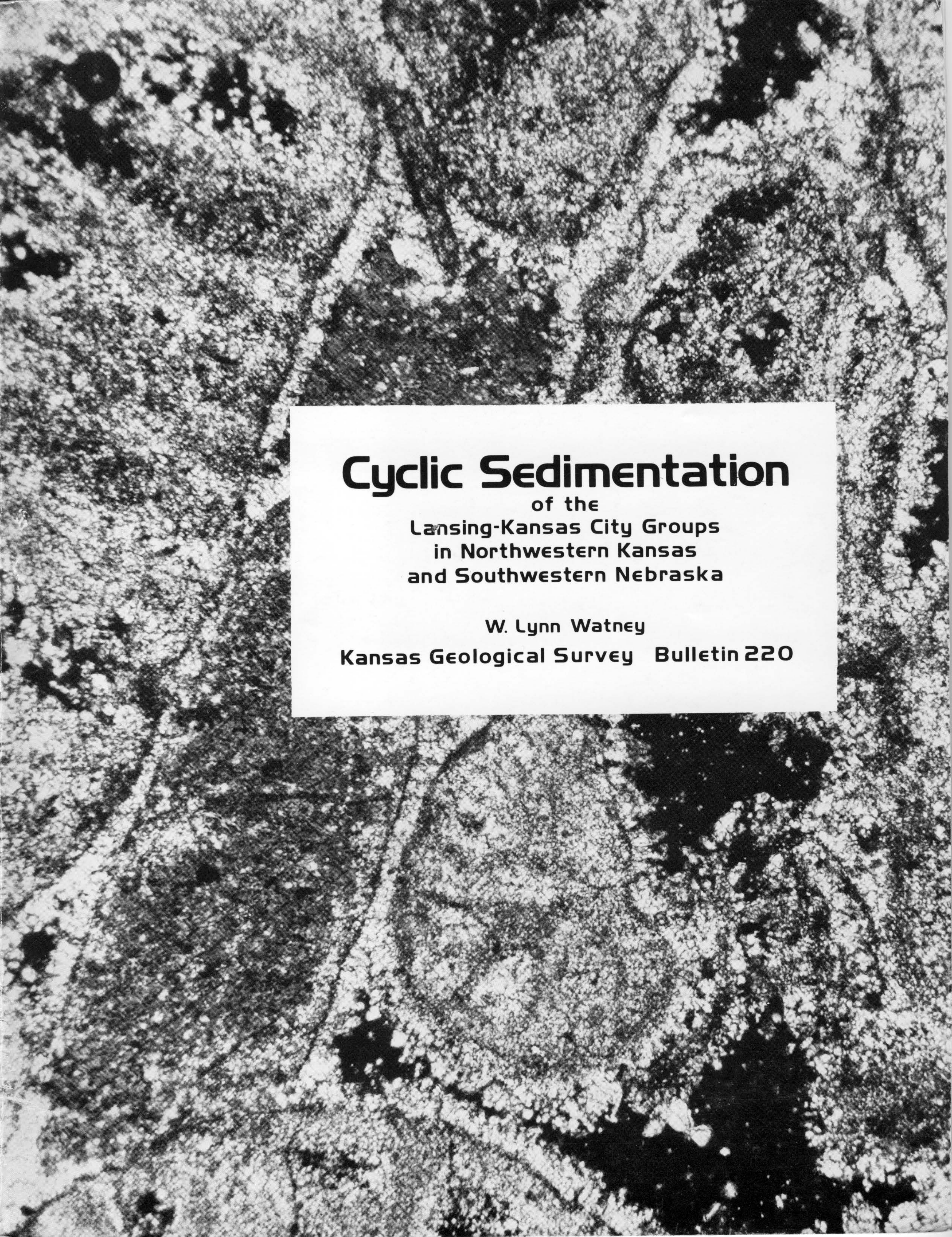

Cyclic Sedimentation

of the

Lansing-Kansas City Groups in Northwestern Kansas and Southwestern Nebraska

W. Lynn Watney

Kansas Geological Survey Bulletin 220

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BULLETIN 220

Cyclic Sedimentation of the Lansing-Kansas City Groups in Northwestern Kansas and Southwestern Nebraska

A Guide for Petroleum Exploration

By

W. Lynn Watney

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EXECUTIVE SUMMARY

Accumulations of oil and gas that are small in size and difficult to find are being sought in Kansas because of the incentive of higher prices for newly discovered petroleum. Many of these smaller deposits are localized in subtle stratigraphic or combination structure-stratigraphic traps. Discovery of these traps requires the efficient use of all data, which also reduces the risk in drilling.

Carbonate reservoirs, such as those of the Upper Pennsylvanian Lansing-Kansas City Groups in western Kansas—the subject of this study—occur at intermediate depths (3000 to 4500 feet below the surface) and are generally small in size; furthermore, the void space (porosity) and ability to transmit fluids (permeability) of these carbonate rocks are highly variable.

This study integrates the examination of cores and cuttings with the analysis of geophysical logs in this sequence of reservoir rocks. This information is used to construct maps and cross sections that describe the depositional environments and post-depositional alteration of these rocks. Trends of increases in porosity and permeability, critical to a petroleum reservoir, can be identified by following this procedure. This analysis, with emphasis on the description and interpretation of the rock record, can be combined with mapping of subsurface structure from well-log and seismic data to lower the risk in exploring for petroleum reservoirs in these and similar rock units of western Kansas. Admittedly, the investment of time and money is greater than in a purely structural approach to prospect definition, but the resulting success ratio should also improve. As the data base grows, details of the reservoir characteristics will be better understood, which should lead to further increases in successful drilling.

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W. LYNN WATNEY [1]

Cyclic Sedimentation of the Lansing-Kansas City Groups in Northwestern Kansas and Southwestern Nebraska

ABSTRACT

The Upper Pennsylvanian Lansing and Kansas City Groups of much of the western Midcontinent consist of cyclic terrigenous clastic and carbonate strata. Individual cycles less than 30 meters in thickness were deposited in northwestern Kansas as a response to fluctuations of sea level and progradation of sediments. Each cycle in this area is characterized by four basic components: a thin but distinctive basal transgressive unit (deposited as sea level rose), overlain by a marine shale, followed by the regressive carbonate and a regressive shale (regression the result of sea-level drop).

Analysis of a few strategically located full-diameter cores allows lithologic characterization of the cycles and permits correlation of cycles to signatures on geophysical logs. After a stratigraphic framework is developed with cores, interpretation of logs and samples provides details of the depositional environment through the preparation of maps, cross sections, and cross-plots that illustrate spatial variations and trends of facies and thickness. Furthermore, maps are used to display other log-derived reservoir characteristics such as structural configuration, porosity-feet variation (an estimate of the reservoir quality), and apparent water resistivity (a quick-look method of recognizing hydrocarbon saturation).

Although most strata were deposited in a simple layered fashion over the study area, thickness and facies changes are mappable and can be related to porosity development and sometimes petroleum accumulation. Subtle bathymetric relief and variation in bottom slope produce *local* changes in rock strata that can be resolved using the techniques described in this report. General landward (northward) shallowing and terrigenous clastic influx control facies distribution in the area of study, but on a larger scale.

Patterns exhibited by carbonate depositional facies vary in shape from elongate and trend-forming to irregular and isolated. Furthermore, the size of these facies patterns varies from square miles to tens of square miles. Maps of the thickness of cycle components defined on geophysical logs help to define these facies patterns.

Extensive early freshwater diagenesis results from subaerial exposure that occurred late in a cyclic sequence as a result of the withdrawal of the sea to the south. This has substantially modified porosity and permeability. Porosity and permeability were enhanced by partial dissolution of carbonate skeletal debris and lime mud producing moldic, granular, fractured, and sometimes brecciated carbonate textures. Freshwater diagenesis apparently was prolonged and more intense landward (northward) and locally basinward over and adjacent to areas with bathymetric relief. Secondary porosity development or destruction, critical to reservoir development, is generally erratic although large-scale patterns of diagenesis can be distinguished. Intense diagenesis results in occlusion or disruption of most porosity by shale infiltration as the carbonate disintegrates into rubble. This does not appear to be a significant problem basinward over western Kansas. Whole cores are the primary means of accurately defining this stage of diagenesis.

Significant porosity formation in the carbonates of each cycle is the result of processes of both sedimentation and diagenesis that occurred prior to deposition of the younger overlying cycle. Thus it is important to describe each individual cycle in order to use this subsurface information most effectively in an exploration program.

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INTRODUCTION

PURPOSE AND SCOPE OF INVESTIGATION

The Upper Pennsylvanian, Missourian, Lansing-Kansas City Groups are of interest to oil explorationists in Kansas, as they are very prolific oil-producing sections of rock, particularly in southern and west-central Kansas. Areas of present and past oil and gas production are shown in Figure 1. Recent exploration drilling has focused attention on northwestern Kansas as an area of additional discoveries. Studies of outcrops in eastern Kansas have provided much data on sequences of rock types in these cyclic deposits, but the detailed rock facies relationships in the producing areas of western Kansas are still not clear.

The objective of this study is to describe the stratigraphy and sedimentation of the Lansing-Kansas City section in a portion of northwestern Kansas and southwestern Nebraska, emphasizing the distribution and predictability of hydrocarbon reservoirs occurring in the carbonate rocks of this interval. To this end, data used here are those available to explorationists working in the area, specifically well logs, drilling samples, and well cores; and the methods, then, should be applicable in company offices and in the field. Cores and cuttings reveal the characteristic cyclicity of rock units. These data assist in choosing the critical parameters of the well logs to be used in mapping. This complementary approach facilitates extrapolation of rock observations to areas between points of sample control.

A regional lithofacies framework is interpreted in terms of the depositional facies of the original sediment. Well-log data and sample descriptions are integrated for interpretation of these facies and are illustrated through the use of geologic cross sections, maps of log-parameters, isopach maps, and lithofacies maps. It is hoped that this report will augment present oil and gas investigations in the study area and provide a model for exploration in other prospective areas of western Kansas.

AREA OF INVESTIGATION

The study area, illustrated in Figure 2, includes parts of northwestern Kansas and southwestern Nebraska. Rawlins County, Kansas, was chosen for detailed evaluation of information from logs, cores, and well cuttings. Cores and related data from wells in Red Willow and Hitchcock counties, Nebraska, and Sheridan and Decatur counties, Kansas, were also examined.

PREVIOUS STUDIES

R. C. Moore made extensive studies of the Pennsylvanian and Permian formations in Kansas both in surface exposures and in the subsurface. He was among the early workers to apply the recognition of cyclical repetitions in this rock sequence in the Mid-continent to understanding their origin and to their stratigraphic classification (Moore, 1929, 1949, 1964). His early work has been the starting point for much of the later work that has been done regarding the timing, extent, and causes of transgression and regression of ancient seas over the continental interior during Pennsylvanian time.

Morgan (1952) established a correlation and informal letter-classification for the Lansing-Kansas City Groups in west-central Kansas using gamma ray-neutron logs. These designations have been widely accepted and are used in this study with a minimum of modification.

Wilson (1957) was the first to describe carbonate buildups in the outcrop sequences of the Lansing Group. Harbaugh (1959, 1962) recognized the significance of calcareous phylloid algae in the construction of these buildups.

A correlation network of well logs from the outcrop in eastern Kansas to the subsurface of northwestern Kansas by Parkhurst (1959) allowed him to apply formation names to the subsurface Lansing-Kansas City formations. The correlations and cyclic facies established by the writer in this report indicate differences from Parkhurst's designation of the base of the Stanton Limestone and the top of the Iola Limestone. Several additional carbonate units are also recognized in the southern portion of the study area. The genetic relationship of these new units and the formations cropping out in eastern Kansas is uncertain at present and is the subject of continuing study.

Parkhurst did note that the Lansing-Kansas City Groups become thinner over the Central Kansas Uplift and thicker in the Hugoton Embayment. In examining the oil production from fields over the Cambridge Arch (Fig. 2), he found no relationship

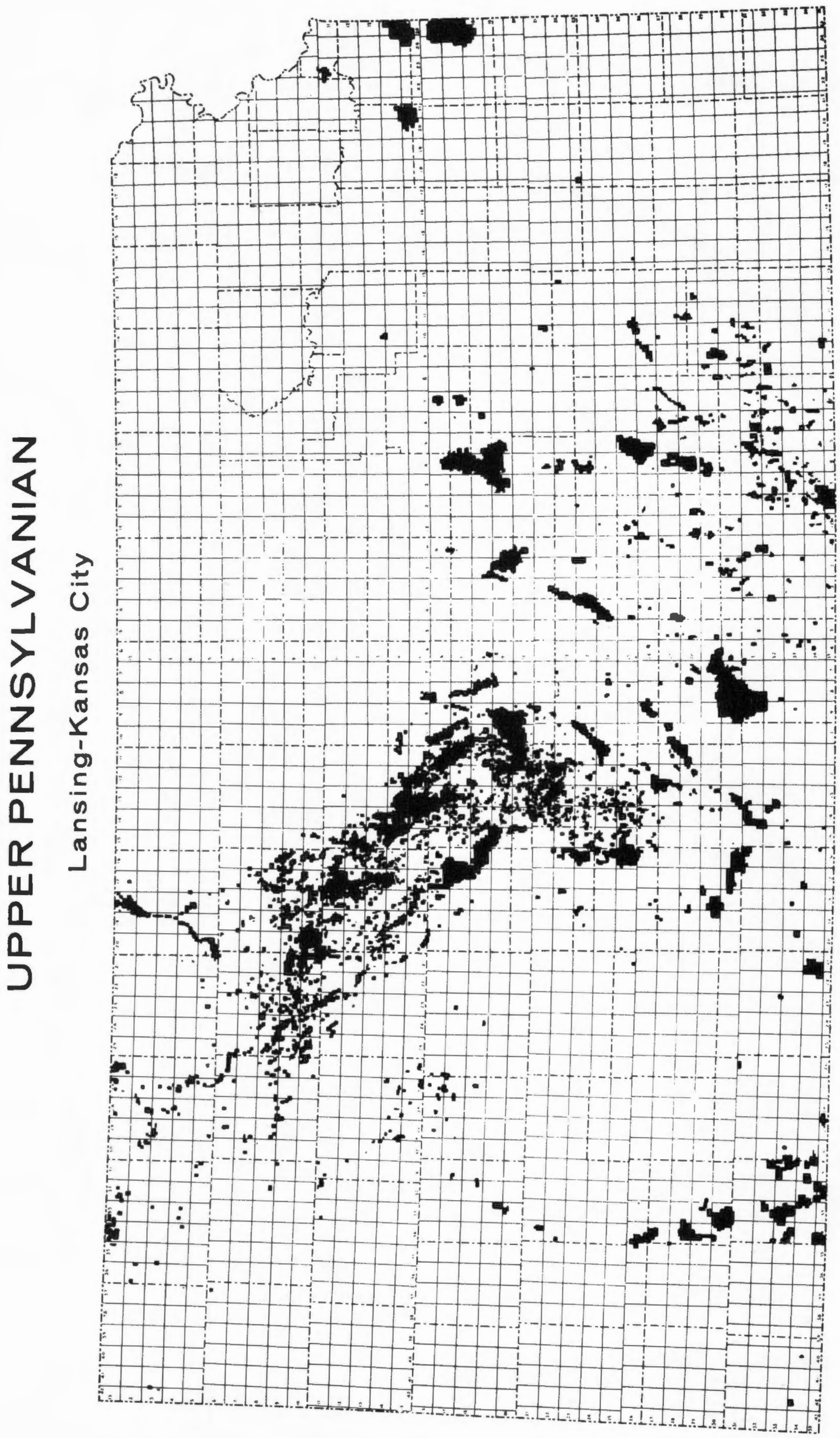
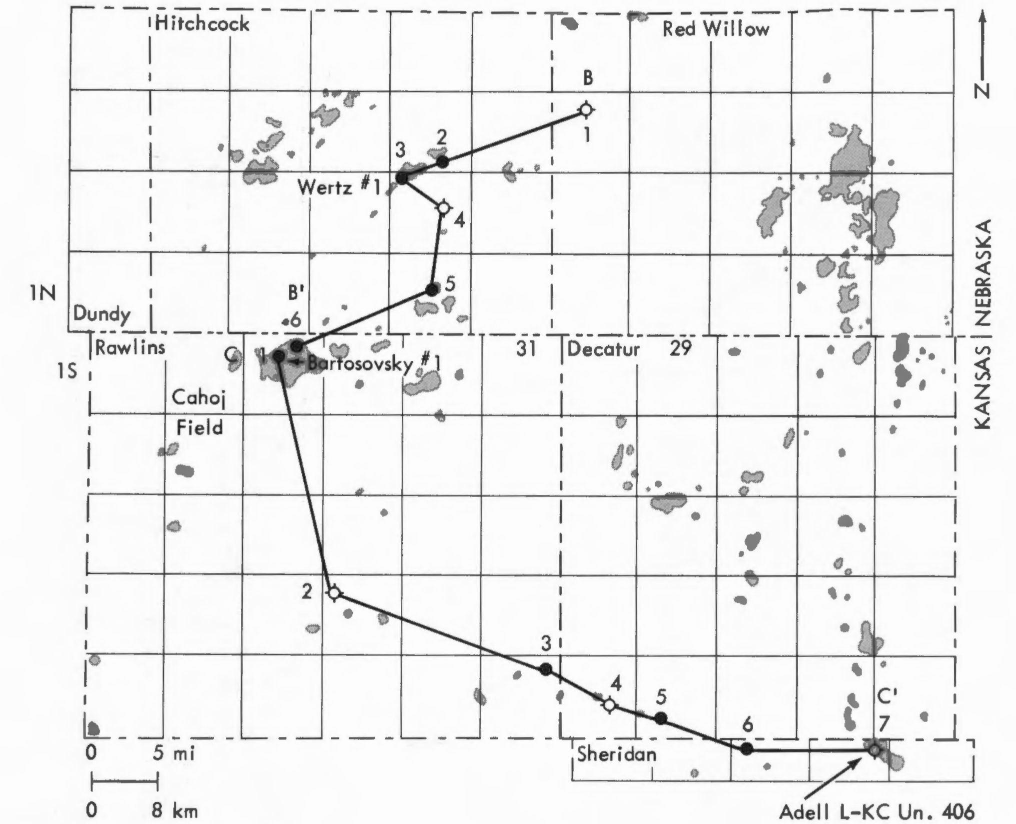


FIGURE 1. Map illustrating areas of past and present oil and gas production from the Lansing-Kansas City Groups in Kansas. (Compiled by Oros, Saile, D., Saile, C., and Kristensen, 1973, in Ebanks, 1974.)



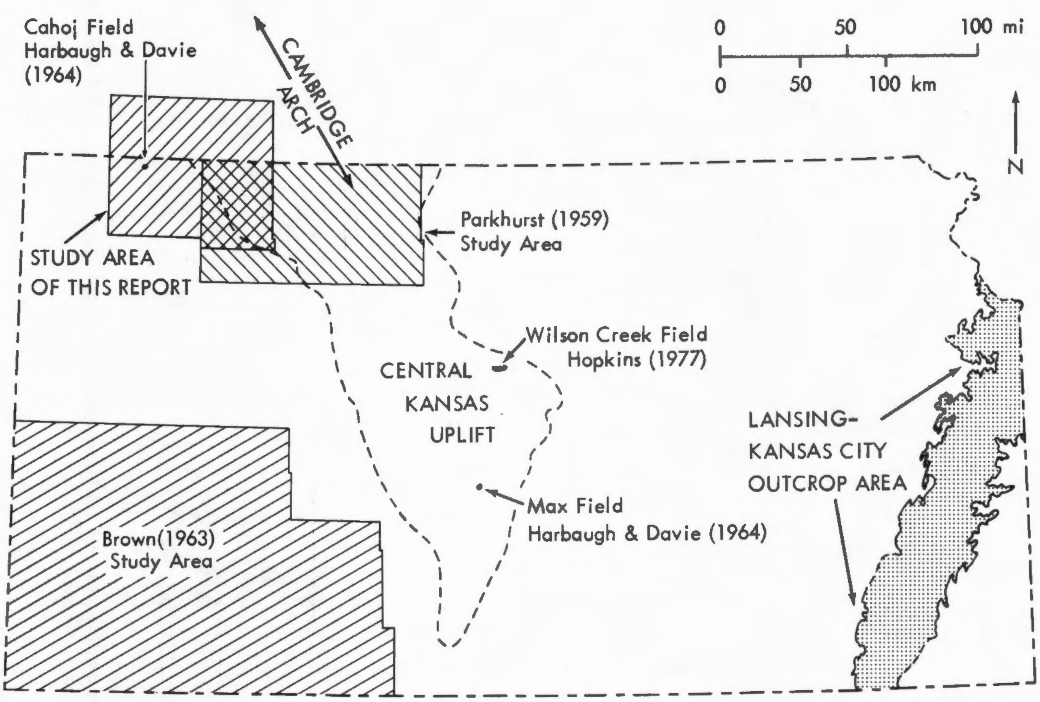


FIGURE 2. Study area in northwestern Kansas and southwestern Nebraska. Black areas are oil fields. Cahoj Field, in north-central Rawlins County, is labeled. Three cored wells, Gore Wertz #1, Skelly Bartosovsky #1, and Conoco Adell L-KC Un. 406, are included along cross section index lines, B-B′ and C-C′. Lined divisions within counties define townships.

Map of Kansas shows relation of study area to Central Kansas Uplift and to Cambridge Arch (Jewett and Merriam, 1959). The Lansing-Kansas City outcrop belt is identified in eastern Kansas (Kansas Geological Survey, 1964). The study area of Brown (1963), Hopkins (1977), and Parkhurst (1959) and the two wells from the study of Harbaugh and Davie (1964) (Bartosovsky #1 and Denker #3) are also indicated.

between the local thickness of a carbonate formation and its porosity.

Brown (1963) described the Middle and Upper Pennsylvanian carbonate banks in southwestern Kansas. The bank-forming carbonates were described as parts of "shoaling-upward cycles." Facies formed in shallow, high-energy environments capped the cycles. A correlation between carbonate formation thickness and lithology exists in certain zones in Brown's study area, but pre-existing structure appears not to have influenced carbonate facies distribution. Primary intergranular porosity was found to be essential to formation of oil reservoirs.

Harbaugh and Davie (1964) compared two well cores from the Lansing-Kansas City Groups, one in Stafford County on the Central Kansas Uplift and the other in Rawlins County immediately off the flank of the Cambridge Arch. Similarities are recognized in depositional environments and diagenesis of the rocks in these two areas; and, importantly, rocks in these cores have more secondary porosity than was noted in the rocks studied in Brown (1963).

Payton (1966) interpreted regional patterns of facies in the outcropping Swope and Dennis Limestones in Missouri and Iowa. He remarks on the similarity of the types, temporal sequence, and geographic position of facies within the Bethany Falls Limestone and the overlying Winterset Limestone. Change in the depth of water during deposition was concluded to be the factor that most controlled the patterns of facies and facies migration that Payton describes.

Heckel and Cocke (1969) summarized the character and distribution of the Upper Pennsylvanian, Midcontinent, algal-mound complexes in the outcrop belt. Heckel (1975) and Heckel and Baesemann (1975) added details on the stratigraphy and depositional framework of these rock units in southeastern Kansas. Mossler (1973) extended the description of facies in the Swope Limestone into southeastern Kansas and, using data of Payton (1966) and Heckel (1968), suggested an analogy between these shelf facies and those forming today in the Bahamas.

Frost (1975) described the Winterset Limestone south of the area examined by Payton. Frost recognized an algal-bank complex in southeast Kansas, which is laterally equivalent to shallow-water facies farther north. Banks appear to have developed on local bathymetric highs. Dolomitizing waters apparently flowed downward and laterally through grainstones to dolomitize the underlying mudbank deposits.

GENERAL GEOLOGY IN THE VICINITY OF THE STUDY AREA

Structure—The study area is on the southwest flank of the southeast-northwest trending Cambridge Arch (Fig. 2). This structural feature is a large antiform feature separated from the Central Kansas Uplift to the southeast by only a slight structural depression. Major periods of movement on these structures occurred during pre-Mississippian and Middle Pennsylvanian times. Movement of the Cambridge Arch also occurred during Mesozoic time. In places, Precambrian rocks are directly overlain by beds of Pennsylvanian age (Merriam, 1963).

The Cambridge Arch is flanked by several smaller, parallel anticlinal and synclinal structures. Adell Field, in Sheridan County, where a core described in this study is located, lies along one of these anticlines.

South of the study area is the Hugoton Embayment, a broad, southward-dipping, shelf-like extension of the Anadarko Basin, which occupies the western one-third of Kansas. An isopach map of the interval from the top of the Mississippian to the top of the Lansing in Kansas (Merriam, 1963, p. 214) exhibits a number of southwest-northeast trending areas of thick and thin sections that are particularly evident in the area of the present study. In general, the Pennsylvanian sediments thicken basinward, to the southwest. Minor local structural movements, contemporaneous with deposition, are inferred here to have affected depositional conditions during Missourian time.

The mature, well-developed areas of production of oil and gas from Lansing-Kansas City rocks are located principally on the Central Kansas Uplift (Fig. 1). Production from flanking areas such as Rawlins County are still in the early to middle stages of development. Although the basin area may never be as prolific as that on the Uplift, a fair comparison cannot be made until further exploration is conducted. Graham County, for example, is located on the Central Kansas Uplift and has produced over 136 million barrels of oil from nearly 1400 wells.

Regional Stratigraphy—The Lansing-Kansas City Groups are part of the Missourian Stage of the Upper Pennsylvanian Series (Fig. 3). The Lansing-Kansas City Groups in Kansas are composed of interbedded carbonates and shales with occasional minor coals and sandstones. In the outcrop belt in eastern Kansas (Fig. 2), the carbonate units display a variety of depositional environments ranging from phylloid algal-bearing, lime-mud banks to oölite shoals (Heckel, 1975; and Mossler, 1973). In northwestern Kansas and southwestern Nebraska, carbonate facies

Group	Stage	Series
WABAUNSEE	VIRGILIAN	UPPER PENNSYLVANIAN
SHAWNEE		
DOUGLAS		
LANSING	MISSOURIAN	
KANSAS CITY		
PLEASANTON		
MARMATON	DESMOINESIAN	MIDDLE PENN.
CHEROKEE		

FIGURE 3. Stratigraphic position of rocks of the Upper Pennsylvanian Series in Kansas (Zeller, 1968).

in the Lansing-Kansas City are also highly variable. Interbedded terrigenous clastics range from red-brown, very silty shales to black claystone.

Rascoe (1962) describes the Lansing-Kansas City limestones as thickening, merging, and becoming massive southward toward the Anadarko Basin (Fig. 4). Southward of the carbonate shelf, the Missourian sequence becomes a basin facies consisting of dark gray shales, sands, and dense, thin limestones. The Anadarko Basin was subsiding and expanding northward from Morrowan through Missourian time, after which subsidence decreased, resulting in shoreline regression and basin filling during Virgilian and later time. Rascoe (1962) states, "The Missourian time marked the apex of the marine transgression over the western Midcontinent during Pennsylvanian time."

The study area is approximately 200 miles north of the Missourian shelf margin, near the northern limit of deposition of marine sediments at that time. Subsidence was less along this upper shelf than in the basin, as is evident from the northward thinning of the section (Fig. 5). Variations in the rate of subsidence and minor vertical fluctuations across the shelf could have affected the distribution of facies of Missourian sediments. Small changes in sea level could also have had important effects on shoreline positions during Lansing-Kansas City time.

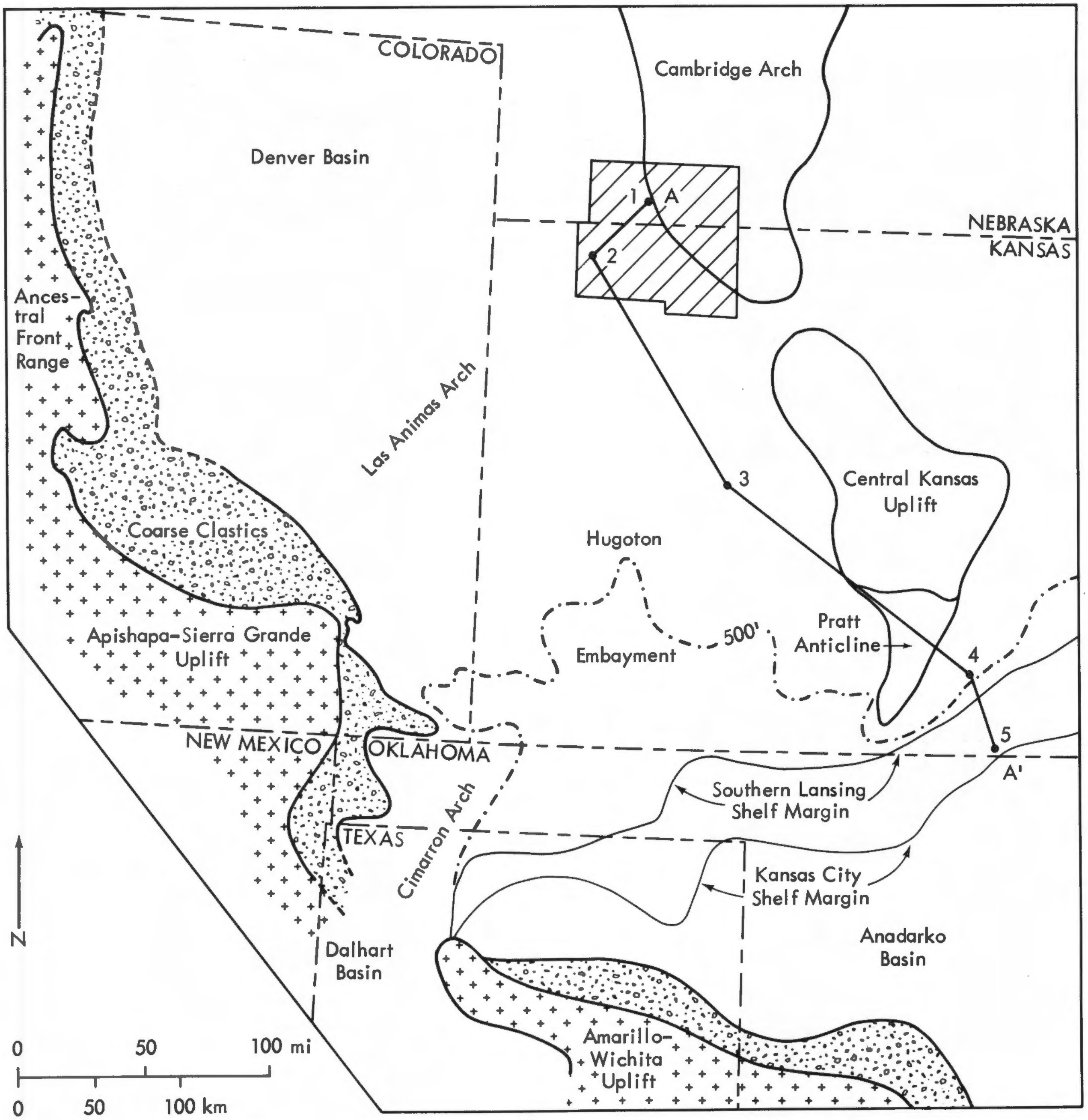
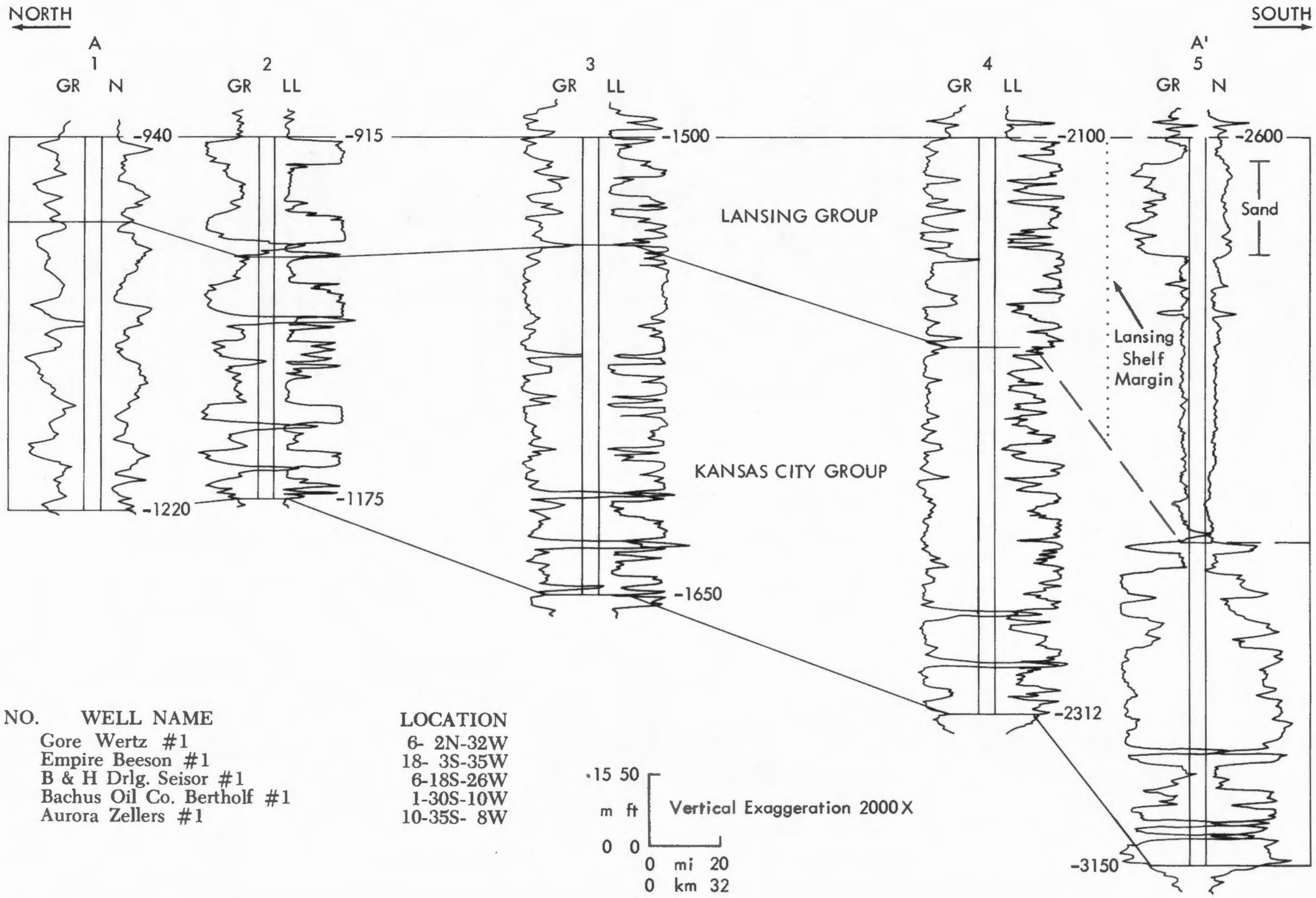


FIGURE 4. Missourian (Late Pennsylvanian) paleogeographic map of western Kansas and adjacent areas. Positive structural elements in southern and western map area: Amarillo-Wichita Uplift to south, Apishapa-Sierra Grande Uplift to the southwest, and Ancestral Front Range in the west. Cross section index line, A-A′, ties study area, along upper landward shelf, with basinward shelf-edge location at A′. Southern shelf hinge-line, defining northern limit of Anadarko Basin, is based on position of abrupt decrease of carbonate thickness to the south. Data for map from Rascoe (1962), Maher (1953), and Martin (1965). The 500 foot Missourian interval isopach is after Rascoe (1962). The hatchured area represents the study area. Numbers on line A-A′ represent well locations.



