper middle Cenomanian *A. amphibolum* Zone in west-central New Mexico (Cobban and Hook 1989, fig. 5E, identified as *T. acutus* Passy) and (2) the upper lower Cenomanian zone of *Budaiceras hyatti* in the Sarten Sandstone of southwest New Mexico (Cobban 1987b). Wright and Kennedy (1996, p. 358) record the species from Texas, California, and Mexico.

The magnitude of the disconformity associated with the exhumation of the prefossilized internal mold of *Turrilites costatus*, its subsequent phosphatization, and the erosion that produced the breccia containing *C. tarrantense* can be (1) the entire rock record associated with the uppermost lower Cenomanian ammonite zone of *Forbesiceras brundrettei*, which is missing or (2) only a portion of the rock record associated with the middle Cenomanian *C. tarrantense* Zone, which continues above the breccia.

The larger magnitude unconformity, case (1), is common in Texas and the Gulf Coast, where it is referred to as the Gulfian–Comanchean unconformity. In New Mexico the Gulfian–Comanchean unconformity has been documented only in the southern part of the state in the Cookes Range (Cobban 1987b; Cobban et al. 1989) and at Cerro de Cristo Rey, near El Paso, Texas (Lovejoy 1976; Kennedy et al. 1988).

Although the rock record preserved on Sevilleta is not definitive enough to differentiate between the two end-member cases, the regional record indicates that the disconformity occurs wholly within the *C. tarrantense* Zone. At the north end of the Jornada del Muerto coal field, 10 mi (16 km) southeast of Sevilleta (Fig. 1), we collected *C. tarrantense* (D14472) from a phosphate nodule bed near the top of the Dakota Sandstone. The specimen is a crushed internal mold of sandstone composition. It was collected 28 inches (0.7 m) below a 17-inch (0.4-m)-thick, ridge-forming sandstone containing *A. muldoonense* (D14469). This occurrence strongly suggests that the regional disconformity marked by the phosphate nodules lies entirely within the *C. tarrantense* Zone. The phosphate nodule inside the body cavity of an internal mold of *C. tarrantense* in the breccia at PRS also supports this interpretation.

Therefore, the time value of the unconformity, that is the time it took to deposit the missing section, which is now represented by the phosphate bed, has to be less than 154 k.y., the average duration of a middle Cenomanian ammonite zone. *Conlinoceras tarrantense* occurs with the nodules in the breccia and ranges through another 5 ft (1.5 m) of section.

The 16 ft (4.9 m) of section containing the "Thatcher" limestones at Laguna (Fig. 9) provides some insight into the minimum amount of section that may have been eroded at Sevilleta. Assuming that these Thatcher beds were deposited, then eroded, and that the sedimentation rate was constant at PRS, the total potential stratigraphic section for the entire *C. tarrantense* Zone would have been 21 ft (6.3 m), three-quarters of which has been eroded. The time value of the unconformity is approximately 118 k.y.

The long-term depositional rate at PRS of 175.5 ft/m.y. (53.5 m/m.y.) would yield a potential stratigraphic section of 27 ft (9 m) for the *C. tarrantense* Zone. This approach yields a time value of about 128 k.y., which is quite close to the first estimate.

Cobban (1977a, p. 23) states that *C. tarrantense* occurs in the upper part of the Oak Canyon Member as well as in the lower part of the Cubero Sandstone Tongue of the Dakota Sandstone in west-central New Mexico. This means that the potential stratigraphic section and time value would both be greater than the previous estimate.

The long-term depositional rate method predicts that the other middle Cenomanian zones would be represented by approximately 27 ft (9 m) of section as well.

#### Offshore, high-energy deposits

Two offshore, high-energy deposits stratigraphically higher than the Dakota Sandstone on Sevilleta deserve mention because they indicate that erosion of the sea floor occurred in offshore areas many tens of miles from the shoreline. These deposits are the several calcarenite beds (1) in the uppermost Bridge Creek Limestone Beds (Fig. 3, D14590 level) and (2) of Juana Lopez aspect in the basal 10 ft (3 m) of the D-Cross Tongue of the Mancos Shale (Fig. 3, D11350 and D14541 levels). Both sets of calcarenites are widespread in west-central New Mexico and consist primarily of the comminuted remains of inoceramid clams. The breakdown of clam shells to sand-size grains requires sustained high energy. The Bridge Creek Beds were deposited near the beginning of R1, whereas the beds of Juana Lopez aspect were deposited during the middle of T2. The Juana Lopez beds on Sevilleta are lithologically and faunally identical to only the upper part of the Juana Lopez Member of the Mancos Shale farther north and northwest in the San Juan Basin (see Hook and Cobban 1980).

