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UPPER CRETACEOUS STRATIGRAPHY AND BIOSTRATIGRAPHY OF SOUTH-CENTRAL NEW MEXICO

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Abstract—Upper Cretaceous rocks exposed at isolated outcrops in south-central New Mexico contain a marine molluscan record that spans at least 30 biostratigraphic zones from the middle Cenomanian to the middle Coniacian. Formational names applied to these rocks are, in ascending order: Dakota Sandstone (main body and one tongue), Mancos Shale (four tongues), Tres Hermanos Formation, Gallup Sandstone, and Crevasse Canyon Formation. Five small-scale graphic sections ranging from Doña Ana County on the south to Socorro County on the north and Lincoln County on the east are presented with generalized lithologies and depositional environments. Key faunal collections from each section are tied to their stratigraphic positions in order to facilitate correlation from one area to another.

The index fossils for 20 of the 30 biostratigraphic zones used in south-central New Mexico have been recovered from the five representative sections although there is no one section that contains all 20. The remaining 10 zones for which there are no fossils recorded in the study area are probably present as well; most of these zones are known from the Upper Cretaceous to the north and west of the study area. If these 10 zones are present, they are represented by a rock record that is barren of megafossils in the study area.

The detailed biostratigraphy presented in this study documents the time-transgressive nature of the rock-stratigraphic units, which was a response to three cycles of shoreline movement across this part of New Mexico. The two earliest cycles of transgression and regression (T-1, R-1 and T-2, R-2 of Molenaar, 1983) are present throughout the study area. However, only Socorro County has a complete third cycle (T-3, R-3).

INTRODUCTION

The area of south-central New Mexico covered by this Upper Cretaceous stratigraphic and biostratigraphic summary includes parts of Doña Ana, Sierra, Socorro, and Lincoln Counties (Fig. 1). At least one representative measured section from each county is presented in order to show rock units and stratigraphic positions of key marine fossils. These sections include the Sevilleta National Wildlife Refuge (SNWR) and Carthage coal field in Socorro County, Mescal Canyon in Sierra County, Love Ranch in Doña Ana County, and a composite section for Lincoln County taken from partial sections at Jackson well, Bull Gap Canyon and Rimrock Canyon (Fig. 1). Rock stratigraphic units in these four counties are assigned to the following five formations, in ascending order: Dakota Sandstone (main body and Twowells Tongue), Mancos Shale (four tongues), Tres Hermanos Formation, Gallup Sandstone, and Crevasse Canyon Formation. Two of these formations and associated members and beds (Mancos and Gallup) are entirely marine. The Dakota Sandstone, Tres Hermanos Formation, and Crevasse Canyon Formation contain both marine and nonmarine strata.

Marine Upper Cretaceous rocks in Doña Ana and Sierra Counties range in age from late middle Cenomanian to late Turonian, those to the north in Socorro and Lincoln Counties range in age from earliest middle Cenomanian to latest early Coniacian. Middle Cenomanian through lower Coniacian Stages in south-central New Mexico have been subdivided into 30 biostratigraphic zones (Fig. 2). Twenty-seven representative ammonite species serve as the zonal indices for the middle Cenomanian and Turonian and three inoceramid bivalve species serve as the indices for the lower Coniacian. Twenty of these index species have been collected from the rocks in the study area. The thirty fossil zones average less than 250 ka in duration and provide high-resolution correlation from one isolated outcrop to the next in the study area and are useful elsewhere in New Mexico.

The fossil collections on which this report is based are stored in the U.S. Geological Survey Mesozoic Invertebrate Collections at the Federal Center in Denver, Colorado. These collections have unique locality numbers that begin with the letter "D." If an individual specimen from a collection has been published, it has been issued a U.S. National Museum number (USNM) and is reposited in the Smithsonian Institution in Washington, D.C. As of January 1, 2012, the number of USGS Mesozoic Invertebrate collections from Doña County is 25 (with 16 from the Love Ranch area), from Sierra County is 131 (with 78 from Mescal Canyon), from Socorro County is 429 (with 149 from the Carthage coal field and 86 from the area of the Sevilleta National Wildlife Refuge), and from Lincoln County is 153 (with 98 from Bull Gap and Rim Rock Canyons and Jackson well). These collections span more than 50 years of research on the Upper Cretaceous of New Mexico. The earliest collection was made on April 11, 1959 in the Carthage coal field (D2042) by W. A. Cobban and the latest collection was made on November 28, 2011 near Bull Gap Canyon (D15024) by S. C. Hook. More than 95% of these collections were made by the authors. The remaining 5% were made primarily by colleagues of the authors at the U.S. Geological Survey or the New Mexico Bureau of Geology and Mineral Resources.

MOLLUSCAN ZONATION

The fossil zonation shown on Figure 2 has been modified from Cobban et al. (2008, fig. 2) for use in south-central New Mexico. For example, the ammonite zones in the lower Coniacian in the earlier zonation have been replaced by inoceramid zones, because

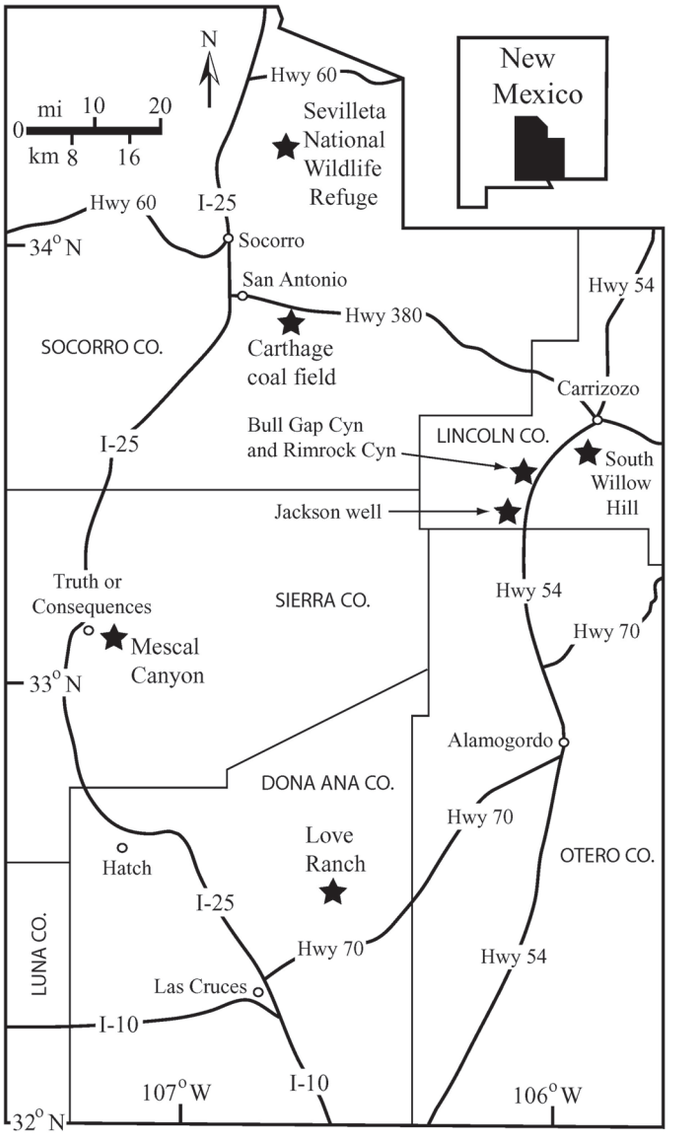

FIGURE 1. Index map of south-central New Mexico showing measured sections and localities mentioned in the text.

of the scarcity of ammonites in that part of the section in Socorro and Lincoln counties. The four scaphitid zones in the middle and upper Turonian have been replaced by three prionocyclid zones, because scaphitids are rare faunal elements in southern New Mexico, but the prionocyclids are common. Finally, because *Dunveganoceras* has never been found in New Mexico, the four *Dunveganoceras* zones near the base of the upper Cenomanian have been replaced by *Calycoceras canitaurinum* at the base, an unnamed zone representing the middle two zones, and *Metoicoceras mosbyense* representing the fourth and uppermost zone. Brief summaries of the fossils found in each of the zones in the representative measured sections are presented below.

Although no fossils are illustrated in this paper, photographs of most of the key taxa from New Mexico have been published in Cobban and Hook (1989). Cenomanian through Coniacian fossils from throughout Lincoln County are illustrated in Cobban (1986). Particularly good illustrations of the following fossils collected from elsewhere in the study area can be found in the cited literature: *Conlinoceras tarrantense* and *Plesiacanthoceras muldoonense* from the Dakota Sandstone on SNWR in Hook and Cobban (2007*); Mytiloides mytiloides* from the Atarque Sandstone Member of the Tres Hermanos Formation at Mescal Canyon in Cobban (1984); *Collignoniceras woollgari woollgari* from the Atarque Sandstone Member of the Tres Hermanos Formation in the Carthage coal field in Cobban and Hook (1979); *Cameleolopha bellaplicata* and *Prionocyclus macombi* from the Fite Ranch Sandstone Member of the Tres Hermanos Formation in the Carthage coal field in Hook and Cobban (2011); and *Mytiloides incertus* and *Prionocyclus germari* from the D-Cross Tongue of the Mancos Shale at Love Ranch in Walaszczyk and Cobban (2000) and Kennedy et al. (2001), respectively.

Middle Cenomanian Zone of *Conlinoceras tarrantense* (Adkins*)*

This zone is the oldest macroinvertebrate zone found in strata deposited in the Late Cretaceous Western Interior Seaway. In the study area *Conlinoceras tarrantense* has been found only in Socorro County on SNWR. Associated fauna include a few snails, a crab carapace, a small, nondescript oyster, and the ammonites, *Cunningtoniceras* cf. *C. cunningtoni* (Sharpe) and *Turrilites costatus* Lamarck.

Middle Cenomanian Zone of *Acanthoceras granerosense* Cobban and Scott

Acanthoceras granerosense has never been found in New Mexico. In fact, it has never been found outside southeastern Colorado. However, Cobban and Scott (1972, p. 68-70) named the species for ammonites found in the Graneros Shale near Pueblo, Colorado, in rocks above the Thatcher Limestone Member, where *Conlinoceras tarrantense* occurs, and below those containing *Plesiacanthoceras muldoonense*, which had never been found in New Mexico until it was discovered on SNWR in 2004 (Hook and Cobban, 2007).

Middle Cenomanian Zone of *Plesiacanthoceras muldoonense* Cobban and Scott

Within the study area, *Plesiacanthoceras muldoonense* has been found only in Socorro County on SNWR, where it occurs in association with the helically coiled ammonite *Turrilites* (*Euturrilites*) *scheuchzerianus* Bosc.

Middle Cenomanian Zone of *Acanthoceras bellense* Adkins

Acanthoceras bellense has been found only on SNWR and at Carthage. Fossils associated with it on SNWR are the bivalve *Inoceramus arvanus* Stephenson and the ammonites *Paraconlinoceras leonense* (Adkins) and *Turrilites acutus* Passy. At Carthage, it was associated with the oyster *Ostrea beloiti* Logan.

series	stage		Biostratigraphic zones, south-central New Mexico		radioisotopic age (Ma)
Upper Cretaceous (part)	Coniacian	Lower	*Cremnoceramus crassus*		88.55 ± 0.59
			Cremnoceramus deformis		
			Cremnoceramus erectus		
	89.3				
	Turonian	Upper	*Forresteria peruana*		
			Prionocyclus germari		
			Prionocyclus quadratus		
			Prionocyclus novimexicanus		
		Middle	*Prionocyclus wyomingensis*	*Scaphites ferronensis* Subzone	
				Scaphites warreni Subzone	
			Prionocyclus macombi	*Coilopoceras inflatum* Subzone	90.21 ± 0.54
				Coilopoceras colleti Subzone	
			Prionocyclus hyatti		92.46 ± 0.58
			Collignoniceras woollgari	*C. woollgari regulare* Subzone	
				C. woollgari woollgari Subzone	
		Lower	*Mammites nodosoides*		
			Vascoceras birchbyi		94.48 ± 0.58
			Pseudaspidoceras flexuosom		93.19 ± 0.42
			Watinoceras devonense		
	93.5				
	Cenomanian	Upper	*Nigericeras scotti*		
			Neocardioceras juddii		93.32 ± 0.38 93.82 ± 0.30
			Burroceras clydense		
			Euomphaloceras septemseriatum		93.68 ± 0.50
			Vascoceras diartianum		93.99 ± 0.72
			Metoicoceras mosbyense		
			unnamed zone (=*Dunveganoceras* spp.)		
			Calycoceras canitaurinum		94.71 ± 0.49
		Middle	*Plesiacanthoceras wyomingense*		
			Acanthoceras amphibolum		94.96 ± 0.50
			Acanthoceras bellense		
			Plesiacanthoceras muldoonense		
			Acanthoceras granerosense		
			Conlinoceras tarrantense		95.73 ± 0.61

FIGURE 2. Molluscan biostratigraphic zones from middle Cenomanian through lower Coniacian for south-central New Mexico, modified from Cobban et al. (2008). The age of the stage boundaries are taken from Walker and Geissman (2009).

