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Petrology and Diagenesis of the D-zone Cyclothem of the
Lansing-Kansas City Groups, Hitchcock County, Nebraska

by

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OF
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PETROLOGY AND DIAGENESIS OF THE
D-ZONE CYCLOTHEM OF THE
LANSING-KANSAS CITY GROUPS
HITCHCOCK COUNTY, NEBRASKA

A Thesis Presented to the
Faculty of the Graduate School
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By

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PETROLOGY AND DIAGENESIS OF THE D-ZONE
CYCLOTHEM OF THE LANSING-KANSAS CITY GROUPS
HITCHCOCK COUNTY, NEBRASKA

ABSTRACT

The D-zone cyclothem of the Lansing-Kansas City Groups of southwestern Nebraska was deposited during one major oscillation of the epeiric sea in the Late Pennsylvanian (Missourian). This cyclothem records transgression followed by a major regressive phase, during which time a brief transgression of sea level occurred.

The D-zone cyclothem consists of the four basic lithofacies common to most cyclic deposits of this age in northwestern Kansas and southwestern Nebraska: (1) a thin Lower Carbonate unit deposited in a shallow-marine environment; (2) a laterally extensive Lower Shale unit of marine origin resulting from a terrigenous influx from the north; (3) a complex Upper Carbonate unit deposited in shoaling water during waning terrigenous influx; and (4) an Upper Shale unit deposited in supratidal and non-marine environments.

Core data and an isopachous map of the Upper Shale unit suggest that several shoal areas existed in the area of Hitchcock County during part of Missourian time. Ooid grainstone deposition was localized on these bathymetric highs. The bathymetric highs may have been formed by a combination of differential compaction of the Upper Shale unit around former topographic highs in the underlying E-zone and movement on the ancestral Las Animas Arch.

The distribution of meteoric-phreatic cements and of secondary and preserved primary porosity in the grainstones indicate that the shoal areas were subaerially exposed at one time. Formation of dolomite cements, dolomite replacement of framework grains, and dolomitization of muddy carbonate facies was the result of the mixing of marine and fresh waters early in the diagenetic history of the cyclothem. The distribution of skeletal fragments replaced by red silica, dissolution cracks infiltrated with non-marine clay, and authigenic gypsum indicate a later stage diagenesis below a perched water table. This took place contemporaneously with soil formation and calichification in the Upper Shale in a semiarid or arid environment.

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I owe a debt of gratitude to Ray Burchett of the Nebraska Geological Survey and Lynn Watney of the Kansas Geological Survey for help in acquisition of samples. Especially Lynn, whose expertise in Lansing-Kansas City Groups rocks became very valuable to me throughout my research and writing.

I would like to thank my thesis committee, William C. Ward and William C. Craig of the Department of Earth Sciences at the University of New Orleans, and W. J. Ebanks of Cities Service for their critical review of the manuscript. A special thanks goes to Dr. Ward who had the unenviable task of trying to keep my head on straight while I was wildly waving my arms.

Last, but not least, I would like to thank Eva. You claim you have no patience; girl, to put up with just anyone who is writing a thesis is a good trick, but to put up with me is an act of supreme sacrifice and saintly disregard for one's own sanity.

DEDICATION

This thesis is dedicated to my parents without whose love and support it would not even have been started. My love and thanks go to both of you.

INTRODUCTION

Hitchcock County, Nebraska (Figure 1), has been the site of active oil exploration and production since the early 1950's. Fifteen oil fields have been discovered since that time (Svoboda, 1962). The most significant of those are the Meeker Canal and Republican River fields, shown with other noteworthy fields on Figure 2. Major reservoir rocks in these fields are limestones of the Lansing-Kansas City Groups.

It has been recognized that oil entrapment in the rocks of the Lansing-Kansas City Groups in southwestern Nebraska is a combination of both structural and stratigraphic factors. Larson (1962) believes that the occurrence of good-quality reservoir rocks is related to formation of organic build-ups on paleobathymetric highs which had relief of 3 to 10 feet (1 to 3 meters). He also believes these highs were related to present-day structures, but noted many structures tested were nonproductive because of the lack of porous rocks.

Not until recently has the influence of diagenesis, particularly development of secondary porosity, been recognized as an important factor controlling the quality of reservoir rocks in this area. Dubois (1979) pointed out that the occurrence of reservoir-quality rocks is related to diagenetic processes isolated on the tops of topographic highs during subaerial exposure. Watney (1980) and Watney and Ebanks (1978) described the effects of basin margin diagenesis during subaerial exposure in many zones of the Lansing-Kansas City Groups.

Previous Work

R. C. Moore first applied the recognition of cyclic sedimentation to interpretations of Permian and Pennsylvanian rock sequences throughout the Mid-Continent (Moore, 1929, 1949, 1957, 1964). He laid the groundwork

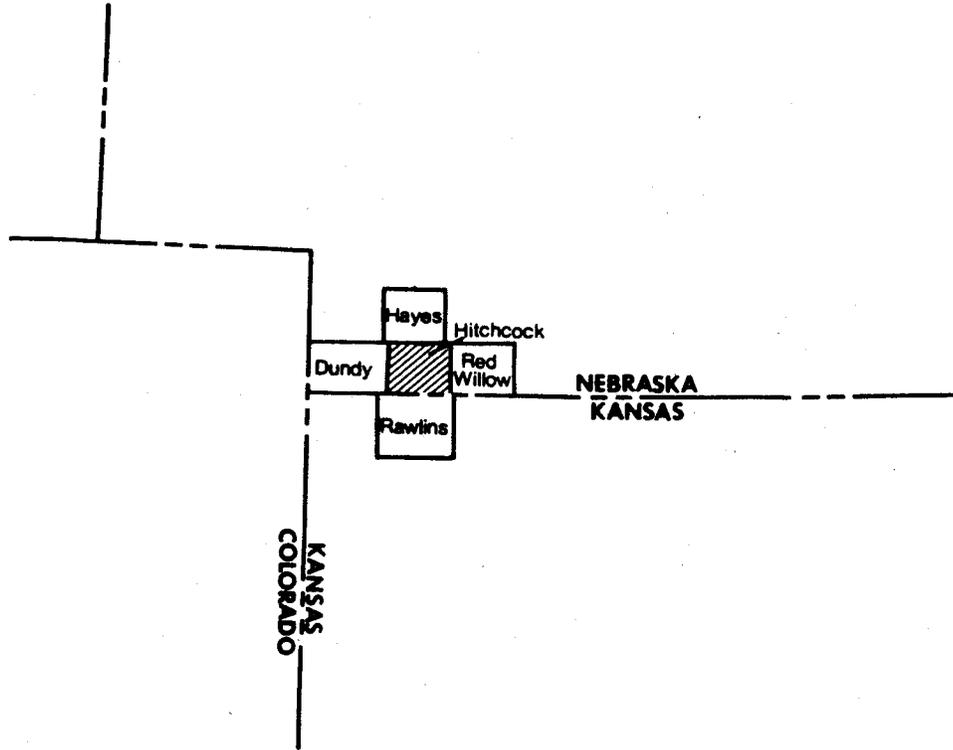
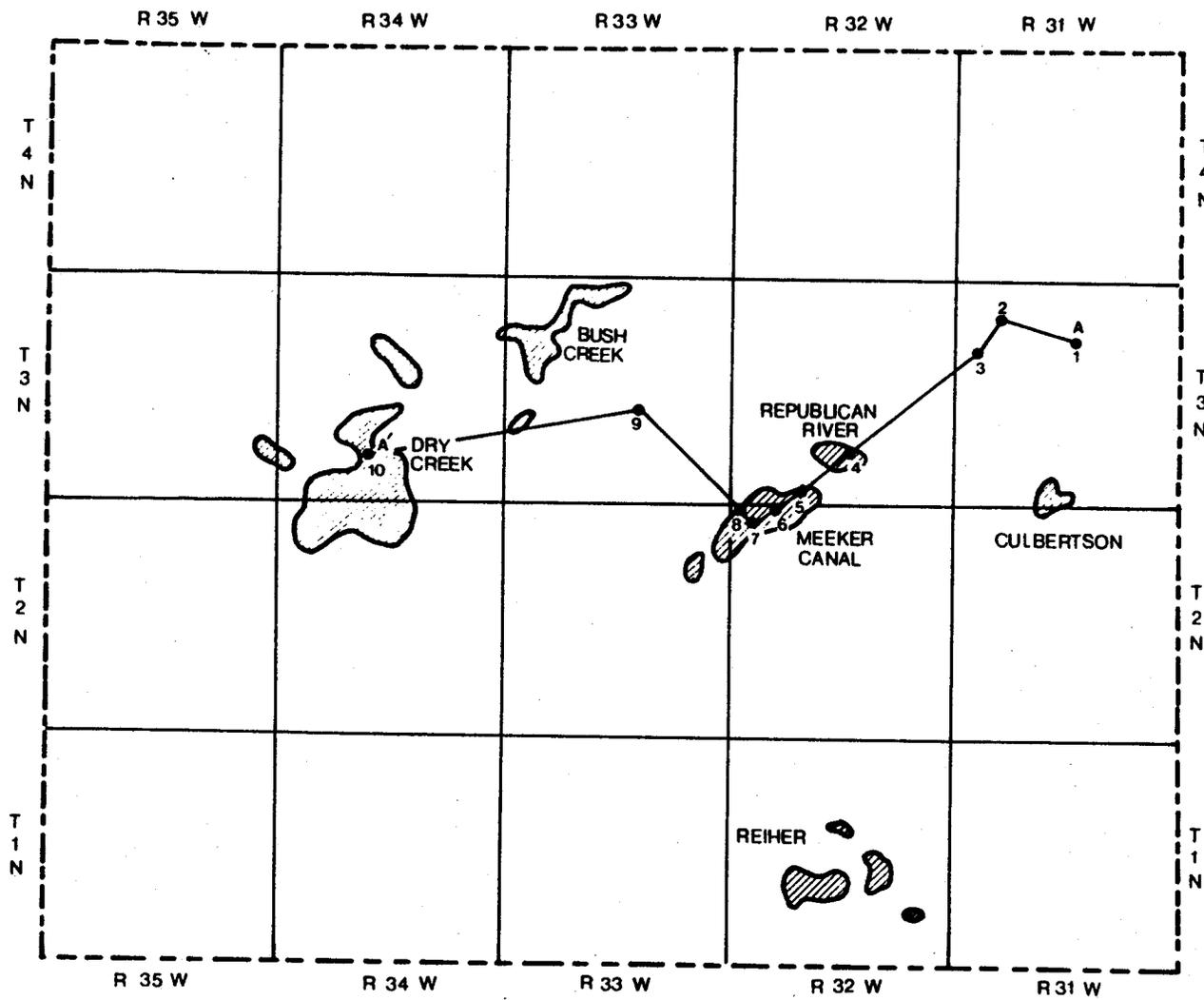


Figure 1. *Map showing location of Hitchcock County and surrounding counties in Nebraska and Kansas.*

Figure 2. *Largest oil fields in Hitchcock County, Nebraska, and location of cross section AA'.*



HITCHCOCK COUNTY, NEBRASKA

OIL FIELDS

for many of the later studies regarding rocks deposited during oscillations of ancient epeiric seas.

In an effort to apply surface nomenclature of the Lansing and Kansas City groups to the subsurface of northwestern Kansas, Parkhurst (1959) correlated 30 logs from the subsurface of eastern Kansas near outcrops of the Lansing and Kansas City Groups westward over the Central Kansas Uplift and into the Hugoton Embayment. Although the resulting classification scheme is not widely employed by operators in that region, his work clearly demonstrates the great expanse and continuity of Late Pennsylvanian epeiric seas.

Heckel (1975 and 1977) used the concepts of glacial-related eustatic rise and fall of sea level and the distribution of conodonts to interpret the origin of black shale lithofacies in Pennsylvanian cyclothem of eastern Kansas. Compiling data acquired by many workers, he constructed maps showing regional lithofacies distribution during a typical eustatically-controlled sedimentary cycle (Heckel, 1980).

Working with subsurface data from Hitchcock County, Dubois (1979) determined the stratigraphy of the E-zone of the Lansing-Kansas City Groups. He stressed the importance of secondary porosity to hydrocarbon accumulation. Secondary porosity apparently was generated during subaerial exposure of E-zone carbonates on topographic highs during the Late Pennsylvanian.

Watney (1979) detailed the possible application of gamma ray-neutron log signatures to interpretations of the sedimentology of cyclic deposits in the Lansing-Kansas City Groups of northwestern Kansas and southwestern Nebraska. He integrated core and cuttings analyses with geophysical logs to construct maps and cross sections of Lansing-Kansas

City rocks in a four-county area in Kansas and Nebraska (Watney, 1980). Watney and Ebanks (1978) described stratigraphic and diagenetic relationships in Lansing-Kansas City rocks near the basin margin in southern Nebraska and northwestern Kansas.

Purpose

The purpose of this study is to determine what may have controlled the distribution of microfacies, particularly the lime grainstones, in rocks of the D-zone of the Lansing-Kansas City Groups and to determine the nature, distribution and possible origin of the diagenetic features. The D-zone was selected for study because it contains one complete cyclothem and overlies a previously studied zone.

Geologic Framework

Regional Structural Geology - Movement of early Pennsylvanian regional structures (Figure 3) may have influenced deposition of the Lansing-Kansas City Groups rocks in Hitchcock County. These structures include: (1) the Cambridge Arch, (2) the ancestral Las Animas Arch, and (3) the Hugoton Embayment.

The study area is located on the southwestern flank of the Cambridge Arch, a large anticline plunging southeastward from the Transcontinental Arch. The Cambridge Arch lies on the same axis as the Chadron Arch of Nebraska, the Central Kansas Uplift, and possibly the Black Hills of South Dakota. From subsurface data, Merriam and Atkinson (1955) determined that no major structural movement on the arch took place during the time of Lansing-Kansas City deposition. However, minor structural movements resulting from compaction of Pennsylvanian sediments on a sub-Pennsylvanian unconformity did take place prior to deposition of the

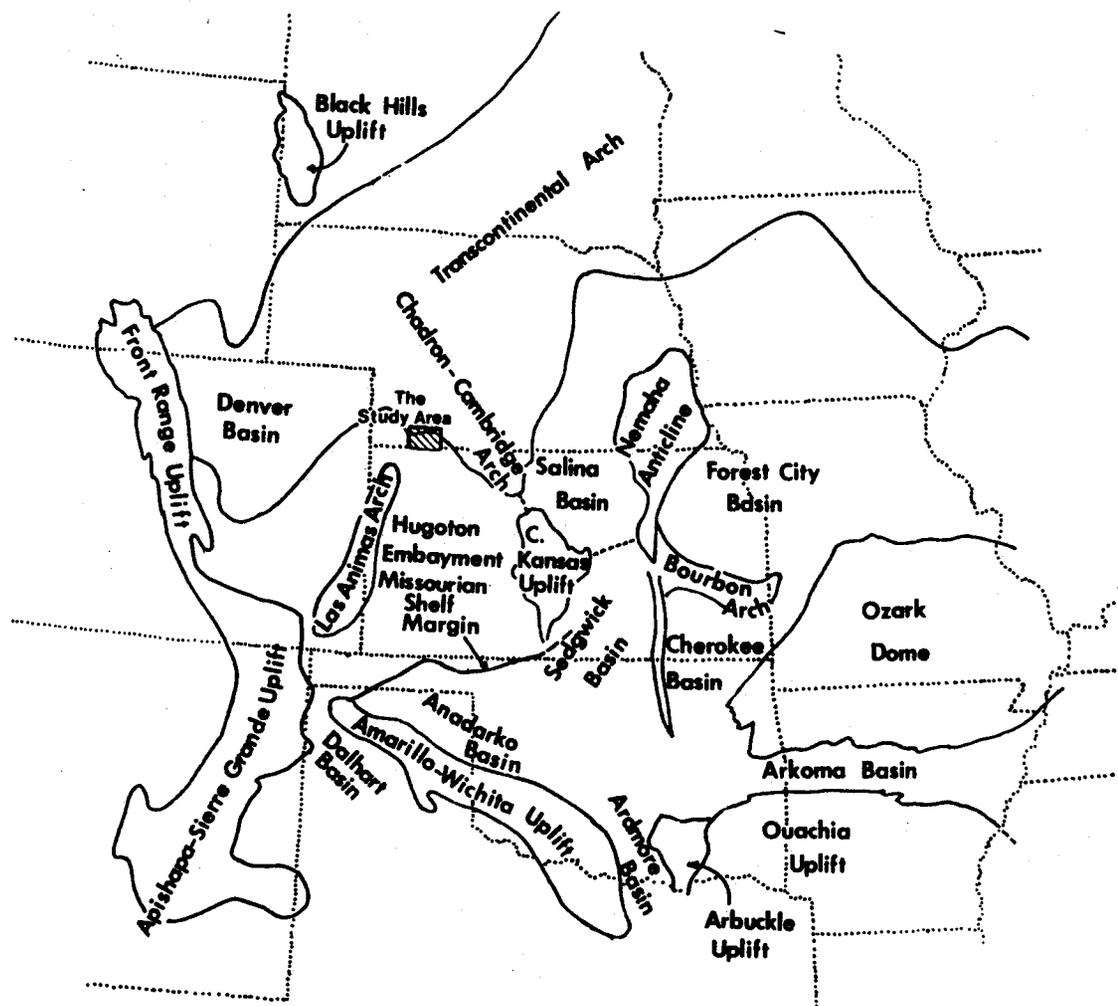


Figure 3. The structural and tectonic features that controlled regional sedimentation patterns in the Mid-Centent during Late Pennsylvanian (compiled from Moore, 1929; Branson, 1961; Roscoe, 1962; Heckel, 1980; and Watney, 1980).

Lansing-Kansas City Groups. This unconformity was formed during epeirogenic upwarping and erosion on the Cambridge and Transcontinental Arches (Rascoe, 1962) during the Mississippian (Chesteran).

The Las Animas Arch is presently a broad anticline plunging northeastward away from the Apishapa Uplift in southeastern Colorado. Isopachous and facies maps of Pennsylvanian and Permian rocks, however, reveal that an ancestral Las Animas Arch dipped southwestward away from the Cambridge Arch (Rascoe, 1978). Rascoe (1978, p. 113) believes that early movement associated with the ancestral arch "...exerted a considerable influence on the sediment accumulation and depositional environments over a large region in Late Paleozoic time."

The study area also lies within the northernmost limit of the Hugoton Embayment, which is a large, broad "shelf-like" extension of the Anadarko Basin into western Kansas. Initial downwarp of the embayment is thought to have occurred in the Precambrian and is associated with inundation by Early Paleozoic seas and deposition of predominantly marine sediments. During the Late Paleozoic, periods of deposition and periods of erosion were related to transgressing and regressing of epeiric seas (Merriam, 1954).

Regional Stratigraphy of the Lansing-Kansas City Groups - The Lansing-Kansas City Groups are the upper two groups of the Missourian Stage of the Upper Pennsylvanian Series (Figure 4). Where they crop out in eastern Kansas, these groups consist of limestone, shale, and sandstone units with local coal seams. In the study area, similar units of the Lansing-Kansas City Groups are found at a depth of about 3,500 feet (910 meters).

Group	Stage	Series
Wabaunsee	Virgilian	UPPER PENNSYLVIAN
Shawnee		
Douglas		
Lansing	Missourian	
Kansas City		
Pleasanton		
Marmaton	Desmoinesian	MIDDLE PENN.
Cherokee		

Figure 4. The stratigraphic position of the Lansing-Kansas City Groups (Zeller, 1968).

South of the study area, rocks of the Lansing-Kansas City Groups generally thicken in the Hugoton Embayment toward the Anadarko Basin. The shelf limestones abruptly change to a basin facies of dark gray shales with some sandstones and dense limestones in the Anadarko Basin (Rascoe, 1962). This facies change occurs at the Missourian Shelf Margin (Figure 3).

The thickness of the combined groups ranges from 250 feet (75 meters) over the Cambridge Arch to 450 feet (125 meters) at the edge of the Missourian shelf margin (Watney, 1980). The southward rate of thickening of the Missourian rocks is approximately 4 feet per mile (1 meter per kilometer) on the shelf area and 18 feet per mile (3 meters per kilometer) in the Anadarko Basin. The difference in subsidence rates caused northward migration of the shelf margin throughout Missourian time (Rascoe, 1962). Rascoe (1962, p. 1369) also states that "Missourian time marked the apex of the marine transgression over the western Mid-Continent during Pennsylvanian time."

