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STRATIGRAPHY, PALEONTOLOGY, DEPOSITIONAL FRAMEWORK, AND NOMENCLATURE OF MARINE UPPER CRETACEOUS ROCKS, SOCORRO COUNTY, NEW MEXICO

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INTRODUCTION

During Late Cretaceous time, New Mexico was covered by part of the epicontinental seaway that extended from the Arctic Ocean to the Gulf of Mexico and was as much as 1,600 km wide. The western shoreline of this seaway advanced and retreated across New Mexico many times and left a complex record of intertongued marine and nonmarine sediments. These clastic sediments once covered most of New Mexico; subsequent uplift led to erosion of much of the Upper Cretaceous deposits. The rock record that remains is sufficient to document five major cycles of transgression and regression of the western shoreline across New Mexico (Molenaar, 1983a). The Upper Cretaceous rocks preserved in Socorro County record only the two earliest of these five cycles of transgression and regression.

The earlier of these cycles, which began in middle Cenomanian time and lasted until middle Turonian, is called the Greenhorn Cycle (Hattin, 1964; Kauffman, 1969). The latter cycle, which lasted from middle Turonian until early Coniacian time in New Mexico, is herein called the Carlile Cycle (see Hook and Cobban, 1979). The Carlile Cycle is equivalent to the early part of the Niobrara Cycle of Kauffman (1967, 1969). The regressive phase of the Carlile Cycle—the Gallup regression—is unique to New Mexico and northeasternmost Arizona (Molenaar, 1983a). Figure 1 shows the relationship of these cycles to the biostratigraphic/radiometric age framework for the middle Cenomanian through Coniacian stages. Absolute dates with an asterisk are from Fouch and others (1983); those without asterisks are estimates at the beginning of each half cycle of deposition.

Figure 2 shows the approximate positions of the western shoreline at maximum transgression and maximum regression for both cycles. The transgressive and regressive portions of each cycle are named for prominent rock units in New Mexico representative of that subcycle. Two of these units—the Tres Hermanos Formation and the D-Cross Tongue of the Mancos Shale have their type sections in Socorro County.

The major rock units in Socorro County associated with the two cycles consist of the following formations: Dakota Sandstone, Mancos Shale, Tres Hermanos Formation, Gallup Sandstone, and Crevasse Canyon Formation. Each formation will be discussed in the sections that follow.

GREENHORN CYCLE

The Greenhorn Cycle began in New Mexico during middle Cenomanian time and lasted until middle Turonian time, a period of approximtely five million years (fig. 1). During the transgressive phase of the cycle—the Dakota transgression—all of New Mexico was covered by marine water (fig. 2). The Dakota transgression began in middle Cenomanian time and lasted until late Cenomanian time. Rock units associated with this transgression include the various tongues and members of the Dakota Sandstone and Mancos Shale, which are best developed in west-central New Mexico (Landis and others, 1973). The regressive phase of the cycle—the Tres Hermanos regression—began in late Cenomanian time and lasted until middle Turonian time. Rock units associated with this regression include the Rio Salado Tongue of the Mancos Shale and the Atarque Sandstone and Carthage Members of the Tres Hermanos Formation. The Dakota transgression lasted about two million years, whereas the Tres Hermanos regression lasted about three million years.

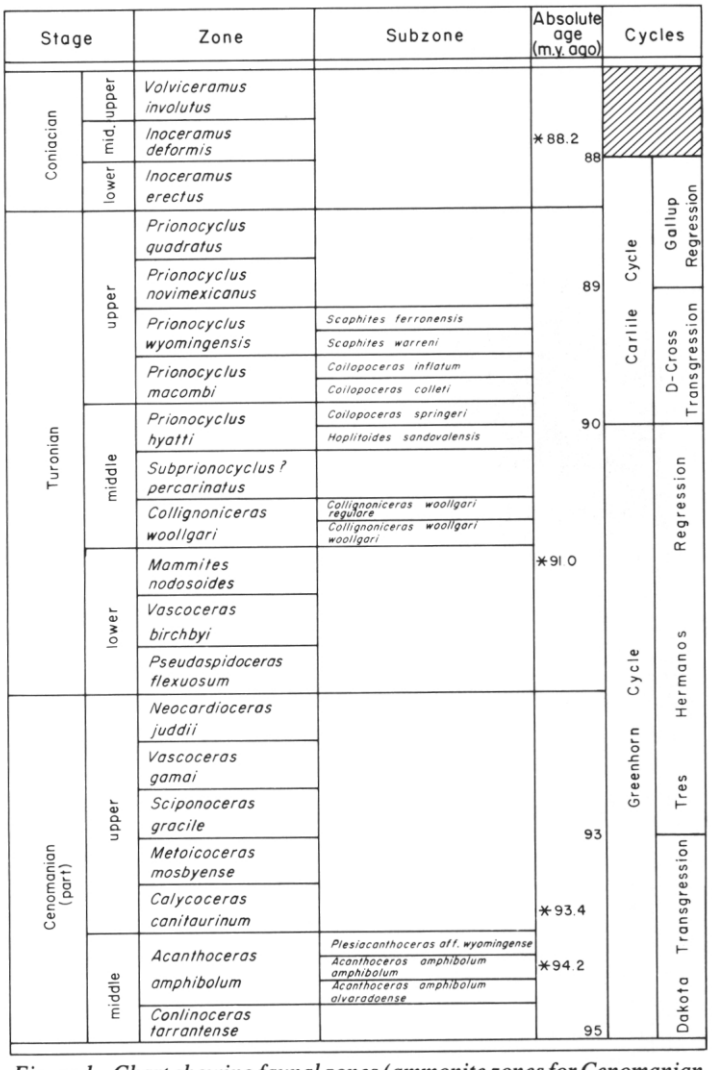

Figure 1. Chart showing faunal zones (ammonite zones for Cenomanian and Turonian stages; inoceramid zones for Coniacian stage), absolute ages, and depositional cycles for the lower part of Upper Cretaceous strata in New Mexico. Absolute ages with asterisks represent dated bentonites with faunal zones (from Fouch and others, 1983); those without asterisks are estimates at the beginning of each half depositional cycle.