In both cases, the western shoreline of the Late Cretaceous seaway was well to the south of Truth or Consequences, New Mexico (Hook and Cobban 1977, 1979). Calcarenites in the Bridge Creek Beds of the lower tongue of the Mancos Shale near Truth or Consequences contain wave-oscillation ripples, implying a fairly shallow water depth, even though the area was approximately 125 mi (200 km) seaward from the western shoreline (Cobban 1984b, fig. 2).

Elsewhere in New Mexico submarine erosion surfaces within higher strata of the Upper Cretaceous are fairly common. The Colorado Formation in southwest New Mexico near Deming contains at least three discontinuity surfaces in lower Turonian strata deposited during the early part of the R1 regression. These surfaces are marked by corroded, oyster-encrusted, and partially phosphatized internal molds of ammonites, along with limestone conglomerates containing rip-up clasts of older limestone (Hook and Cobban 1981). In 1981 we discovered a 6-inch (15-cm)-thick bed of limestone conglomerate in the lower tongue of Mancos Shale at Mescal Canyon, east of Truth or Consequences, New Mexico, that contained rip-up clasts of older limestone and a rare occurrence of the coral *Archohelia dartoni* (D11564). This conglomerate was deposited during the early part of R1, as well, but is 70 ft (21 m) above the top of the Bridge Creek Beds. Lucas and Anderson (1998, fig. 2) describe this coral occurrence and illustrate four hand specimens of the conglomerate. These conglomerates are probably the result of storm-generated currents.

Evidence for high-energy conditions affecting offshore strata are fairly common in the Upper Cretaceous of New Mexico. So, encountering evidence for nearshore erosion, similar to what we observed on Sevilleta, should probably be expected, especially considering the amount of geologic time involved for a single ammonite zone.

## Systematic descriptions

This section contains brief descriptions and illustrations of the four middle Cenomanian zonal ammonite species found in the Dakota Sandstone on Sevilleta National Wildlife Refuge. The descriptions are modified from Cobban (1977a, 1987a) and Cobban and Scott (1973). The illustrated specimens were collected on Sevilleta from the Principal Reference section and the Palo Duro Canyon section.

***Conlinoceras tarrantense* (Adkins 1928)**

Figure 13A, B

*Conlinoceras tarrantense* is a robust, moderately evolute ammonite with a rounded whorl section. It is characterized by sparse ribs that alternate in length and either lack umbilical tubercles or show a light thickening where the tubercles would be. Specimens less than 80 mm in diameter have lower and upper ventrolateral tubercles on all ribs and clavate midventral tubercles.

*Conlinoceras tarrantense* was named for Tarrant County, Texas.

The species occurs in the *Conlinoceras tarrantense* Zone of central Texas (Woodbine Formation), Colorado (Thatcher Limestone Member of the Graneros Shale), and New Mexico (main body, Oak Canyon Member, and Cubero Tongue of the Dakota Sandstone).

Associated fauna in the Dakota Sandstone at Sevilleta National Wildlife Refuge include gastropods, crabs, an oyster, shipworms, *Cunningtoniceras* cf. *C. cunningtoni* (Sharpe) and *Turrilites costatus* Lamarck. This is the first report of *Cunningtoniceras* cf. *C. cunningtoni* in New Mexico and only the third report of *Turrilites costatus*.

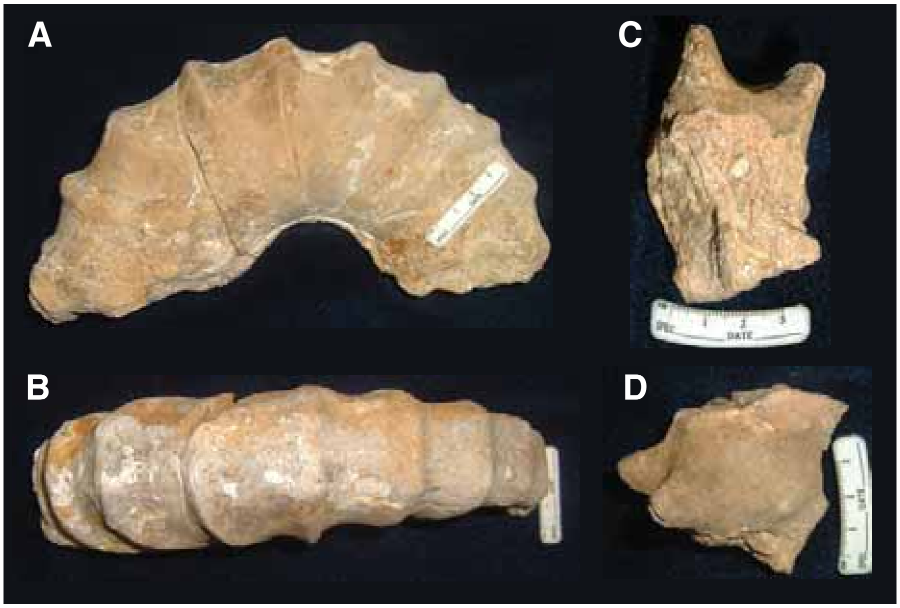



FIGURE 13—Representative fossils of the zonal ammonite species from the Dakota Sandstone on Sevilleta National Wildlife Refuge. **A, B**: *Conlinoceras tarrantense* (Adkins, 1928), side and top views (x 0.33) of USNM 535224, from USGS locality D11245 at the Principal Reference section. **C, D**: *Acanthoceras muldoonense* Cobban and Scott, 1973, front and side views (x 0.50) of USNM 535225, from USGS locality D14249 at the Palo Duro Canyon section. Note the incomplete nature of both internal molds and the coarse clastic filling of *Acanthoceras muldoonense*.