The Lansing-Kansas City Groups can be divided into seven units, each containing rocks deposited during a sedimentary cycle associated with eustatic rise and fall of sea level. During each cycle, four basic lithofacies were deposited (Figure 5): (1) a thin Lower Carbonate unit interpreted to have been deposited in a restricted, shallow-marine or shoreline environment which changed abruptly to a deeper subtidal environment; (2) a laterally extensive lower marine shale unit, resulting from a terrigenous influx from the north; (3) an Upper Carbonate unit, thought to be a regressive unit deposited in less turbid, shoaling water; and (4) an Upper Shale unit with locally abundant quartz siltstones, which is interpreted to be a regressive unit characterized by soil formation (Watney, 1979, and Watney and Ebanks, 1978).

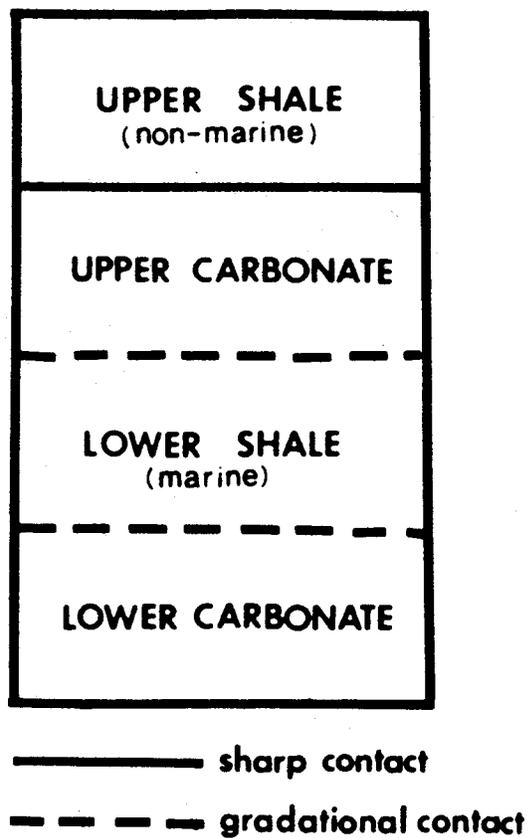


Figure 5. *The typical sequence of lithologies common to most cyclic deposits in the study area (after Watney, 1979).*

Informal Stratigraphic Classification

The Lansing-Kansas City Groups, where they crop out in eastern Kansas, are treated as separate groups and each is further divided into subgroups, formations, and members. Parkhurst (1959), using log data, correlated those formations along the outcrop into the adjacent subsurface and on into western Kansas where he attempted to apply outcrop nomenclature to their correlative subsurface equivalents. Because of the complexity of the formal classification he devised many operators in northwestern Kansas and southwestern Nebraska have chosen to use informal classification schemes for the subsurface rocks of the Lansing-Kansas City Groups (Figure 6). The writer knows of at least four such classifications, three reported by Dubois (1979) and one additional scheme employed by Cities Service Oil Company. The classification used in this study (Figure 6) is taken from Dubois (1979). This classification is modified from Kincaid, Trimble, and Larson (in J. M. Parker, ed., 1961), with the addition of a G-zone (After Dubois, 1979). This classification most closely approximates the division of the Lansing-Kansas City Groups into separate sedimentary cycles. The rocks reported on in this study are from the fourth cyclothem from the top of the Lansing-Kansas City Groups. This is the D-zone which, according to Parkhurst, is equivalent to the Chanute Shale and Drum Limestone Formations and the Quivira Shale and Westerville Limestone members of the Cherryvale Shale Formation.

D-ZONE CYCLOTHEM

Methods

Dubois (1979) pointed out that an isopachous map of the Upper Shale unit would reveal the nature of the paleo-topography prior to deposition of that unit. Taking this into account, I selected 73 gamma ray-neutron logs in a roughly even distribution throughout Hitchcock County. From these, an isopachous map of the D-zone Upper Shale unit was constructed.

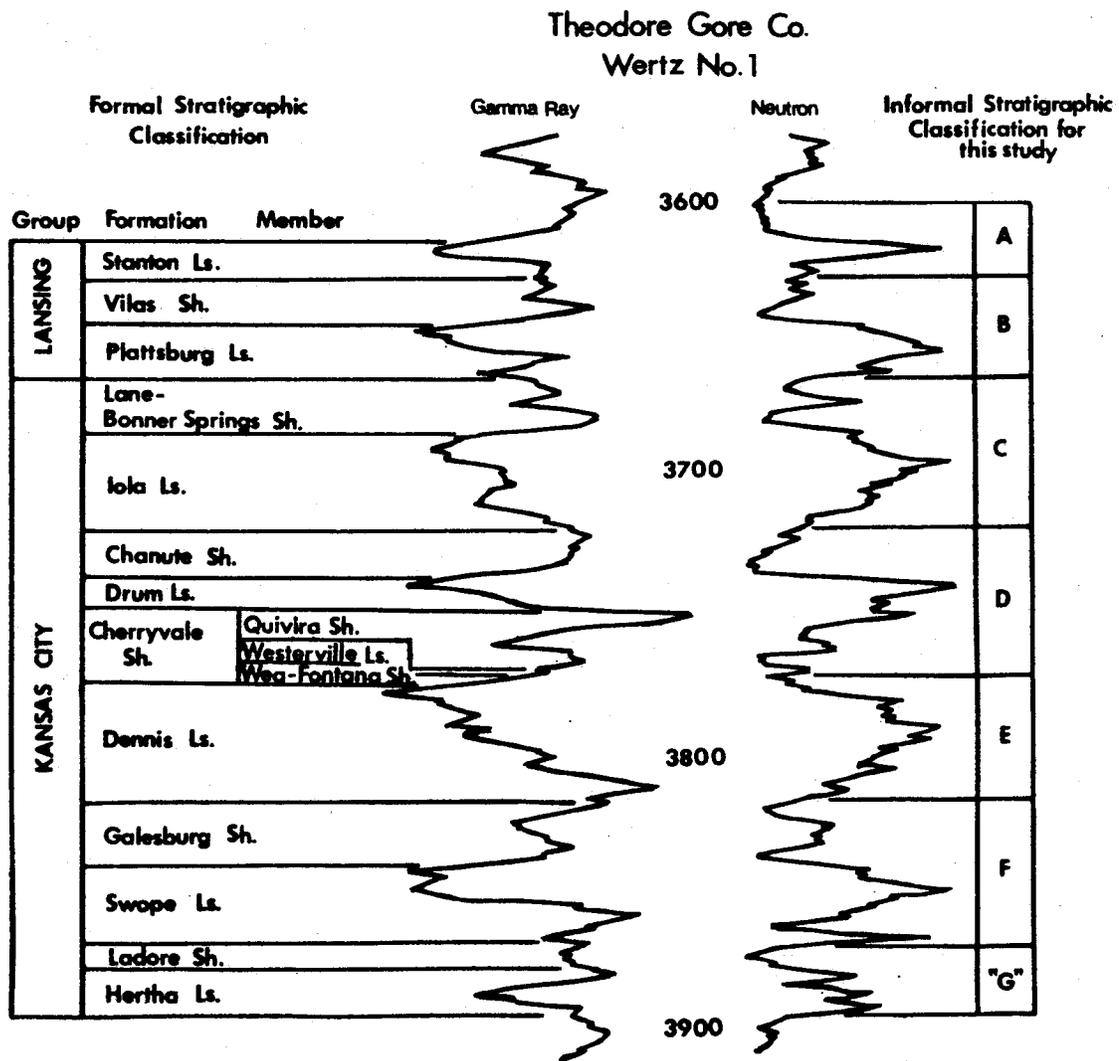


Figure 6. Stratigraphic classification schemes for the Lansing-Kansas City Groups (after Dubois, 1979).

In addition, core from twelve wells was sampled, and megascopic descriptions were made (Table 1). 250 thin sections representing 450 feet (137 meters) of core were described in detail. Data from the core descriptions and thin section descriptions were analyzed and plotted to form an east-west cross section. From this, relationships between the lateral and vertical distribution of lithofacies could be observed (Figure 7). The diagenetic features were plotted on cross sections in much the same manner.

Lithofacies

The Lower Carbonate - (Unit 1) This lithofacies is the lowest unit of the cyclothem (Figure 8). It is moderate yellowish brown at the base grading upwards to greenish gray. Its thickness ranges from one to three feet (30 to 100 centimeters). The contact with the underlying E-zone shale is sharp. The limestone textures range from mudstone and wackestone to silty packstone and grainstone. The Lower Carbonate generally is composed of two to three microfacies and locally as many as five (Figure 9).

Lowermost portion of Unit 1 locally may be peloid mudstone or phylloid algal wackestone, which is overlain by the most common lithology of the Lower Carbonate, silty peloid, algae- and foraminifer-encrusted-grain wackestone-packstone. The algae- and foraminifer-encrustations are known as Osagia (Toomey, 1969). This, in turn, grades upward into silty skeletal, peloid, Osagia oncoïd grainstone with abraded brachiopods, ostracodes, bryozoans, dasyclads, echinoderms, and fusulinids. Above this interval, fusulinid grainstone is locally present. Fusulinid fragments are also the most abundant biotic constituents through the gradational contact of the Lower Carbonate into the overlying Lower Shale.

TABLE 1

	<u>WELL NAME</u>	<u>COUNTY</u>	<u>STATE</u>	<u>LOCATION</u>	<u>CORE INTERVALS DESCRIBED</u>
1.	Theodore Gore No. 1 Blackwood Farms	Hitchcock	Nebraska	C-NW-SW, 10-3N-31W	3656-3684
2.	Theodore Gore Sitzman No. 1	Hitchcock	Nebraska	C-SW-SW, 5-3N-31W	3751-3770
3.	Theodore Gore Poore No. 1	Hitchcock	Nebraska	C-SW-SE, 7-3N-31W	3676-3700
4.	Theodore Gore No. 1 Bauerle*	Hitchcock	Nebraska	C-SW-SW, 27-3N-32W	3698-3717 3725-3733
5.	Theodore Gore Schaffert B-1	Hitchcock	Nebraska	100' W of C-SE-SE 32-3N-32W	3730-3751 3761-3766
6.	Theodore Gore Poindexter No. 1	Hitchcock	Nebraska	SW-NW, 5-2N-32W	3744-3783
7.	Theodore Gore Poindexter No. 3	Hitchcock	Nebraska	100' S of C-NE-NW 5-2N-32W	3743-3755
8.	Theodore Gore Wertz No. 4	Hitchcock	Nebraska	C-NE-NW, 6-2N-32W	3720-3740 3754-3763
9.	Theodore Gore Hidy No. 1	Hitchcock	Nebraska	C-SE-SW, 15-3N-33W	4021-4041 4045-4057
10.	Ladd Petroleum Corp. No. 2-3A Dry Creek Unit	Hitchcock	Nebraska	C-SW-SE, 21-3N-34W	4097-4147
	Theodore Gore George No. 1**	Hitchcock	Nebraska	C-NW-SW, 5-2N-32W	3656-3778

Table 1. Wells used in construction east-west cross-section AA'.

* Core described by an unknown geologist at the Nebraska Geological Survey.

** Core from this well was described, but not used in cross section.

Well numbers refer to those along line of section AA' on Figure 2.

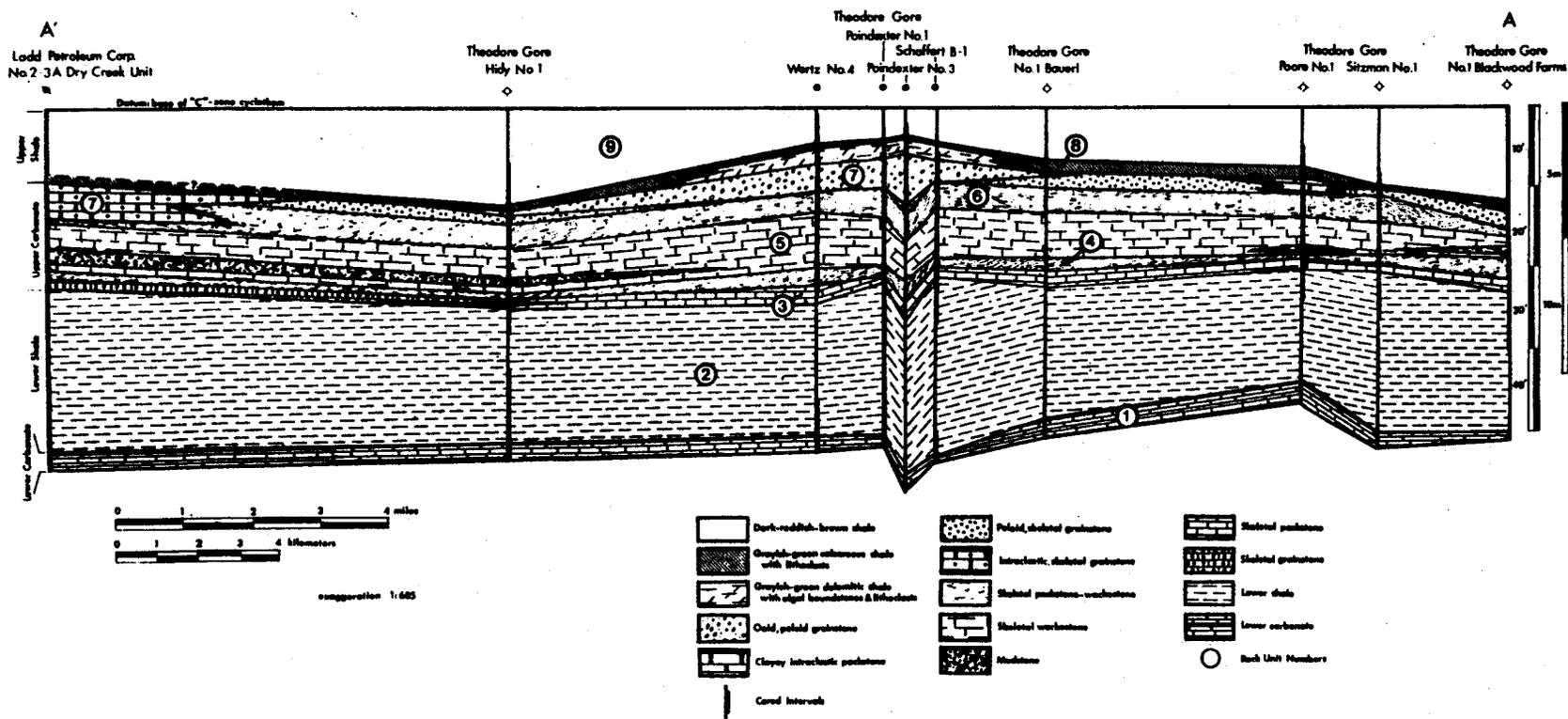


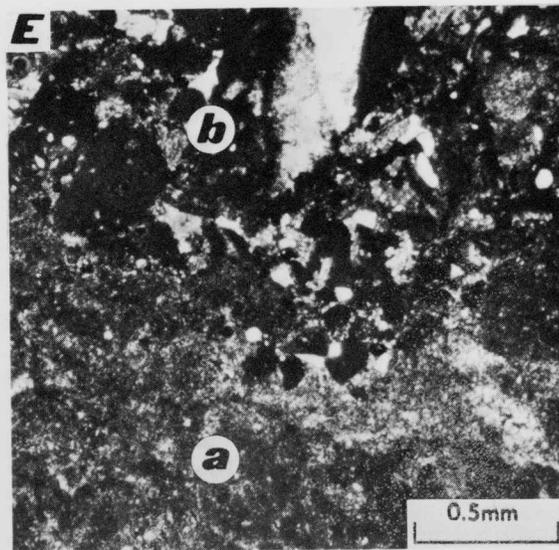
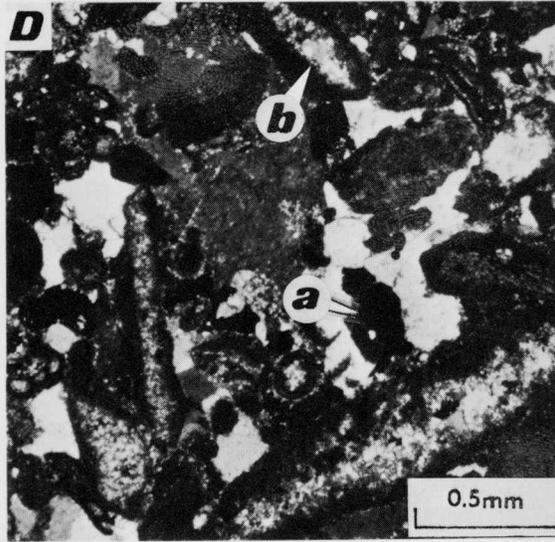
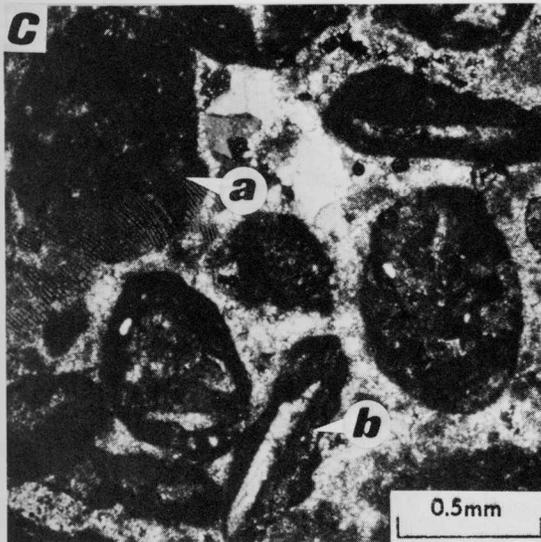
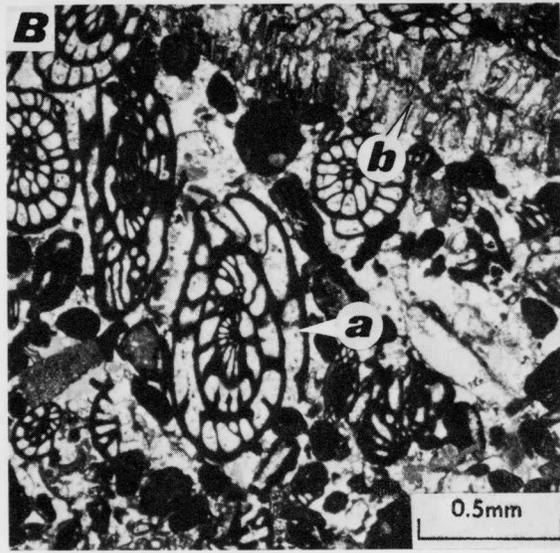
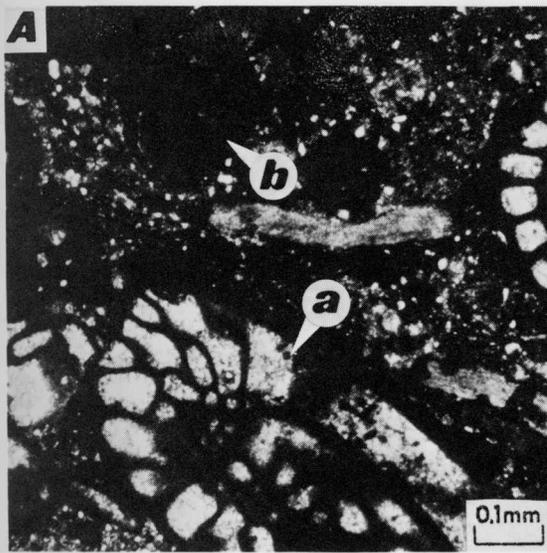
Figure 7. East-West cross section AA', showing lithologic units of the D-zone, Hitchcock County, Nebraska. Line of section shown on Figure 2.

Figure 8. *Composite stratigraphic section of the D-zone cyclothem showing the vertical distribution of fauna and other constituents and changes in the depositional environment through time.*

FIGURE 9

Examples of the five microfacies comprising the Lower Carbonate Unit.