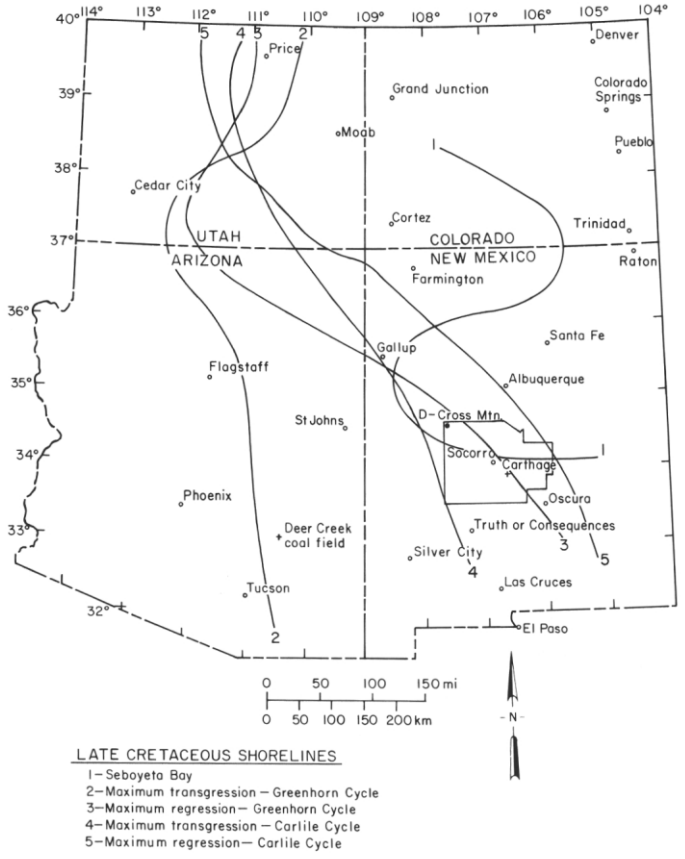

Figure 2. Map of the southwestern part of the Western Interior showing approximte position of the western shoreline during the times represented by the ammonite zones of Conlinoceras tarrantense *(1),* Metoicoceras mosbyense *(2),* Prionocyclus hyatti *(3), and* Prionocyclus novimexicanus *(4); and the inoceramid zone of* Inoceramus erectus *(5). Shorelines 1–4 are from Cobban and Hook (1983a); shoreline 5 is from Hook and Cobban (1981b).*

The Dakota Transgression

The Greenhorn depositional cycle began in the middle Cenomanian during the time represented by the ammonite zone of *Conlinoceras tarrantense,* when the Cretaceous epeiric sea transgressed from the east across the northeast part of New Mexico (fig. 2). A conspicuous embayment, Seboyeta Bay, extended into west-central New Mexico, where the Oak Canyon Member and the Cubero Tongue of the Dakota Sandstone were deposited (Hook and others, 1980, p. 44). The western edge of Seboyeta Bay was probably a little east of Gallup inasmuch as diagnostic marine fossils have not been found west of Crownpoint. The southern edge of the embayment was approximately at Socorro, inasmuch as *Conlinoceras tarrantense* occurs only 30 cm above the top of the Dakota Sandstone in the Joyita Hills area, 20 km north of Socorro, whereas the top of the Dakota is of *post-tarrantense* age at Carthage, 18 km south of Socorro (figs. 3 and 4). Elsewhere in Socorro County, fossils diagnostic of the faunal zone of C. *tarrantense* have only been found at D Cross Mountain, where the bivalve *Plicatula arenaria* Meek occurs in limestone concretions in the lower part of the Mancos Shale 3 m above the top of the Dakota (fig. 4). As Seboyeta Bay expanded during middle and late Cenomanian time, the Cubero Tongue was succeeded upward by the Clay Mesa Tongue of the Mancos Shale, the Paguate Tongue of the Dakota Sandstone, the Whitewater Arroyo Tongue of the Mancos Shale, and the Twowells Tongue of the Dakota Sandstone (Landis and others, 1973). The Twowells Tongue, which is as much as 27 m thick in the Joyita Hills (fig. 3), is the most widespread of the tongues of Dakota Sandstone in Socorro County. The Twowells is present at D Cross Mountain and Puertecito in the northwest part of the county, but pinches out into Mancos Shale between Puertecito and Riley (fig. 4), and reappears in the Joyita Hills. The informal "lower part of the Mancos Shale" used on Figures 3 and 4 includes rocks of different thicknesses and different time equivalency throughout the county. The "lower part" includes lateral and temporal equivalents of formally named member-rank units of the intertongued Dakota-Mancos sequence present in Socorro County. Hook and others (1980, fig. 2) recognized both the Paguate Tongue of the Dakota Sandstone and the Clay Mesa Tongue of the Mancos Shale at the extreme northern end of D Cross Mountain. The Paguate, however, pinches out into undifferentiated Mancos Shale about 3 km north of our measured section at D Cross Mountain (fig. 4).

The Dakota transgression lasted from early middle Cenomanian until late Cenomanian time and encompassed about 2 million years. The Greenhorn Sea reached maximum transgression (fig. 2) during the time represented by the ammonite zone of *Metoicoceras mosbyense,* or about the time deposition of the Twowells Tongue ceased in Socorro County (Cobban and Hook, 1983a).

The Paguate Tongue, which is only locally present in Socorro County, and the Twowells Tongue are extensive, shallow-water, marine-shelf sandstones derived from a southwesterly source (Landis and others, 1973). Both pinch and swell and are fine-grained, upward-coarsening sandstones that are burrowed and bioturbated. Their lower contacts are gradational, whereas their upper contacts are generally sharp. These sandstones were interpreted to represent minor regressive pulses in the transgressive part of the depositional cycle by Peterson and Kirk (1977, p. 171). However, there is no evidence of a significant seaward shift of the shoreline during the time these sandstones were deposited. Molenaar (1983a) considered these sandstones to have been deposited during stillstands of the shoreline during which sand was spread widely over a shallow shelf.