Middle Cenomanian Zone of *Acanthoceras amphibolum* Morrow

Acanthoceras amphibolum is a very widespread ammonite in New Mexico. It has been collected from all but the Love Ranch section of the measured sections in the study area. Associated fauna include the bivalves *Inoceramus arvanus* Stephenson and *Inoceramus rutherfordi* Warren, the oyster *Ostrea beloiti* Logan, and the ammonites *Turrilites acutus americanus* Cobban and Scott and *Tarrantoceras sellardsi* (Adkins). The Western Interior-wide x-bentonite occurs near the top of the *Acanthoceras amphibolum* Zone and provides the radiometric date for this zone.

Middle Cenomanian Zone of *Plesiacanthoceras wyomingense* (Reagan)

Plesiacanthoceras wyomingense has been found at only one locality in the study area. A fragment of an ammonite identified as *Plesiacanthoceras wyomingense*? was collected from a thin sandstone in the lower tongue of the Mancos Shale on SNWR. The only associated fauna were fragments of the oyster *Ostrea beloiti* Logan.

Upper Cenomanian Zone of *Calycoceras canitaurinum* (Haas)

Calycoceras canitaurinum has been found only at the Carthage coal field in the study area. It ranges over approximately 24 m of section in the lower tongue of the Mancos Shale. Associated fossils include a rare occurrence of the ammonite *Metengonoceras* sp., along with the ammonite *Tarrantoceras* sp., and the bivalve *Inoceramus* sp. A very large *Inoceramus prefragilis stephensoni* Kauffman, Hattin, and Powell at Carthage is probably from this zone as well.

Upper Cenomanian unnamed(?) zone

Farther north in the Western Interior, the stratigraphic interval between *Plesiacanthoceras wyomingense* and *Vascoceras diartianum* is occupied by four chronological species of the ammonite genus *Dunveganoceras* (*D. pondi*, *D. problematicum*, *D. albertense*, and *D. conditum*). However, *Dunveganoceras* has never been found in New Mexico. *Calycoceras canitaurinum* occurs with *D. pondi*, the oldest of the four species, and *Metoicoceras mosbyense* with *D. conditum*, the youngest. This unnamed zone represents the middle two species, an interval that is generally barren of megafossils in New Mexico.

Upper Cenomanian Zone of *Metoicoceras mosbyense* Cobban

Metoicoceras mosbyense is widespread in western New Mexico, where it occurs in the Twowells Tongue of the Dakota Sandstone. This ammonite has been collected from only one locality in the study area from the Twowells Tongue on SNWR. No other fossils were associated with it. However, farther to the south on SNWR, the oyster *Pycnodonte* aff. *P. kellumi* (Jones) was collected from the equivalent part of the lower tongue of Mancos Shale south of the apparent pinchout of the Twowells Tongue. *Inoceramus ginterensis* Pergament collected at Love Ranch is probably from this zone.

Upper Cenomanian Zone of *Vascoceras diartianum* (d'Orbigny)

Vascoceras diartianum has not been found in the study area. It is, however, fairly common in southwest New Mexico, primarily in Luna and Grant Counties (Cobban et al., 1989). Indirect evidence in the form of the bivalve *Inoceramus pictus*? from the lower tongue of the Mancos Shale at Mescal Canyon suggests this zone.

Upper Cenomanian Zone of *Euomphaloceras septemseriatum* (Cragin)

Euomphaloceras septemseriatum is found in the nodular limestones at the base the Bridge Creek Limestone Beds of the lower tongue of the Mancos Shale throughout the study area and elsewhere in New Mexico. It is fairly abundant and occurs with a diverse fauna that includes the ammonites *Metoicoceras geslinianum* (d'Orbigny), *Allocrioceras annulatum* (Shumard), *Sciponoceras gracile* (Shumard), *Worthoceras vermiculus* (Shumard), along with the oysters *Pycnodonte newberryi* (Stanton) and *Rhynchostreon levis* (Stephenson), the bivalves *Inoceramus pictus* Sowerby and *Plesiopinna* sp., and the echinoid *Hemiaster jacksoni* Maury.

The thin nodular limestones at the base of the Bridge Creek Limestone Beds form a distinctive lithology that can be recognized over much of central New Mexico. Whether there are four (at Mescal Canyon and Carthage), or more beds (near Three Rivers, Otero County), they all lie in the *Euomphaloceras septemseriatum* Zone. Prior to 1989 these nodular limestones were called, informally, the "Scip Zone limestones." Cobban et al. (1989) showed in southwestern New Mexico that *Sciponoceras gracile* ranged upward into the *Neocardioceras juddii* Zone. After 1989, *Euomphaloceras septemseriatum*, which has a shorter vertical range, was chosen as the zonal index.

The "Scip Zone limestones" are a key lithologic unit in New Mexico. The consistent and distinctive lithology combined with a short-lived megafauna that is developed over a wide area of the Western Interior has led to the concept that the base of these limestones is an isochronous surface. In addition, Elder (1988) correlated four ash beds (given the informal designation of marker beds A-D) over much of the Western Interior and Texas. At Carthage marker bed "A" is a 2.5-cm-thick bentonite that lies 0.3 m below the initial Scip Zone limestone. This bentonite is correlated with a 5-cm-thick bentonite that is directly below the initial Scip Zone limestone in Mescal Canyon.

Upper Cenomanian Zone of *Burroceras clydense* Cobban, Hook, and Kennedy

Burroceras clydense has not been found in the study area. It is, however, fairly common in southwest New Mexico, primarily in Luna and Grant counties (Cobban et al.,1989).

Upper Cenomanian Zone of *Neocardioceras juddii* (Barrois and de Guerne)

Neocardioceras juddii is common in southwest New Mexico (Cobban et al.,1989), but has not been collected by the authors within the study area. However, Elder (1989) reports *N. juddii* from large blocks of processed shale just above the uppermost nodular limestone near the base of the Bridge Creek Limestone Beds at Carthage.

Upper Cenomanian Zone of *Nigericeras scotti* Cobban

The presence of the *Nigericeras scotti* Zone is inferred at Carthage from a collection of the bivalve *Mytiloides hattini* Elder from 4.7 m above the base of the Bridge Creek Limestone Beds. Although the oyster *Pycnodonte newberryi* does not occur in the limestone with *Mytiloides hattini*, it occurs in the shales both above and below it.

Lower Turonian Zone of *Watinoceras devonense* Wright and Kennedy

The presence of the lowermost Turonian *Watinoceras devonense* Zone is inferred at: 1) Carthage from a collection of the bivalve *Mytiloides puebloensis* Kennedy, Walaszczyk, and Cobban from a 20-cm-thick limestone bed that is 6.3 m above the base of the Bridge Creek Limestone Beds, and 2) Bull Gap Canyon from a collection of *M. puebloensis* from 9-cm-thick limestone at the top of the Bridge Creek Limestone Beds. No other fossils were recovered from these beds. The Cenomanian/Turonian boundary is drawn at the base of this limestone bed.

Lower Turonian Zones of *Pseudaspidoceras flexuosum* Powell and *Vascoceras birchbyi* Cobban

These two ammonites are fairly common in southwest New Mexico (Cobban et al.,1989), but have not been collected by the authors within the study area. However, these zones are inferred to be present at Carthage, where 13.6 m of section lie between the collection of *Mytiloides puebloensis* and the first appearance of *Mammites nodosoides*.

Lower Turonian Zone of *Mammites nodosoides* (Schüter)

The latest early Turonian ammonite *Mammites nodosoides* is fairly abundant, often as impressions on bedding planes, in the calcarenites that mark the top of the Bridge Creek Limestone Beds at Carthage, Mescal Canyon, and SNWR. Associated fauna in the Bridge Creek is limited to countless fragmented specimens of the bivalve *Mytiloides mytiloides* (Mantell). It is the comminuted remains of this bivalve that form the matrix of the calcarenite at Carthage and SNWR. A single impression of the rare ammonite *Cibolaites molenaari* Cobban and Hook has been collected from the top of the Bridge Creek at Mescal Canyon.

Except at Love Ranch, where there are no Bridge Creek lithologies developed, *Mammites nodosoides* has not been found above the top of the Bridge Creek Limestone Beds in the study area. However, the bivalve *Mytiloides mytiloides*, which is confined to the *M. nodosoides* Zone, extends the zone several tens of meters higher. At Mescal Canyon, *M. mytiloides* forms coquina-like masses near the base of the overlying Atarque Sandstone Member of the Tres Hermanos Formation. Additional fauna found within that interval at Mescal Canyon include the ammonite *Morrowites subdepressus* Cobban and Hook and the coral *Archohelia dartoni* Wells.

Middle Turonian Zone of *Collignoniceras woollgari* (Mantell)

The *Collignoniceras woollgari* Zone is subdivided into two subzones: a lower *C. woollgari woollgari* (Mantell) subzone and an upper *C. woollgari regulare* (Haas) subzone. Fossils from the lower subzone are found in Socorro and Lincoln Counties, whereas fossils from the upper subzone have been found only in Socorro County. At Carthage and Bull Gap Canyon, *Collignoniceras woollgari woollgari* is found in limestone concretions in the upper part of the lower tongue of the Mancos Shale and in sandstone concretions in the lower portion of the overlying Atarque Sandstone Member of the Tres Hermanos Formation. Common associates in the lower tongue are the ammonites *Morrowites depressus* (Powell) and *Spathites rioensis* Powell.

Collignoniceras woollgari regulare has been found at only one locality in the study area. It occurs in limestone concretions high in the Rio Salado Tongue of the Mancos Shale in the northwestern part of the SNWR. An oyster coquina in the lower part of the Atarque Sandstone Member contains *Crassostrea* aff. *C. subtrigonalis* Evans and Shumard, apparently from the same subzone.

A large and diverse fauna is found in sandstones of the Atarque Member at Carthage. The non-cephalopod portion of this fauna was apparently facies controlled and was regarded by Hook et al. (1983, p. 22) as the characteristic fauna of the Atarque Sandstone Member. It consists of at least 21 bivalve and 9 gastropod species. The bivalves are *Modiolus* sp., *Pinna* cf. *P. guadalupe* Böse, *Phelopteria gastrodes* (Meek), *Pseudopteria* sp., *Inoceramus cuvieri* Sowerby, *Mytiloides subhercynicus* (Seitz), *Crassostrea soleniscus* (Meek), *Ostrea* sp., *Lopha* sp., *Pleuriocardia pauperculum* (Meek), *Cymbophora emmonsi* (Meek), *C. utahensis* (Meek), *Tellina modesta* Meek, *Protodonax* sp., *Veniella mortoni* Meek and Hayden, *Aphrodina* sp., *Cyprimeria* sp., *Legumen ellipticum* Conrad, *Pholadomya* sp., *Laternula lineata* Stanton, *and Psilomya concentrica* (Stanton). The gastropods are *Perissoptera*? sp., *Pugnellus fusiformis* Meek, *Gyrodes conradi* Meek, *G. depressa* Meek, *Pyropsis coloradoensis* Stanton, *Tectaplica*? *utahensis* (Meek), *Rostellinda dalli* (Stanton), *R. ambigua* (Stanton), and Olividae n. gen. and n. sp.