- A. Photomicrograph of the clayey fusulinid (a), Osagia-oncoid (b), packstone. Theodore Gore Schaffert B-1, 3763.8'.
- B. Photomicrograph of a fusulinid (a), dasyclad (b), grainstone. Ladd Petroleum Hidy No. 1, 4055.6'.
- C. Photomicrograph of a silty peloid (a), Osagia-oncoid (b), packstone-grainstone. Ladd Petroleum Hidy No. 1, 4056.3'.
- D. Photomicrograph of a peloid (a), skeletal, Osagia-oncoid (b), wackestone-packstone. Theodore Gore Schaffert B-1, 3764.4'.
- E. Photomicrograph of the sharp contact between the phylloid algal-bearing, peloid wackestone (a), and the overlying silty skeletal, Osagia-oncoid wackestone-packstone (b). Theodore Gore Schaffert B-1, 3764.4'.



Terrigenous constituents in the Lower Carbonate are dominantly clay, quartz silt, and locally small amounts of quartz sand. In addition, there are trace amounts of fresh, silt-sized plagioclase. Quartz sand is found only in the lowest portions of Unit 1 and where present, it grades upwards to silt-sized quartz and silty-clay at the upper gradational contact.

Grains are well rounded because most are Osagia-coated and abraded skeletal fragments. Most framework grains range in size from coarse silt to coarse sand. Sorting in Unit 1 is best in the middle portion, and it decreases both toward the top and bottom of the unit.

No biogenic or nonbiogenetic sedimentary structures were observed in this unit. However, wavy-laminae of green clay are present in the silty and sandy Lower Carbonate of the Theodore Gore Hidy No. 1 core.

The Lower Carbonate is typically well cemented. Locally, porosity is completely occluded by two generations of calcite cement: (1) a locally developed fine-crystalline bladed to equant discontinuous calcite crust, followed by (2) an occlusive, very coarse-crystalline blocky mosaic calcspar. These cements are followed by a stage of vug-filling gypsum cement which postdates both generations of calcite cement. Echinoderm and Composita sp. brachiopod fragments take on large syntaxial calcite overgrowths during the first stage of cementation.

Porosity is rarely preserved in this unit, but where vuggy, moldic, and interparticle porosity is preserved, it is present because the second generation of cement is absent. At these locations, porosity can be as high as 20 percent.

The Lower Shale - (Unit 2) This unit is greenish gray at its base and grades upward through dark reddish brown with grayish-green mottling in the middle into grayish green at the top. Its thickness

FIGURE 10

Slabbed core of the Lower Shale near the Upper Carbonate contact. Note mottling (a) and carbonate interbeds (b). Theodore Gore No. 1 Blackwood Farms, 3677.7' to 3679.8'.



ranges from six feet (1.8 meters) in southern regions of the study area to 22 feet (6.6 meters) in the north. The contact with the underlying Lower Carbonate is gradational. This unit is dominantly shale, but, locally it may be mottled with more calcareous shale and intercalated with silty and clayey wackestone and packstone (Figure 10).

The lowest four to six feet (1.2 to 1.8 meters) of this unit is greenish-gray fissile sparsely fossiliferous shale, which grades upward into nonfissile dark reddish-brown shale. Middle and upper portions of the dark reddish-brown shale are locally mottled with irregular lenses of grayish-green calcareous shale. These mottled zones become progressively more calcareous upward, eventually becoming silty and clayey skeletal wackestone and packstone interbeds that intercalate with the uppermost Lower Shale. The number of these carbonate interbeds increases upward in the section and represents a transitional contact with the overlying Upper Carbonate.

The interbeds found nearest the overlying Upper Carbonate contain an assemblage of skeletal fragments more similar to the Upper Carbonate than to the grayish-green calcareous lenses below. Within approximately six inches to one foot (30 to 60 centimeters) of the Upper Carbonate contact, the intercalated dark reddish-brown shale grades into a grayish-green, highly calcareous shale. This interval locally has dark reddish-brown clay- and silt-filled cracks.

The Lower Shale is composed of calcareous clay with approximately 30 percent fine-to medium-grained quartz silt. In the calcareous interbeds, the non-skeletal carbonate is composed of microspar and limpid dolomite rhombs. Brachiopod, ostracode, bryozoan, and echinoderm fragments are the skeletal constituents. The skeletal grains are not as abraded as

those in the Lower or Upper Carbonate, and whole brachiopods are locally encountered.

Two generations of cement, (1) early bladed calcite crust and (2) occlusive blocky mosaic calcspar, fill all available early vuggy porosity and intraparticle porosity found within the bryozoan fragments distributed along bedding planes throughout the Lower Shale.

The Upper Carbonate - This lithologically highly variable rock unit ranges in thickness from 20 feet (6 meters) in the central portions of the study area to 7 feet (2 meters) in the north. It is divided into a less complex "Lower Interval" and a more complex "Upper Interval" (Figure 7) (after Watney, 1980).

Lower Interval

The lower part of the Upper Carbonate (Units 3, 4, 5, and 6) (Figure 8) is the carbonate mud-rich subfacies of that lithofacies. The contact with the Lower Shale is transitional. This transitional contact usually occurs over a one- to two-foot (15 to 30 centimeters) interval.

From the top of Unit 2 upward, the sequence of lithologies is light bluish-gray skeletal packstone, which grades laterally from the eastern portion of the study area to a skeletal grainstone in the west (Unit 3). These rocks are overlain in ascending order by light bluish-gray nodular packstone-wackestone with wavy laminae of green clay (Unit 4), very dusky-red skeletal wackestone and mudstone mottled with very light-gray calcareous burrows (Unit 5), and light bluish-gray nodular packstone-wackestone with wavy laminae of green clay (Unit 6) (Figures 11 and 12). All of these units have gradational boundaries.

The Lower Interval contains abraded brachiopod, echinoderm, ostracode, bryozoan, and mollusk fragments. In the packstone and grainstone of Unit 3, fusulinids are abundant. Peloid-grainstone intraclasts

FIGURE 11

Slabbed Cores

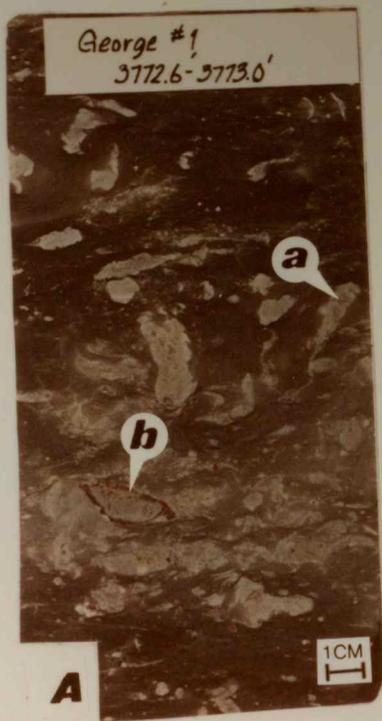
- A. Intraclastic grainstone. This unit contains a large number of intraclasts (a) in the ostracode, ooid, echinoderm grainstone matrix (b). Note the root casts (c) in some of the intraclasts. Ladd Petroleum Dry Creek Unit 2-3A, 4109.5' to 4111.0'.
- B. The light bluish-gray packstone (a) with the overlying nodular packstone-wackestone with wavy laminae of green clay (b). Theodore Gore Poindexter No. 1, 3759.2' to 3760.2'.



FIGURE 12

Slabbed Cores. Examples of rock types in the Lower Interval.

- A. Mudstone microfacies of Unit 5. Note the light colored burrows (a) and (b) the red chalcedony-replaced whole brachiopod shell. Theodore Gore George No. 1, 3772.6' to 3773.0'.
- B. Wackestone microfacies of Unit 5. Note (a) the large number of red chalcedony-replaced grains and the extensive in situ breccia and dark reddish-brown clay-filled cracks (b). Theodore Gore Schaffert B-1, 3745.8' to 3746.5'.
- C. Wackestone-packestone microfacies (a) and red clay-infilled cracks (b) of Unit 6. Theodore Gore Sitzman, 3757.0' to 3757.9'.



similar to the peloid-grainstone microfacies of the Upper Interval are in Unit 5 of the Theodore Gore George No. 1 core (Figure 13D).

Terrigenous clay and silt comprise 15 to 30 percent of the mudstone and wackestone and 10 to 15 percent of the packstone-wackestone. Unit 3 has virtually no terrigenous constituents.

The carbonate matrix in the mudstone, wackestone, and packstone is composed of microspar with scattered limpid dolomite rhombs. Red length-slow chalcedony and amorphous red chert replace some echinoderm and brachiopod fragments. Cracks containing finely laminated dark reddish-brown clay and quartz silt occur throughout Units 4, 5, and 6, but are most abundant in Unit 5 (Figures 12C and B). These cracks commonly contain euhedral gypsum crystals. Whole fossils are rarely encountered in the Lower Interval.

Two generations of cement are present in the Lower Interval:

- (1) a fine- to medium-crystalline, bladed to equant, calcite crust, and
- (2) a coarse-crystalline, occlusive, blocky mosaic calcspar. Some voids in the uppermost portions of Unit 6 are occluded by an early rhombic dolomite crust. Many echinoderm and brachiopod fragments have large syntaxial overgrowths of the first generation of calcite cement (Figure 14A).

The Lower Interval is generally nonporous. However, small amounts of intercrystalline, intraparticle, and moldic porosity do exist predominantly in the grainstones and packstones of Unit 3.

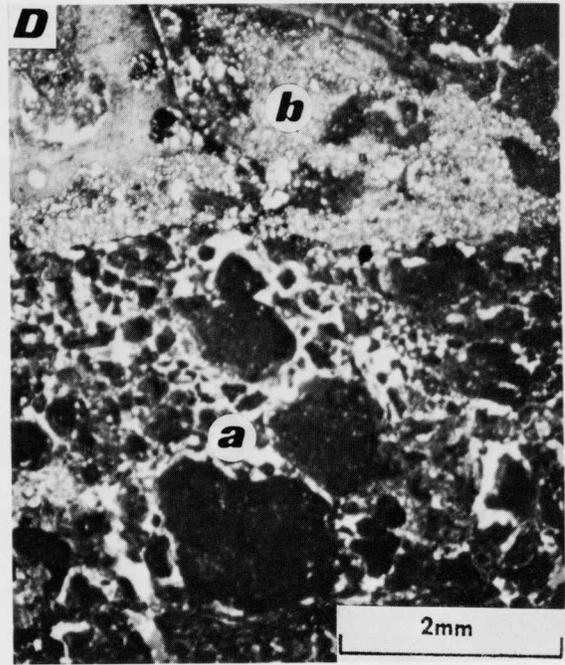
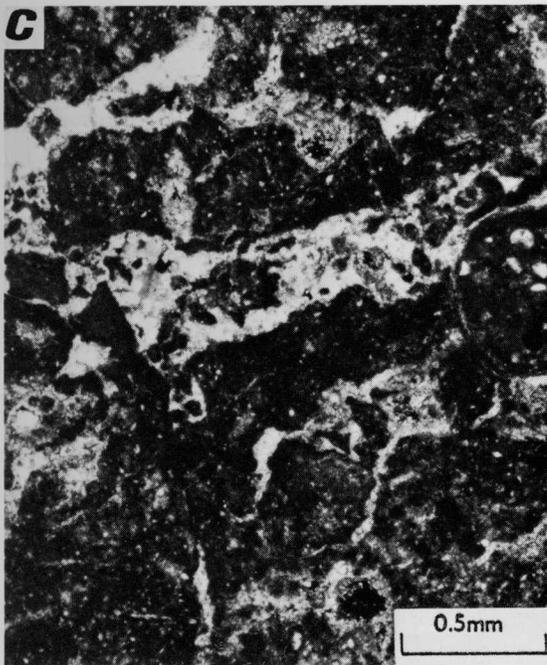
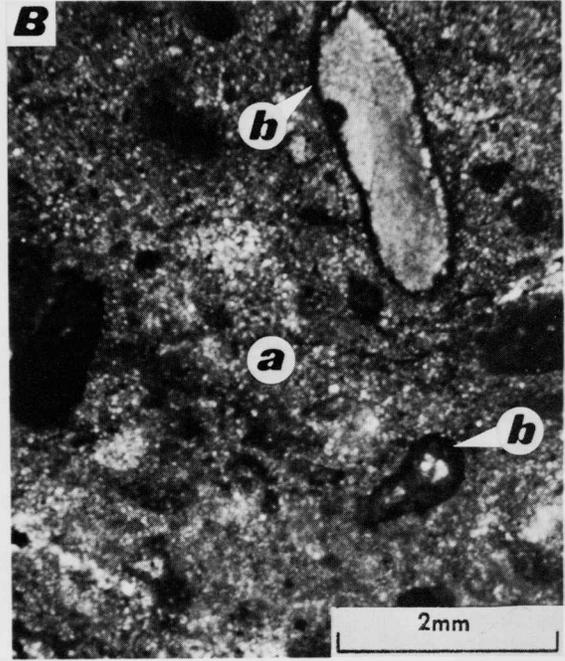
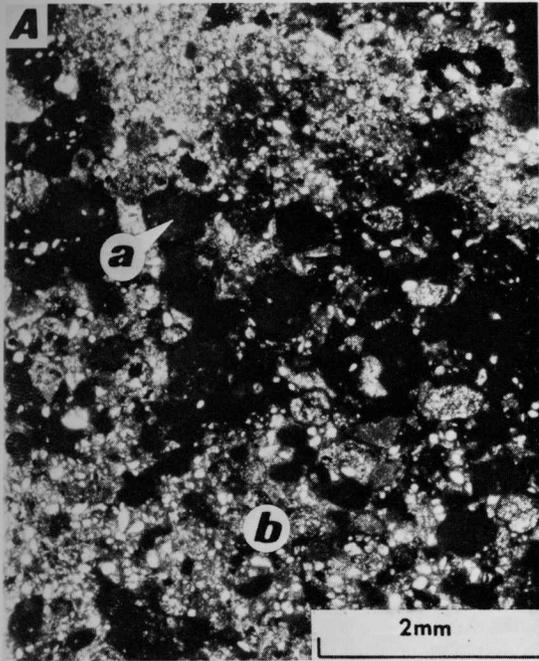
Upper Interval

The Upper Interval (Unit 7) (Figure 8) is light colored, where it is not saturated with oil. The lithologic and diagenetic characteristics vary widely both laterally and vertically, making this the most complex unit in the cyclothem. The limestone textures include grainstone, packstone, intraclastic grainstone, clayey intraclastic packstone, and

FIGURE 13

Examples of various rock types in the D-zone cyclothem.

- A. Photomicrograph of mud clasts (a) and microspar with fine-grained sand (b) in the Upper Shale. Theodore Gore Poindexter No. 3, 3643.5'.
- B. Photomicrograph of the dolomitic shale matrix (a) in Unit 8. Note hematite coatings (b) on some of the bioclasts. Theodore Gore Wertz No. 4, 3725.7'.
- C. Photomicrograph of the caliche horizon in Unit 8. Theodore Gore Wertz No. 4, 3724.1'.
- D. Photomicrograph of the peloid grainstone intraclasts (a) found in Unit 5. Note this intraclast is surrounded by a silty wackestone-packstone matrix (b). Theodore Gore George No. 1, 3769.4'.



fenestral algal-laminated boundstone (Figures 15A and B). Thickness of this unit ranges from one foot to six feet (30 to 180 centimeters).

Framework grains are usually well-rounded and locally are well-sorted. Skeletal grain types present in the Upper Interval are dominated by ostracode and echinoderm fragments with minor amounts of brachiopod, bryozoan, echinoderm, encrusting foram, and mollusk fragments. Many of these grains have Osagia coatings. Micrite rinds presumably formed by boring algae and fungi (Bathurst, 1966; Wilson, 1975, p. 69) coat most other grains. Typically, most of the skeletal grains are abraded and fairly well rounded.

The nonskeletal constituents are dominated by peloids, locally abundant ooids, and intraclasts. The peloids are usually completely micritized and altered to microspar. They are ubiquitous throughout the Upper Interval. The ooids are most abundant in the cores from the Meeker Canal and Republican River oil fields. The calcite coats form around pellets and fine-grained skeletal debris. Fenestral algal-laminated boundstone cap Unit 7 in the core from Theodore Gore No. 3 Poindexter, Meeker Canal Field.

The intraclastic deposits are present in the eastern and western portions of the study area on the flanks of the Dry Creek and Meeker Canal oil field (Figure 7). Intraclasts found in the western deposit are skeletal wackestone and packstone, some with root traces (Figures 11A and 16). These intraclasts are deposited with ostracode-echinoderm grainstone. The eastern intraclastic deposit has intraclasts of skeletal packstone and wackestone surrounded by a matrix of green silty shale (Figure 17B).

FIGURE 14

Examples of calcite and dolomite in the D-zone.

- A. Photomicrograph of syntaxial overgrowths formed around echinoderm fragments (a) in Unit 7. Theodore Gore Poindexter No. 1, 3647.1'.
- B. Photomicrograph of a broken trilobite fragment. Note that the poorly developed or corroded first stage of calcite cement (a) is broken and followed by the later stage coarse-crystalline calcspar cement (b). Theodore Gore Poindexter No. 1, 3748.3'.
- C. Photomicrograph of dolomite crust cement (a) lining pores in grainstone from Unit 7. The pore is occluded by a coarse-crystalline calcspar cement (b). Ladd Petroleum Dry Creek Unit 2-3A.
- D. Photomicrograph of dolomite/calcite cement stratigraphy from Unit 6. Note that dolomite cements in pores within a bryzoan fragment both precede (a) and follow (b) stages of calcite cementation. This thin section was treated with Alizarin Red S stain; as a result, the calcite takes a red stain which appears dark gray, as compared to the dolomite, which does not take the stain.
- E. Photomicrograph of subhedral tightly packed dolomite rhombs and clay matrix (a) in dolomitic shale microfacies. Note hematite coating (b) around the echinoderm fragment. Theodore Gore Poindexter No. 3, 3746.8'.
- F. Photomicrograph of limpid dolomite rhombs (a) in mudstone from Unit 5. Theodore Gore Poindexter No. 3, 3777.2'.

