DEPOSITIONAL ENVIRONMENTS IN THE TRANSITION FROM MANCOS SHALE TO MESAVERDE GROUP NEAR CARTHAGE, SOCORRO COUNTY, NEW MEXICO

by

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ABSTRACT

Mesaverde Group, of Late Cretaceous age, is regarded as continental deposits conformable with the underlying marine Mancos Shale in the Carthage area. The nature of the transition from marine to continental deposits bears on the geometry and orientation of the coal bodies in the study area. Based on the lithology, sedimentary structures, paleontology, and lateral continuity of units described along a 1.4-kilometer (.9-mi.)-transect, the following sequence of depositional environments is interpreted: 1) transition zone between the offshore zone and the beach, 2) the shoreface zone of a beach, 3) marsh/lagoon, 4) floodplain, and 5) a restricted coastal body of water such as a bay, lagoon, or estuary. The proposed modern analog for these depositional environments is the Georgia coast which is characterized by barrier islands separated from the mainland by a lagoonal/salt-marsh zone.

The major coal body in the study area, a 1.5-meter (5') -thick seam which has been mined in the past, is interpreted as a coastal-marsh/lagoonal deposit. As such deposits are elongate parallel to the shoreline, the predicted orientation of the long axis of this coal body is N-S to NW-SE which corresponds to the paleoshoreline orientation, based on analysis of paleocurrent data from cross-stratification in the shoreface deposits. Discontinuous coal seams less than 30 cm (1') thick which occur above the major coal seam are interpreted as floodplain-swamp deposits and thus, should be elongate

approximately perpendicular to the shoreline.

Semi-quantitative X-ray diffraction analysis of clay minerals from one measured section yields an assemblage of illite, kaolinite and mixed-layer clays. The general trend of increasing proportions of kaolinite and decreasing proportions of mixed-layer clays upwards in the stratigraphic section, corresponds to the transition from marine to continental deposits. Proportions of illite remain relatively constant throughout the stratigraphic section.

ACKNOWLEDGMENTS

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Finally, I would like to thank my friends, particularly Piero DeSimone, for their support and encouragement throughout the process of accomplishing this study.

Chapter 1

INTRODUCTION

Purpose of the Study and Approaches Used: The Mesaverde Group, of Late Cretaceous age, is regarded as continental deposits conformable with the underlying marine Mancos Shale in the Carthage area. The Mesaverde Group is generally considered to be interbedded fluvial sandstones, floodplain shales, and floodplain swamp coals. The nature of the transition from marine to continental deposits has not been previously studied. The depositional environments are of economic importance with respect to exploration and recovery of coals within the Mesaverde Group. Coals deposited within coastal lagoons would be elongate parallel to the shoreline but coals deposited on fluvial floodplains or in oxbow lakes would be elongate parallel to the mean trend of the river channels, approximately perpendicular to the shoreline. The purpose of this study is to determine the depositional environments of units within the Mesaverde Group, near the contact with the Mancos Shale.

The following approaches for determining the environments of deposition are used:

1) Measurement of stratigraphic sections showing vertical sequences of units characterized by lithology, sedimentary structures and paleontology,
2) Lateral tracing of these units,
3) Paleocurrent analysis,

4) Petrographic analysis, and
5) Semi-quantitative clay mineral analysis of shales and mudstones by X-ray diffraction methods.

Sieve analysis was not attempted because petrographic analysis indicates that measurement of original grain-size distribution is impossible due to post-depositional alteration. Thus, grain-size distribution cannot be used to aid interpretation of depositional environments in this study.

Literature Review: The Mesaverde Group was first described by Holmes (1877) in the northern portion of the San Juan Basin in northwest New Mexico and southwest Colorado. Since then, the Mesaverde Group has been extensively mapped and studied; for a review of the literature written during the first half of the century, the reader is referred to Beaumont and others (1956). Within the San Juan Basin, the Mesaverde Group represents continental to nearshore deposition during part of the Late Cretaceous. The varying thickness and intertonguing of strata across the basin is a result of the transgressions and regressions of the land-sea interface which trended in WNW-ESE to W-E direction. The Late Cretaceous sea was located to the north and east of this interface. The Mesaverde Group in the south and east portions of the basin is thicker and shows more complex intertonguing relationships than in the northwest portion. Figure 1 illustrates the nomenclature in present use and the relationships of the various members of the Mesaverde

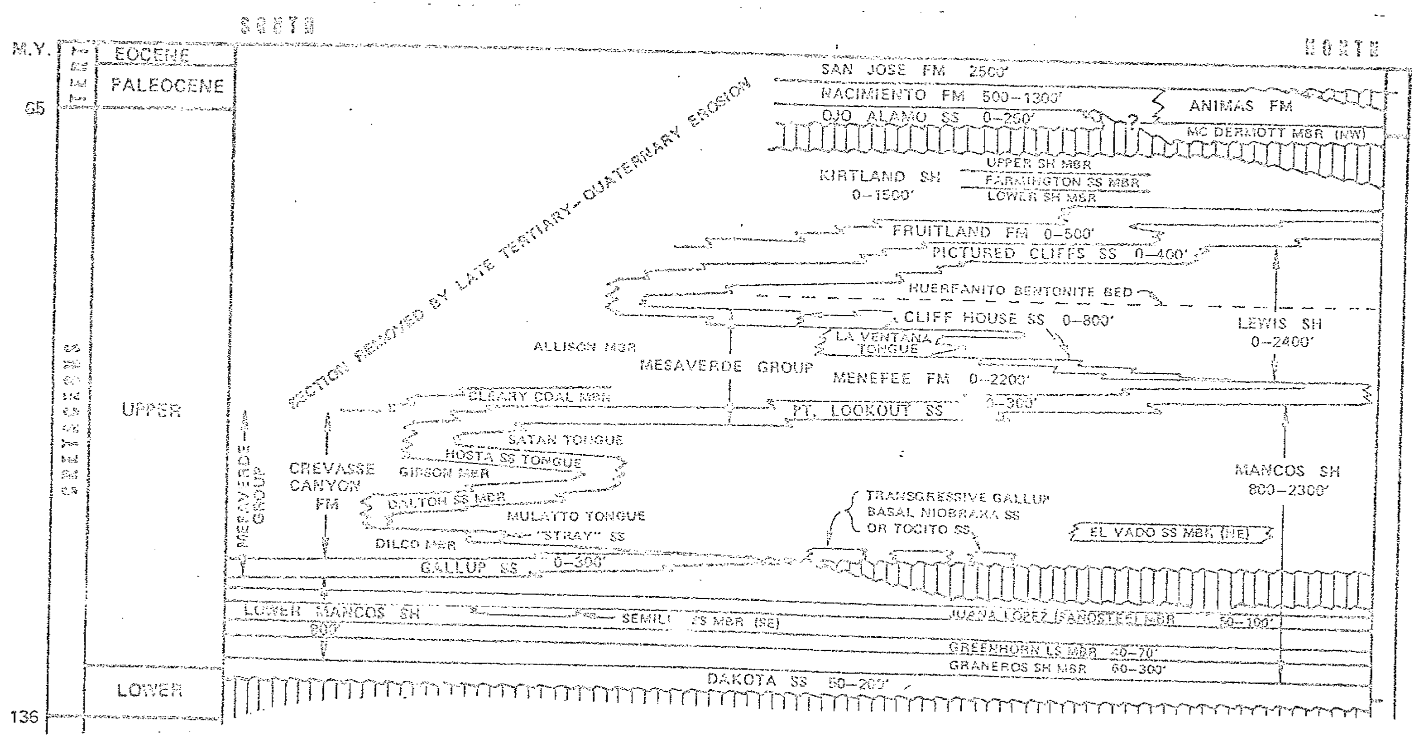

Figure 1 - Stratigraphic nomenclature of the Mesaverde Group and adjacent units in the San Juan Basin. Compiled by Molenaar (1977).

Group to each other.

Gardner (1910) was the first to map the Carthage area and he subdivided the Upper Cretaceous strata into three units; Dakota (?), Colorado, and Montana. Based on fossil evidence and characteristics of the coal-bearing unit, the Montana strata were correlated with the Mesaverde Group of the San Juan Basin. Lee (1915) tentatively correlated the marine deposits of Colorado age with the Mancos Shale and the overlying coal-bearing deposits with the Mesaverde Group. Rankin (1944) and Pike (1947) further subdivided and correlated the Upper Cretaceous strata. Table 1 illustrates the development of stratigraphic nomenclature of the Mesozoic strata in the Carthage area.

In 1951, Wilpolt and Wanek remapped the area and developed the stratigraphic nomenclature which has been in use to the present. Their nomenclature will be used in this study with one modification: the Mesaverde strata will be considered as a group rather than as a formation in keeping with the revised nomenclature of the Mesaverde Group in the San Juan Basin as proposed by Beaumont and others (1956). The following is taken from Wilpolt and Wanek's (1951) lithologic descriptions of the units in the Carthage area. The Upper Cretaceous Dakota Sandstone is a 75-foot (23m)-thick ridge-former of buff, thick-bedded, medium-grained sandstone which unconformably overlies the Triassic Dockum Formation characterized by maroon sandstones, siltstones, and shales. The Mancos Shale which overlies the Dakota Sandstone, is

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1: Stratigraphic nomenclature for the Mesozoic strata in the Carthage area

Gardner (1910)	Lee (1915)	Rankin (1944)	Pike (1947)	Wilpolt & Wanek (1951)	Molenaar (1974)	Cobban & Hook (in press)		U. S. G. S. Geologic Names Committee (Jan. 10, 1979)	This Study (1979)	
Montana 5' (206m)	Mesaverde Formation (tentatively) 685' (206m)	Mesaverde Formation	Dilco-lower Gibson Zone 600' (180m)	Mesaverde Formation 987'+ (297m+) (Drill hole data)	Crevasse Canyon Formation 25'+ (8m+)			Dilco Coal Member of the Crevasse Canyon Formation	oyster-bearing assemblage 17-23' (5-7m) coal-bearing assemblage 133-167' (40-50m)	Mesaverde Group
			Upper part of Gallup Member of the Mesaverde Formation 20' (6m)		Gallego Sandstone " C " ~50' (~15m)			Gallup Sandstone	basal assemblage 30-47' (9-14m)	
Colorado 5' (269m)	Mancos Shale (tentatively) 895' (269m)	Niobrara Formation 200'+ (60m+)	Pescado Tongue of the Mancos Shale 375' (113m)	Mancos Shale 225-290'(68-87m)	D-Cross Shale Tongue ~300' (~90m)	D-Cross Shale Tongue	Mancos Shale		transition assemblage ~13 (4m)	Mancos Shale
		Carlile Shale 330' (99m)	Lower part of Gallup Member of the Mesaverde Formation 40' (12m)	Sandstone Member of Mancos Shale 240' (72m)	Lower Gallup (Atarque Member) ~250' (~75m)	Tres Hermanos Sandstone Member				
		Greenhorn Limestone 30' (9m) Graneros Shale 157' (47m)	" Drab marine shale" 500' (150m)	Mancos Shale 295-340'(89-102m)	Lower Mancos Shale 100'+ (30m+)	Lower Shale Tongue				
akota(?) 75' (23m)	Dakota(?) or Tres Hermanos Sandstone Member of the Mancos Shale	Dakota(?) Sandstone	Dakota(?) ± Tres Hermanos Sandstone 200' (60m)	Dakota Sandstone 71' (21m)		Dakota Sandstone				
iassic(?)				Dockum Formation						

divided into three members. The lower shale member, ranging from 295 to 340 feet (89 to 102m) thick, consists of dominantly gray calcareous shale with a few limestone beds in the middle. The Sandstone Member, 240 feet (72m) thick, is characterized by medium- to fine-grained, medium-bedded sandstones interbedded with shales of various colors. The upper shale member, ranging from 225 to 290 feet (68 to 82m) thick, is composed of gray calcareous shale containing septarian concretions with cone-in-cone structure in the upper part. Conformably overlying the Mancos Shale, is the Mesaverde Group which is characterized by yellow and buff sandstones, shales, and thin coal beds. The entire Mesaverde Group is not exposed at the surface; 987 feet (296m) has been penetrated by the Stackhouse No. 3 drill hole in section 1, T.5S., R.2E. A geologic road log and field trip through the Carthage area can be found in Foster and Luce (1963) and Budding (1963).

Recent geological work has led to the extension of more detailed stratigraphic nomenclature of the San Juan Basin to the Carthage area. Subdivision and correlation of the Mancos Shale was discussed by Molenaar (1974) and Cobban and Hook (in press). With the Mesaverde Group in the Carthage area, Molenaar (1974) referred to the 50-foot (15m)-thick sandstone at the base as the Gallego Sandstone and the strata above as the Crevasse Canyon Formation. During an informal meeting on January 10, 1979, the U.S. Geologic Survey Geologic Names Committee changed Molenaar's nomenclature of the Gallego Sandstone to the Gallup Sandstone and applied the nomenclature of the Dilco Coal Member of the Crevasse Canyon Formation to the Carthage area (Hook, personal communication, 1979, Paleontologist, New Mexico Bureau of Mines and Mineral Resources, Socorro, New Mexico). This formal stratigraphic nomenclature will not be used in this study; instead, informal rock assemblages will be defined for the purpose of discussing depositional environments.

Various workers have considered the age of the base of the Mesaverde Group in the Carthage area as summarized on Figure 2 which also shows the relationships between the European and Western Interior classification schemes for this time interval. Cobban and Reeside (1952) placed the age at the Turonian/Coniacian boundary while Molenaar (1974) stated the age to be mid-Turonian (early Carlile). Hook (personal communication, 1978, Paleontologist, New Mexico Bureau of Mines and Mineral Resources, Socorro. New Mexico) considered the age to be very latest Turonian, just below the lower boundary of the Coniacian or Niobrara at approximately 87 million B.P.

The coal in the Carthage area occurs in a thick seam (average 5 feet (1.5m) thick) above the basal sandstone and in smaller discontinuous seams 1 to 8 inches (2 to 20 cm) thick. Only the thick seam, known as the Carthage coal bed, has been mined. The coal from this bed is relatively pure and is reported to have produced excellent coke. An analysis of a sample from the Hilton mine contained 7.4% ash content and slightly less than 1% sulfur (Gardner, 1910).

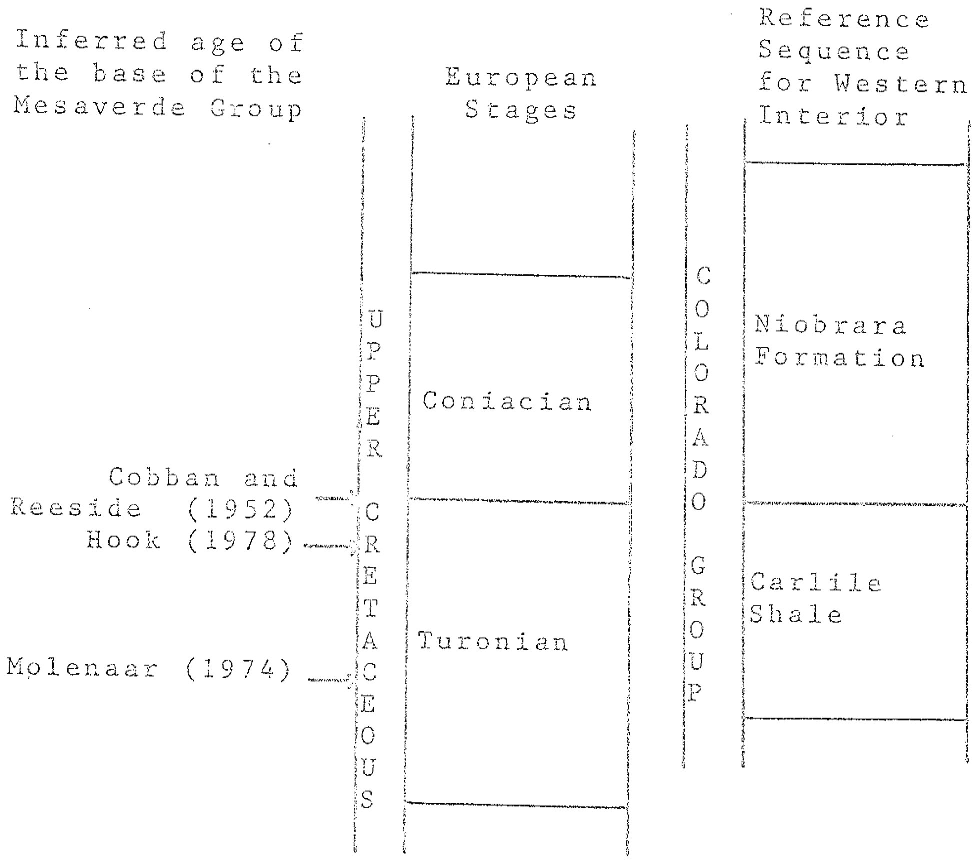


Figure 2 - Age of the base of the Mesaverde Group in the Carthage area according to various workers. Classification systems from Cobban and Reeside (1952).

The coal in the Carthage area was first mined by government troops encamped on the Rio Grande in 1861. At the time of Gardner's study in 1910, coal was being produced from four mines; the Government, Bernal and Hilton mines of the Carthage Fuel Company, and the Emerson mine of Emerson and Allaire. By 1920, production in these mines had ceased. During the late twenties and early thirties, coal was produced primarily from the newly opened Kinney mines. Coal production in existing mines experienced a resurgence during World War II, but at the end of the war, production gradually declined until the final shipment in 1963 (Smith, personal communication, 1978, Professor of Geology, New Mexico Institute of Mining and Technology, Socorro, New Mexico).

Geologic conditions in the Carthage area have limited coal production to small-scale operations for local use only. Due to numerous faults and changes in dip of the strata, following the coal seams is extremely difficult underground and below 20 feet (6m) is further hampered by pooling of water seeping along the fault planes (Gardner, 1910).

Geographic Setting of the Study Area: The study area encompasses about three square miles of outcrop of the Mesaverde Group surrounding Carthage, an abandoned coal mining town (Wilpolt and Wanek, 1951). Carthage is located within the southern extension of La Joyita Hills about nine miles east of San Antonio in Socorro County, New Mexico (Figure 3). The study area is located along the east-west, two-

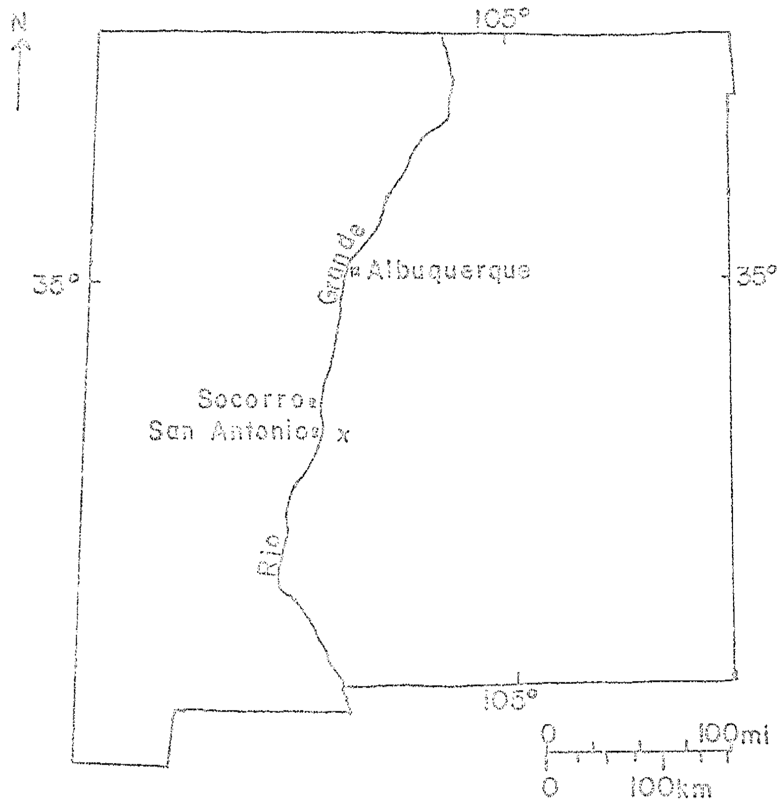


Figure 3 - Geographic location of the study area is indicated by the x.

lane U.S. Route 380 and is easily reached by a short walk from this highway or from the improved dirt Fite Ranch Road.

The elevation of the study area ranges from 4900 to 5100 feet (1470 to 1530m). The average annual precipitation is approximately eight inches (twenty centimeters); slightly more than half is received from local thunderstorms during June through September. Average temperatures in ^{o}F range in the 90's during the summer and in the 30's during the winter (Bureau of Land Management, 1978). Due to the semiarid climate, the vegetation is sparse. The vegetative type is Creosotebush which includes fluffgrass, dropseed, black grama, galleta, broom snakeweed and creostebush. The soils range from dominantly shallow and stony loams to sandy loams (Higgins, 1977).

Structural Setting of the Study Area: The study area lies within a N-S trending horst which is located between the grabens of the Rio Grande and Jornada del Muerto valleys. The Upper Cretaceous strata have been folded into at least one broad southward plunging syncline and anticline pair. The anticline, located to the west of the syncline, has been offset near its axial plane by one of the N-S trending faults dividing the horst from the graben. The strata have also been intensely faulted by vertical to nearly vertical faults trending from approximately N30^{o}W to N20^{o}E (Smith, personal communication, 1978, Professor of Geology, New Mexico Institute of Mining and Technology).

The structure and, stratigraphy of the study area is expressed as a series of offset, generally south-dipping, small cuestas of more resistant sandstone alternating with approximately E-W-trending strike valleys of less resistant shale. Typically, the transition between the Mancos Shale and the Mesaverde Group is located on the steeper north side of a cuesta.

Chapter 2

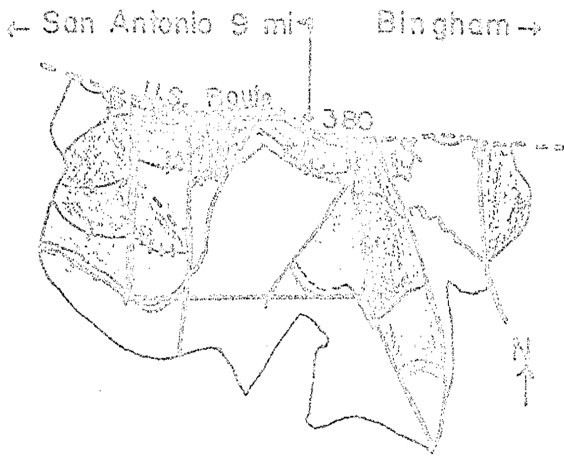
GENERAL FIELD DESCRIPTION OF THE ASSEMBLAGES

The Mesaverde Group crops out in sections 9, 10, 15, 16, 17, and 21 of T.5S. and R.2E. Exposures of the transition between the Mancos Shale and the Mesaverde Group are found in sections 9, 10, 15, and 17. In section 17, the Mesaverde Group is unconformably overlain by the Santa Fe Group (Tertiary).