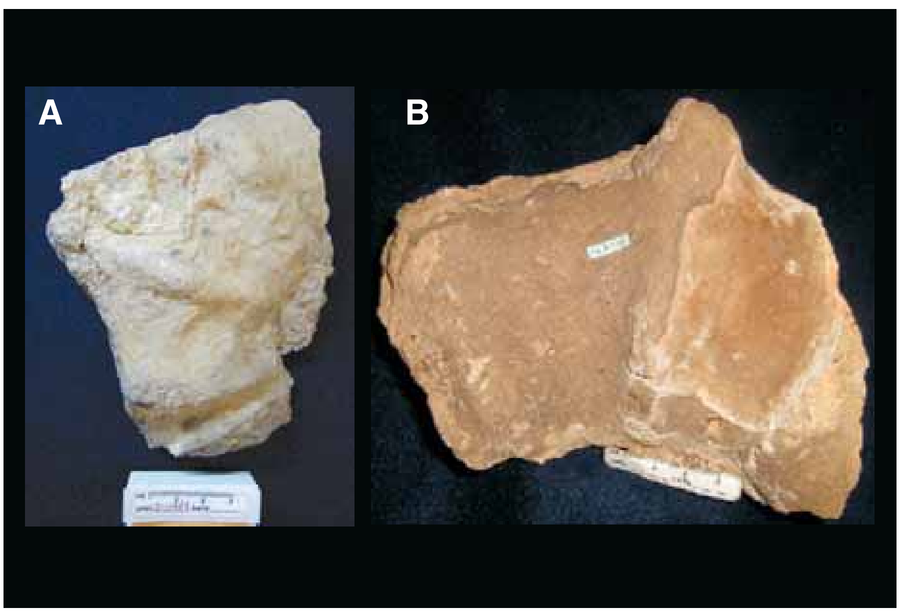



FIGURE 14—Representative fossils of the zonal ammonite species from the Dakota Sandstone on Sevilleta National Wildlife Refuge. **A**: *Acanthoceras bellense* Adkins, 1928, side view (x 0.50) of USNM 535226, from USGS locality D11468 at the Palo Duro Canyon section. **B**: *Acanthoceras amphibolum* Morrow, 1935, side view (x 0.50) of USNM 535227, from USGS locality D14230 at the Principal Reference section. Note the incomplete nature of both internal molds; both are corroded on the reverse (hidden) side.

### *Acanthoceras muldoonense* Cobban and Scott 1973

Figure 13C, D

*Acanthoceras muldoonense* is a moderately evolute ammonite characterized by sparse ribbing and early loss of siphonal and upper ventrolateral tubercles. Ribs are strongest on the outer parts of the flank and venter. The nodate lower, upper, and siphonal tubercles become clavate as the shell enlarges. At large diameters the lower ventrolateral tubercles increase in size and rise high above the venter into conspicuous horns that are directed outward from it at angles of 30–45°. These outward directed, clavate horns make *Acanthoceras muldoonense* one of the most distinctive and easily recognized of the middle Cenomanian ammonites.

*Acanthoceras muldoonense* was named for Muldoon Hill, Pueblo County, Colorado. Muldoon Hill was the burial site of the 7-ft-tall, 450-lb "Solid Muldoon," a supposed prehistoric human body that was thought to be the missing link between man and ape, but was made of mortar, rock dust, and ground bones. This missing link, a hoax perpetrated by the same man who was responsible for the Cardiff Giant, was dug up near Beulah, Colorado, in 1876. It was named after William Muldoon, a famous strongman of the time, who had been celebrated in song. A roadside sign on Colorado Highway 78, near Beulah, Colorado, commemorates the Solid Muldoon.

The species occurs in the *Acanthoceras muldoonense* Zone of southeastern Colorado (Graneros Shale) and New Mexico (main body of the Dakota Sandstone). Associated fauna in the Dakota Sandstone at Sevilleta National Wildlife Refuge is *Turrilites* (*Euturrilites*) *scheuchzerianus* Bosc, which is reported from New Mexico for the first time.