The Tres Hermanos Regression

The regressive phase of the Greenhorn Cycle, here called the Tres Hermanos regression, began during the time represented by the ammonite zone of *Sciponoceras gracile* (Cobban and Hook, 1983a). This interpretation is based on the age and stratigraphic relationships of marine Upper Cretaceous rocks in the Deer Creek coal field, 100 km northeast of Tucson, Arizona. The initial phase of this regression may have been marked by stillstands of the seaway during which elastic influx was low and highly calcareous clays and interbedded thin ashfalls were widely deposited. The rock record for this period of time is now marked by a series of thin, distinctive, concretionary limestone beds interbedded with highly calcareous shale—the basal part of the Bridge Creek Limestone Beds of the Mancos Shale (Hook and Cobban, 1981a, and Hook and others, 1983). These limestone beds occur in the basal part of the Rio Salado Tongue (or time-equivalent part) of the Mancos Shale.

The remainder of the Tres Hermanos regression is recorded in the upper part of the Rio Salado Tongue and the overlying, lower part of the Tres Hermanos Formation. This regression began during the time represented by the late Cenomanian zone of *Sciponoceras gracile* and ended about the time represented by the middle Turonian zone of *Prionocyclus hyatti—a* total time of about three million years.

Rio Salado Tongue of the Mancos Shale

The shale lying between the Twowells Tongue of the Dakota Sandstone and the Tres Hermanos Formation was named the Rio Salado Tongue of the Mancos Shale by Hook and others (1983) for typical exposures along the Rio Salado in northwest Socorro County. At its

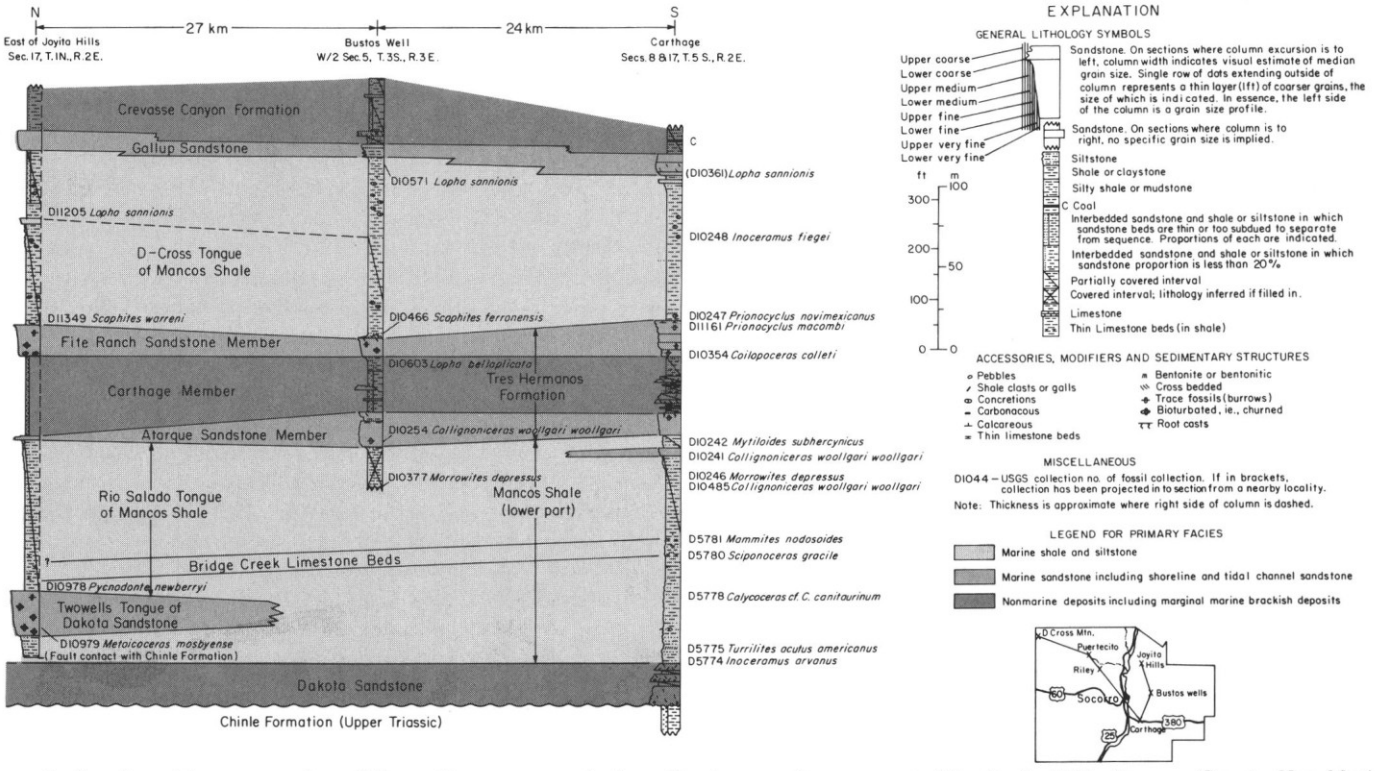

Figure 3. Stratigraphic cross section of Upper Cretaceous rocks from Carthage to the area east of the Joyita Hills, Socorro County, New Mexico (provided by C. M. Molenaar).