Four stratigraphic sections were measured in sections 9 and 10, in an approximate W-E direction relative to each other (Figure 4). Sections II and III are separated by a fault with relatively minor displacement but Sections III and IV are separated by a fault with major displacement and several with minor displacement. The reader is referred to Plate 1 and Appendixes A and B respectively, for stratigraphic columns, descriptions of the units, and terminology used in the field.

In order to facilitate the interpretation and discussion of depositional environments, units will be grouped into distinct assemblages based on differences in lithology, paleontology, and sedimentary structures (Plate 1). Four assemblages are defined: in ascending order they are the transition assemblage, the basal assemblage, the coal-bearing assemblage, and the oyster-bearing assemblage.

The transition assemblage is usually covered and consists of fine-grained sandstone or alternating fine-grained



Mesaverde Group

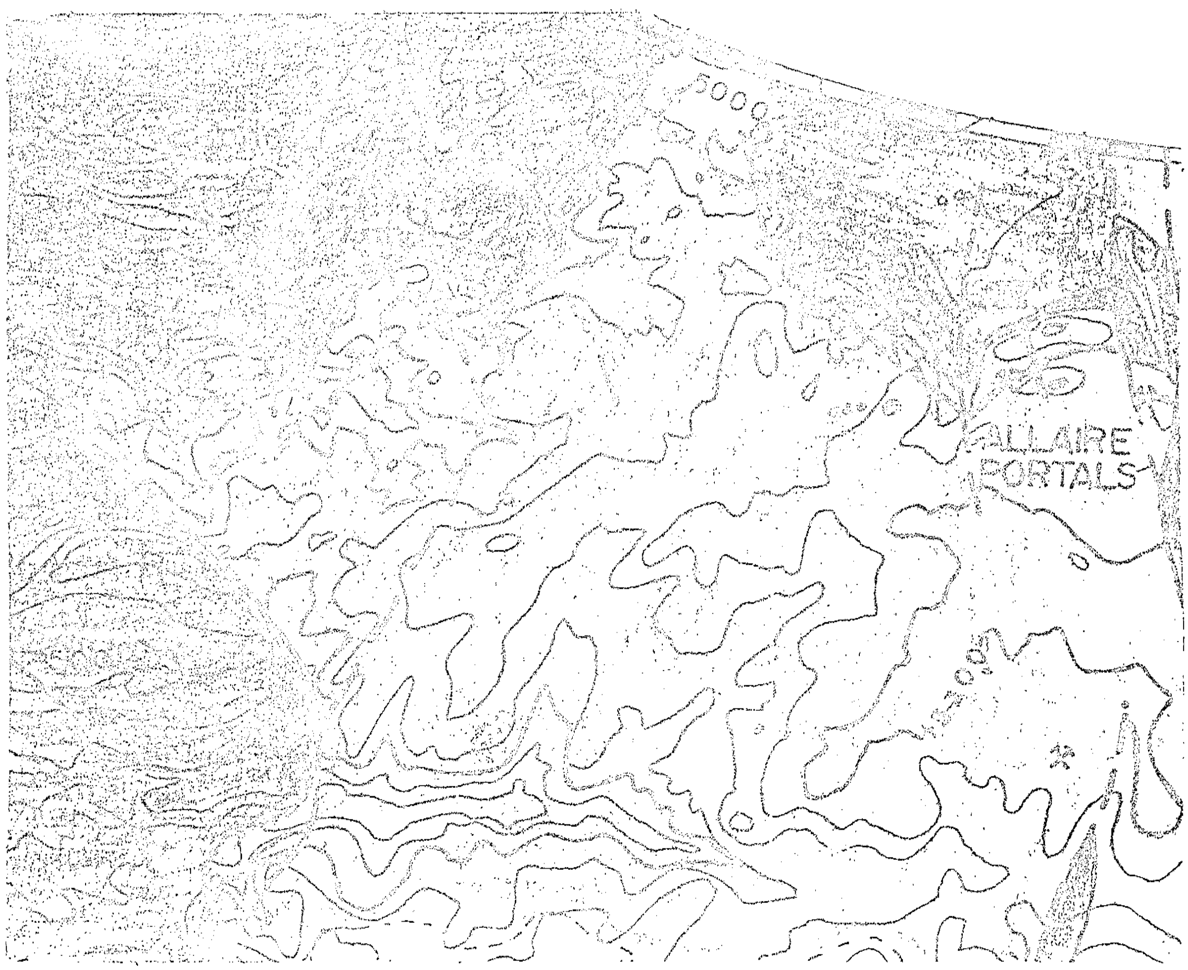
Upper Shale Member of the Mancos Shale

Middle Sandstone Member of the Mancos Shale

Lower Shale Member of the Mancos Shale

Coal seam

Figure 4 - Geologic map of the study area
A (above) - From Wilpolt and Wanek (1951), 1"=1mi (1cm=.63km). Square outlined in brown indicates area of B.
B (below) - From Smith (unpublished map), 1"=1000' (1cm=120m). Contour interval = 25'. Locations of measured sections are in brown.



sandstone, siltstone and shale grading downward into shale within a 4-meter (13')-thick interval (Figure 5).

The basal assemblage consists of a 9- to 14-meter (30 to 47')-thick, cliff-forming, moderately-sorted, fine- to medium-grained sandstone (Figure 6). The sandstone is dominantly planar-parallel laminated, locally structureless, and cross-stratified only in the upper half or third of the assemblage. The cross-stratification consists of small- and medium-scale, low-angle, trough-shaped sets and medium- (including to near large-) scale, low-angle, tabular- to wedge-shaped sets of tangential cross-laminae or very thin cross-beds. Isolated examples of inclined lamination and current lineations occur within the assemblage. Marine invertebrate fossils occur at or near the base of the basal assemblage and burrows occur generally within the lower half of the assemblage. The top of the assemblage locally contains plant-fragment impressions.

The contact between the transition and the basal assemblages coincides with the contact between the Mancos Shale and the Mesaverde Group. In Sections I, II, and III, the contact is distinct (Figures 5 and 6). In Section IV, the contact is difficult to place due to the outcropping beds of sandstone alternating with covered intervals of finer grained lithologies. In this study, the contact has been placed at the base of a sandstone which contains invertebrate fossils and thus, can be traced laterally (Figure 7).

The coal-bearing assemblage, ranging from 40 to 50

Figure 5 - Transition assemblage (A) at Section III; note sharp contact with the basal assemblage (B).

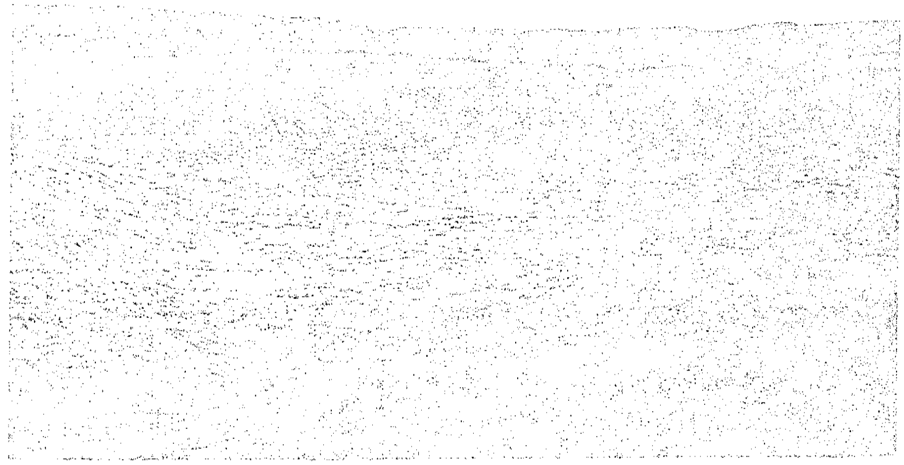


Figure 6 - Cliff-forming basal assemblage (B) at Section III; note sharp contact with the transition assemblage (A). Coal dump (C).

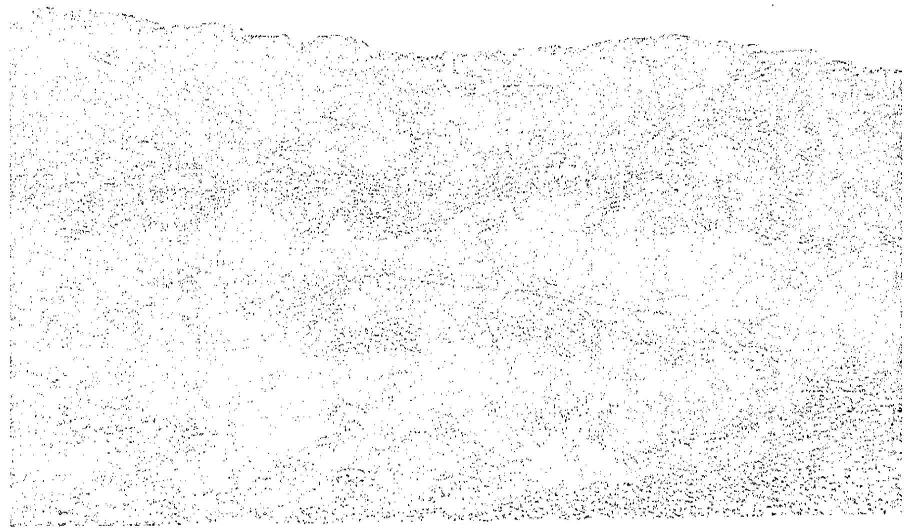


Figure 7 - Contact between the transition and basal assemblages at Section IV. The contact was placed at the base of sandstone A (Unit #4) because it contains invertebrate fossils and therefore is easier to trace laterally than sandstone B (Unit #2).

meters (133-167') thick, is characterized by a variety of lithologies ranging from coal, carbonaceous shale, and mudstone to siltstone and moderately- to poorly-sorted, fine- to medium-grained sandstone. The assemblage is dominated by covered intervals of predominantly finer grained material. Siltstone to sandstone bodies are usually laterally discontinuous. Individual beds often pinch and swell, and locally exhibit channel-scale cut and fill structures (Figure 8). Internally, the beds usually either exhibit planar-parallel lamination or appear structureless. Less commonly, the beds exhibit irregular lamination or low-angle, medium-scale, trough-shaped sets of cross-laminae. Ripple marks occur on some bedding planes. Organic remains include a 1.5-meter (5')-thick coal seam near the base of the assemblage, carbonaceous debris within the shales and mudstones throughout the assemblage, and a few fossilized logs. A lens of poorly-sorted, medium-grained sandstone occurs in Section I and has a lateral extent of approximately 180 meters (600') (Figure 9). In the area in which the lens attains the greatest thickness, about 7 meters (23'), the strata of the lens truncates the upper portion of the major coal seam. The internal structure of the lens is generally structureless with local areas of abundant medium-scale, high- to low-angle, tabular- to wedge-shaped sets of tangential cross-lamination.

The base of the oyster-bearing assemblage occurs between 56 and 62 meters (187 and 207') above the base of the

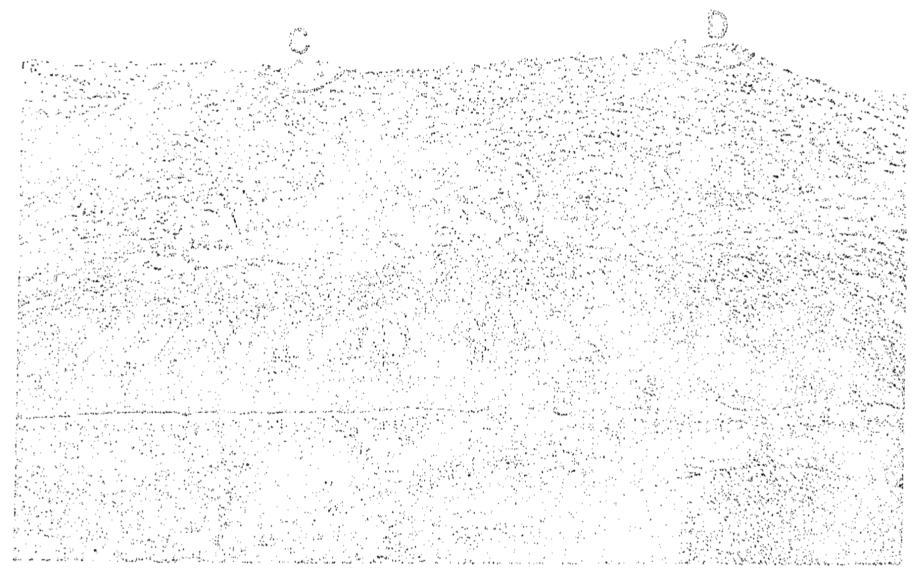


Figure 8 - Coal-bearing assemblage at Section III (Units #8-16). (A) Very light gray sandstone which serves as a distinct marker bed (Unit #9), (B) major coal seam (Unit #12), and (C) and (D) channel-scale cut and fill structures (Unit #16). (C) is 2m (7') deep, 6m (20') wide, and has a symmetrical cross section, and (D) is 1.5m (5') deep, 5m (17') wide, and has an asymmetrical cross section.

Figure 9 - Sandstone lens (L) in the coal-bearing assemblage at Section I (Unit #9). Can be traced laterally for approximately 180m (600') but is truncated at one end by a fault (F). In areas of greatest thickness (7m; 23'), the lens is in erosional contact with the major coal seam.

Mesaverde Group as determined from the two sections that could be measured to that stratigraphic position. The assemblage is comprised of a 5- to 7-meter (17 to 23')-thick sequence of a basal medium to thick bed of moderately-sorted, very fine- to fine-grained sandstone, an intermediate 3- to 6-meter (10 to 20') thick covered interval, and an overlying thick bed of moderately-sorted, very fine- to fine-grained sandstone. The basal bed of sandstone and the float in the lower one third of the covered interval contain relatively abundant whole oysters, Flemingostrea aff. prudencia. The basal bed of sandstone also contains less abundant fragments of the oyster Crassostrea solemiscus and whole articulated valves of pelecypods. The upper bed of sandstone contains relatively sparse debris of thin shells, poorly preserved pelecypods and fragments of the oyster Flemingostrea aff. prudencia.

Several units and groups of units within the Mesaverde Group occur in every section and are distinctive enough to use for correlation. The basal assemblage can be used to mark the base of the Mesaverde Group due to its characteristic cliff-forming sandstone. A 3.5-meter (11.5')-thick interval of sandstone concretions provides a marker horizon within the middle portion of the basal assemblage. The oyster-bearing assemblage, although lithologically indistinct from the surrounding strata, is distinctive due to its fossil content. The coal-bearing assemblage is characterized by the complete lack of marker horizons with the exception of two units which occur near the base of the assemblage. The first marker bed is the major coal seam which is usually exposed due to the previous mining activity in the area. The second marker bed crops out within the generally covered interval above the top of the basal assemblage and below the major coal seam. The marker bed is a structureless, thick to very thick bed of moderately-sorted, fine- to medium-grained sandstone. The sandstone is dominantly very light gray to light gray in color in contrast to the grayish orange or yellowish brown colors of the surrounding sandstones. The sandstone is dissected by sand-filled fractures which are perpendicular or oblique to bedding and form polygonal patterns on bedding surfaces. The sand in the fractures is often stained with a reddish brown pigment which dies out within a few to several centimeters (a few inches) away from the fractures.

Chapter 3

SEDIMENTARY STRUCTURES

Planar-Parallel Stratification: Planar-parallel stratification is the most common type of stratification in the study area, particularly in the basal assemblage. Planar-parallel lamination, generally thick rather than thin, is characteristic of the transition and basal assemblages. It is less common in the exposed sandstones of the coal-bearing assemblage. Discontinuous, even parallel beds as defined by Campbell (1967) form the units defined in the basal assemblage (Figure 6).

Structureless Units: Many units within the Mesaverde Group appear to be locally to entirely internally structureless in the field. Some of the locally structureless units within the basal assemblage can be definitely attributed to bioturbation as indicated by the presence of burrows. However, in most of the structureless units, post-depositional features such as intense fracturing or weathering mask or obliterate the original sedimentary structure. Thus, probably only a small percentage of the units reported as structureless are truly structureless.

Cross-stratification: The classification of cross-stratification used in this study is modified from the classification schemes proposed by McKee and Weir (1953) and Allen (1963), and is described in Appendix B.

The most abundant type of cross-stratification is medium-scale, low-angle, tabular-shaped sets of tangential thick cross-laminae and very thin cross-beds with both erosional and nonerosional lower contacts. Individual sets occur as solitary sets or as grouped sets (Figure 10). Sets of these cross-strata within the same unit often dip in opposite directions to each other forming "herringbone" cross-stratification (Reineck and Singh, 1975, p. 86). These tabular-shaped sets of cross-strata occur in every measured section within the upper portion of the basal assemblage.

The next most abundant type of cross-stratification is medium-scale, low-angle, trough-shaped sets of tangential thin to thick laminae with erosional lower contacts (Figure 11). This type of cross-lamination occurs in the upper portion of the basal assemblage and in some of the sandstones of the coal-bearing assemblage. Individual sets are almost always solitary and in the basal assemblage, are often associated (Figure 12) with the medium-scale, low-angle, tabular-shaped sets of cross-stratification discussed previously.

Grouped sets of small-scale, low-angle, trough-shaped sets of thin to thick cross-laminae with erosional lower contacts occur only in the middle portion of the basal assemblage at Section IV (Figure 13).

Grouped and solitary sets of medium- (to near large-) scale, low-angle, tabular- to wedge-shaped sets of tangential thick cross-laminae with both erosional and nonerosional lower contacts occur only in the upper portion of the basal

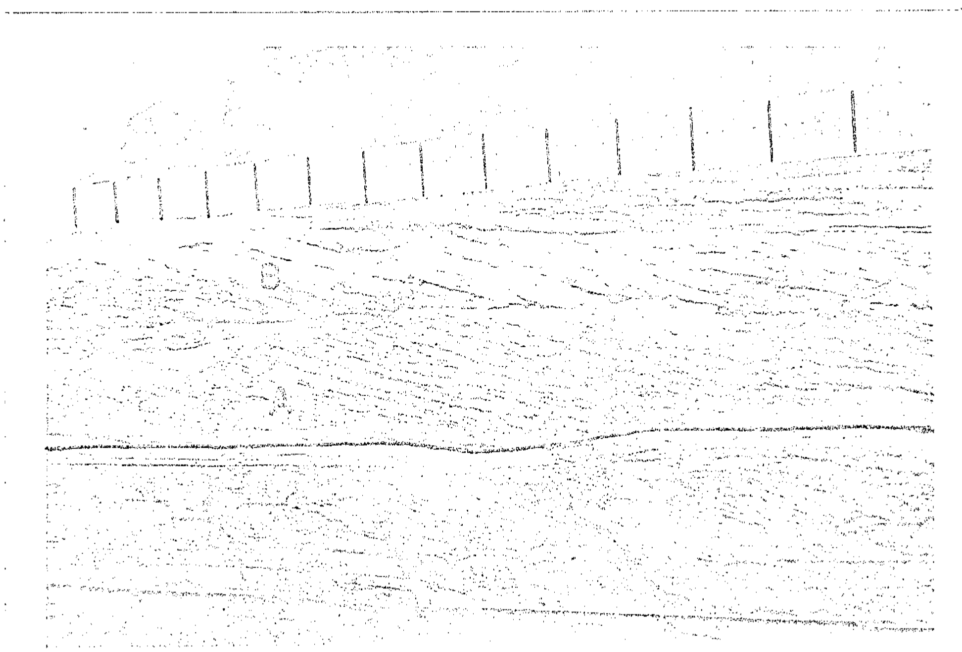


Figure 10 - Grouped, medium-scale, low-angle, tabular-shaped sets of tangential cross-laminae with both non-erosional (A) and erosional (B) lower contacts. From basal assemblage at Section IV (Unit #7). Tick marks on the Jacob's staff represent 5 cm (2") intervals.

Figure 11 - Solitary, medium-scale, low-angle, trough-shaped set of tangential cross-laminae with erosional lower contact. From basal assemblage at Section II (Unit #7). Tick marks on the Jacob's staff represent 5 cm (2") intervals.

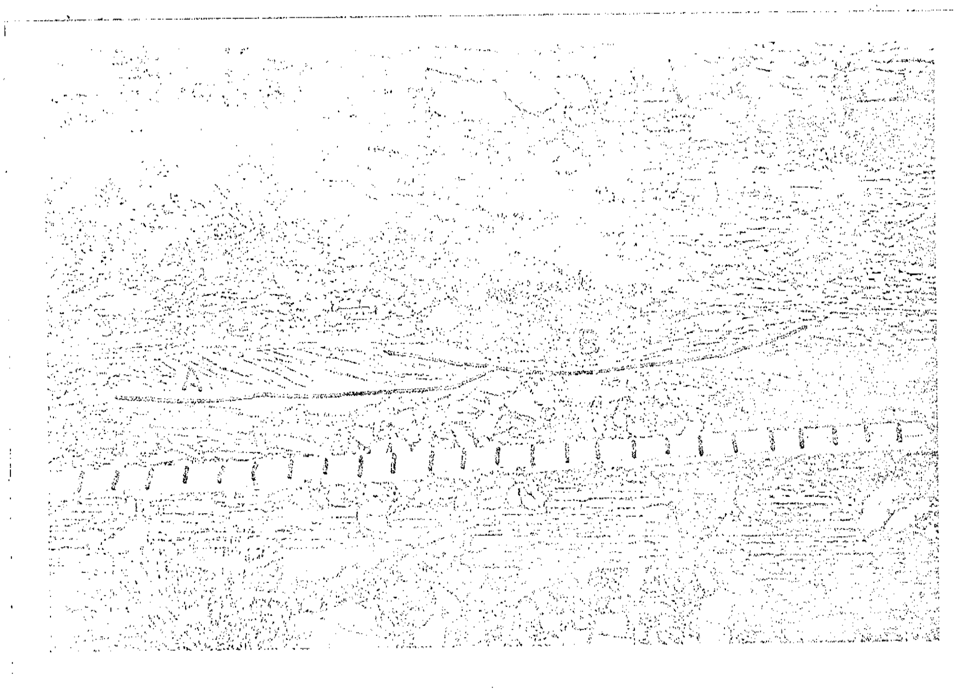


Figure 12 - Medium-scale, low-angle, tabular-shaped (A) and trough-shaped (B) sets of tangential cross-laminae with erosional lower contacts. From basal assemblage at Section II (Unit #7). Tick marks on the Jacob's staff represent 5 cm (2") intervals.