### *Acanthoceras bellense* Adkins 1928

Figure 14A

*Acanthoceras bellense* is a medium-size, moderately evolute species that is characterized by its conspicuous tuberculated phragmocone and its sparsely ribbed body chamber. Ornament consists of low narrow ribs, weak umbilical bullae, stronger inner and outer ventrolateral tubercles, and weak siphonal calvi on a low rounded siphonal ridge.

*Acanthoceras bellense* was named for Bell County, Texas.

The species occurs in the *Acanthoceras bellense* Zone of central Texas (Eagle Ford Formation), eastern Wyoming (Belle Fourche Shale), and New Mexico (main body of the Dakota Sandstone.) Associated fauna in the Dakota Sandstone at Sevilleta National Wildlife Refuge include *Paraconlinoceras leonense* (Adkins), reported for the first time from New Mexico, *Turrilites acutus* Passy, and *Inoceramus arvanus* Stephenson.

### *Acanthoceras amphibolum* Morrow 1935

Figure 14B

The inner whorls of *Acanthoceras amphibolum*, another moderately evolute species, have nodate umbilical and lower ventrolateral tubercles and clavate upper ventrolateral and siphonal tubercles. Upper ventrolateral and siphonal tubercles, which are located on broad ridges that cross the venter, are usually asymmetrically clavate with the steep side toward the front. Adult whorls have ventrolateral horns and a broadly arched venter that supports a low midventral ridge.

*Acanthoceras amphibolum* was assigned its specific name for its doubtful assignment to the genus *Acanthoceras*. *Amphibolos* (Gk) means ambiguous or doubtful in English.

The species is widespread in the middle Cenomanian *Acanthoceras amphibolum* Zone of Trans-Pecos and central Texas (Boquillas Formation), New Mexico (main body and Paguate Tongue of the Dakota Sandstone), Kansas, Colorado (Graneros Shale and Greenhorn Limestone), Wyoming (Frontier Formation), South Dakota, and Montana. It has also been reported from Japan, Nigeria, and Tunisia.

Associated fauna in the Dakota Sandstone at Sevilleta National Wildlife Refuge include *Inoceramus arvanus* Stephenson and *Ostrea beloiti* Logan.

## Summary

The upper part of the main body of the Dakota Sandstone and the basal part of the overlying Mancos Shale tongue exposed on the Sevilleta National Wildlife Refuge, northern Socorro County, New Mexico, contain one of the most complete middle Cenomanian ammonite sequences in the Western Interior of the United States. Of the six ammonite zones that characterize the middle Cenomanian of the Western Interior, five are found on Sevilleta. The six zones are, in ascending order, *Conlinoceras tarrantense* (oldest), *Acanthoceras granerosense*, *A. muldoonense*, *A. bellense*, *A. amphibolum*, and *Plesiacanthoceras wyomingense* (youngest). Outcrops on Sevilleta contain representatives of all but the *A. granerosense* Zone, although there is room stratigraphically for this zone. The relative order of these zonal species on Sevilleta is exactly that predicted for the Western Interior as a whole. Occurrences on Sevilleta show unequivocally that *A. bellense*, the newest member of the zonation, lies between *A. muldoonense* below and *A. amphibolum* above.

The stratigraphic section on Sevilleta that contains the *C. tarrantense* through *A. amphibolum* Zones is abnormally thin compared to key middle Cenomanian reference sections near Pueblo, Colorado, and Laguna, New Mexico. In the Pueblo area, the time-equivalent portions of the Graneros Shale and Greenhorn Limestone are five times thicker than the Dakota on Sevilleta. Near Laguna, the time-equivalent portion of the intertongued Dakota Sandstone and Mancos Shale sequence is 13 times thicker than that on Sevilleta.

This condensed succession appears to be the result of: (1) several intervals of submarine erosion that are supported by three zones of corroded ammonite internal molds and a breccia containing rip-up clasts of sandstone with ammonite impressions; and (2) at least one episode of nondeposition (or highly reduced deposition) supported by a widespread bed of white-weathering phosphate nodules that now litter the outcrop. We observed no evidence for subaerial exposure of the upper part of the Dakota Sandstone on Sevilleta.

Evidence for erosion within biostratigraphically complete condensed successions is highly unusual. Therefore, we define the condensed succession on Sevilleta as a relatively thin, but apparently faunally complete, stratigraphic succession of middle Cenomanian age that is represented elsewhere in the region by time-equivalent sections that are more than an order of magnitude thicker.

Ammonites dominate the invertebrate faunas on Sevilleta. This report marks the first occurrences of the middle Cenomanian zonal indices *A. muldoonense* and *A. bellense* in New Mexico. Previously, *A. muldoonense* had been reported from north-central Wyoming and southern Colorado. *Acanthoceras bellense* had been found only in eastern Wyoming and east-central Texas. Their occurrences in New Mexico not only increase their geographic ranges, but also increase the biostratigraphic resolution in the middle Cenomanian of New Mexico.