INDEX NO.	WELL NAME	LOCATION
1	Gore Wertz #1	6- 2N-32W
2	Empire Beeson #1	18- 3S-35W
3	B & H Drlg. Seisor #1	6-18S-26W
4	Bachus Oil Co. Bertholf #1	1-30S-10W
5	Aurora Zellers #1	10-35S- 8W

FIGURE 5. North-south stratigraphic well-log cross section (A-A′) of subsurface Missourian formations across western Kansas (see Fig. 4 for location). Shelf-basin transition illustrated for Lansing Group. Section datum is top of Lansing Group. Correlation lines from upper to lower are top of Lansing Group, top of Kansas City Group, and base of Kansas City Group. Subsea elevations of the top of Lansing and base of Kansas City Groups are included in the figure.

STRATIGRAPHY

CORE AND SAMPLE EXAMINATION

Slabs from 940 feet of core from 14 wells were examined with a binocular microscope. Thin sections of 160 selected samples were examined with a petrographic microscope. Alizarin Red-S stain was used to differentiate dolomite from calcite. Detailed graphic and written lithologic logs of core sections were constructed, and environments of deposition were interpreted. Cores used in the study are in the core collection located at the Kansas Geological Survey in Lawrence.

Well cuttings (samples) from the entire Lansing-Kansas City stratigraphic section in 10 wells in Rawlins County were described; samples from two selected intervals in 25 other wells in Rawlins County also were examined. Description of samples was begun at least 100 feet above the zone of interest, rectifying the changes in samples to a well log to establish the sample quality and correctness of depth. Samples represent intervals of five to 10 feet; those used in this study are available from the Kansas Geological Survey Wichita Well Sample Library. Numerous wells in the area of interest have been drilled since completion of this report, and samples from most of these are available in Wichita. Selected cuttings, representative of an interval, were placed on a wire screen and gently bathed in 10 percent HCl for several seconds to remove the surface powder and polish the surface of the cuttings. When differential dolomitization or large differences in texture existed, etching made the dolomite or coarse crystalline areas stand out in relief and enhanced interpretations of the rock. After rinsing in distilled water, the samples were placed in a ceramic dimple-tray filled with water. In water, the samples were more clearly observed under the binocular microscope at magnifications varying from 10 to 40 times actual size. Selected cuttings were stained with a solution of Alizarin Red-S for 15 seconds to distinguish dolomite from calcite (Dickson, 1965). Thin sections were prepared from 35 selected intervals of cuttings for more detailed examination of rock fabric and for comparison with thin sections of samples from cores.

LOG CORRELATION AND FORMATION EVALUATION

A subsurface correlation scheme was developed by Morgan (1952) using the radioactivity logs in central Kansas. The gamma ray-neutron combination is still the most common log used for evaluating the Lansing-Kansas City Groups. The limestones have also been named by some geologists according to their depth below the top of Lansing. In northwestern Kansas and along the Central Kansas Uplift both systems of nomenclature are usually in agreement; for example, the 180-foot zone corresponds with the "J" Zone. This suggests a rather consistent and predictable interlayering of carbonate and shale formations; Morgan, however, indicates that identification of beds based on penetration depth is incorrect over large lateral distances.

Northward on the Pennsylvanian shelf, including the present study area, frequent changes in composition of the rocks occur; in fact, in Nebraska, the carbonates are labeled differently because of the disappearance of several carbonate members. Morgan suggests that, in evaluating the Lansing-Kansas City, close attention should be paid to the thicknesses of the carbonates, because the highest subsurface elevation of a carbonate bed may not coincide with the highest structure at the top of Lansing. Thickening also is commonly associated with oil production. Identifying and explaining the significance of these areas of thickening is obviously important in locating and predicting trends of oil and gas occurrence.

Once a well is drilled, sufficient knowledge about the composition of each carbonate member is needed to make a conclusive evaluation. Zones with low permeability and high porosity may be treated with acid and result in a good completion. The bottom-hole pressure during a drill-stem test (DST) may be insufficient to allow significant in-flow of formation fluids, but additional information on properties of the rocks from samples or, preferably, cores and core analysis may provide the information needed to correctly relate the log and DST data and, in some cases, may result in a decision to complete a well that otherwise would have been abandoned. General knowledge of the type of carbonate facies in an area also would improve the selection of evaluation procedures in a drilling program. Accurate correlation throughout the area is, naturally, the first step in this procedure.

The log of the Conoco Adell L-KC Unit 406 well (Fig. 6) illustrates the correlation scheme used in this study. The carbonate units described here are referred to throughout the study as "carbonate zones," e.g., "A" carbonate zone. The intervening shales are not designated by letters but their relation to the carbonate zones is discussed in the next section.

Structural and stratigraphic well-log cross sections (Figs. 7 and 8), using these letter-designated correlations, illustrate certain important aspects of the Lansing-Kansas City Groups: There is southward, basinward, thinning of clastic intervals between generally continuous or irregularly varying carbonates; the F and C carbonate zones pinch out northward toward the basin margin; and the contrast between the shales and carbonates in well logs diminishes northward.

In the Skelly Bartosovsky No. 1 well in Cahoj Field, Rawlins County (Fig. 2), there are four productive zones. The initial production of oil from that specific well was reported as 3,000 barrels of oil per day. Cahoj Field and immediately surrounding Cahoj East, Northeast, Northwest, and West alone include approximately 3,600 productive acres from which cumulative production from 10 carbonate zones (to 1978) has been 7,600,000 barrels of oil, or 70 percent of the oil from Rawlins County (Beene, 1979). One of the objectives of this study has been to compare Cahoj Field in northern Rawlins County with the surrounding area in southern Rawlins County in order to identify the factors that are important to the occurrence of oil in this part of Kansas.

LITHOFACIES

Cores described during this study are identified in Table 1. Three of the cores form a nearly complete representation of the Lansing-Kansas City Groups. One sedimentological characteristic is common to all cores, i.e., a basic 25 to 60 foot-thick sequence of certain types of carbonates and shales, which occurs repeatedly in the Missourian section and which comprises a cycle of sedimentation. Individual units of these cycles are more similar to equivalent units in other cycles than to other units in the same cycle. In this section, the individual units of a cycle are described and interpreted.

TABLE 1.—List of names and locations of cored wells and carbonate unit(s) which were cored.

Well Name	Spot Location	Cored Interval (feet)	Carbonate Zones Found in Core
	— KANSAS —		
Empire Palmer #10	NENESE 6-1S-33W	4055-73	J
Murfin Souchek #1	CSENE 2-1S-34W	3959-65 *4004-4037 4100-09 4121-25 4140-54	A D, E H H' J
Skelly Bartosovsky #1	SESWSW 9-1S-34W	3960-4250	A through M
Skelly Kisling #7	CNWNW 10-1S-34W	3994-4030 4171-74	A J
Cities Service Miller #2-1	SENESE 31-2S-27W	*3680-3762	A through H
Murfin Prentice # 1	CNENE 30-2S-35W	4238-4278 4297-4323	D, E G
Cities Service Holmdahl A-1	NESWSW 29-3S-31W	3955-3991.5	C through E
Conoco Adell Un. 406	SESESW 2-6S-27W	3583-3808	A through M
	— NEBRASKA —		
Farmer Nicholson #1	CSWSW 12-1N-27W	3160-74	D
Farmer Nicholson #3	CNENE 14-1N-27W	3153-68	D
Farmer Nicholson #5	CSWNE 14-1N-27W	*3154-70.5	D
Gore Wertz #1	CSESW 6-2N-32W	3640-67 3688-3717 3738-53 3769-3814 3836-56	D, E G H J K
Empire Rathe # 1	CNWSW 9-3N-30W	3618-42 3653-74 3742-70	D G J

* Incomplete interval

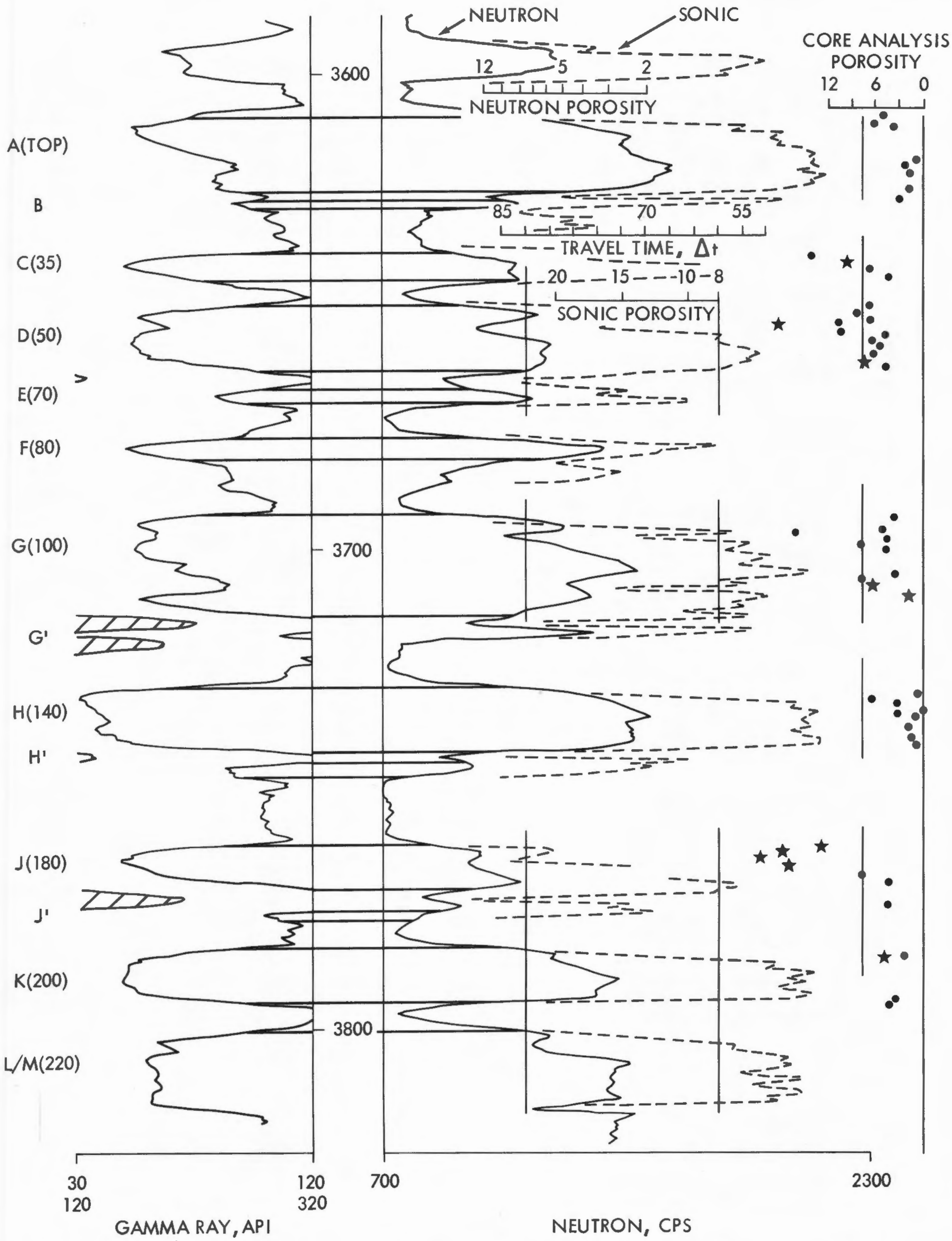
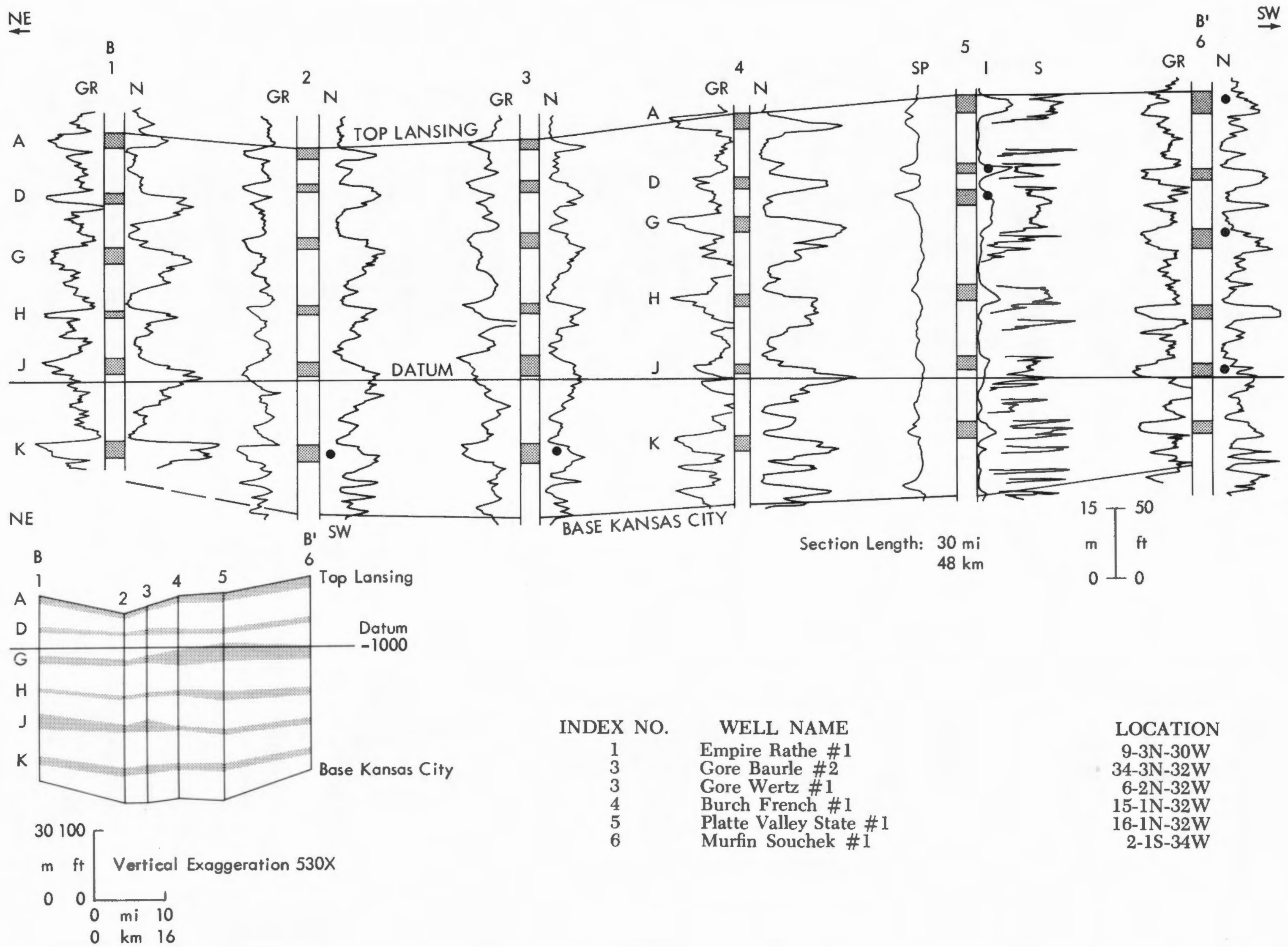
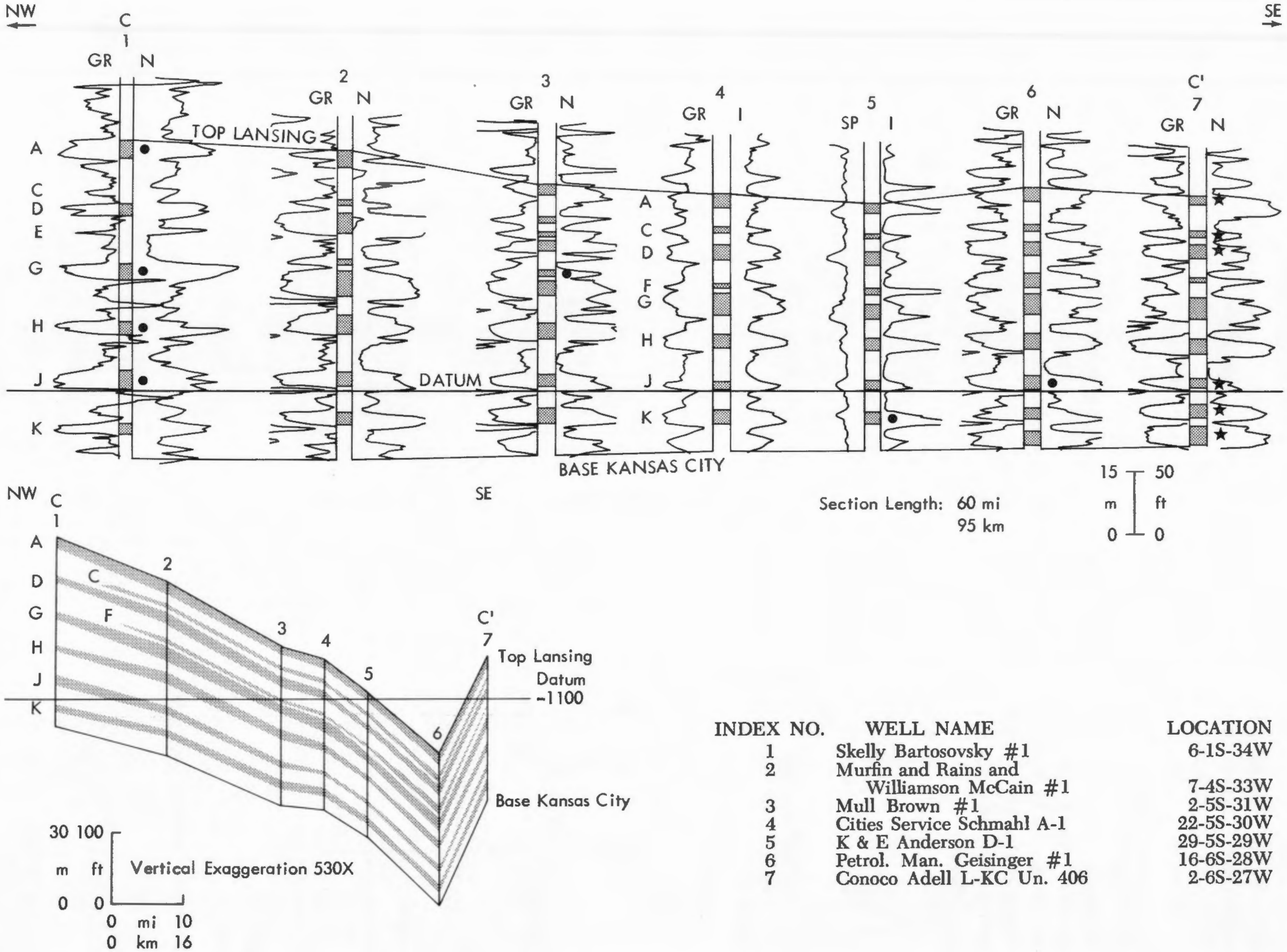


FIGURE 6. Well log of the Conoco Adell L-KC Unit 406 from section 2-T6S-R27W. Letter system of correlation of carbonate zones is similar to that of Morgan (1952). Numbers indicate correlation system based on depth below top of Lansing. Vertical line segments along neutron, sonic, and core analysis porosity curves define eight percent porosity. In core analysis porosity data shown along right margin, data points indicated by stars have permeability greater than 0.4 md. Depths shown on logs are in feet.



INDEX NO.	WELL NAME	LOCATION
1	Empire Rathe #1	9-3N-30W
3	Gore Baurle #2	34-3N-32W
3	Gore Wertz #1	6-2N-32W
4	Burch French #1	15-1N-32W
5	Platte Valley State #1	16-1N-32W
6	Murfin Souchek #1	2-1S-34W

FIGURE 7. Northeast-southwest stratigraphic cross section (B-B′) of subsurface Lansing-Kansas City Groups across northern portion of study area. B-B′ index line is found in Fig. 2. Datum is the base of the J-Zone carbonate. Upper and lower correlations are the top of Lansing and base of Kansas City Groups, respectively. Dots beside well logs define producing intervals of each well. Abbreviations for well logs are: GR = gamma ray; SP = spontaneous potential; N = neutron; S = sonic; I = induction. Inset section is a structure cross section along B-B′. Cleaner portions of major carbonate units are illustrated on this inset section.



INDEX NO.	WELL NAME	LOCATION
1	Skelly Bartosovsky #1	6-1S-34W
2	Murfin and Rains and Williamson McCain #1	7-4S-33W
3	Mull Brown #1	2-5S-31W
4	Cities Service Schmahl A-1	22-5S-30W
5	K & E Anderson D-1	29-5S-29W
6	Petrol. Man. Geisinger #1	16-6S-28W
7	Conoco Adell L-KC Un. 406	2-6S-27W

FIGURE 8. Northwest-southeast subsurface stratigraphic cross section (C-C′) of Lansing-Kansas City Groups across southern portion of study area. C-C′ index line is found in Fig. 2. Datum is the base of the J-Zone carbonate. Upper and lower correlations are the top of Lansing and the base of the Kansas City Group, respectively. Dots define producing intervals of each well except well #7, where water injection zones are indicated. (Abbreviations as in Fig. 7.) Inset section is a structure cross section along C-C′. Cleaner portions of major carbonate units are illustrated on this inset section.

A typical cycle observed here is characterized by a thick "upper carbonate" unit and a thinner "lower carbonate" unit separated by a shale ("lower shale") of variable thickness. The "upper carbonate" zone is overlain by another shale ("upper shale"), as depicted in Figure 9. Each unit of the cycle has its unique characteristics, which allow recognition of the cycles throughout the Lansing-Kansas City section. The thick "upper carbonate" units include the A, D, G, H, J, K, and M zones in Figure 6. C and F zones develop into similar "upper carbonate" units south of the study area (Fig. 8). B, E, G′, H′, and J′ zones represent the "lower carbonate" units. This system of letter-designated units corresponds to the usage established by Morgan (1952).

The terms used to describe carbonate textures in this report are those proposed by Dunham (1962). "Lime mudstone" refers to a limestone with less than 10 percent grains in a lime-mud matrix. "Wackestone" refers to a mud-supported rock with more than 10 percent grains. "Packstone" is a limestone that is grain supported, but contains significant lime-mud matrix. "Grainstone" refers to grain-supported limestone that is mud-free.

Lower Carbonate Unit—Beginning at the base of a cycle (Table 2), the lower carbonate (limestone) varies from tan or brown color near the base to brown or gray-green at the top. The texture in the bottom usually is packstone or grainstone, which grades to wackestone or lime mudstone at the top. The contact at the base is sharp, and the top is gradational with the overlying shale. The lower grainstone or packstone, which is commonly burrowed, is composed of fine to coarse abraded bioclasts, predominantly fusulinids, crinoids, brachiopods, gastropods, pelecypods, and bryozoa. Recrystallized plate-like grains, possibly algae, are also common. These bioclasts usually are coated with algae and encrusting forams (Fig. 10). This coating is referred to as *Osagia.* Lime-mud intraclasts and quartz silt and sand grains are common.

In the upper, muddier part of the lower carbonate unit, brachiopods, fusulinids, and crinoids are the most common skeletal particles. Laminated and dispersed terriginous clay and silt increase upward. Dissemi-

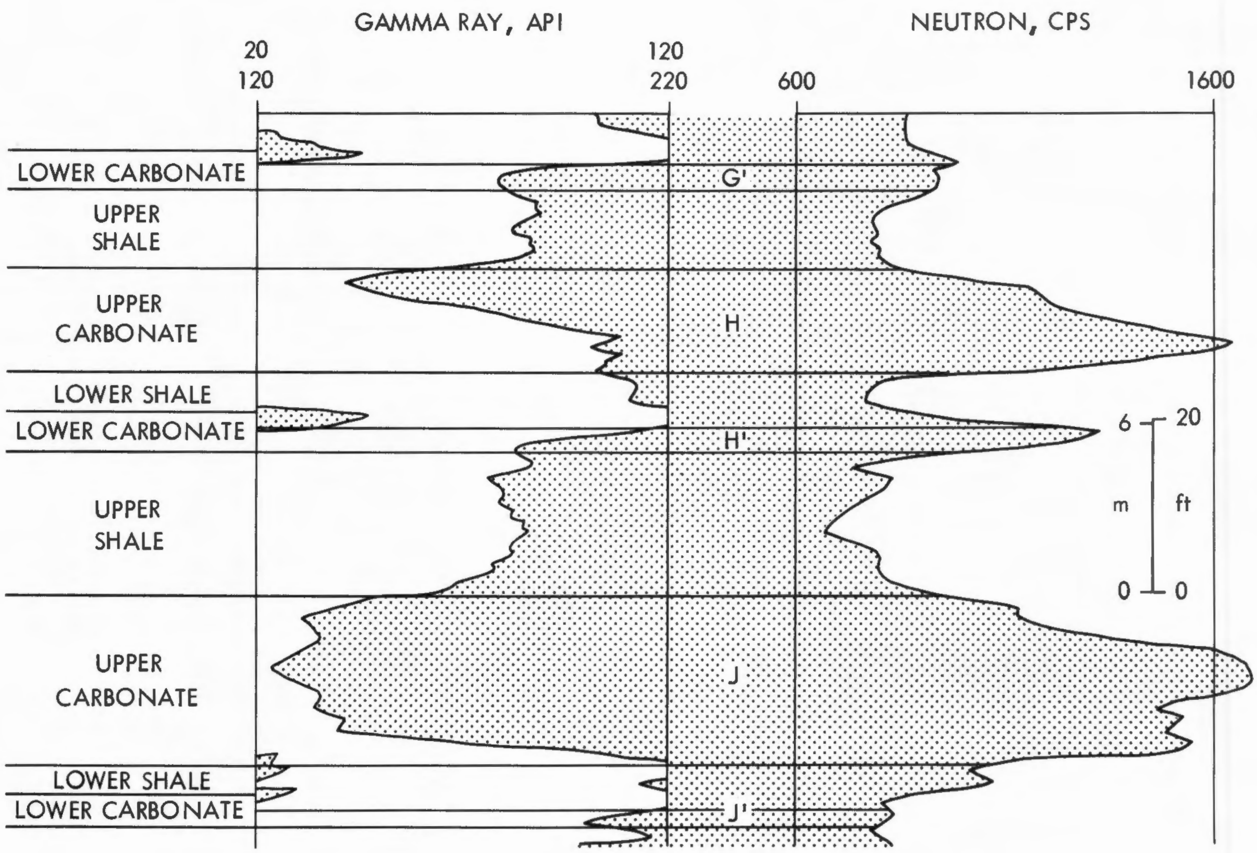


FIGURE 9. Gamma ray-neutron well-log signature of cyclic facies from an interval within the Kansas City Group. From bottom to top of a single cycle: Lower carbonate—lower shale—upper carbonate—upper shale. (Chief Drlg. Co., VAP A-1, 21-1S-33W, Rawlins Co., Ks.).

TABLE 2.—Description and interpretation of facies comprising the typical sedimentary cycle, which is the basis for the interpretation presented in the text.

Descriptive Facies	Thickness (Ft.)	Lithology	Diagenetic Alternation	Facies Contacts	Equiv. # in Fig. 36	Genetic Facies	Depositional Environment
Upper Shale	<5-30	Red-brown, unbedded silty shale	intense		7	Regressive Shale	oxidized, continental clastics
				S			
Upper (upper)	<1-15	Lime-mudstone to grainstone common; occ. dolomitic; sparse to very fossiliferous	moderate to intense		3,3a,4 5,6	Regressive Carbonate	shallow, clear-water carbonate; tidal flat, lagoon, and open marine; high and low energy
Carbonate (lower)	5-25	Lime-mudstone or wackestone, argillaceous at bottom; fossiliferous			2		Subtidal, low-energy, clear-water, open-marine carbonate grading downward to mixed turbid argillaceous carbonate
				G			
Lower Shale	2-20	Fossiliferous, gray-green; occ. black	minimal		1	Marine Shale	Subtidal, low energy, marine; restricted, anoxic conditions prevalent to south and to north locally shallow water
				G			
Lower (upper)	0-15	Lime-mudstone to wackestone, fossiliferous	minimal to locally moderate		2	Transgressive Carbonate	Subtidal, low energy, open marine; clear to turbid water conditions
Carbonate (lower)	0-8	Silty grainstone to packstone; occasionally, base rich in quartz sand or silt			unique combination of 2,3,4,5		Sandy or silty reworked shoal water, intermittent restricted to open marine
				S			

S = Sharp Contact
G = Gradational Contact

FIGURE 10. Thin section photomicrograph of a lower carbonate unit (J', 4196 ft., Bartosovsky #1). *Osagia* (blue-green algae and encrusting forams) coating on pelecypod fragments in silty, bioclastic lime-mud matrix. Bar scale equals 1 mm. PLANE-POLARIZED LIGHT.

nated organic matter is present with or without the association of disseminated pyrite. Locally, the muddy facies consists of an abundance of calcareous phylloid algae with associated encrusting forams (Fig. 11). This facies may thicken locally to nearly 20 feet, whereas it is more commonly one to 10 feet thick. The top of the zone is gradational with the overlying shale.

The rocks in one core suggest that quartz silt and sand locally may develop in the lower part of this lower carbonate (Fig. 12) and may become a recognizable and distinct facies. This 10 feet of sand and siltstone is capped by a coarser, thin, sandy, grainstone bed, as described above.

Sedimentary structures include primarily burrow features that indicate reworking of the grain-rich sediment, including the quartz silt and sand facies. Ripple cross-laminations are common in the siltstone.

Diagenetic effects are generally minimal in the lower carbonate. Except for the addition of cement, the original texture is usually well preserved. At Cahoj Field, Rawlins County, oil is produced from a lower carbonate (E), which locally is a grainstone facies with intergranular and vuggy, secondary, leached porosity.

The environment in which the lower carbonate was deposited was relatively consistent for the equivalent members in each of the sedimentary cycles of the Lansing-Kansas City Groups. The bottom of the lower carbonate generally represents a high-energy, shallow marine environment. The *Osagia* coatings, scattered cerithid (high-spired) gastropods, encrusting forams, and presence of intraclasts probably indicate very shallow water. Crowley (1969) indicates that the *Osagia* may be analogous to modern oncolites (grains encrusted by blue-green algae). Ginsburg (1960) reports that oncolites are formed in low intertidal and shallow subtidal zones. Oncolites are present at depths of six feet and less on the Bahama Banks, in moderately agitated waters. Wilson (1975) indicates their formation in restricted marine bays and lagoons. The diverse fauna may indicate environmental conditions which fluctuated between open and restricted marine, or it may simply indicate organic mixing by burrowing organisms.

FIGURE 11. Core slab of a lower carbonate unit (E, 4271 ft., Prentice #1). Buff-colored phylloid algal wackestone with zones of oil-stained, partly recrystallized matrix and grains. Some matrix fracture and collapse. Divisions on bar scale equal 1 cm for each core slab.

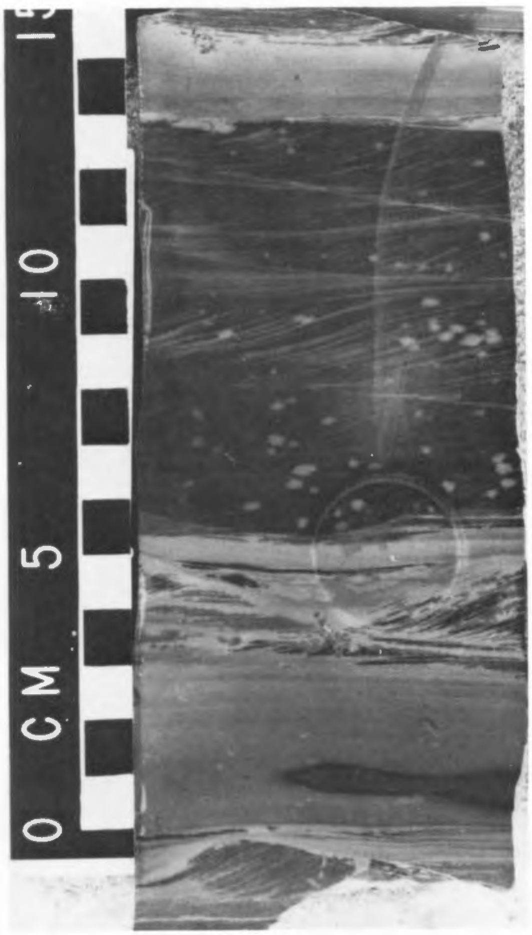


FIGURE 12. Core slab of a lower carbonate unit equivalent (B, 4029 ft., Kisling #7). Selectively oil-stained, climbing ripple-laminated, quartz siltstone to sandstone.

FIGURE 13. Core slab of a lower shale unit (immediately above E, 3985 ft., Holmdahl #1). Dark green, massive, brachiopod- and crinoid-bearing shale.

Quartz sand and silt at the base of the deposit, including scattered fossils as described above, suggest reworking of underlying clastic sediments in a shallow, moderately open or restricted, marine environment. The top of the lower carbonate unit represents a low-energy, subtidal, open marine environment in which turbidity increased with time.

