PALEOENVIRONMENTAL ANALYSIS OF UPPER CRETACEOUS STRATA, JORNADA DEL MUERTO COAL FIELD, SOCORRO COUNTY, NEW MEXICO

BY

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ABSTRACT

Approximately 1600 feet of Upper Cretaceous strata unconformably overlie the Triassic Dockum Formation in the Jornada del Muerto coal field and consist of interbedded sandstones, siltstones, shales and coals. The Upper Cretaceous sequence extends from the Dakota Sandstone to the Crevasse Canyon Formation of the Mesaverde Group. These siliciclastic rocks were deposited during the wide spread middle Cenomanian-early Coniacian transgression and regression of the Western Interior Seaway.

The rocks studied represent deposition in marine to marginal marine to continental environments and, based on lithologic and paleontologic characteristics of the stratigraphic units, the following depositional environments are interpreted:

1) Dakota Sandstone: - beach-upper shoreface to lower shoreface of a barrier beach
2) Lower tongue of Mancos Shale: - transition from near shore to shallow water open marine
3) Atarque Sandstone Member: - upper shoreface to lower shoreface of a barrier beach
4) Carthage Member: - flood basin associated with a broad, very low relief coastal plain
5) Fite Ranch Sandstone Member: - coastal-barrier (regionally)
6) D-Cross Tongue: - transition zone to shelf mud of a shallow water open marine environment
7) Gallup Sandstone: - shoreface zone of a barrier beach

8) Crevasse Canyon Formation: - Marsh/lagoon complex and flood basin

Semi-quantitative clay mineral analysis of mud rocks yields an assemblege of kaolinite, illite, smectite (montmorillonite), mixed layer clays, and chlorite. A well defined trend showing an increase or decrease in relative proportions of the clay mineral groups from marine to continental depositional environments is not observed. However, discriminant function analysis shows that there are statistically significant differences in the relative proportions of clay mineral groups in the mud rocks as a function of their depositional environments.

The coals in the Crevasse Canyon Formation are laterally discontinous and occur as lenses. Proximate analysis of the coals indicates that they are low in calorific value and sulfur content, and fall in the Lignite A group.

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INTRODUCTION

PURPOSE

The Jornada del Muerto coal field (hereafter referred to as the Jornada field) in central New Mexico is a small coal field without recorded production in contrast to the nearby Carthage coal field. The depositional environments of the coal bearing Mesaverde Group in the Jornada field have not been determined, again in contrast to the Carthage field. In the Carthage field, the Mesaverde Group of Late Cretaceous age is regarded as continental deposits conformable with the underlying marine Mancos shale and generally considered to be interbedded fluvial sandstones, flood plain shales, and flood plain swamp coals. The purpose of this study is to determine the paleoenvironments (depositional environments) of the Mesaverde Group in the Jornada field through detailed surface stratigraphic section measurements.

METHODS OF INVESTIGATION

A geologic map of the Jornada field (Tabet, 1979), and a topographic map (Bustos Well - 7½ minute series) at a scale of 1:24,000 are used to determine suitable locations for stratigraphic section measurement. Four partial sections have been measured using a Jacob's staff, a steel measuring tape, and a silva (Type 15 T) compass. Stratigraphic section measurement was concentrated near the northern portion of the study area where relatively good exposures occur. As a result of alluvium and soil cover, bed rock exposures are poor over a sizeable portion of the Jornada field. Thus units are laterally traced for a reasonable distance, and where concealed by soil or slope wash in one place, measurements are offset along traceable beds to a locality of better exposure.

Even though the main concern of this study is the paleo-environment(s) of the Mesaverde Group, Upper Cretaceous strata underlying the Mesaverde Group are measured at one locality (Sec 19, T3S, R3E) and are discussed in a relatively detailed manner below.

Field description of the stratigraphic units emphasize lithologies, and their stratigraphic association, and paleontology. Lithology includes the rock type, mineral content, thickness, grain size (and trends of grain size changes), nature of contacts between lithologies, and sedimentary structures. Paleontological analysis includes indentification of macrofossils and tracefossils, and their biostratigraphic and paleoecologic significance.

Eight shale and/or mud samples, from different stratigraphic horizons, have been collected and the relative abundance of clay mineral groups is determined by semi-quantitative clay mineral analysis by x-ray diffraction methods. The relative proportions of clay mineral groups in the clay size fraction could be used in paleoenvironmental interpretations.

GEOGRAPHIC SETTING OF THE STUDY AREA

The Jornada field is located in T.3 and 4S. R3E five miles northeast of the Carthage coal field in eastern Socorro County (Fig. 1). The study area is accessible by travelling north from the US-380 on the Del Curto or Williams ranch roads that lie approximately 11 and 20 miles, respectively, east of San Antonio. These graded roads are passable, but 4-wheel drive vehicles are recommended.

Elevation ranges from 6,200 ft. above sea level in the north to 5,100 ft. above sea level in the southern portion of the field. The relief is as great as 300 ft. in the north and to the south the ridges pass into gently rolling hills and valleys and the maximum relief is about 60 ft. (Tabet, 1979). Vegetation in the area consists primarily of range grasses in the lower, nearly level southern portion and grasses along with pinon, juniper, and scrub oak in the higher slopes and hilltops in the north. Cacti of various types are common (Tabet, 1979).

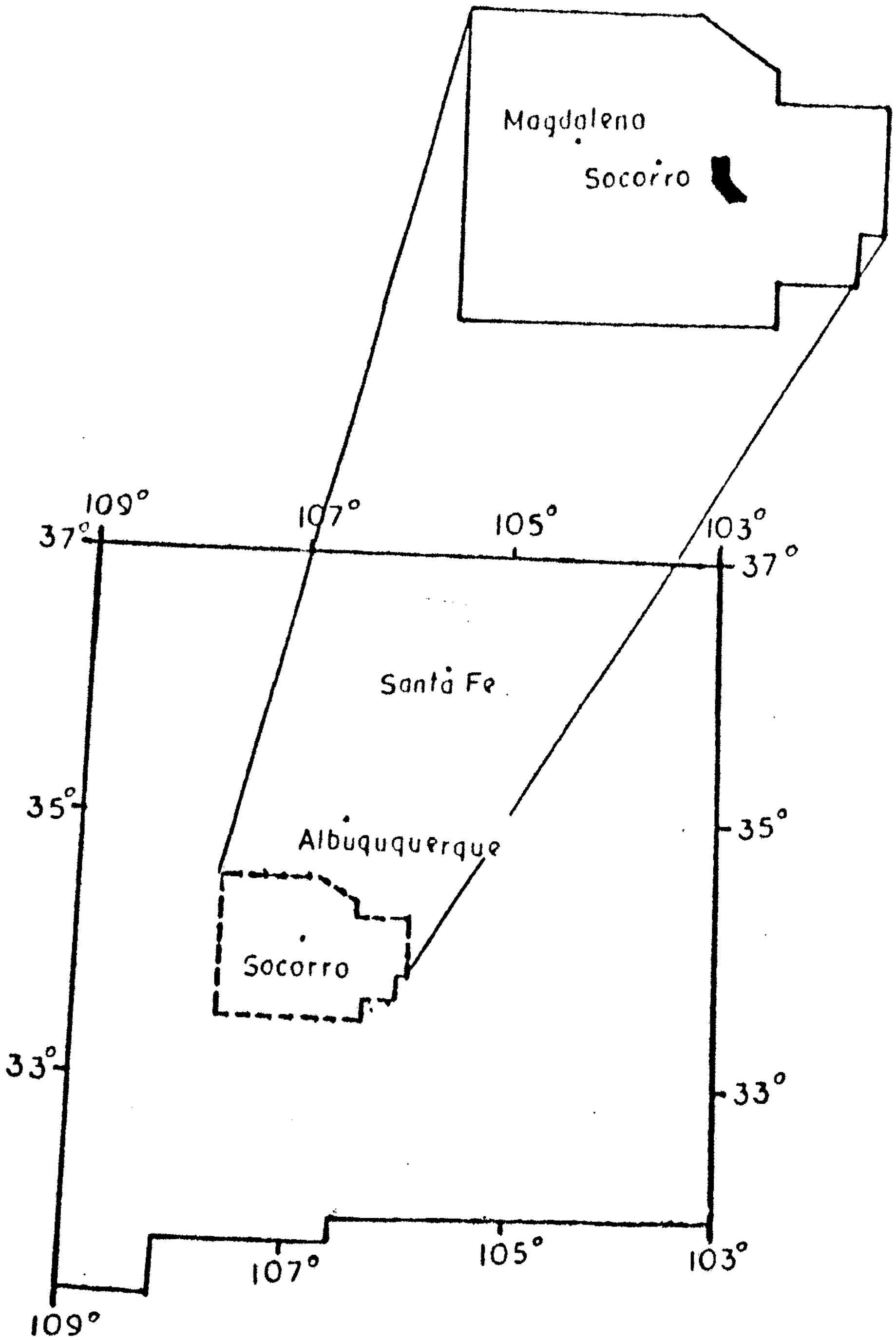


Fig. 1 Geographic location of the Jornada del Muerto coal field in Socorro County, New Mexico; indicated by the dark shaded area.

STRUCTURAL SETTING OF THE STUDY AREA

The Jornada field lies on the moderately dipping western flank of the southward plunging Prairie Springs anticline (Wilpolt and Wanek, 1951). The strike of the beds is in a north-south direction in the northern part of the field and changes to a more westerly direction to the south. The dip of the beds ranges from 15° - 20° south in the southern part of the field (Sec. 19, T.3S., R.3E.) and 30° - 36° in the northern portion of the field (Sec. 8, T3S., R.3E.).

Two sets of faults are apparent in the area. Faults oriented diagonally to the north-south fold axis of the Prairie Springs anticline are probably shear fractures related to the east-west compressional forces that caused the folding. Another set of faults, most oriented north-south, but also some oriented east-west, appear to be extensional normal faults. Prominent north-south trending normal faults run through several sections in the north western part of the area (Tabet, 1979).

According to preliminary gravity data (Schlue, 1978), the Cretaceous rocks of the Jornada field are the northeastern exposure of an asymetrical filled basin with a very steep southwestern margin near Carthage and a moderate slope on the northeastern side (Tabet, 1979).

PREVIOUS STUDIES

The geology of the coal-bearing Cretaceous rocks in the Jornada field has received little study in the past. Gardner (1910) devoted two paragraphs to the description of an exposure of coal in the Jornada field in his paper on the Carthage coal field. The geology (surface and subsurface), previous literature, coal occurrences and economic potential of the Jornada field were recently determined and summarized by Tabet (1979), but without concern for paleoenvironment(s) (depositional environments).

The stratigraphic nomenclature of Upper Cretaceous rocks used by selected studies in the Jornada field, Carthage, and surrounding areas is listed in Table 1. This study follows the stratigraphic nomenclature used by Hook, Molenaar, and Cobban (1983).

GENERAL DISCUSSION OF STRATIGRAPHIC UNITS

INTRODUCTION

A complex record of intertongued marine and non-marine sediments resulted from the advances and retreats of the Western shoreline of the epicontinental seaway that covered New Mexico during the Late Cretaceous Epoch. The Upper Cretaceous rocks preserved in Socorro County record two cycles of trangression and regression; the Greenhorn cycle which began in middle Cenomanian time and lasted until middle Turonian and the Carlile cycle which lasted from middle Turonian until early Coniacian time in New Mexico (Hook, 1983). The relationship of these cycles to the biostratigraphic/radiometric age framework of the middle Cenomanian through Coniacian stages is illustrated in Fig. 2.

The Upper Cretaceous strata in the study area can be divided into the Dakota Sandstone, Mancos Shale, Tres Hermanos Formation, and the Mesaverde Group. These major rock units were deposited during the wide spread middle Cenomanian - early Coniacian transgression and regression of the Western Interior Seaway.

Tabel 1. Stratigraphic nomenclature applied to Cretaceous rocks in the Jornada del Muerto coal field, Carthage and surrounding areas, New Mexico.

	Gardner (1910) Carthage	Wilpolt & Wanek (1951)	Molenaar (1974) Carthage	Tabet (1979) Jornada field	McLafferty (1979) Carthage	Baker (1981) Sevilleta Grant	Hook, Molenaar, and Cobban (1983) Carthage
Upper Cretaceous	Montana	Mesaverde Formation	Crevasse Canyon Formation	Dilco Coal member of the Crevasse Canyon Formation	Mesaverde Group: Oyster-bearing assemblage	Crevasse Canyon Formation	Crevasse Canyon Formation
					Mesaverde Group: Coal-bearing assemblage		
			Gallego Sandstone "C"	Gallup Sandstone	Mesaverde Group: Basal assemblage	Gallup Sandstone	Gallup Sandstone
	Colorado	Mancos Shale	Mancos Shale: D-Cross Shale Tongue	Mancos Shale: D-Cross Shale Tongue	Transition assemblage	Mancos Shale: D-Cross Shale Tongue	Mancos Shale: D-Cross Shale Tongue
		Sandstone Member of Mancos Shale	Lower Gallup (Atarque Member)	Tres Hermanos Sandstone Member		Tres Hermanos Formation: Fite Ranch Sandstone Member	Tres Hermanos Formation: Fite Ranch Sandstone Member
						Tres Hermanos Formation: Carthage Member	Tres Hermanos Formation: Carthage Member
						Tres Hermanos Formation: Atarque Sandstone Member	Tres Hermanos Formation: Atarque Sandstone Member
		Mancos Shale	Mancos Shale: Lower Mancos Shale	Lower Tongue of Mancos Shale		Rio Salado Tongue of Mancos Shale	Mancos Shale: Lower Tongue of Mancos Shale
						Two Wells Tongue of Dakota Sandstone	
						Lower Tongue of Mancos Shale	
	Dakota (?)	Dakota Sandstone	Dakota Sandstone	Dakota Sandstone		Dakota Sandstone	Dakota Sandstone
Upper Triassic	Triassic (?)	Dockum Formation		Dockum Formation		Dockum Formation	

Stage		Zone	Subzone	Absolute age (m.y. ago)	Cycles	
Coniacian	upper	*Volviceramus involutus*				
Coniacian	mid.	*Inoceramus deformis*		* 88.2 88		
Coniacian	lower	*Inoceramus erectus*			Carlile Cycle	Gallup Regression
Turonian	upper	*Prionocyclus quadratus*			Carlile Cycle	Gallup Regression
Turonian	upper	*Prionocyclus novimexicanus*		89	Carlile Cycle	Gallup Regression
Turonian	upper	*Prionocyclus wyomingensis*	*Scaphites ferronensis* *Scaphites warreni*		Carlile Cycle	D-Cross Transgression
Turonian	upper	*Prionocyclus macombi*	*Coilopoceras inflatum* *Coilopoceras colleti*		Carlile Cycle	D-Cross Transgression
Turonian	middle	*Prionocyclus hyatti*	*Coilopoceras springeri* *Hoplitoides sandovalensis*	90	Carlile Cycle	D-Cross Transgression
Turonian	middle	*Subprionocyclus? percarinatus*			Greenhorn Cycle	Tres Hermanos Regression
Turonian	middle	*Collignoniceras woollgari*	*Collignoniceras woollgari regulare* *Collignoniceras woollgari woollgari*		Greenhorn Cycle	Tres Hermanos Regression
Turonian	lower	*Mammites nodosoides*		* 91.0	Greenhorn Cycle	Tres Hermanos Regression
Turonian	lower	*Vascoceras birchbyi*			Greenhorn Cycle	Tres Hermanos Regression
Turonian	lower	*Pseudaspidoceras flexuosum*			Greenhorn Cycle	Tres Hermanos Regression
Cenomanian (part)	upper	*Neocardioceras juddii*			Greenhorn Cycle	Tres Hermanos Regression
Cenomanian (part)	upper	*Vascoceras gamai*			Greenhorn Cycle	Tres Hermanos Regression
Cenomanian (part)	upper	*Sciponoceras gracile*		93	Greenhorn Cycle	Tres Hermanos Regression
Cenomanian (part)	upper	*Metoicoceras mosbyense*			Greenhorn Cycle	Dakota Transgression
Cenomanian (part)	upper	*Calycoceras canitaurinum*		* 93.4	Greenhorn Cycle	Dakota Transgression
Cenomanian (part)	middle	*Acanthoceras amphibolum*	*Plesiacanthoceras aff. wyomingense* *Acanthoceras amphibolum amphibolum* *Acanthoceras amphibolum alvaradoense*	* 94.2	Greenhorn Cycle	Dakota Transgression
Cenomanian (part)	middle	*Conlinoceras tarrantense*		95	Greenhorn Cycle	Dakota Transgression

Fig. 2 Chart showing faunal zones, absolute ages, and depositional cycles for the lower part of Upper Cretaceous strata in New Mexico (from Hook, 1983).

DAKOTA SANDSTONE

The Dakota Sandstone is the lowermost of the Upper Cretaceous strata exposed in the study area. It overlies the Triassic Dockum Formation with angular unconformity.

The term Dakota was first used to describe the basal sandstone of the Upper Cretaceous series near Dakota, Nebraska (Meek and Hayden, 1862). This term was applied to the basal sandstone at Carthage, New Mexico by Gardner (1910). The great lateral continuity of the Dakota Sandstone was first recognized by Dutton (1885).

The Dakota Sandstone in this study area is well exposed (Fig. 3) at one locality (Sec. 19, T.3S, R.3E) by east-west and north-south trending normal faults and is 132 ft. 8 in. thick although Tabet (1979) measured 74 ft. 7 in. of the Dakota Sandstone at NE¼ Sec. 17, T.3S., R.3E.

The Dakota Sandstone is a grayish-white to brownish-gray, well sorted, moderately to well-indurated, fine-to medium-grained, quartz sandstone. The sandstone is commonly structureless but shows some crude laminations and cross-laminations locally. Bedding is uneven, ranging from thin- to medium-bedded, and individual beds vary in thickness laterally. Limonite and/or hematite and manganese staining (toward the top) is fairly common. Iron oxide nodules occur locally. Toward the top, the Dakota Sandstone is bioturbated and contains plant impressions and some carbonaceous material. The top of the sandstone forms a dip slope. An ammonite impression, Acanthoceras sp., and the dental cap of a shark tooth, Cf. batoid occur at 83 ft. 10 in.

Fig. 3 Cliff-forming Dakota Sandstone at Section I. View to the south.

and 77 ft. 7 in. respectively, from the base of the section (Section I at Sec. 19, T.3S, R.3E).

Lobster and/or crab trails and a mold of what could be an arm of a starfish (Wolberg, pers. comm., 1986) also occur toward the top of the section. The oyster Lopha sp. occurs as float 96 ft. from the base of the section. Vertical and horizontal burrows in the Dakota Sandstone range from about 1 or 2 mm in diameter to 2.5 cm in diamter and are smooth walled, and circular to oval shaped in cross section.

MANCOS SHALE

The name Mancos was first applied by Cross (1899) to a dark shale exposed in the Mancos River valley near Mancos, southwestern Colorado. Due to the intertonguing of the Mancos Shale with sandstones of the Dakota Sandstone, Tres Hermanos Formation, and Mesaverde Group, the Mancos Shale has been divided into several tongues. In west-central New Mexico, where these sandstones are not always present, the informal term lower tongue of Mancos Shale is used (Baker, 1981). The D-Cross Shale tongue of the Mancos Shale was first described by Dane and others (1957) for expsoures at D Cross Mountain, Socorro County, New Mexico.

In the study area the Mancos Shale conformably overlies the Dakota Sandstone and is separated into two shale members: a lower tongue and the D-Cross Tongue separated by the intervening Tres Hermanos Formation.

The lower shale tongue is 526 ft. 5 in. thick at Section I

(Sec 19, T.3S, R.3E). It is covered by soil and/or alluvium except where exposed in a small arroyo 287 ft. 7 in. from the top of the Dakota Sandstone. The valley forming nature of this shale has made it difficult to accurately measure its thickness. The lower shale tongue is light to dark-gray shale; locally fissile, silty and calcareous. It contains abundant molluscan fragments. Several 3 - 6 inch thick limestone beds occur interbedded within this shale (Fig. 4). Teredo-like shells are collected from the upper limestone bed which is 4 in. thick.

