Kansas Geological Survey
Subsurface Geology Series 6

Core studies in Kansas

Sedimentology and diagenesis of economically important rock strata in Kansas

compiled by

W. L. Watney
A. W. Walton
J. H. Doveton

Lawrence, Kansas
1985

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Kansas Geological Survey
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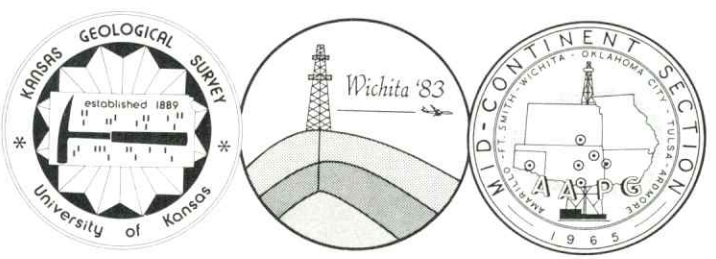

Proceedings of a core workshop held at the 1983 Midcontinent American Association of Petroleum Geologists (AAPG) meeting in Wichita, Kansas. Workshop sponsored and supported by the Kansas Geological Society, Kansas Geological Survey, and the Department of Geology at Wichita State University.

Preface

As geologists have become more sophisticated in the interpretation of the rock record, studies of cores have progressed beyond their traditional level of determining porosity, permeability, and fluid saturations. These investigations have a variety of industrial and academic objectives. Oil in Kansas is found in traps that result from a combination of structural and stratigraphic components. Since the more obvious structures have been tested, industry interest is focused increasingly on traps in which the stratigraphic component is the dominant control. Exploration for such traps requires an understanding of the distribution of porous, permeable rock in the subsurface. Furthermore, secondary and tertiary oil recovery projects can be optimized where the distribution of reservoir rocks is well understood. Although subsurface studies may employ well logs and geophysical techniques, core studies of lithofacies and comparison with modern analogs are fundamental to any detailed geological interpretation.

Several features of rock bodies beside basic lithofacies affect reservoir quality. Cores provide a unique opportunity to examine directly sedimentary structures, directional permeability, reservoir discontinuities, and diagenetic minerals. These results guide not only recovery efforts, but also provide a basis for understanding diagenetic and burial histories of sedimentary basins from which the cores were taken.

Fourteen authors representing industry, government, and academia presented results of their studies of stratigraphy, facies analysis, and diagenesis at the Kansas Core Workshop held at the Department of Geology at Wichita State University on October 16, 1983. One hundred and forty-six geologists registered to examine the cores and discuss the results. The papers in this volume are edited and revised versions of the manuscripts that were available at the workshop. Several of the articles have been expanded and one has been added.

Most of the cores described during the workshop were donated to the Kansas Geological Survey (KGS) by various companies and are available for inspection at the KGS Core Repository in Lawrence.

Papers in this volume were critically reviewed by A. W. Walton, Paul Enos, J. W. Ebanks, Jr., and W. L. Watney.

Daniel Merriam, chairman of the Department of Geology at Wichita State University, arranged for use of the facilities for the workshop. The 1983 AAPG Midcontinent Meeting Committee of the Kansas Geological Society, chaired by Larry Richardson, provided supplemental financial assistance for the workshop. The Kansas Geological Survey provided staff time and financial support for the workshop itself as well as underwriting publication of the original notes and this revised version. David Killen and Talat Abdullah of the KGS and Gu Xiaozhong of the People's Republic of China, Visiting Scientist at the KGS, assisted with the workshop. Marla Adkins-Heljeson edited this publication and Patricia Acker provided graphic support. The convenors wish to thank all of these individuals and agencies.

W. Lynn Watney, Kansas Geological Survey
Anthony W. Walton, Department of Geology, The University of Kansas
John Doveton, Kansas Geological Survey

COVER PHOTOGRAPH—Slabbed core from 3742.5 to 3743 ft below the surface in the Gore #4 Findley located in S1/2SENE sec. 23, T. 11 S., R. 21 W., Trego County, Kansas.