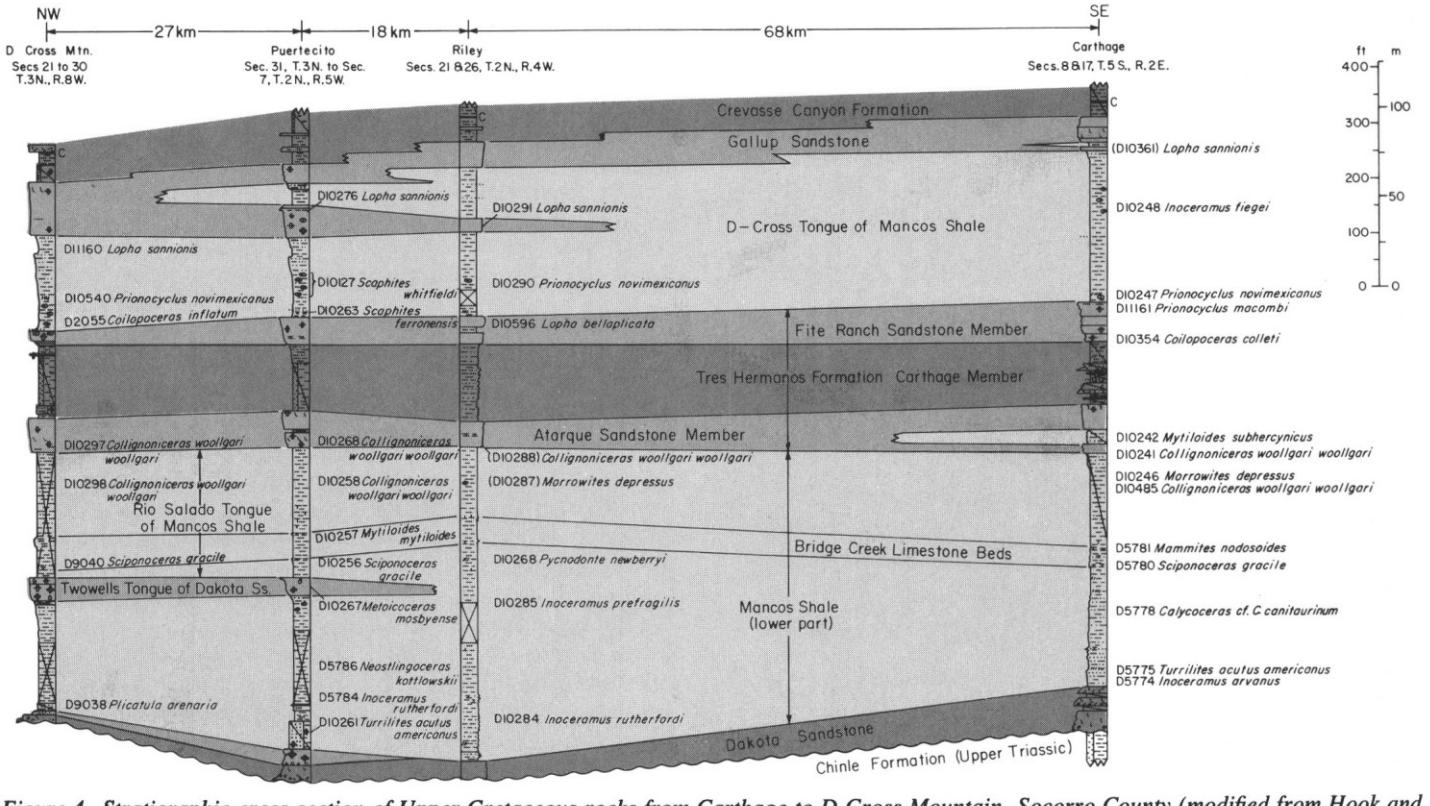

Figure 4. Stratigraphic cross section of Upper Cretaceous rocks from Carthage to D Cross Mountain, Socorro County (modified from Hook and others, 1983). See Figure 3 for explanation of symbols. Riley section from Massingill, 1979.

type section near Puertecito (fig. 4), the Rio Salado Tongue is 72 m thick and consists of a lower calcareous shale and limestone unit 38 m thick and an upper noncalcareous shale unit 34 m thick. The contact between these two units is sharp and where well exposed is marked by a pronounced change in color from light below to dark above. These two informal units can be distinguished on electric logs; their contact has been called the Greenhorn-Carlile time-stratigraphic boundary by Molenaar (1977). However, Hook and Cobban (1981a) and Hook and others (1983) have pointed out that this boundary in New Mexico is not equivalent to the Greenhorn-Carlile time-stratigraphic boundary because: (1) the contact between the Greenhorn Limestone and the Carfile Shale in their type areas is between limestone (below) and calcareous shale (above), and (2) this contact between calcareous shale and noncalcareous shale in New Mexico is older than the boundary between the Greenhorn and the Carlile in their type areas.

The basal calcareous shale and limestone unit in the Rio Salado Tongue, or its lithogenetic equivalent, has been called either the Greenhorn Limestone or the Greenhorn Limestone Member of the Mancos Shale (see Rankin, 1944; Molenaar, 1973). Hook and others (1980) and Hook and Cobban (1981a) have shown that the calcareous interval in the Rio Salado Tongue is the lithologic and faunal equivalent of the lower portion of the Bridge Creek Limestone Member of the Greenhorn Limestone, the uppermost of the three members of the Greenhorn. Hook and Cobban (1981a) preferred the name Bridge Creek Limestone to Greenhorn Limestone because it more accurately conveyed the stratigraphic and biostratigraphic relationships of these rocks to the type Greenhorn Limestone of southeast Colorado. Accordingly, Hook and Cobban (1981a) formally extended the name Bridge Creek Limestone into southern New Mexico as a member-rank or bed-rank unit in both the Mancos Shale and Colorado Formation.

The contact between the Bridge Creek Limestone Beds and the underlying calcareous shale is drawn at the base of the lowest persistent bed of limestone. In Socorro County, this basal limestone lies 2 to 12 m above the top of the Twowells Tongue and is generally nodular to concretionary and as much as 15 cm thick. This limestone is generally overlain by an interbedded sequence of thin limestones separated by highly calcareous shale (see Hook and Cobban, 1981a, figs. 4, 5). The contact between the top of the Bridge Creek Limestone and the overlying calcareous shale is drawn at the top of the highest persistent bed of limestone, generally a 5-to-10-cm-thick calcarenite composed of *Inoceramus* or oyster debris. The greatest measured thickness of the Bridge Creek Limestone Beds in southern New Mexico is at Carthage, where it is 15 m thick and approximately 65 m above the top of the Dakota Sandstone (figs. 3 and 4). At the type section of the Rio Salado tongue at Puertecito, the Bridge Creek Limestone Beds are 14 m thick and lie 11 m above the top of the Twowells Tongue of the Dakota Sandstone (fig. 4).

The base of the Bridge Creek Limestone Beds in west-central New Mexico always lies within the late Cenomanian ammonite zone of *Sciponoceras gracile* and is regarded by me as an isochronous surface. The top of the unit is diachronous and can lie as low as the early Turonian ammonite zone of *Pseudaspidoceras flexuosum* or as high as the late early Turonian ammonite zone of *Mammites nodosoides*. In addition to being highly distinctive lithologically and faunally in outcrop, the Bridge Creek Limestone has a distinctive electric-log signature that is useful for subsurface correlation.