Ammonite touch marks from Mescal Canyon attributed to *Collignoniceras woollgari* by Landman and Cobban (2007, fig. 18.18) were probably made by *C. woollgari*'s ancestor, *Cibolaites molenaari*. The specimens (USNM 53443 and 53444) from 9 m above the "Scip zone" limestones lie within the lower Turonian *Mammites nodosoides* Zone and cannot be *C. woollgari*.

Middle Turonian Zone of *Prionocyclus hyatti* (Stanton)

Fossils representing the *Prionocyclus hyatti* Zone have been found only on the east side of the study area in Lincoln County. At Bull Gap Canyon *Prionocyclus hyatti* occurs near the base of the Fite Ranch Sandstone Member of the Tres Hermanos Formation in association with the oysters *Cameleolopha* aff. *C. bellaplicata* (Shumard), *Cameleolopha* cf. *C. bellaplicata*, and the ammonite *Coilopoceras springeri* Hyatt. The zone extends to just below the top of the Fite Ranch Sandstone. Associated fauna include the ammonite *Romaniceras mexicanum* Jones, the bivalve *Pholadomya* sp., and the oyster *Cameleolopha bellaplicata*.

Middle Turonian Zone of *Prionocyclus macombi* Meek

The zonal index *Prionocyclus macombi* is the most widespread and abundant ammonite species in the study area. It occurs in all but the southernmost section, where rocks of this age are nonmarine and included in the Carthage Member of the Tres Hermanos Formation. Elsewhere in the study area, *P. macombi* is a key component of faunas in, and therefore a guide to, the Fite Ranch Sandstone Member of the Tres Hermanos Formation.

The *Prionocyclus macombi* Zone is often subdivided into two subzones: the lower *Coilopoceras colleti* Subzone and the upper *Coilopoceras inflatum* Subzone. This subzonation scheme works well in the study area. The *Coilopoceras colleti* Subzone is confined to the Fite Ranch Sandstone and the *Coilopoceras inflatum* Subzone is confined to the basal few meters of the D-Cross Tongue, especially the basal arenite of the Juana Lopez beds at Bull Gap Canyon.

The *Coilopoceras colleti* Subzone fauna is well preserved at Carthage, where it consists of the ammonites *P. macombi* and *C. colleti*, the bivalves *Pinna petrina* White, *Aphrodina* sp., *Legumen ellipticum* Conrad, *Homomya* sp., *Pholadomya* sp., *Psilomya meeki* (White), *Psilomya concentrica* (Stanton), and *Inoceramus dimidius* White, the oyster *Cameleolopha bellaplicata* (Shumard), and the gastropods *Pyropsis* sp., *Rostellities gracilis* Stanton? and *Carota dalli* (Stanton). The *Coilopoceras inflatum* Subzone fauna is well preserved at Bull Gap Canyon, where it consists of the ammonites *P. macombi*, *C. inflatum*, *Hourcquia mirabilis* (Collignon), and *Placenticeras* sp., the bivalve *Inoceramus dimidius* White, and the oyster *Cameleolopha lugubris* (Conrad). This fauna occurs in the basal sandstone of the Juana Lopez beds. A similar fauna occurs in concretions near the base of the D-Cross Tongue at Mescal Canyon, although the oyster is not present there.

Middle Turonian Zone of *Prionocyclus wyomingensis* Meek

The zone of *Prionocyclus wyomingensis* is poorly represented in the study area. The index species usually occurs as impressions in calcarenites at or near the base of the Juana Lopez beds of the D-Cross Tongue. This zone is divided into two subzones: a lower *Scaphites warreni* Meek and Hayden Subzone and a higher *Scaphites ferronensis* Cobban Subzone. Surprisingly, both subzones species are found in the study area, but not in the same bed, and only in the northernmost section at SNWR. Both subzones contain low diversity faunas, which differ only in the associated scaphitid. In addition to the scaphitid, the fauna consists of the ammonite *Prionocyclus wyomingensis*, the bivalve *Inoceramus dimidius*, and the oyster *Cameleolopha lugubris*.

Upper Turonian Zone of *Prionocyclus novimexicanus* (Marcou)

The zonal index *Prionocyclus novimexicanus* occurs in concretions in the D-Cross Tongue of the Mancos Shale at Mescal Canyon, Carthage, and SNWR. It has not been found in the D-Cross Tongue at Bull Gap Canyon probably because of poor outcrop. At Love Ranch, *Scaphites whitfieldi* Cobban, a common associate of *P. novimexicanus*, occurs near the top of the Fite Ranch Sandstone Member of the Tres Hermanos Formation. The associated fauna is of low diversity; it is best developed at Carthage, where it includes the bivalve *Inoceramus perplexus* Whitfield and the straight ammonite *Baculites yokoyamai* Tokunaga and Shimizu. A rare occurrence of the geniculated inoceramid *Inoceramus dakotensis* Walaszczyk and Cobban at Mescal Canyon is indicative of the upper part of this zone (Walaszczyk and Cobban, 2000, table 1).

Upper Turonian Zone of *Prionocyclus quadratus* Cobban

Fossils diagnostic of the *Prionocyclus quadratus* Zone have not been found in the study area, although parts of the D-Cross Tongue throughout the area and part of the Gallup Sandstone at Mescal Canyon could be of *P. quadratus* age. The bivalve *Mytiloides incertus* is known to range as low as the *P. quadratus* Zone, so it is possible that some of the monospecific collections of *M. incertus* come from in this zone.

Upper Turonian Zone of *Prionocyclus germari* (Reuss)

Specimens of *Prionocyclus germari* are known from three sections, Love Ranch, Mescal Canyon, and Carthage, where they occur in the upper part of the D-Cross Tongue or in age-equivalent marine shales included in the Gallup Sandstone. The most diverse and well-preserved fauna occurs near the top of the D-Cross Tongue at Love Ranch, where the helically coiled ammonite *Eubostrychoceras matsumotoi* Cobban, the straight ammonite *Baculites yokoyamai* Tokunaga and Shimizu, the planispirally coiled ammonite *Placenticeras cumminsi* Cragin, the bivalves *Mytiloides incertus* (Jimbo), *Lima utahensis* Stanton, *Veniella* sp., *Pleuriocardia pauperculum* (Meek), *Syncyclonema* sp., and *Laternula* sp., and the oyster *"Lopha" sannionis* (White) occur with *Prionocyclus germari*.

The only known occurrence of the brackish water oyster *Crassostrea glabbra* (Meek and Hayden) in New Mexico occurs near the top of the Gallup Sandstone at Mescal Canyon. Elsewhere in New Mexico, including the study area, coquina-like accumulations of brackish water oysters in the Gallup Sandstone are composed of the shells of *Crassostrea soleniscus* (Meek).

Upper Turonian Zone of *Forresteria peruana* (Brüggen)

Fossils indicative of this zone, such as *Scaphites mariasensis* Cobban and *Cremnoceramus waltersdorfensis* (Andert), have not been identified definitively in the study area. A poorly preserved specimen on SNWR from the basal sandstone of the Gallup Sandstone, identified only as *Forresteria* sp., is probably *F. peruana*. It occurs with the small (early form) of "*Lopha*" *sannionis*, which is confined to the late Turonian, and below the first occurrence of *Cremnoceramus erectus* in the Gallup Sandstone.

Lower Coniacian Zone of *Cremnoceramus erectus* (Meek)

Fossils of early Coniacian age are known only from the northern and eastern parts of the study area. The index species for the lowermost Coniacian, *Cremnoceramus erectus*, has been collected from the Gallup Sandstone on SNWR and from the upper part of the D-Cross Tongue and the Gallup Sandstone in Lincoln County.

The most diverse fauna from this zone occurs at Rim Rock Canyon, Lincoln County, near the top of the D-Cross Tongue of the Mancos Shale. There, the index species was collected along with the ammonites *Forresteria* sp., *Scaphites frontierensis* Cobban, *Baculites yokoyamai* Tokunaga and Shimizu, the bivalves *Ostrea* sp., *Syncylconema* sp., *Pleuriocardia* sp., *Cymbophora* sp., *Laternula* sp., *Corbula* aff. *C. kanabensis* Stanton, *Psilomya* sp., and the gastropods *Acmaea cerrillosensis* Johnson, *Gyrodes depressa* Meek, *Amaurpsis* sp., *Pyropsis* sp., and *Anchura* sp.

Lower Coniacian Zone of *Cremnoceramus deformis* (Meek)

Fossils diagnostic of the middle lower Coniacian *Cremnoceramus deformis* Zone have not been found in the study area, although parts of the Gallup Sandstone in Lincoln County could be of *C. deformis* age and parts of the nonmarine Crevasse Canyon Formation at Love Ranch, Mescal Canyon, Carthage, and SNWR may be of *C. deformis* age.

Lower Coniacian Zone of *Cremnoceramus crassus* (Petrascheck)

Cremnoceramus crassus has been collected within the study area only from Lincoln County, where it occurs in the upper part of the Gallup Sandstone. Associated fauna include the bivalve *Pleuriocardia curtum* (Meek) and the oyster *Flemingostrea elegans* Hook. At Bull Gap Canyon the brackish water bivalve *Hendersonia* sp. and brackish water oyster *Crassostrea soleniscus* (Meek) appear near the top of this zone.

THE FIVE REPRESENTATIVE STRATIGRAPHIC SECTIONS

The stratigraphic units and faunal makeup of the five representative sections are described below. Graphic sections showing generalized lithologies, stratigraphic names and thicknesses, and compositions of key fossil collections are presented for each sec-

tion, beginning at the southern end of the study area in Doña Ana County, working progressively northward to Sierra County, then to Socorro County, and finishing on the east in Lincoln County (Fig. 1).

The major stratigraphic units in the study area are consistent lithologically from south to north although their contacts are diachronous. They consist, from bottom to top, of the Dakota Sandstone, lower tongue of the Mancos Shale, Tres Hermanos Formation, D-Cross Tongue of the Mancos Shale, Gallup Sandstone, and Crevasse Canyon Formation. In Socorro County, the Mulatto Tongue of the Mancos Shale makes an appearance at the top of the section. At the northern end of SNWR, the lower tongue of the Mancos Shale is split into two named tongues by the Twowells Tongue of the Dakota Sandstone. The shale below the Twowells is the Whitewater Arroyo Tongue of the Mancos; the shale above, is the Rio Salado Tongue. The Tres Hermanos Formation is subdivided into three members, which in ascending order are the Atarque Sandstone Member, Carthage Member, and Fite Ranch Sandstone Member. The Fite Ranch Sandstone Member is not conspicuous at Mescal Canyon. Its stratigraphic position at the base of the D-Cross Tongue is occupied by a thin (30-50 cm), dark sandstone that locally contains fragments of shark teeth.

Three lesser-rank units are shown in the Mancos Shale on the sections where they occur. In ascending order these units are the x-bentonite and the Bridge Creek Limestone Beds in the lower tongue, and the Juana Lopez beds in the D-Cross Tongue.

The summaries of the stratigraphic sections that follow are intended to provide a stratigraphic foundation for the biostratigraphy. They are not intended to be all inclusive, especially as to previous work.

Love Ranch Section

The Upper Cretaceous rocks in the southern San Andres Mountains near Love Ranch and Davis well, Doña Ana County, have been studied by Darton (1928, p. 191-192), Kotttlowski et al. (1956, p. 119-120), Bachman and Myers (1969), Seager (1981), and Lucas and Estep (1998). The fossil collections on which this section is based were made on the Bear Peak quadrangle by G. O. Bachman and D. A. Myers in 1960 and by W. A. Cobban and S. C. Hook in 1977 and 1980. The composite graphic section (Fig. 3) was furnished by W. R. Seager (written communication July 2, 2008) and is a slightly modified version of the section presented by Seager (1981, sheet 3). The Mancos Shale nomenclature presented by Seager (1981, sheet 3) has been updated to reflect contemporary usage. The Tres Hermanos has been removed from the Mancos Shale and raised to formational rank and the upper tongue is now called the D- Cross Tongue. Seager's (1981) lower tongue terminology is retained because there is no intertongued Twowells Tongue of the Dakota Sandstone that would warrant using the Rio Salado Tongue of the Mancos Shale (above) and Whitewater Arroyo Tongue of the Mancos Shale (below).