Tan, quartz-silt rich, bioclastic grainstone sharply overlying mottled red-brown, gray-green argillaceous quartz siltstone. Grainstone contains poorly sorted (up to centimeter-sized) blue-green algal-bryozoan-tubular foram-encrusted fragments of brachiopods, mollusks, and crinoids with lithoclasts of caliche, darkened lime mudstone, and green siltstone. Underlying siltstone contains tan, microcrystalline calcitic caliche resembling lithoclasts containing pedotubules and shrinkage cracks filled by calcite spar and quartz silt.

Siltstone represents topmost portion of K-Zone cyclothem (Missourian, Swope Limestone, Kansas City Group) and is interpreted to be a paleosol deposited during latest regression. Erosional contact with thin overlying marine limestone, representing the basal transgressive unit of the J-Zone (Dennis Limestone). Brief, wide-spread subaerial environment on shelf late during K-Zone accumulation in western Kansas was ended by rapid marine inundation at the beginning of the J-Zone. Marine succession of J-Zone is dominated by shallowing-upward carbonate rock.

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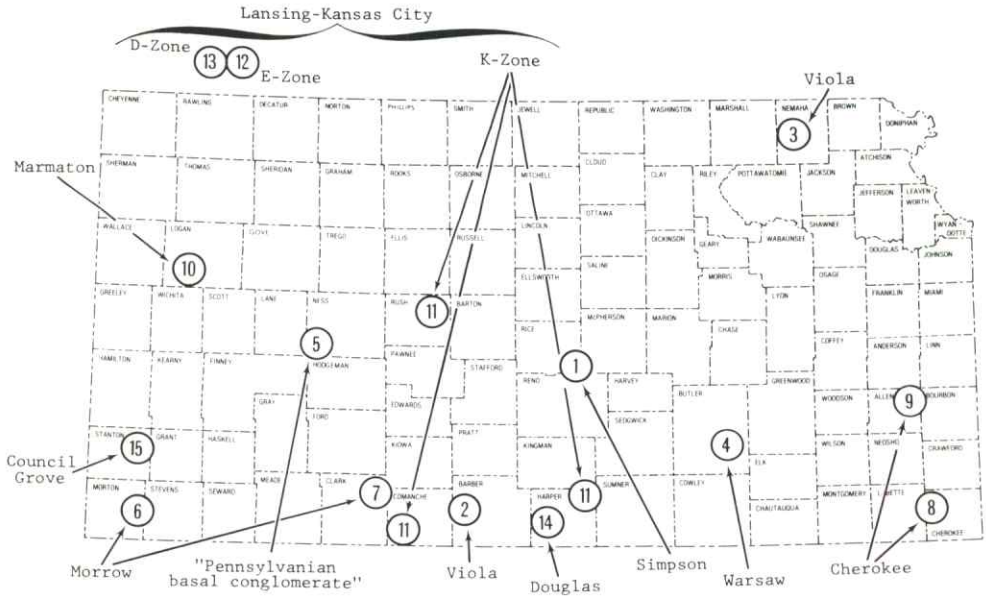