Lower Shale Unit—The lower shale unit (Table 1 and Fig. 13) is green, olive to gray-green, gray, or black in color. The thickness ranges generally from around two feet in the southern study area to 20 feet in the northern study area. The fauna in this shale is usually diverse, with brachiopods, crinoids, and fusulinids being most common. Darker-colored intervals commonly contain phosphatic, inarticulate brachiopods. The upper portion of the shale may contain lime mudstone lenses and may be quite calcareous as it grades into the overlying upper carbonate unit. In the northern parts of the study area, the carbonate lenses also occur in the lower part of this shale interval. These lenses contain many cerithid gastropods and scattered ostracods.

The lower shale may be burrowed, but usually the unit varies from massive to thinly laminated, to almost fissile. Obvious diagenetic alteration of the shale is limited to the northern part of the study area, where secondary discoloration due to oxidation occurs, resulting in mottled yellow and red colored or tinted shales. Fossil molds and fine fractures also are associated with this secondary alteration process.

Significant diagenetic effects in the lower shale are limited to the northerly areas. These include dissolution of calcareous fossils, oxidation of shale, and occasional fracturing, which are probably the result of percolating meteoric surface waters. These diagenetic events probably occurred before the shale was completely lithified and while fossil fragments were susceptible to dissolution.

The lower shales thicken northward, suggesting a source of fine, terrigenous clastic sediment in that direction. Changes in the character of the shale in some cycles suggest that the earliest deposition may have occurred in deeper, more restricted, low-energy, marine environments, or perhaps in marginal marine embayments, with temperature stratification and poor water circulation. Exceptions to this include those areas in which carbonate beds with fossils suggesting clear, shallow-water environments occur in these shales farther north. The carbonate beds that commonly occur in the tops of these shales indicate that the environment may have become shallower and less turbid with time, eventually leading to deposition of the upper carbonate unit.

Upper Carbonate Unit—The upper carbonate unit contains a diversity of carbonate rock-types that occur repeatedly at the same position within different zones. A division of the unit into an upper and lower interval is appropriate in this discussion (Table 2).

Lower Interval—The lower interval may be brown, gray, green-tinted tan, buff, or white lime mudstone or wackestone. Generally, the color becomes lighter and the carbonate contains less terrigenous clay and silt upward in the interval. The thickness range is from five to 25 feet. A diversity of fossils is present, with brachiopods, crinoids, and fusulinids being dominant. Corals, pelecypods, encrusting forams, benthenic forams, and bryozoans also are common.

Phylloid algae are locally abundant in this lower part of the upper carbonate (Fig. 14). The wavy, crinkled plates are usually jumbled in a mud matrix with no evidence of preferred orientation. Locally, the limestone is a packstone that consists, almost exclusively, of algae and smaller encrusting forams. In the northern part of the study area, in Hitchcock County, Nebraska, and locally over Cahoj Field, thin packstone and grainstone beds composed of mixed, fragmented skeletal grains are included in this lower interval. Burrowing is very apparent near the base of this more argillaceous interval (Fig. 15). Fragmented skeletal debris, which is common throughout the interval, suggests some biogenic reworking.

FIGURE 14. Core slab of an upper carbonate-lower interval (G, 4308 ft., Prentice #1). Long, wavy blades of phylloid algae. Also fusulinids, brachiopods, and encrusting forams. Some burrowing and collapse of matrix. Coarse calcite-spar filled voids.

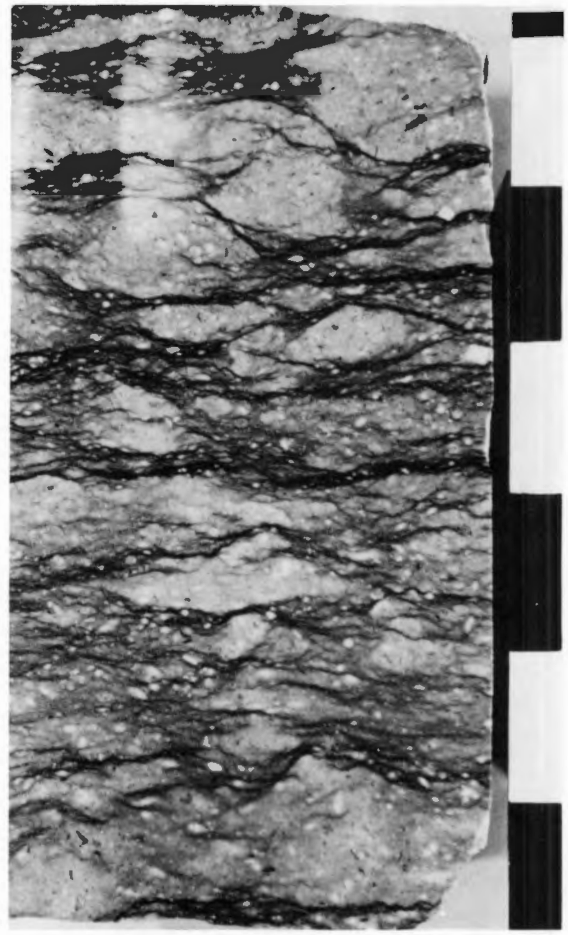


FIGURE 15. Core slab of an upper carbonate-lower interval (H, 4136 ft., Bartosovsky #1). Burrow-mottled, argillaceous, fusulinid, crinoidal wackestone. Burrows are light-colored, mottled areas among the wispy shale laminations.

Diagenetic effects are more important in the alteration of this interval than in the lower units of the cycle, especially in the more northern parts of the area. Typical postdepositional alteration in this interval includes the formation of molds, vugs, fractures, and fissures (Figs. 16, 17). The major effects of diagenesis in this facies, then, appear limited to an early period of freshwater percolation through mineralogically unstable and incompletely lithified carbonate sediment, with formation of some secondary porosity. The preceding illustrations and following discussion of the

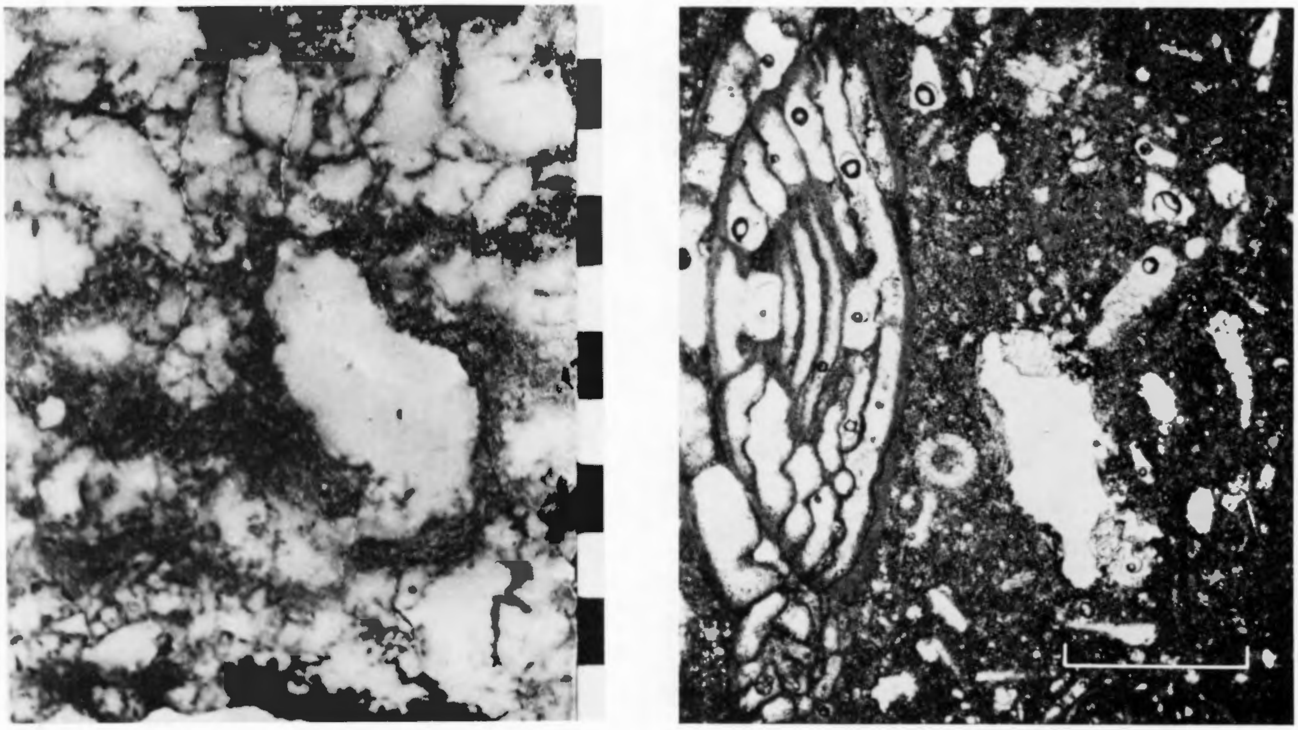


FIGURE 16. Upper carbonate-lower interval illustrated by a photo pair (Slab: D, 3174 ft., Nicholson #1; and thin section photomicrograph: A, 3988 ft., Bartosovsky #1). Intense diagenetic alteration of wackestone with lime-mud dissolution, recrystallization, and fracturing. Both intervals were perforated for oil production. Photomicrograph taken under PLANE-POLARIZED LIGHT. Bar scale equals 1 mm.

upper interval support this interpretation. In contrast, appreciable secondary effective (interconnected) porosity in the upper carbonate was formed in many areas, and in every upper carbonate unit of the Lansing-Kansas City cyclic sequence. Diagenetic processes may also have been related to the cause of the cycles.

The rocks formed in a low-energy, subtidal, marine environment, but a few beds of abraded, grain-rich carbonates suggest occasional strong currents, with local winnowing and redeposition of sediment, perhaps by storms. Textural and compositional changes indicate that the water became less turbid with time. Phylloid algae developed during these periods of clear water.

Phylloid algae commonly occur in carbonate buildups, but are also found in horizontally bedded strata. They are thought to have been able to baffle and trap mud, which results in creation of depositional relief, in a manner similar to the effect of marine grasses in modern seas (Harbaugh, 1959). Wilson (1975) indicates that the algal mound may not originate from this trapping of mud, but that growth of the mound is encouraged by it. Ball and others (1977) conclude that the phylloid algae "were not builders of depositional topography, but rather were a source of building material." Regardless of these differences, apparent original relief above phylloid algal-bearing carbonate buildups is noted in many studies, including the present report. The mounds probably formed in water depths of 65 to 250 feet or less, and below wave base (Wilson, 1975).

Upper Interval—The facies of the upper interval of the upper carbonate unit (Table 2) are more complex and more variable laterally than those of the lower interval. The upper interval is generally light colored, with textures ranging through the spectrum from grainstones to lime mudstones. It is thinner than the lower interval, with thicknesses ranging from near zero to approximately 15 feet; average thickness is usually about three to five feet.

Diversity of fossils generally decreases toward the top of the interval, either gradually or rather abruptly. Grainstones may consist of coarse, abraded, mixed bioclasts (Fig. 18) or, in contrast, fine-grained, mixed pelloids, intraclasts, ostracods, forams, encrusting forams, and small bivalves. The muddy facies typically includes algal stromatolites and small numbers of organisms that occur only in restricted environments (Fig. 19). Disseminated quartz sand and silt are

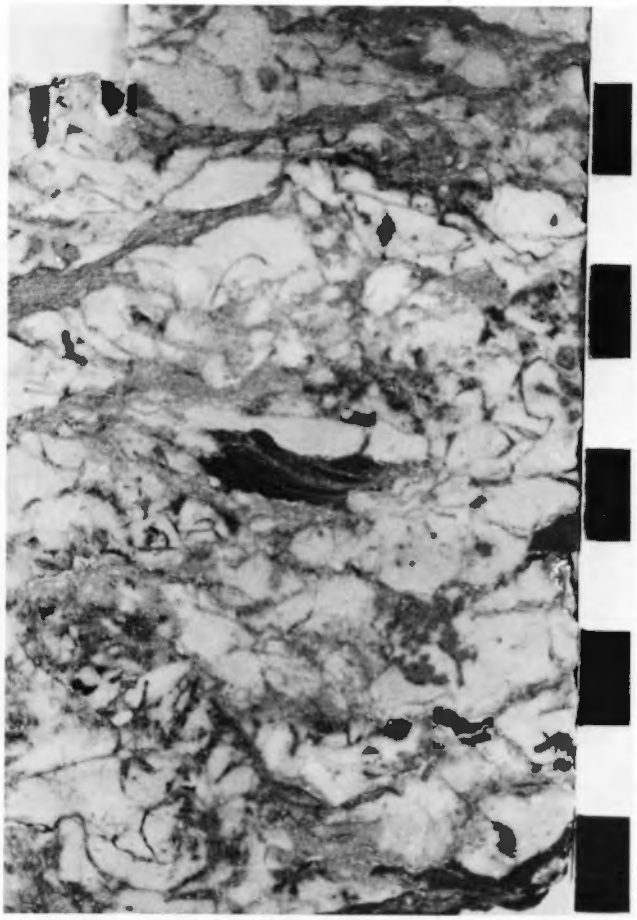


FIGURE 17. Core slab of an upper carbonate-lower interval (D, 4249 to 4250 ft., Prentice #1). Solution-altered, brecciated and fissured phylloid algal wackestone. Finely graded and laminated quartz silt and sand filling voids. Lies above interval with open, oil-filled vugs.

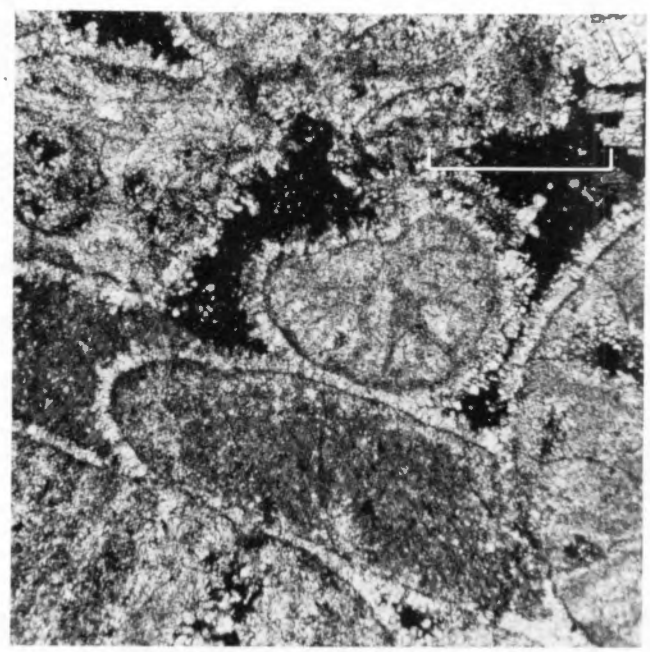


FIGURE 18. Upper carbonate-upper interval (J, 3761 ft., Adell Un. 406). Abraded fusulinid, brachiopod, crinoid, bioclastic grainstone; grains moderately to heavily micritized; grain surfaces darkened prior to precipitation of thin, bladed, isopachous carbonate rim (now calcite); scattered chert replacement of crinoids; abundant intergranular porosity. On crinoid fragments are coarsely crystalline, calcite, syntaxial overgrowths, which precipitated later than the early isopachous (probably marine) cement. (Core analysis Ø = 18%, k = 42 md.) CROSS-POLARIZED LIGHT. Bar scale equals 0.25 mm.

FIGURE 19. Thin section photomicrograph of an upper carbonate-upper interval (F, 3675 ft., Adell Un. 406). Silty, dolomitized, algal stromatolite showing generally horizontal laminations of darker calcite or dolomite between finely graded silty to muddy carbonate layers. Laminations occasionally disturbed by vertical burrows and fluid-escape structures. Other evidence of fauna is generally lacking. CROSS-POLARIZED LIGHT. Bar scale equals 1 mm.

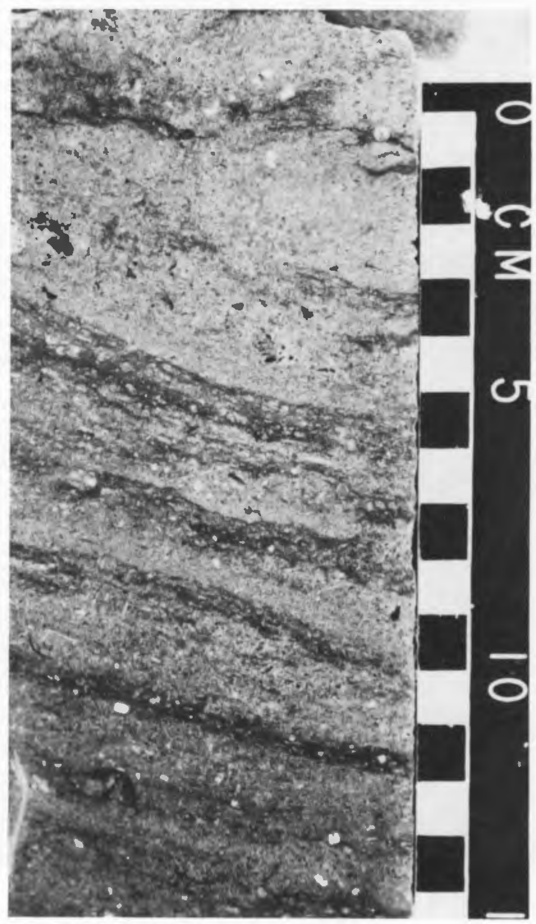


FIGURE 20. Core slab of an upper carbonate-upper interval (J, 4149 ft., Souchek #1). Cross-stratified, leached, fusulinid, robust brachiopod, crinoid, bioclastic packstone (productive facies; well completed in three zones for 152 BOPD).

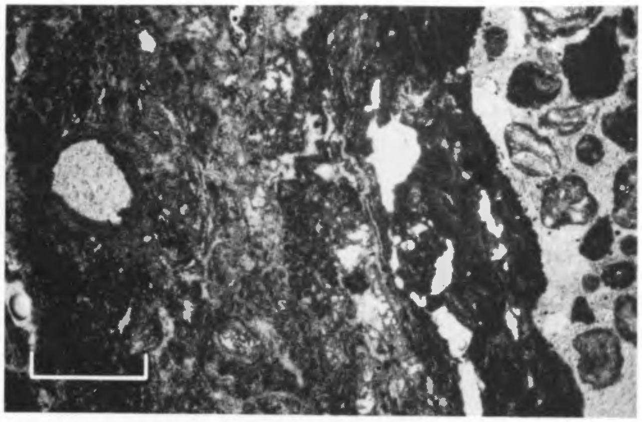
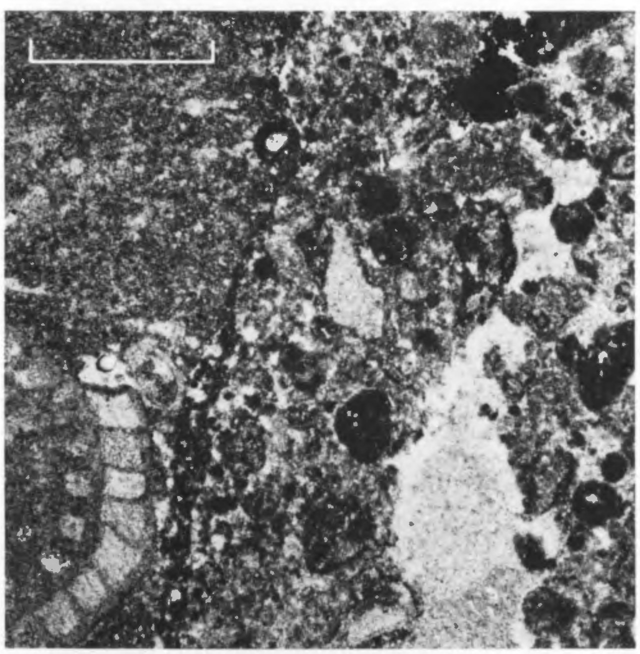


FIGURE 21. Thin section photomicrograph of an upper carbonate-upper interval (J, 4063 ft., Palmer #10). A fissure several mm wide, on far left, is loosely filled with resistant, micritized bioclasts and wall rock fragments cemented by blocky, coarse calcite spar. Wall of fissure illustrates heavily altered carbonate (diagenetic overprinting). Dissolution, recrystallization, and precipitation products include a dark, poorly laminated, very thin carbonate crust adjacent to the fissure, coating a finely pelletoid and mottled packstone. Note the circular void surrounded by dense micritic lime mud at right center; this is a root cast, similar in form to those which occur in the overlying upper shale. PLANE-POLARIZED LIGHT. Bar scale equals 1 mm.

locally important in this facies in the northern part of the study area. Sedimentary structures include high-angle cross-stratification (Fig. 20) in coarse mixed-skeletal packstone, algal stromatolite (as noted above), lime mudstone intraclast conglomerate, and, most commonly, organically disturbed or burrowed beds of packstone or grainstone.

Diagenetic effects are much more evident in this facies than in the underlying lower interval. Internal sediment commonly occurring in vugs and fissures is composed of shale like that overlying this unit, silt, or clasts of carbonate wall rock and resistant bioclasts (Figs. 21, 22). Associated features include overcompacted grainstone fabrics with individual grains, which are highly micritized and embayed (Fig. 23). Intergranular porosity may be either enhanced by dissolution or occluded by coarse, sparry calcite cement. More extreme effects include *in situ* brecciation and erosion of the top of this carbonate zone (Figs. 24, 25).

The upper interval of the upper carbonate unit typically includes shoal-water facies, which may be capped by deposits formed in restricted, shallow-water environments. The high-energy, shoal-water, marine deposits (Fig. 18) consist of coarser-grained,



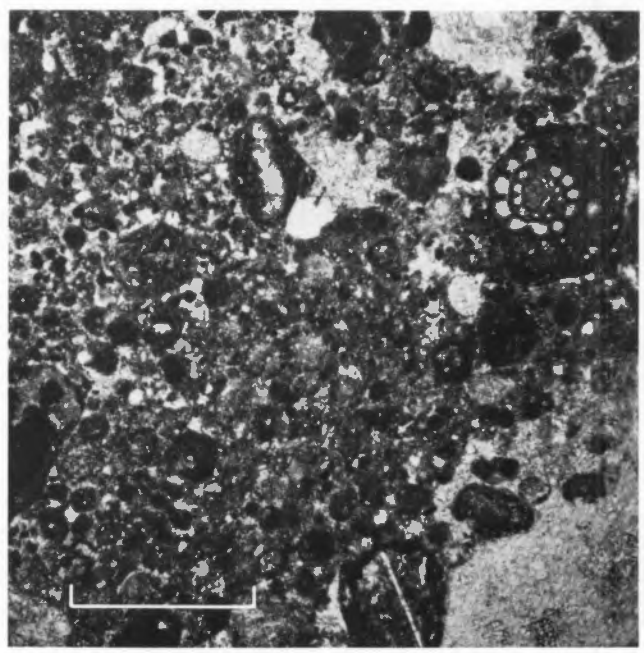


FIGURE 22. Thin section photomicrographs of an upper carbonate-upper interval (J, 4064 ft., Palmer #10). Areas illustrated are adjacent in specimen, and they illustrate a fissured area completely filled with rounded, resistant bioclasts and wall rock debris. Note corroded fusulinid in the upper right in the right-hand photo. In contrast, the fusulinid in the unaltered wackestone on the left in the left-hand photo is well preserved. Note the sharp vertical contact between the unaltered wall rock and the "crumbly fracture" (Dunham, 1969). Photographed in PLANE-POLARIZED LIGHT. Angular shaped, black-colored areas are pyrite. Bar scale equals 1 mm.

FIGURE 23. Thin section photomicrograph of an upper carbonate-upper interval (D, 3160 ft., Nicholson #1). Brachiopod, fusulinid, crinoid, bioclastic grainstone-packstone. Brown-stained, leached, embayed grains, moderate to heavily micritized. Solution-enhanced intergranular porosity between grains illustrates overcompaction. (Zone perforated for production.) PLANE-POLARIZED LIGHT. Bar scale equals 1 mm.

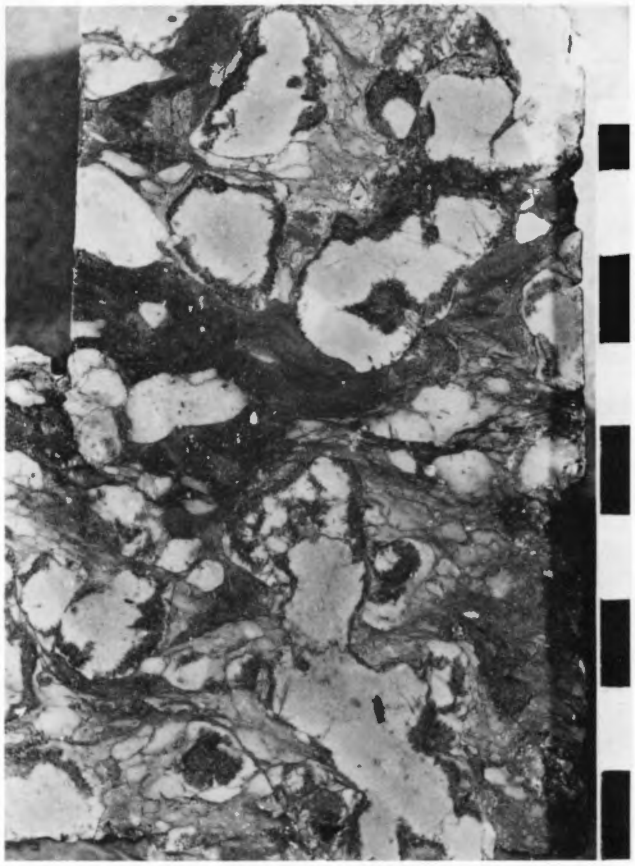


FIGURE 24. Core slab of an upper carbonate-upper interval (A, 3981 ft., Bartosovsky #1). *In situ* brecciation of lime mudstone-wackestone with "clasts" in green shale. Adjacent carbonate contains solution cavities filled with the same green shale. Surface corrosion and fracturing of carbonate are common. Top 2 ft. (0.7 m) of the interval contain corroded, desiccated carbonate clasts in red shale matrix. Note elongate, irregular shapes of some of the carbonate "clasts."

FIGURE 25. Core slab of an upper carbonate-upper interval (G, 3663 ft., Rathe #1). Mixed-size and -type, rounded to angular, solution-embayed carbonate clasts (generally containing restricted, or no, fauna) in red-brown shale matrix, which itself contains residual, resistant bioclasts. Top of interval (1 ft.) contains floating carbonate clasts in red shale. Note that clasts are surrounded by pink-to-tan, micritic calcite (see also Fig. 32).

abraded bioclasts, many of which are highly micritized and worn in appearance because of the activity of boring organisms and the abrasion resulting from transport by waves and currents. Although sorting of grain sizes is good in these deposits, there are few coated grains present. Actual oölite grainstone occurs only in the core from Adell Field (Fig. 26), in the extreme southeastern part of the study area. The grainstones usually are several (two to six) feet thick, but not as thick as those reported in Lansing-Kansas City formations farther south (Brown, 1963; Hopkins, 1977).

Wave and current energy appears to have been more limited on this upper shelf location than it was farther south. Where present, the high-energy deposits may represent beaches, offshore shoals, or tidal bars. Their location probably depended on local bathymetric relief or on local change in slope of the bottom, which would have focused current and wave energy and resulted in well-winnowed deposits. Carbonate buildups or other prominences on the shallow shelf would be obvious places to look for these types of deposits.

Restricted marine, intertidal, or supratidal carbonate deposits (Fig. 27) commonly cap this upper carbonate interval. The restriction may have resulted from poor circulation over a broad shallow shelf, from the lack of strong currents in a lagoon blocked off from open water by a shoal, or from the presence of tidal flats or low-relief islands. The salinity in these environments varies from normal marine to hypersaline or, possibly, brackish. Morphologic features include mud flats, ponds, marshes, tidal channels and levees, and storm berms. These conditions comprise a highly variable stress environment; consequently, few indigenous skeletal particles occur in the deposits. The fine-grained carbonate formed there commonly includes occurrences of microcrystalline dolomite (Deffeyes and others, 1965).

Microcrystalline dolomite replaces lime-mud and scattered skeletal grains and also is present filling voids left by the dissolution of some particles (Land,

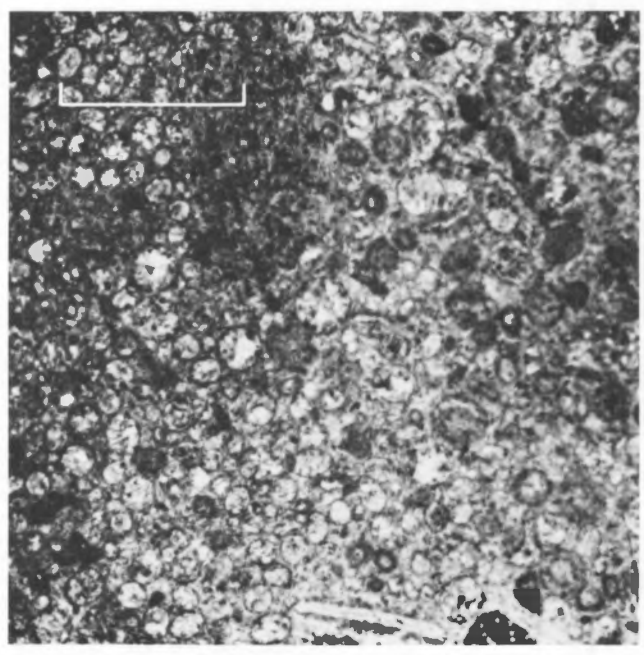


FIGURE 26. Thin section photomicrograph of an upper carbonate-upper interval (F, 3672 ft., Adell Un. 406). Fine-grained oölitic grainstone containing finely recrystallized oöids, voided oöids filled with coarse blocky spar, occasional bivalves including brachiopods, scattered quartz silt, all cemented by finely crystalline calcite. PLANE-POLARIZED LIGHT. Bar scale equals 1 mm.

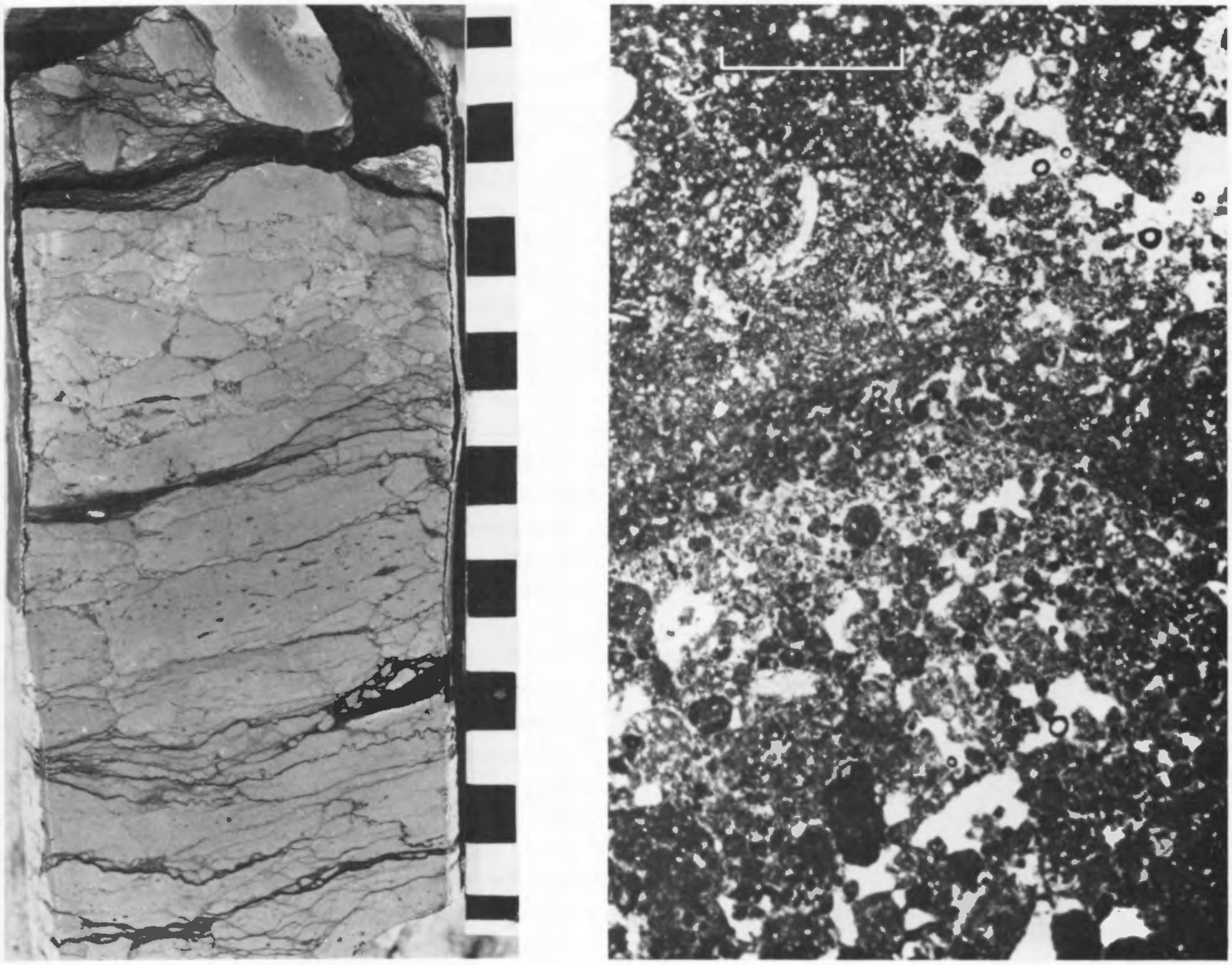


FIGURE 27. Core slab and thin section of an upper carbonate-upper interval (slab photo: H, 3756 ft., #1 Miller "Z"; photomicrograph: J, 4181 ft., Bartosovsky #1). *Slab:* Very top of carbonate containing rotated carbonate clast in gray-green shale at top, fragmental "fitted" clasts below this, and horizontally and vertically fractured buff-colored carbonate mud at bottom. Note small fenestral, spar-filled voids within the carbonate along the center of the core. *Photomicrograph:* Partly dolomitized, pelletoid, ostracod-bearing packstone-wackestone containing scattered irregular cavities, some apparently circumgranular-type, partly filled with coarsely crystalline dolomite. PLANE-POLARIZED LIGHT. Bar scale equals 1 mm.