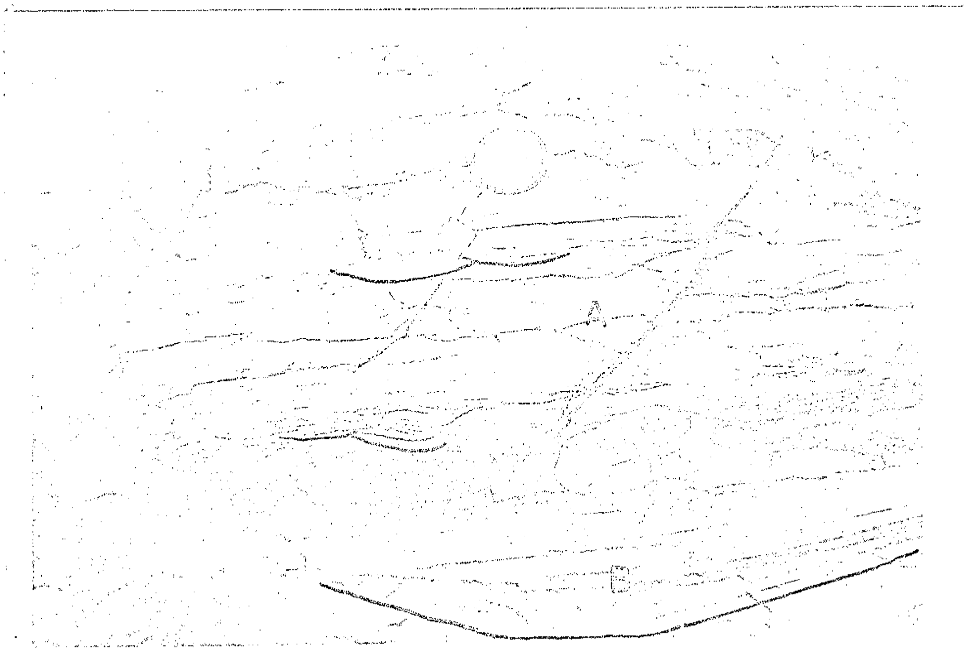


Figure 13 - Grouped, small-scale, low-angle, trough-shaped sets of tangential cross-laminae with erosional lower contacts (A), and solitary, medium-scale, low-angle trough-shaped set of tangential cross-laminae with erosional lower contact (B). From basal assemblage at Section IV (Unit #7). Lens cap is 6.5 cm (2.5") in diameter.

assemblage at Section IV (Figure 14).

Medium-scale, high- to low-angle, tabular- to wedge-shaped sets of tangential thin to thick cross-laminae with erosional and nonerosional lower contacts occur only within the sandstone lens (Unit #9) in the coal-bearing formation at Section I. Individual sets usually occur as grouped sets (Figure 15) and rarely as isolated sets.

The solitary sets of medium-scale, low-angle, tabular-shaped sets of cross-strata correspond to Allen's (1963) Alpha-, Beta- and Gamma- cross-stratification. The grouped sets of medium-scale, low-angle, tabular-shaped sets of cross-strata correspond to the Omikron-cross-stratification. Two modes of origin are proposed for the Alpha-, Beta-, Gamma-, and Omikron-cross-stratification. The first mode is the "building of solitary banks with straight or curving leading edges above slip-off faces" (Allen, 1963, p. 101) in shallow water. Solitary banks are common in modern rivers, estuaries, on beaches, and in shallows just off beaches. Reineck and Singh (1975, p. 86) interpreted the "herringbone" cross-stratification as indicative of tidal environments. The second mode of origin according to Allen (1963), is the migration of one or more trains of large-scale asymmetrical ripple marks with essentially straight crests. This type of ripple is found in channels or in the open sea in depths many times the depth of the ripple height.

The solitary sets of medium-scale, trough-shaped sets of cross-laminae correspond to Allen's (1963) Zeta-, Theta-,

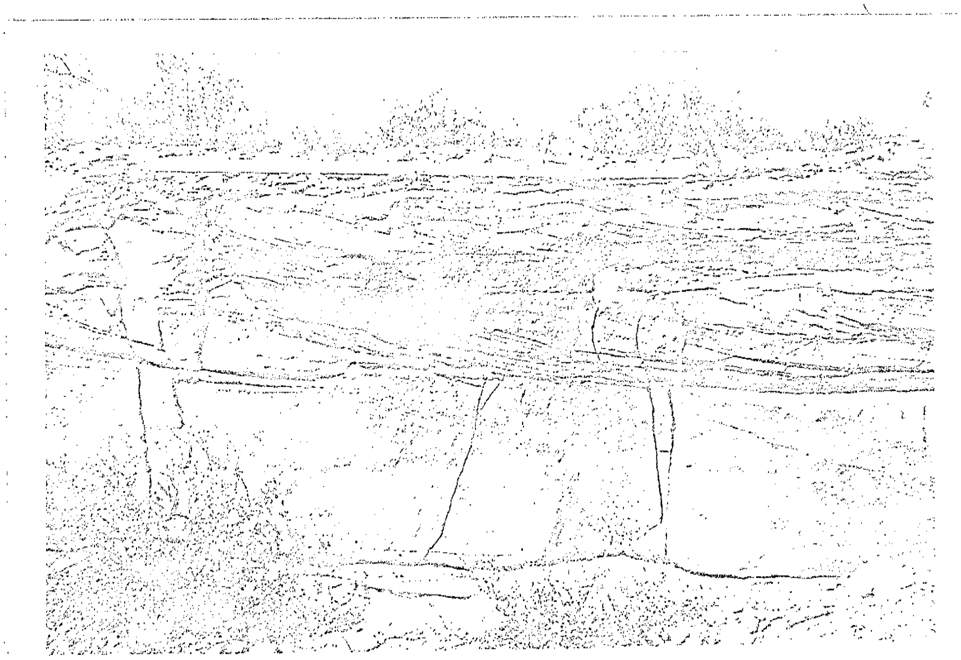


Figure 14 - Grouped, medium- (to near large-) scale, low-angle, tabular- to wedge-shaped sets of tangential cross-laminae with erosional lower contacts. From basal assemblage at Section IV (Unit #8). Jacob's staff is 1.5 m (5') long.

Figure 15 - Grouped, medium-scale, high- to low-angle, tabular- (A) to wedge- (B) shaped sets of tangential cross-laminae with erosional (B) and nonerosional (A) lower contacts. Only occurs in the sandstone lens within the coal-bearing assemblage at Section I (Unit #9). Lens cap is 6.5 cm (2.5") in diameter.

or Iota-cross-stratification; the specific type cannot be identified due to the lack of exposure of three-dimensional geometry. The Zeta-cross-stratification has been formed experimentally by channel fill but examples of this mechanism in modern environments have not been observed. The Theta- and Iota-cross-stratification are interpreted as scour and fill structures. Scours similar in geometry to the lower boundary surface of the Theta-cross-stratification occur on sandy beaches after strong tides.

The grouped sets of small-scale, trough-shaped sets of cross-laminae correspond to Allen's (1963) Nu-cross-stratification and are interpreted as the result of the migration of trains of linguoid small-scale asymmetrical ripples.

Irregular Lamination: Irregular lamination is a field term used by the author to describe discontinuous laminae which form sets that are wavy and nonparallel in shape as defined by Campbell (1967). This feature occurs in some of the sandstones in the coal-bearing assemblage particularly at Section III and in the oyster-bearing assemblage at Section III. Individual laminae are continuous over two to ten centimeters and sets are usually a few centimeters or less in thickness (Figure 16). Some individual sets can be identified as having wedge, tabular or trough shapes used in describing cross-stratification. The irregular lamination in the study area corresponds to Reineck and Singh's (1975, p. 87) small-ripple bedding which is comprised of foreset laminae produced by the migration of small-current

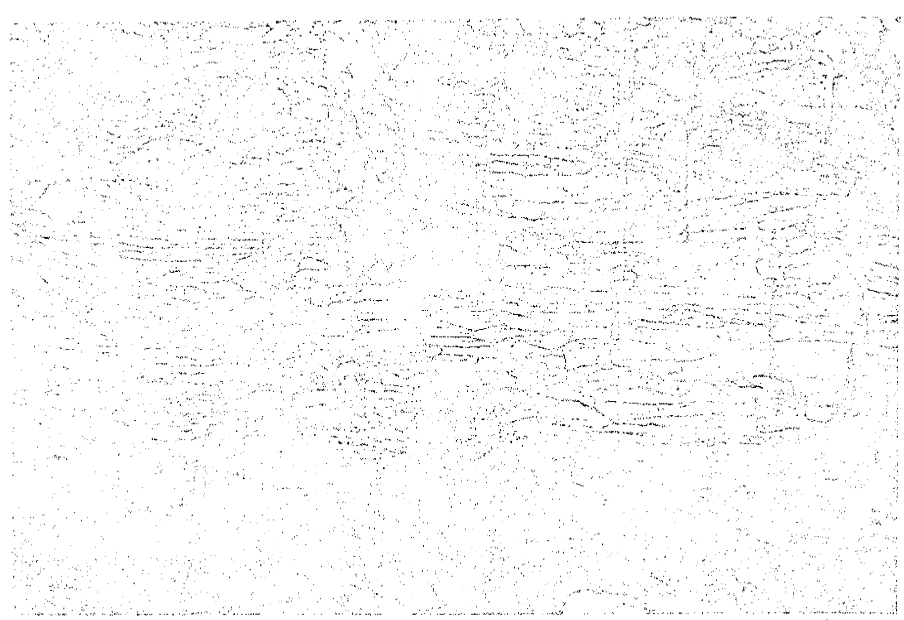


Figure 16 - Irregular lamination characterized by discontinuous laminae which form sets that are wavy and nonparallel in shape. From the coal-bearing assemblage at Section III (Unit #15). Lens cap is 6.5 cm (2.5") in diameter.

ripples.

Inclined Lamination: Inclined lamination occurs at the base of the basal assemblage in Section III. Stereonet analysis of two sets of inclined lamination yields paleo-dips of 8°,N69°E and 6°,S76°E. These dip directions are approximately perpendicular to the primary mode of paleo-current directions; N-N30°E as measured in this section from medium-scale, low-angle, tabular-shaped sets of tangential cross-stratification. Due to weathering effects on the outcrop surfaces, and to the difficulty of observing small angular differences between lamina compared to the relatively large dip of the strata, inclined lamination may be more abundant than described by the author.

Channel Cut and Fill Structures: Channel cut and fill structures occur above the major coal seam of the coal-bearing assemblage at Section III (Figure 8). The term channel implies only scale; these structures attain maximum dimensions of 2 meters (7') thick and 6 meters (20') wide with both symmetric and asymmetric cross sections. The cut and fill structures characteristically contain thinly to thickly laminated, moderately-sorted, fine-grained sandstone. Internal structures include local in-phase ripple cross-lamination near the base, and possible medium-scale, low-angle, trough-shaped sets of tangential cross-laminae in the upper portion of the cut and fill structures. Clay clasts, which occur in the float from the cut and fill structures, are characterized by circular to elongate shapes to one centimeter long lying on the lamination planes but are relatively flat and thin parallel with the lamination as viewed in cross sections.

Soft-Sediment Deformation: A zone of soft-sediment deformation occurs within a thick bed of medium-grained sandstone at the base of the basal assemblage at Section III. This zone is approximately 15 centimeters (6") thick and can be traced 5 to 6 meters (17-20') laterally. The zone occurs within the middle of an otherwise planar-parallel, thickly laminated, thick bed of medium-grained sandstone. The zone is characterized by continuous laminae which are folded, ranging in appearance from broad regularly spaced troughs and crests, to narrower more irregularly shaped, crumpled folds. The amplitude of the folds is the greatest in the middle portion of the zone and dies out above and below. The largest fold observed attains an amplitude of approximately 10 centimeters (4") and a wavelength of approximately 40 centimeters (14") (Figure 17). The amplitudes and wavelengths of adjacent folds decrease to a few centimeters within a lateral distance of half a meter (<2').

The type of soft-sediment deformation is probably either convolute lamination or slump structure. Convolute lamination is characterized by continuous laminae which are generally folded into sharp anticlines and broad synclines. The amplitude of the folds is largest in the center or upper part of the disturbed zone which is characterized by

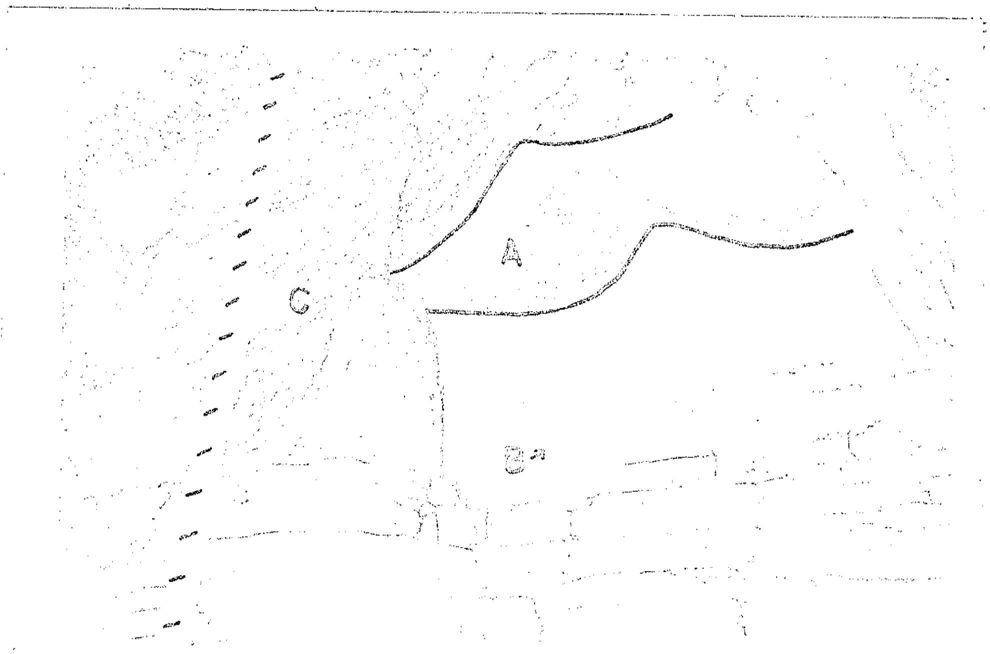


Figure 17 - Fold (A) within deformed zone of laminae, liesegang rings (B), and dark stain (C) on surface of outcrop. From basal assemblage at Section III (Unit #2). Tick marks on the Jacob's staff represent 5 cm (2") intervals.

generally planar upper and lower surfaces (Blatt, Middleton and Murray, 1971, p. 171). Convolute lamination most commonly occurs in fine-grained sandstones to coarse-grained siltstones in zones of 2.5 to 25 centimeters thick. The thickness of the bed and magnitude of the convolutions increase with an increase in coarseness of the sand sized particles (Potter and Pettijohn, 1963, p. 153).

Slump structures can be distinguished from convolute lamination by the following criteria; slump structures do not have continuous lamina, they are commonly faulted, and the thickness of the disturbed zone is uneven (Potter and Pettijohn, 1963, p. 153). Based on the physical description, the features in the study area appear to be convolute lamination rather than slump structures.

No definite conclusions can be made from the directional significance of the fold axis of the large fold shown in Figure 17. The axis of this fold trends N18°E-S18°W which falls into the primary mode of paleocurrent directions; N-N30°E as measured in this section from medium-scale, low-angle, tabular-shaped sets of tangential cross-stratification (Plate 1). According to Potter and Pettijohn (1963, p. 153), the directional significance of fold axes in convolute lamination is not always certain; some reported examples show trends perpendicular to the current directions with folds overturned in the downcurrent direction. One study on slump structures (Murphy and Schanger, 1962) showed that the fold axes were perpendicular to the paleoslope and parallel with the paleocurrent direction which followed along the strike of the paleoslope.

The axial surface of the large fold dips steeply to the west. If this structure is the result of sliding downslope, the paleoslope was dipping eastward. It is interesting to note that this direction corresponds to the eastward paleodip direction of inclined lamination (previously discussed) which occurs above the large fold in the same unit (#2).

Bedding Plane Features: Current lineations are exposed on the bedding plane surfaces of large float blocks from the basal assemblage in an area that was not measured (NW¼ of section 17). The original position of the float blocks could not be located along the outcrop, and thus no paleocurrent measurements could be taken.

One occurrence of straight-crested asymmetrical ripple marks was observed above the major coal seam of the coal-bearing assemblage at Section II. The ripple length averaged 1.5 cm and the height averaged 2mm. The ripples indicate a paleocurrent direction of N28^{o}W. Some of the bedding plane surfaces of the sandstones in the coal-bearing assemblage are irregular surfaces and are suggestive of poorly preserved ripple marks.

Post-depositional Features: Post-depositional features caused by both chemical and physical processes affect the appearance of the outcrops of the Mesaverde Group. Locally, the strata have been intensely fractured. The intense fracturing often grades into cone-in-cone structure near the top of individual sandstone beds within the coal-bearing and oyster-bearing assemblages. Fractures are often filled with calcite and occasionally with gypsum. Many of the surfaces of the sandstones are coated with a reddish brown to black pigment (Figure 17) which makes it very difficult to determine the internal sedimentary structures.

Liesegang rings occur in most of the sandstones in the Mesaverde Group and are particularly well exposed in the sandstones of the basal assemblage (Figures 17 and 18). The colors of the rings or bands range from grayish orange or grayish red, to dark reddish brown. Most of the liesegang rings appear to cut across the sedimentary structure; however, some rings do follow the internal structure, especially in the case of the trough-shaped sets of cross-strata.

Nodules occur most commonly in the sandstones of the basal assemblage. The nodules are generally dark reddish brown in color, are harder than the surrounding sandstones, and exhibit internal concentric banding. The nodules occur in thin layers or lenses, or as ellipsoidal to irregular-shaped bodies. The thin layers or lenses usually follow the bedding planes but can be oriented in any direction (Figure 19). Nodules are sometimes associated with liesegang rings and a complete gradation from liesegang rings to irregular-shaped nodules can be observed.

Sandstone concretions occur within an interval of 4.5

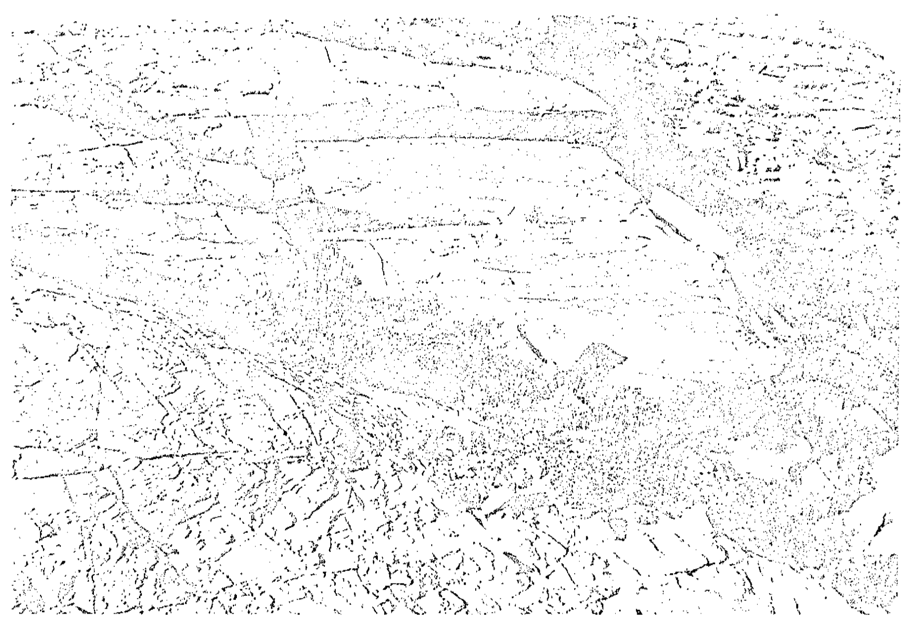


Figure 18 - Liesegang rings exposed on dipslope at the top of the basal assemblage at Section III (Unit #7).

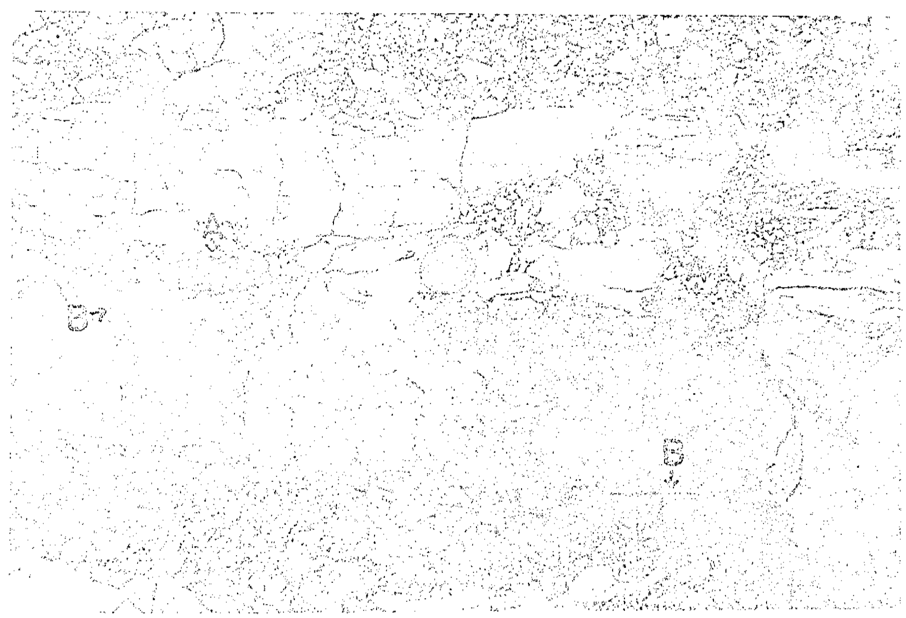


Figure 19 - Ellipsoidal shaped (A) and thin lenses or layers (B) of nodules. From basal assemblage at Section II (Unit #4). Lens cap is 6.5 cm (2.5") in diameter.

to 8 meters (7.5 to 10') above the base of the Mesaverde Group in every measured section of the basal assemblage. The concretions are shaped like oblate spheroids (flattened parallel to the stratification) with diameters ranging from 0.3 to 1 meter (1 to 3') and thicknesses ranging from 0.2 to 0.4 meters (8 to 16") (Figure 20). The concretions have the same grain size as the surrounding sandstones, ranging from fine to medium sand, but the concretions are slightly more calcareous than the surrounding host rock.

Sandstone concretions occur as distinct outcrops within covered intervals at Section II and IV of the coal-bearing assemblages (Figure 21). These concretions are characterized by somewhat more irregular shapes and larger sizes than those of the basal assemblage. The concretions of the coal-bearing assemblage range in size from 1 to 1.5 meters (3 to 5') in diameter and 0.75 to 1 meter (2.5 to 3') thick. The lithology consists of hard calcareous, fine-grained sandstone. The concretions are intensely fractured and frequently exhibit cone-in-cone structure around the upper portion of the concretions; the axes of the cone-in-cone structures are normal to the surface of the concretion.