Most of the marine portion of the Dakota Sandstone on Sevilleta was deposited near the southern shoreline of Seboyeta Bay, a narrow, east-west tongue of the Late Cretaceous seaway that transgressed westward into east-central New Mexico during earliest middle Cenomanian time. An occurrence of *A. bellense* near the base of the marine portion of the Dakota Sandstone in the Carthage coal field 24 mi (38 km) south of Sevilleta suggests that the southern shoreline of Seboyeta Bay was essentially stationary between the refuge and Carthage during much of early middle Cenomanian time. This stationary shoreline ensured that Sevilleta was in a nearshore, shallow-water environment during much of middle Cenomanian time. It also ensured that deposited sediments would be subjected, at least periodically, to erosion by nearshore waves and currents. During later middle Cenomanian time Seboyeta Bay expanded westward, northward, and southward until the seaway covered most of New Mexico by the end of *A. amphibolum* time.

## Acknowledgments

We thank the U.S. Fish and Wildlife Service for allowing us access to these important Upper Cretaceous outcrops on the Sevilleta National Wildlife Refuge, Socorro County, New Mexico. We are especially grateful to Dennis Pritchard, Assistant Refuge Manager, for his help and encouragement.

Kevin C. McKinney, U.S. Geological Survey, Denver, Colorado, photographed the fossils and the phosphate nodules for us. He also delivered many urgent e-mail messages and images to Bill from Steve.

Hook's work on Sevilleta was supported by the New Mexico Bureau of Mines and Mineral Resources where he worked from 1976 to 1981, and has been partially supported by the New Mexico StateMap Program, managed by the New Mexico Bureau of Geology and Mineral Resources, during 2004 and 2007. Major field support has come from Atarque Geologic Consulting, LLC from 2004 to 2007. Cobban's work has been supported by the U.S. Geological Survey. Fossil collections have been assigned U.S. Geological Survey Mesozoic locality numbers: Those with the prefix "D," for Denver, are stored at the Federal Center in Denver, Colorado; the single collection without a prefix is stored at the U.S. National Museum, Washington, D.C. Illustrated fossils have been assigned USNM numbers and are reposited in the U.S. National Museum, Washington, D.C.

We thank Glenn R. Scott (U.S. Geological Survey), Thomas W. Judkins (U.S. Geological Survey), and David W. Love (New Mexico Bureau of Geology and Mineral Resources) for thoughtful reviews. Incorporation of their suggestions has resulted in a vastly improved paper. However, we are responsible for the content of the paper, and any errors that remain in it are ours and ours alone.

We owe a sincere debt of gratitude to the editors and staff of *New Mexico Geology*: Jane C. Love, Nancy S. Gilson, and Leo Gabaldon. This issue of *NMG* sparkles from front cover to layout and understated but highly effective editing, all the way to redrafted figures that seem to jump off the pages.

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Editors' note: This paper was presented orally at *A symposium on the Paleontology, Geology, and Stratigraphy of the Late Cretaceous Western Interior Seaway*—a tribute to the life of William Aubrey "Bill" Cobban, on August 26, 2006, at the Colorado School of Mines, Golden, Colorado. The title of the paper at that time was "Middle Cenomanian (Upper Cretaceous) reference section from the Sevilleta National Wildlife Refuge, Socorro County, New Mexico."

## Appendix 1
## Speculation on the origin of the Dakota Sandstone phosphate nodules

We originally interpreted these phosphate nodules as large, marine coprolites that had been burrowed by elongate animals, perhaps worms, that deposited the quartz grains on the burrow wall for support. The Dakota Sandstone nodules resemble, at least superficially, coprolites from the Upper Cretaceous Smoky Hill Chalk Member of the Niobrara Formation of western Kansas.

As we observed more characteristics of the nodules we realized that this burrowed-coprolite hypothesis was unsupportable because: (1) the nodules were composed of a groundmass of homogeneous, amorphous phosphate with as much as 50% detrital grains, in places arranged in two or three crudely concentric bands, with no recognizable, undigested organic material (e.g., bones); (2) the central cavity was always aligned with the long axis of the cylindrical nodules and was missing from the spherical nodules; and (3) the now phosphatized internal molds of fossils could not have passed intact through the guts of large animals, such as sharks.

Their association with a condensed, marine section suggests that the nodules may be of bacterial origin (see Soudry and Lewy 1988), but does not explain the presence of the axial cavity with its consistent circular cross section and its quartz-grain lining. Similar phosphate nodules with axial hollows (but no quartz grains) have been reported from the Virgin Creek Member of the Pierre Shale in South Dakota by Searight (1937, p. 37), who thought they might be serpulid tubes. Gries (1940, pp. 32–33), studying the same stratigraphic section in South Dakota, called the nodules "Indian beads" but thought they were more likely some type of plant.