1973). The dolomite occurs predominantly in the restricted marine or intertidal-supratidal deposits, but is found also in underlying open-marine carbonates. Smaller results of dissolution such as embayed grains and smaller vugs and molds may also be due to the dolomitization process (Deffeyes and others, 1965). Several samples have coarse anhydrite crystals filling previously open voids and replacing some of the coarser void-filling dolomite. This microcrystalline dolomite may be similar to dolomite occurring in modern mud-flat deposits, which results from contact of the fine carbonate sediment with magnesium-rich brine soon after deposition. But some of the dolomite, especially that in the underlying marine carbonate units, may have resulted from contact of these deposits by meteoric water percolating downward through the overlying dolomite after the sediments were above sea level, but before they were mineralogically stable (Land, 1973).

Evidence of early subaerial exposure and of diagenesis caused by freshwater is common in the upper interval of the upper carbonate unit. During deposition, tidal-flat, fine-grained carbonate deposits developed fenestral fabric and desiccation cracks in response to repeated wetting and drying (Fig. 27).

Soil profiles and related structures formed at the top of the upper carbonate in several zones of the Lansing-Kansas City Groups. These features occur in different parts of the study area in different zones (Fig. 28), implying that exposure of the carbonate deposits to subaerial weathering happened repeatedly and involved actual relative changes in sea level that differed in magnitude through time. This subaerial exposure was very important in enhancing or modi-

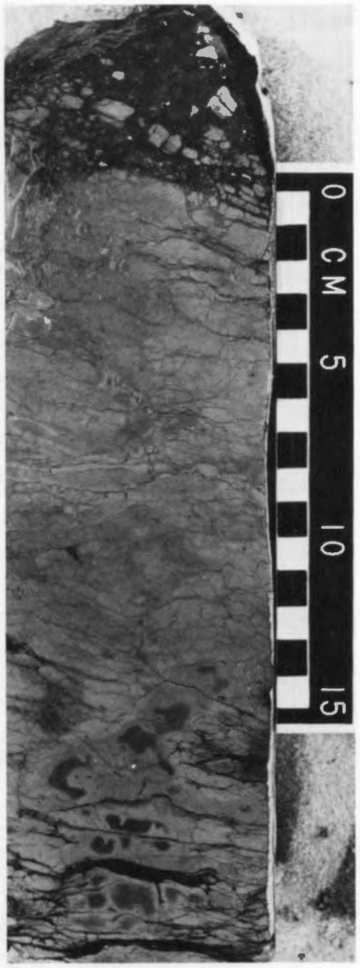


FIGURE 28. Core slab of an upper carbonate-upper interval (F, 3755 ft., Miller Z-1). Dolomitized, finely discontinuous laminated lime-mud containing scattered altered skeletal fragments including crinoids. Intensely altered carbonate with dominant horizontal and minor vertical fractures, some filled with red shale. Overlying red shale contains carbonate clasts. Note near-original orientation of the clasts in the lower right portion of the shale just above the more continuous carbonate surface.

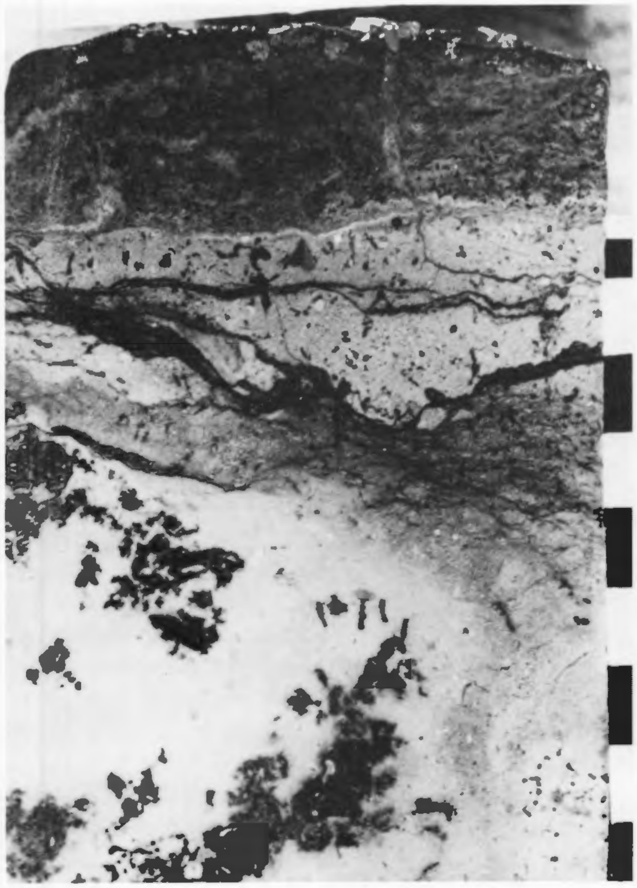
fying the reservoir quality of some of the limestones. The processes of soil formation were more intense northward and were continued during deposition of the shale above the upper carbonate.

Crinkly laminated crusts (Fig. 29) capping some limestones are similar to those forming on the Pleistocene limestone exposed in south Florida (Multer and Hoffmeister, 1968) and other areas. Clotted and laminated texture (Fig. 29), circumgranular cracks (Fig. 30), non-tectonic crumbly fractures (Dunham, 1969) (Fig. 22), and fossil root tubes (Figs. 21, 29) are further testimony to the soil-forming processes that altered the original fabric of these rocks (Enos and Perkins, 1977; Harrison and Steinen, 1978). In-place brecciation, dissolution, fragmentation, and possibly erosion and transportation caused more drastic changes in the limestones. These processes were more intense northward, suggesting that the frequency of occurrence of nonmarine environments increased in that direction.

Diagenesis significantly altered the porosity distribution in the upper carbonate units of several Lansing-Kansas City zones. Primary porosity is either enhanced by dissolution or occluded with calcite cement. Secondary porosity developed in some units is substantial, and these limestones constitute good, permeable reservoir rocks. This secondary porosity may be predictable, because certain facies are more susceptible to leaching by freshwater; i.e., more metastable bioclasts are present, and secondary porosity is best developed where these units approach their northward limit or at a location of local paleotopographic development (Fig. 31).

Upper Shale Unit—The upper shale unit caps each sedimentary cycle (Table 2). This clastic unit characteristically has a red-brown color, except that, locally, it may be green, olive, or gray. Intervals may be quite silty or sandy, but the deposit is predominantly a silty, micaceous claystone. Thickness ranges from less than five to 30 feet, and it may vary substantially over short distances.

The upper shale is very sparsely fossiliferous. Locally, a thin layer of marine fossils occurs near the base of the unit, where it may contain soft, green, pyritic claystone with tan lime mudstone lenses. Nodules of pink or buff-colored microcrystalline calcite or dolomite are scattered through the shale, contributing to its mottled appearance. The shale is usually massive, with occasional slickensides, and it breaks with a blocky fracture. It contains tubular, shale- or calcite-filled structures with diameters of one to five mm.



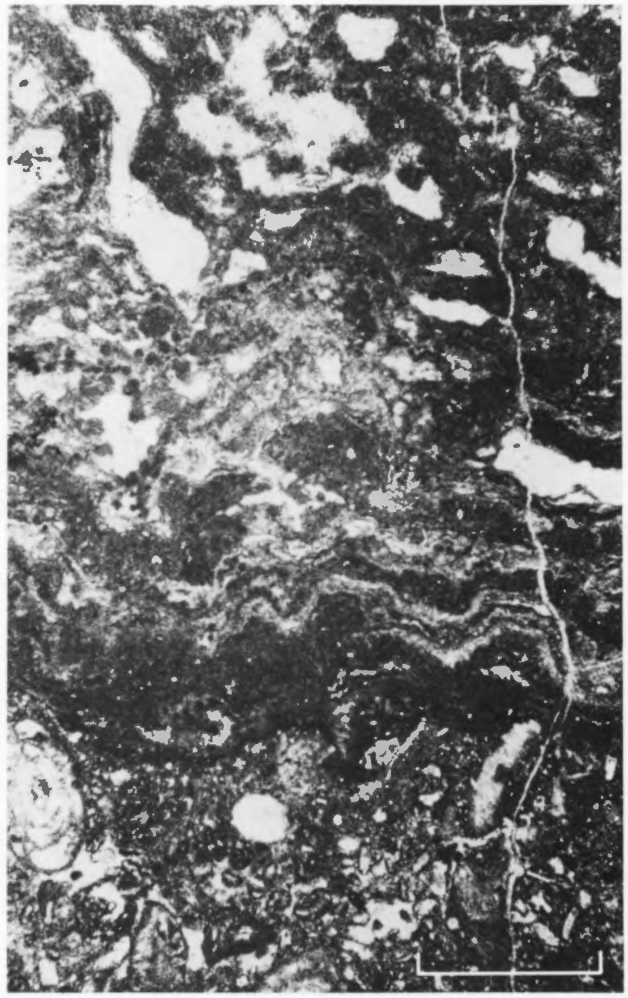


FIGURE 29. Core slab and thin section of an upper carbonate-upper interval (G, 4301 ft., Prentice #1). The slab's upper 2 cm is a brown crustose, micritic, vuggy layer capped by a surface of pyrite. This carbonate layer contains fine tube-like cavities (pedotubules) lined with dense micritic carbonate sometimes stained dark red-brown. This crust-like layer is in abrupt contact with underlying bioclastic packstone, which is cut by vugs and extensive horizontal fractures. The photomicrograph reveals a crinkly, laminated, probably accretionary deposit of dense, micritic carbonate cut by numerous tube-like voids. Some portions appear pelletoid. This micritic carbonate lies directly on a bioclastic packstone. PLANE-POLARIZED LIGHT. Bar scale equals 1 mm.

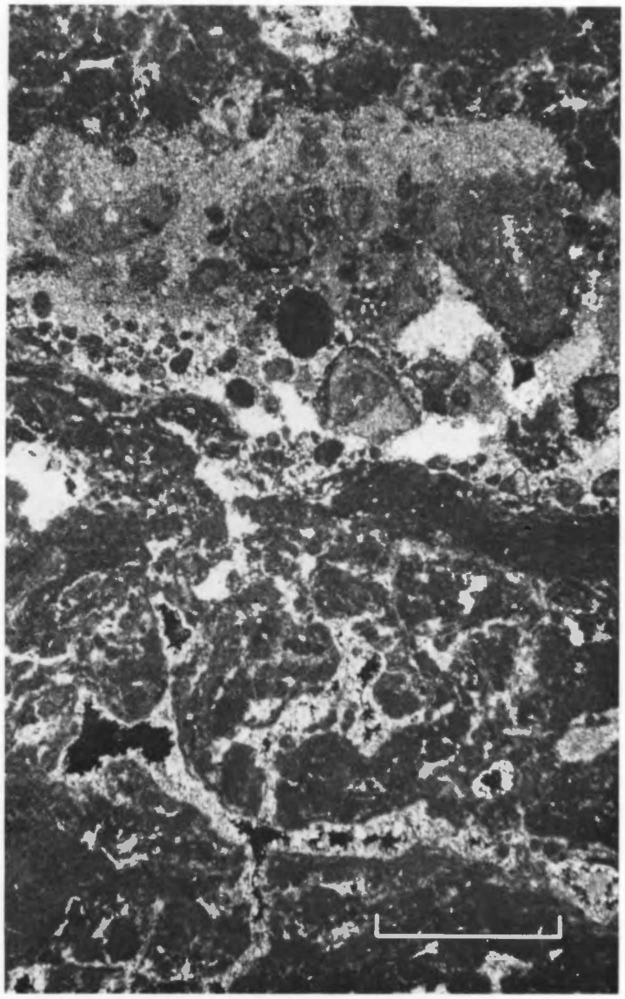


FIGURE 30. Thin section photomicrograph of an upper carbonate-upper interval (F, 3718.5 ft., Miller Z-1). The upper, light-colored area is a portion of a large subhorizontal sheet crack partly filled with debris of resistant bioclasts and wall rock. Both fine micritic calcite and coarser blocky spar fill this void. Many of the fractures and solution-enhanced fissures below this sheet crack and within the dense pelletoidal matrix surround "grains," i.e., they are circumgranular. Coarse, blocky calcite crystals fill remaining void space. CROSS-POLARIZED LIGHT. Bar scale equals 1 mm.

Diagenetic effects in the upper shale are important to understanding its origin. The typical red-brown color may be, in part, post-depositional. Calcite nodules commonly occur with shrinkage fractures, circular and elongate vugs and fissures, and with gray-green, yellow, red, and maroon mottling in the shales. Vugs are frequently filled with limonitic, dull yellow-green or hematitic, maroon-colored shale (Figs. 32, 33, 34).

The environment of deposition of the upper shales is closely related to the processes of diagenesis that affected them. The absence of fossils, the oxidized appearance, and the nodular carbonate in some layers all suggest a subaerially exposed continental deposit. The absence of primary bedding, the tubule structures, and calcite nodules may be a result of soil-forming processes and of plant-root action similar to that observed in some ancient fresh- and brackish-water lake and marsh deposits (McBride, 1974). The observed green patches and fine mottling are thought to result from removal of limonite grain coatings as ferrous-organic complexes in reducing soil water (Hubert, 1977). The process may have been related to decay of plant roots.

These features of upper-shale units probably represent paleosoils. The carbonate nodules closely resemble the properties of caliche micrite (Reeves, 1970). The circular and elongate vugs, with associated cryptocrystalline calcite, and iron oxide-rich clay are similar to pedotubules described in Recent soils (H. Dickey, personal communication, 1978).

Analyses of samples from a paleosoil horizon (Table 3) indicate that the proportion of feldspar decreases and of mixed-layer clay minerals increases with depth in the paleosoil. The total amount of clay is highest and of carbonate is lowest at the base of the soil zone. This variation in composition may be related to the original composition of the parent material of the soil or to the soil-forming process itself. Gile and Grossman (1968) describe reddish-brown, sometimes very calcareous, horizons in the

TABLE 3.—Estimated major-mineral composition of the paleosoil above J-Zone carbonate in Skelly Bartosovsky #1. X-ray diffraction analyses by G. W. James.

Position	Depth (feet)	Major Minerals (Volume %) Qtz	Feld-spar	Clay	Calcite	Comment
Above soil	4162	40	20	20	20	Minor mixed-layer clays
Near top paleosoil	4165	35	15	20	20	Increase mixed-layer clays
Near btm. paleosoil	4167	40	10	40	10	Further increase mixed-layer clays

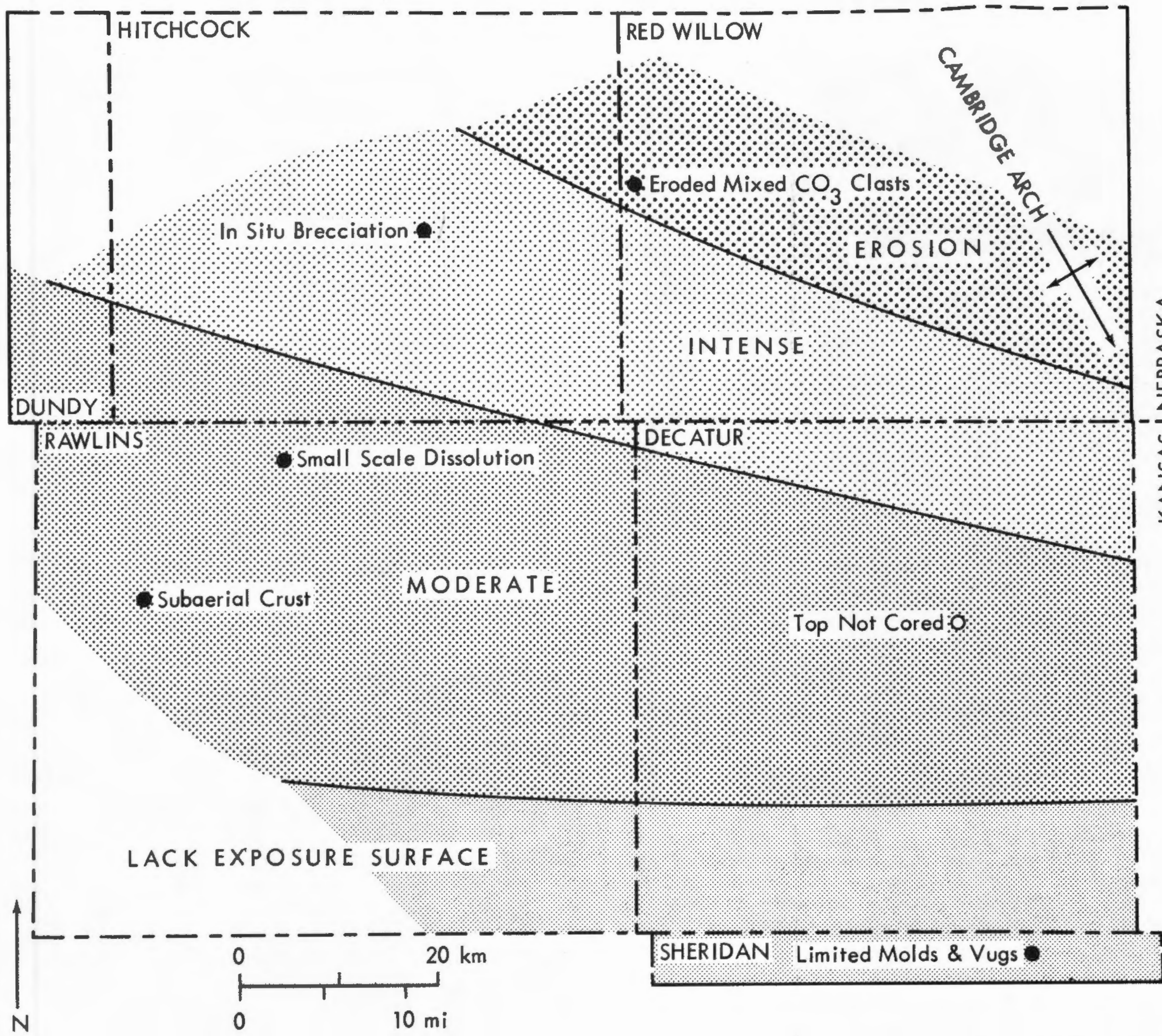


FIGURE 31. Variation in intensity of freshwater diagenesis and subaerial exposure across the area of study affecting the G-Zone carbonate (based on available core data). Limited data suggest northward (landward) increase in intensity of freshwater diagenesis with appreciable subaerial exposure.

FIGURE 32. Core slab of an upper shale (J, 4164 ft., Bartosovsky #1). Red-brown silty shale containing abundant fine, white, calcareous tube-like concretions (pedotubules) and cm-sized pink to buff-colored micritic carbonate mottling (incipient calichification) cut by occasional fractures.

FIGURE 33. Thin section photomicrograph of an upper shale (J, 4166 ft., Bartosovsky #1). Pedotubule consisting of a rounded void surrounded by micritic carbonate, partly filled by black (opaque) hematite along the upper portion of the void with the remainder filled by clear, coarse calcite. The surrounding grains are quartz silt. PLANE-POLARIZED LIGHT. Bar scale equals 0.25 mm.

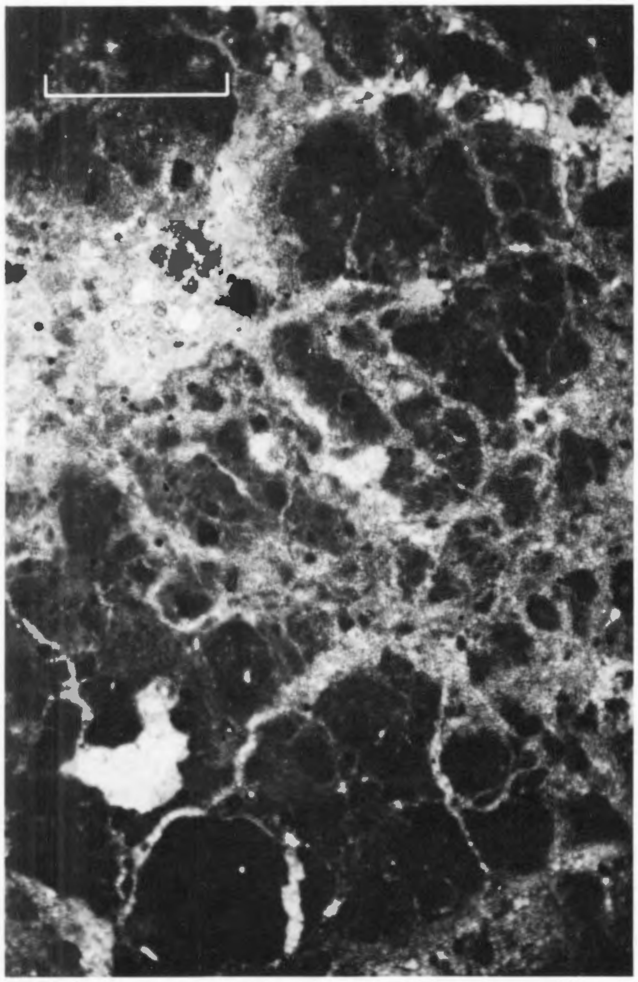


FIGURE 34. Thin section photomicrograph of an upper shale (D, 3648 ft., Wertz #1). Clotted, Fe-oxide-stained, cryptocrystalline calcite (caliche) with well-developed circumgranular fractures filled with sparry calcite. Quartz silt grains have been displaced or dissolved during formation of caliche. PLANE-POLARIZED LIGHT. Bar scale equals 1 mm.

desert soils of southern New Mexico. Montmorillonite in these desert soils is an important component of the clay. It may be the precursor to the mixed-layer clay observed in this study. Microcrystalline aggregates, which are mostly altered feldspars, are common in New Mexico desert soil. The decrease in feldspar and increase in mixed-layer clays noted in this Pennsylvanian paleosoil may be associated with the destruction of feldspar during soil formation. Oriented clay-coated sand grains and clay-lined pedotubules are also found in the desert soil mentioned above. The clay coatings on the grain surfaces are preferred sites for initial carbonate precipitation. If enough carbonate accumulates, it can obliterate these coatings and can completely engulf parts of the soil horizon.

Soils that are similar to the paleosoils described here also occur in the Texas Panhandle (U.S.D.A., 1976, p. 223, 249), suggesting that the ancient climatic conditions may have been similar (semiarid) to those in northwestern Texas. These subaerial conditions are an extension of those that affected the upper carbonate zone and that were so important in modification of porosity in the carbonate.

EPEIRIC SHELF SEDIMENTATION

EPEIRIC SEDIMENTATION OF THE LANSING-KANSAS CITY GROUPS

A vertical sequence of four basic lithofacies units, which is repeated several times to form the Lansing-Kansas City Groups, has been described. Each sequence comprises a cyclothem, or a cycle of sedimentation. A brief genetic description of these units is provided in Table 2.

A similar vertical sequence has been recognized in other localities in other basins. The lower carbonate at the base of the sequence records an inundation of the area by seawater and local reworking of underlying clastics. The lower shale represents a period of clastic influx that occurred at a time of maximum inundation. As the water began to clear, carbonate deposition began under still intermittently turbid conditions. The clearing of the water also corresponded with a period of shallowing when low-energy, open-marine carbonates were overlain by shallow-water facies of the upper carbonate zone. Shallowing continued to a point at which the area was emergent, and subaerial processes became dominant during deposition of the upper shale. Each succeeding cycle represents transgression and regression of the different environments of deposition across a broad epeiric shelf (Heckel, 1977, 1980).

Shaw (1964) and Irwin (1965) proposed a deductive model of clear-water, epeiric-shelf sedimentation to describe similar lateral and vertical aspects of some ancient carbonate stratigraphic sequences. One of the basic requirements for this model is a broad, low-relief, marine shelf with a slight depositional slope, such as that in western Kansas and adjacent areas during Lansing and Kansas City time (Fig. 4). According to this model, differences in direction and strength of water circulation and degree of agitation were present across the Lansing-Kansas City shelf. Several trends of sedimentary environments lay parallel to the northern strandline or to the southern shelf margin, each reflecting hydrographic, climatic, and other ecologic factors, and proximity to a northern source of terrigenous clastic sediment.

Relative rise or fall of sea level resulted in the migration of these environmentally controlled facies across the shelf. This lateral migration and overlapping of facies is also recognizable in the vertical succession of rock types in the Lansing-Kansas City. As the western Kansas shelf subsided, generally similar types of sediments were repeatedly deposited (Fig. 35). Variations in this typical cycle of sedimentation resulted from differences in the relative changes of sea level, rates of subsidence, or other factors. Diagenesis of parts of these cyclic sequences also varied with these same factors, especially in the northern part of the shelf where subaerial exposure of the regressive units was accompanied by alteration by freshwater.

Wilson (1970) and Armstrong (1974) also suggest pertinent details of facies distribution across a low-relief carbonate shelf. This conceptual model (Fig. 36) applies well to the sediments described in this report. In seaward areas of the shelf, a low-energy zone exists below wave base. Marine shales are deposited farthest off shore and open-marine lime mudstones and wackestones are deposited closer to shore. Landward, waves and stronger currents winnow the bottom sediments. Maximum organic productivity is generally associated with the shallow agitated environments, resulting in abundant skeletal debris being available to form deposits of abraded grainstone and packstone. Oölite grainstones formed in a similar high-energy environment where carbonate-saturated seawater was agitated, perhaps by currents interacting with bathymetric prominences.

The action of waves and currents was minimal in some other locations on the shelf, which may have been too flat and shallow over broad areas. Poor circulation of shallow water produces mud-supported facies landward of the high-energy accumulations, representing restricted lagoonal or tidal flats. Finely crystalline dolomite is common in the restricted facies, and is probably the result of early dolomitization of lime-mud in the nearshore environments. In the study area, elements of this carbonate platform model are extended landward to include red-brown shales and silts that interfinger with the adjacent shallow marine carbonates.

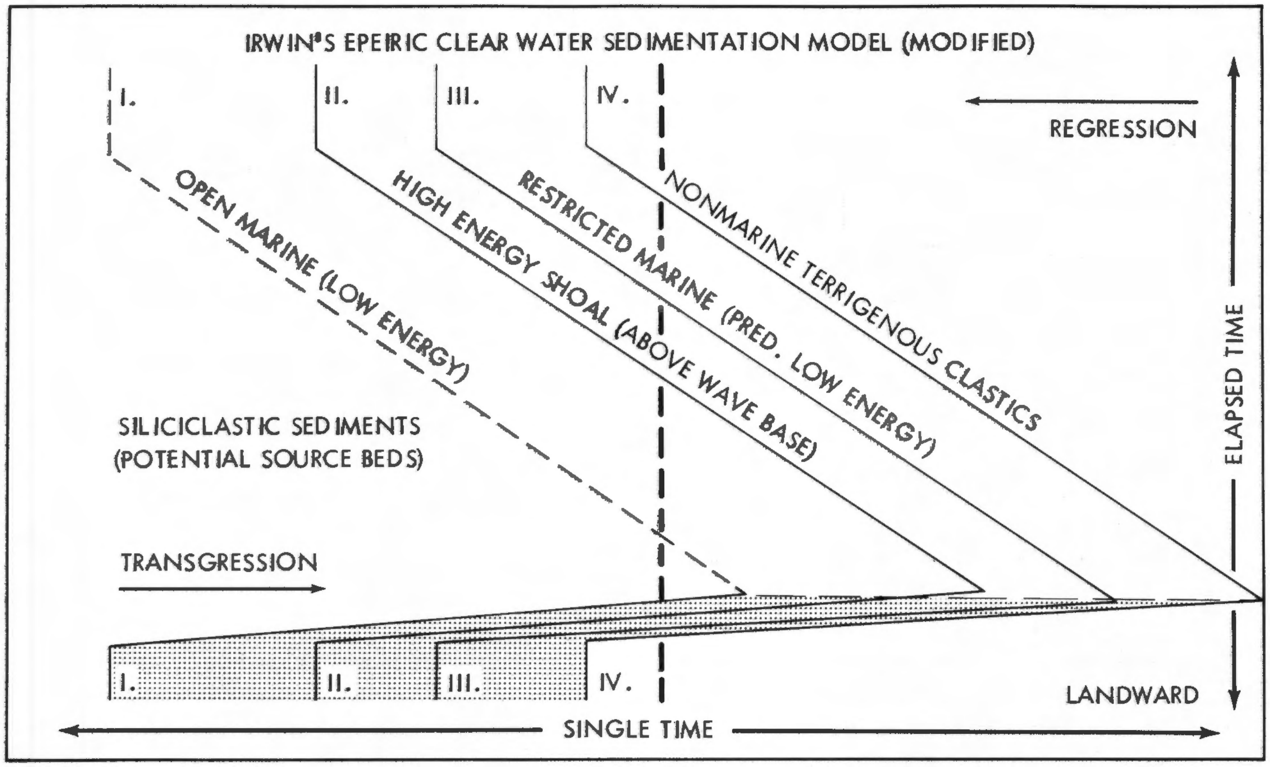


FIGURE 35. Modified version of Irwin's epeiric, clear-water, sedimentation model similar to that proposed by Coogan (1969). The illustration portrays greatly simplified variations in facies across the shelf with time during a complete cycle of transgression and regression. Distribution of facies at any instant in time would be the facies that occur along a single horizontal line through the diagram. The transgressive event is relatively rapid and is represented by a distinctive, unique deposit (patterned area) similar to facies II, III, and IV in the regressive phase of the cycle. The vertical dashed line represents the typical facies components of a cycle, as observed in this study.

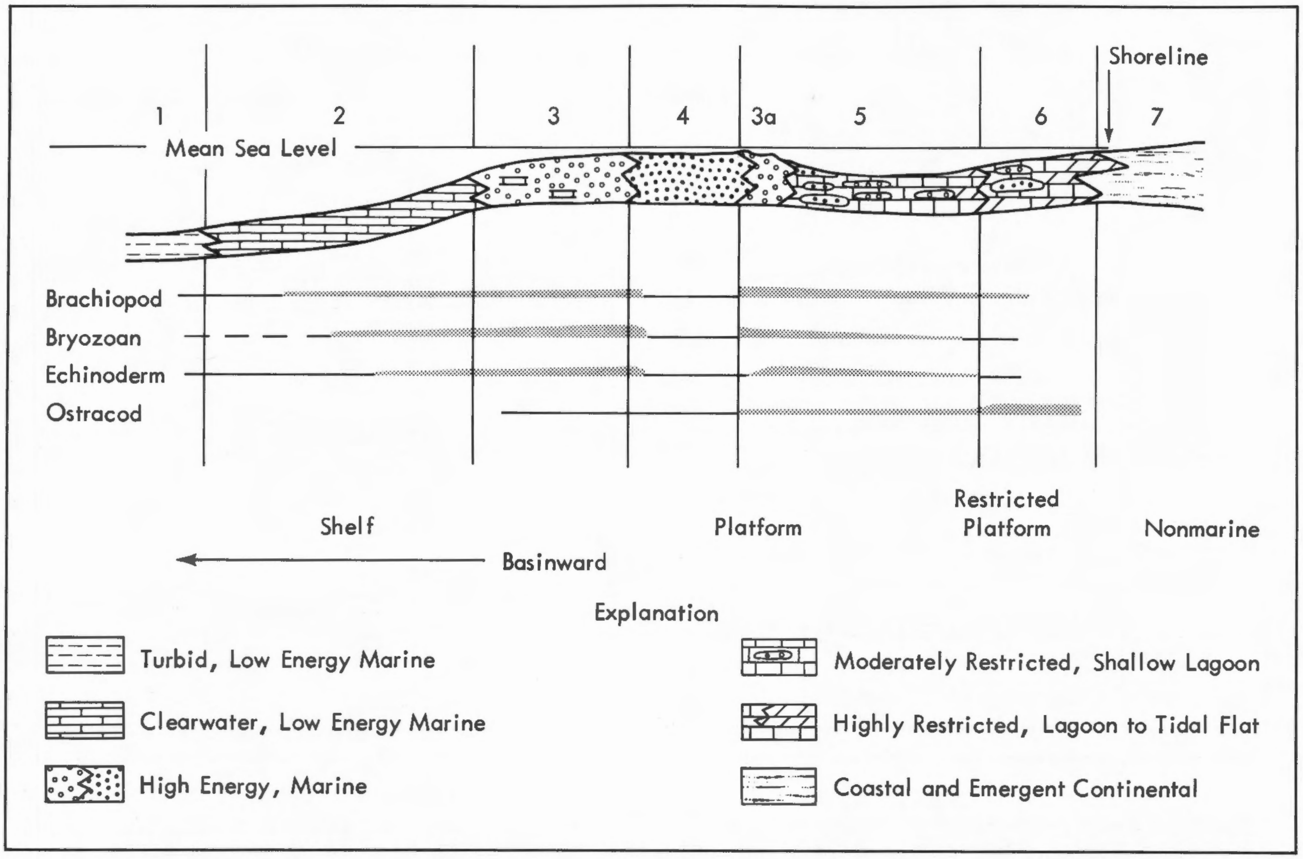


FIGURE 36. Modified version of a platform depositional model after Wilson (1970) and Armstrong (1974). Seven basic contemporaneous depositional environments are shown, including subtidal marine deposition most distant from shore, through facies representing coastal and an emergent continental environment. Environments are numbered as described in Table 2.

LANSING-KANSAS CITY CYCLES OF SEDIMENTATION—INTERPRETATION

The idealized models described above may be used to interpret the cyclic events that resulted in the Lansing-Kansas City Groups in northwestern Kansas and contiguous areas. According to the epeiric model, the shelf is first inundated through subsidence and/or eustatic sea-level rise. This transgression results in a rapid landward shift of facies (Fig. 35). The shelf, being essentially flat, receives deposition of a thin, very widespread *transgressive unit*, the lower carbonate unit described in Table 2. This deposit is a unique condensed section containing fossils, representing rapid change from shallower- to deeper-water carbonate platform conditions. It may consist of any of a number of types of sediment, including phylloid algal limestone, sandy bioclastic limestone, quartz sandstone, fusulinid-bearing lime mudstone, and others, depending on local conditions (Elias, 1962; McCrone, 1963; Wilson, 1967; Toomey, 1969; Heckel, 1975, 1980).

Approximately at the culmination of transgression (maximum marine inundation on the shelf), *marine shale*, equivalent to the lower shale unit described earlier, was deposited. Terrigenous clastics are also important later in the cycle and are probably related to renewal of a northern, landward source. Clastic influx may have begun early during transgression and could have overcome the general shelf inundation in some areas during this phase, particularly along the upper shelf margin near the source area. As noted in other areas (Wilson, 1967), these clastics, deposited during transgression of the sea, may cause a local "regression" of the shoreline, thus complicating the cycle. With delta abandonment or other change in clastic influx, relative sea-level rise again dominates.