Seager's (1981) "gray brown sandy limestone with *Ostrea*", about 3 m above the top of the Dakota Sandstone, contains the key guide fossil *Ostrea beloiti* (D10102). *Ostrea beloiti* was also recovered from a thin bed of limestone at the base of the Boquil-

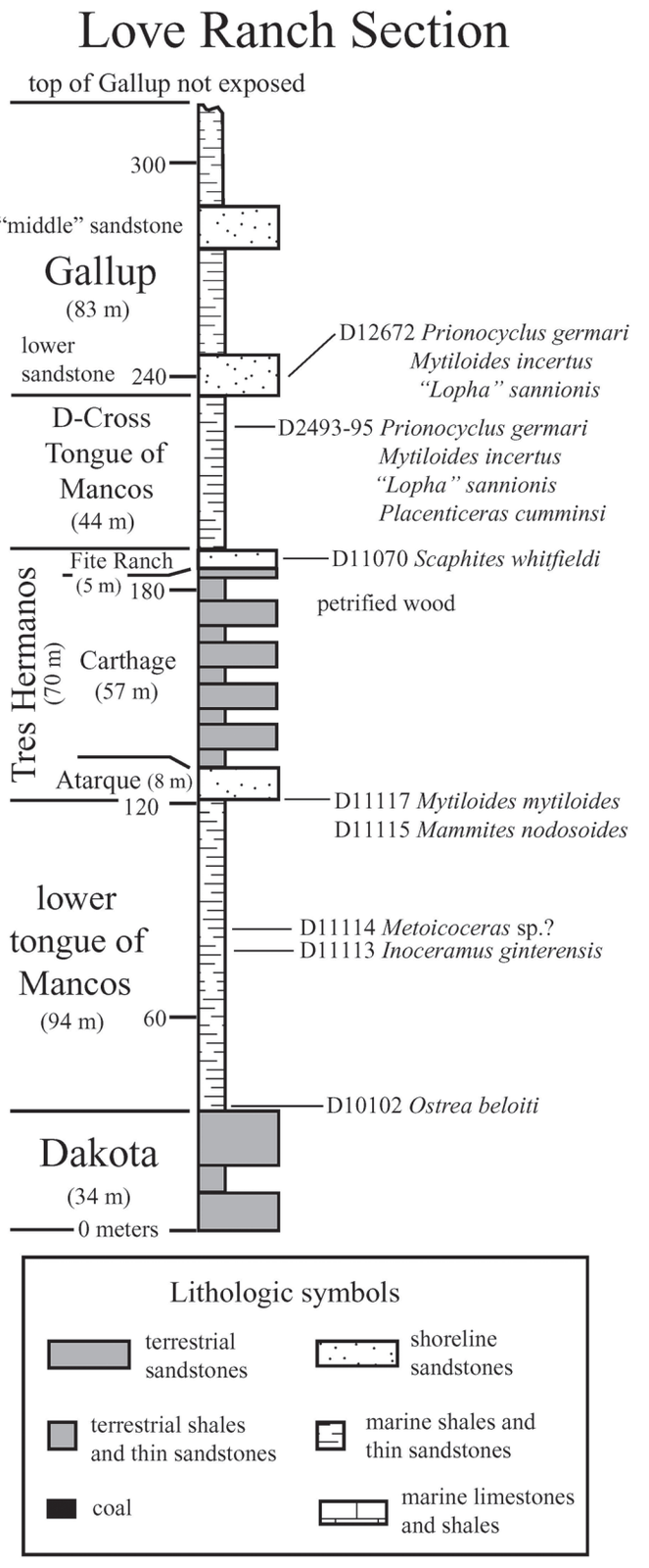

FIGURE 3. Measured section at Love Ranch, Doña Ana County, New Mexico, showing generalized lithologies, stratigraphic names, and positions of key fossil collections. Key to lithologic symbols applies to Figures 3-7. Measured section at Love Ranch provided by W.R. Seager (written communication, July 2, 2008).

las Formation (= lower tongue of the Mancos Shale) at Cerro de Muleros, Doña Ana County, 83 km south of Love Ranch, by Kennedy et al. (1988). There, at locality D10142, the oyster is associated with the ammonite *Acanthoceras amphibolum*, the bivalve *Inoceramus arvanus*, and other fauna from the *Acanthoceras amphibolum* Zone. If D10102 represents approximately the same level, it would mean that the base of the lower tongue at Love Ranch is at or very near the position of the x-bentonite, which occurs at the base of the Lincoln Limestone Member of the Greenhorn Limestone, about two-thirds of the way through the middle Cenomanian *A. amphibolum* Zone, at Pueblo, Colorado.

About 37 m above the Dakota, Seager's (1981) "orange-brown weathering limestone about 1 ft thick" contains *Inoceramus ginterensis* (D1113), which is indicative of the *Metoicoceras mosbyense* Zone. An orange-weathering, nodular concretion within gray shale a few meters higher carries a poorly persevered ammonite, tentatively identified as *Metoicoceras* sp. (D1114). The lithology suggests it may belong to Bridge Creek Limestone Beds, perhaps from the *Euomphaloceras septemseriatum* Zone. However, there are no laterally persistent, nodular limestones, calcarenites or fauna to warrant using the Bridge Creek Limestone terminology here.

Brown-weathering sandy concretions in the transitional interval at the top of the lower tongue of the Mancos contain the ammonite *Mammites nodosoides* (D11115), the name–bearer for the uppermost lower Turonian zone. The bivalve *Mytiloides mytiloides* (D11117) from the base of the Atarque Sandstone Member is confined to the *Mammites nodosoides* Zone.

Seager (1981, sheet 3 and personal communication July 2, 2008) reports petrified wood in the upper half of the Tres Hermanos. The authors interpret this petrified wood as evidence that this portion of the Tres Hermanos is nonmarine and assign it to the Carthage Member. Two collections containing the scaphitid ammonite *Scaphites whitfieldi* (D11069-70) from the top of the Tres Hermanos Formation indicate marine conditions; these rocks are assigned to the Fite Ranch Sandstone Member. *Scaphites whitfieldi* is confined to the upper Turonian *Prionocyclus novimexicanus* Zone.

The highest collections are from the upper part of the D-Cross Tongue (D2493-95) and the base of the Gallup Sandstone (D12672). They both contain the ammonite *Prionocyclus germari*, the bivalve *Mytiloides incertus*, and the oyster "*Lopha*" *sannionis*, all of which are from the penultimate upper Turonian zone of *Prionocyclus germari*. The section above this level is truncated by erosion.

A fundamentally different interpretation of the Upper Cretaceous in the Love Ranch area can be found in Lucas and Estep (1998), which contains photographs of many of the fossils. However, there are major areas of disagreement between the interpretation presented in Lucas and Estep (1998) and that presented above and on Figure 3. These areas of disagreement include stratigraphic thickness, stratigraphic nomenclature, assignment of faunas to stratigraphic units, and species identifications. A few of these differences are highlighted below.

Lucas and Estep (1998, p. 187) assign up to 13 m of shaly strata that overlie the Dakota Sandstone to the lower Turonian Rio Salado Tongue of the Mancos Shale. In contrast, 94 m of shaly strata overlying the Dakota Sandstone are assigned to the lower tongue of the Mancos Shale on Figure 3; these strata contain fossils from middle Cenomanian through lower Turonian zones.

Lucas and Estep (1998, p. 189) assign a faunal assemblage dominated by the bivalve *Mytiloides incertus* and the ammonite *Placenticeras cumminsi* to the lower Turonian Rio Salado Tongue of the Mancos Shale. In contrast, this assemblage is assigned to the upper Turonian D-Cross Tongue of the Mancos Shale (D2493-95) and the overlying Gallup Sandstone (D12672) on Figure 3.

Lucas and Estep (1998, p. 194 and fig. 5H-J) identify an oyster that is common high in the section as *Lopha bellaplicata*; they assign it to the Rio Salado Tongue and overlying Atarque Sandstone, both units in the lower Turonian. In contrast, this oyster is identified as "*Lopha" sannionis* on Figure 3 and assigned to the D-Cross Tongue (D2493-95) and overlying Gallup Sandstone (D12672), both units in the upper Turonian. One of the consequences of identifying the oyster as *L. bellaplicata* for Lucas and Estep (1998) is that it results in a faunal inversion in their interpretation: a late Turonian fauna dominated by *Mytiloides incertus* is succeeded upsection by a middle Turonian fauna containing *L. bellaplicata*.

This list of major differences is not inclusive, but will give the interested reader an idea of how fundamentally different the two interpretations are from one another.

Mescal Canyon Section

The two most important published studies that contain key information on the marine Upper Cretaceous rocks in the Caballo Mountains east of Truth or Consequences, Sierra County, are Kelly and Silver (1952, p. 109-113) and Seager and Mack (2003, p. 37-47). For a comprehensive list of previous contributions dealing with the geology of the Caballo Mountains, the reader is referred to Seager and Mack (2003, p. 5-6). The fossil collections on which this section is based were made on the Elephant Butte quadrangle, primarily by W. A. Cobban and S. C. Hook beginning in 1968 and continuing through 2011with assistance by G. Mack in 2011. The composite graphic section (Fig. 4) for the Dakota Sandstone, Tres Hermanos Formation, D-Cross Tongue of the Mancos Shale, and Gallup Sandstone was measured by G. Mack as part of this study. The thickness of the lower tongue of the Mancos, which was incorrectly called the Rio Salado Tongue by Seager and Mack (2003, p. 39-41), is based on a previously unpublished section measured and collected by S. C. Hook. There are 67 bentonites, including the x-bentonite, in the lower tongue of the Mancos Shale, with 64 of the bentonites below the Bridge Creek Limestone Beds.

The lowest megafossil collections from the lower tongue of the Mancos are from just below the X-bentonite (D14758-59) and contain fossils that are indicative of the *Acanthoceras amphibolum* Zone. The lowest collection (D14758) from 4 m above the base of the tongue contains an impression of the coiled ammonite *Tarrantoceras* sp., which is probably *Tarrantoceras sellardsi*. The other