The D-Cross Shale is also covered at most places. At Section II (Sec. 8, T.3S, R.3E), the D-Cross Tongue is exposed in a small gully below the Gallup Sandstone of the Mesaverde Group. The contact with the overlying Gallup Sandstone is covered by soil and/or alluvium so an exact thickness has not been measured. The D-Cross Tongue consists of a light to dark-gray fissile shale which weathers to yellowish-orange, with at least two interbedded limestone beds (Fig. 5) that are 3-5 inches thick.

Tabet (1979) described both the lower shale tongue and D-Cross Tongue as consisting of dark-gray or tan shale or silty shale with a few thin beds of tan quartz sandstone and limestone and large, locally fossilferous, septarian concretions occur at various horizons.

Pycnondonte newberryi (Stanton), and Sciponoceras gracile (Shumard), were collected by Tabet (1979) from a 1-foot-thick, light gray, micritic limestone in the upper part of the lower

Fig. 4 Thin limestone beds (L) in the lower tongue of the Mancos Shale(s) exposed in a small arroyo (at Section (1). Rock hammer 32.5 cm long.

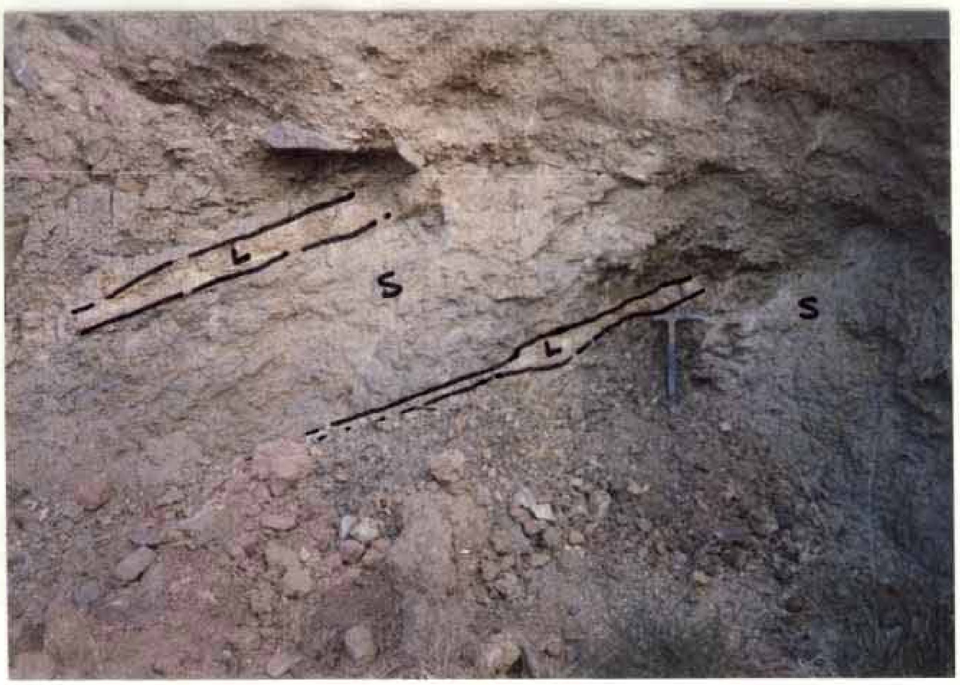


Fig. 5 Thin limestone beds (L) in the D-Cross tongue of Mancos Shale(s) exposed in a gully (at Section II, SW¼ NE¼ Sec. 8, T.3S., R.3E.). Rock hammer 32.5 cm long.

tongue of the Mancos Shale. *Inoceramus* sp. fragments and shark teeth also occur in this part of the section. Tabet (1979) identified various types of fossils from four thin limestone beds in the D-Cross Tongue. These include *Scaphites whitfieldi* (Cobban), *Prionocyclus novimexicanus* (Marcou), and *Inoceramus perplexus* (Whitfield), in the lower part, *Baculites yokoyami* Tokunaga and Shimizu, and *Prionocyclus* sp. occur in the middle part and *Lopha sannionis* White toward the top.

TRES HERMANOS FORMATION

The name Tres Hermanos Sandstone was introduced in the geologic literature of New Mexico by Herrick (1900) for a concretion bearing sandstone east of Tres Hermanos peak in the Rio Salado Valley, New Mexico. In the past the name Tres Hermanos Sandstone has been applied to different sandstone units low in the Mancos Shale (Hook, Molenaar, and Cobban, 1983). The Tres Hermanos Sandstone of Herrick (1900), later changed to the Tres Hermanos Sandstone Member of the Mancos Shale by Lee (1912), is raised in stratigraphic rank to the Tres Hermanos Formation by Hook, Molenaar, and Cobban (1983).

The Tres Hermanos Formation in the study area is subdivided into a basal sandstone unit, a medial shale and sandstone unit, and an upper sandstone unit. These three members are named, in ascending order, the Atarque Sandstone Member, the Carthage Member, and the Fite Ranch Sandstone Member (Hook, Molenaar, and Cobban, 1983).

ATARQUE SANDSTONE MEMBER

The term Atarque Member is used for the lower sandstone unit of the Tres Hermanos Formation. The name was taken from the now abandoned community of Atarque, 55 miles south of Gallup, New Mexico (Hook, Molenaar, and Cobban, 1983). Because of poor exposures and much slumping in the type section of the Atarque Sandstone Member (near Horsehead Canyon in the SW¼ Sec. 32, T.10N, R.17W), a principal reference section is designated for the Atarque a few miles farther north along the north side of Pescado Creek in the SW¼ Sec. 5, T.10N, R.17W (Hook, Molenaar, and Cobban, 1983).

The Atarque Sandstone is 321 ft. thick, mostly covered, at Section I (Sec. 19, T.3S, R.3E) and consists of thinly-to-medium-bedded, grayish-white to grayish-orange, moderately to well-sorted, friable to moderately indurated, fine-to-medium-grained sandstones. There are fossiliferous calcareous sandstone concretions toward the top. The sandstones are mostly plane bedded and show some internal laminations locally. A set of small scale, high angle, tabular tangential cross-laminations occurs at one place.

The Atarque Sandstone contains abundant horizontal and vertical (to the bedding plane) burrows and is highly bioturbated toward the top. <u>Ophiomorpha</u> burrows are common at lower horizons. The horizontal burrows are smooth walled, cylindrical in shape, and averagely 0.5 cm in diameter and up to 7 cm long. The vertical burrows are mainly smooth walled, with few exhibiting ornamented walls, and smaller in size than the horizontal burrows.

Two yellowish-orange, calcareous sandstone concretions (267 ft. 9 in. and 279 ft. 5 in. from the base of the Atarque Sandstone Member) contain *Granocardium* sp., *Inoceramus* sp., *Lopha* sp., *Lopha bellaplicata* (Shumard), *Lopha lugbris*, *Exogyra* sp., and *plicatula* sp.

Collignoniceras woollgari woollgari (Mantell), and *Mammites depressus* Powell (as float 110 ft below the base of the Tres Hermanos Formation) were collected by Tabet (1979).

THE CARTHAGE MEMBER

The Carthage Member is named for the abandoned coal mining community of Carthage approximately 16 miles southeast of Socorro, New Mexico. The type section, about 116 ft. thick, is in the SE¼ SE¼ Sec. 8 and NE¼ NE¼ Sec. 17, T.5S, R.2E (Hook, Molenaar, and Cobban, 1983).

The Carthage Member is 20 ft. 9 in. thick at Section I (Sec 19, T.3S, R.3E). It consists of interbedded light to dark gray shales that weather to yellowish-orange to reddish-brown, and yellowish-orange fossiliferous calcareous sandstone. The shale units contain broken oyster shells and petrified wood fragments. The sandstone is 2 ft. thick and contains *Inoceramus* sp., *Texigryphea* sp., *Crassostrea* sp., *Scaphites* and pectinoids indet. *Lopha bellaplicata* (Shumard) and *Ostera* sp. were collected by Tabet (1979) from the Carthage Member at Sec. 5, T.3S., R.3E.

The Carthage Member is overlain by Tertiary volcanics at the measured section (Section I).

THE FITE RANCH SANDSTONE MEMBER

The Fite Ranch Sandstone Member is named for Fite Ranch, which is approximately 1 mile south of the abandoned coal mining community of Carthage and the type section is in the NE¼ NE¼ Sec. 17, T.5S., R.2E (Hook, Molenaar, and Cobban, 1983).

The Fite Ranch Sandstone Member has not been measured in this study. However, Tabet (1979) measured 41 ft. of this member at Sec. 5, T.3S., R.3E., and it consists of transgressive deposits of silty, bioturbated sandstone; cream to white near the base and reddish near the top.

THE MESAVERDE GROUP

Holmes (1877, pp. 244) described Upper Cretaceous sandstones and shales in Mesa Verde National Park in southwestern Colorado, and named these strata the Mesaverde Group. Since then, the nomenclature of Upper Cretaceous strata have undergone numerous revisions and reinterpretations. The reader is referred to Beaumont and others (1956) for a review of the literature written during the first half of the century. The Mesaverde Group consists of, from oldest to youngest, the Gallup Sandstone, Crevasse Canyon Formation, Point Lookout Sandstone, Menefee Formation, and Cliff House Sandstone (Baker, 1981).

The Mesaverde Group in this study area is subdivided into the Gallup Sandstone and the overlying Crevasse Canyon Formation.

GALLUP SANDSTONE

Sears (1925) applied the name "Gallup Sandstone Member of the Mesaverde Formation" to a mappable sequence of rocks near Gallup, New Mexico and described the Gallup Sandstone as ranging from 180 to 250 ft. in thickness and consisting of three massive sandstone beds interbedded with shale and coal. Later, the Gallup nomenclature was extended throughout northeast and west-central New Mexico, and in 1956 Beaumont, Dane and Sears raised the Gallup Sandstone from member to formation rank and the Mesaverde from formation to group rank (Molenaar, 1983). The principal reference section of the Gallup Sandstone is in the SE¼ NE¼ Sec. 13, T.15N., R.18W., on the north side of Puerco Gap 2 miles east of the city of Gallup, New Mexico (Molenaar, 1983).

The Gallup Sandstone measured at Sec. 8, T.3S., R.3E. (Section II) consists of a 108 ft. thick sequence of thinly to medium-bedded, grayish-white to yellowish-orange, moderately to well-sorted, moderately to well-indurated, fine-to medium-grained sandstones (Figs. 6, 7, and 8).

The sandstones are dominantly planar parallel bedded and locally structureless (Fig. 9). Individual beds are internally laminated locally (Fig. 10). Sets of small scale, low angle tabular planar and tangential cross-stratification, small scale wedge shaped planar and tangential cross-laminations (Fig. 11) and trough cross-laminations occur locally. Due to relatively poor exposure of the sandstones, locally sedimentary structures are hard to recognize and thus the sandstones may appear to be

Fig. 6 Exposures of Gallup Sandstone at Section II. Arrow indicates a calcareous sandstone (unit #14) containing abundant oysters. View to the west.

Fig. 7 Exposures of Gallup Sandstone 0.4 mi. north of Section II. Arrow indicates calcareous sandstone containing abundant oysters.

Fig. 8 Uniformly and rhythmically bedded sandstones in the Gallup Sandstone (base of Section II). Each segement on the Jacob's staff is 4 inches long.

Fig. 9 Tabular-planar stratification (A) in the Gallup Sandstone (at Section II). Each segement on the Jacob's staff is 4 inches long.

Fig. 10 An example of internal laminations in individual beds in the Gallup Sandstone (unit #3 at Section II). Rock hammer 32.5 cm long.

Fig. 11 A set of small scale, low angle wedge shaped tangential cross-laminations (A) in the Gallup Sandstone (unit #13 at Section II). Note: Erosional lower contact. Rock hammer 32.5 cm long.

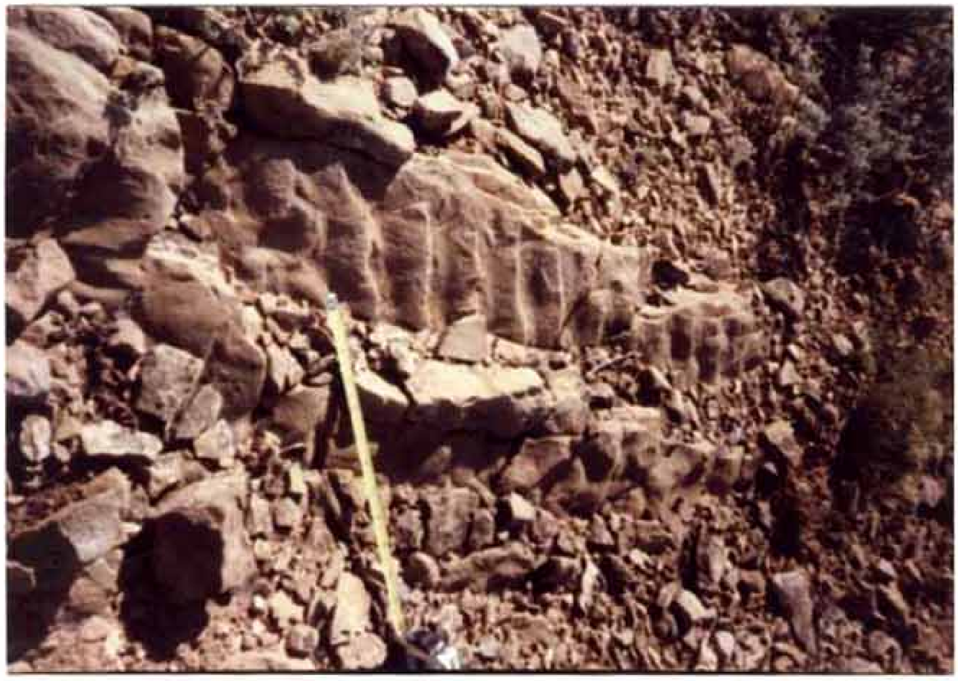


Fig. 12 Small scale, nearly symmetrical ripple marks in the Gallup Sandstone (unit #15 at Section II). The red mark on the measuring tape indicates the 1 ft (30.5 cm) mark.

structureless. One example of small scale, nearly symmetrical ripple marks occurs toward the top of the Gallup Sandstone (Fig. 12).

Horizontal and vertical burrows occur locally and are sparingly common toward the top. The burrows are mainly smooth walled, with a few exhibiting knobby surfaces, and circular in outline. The horizontal burrows are, on average, 0.5 cm in diameter and up to 6 cm long. The vertical burrows also have an average diameter of 0.5 cm.

A tan to yellowish-brown calcareous sandstone (Figs. 13 and 14) occurs 75 ft. above the base of Section II and contains Cardium sp., Gyrodes sp., Turritella sp., and abundant oyster fragments. This sandstone exhibits wavy parallel continous and discontinous laminations toward the top and planar parallel laminations at the base.

CREVASSE CANYON FORMATION

Allen and Balk (1954) defined the Crevasse Canyon Formation of the Mesaverde Group for sedimentary rocks lying between the top of the Gallup Sandstone and the base of the Point Lookout Sandstone, about 3 miles southwest of the mouth of Crevasse Canyon near Gallup, New Mexico. The name Crevasse Canyon Formation has been used in the Puertecito Quadrangle for the beds between the top of the Gallup Sandstone and the base of the unconformably overlying Baca Formation (Dane et al, 1957). Tabet (1979) used the name Dilco Coal Member of the Crevasse Canyon Formation for a sequence of drab-gray and tan shales, thin tan sandstones, and lenticular coal beds overlying the basal

Fig. 13 Oyster bearing calcareous sandstone in the Gallup Sandstone (unit #14 at Section II). Rock hammer 32.5 cm long.

Fig. 14 Close up of Figure 13. Rock hammer 32.5 cm long.

Sandstone (Gallup Sandstone) in this study area.

The Crevasse Canyon Formation is 478 ft. 9 in. thick (although 214 ft. 6 in. are covered) at Sec. 8, T.3S., R.3E., (Section III). It consists of interbedded sandstones, siltstones, and lenticular coal beds.

The sandstones in the lower part of the Crevasse Canyon Formation are very thickly laminated to medium-bedded, yellowish-orange, brownish-gray, grayish-orange, and grayish-white; moderately to well-sorted, moderately to well-indurated, and very fine- to medium-grained. Iron oxide nodules and plant impressions are fairly common and occur locally.

Sedimentary structures observed in the lower part of the Crevasse Canyon Formation include: internal, planar-parallel laminations which are common; sets of small scale, low angle trough shaped tangential and planar cross-laminations (Fig. 15); small scale, low angle tabular planar cross-laminations (Fig. 15); and wavy parallel and non-parallel continuous and discontinuous laminations less commonly. Erosional lower contacts are observed locally.

The interbedded shales in the lower part of the Crevasse Canyon Formation have color varying from light gray to dark gray to yellowish-brown. The shales are silty and fissile locally and thin laterally. Plant fragments are common and iron oxide nodules occur locally.

Horizontal and vertical burrows are fairly common in the lower part of the Crevasse Canyon Formation (Fig. 16). The vertical burrows are smooth walled, circular in outline, and

Fig. 15 Sets of small scale, low angle trough shaped cross-laminations (A) and small scale, low angle tabular-planar cross-laminations (B) in the Crevasse Canyon Formation (unit #24, at Section II). Note: Erosional contacts in both types of cross-stratifications. Rock hammer 32.5 cm long.

Fig. 16 Randomly oriented horizontal (A) and vertical (B) (to the bedding plane) burrows in the lower part of the Crevasse Canyon Formation (unit #33 at Section II). Rock hammer 32.5 cm long.

up to 1.3 cm in diameter. The horizontal burrows are smooth walled, 0.5 - 1 cm in diameter and up to 22 cm long.

The sandstones in the upper part of the Crevasse Canyon Formation are thinly to medium-bedded, light gray, brownish-gray, yellowish-orange, grayish-orange, and grayish-white; moderately to well-sorted, indurated, and very fine-to medium grained. Sedimentary structures in the upper part include channel scale cut and fill structures (Figs. 17 and 18), small scale, low angle trough cross-laminations (Fig. 19), herring bone cross-bedding (Fig. 20), small scale, low angle tabular planar and tangential cross-bedding (Figs. 20 and 21), small scale, high angle tabular tangential cross-bedding (Fig. 20) with erosional and non erosional contacts, sets of small scale, low angle wedge shaped planar cross-laminations with erosional and non erosional contacts (Fig. 21), planar-parallel cross-laminations (Fig. 21), and at one place hummocky cross-stratification (Fig. 19).

Calcareous sandstone concretions (Fig. 22) commonly exhibit cone-in- cone structures in their weathered portions. Plant impressions and carbonaceous material are fairly common and occur locally. Iron oxide (hematite and limonite) staining or coating is common.

Cardium sp., and Turritella sp., were collected from a grayish-white silty sandstone, with coaly fragments (unit #34 at Section III). The shells occur as lag deposit at the base of a channel scale cut and fill structure (Fig. 17). A yellowish-orange, fine-grained calcareous sandstone (unit #13, 77 ft.

Fig. 17 Channel scale cut and fill structures (1-6) in the Crevasse Canyon Formation. Grouped sets of small scale, low angle trough corss-laminations (A) (unit #34 at Section III). Rock hammer 32.5 cm long.

Fig. 18 Channel scale cut and fill structures (1-5) in the Crevasse Canyon Formation. This picture shows the same structures as Figure 17 but taken from a different angle of view. Rock hammer 32.5 cm long.

Fig. 19 Hummocky cross-stratification (H) and sets of small scale, low angle trough shaped tangential cross-laminations (A) in the Crevasse Canyon Formation (unit #59 at Section III). Rock hammer 32.5 cm long.