The upper portion of each cycle constitutes a regressive, or progradational, phase of deposition (upper shale and carbonate units of Table 2). In a dip direction (basinward), these facies are diachronous and seem to become younger seaward. Rates of local regression may exceed regional regression as carbonate buildups develop. Rates of subsidence and eustatic sea-level change also were important in determining the extent and nature of these regressive sediments.

The upper carbonate unit (Table 2) includes facies deposited in open-marine to restricted-marine environments (Fig. 36). Because it represents regressive sedimentation, this carbonate is also referred to as the *regressive carbonate* unit.

Shelf location, sea-bottom configuration, water-circulation patterns, and other factors affect the trends and development of the shoal carbonates in this unit as they prograde out onto the shelf. These shoal-water carbonates have been the most attractive targets for oil exploration in this area thus far.

Continued regression resulted in subaerial exposure of the regressive carbonate zone in the northern portion of the study area. Subaerial crust formation, *in situ* brecciation, and erosion affected the carbonate in this area. The duration and intensity of exposure to subaerial weathering increased northward. Early freshwater diagenesis significantly influenced the present distribution of porosity in these rocks.

Oxidized, subaerially exposed upper shale (Table 2) is characteristic of the study area. This deposit is the culmination of the regressive process, as the shoreline advanced basinward and continental sedimentation became the important process. This shale is referred to as the *regressive shale*.

The thinness or general absence of channel sands, gray shale, coals, and underclay suggest the absence in northwestern Kansas of active delta growth that is so commonly associated with rocks of equivalent age in eastern Kansas (Heckel, 1977, 1980). In eastern Kansas, fluvial channel sands in thick shales and erosion of these channels into the underlying regressive carbonates are common and, in some cycles, the influx of clastic sediment periodically overwhelmed and terminated regressive carbonate deposition (Heckel and Baesemann, 1975, p. 499).

The abundant terrigenous clastics that complicate the cycles in eastern Kansas and in north-central Texas (Van Siclen, 1964) are probably related in part to higher rates of rainfall than occurred during deposition in northwestern Kansas. The aridity of the Upper Pennsylvanian climate increased from the Appalachians to the Ancestral Rockies during the late Pennsylvanian (Heckel, 1977). Evaporites and eolian red beds are more common in rocks of equivalent age to the west, including localities in South Dakota and Wyoming.

In the southern part of the study area, two of the regressive shales include thin carbonate units that become thicker southward (the C and F carbonate zones in Figure 8). Associated with these carbonates are green and gray shales. The carbonates have the characteristics of marine to restricted marine, or tidal-flat, deposits. Core from an updip, equivalent, red-brown shale interval contain embayed and fractured pieces of dolomitic, tidal-flat carbonate. These thin, unusual carbonates represent a relatively limited transgression, probably more as the result of a brief sea-level rise than of a variation in sediment progradation. South of the study area these carbonates are thicker, sometimes capped with grain-rich carbonate including oölite. Landward, beyond the carbonate pinchout, the equivalent shale interval includes dark gray-green and unfossiliferous shale between red-brown oxidized shale (Bartosovsky, 4158 ft. to 4162 ft.). Compared to other transgressions, only partial inundation of the landward shelf could readily account for this sediment sequence.

The updip limits of these limestones coincide with an area of intense freshwater diagenesis in carbonates that are dominated by shoal-water facies. Similar facies relationships probably also are present in the extreme updip extensions of the major regressive carbonate zones where they wedge out northward (in Nebraska) into terrigenous clastics.

Figure 37 is a generalized model of cycles such as those of the present study, in the area of transition from mainly carbonate to clastic sediments, illustrating the lateral facies variation through time. With very low-angle depositional slopes and rather broad facies belts, the contacts between the succeeding facies are essentially flat. A typical cycle of sedimentation includes transgressive and regressive components, including a regressive carbonate zone that is most likely to become porous oil and gas reservoir rock.

Each cycle of sedimentation will be referred to in following discussion as a zone cycle, e.g., G-Zone Cycle, which includes the G regressive carbonate zone (Fig. 6). The components of these cycles are equivalent to those of Heckel (1977), e.g., transgressive (or lower) carbonate = middle limestone; marine (or lower) shale = core shale; regressive (or upper) carbonate = upper limestone; regressive (or upper) shale = outside shale.

Environments of deposition and of subsequent diagenesis were very important in the development of potential hydrocarbon reservoir rocks in these cyclic sequences. Of particular note, early freshwater diagenesis was extremely important in the northern part of the study area and over local topographic highs. It is readily apparent from cores of wells (Table 4) that both grain-supported and matrix-supported carbonates have become reservoir rocks. Only with secondary diagenetic changes could the low-energy, mud-supported carbonates have become porous and permeable, e.g., through partial dissolution and non-tectonic fracturing (Figs. 11, 16). Most of the grainstone reservoirs also show evidence of enhancement of porosity by these same processes (Fig. 23). Overall, evidence indicates that freshwater diagenesis had a substantial positive effect on the development of oil and gas reservoirs in the study area (Watney and Ebanks, 1978).

Oil- and gas-producing intervals within the study area include every carbonate zone present. Seven zones are productive in a single well in Cahoj Field, Rawlins County, Kansas. Ninety-seven percent of the production and 90 percent of the wells are located on the Cahoj structure complex in northern Rawlins County. The J- and G-Zones have been perforated most frequently in this area. In Red Willow County, Nebraska, the D-Zone is the most commonly productive unit; in Hitchcock County, Nebraska, it is the J- and K-Zones (Fig. 2). Facies variations within a single zone result in different reservoir types occurring in different areas; consequently, evaluation and completion practices may differ for the same producing zone from place to place.

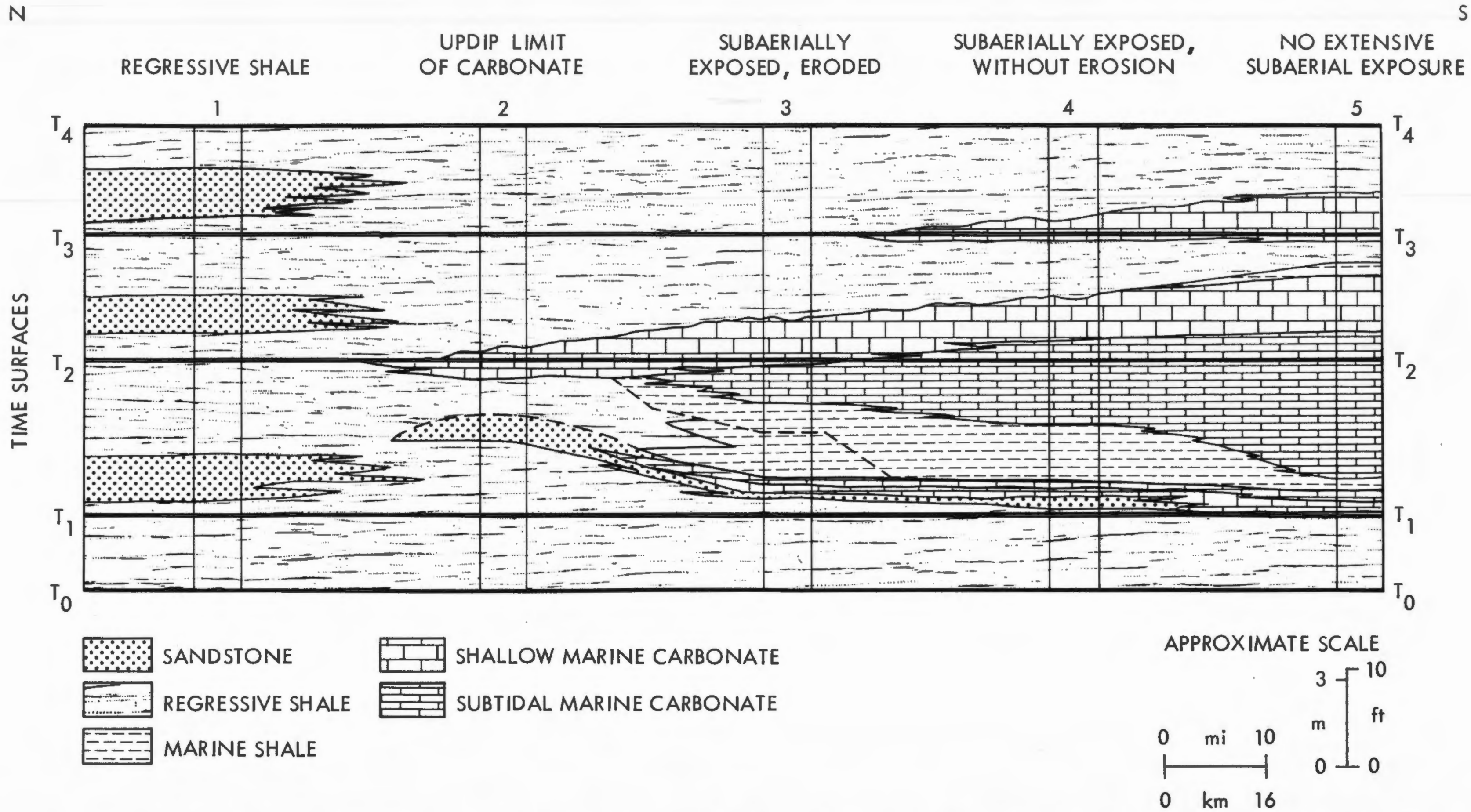


FIGURE 37. A conceptual stratigraphic model that depicts lateral and vertical relationships of facies within a major sedimentary cycle in the study area. This model is based on analysis of seven Lansing-Kansas City cycles. The updip pinchout of the regressive carbonate zone into the regressive shale is based indirectly on known pinchouts of the F and D carbonate zones within the study area. Subaerial exposure is indicated along the northerly updip surface of the regressive carbonate (illustrated by the wavy upper surface). Updip sands in the regressive shale interval are hypothetical. Oblique dashed line in the marine shale divides restricted (left) from more open marine (right) conditions. The well log in Figure 44 is divided into cycle-divisions that are the same as those illustrated here.

TABLE 4.—Representative cored reservoir facies in study area.

Well	Spot Location	Initial Production	Producing Zone	Porosity Thickness	Maximum Poros. (%)	Maximum Perm. (MD)	Reservoir Description
Skelly Bartosovsky #1	9-1S-34W seswsw	1000 BOPD	H_{MID}	5′	22	211	Wackestone with heavy freshwater alteration—lime-mud dissolution
			J_{MID}	4′	20	160	Dolomitized lime-mudstone with appreciable mud recrystallization
			J_{LOWER}	3′	16	2150	Freshwater altered wackestone (as H)
Murfin Drlg. Co.—Prentice #1	30-2S-35W cnene	16 BOPD	D_{MID}	7′	NA[1]	NA	Freshwater altered phylloid algal wackestone to packstone
Conoco Adell L-Kc Un. 406	2-6S-27W seswsw	wtr. injection	C_{TOP}	4′	14	3.5	Freshwater altered bioclastic packstone
			J_{TOP}	6′	21	69	Coarse-grained, diverse bioclastic grainstone with preserved primary porosity
Gore Wertz #1	6-2N-32W csenw	105 BOPD twtr.	K_{TOP}	4′	NA	NA	Heavy freshwater altered, fine bioclastic; pelloid wackestone to packstone
Farmer Nicholson #1	12-1N-27W cswsw	25 BOPD + 25% wtr.	D_{TOP}	2′	11	10	Fine to coarse grained, diverse bioclastic packstone to grainstone with heavy freshwater alternation and mud dissolution
			D_{LOWER}	2′	13	27	Heavy freshwater altered wackestone with abundant grain and mud dissolution with fine fractures

[1] NA: not available

EXPLORATION TECHNIQUES

QUALITATIVE WELL-LOG ANALYSIS AS AN AID TO EXPLORATION

Most wells in the study area have been logged and well cuttings are available. Cores are limited in number, but, where present, assist greatly in the interpretation of samples and logs. Exploration for oil and gas requires the integration of these types of data in order to establish favorable trends of potential reservoir rock units.

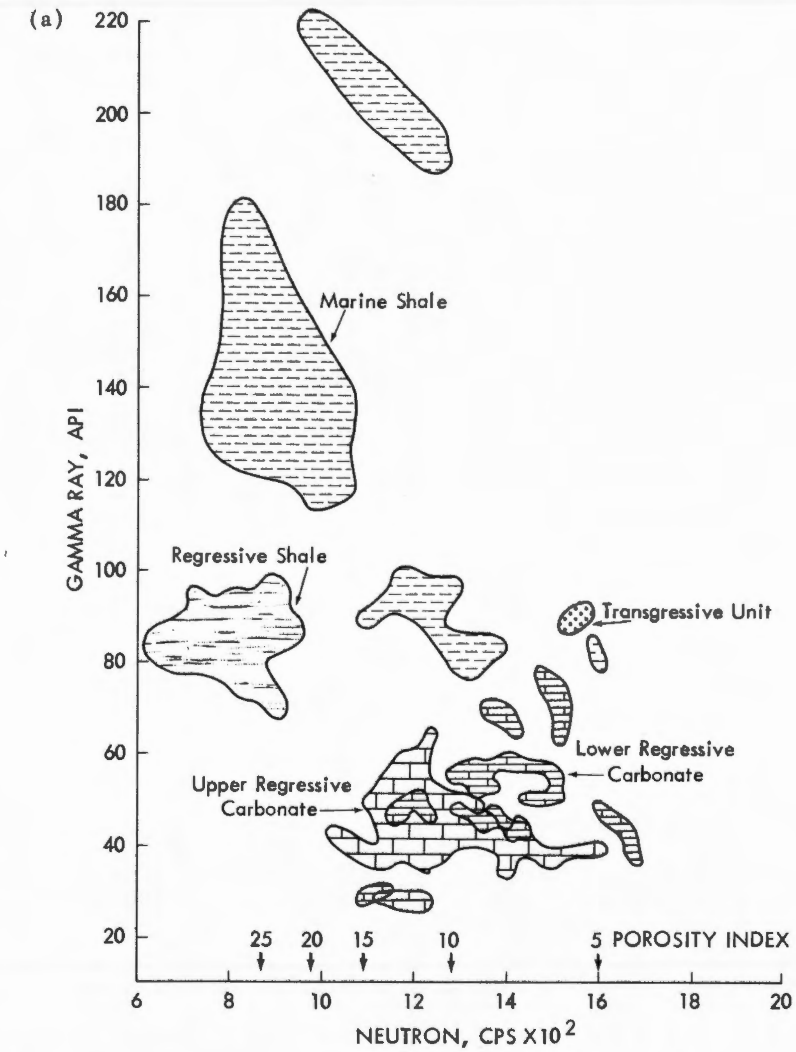
General trends in composition of the alternating shales and limestones in the Lansing and Kansas City Groups are discernible from geophysical well logs, provided that comparisons of the logs with cores are available for parts of the area (Figs. 7, 8). The log responses indicate sharper transitions between dissimilar rock types in a southward, or basinward, direction. Having identified the various members of cyclic zones in cores of several wells, it has been possible to recognize compositional variations in these zones on the basis of graphic cross-plots of log values from Gamma Ray (GR) versus Neutron (N) logs (Figs. 38, 39). The relative positions of groups of data points representing different kinds of units in the cycles suggest that such plots may be used to differentiate between the units in cases where identification is in doubt and no core is available. This may aid in correlating logs, in recognizing the appearance of additional limestones in the vertical sequence, and in mapping compositional change of the rocks as an indication of basin shape and direction to sources of terrigenous sediment. For instance, some of the lower intervals of regressive carbonate units are more distinct, on the logs, from underlying marine shales in a basinward well than in a more northern, landward well (Fig. 38).

The regressive carbonates become more distinct and well developed basinward due to a decreasing clastic component. Some of the lower regressive carbonates in the Adell well are distinctly denser carbonate than occur landward (low GR and high neutron cps). Marine shales in a more basinward position commonly have a distinctly higher GR response (200 API units) than that of the average shale base line. Northward, the GR response of the marine shales progressively decreases and becomes more like that of the regressive shales. Northward, all the facies tend to converge toward the regressive shale position depending on the abundance of clastic influx throughout the cycle.

According to the epeiric sedimentation model described earlier, the period of marine-shale deposition was longer farther basinward than it was landward, and the sedimentation rate was lower basinward. X-ray diffraction and core description suggest marine shale can be distinguished from regressive shales because of the higher carbonate content and greater clay fraction. (Watney, 1979). Probably the lower intervals of regressive limestone units are more distinct from marine shales in basinward areas because they are less argillaceous, more dense, pure limestones. There was not the almost continual influx of terrigenous sediment in basinward areas that there was farther landward. Slower basinward clastic sedimentation and reducing redox potential during burial with organic matter preservation also would have resulted in the enrichment of marine shales in heavy metals and possibly uranium, which would have caused an increase in their radioactivity.

Specific carbonate facies can be identified in the cross-plot in conjunction with limited core information. A plot of six cycles in the No. 1 Prentice well distinguishes the relatively clean, but low-porosity, portion of the phylloid algal carbonate of the D-Zone carbonate from the other regressive carbonates (Fig. 39). Similarly, the phylloid algae-bearing transgressive E-Zone is distinguished on this plot from the other transgressive carbonates. The porous upper regressive carbonate grainstone-packstone of G is identifiable on the plot (low GR-N).

The cross-plots (Figs. 38, 39) do show distinctions among the facies; the positions of various units on the plots do appear to be a function of their location in the basin. Nevertheless, the overlap of some plots and the imprecision of the technique demonstrates the importance of cores and samples in providing specific identifications of facies. It is not possible to interpret and map accurately the detailed changes of facies with only data from well logs. This technique is appropriately used as a reconnaissance tool. It provides another insight into basin development by illustrating the differences and similarities of the cycles within and between wells. The technique does not preclude other conventional forms of analysis, but complements cross-section and isopach studies.



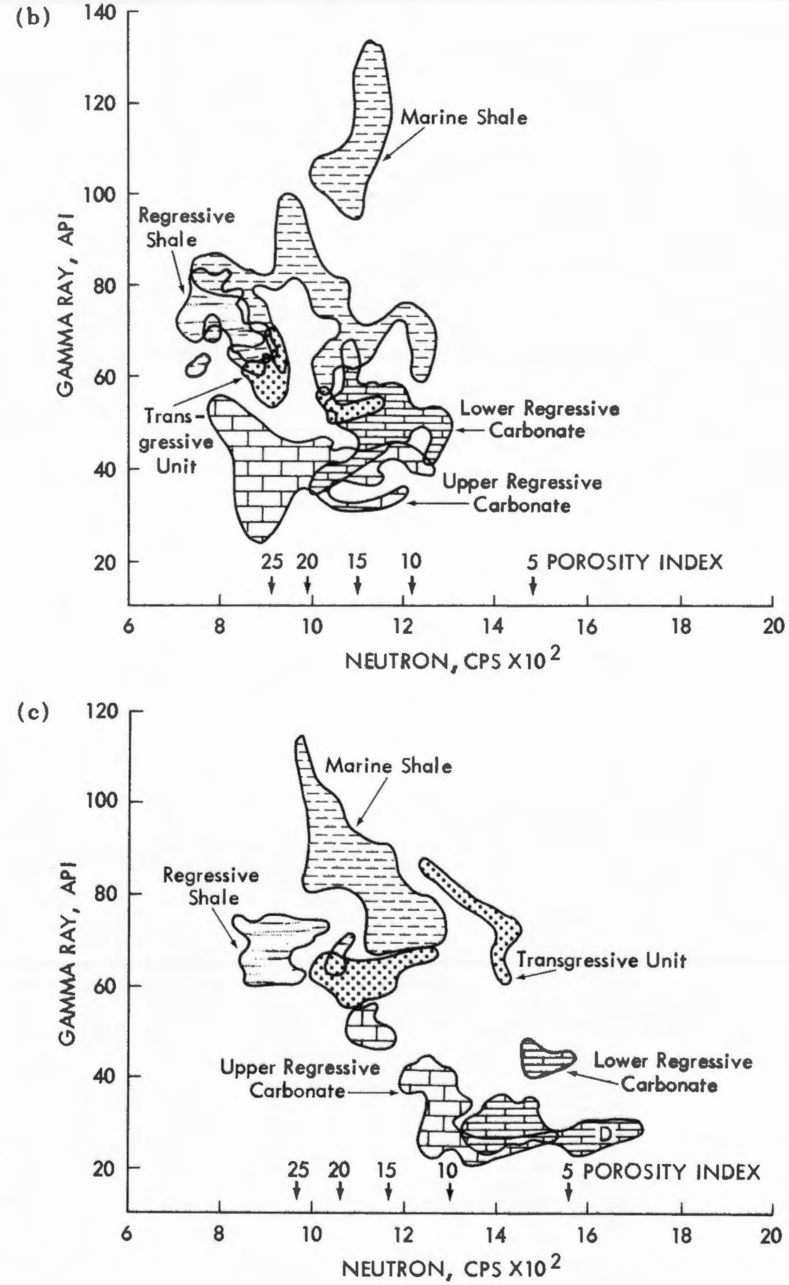


FIGURE 38. Cross-plots of gamma ray-neutron well log readings for each of six different Lansing-Kansas City cycles. Rock facies are identified by core-well log correlation. Clusters of points representing five different facies are identified by individual patterned areas. An empirical porosity index is placed along the neutron axis. Each plot represents data from an individual well: (a) is typical of a basinward well with good contrast between facies; (b) represents a landward well, where influx of clastics was high; and (c) is another landward well east of (b), where clastics were somewhat less important.

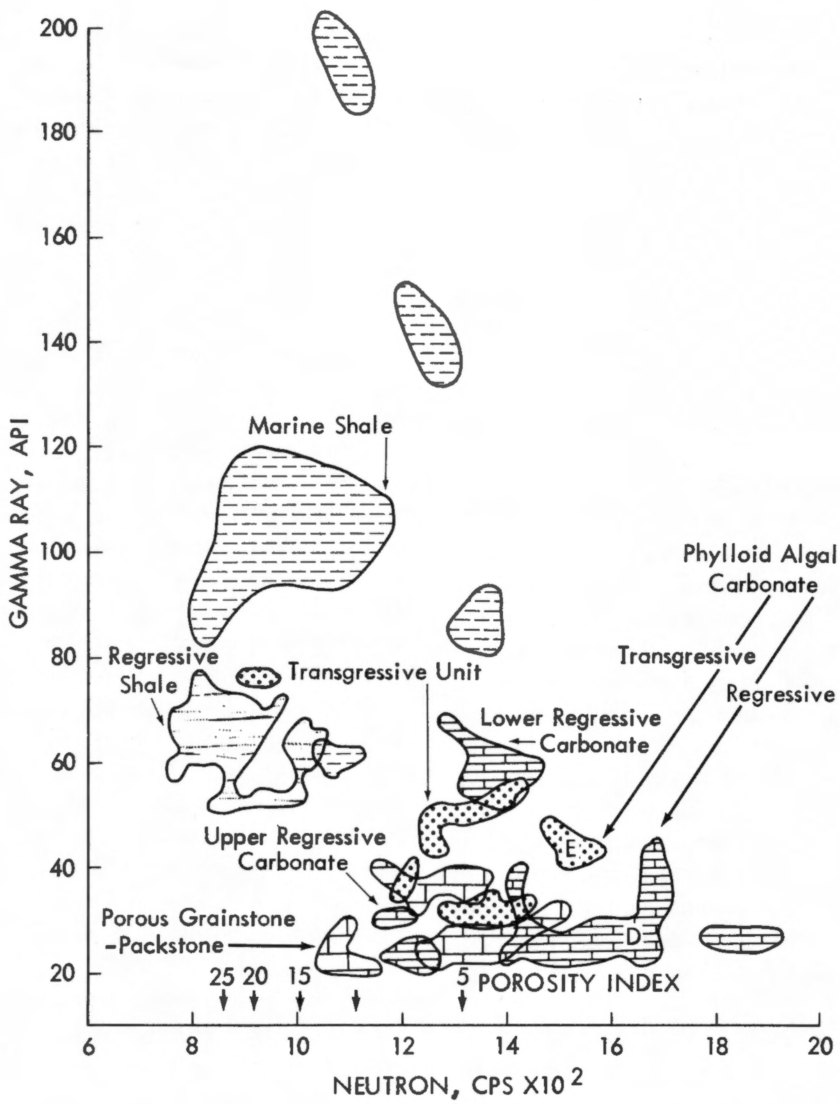


FIGURE 39. Gamma ray-neutron cross-plots for six cycles from the Prentice #1 well. Areas that include phylloid algal regressive and transgressive carbonates, D- and E-Zones, respectively, are identified in the figure by D and E.

QUANTITATIVE WELL-LOG ANALYSIS AS AN AID TO EXPLORATION

Another method of exploration that may be useful for suggesting trends of potentially porous reservoir rocks in the study area and farther south is the use of quantitative log analysis to map trends of thickness and porosity, and of estimated oil saturation of individual prospective limestones. The present study offered the unusual opportunity to examine various log-evaluation techniques in comparison to core analysis data. This resulted in recognition of some pitfalls of which the geologist must be aware, and of graphic techniques that maximize the utility of log-derived information in sparsely drilled areas, especially where cores are also available.

Thickness—The determination of thickness is usually straightforward, but, in working with relatively thin carbonate beds and even thinner porous zones, it is important in mapping small but possibly significant changes to have logs that accurately record these thin intervals. Logging tools with a source-to-detector spacing greater than the interval of interest do not accurately record its thickness. Porosity-recording tools commonly offer good bed definition, but the older, long-spaced resistivity tools do not. A focused-resistivity tool, such as a "Guard" or "Laterolog" is excellent in this use, particularly when the ratio of formation resistivity to mud resistivity is high, and formations present a large resistivity contrast. Previous workers (Hartman, 1975) have described the bed-resolution capability of types of logs common to the study area.

Porosity—In this study, porosity is derived from several types of logs, including the commonly used thermal-neutron, gamma-neutron, sidewall-neutron, compensated density, and sonic logs. In the absence of other porosity-logging tools, resistivity from a "Microlaterolog" has been used to calculate porosity.

It is common practice to determine the log response corresponding to zero porosity (so called "matrix value") in limestones by cross-plotting readings from sonic and density logs in the same interval. Various inaccuracies arise from using these "matrix values" in the study area, as revealed by observation of cores. The carbonates are quite variable in composition, ranging from clean limestones and dolomites to cherty, silty, and argillaceous carbonates. The "matrix values" typically are derived from the more dense carbonates in the somewhat shaly lower part of the regressive carbonate units. These intervals commonly are not the same type of rock as is being evaluated in the reservoir interval. Consequently, the porosity that is calculated is not correct.

In areas of frequent lateral change in composition where samples or cores are not examined, formations may change undetected from limestone to dolomite. In such a case, "limestone porosity" values calculated from a sonic log are lower than actual porosity of the dolomite. Cherty and silty limestone zones, conversely, would have actual porosities that are less than the calculated porosity. Two porosity devices, though, would allow discrimination between two lithologies or mixtures thereof.

Some allowance or correction for this "shaliness" effect in the carbonates is possible, but the results must be used with care. In a shaly carbonate, with two porosity tools run simultaneously (e.g., density-sonic or density-neutron), the relative abundance of two lithologies (clay and carbonate) can be determined and porosity can be adjusted. Clay increases the apparent porosity, approximately proportionately to the amount of clay present; from this relationship, a correction for porosity vs. clay content can be derived. In attempting to make accurate estimates of clay content of a carbonate, based on GR logs, it must be understood that the clay in the carbonate is probably not the same type of clay as in the adjacent shales, particularly if those are the red-brown, regressive shales. Another difficulty arises from the fact that, as noted above, the marine shales typically have an unusually high GR response; thus, finding a shale base line (100 percent shale) that is appropriate for correcting porosity of limestones for their shale content is difficult.

Another consideration is the apparent radioactivity of some cherts in the study area. The GR response in a chert zone may be nearly as high as that of a marine shale. Some chert samples have scattered specks of fine, organic(?), black material or dark mottling that apparently produce the abnormally high GR responses (Fig. 40). This dark matter is probably organic material with a high uranium or thorium content (Hassan and others, 1976).

The porous zones that are present in carbonate units in the study area usually occur in limestone or dolomitic limestone that is not shaly. Reconnaissance estimates of porosity made in these types of rocks are slightly pessimistic if dolomite is present. Effective porosity is that which represents interconnected pores in the rock. An average threshold, or minimum, porosity can usually be defined above which there is some assurance that the rock is permeable (Fig. 41). In the present study, carbonate units with porosity above eight percent are usually permeable. The high permeability-high porosity samples in both wells represented in Figure 41 have complex, primarily

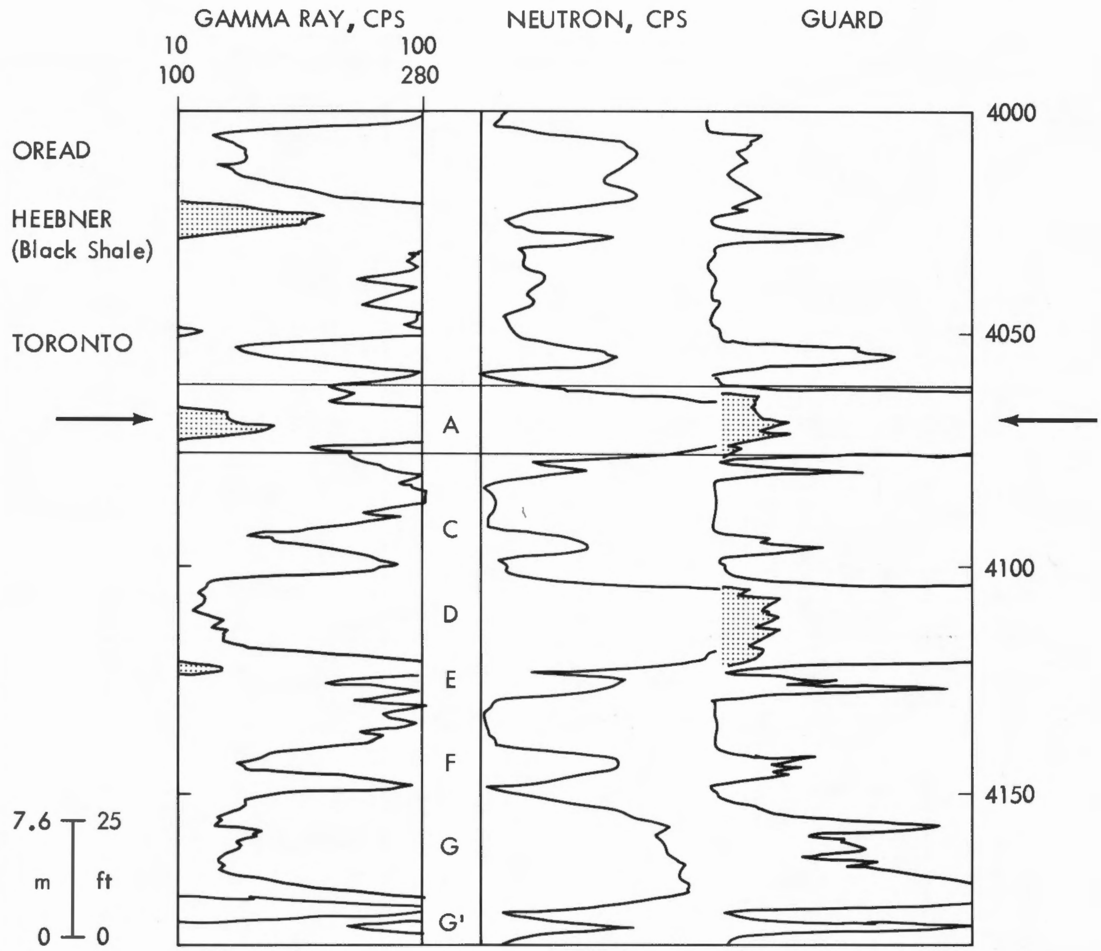


FIGURE 40. Cuttings from the A-Zone identified on this well log contain abundant orange chert with pinpoint-sized, scattered black (organic) material and dark mottling. Note the high GR record and also high neutron and guard log response in the middle of the A-Zone at the position of the arrows. The neutron and guard logs both suggest a nonshaly, tight carbonate interval contrary to the indication of the GR log. (Murfin McCain #1, 7-4S-33W)

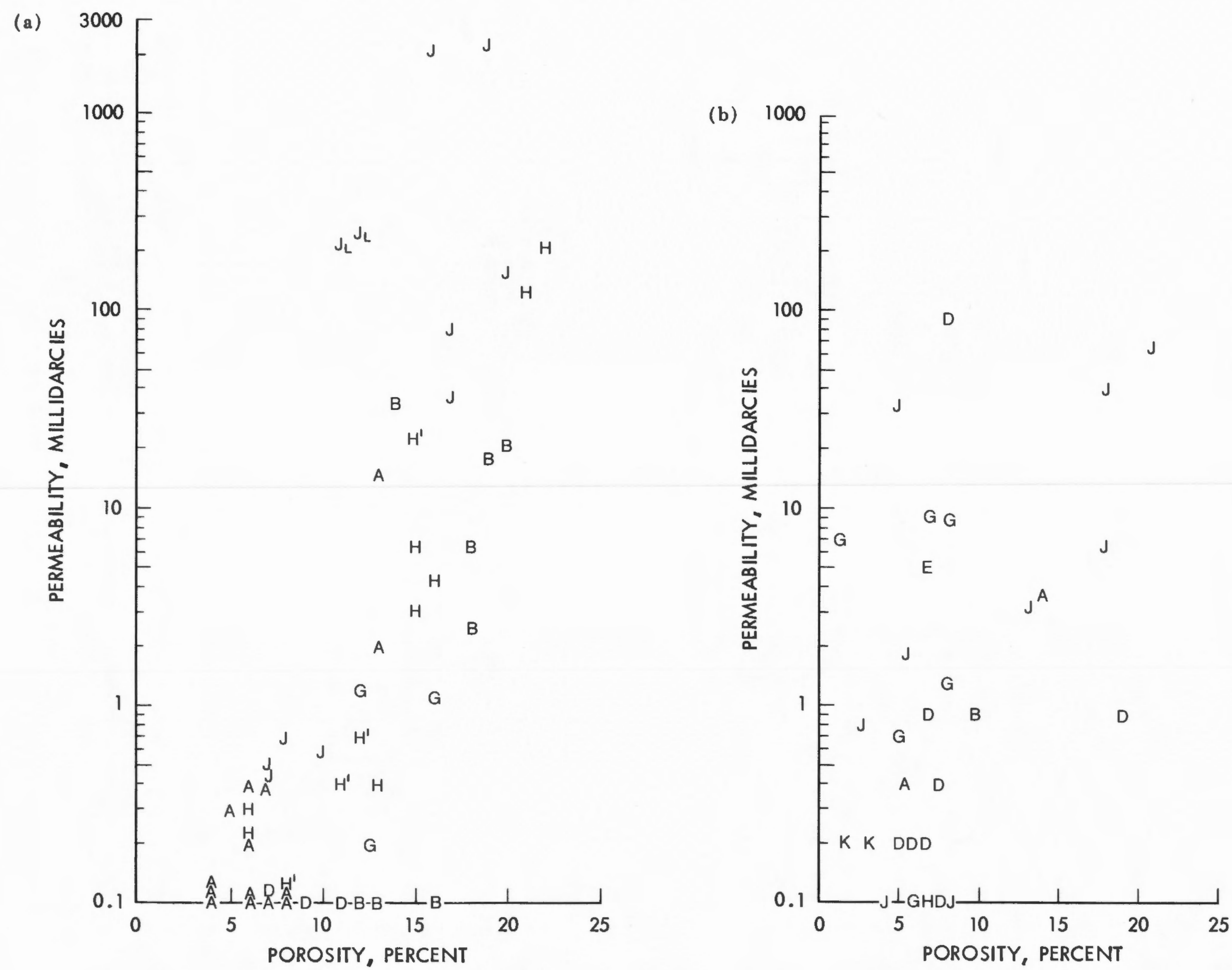


FIGURE 41. Semi-log plot of core analysis permeability versus porosity for (a) Skelly Bartosovsky #1 (9-1S-34W) in Rawlins County, and (b) Conoco Adell L-KC Unit 406 (2-6S-27W) in Sheridan County. The increase in permeability with increasing porosity is more evident in the Bartosovsky data set. Generally, rock whose porosity is greater than eight percent is also permeable.

intergranular porosities, with varying amounts of vugs, solution molds, and fractures. The low porosity-high permeability zones are vuggy, fractured lime mudstone, wackestone, or packstone. Good results of drill-stem tests of these units correlate positively with trends of higher porosity and permeability as shown on this plot (Fig. 41). Porosity determined separately from analyses of a well log and core (Fig. 6) shows close correspondence between the two techniques, although, in detail, there are differences. The core-analysis data are derived from measurements on a one-inch core plug and the log values are actually averages over intervals of approximately two feet.