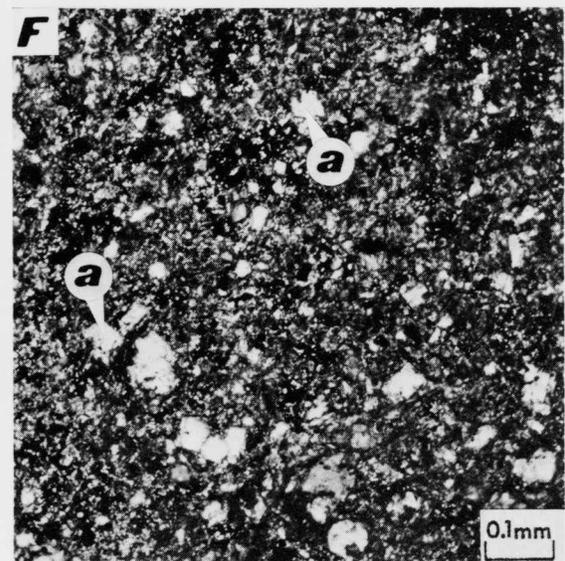
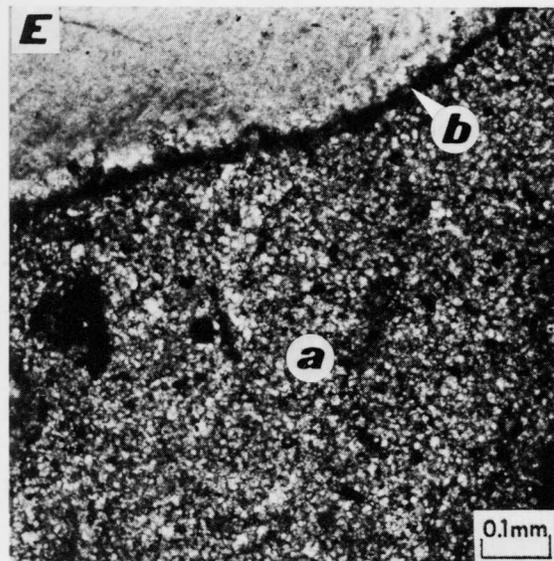
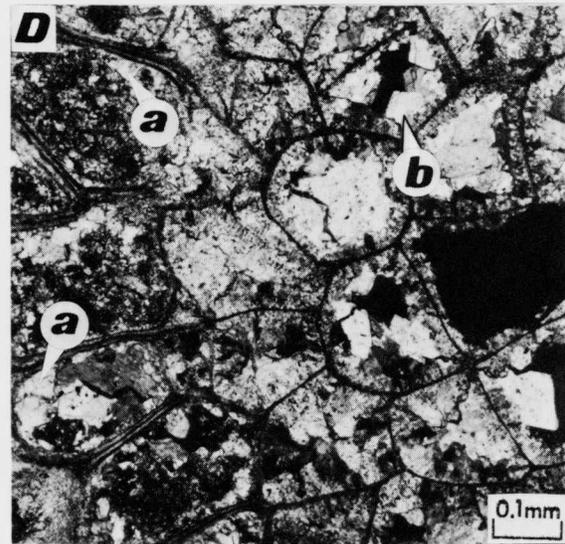
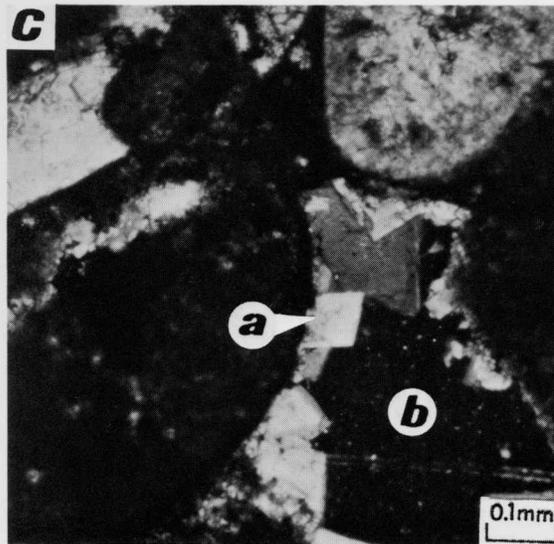
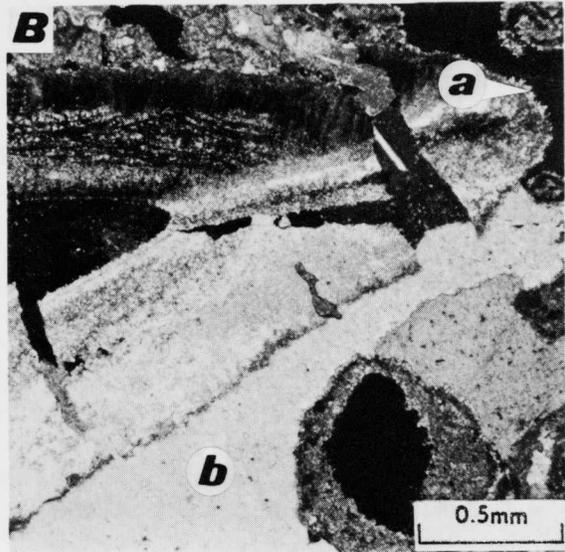
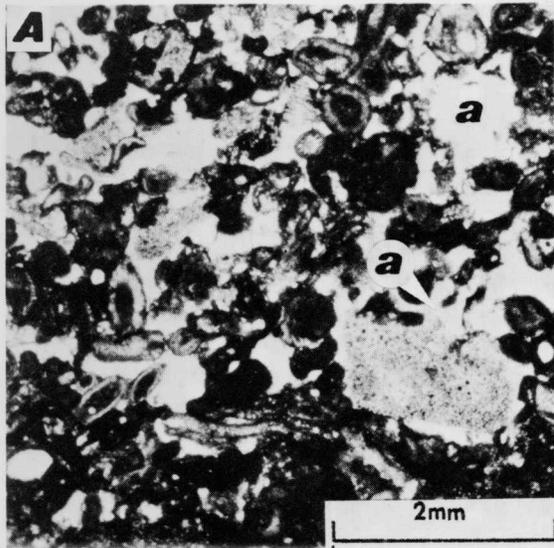


FIGURE 15

Slabbed Cores. Examples of rock types from the Upper Interval of the Upper Carbonate and Unit 8 of the Upper Shale.

- A. Gradational contact between the grainstones (a) of the Upper Interval and the underlying packstone-wackestone (b). Theodore Gore Sitzman No. 1, 3755.2' to 3755.8'.
- B. Peloid, ooid grainstone. Note the lighter colored burrows (a). Theodore Gore George No. 1, 3766' to 3767'.
- C. Algal-laminated, fenestral, boundstone intraclasts (a) and mats (b) in a dolomitic shale matrix (c). Theodore Gore Poindexter No. 3, 3746.6' to 3747.1'.

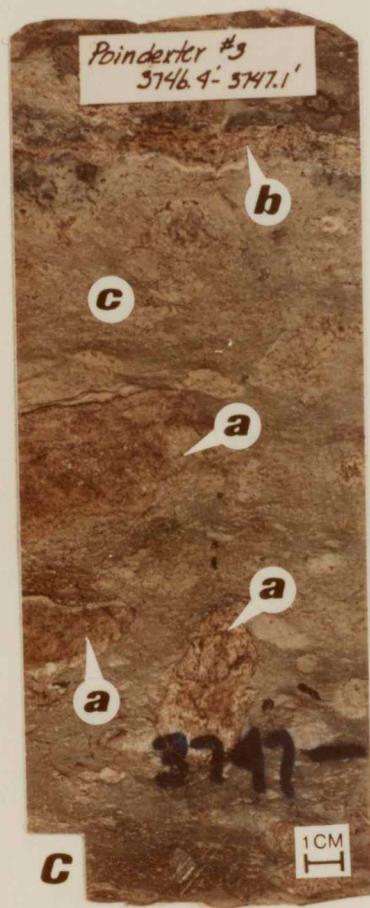


FIGURE 16

Examples of the lithoclasts that occur in Unit 8.

- A. Photomicrograph of a root cast surrounded by micrite sheath (a) in sparsely fossiliferous lithoclast. Theodore Gore No. 1 Blackwood Farms, 3668.2'.
- B. Photomicrograph of dolomitized peloid (a) packstone lithoclast. Note the fine-grained texture and circumgranular cracks (b). This dolomite resembles dolomites formed in supratidal environments (Illing, et al, 1965) and was probably reworked into the Upper Shale from an updip direction where rocks of that kind were being deposited during higher stands of sea level. Note gypsum filling vugs (c). Theodore Gore No. 1 Blackwood Farms, 3667.1'.
- C. Photomicrograph of a skeletal grainstone lithoclast (a) note the dolomitic green shale matrix (b). Theodore Gore Wertz No. 4, 3725.7'.
- D. Photomicrograph of nonfossiliferous calcite microsparite lithoclast. Theodore Gore Sitzman, 3753.5'.

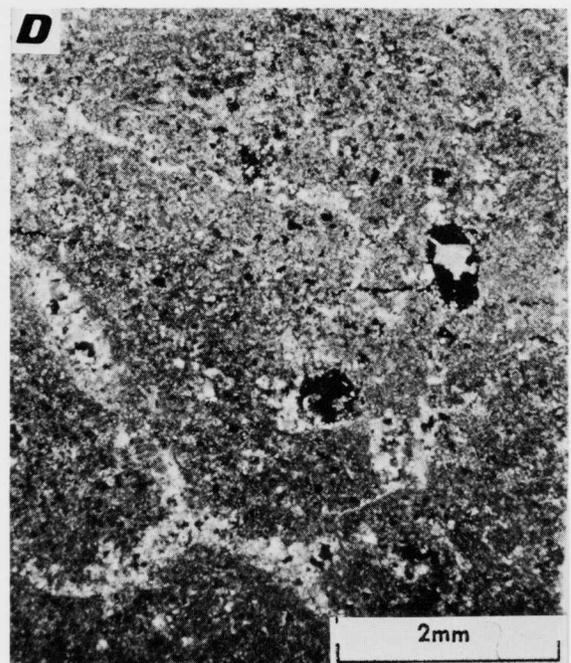
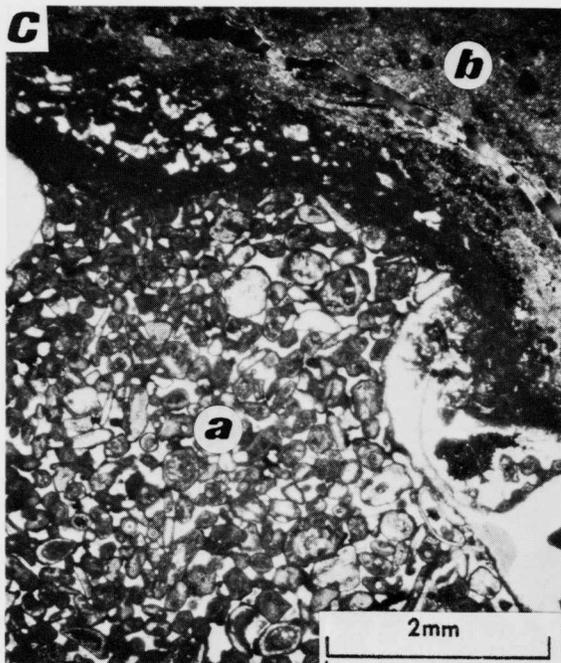
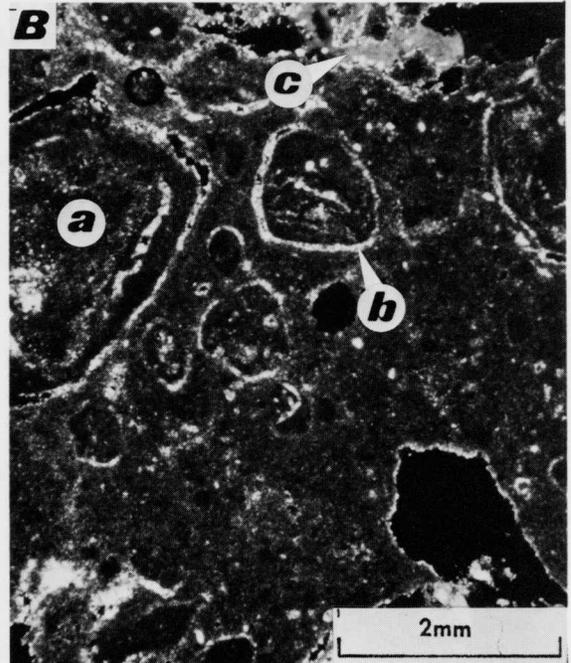
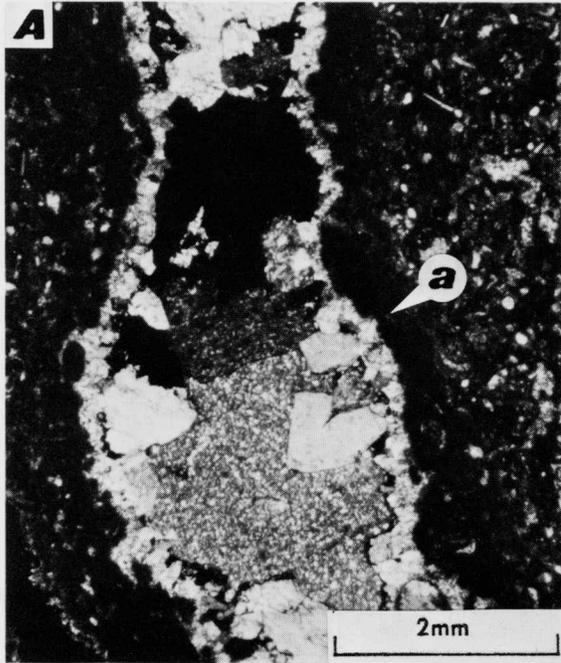


FIGURE 17

Slabbed Cores. Examples of the Upper Interval of the Upper Carbonate and Unit 8 of the Upper Shale. Theodore Gore Poore No. 7, 3726' to 3730'.

- A. Upper Shale Unit 8. Red color is result of alteration of green shale by flow of oxidizing waters. Note the rounded lithoclasts (a).
- B. Clayey intraclastic packstone (a) overlain by the Upper Shale which contains lithoclasts (b) surrounded by remnant green shale (c) Unit 8.
- C. Nodular packstone-wackestone with wavy green clay laminae and oxidized areas (a) (red-brown).



The major terrigenous constituent is quartz silt with trace amounts of plagioclase silt. The silt accounts for no more than ten percent of the rock.

This unit has a complex assemblage of cement and porosity types. The cements are: (1) early equant to bladed calcite crusts which are locally corroded, (2) rhombic dolomite crusts which are locally contemporaneous with the calcite crust cement (see section on Diagenetic History), (3) pore-occluding coarse-crystalline blocky mosaic calcspar, and (4) late coarse-crystalline, vug-filling gypsum, which postdates both calcite and dolomite cements.

The porosity types are equally diverse. Porosity types are predominantly interparticle and vuggy with minor amounts of intraparticle, moldic, and intercrystalline porosity. Locally, the Upper Interval is completely cemented, but where porosity is present it is as high as 25 percent. In most cases, there are no sedimentary structures in Unit 7. In only a few cores, burrows are present and in only the Theodore Gore Poindexter No. 3 are there thin cross-stratified carbonate sands.

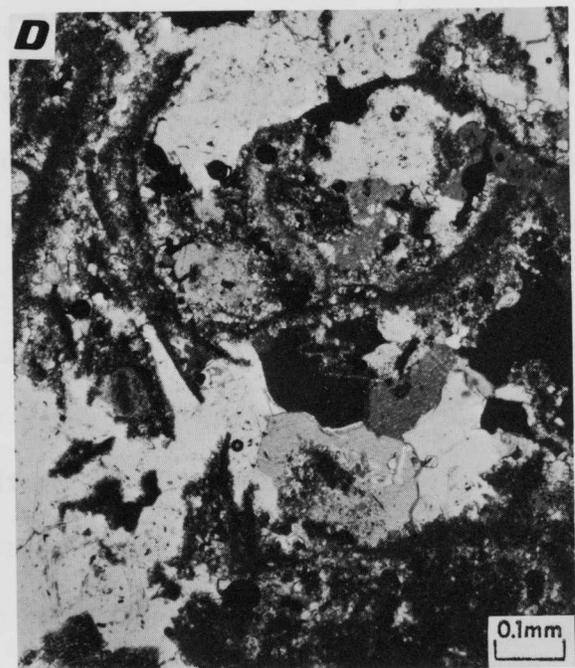
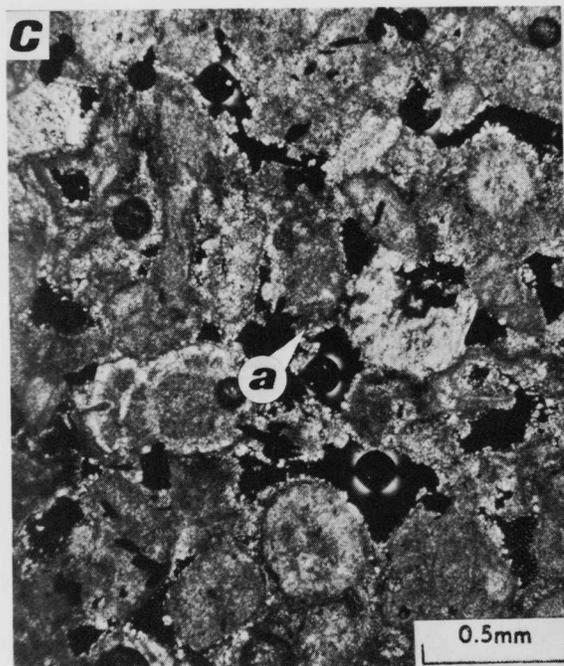
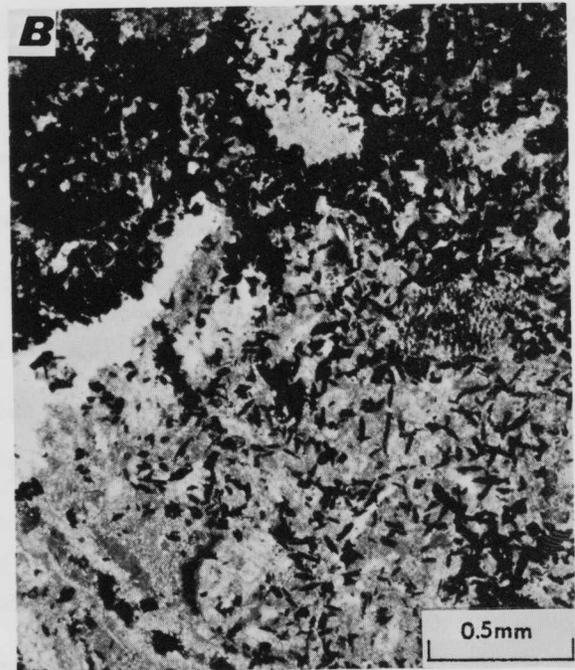
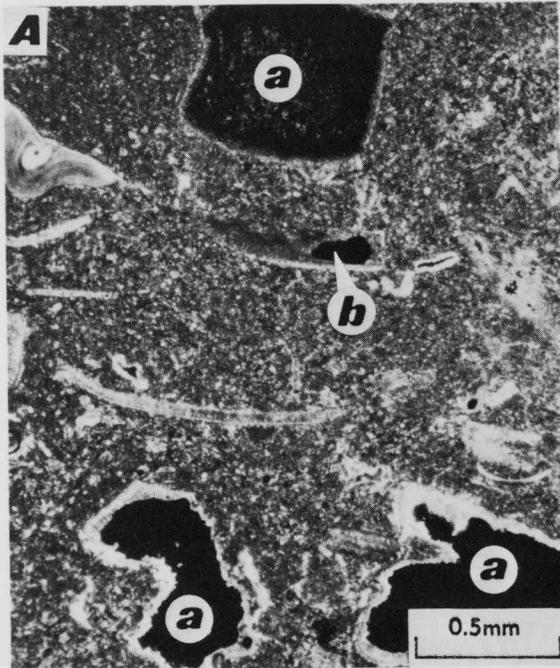
Brachiopod and echinoderm skeletal fragments commonly take on large syntaxial overgrowths and are locally replaced by red length-slow chalcedony and red amorphous chert (Figure 18A). The silica-replaced grains are encountered throughout Unit 7, but in cores from the Meeker Canal and Republican River oil fields, they are restricted to the lowermost portions of the Upper Interval. Disseminated pyrite and pyritized skeletal fragments occur locally throughout the Upper Interval (Figure 18B).

The Upper Shale - (Units 8 and 9) This lithofacies is grayish green at the base, dark reddish-brown mottled with grayish-green patches in the middle, and grayish green at the top. Its thickness ranges from

FIGURE 18

Examples of some diagenetic features.

- A. Photomicrograph of echinoderm (a) and brachiopod (b) fragments replaced by amorphous red chert and red length-slow chalcedony. Because the red hematite stain is so dark, the fibrous habit of the chalcedony is not readily visible. Ladd Petroleum Hidy No. 1, 4034.3'.
- B. Photomicrograph of disseminated pyrite in a grainstone of Unit 7. Theodore Gore Poindexter No. 3, 3746.8'.
- C. Photomicrograph of a portion of Unit 7 displaying enlarged pores created by leaching of an earlier formed phreatic calcite cement (a). Theodore Gore Poindexter No. 3, 3749.8'.
- D. Photomicrograph of pseudospar formed by porphyroid neomorphism of carbonate mud in a carbonate interbed of the Lower Shale. Theodore Gore Shaffert B-1, 3745.2'.



6 to 15 feet (1.8 to 4.5 meters). The variation in thickness reflects predepositional topography (Figure 19). The unit is predominantly silty-shale but locally contains well-rounded, presumably reworked, limestone lithoclasts and fenestral algal-laminated boundstone mats and intraclasts (Figures 17A and 20B).