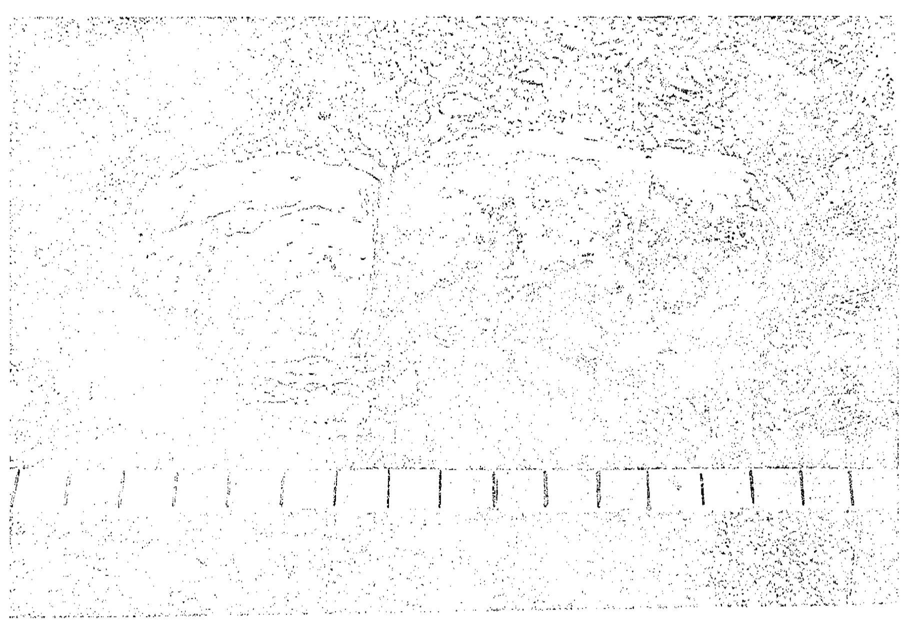


Figure 20 - Oblate spheroid-shaped sandstone concretions. From the basal assemblage at Section II (Unit #6). Tick marks on the Jacob's staff represent 5 cm (2") intervals.

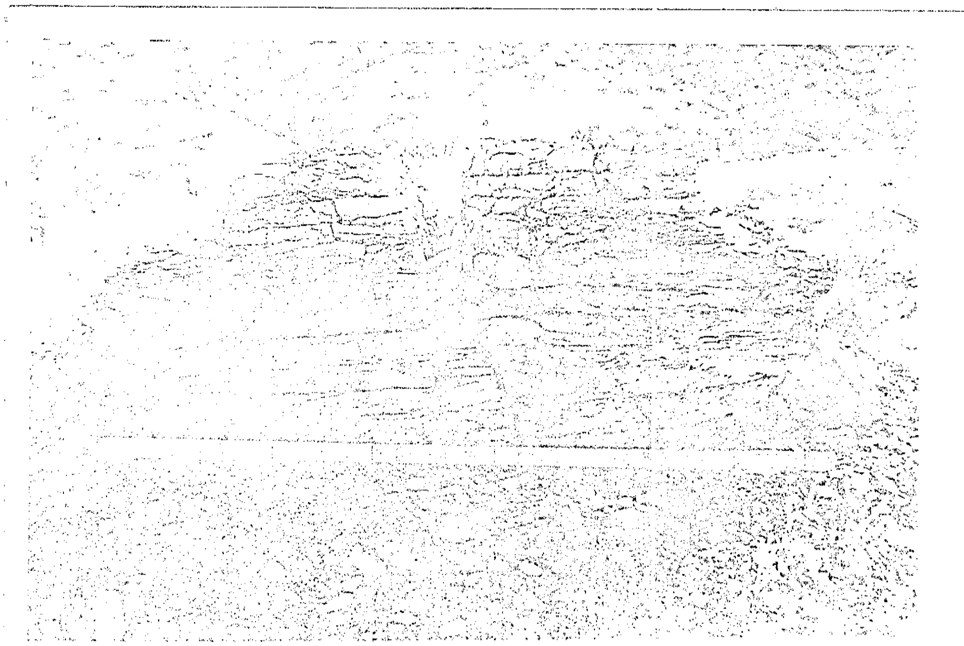


Figure 21 - Intensely fractured sandstone concretions. From the coal-bearing assemblage at Section II (Unit #13). Jacob's staff is 1.5 m (5') long.

Chapter 4

PALEONTOLOGY

Invertebrate Fossils: A diverse assemblage of marine invertebrate fossils occurs near the base of the basal assemblage at Sections III and IV. The assemblage includes four unidentified species of gastropods (Figure 22; A-D), pelecypods (Figure 22; E) including Cardium, and two species of oysters, Ostrea anomioides (Figure 22; F) and Crassostrea solemiscus (Figure 22; G). The gastropods and pelecypods are usually preserved whole as sandstone casts and molds with small amounts of white calcareous shell material. The oysters are characterized by gray calcareous shell material with a pearly luster. Crassostrea solemiscus is rarely preserved whole but can usually be distinguished from the commonly whole Ostrea anomioides by its very thick shell layer.

Two types of oysters occur in the oyster-bearing assemblage, Crassotrea solemiscus and Flemingostrea aff. prudencia (Figure 22; H). As in the basal assemblage, the oysters of the oyster-bearing assemblage are characterized by gray calcareous shell material with a pearly luster. Crassostrea solemiscus is preserved only as fragments but Flemingostrea aff. prudencia is usually preserved as whole articulated specimens which can be found weathered out on the lower surface of the covered interval within the oyster-bearing assemblage. The assemblage also contains sparse pelecypods which are preserved as sandstone casts and molds.

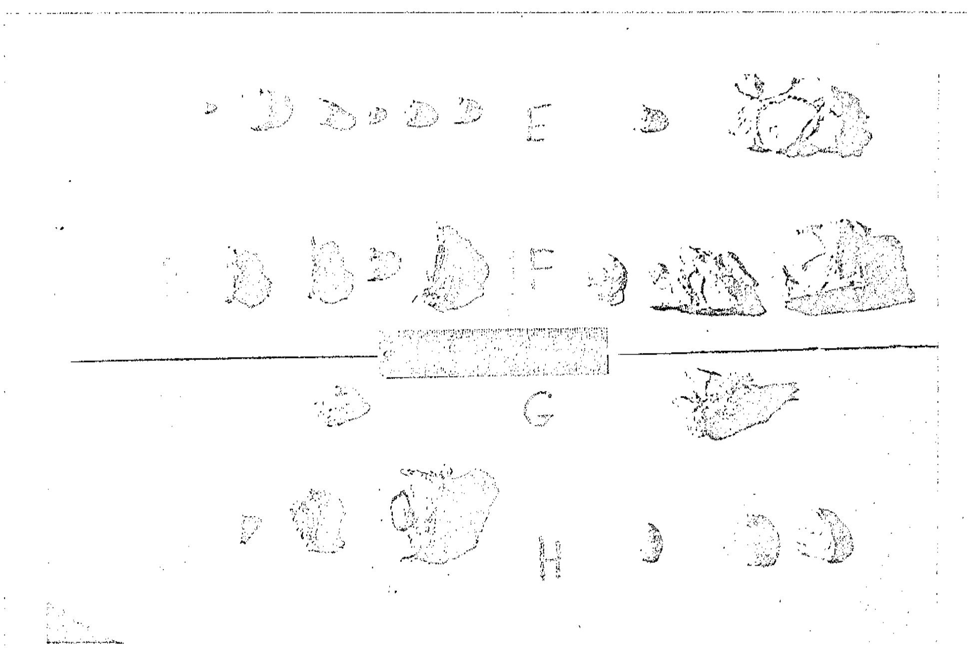


Figure 22 - Invertebrate fossils: (A), (B), (C), and (D) represent four species of gastropod, (E) pelecypods, (F) Ostrea anomioides, (G) a fragment of Crassostrea solemiscus, and (H) Flemingostrea aff. prudencia. Ruler is 15 cm (6") long.

Crassostrea solemiscus occurs in a wide range of salinities but Flemingostrea aff. prudencia occurs only in brackish water (Hook, personal communication, 1978, Paleontologist, New Mexico Bureau of Mines and Mineral Resources, Socorro, New Mexico). Thus, the presence of these oysters indicates a brackish water environment of deposition within the oyster-bearing assemblage.

Flora: The most abundant preservation of plant life occurs as carbonaceous debris and as impressions of stems and leaves located within the shales and mudstones in the coal-bearing assemblage. The presence of coal, of course, indicates locally concentrated accumulations of plant life.

Fossilized logs from 1.5 to 7.5 meters (5 to 23') long occur above the major coal seam of the coal-bearing assemblage at Section II (Figure 23). The long axis of the logs is oriented in a N-S direction. The logs are very well preserved and cross sections exhibit the radiating and concentric textures observed in cross sections of modern tree logs. Laterally adjacent to these fossilized logs are probable fossilized logs which are composed of a hard, light brown to brackish red ferrugenous material which exhibits elongate cellular to fibrous texture suggestive of petrified wood.

Plant-fragment impressions occur on stratification planes exposed along the dipslope formed by the uppermost sandstone unit in the basal assemblage of every section (Figure 24). The impressions usually occur in randomly oriented patterns of elongate fragments ranging in size up to 20 centimeters long and 3 centimeters wide. The impressions

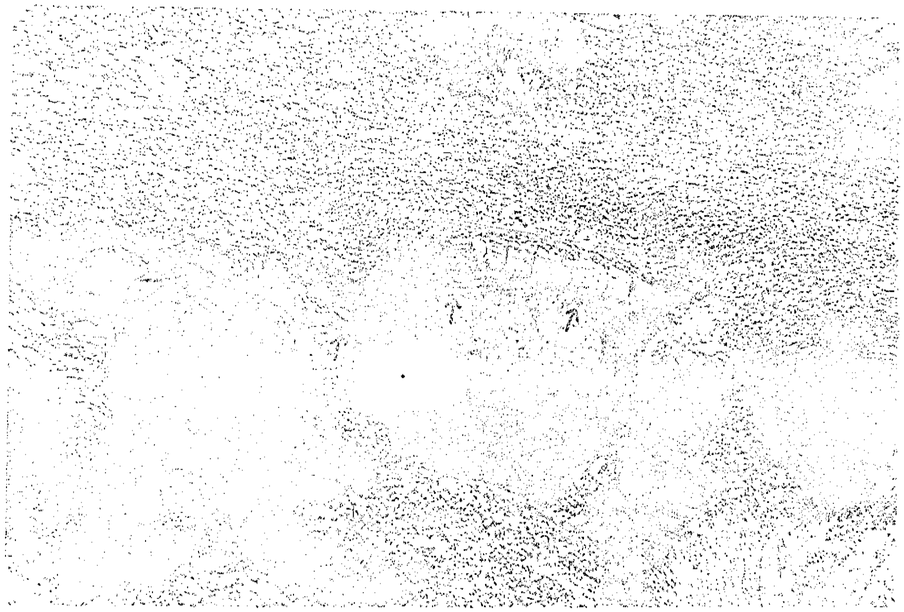


Figure 23 - Fossilized logs (indicated by arrows). From the coal-bearing assemblage at Section III (Unit #15). Jacob's staff is 1.5 m (5') long.

Figure 24 - Fragmental plant impressions which are characterized by a darker color than the surrounding sandstone. Exposed on the dipslope at the top of the basal assemblage at Section I (Unit #5). Lens cap is 6.5 cm (2.5") in diameter.

are characterized by a light brown to blackish red color in contrast to the surrounding grayish orange sandstone.

Trace Fossils: Two types of burrows are distinguished by their distinct size ranges. The smaller type (Figure 25) is characterized by a circular to slightly oval cross section which ranges from 0.5 to 1 centimeter in diameter, and by a smooth outer surface. The burrows appear to be randomly oriented, show Y-shaped to perpendicular branching and are enlarged at the junctions. A few individuals make an abrupt turn from a vertical to horizontal orientation with respect to stratification.

The larger type of burrows (Figure 26) is characterized by an oval cross section which ranges from 2.5 to 4 centimeters in the long dimension and from 1.5 to 2.5 centimeters in the short dimension. The outer surface of the burrows is smooth to irregular. The burrows often curve in the plane passing through the long dimensions of the cross sections and show Y-shaped branching with little or no enlargement at the junctions. In the field, the burrows often break into approximately 1-centimeter-thick transverse segments which are generally not related to stratification.

Both types of burrows occur within the lower to middle portions of the basal assemblage. Within the middle portion of the basal assemblage at Section I, a 2-meter-interval containing abundant, randomly oriented burrows of both types is overlain by a 2-meter-interval containing sparse burrows of the smaller type. No burrows were observed at Section II. Randomly oriented burrows of the smaller type are exposed

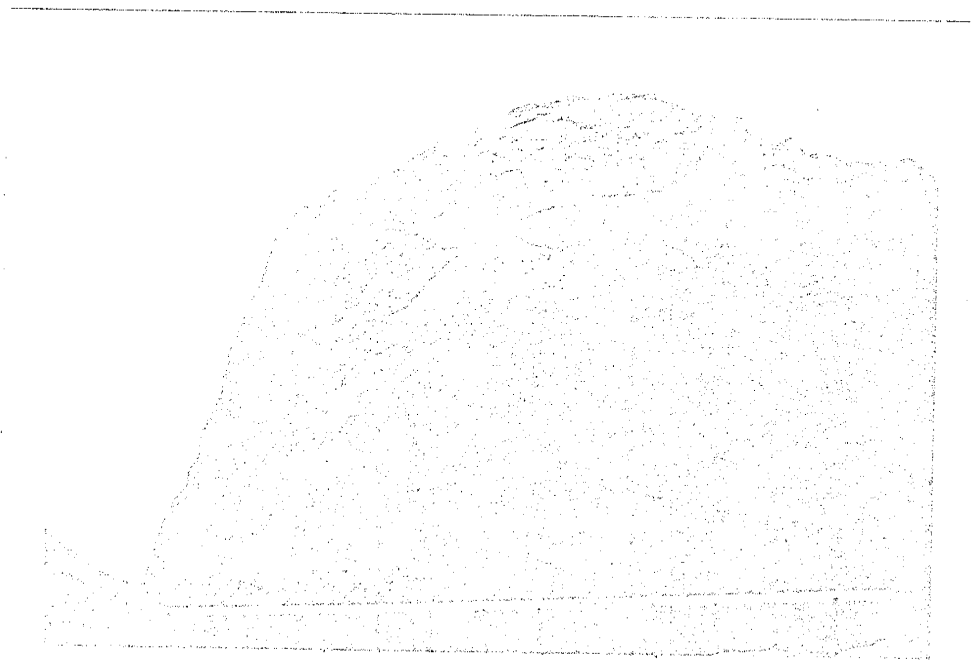


Figure 25 - Randomly oriented Thalassinoides exposed at the base of an overhang. From the basal assemblage at Section I (Unit #5). Tick marks on the Jacob's staff represent 5 cm (2") intervals.

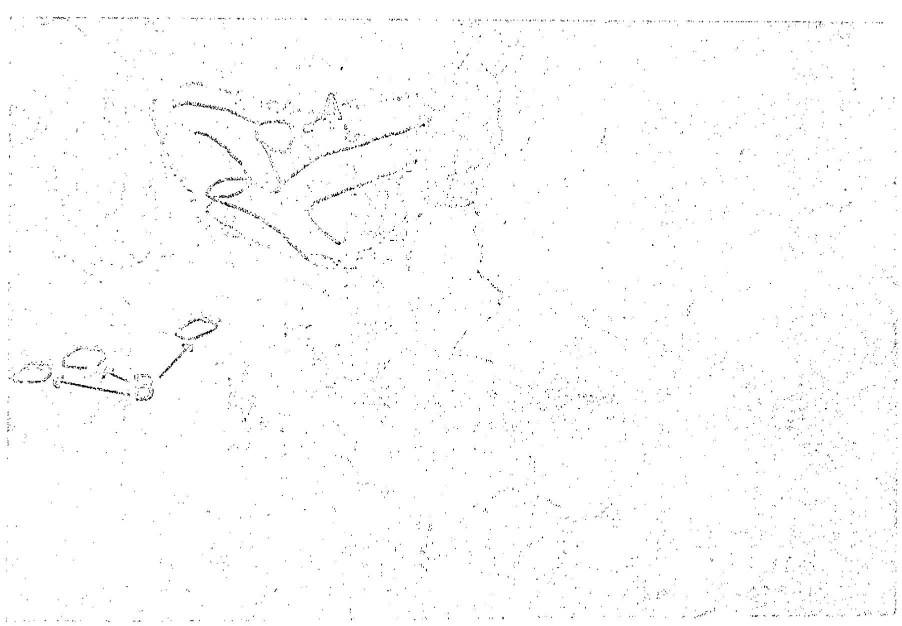


Figure 26 - Arthrophycus/Ophiomorpha: (A) two burrows with Y-shaped branching oriented oblique to bedding and (B) cross sections of burrows. From the basal assemblage at Section I (Unit #5). Lens cap is 6.5 cm (2.5") in diameter.

on the underside of an overhang located in the middle portion of the basal assemblage at Section III. One oblique burrow of the larger type occurs about 20 centimeters above a layer of diverse invertebrate fossils near the base of the basal assemblage at Section IV.

These types of burrows were compared with illustrations and descriptions of Upper Cretaceous ichnofaunas from Utah and Kansas (Frey and Howard, 1970). After preliminary identification, further comparison was made with the photographs and descriptions in Part W of Treatise on Invertebrate Paleontology, (Häntzschel, 1975).

The smaller type of burrow is identified with reasonable confidence as *Thalassinoides*. The larger type of burrow in the study area cannot be uniquely identified by the author because it has characteristics common to both *Arthrophycus* and *Ophiomorpha* sp. B. The burrows in the study area have the transverse features in common with *Arthrophycus* from Utah and Kansas, but are not comparable in shape and size of cross section; *Arthrophycus* is circular in shape and ranges from .5 to 3 cm in diameter. The burrows have the same shape and size of cross section as *Ophiomorpha* sp. B. from Utah, but do not have the knobby exterior surface characteristic of *Ophiomorpha*. Thus, the larger type of burrows from the study area will be referred to as *Arthrophycus*/*Ophiomorpha*.

The presence of the burrows at Carthage indicates shore, nearshore, and perhaps offshore environments of deposition. Frey and Howard (1970) assign Thalassinoides from Utah to a nearshore and shore facies, Arthrophycus to a nearshore facies, and Ophiomorpha sp. B. to an offshore facies. Hantzschel (1975) considers Thalassinoides to be feeding and dwelling burrows of crustaceans living in a sublittoral environment. Ophiomorpha is generally considered to represent marine environments including littoral, sub-littoral and upper neritic environments. Ophiomorpha has been compared with burrows of a modern marine decapod, Callianassa Major Say which is confined to high energy littoral and shallow neritic environments (Weimer and Hoyt, 1964).

Chapter 5

PALEOCURRENT ANALYSIS

Paleocurrent directions were measured solely from the orientation of cross-stratification. Orientations of the tabular- or wedge-shaped sets were obtained from the direction of dip of the foresets and orientations of the trough-shaped sets were obtained from the direction of dip of the trough axes. The effects of tectonic tilting of the strata were removed through the use of a stereonet in order to obtain the original orientation of the cross-strata. It is highly likely that at least some of the fault blocks in the Carthage area have been rotated during faulting. Unfortunately, there are insufficient field data to allow for correction of this event. It is hoped that this possible structural event will not significantly affect the results of the paleocurrent analysis.

Rose diagrams compiled from individual measured sections for each type of cross-stratification are shown to the left of the stratigraphic columns on Plate 1. Composite rose diagrams from all measured sections for each type of cross-stratification are shown in Figure 27 A-C.

The rose diagram in Figure 27 A is comprised of 44 measurements collected from medium- (including to near large-) scale, low-angle, tabular- to wedge-shaped sets of tangential cross-stratification with both erosional and non-erosional lower contacts which occur in the upper third to half of the basal assemblage. After correction for tectonic

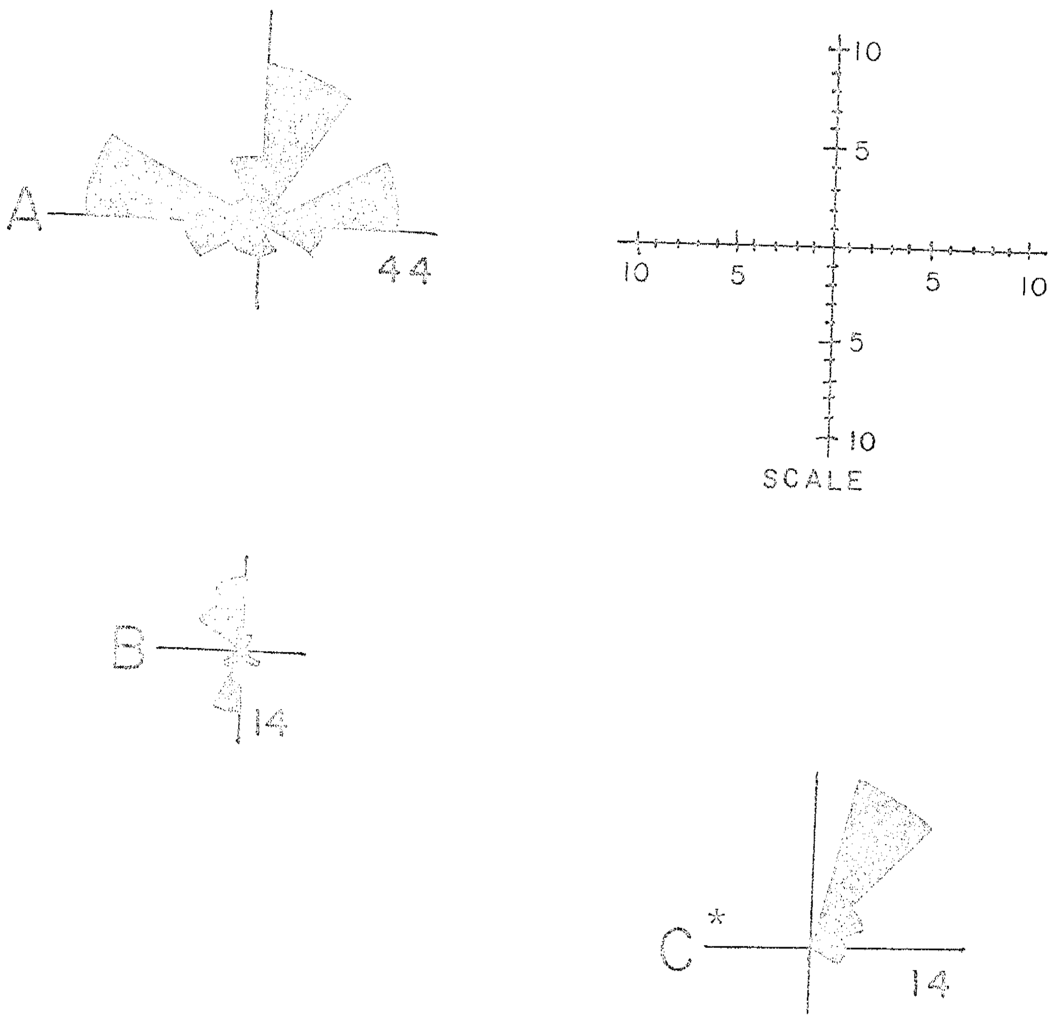


Figure 27 - Composite Paleocurrent Rose Diagrams

A) From medium- (including to near large-) scale, low-angle, tabular- to wedge-shaped sets of tangential cross-stratification in the upper portion of the basal assemblage.