The upper part of the Rio Salado Tongue at its type section consists of 13 m of calcareous shale, succeeded upward by 34 m of noncalcareous shale that contains numerous fossiliferous concretions. In the D Cross Mountain to Puertecito area, worn, phosphatized, oyster-encrusted internal molds of the ammonite *Morrowites depressus* (Powell) seem to be concentrated on a single horizon, suggesting to Hook and Cobban (1981a) that they had formed on a widespread discontinuity surface. This surface may extend as far east as Jeff Davis County, Texas, where Hook and Cobban (1983) have documented an important unconformity of middle Turonian age in the Boquillas Limestone.

Tres Hermanos Formation

The Tres Hermanos Formation, as revised by Hook and others (1983), is a northeasterly pointing, regressive-transgressive wedge of nearshore marine and nonmarine deposits that separates the Mancos Shale of west- central New Mexico into two parts—the Rio Salado Tongue or lower part below and the D-Cross or Pescado Tongue above (figs. 3 and 4). The Tres Hermanos Formation consists of a basal regressive marine sandstone unit (the Atarque Sandstone Member), a medial marginal- marine to nonmarine sandstone and shale unit (the Carthage Member), and an upper transgressive sandstone unit (the Fite Ranch Sandstone Member). Figures 3 and 4 show the distribution of facies trends of the Tres Hermanos Formation in Socorro County. The southwestern or landward extent of the Tres Hermanos Formation is, by definition, at the landward pinchout of the overlying D-Cross or Pescado Tongue. The northeastern or seaward limit of the Tres Hermanos is the north- eastern extent of the sandstone units at the base and top of the formation. Unlike most regressive-transgressive wedges in which the basal re- gressive sandstone merges with the upper transgressive sandstone, the upper and lower sandstones of the Tres Hermanos remain separated and become thinner in a seaward direction as the medial nonmarine unit grades directly into Mancos Shale, as it does in the Jornada del Muerto coal field (fig. 3, Bustas well section).

The Tres Hermanos Formation ranges in thickness from 60 to 90 m, except at its seaward extent, where it grades into Mancos Shale. In Socorro County, the Tres Hermanos conformably overlies the Rio Salado Tongue or lower part of the Mancos Shale and is conformably to disconformably overlain by the D-Cross Tongue.

At the principal reference section at Carthage (figs. 3 and 4), the Tres Hermanos Formation is exceptionally well exposed and easily accessible. The formation is 84 m thick and consists of: (1) a lower 26-m-thick, regressive coastal-barrier sandstone unit (Atarque Sandstone Member); (2) a medial 35-m-thick nonmarine sandstone and shale unit (Carthage Member); and (3) an upper 23-m-thick marine sandstone unit (Fite Ranch Member). Each member is briefly discussed below. More detailed information can be found in Hook and others (1983).

The Atarque Sandstone Member is a regressive coastal-barrier sandstone or shoreface complex that prograded northeasterly into the Greenhorn seaway during late to early middle Turonian time. Throughout west-central New Mexico the Atarque ranges in thickness from 3 to 30 m. The thicker sections, as at Carthage, are commonly multicyclic. Individual sandstones coarsen upward from very fine to lower fine grained and contain substantial amounts of interstitial clay. Bedding is generally planar, although minor medium-scale crossbeds occur. Scattered burrows are common. In many areas, tidal-channel sandstones are more common than shoreface sandstones. The Atarque was probably deposited along a relatively low-energy shoreline adjacent to a very shallow seaway. Wave energy was not great; tidal currents were important depositional agents. The shoreline was probably digitate and embayed as indicated by the ranges in thickness and variations of shoreline sandstones. The Atarque resulted from nondeltaic to deltaic coastal progradational processes. The seaward part of the Atarque is probably equivalent to the Semilla Sandstone Member of the Mancos Shale, an offshore marine sandstone on the southeast side of the San Juan Basin (Dane and others, 1968; Molenaar, 1974, 1977). The Atarque Sandstone Member is diachronous and becomes younger from southwest to northeast. In Socorro County, the Atarque is of early middle

Turonian age and contains the *Collignoniceras woollgari woollgari* ammonite fauna (Cobban and Hook, 1979, figs. 3 and 4).

The Carthage Member, named for the abandoned coal-mining town in Socorro County, is the medial, marginal marine and nonmarine shaly part of the Tres Hermanos Formation. At its type section, the Carthage is 35 m thick (figs. 3 and 4) and is predominantly shale, although several sandstone beds occur in the lower two-thirds of the unit. These sandstones are thin and are either very fine grained, paludal-lacustrine sandstones; or crevasse-splay, bay-fill deposits; or thin, discontinuous, fine-grained, crossbedded channel sandstones. Three kilometers to the east of the type section, sandstones are only a very minor constituent of the member. Throughout west-central New Mexico, the Carthage Member ranges in thickness from 30 to 68 m. Thin coal beds occur in some areas. Petrified wood and tree stumps are common at Carthage. The Carthage Member does not thin uniformly toward its seaward limit. Instead, paludal shales grade directly into marine shales (Molenaar, 1973, 1974, 1983a, b; Hook and others, 1983). Deposition of the member probably occurred on a broad, very low relief coastal or delta plain. The age of the Carthage Member is usually based on the ages of the underlying and overlying marine sandstones. On this basis, the Carthage Member ranges in age from middle to early late Turonian. However, the marine oyster *Lopha bellaplicata* (Shumard) has been collected from it in the Jornada del Muerto coal field (Tabet, 1979, p. 14). *Lopha bellaplicata* ranges from the late middle Turonian ammonite zone of *Prionocyclus hyatti* into the earliest late Turonian zone of the ammonite *P. macombi.*

The Fite Ranch Sandstone Member is a coastal-barrier sandstone associated with the overlying transgressive D-Cross Tongue of the Mancos Shale.

CARLILE CYCLE

The Carlile Cycle began in latest middle Turonian time and lasted until early Coniacian time, or about two million years. During the D-Cross transgression only the southwestern part of New Mexico was not covered by marine water. The regressive phase of this cycle—the Gallup regression—seems to be unique to New Mexico and northeasternmost Arizona (Molenaar, 1983a). The transgressive and regressive phases of the Carlile Cycle are of approximately equal duration (fig. 2).