Fig. 20 Herring bone cross-bedding (H) in the Crevasse Canyon Formation (unit #45 at Section III). Note: The opposed directions of the two sets of cross-beddings A and B, (A) = set of small scale, low angle tabular tangential cross-bedding. (B) = set of small scale, high angle tabular tangential cross-bedding. Rock hammer 32.5 cm long.

Fig. 21 Sets of small scale, low angle wedge shaped planar cross-laminations (A and B); note: erosional contancts. Set of small scale, low angle tabular planar and tangential cross-bedding (C) and planar-parallel laminations (D) in the Crevasse Canyon Formation (unit #45 at Section III). Rock hammer 32.5 cm long.

Fig. 22 Sandstone concretions in the Crevasse Canyon Formation; above unit #45 at Section III. Rock hammer 32.5 cm long.

above the base of Section IV, Sec. 8, T.3S., R.3E.) contains abundant oysters. _Exogyra_ sp., _Pteria_ sp., and _Inoceramus_ sp., are identified from this unit.

The shales in the upper part of the Crevasse Canyon Formation, immediately overlying the sandstone units showing channel scale cut and fill structures, are light gray to dark gray and fissile, and weather to grayish-orange and yellowish-orange. The shales are intercalated with very thin beds of grayish-white siltstone locally. Plant and carbonaceous materials occur locally.

The shales immediately overlying and underlying the coal lenses are brown to dark brown in color and contain abundant plant and carbonaceous materials. Fissile and non fissile light gray to dark gray shales occur toward the top of the measured sections above the lenticular coal beds. These shale units are covered at most places and locally contain a fair amount of plant and carbonaceous materials.

Throughout the whole Crevasse Canyon Formation plant impressions, petrified wood fragments, and carbonaceous material are fairly common within the shales and siltstones and less common in the sandstones.

Four coal beds at Section III and one coal bed at Section IV occur in the upper part of the Crevasse Canyon Formation. These coal beds are laterally discontinous and occur as lenses.

SEMI-QUANTITATIVE CLAY MINERAL ANALYSIS

Clay mineral analysis of shale and/or mudstone samples was done to: 1) identify clay mineral groups in the clay size fraction 2) determine the relative abundances of the clay mineral groups within each sample by x-ray diffraction methods 3) determine if there are variations in type and relative abundances of the clay mineral components in the different samples with respect to their stratigraphic positions, and 4) determine if these variations can be used to aid in paleoenvironmental interpretations.

Eight samples were collected from different stratigraphic horizons from the four partial sections measured in this study. The stratigraphic locations of each sample are indicated by asterisks on the respective stratigraphic columns in Plate 2. Samples 1, 2, and 3 were collected from the lower tongue of Mancos shale, the Carthage Member of the Tres Hermanos Formation, and the D-Cross tongue of the Mancos shale respectively. Samples 4 to 8 were collected from the Crevasse Canyon Formation. Sample 7 was collected 3 feet below a coal bed in Section III and sample 8 was collected direclty above a coal bed in Section IV.

Oriented sedimented mounts were made following procedure for preparation of oriented clay mineral aggregates currently in use at the New Mexico Bureau of Mines and Mineral Resources (Austin, pers. comm., 1986, Deputy Director, NMBM&MR, Socorro, New Mexico). A sample weighing 20-25 grams is placed in a 100 ml beaker with deionized or distilled water. The contents of the beaker are mixed and re-mixed after 5 minutes of first mixing. Then after 15 seconds the suspension is poured into another 100 ml beaker.

If clay flocculates, the clear water is poured off and more deionized water is added and the content of the beaker is re-mixed. This step is repeated several times if clay did not disperse. Wet grinding samples in distilled or deionized water in a mortar until slurry is developed is done for some samples where the clay still flocullated after washing several times. The slurry is placed in 100 ml beaker filled with deionized water. Once the clay is in a dispersed state, the contents of the beaker are allowed to remain undisturbed for 10 minutes and using an eye-dropper, enough material to cover a glass slide is drawn off from the surface of the suspension. This fraction is less than 2 micrometers in size. The glass slides are allowed to air dry.

Each sedimented slide was run on the x-ray diffractometer four ways:

1) untreated sample - 2° to 35° 2θ at 2°2θ/minute
2) untreated sample - slow run 24° to 26° 2θ at 0.5°2θ/minute
3) after 24 hours in an ethylene glycol atmosphere - 2° to 15° 2θ at 2°2θ/minute and
4) after heating for ½ hour at 375° C - 2° to 15° 2θ at 2°2θ/minute

The instrumental settings used to obtain the diffraction patterns are:

Radiation/filter	Cu/Ni
Kilovolt/milliampere	40/25
Counts per second	2000 to 4000
Standard deviation	3%

Time constant	0.5 seconds
Slits	1° - 4° - 1°
Scan speed	2°/minute or 0.5°/ minute
Chart speed	20 mm/min

The relative abundances of the clay mineral components are calculated using the method suggested by Austin (pers. comm., 1986). The method is based on peak heights rather than peak areas, and is outlined below; abundances are given in parts of 10.

$$\text{Illite} = \frac{I(1G)}{T} \times 10$$

$$\text{Smectite (Montmorillonite)} = (M(1)/4/T) \times 10$$

$$\text{Chlorite} = \frac{C(3)}{I(2)} \times \frac{I(1G)}{T} \times 10$$

$$\text{Mixed-layer clay minerals} = \frac{I(1H) - [I(1G) + \frac{M(1)}{4}]}{T} \times 10$$

$$\text{Kaolinite} = \frac{K(1)}{T} \times 10 \quad \text{or, if chlorite is present}$$

$$= \frac{K(2)}{2C_{(4)}} \times \frac{C(3)}{I_{(2)}} \times \frac{I(1G)}{T} \times 10$$

Where T is equal to "total counts" and is calculated thusly:

$T = I(1H) + K(1)$ or, if chlorite is present:

$$T = I(1H) + \left[\frac{C(3) \times I(1G)}{I(2)}\right] + \left[\frac{K(2) \times C(3) \times I(1G)}{2C(4) \times I(2)}\right]$$

K(1) = first order kaolinite peak on untreated run; at 7Å, 12.4° 2θ

K(2) = second order kaolinte peak on untreated slow run; at 3.6Å, 24.9° 2θ

I(2) = second order Illite peak on untreated run; at 5Å, 17.8° 2θ

C(3) = third order chlorite peak on untreated run; at 4.6 to 4.8Å, 18.4° to 18.9° 2θ

C(4) = fourth order chlorite peak on untreated slow run; at 3.5Å, 25.1° 2θ

M(1) = first order smectite (Montmorillonite) peak on glycolated run; at 17Å, 5.2° 2θ

I(1G) = first order illite peak on glycolated run; at 10Å, 8.8° 2θ

I(1H) = first order illite peak on heated run; at 10Å, 8.8° 2θ

All the peak heights (peak intensities) were taken above background. Tables 2 and 3 show peak intensity data and relative abundances of clay mineral groups respectively. The clay mineral relative abundances can easily be observed in the histograms of Figure 23.

Lateral variations of clay mineral assemblages have been used to aid in the interpretation of depositonal environments, particularly in the transition from marine to non marine depositional environments. Parham (1966) and Weaver (1967) discuss the general trend of clay mineral assemblages with respect to depositional environments, compiled from the results of various workers. Figure 24 shows the order of first appearance and generalized lateral variations of major clay mineral groups from shoreward to basinward areas.

Table 2. Peak intensity data for relative clay mineral abundances - parts per 100.

SAMPLE NUMBER	T	$I_{(1H)}$	$I_{(1G)}$	$I_{(2)}$	$K_{(1)}$	$K_{(2)}$	$M_{(1)}$	$C_{(3)}$	$C_{(4)}$
1	76.6	10.6	5.0	5.5	15.5	11.2	21.0	5.2	2.6
2	198.3	12.5	7.5	6.0	94.0	67.2	0.5	3.6	7.0
3	59.1	15.0	5.0	6.0	7.2	4.5	13.0	6.4	2.0
4	60.3	15.8	7.0	8.5	12.0	4.5	2.0	6.5	4.0
5	199	66.0	11.5	11.5	54.0	25.0	5.0	6.0	20.0
6	111.1	23.2	5.0	6.0	25.0	12.0	28.0	5.0	6.9
7	177.6	15.6	6.5	5.0	65.0	41.5	29.0	5.0	10.0
8	200.7	18.2	8.0	7.0	74.0	40.0	34.0	4.0	15.5

T = total counts

$I_{(1H)}$ = first order illite peak on heated run

$I_{(1G)}$ = first order illite peak on glycolated run

$I_{(2)}$ = second order illite peak on untreated run

$K_{(1)}$ = first order kaolinite peak on untreated run

$K_{(2)}$ = second order kaolinite peak on untreated slow run

$M_{(1)}$ = first order montmorillonite peak on glycolated run

$C_{(3)}$ = third order chlorite peak on untreated run

$C_{(4)}$ = fourth order chlorite peak on untreated slow run

Table 3. Relative abundances of clay minerals in parts per 10 (numbers in parentheses indicate calculated values not rounded to one significant figure).

SAMPLE NUMBER	ILLITE	SMECTITE	CHLORITE	MIXED LAYER CLAY MINERALS	KAOLINITE
1	2 (1.96)	2 (2.06)	2 (1.89)	0 (0.13)	4 3.99
2	2 (1.94)	0 (0.03)	1 (1.17)	1 (1.26)	6 5.99
3	2 (1.90)	1 (1.23)	2 (2.03)	3 (2.56)	2 (2.28)
4	3 (2.79)	0 (0.20)	2 (2.13)	3 (3.31)	1 (1.20)
5	2 (1.52)	0 (0.17)	1 (0.79)	7 (7.03)	0 (0.50)
6	2 (1.61)	2 (2.26)	1 (1.34)	4 (3.61)	1 (1.17)
7	2 (1.83)	2 (2.04)	2 (1.83)	0 (0.52)	4 (3.79)
8	3 (2.79)	3 (2.96)	2 (1.59)	0 (0.59)	2 (2.06)

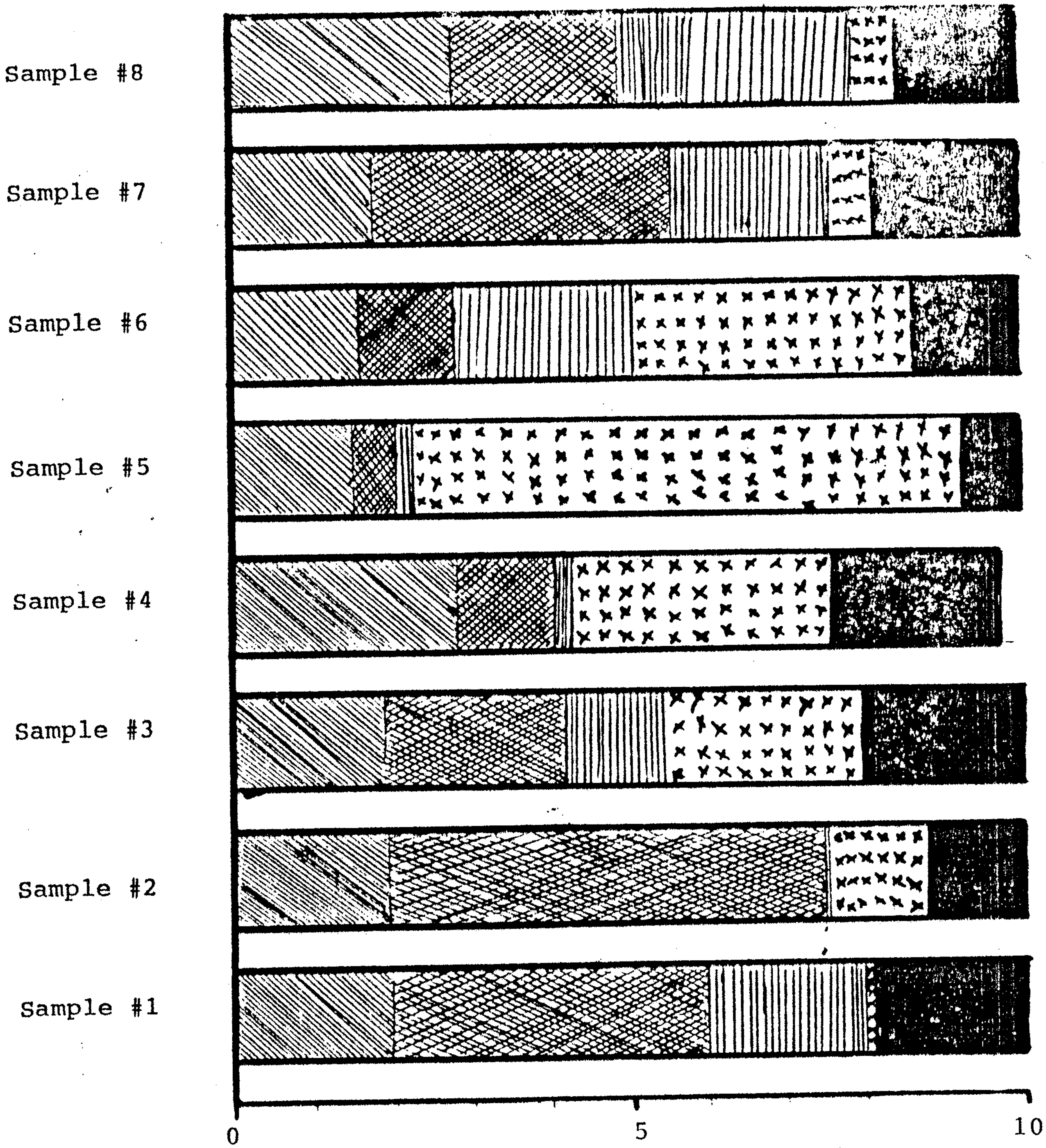
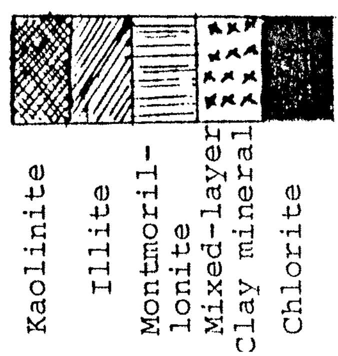


Fig. 23 Histograms of clay mineral relative abundances in parts per 10.



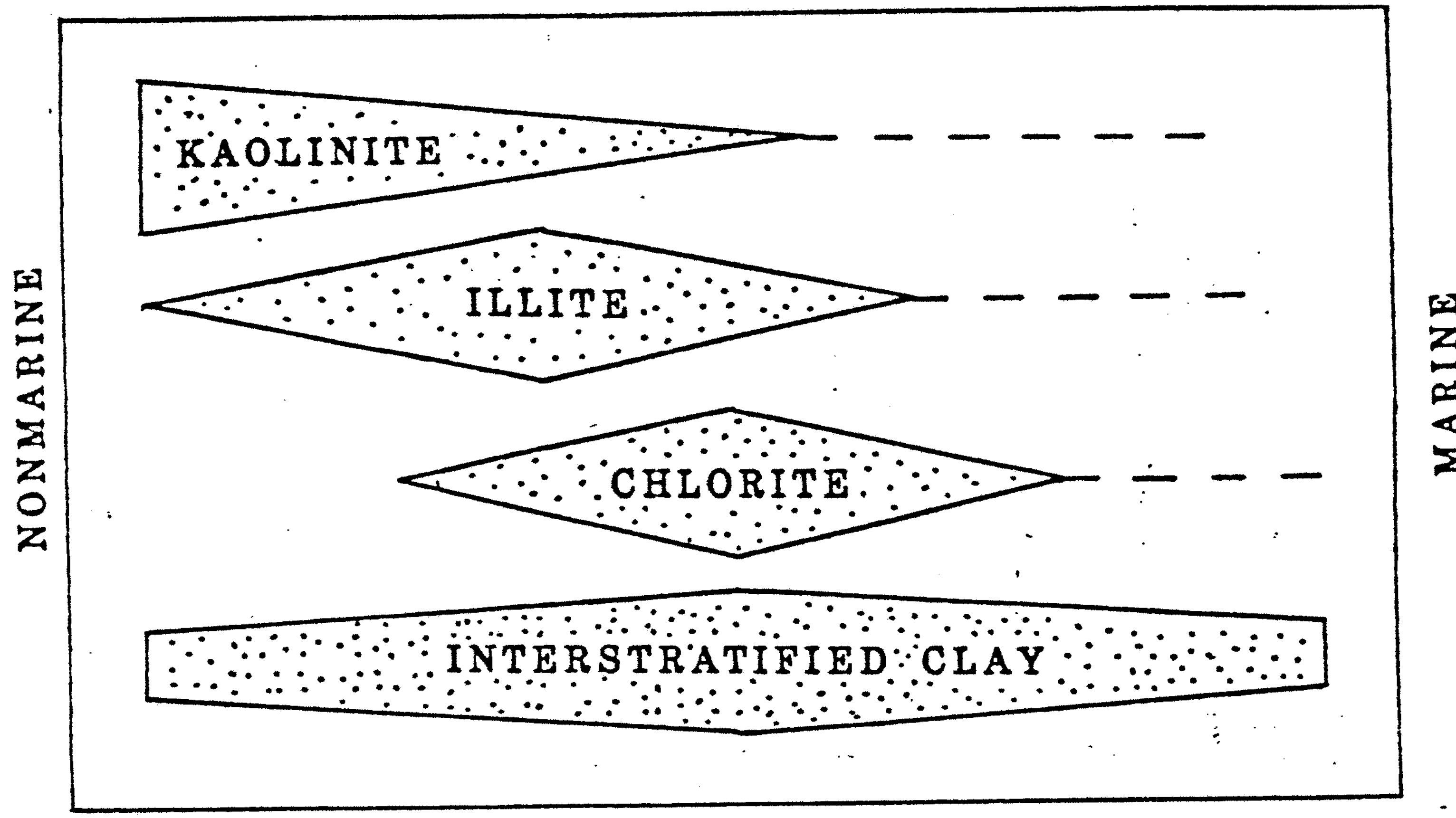


Fig. 24 Generalized lateral variations in clay mineral assemblages from shoreward to basinward areas (from Krukowski, 1983; modified from Parham, 1966).

Murray (1954) showed that in some Pennsylvanian cyclothems from Illinois illite was always dominant but that chlorite and kaolinite decreased in going from non-marine to brackish to marine shales.

In Cretaceous sediments in the upper Mississippi embayment, kaolinite is dominant in the continental, montmorillonite in the marine and illite with kaolinite and montmorillonite dominant in the near-shore transitional environments (Pryor, 1960).

Study on the Cretaceous-Tertiary clay mineralogy of the upper Mississippi Embayment by Pryor and Glass (1961) shows kaolinite as the dominant clay mineral in the fluviatile environment and montmorillonite the dominant clay mineral in the outer neritic environment and the inner neritic environment to be composed of nearly equal amounts of kaolinite, illite, and montmorillonite.

A decrease in illite and an increase in kaolinite and mixed-layer clay minerals is observed in a study of middle Pennsylvanian deltaic deposits, corresponding to the transition from marine to non marine depositional environments (Brown, et al, 1977).

The amount of illite appears to remain relatively constant in all the samples in this study and the general trend of increasing kaolinite inland is not observed. A slight increase in montmorillonite is observed going from the lower tongue of Mancos shale (transition to shallow, open normal marine shelf) to the Crevasse Canyon Formation (swamp-lagoonal marsh). There appears to be an inverse relation between the relative proportions of kaolinite and montmorillonite, and mixed-layer clay minerals. The mixed-layer minerals seem to be formed at the expense of kaolinite and montmorillonite. Chlorite remains relatively constant in all samples and is assumed to be detrital (Austin, pers. comm., 1986).