B) From medium-scale, low-angle, trough-shaped sets of tangential cross-laminae in the upper portion of the basal assemblage.

C) From medium-scale, high- to low-angle, tabular- to wedge-shaped sets of tangential cross-laminae in the sandstone lens within the coal-bearing assemblage.

Numbers in the lower right quadrant indicate number of measurements.

*Note that the boundaries of the 30° wedges have been rotated 15° in order to better define the modal direction.

tilt, the dips of the cross-strata range from 15° to 24°. The paleocurrent pattern appears to be polymodal with two modes that are roughly bipolar.

The rose diagram in Figure 27 B is comprised of 14 measurements collected from medium-scale, low-angle, trough-shaped sets of tangential cross-laminae with erosional lower contacts which also occur in the upper third to half of of the basal assemblage. After correction for tectonic tilt, the dips of the trough axes range from 1° to 11°. It should be noted that due to these low dip angles, an error of a few degrees in the measurement of the regional dip of the strata and dip of the trough axis could result in trough axes dipping in the opposite direction after correction for tectonic tilt. The paleocurrent pattern may possibly be bimodal; however, Pettijohn and others (1963) recommend the use of twenty or more measurements to establish bimodality. The primary mode is roughly aligned with the northern mode of the paleocurrent pattern for the tabular-shaped sets of cross-stratification.

The rose diagram in Figure 27 C is comprised of 14 measurements collected from medium-scale, high- to low-angle, tabular- to wedge-shaped sets of tangential cross-laminae with both erosional and nonerosional lower contacts which occur only in the sandstone lens within the coal-bearing assemblage at Section I. After correction for tectonic tilt, the dips of the cross-laminae range from 20° to 36°. The paleocurrent pattern is unimodal with the modal direction to the northeast.

Certain environments of deposition produce characteristic paleocurrent patterns from cross-stratification that are unimodal, bimodal or polymodal. The following summary is taken from Pettijohn and others (1973) and Selley (1968). Polymodal patterns are produced as the result of either a mixture of different current systems or of one very variable current system. Polymodal patterns are typical of shoreline environments which are characterized by polydirectional traction currents unrelated to the paleoslope. Bimodal paleocurrent patterns are also typical of a shoreline or beach environment. The bimodal patterns are suggestive of tidal influence and are oriented at some angle to the strand line. Bipolar patterns within an estuary are oriented parallel with the estuary and thus generally at right angles to the strand line. Unimodal patterns are generally indicative of fluvial or deltaic environments although this type of pattern can occur in estuarine or marine environments. Polymodal, bimodal or unimodal paleocurrent patterns can also occur in eolian environments.

The amount of variability of the data is also indicative of the environment of deposition. Jungst (1938; as cited in Potter and Pettijohn, 1963) found that in stream deposits, most measurements of cross-stratification occur within a 90°-120° sector while in deltaic and littoral environments, most measurements occur within a 180°-220° sector.

Thus, the polymodal and bimodal natures of paleocurrent roses A and B, and the 180° spread of data is highly suggestive of a shoreline environment. In contrast, the unimodal nature of paleocurrent rose C, and the 90° spread of data is suggestive of a fluvial environment although a deltaic, estuarine or marine environment may be possible. The directional significance of the individual modes will be discussed after the depositional environments have been better defined through other lines of evidence.

Chapter 6

PETROLOGY

The purpose of this petrographic analysis is 1) to augment the lithological description of the sandstones from the Mesaverde Group and 2) to determine the nature and extent of diagenetic changes, especially those that would affect the original grain-size distribution.

Hand Specimen Description: Existing hand specimens and thin sections used in previous studies under Dr. John MacMillan (Associate Professor of Geology, New Mexico Institute of Mining and Technology, Socorro, New Mexico) were obtained. The exact locations and stratigraphic positions of these samples are unknown; two samples were chosen which are most likely from the basal assemblage based on the color, grain size, sorting and internal structure of the hand specimens. The hand specimens are grayish orange, moderately indurated but somewhat friable sandstones which appear internally structureless and do not contain carbonate when tested with dilute HCl. Sorting is moderate and average grain size is fine sand for sample K-1 and medium sand for sample K-3. The detrital grains which show no preferred orientation are subangular to subrounded. The mineral composition of the grains appears to be dominantly quartz (light-colored) with dark grains which may be chert or a heavy mineral.

Petrographic Analysis: Aids used in petrographic analysis include 1) Kerr (1959) for mineral identification, 2) sorting images from Folk (1968), 3) a chart for visual estimation of percentage composition and porosity from Terry and Chilingar (1955) and 4) a chart for visual estimation of roundness and sphericity from Figure 4-10, page 111 of Krumbein and Sloss (1963). Descriptions of grain size and texture are listed in Table 2, and percentages, varieties and diagenetic changes of the detrital components are listed in Table 3.

Several difficulties were encountered during petrographic analysis which affect estimations of the various components. Due to gradations from distinct lithic fragments to matrix, and from pure chert to lithic fragments composed of clay minerals and very finely crystalline micas, distinctions between the respective end members were difficult and somewhat arbitrary. Distinctions of limonite/hematite acting as cement and of clay minerals of detrital origin, from those components in the lithic fragments and matrix are also somewhat arbitrary.

Much of the matrix can be classed as pseudomatrix (Dickinson, 1970) which is formed by the deformation of weak detrital grains, in this case, argillaceous lithic fragments. This conclusion is based on the nature of the matrix and the examples of both plastic and brittle deformation in thin section. The matrix is inhomogeneous, and has the composition and texture of the lithic fragments.

Table 2: Petographic texture

	K-1	K-3
Average grain size	Fine sand	Medium sand
Sorting	Poor	Moderate
Overall roundness	Subangular	Subangular to subrounded
% Detrital grains	80%	82%
% Cement	5%	3%
Types	Mostly limonite/ hematite which outlines the grains; trace quartz syntaxial rim cement	Mostly quartz syntaxial rim cement; trace limonite/ hematite
% Matrix	13%	10%
Composition	Same material as lithic fragments; some clay minerals	Same material as lithic fragments; some clay minerals
% Present pore space	3%	5%
Types of grain to grain contacts	line $\geq$ point	line $\geq$ point

Table 3: Detrital components

	K-1	K-3
% Quartz	40%	50%
Varieties	Most monocrystalline with straight to slightly undulose extinction; few polycrystalline with <5 crystals/grain, and line and sutured contacts between crystals	Most monocrystalline with strong undulose extinction; some polycrystalline with both <5 and >5 crystals/grain, and line and sutured contacts between crystals
Diagnetic changes	Some embayed or irregular outlines suggestive of dissolution	Common embayed or irregular outlines suggestive of dissolution
% Potassium feldspar	1%	6%
Varieties	Subequal amounts of orthoclase and microcline	Subequal amounts of orthoclase and microcline
Diagenetic changes	Slight alteration to/replacement by micas and/or clay minerals	Slight alteration to/replacement by silica (chert) or phyllosilicates
% Plagioclase feldspar	1%	2%
Varieties	Oligoclase range	Oligoclase range
Diagenetic changes	Some alteration to/replacement by micas and/or clay minerals	Some alteration to/replacement by silica (chert) or phyllosilicates; offset twin lamellae (brittle deformation)
% Chert	40%	30%
Diagenetic changes	None observed	None observed

(Continued)

Table 3: (Continued)

	K-1	K-3
% Lithic fragments	15%	10%
Varieties	Most argillaceous; few contain silt size quartz grains or small elongate crystals. Most inhomogeneous; some banded. Usually stained by limonite/hematite. Generally do not show mass extinction.	Most argillaceous, many contain very finely crystalline mica. Few stained by limonite/hematite. Generally do not show mass extinction.
Diagenetic changes	Elongate fragments often deformed between more competent grains; gradation from distinct fragments to irregular masses with wisps extending between other grains.	Gradation from distinct fragments to irregular masses with wisps extending between other grains.
% Micas	1%	Trace
Varieties	Most light mica; trace dark mica.	Most light mica; trace dark mica.
Diagenetic changes	Elongate grains often deformed between more competent grains.	None observed.
% Clay minerals	Trace	Trace
Occurrence	Detrital clay minerals impossible to distinguish from lithic fragments and matrix.	One homogeneous medium sand size grain; other detrital clay minerals impossible to distinguish from lithic fragments and matrix.

(Continued)

Table 3: (Continued)

	K-1	K-3
% Opaque heavy minerals	Trace	Trace
Varieties	Hematite	Hematite; one grain of leucoxene.
Diagenetic changes	None observed.	None observed.
% Nonopaque heavy minerals	Trace	None observed.
Varieties	Glauconite	
Diagenetic changes	Some alteration to/ replacement by clay minerals	

The gradation from lithic fragments to matrix ranges from distinct detrital grains to indistinct irregular masses, frequently with wisps extending between other grains. Elongate lithic fragments and mica grains are often "crinkled" between more competent grains such as quartz. A few plagioclase grains exhibit offset twin lamellae.

Other matrix material, especially in K-3, is silica with a cherty texture. Possible origins for this intergranular material are: precipitation of silica in previously open pores or pores containing some detrital clays, or replacement of/alteration to silica with a cherty texture of feldspar grains and/or lithic fragments.

Lack of Granulometric Analysis: The presence of 10-13% pseudomatrix as determined from petrographic analysis is the reason why the sandstones are somewhat friable and never better sorted than moderately sorted. The very nature of pseudomatrix precludes the determination of the original grain size distribution by any method. Thus, the approaches used by such workers as Friedman (1967) and Visher (1969) to interpret environments of deposition based on sieve analysis cannot be used. Furthermore, sieve analysis of the present grain-size distribution would be hampered by the further disintegration of the relatively weak argillaceous lithic fragments during disaggregation and sieving. For these reasons, no sieve analyses were attempted in this study.

Semi-quantitative Clay Mineral Analysis: The purpose of the clay-mineral analysis is to 1) identify the clay mineral components of the samples by X-ray diffraction methods, 2) determine the relative proportions of the clay mineral components within each sample, 3) plot variations in types and relative proportions of the clay mineral components with respect to stratigraphic position, and 4) determine if these variations can be used as an aid in the interpretation of depositional environments. Carroll's (1970) paper on X-ray identification of clay minerals provided the basic reference for the analysis in this study.

Ten samples of shale or mudstone were collected for analysis by first removing the outer weathered surface with a rock hammer and trowel. A small glass test tube was then filled with sample and stoppered with a cork. Samples were collected from Section III; their stratigraphic locations are indicated by asterisks to the left of the column for Section III in Plate 1. Samples 1-3 were collected from the transition assemblage and sample 4 was collected from a small covered interval about one meter above the base of the basal assemblage. The remaining samples were collected from the coal-bearing assemblage; samples 5 and 6 were collected below the major coal seam. Sample 8 was collected just below a channel cut and fill structure. Sample 10 was collected about 0.5 meters below the base of the oyster-bearing assemblage.

In the lab, samples were ground with a mortar and pestle, sieved with a 75μ (200 mesh)-sized sieve, and placed in a small beaker with distilled water. The contents of the beaker were mixed by a sonifier and allowed to settle. If the sample flocculated or if a residue floated to the top of the sample, the sample was washed in a centrifuge, re-mixed with distilled water and allowed to settle. Sediment-ed slides were then prepared from gravity settled clay fractions less than 2μ. The process of boiling the samples in EDTA was deemed unnecessary based on results from a trial run of one slide on the X-ray diffractometer, which showed little or no carbonate or other salts present.

Each slide was run on the X-ray diffractometer three times; air-dried, glycolated for one hour at 60°C, and after heating for at least one hour at 375°C. One sample was also run after heating for several hours at 550°C to verify the lack of discrete chlorite. The following are the instrumental settings used to obtain the diffraction patterns:

Radiation/filter	Cu/graphite
Kilovolt/milliampere	40/20
Counts per second	2500 or 5000
Standard deviation	3%
Time constant	0.1 or 0.2 seconds
Slits	1°-4°-1°
Scan rate	2°/minute
Chart drive	1"/minute

The slides were scanned from 2° to 35° 2θ.

Interpretation of the X-ray diffraction patterns show that all samples contain significant amounts of kaolinite, illite, and mixed-layer clays. Discrete montmorillonite may be present in very small amounts (<3%) but its presence is dependent upon the operator's interpretation of the location of the background curve. Quartz is also present in significant amounts but will not be discussed further in this analysis. An example of an X-ray diffraction pattern is shown in Figure 28.

The method used in this analysis to calculate the relative proportions of the clay mineral components has been modified from Johns and others (1954) by Austin (personal communication, 1979, Deputy Director, New Mexico Bureau of Mines and Mineral Resources, Socorro, New Mexico). The method is based on peak heights rather than peak areas:

$$T = Ih + K_1$$

$$I = Ig/T$$

$$M = Mg/4T$$

$$Mx = Ih/T - I - M$$

$$K = K_1/T$$

Ih = heated illite peak height at 10 Å

K_1 = kaolinite peak height at 7.15 Å

Ig = glycolated peak height at 10 Å

Mg = glycolated peak height at 17 Å

I = calculated proportion of illite

M = calculated proportion of montmorillonite

Mx = calculated proportion of mixed-layer clays

K = calculated proportion of kaolinite

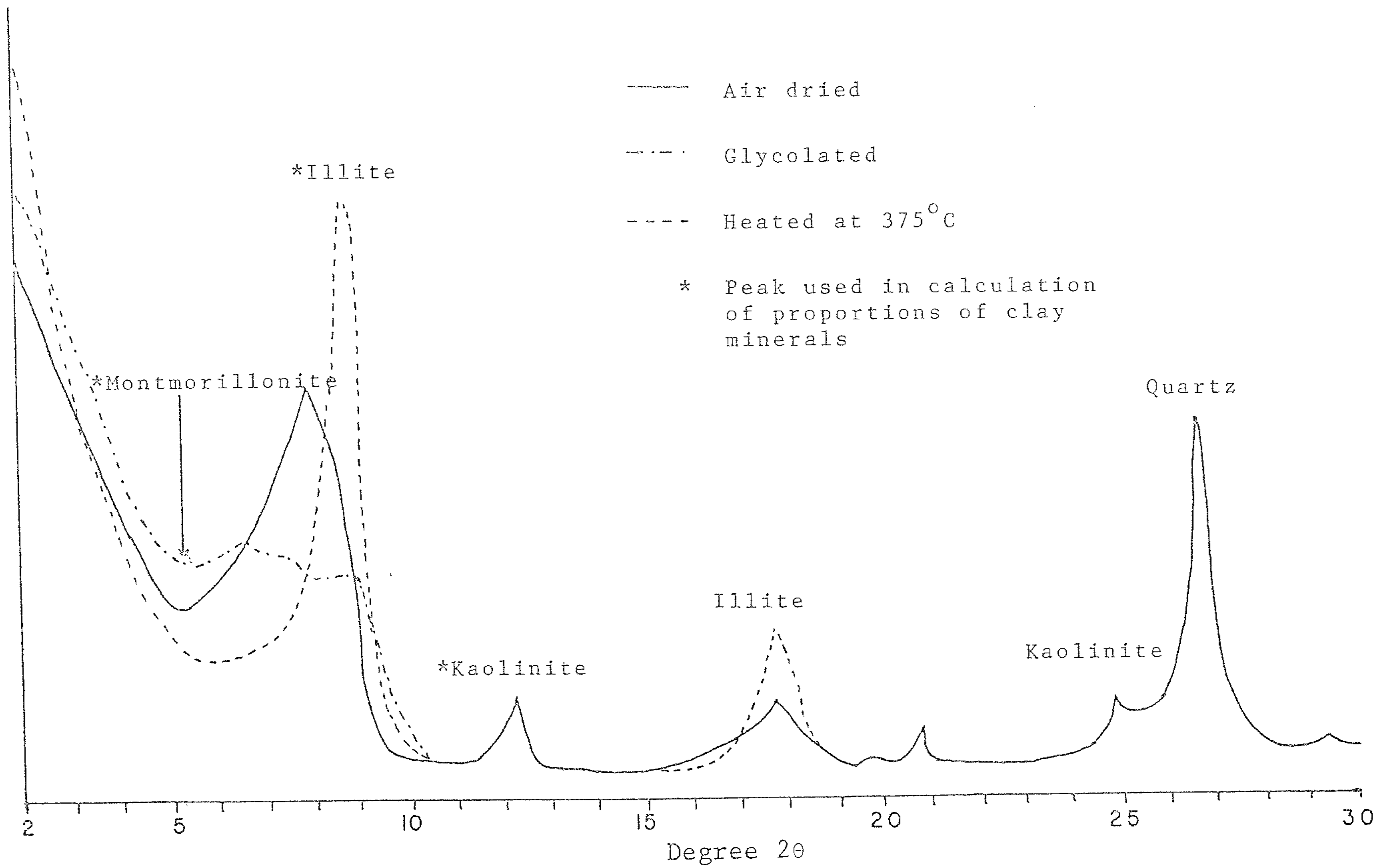


Figure 28 - X-ray diffraction pattern from sample #1.

The calculated proportions are in parts per one and are multiplied by ten to produce proportions in parts per ten. Following the recommendations of Austin and Leininger (1976), results are reported to only one significant figure. Thus possible values of montmorillonite are too small to be considered in the discussion of the results.

Figures 29 and 30 show the variations of proportions of clay mineral components as a function of sample number and as a function of stratigraphic position. The proportion of illite remains relatively constant; two or three parts per ten. The values of kaolinite vary inversely with values of the mixed-layer clays. Samples from the transition assemblage and near the base of the basal assemblage contain zero to two parts per ten of kaolinite and six or seven parts per ten of mixed-layer clays. Samples from the coal-bearing assemblage contain two to five parts per ten of kaolinite and three to six parts per ten of mixed-layer clays.

Although no distinct clay mineral assemblage can be assigned to any particular depositional environment, lateral variations of clay mineral assemblages have been used to aid in the interpretation of depositional environments, particularly in the transition from marine to nonmarine environments. Parham (1966) provides an excellent summary of the results of various workers and discusses the general trends of clay mineral assemblages with respect to depositional environments. Direct comparison of the analysis

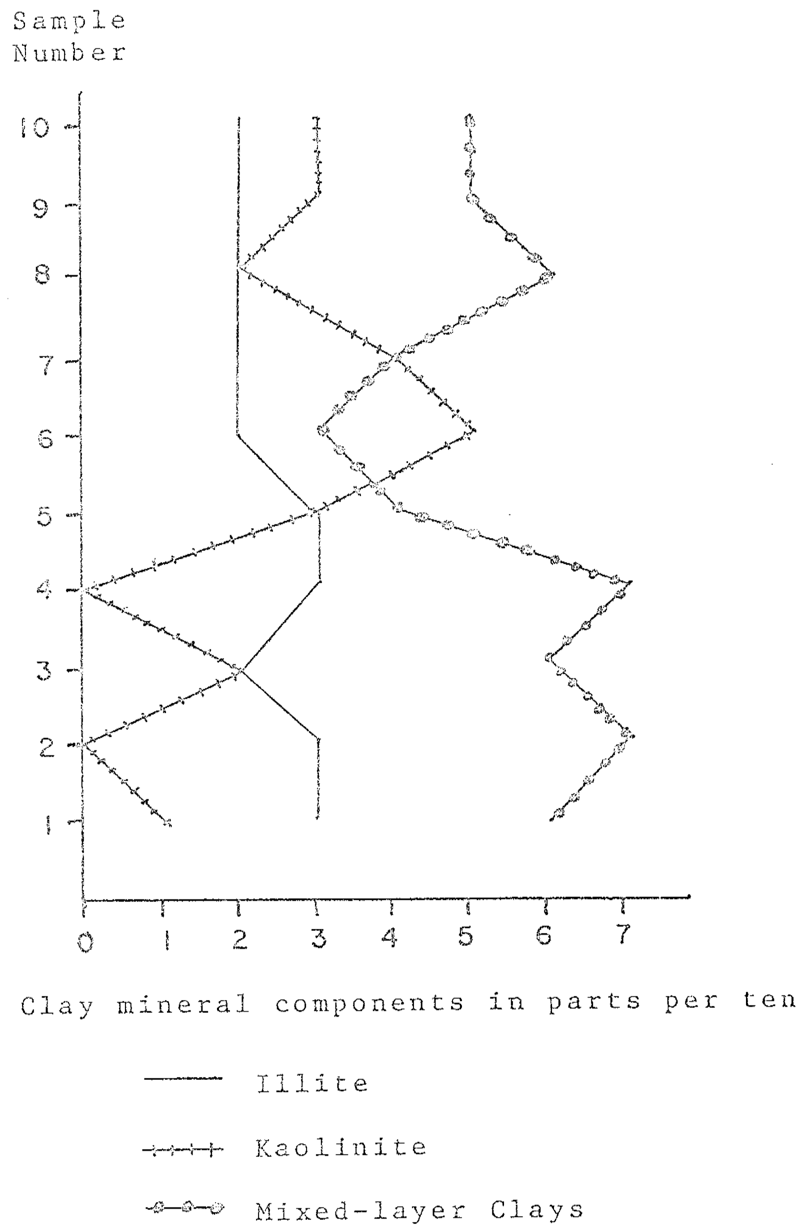


Figure 29 - Clay mineral components vs. sample number

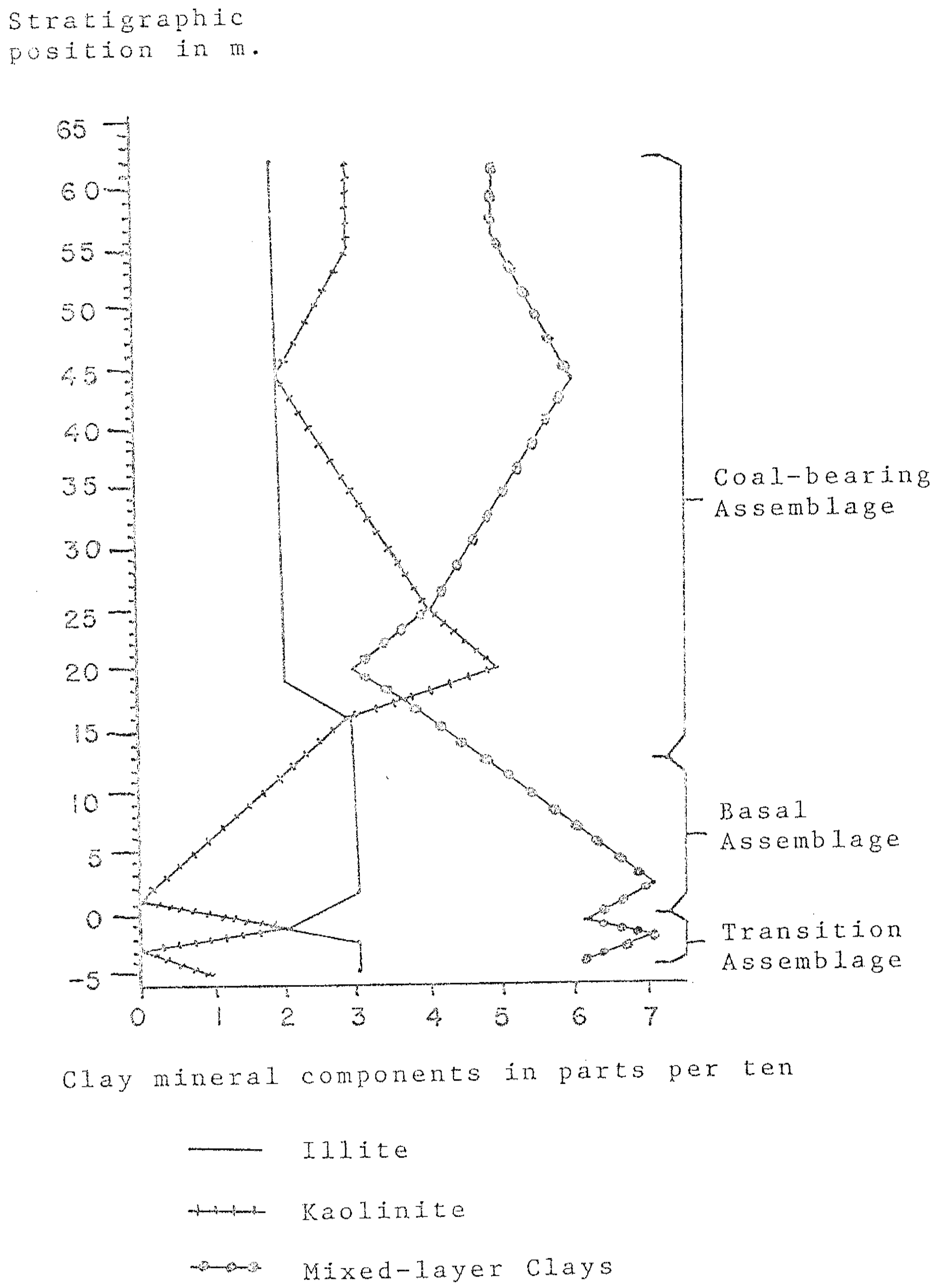


Figure 30 - Clay mineral components vs. stratigraphic position

of this study with trends found by the majority of investigators is difficult due to differences between clay mineral assemblages found in their studies and the kaolinite-illite-mixed-layer clay mineral assemblage of this study.