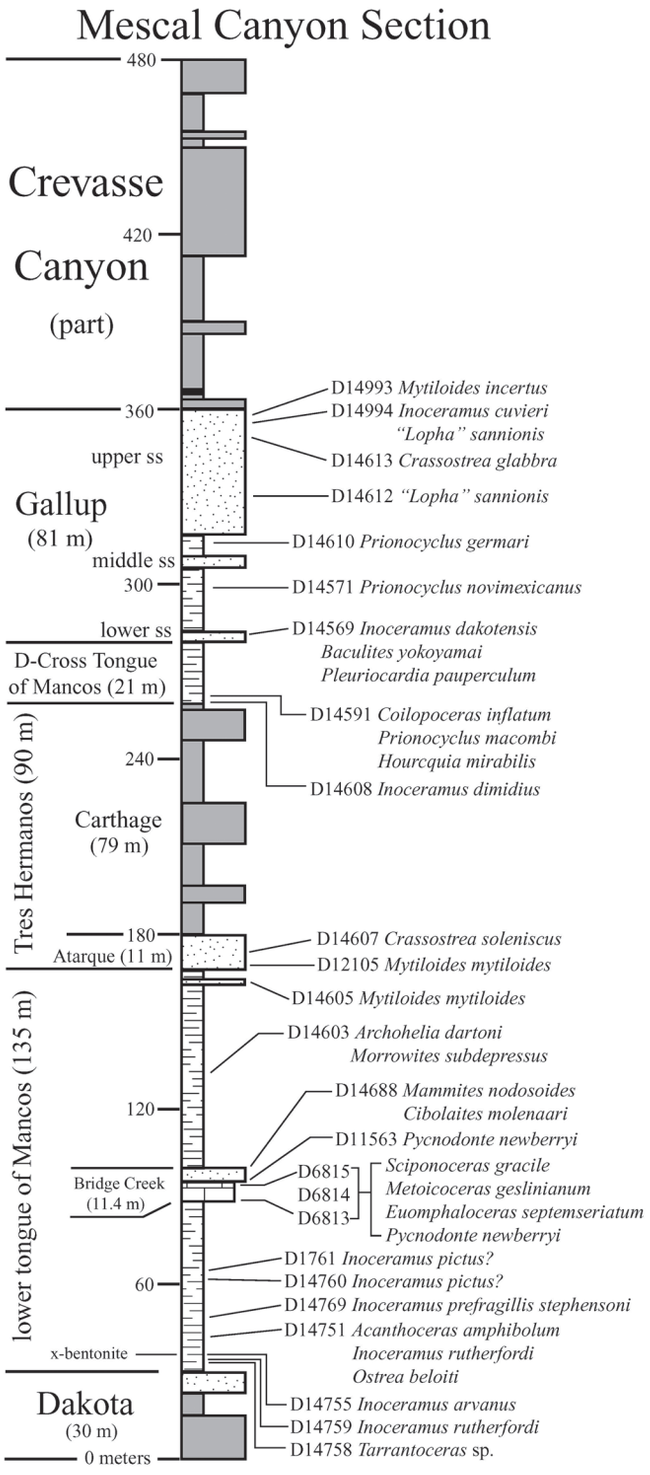

FIGURE 4. Measured section at Mescal Canyon, Sierra County, New Mexico, showing generalized lithologies, stratigraphic names, and positions of key fossil collections. The thickness of the lower tongue of the Mancos Shale is from a previously unpublished section by S.C. Hook; the remaining thicknesses and lithologies were measured by G.H. Mack in 2011.

collection (D14759) from 4.1 above the base of the tongue contains the bivalves *Inoceramus rutherfordi* and *I. arvanus*, along with the oyster *Ostrea beloiti*, all known associates of *Acanthoceras amphibolum*. The *A. amphibolum* Zone extends upward another 8 m, where D14751 contains *A. amphibolum, I. rutherfordi,* and *O. beloiti.* The bivalve *Inoceramus prefragilis stephensoni* (D14769), probably indicative of the upper Cenomanian *Calycoceras canitaurinum* Zone, was collected 19 m above the base of the tongue. *Inoceramus pictus*? (D14760-61) occurs 31 and 34 m above the base of the tongue. *Inoceramus pictus* is a long-ranging, rather generalized inoceramid, that continues upward through the next three zones. However, its appearance here, 25 m below the first occurrence of *Euomphaloceras septemseriatum* (D6813) suggests it is in the *Vascoceras diartianum* Zone.

The next megafossils come into the section at the base of the Bridge Creek Limestone Beds, 59 m above the base of the lower tongue of the Mancos. The three thin, nodular limestones at the base of the Bridge Creek (D6813, -14, -15) carry the ubiquitous *Euomphaloceras septemseriatum* assemblage zone fossils of central New Mexico: the ammonites *E. septemseriatum*, *Sciponoceras gracile*, and *Metoicoceras geslinianum*, the oyster *Pycnodonte newberryi*, and the echinoid *Hemiaster jacksoni*. *Pycnodonte newberryi* (D11563) extends upward another 4 m into the base of the sandstones at the top of the Bridge Creek.

Impressions of the ammonites *Mammites nodosoides* and *Cibolaites molenaari* (D14688) are found in the uppermost portion of the Bridge Creek sandstones, 70 m above the base of the lower tongue of the Mancos. The lower Turonian *Mammites nodosoides* Zone extends upward into the basal part of the Atarque Sandstone Member of the Tres Hermanos Formation in the form of the bivalve *Mytiloides mytiloides* (D12105). A rare occurrence of the coral *Archohelia dartoni* (D14603) occurs between these two collections, 104 m above the base of the lower tongue of the Mancos Shale. This occurrence was discovered by S. C. Hook in 1976 and cited in Hook and Cobban (1981, # 4, p. 13-14) as evidence for widespread discontinuity surfaces within upper Cenomanian and lower Turonian rocks in New Mexico. Lucas and Anderson (1998) described this occurrence, assigning it to the lower part of the Rio Salado Tongue and noting that were only three other documented reports of Late Cretaceous corals from New Mexico in the published literature.

The upper part of the Atarque Member contains a brackish water coquina composed of the disarticulated shells of the oyster *Crassostrea soleniscus* (D14607). Above that, the section becomes nonmarine. The upper 79 m of the Tres Hermanos Formation is assigned to the nonmarine Carthage Member.

Dark, sandy concretions at the base of the D-Cross Tongue of the Mancos Shale contained a single specimen of the geniculated bivalve *Inoceramus dimidius* (D14608), indicative of the middle Turonian *Prionocyclus macombi* Zone. Less than 1 m higher, larger, lighter-colored concretions contain an ammonite fauna that occurs at the base of the Juana Lopez Member of the Mancos Shale in the San Juan Basin (Hook and Cobban, 1980). This fauna (D14591) consists of the ammonites *Coilopoceras inflatum*, *Prionocyclus macombi*, and *Hourcquia mirabilis*, and the bivalve *Inoceramus* sp., which indicate the *C. inflatum* subzone of the *P. macombi* Zone. Surprisingly, the oyster *Cameleolopha lugubris*, which is generally common in this assemblage, is lacking at this level in Mescal Canyon.

Another geniculated bivalve, *Inoceramus dakotensis* Walaszczyk and Cobban, occurs in the lower Gallup Sandstone (D14569), along with the ammonite *Baculites yokoyamai* and the bivalve *Pleuriocardia pauperculum*. According to Walaszczyk and Cobban (2000, table 1) *I. dakotensis* is confined to the upper part of the *Scaphites whitfieldi* Zone, which puts it in the *Prionocyclus novimexicanus* Zone as used in southern New Mexico.

Prionocyclus novimexicanus (D14571) is found in concretions in the overlying shale. Fossils indicative of the underlying *Prionocyclus wyomingensis* Zone have not been found in Mescal Canyon, although there is room in the section to accommodate the zone.

Prionocyclus quadratus has not been identified at Mescal Canyon, but *Prionocyclus germari* (D14610) has been collected from concretions in the shale below the upper sandstone of the Gallup Sandstone. Bivalves from the near the top of the upper Gallup Sandstone are *Mytiloides incertus* (D14993), which does not range above the *P. germari* Zone. A brackish water oyster-coquina near the top of the upper Gallup is composed of shells of *Crassostrea glabbra* (D14613), which constitutes the only known occurrence of this oyster in New Mexico. The section above the Gallup is nonmarine and assigned to the Crevasse Canyon Formation.

Carthage Coal Field Section

The Carthage coal field (Fig. 5), Socorro County, is the key Upper Cretaceous stratigraphic and biostratigraphic control point in central New Mexico because it (1) provides the lithologic and paleontologic links from the better known, more or less continuous exposures in the San Juan Basin to the lesser known, isolated outcrops in central and southern New Mexico and (2) contains the principal reference section of the Tres Hermanos Formation and the type localities for the Carthage and Fite Ranch Sandstone Members of the Tres Hermanos Formation (Hook et al., 1983). Hook (2009, p. 25) reported that the lower tongue of Mancos Shale in the Carthage coal field contained more discrete bentonite beds (77) of middle to late Cenomanian age than any other published section in the Western Interior. In addition, the lower tongue contains the Cenomanian/Turonian boundary limestone.

The geologic literature on the Carthage coal field spans more than 140 years from Le Conte (1868, p. 136), who worked on the coal, to Hook and Cobban (2011), who studied the middle Turonian oyster *Cameleolopha bellaplicata* (Shumard). For a history of Upper Cretaceous stratigraphic nomenclature in Socorro County through 1984 the reader is referred to Hook (1984); for nomenclature applied to the Tres Hermanos Formation, to Hook et al. (1983).

Detailed stratigraphic and biostratigraphic information has been published recently on the following units: the lower tongue of the Mancos Shale (Hook, 2009), the Tres Hermanos Formation and lower part of the D-Cross Tongue of the Mancos Shale (Hook and Cobban, 2011), and the Mulatto Tongue of the Mancos Shale (Hook, 2010). The reader is referred to those publications for details lacking in the following summary.

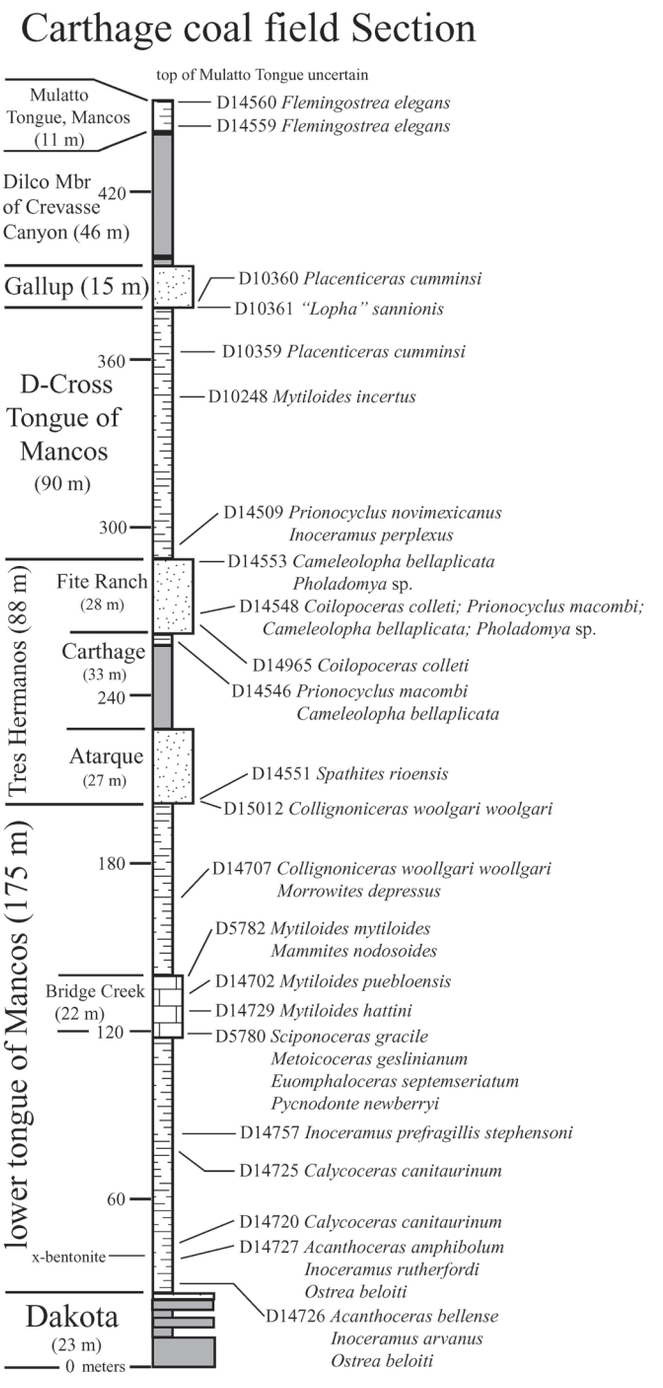

FIGURE 5. Measured section in the Carthage coal field, Socorro County, New Mexico, showing generalized lithologies, stratigraphic names, and positions of key fossil collections. The thickness of the lower tongue of the Mancos Shale is from a previously unpublished section by S.C. Hook; the remaining thicknesses and lithologies are modified from Hook et al. (1983, chart 1), Hook (2010, fig. 6) and Hook and Cobban (2011, fig. 8).