One of us (WAC) has collected cylindrical phosphate nodules with longitudinal, cylindrical cavities from the Lake Creek Member of the Pierre Shale in Wallace County, Kansas (D4905). Interestingly, a spheroidal nodule from that same collection does not have an axial cavity. We have also collected several nodules with axial cavities from the Dakota Sandstone at the Jornada del Muerto section (D14472) and one (and only one) cylindrical phosphate pebble with an axial cavity from the basal D-Cross Tongue at the Principal Reference section (D14495 level on Fig. 3). The D-Cross phosphate pebbles consist almost exclusively of internal molds of bivalves.

Soudry and Lewy (1988, p. 32) worked with phosphate nodules in limy sediments that formed in a nearshore environment in the Maastrichtian of Israel. They concluded that the nodules originated from plastic microbial mats that were lithified by apatite-precipitating bacteria. In trying to apply their model to the Dakota Sandstone on Sevilleta, we were faced with a major problem: a lack of carbonate rocks in the preserved Dakota section on the refuge.

However, carbonate sediments equivalent to the Thatcher Limestone Member of the Graneros Shale were deposited and preserved in the Oak Canyon Member of the Dakota Sandstone at Laguna (Landis et al. 1973; Fig. 9). These carbonate sediments were deposited in a nearshore setting similar to that at Sevilleta. We do not think it unreasonable to assume that carbonate sediments of Thatcher age were deposited on Sevilleta and subsequently eroded.

The long-term depositional rate of the Upper Cretaceous at Sevilleta is very close to that for the intertongued Dakota–Mancos sequence at Laguna (Table 1), suggesting that a considerable quantity of middle Cenomanian sediment could have been eroded at Sevilleta. However, the evidence for this assertion lies in the now phosphatic internal molds of an ammonite (*Turrilites costatus*) and several gastropods. These internal molds had to be composed originally of carbonate that was replaced on the sea floor by phosphate. The gastropod molds served as nucleation centers for additional phosphate that now surrounds them (Fig. 12, central nodule).

Several investigations of phosphatized internal molds in Upper Cretaceous rocks (e.g., Kennedy and Garrison 1975) suggest a two-stage process for phosphate-nodule formation: (1) gradual lithification of the carbonate sediment that fills the shells along with dissolution of the aragonitic shells during burial and (2) exhumation of the pre-fossilized internal molds that are subsequently phosphatized on the sea floor. Tourtelot in (Tourtelot and Cobban 1968, p. 18) interpreted phosphate nodules at the base of the Niobrara Formation in South Dakota to be the result of phosphate replacement of fine-grained calcite at a shallow but indeterminate depth before erosion. Both scenarios require carbonate sediments. This interpretation accounts for the phosphatized internal molds at Sevilleta, but does not account for the majority of nodules that are not recognizable as fossils.

If, however, there were also microbial mats that were rolled around the sea floor by waves or currents, they could assume spheroidal shapes. These mats would undoubtedly be sticky and would agglutinate any detritus they encountered, including sand grains, shark teeth, and internal molds.

The cylindrical nodules, however, would have had to nucleate on abundant cylindrical objects that had lengths much greater than their diameters. Whatever these objects were, they did not lend themselves to fossilization, suggesting that they were organic, but without preservable hard parts.

Gries's (1940) conclusion that the South Dakota "Indian beads" were likely to be some type of plant provides the possible origin for the cylindrical nodules with axial cavities. Although there are no direct records of marine plants from the Upper Cretaceous of the Western Interior, there is one indirect record. Landes (1940, p. 140) describes the long, narrow attachment scar of *Ostrea russelli* Landes that suggests that the oyster might have lived attached to the stems of marine plants. His plate III, figure 6 (Landes 1940, p. 207), shows an attached valve whose height is 53 mm. The deep, subcylindrical attachment scar runs the entire 53 mm, from umbo to ventral margin, and is about 8mm across. The surface of the scar is smooth.

Nucleation around the stems of marine plants could produce cylindrical nodules with smooth axial cavities. Agglutination of detrital grains would account for the quartz-grain lining on at least the upper surface, but would not account for the consistent one or two layers of quartz grains surrounding the cavity.

The explanation presented above accounts for many, but not all of the observed features of the Dakota phosphate nodules. It seems plausible as far as it goes, but it requires several assumptions that cannot be verified. Detailed chemical and petrological studies of these nodules may answer some of the questions regarding their origin but are beyond the scope of this study.

Whatever the origin of these nodules, they are abundant over a wide area at the same biostratigraphic position. They are a valuable correlation aid and signify that the environmental conditions that produced them were widespread in central New Mexico during middle Cenomanian time. According to Ames (1959, p. 89) the environmental conditions necessary for apatite replacement of carbonate include: (1) nondeposition, (2) limy sediments or detritus, (3) calcium-saturated seawater, (4) pH $\geq$ 7, and (5) phosphate ion concentrations $\geq$ 0.1 ppm. Condition (1) is preserved in the rock record at Sevilleta, and condition (2) is inferred from the phosphatic internal molds of fossils. Condition (3) seems unlikely because of the lack of carbonate rocks at and above the level of the nodules. The remaining conditions are chemically necessary for the replacement process.