In a study of modern river sediments, Brown and Ingram (1954) reported a decrease of kaolinite and an increase of mixed-layer clays downstream. The change was most pronounced at the mouth of the river and the head of the estuary. Brown and others (1977), in a study of Middle Pennsylvanian deltaic deposits, found that the transition from marine to nonmarine depositional environments corresponded with a decrease in illite and an increase in kaolinite and mixed-layer clays. The trend of increasing kaolinite inland, indicated by these two studies, is also supported by the same trend observed in several studies of clay mineral assemblages containing kaolinite and montmorillonite (Parham, 1966). This general trend of increasing kaolinite inland is compatible with the finding in this study that kaolinite increases from the marine Mancos Shale to the continental Mesaverde Group. In the transition from marine to nonmarine depositional environments, the findings of Brown and others (1977) that illite decreases and mixed-layer clays increase, conflicts with the findings of this study that illite remains relatively constant and mixed-layer clays decrease from the marine Mancos Shale to the continental Mesaverde Group. However, the decrease of mixed-layer clays observed in this study corresponds to the finding of Brown and Ingram (1954) that mixed-layer clays decrease inland.

In conclusion, variations of clay mineral assemblages appear to be useful, in at least a general way, in determining depositional environments in the study area. Much more extensive work in the study area will be needed in order to determine the extent of usefulness of this approach.

Chapter 7

INTERPRETATION OF DEPOSITIONAL ENVIRONMENTS

Basal and Transition Assemblages: As the basal assemblage consists of a 9- to 14-meter (30-47') -thick sequence of sandstone, the basal assemblage can be considered as a distinct sand body or sand deposit. The approach used in this study to determine the general depositional environment is to compare the characteristics of the basal assemblage with established criteria for recognizing sand bodies deposited in particular environments, based on distinguishing groups of characteristics. Potter (1967) discusses sand bodies deposited in six environments; alluvial, tidal, barrier-island, shallow-water marine, desert eolian and turbidite. Shelton (1967) discusses deposits that are produced in three environments; alluvial, barrier-bar and turbidite. Parameters used to distinguish sand bodies deposited in each of these environments include the geometry of the sand body, sedimentary structures, paleontology, grain size, and sorting.

Of the three parameters which define the geometry of a sand body; thickness, width, and length, only the thickness of the sand body could be determined in this study, due to the limited extent of the study area and the structural complexities in the study area. Due to the presence of psuedomatrix as determined in petrographic analysis, the sorting parameter will be ignored. In this discussion, the transition assemblage will be considered as characterizing the nature of the lower contact of the sand body.

The characteristics of the basal assemblage clearly fit the criteria for the depositional environments of barrier-island and barrier-bar, and not for any other depositional environments. Table 4 provides a comparison of the criteria used to distinguish deposits of the barrier-island and barrier-bar environments with the characteristics of the basal assemblage. Potter defines the barrier-island as an elongate sand body which parallels the strand line and separates marine from nonmarine environments which may include lagoonal or alluvial environments. The barrier-island includes sand bodies that formed from offshore bars, beaches and dunes. Shelton defines the barrier-bar as a coastal sand-barrier feature which separates the marine environment on one side and a brackish water, either lagoonal or marsh, on the other side. Both authors compare their depositional environments to the recent barrier islands located along the northwestern coast of the Gulf of Mexico. However, the strict definition of a modern barrier island requires that a lagoon or standing body of water be located to the landward side of the barrier island (Davies, Ethridge and Berg, 1971). Thus the basal assemblage will not be considered as a barrier-island deposit until the existence of lagoonal deposits overlying the basal assemblage can be established. The basal assemblage can be considered as a coastal sand deposit which separates marine from the nonmarine deposits.

Table 4: Criteria for recognition of coastal sand deposits and comparison with the basal assemblage

	Potter (1967)	Shelton (1967)	This study (1979)
Model	Barrier-island sand bodies	Barrier-bar sand deposits	Corresponds to basal assemblage
Associated lithologic types for regressive sequence	Marine deposits below; lagoonal or terrestrial deposits above.	Marine deposits below; brackish (lagoonal-marsh) deposits above.	Marine shale below; terrestrial (coal) deposits above.
Thickness of sand body	20-60' (6-18m)	<100' (<30m)	40-50' (12-15m)
Nature of basal contact	Fairly even; may be transitional.	Gradational.	Transitional.
Sedimentary structures	Asymmetrical ripple marks, abundant gently inclined bedding, lamination, lineation, and moderately abundant cross-bedding.	Mottled and burrowed in lower part; horizontal bedding and medium-scale cross-bedding in upper part.	Dominantly planar parallel laminated, locally structureless and abundant medium-scale cross-stratification in upper part. Rare small-scale cross-lamination, inclined lamination and contorted laminae.
Nature of paleocurrent pattern	Moderate to large variability from cross-bedding; bimodal distributions may occur.	Paleocurrent direction parallel to trend of strong longshore current and perpendicular to trend of wave fronts.	Polymodal to unimodal with 180° spread. Orientation of shoreline not yet established.
Grain size	Fine to medium sand; vertical increase in grain size.	Sand; upward increase in grain size.	Fine to medium sand; overall vertical increase in grain size.

(Continued)

Table 4: (Continued)

	Potter (1967)	Shelton (1967)	This study (1979)
Diagnostic detrital constituents	Heavy mineral constituents common. Skeletal debris, collophane and minor glauconite.	Glauconite.	Possible trace glauconite in thin section K-1.
Fauna	Shells; generally more robust forms.	Very shallow water marine fauna.	Marine mollusks including pelecypods, gastropods and oysters.
Flora	None mentioned.	Finely divided plant material.	Fragmental plant impressions at the top.
Trace fossils	Burrows and trails abundant.	Some trails and burrows.	Local occurrences of two types of burrows.

In order to further define the depositional environments of the transition and basal assemblages, the characteristics of the various facies of a beach will be discussed. Terminology related to a beach profile that will be used in this discussion is illustrated in Figure 31.

Workers who have studied sedimentary structures on modern beaches include Thompson (1937), McKee (1957), Hoyt (1962), and Hoyt and Weimer (1963). The foreshore is characterized by low angle seaward dips from a few degrees up to 8-10^{o} depending on the geographic location of the beach. Small sand bars which are elongate parallel to the shoreline often develop and migrate landward. The bars are characterized by seaward dips of 1-2^{o} and landward dips of up to 30^{o}. The backshore may represent an area of bar and trough topography with axes parallel to the coastline or an area of washover of the beach crest. Moderate to high landward dips are characteristic of the backshore area.

The method of trenching to study sedimentary structures is difficult to apply to the shoreface, because by definition, the shoreface is always under water. Thus, the description of sedimentary structures in the shoreface must be obtained from studies of ancient beach deposits. Three studies of regressive beach sequences deposited during the Late Cretaceous in the Western U. S. will be discussed because they are analogous to both the time and general depositional environment of the basal assemblage. The authors, of these studies, Campbell (1971), Land (1972) and Molenaar (1973),

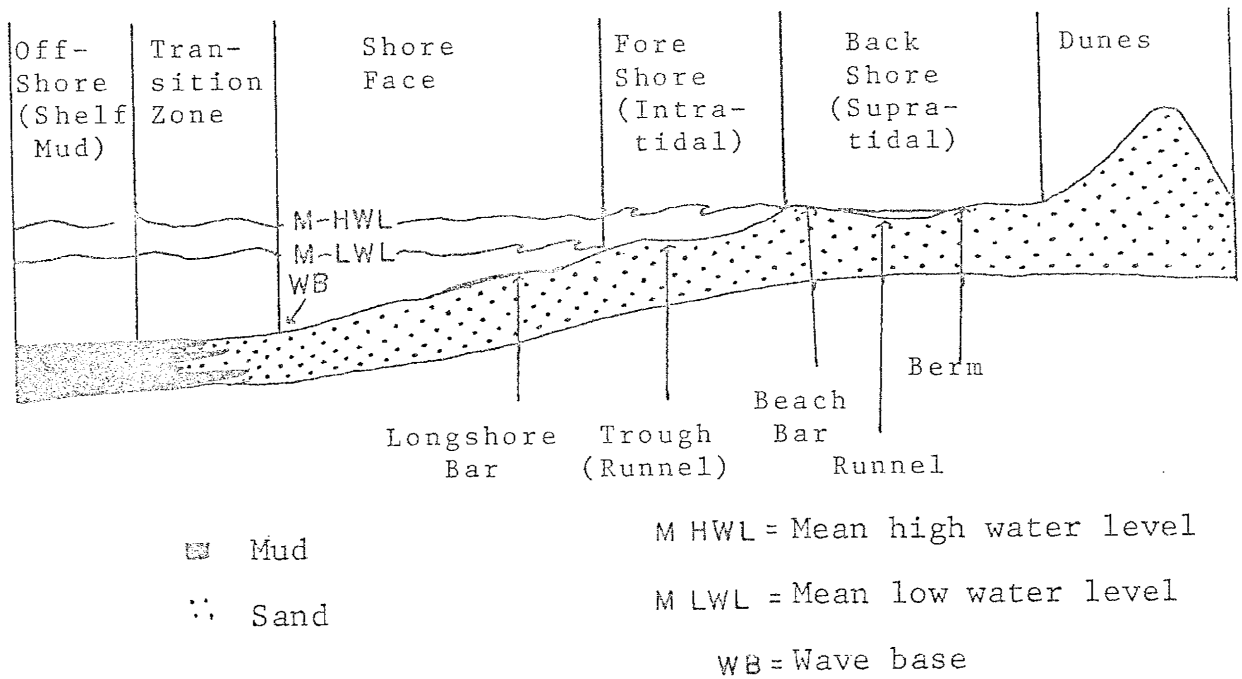


Figure 31 - Schematic representation of the terminology of the various geomorphic units and features of a beach profile, and the transition to shelf mud. From Figure 410, p. 285 of Reineck and Singh (1975).

provide criteria for recognition of the foreshore, shoreface, and the facies located seaward of the shoreface. The criteria include thickness of the unit, grain size or lithology, sedimentary structures, and paleontology. Tables 5, 6, and 7 provide comparisons of the criteria used to distinguish the different facies with the characteristics observed in this study. In this discussion, the transition assemblage will be considered as a deposit characteristic of a particular environment of deposition.

The characteristics of the transition assemblage correspond to the criteria for recognition of the facies located seaward of the shoreface, which is called the offshore-beach transition by Campbell, subshoreface by Land, and transitional zone by Molenaar. The transition assemblage was so named because it represented the lithologic transition between the underlying shale and the overlying sandstone of the basal assemblage. The transition assemblage can now be established as representing deposition in the transition between the offshore zone and the shoreface.

The description of the basal assemblage corresponds to the criteria for recognition of the shoreface facies except in the criteria for grain size. The sandstone in the basal assemblage ranges in grain size from fine to medium sand as compared to the very fine to fine sand observed in the other studies. The sandstone of the basal assemblage does follow the trend of grain size increasing upward in the sequence.

Table 5: Criteria for recognition of the facies located seaward of the shoreface and comparison with the transition assemblage

	Name applied	Thick-ness	Lithology	Sedimentary structures
Campbell (1971)	Offshore-beach transition	---	Sandstone, siltstone and shale.	Even parallel beds, truncated wave-ripple laminae, wave-ripple marks, rare current-ripple and contorted laminae; churned by burrowing organisms.
Land (1972)	Subshoreface	10-40' (3-12m)	Sandstone with equal amounts of siltstone and silty shale; individual beds of sandstone and siltstone range from a few inches to several feet thick.	Even and subparallel stratified; can be heavily bioturbated.
Molenaar (1973)	Transitional zone	to 30' (to 9m)	Transitional from shale to sandstone.	None mentioned.
This study (1979)	Corresponds to the transition assemblage	∿15' (∿5m)	Sandstone, or alternating beds of sandstone, siltstone and shale grading downward to shale.	Sedimentary structure difficult to determine due to covered nature of this interval; appears to be even parallel stratified.

Table 6: Criteria for recognition of the shoreface facies and comparison with the basal assemblage

	Thickness	Grain size	Sedimentary structures	Fauna and trace fossils
Campbell (1971)	---	Sand; grain size increases upward.	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.
Land (1972)	3-50' (1-15m)	Very fine to fine sand; grain size increases upward. Thin interbeds of shale and siltstone near base.	Lower part dominantly subparallel 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) Lower shoreface	15-50' (5-15m)	Very fine to fine sand; grain size increases upward.	Bedding generally flat; some small-scale, low-angle inclined beds.	Fossils not common; locally abundant pelecypods. Burrows common to abundant.
Upper shoreface	15-30' (5-9m)	Fine sand with some medium grains; grain size increases upward.	Moderate to high abundance of trough cross-bedding; sets are 1-2' thick with dip directions parallel to shoreline (longshore currents).	Fossils rare. Burrows minor.

(Continued)

Table 6: (Continued)

	Thickness	Grain size	Sedimentary structures	Fauna and trace fossils
This study (1979)	30-47' (9-14m)	Fine to medium sand; overall grain size increases upward. Small covered intervals of shale and siltstone near base.	Dominantly planar-parallel stratified, commonly structureless particularly in the lower part and medium-scale, tabular and trough cross-stratified in upper part. Rare contorted laminae and inclined 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.

Table 7: Criteria for recognition of the foreshore facies

	Thickness	Grain size	Sedimentary structures	Fauna and trace fossils
Campbell (1971)	---	Sand; grain size increases upward.	Even parallel beds which dip seaward at angles of usually <6°. Uncommon wave and current ripple marks, wave- and current-ripple laminae, parting lineation, and swash and rill marks.	Oyster fragments. Uncommon vertical burrows.
Land (1972)	5-12' (1-4m)	Very fine to fine sand.	Sub-parallel bedded; stratification dips 1-3° seaward.	No fossils. Suspension feeders.
Molenaar (1973)	3-20' (1-6m) Locally may be completely missing	Fine sand.	Bedding is flat or inclined at very low angles.	Fossils rare. Burrows common. When overlain by paludal mud, burrows and root tubes common in upper foot or so.
This study (1979)	0': This facies appears to be missing in the study area.			

The sequence of sandstone of the basal assemblage does not appear to include deposition within the foreshore facies.

Orientation of the Paleoshoreline: Knowledge of the orientation of the paleoshoreline would provide a useful tool for the exploration of the coal bodies; coal bodies would be elongate either parallel or perpendicular to the shoreline depending on the environment in which the coal was deposited. Depending on the exact time and location, the shoreline during the Late Cretaceous in New Mexico trended from east-west to north-south with the land located to the west and/or south (Steve Hook, personal communication, 1979, Paleontologist, New Mexico Bureau of Mines and Mineral Resources, Socorro, New Mexico).

The orientation of the paleoshoreline is often determined from the axis of elongation of the sand body which parallels the trend of the shoreline. However, due to the limited extent of the study area and to the structural complexities within the area, the geometry of the sand body cannot be determined. Thus, other approaches will be needed to determine the trend of the paleoshoreline.

According to Molenaar (1973), the flat bedding and small-scale, low-angle beds of the lower shoreface are produced in a zone that is seaward of the agitating effects of the breaker zone and of the stronger longshore currents. The inclined lamination in the study area was probably produced in the lower shoreface and dips at an angle of 6-8° in an easterly direction (N69°E and S76°E). The author of this study did not find any information concerning the directional significance of low-angle stratification in the shoreface zone in the literature; however, the similarity in stratification between the lower shoreface and the foreshore zone would suggest that, as in the foreshore zone, inclined strata would dip seaward in the lower shoreface.

Since the basal assemblage represents deposition within the shoreface of a beach, knowledge of the dynamic conditions that produced the cross-stratification in the basal assemblage can be used to construct a genetic model for the directional significance of the various modes of the paleocurrent rose diagrams (Figure 27). Shoaling waves along the shoreface produce symmetrical wave ripples with straight, long crests oriented parallel with the shoreline. Longshore currents flow almost parallel to the shoreline, usually following the ridge and runnel system, and terminate in rip currents which flow seaward. Current ripples can be produced by both longshore and rip currents. Thus, along the shoreface, symmetrical and asymmetrical wave ripples, small-current ripples and megacurrent ripples can be produced with cross-stratification oriented generally perpendicular and/or parallel with the shoreline (Reineck and Singh, 1975).

Campbell (1966) described truncated wave-ripple laminae which occur on the shoreface and are comparable in scale and description with much of the medium-scale, low-angle tabular-shaped sets of cross-stratification found in the basal assemblage. According to Campbell (1966; 1971), the overall trend of the crests of the wave ripples is parallel with the shoreline and thus, the laminae should dip in both seaward and landward directions perpendicular to the shoreline. Molenaar (1973) found that the dip directions from trough cross-bedding paralleled the shoreline and thus, were the result of longshore currents.

The three paleocurrent modes from the tabular-shaped sets of cross-stratification (Figure 27A) are oriented roughly west, north and east. The paleocurrent mode from the trough-shaped sets of cross-lamination is oriented roughly north with a minor mode oriented to the south (Figure 27B). A reasonable model for the origin of these modes would be that the east and west modes are produced as the result of wave action and the north modes are produced as the result of longshore currents. This model, the eastern dip of the inclined lamination, and knowledge of the Late Cretaceous shoreline orientation, suggest a north-south to northwest-southeast orientation of the paleoshoreline in the study area, with the land located to the west.

Coal-bearing and Oyster-bearing Assemblages: According to Reineck and Singh (1975), a prograding coast would produce the following vertical sequence of deposits:

Alluvium
Marsh deposits (peat and coal)
±Tidal flat and lagoonal deposits
Coastal sand
Transition zone deposits
Shelf mud

Because regression and progradation produce the same vertical sequence of deposits, the above sequence can be applied to the regressive sequence of deposits described in this study. The transition and basal assemblages represent the transition zone deposits and the coastal sand, respectively. Because the characteristics of the beach zone of a mainland beach and a barrier island or spit are the same, the nature of a coastal sand body is defined by the nature of adjacent environments. If the sand body is separated from the mainland by a lagoon, then the sand body is considered as a barrier island. If there is no lagoon present, then the sand body is considered as a mainland beach. Thus, the presence or absence of tidal flat and lagoonal deposits in the vertical sequence defines whether the coastal sand body represents a barrier-beach or a mainland-beach deposit.

The coal-bearing assemblage can be divided roughly into two portions; the lower portion which contains two distinct marker beds which are present in every section, and the upper portion which contains discontinuous, non-correlative units of variable lithology. The marker beds include the major coal seam, and the stratigraphically lower, distinctive sandstone bed. According to the vertical sequence previously outlined, the major coal seam represents a marsh deposit.

Recognition of tidal-flat (which will be considered part of the lagoon in this discussion) and lagoonal deposits is diffcult due largely to the wide variability of deposits that can be produced in a lagoon. 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. The characteristics of both modern and ancient deposits of these sub-environments, according to various sources, are listed in Table 8. In general, lagoonal deposits are characterized by the interlaying of lagoonal 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 and others, 1972; Reineck and Singh, 1975).

Recognition of lagoonal deposits in the coal-bearing assemblage is hampered by the fact that much of the assemblage consists of covered intervals. However, a few exposed units in the lower portion of the assemblage may represent such deposits. Unit #13 at Section III which is composed of shale alternating with irregular-shaped beds of small-ripple cross-laminated, fine-grained sandstone is suggestive of the general interlaying of muds and sands characteristic of lagoonal deposits.

Table 8: Characteristics of deposits of various sub-environments associated with a lagoon

Lagoonal or lagoonal-pond deposits

Source	Characteristics
Berg and Davies (1968) Lower Cretaceous Muddy Sandstone of Bell Creek Field, Montana	Siltstone with irregular and discontinuous laminae and thin vertical shale-filled burrows or tubes. Based on well cores.
Bernard, LeBlanc and Major (1962) Recent lagoonal and bay deposits landward of Galveston Island and Bolivar Peninsula, eastern Texas coast	Mostly silt and clay containing shells. Commonly bioturbated.
Land (1972) Late Cretaceous Foxhills Sandstone and associated formations of Rock Springs Uplift and Wamsutter Arch area, Sweetwater County, Wyoming	Gray to brown shale with common brackish-water pelecypods, small amounts of carbonaceous debris and no root markings or plant imprints.
Masters (1967) Upper Cretaceous Mesaverde Group of Williams Fork Mountains, Colorado	Finely laminated, contorted or burrowed shales.
Molenaar (1973) Upper Cretaceous Gallup Sandstone and associated formations of northwestern New Mexico	One to five feet of fissile black shale which is overlain by three to ten feet of burrowed, fine-grained sandstone and underlain by a beach sandstone.