The oldest fossils in the lower tongue of the Mancos Shale include the ammonite *Acanthoceras bellense*, the bivalve *Inoceramus arvanus* and the oyster *Ostrea beloiti* (D14726). The best

constrained collection containing *A. bellense* (D14490) is from 1.2 m above the base of the lower tongue. This collection places the base of the lower tongue in the middle Cenomanian *Acanthoceras bellense* Zone, one faunal zone lower than at Mescal Canyon. This age difference is consistent with the position of the x-bentonite in the lower tongue as well: it is 12 m above the base at Carthage and 4.4 m above the base at Mescal Canyon.

Megafossils are scarce in the 80 m of section between the x-bentonite and the base of the Bridge Creek Limestone Beds, possibly because of the large amount of volcanic ash in the seawater restricted the populations of filter-feeding organisms. Fossils indicative of the *Plesiacanthoceras wyomingense* Zone have not been found a Carthage. The presence of the *Calycoceras canitaurinum* Zone is demonstrated by two collections containing *Calycoceras canitaurinum* (D14720 and D1427) that begin 25 m above the base of the tongue. The top of this zone is placed 30 m higher at an occurrence of the bivalve *Inoceramus prefragilis stephensoni* (D14757). The 37 m of section between D14757 and the base of the Bridge Creek is barren of megafossils, but probably represents the next three upper Cenomanian zones.

The four thin, nodular limestones at the base of the Bridge Creek Limestone Beds, represented by D5780, carry the ubiquitous *Euomphaloceras septemseriatum* assemblage zone fossils of central New Mexico, including the ammonites *E. septemseriatum*, *Sciponoceras gracile*, and *Metoicoceras geslinianum*, the oyster *Pycnodonte newberryi*, and the echinoid *Hemiaster jacksoni*. About midway through the Bridge Creek, the bivalve *Inoceramus hattini* (D14729) indicates the uppermost Cenomanian *Nigericeras scotti* Zone. A white-weathering, bedded limestone, 1.3 m higher, contains *Mytiloides puebloensis* (D14702) from the lowermost Turonian *Watinoceras devonense* Zone. This 22 cm-thick limestone marks the Cenomanian-Turonian boundary. A 1.4-m-thick calcarenite ledge at the top of the Bridge Creek Limestone Beds contains the ammonite *Mammites nodosoides* and abundant impressions of the bivalve *Mytiloides mytiloides* (D5782). The uppermost lower Turonian *M. nodosoides* Zone continues upward for another 27 m, where it is overlain by a concretion bed containing the ammonites *Collignoniceras woollgari woollgari* and *Morrowites depressus* (D14707). The lower Turonian *Collignoniceras woollgari woollgari* Subzone continues into the basal part of the Atarque Sandstone Member of the Tres Hermanos Formation. No megafossils have been found in the upper part of the Atarque, which may have been deposited during the time represented by the *Collignoniceras woollgari regulare* Subzone. The uppermost sandstones of the Atarque contain the *Skolithos* ichnofacies (Hook, 2011, p. 96). The overlying, mostly nonmarine Carthage Member was deposited primarily during the time represented by the *Prionocyclus hyatti* Zone. The uppermost Carthage Member contains *P. macombi* and the oyster *Cameleolopha bellaplicata* (D14546). The middle Turonian *P. macombi* Zone continues upward through the entire 28-m-thick Fite Ranch Sandstone Member.

The next fossils in the section include the upper Turonian ammonite *Prionocyclus novimexicanus*, which occurs in pancake concretions 2.8 m above the base of the D-Cross Tongue of the Mancos Shale (D14509). Fossils from the upper part of the *P. macombi* Zone and the entire *P. wyomingensis* Zone that are common at SNWR and in Lincoln County in beds of Juana Lopez aspect are absent here. This, and other evidence, prompted Hook and Cobban (2011, p. 77-78) to interpret an unconformity here. However, it is also possible that 2.8 m of shale below D14509 represents a condensed zone.

The remaining 87 m of the D-Cross Tongue at Carthage is almost barren of fossils, even though it contains several zones of concretions. A ridge-forming zone of large septarian concretions near the top of the tongue contains *Mytiloides incertus* (D10248), indicative of the *Prionocyclus germari* Zone. This leaves room to accommodate the *P. quadratus* Zone between this collection and D14509. *Placenticeras cumminsi* (D10359) occurs 15 m below the top of the D-Cross Tongue as well as in the base of the Gallup Sandstone (D10360). The presence of the small form of *"Lopha" sannionis* (D10361) in the basal Gallup indicates these last two occurrences are in the upper Turonian.

Above the Gallup, the base of the Dilco Coal Member of the Crevasse Canyon Formation contains petrified logs and the major coal seam mined at Carthage. The Mulatto Tongue of the Mancos Shale overlies the Dilco Coal Member. The exact thickness of the Mulatto is unknown at Carthage because its upper contact has not been determined due to structural complications. Concretions and concretionary sandstones in the Mulatto contain a normal marine fauna of oysters and bivalves. The key datable fossil is the oyster *Flemingostrea elegans* (D14559-60), which is known to be early Coniacian, ranging from approximately midway through the *Cremnoceramus erectus* Zone to the top of the *C. crassus* Zone (Hook, 2010).

Sevilleta National Wildlife Refuge Composite Section

The Upper Cretaceous strata on the Sevilleta National Wildlife Refuge (SNWR) have not been studied as extensively as many of the areas to the south. Darton (1928, p. 75-76) mentioned fossils collected from the Mesa del Yeso area. Hook (1983, fig. 3) showed a small-scale graphic section with key fossils in a correlation diagram on the east side of the Rio Grande in Socorro County; Hook and Cobban (2007, fig. 3) presented a larger-scale, composite section of the entire Upper Cretaceous and detailed sections of the Dakota Sandstone (figs. 4, 6, and 8). Figure 6 is a compilation of sections measured on and fossils collected from the following four 7.5 minute quadrangles: Becker SW, Ladron Peak, La Joya, and Mesa del Yeso.

SNWR is far enough to the north (Fig. 1) that the Twowells Tongue of the Dakota Sandstone splits the lower tongue of Mancos Shale into two parts: the underlying Whitewater Arroyo Tongue and the overlying Rio Salado Tongue. These three stratigraphic units are common in the San Juan Basin to the west and northwest of SNWR. Within the Rio Salado Tongue, only the upper calcarenites of the Bridge Creek Limestone Beds are recognized; the lower nodular limestones are not developed, but are represented by very calcareous shale just above the top of the Twowells Tongue. Thin calcarenites of Juana Lopez aspect are developed about 1 m above the base of the D-Cross Tongue.

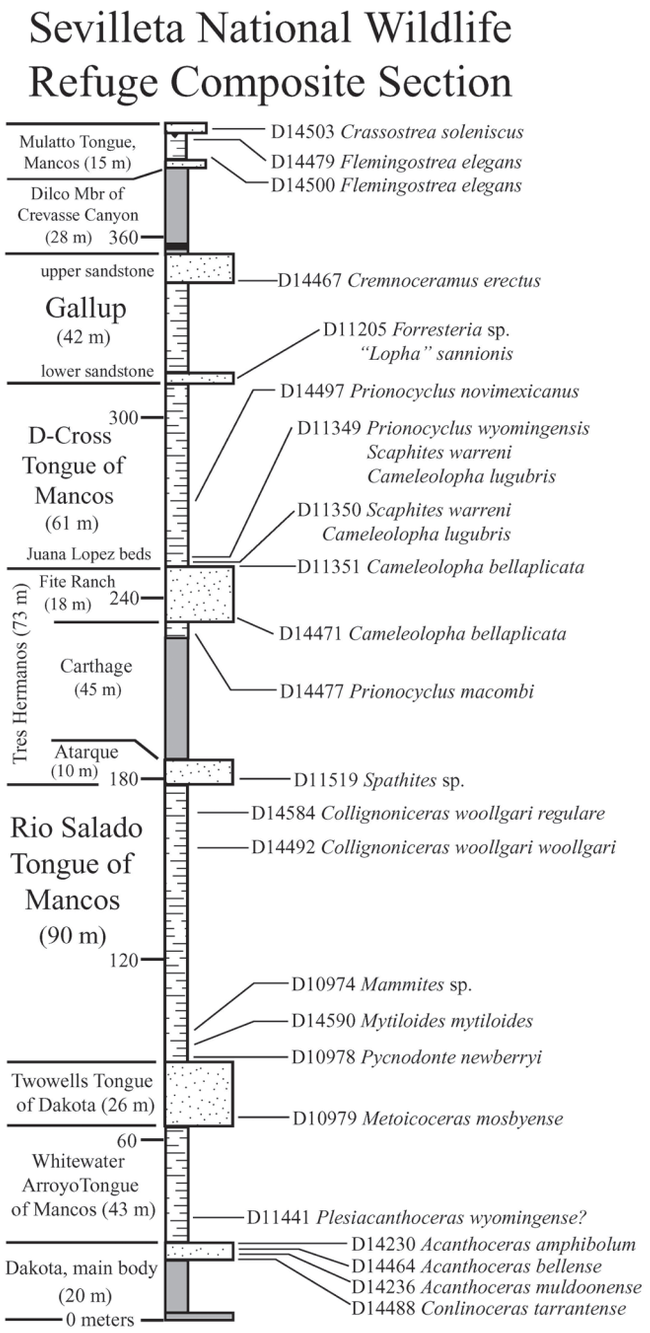

FIGURE 6. Composite measured section on the Sevilleta National Wildlife Refuge, Socorro County, New Mexico, showing generalized lithologies, stratigraphic names, and positions of key fossil collections (modified from Hook and Cobban, 2007, fig. 3).

The main body of the Dakota Sandstone exposed on SNWR (Fig. 6) contains the oldest megafauna found within the study area. The upper three meters of the Dakota contain the nominative species for four of the initial five middle Cenomanian zones: *Conlinoceras tarrantense* (D14488), *Plesiacanthoceras muldoonense* (D14236), *Acanthoceras bellense* (D14464), and *Acanthoceras amphibolum* (14230). Absent at SNWR is the second oldest zone, *Acanthoceras granerosense*, which is known only from southeastern Colorado. These fossils indicate that the upper part of the main body of the Dakota Sandstone on SNWR is correlative with the combined Oak Canyon Member and Cubero Tongue of the Dakota Sandstone, the Clay Mesa Tongue of the Mancos Shale, and (at least) the lower part of the Paguate Tongue of the Dakota Sandstone in the southeastern San Juan Basin (Hook and Cobban, 2007, fig. 9).

Even though the shales of the Whitewater Arroyo Tongue or their temporal equivalent are relatively well exposed on SNWR, a thick bentonite that would correlate with the x-bentonite was not observed near its base. This suggests that either the x-bentonite was not preserved within the shale or the top of the main body of the Dakota lies at a higher level than the x-bentonite, which is also in the *Acanthoceras amphibolum* Zone. The only fossils found in the Whitewater Arroyo Tongue or its temporal equivalent are from 14 m above the base and include a poorly preserved ammonite assigned to *Plesiacanthoceras wyomingense*? and the oyster *Ostrea beloiti* (D11441). This is the only potential occurrence of the name-bearer of the uppermost middle Cenomanian zone in the study area.

The next higher collection is a float specimen of the upper Cenomanian ammonite *Metoicoceras mosbyense* from the Twowells Tongue (D10979). Although no fossils from the intervening two zones have been found on SNWR, there is room to accommodate them in upper part of the Whitewater Arroyo Tongue or its temporal equivalent.

Fossils common to the Bridge Creek Limestone Beds have been found in the basal part of the Rio Salado Tongue. They include the oyster *Pycnodonte newberryi* (D10978), the bivalve *Mytiloides mytiloides* (D14590), and the ammonite *Mammites nodosoides* (D10974). The bivalve occurs in a calcarenite similar to the one that marks the top of the Bridge Creek at Carthage. This part of the section includes the upper Cenomanian *Euomphaloceras septemseriatum* Zone through the lower Turonian *Mammites nodosoides* Zone. Concretions near the top of the Rio Salado Tongue contain the ammonites *Collignoniceras woollgari woollgari* (D14492) followed by *Collignoniceras woollgari regulare* (D14584). D14584 marks the only occurrence of *Collignoniceras woollgari regulare* in the study area, making the base of the overlying Atarque Sandstone Member of the Tres Hermanos Formation the youngest in the study area. Although the base of the Atarque contains an abundant and diverse bivalve and gastropod fauna, only one ammonite specimen has been found. This specimen is a fragment of *Spathites* that is specifically indeterminate (D11519).