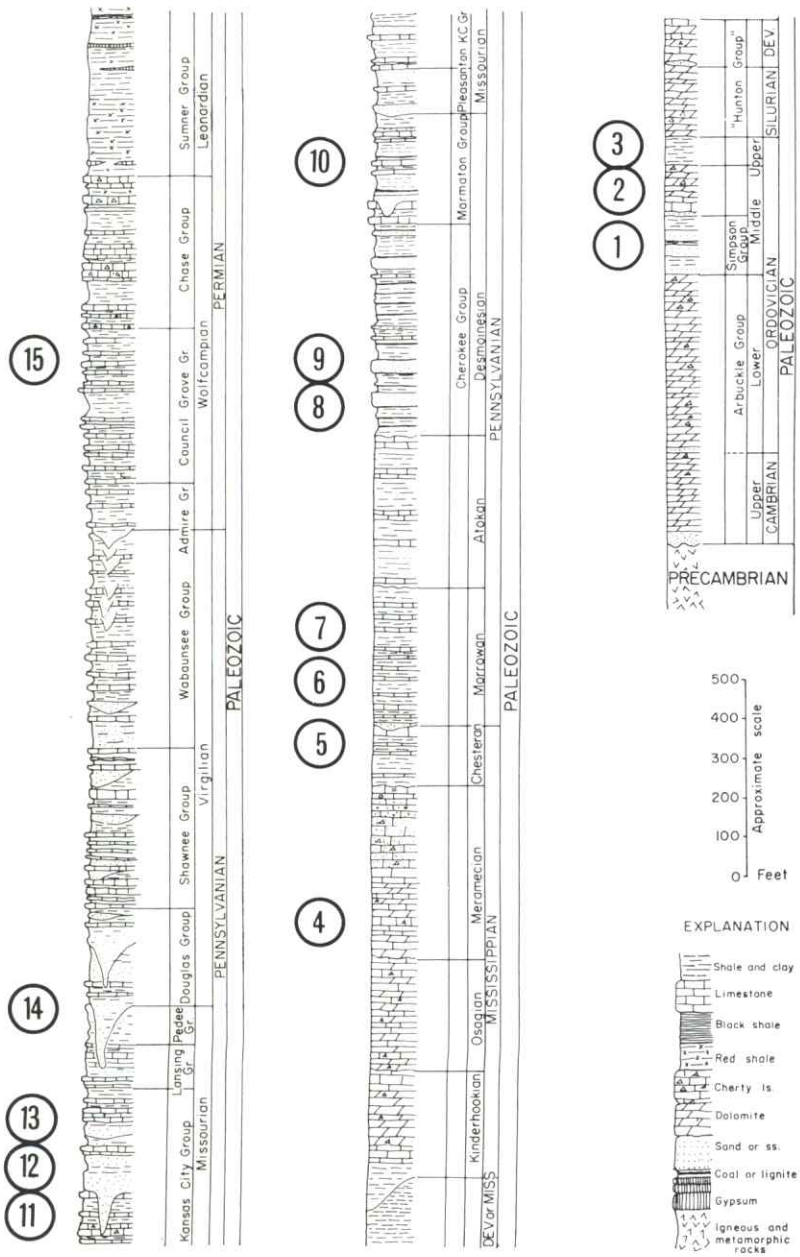

Location map and stratigraphic section showing areas and lithologic units covered by the papers of this volume; 1—Autio, 2—St. Clair, 3—Caldwell and Boeken, 4—Coffey, 5—Nodine-Zeller, 6—Franz, 7—Robinson, Chaudhuri, and Jones, 8—Harris, 9—Rofheart, 10—Caldwell, 11—Watney, 12—Dubois, 13—Prather, 14—Walton and Griffith, and 15—Abdullah.

Lithofacies and depositional environments of the Simpson Group of central Kansas

by *Wendy Autio*, The University of Kansas, Lawrence, Kansas

Introduction

The principal objectives of this study are to interpret the depositional environments and facies relationships of the Simpson Group in the subsurface of Rice, Reno, and McPherson counties, Kansas (fig. 1 and table 1). Simpson deposition may have been affected by structures that formed during the Middle Ordovician, especially a large, northwest-trending positive feature, including the Chautauqua arch, an unnamed hinge area, and the ancient Central Kansas uplift. This positive feature separated the North Kansas Basin from a basin that extended into Oklahoma. This study is concerned with the hinge area and how it affected the deposition of the Simpson Group. Recently discovered magnetic anomalies show evidence of basement lineaments within the study area (Yarger, 1981). Recurrent basement movement along these lineaments may have affected the depositional facies of the Simpson Group.