Analysis of data, from the Carthage area (McLafferty, 1979) and Sevilleta Grant area (Baker, 1981), by MANOVA (multivariate analysis of variance) showed that there are statistically significant differences in the relative proportions of clay mineral groups in mudstones as a function of their depositional environment (MacMillan, pers. comm., 1986). A discriminant function analysis (a SPSSX packaged program available at the Tech computer center) was applied to develop a discriminant function so that the relative proportions of the clay mineral groups in the clay size ($<$2 micron) fraction of the mudrock could be entered and its probable depositional environment would be predicted. Data from 8 samples from this study area and 21 samples from the Carthage and Sevilleta Grant areas were used in the discriminant function analysis. The data were grouped into four groups of depositional environments and entered. 62.07% of the grouped cases were correctly classified and 37.93% of the grouped cases (11 samples) did not fall in their respective predicted group. Summary of the data used in the discriminant function analysis is given in Table 4 and Table 5 gives the classification results after the discriminant analysis was done.

Table 4. Summary of data used in the discriminant function analysis.

SAMPLE AREA	STRATA AND SAMPLE NO.			RELATIVE ABUNDANCE OF CLAY MINERALS					PROBABLE ENVIRONMENT OF DEPOSITION
				K	Mx	I	Sm	C	
Cth	Kc	10		3	5	2	-	-	Alluvial plain to flood plain (Group 1).
Cth	Kc	9		3	5	2	-	-	
Cth	Kc	8		2	6	2	-	-	
Jdm	Ktc	2		6	1	2	-	1	
			$\overline{X}$	3.5	4.25	2.0	0.0	0.25	
			S.D	1.73	2.22	0.0	0.0	0.50	
Cth	*Kc	7		4	4	2	-	-	Coastal swamp-lagoonal marsh and lagoonal tidal flat (Group 2).
Cth	*Kc	6		5	3	2	-	-	
Cth	*Kc	5		3	4	3	-	-	
Svgr	Kc	11		4	2	1	1	-	
Svgr	*Ktc	6		4	3	1	2	-	
Svgr	Ktc	5		4	2	1	1	-	
Jdm	Kc	4		1	3	3	-	2	
Jdm	*Kc	5		-	7	2	-	1	
Jdm	Kc	6		1	4	2	2	1	
Jdm	Kc	7		4	-	2	2	2	
Jdm	Kc	8		2	-	3	3	2	
			$\overline{X}$	2.91	2.91	2.0	1.0	0.73	
			S.D	1.64	1.97	0.77	1.09	0.9	
Cth	Kg	4		1	7	3	-	-	Shallow, near shore transition from open, normal marine shelf (Group 3).
Cth	*Kmd	3		2	6	2	-	-	
Cth	Kmd	2		1	7	3	-	-	
Cth	*Kmd	1		1	6	3	-	-	
Svgr	*Kmd	10		7	3	-	-	-	

Table 4. (con't) Summary of data used in the discriminant function analysis.

SAMPLE AREA	STRATA AND SAMPLE NO.			RELATIVE ABUNDANCE OF CLAY MINERALS					PROBABLE ENVIRONMENT OF DEPOSITION
				K	Mx	I	Sm	C	
Svgr	Kmd	9		6	2	2	1	-	
Jdm	*Kml	1		4	-	2	2	2	
Jdm	*Kmd	3		2	3	2	1	2	
			$\overline{X}$	3.0	4.25	2.13	0.50	0.50	
			S.D	2.39	2.60	0.99	0.76	0.93	
Svgr	Kmd	8		3	1	6	-	-	Open, normal marine shelf (Group 4).
Svgr	*Kmd	7		4	4	2	-	-	
Svgr	Kmr	4		4	2	2	2	-	
Svgr	Kmr	3		2	5	2	2	-	
Svgr	Kml	2		4	2	2	2	-	
Svgr	Kml	1		3	-	2	5	-	
			$\overline{X}$	3.33	2.33	2.67	1.83	0.0	
			S.D	0.82	1.86	1.63	1.83	0.0	

* Samples that did not fall in their respective predicted group.

Cth = Carthage area - samples collected and analyzed by McLafferty (1979).

Svgr = Sevilleta Grant area - samples collected and analyzed by Baker (1981).

Jdm = Jornada del Muerto coal field - this study.

Kml = Lower Tongue of Mancos Shale.

Kmd = D-Cross Tongue of Mancos Shale.

Table 4. (con't) Summary of data used in the discriminant function analysis.

Kmr = Rio Salado Tongue of Mancos Shale.

Ktc = Carthage Member of the Tres Hermanos Formation.

Kc = Crevasse Canyon Formation.

K = Kaolinte

Mx = Mixed-layer clay minerals.

I = Illite.

Sm = Smectite (montmorillonite).

C = Chlorite.

$\overline{X}$ = Group mean.

S.D. = Group standard deviation.

Table 5. Classification results after discriminant function analysis of 29 samples.

ACTUAL GROUP	NUMBER OF CASES	PREDICTED GROUP MEMBERSHIP			
		1	2	3	4
Group 1	4	4 (100.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)
Group 2	11	3 (27.3%)	6 (54.5%)	1 (9.1%)	1 (9.1%)
Group 3	8	3 (37.5%)	2 (25.0%)	3 (37.5%)	0 (0.0%)
Group 4	6	1 (16/7%)	0 (0.0%)	0 (0.0%)	5 (83.3%)

Percentage "grouped" cases correctly classifed - 62.07%.

COAL

SURFACE COAL EXPOSURES

Thin coal beds occur within the Crevasse Canyon Formation. These coal beds are mostly covered, laterally discontinous and occur as lenses. Where they occur, the coal lenses are underlain and overlain by dark brown shale, locally fissile, containing abundant plant material and some carbonaceous material locally. The exposures are weathered or oxidized. Thickness of the coals ranges from 3 inches to 2 feet with the thickest exposure at SE¼ SW¼ Sec. 8, T.3S., R.3E. This bed thins laterally within a few yards. Tabet (1979) reported two coal beds, separated by a foot of shale, exposed in the abandoned Law mine in SW¼ NW¼ Sec. 3, T.4S., R.3E. The lower coal is 28 inches thick and the upper coal is 8 inches thick. Figure 25 shows a weathered or oxidized surface of a lignitic coal.

COAL ANALYSES

Two samples were collected from unit #52 (Section III) and unit #16 (Section IV) and proximate analysis of them was done by Frank Campbell (Coal Geologist, New Mexico Bureau of Mines and Mineral Resources, Socorro, New Mexico). Table 6 shows the proximate analyses results of the two samples. According to the specifications for classification of coals by rank (American Society for Testing and Materials, 1986), the results listed in Table 6 show that the coal from the two samples falls in the Lignitic class and the Lignite A Group. This rank, however, can

Fig. 25 Weathered or oxidized coal (lignitic) exposure (C) in the Crevasse Canyon Formation (unit #52 at Section III). Rock hammer 32.5 cm long.

not be taken as representative of the rank of coals in the Jornada field as the samples were taken from surface outcrops where the coal is weathered or oxidized. The rank given here is assumed to be a minimum rank and the actual rank of fresh coal samples is expected to be higher. Analytical results from a channel sample from the lower coal bed from the Law mine in the Jornada field, show the coal to be high-volatile C-bituminous coal (Tabet, 1979).

Table 6. Analyses of coal samples from the Crevasse Canyon Formation in the Jornada coal field.

	Sample 1 Crevasse Canyon Formation (unit #52, Section III)	Sample 2 Crevasse Canyon Formation (unit #6, Section IV)
	As Received	As Received
Proximate analysis (%)		
Moisture	17.07	13.36
Ash	19.88	27.20
Volatile matter	31.88	28.44
Fixed carbon	31.67	31.0
Calorific value (Btu/lb)	6077	5607
Sulfur (%)	0.32	0.38
Dry mineral matter free (dmmf) fixed carbon	51.6%	54.23%
Moist mineral matter free (mmmf) Btu/lb	7735.45	8089.66

INTERPRETATION OF PALEOENVIRONMENTS (AND AGE)

Deposition during the late Cretaceous Epoch in New Mexico, occurred in transgressive-regressive cycles with minor cycles within them producing intertongued stratigraphic units (Molenaar, 1973). The Upper Cretaceous Series in Socorro County was deposited during the Greenhorn cycle, which began in early middle Cenomanian time and lasted until middle Turonian, and the Carlile cycle which lasted from middle Turonian until early Coniacian time in New Mexico (Hook and Cobban, 1979). The Greenhorn cycle is divided into the Dakota transgression and the Tres Hermanos regression phases.

The various tongues and members of the Dakota Sandstone and Mancos Shale are associated with the Dakota trangression of the Greenhorn cycle that began in early middle Cenomanian time and lasted unitl late Cenomanian time encompassing about 2 million years. The beginning of this cycle is represented by the ammonite zone of *Colinoceras tarrantense*. The Greenhorn sea reached maximum trangression during the time represented by the ammonite zone of *Metoioceras mosbyense* (Hook, 1983).

The Rio Salado Tongue of the Mancos Shale and the Atarque Sandstone and Carthage Members of the Tres Hermanos Formation are associated with the Tres Hermanos regression of the Greenhorn cycle which began in late Cenomanian time and lasted until middle Turonian time. The beginning and end of this cycle of regression are represented by the upper Cenomanian zone of *Sciponoceras gracile* and the middle Turonian zone of *Prionocyclus hyatti* respectively (Hook, 1983).

The Carlile cycle has two transgressive and regressive phases of approximately equal duration. These are the D-Cross transgression and the Gallup regression which seems to be unique to New Mexico and northeasternmost Arizona (Molenaar, 1983). In Socorro County, the upper part of the Carthage Member, the Fite Ranch Sandstone Member, and the lower part of the D-Cross Tongue of Mancos Shale are associated with the D-Cross transgression which began during the highest middle Turonian ammonite zone of *Prionocyclus hyatti* and probably lasted until the lower part of the late Turonian ammonite zone of *Prionocyclus novimexicanus*. The upper part of the D-Cross Tongue, the Gallup Sandstone, and the lower part of the Crevasse Canyon Formation are associated with the Gallup regression which began in middle late Turonian time and probably lasted until early Coniacian time. The maximum regression reached is represented by the inoceramid zone of *Inoceramus erectus* (Hook, 1983).

Figures 26 through 30 show the approximate positions of the Western shoreline, in the southwestern part of the Western Interior, during the times represented by ammonite and inoceramid zones.

Comparison of groups of paleontological and lithological (including sedimentary structures) characteristics of the rocks studied with established criteria for recognizing modern and ancientdepositional environments is used as an aid in the interpretation of paleoenvironments of the Upper Cretaceous rocks in this study area.

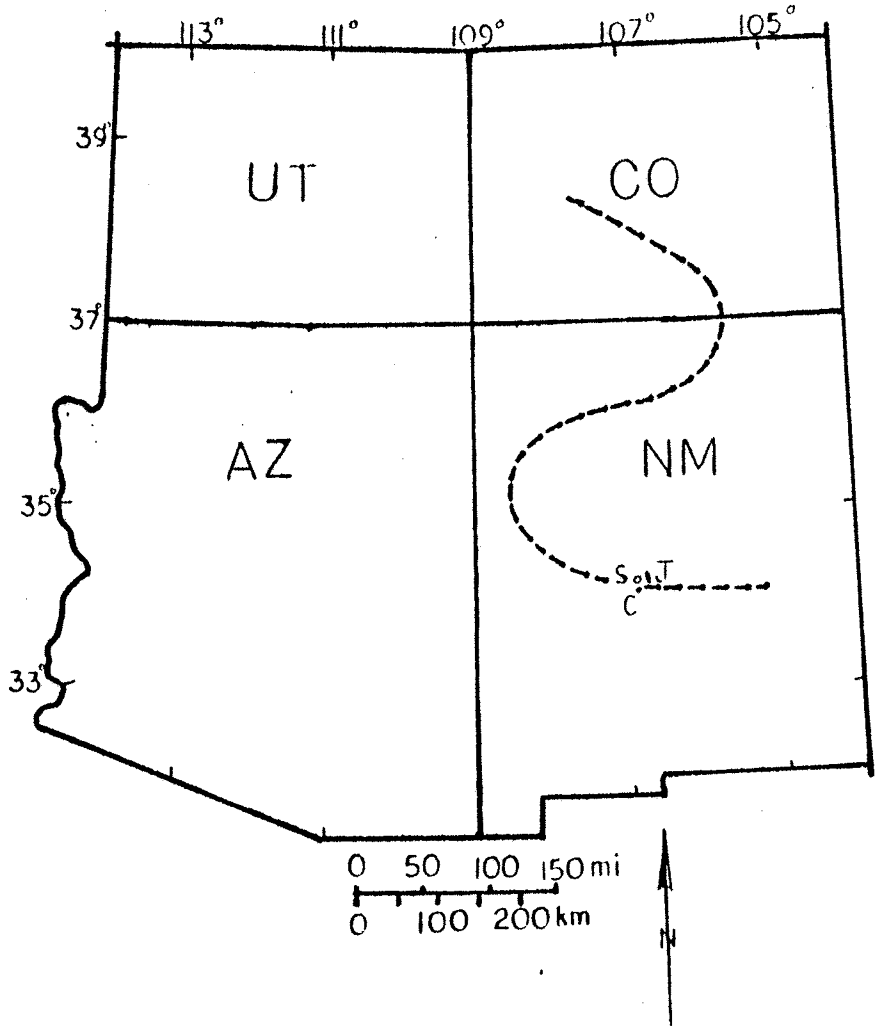


Fig. 26 Map of the southwestern part of the Western Interior showing approximate position of the western shoreline during the early middle Cenomanian represented by the ammonite zone of *Conlinoceras tarrantense* (modified from Hook, 1983)
S = Socorro
C = Carthage
J = Jornada de Muerto coal field

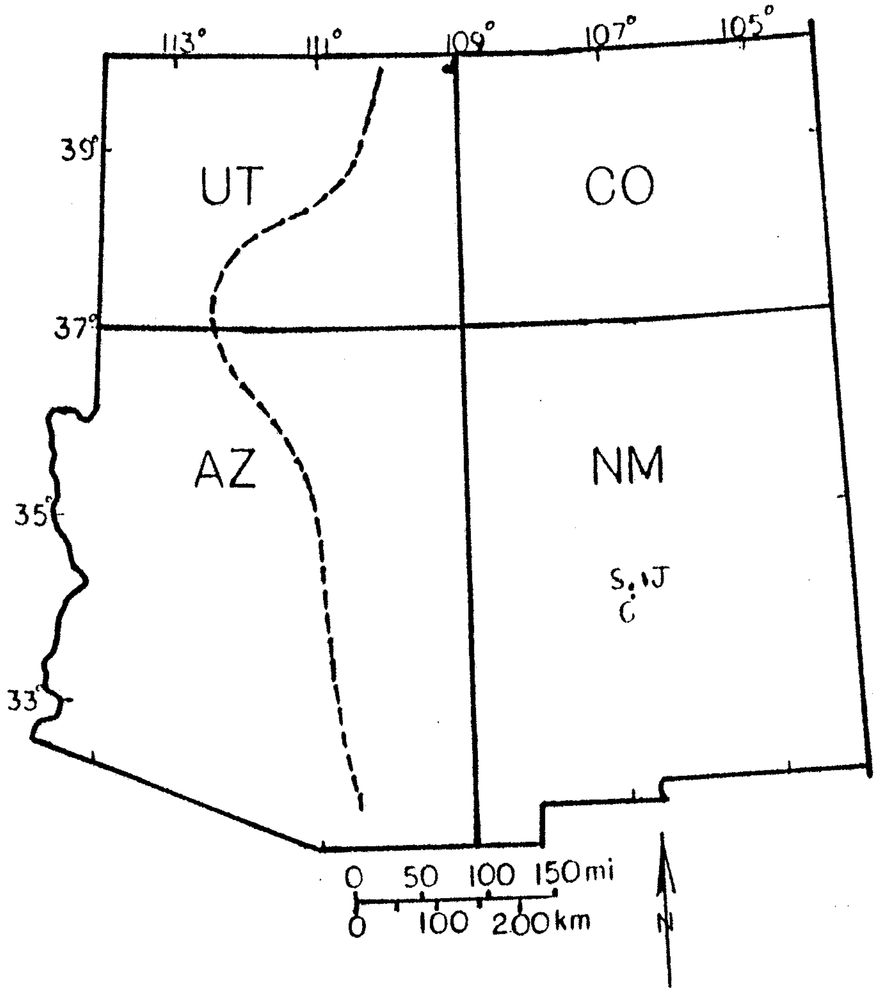


Fig. 27 Map of the southwestern part of the Western Interior showing approximate position of the western shoreline during the early to medial upper Cenomanian, represented by the ammonite zone of Metoicoceras mosbyense. (modified from Hook, 1983).
S = Socorro
C = Carthage
J = Jornada del Muerto coal field

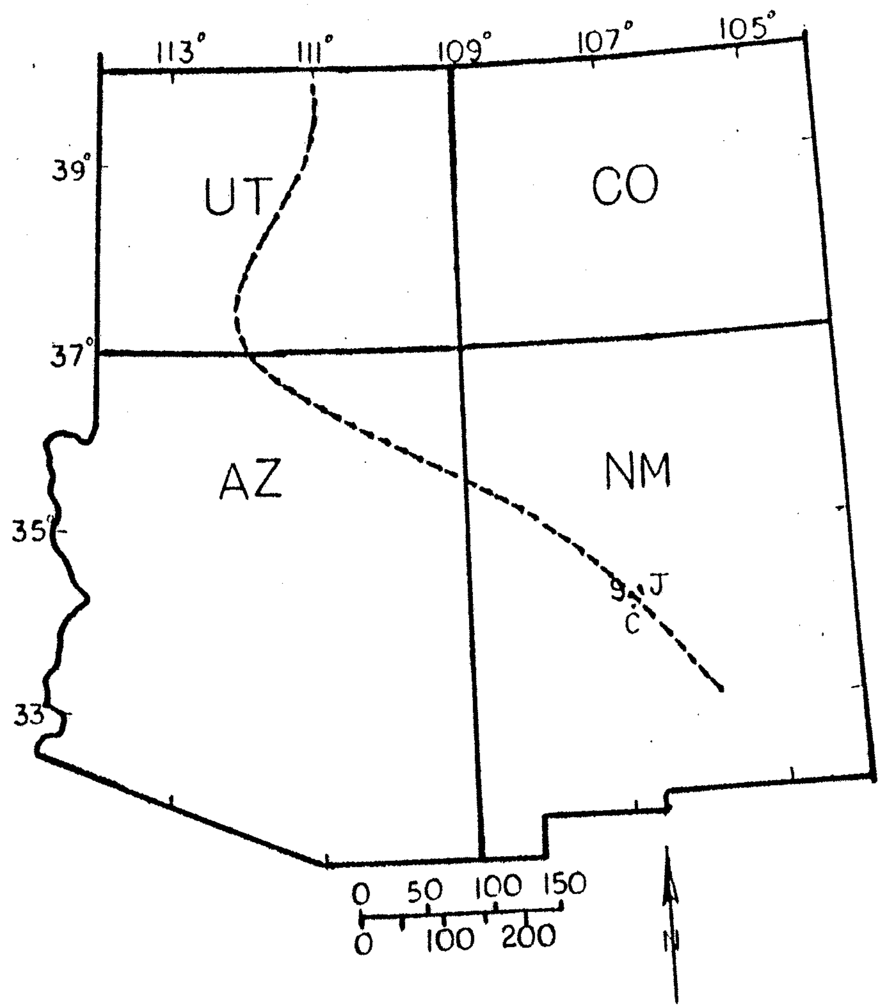


Fig. 28 Map of the southwestern part of the Western Interior showing approximate position of the western shoreline during the late middle Turonian, represented by the ammonite zone of <u>Prionocyclus hyatti</u> (modified from Hook, 1983).
S = Socorro
C = Carthage
J = Jornada del Muerto coal field

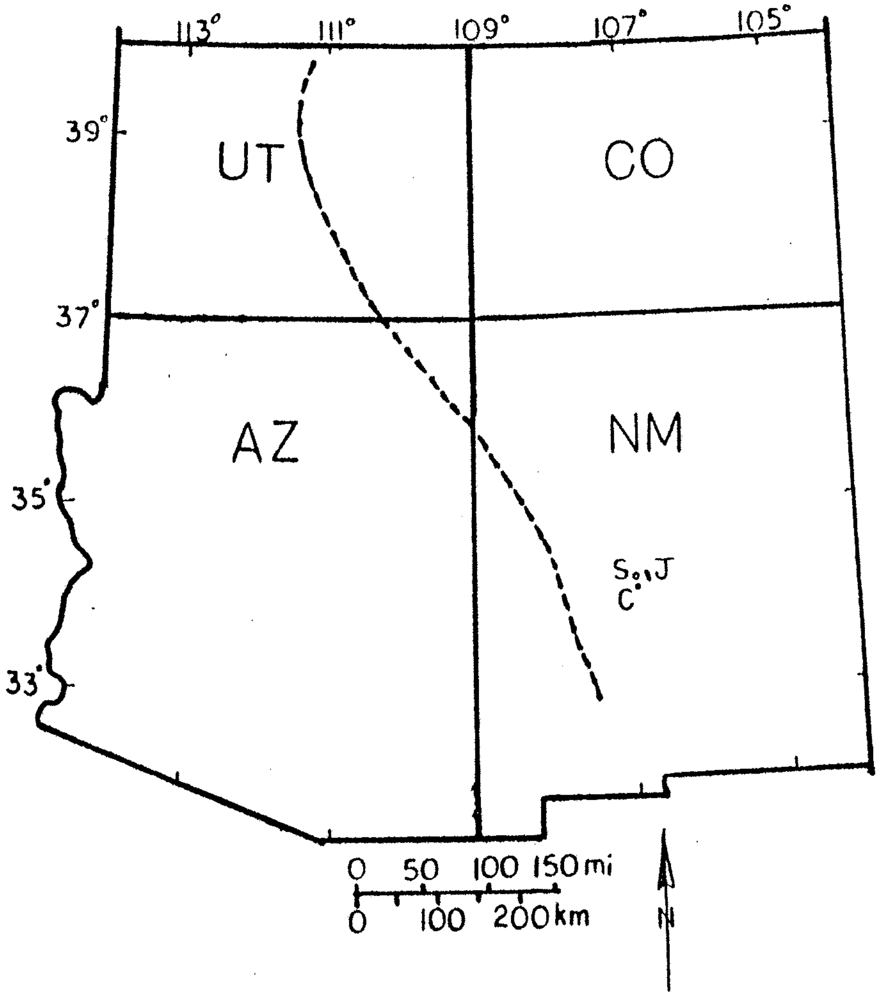


Fig. 29 Map of the southwestern part of the Western Interior showing approximate portion of the western shoreline during the medial upper Turonian, represented by the ammonite zone of *Prionocyclus novimexicanus* (modified from Hook, 1983).