The next fossil in the sequence is a well-preserved specimen of the ammonite *Prionocyclus macombi* (D14477) from concretions in the upper part of the Carthage Member. The nonmarine portion of the Carthage Member was deposited during the time represented by the *P. hyatti* Zone. A few specimens of the oyster *Cameleolopha bellaplicata* from near the base of the Fite Ranch Sandstone (D14471) and many worn specimens of *C. bellaplicata* from the base of the overlying D-Cross Tongue (D11351) bracket the Fite Ranch into the *P. macombi* Zone.

The presence of the ammonites *Scaphites warreni* (D11350) and *Prionocyclus wyomingensis* (D11349) in calcarenites of Juana Lopez aspect, 1-2 m above the base of the D-Cross Tongue, are the first direct evidence of the upper Turonian *Prionocyclus wyomingensis* Zone in the study area. The oyster *Cameleolopha lugubris* occurs in both calcarenites.

Hook and Cobban (2007, p. 91-92) interpret the top of Fite Ranch Sandstone on SNWR as a submarine erosion surface because of worn, disarticulated shells of *Cameleolopha bellaplicata* and worn, phosphatized internal molds of bivalves (D11351) that accumulated on it. Ammonites from the uppermost part of the *Prionocyclus macombi* Zone, e.g., *Coilopoceras inflatum and Hourcquia mirabilis,* which are common in Lincoln County (Fig. 7), are missing here. Merewether et al. (2007, p. 109) report a disconformity of similar age below the Juana Lopez in south-central Colorado. However, the meter or so of section between the calcarenites, shown as the Juana Lopez beds of the D-Cross Tongue on Fig. 6, and the top of the Fite Ranch could be a condensed section.

Several specimens of *Prionocyclus novimexicanus* (D14497) have been collected from a 3 m-thick zone of limestone concretions that are 22 m above the base of the D-Cross. The 36 m of shale above D14497 are barren of megafossils, but probably represent the *Prionocyclus quadratus* and *Prionocyclus germari* Zones.

The lower sandstone of the Gallup contains the ammonite *Forresteria* sp. (D11205). This occurrence is interpreted to be in the latest Turonian *F. peruana* Zone because of the association with the early form of the oyster "*Lopha*" *sannionis*. The upper sandstone of the Gallup contains the first occurrence in the study area of the bivalve *Cremnoceramus erectus* (D14467) in dark brown sandstone concretions. *Cremnoceramus erectus* is the index fossil for the initial zone of the lower Coniacian. For mapping purposes, the base of the Gallup Sandstone on SNWR is usually drawn at the base of the upper sandstone because of extensive cover that obscures the lower sandstone.

The Dilco Coal Member of the Crevasse Canyon Formation has a meter-thick coal seam near its base that was mined in early 1900s (Darton, 1928, p. 75). The nonmarine shales of the Dilco are followed by marine sandstones and shales assigned to the Mulatto Tongue of the Mancos Shale. The Mulatto Tongue is truncated by an erosion surface, but is at least 8.5 m thick. It carries a marine fauna consisting of the oyster *Flemingostrea elegans* and the bivalves *Pleuriocardia pauperculum*, *P. curtum*, and *Phelopteria* sp. (D14500 and D14479). The sandstone that caps the exposure is a coquina of the brackish-water oyster *Crassostrea soleniscus* (D14503), suggesting that it is at or very near the top of the tongue.

Lincoln County Composite Section

Upper Cretaceous biostratigraphy in Lincoln County (Fig. 7) is less well known than that of sections to the west and south, especially Carthage and Mescal Canyon. Cobban (1986) illustrated the molluscan fossil record for the county; both Cobban (1986) and Arkell (1986) applied up-to-date stratigraphic names to the

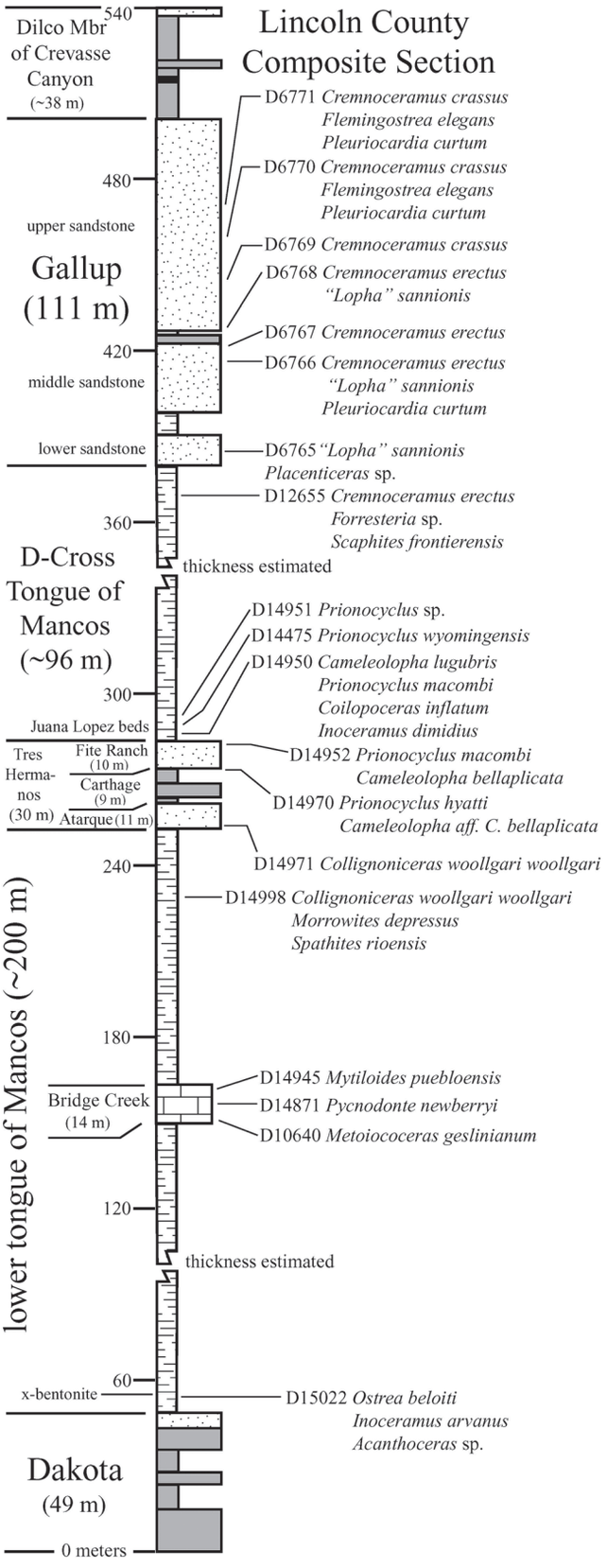

FIGURE 7. Composite measured section for Lincoln County, New Mexico, showing generalized lithologies, stratigraphic names, and positions of key fossil collections (modified from Hook, 2011, figs. 11 and 12, and Hook and Cobban, 2012, in press, fig.2).

rocks. Hook (2010) provided the lower Coniacian biostratigraphic framework used in this report, and Hook and Cobban (2012, in press) provide a detailed picture of the evolution of the middle Turonian oyster *Cameleolopha bellaplicata* at Bull Gap Canyon. In this study, thicknesses and fossils for the Dakota through the top of the D-Cross are from Bull Gap Canyon, whereas the thickness and fossils from the Gallup are from Jackson well (Figs. 1 and 7).

The oldest fossils from the lower tongue of the Mancos Shale are the ammonite *Acanthoceras* sp., the bivalve *Inoceramus arvanus*, and the oyster *Ostrea beloiti* (D15022), all indicative of the middle Cenomanian *Acanthoceras amphibolum* Zone. These fossils come from a calcarenite that underlies a thick bentonite correlated with the x-bentonite and suggest that the base of the marine section at Bull Gap is about the same age as that at Mescal Canyon (Fig. 5). The section between the x-bentonite and the three nodular limestones at the base of the Bridge Creek Limestone Beds is mostly covered. Fossils from the basal Bridge Creek are sparse, but contain the ammonite *Metoicoceras geslinianum* (D10640) and the oyster *Pycnodonte newberryi* (D14871). The top of the Bridge Creek is a 15-cm-thick, white-weathering, bedded limestone that contains abundant specimens of the bivalve *Inoceramus puebloensis* (D14945). This limestone marks the Cenomanian /Turonian boundary. The section above D14945 is concealed, but a specimen of the bivalve *Mytiloides mytiloides* (D15015) was found as float in the alluvium without any nearby outcrop. About 25 m below the Atarque Sandstone Member, sandy limestone concretions produce an abundance of internal molds of the ammonites *Collignoniceras woollgari woollgari* and *Morrowites depressus* (D14998), indicating that the top of the lower tongue is middle Turonian.

Collignoniceras woollgari woollgari (D14971) continues into the base of the Atarque Sandstone Member, just as it does at Carthage (Fig. 5). Here, the lithologic and faunal similarity to Carthage changes. The entire Tres Hermanos Formation is only about a third as thick as it is at the Carthage coal field. The Carthage Member at Bull Gap is a fluvial channel complex with no marine shale at the top. The basal Fite Ranch Sandstone Member contains *Prionocyclus hyatti* (D14970), making it the oldest known Fite Ranch in New Mexico. The uppermost Fite Ranch at Bull Gap Canyon is very similar to Carthage, containing *Prionocyclus macombi* and *Cameleolopha bellaplicata* (D14952). However, south of the canyon, erosion has removed the upper part of the section down to the D14970 level (see Hook and Cobban, 2012, in press, for details).

About 2 m above the base of the D-Cross Tongue, a thin bed of sandstone concretions contains one of the most prolific ammonite faunas in New Mexico. Collections from this bed (D14950) contain numerous, well-preserved specimens of *Prionocyclus macombi*, *Coilopoceras inflatum*, *Hourcquia mirabilis*, and *Placenticeras* sp., including the largest specimen of *C. inflatum* known. In addition the bed contains well-preserved specimens of the bivalve *Inoceramus dimidius*, the oyster *Cameleolopha lugubris*, and teeth of the shark *Ptychodus whipplei*. This 18-cm-thick bed is regarded as the base of the Juana Lopez beds of the D-Cross Tongue (Fig. 7). The Juana Lopez beds include thin calcarenites and interbedded noncalcareous shale that are at least 5 m thick; the shale contains specimens of *Prionocyclus wyomingensis* (D14475) to the south.

The middle part of the D-Cross Tongue is concealed in the Bull Gap/Rim Rock Canyons area, although a specimen of the bivalve *Mytiloides incertus* (D14955) was recovered from a contact-metamorphosed shale in the lower part of this covered interval (not shown). The D-Cross Tongue immediately under the Gallup Sandstone is fairly well exposed. Large limestone concretions ~ 15 m under the Gallup contain a lower Coniacian fauna including the bivalve *Cremnoceramus erectus* and the ammonites *Forresteria* sp. and *Scaphites frontierensis* (D12655).

The best exposure of the Gallup Sandstone in the area occurs at Willow Hill, where 111 m of section, primarily sandstones, were measured. Unfortunately, this section is poorly fossiliferous. Hook (2010, figs. 11 and 12) showed two sections of Gallup Sandstone that are better constrained biostratigraphically: one at Bull Gap Canyon and the other at Jackson well, 7 km to the southwest. The Jackson well section was chosen for Fig. 7 because it is fossiliferous and well exposed from base to top; also, there is a complete section of the Dilco Coal Member of the Crevasse Canyon Formation above it. The Gallup is 121 m thick and lies entirely within the lower Coniacian. The late (early Coniacian) form of the oyster "*Lopha*" *sannionis* occurs 3.7 m above the base (D6765), followed by the index bivalve *Cremnoceramus erectus* (D6766), 32 m higher. *Cremnoceramus crassus* (D6769-71) occurs in concretions 65 m, 89 m, and 87 m above the base. The key marine oyster *Flemingostrea elegans* occurs with *C. crassus* in the latter two collections. *Cremnoceramus deformis*, the name-bearer for the middle lower Coniacian faunal zone, has not been found in Lincoln County, but there are 21 m of section between the last occurrence of *C. erectus* (D6768) and the first occurrence of *C. crassus* (D6770) that could accommodate the *Cremnoceramus deformis* Zone.