Tidal-flat deposits

Dickinson, Berryhill and Holmes (1972) Recent deposits associated with Padre Island, south Texas coast	Clayey silty sand, partly laminated with algal mats, shells, ripple marks, megaripple marks, slump structures and mudcracks. Borders lagoon or bay margins.

(Continued)

Table 8: (Continued)

Tidal-flat deposits (continued)

Source	Characteristics
Masters (1967) Upper Cretaceous Mesa-verde Group of Williams Fork Mountains, Colorado	Clean silt or sand with long crested ripple forms of diverse orientation. Located along margin of lagoon.
Reineck and Singh (1975) Recent deposits of various geographic localities	Sand flats with small-scale cross-bedding of current ripples, or mixed sand and mud flats, finely interlayed with flaser, wavy and lenticular bedding. Biota consists of limited number of species and large numbers of individuals.
Washover-fan deposits	
Dickinson, Berryhill and Holmes (1972) Recent deposits associated with Padre Island, south Texas coast	Shelly sand on bottom, pond deposits in the middle and eolian sand on top.
Fisk (1959) as cited in Berg and Davies (1968) Recent deposits of Padre Island and Laguna Madre, south Texas coast	Structureless sand which is blown or washed from the beach ridge toward the lagoon.
Hoyt, Weimer and Henry (1964) Recent deposits of central Georgia coast	Very fine to medium sand from barrier islands.
Molenaar (1973) Upper Cretaceous Gallup Sandstone and associated formations of northwestern New Mexico	Three to ten feet of burrowed fine-grained sandstone; may also represent a tidal-delta deposit.
Reineck and Singh (1975) Recent deposits of St. Joseph Island, central Texas coast	Several superimposed sandy blankets composed of basal shell rich layer with erosional contact at base and upper thin sandy layer with well-developed even lamination. Small-ripple bedding and antidune cross-bedding in washover channels and

(Continued)

Table 8: (Continued)

Washover-fan deposits (continued)

Source	Characteristics
Reineck and Singh (1975) (continued)	distributaries. Burrows and root mottles common. Thickness of fan deposit ranges from 75 to 125 cm and area of fan deposit covers 7 km.

Tidal-delta deposits

Source	Characteristics
Bernard, LeBlanc and Major (1962) Recent deposits of Galveston Island, Bolivar Peninsula and associated tidal deltas, eastern Texas coast	Sand; cross-bedding may be common.
Dickinson, Berryhill and Holmes (1972) Corpus Christi Pass, south Texas coast	Sand and clayey sand with scour channels and algal mats. Sand is structureless on subaerial vegetated parts. Deposits overlie lagoonal sediments and have been built above sea level.
Masters (1967) Upper Cretaceous Mesaverde Group, Williams Fork Mountains, Colorado	Sandstone with multiple sets of foreset laminae dipping in the same direction and bounded by bedding planes. Overlies barrier-island sandstone.
Molenaar (1973) Upper Cretaceous Gallup Sandstone and associated formations of northwestern New Mexico	Three to ten feet (one to three meters) of burrowed fine-grained sandstone. May also represent washover fan deposits. Overlies shale interpreted as lagoonal deposits.
Reineck and Singh (1975) Recent deposits of various geographic localities	Clean sand, laminated with occasional mud layers. Some small ripples and megaripples.

(Continued)

Table 8: (Continued)

Tidal-Channel deposits

Source	Characteristics
Bernard, LeBlanc and Major (1962) Recent deposits associated with Galveston Island and Bolivar Peninsula, eastern Texas coast	Sand; commonly burrowed and churned. Former tidal channels trend at an angle (30°-70°) to long axis of barrier islands.
Davies, Ethridge and Berg (1971) Recent deposits associated with Galveston Barrier Island, eastern Texas coast	Vertical succession of structures and textures akin to fluvial channels. Overlies barrier island. Lateral migration of tidal channels obliterate much of typical shoreface sediments.
Masters (1967) Upper Cretaceous Mesaverde Group, Williams Fork Mountains, Colorado	Lenticular sandstone body with a vertical decrease in grain size. Channels are commonly filled with fines. Located within lagoonal deposits.
Molenaar (1973) Upper Cretaceous Gallup Sandstone and associated formations, northwestern New Mexico	Fine- to medium-grained sandstone with a vertical increase in grain size. Thickness 5 - 25 feet (1.5-7.5m). Abrupt basal and upper contacts. Common clay clasts and carbonaceous fragments at base, burrows, internal scouring and medium-scale cross-bedding. Ripple marks and thin siltstone or shale interbeds sometimes present. Dip directions of cross-bedding variable but often normal to shoreline with frequent opposed directions.
Reineck and Singh (1975) Recent deposits of various geographic locations	Sand; somewhat coarser than in sand tidal flats. Sand can be ripple-bedded, laminated or extensively bioturbated.

Tidal-inlet deposits

Dickinson, Berryhill and Holmes (1972) Recent deposits associated with Padre Island, south Texas coast	Lag gravel in center; decrease in grain size toward lagoon or marsh. Cross-bedding, and ripple marks including megaripples. Beds dip toward center of inlet, perpendicu-

(Continued)

Table 8: (Continued)

Tidal-inlet deposits (continued)

Source	Characteristics
Dickinson, Berryhill and Holmes (1972) (continued)	lar to inlet margins at angles of up to 30°.
Hoyt and Henry (1965) and Hoyt, Weimer and Vernon (1964) Recent deposits of central Georgia coast	Sand from eolian and littoral sands. Depositional interface dips up to 30° perpendicular to trend of channel and in direction of longshore drift. Megaripples and sand waves superimposed on depositional interface. Resulting cross-beds dip predominantly landward or seaward with a component in direction longshore drift.

The distinctive sandstone bed may represent a washover-fan deposit. Washover fans are the result of the flood tide of heavy storms breaching the beach ridge and depositing beach or nearshore sediments in a semicircular area (Dickinson and others, 1972). The grain size of the sandstone ranges from fine to medium sand which corresponds to the range of grain size of the shoreface deposits of the basal assemblage. Washover fans may be structureless, burrowed, small-ripple cross-bedded or antidune cross-bedded. Some fans contain shell-rich layers. The sandstone in the study area is structureless which may be the result of bioturbation, although no distinct burrows were observed. A recent washover fan behind St. Joseph Island, central Texas coast ranges in thickness from .75 to 1.5 meters (2.5 to 5') and extends over an area of 7 kilometers (4.4mi) (Reineck and Singh, 1975). The sandstone in this study ranges in thickness from .5 to 1.5 meters (2 to 5') and occurs in every section which represents a lateral extent of approximately 1.5 kilometers (1 mi).

Tidal channels are channels which separate barrier islands and extend into the lagoon. These channels have characteristics of fluvial channels but are affected by tidal action. In this discussion, tidal channels will include estuaries, defined as the lower courses of rivers which are affected by tidal action (Curray, 1969). Tidal deltas are associated with tidal channels, and form both landward and seaward of the barrier islands, although seaward deltas are usually destroyed by littoral processes. Tidal inlets are the portion of the tidal channel located between the barrier islands.

The sandstone lens (Unit #9) at Section I may represent a tidal-channel or possibly a tidal-delta deposit. The lens which is composed of medium-grained sandstone, attains a maximum thickness of seven meters, can be traced for approximately 180 meters laterally and is in erosional contact with the underlying sediments including the major coal seam. Internally, the lens is structureless with local areas of abundant medium-scale, high- to low-angle, tabular- to wedge-shaped sets of cross-laminae. The description of this type of cross-lamination corresponds to that of cross-stratification produced by migration of sand waves in the Red River, Louisiana (Harms, MacKenzie and McCubbin, 1963) and by migration of megaripples (Reineck and Singh, 1975). The grain size, type of sedimentary structures, and stratigraphic location of the sandstone lens are comparable with those characteristic of tidal-delta and tidal-channel deposits as described in Table 8.

The paleocurrent pattern from dips of cross-lamination within the sandstone lens, is unimodal with a 90° spread of directions. The modal direction is to the NE which is approximately perpendicular to the suggested trend of the paleoshoreline (N-S to NW-SE) in a seaward direction with a component in the direction of the northerly longshore drift. Dip directions of cross-stratification in tidal channels range from perpendicular to oblique to the shoreline trend in either landward and/or seaward directions. Due to migration of tidal inlets in the direction of longshore drift, Hoyt and Henry (1965) found that cross-bedding dipped in predominantly landward or seaward directions with a component in the direction of longshore drift.

Thus, the presence of deposits within a lagoonal complex in the lower portion of the coal-bearing assemblage is suggested by units which may represent deposition in a washover fan and a tidal channel or tidal delta. Deposition within tidal flat or lagoonal pond environments cannot be ascertained due to the covered nature of the finer grained deposits within this assemblage. Brackish water fauna which would distinguish a lagoonal pond environment, is not present; rather the mudstones and shales contain carbonaceous debris and fragmental plant impressions. Thus, the lower portion of the coal-bearing assemblage will be considered as marsh/lagoon deposits.

The upper portion of the coal-bearing assemblage is characterized by predominantly covered intervals of shale or mudstone, and outcropping, laterally discontinuous beds of siltstone and sandstone which pinch and swell and occasionally exhibit cut and fill structures. Internally, these beds are commonly planar-parallel laminated or structureless, and less commonly exhibit medium-scale, low-angle, trough-shaped sets of cross-lamination. Ripples marks occur on some of the bedding planes. Abundant carbonaceous debris and rare petrified logs occur in the shales and mudstones.

According to Potter (1967), alluvial sand bodies which include deposits on alluvial fans, floodplains and deltas are lenticular with erosional scour. Thickness of the sand bodies range from less than 10 feet (3m) to greater than 100 feet (30m). Conglomerate may occur near the base, and grain size and bed thickness decrease upward. Sedimentary structures include asymmetrical ripple marks and abundant well oriented cross-bedding, commonly unimodal. Associated lithologic types include siltstones and shales, and possible peat and coals. Carbonaceous debris, fragmental plant remains, rootlets and logs are characteristic of alluvial deposits. Due to the non-layer cake nature of the sand bodies, correlation is difficult unless coal or peat marker beds are present.

Based on the above criteria, the upper portion of the coal-bearing assemblage can be interpreted as alluvial deposits. Furthermore, these deposits can be interpreted as floodplain deposits rather than alluvial-fan or deltaic deposits due to the stratigraphic position above the coastal sand and marsh/lagoon deposits, and to the predominantly fine-grained nature of these deposits. Thus, the upper portion of the coal bearing assemblage corresponds to the fluvial sands and floodplain shales considered to be the typical deposits of the Mesaverde Group.

The oyster-bearing assemblage consists of a five-to seven-meter (17 to 23')-thick interval which contains the brackish-water oyster, Flemingostrea aff. prudencia. Brackish water conditions are indicative of somewhat restricted coastal bodies of water such as bays, lagoons or estuaries. Estuaries have been defined and are regarded in this discussion as drowned river valleys such as the Chesapeake Bay (Curray, 1969). Thus, the oyster-bearing assemblage represents deposition within one of these restricted coastal bodies of water.

Proposed Modern Analog: A proposed modern analog of the depositional environments in the transition from the Mancos Shale to the Mesaverde Group is the Georgia coast, U.S.A. The following description is taken from Hoyt and Henry (1965) and Hoyt and others (1964). The Georgia coast is a barrier island coastline with relatively short broad barrier islands, 7-18 miles (11-29 km) in length, and 2-5 miles (3-8 km) wide. Channel inlets which separate the barrier islands average two miles in width and over 50 feet (15m) in maximum depth. The barrier islands are separated from the mainland by 4-6 miles (6-10 km) of salt marsh and meandering tidal channels. Beach and channel sands are deposited by flood tides as much as one mile inland in the tidal channels. Due to abundant fine sediment and luxuriant flora, partial filling of the lagoonal area and conversion to salt marshes have taken place.

The barrier islands are composed of littoral, shallow neritic and eolian deposits consisting of fine to coarse sand. The presence of closely spaced tidal inlets is due to the lack of sand. The 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-saltmarsh 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 (10-13 km) wide. The mechanism of shifting tidal inlets may explain why, in the basal assemblage, no deposits of the foreshore zone are preserved.

The deposits of the salt marshes along the Georgia coast are composed 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. Each type of these deposits are represented in the lower portion of the coal-bearing assemblage except for the presence of Ostrea; Ostrea occurs in the oyster-bearing assemblage, however.

The Georgia coast is characterized by an association of depositional environments, including a potential coal-forming environment, which corresponds to the interpreted depositional environments of this study. Depositional environments common to both the analog and this study include the beach environment, and the marsh/lagoonal environments with associated tidal-channel and washover-fan features. The Georgia mainland near the coast corresponds to the floodplain depositional environment of this study. Due to the humid climate of the Georgia coast, plant life is abundant which provides the source for organic deposits. The salt marsh is an environment in which such deposits accumulate along the coast. The lower portion of the coal-bearing assemblage which includes the major coal seam is interpreted as a coastal-marsh/lagoonal deposit. The major coal seam may represent deposition in a salt marsh, as suggested by the analog. However, further evidence would be needed before such a conclusion could be reached. Results of a paleobotanical study might provide evidence for a salt-marsh environment.

Examination of the association of environments of the modern analog provides additional insight into the problem of interpreting a coastal sand body as a barrier- or mainland-beach deposit based on the presence or absence of lagoonal deposits. First, the close association of the salt-marsh and lagoonal environments in the analog illustrates that distinction between ancient marsh and lagoonal deposits would not always be possible. Both types of environments would produce deposits of predominantly clay, silt, and fine sand with associated tidal-channel and washover-fan sand deposits. Second, the analog illustrates that a coastal sand body can be a barrier if it is separated from the mainland by a salt-marsh as well as a lagoonal environment. Thus, by analogy, the sandstone of the basal assemblage represents a barrier-beach rather than a mainland-beach deposit.

Chapter 8

SUMMARY AND CONCLUSIONS

The nature of the transition from the marine Mancos Shale to the continental deposits of the Mesaverde Group in the Carthage area has been studied along a 1.4-kilometer (.9-m)-transect. Assemblages have been defined on the basis of lithology, sedimentary structures, paleontology, and lateral continuity of units and correspond to the following depositional environments:

1) Transition assemblage - transition zone between the offshore zone and the beach,
2) Basal assemblage - the shoreface zone of a beach,
3) Lower portion of the coal-bearing assemblage - marsh/lagoon
4) Upper portion of the coal-bearing assemblage - floodplain, and
5) Oyster-bearing assemblage - a restricted coastal body of water such as a bay, lagoon or estuary.

The proposed modern analog for these depositional environments is the Georgia coast which is characterized by barrier islands separated from the mainland by a lagoonal/ salt-marsh zone. Analogy with this modern association of depositional environments suggests that the basal assemblage represents a barrier-island rather than a mainland-beach deposit. Reworking of barrier-island and marsh deposits by tidal inlets along the Georgia coast suggests a mechanism to account for the lack of foreshore deposits in the study area.

The continuous major coal seam in the lower coal-bearing assemblage represents deposition within a lagoonal-marsh environment located landward of the coastal sand. Thus, this coal body should be elongate parallel to the shoreline; N-S to NW-SE as previously determined from the trend of the paleoshoreline. The thin, discontinuous carbonaceous shales and coals in the upper portion of the coal-bearing assemblage represent deposition in floodplain swamps and thus, should be elongate parallel to the trend of the river channels; approximately perpendicular to the shoreline trend.

Semi-quantitative analysis of clay minerals from one measured section yields an assemblage of illite, kaolinite and mixed-layer clays. The general trend of increasing proportions of kaolinite and decreasing proportions of mixed-layer clays upwards in the stratigraphic section, corresponds to the transition from marine to continental deposits. Proportions of illite remain relatively constant throughout the stratigraphic section.

Suggestions for Further Work: Further work may prove useful in more specifically defining the depositional environments, particularly of those deposits overlying the basal assemblage. Suggestions for additional field work include detailed examination of the sedimentary structures in the covered intervals and continuous examination of the top of the basal assemblage for evidence of tidal inlets. X-ray radiography of the structureless sandstones would reveal the true nature of the internal stratification. A paleobotanical study might provide information concerning the nature of the lagoonal/marsh environment of deposition. If present in the deposits, assemblages of various species of foraminifera may serve as environmental indicators; an example of assemblages of foraminifera as related to Recent depositional environments is provided by Dickinson and others (1972). Finally, results from the limited clay mineral analysis in this study show that the proportions of clay minerals do vary stratigraphically and thus, a more extensive clay mineral study may provide more refined criteria for interpreting depositional environments.

REFERENCES CITED

Allen, J. R. L., 1963, The classification of cross-stratified units with notes on their origin: Sedimentology, v. 2, p. 93-114

Austin, G. S., and Leininger, R. K., 1976, The effect of heat-treating sedimented mixed-layer illite-smectite as related to quantitative clay mineral determinations: Jour. Sed. Petrology, v. 46, p. 206-215

Beaumont, E. C., Dane, C. H., and Sears, J. D., 1956, Revised nomenclature of Mesaverde Group in San Juan Basin, New Mexico: Am. Assoc. Petroleum Geologists Bull., v. 40, p. 2149-2162

Berg, R. G., and Davies, D. K., 1968, Origin of Lower Cretaceous Muddy Sandstone at Bell Creek Field, Montana: Am. Assoc. Petroleum Geologists Bull., v. 52, p. 1888-1898

Bernard, H. A., LeBlanc, R. J., and Major, C. F., 1962, Recent and Pleistocene geology of southeast Texas, in Rainwater, E. H., and Zingula, R. P., eds., Geology of the Gulf Coast and central Texas and guidebook of excursions: Houston Geol. Society (for Geol. Soc. America 1962 Meeting), p. 175-224

Blatt, H., Middleton, G., and Murray, R., 1972, Origin of sedimentary rocks: New Jersey, Prentice-Hall, Inc., 634 p.

Brown, C. Q., and Ingram, R. L., 1954, The clay minerals of the Neuse River sediments: Jour. Sed. Petrology, v. 24, p. 196-199

Brown, L. F., Bailey, S. W., Cline, L. M., and Lister, J. S., 1977, Clay mineralogy in relation to deltaic sedimentation patterns of Desmoinesian cyclothems in Iowa-Missouri: Clays and Clay Minerals, v. 25, no. 3, p. 171-186

Budding, A. J., 1963, Field trip 7, Carthage area, in Kuellmer, F. J., ed., New Mexico Geological Society Fourteenth Field Conference, Socorro Region, p. 74-77

Bureau of Land Management, 1978, Environmental statement on grazing management in the East Socorro ES area: Socorro, New Mexico, November 20, 1978 draft

Campbell, C. V., 1966, Truncated wave-ripple laminae: Jour. Sed. Petrology, v. 36, p. 825-828

——1967, Lamina, laminaset, bed and bedset: Sedimentology, v. 8, p. 7-26

——1971, Depositional model - Upper Cretaceous beach shoreline, Ship Rock area, northwestern New Mexico: Jour. Sed. Petrology, v. 41, p. 395-409

Carroll, D., 1970, Clay minerals: a guide to their X-ray identification: Geol. Soc. America Spec. Paper 126, 80 p.

Chilingar, G. V., 1956, Soviet classification of sedimentary particles and Vasil'evskiy graph: Am. Assoc. Petroleum Geologists, v. 40, p. 1714-1715

Cobban, W. A., and Hook, S. C., (in press), Collignoniceras woollgari woollgari (Mantell) ammonite fauna from Upper Cretaceous of the Western Interior of the United States: New Mexico Bureau of Mines and Mineral Resources Mem. 37

Cobban, W. A., and Reeside, J. B., Jr., 1952, Correlation of the Cretaceous formations of the Western Interior of the United States: Geol. Soc. America Bull., v. 63, p. 1011-1044

Curray, J. R., 1969, Estuaries, lagoons, tidal flats and deltas, in Stanley, D. J., convener, Concepts of continental margin sedimentation, application to the geological record, Short Course Lecture Notes, 7-9 November 1969, Philadelphia: Washington, D. C., American Geological Institute, p. JC-3-1 to JC-3-30

Davies, D. K., Ethridge, F. G., and Berg, R. R., 1971, Recognition of barrier environments: Am. Assoc. Petroleum Geologists Bull., v. 55, p. 550-565

Dickinson, W. R., 1970, Interpreting detrital modes of graywacke and arkose: Jour. Sed. Petrology, v. 40, p. 695-707

Dickinson, K. A., Berryhill, H. L., Jr., and Holmes, C. W., 1972, Criteria for recognizing ancient barrier coastlines, in Rigby, J. K., and Hamblin, W. K., eds. Recognition of ancient sedimentary environments: Society of Econmic Paleontologists and Mineralogists Spec. Pub. No. 16, p. 192-214

Folk, R. L., 1968, Petrology of sedimentary rocks: Austin, Texas, Hemphill's Book Store, 170p.

Foster, R., and Luce, P., 1963, Road log E, San Antonio, New Mexico (at junction U. S. 380 and U. S. 85) to Lincoln County line via U. S. 380, in Kuellmer, F. J., ed., New Mexico Geological Society Fourteenth Field Conference, Socorro Region, p. 31-37

Friedman, G. M., 1967, Dynamic processes and statistical parameters compared for size frequency distribution of beach and river sands: Jour. Sed. Petrology, v. 37, p. 327-354

Frey, R. W., and Howard, J. D., 1970, Comparison of Upper Cretaceous ichnofaunas from siliceous sandstones and chalk, in Crimes, T. P., and Harper, J. C., eds., Trace fossils: Liverpool, Seal House Press, p. 141-166

Gardner, J. H., 1910, The Carthage coal field, New Mexico: U. S. Geol. Survey Bull. 381-c, p. 452-460

Häntzshcel, W., 1975, Treatise on invertebrate paleontology, Part W, Supplement 1, Trace fossils: Boulder, Colorado and Laurence, Kansas, Geological Society of America, Inc. and University of Kansas Press, 269 p.