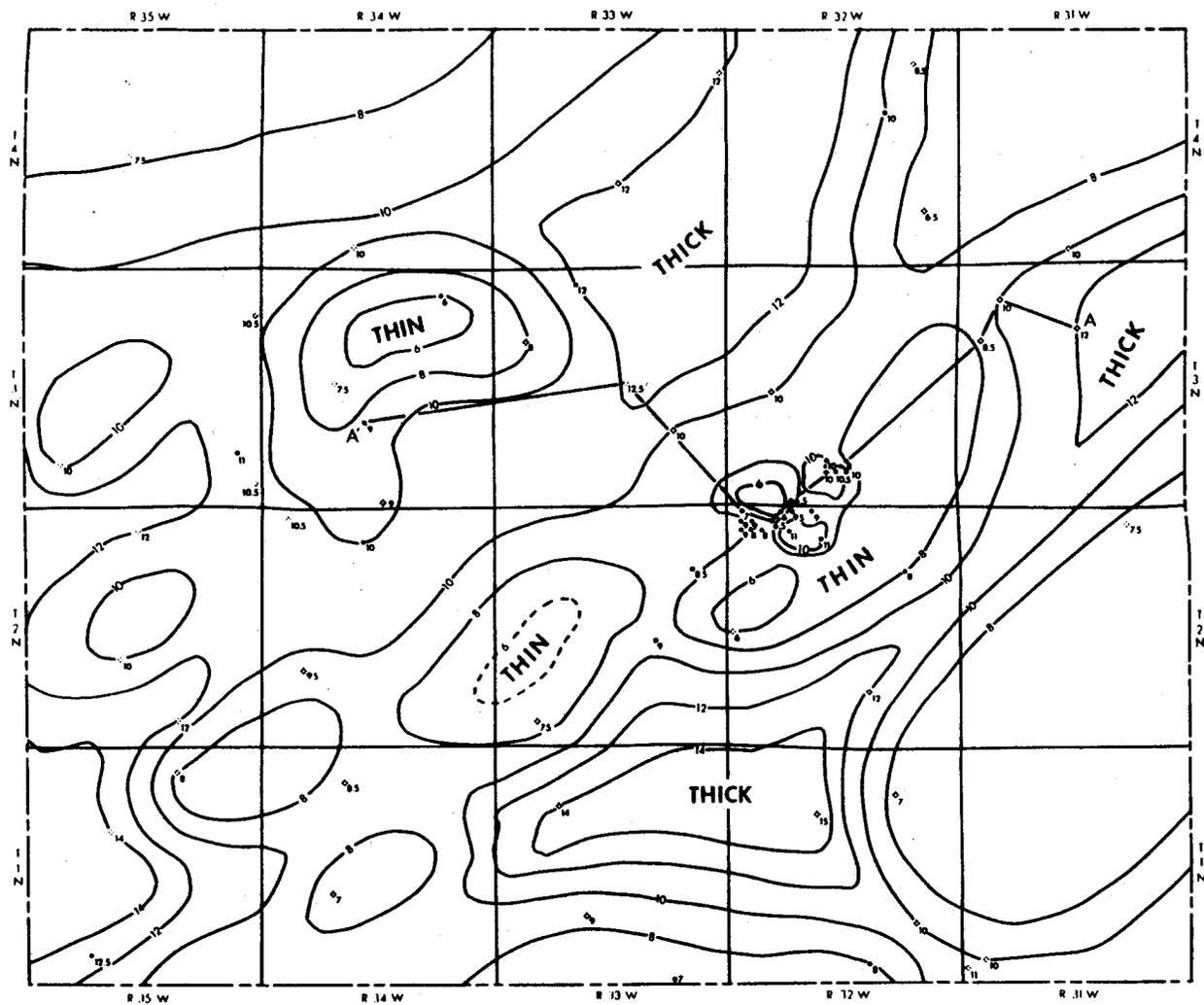
The lower three to four feet (90 to 120 centimeters) of the Upper Shale (Unit 8) is a grayish-green dolomitic to calcareous shale that locally contains well-rounded limestone lithoclasts ranging from one to six inches (2 to 15 centimeters) across. The lithologies of the clasts (Figure 16) range from skeletal grainstone and packstone to sparsely fossiliferous and nonfossiliferous, locally dolomitized, microsparite and micrite (caliche).

The grainstone and packstone lithoclasts are composed of rounded, well-sorted and locally micritized ostracode, echinoderm, bryozoan, mollusk, and brachiopod skeletal fragments. Many are coated with Osagia, others are surrounded with micrite rinds. Peloids and ooids comprise the nonbiotic constituents. Pellets and fine-grained skeletal material serve as nuclei for the ooids. Roots casts with micrite sheaths are encountered in several of the lithoclasts.

The skeletal grainstone and packstone lithoclasts are nonporous and are well cemented with (1) early equant discontinuous pore-lining rhombic dolomite crust, (2) equant discontinuous pore-lining calcite crust, and (3) occlusive rhombic dolospar.

The sparsely fossiliferous to nonfossiliferous lithoclasts are very light gray to moderate olive gray and are not oil-stained. They are composed of microcrystalline to cryptocrystalline calcite or dolomite. In thin section, the lithoclasts appear vaguely clotty with abundant

Figure 19. *D-zone Upper Shale thins correspond to local shoal areas where ooid grainstone of the Upper Carbonate was deposited. Compare this map to the Upper Shale isopachous map of the E-zone Figure 13.*



HITCHCOCK COUNTY, NEBRASKA

ISOPACHOUS MAP
D-ZONE UPPER
SHALES

contour interval: 2'

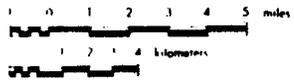


FIGURE 20

Slabbed core from Theodore Gore Wertz No. 4, 3720' to 3726'. Unit 8.

- A. Example of clayey caliche horizon (a) overlain by grayish-green shale (b). Note calcareous caliche nodules (c).
- B. Example of lithoclasts (a) encased in the dolomitic shale (b) of Unit 8. Note laminated nature of dolomitic shale (c).



circumgranular cracks filled with dolospar, calcspar, and microspar. Locally, these lithoclasts contain root casts. Cement types include (1) early equant pore-lining dolomite crust, (2) a blocky mosaic calcspar, and (3) a late coarse-crystalline gypsum.

The fenestral algal-laminated boundstone intraclasts and mats in the Poindexter No. 3 core are composed of echinoderm, bryozoan, mollusk, brachiopod, and encrusting-foram skeletal fragments with peloids and ooids in an algal-laminated fenestral-fabric matrix. The boundstones are cemented with an early isopachous calcite crust followed by a blocky mosaic calcspar (Figure 21C).

The calcareous grayish-green shale matrix surrounding the lithoclasts is composed of dominantly echinoderm, ostracode, and mollusk fragments, many with Osagia coatings. The nonbiotic constituents are peloids and intraclasts. Pyrite is disseminated locally throughout Unit 8. Hematite coats surround many grains. Lower portions of Unit 8 are locally intensely dolomitized (Figure 13B).

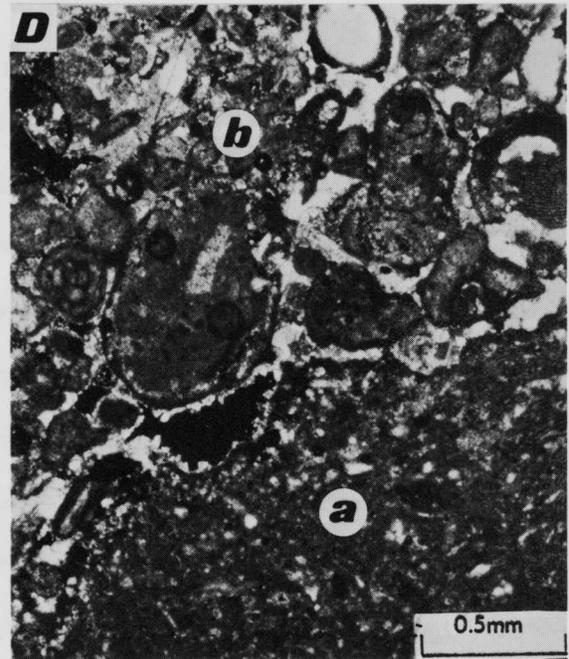
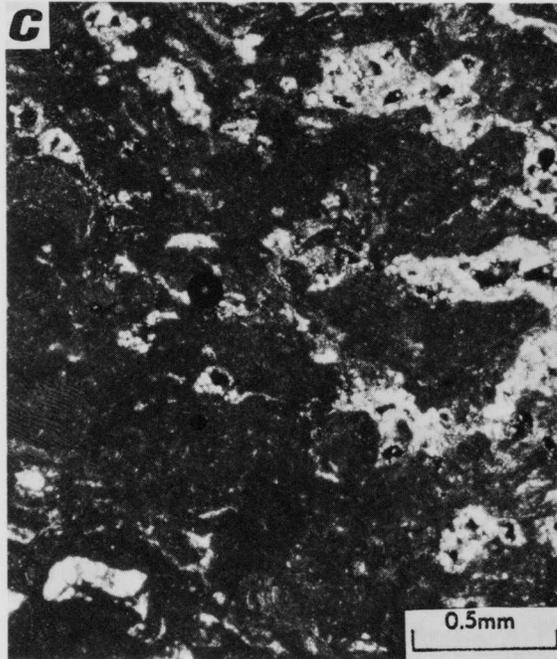
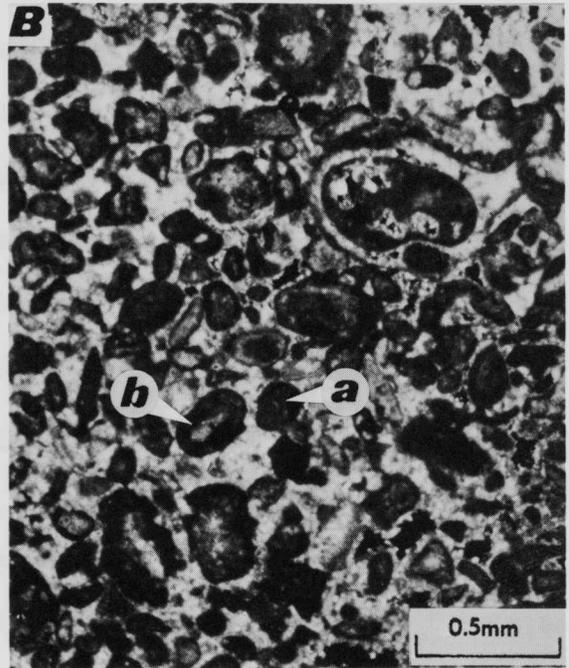
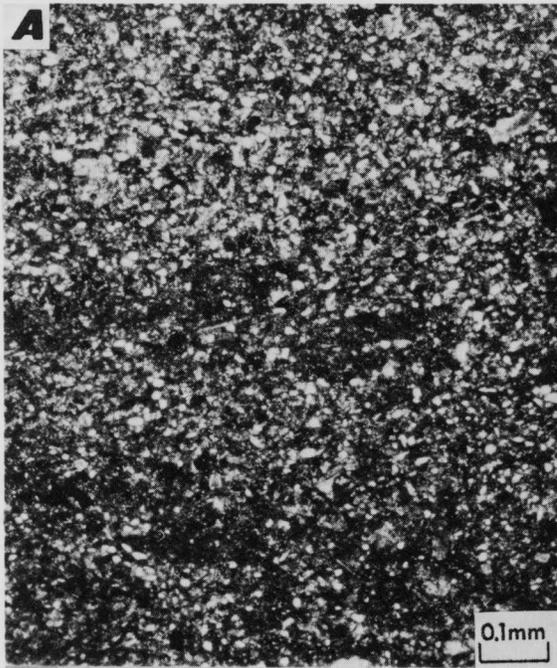
Within upper portions of Unit 8 in the cores from the Meeker Canal and Republican River oil fields, there are locally distributed nodules of cryptocrystalline dolomite in a matrix of calcareous green shale (Figure 13C). Cracks within the nodules are lined with isopachous dolomite crust, followed by a coarse-crystalline rhombic dolomite crust and an occlusive calcspar.

The dark reddish-brown shale (Unit 9) overlies and is in gradational contact with the grayish-green calcareous shale. This unit is essentially a redbed composed of dominantly clay and hematite-coated quartz silt. It locally contains small mud clasts, microspar, and is mottled with grayish-green clay (Figure 13A). Authigenic gypsum, possible

FIGURE 21

Examples of some rock types of the D-zone cyclothem.

- A. Photomicrograph of the mudstone microfacies. Theodore Gore George No. 1, 3773.3'.
- B. Photomicrograph of the peloid (a), ooid (b) grainstone microfacies. Theodore Gore Poindexter No. 3.
- C. Photomicrograph of a fenestral algal-laminated boundstone intra-clast from Unit 8. Theodore Gore Poindexter No. 3, 3646.8'.
- D. Photomicrograph of the intraclasts (a) in the ostracode, peloid (b) grainstone. Ladd Petroleum Dry Creek Unit 2-3A, 4109.5'.



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root casts, and micrite nodules are present in the upper portions of Unit 9 in the Ladd Petroleum, Dry Creek Unit 2-3A and the Theodore Gore No. 1 Blackwood Farms cores. Other than these, Unit 9 seems devoid of any additional biogenic or nonbiogenic sedimentary structures. Throughout Unit 9 occur solution and/or desiccation cracks similar in shape and distribution to those found in the Upper Carbonate.

The dark reddish-brown shale grades vertically into a nonfossiliferous grayish-green shale just below the C-zone Lower Carbonate. This subfacies is six to eight inches (15 to 20 centimeters) thick.

Log Response

Typically, three types of logs are run simultaneously by most operators in the study area: (1) gamma ray, (2) neutron-density, and (3) guard (resistivity). This combination of logs gives good resolution of carbonate and shale beds and is moderately successful in hydrocarbon evaluation (Watney, 1979).

The typical log response produced by rocks of the D-zone cyclothem is illustrated in Figure 22. The four major lithofacies are discernible, while subfacies of the limestones and shales are less obvious.

Picking the base of the cyclothem can be difficult. In the example (illustrated in Figure 22) case, three zones below 4,050 feet have log character similar to that of Lower Carbonate units. The actual Lower Carbonate (Unit 1) as determined by core descriptions of the D-zone is indicated. The next lower "kick" represents a siltstone lens in the Upper Shale of the E-zone. The source of the second lower "kick" is unknown. It seems, therefore, that without core control over this interval, distinguishing the Lower Carbonate from other lithologic units can be difficult. Farther southward in the basin, the Lower Carbonate unit for

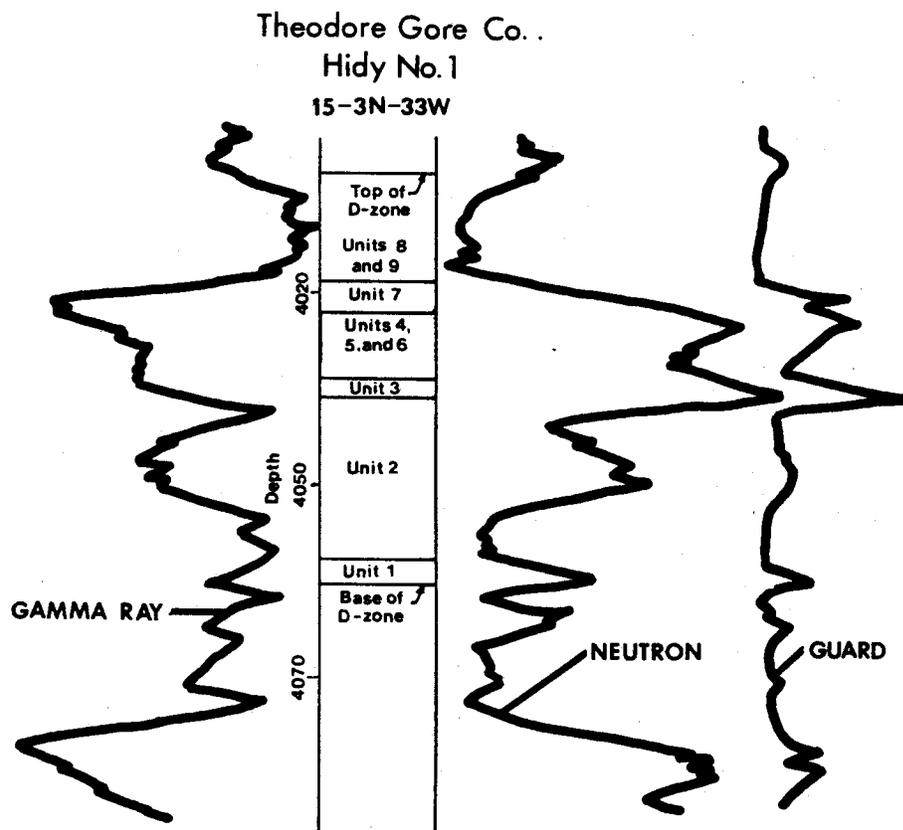


Figure 22. Typical gamma ray/neutron/guard log trace of the D-zone cyclothem showing the correlation of lithofacies with log character (refer to Figure 7).

most wells is easily recognizable as having large deflections on the gamma ray and neutron logs; however, in this study area, they are subdued because of the abundance of terrigenous material incorporated in the carbonate.

Unit 2 is represented by a more intense gamma ray/neutron response just above the Lower Carbonate; this corresponds to the grayish-green fissile shale. This is followed by a less intense response corresponding to the overlying reddish-brown shale. Another intense gamma ray/neutron response marks the top of Unit 2; this corresponds to the calcareous green shale just below the Upper Carbonate.

The base of the Upper Carbonate is easily recognizable because Unit 3 produces such a prominent "kick" on the neutron and guard logs. Thickness of that unit as measured in cores corresponds well with the thickness indicated by the logs.

The top of the Upper Carbonate is not always easily distinguished from the Upper Shale by just gamma ray/neutron/guard log character. A caliper log (not shown in example) can aid in this pick and can help resolve the top within a few feet. Watney (1979) pointed out that in landward, clastic-dominated areas of the Hugoton Embayment, log character contrasts generally become diminished as a result of freshwater diagenesis and in situ brecciation accompanied by clay infiltration within carbonate units. The thickness of Unit 7 as measured in cores corresponds fairly well with the thickness indicated by the corresponding gamma ray trace. Subfacies of the Upper Carbonate, other than Units 3 and 7, cannot be distinguished. However, these rocks can be grouped into a carbonate mud-rich subunit facies (Units 4, 5, and 6) represented by a slightly more intense neutron and guard response between the base of Unit 7 and the top of Unit 3.

The Upper Shale generally corresponds well with the thickness represented by the distance between top of the D-zone cyclothem (base of C-zone cyclothem) and the top of the Upper Carbonate. Resolution of Unit 8 within the Upper Shale is generally not possible. The Upper Shale is commonly characterized by "wash-out" as indicated by the caliper log.

Locally, the base of the C-zone is difficult to distinguish. Presumably, this is because of local variations of terrigenous content in the C-zone Lower Carbonate, similar to that observed in the D-zone. Lower Carbonate units in the Lansing-Kansas City Groups are known to vary with respect to the amount of incorporated terrigenous material (Watney, 1979 and 1980).

Depositional History of the D-zone Cyclothem

The general basis for interpretations about the depositional history of the D-zone is the theory of epeiric clear-water sedimentation (Irwin, 1965). This theory pertains to processes that produce sediments in epeiric, shallow-marine waters that experience no influx of terrigenous material. The theory deals with shallow-marine sedimentation that occurs in nonoceanic, shoaling epeiric seas with low-angle depositional slopes, very wide shelf areas, and sufficiently shallow water so as to restrict or eliminate circulation over large areas. Under these conditions, lateral variations in organic activity, hydraulic energy, dissolved chemicals, temperature, depth, and water clarity can produce several contemporaneous but dissimilar sedimentary environments (Figure 23).