S = Socorro
C = Carthage
J = Jornada del Muerto coal field

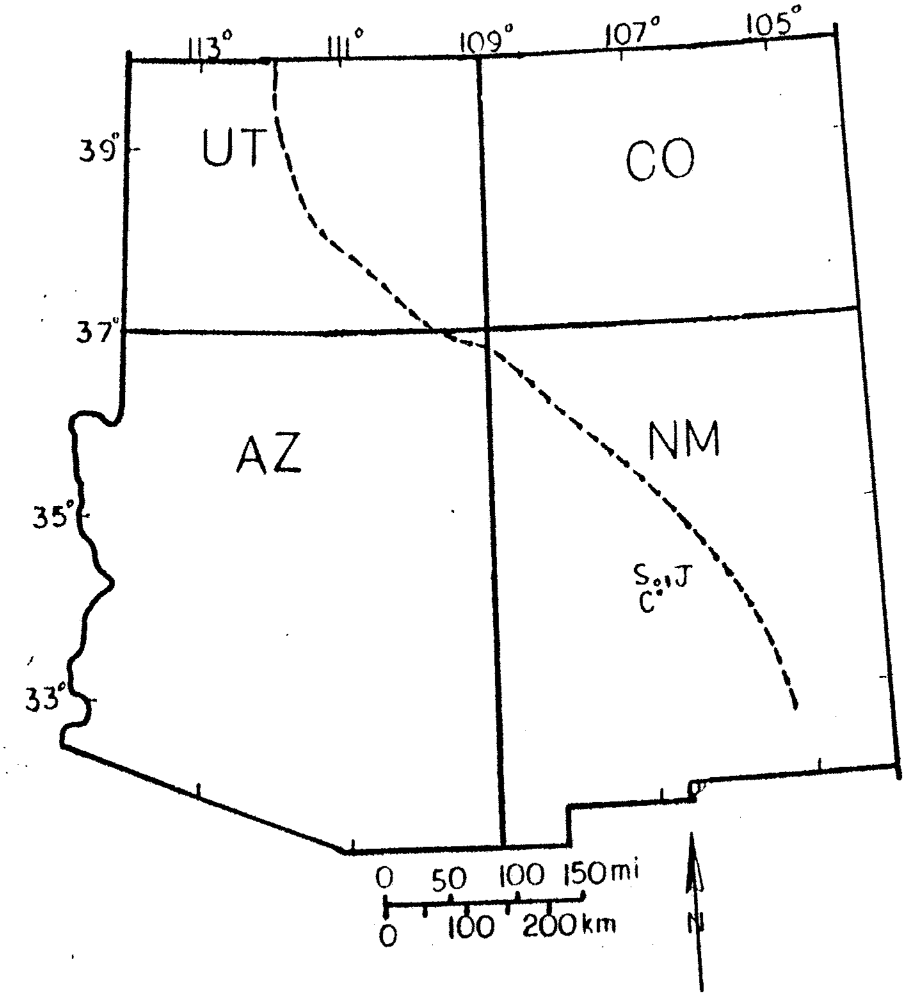


Fig. 30 Map of the southwestern part of the Western Interior showing approximate portion of the western shoreline during the lower Coniacian, represented by the inoceramid zone of Inoceramus erectus (modified from Hook, 1983).

S = Socorro

C = Carthage

J = Jornada del Muerto coal field

DAKOTA SANDSTONE

The Dakota Sandstone is characterized by moderately to well-indurated, well-sorted, fine-to medium-grained quartz sandstone. Properties of the grain-size distribution are fairly constant throughout the section (Section I). The lower part is structureless but shows some internal lamination and crude cross-laminations. Toward the top, the sandstone is bioturbated and carbonaceous material and plant impressions are fairly common.

The Dakota Sandstone has similar features with the middle to lower shoreface deposits displayed by the low energy, beach-shelf profile at Gulf of Gaeta, Mediterranean Sea, Italy (Reineck, and Singh, 1975) and the beach-upper shoreface to middle shoreface deposits of Galveston Barrier Island, Texas, and the Lower Cretaceous Muddy Sandstone at Bell Creek field, Montana. The internal sequence of textures and sedimentary structures of the Holocene barrier (Galveston Island) and the beach-shelf mud profile of Gulf of Gaeta are listed in Tables 7 and 8 and are used as standards with which the internal features of the barrier sequences in this study may be compared. In many cases, the thickness of sands in the study area does not compare with those of the Galveston Island or the Gulf of Gaeta. However, this can be expected as the thickness of the sands depends upon the complex interrelation of sediment supply and rate of subsidence.

The Dakota Sandstone is interpreted as a coastal sandstone body deposited in a nearshore (coastal) environment during the Dakota transgression of the Greenhorn cycle. The lower part which is commonly structureless but shows some internal laminations and crude cross-laminations locally is compared to the beach-upper shoreface facies at Galveston Island and the middle shoreface facies at the Gulf of Gaeta. However, there is a difference in grain size in the sediments of the lower part of the Dakota Sandstone and the beach-upper shoreface and middle shoreface facies of the Galveston Island and the Gulf of Gaeta respectively. The top most bioturbated sandstone is regarded as being deposited in the middle to lower shoreface. The presence of plant impressions and carbonaceous material is indicative of a low energy environment during the deposition of the top part of the Dakota Sandstone in this study area.

The assemblage of fossils and trace fossils (lobster and/or crab trails and an arm of a starfish(?)) indicate a nearshore, shallow water environment. The presence of a shark tooth [only one specimen] associated with oyster fragments probably indicates a tropical-subtropical warm shallow sea inhabited by sharks that fed on oysters (Wolberg, pers. comm., 1986).

The burrows in the Dakota Sandstone were compared with illustrations and descriptions of Upper Cretaceous ichnofaunas from Utah and Kansas (Frey and Howard, 1970), photographs and descriptions in part W of Treatise on invertebrate paleontology (Hantzschel, 1975), and photographs and descriptions of burrows in the basal assemblage, Carthage Field (McLafferty, 1979) and are identified with reasonable confidence as Thalassinoides and Skolithos. Hantzschel (1975) considers Thalassinoides to

Table 7. Summary of the vertical sequence of sedimentary features, from bottom to top (proceeding landward), of barrier island sediments from Galveston Island (after Davies et al, 1971).

FACIES	SEDIMENTARY FEATURES
Eolian	Fine-to very fine-grained sands, generally cross-laminated (festoon and planar) and parallel-laminated, and generally 2 to 8 ft thick. Structures progressively destroyed with increasing age.
Beach-Upper shoreface	Sediments gradationally succeed and lie shoreward of middle shoreface deposits and consist of fine-to very fine-grained, well laminated sands 3 to 10 ft thick. The most characteristic sedimentary structure is planar, low-angle, cross-lamination with localized developments of microcross-lamination. Burrowing is scarce and shells may be locally abundant.
Middle shoreface	Sediments are deposited shoreward of lower shoreface sediments and consist of very fine-grained sand which is extensively bioturbated. Some cross-laminated, shelly sand layers and interlaminae of silty clay are present sparingly. Sediments are deposited in from 5 to 30 ft of water, and thickness ranges from 10 to 34 ft.
Lower shoreface	Sediments are deposited seaward of the break in offshore slope, within the depth interval of 30 to 40 ft and consists of interbedded, burrowed, and churned (bioturbated), very fine-grained sand, silt, and silty clay which may reach a thickness of 6 ft.

Table 8. Summary of the vertical sequence of sedimentary features, from bottom to top (proceeding landward), of the beach-shelf mud profile off Licola, Gulf of Gaeta, Italy (after Reineck and Singh, 1975).

FACIES	SEDIMENTARY FEATURES
Eolian Sanddunes	Cross-bedded sands with plant roots and their burrows.
Foreshore	Laminated sands with heavy mineral concentrations.
Upper Shoreface	Fine-to medium-grained cross-bedded sands with minor bioturbation and laminations.
Middle Shoreface	Burrowed sands with some laminations and ripple cross-bedding.
Lower Shoreface	Very fine-to fine-grained extensively bioturbated sands with some laminations.
Transition-zone	Extensively bioturbated, very fine-grained sands with almost no primary sedimentary structures.
Shelf-mud	Extensive bioturbation with intercalations of storm-silt layers, laminated and weakly graded.

be feeding and dwelling burrows of crustaceans living in a sublittoral environment. The presence of Thalassinoides is an indicator of a nearshore environment (Frey and Howard, 1970). Skolithos occurs in the Skolithos ichnofacies which is indicative of relatively high levels of wave or current energy, and typically develops in clear, well-sorted, loose or shifting particulate substrates. Abrupt changes in rates of depositions, erosion, and physical reworking of sediments are frequent and such conditions commonly occur on the foreshores and shorefaces of beaches, bars, and spits (Frey and Pemberton, 1984). The presence of plant impressions and carbonaceous materials indicating a low energy environment and Skolithos indicating a relatively higher energy condition may suggest local fluctuations of wave or current energy during deposition of the Dakota Sandstone in this study area.

LOWER TONGUE OF MANCOS SHALE

The lower tongue of Moncos Shale is mostly covered and this has made it difficult to discuss the vertical succession of units in the lower tongue shale and their respective paleoenvironmental interpretation. The interpretation given here is based on the description of the lower tongue of Mancos Shale by Tabet (1979). The lower part consists of interbedded very fine-grained, silty and calcareous sandstones, and silty shales. Toward the top, the silty shales, sometimes calcareous, are interbedded with concretionary limestone beds. These interbedded units were probably deposited during still stands of the Late Cretaceous epicontinental seaway during which clastic influx was low and highly calcareous clays and interbedded thin ash falls were widely deposited (Hook, 1983). The interbedded silty shale and very fine-grained sandstone beds at the lower part of the lower tongue of Mancos Shale are regarded as being deposited in the transition-zone (Reineck and Singh, 1975) and are transitional between the underlying beach-upper shoreface to lower shoreface sands of the Dakota Sandstone and the shales and limestone beds of the upper part of the lower tongue of Mancos Shale which are interpreted as being deposited in a shallow water open marine environment.

Pycnondonte newberryi (Stanton) and *Sciponoceras gracile* (Shumard) were collected from a limestone bed 342 ft. above the top of the Dakota Sandstone (Tabet, 1979). *Inoceramus* sp. fragments and shark teeth occur 54 ft. above this bed.

Inoceramus sp. is an indicator of an open, normal marine water environment (Sabins, 1963). The presence of shark teeth probably indicates a tropical-subtropical warm shallow water marine environment (Wolberg, pers. comm., 1986).

The late Cretaceous oyster Pycnondonte newberryi (Stanton) is one of the most common guide fossils to the late Cenomanian and early Turonian in New Mexico and the adjacent four corners states. Occurrences of P. newberryi are known with certainity only from the four corners states. This geographic distribution is the result of several independent constraints. Temperature and facies are believed to be the main controlling factors to the distribution in the west and the north respectively (Hook and Cobban, 1977). Sciponoceras gracile (Shumard) is one of the standard ammonite zones for the Western Interior Cretaceous, and the Cenomanian-Turonian boundary is generally drawn at the top of the S. gracile Zone (Hook and Cobban, 1977). The presence of P. newberryi (Stanton) in association with S. gracile (Shumard) gives the lower tongue an age ranging from the latest Cenomanian into the earliest Turonian.

ATARQUE SANDSTONE MEMBER

The Atarque Sandstone Member is associated with the Tres Hermanos regression of the Greenhorn cycle and consists of thinly- to medium-bedded, moderately to well-sorted, fine-to medium-grained quartz sandstones with calcareous fossiliferous sandstone concretions locally. Ophiomorpha burrows are common in the lower part and the upper part is highly bioturbated. At Sec. 5, T.3S., R.3E., the Atarque is medium-to thick bedded and beds are structureless and mottled or show thick planar parallel or ripple lamination near the base of the unit, and low- to high angle cross-laminations is common near the top (Tabet, 1979). The Atarque Sandstone Member is interpreted as being deposited in a barrier-beach environment and this is supported by the transition from the underlying shallow water, open marine Mancos Shale and the presence of overlying non marine sediments of the Carthage Member. Deposition in the lower shoreface to middle shoreface of a barrier-beach is indicated by the structureless and mottled beds which sometimes show thick planar parallel or ripple laminations. Low-to high-angle cross-laminations indicate a middle shoreface to upper shoreface deposition succeeding (overlying) the middle shoreface to lower shoreface sediments at the lower part.

Lopha bellaplicata (Shumard) and Inoceramus sp. indicate an open normal marine environment. The association of abundant ophiomorpha in well-sorted, massive-bedded sandstone indicates wave-agitated littoral or shallow neritic conditions (Weimer and Hoyt, 1964).

Tabet (1979) reported Collignoniceras woollgari woollgari (Mantell) from the base of the Atarque Sandstone Member and Mammites depressus (Powell) as float 110 ft. below the base of the Atarque Sandstone Member. Fossils in the subzone of Collignoniceras woollgari woollgari in the Western Interior vary according to lithology and locality and the most diverse faunas are found in nearshore marine sandstone (Cobban and Hook, 1979). This has been observed in the Atarque Sandstone where the calcareous sandstone concretions contain diverse faunas. The middle Turonian is assigned for the range zone of C. woollgari and a very low or basal position in the middle Turonaian for the subzone of C. woollgari woollgari (Cobban and Hook, 1979). Lopha bellaplicata occurs in the Prionocyclus hyatti Zone and in the basal part of the overlying Prionocyclus macombi Zone and, therefore, has an age range of late middle to earliest late Turonian. The age of the Atarque Sandstone is suggested to range from the early middle Turonian to the late middle Turonian. Hook (1983) considers the Atarque Sandstone to be of early middle Turonian age in Socorro County.

CARTHAGE MEMBER

The Carthage Member consists of interbedded light to dark gray shales and a calcareous fossiliferous sandstone at the measured section. The calcareous sandstone contains a diverse fauna. Petrified wood fragments and fragments of oyster shells are common. The Carthage Member measured by Tabet (1979) at Sec. 5, T.3S., R.3E., consists of interbedded very fine-grained to medium-grained sandstones, shales, and siltstone that are locally calcareous and contain petrified wood or wood impressions. The sandstones in the lower part exhibit low-to high-angle planar cross-laminations, or are mottled and structureless showing some knobby walled ophiomorpha. Toward the top, two sandstone beds exhibit planar and signoidal, low-to high-angle cross-laminations at the base and planar parallel laminations at the top and contain petrified wood or wood impressions. Fining upward of grain size is observed in these sandstones.

The Carthage Member is interpreted to have been deposited in a flood basin associated with a broad, very low relief, coastal or delta plain. River deposits associated with coastal-deltaic plains are extensive fluvial deposits, occupying large areas of the lower reaches of rivers and producing thick deposits of fluvial sediments, gradually grading into upper deltaic plains, coastal sands, and tidal flat sediments. Sediments of coastal plains are fine-grained in nature and can be regarded as mainly suspended load deposits. Flood basins in which muddy sediments are deposited are well developed. In humid climates swamps may develop, and peat is commonly associated with flood basin deposits. Lenticular and sheet-like sand bodies are embedded in thick deposits of silty and clayey sediments. Such big rivers as the Indus and Brahmaputra-Ganges make extensive coastal plains in their lower reaches (Reineck and Singh, 1975). In flood basins thick deposition of clayey sediments takes place, associated with accumulation of organic matter, especially plant debris. Flood basin sediments are generally fine silt and clay. There maybe a slight upward fining in each flood basin sequence of silty-clayey sediments. Mostly uniform, finely laminated mud is present, interrupted by some sandy or silty intercalations. Sometimes small channels with sandy-silty sediments occur. Organic debris and mottled structures are important features. Locally, pockets of fresh water mollusc shells and bones of vertebrates maybe present (Reineck and Singh, 1975).

The two sandstone beds (at Sec. 5, T.3S., R.3E.) exhibiting planar and sigmoidal, low-to high-angle cross-laminations and containing petrified wood or wood impressions are interpreted as fluvial-channel deposits. A fining upward trend is observed in these beds.

The marine oyster <u>Lopha</u> <u>bellaplicata</u> (Shumard) has been collected from the upper part of the Carthage Member in this study area (Tabet, 1979). <u>Lopha</u> <u>bellaplicata</u> has also been collected from the basal part of the overlying Fite Ranch Sandstone Member at NE¼ NE¼ Sec. 17, T.5S., R2E., in the Carthage area and this suggests that the top of the Carthage Member or base of the Fite Ranch Sandstone Member at these areas represents a transgression followed by an offlap or regression during which the major part of the Fite Ranch was deposited (Hook, Molenaar, and Cobban, 1983).

An age range of late middle to earliest late Turonian is suggested for the Carthage Member

FITE RANCH SANDSTONE MEMBER

The Fite Ranch Sandstone Member has not been measured in this study. Tabet (1979) reported 41 ft. of this sandstone member which consists of a transgressive deposit of silty bioturbated sandstone. Regionally, this sandstone is interpreted as a coastal-barrier sandstone associated with the overlying D-Cross Tongue of the Mancos Shale (Hook, 1983, Hook, Molenaar, and Cobban, 1983).