The DCross Transgression

The D-Cross transgression began during the latest middle Turonian ammonite zone of *Prionocyclus hyatti* and probably lasted until the early part of the late Turonian ammonite zone of the ammonite *Prionocyclus novimexicanus.* Rock units associated with this transgression in Socorro County include the upper part of the Carthage Member, the Fite Ranch Sandstone Member, and the lower part of the D-Cross Shale.

The Fite Ranch Sandstone Member of the Tres Hermanos Formation has its type section at Carthage, where it is a well-developed coastal barrier sandstone 23 m thick (figs. 3 and 4). The member is much thinner in most other areas and is locally absent. Sandstones within the Fite Ranch generally consist of a upward-coarsening sequence that ranges from very fine grained at the base to lower fine grained at the top. Interstitial clay is common, but not as prevalent as in the Atarque. Planar bedding predominates, but is generally obscured by burrows and bioturbation. At the type section, the Fite Ranch sandstone has a gradational base with a 5-m-thick section of locally fossiliferous silty shales or very fine grained sandstone resting on the Carthage Member. The oyster *Lopha bellaplicata* (Shumard) in this interval indicates a normal marine environment, which suggests that the top of the Carthage Member or base of the Fite Ranch Sandstone represents a transgression followed by an offlap or regression during which the major portion of the Fite Ranch Member was deposited.

The Fite Ranch Sandstone Member of the Tres Hermanos Formation is a diachronous unit that becomes younger to the south. However, in the Acoma Basin, at Carthage, near Truth or Consequences and in the Oscura Mountains area, the top of the Fite Ranch Member seems to be virtually synchronous. In those areas the ammonite *Coilopoceras inflatum* occurs either in the uppermost part of the Fite Ranch Member or in the overlying meter or two of the D-Cross Tongue. Other fossils occurring with C. *inflatum* include the ammonite *Prionocyclus macombi* Meek (late form), the oyster *Lopha lugubris* (Conrad), and the bivalve *Inoceramus dimidius* White. This faunal assemblage is identical to that found in the basal part of the Juana Lopez Member of the Mancos Shale (Dane and others, 1966; Hook and Cobban, 1980b).

The shale overlying the Tres Hermanos Formation in the Acoma basin was named the D-Cross Tongue of the Mancos Shale by Dane and others (1957). Dane and others (1957) thought that the Pescado Tongue of Pike (1947) in the Zuni basin was a distinct tongue of Mancos Shale, lower stratigraphically than the D-Cross Tongue. Subsequent work (Molenaar, 1973; Hook and Cobban, 1980a; Hook and others, 1983) has shown that the Pescado Tongue is equivalent to the lower part of the D-Cross Tongue. The tongue of Gallup Sandstone overlying the Pescado thins to the east and grades into the middle of the D-Cross Tongue (Molenaar, 1974, fig. 5; Hook and others, 1983, fig. 4). At its type section at D Cross Mountain, the D-Cross Tongue is 55 m thick; at Carthage it is 91 m thick (fig. 4). The Pescado at its type section is only 15 m thick.

The D-Cross Tongue is composed of noncalcareous clay shale that contains large septarian to fossiliferous limestone concretions. The concretions are especially fossiliferous in the Puertecito area, where they have yielded some especially well-preserved specimens of the ammonite *Prionocyclus novimexicanus* (Hook and Cobban, 1979). The basal part of the D-Cross Tongue in the Jornada del Muerto coal field and the Joyita Hills contains thin calcarenite beds that are lithologically similar and faunally identical to those in the upper part of the Juana Lopez Member of the Mancos Shale (Dane and others, 1966; Tabet, 1979; Hook and Cobban, 1980a, b).

The contact of the D-Cross Tongue with the underlying Tres Hermanos Formation is sharp and ranges from conformable to disconformable. The disconformable contact has been demonstrated at only two localities in Socorro County—Carthage and the Joyita Hills area. Evidence for this disconformity includes missing faunal zones and worn, encrusted, often phosphatized, internal molds of bivalves and ammonites lying on the contact surface. The contact with the overlying Gallup Sandstone ranges from gradational to intertonguing.

In Socorro County, the D-Cross Tongue ranges in age from early late Turonian to possibly early Coniacian. The oldest fossils, representative of the early part of the ammonite zone of *Prionocyclus wyomingensis,* have come from a thin calcarenite bed 1.5 m above the top of the Tres Hermanos Formation in the Joyita Hills area and include the ammonite *Scaphites warreni* Meek and Hayden. The ammonite *Scaphites ferronensis* Cobban, indicative of the late part of the zone of *P. wyomingensis* has been collected 1.5 m above the top of the Tres Hermanos Formation at Puertecito. Rocks representative of the zone of *P. wyomingensis* are missing at Carthage, where the oyster *Lopha sannionis* (White), which ranges no lower than the base of the *Prionocyclus novimexicanus* Zone (Hook and Cobban, 1981b), occurs in the same bed with the ammonites *P. macombi* (late form) and *Coilopoceras inflatum* (the D11161 level at Carthage, figs. 3 and 4).

Fossils definitely of Coniacian age have not been collected from the D-Cross Tongue in Socorro County. However, I have collected a fragment of what appears to be the Coniacian ammonite *Forresteria* from the intertongued Gallup Sandstone in the Joyita Hills area (the D11205 level, fig. 3). In support of this Coniacian age determination are the

increased thickness of the D-Cross Tongue from D Cross Mountain to Carthage to the Joyita Hills (55 m to 91 m to 106 m, respectively) and the presence of the oyster *Lopha sannionis,* which ranges in age from late Turonian to middle Coniacian (Hook and Cobban, 1981b), in the overlying Gallup Sandstone.

The Gallup Regression

The Gallup regression began in middle late Turonian time, about the time the middle part of the D-Cross Tongue was being deposited in Socorro County. Rock units associated with this regression—the upper D-Cross Tongue, the Gallup Sandstone, and the lower part of the nonmarine Crevasse Canyon Formation—form a unique record that is only known from New Mexico and northeasternmost Arizona (Molenaar, 1983a). Maximum regression probably occurred during early Coniacian time, giving the Gallup regression a total time of approximately one million years. The seaway over the rest of the Western Interior seems to have continued transgressing (Hook and Cobban, 1981b, fig. 2).