Concretions with morphologies similar to the cylindrical phosphate nodules from the Dakota on Sevilleta can be produced under drastically different conditions from those interpreted at the refuge. Clari et al. (2004, figs. 17 and 18) sectioned cylindrical limestone concretions from a Miocene mud volcano in Italy that have circular axial cavities like those from the refuge. These cylindrical concretions differ, however, in size, composition, and orientation from the Dakota nodules. They are about 10 cm in diameter and more than a meter long. They are composed of limestone and lie at high angles to bedding. Clari et al. (2004, p. 672) interpret them to be chimneys that served as part of a cold-seep plumbing network that crosscut the mud volcano. They acted as fluid conduits along which cementation took place.

## Appendix 2

| Fossil species | Number | Formation | Range | Collector(s) | Date |
|---|---|---|---|---|---|
| **Ammonite** | | | | | |
| *Acanthoceras amphibolum* | D14229 | Dakota Sandstone (main body) | Middle Cenomanian | S. C. Hook | 6/17/04 |
| *Acanthoceras amphibolum* | D14230 | Dakota Sandstone (main body) | Middle Cenomanian | S. C. Hook | 7/1/04 |
| *Acanthoceras amphibolum* | D5149 | Greenhorn Limestone (Lincoln Member) | Middle Cenomanian | W. A. Cobban | 12/7/65 |
| *Acanthoceras amphibolum* | D7084 | Dakota Sandstone (Paguate Tongue) | Middle Cenomanian | C. Maxwell, W. A. Cobban, and E. R. Landis | 10/4/69 |
| *Acanthoceras bellense* | D14225 | Dakota Sandstone (main body) | Middle Cenomanian | S. C. Hook | 6/17/04 |
| *Acanthoceras bellense* | D14464 | Dakota Sandstone (main body) | Middle Cenomanian | S. C. Hook | 6/28/06 |
| *Acanthoceras bellense* | D14466 | Dakota Sandstone (main body) | Middle Cenomanian | S. C. Hook | 7/24/06 |
| *Acanthoceras muldoonense* | D14236 | Dakota Sandstone (main body) | Middle Cenomanian | S. C. Hook | 7/22/04 |
| *Acanthoceras muldoonense* | D14249 | Dakota Sandstone (main body) | Middle Cenomanian | S. C. Hook | 6/17/04 |
| *Acanthoceras muldoonense* | D5144 | Graneros Shale | Middle Cenomanian | W. A. Cobban | 12/7/65 |
| *Collignoniceras woollgari regulare* | D14584 | Mancos Shale (Rio Salado Tongue) | Middle Turonian | R. Chamberlin and S. C. Hook | 4/19/07 |
| *Collignoniceras woollgari woollgari* | D14492 | Mancos Shale (Rio Salado Tongue) | Middle Turonian | R. Chamberlin and S. C. Hook | 9/22/06 |
| *Conlinoceras gilberti* | *22883 | Graneros Shale (Thatcher Limestone Member) | Middle Cenomanian | W. A. Cobban | 7/6/50 |
| *Conlinoceras tarrantense* | D11245 | Dakota Sandstone (main body) | Middle Cenomanian | B. Baker and S. C. Hook | 7/30/80 |
| *Conlinoceras tarrantense* | D14228 | Dakota Sandstone (main body) | Middle Cenomanian | S. C. Hook | 6/17/04 |
| *Conlinoceras tarrantense* | D14488 | Dakota Sandstone (main body) | Middle Cenomanian | S. C. Hook | 7/13/04 |
| *Cunningtoniceras* cf. *C. cunningtoni* | D11245 | Dakota Sandstone (main body) | Middle Cenomanian | S. C. Hook | 7/30/80 |
| *Forresteria* sp. | D11205 | Mancos Shale (D-Cross Tongue) | Upper Turonian–Coniacian | B. Baker and S. C. Hook | 6/20/80 |
| *Mammites* sp. | D10974 | Mancos Shale (Rio Salado Tongue) | Lower Turonian | S. C. Hook | 9/24/79 |
| *Metoicoceras muelleri* | D10979 | Dakota Sandstone (Twowells Tongue) | Upper Cenomanian | S. C. Hook | 9/24/79 |
| *Paraconlinoceras leonense* | D14225 | Dakota Sandstone (main body) | Middle Cenomanian | S. C. Hook | 6/17/04 |
| *Plesiacanthoceras wyomingense*? | D11441 | Mancos Shale (lower tongue) | Middle Cenomanian | B. Baker and S. C. Hook | 12/18/80 |
| *Prionocyclus macombi* | D14477 | Tres Hermanos Formation (Carthage Member) | Middle Turonian | S. C. Hook | 8/22/03 |
| *Prionocyclus novimexicanus* | D11184 | Mancos Shale (D-Cross Tongue) | Upper Turonian | B. Baker | 4/1/80 |
| *Scaphites ferronensis* | D14541 | "Mancos Shale (D-Cross Tongue, Juana Lopez Beds)" | Middle Turonian | S. C. Hook | 12/6/06 |
| *Scaphites warreni* | D11350 | "Mancos Shale (D-Cross Tongue, Juana Lopez Beds)" | Middle Turonian | B. Baker and S. C. Hook | 10/1/80 |
| *Spathites* sp. | D11519 | Tres Hermanos Formation (Atarque Sandstone Member) | Lower–middle Turonian | D. A. Meyers | 5/18/81 |