D-CROSS TONGUE OF THE MANCOS SHALE

The D-Cross Tongue consists of light to dark-gray, fissile shales with a few calcareous sandstone and limestone beds and large, locally fossiliferous, septarian concretions at various horizons. The basal part of the D-Cross Tongue in the study area 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 in the San Juan Basin (Tabet, 1979; Hook, 1983). The calcarenites may have been deposited during a period of widespread shoaling in which there was little clastic influx (Hook, Molenaar, and Cobban, 1983).

The presence of <u>Lopha sannionis</u> (White) indicates a shallow water or nearshore environment (Hook and Cobban, 1981). The open marine shales that are gradational into interbedded fine-grained sandstone and siltstone and the associated open shallow marine water fauna indicate deposition in a shelf mud to transitional zone.

The D-Cross Tongue ranges in age from early late Turonian to possibly early Coniacian. The early part of the late Turonian is indicated by the ammonite zone of the ammonite Prionocyclus novimexicanus (Marcou) (Hook and Cobban, 1979; Hook, 1983). The early Coniacian age is suggested by the presence of the oyster Lopha sannionis (White) which ranges in age from late Turonian to middle Coniacian (Hook, 1983).

GALLUP SANDSTONE

The Gallup Sandstone consists of thinly-to medium-bedded, moderately to well-sorted, fine-to medium-grained sandstones. Planar parallel lamination (and bedding) is dominant. Low angle, small scale tabular planar and tangential cross-stratification and wedge and trough shaped sets of cross-stratification are present locally. Small scale, assymetrical to nearly symmetrical ripple marks occur at one place. Burrows are sparingly present toward the top and are identified, with relatively low confidence, as Ophiomorpha and Skolithos. The sedimentary features of the Gallup Sandstone could be compared to those observed from the beach-upper shoreface units at Galveston Island and the Muddy Sandstone in the Bell Creek field, Montana (Davies, et al, 1971) and middle shoreface to upper shoreface units of the beach-shelf mud deposits of the Gulf of Gaeta, Italy (Reineck and Singh, 1975).

The transition from the underlying open marine shale (D-Cross Tongue), the presence of trough and wedge shaped and tabular cross-stratification, and the presence of overlying non-marine sediments [of the Crevasse Canyon Formation] indicate deposition in the shoreface zone of a barrier-beach environment. Criteria for recognition of the shoreface facies and comparison with the Gallup Sandstone in this study area are given in Table 9.

Ophiomorpha and Skolithos indicate wave-agitated (relatively high levels of wave or current energy) littoral or shallow neritic conditions (Weimer and Hoyt, 1964; Frey, 1984). These burrows are minor but can be used together with other sedimentary features to indicate a beach (near shore) environment.

The Gallup Sandstone in this study area shows similar characteristics as the upper part of the Gallup at Mescal Creek described by Wallin (1983). The top of the Gallup at Mescal Creek, consists of thick-bedded, yellowish-gray, well sorted, fine-to medium-grained sandstone which exhibits planar horizontal laminations. Isolated, small to medium-scale, trough-shaped sets of low angle tangential cross-lamination with sharp, curved, erosional lower contacts are encased within laminated sandstone. Rare Skolithos burrows occur throughout the unit. This thick-bedded, ripple cross-laminated sandstone represents sand deposited at the toe of the upper shoreface under the persistent influence of oscillatory wave energy. The overlying trough cross-laminated sandstone represents the 'surf zone' where energy expended by breaking waves continually reworked sediment. The paucity of biogenic structures in these units is assumed to be probably due to their initially low preservation potential, although the

Table 9. Criteria for recognition of the shoreface facies and comparison with the Gallup Sandstone in this study area.

	Grain Size	Sedimentary Structures	Fauna & Trace Fossils
Campbell (1971)	Grain size of sands increase upwards (grain size not specified).	Even parallel beds. Commonly bioturbated and abundant truncated wave-ripple laminae with overall trend of crests parallel with the shoreline. Wave-ripple marks and contorted (convolute) laminae	Oyster fragments. Burrows common to abundant.
Land (1972)	Very fine- to fine sand; grain size increases upward. Thin interbeds of shale and siltstone near base.	Lower part dominantly sub-parallel bedded and commonly destroyed by burrowing. Upper part dominantly cross-stratified in shallow trough sets.	Very sparse Pelecypods; few abraded oyster shells. Burrows of deposit feeders
Molenaar (1973) Upper Shoreface	Fine sand with some medium grains; grain size increases upward.	Moderate to high abundance of trough cross-bedding; sets are 1-2 ft. thick with dip directions parallel to shoreline (longshore currents)	Fossils rare. Burrows minor.
McLafferty (1979) basal assemblage	Fine to medium sand; overall grain size increases upward. Small covered intervals of shale and siltstone near base.	Dominantly planar-parallel stratified, commonly structureless particulary in the lower part and medium scale, tabular and trough cross-stratified in upper part. Rare contorted laminae near base; small-scale trough cross-lamination in middle part.	Locally abundant mollusks including oysters, pelecypods and gastropods near base. Locally, in lower part, common burrows of two types.
This study (1986) Gallup Sandstone	Fine to medium sand with some very fine sand locally; no systematic change in grain size upward.	Dominantly planar-parallel stratified and structureless particulary in the lower part. Low angle, small-scale, tabular planar and tangential cross-stratification, and wedge and trough shaped sets of cross-stratification occur sporadically in the middle and upper part. Small-scale, assymetrical to nearly symmetrical ripple marks toward the top.	Gastropod, pelecypod, and oyster fragments locally. Burrows minor.

relatively high energy regime of this environment may have been hostile to many organisms (Wallin, 1983).

The Gallup Sandstone in this study area also has comparable features with the basal assemblage in the Carthage area, which is interpreted as representing deposition within the shoreface of a beach (McLafferty, 1979) and is interpreted as being deposited in the middle to upper shoreface zone of a barrier-beach environment (see Table 9 for comparison). Middle shoreface deposits extend over the zone of shoaling and breaking waves (Fig. 31) and are generally fine-to medium-grained, clean sands, with minor amounts of silt and shale layers. Middle shoreface deposits maybe extensively bioturbated and depositional structures include low-angle wedge-shaped sets of planar laminae, but ripple laminae and trough cross laminae are common (Campbell, 1971; Howard, 1972; Land, 1972). Upper shoreface sediments are situated in the high energy surf zone just seaward of the beachface and landward of the breaker zone (Fig. 31). The complex hydraulic environment of the surf zone, with shore normal currents generated by plunging waves superimposed on shore-parallel wave-driven currents, gives rise to the complex sequence of multidirectional sedimentary structures and variable sediment textures characteristic of these deposits. Textures range from fine sand to gravel, and biogenic structures are common but not abundant. The predominant upper shoreface depositional structures are multidirectional trough cross-bed sets, but low-angle bidirectional planar cross-bedded sets and subhorizontal plane beds may also be present. The trough cross-beds are thought to indicate the multidirectional

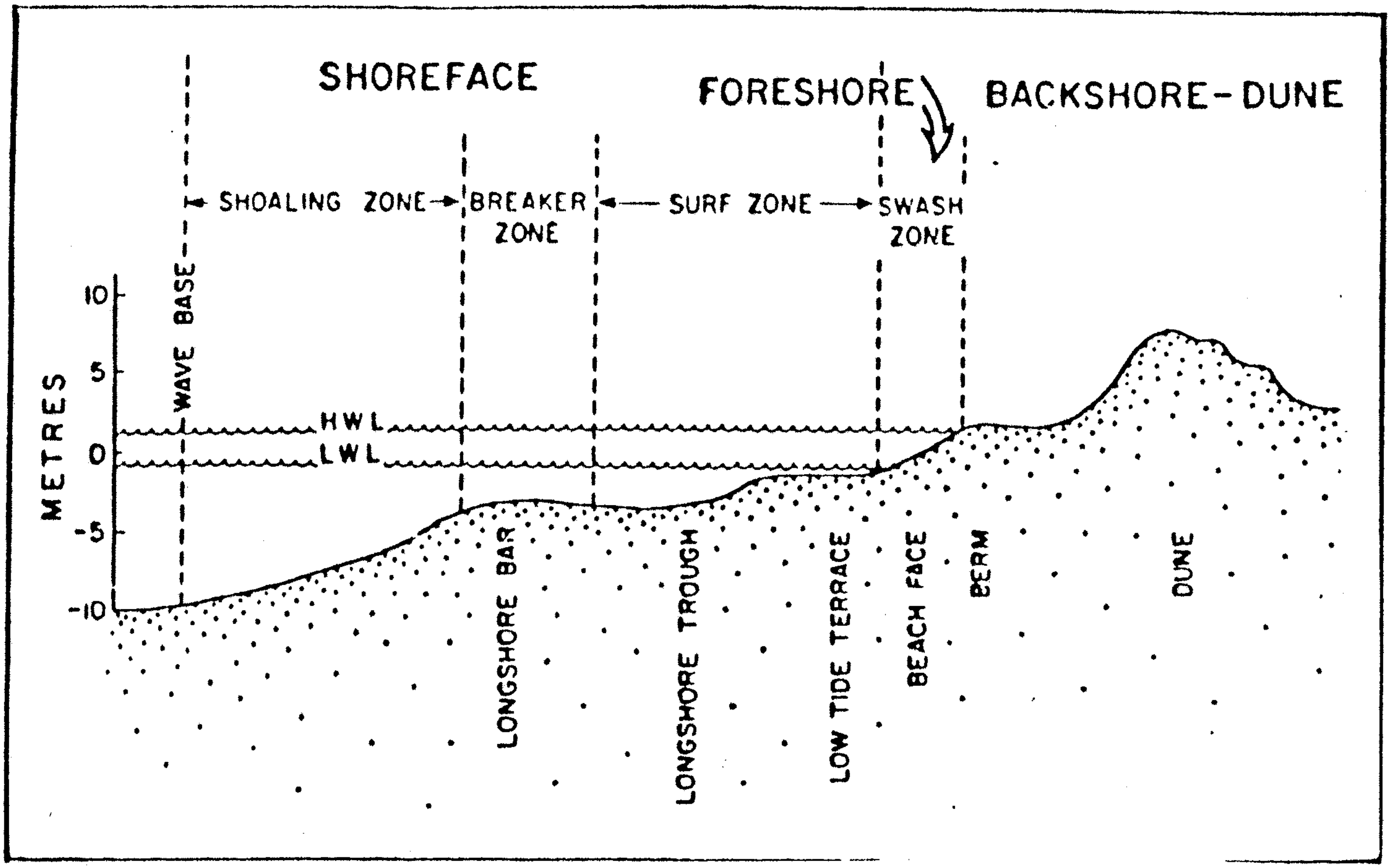


Fig. 31 Generalized profile of the barrier beach and shoreface environments (after Reinson, 1984).

current flow in the surf zone. Predominantly bidirectional trough cross-beds oriented parallel to depositional strike are common in upper shoreface deposits, and may be indicative of deposition under strong longshore current conditions (Reinson, 1984).

CREVASSE CANYON FORMATION

The Crevasse Canyon Formation consists of interbedded shales (locally carbonaceous), lenticular coal beds, fine-to medium-grained sandstones, and siltstones. The Crevasse Canyon Formation represents deposition in a complex of sub-environments in a back barrier environment. This is suggested by the transition from the underlying barrier-beach deposits of the Gallup Sandstone, local variations in thickness and lithology, and the presence of organic-rich shales, siltstones with lenticular beds. According to Reineck and Singh (1975) a prograding coast would produce the following vertical sequence of deposits:

Alluvium

Marshes (peat and coal)

Tidal flat and lagoonal deposits

Coastal sand

Transition zone

Shelf mud

Depending upon the rate of transgression or regression, one or more units of this ideal sequence may be ill-developed or completely missing (Fischer, 1961). The above sequence has been applied to the regressive sequence of deposits in the Carthage area (McLafferty, 1979) and will be considered in this study.

The lower part of the Crevasse Canyon Formation consists of interbedded fine-to medium-grained sandstones and shales containing plant fragments. The sandstones are dominantly planar-parallel laminated, locally structureless and burrowed. Sets of small-scale, low angle trough shaped tangential and planar cross-laminations, tabular planar cross-laminations, and wavy parallel and non parallel continous and discontinous laminations occur locally and less commonly. These alternating shale and sandstone units are regarded as lagoonal deposits. A lagoon can be considered as a complex of sub-environments such as lagoonal ponds, tidal flats along the margin of the pond, washover fans, tidal deltas, tidal channels, and tidal inlets. In general lagoonal deposits are characterized by the interlayering of muds, sand derived from the barrier island, and sediments derived from the mainland. The sand layers of a lagoonal deposit may exhibit wave ripples on bedding surfaces, and internally are either horizontally laminated or wave-ripple cross-bedded. Lagoonal deposits may be extensively bioturbated, and may contain peat, oyster reefs, abundant shells or evaporites (Dickinson, et al, 1972; Reineck and Singh, 1975).

The fine-to medium-grained, planar-parallel laminated and cross-laminated, and locally bioturbated sandstones may represent washover fan deposits. Washover fans result from sediment being eroded from the seaward side of the barrier and transferred into the lagoon during storm periods. Sedimentary structures observed in washover fans include parallel to sub-parallel laminations, small ripples, and medium-scale landward dipping foreset laminae. Washover sands maybe structureless, and maybe bioturbated shortly after deposition whilst the sediment is still moist (Elliott, 1978).

Tabular planar and tangential cross-beds and trough cross-laminations charaterize the lower portion of the upper part of the Crevasse Canyon Formation below the coal beds. These sandstones exhibit channel scale cut and fill structures and have internally scoured bases and may represent channel-fill sequences. The presence of marine oysters at the base of the channels may indicate transportation of sediments from the nearshore deposits seaward of the barrier. The studies of Hayes (1980), Hubbard and Barwis (1976), and others indicate that channel-fill sequences resulting from barrier-inlet (or tidal channel) migration have the following general characteristics:
1) an erosional base often marked by a coarse lag deposit;
2) a deep channel facies consisting of bidirectional large-scale planar and/or medium-scale trough cross-beds;
3) a shallow channel facies consisting of bidirectional small to medium-scale trough cross-beds and/or plane-beds and "washed out" ripple laminae; and 4) a fining-upward textural trend and a thinning upward set thickness of cross-strata.
The difference in size, orientation and type of sedimentary structures in the deep channel and shallow channel deposits generally reflects an increase in current-flow conditions in the shallow channel relative to the deep-channel environment. The planar cross-beds are suggestive of sand-wave deposition under

ebb-dominant channel flow, whereas the trough cross-beds record deposition as megaripples under stronger currents and alternating reversal of flow directions (Reinson, 1984). The sequence of units in the upper part of the Crevasse Canyon Formation are comparable to those observed in the Upper Cretaceous Blood Reserve-St. Mary River Formations, southern Alberta (Reinson, 1984) which are similar to the hypothetical inlet sequences of Hayes (1980) and Hubbard and Barwis (1976). The deep channel deposits are missing in the channel-fill sequence in this study and the fining-upward trend is not well defined. The channel-fill sequence is overlain by interbedded very fine- to fine-grained plane-bedded to locally cross-laminated sandstones, siltstones, and shales containing plant debris and oyster fragments. These units may represent washover fan deposits. Tidal influence is indicated by the presence of herring bone cross-bedding. The superimposed sets of oppositely dipping cross-strata are thought to preserve both ebb and flood tidal flows (Johnson, 1978) and thus more likely to occur in tidal regimes. The units described so far are regarded as marsh/lagoon deposits. The presence of washover fan and tidal-inlet deposits suggests deposition in a lagoonal complex, and the carbonaceous debris and plant impressions in the sandstones, siltstones, and shales may indicate a marsh-tidal flat environment.

Toward the top the upper portion of the Crevasse Canyon Formation is characterized by interbedded dominantly planar-parallel laminated sandstones, siltstones, shales and coal lenses. Sets of small scale, low angle, tabular planar and tangential cross-bedding and wedge shaped, planar cross-laminations occur locally. Abundant plant fragments and carbonaceous material occur in the sandstones and shales. These units can be interpreted as flood basin deposits. In flood basins thick deposition of clay sediments takes place, associated with accumulation of organic matter, especially plant debris. In humid climates swamps may develop and peat is commonly associated with flood basin deposits and lenticular and sheet-like sand bodies are embedded in the silty and clayey sediments (Reineck and Singh, 1975).

The stratigraphic position of the deposits, in the upper portion, above the coastal sand and marsh/lagoon deposits and their fine-grained nature suggests that they are flood basin deposits rather than alluvial-fan deposits which may show similar sedimentary features. The upper portion of the Crevasse Canyon Formation in this study corresponds to the fluvial sands and flood plain shales considered to be the typical deposits of the Mesaverde Group.

The uppermost part of the Crevasse Canyon Formation contains brackish-water oysters such as Exogyra sp. which may be indicative of restricted coastal bodies of water such as bays, lagoons or estuaries and this unit is regarded as being deposited within one of these restricted coastal bodies of water.

The Crevasse Canyon Formation in this study area can be compared to the coal-bearing and oyster-bearing assemblages described by McLafferty (1979) in the Carthage area. The lower part, and the upper part containing coal lenses show similar features as the coal-bearing assemblage and the uppermost part that contains brackish-water oysters is similar to the oyster-bearing assemblage.

The presence of cone-in-cone structures and abundant iron oxide staining in the upper portion indicates a carbonate association. Cone-in-cone structures mainly develop in muddy carbonates which are, in part ankeritic or sideritic (Pettijohn, 1975) and reflect the stress field set up by the growth of the concretionary cement (Collinson and Thompson, 1982).

Hummocky cross-stratification, although local and rare, has been observed in the upper part of the Crevasse Canyon Formation. This structure is not very widely recognized and its occurrences and description to date are restricted to ancient sandstones. It occurs in interbedded sandstone/mudstone sequences, both within thicker units of sandstone and also within sharp-based sandstone beds. It is thought to result from the action of storm waves on the shelf in areas below the depth for normal, fair-weather wave-reworking, but no well described modern analog is known (Collinson and Thompson, 1982). The hydrodynamic conditions required for the formation of this enigmatic structure are still being debated and this is primarily due to the fact that the structure has not been constructed in wave tank experiments (Rosenthal, et al. 1984).

PROPOSED MODERN ANALOG

The Georgia coast, U.S.A., has been proposed as a modern analog of the depositional environments in the transition from the Mancos Shale to the Mesaverde Group in the Carthage area (McLafferty, 1979). The Mesaverde Group in this study area displays similar sedimentary features and depositional environments as in the Carthage area and the Georgia coast is used as a modern analog in this study area. As described by Hoyt and others (1964) and Hoyt and Henry (1965), the Georgia coast is a barrier island coastline with relatively short broad barrier islands separated by channel inlets from each other and by salt marsh and meandering tidal channels from the mainland. The Georgia coast is characterized by an association of depositional environments including the beach, marsh/lagoon, and flood plain (flood basin) environments.

The barrier islands are composed of littoral, shallow neritic and eolian deposits consisting of fine to coarse sand. The Gallup Sandstone is compared with these deposits and is thought to be deposited in the same environment. However, foreshore and backshore-dune (eolian)deposits are absent in the Gallup Sandstone. Tidal inlets which intersect the barrier islands migrate southward over time in response to the longshore drift. The significance of the migration of these tidal inlets is that the shallow neritic, littoral, eolian and lagoonal-salt marsh sediments may be reworked depending on the potential of the shifting inlet and the depth of the inlet. An individual inlet may affect a strip 6-8 miles wide. The absence of foreshore and backshore-dune (eolian) deposits in the Gallup Sandstone maybe explained by the mechanism of shifting tidal inlets.

The deposits of the salt marshes along the Georgia coast consist of: 1) silts, clays and very fine sand brought in by tidal action, 2) organic debris from marsh grass and plants, 3) very fine to medium sand from the barrier island as washover fans, 4) medium to coarse sands within the sounds and larger tidal channels, and 5) indigenous fauna including Ostrea. These deposits are similar to the lower and upper part (below the coal lenses) of the Crevasse Canyon Formation in this study area. Ostrea has not been identified from the Crevasse Canyon Formation.