The Gallup Sandstone was named by Sears (1925) for exposures in the hogback east of Gallup, New Mexico. Although no type section was established, Sears (1925, plate 5) annotated the upper and lower contacts of the Gallup Sandstone on a photograph of the hogback taken in 1901 by W. H. Darton. This photograph has been used in subsequent reports as the "type" section of the Gallup Sandstone (for example, Sears and others, 1941, pl. 27-8; and O'Sullivan and others, 1972, fig. 12). Molenaar (1973, fig. 12) presented the first published measured section of the Gallup Sandstone from the type area, about 4 km south of Darton's photograph locality. Recently, Molenaar (1983b) established this locality as the principal reference section of the Gallup Sandstone.

Regionally, the Gallup Sandstone consists of a series of northeasterly prograding coastal-barrier or delta-front sandstones that grade seaward into more offshore marine mudstones of the Mancos Shale and intertongue landward with nonmarine coastal deposits.

As defined by Molenaar (1983b), the Gallup Sandstone is composed of a sequence of strata that can be recognized and mapped over a wide area of western New Mexico. Where map scale permits, the marine shale tongues that separate marine sandstones—as at Puertecito can be mapped as tongues of Mancos Shale. Nonmarine shale tongues in the upper part of the Gallup can be mapped as tongues of the Crevasse Canyon Formation. The Torrivio Member, the uppermost, pink, coarse-grained, fluvial sandstone member of the Gallup Sandstone in the type area, is not recognized in Socorro County. Consequently, the top of the Gallup Sandstone is placed at the top of the uppermost marine sandstone from D Cross Mountain to Carthage.

The Gallup Sandstone reaches its maximum development in Socorro County at D Cross Mountain, where it occurs as a single sandstone unit, 33 m thick. At Puertecito, the Gallup is split into two sandstones, 18 m and 10 m thick, by a 12-m-thick tongue of Mancos Shale. At Riley, the shale tongue is 29 m thick, and the Gallup Sandstone tongues are 9 m and 15 m thick. At Carthage, the lower Gallup Sandstone tongue has pinched out (fig. 4).

Fossils are relatively abundant in the Gallup Sandstone in Socorro County in comparison to the Gallup area and the Zuni basin. The oyster *Lopha sannionis,* which ranges in age from late Turonian to middle Coniacian, is a good guide fossil to the Gallup, although not restricted to it (figs. 3 and 4; Hook and Cobban, 1981b). Because the Gallup Sandstone is largely a prograding sequence of time-transgressive sandstones, the oldest marine unit in it is at its landward (southwestern) extent. The oldest fossils from the Gallup have come from the southern Zuni basin and are probably indicative of the early late Turonian zone of the ammonite *Prionocyclus wyomingensis.* In contrast, the oldest fossils from the Gallup Sandstone in Socorro County include fossils indicative of the late late Turonian zone of the ammonite *P. novimexicanus.* The youngest fossils from the Gallup Sandstone in Socorro County have come from Puertecito, where the early Coniacian bivalve *Inoceramus erectus* Meek occurs at the top of the lower Gallup Sandstone, and from the Joyita Hills area, where the early Coniacian ammonite *Forresteria* occurs in thelower Gallup Sandstone.

Pike (1947) first introduced the Gallup terminology to Socorro County at D Cross Mountain. An earlier name, the Gallego Sandstone of Winchester (1920), for what is now the Gallup Sandstone, was formally abandoned by Molenaar (1983b).

The nonmarine rocks above the Gallup Sandstone in Socorro County are now included in the Crevasse Canyon Formation. The Crevasse Canyon Formation was named by Allen and Balk (1954) for strata in the Tohatchi area, 40 km northwest of Gallup, that lie between Gallup Sandstone below and the Point Lookout Sandstone above. The Crevasse Canyon Formation was formally extended into Socorro County by Tonking (1957). Only the basal part of the Crevasse Canyon is shown on the cross sections (figs. 3 and 4).

PALEONTOLOGY

Marine Cretaceous rocks in Socorro County range in age from middle Cenomanian to early Coniacian. The ammonite and inoceramid zonation for this age span in New Mexico is shown in Figure 1. Not all of these zones have been documented in Socorro County. Brief summaries of the known zones are treated in the following section. Illustrations and descriptions of many of the species can be found in Cobban (1977), Cobban and Hook (1979, 1980, 1983b), and Hook and Cobban (1977, 1979, 1980a, 1981b).

Zone of *Conlinoceras tarrantense* (Adkins)

Molluscan fossils from this zone have been collected from only three localities, all in northern Socorro County—at D Cross Mountain, in the Joyita Hills area, and questionably in the Puertecito area. All have come from the lower 15 m of the Mancos Shale. The few fossils from this zone are

bivalves: *Plesiopinna* sp.
Plicatula arenaria Meek
Camptonectes sp.
ammonites: *Conlinoceras gilbert.* Cobban and Scott

Zone of *Acanthoceras amphibolum* Morrow

Mollusks of this zone have been found at many localities in Socorro County. Three subzones are recognized.

Subzone of *Acanthoceras alvaradoense* Moreman

Fossils of this subzone have been found only in the Carthage area in the lower 8 m of the Mancos Shale.

bivalves: *Inoceramus arvanus* Stephenson
oysters: *Ostrea beloiti* Logan
ammonites: *Acanthoceras* sp.

Subzone of *Acanthoceras amphibolum* Morrow

Widely distributed in Socorro County in the lower 30 m of the Mancos.

bivalves: *lnoceramus rutherfordi* Warren
Plicatula sp.
oysters: *Ostrea beloiti* Logan
ammonites: *Acanthoceras amphibolum* Morrow
Tarrantoceras sp.
Turrilites acutus americanus Cobban and Scott

Subzone of *Plesiacanthoceras* cf. *P. wyomingense* (Reagan)

Found at only two localities in Socorro County.

ammonites: *Plesiacanthoceras* cf. *P. wyomingense* (Reagan)

Zone of *Calycoceras canitaurinum* (Haas)

Fossils of this zone were collected at only one locality near Puertecito from sandy beds in the middle of the lower part of the Mancos Shale.

bivalves: *Idonearca* sp.
Inoceramus sp.
oysters: *Astarte* sp.
Pycnodonte aff. *P. kellumi* (Jones)

ammonites: *Acanthoceras* cf. A. *cuspidum* Stephenson
Calycoceras cf. *C. canitaurinum* (Haas)
Metoicoceras cf. *M. latoventer* Stephenson
Hamites (Stomohamites) sp.
Neostlingoceras kottlowskii Cobban and Hook