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|---|---|---|---|---|---|
| *Turrilities costatus* | D14488 | Dakota Sandstone (main body) | Lower–middle Cenomanian | S. C. Hook | 7/13/04 |
| *Turrilities (Euturrilities) scheuchzerianus* | D14236 | Dakota Sandstone (main body) | Middle Cenomanian | S. C. Hook | 7/22/04 |
| *Turrilities acutus* | D14225 | Dakota Sandstone (main body) | Middle Cenomanian | S. C. Hook | 6/17/04 |
| **Clam** | | | | | |
| *Cremnoceramus deformis erectus* | D14467 | Gallup Sandstone | Lower Coniacian | S. C. Hook | 1/3/04 |
| *Inoceramus arvanus* | D14225 | Dakota Sandstone (main body) | Middle Cenomanian | S. C. Hook | 6/17/04 |
| *Inoceramus arvanus* | D14230 | Dakota Sandstone (main body) | Middle Cenomanian | S. C. Hook | 7/1/04 |
| *Mytiloides mytiloides* | D14590 | Mancos Shale (Rio Salado Tongue) | Lower Turonian | S. C. Hook | 4/27/07 |
| *Pleuriocardia pauperculum* | D14502 | Mancos Shale (Mulatto Tongue) | Upper Cenomanian–lower Coniacian | S. C. Hook | 11/3/06 |
| *Plicatula arenaria* | D7081 | Dakota Sandstone (Oak Canyon Member) | Middle Cenomanian | W. A. Cobban and E. R. Landis | 10/4/69 |
| **Coral** | | | | | |
| *Archohelia dartoni* | D11564 | Mancos Shale (lower tongue) | Upper Cenomanian–Turonian | S. C. Hook | 3/19/81 |
| **Oyster** | | | | | |
| *Crassostrea soleniscus* | D14484 | Tres Hermanos Formation (Atarque Sandstone Member) | Upper Cretaceous | S. C. Hook | 2/4/04 |
| *Crassostrea soleniscus* | D14503 | Mancos Shale (Mulatto Tongue) | Upper Cretaceous | S. C. Hook | 11/3/06 |
| *Exogyra columbella* | D7080 | Dakota Sandstone (Oak Canyon Member) | Middle Cenomanian | W. A. Cobban and E. R. Landis | 10/4/69 |
| *Flemingostrea elegantula* | D14479 | Mancos Shale (Mulatto Tongue) | Lower Coniacian | S. C. Hook | 9/2/03 |
| *Flemingostrea elegantula* | D14500 | Mancos Shale (Mulatto Tongue) | Lower Coniacian | S. C. Hook | 11/3/06 |
| *Nicaisolopha bellaplicata novamexicana* | D14495 | Mancos Shale (D-Cross Tongue) | Middle Turonian | S. C. Hook | 11/9/06 |
| *Nicaisolopha sannionis* (small form) | D11205 | Mancos Shale (D-Cross Tongue) | Upper Turonian | B. Baker and S. C. Hook | 6/20/80 |
| *Ostrea beloiti* | D11441 | Mancos Shale (lower tongue) | Middle Cenomanian | B. Baker and S. C. Hook | 12/18/80 |
| *Ostrea beloiti* | D14230 | Dakota Sandstone (main body) | Middle Cenomanian | S. C. Hook | 2/1/04 |
| *Pycnodonte newberryi* | D14485 | Mancos Shale (lower tongue) | Upper Cenomanian | S. C. Hook | 7/6/04 |
| *Pycnodonte* aff. *P. kellumi* | D14294 | Mancos Shale (lower tongue) | Upper Cenomanian | S. C. Hook | 10/15/04 |
| *Pycnodonte newberryi* | D10978 | Mancos Shale (Rio Salado Tongue) | Upper Cenomanian | S. C. Hook | 9/24/79 |
| **Plant debris** | D14486 | Dakota Sandstone (main body) | Upper Cretaceous | S. C. Hook | 2/14/04 |

* = Washington, D.C. collection
D = Denver collection