The Georgia mainland near the coast may correspond to the flood basin depositional environment in the upper coal-bearing portion of the Crevasse Canyon Formation in this study. Due to the humid climate plant life is abundant along the Georgia coast and this provided the source for organic deposits. The salt marsh is an environment in which such deposits accumulate along the coast.

The close association of the salt marsh and lagoonal environments in the Georgia coast illustrates that distinction between ancient marsh and lagoonal deposits could be difficult and would not always be possible. Both these environments would produce deposits of predominantly clay, silt, and fine sand with associated tidal-channel and washover fan sand deposits. This problem is encountered in this study when interpreting the lower and upper part (below the coal lenses) of the Crevasse Canyon Formation.

SUMMARY AND CONCLUSION

The Upper Cretaceous sequence in the study area extends from the Dakota Sandstone to the Crevasse Canyon Formation [of the Mesaverde Group] and consists of interbedded sandstone, siltstone, shale, and coal beds. These rock units were deposited during the widespread middle Cenomanian-early Coniacian transgression and regression of the Western Interior Seaway. Interpretation of paleoenvironments is done by comparing groups of paleontological and lithological characteristics of the rocks studied with estabilished criteria for recognizing modern and ancient depositional environments. The following depositional environments are identified in this study area.

1) Dakota Sandstone: - beach-upper shoreface to lower shoreface of a barrier beach
2) Lower Tongue of Mancos Shale: - transition from nearshore to shallow water open marine
3) Atarque Sandstone Member: - upper shoreface to lower shoreface of a barrier beach
4) Carthage Member: - flood basin associated with a broad, very low relief coastal plain
5) Fite Ranch Sandstone Member: - coastal barrier (regionally)
6) D-Cross Tongue: - transition zone to shelf mud of a shallow water open marine environment
7) Gallup Sandstone: - Shoreface zone of a barrier beach
8) Crevasse Canyon Formation: - marsh/lagoon complex and flood basin

Semi-quantitative clay mineral analysis of 8 samples yields an assemblage of kaolinite, illite, smectite (montmorillonite), mixed-layer clays and chlorite. Proportions of illite remain relatively constant and the general trend of increasing proportions of kaolinite and decreasing proportions of mixed-layer clay minerals from marine to continental deposits is not observed in this study. Discriminant function analysis of the relative proportions of the clay minerals from mudrock samples in this study area and surrounding areas showed that there are statistically significant differences in the relative proportions of clay mineral groups in mudrocks as a function of their depositional environment.

The coal in this study area is low in calorific value and sulfur content and falls in the Lignite A group of the ASTM classification scheme. The coal, at the present time, is considered uneconomical.

SUGGESTION FOR FURTHER WORK

Further work in the study area may prove useful in refining the depositional environments, particulary of the Crevasse Canyon Formation, and determining the thickness and quality of the coals. Thin section analysis of grain size and quartz content of the barrier deposits could yield textural and compositional parameters which may be as environmentally sensitive as sedimentary structures. As the rock units are covered at most places, subsurface stratigraphic studies using core samples could show details of sedimentary structures and help construct depositional models, particularly for the Crevasse Canyon Formation.

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APPENDIX 1

Appendix 1a - Abbreviations Used

bl.	blackish[±]
br.	brown, brownish[±]
cm.	centimeter(s)
dk.	dark
fine(u)	fine upper*
fine(l)	fine lower*
gr.	grayish[±]
grn.	grained
in.	inches
ind.	indurated
lam.	laminated, lamination(s)
lt.	light[±]
m.	meter(s)
med.	medium
mod.	moderate, moderately
or.	orange[±]
p.	pale
red.	reddish[±]
ss.	sandstone
v.	very
v. fine(u)	very fine upper*
v. fine(l)	very fine lower*
wh.	white[±]

* see also Appendix 2c for correspondence to grain sizes.

± see also Appendix 2a for correspondence to GSA color chart.

Appendix 1b - Description of Units

Jornada del Muerto Section I - Bustos well 7½-minute quadrangle, SW¼ NE¼ Sec. 19, T.3S., R.3E., and NW¼ and SW¼ of SE¼ Sec. 19, T.3S., R.3E., Socorro County, New Mexico; measured by Abraham Araya using a silva (type 15 T) compass and a Jacob Staff. Section Covers interval from the base of the Dakota Sandstone to the 'top' of the Carthage Member of the Tres Hermanos Formation.

Unit	Lithology	Thickness feet	Thickness inches
	Top of measured section Carthage Member (total measured thickness)	20	9
31	Lt. gr., to gr. wh., shale. Weathers to yel. or., and red. br., petrified wood fragments fairly common.	2	5
30	Yel. or., mod. to well sorted, ind., fine(u)-grn. ss., locally fossiliferous *Inoceramus* sp. *Texigraphea* sp. *Crassostrea* sp. *Scaphites* (?) Pectinoids *indet*.	2	0
29	Lt. gr., to gr. wh., shale. Weathers to yel. or. and red. br., petrified wood fragments fairly common.	16	4
	Atarque Sandstone Member (total measured thickness)	321	0
28	Red. br., mod. sorted, friable to slighty Ind., med(l)-grn. ss., thinly to med. bedded, abundant horizontal and vertical burrows.	19	6
27	Gr. wh., poorly to mod. sorted, friable, fine(u) to fine(l)-grn. ss., weathers to slightly pinkish, bioturbated.	12	4
26	Yel. or., poorly to med. sorted, friable, fine(u) to fine(l)-grn. ss., bioturbated toward the top, vertical and horizontal burrows with smooth and ornamented walls common, calcareous ss. concretions at 7 ft. 10 in. and 9 ft. 6 in. from the base of unit contain: *Granocardium* sp. *Inoceramus* sp. *Lopha* sp. *Lopha bellaphicata* (Shumard) *Lopha lugbris* *Exogyra* sp. *Legumen* sp. *Plicatula* sp.	29	3

Unit	Lithology	Thickness feet	inches
25	Covered interval	48	9
24	Mostly covered. gr. or., to yel. or., mod. sorted, mod. Ind., fine(u), grn. ss., v. thinly to thinly bedded, locally calcareous, abundant iron oxide staining and nodules, smooth walled horizontal and vertical burrows locally.	39	0
23	Covered interval	26	11
22	Red. br., mod. sorted, friable to slightly Ind., med(l) to fine(u)-grn. ss., weathers to dk. red. br., horizontal planar-lam. locally.	12	8
21	Mostly covered. gr. wh., mod. to well sorted, friable, med(l)-grn. ss., weathers to slightly br., structureless at the bottom, horizontal planar-lam. toward the top, a small scale, high angle tabular-tangential cross-lam. observed at one place.	36	4
20	Gr. wh., mod. to well sorted, mod. Ind., med(l)-grn. ss., weathers to br. gr., structureless, crudely lam. locally, thinly to med. bedded, horizontal burrows present locally.	47	1
19	Lt. br., mod. sorted, Ind., fine(u)-grn. ss., weathers to gr. or., structureless, abundant iron oxide staining, vertical and horizontal burrows common.	9	1
18	Gr. wh. (weathered), mod. sorted, mostly friable but Ind. locally, med(l) to med(u)-grn. ss., crudely lam. toward the top, vertical and horizontal burrows common.	5	8
17	Gr. or., mod. to well sorted, Ind., fine(l) to fine(u)-grn. ss., weathers to yel. or., thinly to med. bedded, mostly structureless, individual beds exhibit internal lam. locally, oyster fragments and Ophiomorpha burrows common.	19	10
16	Covered interval. Abundant float gr. or., fine(l)-grn. ss.	14	7
	Lower Tongue of Mancos Shale (total measured thickness)	526	5
15	Covered interval. Dk-gr., shale weathers to gr. or., fissile, silty, and calcareous locally. Exposed in a small arroyo 287 ft. 7 in. above base. 4 in. to 6 in. thick inter-		

Unit	Lithology	Thickness feet	Thickness inches
	calated limestone beds, abundant oyster fragments, Teredo-like shells.		
	Dakota Sandstone (total measured thickness)	132	8
14	Covered interval. Probably light gr., to dk. gr., fine(l)-grn. ss., Lopha sp. Collected at 12 ft. 5 in. from base of unit.	48	9
13	Lt. gr., to dk. gr., mod. to well sorted, Ind., fine(l)-grn. ss., weathers to br. gr., thinly lam. toward the top, abundant trace fossils, Acanthoceras sp., and cf. batoid collected from the base and top of unit respectively.	6	3
12	Gr. wh. (weathered surface), mod. sorted, friable, and locally Ind., med(u)-grn. ss., slightly bioturbated, iron oxide nodules locally.	1	8
11	Dk. gr. (weathered surface), med(l)-grn. ss., bioturbated, few plant impressions, iron oxide staining locally, some carbonaceous material locally.	0	10
10	Covered interval. Probably gr., med (l)-grn. ss.	24	4
9	Lt. gr., well sorted, Ind., med(l)-grn. ss., weathers to gr. wh., highly cemented, structureless, horizontal and vertical burrows fairly common.	4	10
8	Gr. wh., well sorted, Ind., fine(l)-grn. ss., structureless, silty at the bottom, hematite staining locally.	0	8
7	Lt. gr., well sorted, Ind., med(l)-grn. ss., weathers to gr. wh., highly cemented, structureless, horizontal and vertical burrows fairly common.	2	5
6	Lt. gr., siltstones, weathers to gr. wh., horizontal and vertical burrows common.	0	5
5	Gr. wh., well sorted, Ind., fine(u)-grn. ss., structureless, abundant hematite and limonite staining.	0	4
4	Lt. gr., siltstone, weathers to gr. wh., randomly oriented clay clasts and plant impressions present locally.	3	2
3	Gr. wh., well sorted, friable, med(l)-grn. ss., mostly structureless, shows crude cross-lam. toward the top, vertical burrows toward the top.	23	9

Unit	Lithology	Thickness feet	inches
2	Gr. wh., well sorted, friable, fine(u)-grn. ss., thinly lam.	0	8
1	Gr. wh., well sorted, friable, med(l)-grn. ss., mostly structureless, individual beds show crude cross-lam. locally, iron oxide staining and concretions occur locally.	14	7
	Base of Section.		

Jornada del Muerto Section II - Bustos Well 7½-minute quadrangle, SW¼ NE¼ Sec. 8, T.3S., R.3E., and SE¼ Sec. 8, T.3S., R.3E., Socorro County, New Mexico; measured by Abraham Araya using a Silva (Type 15 T) compass and a Jacob Staff. Section covers interval from the base of the Gallup Sandstone to the top of the Crevasse Canyon Formation.

Unit	Lithology	Thickness feet	Thickness inches
	Top of measured section Crevasse Canyon Formation (total measured thickness)	150	0
34	Red. br., mod. sorted, friable to mod. Ind., med(u)-grn. ss., color lam. toward the top, horizontal and vertical burrows common.	21	4
33	Gr. wh., well sorted, Ind., med(l) to fine(u)-grn. ss., weathers to p. yel. br., thinly to med. bedded, vertical and horizontal burrows common, irregular shaped fractures (up to 7 ft. long) occur on the top of the bedding plane at the top part and are filled with iron oxides (hematite and/or limonite?).	19	4
32	Yel. or., well sorted, Ind., fine (u)-grn. ss., plant impressions common, wavy parallel and non-parallel discontinous and continous lam. Locally thins laterally.	9	8
31	Covered interval. Probably dk. gr., fissile shale that weathers to yel. or.	24	2
30	Gr. wh., mod. sorted, Ind., med(u)-grn. ss., weathers to br. gr., iron oxide staining common, iron oxide nodules occur locally, thin discontinous siltstone and shale intercalations, thinly to med. bedded, small scale, low angle trough shaped set of planar cross bedding observed at one place.	14	6
29	Shale, color variable; lt. to dk. gr., at the base and toward the top, mod. yel. br., and greenish gr. at the middle, plant material occur locally, silty at base and top, some iron oxide nodules occur locally, v. thickly lam. and fissile at lower part.	10	4

Unit	Lithology	Thickness feet	inches
28	Gr. wh., well sorted, Ind., v. fine(u)-grn. ss., weathers to gr. or., v. thinly to thinly bedded, becomes silty toward the top.	1	10
27	Covered interval. Probably yel. br., shale.	4	10
26	Gr. wh., well sorted, Ind., v. fine(u)-grn. ss., weathers to gr. or., structureless, few oxidized plant impressions.	1	4
25	Mostly covered. Lt. gr., shale. Weathers to gr. or., plant fragments fairly common.	3	10
24	Yel. or., mod. sorted to well sorted, Ind., med(u) to med(l)-grn. ss., thinly to med. bedded, few plant impressions, iron oxide staining and iron oxide nodules occur locally, few vertical burrows, small scale, low angle trough shaped tangential and planar cross-lam. locally, small scale low angle, tabular planar cross-lam. locally, top of unit forms dip slope.	9	8
23	Mostly covered. Dr. gr., to p. yel. br. (toward the top) shale, thickness varies laterally, plant fragments common at the base and amount decreases upward.	4	10
22	Gr. or., to br. gr., well sorted, mod. to well Ind., fine(l) to v. fine(u)-grn. ss., few tiny plant impressions locally, limonite and hematite staining common toward the top.	4	0
21	Covered interval. Probably gr. shale.	12	9
20	Gr. or., mod. to well sorted, Ind., fine(l) to v. fine(u)-grn. ss., thinly bedded, few vertical and horizontal burrows, hematite staining locally.	3	10
19	Lt. gr., to red. br. (toward top), shale. Silty at base, iron oxide nodules locally present, few vertical burrows at base, laterally discontinous bedding.	3	9
	Gallup Sandstone (total measured thickness)	107	8

Unit	Lithology	Thickness feet	inches
18	Mostly covered. Yel. or., to mod. yel. br., well sorted, Ind., fine (u)-grn. ss., calcareous locally, thinly bedded, individual beds internally lam., a few horizontal and vertical burrows present.	3	8
17	Gr. wh., mod. sorted, Ind., med(u) to med(l)-grn. ss., weathers to br. gr., slightly calcareous, abundant iron oxide staining, slightly bioturbated, petrified wood fragments locally observed, some beds exhibit horizontal lam., small scale, low angle tabular planar cross-lam. occur locally.	8	5
16	Covered interval	13	9
15	Gr. or., mod. sorted, Ind., med(l) to fine(u)-grn. ss., alternatingly thinly to med. bedded, few vertical and horizontal burrows, small scale, low angle trough and wedge shaped sets of planar cross-lam. locally, small scale, nearly symmetrical ripple marks observed at one place, top of unit forms dip slope.	28	0
14	Tan to yel. br., mod. sorted, Ind., fine(u)-grn. ss., calcareous, fossiliferous, wavy parallel discontinous and continous lam., abundant oyster fragments. *Cardium* sp. *Gyrodes* sp. *Turritella* sp.	4	6
13	Yel. or., mod. sorted, Ind., med(l) to fine(u)-grn. ss., thinly to med. bedded, slightly calcareous toward the top, some beds are internally lam., small scale, low angle trough cross-lam., and small scale, low angle wedge shaped tangential cross-beddings with erosional and non-erosional lower contact occur locally.	15	7
12	Gr. or., to yel. or., mod. sorted, Ind., med(u) to med(l)-grn. ss., v. thinly to thinly bedded, small scale, low angle trough shaped sets of cross-lam observed at one place.	8	2

Unit	Lithology	Thickness feet	inches
11	Gr. or., to yel. or., mod. to well sorted, Ind., med(u) to med (l)-grn. ss., thinly bedded, individual beds exhibit v. thin lam., small scale, low angle wedge shaped sets of planar cross lam. locally, erosional and non-erosional lower contact.	3	11
10	Yel. or., mod. sorted, friable to mod., Ind., med(l) to fine(u)-grn. ss., thickly laminated to thinly bedded, color lam. and horizontal burrows at lower part, small scale, low angle, wedge shaped sets of planar cross-lam. locally.	3	2
9	Yel. or., mod. to well sorted, Ind., med(u) to med(l)-grn. ss., individual beds exhibit color lam. locally.	3	2
8	Gr. wh., to gr. or., mod. sorted, mod. Ind., med(l) to fine(u)-grn. ss., v. thinly to thinly bedded.	2	0
7	Yel. or., mod. sorted, Ind., med(u)-grn. ss., individual beds exhibit color lam. locally.	2	0
6	Gr. wh., to gr. or., mod. sorted, mod. Ind., med(l)-grn. ss., fines upward, small scale, low angle, wedge shaped sets of planar cross-lam. locally.	1	11
5	Yel. or., mod. sorted, Ind., med(u)-grn. ss., individual beds exhibit color lam., v. few smooth walled and knobbed burrows locally.	3	5
4	Gr. wh., to gr. or., mod sorted, mod. Ind., med(l)-grn. ss., fines upward, v. thinly bedded.	1	0
3	Yel. or., mod. to well sorted, Ind., med(u) to med(l)-grn. ss., individual beds exhibit internal lam.	1	4
2	Gr. wh., to gr. or., mod. sorted, mod. Ind., med(l)-grn. ss., fines upward, v. thinly bedded.	1	8
1	Yel. or., mod. sorted, Ind., med(u)-grn. ss., weathers to gr. or., horizontal planar bedding. Base of Section.	2	0

Jornada del Muerto Section III - Bustos Well 7½-minute quadrangle, NW¼ SE¼ Sec. 8, T.3S., R.3E., and NE¼ SW¼ Sec. 8, T.3S., R.3E., Socorro County, New Mexico; measured by Abraham Araya using a Silva (Type 15 T) compass and a Jacob Staff. Section covers interval from the base of the Gallup Sandstone to the top of the Crevasse Canyon Formation.