Although ammonites are rare in the Gallup Sandstone in Lincoln County, a single specimen of the ammonite *Placenticeras* sp. (D6765) was recovered from the base of the Gallup at Jackson well. This specimen is probably *Placenticeras kaffrarium* Etheridge. At Rimrock Canyon, 1 km north of Bull Gap Canyon, *P. kaffrarium* was collected from the Gallup Sandstone, along with *Cremnoceramus erectus* and *Flemingostrea elegans* at USGS locality D12660, about 18 m above the base (see Hook, 2010, fig. 12).

Cobban (1986, p. 88) reported that still younger fossils have been collected farther to the north in Lincoln County. These fossils include a bivalve related to the earliest middle Coniacian bivalve *Volviceramus koeneni* at USGS locality D8431 near White Oaks and the late Coniacian bivalve *Magadiceramus* sp. at USGS locality D7851 near Capitan.

SEA-LEVEL CYCLES

The intertongued marine and nonmarine rocks in Doña Ana and Sierra Counties record the two earliest cycles of transgression and regression (T-1, R-1 and T-2, R-2) of the western shoreline of the Late Cretaceous Seaway (Fig. 8; Molenaar, 1983).

Those in Socorro County record the third cycle (T-3, R-3) as well. The third cycle in Lincoln County is incomplete (or incompletely known at present). By the end of the first transgression about 93.68 Ma, the western shoreline had established a northwest-southeast trend in New Mexico. Each succeeding transgression penetrated less far to the southwest into the state than the one that preceded it and each regression retreated farther to the northeast. At the present time (January 2012), the youngest marine fossils from Sierra and Doña Ana Counties are late Turonian and the rock record indicates only two cycles of transgression/regression. Those from Socorro County are early Coniacian and the rock record indicates three cycles. The youngest fossils known from Lincoln County are late Coniacian (Cobban, 1986), making them the youngest within the study area. However, the rock record presented above documents completely only the two earlier cycles of transgression/regression, with an incomplete record of the third transgression.

The fossil zonation and emboldened radiometric dates shown on Figure 8 have been modified from those shown in Cobban et al. (2008, fig. 2). The radiometric ages shown in bold were determined from bentonites sampled in the zones somewhere within the Western Interior basin. The additional ages were calculated using the following assumptions: 1) the determined ages were from bentonites at or near the base of the zone, and 2) all zones between these determined ages are of equal duration. Both of these assumptions are probably not true, but the results provide a means to determine the approximate durations of events of interest, such as the length of time for each of zones or the three major depositional cycles represented in the study area. They can also be used to calculate and compare compacted depositional rates between key sections (e.g., Hook and Cobban, 2007, table 1).

Using a composite of the stratigraphic sections at Carthage and SNWR, Socorro County, the following estimates can be made for the three major depositional cycles (Fig. 8). The initial depositional cycle (T-1, R-1) had a duration of approximately 5 Ma; the second cycle (T-2, R-2), approximately 2 Ma; and the third cycle (T-3, R-3), which is incomplete, an estimated 0.9 Ma.

The T-1 transgression began during the middle Cenomanian *Conlinoceras tarrantense* Zone with deposition of the lower part of the Dakota Sandstone at SNWR and lasted until the upper Cenomanian *Euomphaloceras septemseriatum* Zone, when the deposition of the basal Bridge Creek Limestone Beds of the lower tongue of the Mancos Shale at Carthage were deposited, a time span of ~2.05 Ma. As a result of this transgression, the Dakota-Mancos contact rises three ammonite zones from SNWR to Carthage, from the *Conlinoceras tarrantense* Zone to the *Acanthoceras bellense* Zone. From Carthage it rises one zone to the southern sections, where it is in the *Acanthoceras amphibolum* Zone.

The R-1 regression lasted until the middle Turonian *Prionocyclus hyatti* Zone, when the middle part of the nonmarine portion of the Carthage Member of the Tres Hermanos Formation was deposited, a time span of ~2.97 Ma. The time-transgressive nature of the R-1 regression is well illustrated in the age of the Atarque Sandstone Member of the Tres Hermanos Formation. The base of the Atarque Sandstone Member rises stratigraphically from south to north (Fig. 8) through at least three biostratigraphic zones, reflecting the northeastward retreat of the shoreline in southern New Mexico during R-1. At Love Ranch, the base of the Atarque is low in the lower Turonian *Mammites nodosoides* Zone; 50 km northwest at Mescal Canyon, it is higher in the same zone. Although the Atarque at both Love Ranch and Mescal Canyon contain the same fossil, *Mytiloides mytiloides*, the stratigraphic rise is justified on the basis of a thinner section of the lower tongue of the Mancos Shale at Love Ranch and on the first occurrence of *Mammites nodosoides* at Love Ranch in the basal Atarque as opposed to the top of the Bridge Creek Limestone Beds at Mescal Canyon. At Carthage, 54 km northeast of Mescal Canyon, the base of the Atarque has risen to the middle of the *Collignoniceras woollgari woollgari* Subzone, and 26 km farther north at SNWR, it has risen to at least the *Collignoniceras woollgari regulare* Subzone.

The stratigraphically oldest marine rocks of the T-2 transgression are at the base of the Fite Ranch Sandstone in Lincoln County, which is in the *Prionocyclus hyatti Zone*. The shoreline continued to transgress to the southwest, such that marine shales in the uppermost part of the Carthage Member at Carthage are in the *Coilopoceras colleti* Subzone of the *Prionocyclus macombi* Zone. Marine shale in the uppermost Carthage Member at SNWR also contains *Prionocyclus macombi*, but the ammonites that define the subzones of the *P. macombi* Zone are not present. The first evidence of marine rocks of the T-2 transgression at Mescal Canyon corresponds to the *Coilopoceras inflatum* Subzone of the *P. maco*mbi Zone at the base of the D-Cross Tongue, one subzone higher than at Carthage.

The top of the Fite Ranch Sandstone Member rises stratigraphically from north to south through three biostratigraphic zones, reflecting the southwestward advance of the T-2 shoreline (Fig. 8). At Carthage, the top lies in the upper, but not uppermost part of the middle Turonian *Prionocyclus macombi* Zone, whereas at Love Ranch it contains *Scaphites whitfieldi*, which is confined to the upper Turonian *Prionocyclus novimexicanus* Zone. The T-2 transgression lasted until the upper Turonian *Prionocyclus quadratus* Zone, when the middle part of the D-Cross Tongue of the Mancos Shale was deposited, a time span of ~1.12 Ma. The R-2 regression lasted until the lower Coniacian *Cremnoceramus deformis* Zone when the middle part of the Dilco Coal Member of the Crevasse Canyon Formation was deposited at Carthage and SNWR, a time span of ~0.84 Ma.

The T-3 transgression lasted until the lower Coniacian *Cremnoceramus crassus* Zone, when the middle part of the Mulatto Tongue of the Mancos Shale was deposited, a time span of appoximately 0.20 Ma. The timing of the R-3 regression cannot be determined precisely in the study area. If it lasted until the beginning of the middle Coniacian *Volviceramus koeneni* Zone, it would have had a duration of ~0.70 Ma.

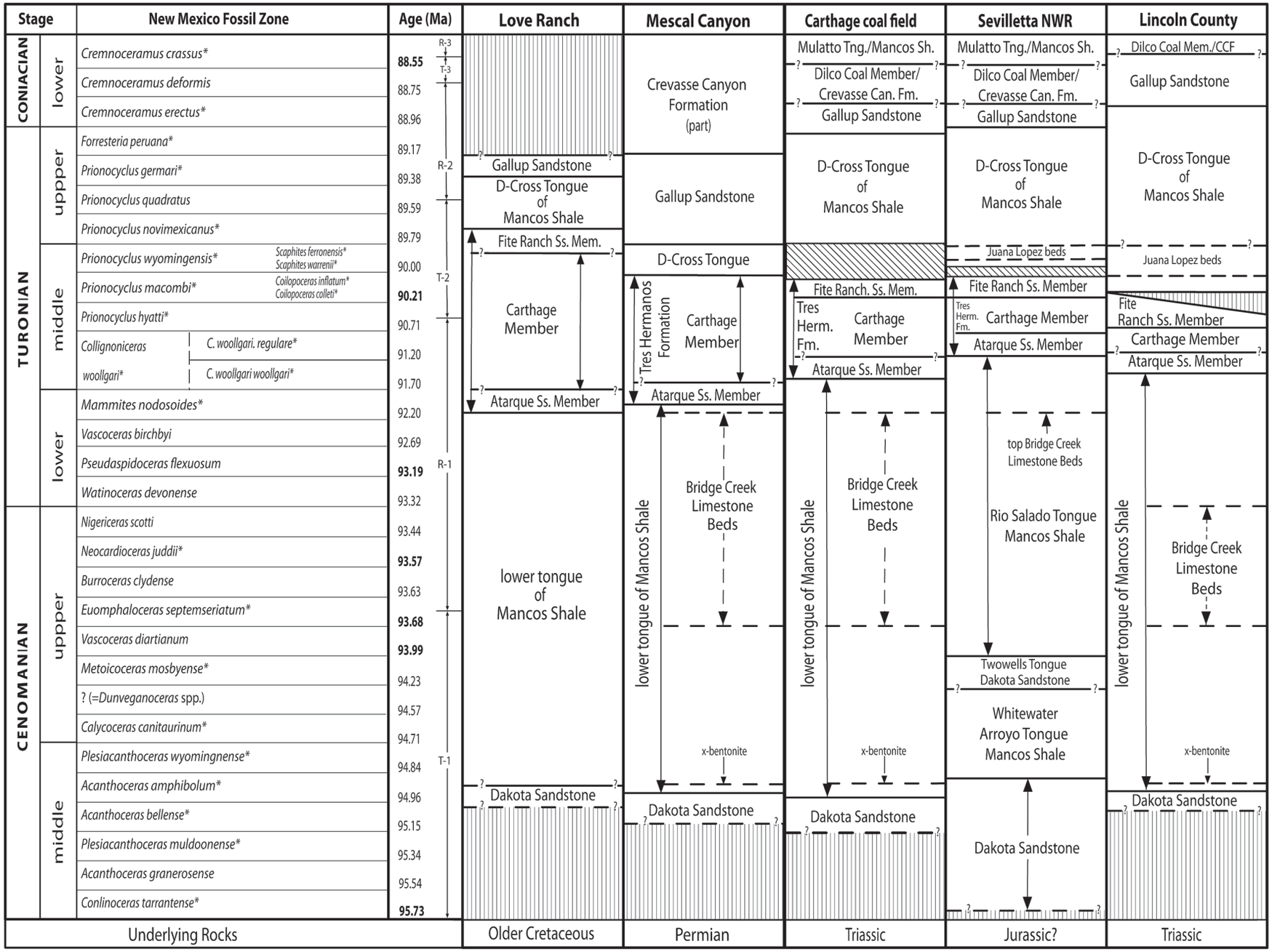

FIGURE 8. Upper Cretaceous chronostratigraphic diagram of south-central New Mexico, showing strata from five representative sections plotted against middle Cenomanian through lower Coniacian fossil zones and radiometric ages. Ages shown in bold are derived from bentonites within the fossil zone; others are interpolated (see text for details). An asterisk following the index species indicates that the index fossil has been collected from the study area. Modified from Cobban et al. (2008, fig. 2). Transgressive (T-1, T-2, and T-3) and regressive (R-1, R-2, and R-3) cycles are based on those of Molenaar (1983)

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