Irwin defines three marine-hydraulic energy zones which are in effect environments of deposition that are thought to have occurred in ancient epeiric seas: (1) a hundreds-of-miles-wide, low-energy zone prevailing in the open ocean below wave base where marine currents are

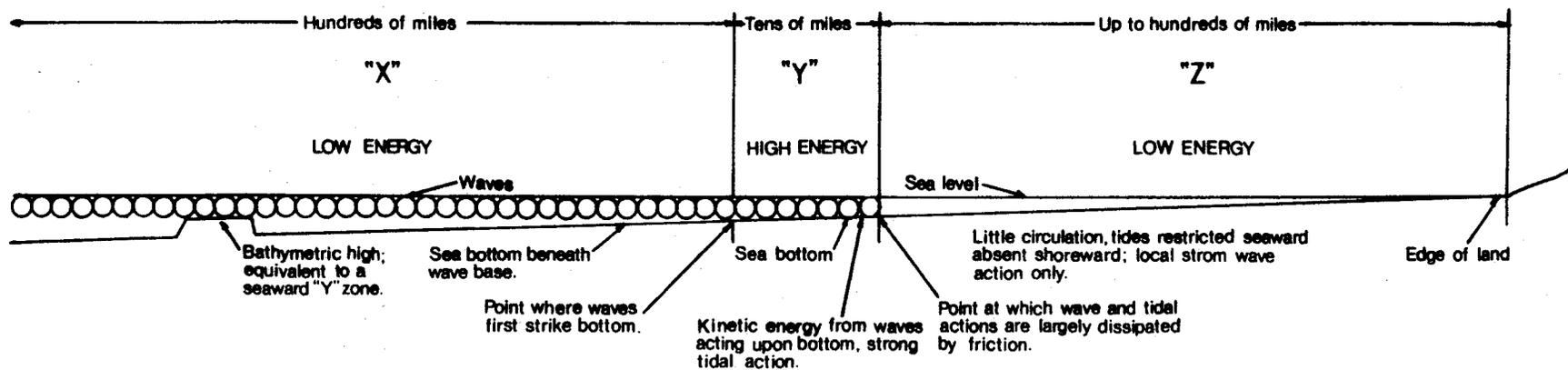


Figure 23. Idealized depositional environments in an epeiric sea (from Irwin, 1965).

the only form of hydraulic energy sorting and transporting sediments on the bottom (Zone X); (2) an intermediate high-energy belt, tens-of-miles wide, beginning where waves first impinge on the sea floor and expend their kinetic energy upon the bottom sediment (Zone Y); and (3) shallow, low-energy zone, tens- to hundreds-of-miles wide, occurring landward of Zone Y in which little water circulation occurs and where the only wave action is that produced by local storms (Zone Z).

In addition, within Zone X, the sea floor can be elevated above wave base by structural movements. In effect, this produces a localized "Y" Zone in a more seaward position.

During marine transgression, each zone of sedimentation migrates in a landward direction overlapping more landward, older sediments. In this manner, sediments in ascending order reflect deposition in environments becoming progressively less restricted. During regression, each zone of sedimentation migrates seaward producing a vertical sequence reflecting sedimentation in progressively more restricted environments.

The following is the inferred sequence of deposition that occurred during each of the transgressive and regressive rhythms in the D-zone cyclothem in Hitchcock County.

The Lower Transgressive Rhythm - Deposition of the Lower Carbonate (Unit 1) and the fissile greenish-gray shale (lower Unit 2) occurred during initial transgression of the epeiric sea over the Upper Shale in the E-zone. Early environments of deposition were locally developed, low-energy, and restricted, as indicated by the deposition of phylloid-algal wackestone. Some phylloid algae are considered to be comparable to Holocene calcareous green algae, which are typical of "shallow-marine water" (Wray, 1964). Deposited with the phylloid algae are peloid mudstones.

As transgression continued, the environment of deposition changed, becoming more widespread, less restricted, and slightly higher in energy. This brought on deposition of a microfacies composed of silty, peloid, Osagia-oncoid packstone-wackestone with diverse faunal assemblages. Osagia oncolites may be analogous to modern blue-green algal oncolites (Crowley, 1969) and, therefore, may indicate shallow-marine water with moderate circulation over an open shelf area (Wilson, 1975).

The water depth gradually increased, eventually reaching a depth where wave energy, previously dampened by the shallowness of the water in the restricted environments, effectively sorted sediment on the sea floor. This resulted in the deposition of laterally extensive, skeletal, peloid, Osagia-oncoid grainstone and local fusulinid grainstone. Fusulinids, considered typical of open-shelf environments (Moore, 1929 and 1952; and Thompson, 1948), occur in this microfacies.

The terrigenous influx that was ultimately responsible for the deposition of the Lower Shale (Unit 2) began to dominate the environment as upper portions of the Lower Carbonate were deposited. As the clay and silt influx increased, shelled invertebrates became progressively less abundant, in some places absent. This may have resulted either from the onset of reducing conditions associated with poorer circulation as the wave base rises or from the "smothering" effect of the terrigenous influx. Locally, however, fusulinids are abundant in lower parts of this interval.

The fissile greenish-gray shale in the lower portion of the Lower Shale is indicative of deposition during maximum transgression of sea level. This subfacies is characterized by a sparse faunal assemblage consisting of ostracodes, brachiopods, and echinoderms (Figure 8). It

interfingers with a black phosphatic-shale facies farther out in the basin (Heckel, 1980). According to Heckel (1977), black shales in "Kansas-type" cyclothems record deposition in deep water below a thermocline, under which a quasi-estuarine circulation cell caused oxygen depletion and phosphate enrichment to take place (Figure 24). Heckel also believes that the typical gray shale facies in the Lansing-Kansas City Groups grades laterally into a black shale facies and records a time of low-oxygen conditions around the periphery of a deep anoxic water mass.

The vertical distribution of these lithologic units indicates that deposition during the transgressive rhythm initially occurred in shallow, low-energy restricted environments, similar to Irwin's Zone Z, followed by units deposited in environments becoming progressively less restricted and higher in energy (similar to Irwin's Zone Y) until water depths increased to a point where extreme restriction prevailed (Zone X). The occurrence of local fusulinid grainstone in the uppermost portions of the Lower Carbonate indicates transgression had continued to a point where local open-shelf, high-energy conditions prevailed. These deposits may correspond to the basinward edge of Irwin's Y Zone and possibly localized bathymetric highs similar to Irwin's localized "Y" Zone. The occurrence of fusulinids in the silty and clayey packstone of the Lower Carbonate indicates deposition in a terrigenous sediment-bearing equivalent to Irwin's Zone X.

The vertical distribution of lithofacies and the fact that all of the changes in microfacies occur in a relatively thin rock unit suggests deposition of the Lower Carbonate and the fissile greenish-gray shale took place during a rapid transgression of an epeiric sea, accompanied in later stages by a terrigenous influx. This interpretation is consistent

with those made of similar rock sequences in cyclothems throughout the Mid-Continent (e.g., Elias, 1962; Laporte and Imbre, 1964; Laporte, 1969; Watney, 1979; Heckel et al, 1979; and Heckel, 1980).

The Lower Regressive Rhythm - The fissile greenish-gray shale (lowest Unit 2) graded upward into the overlying dark reddish-brown shale as the lower regressive rhythm of the cycle began. With regression, the water stratification that was necessary for deposition of the black shale was destroyed in the landward shelf regions, resulting in reoxygenation of the marine waters over most of the Mid-Continent (Heckel, 1980). Continued regression brought with it an increase in the influx of iron-rich terrigenous material, resulting in deposition of the dark reddish-brown shale. The rate of sediment accumulation and burial must have been high in order to preserve the red color of the clay and silt during deposition in an environment that must have been, at least, mildly reducing (Grim, 1951). Heckel (1980) states that red soils typically began to form during regressive phases, in most Lansing-Kansas City sedimentary cycles. These soils formed on exposed tidal flats in the north, which were deposited during earlier high sea level stands, and which were the source for the terrigenous material in the Lower Shale.

The green mottling found throughout the Lower Shale is usually associated with silty and clayey carbonate interbeds. This relationship may indicate periodic waning of the terrigenous influx, allowing both water clarity to improve, resulting in deposition of carbonate, and reduction of the iron oxides in the clay. The relatively high abundance of fenestrate bryozoa in some of these zones may indicate considerable water clarity (Moore, 1952) in a subtidal environment (Elias, 1937).

The presence of fossils that are typical of open-marine waters and textures that are typical of fairly high-energy environments in the carbonate interbeds suggests that regression during the deposition of the Lower Shale may have continued to a point where, during periods of little terrigenous input, carbonates typical of an environment just below wave base (Zone X) were being deposited. The terrigenous deposits limit the applicability of Irwin's model in determining the extent of the regression in the lower regressive rhythm.

Deposition of the Lower Shale (Unit 2) took place as the terrigenous influx continued during further regression of sea level. The Lower Shale thickens and coarsens to the north as do most of the Lower Shale units of the Lansing-Kansas City Groups in the study area (Watney, 1980). This suggests a persistent northern source of terrigenous material throughout the time of Lansing-Kansas City deposition.

The Upper Transgressive Rhythm - The vertical distribution of lithofacies in the lower half of the Lower Interval (Units 3, 4, and 5) (Figure 8) indicates that a transgression of sea level occurred during initial deposition of the Upper Carbonate. It is difficult to determine when the onset of transgression in this rhythm began and to ascertain the maximum extent of the lower regressive rhythm because the environment was dominated by terrigenous deposition. However, the fact that deposition of the Upper Carbonate began with a packstone-grainstone (Unit 3) suggests that the water was already sufficiently shallow that sediment was sorted by wave action.

With the end to the terrigenous influx, deposition of the Upper Carbonate began. In Unit 3 (lowest unit in the Upper Carbonate), packstone is confined to eastern Hitchcock County, while grainstone occurs

in the west (cross-section AA', Figure 7). The distribution of grainstone in Unit 3 may have been controlled by formation of bathymetric highs related to movement on the ancestral Las Animas Arch or differential compaction of the Upper Shale in the underlying E-zone around former topographic highs (Figure 24).

Shinn et al (1976) surmised that so-called "structural relief" at the margins of some ancient shelves may result from lack of compaction in shelf-margin carbonate sands and reefs and compaction of fine-grained lagoonal sediments. Analogously, this type of differential compaction could have taken place as a result of lithostatic pressure exerted on E-zone Upper Shale by deposition of the D-zone Lower Carbonate and Lower Shale units. As a result, a bathymetric high may have been formed, bringing the sea floor above wave base and creating one of Irwin's localized "Y" Zones in the vicinity of the Theodore Gore Hidy No. 1 and Ladd Petroleum 2-3A Dry Creek Unit wells.

Unit 3 is overlain by a laterally extensive low-energy skeletal packstone-wackestone microfacies (Unit 4). The faunal assemblage in Unit 4 is essentially the same as in Unit 3, except that fusulinids are more abundant and the ostracodes are less abundant. Whether this indicates an environment less restricted than that represented by Unit 3 is equivocal. However, the limestone textures of Unit 4 indicate that deposition took place near or just below wave base, implying a sea level rise took place prior to deposition of Unit 4 or as deposition of Unit 4 began.

These two units are overlain by the wackestone in Unit 5. In eastern and western portions of the study area, this microfacies is intercalated with carbonate mudstone (Figure 7). The mudstone contains fossils

indicative of an open-marine environment and, therefore, represent deposition in the "deepest-shelf" where low-energy mudstones can accumulate in an unrestricted quiet-water environment.

The sequence of deposition in the transgressive rhythm represents migration of environments similar to Irwin's X Zone, represented by mudstone of Unit 5, over environments similar to Irwin's Y Zone, represented by grainstone of Unit 3. Unit 4 in this case would have been deposited during the transition from one zone to the next.

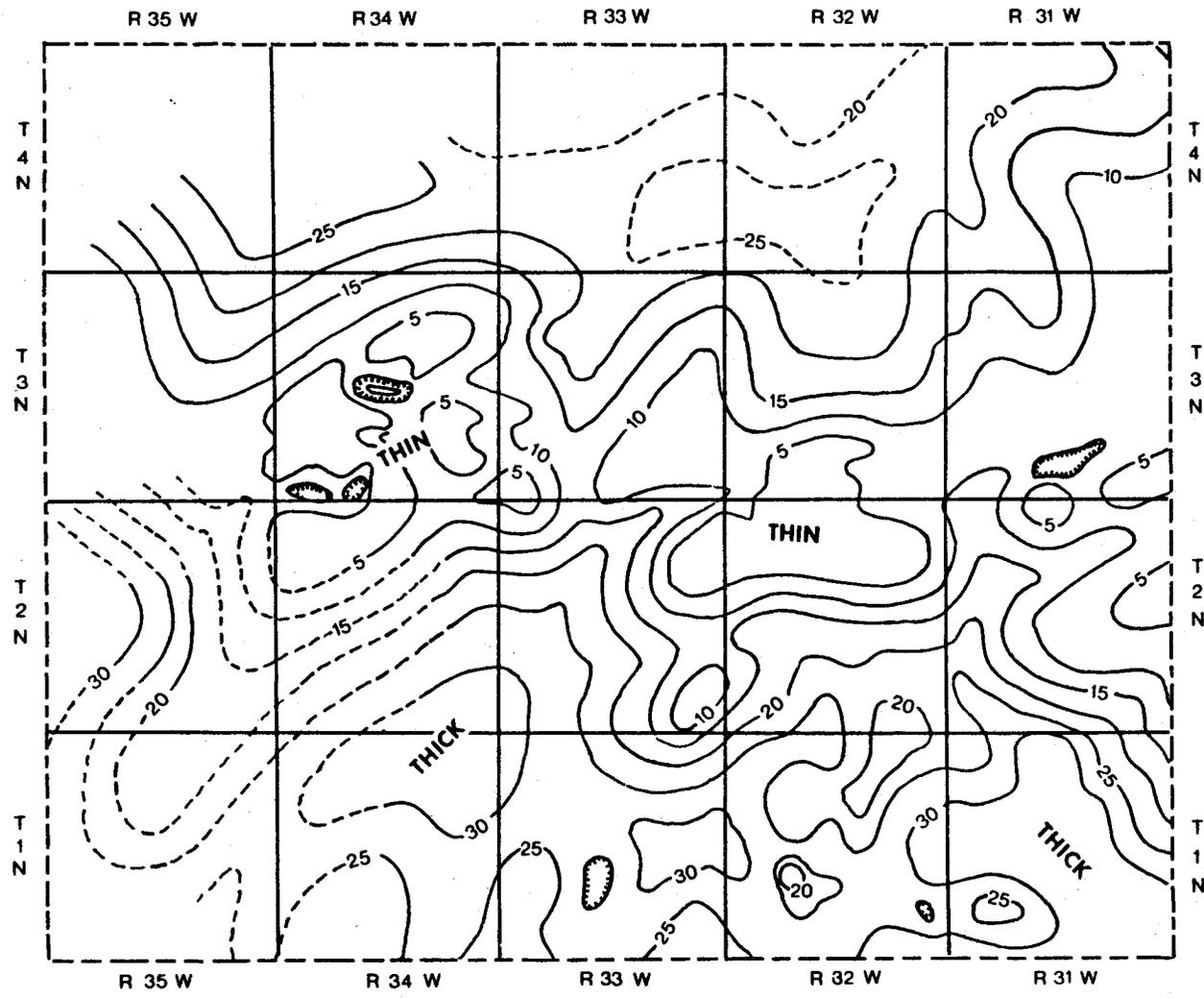
The Upper Regressive Rhythm - The final regression of the epeiric sea during the D-zone cycle lead to the deposition of Units 5, 6, and 7 of the Upper Carbonate and Units 8 and 9 of the Upper Shale.

Following the carbonate mudstone deposition, which marked the maximum transgression of the upper rhythm, regression began. As the waters shoaled, extensive wackestone (Unit 5) was deposited.

Unit 5 is overlain by the laterally extensive skeletal packstone-wackestone microfacies (Unit 6) which represents an environment slightly higher in energy than that represented by Unit 5. Little change in faunal constituents occurred during the transition from an environment well below wave base to an environment nearer wave base, only a change in the proportion of lime mud.

Intraclastic, skeletal grainstone of Unit 7 interfinger with Unit 6 in western Hitchcock County. They indicate the onset of carbonate deposition in shoal areas in the vicinity of the Dry Creek oil field (Figure 2). The grainstone overlies local grainstone deposits in Unit 3 and a former topographic high in the underlying E-zone (Figure 25). The relationship of repeated local grainstone deposition in this shoal area over a former topographic high indicates the continued influence topographic highs in the E-zone had on microfacies distribution in the D-zone cyclothem.

Figure 25. *Thin areas in the isopachous map reflect topographic highs exposed during sea level regression late in the E-zone cycle. Compaction of the Upper Shale around these features may have had an influence on microfacies distribution in the overlying D-zone (from Dubois, 1979). Compare with Figure 9.*



HITCHCOCK COUNTY, NEBRASKA

ISOPACHOUS MAP
 E-ZONE UPPER
 SHALE
 contour interval 5'

These bathymetric highs, revealed as "thins" on an isopachous map of the D-zone Upper Shale (Figure 19), are located directly over paleo-highs in the E-zone and in northeast-southwest linear trends. The linear trends parallel the trend of the ancestral Las Animas Arch and are, therefore, thought to have formed during an episode of structural movement of that feature. Deposition of grainstone, similar to that which occurred in shoal areas related to E-zone compaction, may also have occurred on bathymetric highs along these trends.

The presence of root traces in some intraclasts taken from the Ladd Petroleum 2-3A Dry Creek Unit core indicates that the Dry Creek shoal may have been an island, subjected to erosion by wave action and shedding debris to its flanks. The intraclastic-skeletal-grainstone microfacies would then represent a shallow water, high-energy environment located on the southern flank of the Dry Creek shoal.

Shortly after, the shoal area around Dry Creek developed differential compaction in the E-zone created a local bathymetric high in the vicinity of the Meeker Canal and Republican River oil fields (Figure 19). Across these local highs, ooid, peloid grainstone was deposited.

As regression continued, the laterally extensive peloid, skeletal grainstone microfacies (Figure 7) was deposited. This represents the last deposition in the Upper Carbonate before onset of the terrigenous influx that was responsible for deposition of the overlying Upper Shale. The occurrence of Osagia oncolites in this microfacies indicates deposition in protected subtidal environments. Local fenestral algal-laminated boundstone deposition on top of the Meeker Canal shoal indicates the existence there of a supratidal environment.

Early stages of the terrigenous influx may account for local deposition of the clayey intraclastic packstone in the Theodore Gore Poore No. 1 and Theodore Gore No. 1 Blackwood Farms cores. These deposits represent deposition in quiet water, where terrigenous material washed from the shoal area could accumulate.

As the terrigenous influx became more widespread, deposition of the grayish-green shale (Unit 8) began. This subfacies is present in all wells and grades laterally into the dolomitic shale microfacies over the Meeker Canal shoal. The finely-crystalline subhedral dolomite in the dolomitic shale microfacies is typical of that formed in "sabkha-like" environments. The presence of fenestral algal-laminated boundstone, Osagia oncolites, and peloids in these two facies demonstrates the persistence of carbonate deposition even in terrigenous-dominated environments.

The dolomitic grayish-green shale grades vertically into thin, highly calcareous calichified green shale with possible root traces over the Meeker Canal shoal or dark reddish-brown shale of Unit 9 elsewhere. The calichified nature of the green shales suggests that calichification of highly calcareous shales occurred during exposure to a local subaerial environment, prior to deposition of the non-marine sediments of Unit 9.

The detrital limestone lithoclasts incorporated in Unit 8 are not similar to any of the limestones encountered in the Upper Carbonate of the D-zone. This suggests that their source is from other than local limestones, possibly from very close by. According to Heckel (1980), limestones in this region are typically exposed updip during late regression. These would be subject to erosion and incorporation into the subtidal and supratidal environments that existed then in Hitchcock County.

The vertical sequence of lithologies described above represents movement of a highly terrigenous environment, equivalent to Irwin's Z Zone, represented by the calcareous to dolomitic shale of Unit 8, over grainstone of Unit 7 that was deposited in environments similar to Irwin's Y and localized "Y" Zones.

Controls of coloration in Unit 9 are similar to those discussed earlier, regarding coloration of the Lower Shale (Unit 2). Also as stated earlier, there seems to be persistent northern source of iron-oxide rich (red stained) clay and silt throughout the time of Lansing-Kansas City deposition in this area. Heckel (1980) suggests that although some of the Upper Shale terrigenous material in the south may have formed in place, some probably was also carried there by alluvial and eolian processes from exposed tidal flats to the north.

Initially of the Upper Shale was deposited in protected subtidal and supratidal environments. The initial influx of the red-stained terrigenous material from the north must have been sufficiently slow to allow reduction of the red ferric-oxide clay to green ferrous-oxide clay. This would lead to deposition of the grayish-green calcareous shale (Unit 8), as described earlier. The combination of both regression and increased terrigenous influx gradually would lead to deposition of only red sediment as in the case of Unit 9.

Deposition of the nonfossiliferous dark reddish-brown silty shale (Unit 9) represents a change in the depositional environment from subtidal and supratidal marine to non-marine deposition on a broad alluvial-eolian plain. The terrigenous influx which led to deposition of the Upper Shale began during late regression (represented by Unit 8).