Unit	Lithology	Thickness feet	Thickness inches
	Top of measured section Crevasse Canyon Formation (total measured thickness)	478	9
78	Lt. gr., well sorted, Ind., v. fine(l)-grn. ss., weathers to yel. or., cone in cone structures in weathered portions.	1	0
77	Dk. gr., shale. Few plant material.	5	10
76	Lt. gr., well sorted, Ind., v. fine(l)-grn. ss., weathers to yel. or., cone in cone structures in weathered portions.	3	2
75	Lt. gr., to dk. gr. shale. Few plant material.	3	4
74	Lt. gr., to gr. or., well sorted, Ind., med(l) to fine(u)-grn. ss., fines upward, small scale, low angle tabular-planar cross-lam. locally.	1	4
73	Lt. gr., to dk. gr. shale.	8	10
72	Lt. br., fissile shale.	2	3
71	Coal. Thins and disappear laterally.	0	4
70	Br., fissile shale. Abundant plant material some carbonaceous material locally.	3	0
69	Coal. Covered laterally.	0	7
68	Br., to mod. br., fissile shale. Carbonaceous locally.	0	8
67	Mostly covered. Lt. gr., to dk. gr. shale.	4	9
66	Red. br., to mod. br., v. fine(l)-grn. ss., weathered, laterally discontinous.	0	0
65	Mostly covered. Lt. gr., to dk. gr. shale.	4	10
64	Red. br., to mod. br., v. fine(l)-grn. ss., weathered, thickness varies laterally, laterally discontinous.	0	2

Unit	Lithology	Thickness feet	inches
63	Mostly covered. Lt. gr., to dk. gr. shale.	4	8
62	Gr. wh., well sorted, Ind., v. fine(l)-grn. ss., weathers to yel. or., exhibits cone in cone structures at weathered parts, laterally discontinous layering.	1	6
61	Mostly covered. Lt. gr., to dk. gr. shale.	6	2
60	Gr. or., to yel. or., well sorted, Ind., v. fine(l)-grn. ss., small scale, low angle, tabular-planar and tangential cross-lam. occur locally, hummocky cross-stratification, small fractures filled with iron oxides (Hematite and Limonite) fairly common.	3	4
59	Mostly covered. Dk. gr. shale. gr. wh., locally.	7	10
58	Gr., well sorted, Ind., v. fine(l)-grn. ss., weathers to yel. or., v. thinly bedded, abundant plant impressions, carbonaceous material occurs locally.	3	10
57	Lt. gr., to dk. gr. shale.	9	9
56	Coal. Discontinous laterally, occurs as lenses.	0	9
55	Mostly covered. Lt. gr. to dk. gr., shale.	7	2
54	Coal. Discontinous laterally.	0	3
53	Lt. br., to dk. br., shale. Weathers to gr. wh., and yel. or. silty at bottom, abundant plant and carbonaceous material.	2	9
52	Coal. Underlain by a v. thin layer of dk. br. shale with abundant plant material and carbonaceous material.	0	11
51	Gr. wh., siltstone. Weathers to yel. br., abundant carbonaceous material.	1	0
50	Mostly covered. Yel. br., to br., well sorted, Ind., v. fine(u) to fine(l)-grn. ss., carbonaceous material occurs locally.	2	0
49	Gr. or., to yel. or., shale. Carbonaceous locally.	9	9

Unit	Lithology	Thickness feet	inches
48	Red. br., to pinkish, mod. sorted, Ind. but friable at weathered sections, med(l)-grn. ss., abundant iron oxide coating, thins laterally, intercalated with yel. or., and gr. wh., shale and siltstone locally.	2	0
47	Yel. or., siltstone and v. thin intercalations of yel. or., and dk. gr. shale.		
46	Lt. gr., to dk. gr., fissile shale.	9	9
45	Gr. wh., to yel. or., mod. sorted, Ind., med(l)-grn. ss., herring bone cross-bedding, small scale, low angle, tabular-tangential cross beddings, small scale, high angle tabular-tangential cross-beddings. Erosional and non-erosional lower contacts, sets of wedge-shaped planar cross-lam., planar-parallel laminations.	4	5
44	Yel. or., gr. or., toward the top, mod. to well sorted, Ind., fine(u)-grn. ss., thinly to mod. bedded, the top part exhibits <u>cone in cone</u> structures, plant impressions and carbonaceous material common toward the top.	4	3
43	Mostly covered. Dk. gr. shale.	2	1
42	Lt. gr., poorly to mod. sorted, soft and friable, fine(l) to fine(u)-grn. ss., thickly lam., abundant plant fragments and carbonaceous material.	0	4
41	Mostly covered. Lt. gr., well sorted, Ind., fine(l)-grn. ss., v. thickly lam. to v. thinly bedded.	2	7
40	Mostly covered. Lt. yel. gr., to dk. gr. fissile shale.	2	8
39	Mostly covered. Lt. gr., well sorted, Ind., v. fine(l) to fine(u)-grn. ss., thins laterally.	0	2
38	Mostly covered. Lt. gr., to dk. gr., fissile shale.	1	8
37	Mostly covered. Lt. gr., poorly to mod. sorted, Ind., fine(u)-grn. ss., v. thickly lam., lam. are wavy and discontinous, contains oyster fragments.	1	1

Unit	Lithology	Thickness feet	inches
36	Red. br., to pinkish, poorly to mod. sorted, friable, fine(u)-grn. ss.	0	7
35	Mostly covered. Lt. gr., to gr. wh., well sorted, Ind., v. fine (u)-grn. ss., thickly lam. to v. thinly bedded.	2	1
34	Br. gr., mod. sorted, Ind., fine(l) to fine(u)-grn. ss., silty at the bottom (10 in.) and contains oyster fragments, fines upward, thinly to med. bedded at bottom and v. thinly to thinly bedded toward the top, erosional lower contact (scoured base), small scale, low angle, trough cross-lam. and small scale, low angle, tabular-planar cross-lam. locally.	5	8
33	Gr. or., to yel. or., mod. to well sorted, Ind., fine(l)-grn. ss., thinly bedded to v. thinly bedded toward the top, erosional lower contact.	4	2
32	Lt. gr., mod. sorted, friable, fine(u)-grn. ss., v. thinly bedded.	7	10
31	Covered interval.	214	6
30	Red. br., well sorted, mod. Ind., fine(u)-grn. ss., shows color lam. toward the top, vertical and horizontal burrows common.	9	9
29	Gr. wh., well sorted, mod. Ind., fine(u)-grn. ss., weathers to yel. or., vertical and horizontal burrows fairly common.	9	9
28	Mod. yel. br., and greenish gr. at the bottom and lt. to dk. gr. toward the top, shale mostly covered.	29	3
27	Dk. gr., to gr. wh., well sorted, Ind., fine(u)-grn. ss., v. thinly to thinly bedded, br. calcareous ss. concretions present toward the top.	3	0
26	Covered interval. Probably gr. wh., mod. to well sorted, friable, v. fine(u)-grn. ss., thinly to thickly laminated.	11	8
25	Gr. or. (weathered), becomes gr. wh. toward the top, mod. sorted, Ind., med(l) to med(u)-grn. ss., v. thinly bedded, abundant iron oxide coating, few vertical burrows toward the top, thins laterally, top of unit forms dip slope.	19	6

Unit	Lithology	Thickness feet	inches
24	Mostly covered interval. Lt. gr. shale.	1	2
23	Yel. or., well sorted, Ind., v. fine(u) to fine(l)-grn. ss., v. thinly to thinly bedded, individual beds exhibit internal lam., tiny plant impressions toward the top, thins and disappears laterally.	2	6
22	Mostly covered interval. Lt. to dk. gr., shale, thins laterally.	4	10
21	Gr. or., to br. gr., v. fine(l) to fine(u)-grn. ss., well sorted, mod. to well Ind., abundant plant impressions, iron oxide coating common.	3	9
20	Mostly covered interval. Lt. to dk. gr., shale, weathers to yel. or.	9	9
	Gallup Sandstone (total measured thickness)	98 / 10	11 / 8
19	Mostly coverd interval. Gr. wh., to yel or., well sorted, Ind., fine(l) to fine(u)-grn. ss., horizontal and vertical burrows present locally, few tiny plant impressions, small fractures filled with iron oxides locally.		
18	Gr. or., well sorted, Ind., med(l) to fine(u)-grn. ss., thinly to med. bedded, locally bioturbated at the bottom, few horizontal and vertical burrows present toward the top, some beds show internal laminations, grain size tends to fine upwards, top part forms dip slope.	14	7
17	Gr. or., to yel. or., mod. sorted, Ind., fine(u)-grn. ss., thinly to med. bedded, individual beds show internal lam. locally, covered toward the top.	9	11
16	Covered interval. Abundant float of gr. wh., fine(u)-grn. ss.	2	10
15	Yel. or., becomes red. br. toward the top, well sorted, mod. Ind., fine(u)-grn. ss., thinly to med. bedded, shows color lam locally.	7	4
14	Mostly covered interval. Gr. wh., well sorted, Ind., fine(u)-grn. ss., v. thinly to thinly bedded, structureless.	4	10

Unit	Lithology	Thickness feet	inches
13	Yel. or., well sorted, Ind., fine(l)-grn. ss., thinly to med. bedded, wavy non-parallel bedding, oyster bearing calcareous ss. concretions present toward the top, horizontal burrows common.	8	0
12	Red. br., well sorted, Ind., v. fine(u)-grn. ss., discontinous wavy non-parallel stratification, erosional lower contact locally.	1	2
11	Yel. or., well sorted, Ind., fine(u) to med(l)-grn. ss., v. thinly to thinly bedded toward the top, structureless.	2	8
10	Mostly covered interval. Similar to unit #6 where it is exposed.	2	5
9	Gr. or., mod. to well sorted, Ind., fine(u) to med(l)-grn. ss., v. thinly to thinly bedded toward the top, thins laterally and covered locally, irregular bedding.	1	1
8	Covered interval.	1	9
7	Gr. wh., mod. sorted, mod. Ind., med(l)-grn. ss., v. thinly to thinly bedded, structureless.	1	7
6	Mostly covered. Gr. wh., to gr. or., mod. well sorted, Ind., fine(u)-grn. ss., thinly to v. thinly bedded, small scale, low angle, tabular-planar cross-lam. locally.	7	6
5	Yel. or., well sorted, Ind., fine(u)-grn. ss., small-med. scale, tabular-planar (thin) cross-beddings locally, individual beds show internal lam. Erosional lower contact.	4	2
4	Covered interval. Abundant float of yel. or., fine to med-grn. ss.	3	2
3	Gr. or., to yel. or., mod. sorted, friable to mod. Ind., fine(u) to med(l)-grn. ss., med. bedded, becomes thinly bedded toward the top, individual beds show planar-parallel lam., small scale, low angle tabular tangential and trough-shaped sets of v. thin cross-bedding locally.	8	3

Unit	Lithology	Thickness feet	inches
2	Gr. or., mod. to well sorted, Ind., fine(u)-grn. ss., thinly to med. bedded, becomes very thinly bedded toward the top. Oyster bearing calcareous ss. concretions present, erosional lower contact locally displayed.	3	10
1	Gr. or., to yel. or., mod. sorted, Ind., fine(u) to med(l)-grn. ss., v. thinly to thinly bedded. Small scale, low angle, tabular planar cross beddings locally. Base of Section.	2	2

Jornada del Muerto Section IV - Bustos Well 7½-minute quadrangle, SE¼ SW¼ Sec. 8, T.3S., R.3E., Socorro County, New Mexico; measured by Abraham Araya using a Silva (Type 15 T) compass and a Jacob Staff. Section covers the Crevasse Canyon Formation.

Unit	Lithology	Thickness feet	Thickness inches
	Top of measured section		
	Crevasse Canyon Formation	82	8
13	Yel. or., well sorted, Ind., fine(u)-grn. ss., contains oyster fragments. <u>Exogrya</u> sp. <u>Pteria</u> sp. <u>Inoceramus</u> sp.	5	10
12	Lt. gr., to dk. gr., shale. Contains yel. or., fine(u)-grn. ss., concretions 5 ft. above the base.	28	1
11	Lt. gr., well sorted, Ind., v. fine(l)-grn. ss., weathers to yel. or., weathered portions exhibit <u>cone in cone</u> structures, bedding laterally discontinous.	2	8
10	Mostly covered. Lt. gr., to dk. gr., shale.	2	4
9	Gr. wh., well sorted, friable, fine(u)-grn. ss., v. thinly bedded, individual beds show crude lam.	3	2
8	Mostly covered. Shale. br., at bottom and becomes lt. gr., to dk. gr., toward the top, fissile at bottom.	14	7
7	Mod. br., shale. Abundant plant material, contains carbonaceous material locally.	0	2
6	Mostly covered. Coal. Laterally discontinous, thickness varies laterally.	2	0
5	Mod. br., shale. Abundant plant material, contains carbonaceous material locally.	0	5
4	Lt. gr., fissile shale. Weathers to yel. or., locally silty.	9	9
3	Lt. gr., well sorted, Ind., v. fine(u)-grn. ss.	0	8
2	Gr., well sorted, Ind., v. fine(l)-grn. ss., weathers to yel. or., <u>cone in cone</u> structure in weathered portions.	3	7

Unit	Lithology	Thickness feet	inches
1	Lt. gr., to dk. gr., shale. Interbedded v. thin layers of siltstone locally. Base of Section.	9	9

APPENDIX 2

Terminology used for description of lithology and stratification

2a - Rock Colors

Rock colors are taken from the GSA Rock Color Chart (1979) and describe both weathered and fresh surfaces unless otherwise noted:

Abbreviation	Color	Munsell system
br.	brown	5 YR 5/4
br. gr.	brownish gray	5 YR 5/1
dk. gr.	dark gray	N3
gr. or.	grayish orange	10 YR 7/4
greenish gr.	greenish gray	5 GY 6/1
lt. br.	light brown	5 YR 5/6
lt. gr.	light gray	N7
lt. yel. gr.	light yellowish gray	5 Y 6/2
mod. br.	moderate brown	5 YR 3/4
mod. yel. br.	moderate yellowish brown	10 YR 5/4
p. yel. br.	pale yellowish brown	10 YR 6/2
red. br.	reddish brown	10 R 4/4
wh.	white	N9
yel. or.	yellowish orange	10 YR 7/6

2b - Stratification

Terminology for the thickness of strata from Ingram (1954).

Very thickly bedded	1 m.
Thickly bedded	30 - 100 cm.
Medium bedded	10 - 30 cm.
Thinly bedded	3 - 10 cm.
Very thinly bedded	1 - 3 cm.
Thickly laminated	0.3 - 1 cm.
Thinly laminated	0.3 cm.

2c - Grain Size and Sorting

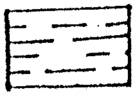
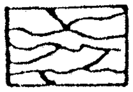
Sorting of the sandstone was determined visually with the use of sorting images from Folk (1968).

Grain size of the sandstones according to the Udden-Wentworth scale (1922) was determined visually using a grain size and roundness chart.

Coarse lower sand	1.0 - 0.5 Ø
Medium upper sand	1.5 - 1.0 Ø
Medium lower sand	2.0 - 1.5 Ø
Fine upper sand	2.5 - 2.0 Ø
Fine lower sand	3.0 - 2.5 Ø
Very fine upper sand	3.5 - 3.0 Ø
Very fine lower sand	4.0 - 3.5 Ø

2d - Shapes of individual beds and cross-stratification (from McLafferty, 1979)

Wavy or pinch and swell  Irregular 

Sets of stratification: Field term in this study		corresponds to Campbell (1967)
		Discontinuous, even parallel
Planar-parallel stratification		Continuous, even parallel
Irregular stratification		Wavy nonparallel

Cross-stratification

Classification of cross-stratified units is modified from McKee and Weir (1953) and Allen (1963):

Small-	low-		tabular-	
Medium-scale,	high-	angle,	wedge-	shaped set of
Large-	high-to-low-		trough-	

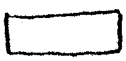
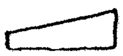
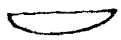
planar	lamination		erosional	
tangential (arching) cross-		with		lower
convex up	bedding		nonerosional	

contact.

Scale based on length of cross-strata: small <30 cm.; medium .3 - 6 m.; large >6 m.

Dip of cross-strata: high angle $>20^{o}$; low angle $<20^{o}$

Shape of set:

tabular  wedge  trough 

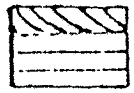
Arching:

planar  tangential  convex up 

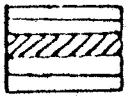
Thickness of cross-strata: lamination <1 cm.; bedding $\geq$1 cm.

Nature of lower contact:

erosional (truncates lower strata) 

nonerosional (does not truncate lower strata) 

Sets of cross-stratification:

solitary 

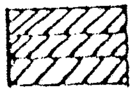
grouped 

PLATE 1

(in figures 6-21, each shaded area = 2.5 mm.)

Figures

1 Cf. batoid(12 x natural size) from the Dakota Sandstone

2 Acanthoceras sp. (2 x natural size) from the Dakota Sandstone

3 Mold of an arm of a star fish(?) (4x) from the Dakota Sandstone

4 Lobster and/or crab trails (approx. natural size) from the Dakota Sandstone

5 Teredo-like shells (3.5x) from the Lower Tongue of Mancos Sahle

6,7 Granocardium sp. from the Atarque Sandstone Member

8,12 Lopha sp. from the Atarque

9 Lopha bellaplicata (Shumard?) from the Atarque

10 Lopha lugbris from the Atarque

11 Exogyra sp. from the Atarque

13 A = Legumen sp. and B = Plicatula sp. from the Atarque

14 Crassostrea sp. from the Carthage Member

15 Texigryphea sp. for the Carthage

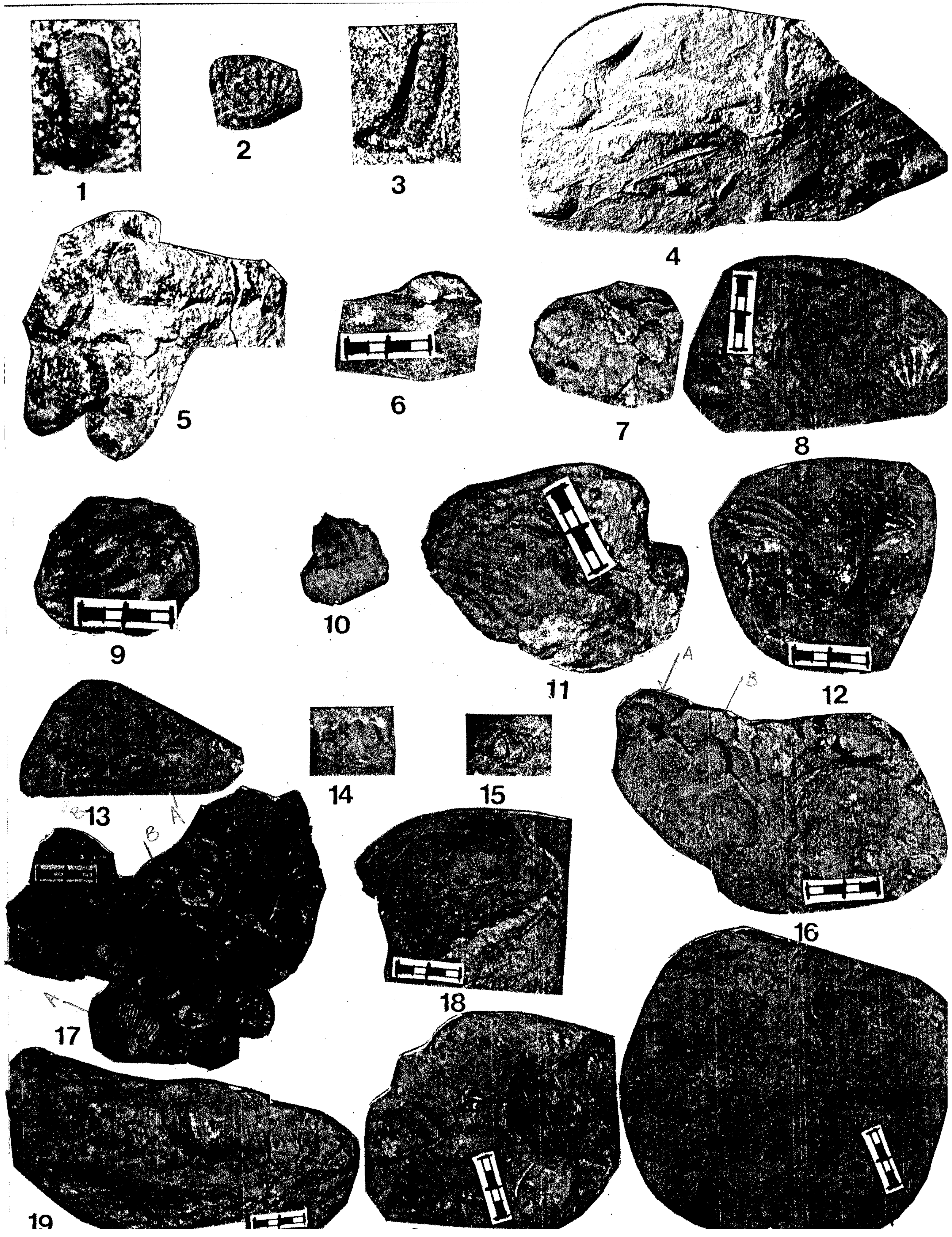
16 Gyrodes sp. (A) and Cardium sp. (B) from the Gallup Sandstone

17 Cardium sp. (A) and Turritella sp. (B) frm the Crevasse Canyon Formation

18 Exogyra sp. from the Crevasse Canyon Formation

19 Pteria sp. from the Crevasse Canyon Formation

20-21 Inoceramus sp. from the Crevasse Canyon Formation


1
2
3
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A
B
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15
16
B
A
17
A
18
19

Stratigraphic Section of the JORNADA del MUERTO Coal Field
Socorro County, New Mexico

PLATE 2

Abraham Araya