Formation Fluid Saturations—Another difficulty in analyzing logs of the Lansing-Kansas City Groups in the study area for porosity and fluid content is the highly variable degree of cementation that results from the complexity of facies and diagenesis of these rocks. As with any shallow-marine sequence, these rocks vary in composition over short distances, and they have been subject to a variety of diagenetic processes. The experience of operators in the area is that log analysis can be very misleading unless it is complemented with attention to the specific type of rock represented by the logs, i.e., by examination of cuttings or cores. The cementation exponent, m, the formation factor, F, and the formation water resistivity, R_w, are essential in most calculations of porosity and fluid saturation, and these are the very factors that are most affected by the variability of the rocks described here.

The need to know R_w can be circumvented when a sufficient number of values of porosity, Ø, and true formation resistivity, R_t, is available from logs to construct a plot such as that shown in Figure 42. This plot may also be used to estimate cementation exponent, m.

This estimation was not made in Figure 42 because of lack of sufficient points representing the water-wet section. The R_o line was calculated on the assumption that the cementation exponent equals two. The equation of the R_o line is:

$$\log R_t = -m \log Ø + \log R_w + \log I$$

$$\text{where } I = R_t/FR_w = R_t/R_o \qquad \text{(Pickett, 1966)}$$

The positions of water saturation (S_w) lines, 50 percent and 30 percent, are calculated by using $S_w = R_t/R_o$, where S_w equals 0.5 for 50 percent and 0.3 for 30 percent values of S_w. R_t, the true formation resistivity, is solved for at least values of porosity to construct the water saturation lines.

In the example cited here (Fig. 42), the value of S_w derived from log analysis for the H- and J-Zones corresponds well with the results of core analysis and drill-stem tests. Core observation demonstrates that these two intervals are dominated by granular-type porosity (altered lime-mud) and are low in clay. The sonic log alone provides a good measure of porosity. In contrast, in the A-Zone porosity is developed as a combination of fine granular, vuggy, and fracture development in a shale-laminated, mud-rich carbonate. Even though the core analyses and drill-stem tests indicate oil, the plot suggests high water saturation.

The sonic log does not respond to discontinuous secondary porosity as fractures and scattered vugs. Rather, most of the acoustic energy travels around these disruptions and is not detected with the sonic log. The core analysis porosity values in the lower A-Zone are up to 13 percent, whereas the sonic values are all under 10 percent with the exception of one value. The higher actual porosity would lower the water saturation as the plot demonstrates.

In addition, the shale laminations that are present probably have depressed the induction resistivity response. Shale tends to "short-circuit" a resistivity log by conducting the electrical current around the oil-filled pores and thus to lower the resistivity. Consequently, the apparent water saturation is high.

The B-Zone is a shale-laminated, sandy quartz siltstone. The shale correction that was applied to the sonic log through this interval was substantial. Core analysis porosity values are over 15 percent while the corrected sonic values using a sandstone matrix are noticeably lower (under 10 percent).

The gamma-ray tool apparently overestimates the shale fraction in this zone and the resulting shale-corrected porosity is too low. The shale fraction is considered proportional to the gamma-ray reading between that of a shale-free formation (0 percent shale) and the average shale gamma-ray intensity (100 percent shale). This overestimation of shale by the gamma ray is not unexpected as this transgressive unit contains shale similar to the marine shale. Indeed, the gamma-ray response in the marine shale may be quite high, exceeding by several times the average shale gamma-ray value. Thus the gamma-ray value may actually be indicating a lower shale fraction. The presence of the shale has substantially lowered the resistivity values for this interval. Compensating for both of these effects would move the points toward lower water saturation (toward the 50 percent S_w average determined by core analysis).

Log analysis of shale-free reservoirs with intergranular porosity is generally routine, but complex lithologies and pore systems normally require running

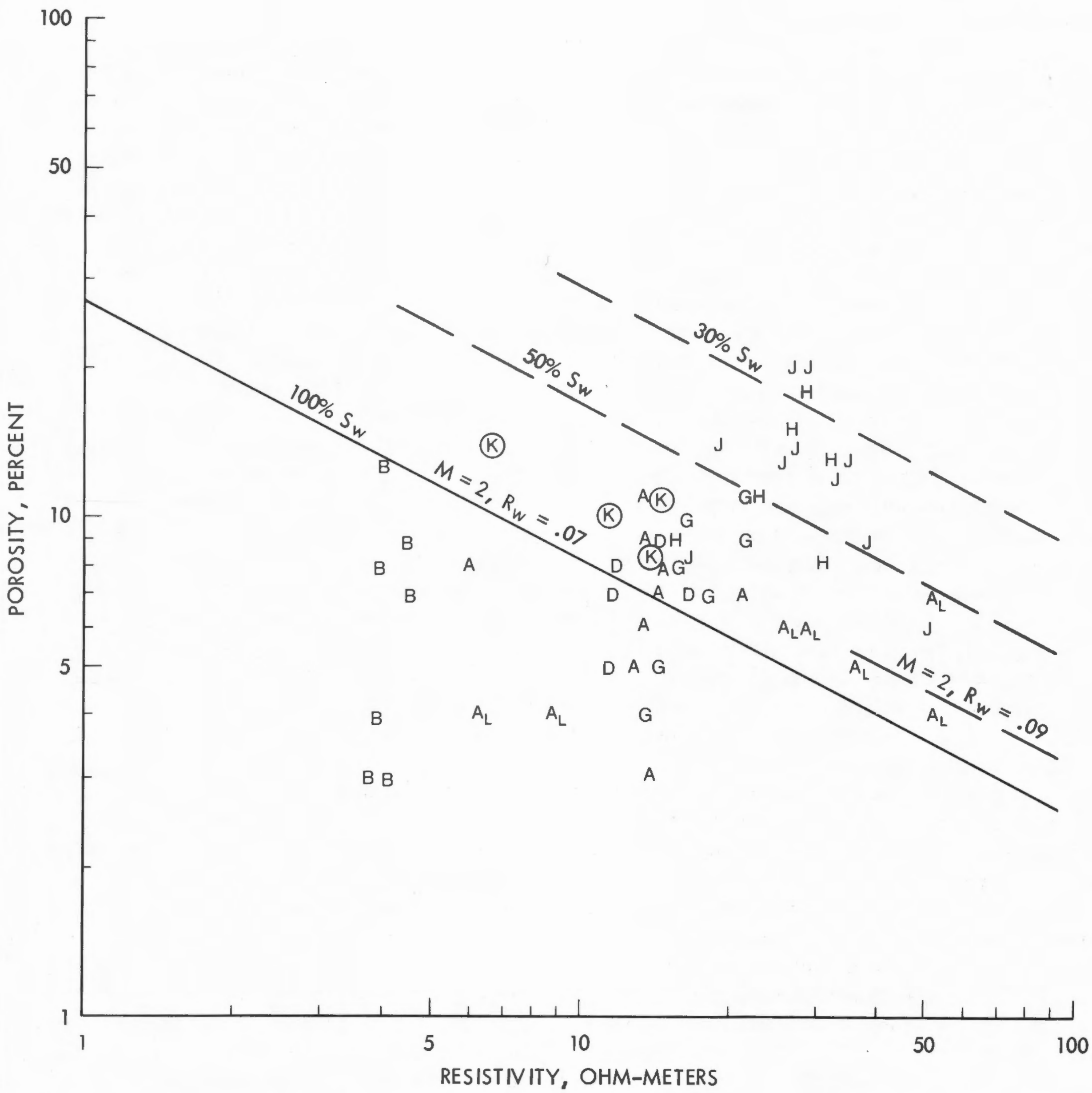


FIGURE 42. Log-log plot of induction well log resistivity versus shale-corrected sonic porosity for porous zones of Skelly Bartosovsky #1. Data points determined on a per-foot basis. Carbonate intervals are labeled accordingly. The solid heavy line is the R_o (water wet) line with slope, m (cementation exponent), equal to 2, and with an intercept of 100 percent porosity at 0.07 ohm-m ($= R_w$), determined by calculating R_w from SP deflection in porous, water-wet zones. Sonic log porosity was corrected for shale effects with a Dresser-Atlas nomograph (p. 7-1 of Log Interpretation) using the gamma-ray response. The points labeled "B" represent the sandstone-siltstone unit immediately below the A-Zone. The circled K values represent water-wet points, which are best represented by a water-wet line with m = 2, R_w = 0.09 shown in part on the lower right of the plot.

DRILL STEM TEST RESULTS (BY ZONE)

ZONE	RESULTS
J	3360′ oil, SIP: 1305-1280#, FP: 160-1250# SWB 144 BO/2 hrs.
H	2249′ gas + 1880′ oil, SIP: 1305-1250#, FP: 135-745#, SWB 132 BO/2 hrs.
A	320′ gas, 160′ oil, SIP: 1280-1120#, FP: 50-80#, SWB 122 BO/2 hrs.
G	3 gallons water/hr. with show oil
D	5′ mud with specks oil, SIP: 130-0#, FP: 0-0#
K	60′ muddy saltwater with specks oil, SIP: 1330-1120#, FP: 0-0#

ABBREVIATIONS

SIP: shut-in-pressure (initial and final)
FP: flowing pressure (initial and final)
SWB: swabbed

additional logs, e.g., density or neutron, to complement the logging suite. Similarly, core and core analyses provide pertinent information for understanding the well logs.

The cementation exponent that applies to these formations varies from 2 to 2.8. Useful reviews of this element in the determination of formation factors in carbonate reservoirs are given by Gomez-Rivero (1976), DeWitte (1972), and Chombart (1960). The exponent, m, in the equation, $F = 1/\emptyset^m$, is approximately equal to 2 for most types of pore systems. For oomoldic systems, a type that is common in the Lansing-Kansas City limestones in areas south of the present area of study, m may be as high as 2.8 (Tixier, 1962). The uncertainty in the value of m results in occasional errors in the calculation of F and, consequently, of S_w (Fig. 43). Formation factor, F, may also be estimated from values of resistivity in the flushed zone if a microresistivity log, such as a "Microlaterolog" or "Proximity log," is available.

A useful technique for detecting changes in formation composition and in the nature of formation fluids is the mapping of R_{wa}, apparent water resistivity, determined by dividing R_t, from a deep-reading resistivity log, by F, derived from a porosity log. R_{wa} is an indication of variations in water resistivity or cementation exponent (nature of the formation), or of the presence of hydrocarbons in part of the pore space. For this reason, maps of R_{wa}, when used in reconnaissance of a region with well logs, assist the geologist in recognizing areas where further study of samples, drill-stem tests, or cores may result in the recognition of apparently anomalous conditions. These areas may be important in the evaluation of prospects for drilling.

MAPPING FACIES FROM WELL LOGS AND SAMPLES—EXAMPLES FROM RAWLINS COUNTY

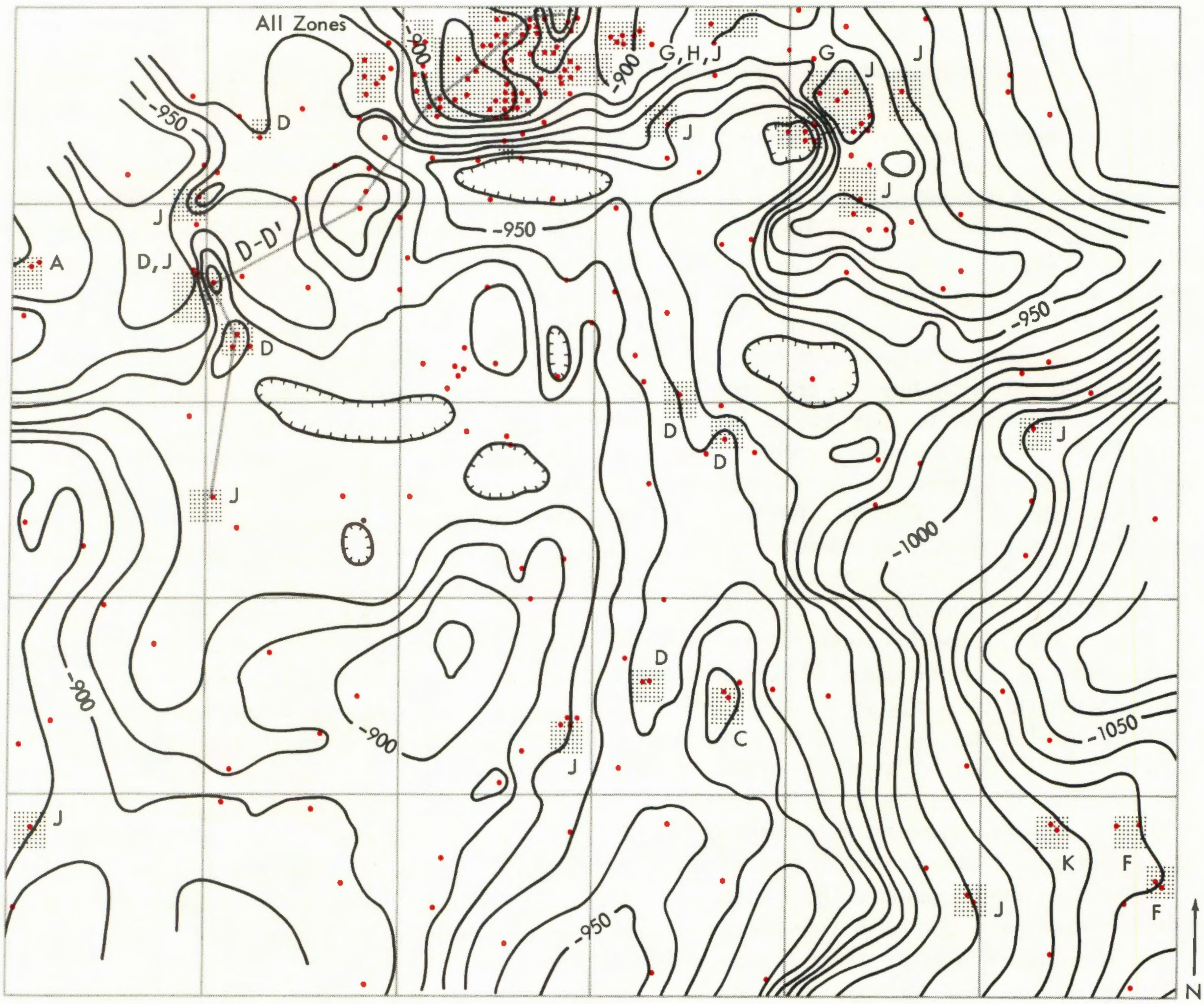
One good method of defining prospective drilling locations as extensions of known oil-producing areas is to establish trends, in these areas, of factors that are associated with production and that can be mapped. Such a trend could be established simply by recognizing an anticlinal fold, a thin or thick area of the reservoir unit, or a similarity in the values of some parameters calculated from logs, such as rock and fluid properties. The actual significance of such a trend depends, of course, on the density of well control and the number of variables that substantiate the trend.

Potential hydrocarbon reservoir carbonates in the Lansing-Kansas City Groups should be mapped as individual sedimentary units, or elements of the cycles discussed above. The location of oil and gas production within each major carbonate unit becomes understandable only in this way. Aggregating information for mapping from several zones results in confusion in many cases. It is important to recognize the development and expression of sedimentary cycles in the Lansing-Kansas City and to incorporate these into the strategy of mapping and exploration. Later "stacking" of maps to compare cycles and to understand their underlying causes can be beneficial as a predictive tool in exploration.

Rawlins County, Kansas, which lies on the flanks of the Cambridge Arch (Figs. 2, 4), was selected for detailed logs and cuttings analysis and as a test area in which to construct various maps that might be useful for establishing prospective exploration trends because of earlier studies in the area, the availability of cores from several wells, and the high level of current activity in this part of Kansas and adjoining states. Cumulative oil production in Rawlins County through 1978 amounted to 10.9 million barrels, with 95 percent of the production having come from the complex of larger fields in the northern part of the county (Beene, 1979). This area is referred to as the Cahoj-Wilhelm structural complex and encompasses 16 fields (Fig. 43). The remainder of the production is from 14 fields in central and southern Rawlins County. The most productive area has been Cahoj Field in Township 1S-34W, with oil production from 10 separate intervals.

Mapping that would suggest reasons for the locations of the various oil reservoirs and whéther they are mainly structural, stratigraphic, or a combination of the two was completed for several cyclic units (Pl. 1). The sedimentary cycle including the J-Zone was examined initially, as it currently is the most productive unit in Rawlins County. For comparison, a stratigraphic analysis was also made of the overlying H-, G-, and D-Zone Cycles. Significant variations in the character of these units have been interpreted in terms of differences in their mode of deposition and the geologic events that have subsequently affected them.

J-Zone Cycle—The J-Zone is the "upper" or "regressive" carbonate unit in the cycle of genetically related units referred to here as the "J-Zone Cycle" (Fig. 44). The structural shape of the top of the J-Zone (Fig. 45) clearly does not account for the distribution of all the oil production from this reservoir. Production is obviously localized on-structure in some areas, such as the Cahoj structural complex;



EXPLANATION

Oil Field

Contour Interval 10 Ft.

0 4 mi
0 5 km

FIGURE 43. Structure contour map, top of Lansing (A-Zone carbonate), Rawlins County. Grid system is six-mile square township divisions. Red dots represent well control. This base map is the same as that used for all succeeding maps. Because of inadequacies in some of the data, not all points of control are used on each map.

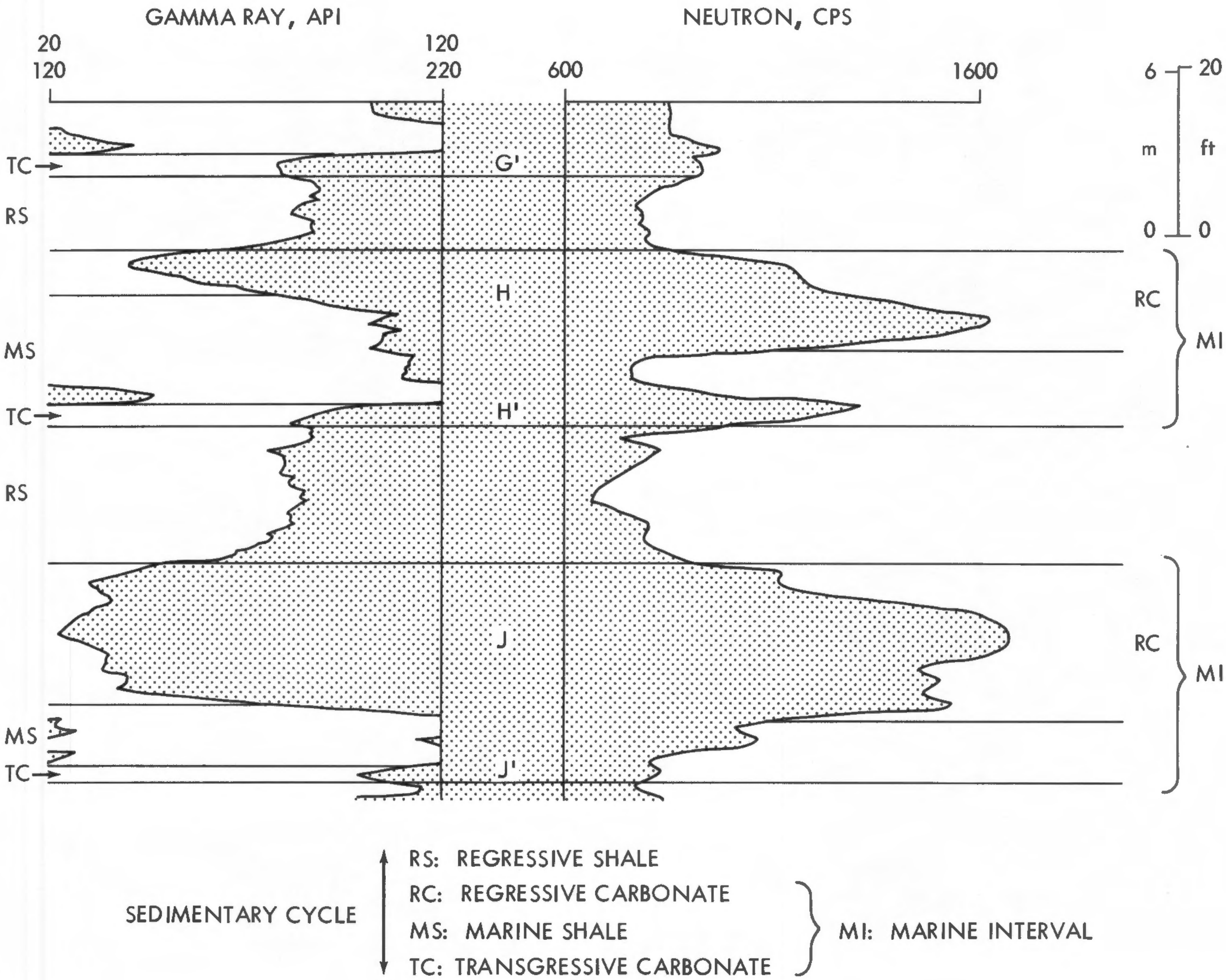


FIGURE 44. Definition on gamma ray-neutron logs of intervals depicted on isopach maps that follow. Intervals are defined and labeled on the appropriate log curve. Note the overlapping interval of the marine shale (defined by the gamma-ray log) and regressive carbonate isopach interval (defined by the neutron log).

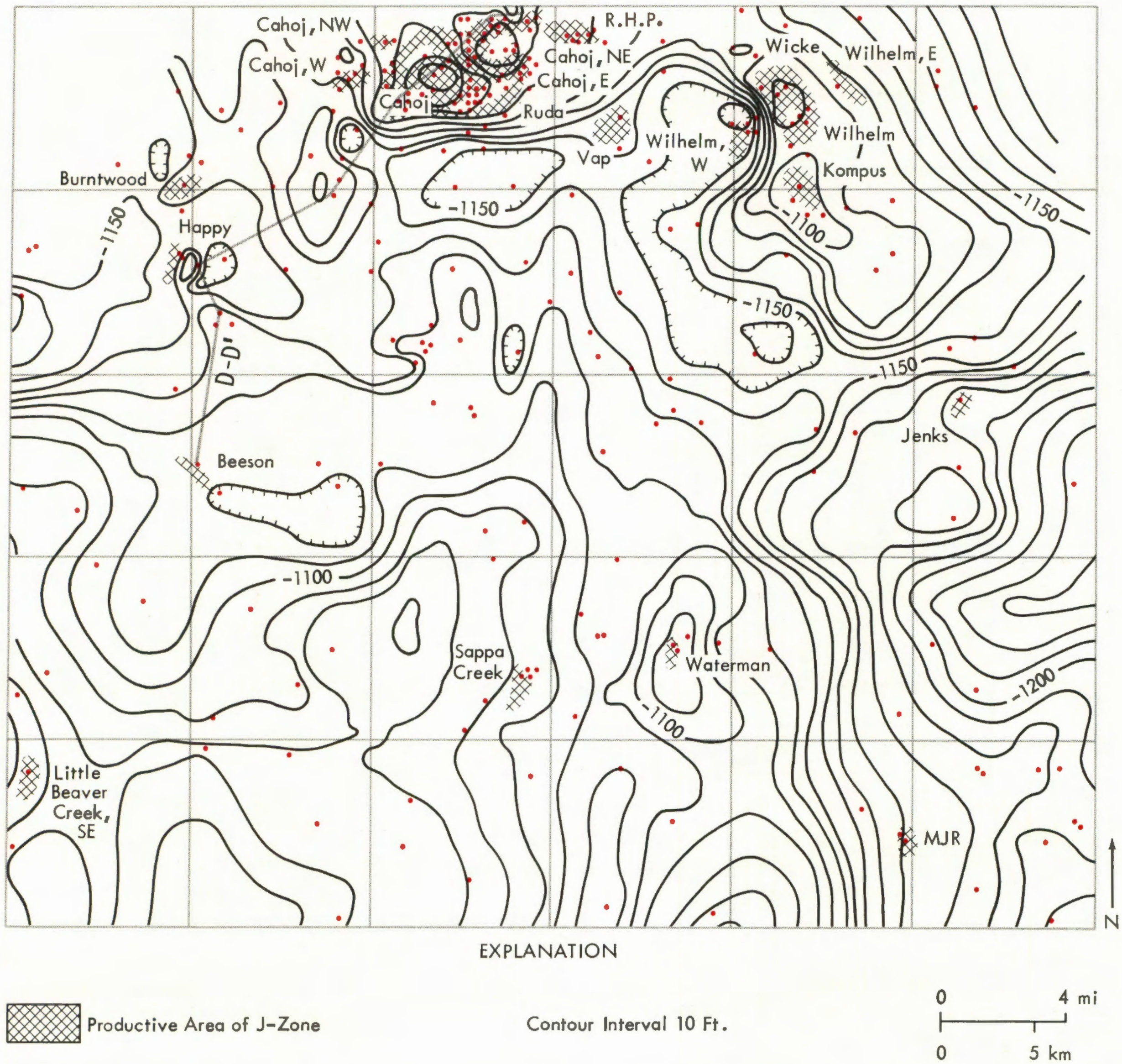


FIGURE 45. Structure contour map, top of J-Zone carbonate, Rawlins County. Productive areas of the J-Zone carbonate are shown. These are estimated from minimum oil/water (min o/w) contacts estimated from well logs. The smaller nonporous areas are omitted from the productive areas over Cahoj and Wilhelm Fields. The minimum o/w's vary from – 1095 to – 1160, a range of 65 feet.

but, in others, production is confined to the flanks of positive anomalies.

Reconnaissance maps of J-Zone in Rawlins County, prepared solely with data from well logs, give some indication of the importance of factors other than structure that may be significant in forming oil traps (Figs. 46, 47). The thickness of J-Zone with effective porosity greater than eight percent, expressed as thickness times porosity (Fig. 46), gives some indication of the attractiveness of the zone as a target for exploration. Recognition from logs that most of the porosity is in the upper parts of the limestone suggests that the sedimentary models discussed earlier may be useful in explaining its origin. Elongate trends of greater porosity occur with no apparent relationship to structure in some areas. An understanding of these features depends on analysis of other kinds of information.

Another type of map that is derived from well-log analysis is the map of apparent water resistivity R_{wa} (Fig. 47). As indicated above, this parameter may reflect a number of variables; but the correspondence of slightly higher R_{wa} values with trends of greater porosity (Fig. 46) and of oil production (Fig. 45) in the J-Zone suggests that these higher values may relate to hydrocarbon saturation. To confirm this, it would be necessary to do additional studies on the lithology of samples (degree of cementation) and to refine estimates of porosity from logs with corrections for shaliness. The usefulness of this type of map is not yet established in this area.

Other maps that are derived from logs, but that can be combined with information from studies of drilling samples or cores to understand the patterns that appear, are maps of the thickness of genetically related units of the J-Zone Cycle (Figs. 48, 49). Reference to Figure 44 indicates the intervals discussed below.

Definition of the marine shale unit with the gamma-ray log results in inclusion of the shaly lowermost part of the regressive limestone (Fig. 44) with the dark radioactive shale in mapping this unit. In most areas the marine shale is fairly thin and uniform in thickness. Nevertheless, there are many isolated areas of marine-shale thickening in Rawlins County that can be directly attributed to thickening of the shaly regressive carbonate. This local thickening of the shaly fraction of the cycle is probably due to an early onset of carbonate mud accumulation.

The seafloor bathymetry and/or bottom currents may have been important factors influencing this onset of regressive carbonate deposition. This idea will continue to be supported in the following discussion.

Trends of thickening of the J-Zone, or regressive, carbonate (Fig. 49) occur both north and south of a central east southeast-west southwest trend of thinness. Lithofacies (Fig. 50) of this J-Zone carbonate indicate that the thicker area in the north consists mainly of peloid, lithoclast, and skeletal grainstones that have undergone freshwater diagenesis; but the thicker area in the south (Fig. 49) is mudstone or wackestone with less evidence of early leaching and disruption. This relationship suggests that the southward thickening reflects the basinward direction from an area of northern nearshore shoals or supratidal deposits. The central area of thinner section was probably an area of slower sedimentation between shoals at the time of deposition, where only a few scattered, current-winnowed grainstone and packstone deposits formed. Increasingly restricted water circulation is indicated by less diverse assemblages of fossils in the deposits of these inter-shoal areas.

The Cahoj-Wilhelm structural complex probably was a positive area during the Pennsylvanian; and it affected patterns of sedimentation in northern Rawlins County, Kansas, and north of there in Nebraska at that time. Concentration of grainstone deposits on its flanks or crest in several depositional cycles and evidence of subaerial weathering and dolomitization of the carbonate units and paleosoil formation in overlying regressive shales (Watney and Ebanks, 1978) support this idea. This important early diagenesis in the J-Zone carbonate has resulted in its becoming the most porous and permeable reservoir in Cahoj Field, despite the fact that originally much of the J-Zone was a lime mud-rich sediment and, probably, impermeable.

These conclusions are supported by isopach maps of the marine interval (Figs. 44, 48) and of the regressive shale unit (Figs. 44, 49). These two mapping units tend to be complementary in thickness and to reinforce the idea that the regressive shale thins basinward from a northern source of terrigenous clastics. The regressive shale fills in the depositional relief on the underlying regressive carbonate. This same relationship occurs in other cycles of the Lansing-Kansas City section.

Isopach and lithofacies maps, when combined with maps of porosity and other log-derived parameters, can be interpreted in terms of the geologic history of a potentially porous carbonate reservoir rock. Trends of grainstones with intergranular porosity or packstones and originally impermeable wackestone or mudstone deposits with secondary porosity can be mapped as they are encountered during drilling if the general basin geometry and sedimentation patterns are known. Knowledge of what trends and patterns

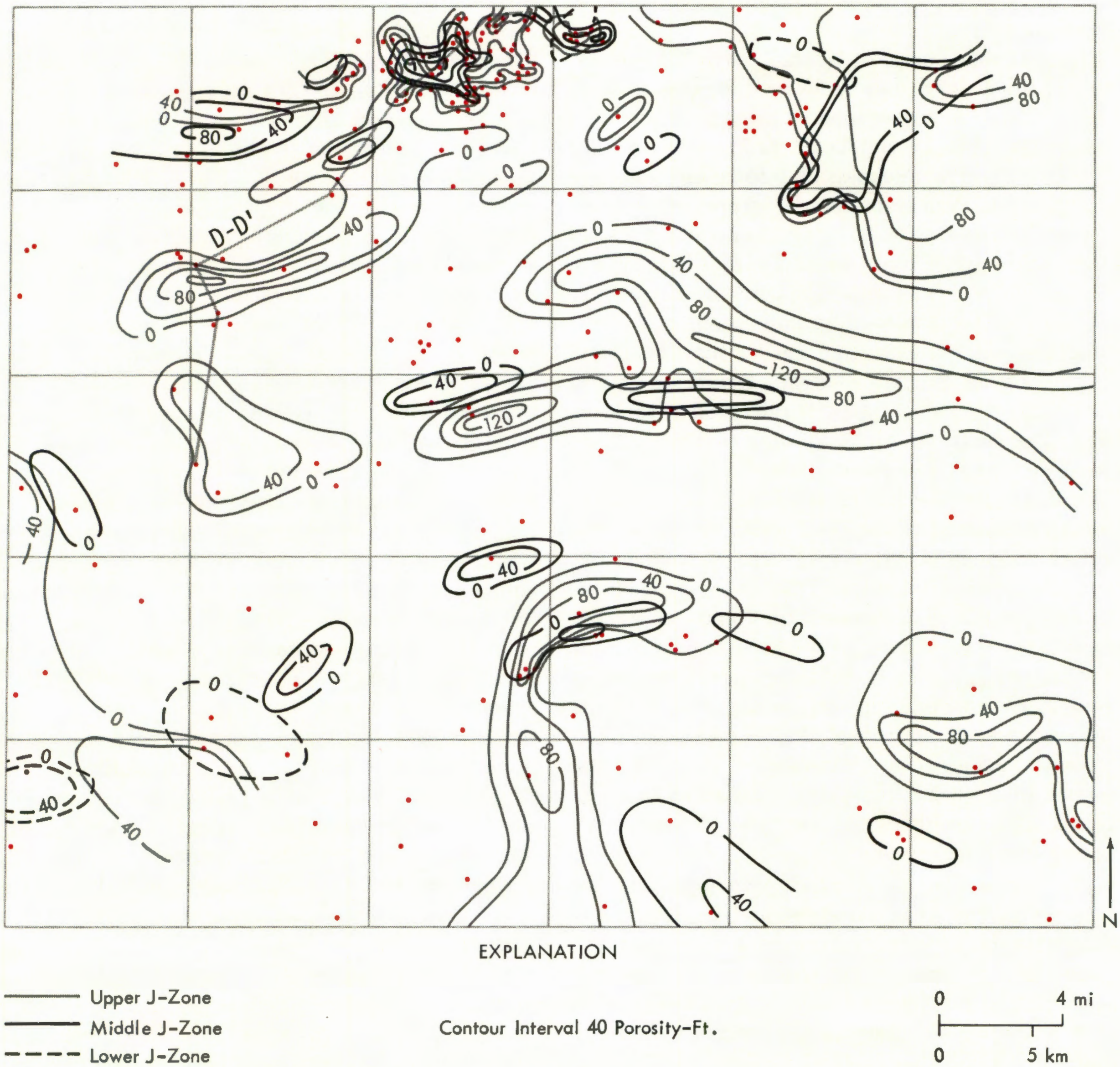


FIGURE 46. Contour map of porosity exceeding eight percent in the J-Zone carbonate in Rawlins County. Porosity is multiplied by the average thickness of the porous interval. Three separate contour sets identify porosity developed in the upper, middle, and lower portions of J-Zone. Highest frequency of occurrence of porosity is in the upper interval of this regressive carbonate in the more shallow water carbonate facies. Rock with porosity exceeding eight percent is usually permeable.