Zone of *Metoicoceras mosbyense* Cobban
This zone is represented in the Twowells Tongue of Dakota Sandstone at several localities in the northern part of the county.

bivalves: *Plicatula goldenana* Stephenson
oysters: *Pycnodonte* aff. *P. kellumi* (Jones)
ammonites: *Metoicoceras mosbyense* Cobban

Zone of *Sciponoceras gracile* (Shumard)
A very fossiliferous zone in the Carthage area and in the northwest part of the county. The following fossils were collected in the Carthage area from the base of the Bridge Creek Limestone Member.

echinoids: *Hemiaster jacksoni* Maury
brachiopods: *Discinisca* sp.
bivalves: *Inoceramus pictus* J. de C. Sowerby
oysters: *Pycnodonte newberryi* (Stanton)
Exogyra levis Stephenson
ammonites: *Euomphaloceras (Kanabiceras) septemseriatum* (Cragin)
Pseudocalycoceras dentonense (Moreman)
Metoicoceras geslinianum (d'Orbigny)
Sciponoceras gracile (Shumard)
Allocrioceras annulatum (Shumard)
Worthoceras vermiculum (Shumard)
W. *gibbosum* Moreman

Zones of *Vascoceras gamai, Neocardioceras juddii, Pseudaspidoceras flexuosum,* and *Vascoceras birchbyi*
Fossils diagnostic of these late Cenomanian—early Turonian ammonite zones have not been identified in Socorro County.

Zone of *Mammites nodosoides* (Schliiter)
This zone is poorly fossilierous in Socorro County. The following species were collected from a limestone bed near the top of the Bridge Creek Limestone Member of the Mancos Shale in the Carthage area.

bivalves: *Mytiloides mytiloides* (Mantell)
ammonites: *Mammites nodosoides* (Schlilter)
Puebloites greenhornensis Cobban and Scott

Zone of *Collignoniceras woollgari* (Mantell)
In northwest Socorro County, the zone of *Collignoniceras woollgari* includes the upper part of the Rio Salado Tongue of the Mancos Shale and the lower part of the Atarque Sandstone Member of the Tres Hermanos Formation. Fossils are abundant, especially in the Atarque Member. Farther southeast in the Carthage area, the zone includes the upper portion of the lower part of the Mancos Shale and the overlying Atarque Sandstone Member. Fossils from the zone in Socorro County were listed by Cobban and Hook (1979, p. 11). The following are among the more diagnostic species.

bivalves: *Mytiloides subhercynicus* (Seitz)
Pleuriocardia (Dochmocardia) n. sp.
Veniella mortoni Meek and Hayden
gastropods: *Pyropsis coloradoensis* Stanton
ammonites: *Spathites rioensis* Powell
Collignoniceras woollgari (Mantell)
Morrowites depressus (Powell)

Zones of *Subprionocyclus? percarinatus* (Hall and Meek) and *Prionocyclus hyatti* (Stanton)
Fossils representing these ammonite zones have not been found in Socorro County. Rocks of this age in Socorro County are of nonmarine origin and are included in the Carthage Member of the Tres Hermanos Formation.

Zone of *Prionocyclus macombi* Meek
Fossils representative of this zone occur in the Fite Ranch Sandstone Member of the Tres Hermanos Formation and in the basal part of the D-Cross Tongue of Mancos Shale. Two subzones can be recognized in Socorro County.

Subzone of *Coilopoceras colleti* Hyatt
Fossils collected from this subzone include the following species in the Carthage area. bivalves: *Pinna petrina* White
Aphrodina sp.
Legumen ellipticum Conrad
Homomya sp.
Pholadomya sp.
Psilomya meeki (White)
P. concentrica (Stanton)
oysters: *Lopha bellaplicata novamexicanus* Kauffman
gastropods: *Pyropsis* sp.
Carota dalli (Stanton)
Rostellites gracilis Stanton?
ammonites: *Coilopoceras colleti* Hyatt
Prionocyclus macombi Meek

Subzone of *Coilopoceras inflatum* Cobban and Hook
A poorly fossiliferous subzone known only from D Cross Mountain and Carthage. The top of the Fite Ranch Sandstone Member of the Tres Hermanos Formation contains the most diverse fauna:

bivalves: *Pholadomya* sp.
ammonites: *Coilopoceras inflatum* Cobban and Hook
Prionocyclus macombi Meek

Zone of *Prionocyclus wyomingensis* Meek
Fossils of low diversity represent this zone in the D-Cross Tongue of Mancos Shale. Two subzones are present in Socorro County.

Subzone of *Scaphites warreni* Meek and Hayden

bivalves: *Inoceramus dimidius* White
oysters: *Lopha lugubris* (Conrad)
ammonites: *Scaphites warreni* Meek and Hayden
Prionocyclus sp.

Subzone of *Scaphites ferronensis* Cobban

bivalves: *lnoceramus dimidius* White
oysters: *Lopha lugubris* (Conrad)
ammonites: *Scaphites ferronensis* Cobban

Zone of *Prionocyclus novimexicanus* (Marcou)
Fossils of this zone in northwest Socorro County from the D-Cross Tongue and the Gallup Sandstone include the following:

bivalves: *Inoceramus perplexus* Whitfield
oysters: *Lopha sannionis* (White)
ammonites: *Scaphites whitfieldi* Cobban
Baculites yokoyamai Tokunaga and Shimizu
Reesidites minimus (Hayasaka and Fukada)
Placenticeras cumminsi Cragin
Prionocyclus novimexicanus (Marcou)

Zone of *Prionocyclus quadratus* Cobban
Fossils diagnostic of this ammonite zone have not been found in Socorro County, although part of the Gallup Sandstone in northwest Socorro County, and part of the D-Cross Tongue in eastern Socorro County should be of *quadratus* age.

Zone of *Inoceramus erectus* Meek
Fossils diagnostic of this Coniacian zone have been collected at Puertecito and in the Joyita Hills area and include:

bivalves: *Inoceramus rotundatus* Fiege
I. erectus Meek
oysters: *Lopha sannionis* (White)
ammonites: *Forresteria?* sp.

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