Dispersed throughout Unit 9 are zones which contain mud-clasts within a clayey microspar matrix. Mud-clasts are common in alluvial sediment. The microspar may be a subsoil accumulation of carbonate, such as is common in many redbeds (McBride, 1974). In the uppermost portions of Unit 9 just below the grayish-green shale, there occur gypsum-filled cracks, root traces, and micrite nodules similar to caliche nodules described by Hubert (1977) as forming in paleosol horizons in the New Haven Arkose. This association may imply soil formation and calichification of the calcareous alluvium in a semiarid environment (McBride, 1974; Hubert, 1977; Reeves, 1970). The source of the calcareous red alluvial clays also may have been from the weathering tidal flat that was to the north. The occurrence of green shale-mottled zones throughout most of Unit 9 may have resulted from removal of ferric-oxide coats from around silt grains by downward percolating ferrous-organic complexes in soil water (Hubert, 1977).

Above the dark reddish-brown shale, there is about six inches of grayish-green shale just below the Lower Carbonate of the overlying C-zone cyclothem. This subfacies may represent reduction of previously deposited red shale by downward percolation of marine waters during initial transgression of the C-zone epeiric sea.

The characteristics of sediments of the Upper Shale suggest initial deposition in near-shore and marginal marine environments, followed by deposition that was dominated by fluvial or eolian processes on an alluvial plain, and finally, by soil formation in a semiarid environment after deposition of the Upper Shale.

Summary - The interplay of regional and local subsidence, pre-existing topography, structural activity, terrigenous influx, and eustatic sea level fluctuations controlled the distribution of microfacies during

deposition of the D-zone cyclothem. Figure 26 illustrates an idealized lateral distribution of lithofacies of a Pennsylvanian cyclothem. This particular example depicts lithofacies distribution during transgression. These same lithofacies also accumulate and, in fact, become thicker during regression. The idealized situation depicted in Figure 26 does not show the variations that would be caused by localized changes in bathymetry, major fluctuation in sea level, or terrigenous influx.

Diagenetic Features

Calcite Cements - In those rocks below the Upper Shale, two forms of calcite cement are present: (1) an equant or bladed crust which occurs as continuous to discontinuous rims lining pores and (2) a later coarse-crystalline blocky-mosaic calcspar which occludes most of the pore space (Figure 27). A third variety of calcite cement is found in the algal boundstone intraclasts and caliche horizons of the Upper Shale Unit 8 (Figure 21C). These cements are generally isopachous and may represent marine "beachrock" cements formed in the intertidal zone. Presumably these cements were aragonite or Mg-calcite that has since undergone alteration to calcite.

Commonly, echinoderm and brachiopod fragments take on large syntaxial overgrowths of the first generation of cement. Syntaxial overgrowths presumably form more rapidly in the freshwater-phreatic environment (Evamy and Shearman, 1965). Equant and bladed calcite crusts followed by coarse-crystalline mosaic calcspar are also typical of meteoric phreatic diagenesis (Land, 1970). Locally in portions of Unit 7, there are areas where the second generation of calcite cement is absent and only the first generation of calcite cement is present (Figure 27).

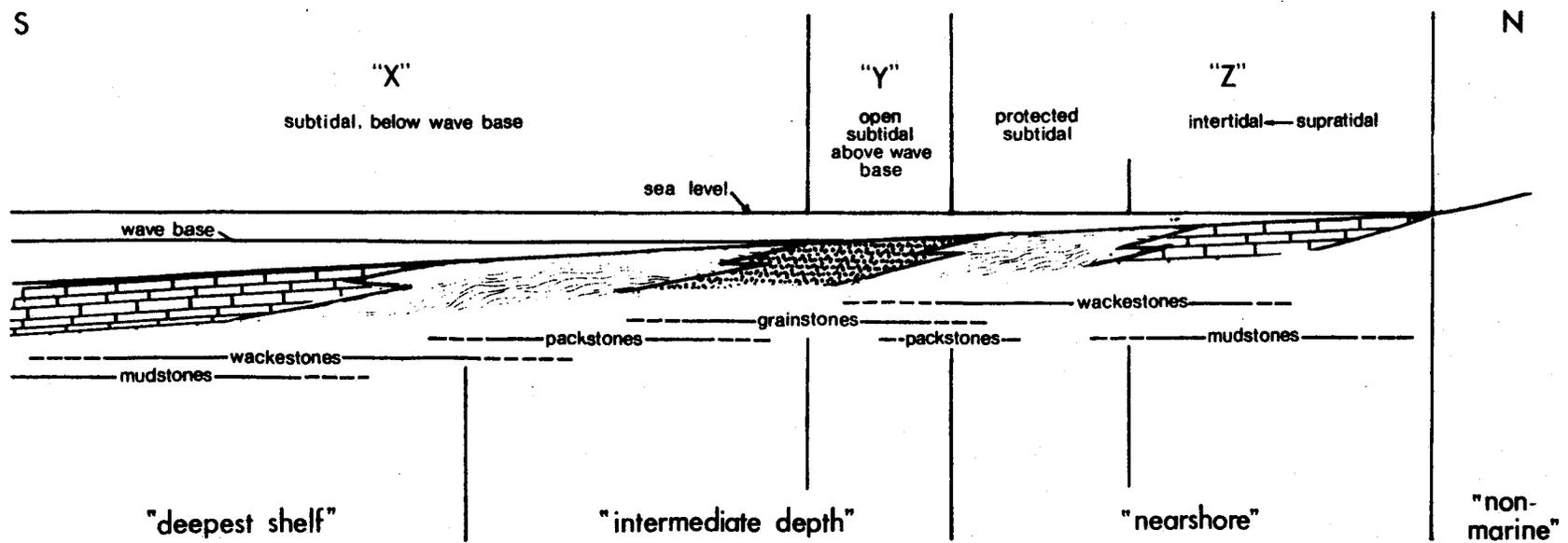
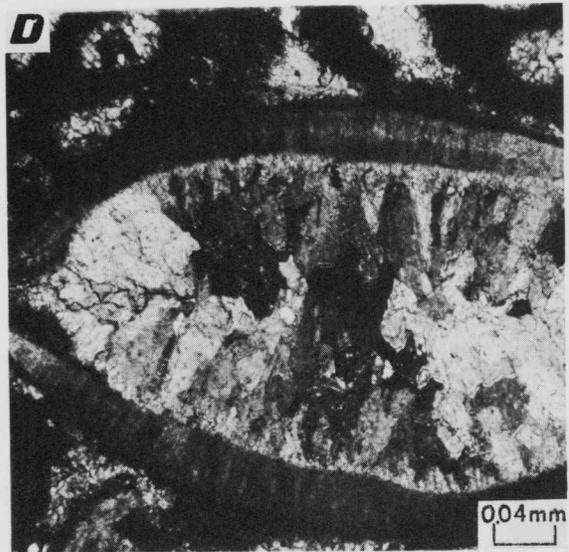
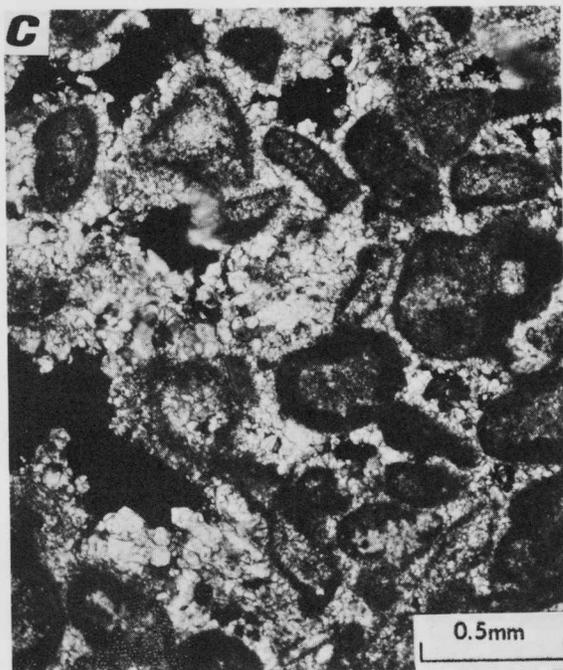
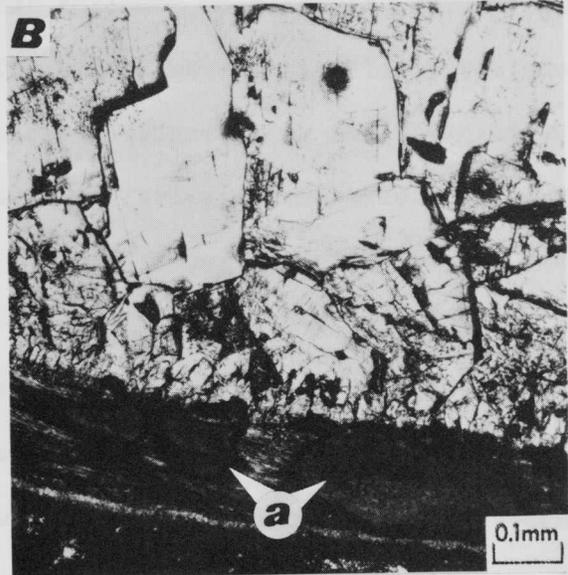


Figure 26. Idealized lateral distribution of microfacies of the D-zone cyclothem. Mudstone and wackestone from the supratidal, intertidal, and "deepest shelf" subtidal environments are affected by terrigenous influxes during the lower regressive rhythm and late upper regressive rhythm in the D-zone cycle. Note there are no bathymetric highs indicated in this example.

FIGURE 27

Examples of calcite cements.

- A. Photomicrograph of bladed calcite crust (a) lining vugs in the Lower Shale followed by second generation of coarse-crystalline occlusive calcspar (b). Theodore Gore Hidy No. 1, 4035.8'.
- B. Photomicrograph of both generations of calcite cement filling cavity within brachiopod shell. Note replacement of a portion of the shell by silica (a). Theodore Gore Schaffert B-1, 3745.2'.
- C. Photomicrograph of calcite crust cement forming rims around framework grains of the Upper Carbonate Unit 7. Note partial preservation of primary porosity after this stage of cementation. Theodore Gore Poindexter No. 3, 3749.8'.
- D. Photomicrograph of bladed calcite crust cement filling cavity within an ostracode shell. Theodore Gore No. 1 Blackwood Farms, 3669.1'.



Locally in the Upper Carbonate, dolomite cements are intergrown with calcite cements. The stratigraphic relationship of the dolomite and calcite crust cements indicate they formed nearly contemporaneously. In grainstone and packstone in lower portions of Unit 7, pores are lined either with (1) bladed calcite cement followed by calcspar, (2) rhombic dolomite followed by calcspar, or (3) bladed or equant calcite followed locally by rhombic dolomite then calcspar (Figures 14D and C). This relationship may be the result of an oscillating water table resulting from seasonal variations in rainfall (this is further discussed in the section on diagenetic history).

The coarse-crystalline calcspar is well developed in carbonates of the cyclothem except in the zone of secondary porosity enhancement and in localized regions just below that zone where only the early crust cement is present. Locally this cement is very coarsely crystalline so much so that often a single crystal occludes one entire pore.

Dolomite - Dolomite occurs in Unit 8 of the Upper Shale, lower portions of Unit 7, and pervasively in Units 3, 4, 5, and 6 in the Lower Interval of the Upper Carbonate. Smaller amounts occur in the uppermost portions of the Lower Shale.

The dolomite in Unit 8 occurs in three forms: (1) very finely-crystalline subhedral crystals that are tightly packed and associated with green clay in the dolomitic shale (Figure 14E), (2) pore-lining cement in caliche horizons (Figure 13C), and (3) as microcrystalline and cryptocrystalline dolomite in some lithoclasts in Unit 8 (Figure 16B).

The finely crystalline dolomite and clay form the matrix between algal-boundstones, bioclasts, oncolites, and lithoclasts in the locally developed supratidal dolomitic shale over the Meeker Canal shoal. Finely-crystalline dolomite is common in supratidal sediment (Shinn et al, 1965).

The pore-lining dolomite cements occur in the cracks of the caliche just above the dolomitic shale microfacies. These cements were probably formed in much the same manner as the sabkha dolomite but a little later during local subaerial exposure on topographic highs prior to the deposition of the redbed in the Upper Shale unit.

The dolomitic lithoclasts may have originated in and been carried basinward into Hitchcock County to the south from exposed tidal flat deposits formed during higher sea level stands.

Dolomite in the grainier microfacies of the Upper Carbonate occurs as limpid, euhedral rhombs which form cements and replace framework grains. In the Lower Interval of the Upper Carbonate and in upper portions of the Lower Shale, dolomite occurs as limpid rhombs distributed throughout the carbonate mud matrix and clay (Figure 14F).

Dolomite is found as crust cement in the lower portions of Unit 7 and upper portions of Unit 6. The dolomite cement is locally contemporaneous with early phreatic cement (discussed earlier). Within this same interval, the dolomite cements are commonly found replacing edges of framework grains. These geometric relationships suggest that dolomitization of the Upper Carbonate began early in the diagenetic history of the cyclothem.

In the muddier carbonate rocks, Units 3, 4, and 5, the dolomite occurs as near perfect water-clear rhombs distributed more or less evenly throughout the carbonate mud matrix. Within these units, little or no dolomite replacement of framework grains occurs.

When the stratigraphically highest occurrence of dolomite is plotted on cross-section AA', the top of the dolomitized section lies along a nearly horizontal line. This line transects facies boundaries (Figure 28). The relationship of the calcite and dolomite crust cements

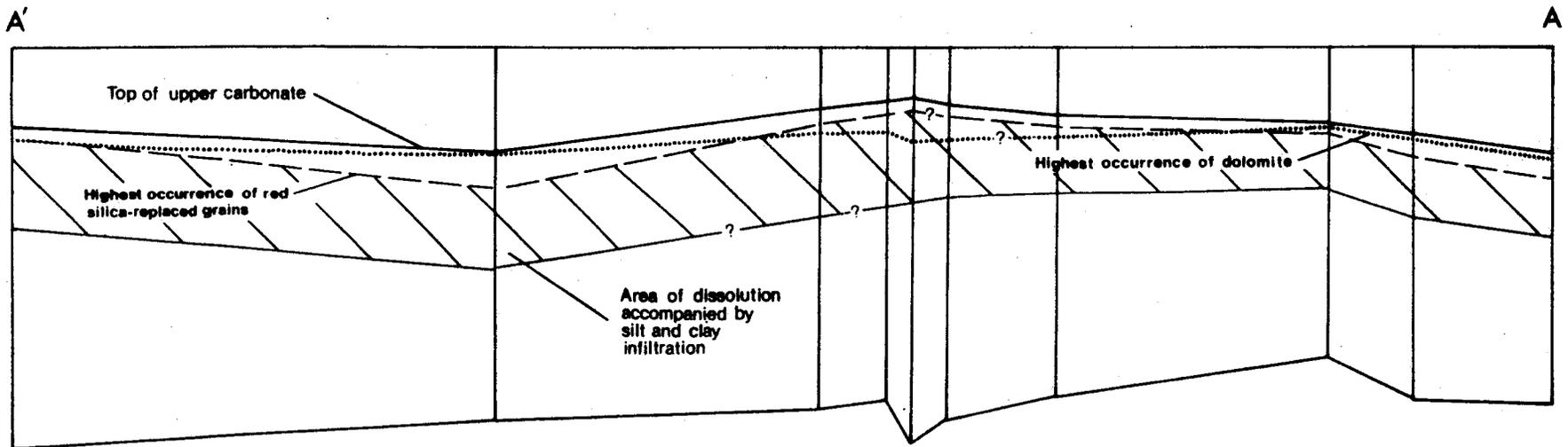


Figure 28. *Distribution of some diagenetic features in the cyclothem. Stratigraphic highest occurrence of red silica and rhombic dolomite of the Upper Carbonate are indicated. Note the relationship of the area of dissolution and clay infiltration to the distribution of silica. Compare with Figure 7.*

suggest their formation was nearly contemporaneous. Since, presumably, the calcite cements were meteoric-phreatic in origin, it is likely that the dolomite cement also formed in the phreatic environment--possibly in a mixed water zone which would form in lower portions of a meteoric-phreatic lens. This would suggest that the line representing the stratigraphically highest position of dolomite in the Upper Carbonate is related to the highest migration of the mixing zone.

Authigenic Gypsum - Gypsum occurs in three forms in the cyclothem: (1) as coarse-crystalline cements, which postdate calcite cementation and fill vugs in the grainy carbonate facies; (2) euhedral crystals, which form in association with the dissolution features mentioned earlier (Figures 29A, C and E); and (3) gypsiferous soil horizons in the Upper Shale.

The first two forms probably have the same origin--the downward percolation of waters rich in CaSO_4 related to formation of the third variety of gypsum, the gypsiferous soil horizons in the Upper Shale.

Replacement by Silica - Red length-slow chalcedony and amorphous red silica (jasper) commonly replace echinoderm and brachiopod fragments throughout the Lower Interval and locally in the Upper Interval of the Upper Carbonate and in upper portions of the Lower Shale.

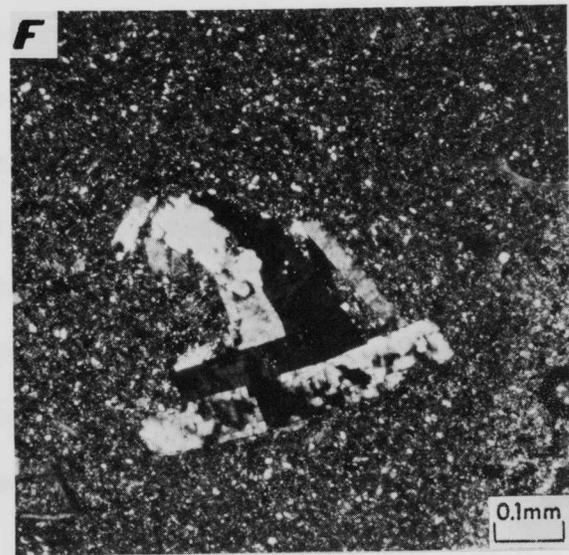
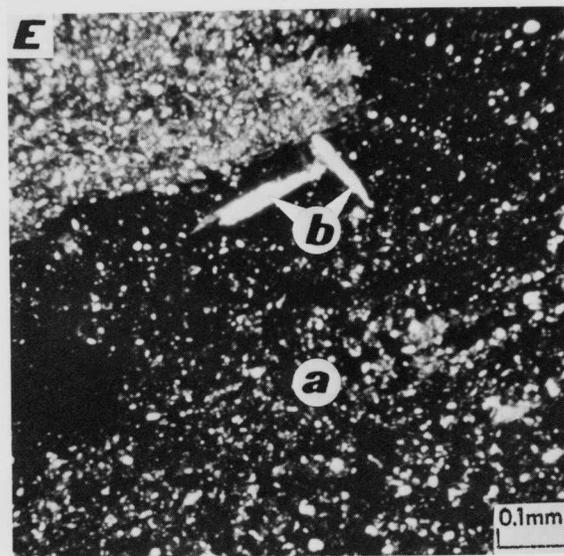
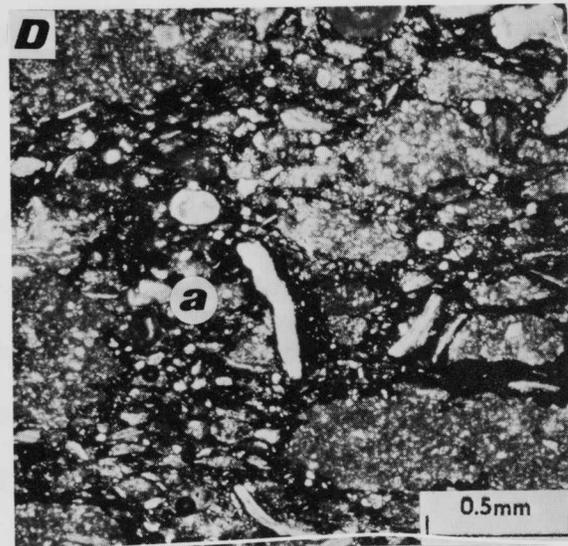
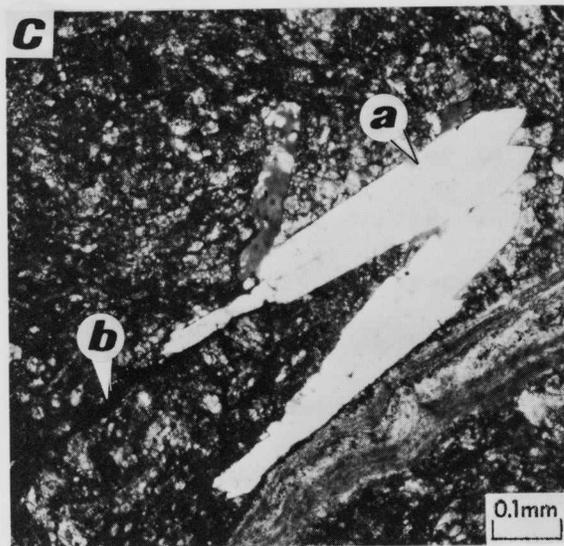
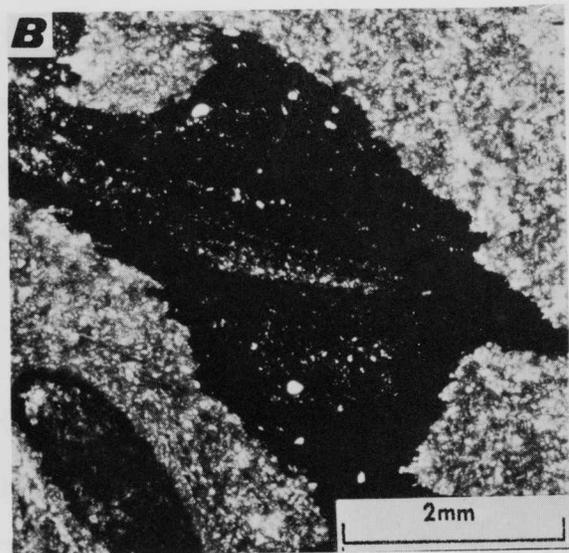
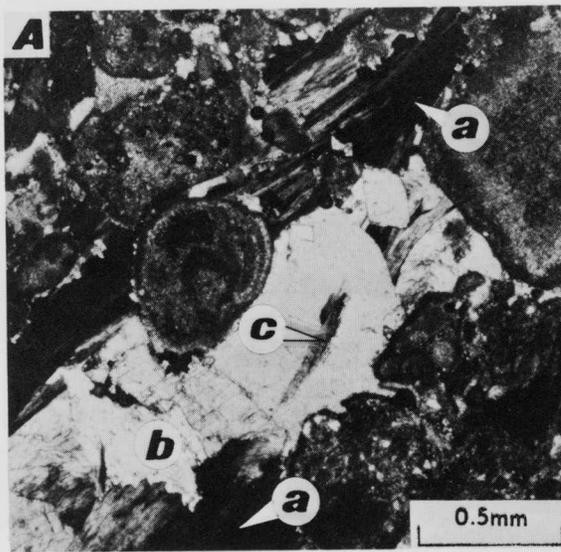
Both chalcedony and amorphous silica encountered in the rocks of this study occur as coalescing spherulites in central portions of echinoderm ossicles and in brachiopod fragments (Figure 18A). Rarely the silica occurs as individual spherulites replacing cements.