Harms, J. C., MacKenzie, D. B., and McCubbin, D. G., 1963, Stratification in modern sands of the Red River, Louisiana: Jour. Geology, v. 71, p. 566-580

Higgins, O. L., 1977, Sand Mountain allotment (0285) of allotment management plan: Socorro, New Mexico, Bureau of Land Management

Holmes, W. H., 1877, Geological Report on the San Juan District, Colorado: U. S. Geol. and Geog. Survey Terr. 9th Ann. Rept., 1875

Hoyt, J. H., 1962, High-angle beach stratification, Sapelo Island, Georgia: Jour. Sed. Petrology, v. 32, p. 309-311

Hoyt, J. H., and Henry, V. J. J., 1965, Significance of inlet sedimentation in the recognition of ancient barrier islands, in DeVoto, R. H. and Austin, A. C., eds., Sedimentation of Late Cretaceous and Tertiary outcrops, Rock Springs Uplift: Wyoming Geol. Assoc. Guidebook, 19th Field Conf., p. 190-194

Hoyt, J. H., and Weimer, R. J., 1963, Comparison of modern and ancient beaches, central Georgia coast: Am. Assoc. Petroleum Geologists Bull., v. 47, p. 529-531

Hoyt, J. H., Weimer, R. J., and Vernon, J. H., 1964, Late Pleistocene and Recent sedimentation, central Georgia coast, U.S.A., in Van Straaten, L. M. J. U., ed., Deltaic and shallow marine deposits: New York, Elsevier Publishing Company, p. 170-176

Ingram, R. L., 1954, Terminology for the thickness of stratification and parting units in sedimentary rocks: Geol. Soc. America Bull., v. 65, p. 937-938

Johns, W. D., Grim, R. E., and Bradley, W. F., 1954, Quantitative estimations of clay minerals by diffraction methods: Jour. Sed. Petrology, v. 24, p. 242-251

Kerr, P. F., 1959, Optical mineralogy: New York, McGraw-Hill Book Company, 442 p.

Krumbein, W. C., and Sloss, L. L., 1963, Stratigraphy and sedimentation: San Francisco and London, W. H. Freeman and Company, 660 p.

Land, C. B., Jr., 1972, Stratigraphy of Fox Hills Sandstone and associated formations, Rock Springs uplift and Wamsutter Arch area, Sweetwater County, Wyoming - a shoreline-estuary sandstone model for the Late Cretaceous: Colorado School of Mines Quart., v. 67, no. 2, 69 p.

Lee, W. T., 1915, Relation of the Cretaceous formations to the Rocky Mountains in Colorado and New Mexico: U. S. Geol. Survey Prof. Paper 95, p. 27-58

McKee, E. D., 1957, Primary structures in some recent sediments: Am. Assoc. Petroleum Geologists, v. 41, p. 1704-1747

McKee, E. D., and Weir, G. W., 1953, Terminology for stratification and cross-stratification in sedimentary rocks: Geol. Soc. America Bull., v. 64, p. 381-390

Masters, C. D., 1967, Use of sedimentary structures in determination of depositional environments, Mesaverde formation, Williams Fork Mountains, Colorado: Am. Assoc. Petroleum Geologists, v. 51, p. 2033-2043

Molenaar, C. M., 1973, Sedimentary facies and correlation of the Gallup Sandstone and associated formations, northwestern New Mexico, in Fassett, J. E., ed., Cretaceous and Tertiary rocks of the southern Colorado Plateau: Four Corners Geol. Soc. Mem., p. 85-110

——1974, Correlation of the Gallup Sandstone and associated formations, Upper Cretaceous, eastern San Juan and Acoma Basins, New Mexico, in Siemers, C. T., ed., New Mexico Geologic Society 25th Ann. Field Conference, Ghost Ranch, central-northern New Mexico, p. 251-258

——1977, San Juan Basin time-stratigraphic nomenclature chart, in Fassett, J. E., ed., New Mexico Geological Society 28th Field Conference, San Juan Basin III, p. xii

Murphy, M. A., and Schlanger, S. O., 1962, Sedimentary structures in Ilhas and São Sabastião formations (Cretaceous), Recônsavo Basin, Brazil: Am. Assoc. Petroleum Geologists, v. 46, p. 457-477

Parham, W. E., 1966, Lateral variation of clay mineral assemblages in modern and ancient sediments: Proceedings of the International Clay Conference, 1966, v. I, p. 135-145

Pike, W. S., 1947, Intertonguing marine and nonmarine Upper Cretateous deposits of New Mexico, Arizona and southwestern Colorado: Geol. Soc. America Mem. 24, 103 p.

Pettijohn, F. J., Potter, P. E., and Siever, R., 1973, Sand and sandstone: New York, Spring-Verlag, 618 p.

Potter, P. E., 1967, Sand bodies and sedimentary environments: a review: Amer. Assoc. Petroleum Geologists Bull., v. 51, p. 337-365

Potter, P. E., and Pettijohn, F. J., 1963, Paleocurrents and basin analysis: New York, Academic Press, Inc., 296 p.

Rankin, C. H., 1944, Stratigraphy of the Colorado Group, Upper Cretaceous, in northern New Mexico: New Mexico Bureau of Mines and Mineral Resources Bull. 20, 30 p.

Reineck, H.-E., and Singh, I. B., 1975, Depositional sedimentary environments: New York, Springer-Verlag, 439 p.

Selley, R. C., 1968, A classification of paleocurrent models: Jour. Geology, v. 76, p. 99-110

Shelton, J. W., 1967, Stratigraphic models and general criteria for recognition of alluvial, barrier-bar, and turbidity current sand deposition: Am. Assoc. Petroleum Geologists Bull., v. 51, p. 2441-2461

Terry, R. D., and Chilingar, G. V., 1955, Visual estimation of percentage composition: Jour. Sed. Petrology, v. 25, p. 229-234

Thompson, W. O., 1937, Original structures of beaches, bars, and dunes: Geol. Soc. America Bull., v. 48, p. 723-752

Visher, G. S., 1969, Grain size distributions and depositional processes: Jour. Sed. Petrology, v. 39, p. 1074-1106

Weimer, R. J., and Hoyt, J. H., 1964, Burrows of Callianassa Major Say, geologic indicators of littoral and shallow neritic environments: Jour. Paleontology, v. 38, p. 761-767

Wentworth, C. K., 1922, A scale of grade and class terms for clastic sediments: Jour. Geology, v. 30, p. 377-392

Wilpolt, R. H., and Wanek, A. A., 1951, Geology of the region from Socorro and San Antonio east to Chupadera Mesa, Socorro County, New Mexico: U. S. Geol. Survey Oil and Gas Investigations, Map OM 121

APPENDIX A

Descriptions of Units

Abbreviations Used

bl.	blackish*
br.	brown, brownish*
cm.	centimeter(s)
di.	diameter
dk.	dark*
gr.	gray, grayish*
grn.	grained
lam.	laminated, lamination(s)
lt.	light*
m.	meter(s)
med.	medium
mod.	moderate, moderately
or.	orange*
p.	pale*
red.	reddish*
sh.	shale*
ss.	sandstone
v.	very
yel.	yellow, yellowish*

*See also Appendix B for correspondence to GSA color chart.

Section I

Transition assemblage

Unit #1 - Covered; probably sh.

Basal assemblage

Unit #2 - Thin beds of thinly to thickly lam., gr. or., mod.-sorted, fine-grn. ss. Small covered interval at top; probably sh. or silty sh.

Unit #3 - Structureless, gr. or., mod.-sorted, fine-grn. ss. with liesegang rings. Weathers as large boulders.

Unit #4 - Structureless, gr. or., mod.-sorted ss. which coarsens upward from v. fine to fine sand. Thin layer of nodules at top.

Unit #5 - Gr. or., cliff-forming unit. Ranges from mod.-sorted, fine sand at base to poorly-sorted, med.

sand at top. Basal 2 m. contain ss. concretions (.4 - .5 m. in di.), and abundant, randomly oriented Thalassinoides and Arthrophycus/Ophiomorpha. Middle to upper portion of unit contains planar-parallel lam.; med.-scale, low-angle, tabular-and trough-shaped sets of tangential cross-lam. with both erosional and nonerosional lower contacts; and sparse Thalassinoides. Top of unit forms dipslope of hill which exposes fragmental plant impressions (up to 20 cm. long and 3 cm. wide), and large-scale fractures associated with red. br. staining.

Coal-bearing assemblage

Unit #6 - Mostly covered. Locally exposed basal med. lt. gr. mudstone with layers of plant debris (preserved stems and leaves).

Unit #7 - V. thick bed of structureless, lt. gr., mod.-sorted, med.-grn. ss. with red. br. stained sand-filled fractures perpendicular to bedding. Unit serves as a distinct marker bed.

Unit #8 - Mostly covered. Top meter exposed by mining road. Coal and carbonaceous sh. alternating with v. thinly to thinly bedded, med. lt. gr. mudstone with carbonaceous debris.

Unit #9 - V. p. or. to gr. or., poorly-sorted, med.-grn. ss. Med.-scale, high-to low-angle, tabular-to wedge-shaped sets of tangential cross-lam. with either erosional or nonerosional lower contacts in basal 1m. and in upper half of unit; elsewhere structureless. Discontinuous v. thin beds of nodules. Erosional lower contact. Unit forms lens which can be traced for approximately 180 m. laterally.

Unit #10 - Mod. yel. br., mod.-sorted, med.-grn. ss., weathers as subangular blocks, and forms dipslope. Typically structureless except one example of med.-scale, high-to low-angle, wedge-shaped set of tangential cross-lam. with erosional lower contact.

Top of section faulted out.

Section II

Transition assemblage

Unit #1 - Covered; probably sh.

Unit #2 - Grades upward from lt. br. gr. sh. to gr. or., mod.-sorted, v. fine-grn. ss.

Basal assemblage

Unit #3 - Gr. or., poorly-sorted, fine-grn. ss. Planar-parallel lam.

Unit #4 - Gr. or., mod.-to poorly-sorted, fine-grn. ss. Small ellipsoidal to thin lenses of nodules near the base. Commonly structureless; locally planar-parallel lam.

Unit #5 - Covered; probably gr. or., mod.-sorted, fine-grn. ss.

Unit #6 - Gr. or., mod.-sorted, fine-grn. ss. Less resistant intervals containing ss. concretions (.5 -.6 m. in di.) alternate with more resistant intervals that are commonly structureless and locally planar-parallel lam.

Unit #7 - Gr. or., mod.-sorted, med.-grn. ss. Med.-scale, low-angle, trough-and tabular-shaped sets of tangential cross-lam. with both erosional and nonerosional lower contacts. Forms top of dipslope; upper contact covered by coal dumps.

Coal-bearing assemblage

Unit #8 - Covered interval; probably mudstone to silty mudstone with plant debris and some carbonaceous sh.

Unit #9 - V. thick bed of structureless, v. lt. gr., mod.-sorted, fine-to med.-grn. ss. with fractures which are perpendicular or oblique to bedding and which form polygonal patterns on the bedding surface. Unit serves as a distinct marker bed.

Unit #10 - Mostly covered by mining road. Coal exposed at top one meter.

Unit #11 - Usually covered. Mudstone with plant debris at base grading upward to alternating mudstones, siltstones and med. to thick beds of fine-grn. ss.

Unit #12 - Gr. or., mod.-sorted ss. grading upward from fine to v. fine sand. Planar-parallel thick lam.

Unit #13 - Covered; probably gr. or., poorly-sorted, med.-grn. ss. at base and possibly some sh. Fractured concretions (.75-1 m. thick, 1-1.5 m. in di.) of calcareous, mod.-sorted, fine-grn. ss. form distinct outcrops. Concretions are mod. yel. br. on weathered surface and med. gr. on fresh surface.

Unit #14 - Irregular thin to thick beds of p. yel. br., mod.-to poorly-sorted, fine-grn. ss. alternating with covered intervals of probable siltstone, and mudstone containing carbonaceous debris. Possible med.-scale, low-angle trough-shaped sets of v. thin cross-bedding in basal portion. Some straight, asymmetrical ripple marks exposed on bedding surfaces. Forms dipslope of hill.

Unit #15 - Mostly covered. Probably alternating intervals of mudstone with carbonaceous debris, siltstone and med. beds of mod.-sorted, v. fine-to fine-grn. ss. with one med. bed of carbonaceous sh.

Unit #16 - Covered interval overlain by a thick bed of mod. yel. br., mod.-sorted, fine-grn. ss. which weathers in subangular blocks ∿25 $cm.^3$

Unit #17 - Covered interval.

Oyster-bearing assemblage

Unit #18 - Thick bed of dk. yel. or., mod.-sorted, v. fine-grn. ss. Contains mod. abundant whole or nearly whole oysters Flemingostrea aff. prudencia, sparse fragments of Crassostrea solemiscus, and sparse pelecypods. Rectangular pore spaces (to several cm.) are associated with planar fractures which form a "honey comb" pattern.

Unit #19 - Covered interval with articulated whole oysters, Flemingostrea aff. prudencia occurring in basal .9 m. of float.

Unit #20 - Thick bed of dk. yel. or., mod.-sorted, v. fine-grn. ss. Top surface has locally abundant thin shell debris and rare whole or nearly whole oysters Flemingostrea aff. prudencia.

Section continues upward; not measured.

Section III

Transition assemblage

Unit #1 - Usually covered. Grades downward from alternating fine-grn. ss., siltstone and sh., to sh.

Basal assemblage

Unit #2 - Gr. or or., mod.-sorted, med.-grn. ss. Dominately planar-parallel lam., slightly inclined lam. at the top and local zones of folded lam. in the middle. Thin lenses of nodules and liesegang rings.

Unit #3 - Covered; possibly alternating siltstone and sh.

Unit #4 - Gr. or., mod.-sorted, fine-grn. ss. Usually planar-parallel lam. with some poorly preserved, small-scale, cross-lam. at top. Lens of whole mollusks near the base; four species of gastropod, pelecypods including Cardium, and sparse oysters Crassostrea solemiscus and Ostrea anomioides. Thin nodule layers.

Unit #5 - Structureless, gr. or, mod.-sorted, med.-grn. ss. Abundant, randomly oriented Thalassinoides at the base. Scattered, irregular shaped and sized nodules. Ss. concretions (.3-.4 m. in di.) near the top.

Unit #6 - Planar-parallel lam. to thin bedded, gr. or., mod.-sorted, fine-to med.-grn. ss.

Unit #7 - Gr. or., mod.-sorted, med.-grn. ss. Med.-scale, low-angle, abundant tabular-and rare trough-shaped sets of tangential very thin cross-beds. Top of unit forms dipslope of hill which exhibits an excellent example of liesegang rings.

Coal-bearing assemblage

Unit #8 - Usually covered. Mostly mudstone with plant debris and a few thin beds of carbonaceous sh. overlain by a thick bed of thinly lam., lt. br. gr., silty mudstone.

Unit #9 - Structureless, v. lt. gr., mod.-sorted, fine-to med.-grn. ss. with red. br. stained sand-filled fractures perpendicular to bedding. Unit serves as a distinct marker bed.

Unit #10 - Mottled lt. br. gr. to mod. yel. br. silty mudstone with plant debris overlain by a thin bed of dk. red. br., mod. sorted, v. fine-grn. ss.

Unit #11 - Med. lt. gr. sh.

Unit #12 - Coal with a very thin bed of carbonaceous sh. near the top.

Unit #13 - Covered intervals of sh. alternating with irregular beds of gr. or., mod.-sorted, fine-to med.-grn. ss. with irregular thin lam. Nodules and irregular shaped bodies of silty mudstone surrounded by cone-in-cone structure are located on top of the ss. and within the sh. intervals.

Unit #14 - Covered interval of sh. grading upwards to carbonaceous sh., overlain by a thick bed of gr. or., poorly-sorted, med.-grn. ss. Structureless except for one, med.-scale, low-angle, trough-shaped set of tangential cross-lam.

Unit #15 - Covered interval of sh. overlain by a thick bed of gr. or., mod.-sorted, v. fine-grn. ss. with irregular lam. Locally large petrified logs 1.5 to 7.5 m. long parallel to bedding within the sh. interval.

Unit #16 - Covered interval overlain by a mod. yel. br., mod.-sorted, fine-grn. ss. Local channel cut and fill structures (1.5-2 m. deep, 5-6 m. wide, symmetric and asymmetric in cross section) which internally are thinly to thickly lam. with local small-scale, in-phase ripple lam. and med.-scale, low-angle, trough (?)-shaped sets of tangential cross-lam. Clay clasts found in float blocks are circular to elongate (up to 1 cm.) in shape lying on the lam. plane surfaces but are relatively flat and thin parallel with lam. as viewed in cross sections.

Unit #17 - Gr. or., mod.-sorted, fine-grn. ss. Planar-parallel thickly lam. with well developed parting parallel to lam.

Unit #18 - Covered interval overlain by a med. bed of dk. yel. or., mod.-sorted, fine-grn. ss. which pinches and swells from 10 to 30 cm.

Unit #19 - Covered interval overlain by a thick bed of dk. yel. br., mod.-sorted, fine-grn. ss. Fractures perpendicular or oblique to the bedding form polygonal patterns on the bedding surface. Unit forms dipslope of hill.

Unit #20 - Usually covered interval of alternating sh., siltstone and fine-grn. ss. with one med. bed of carbonaceous sh.

Oyster-bearing assemblage

Unit #21 - Med. bed of gr. or., mod.-sorted, fine-grn. ss. with whole oysters Flemingostrea aff. prudencia and small pelecypods.

Unit #22 - Covered interval with abundant articulated whole oysters Flemingostrea aff. prudencia occurring in basal 1.3 m. of float.

Unit #23 - Thick bed of irregular lam. to thin bedded, gr. or., mod.-sorted, fine-grn. ss. with sparse poorly preserved pelecypods and fragments of the oyster Flemingostrea aff. prudencia. Some sinuous, asymmetrical ripple marks on bedding surfaces.

Section IV

Transition assemblage

Unit #1 - Covered; probably mod.-sorted, fine-grn. ss. at top grading downward to sh.

Unit #2 - Locally exposed gr. or., mod.-sorted, fine-grn. ss. Planar-parallel lam.

Unit #3 - Covered interval.

Basal assemblage

Unit #4 - Gr. or., mod.-sorted, fine-grn. ss. Dominantly planar-parallel lam.; elsewhere structureless. Locally very abundant, usually whole mollusks; four species of gastropod, pelecypods including Cardium, and two species of oysters, Crassostrea solemiscus and Ostrea anomioides. One Arthrophycus/Ophiomorpha oblique to lam. just above a layer of mollusks. Sparse thin lenses of nodules.

Unit #5 - Gr. or., mod.-sorted ss. grading upwards from v. fine to fine sand. Planar-parallel lam.

Unit #6 - Mostly covered. Sh. at base. Top meter is gr. or., mod.-to poorly-sorted, fine-to med.-grn. ss.

Unit #7 - Gr. or. ss. ranging from mod.-to poorly-sorted, fine to med. sand. Locally planar-parallel lam. Abundant, small-and med.-scale, low-angle trough-shaped sets and rare med.-scale, low-angle, tabular-shaped sets of tangential cross-lam. with either erosional or nonerosional lower contacts. Ss. concretions (.5-1 m. in di. and .3-.4 m. thick) near base. Sparse thin lenses of nodules.

Unit #8 - Gr. or., poorly-sorted, med.-grn. ss. Dominantly planar-parallel lam. Med.-(to near large-)scale, low-angle, tabular-to wedge-shaped sets of tangential cross-lam. with both erosional and nonerosional lower contacts. Scattered lenses of nodules. Fragmental plant impressions (to 5 cm. by 1 cm.) on bedding surfaces near top of unit. Forms dipslope; upper contact covered by coal dumps.

Coal-bearing assemblage

Unit #9 - Covered interval.

Unit #10 - Thick bed of structureless, v. lt. gr., mod.-sorted, fine-to med.-grn. ss. with fractures perpendicular to bedding. Unit serves as a distinct marker bed.

Unit #11 - Mostly covered. Thinly lam. siltstone at base. Top third of the unit grades upward from p. yel. br., mod.-sorted, v. fine-grn. ss. to p. br. sh.

Unit #12 - Coal with a thin bed of white sh. dividing the unit.

Unit #13 - Basal thick bed of planar-parallel thinly lam., p. yel. br. siltstone to v. fine-grn. ss. overlain by a med. bed of coal.

Unit #14 - Covered; probably mostly sh. or mudstone and some carbonaceous sh.

Unit #15 - P. yel. br., mod.-to poorly-sorted, fine-grn. ss. Med. to thick irregular bedding with probable med.-scale, low-angle, trough-shaped sets of tangential thick cross-lam. Liesegang rings and calcite-filled fractures.

Unit #16 - Covered intervals of probable poorly-sorted, fine-grn. ss. alternating with med. beds of lt. br. to bl. red, v. hard ferrugenous material with structure suggestive of petrified log remains. Forms dip-slope.

Unit #17 - Scattered outcrops of fractured concretions (1 m. in di., .75 m. thick) of calcareous, mod.-sorted, fine-grn. ss. Dk. yel. or. to dk. yel. br. on weathered surface and med. gr. on fresh surface.

Covered interval; may represent a fault contact.

APPENDIX B

Terminology Used for Description of Lithology and Stratification

Rock Colors

Rock colors are taken from the GSA Rock Color Chart (1970) and describe both weathered and fresh surfaces unless otherwise noted:

Abbreviation	Color	Munsell System
bl. red	blackish red	5 R 2/2
dk. red. br.	dark reddish brown	10 R 3/4
dk. yel. br.	dark yellowish brown	10 YR 4/2
dk. yel. or.	dark yellowish orange	10 YR 6/6
gr. or.	grayish orange	10 YR 7/4
lt. br.	light brown	5 YR 5/6
lt. br. gr.	light brownish gray	5 YR 6/1
lt. gr.	light gray	N7
med. lt. gr.	medium light gray	N6
mod. yel. br.	moderate yellowish brown	10 YR 5/4
p. br.	pale brown	5 YR 5/2
p. yel. br.	pale yellowish brown	10 YR 6/2
v. lt. gr.	very light gray	N8
v. p. or.	very pale orange	10 YR 8/2
white	white	N9

Grain Size

Grain size of the sandstones according to the Udden-Wentworth Scale (1922) was determined visually with the use of the grain size chart from Chilingar (1956).

Sorting

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

Stratification

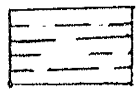
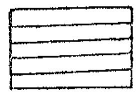
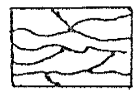
Terminology for the thickness of strata is from Ingram (1954):

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	.3 - 1 cm.
Thinly laminated	<.3 cm.

Shapes of individual beds are defined as follows:

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-	

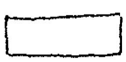
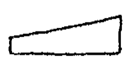
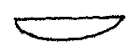
planar		lamination		erosional
tangential (arching)	cross-		with		lower
convex up		bedding		nonerosional

contact.

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

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

Shape of set:

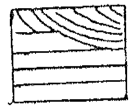
tabular  wedge  trough 

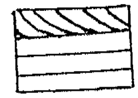
Arching:

planar  tangential  convex up 

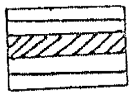
Thickness of cross-strata: lamination <1 cm.; bedding ≥ 1 cm.

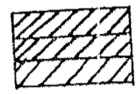
Nature of lower contact:

erosional (truncates lower strata) 

nonerosional (does not truncate lower strata) 

Sets of cross-stratification:

solitary 

grouped 

This thesis is accepted on behalf of the faculty of the Institute by the following committee:

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Date May 4, 1979