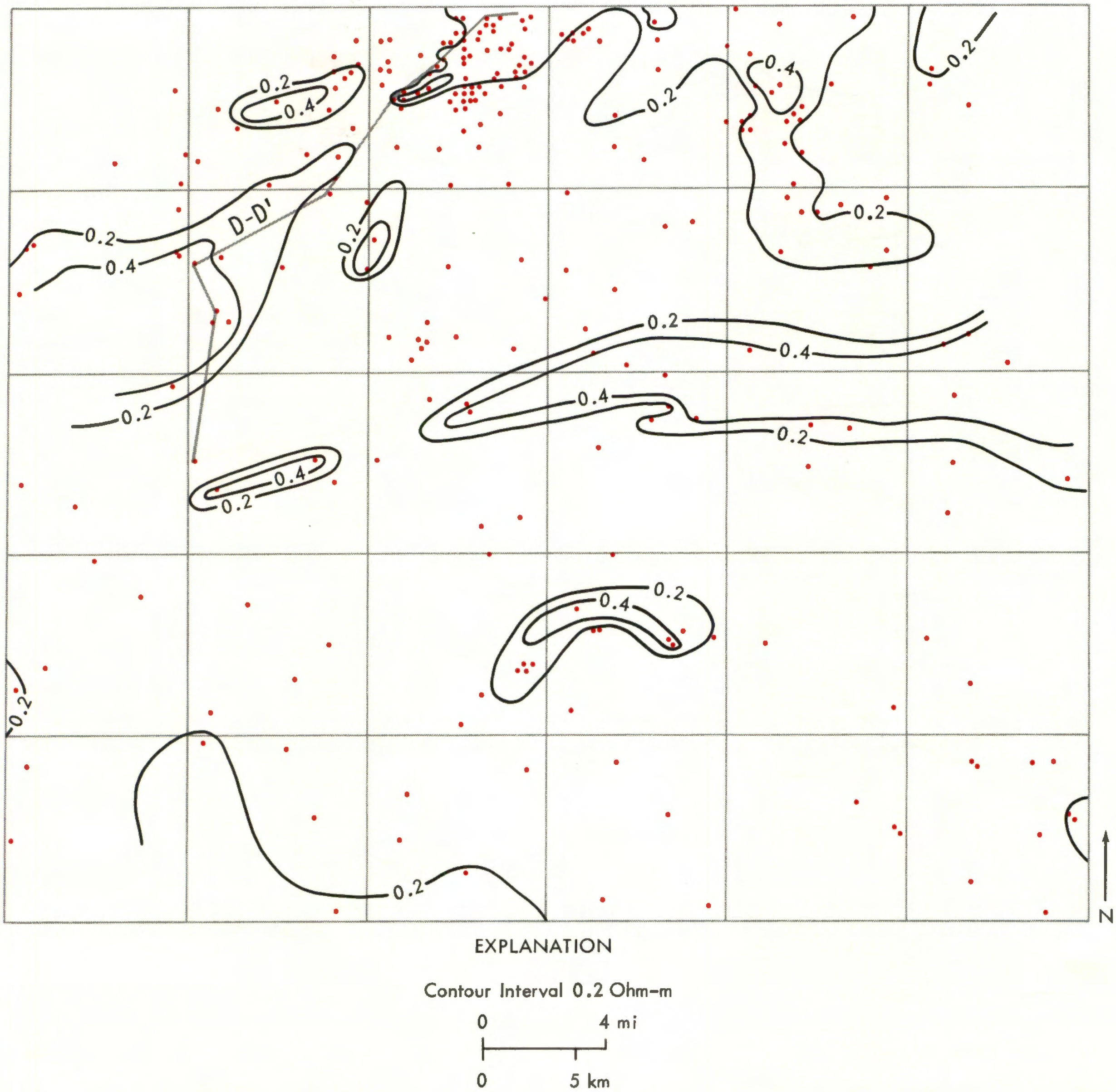
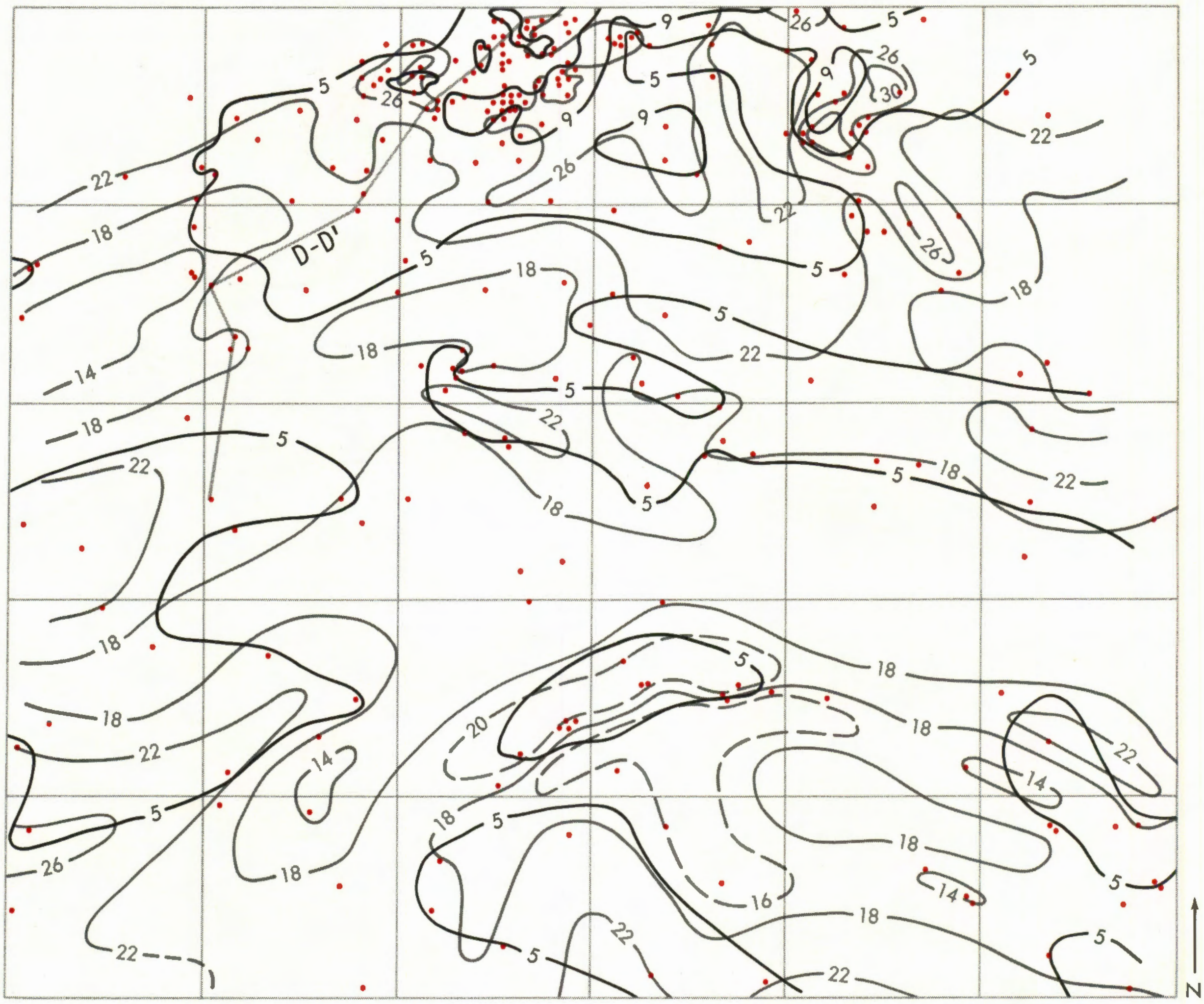


FIGURE 47. Map of the apparent water resistivity (R_{wa}) of the upper J-Zone carbonate in Rawlins County, derived solely from well-log data. $R_{wa} = R_t/F$ where R_t is the reading from the deep-investigating resistivity tool and F is the formation resistivity factor defined as $1/\varnothing^m$, m = 2, $\varnothing$ = porosity. Note that m = 2 is assumed (Fig. 42) and, as indicated in the text, the cementation exponent may be highly variable. A real difference in cementation and tortuosity of pores may account for some of the variation in R_{wa} over the map area.



EXPLANATION

Marine Interval Isopach

Marine Shale Isopach

Added Contour

Contour Interval 4 Ft.

0 4 mi

0 5 km

FIGURE 48. Marine-interval isopach, J-Zone cycle, Rawlins County, derived from porosity or resistivity log includes the top of regressive carbonate to the base of the transgressive carbonate (Fig. 44). Note that the 16- and 20-foot contours are added to this isopachous map. Marine shale isopach is defined from the interval identified on a gamma-ray log, as shown in Figure 44. This method commonly includes a portion of the lower, argillaceous, regressive carbonate.

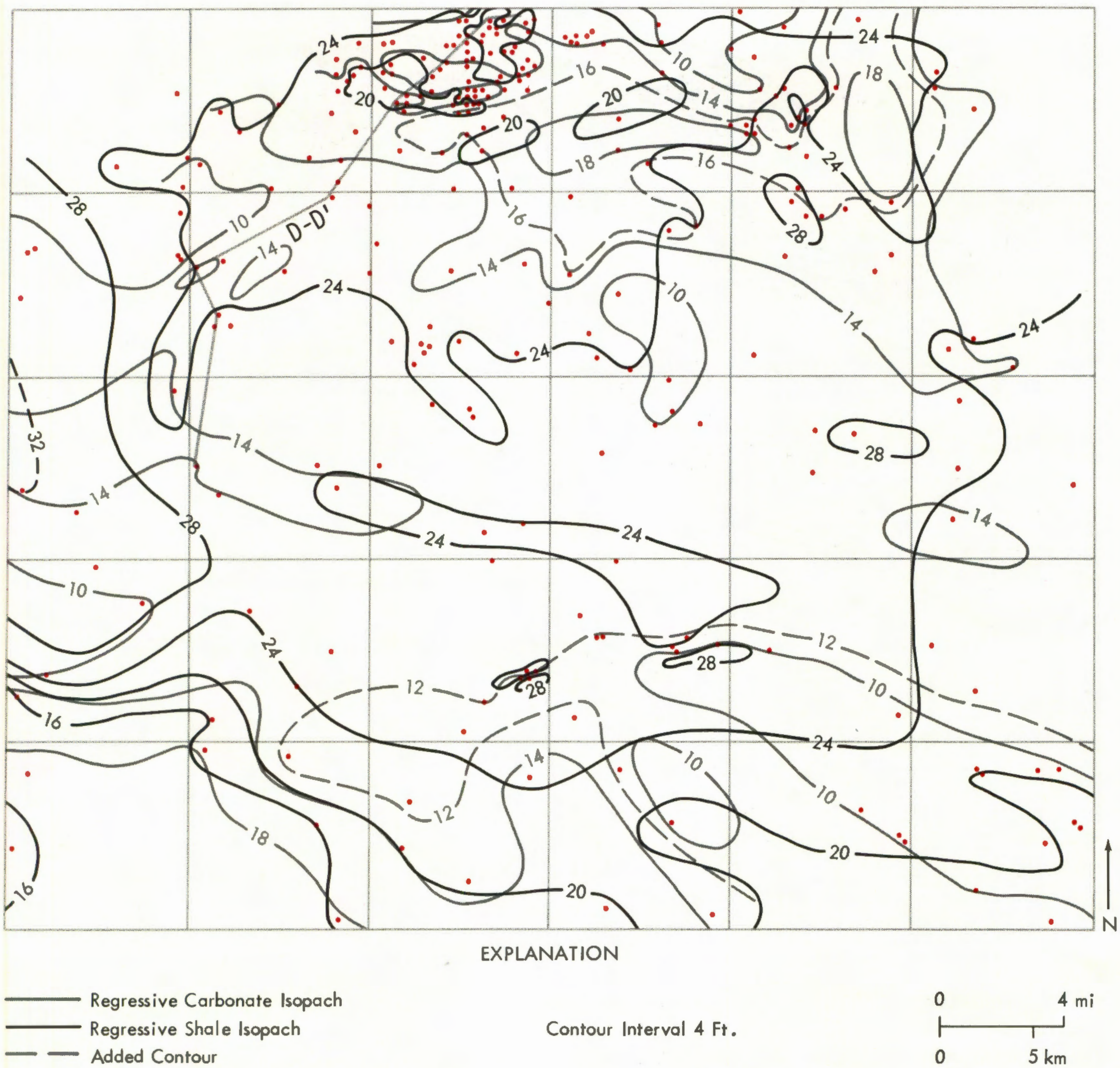


FIGURE 49. Regressive shale isopach interval, defined by gamma-ray logs as in Figure 44. Regressive carbonate isopach derived from porosity log or resistivity log, as shown in Figure 44. Lower portion of carbonate may appear as shale on the gamma-ray log. Note addition of 12- and 16-foot contours.

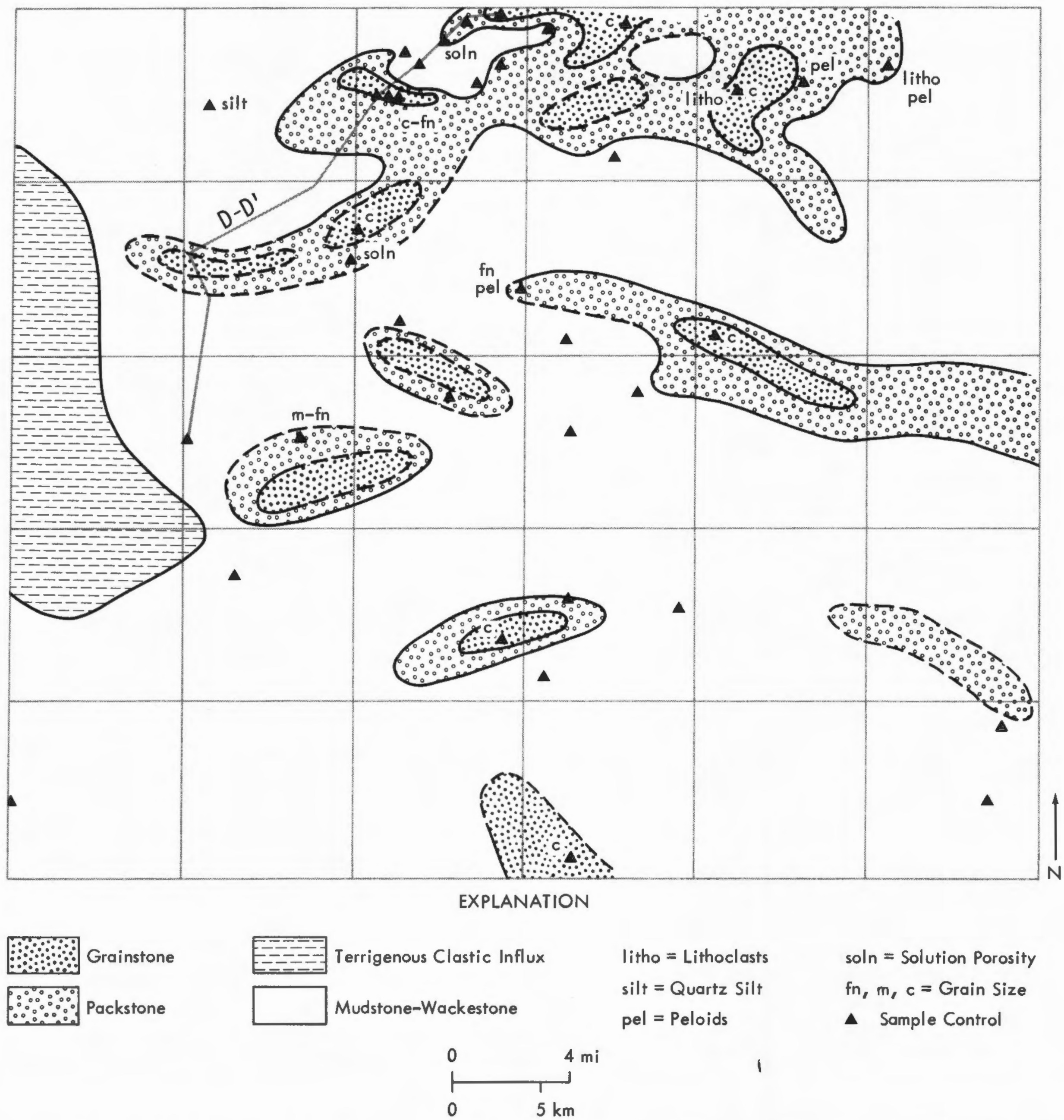


FIGURE 50. Carbonate facies map of the upper portion of the J-Zone in Rawlins County. Thirty-seven sample-control points, supplemented by isopachous maps, provide identification of facies. Facies consist of a simple series of skeletal grainstone shoals, including a variety of grain types among a more extensive area of mudstone-wackestone, identified by the open areas on this map. The areas of occurrence of the grain-supported rocks are probably more complex than shown here. The packstone fringe represents a zone of gradation between the high- and low-energy deposits.

are significant in any exploration area can be gained only by integration of information from logs *and* samples or cores. Examples from other cycles of sedimentation in the Lansing-Kansas City Groups strengthen this conclusion, and they illustrate the fact that there are many facies in Lansing-Kansas City carbonate zones, other than those described from the J-Zone, which should be considered in a regional exploration play.

H-Zone Cycle—The sediments of this cycle may be the product of deposition in deeper, more basinward conditions than those of the J-Zone Cycle, and, as such, may indicate the type of facies that would also be present in J-Zone Cycle south of the study area. Broad trends of facies, tens-of-miles wide, may be present in these deposits, as demonstrated by studies in eastern Kansas (Heckel, 1975).

The "transgressive," or "lower," limestone of the H-Zone Cycle (H′) in Rawlins County (Figs. 44, 51) is thicker and more easily measured on well logs than is the equivalent unit in the J-Zone Cycle (J′) (Fig. 44). Thicker areas in this unit correspond well with general areas of thicker "marine interval" (Figs. 44, 51). The "regressive" carbonate (H-Zone) of this cycle (Figs. 44, 52) also is thicker where the marine interval, overall, is thicker. These thicker trends of H-Zone (Fig. 52), particularly in northernmost and southern Rawlins County, with a thinner area between, are similar to, but more pronounced than, trends in the J-Zone.

Trends of change in thickness of the "regressive" shale above H-Zone (Figs. 44, 52) are complementary to those in the underlying carbonate. Because it is unlikely that a red-brown shale such as this would interfinger with a marine carbonate unit such as the H-Zone, the thinning of the shale probably indicates the presence of carbonate build-ups, that is, areas that had some relief at time of deposition.

Lithofacies of the H-Zone carbonate (Fig. 53) are more varied than those of the J-Zone, and they suggest a reason for the local thickening of this unit in southern Rawlins County. Fragments of phylloid algae (Fig. 8) are abundant in samples and cores of H-Zone in wells located near the areas labeled as mud banks on Figure 53. These algal banks evidently are similar to those in eastern Kansas (Wilson, 1957; Harbaugh, 1959; Heckel and Cocke, 1969), and, perhaps, to others in areas where they are important oil reservoirs (Elias, 1962; Choquette and Traut, 1963; Wilson, 1972; and Wermund, 1975). These banks probably formed on an open-marine shelf where there was good light penetration through clear water. Fragments of a diverse assemblage of fossils and the sparse terrigenous silt or mud in these sediments support this idea. Occasionally, strong currents winnowed and sorted the bioclastic grains on these banks, and formed lenses and layers of skeletal sand, especially on the flanks of the banks. Heckel and Cocke (1969) have reported other types of coarse carbonate deposits, tidal channel-fill, spits, and bars, associated with algal banks.

The algal-bank facies of the regressive carbonate, H-Zone, has not yet proven to be productive of oil and gas, mainly because there is insufficient porosity and permeability. The limited diagenesis that this facies has undergone has not enhanced the properties sufficiently. Other carbonate zones (e.g., D-Zone) in this area that have similar facies appear to be more favorable as reservoir rocks.

The only production of oil and gas from H-Zone has been from grainstone facies in the Cahoj area, northern Rawlins County, where prominent carbonate shoals were formed by waves and currents acting on the pre-existing bathymetrically high area (Figs. 40, 53). Figure 54 is a photomicrograph of a representative cutting from this grainstone facies.

The regressive shale and siltstone that eventually blanketed H-Zone had less influence on carbonate sedimentation than did their counterparts in the J-Zone Cycle. Thick areas of this silty facies are restricted to locations north and northwest of the Cahoj complex (compare Figs. 50 and 53).

G-Zone Cycle—The isopach intervals of the G-Zone cycle illustrate another facet of cycle development. Although the "transgressive" limestone (G′) (Fig. 55) is relatively thin throughout the area, it gradually thickens to the south. The marine interval (Fig. 55) noticeably thickens in the north and central areas of Rawlins County, the latter location along a trend just to the north of the H-Zone Cycle marine interval and carbonate thicks (Figs. 51, 52).

Significantly, the marine interval in the G-Zone Cycle thickens over Cahoj Field without a complementary regressive carbonate thick as found in the northeast and central areas of Rawlins County (Figs. 55, 56). In other areas, the regressive shale thinning complements the thickening of the underlying regressive carbonate (Fig. 56) and suggests depositional relief in these areas analogous to that described in the H-Zone Cycle. This clastic interval thickens in the northwest, like that of the regressive shale in the H-Zone Cycle (Fig. 52), and in the southwest.

Limited sample data of the G-Zone regressive carbonate indicate lithofacies variation between areas. The lithofacies interpretation again aids in the explanation of the isopach map trends. The abundant

FIGURE 51. Transgressive carbonate isopach and marine interval isopach, H-Zone cycle, Rawlins County. Marine interval defined on log in Figure 44. Note addition of 22-foot contour.

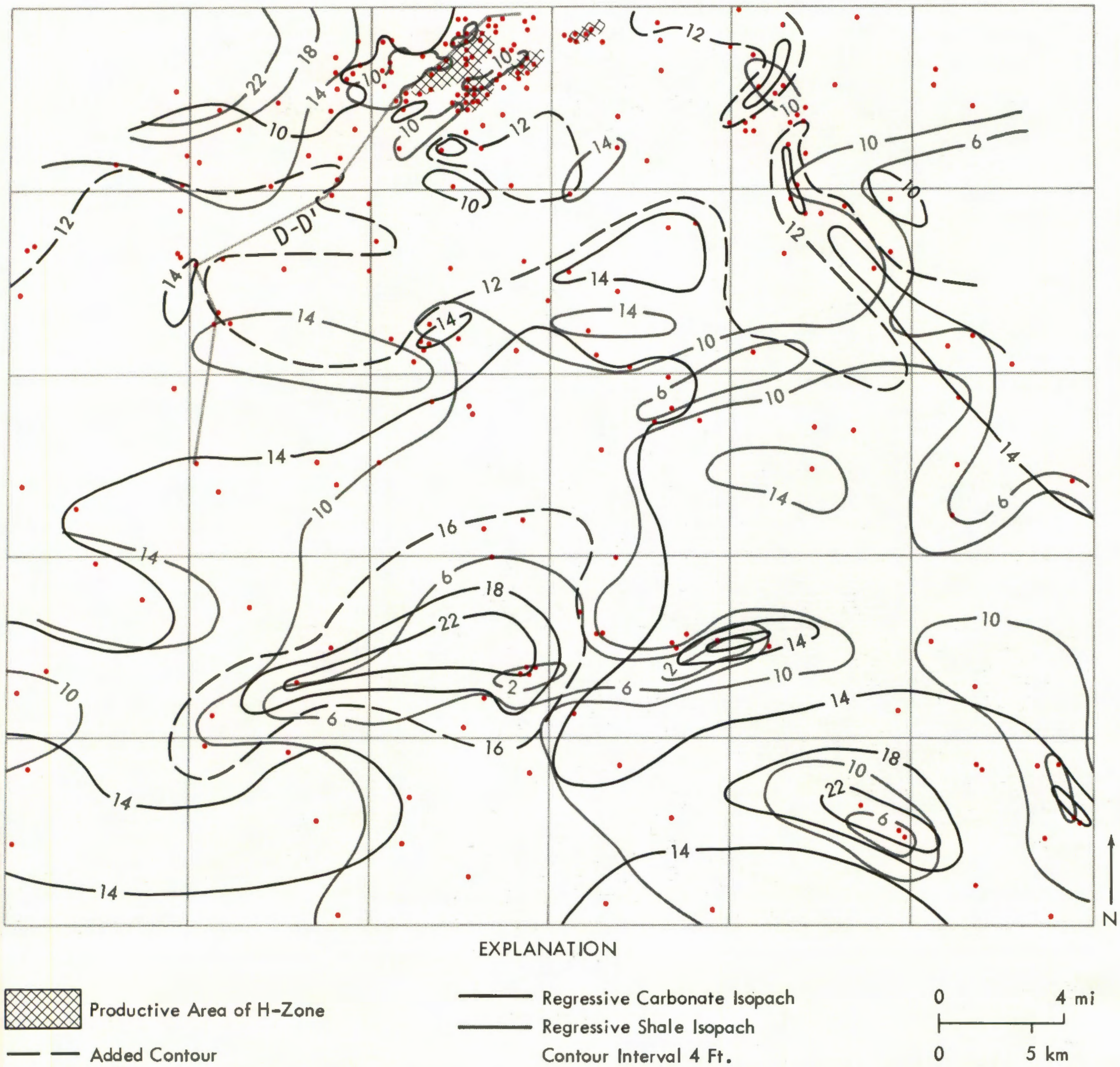


FIGURE 52. Regressive shale and regressive carbonate isopachs, H-Zone cycle, Rawlins County. Regressive-carbonate isopach interval is defined on log in Figure 44. Note addition of 12- and 16-foot contours.

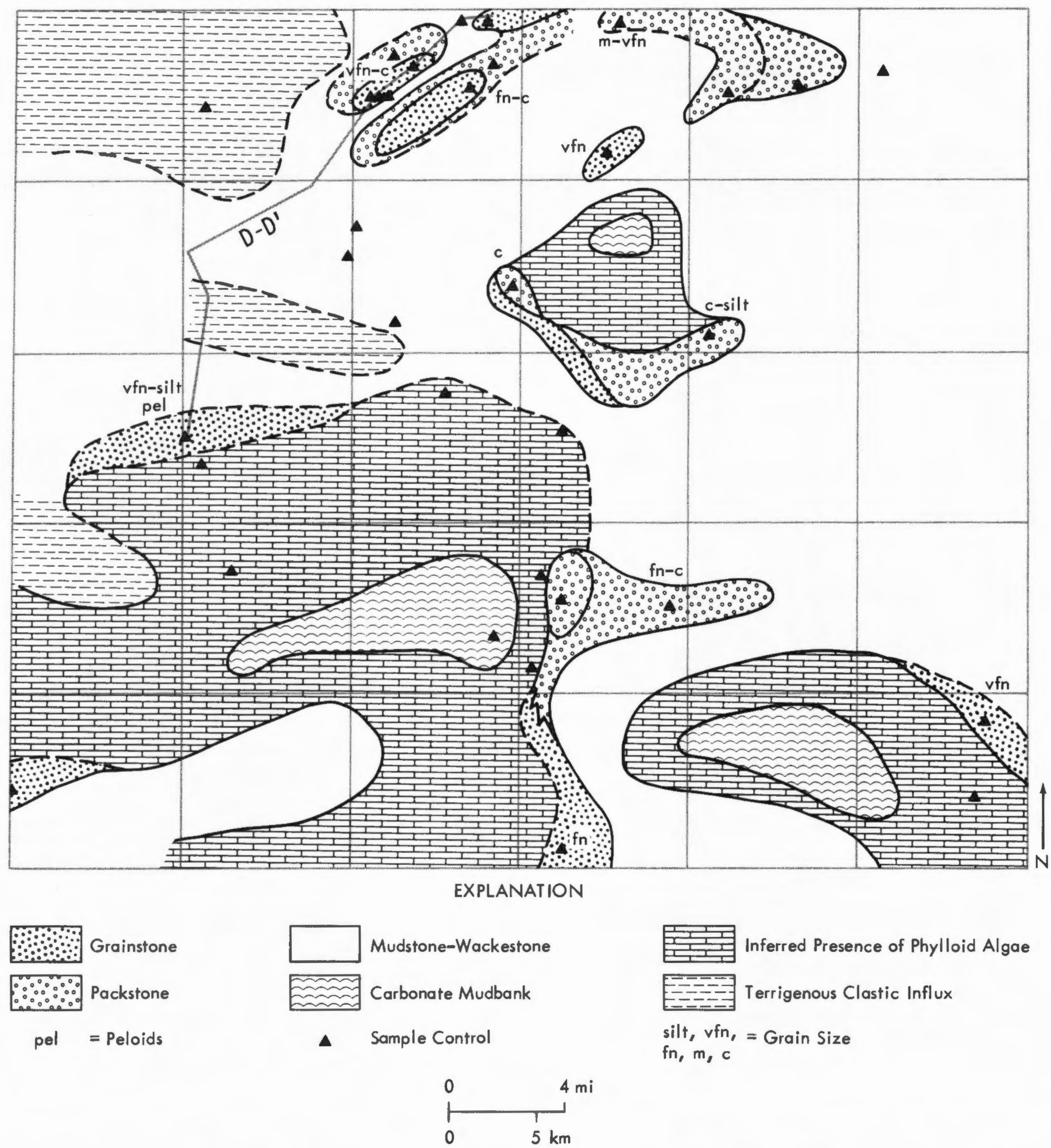


FIGURE 53. Carbonate facies map of upper regressive H-Zone carbonate. Cuttings and core control points labeled. Facies include a thick phylloid algal-mudbank and a grainstone shoal, separated by areas of skeletal lime-mudstone-wackestone. Divisions shown within packstone facies separate areas in which the types of skeletal particles are different.

FIGURE 54. Thin section photomicrograph of cuttings sample from the Skelly Cahoj D-1 (17-1S-34W), located in an area of grainstone shoal facies of the H-Zone carbonate at Cahoj Field. Predominantly a coarse-grained, crinoid, bioclastic grainstone with scattered brachiopods, small bivalves, and forams. Encrusting forams common. Occasional quartz silt grains present. PLANE-POLARIZED LIGHT. Bar scale equals 1 mm.

silty-shale laminations throughout the thin regressive carbonate at the Bartosovsky #1 well location (Fig. 56) reflect the turbidity during carbonate deposition. The thick marine shale in the well also shows the importance of the clastic component in the marine interval (Fig. 55) at this location.

In contrast to this clastic-dominated sequence to the north, the No. 1 Prentice core (Fig. 56), located along the north flank of a thickened regressive carbonate, contains phylloid algae and abundant fossils within a relatively clean regressive carbonate. The marine shale interval is correspondingly thin at this location and is substantially less important in the overall marine interval south and eastward from this location. The cross sections along D-D′ (Pl. 1) illustrate this facies variation in the G-Zone Cycle.

The phylloid algal-bearing G-Zone carbonate in the No. 1 Prentice well is capped by a subaerial crust. Beneath the crust the carbonate shows evidence of leaching by freshwater. The unit, although porous, is water wet at this location. Similar facies in the G-Zone that have undergone freshwater dissolution may prove productive.

Production is now limited to the northern Cahoj structure complex in grainstone and freshwater-altered packstone and wackestone carbonate reservoirs. Grain-rich carbonates are also present south of Cahoj, including the upper regressive carbonate in the No. 1 Prentice well. G-Zone prospects may invoke either or both types of reservoir rocks: secondary porous algal carbonate and primary porous grainstone.

D-Zone Cycle—The uppermost cycle examined is described by an isopach map of the E-Zone carbonate, the transgressive unit of the D-Zone Cycle (Fig. 57), and a generalized isopach of the regressive D-Zone carbonate (Fig. 58) annotated with lithofacies data from core and cutting descriptions.

The transgressive carbonate (Fig. 57) increases in thickness from only two to 16 feet along a narrow east-west trend in central Rawlins County. This trend directly overlies the G-Zone carbonate thick (Fig. 56) and lies slightly north of a superjacent D-Zone carbonate thick (Fig. 58). Significant local thickening also develops over Cahoj Field.