Not all of the replacement chalcedony is red. Locally, the color ranges from yellow to dark brown. Presumably, this results from variations in iron content.

FIGURE 29

Examples of dissolution features and associated authigenic gypsum crystals.

- A. Photomicrograph of coarse-crystalline, vug-filling gypsum cement (most of cement is at extinction) (a). Calcite cement (b) (the lighter colored cement) is also being replaced by the gypsum (c). The filled vug was formed by leaching prior to gypsum cementation.
- B. Photomicrograph of laminated clay and silt internal sediment in a dissolution vug. Theodore Gore Schaffert B-1, 3738.9'.
- C. Photomicrograph of euhedral gypsum crystals (a) in a crack (b) formed along a bedding plane. Theodore Gore Hidy No. 1, 4033.5'.
- D. Photomicrograph of small scale in situ breccia (a). The dark areas are red clay filled cracks. Theodore Gore Poore No. 1, 3732.8'.
- E. Photomicrograph of a large clay and silt-filled void (a) and incorporated gypsum crystals (b). Theodore Gore Wertz No. 4, 3760.6'.
- F. Photomicrograph of gypsum pseudomorph after anhydrite. Theodore Gore Schaffert B-1, 3764.4'.



Similarly to dolomite, the stratigraphically highest occurrence of red silica-replaced grains can also be plotted on cross-section AA'. This line also transects facies boundaries (Figure 28), and may reflect the position of a paleo-water table. Silification or the formation of chert nodules can be used as a criterion for recognizing the level of ancient water tables (Wilson, 1975, p. 70).

Dissolution Features - In all but two cores in situ--brecciated zones and cracks infilled with hematite-stained clay and silt occur. Most commonly the brecciated zones are small, ranging from inches to a fraction of an inch across (Figure 29). Even more abundant are smaller cracks which radiate downward through the core and laterally along bedding planes, locally for several inches. Large-scale brecciated zones (several centimeters across) similar to that shown in Figure 12B are rare.

Along the cracks, the effects of dissolution are common; skeletal fragments are only partly preserved and silt and dolomite rhombs are at various stages of assimilation in the infiltrated red clay. In a few places, finely-laminated clay and silt have infiltrated some cracks. Euhedral gypsum crystals are commonly associated with the clay and silt (Figures 29C and E).

None of the dissolution features are found above the line of highest chalcedony occurrence nor do they extend more than one foot (30 cm) into the Lower Shale. This suggests that there is a relationship between the dissolution phenomenon and silification. Dating the origin of the chalcedony relative to the dissolution episode is difficult, because no cross-cutting relationships can be observed. Chalcedony-replaced skeletal fragments which show signs of dissolution and assimilation in the red clay have not been found. The gypsum crystals formed after the clay

infiltration. This is indicated by the presence of clay inclusions incorporated by the gypsum crystals in the clay filling.

Presumably, the clay was brought downward several feet from the Upper Shale through the crack system in the Upper Carbonate. The silt and dolomite rhombs incorporated in the infiltrated clay are probably an insoluble residue derived locally from dissolution of the carbonate mud matrix deposited with the packstones, wackestones, and mudstones.

Porosity - There is a wide variety of porosity types in the rocks of the cyclothem. Dominant varieties are locally developed secondary vuggy and preserved primary interparticle. Minor varieties include: (1) moldic, (2) intraparticle, (3) intercrystalline, (4) fracture, and (5) framework (after Choquette and Pray, 1972).

The secondary vuggy porosity is most abundant in upper portions of Unit 7 in the Meeker Canal oil field. Here, the early-phreatic (?) cements are dissolved resulting in enlargement of pores (Figure 18C). In a narrow band just below the zone of vuggy porosity, primary interparticle porosity is preserved because the second-generation calcspar cement is not present and the first-generation calcite-crust cement is not well enough developed so as to occlude porosity completely. However, the first generation of cement does substantially reduce porosity.

Vuggy and moldic porosity can form in either meteoric-vadose, meteoric-phreatic, or deep-burial diagenetic environments. The presence of either type of porosity does not serve as a criterion to distinguish between environments (Longman, 1980). In any event, the movement of meteoric water that is undersaturated with respect to CaCO_3 through grainstone in the D-zone cyclothem would lead to dissolution of grains and cement and to formation of secondary vuggy and moldic porosity.

Diagenetic History

Generally, the diagenetic history as summarized in Figure 30 of the Upper Carbonate in the D-zone cyclothem reflects retreat of the epeiric sea from the study area in Hitchcock County. The carbonates of the cyclothem display features that are typical of diagenetic environments changing from early stagnant marine phreatic to meteoric phreatic. This was followed by later-stage diagenesis in groundwater rich in SO_4^{-2} and Fe^{+3} ions supplied by soil formation processes occurring during deposition and diagenesis of the overlying redbed.

Marine-Phreatic Diagenesis - Typically, in the marine-phreatic zone, sediments are saturated with seawater but little circulation of that water occurs, and the cementation processes are inhibited. No distinctly marine cements were observed in carbonates of the cyclothem; however, two features related to diagenesis in the marine-phreatic zone are present: (1) bioturbated layers and (2) micritized grain boundaries.

Shortly after deposition, burrowing organisms effectively eliminated many sedimentary structures which may have been present. This activity resulted in formation of the generally non-bedded and nodular limestone with wavy green clay laminae in most of the mud-rich carbonate microfacies. In fact, bioturbation seems to have been so intense that only rarely are individual burrows recognizable.

Micritization of grain boundaries by boring algae and fungi also takes place in marine-phreatic zones (Bathurst, 1966; Koblok and Risk, 1977). Micritization takes place mostly near the sediment water interface but also occurs more than a meter beneath the interface (May and Perkins, 1979).

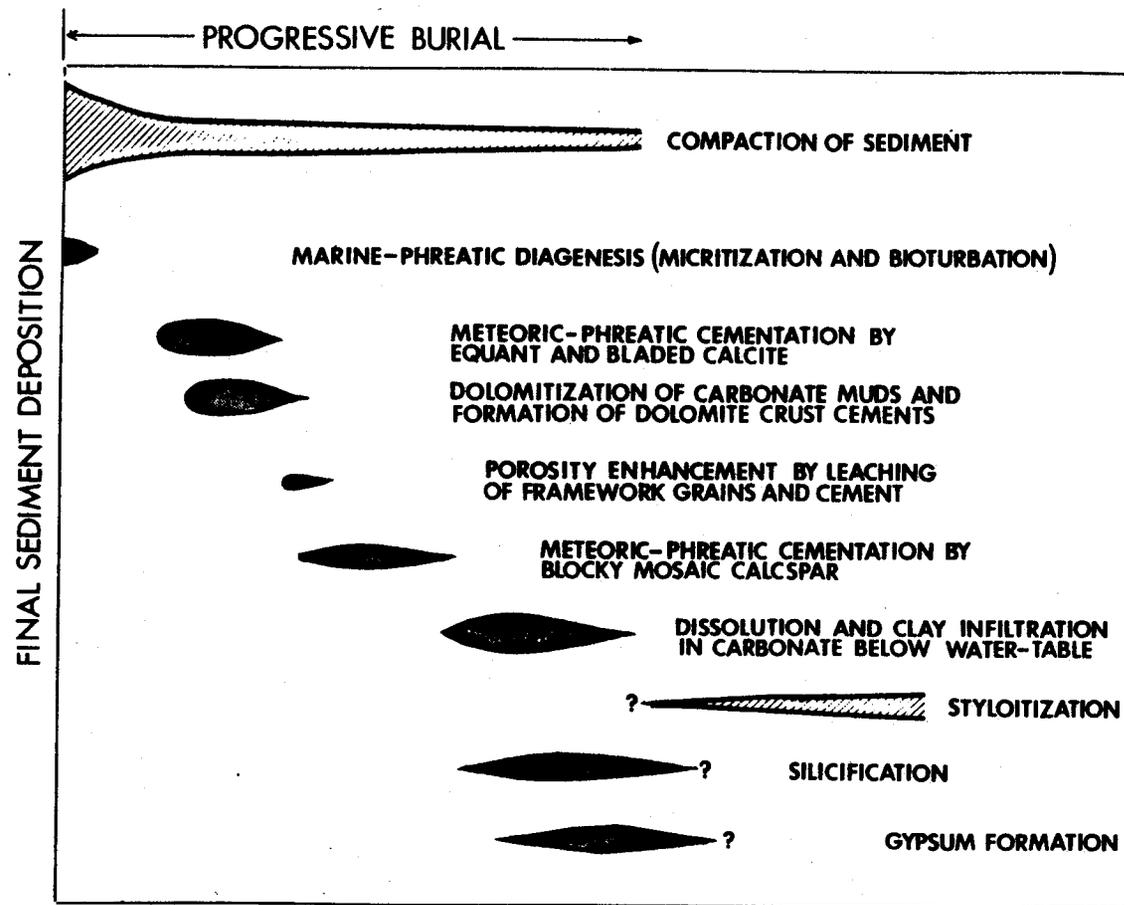


Figure 30. Inferred diagenetic sequence for the Upper Carbonate, D-zone.

Meteoric-Phreatic Diagenesis - Former bathymetric highs, such as the Meeker Canal-Republican River and Dry Creek shoals, were exposed in supratidal environments as the epeiric sea retreated during the upper regressive rhythm. Under these exposed areas, freshwater lenses accumulated, and mixing of fresh and marine waters probably took place. It is in this mixing zone that the limpid dolomite crusts probably formed (Choquette and Steinen, 1980). Also precipitated in the meteoric-phreatic zone was the equant and bladed calcite crust, which apparently was virtually contemporaneous with the dolomite.

Mixing zone diagenesis is poorly understood, but apparently dolomitization, a process that requires circulation of mixed waters, can be controlled by seasonal fluctuations in rainfall (Longman, 1980). In the dry season, the freshwater lens narrows and the mixing zone migrates landward. In the wet season, the freshwater lens thickens and the mixing zone migrates seaward.

During early diagenesis of the D-zone Upper Carbonate, the mixing zone migrated in and out of the sediment pore system several times. As it did so, cements indicative of the mixing zone (rhombic dolomite crust cements) and the meteoric-phreatic zone (equant and bladed calcite) were precipitated. The calcite/dolomite cement stratigraphy, as described earlier, would have been produced during these fluctuations.

The dolomite rhombs present in the muddy carbonate subfacies and replacing edges of grains in some packstone and wackestone presumably formed in the same mixing zone environments. According to Choquette and Steinen (1980), limpid dolomite rhombs can form in muddy carbonate rocks early in the burial history of lime muds. Initial dolomite nucleation

can take place when lime muds had relatively high surface area and moderate to high porosity. Choquette and Steinen also point that the abundance of carbonate ion controls the formation and growth of dolomite crystals. In this regard, the mixing zone is an ideal environment for dolomite formation because of the availability of carbonate from the meteoric-phreatic environment and Mg^{+2} from the marine-phreatic environment.

The lack of marine-phreatic cements in the D-zone indicates that the transition from stagnant marine phreatic to freshwater phreatic conditions occurred without cementation in an intermediate active marine phreatic zone. Cementation of some of the bladed and all of the equant calcite probably took place in the active freshwater phreatic zone. Both of these cements can form in the meteoric-phreatic zone (Land, 1970). In lower portions of the zone, cements typically coarsen toward pore centers and completely occlude porosity. Syntaxial overgrowths form on echinoderm and some brachiopod fragments and grow more rapidly than cement on adjacent grains. Because the water is saturated with respect to $CaCO_3$, little dissolution of grains occurs prior to cementation. Continued exposure to these conditions leads to recrystallization of unstable mollusk grains to calcite.

With time, the upper portions of the freshwater lens established during exposure of the D-zone Upper Carbonate becomes undersaturated with respect to $CaCO_3$ as more freshwater invades the system. Here, dissolution of earlier phreatic low Mg-calcite cement of mixed-water origin occurred. This may be an aspect of the solution-reprecipitation process that is prevalent in freshwater phreatic environments (Harris and Matthews, 1968).

The preserved primary porosity observed locally in Unit 7 may be the result of either one or the combination of two processes:

(1) incomplete cementation as a result of exposure in a semiarid environment--Longman (1980) points out that primary porosity is often preserved in limestones subaerially exposed in semiarid environments; or
(2) with continued regression of sea level, a downward shift in the cementation zones occurs in the freshwater lens and a stagnant phreatic environment or equilibrium environment moves into the sediment pore system before cementation could occlude all porosity. In either case, continued cementation ends, resulting in incomplete occlusion of porosity.

Final stabilization of the carbonate sediment occurs as micrite recrystallizes to microspar. Porosity in lower portions of the limestone is now very low because of extensive cementation and neomorphism.

Meteoric-Vadose Diagenesis - Evidence for the establishment of vadose conditions in the shoal areas in Hitchcock County is generally lacking. The only feature which could be attributed to vadose diagenesis is the secondary vuggy porosity in Unit 7. However, this is equivocal because similar porosity can be produced in the upper meteoric phreatic zone. These facts do not rule out the existence of vadose environments altogether in Hitchcock County. The cores used in this study lie on the flanks of several of the shoal areas (compare Figure 2 and Figure 9), not on the crests of the shoal where a vadose zone might be expected to form.

Later-Stage Diagenesis - The occurrence of (1) in situ brecciated zones and solution cracks infiltrated with clay, (2) replacement of skeletal fragments with red silica, and (3) formation of authigenic gypsum seems to be associated with deposition and diagenesis of overlying redbeds.

With maximum regression of the epeiric sea, redbeds were deposited on a broad alluvial plain. During deposition of the D-zone redbed, gypsiferous soil zones formed in its upper portions, suggesting a semiarid environment. In limestones below the redbed, a water table marked by the highest occurrence of red silica was present (Figure 27). As waters from the redbed percolated downward, the groundwater became saturated with CaSO_4 dissolved from the overlying gypsum soil zone and Fe^{+3} derived from the hematite-stained clays.

Evidence for this type of downward movement is present in the Upper Shale of the Theodore Gore Poore No. 1 core. Here, the once green shale deposited directly on the Upper Carbonate in the vicinity of the well has been altered by oxidation to red shale. The presence of green shale under and around some of the lithoclasts represent remnants of the original green shale. Also, oxidation fronts are observed separating red and green clay-wavy-laminae in some packstone-wackestone lithofacies in the Upper Carbonate. Hematite coats that surround bioclasts in the dolomitic green shale subfacies indicate mobilization of hematite after deposition of the Unit 8.

Length-slow chalcedony, is typically formed in diagenetic environments associated with evaporites (Folk and Pittman, 1979). Although there are no great accumulations of evaporites in adjacent rocks, there are; as pointed out earlier, gypsiferous soil horizons in the overlying redbeds. Folk and Pittman speculated that length-slow chalcedony may form as a result of sulfate enrichment of subsurface waters contemporaneous with soil formation in semiarid environments. This could be the process responsible for formation of some of the jasperized skeletal fragments. The red color imparted to the chalcedony would be supplied by the iron oxide (Fe^{+3}) already in solution.

The occurrence of euhedral and coarse-crystalline gypsum cement attests to the degree of saturation of the subsurface waters with respect to CaSO_4 . Also, the groundwater, although not purely freshwater, was undersaturated with respect to CaCO_3 , resulting in dissolution of carbonate mud-rich subfacies forming the cracks and brecciated zones which were infiltrated with clay. The clay probably infiltrated from the overlying redbed and small amounts may have been locally derived as an insoluble residue from the carbonate mud matrix.

The lack of red-silica replaced grains and clay in-filled cracks in the Lower Shale and Lower Carbonate indicates that it was not subject to the same diagenesis that occurred above it in the Upper Carbonate. If the Lower Shale were relatively impermeable during the later-stage of diagenesis, the groundwater could not circulate within it and the diagenetic features attributed to the groundwater would not be present. This suggests that perhaps the groundwater system may have been perched on the Lower Shale during maximum regression of the epeiric sea.

CONCLUSIONS

1. Deposition of the D-zone cyclothem occurred during one major oscillation of an epeiric sea.
2. Distribution of lithofacies was controlled by the interplay of shelf subsidence, terrigenous influx, and eustatic changes in sea level.
3. In addition to the factors mentioned in No. 2 above, distribution of limestone microfacies, particularly the grain-supported carbonates, was controlled by structural movement related to the ancestral Las Animas Arch and to differential compaction of the E-zone Upper Shale around former topographic highs.
4. Early diagenesis of the cyclothem occurred during late regression of the epeiric sea when carbonate shoals were subaerially exposed.
5. Formation of secondary porosity was controlled by leaching of grain-supported carbonate rocks (Unit 7) as the retreat of the epeiric sea continued.
6. Preservation of primary porosity was the result of shifting of cementation zones in the meteoric-preatic environment or incomplete formation of bladed and equant calcite crust cement in a semiarid subaerial environment.
7. Later-stage diagenesis occurred during maximum regression of the epeiric sea associated with redbed deposition in the study area. During this stage, major diagenetic changes occurred to rocks below a perched paleo-water table in groundwater saturated by ions derived from downward percolating waters from the Upper Shale.

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EXAMINATION AND THESIS REPORT

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Title of Thesis: Petrology and Diagenesis of the D-Zone Cyclothem of the Lansing-Kansas City Groups, Mitchell County, Nebraska

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