The D-Zone carbonate isopach map (Fig. 58), gradually thickening to the south, is interrupted by a thicker trend in central Rawlins County as mentioned above. Core and sample data from this carbonate on either side of this thick area contain abundant phylloid algae just as in the H- and G-Zone carbonates. The thicker carbonate probably represents a local proliferation of phylloid algae. Flank areas, although containing phylloid algae, do not necessarily result in

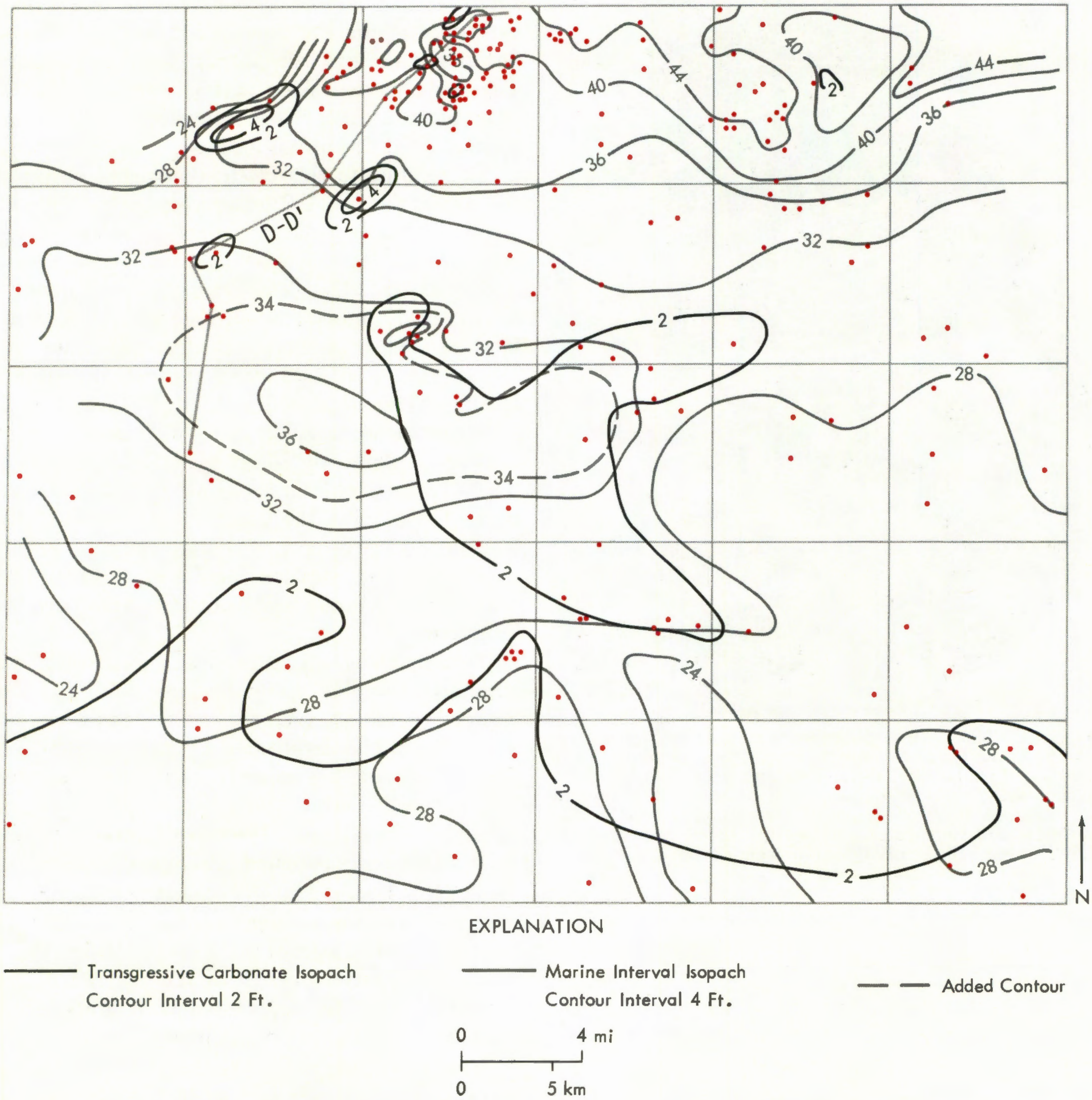
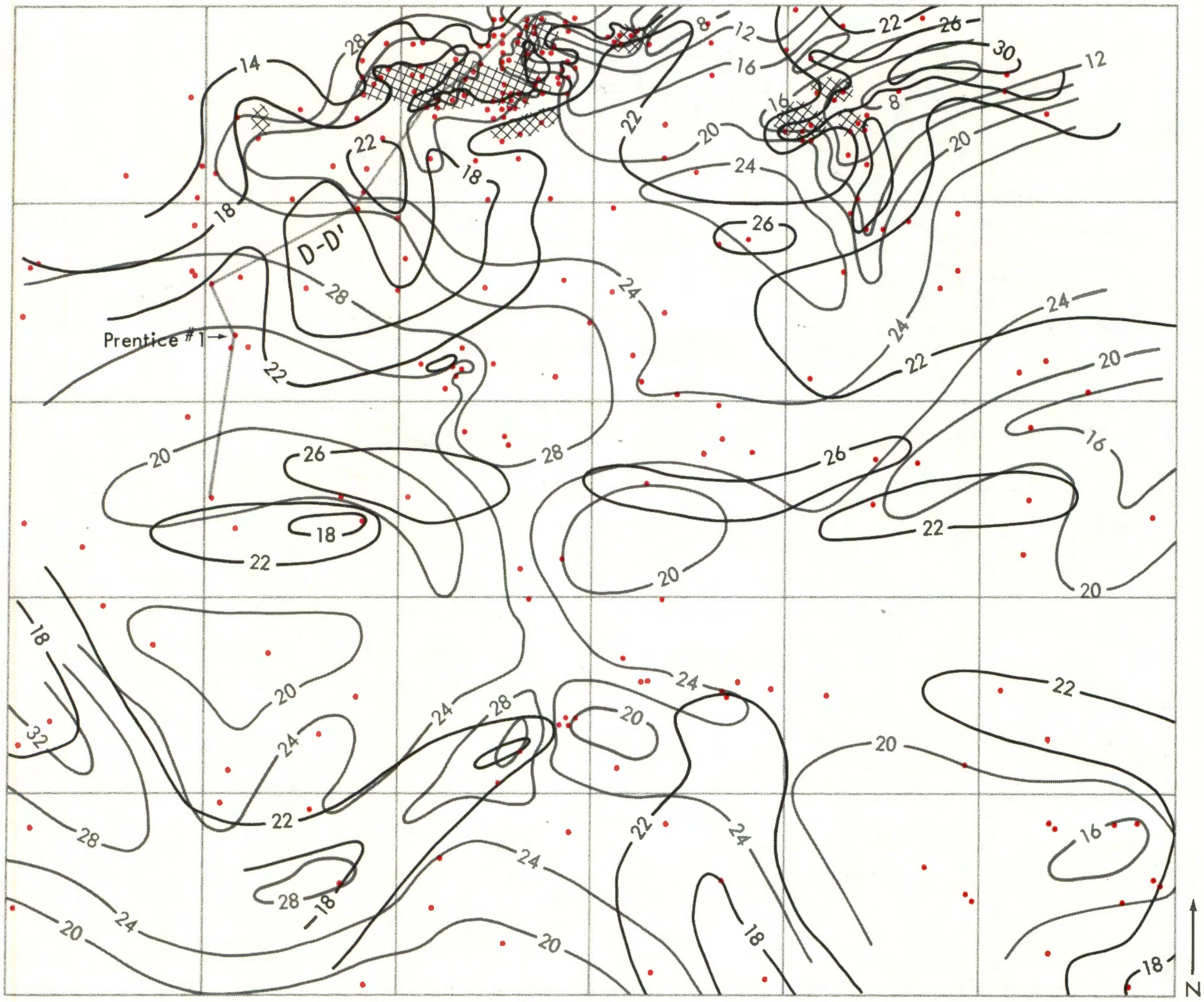


FIGURE 55. Transgressive carbonate and marine interval isopach, G-Zone cycle, Rawlins County. Marine interval thickness is dominated by marine shale to northwest and regressive carbonate over the remaining area. Cross section in Plate 1, defined by index line D-D′ on map, illustrates change from clastic-dominated marine interval of G-Zone cycle in north to carbonate-dominated in the south. Note addition of 34-foot contour.



EXPLANATION

Productive Area of G-Zone

Regressive Carbonate Isopach

Regressive Shale Isopach

Contour Interval 4 Ft.

0 4 mi

0 5 km

FIGURE 56. Regressive shale and regressive carbonate isopachs, G-Zone cycle, Rawlins County.

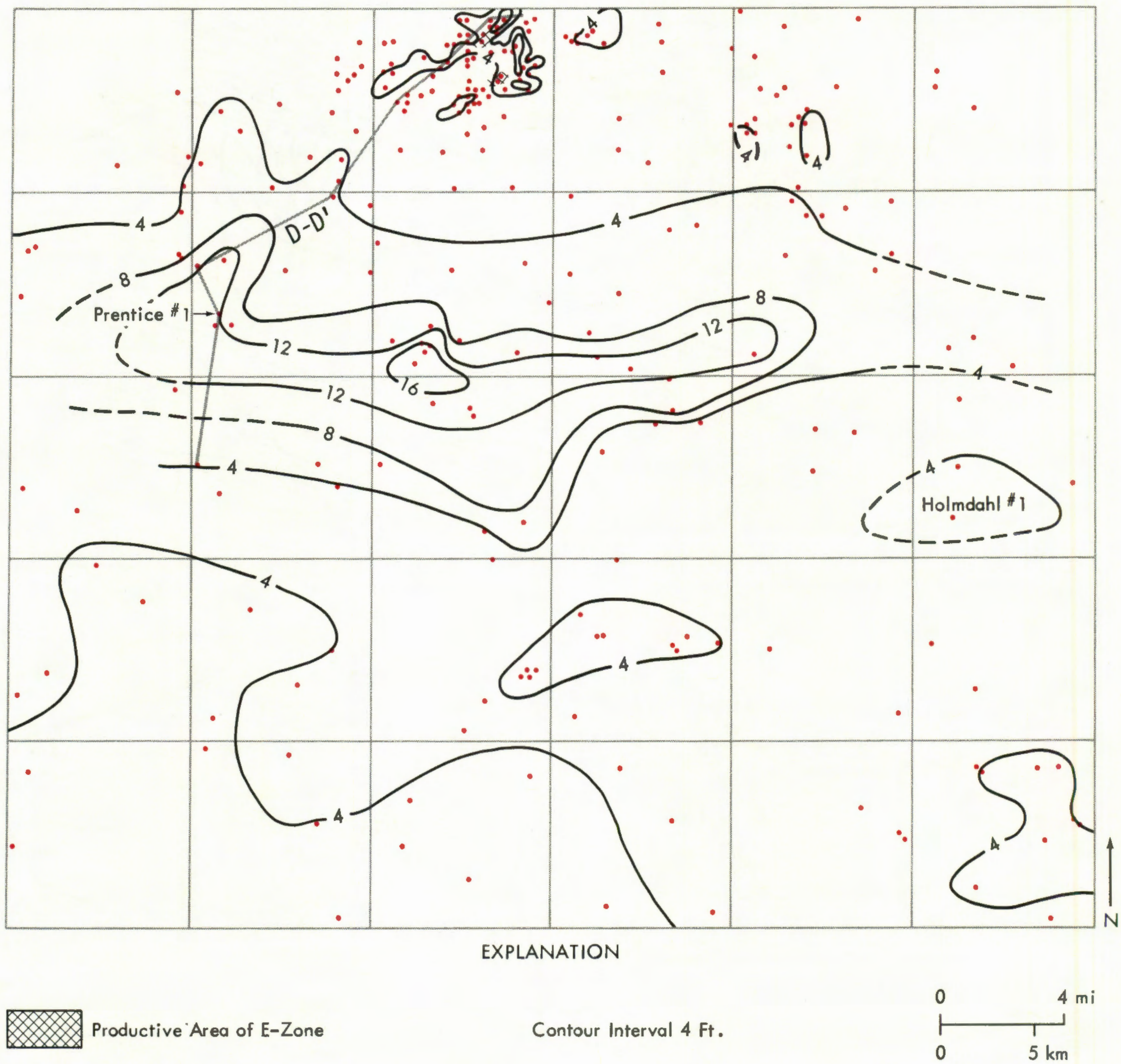


FIGURE 57. Transgressive E-Zone carbonate isopach, D-Zone cycle, Rawlins County. Cross sections along D-D′ (Pl. 1) illustrate the thick central east-west trend attributed to phylloid-algal carbonate buildup.

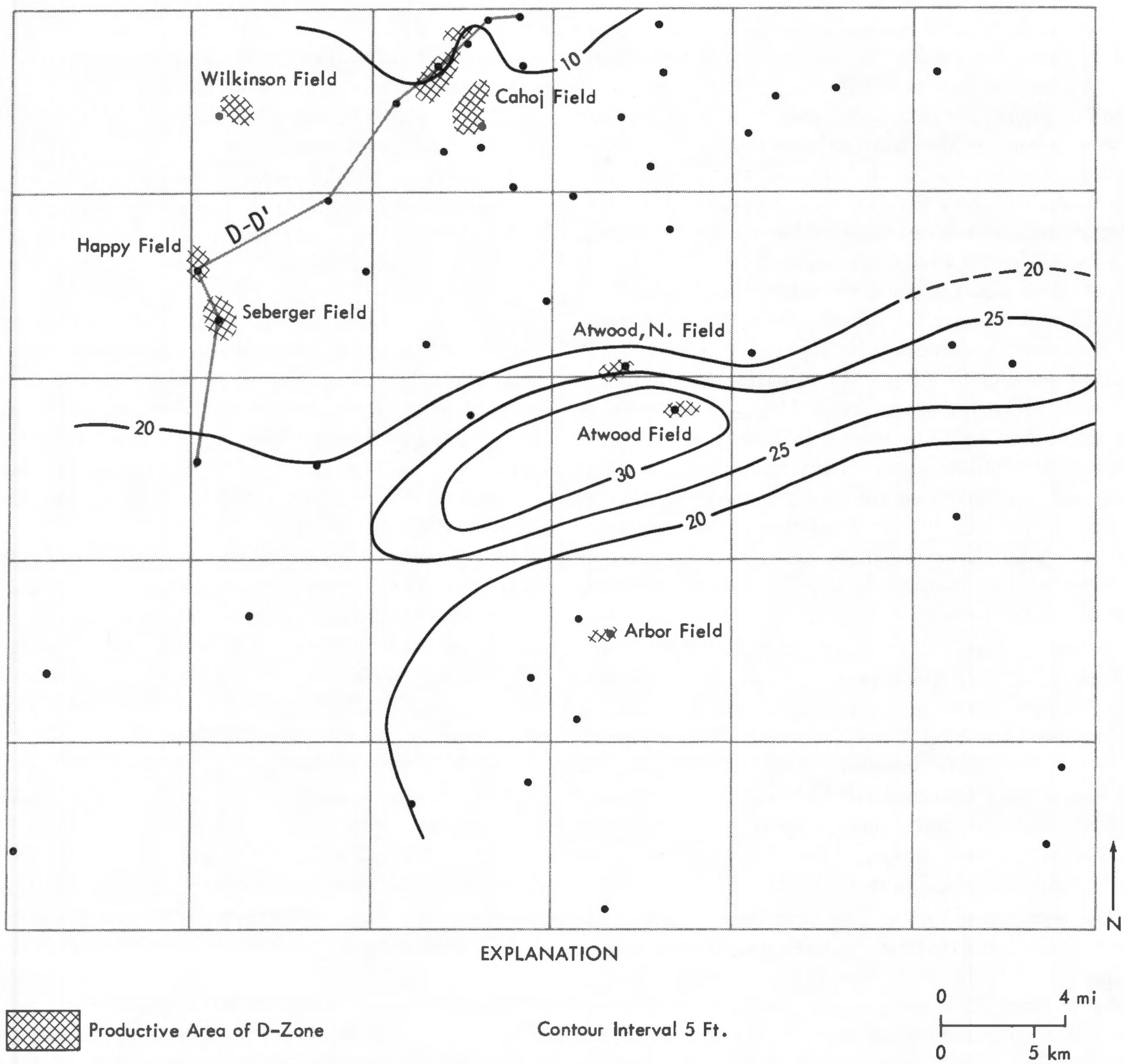


Figure 58. Regressive carbonate isopach, D-Zone cycle, Rawlins County. Productive areas are outlined in the map. Southward thickening is evident in cross section D-D′ (Pl. 1). Note limited well control.

thick carbonate development.

The transgressive E-Zone carbonate locally thickens in a pattern similar to the D-Zone development. The thickening is also attributed to the presence of phylloid algae, the first occurrence recognized in this area of algae in the transgressive carbonate. Interestingly, the E-Zone in the Holmdahl #1 core (Fig. 58) in eastern Rawlins County contains a thin, silty, *Osagia* packstone base; the shoal-water facies is overlain by 3.5 feet of mudstone-wackestone unit, containing phylloid algae in the bottom half foot. In contrast an E-Zone core from the buildup area (Prentice No. 1, 12 feet thick) contains *10* feet of phylloid algal-bearing carbonate (Fig. 11), clearly the dominant facies in this carbonate buildup. During transgression, the carbonate buildup was able locally to maintain more clear shallow-water characteristics by keeping pace with sea-level rise and was not overwhelmed by clastics in prelude to the deposition of the overlying marine shale. Cross sections in Figures 45 and 46 ilustrate this carbonate buildup centered near the Prentice No. 1 well.

In contrast, just to the north over Cahoj Field the E-Zone (Fig. 57) thickened through the accumulation of shoal-water grainstone and packstone. The higher sea floor over the Cahoj location was apparently a focus for the winnowing and accumulation of the lower, early transgressive carbonate. The influx of clastics from the north though, during lower energy conditions present during later transgression, precluded phylloid algal development.

Oil production in the E-Zone occurs in only small areas over Cahoj in the grainstone-packstone facies (Fig. 57). Similarly, in the D-Zone carbonate, this facies is productive over Cahoj and in central Rawlins (Atwood Field) near the crest of the carbonate buildup (Fig. 58).

The phylloid algal wackestone facies of the middle and lower D-Zone is locally productive in Happy and Seberger fields located off the north flank of the buildup in northwest Rawlins County (Fig. 58). The secondary pore space in this algal wackestone is exemplified in the No. 1 Prentice well. Here the D-Zone core contains a 10-foot interval of vugs and fissures, including molds of algae, the result of freshwater leaching and stabilization of this carbonate. The pore space of the upper four feet is filled with graded and laminated deposits of quartz siltstone and very fine grained sandstone (Fig. 17); the deposits closely resemble the overlying clastic sequence. Percolating meteoric waters probably transported this internal sediment down through the carbonate while the unit was subaerially exposed in the vadose zone. Oil-filled porosity underlies the silt-occluded pores. The contact between these may represent the water table at the time of silt infiltration. The pore space below this paleo-water table was saturated with either slow-moving or stagnant water, conditions under which silt could not be transported.

The Prentice No. 1 well produces 16 BOPD from the interval of freshwater-leached, secondary porosity, but in the Frisbie No. 1 well one and one-half miles to the north this same interval had an initial potential of 168 BOPD.

Summary—The four sedimentary cycles have been described through a series of reconnaissance, isopach, and lithofacies maps. Trends of thicks and thins were initially recognized on the reconnaissance and isopach maps. Sample data derived from study of cores and cuttings of the regressive and transgressive carbonates were used to construct lithofacies maps and to describe further these trends.

The reservoir facies of the regressive carbonates in these four cycles are of three types: 1) grainstone and packstone facies, 2) freshwater-leached phylloid algal mudbanks accompanied by flanking or capping grainstone-packstones, and 3) diagenetic, secondary porosity affecting all carbonate rock types. Table 5 describes the various map characteristics used in defining these reservoir facies.

The Cahoj structure in north-central Rawlins County was a positive feature during the deposition of the Lansing-Kansas City cyclic sediments. Evidence presented here of bathymetric relief over Cahoj conforms to deeper subsurface control that indicates a history of positive relief, including basement faulting (Cole, 1976). Isopach and lithofacies maps illustrate lateral cyclic variation over this feature, which relates closely to the Lansing structural configuration. Grainstone and packstone were frequently developed over and along the flanks of Cahoj. Carbonates in which faunal constituents are restricted and that have been altered by freshwater also are abundant on this feature.

The Cahoj structure is producing in 10 different horizons from both primary and secondary porosity. Seventy percent of the Rawlins County production is obtained from this area (Beene, 1979).

Oil fields south of Cahoj in Rawlins County are smaller and more typical of the immediate area. Although not conforming to present structure as in the Cahoj area, favorable facies with primary and secondary porosity are mapped, such as the grainstone facies in J-Zone and the phylloid algal facies of D-Zone. Evidence from isopach maps suggests subtle bottom relief or slope changes were present at the

TABLE 5.—Map characteristics that are useful for identifying reservoir facies.

1. Grainstone and Packstone Facies
   Marine Shale Isopach: Thickening over area of suspected bathymetric relief where concentrations of grain-rich carbonates commonly occur.
   Regressive Carbonate Isopach: Thickening or thinning depending on winnowed or accretion accumulation.
   Marine Interval Isopach: Local thinning common along south flanks of high-energy shoal (e.g., J-Zone Cycle).
   Regressive Shale Isopach: Closed local areas of thinning may indicate positive locations while unit was deposited.
   Porosity-feet Map: Porosity development at or near the top of the carbonate is a positive indication of grainstone.

2. Phylloid-Algal Mudbanks with Flanking or Capping Grainstone-Packstone
   Marine Shale Isopach: Probable thickening over area of nucleating algal mudbank.
   Regressive Carbonate Isopach: Substantial thickening, generally 2× surrounding area; five to ten miles in length.
   Marine Interval Isopach: (same as marine shale)
   Regressive Shale Isopach: Substantial thinning over buildups.
   Porosity-feet Maps: Porosity at any level in the buildup.

3. Early Diagenetic Secondary Porosity
   (in Cahoj area): Thinning or thickening of both regressive carbonate and shale accompanied by associated facies variation (winnowed, silty deposits or thick restricted-marine facies over bathymetric high; focus for early diagenetic processes).
   (in phylloid algal buildups): Local thickening of all intervals except regressive shale; (aragonitic algae very unstable during freshwater diagenesis; topographic relief also tends to focus these early diagenetic processes on the buildup).
   (in association with high-energy carbonate): Look for map properties as described earlier (primary porosity is potential avenue for movement of diagenetic waters; secondary porosity trends may follow mapped grainstone trends).

time of sedimentation across southern Rawlins County.

Mapping the structure from subsurface data indicates production does not always exist on structurally high areas with closed contours. Similarly, present structure may not have any relationship to porosity pinchout. Therefore it is necessary to accompany maps of structure, present production, tests, and log-analysis data with isopach and facies maps. A prospect can then be recommended on the basis of a number of significant criteria.

To the south, beyond the study area, additional carbonate units and changes in the extent of transgression and regression will modify the stratigraphic framework and may change the significance of certain isopachs. Nevertheless, the use of the sedimentary model and the reliance on good samples should allow facies description and the discrimination of potential petroleum reservoirs.

The cycle would be expected to include more marine characteristics and the carbonate-to-clastic ratio should increase, as the cross section A-A′, Figure 5, demonstrates. In places the marine shale or regressive shale may be missing entirely. As suggested by the stratigraphic model (Fig. 37) the regressive shale grades basinward from continental to increasingly marine in character, including additional carbonate units. Accordingly, the complementary nature of the regressive shale and the regressive carbonate may not exist. Rather the regressive shale may drape evenly over the underlying carbonate.

Grainstone deposits and mudbanks similar to those observed here persist southward (basinward) as previous studies and experience indicate. The thickness and constituents of the carbonates will vary, though, according to changes in water circulation, rates of deposition and subsidence, and water depth.

Early diagenesis is less extensive and intense in the southern portion of the study area. Similarly, the intensity of early diagenesis should continue to diminish basinward, but the effects may still be locally significant in formation of porosity. For example, the oomoldic zones in the southerly shelf area of Haskell County, described by Brown (1963), probably occurred during early partial dissolution of unstable aragonitic oölites as a response to flushing by undersaturated waters (brackish or fresh). Notwithstanding the general decrease in intensity of early freshwater diagenesis to the south, diagenesis should be important across much of the shelf.

Drilling prospects may be recognized that originated differently but now are adjacent to each other, such as the grainstone trend over and around Cahoj, and porous, altered wackestone within the algal mudbanks of the H-Zone. Structural mapping alone would not detect the latter development. Knowledge of facies with the aid of the structure would be decidedly useful in indicating the potential step-out locations during field development.

Composite isopach maps of more than one carbonate unit in several sedimentary cycles may not reveal these types of trends. The added thickness of adjacent units may mask the important changes within an individual unit. If carbonate buildups in a vertical sequence offset one another, a composite isopach map may indicate only a nebulous thick area, with no clear delineation of prospects.

The task of defining genetic units of a cycle requires time and an understanding of the stratigraphy, but the rewards are apparent. Methods of saving time are available, such as establishing a computer data base, as used here, which can be updated and retrieved on a routine basis. New well data can be placed on punched cards or into a tape file and then posted or mechanically contoured on a new base map with the original data set.

Good samples and core have inestimable value in an integrated approach such as this. The required knowledge of the stratigraphy can only be gained through detailed sample observation. Whether it is referred to as "ground truth" or "back-to-basic geology," this critical step of examining the rocks is essential.

In exploration, well logs are generally used to correlate and pick stratigraphic data. Quantitative well-log analysis is equally important in an exploration program. Resistivity-porosity cross-plots and maps of R_{wa} and porosity thickness add another dimension to trend evaluation. Probing questions such as the following can be posed and realistically answered, provided good-quality logs from holes in good condition are available: Where and at what levels within the carbonate is porosity developed? Do log "matrix" parameters and resistivities indicating water-wet rocks vary within a single unit? Do the production tests and core analyses in the area confirm or conflict with the log data? Why? Changes in reservoir facies and related types of porosity, changes in water salinity, and changes in irreducible water saturation all affect the log response. With sufficient sampling of water and rock, combined with core analyses and well testing, the log response can be explained and the reservoir more fully understood. This knowledge would be extremely useful in developing a secondary or tertiary recovery program for the zone.

In a logging program, gamma-ray logs are essential. A resistivity tool with good bed resolution is absolutely necessary under the conditions of high resistivity contrast between thin beds of shale and tight limestone or porous limestone. Focused resistivity logs such as Guard or Laterologs are adequate, particularly when run in low-resistivity drilling muds. Porosity logs such as sonic, density, and neutron all have their relative merits, particularly in cost. If the borehole is in good condition, a sonic or density can give more reliable porosity readings than the thermal neutron. A combination of a GR, resistivity, and at least one porosity tool is suggested for adequate evaluation. The procedure in the sedimentologic evaluation for prospective petroleum reservoirs is outlined in Table 6.

TABLE 6.—Suggested procedure for using interpretive method in other areas.

1. Examine the logs and construct reconnaissance maps for the particular carbonate zone or group of zones. This should set up trends of porosity and suspected hydrocarbon saturation.

2. Following the cyclic sedimentary model, define the lithofacies intervals using core and selected cuttings. Construct facies isopach maps from the well-log data.
   It is important here to incorporate the Lansing-Kansas City cycles into a regional lithofacies framework. The distribution of the lithofacies vary according to the modified Irwin model. Early diagenesis that appreciably affects these sediments varies locally and regionally. Cores including both the shale and carbonate provide the foundation for sedimentologic analysis.

3. Describe cuttings from additional well selected with the aid of the isopach maps to further identify the lithofacies distribution.

4. Using the isopach maps, extrapolate the lithofacies determined from cuttings.

5. Integrating the resultant lithofacies map with the porosity-feet and R_{wa} maps should improve the understanding of significant porosity trends.

CONCLUSIONS

1. The Missourian Pennsylvanian sediments in the study area represent cyclic deposition on a portion of a broad epeiric shelf.

   (a) Fluctuations in sea level over the Kansas shelf and variation in terrigenous clastic influx are proposed as the major processes that produced the Lansing-Kansas City alternating sequence of carbonate and clastic sediments representing marine, shoreface, and continental environments.

   (1) Thin but extensive deposits of a transgressive carbonate unit initiate the cycles. The base of this unit closely approximates a time surface. Marine shale accumulation records the period of maximum marine transgression. Regressive deposition in the upper part of a cycle represents, in part, accretion and progradation of facies which are diachronous, building outward (basinward) with time.

   During regression, patterns of sediment accumulation are combined with relative sea-level fall, eventually resulting in deposition of shallow-water facies throughout the study area. Facies belts varying from 10 to more than 100 miles wide are established across the shelf by this process. Local bathymetric relief or slope changes cause recognizable variations in facies distribution.

   The later regressive phase of the cycle is dominated by clastic accumulation deposited under continental conditions. Subaerial exposure and freshwater diagenesis of the regressive carbonates occurred at this time.

   (2) Climate was probably semi-arid or included prolonged dry periods, as inferred from the paleolatitude of the area and the type of age-equivalent deposits in the surrounding western Midcontinent. Regressive shale deposits are also thin and suggest a lack of significant runoff. Paleosoil development is similar to soils developed in the southwestern United States.

2. Early freshwater diagenesis significantly altered the regressive carbonate, such that primary porosity was frequently enhanced and effective secondary porosity was produced.

   (a) Porosity trends, controlled by the depositional environment, generally extend beyond the oil-field limits. Untested areas "along trend" are prospective locations, particularly in areas with structural closure on the top of the prospective reservoir.

   (b) The extent and form of diagenetic alteration and pore cement distribution are functions of the conditions of diagenesis and the composition of the host carbonate. The accessibility and chemistry of diagenetic waters affecting these sediments are important. Similarly, the relative abundance of unstable carbonate components such as phylloid algae (aragonite) versus more stable (less easily dissolved) crinoid debris (Mg-calcite) can significantly change the end product of diagenesis, i.e., porosity enhancement or porosity occlusion.

   (c) Intensity and probably duration of freshwater diagenesis increases northward toward the landward shelf margin. The relative degrees of diagenesis are expressed by formation of subaerial crusts, *in situ* brecciation, and erosion of the regressive carbonate, and by soil development and oxidation within the regressive shale.

3. Subsurface methods including core and sample description and petrophysical well-log interpretation can be integrated to define and understand prospective hydrocarbon trends. Even though well cores may be few in number, the benefits of geological and engineering understanding of the reservoir and its surrounding rock facies more than offset the infrequency of taking cores.

   Occasional cores are justified in a drilling program. A thorough well-site geological description followed by selective laboratory core-analysis measurements proves most useful to the immediate well and to a timely analysis for additional drilling. Likewise a core from an unproductive zone can also be important by providing economically useful information. A water-wet but very porous interval still fulfills one of the reservoir requirements. Knowing why the carbonate is porous *or* tight is very useful when deciding what the next step will be. Using this "dry-hole" core data may provide insight for map modification and suggest additional drilling locations.

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CONVERSION TABLE

1 mile	= 1.609 kilometers
1 foot	= 30.480 centimeters = 3.048 meters
1 inch	= 2.540 centimeters
1 square mile	= 2.590 square kilometers
1 acre	= 0.405 hectares = 4047 square meters
1 gallon	= 3.785 liters
1 barrel (petroleum)	= .1589 cubic meters

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PLATE 1. (a)—Southwest to northeast stratigraphic cross section D-D′ using multiple logs including gamma ray. Datum is the base of the J-Zone regressive carbonate. Carbonate-zone correlations are labeled beside the section. Correlation lines between wells include, from top to bottom: top of Lansing Group, base of E-Zone, base of H-Zone, base of J-Zone, and base of the Kansas City Group. Gamma-ray and resistivity curves are appropriately scaled. A vertical, eight percent-porosity line is shown for the neutron and sonic log curves. Production data and tests are included below each well. Note the high-energy deposits in the Skolout, Ohlson, and Souchek wells on the flank of Cahoj Field, which are observed in a core and in cuttings.

(b)—Lower cross section is an interpretive stratigraphic cross section along D-D′. Well positions and scale are identical to the upper section. Sample intervals examined are listed at the base of each well. Lithology listed without sample observation represents extrapolation from adjacent wells using isopach trends and/or lithofacies maps. Carbonate units are labeled. At the margins of the section are shown vertical boundaries of the sedimentary cycles and their thicknesses. The structure map in Figure 43 shows the structural position of each well in this section.

WELL KEY

Index #	Well Name	Location	Test Results
1	Empire Beeson #1	18-3S-35W cswsw	Dry and Abandoned; DST of A,B: 30 ft. Oil Cut Mud + 120 ft. Oil & Water Cut Mud DST of H: 15 ft. Mud
2	Murfin Prentice #1	30-2S-35W cnene	Seberger Field Confirmation; 16 BOPD + Water; DST of D,E: 120 ft. Oil Cut Mud
3	Murfin Frisbie #1	18-2S-35W 150′ swcnwsw	Happy Field Extension; 168 BOPD from D DST of D: 1750 ft. Oil DST of G: 1300 ft. Oil Cut Water DST of H: 2500 ft. Oil Cut Water
4	Pan American Prochazka #1	2-2S-35W cnwne	Dry and Abandoned; DST of D: 186 ft. Slightly Oil Cut Mud + 2037 ft. Salt Water DST of H,J,K: 90 ft. Very Slightly Oil Stained Mud
5	Skelly Skolout #1	19-1S-34W nwnene	Cahoj Field Development Well; 28 BOPD + 22 BW from G; DST of D: 2 ft. Heavy Oil + 60 ft. Oil Cut Mud; DST of G: 10 ft. Oil + 150 ft. Oil and Gas Cut Mud
6	Skelly Bartosovsky #1	9-1S-34W seswsw	Cahoj Field Discovery; 3000 BOPD from J,H,G,A DST of A,B: 320 ft. Gas + 160 ft. Oil DST of D: 5 ft. Mud DST of H: 2249 ft. Gas + 1880 ft. Gassy Oil DST of J: 3360 ft. Oil DST of K: 60 ft. Muddy Water
7	Allan Ohlson #1	3-1S-34W csene	Dry and Abandoned; DST of A,B: 10 ft. Mud DST of D,G,H: 20 ft. Mud with Oil Specks DST of H,J: 120 ft. Mud + 160 ft. Salt Water Cut Mud
8	Murfin Souchek #1	2-1S-34W 150′ secsene	Cahoj NE Field Discovery; 152 BOPD + No Water from A,B,G,J; DST of A,D: 60 ft. Gas + 70 ft. Oil Cut Mud + 180 ft. Heavy Oil Cut Mud; DST of D: 10 ft. Oil Cut Mud

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