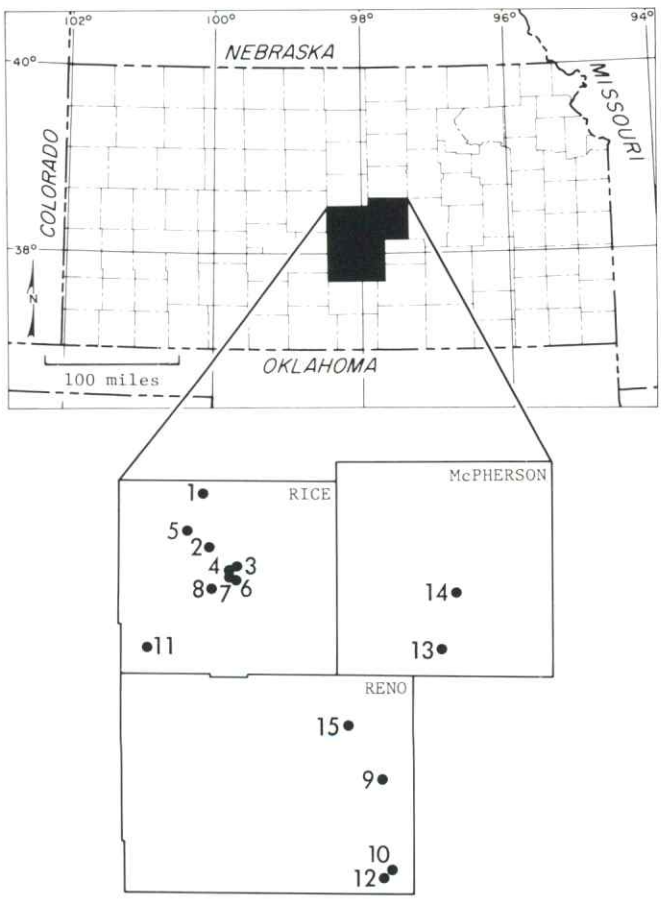

FIGURE 1—Map of Kansas showing study area and location of cores.

Stratigraphic and geologic setting

In Kansas, the Middle Ordovician Simpson Group is found only in the subsurface. It reaches a maximum thickness of 77 m (254 ft) in the Sedgwick Basin. The Simpson unconformably overlies the Arbuckle Group (Early Ordovician) and underlies the Viola Limestone (Middle Ordovician). The Middle Ordovician of Kansas is equivalent to parts of thicker sections in Oklahoma. The Simpson Group consists of white to light-gray quartzose sandstones interbedded with greenish-gray shales, limestones, and dolomites. According to Dapples (1955), the Simpson Group represents a transgressive shoreline deposit that spread into Kansas from a basin centered in Oklahoma. The Simpson probably was deposited throughout eastern and central Kansas, but later erosion removed it from the Chautauqua arch, the Central Kansas uplift, and the northern part of the Nemaha anticline (Goebel, 1968).

Description of lithofacies

Eight lithofacies are recognized in the Simpson Group of central Kansas, based on lithology and sedimentary structures. Some of the lithofacies always are found in the same place in each section, but several lithofacies occur in different positions in the section and may even be repeated.

LITHOFACIES 1—consists of laminated dark-greenish-gray to greenish-black mudshale containing abundant inarticulate and articulate brachiopod shells and shell fragments. The mudshale is thin to medium laminated with laminations from .5 to 3 mm in thickness. Intraclasts are common, and secondary pyrite is abundant. This lithofacies commonly occurs near the base of the Simpson Group, but it also can be found higher up in the section. It is often overlain by bioturbated greenish-gray sandy mudstone (lithofacies 4). Planar lamination is interpreted as representing settling from suspension without traction, based on the fine grain size of the material. Lithofacies 1 makes up 24% of the thickness of all the sections.

LITHOFACIES 2—consists of nonlaminated greenish-gray calcareous mudstone with no observed fossils. This lithofacies is not very abundant as it makes up only 1.3% of the thickness of all the sections. Lithofacies 2 overlies a fine quartz sandstone (lithofacies 6) and underlies a sandy shale (lithofacies 4).

LITHOFACIES 3—consists of structureless greenish-gray siltstone with evidence of bioturbation. Burrowing is pri-

TABLE 1—List of wells shown in fig. 2. Abbreviations in parentheses following well name are code used to label core and thin sections.

Name	Location	Depth of cored interval
1. N.C.R.A. 11W9S Schroeder	NWNENW11, 18S, 9W	3262–3283
2. Champlin 1 Kottman	CNESW19, 19S, 8W	3365–3398
3. Northern Natural Gas 1 Madsen	NENE35, 19S, 8W	3241–3278
4. Northern Natural Gas 35–9 Pulliam	NWSWNE35, 19S, 8W	3258–3290
5. Shell 1 H. Soeken	CW2 10, 19S, 9W	3239–3252
6. Shell 1 W. H. Welsh	CSWNW1, 20S, 8W	3392–3407
7. Northern Natural Gas 1 Caldwell	NENE2, 20S, 8W	3301–3348
8. Champlin 8 Speck	CNWNW18, 20S, 8W	3412–3451
9. J.A. Allison B–1 Collins	NWNENW16, 24S, 4W	3755–3789
10. Midcontinent Marine 1 Hilger	SWCNW34, 25S, 4W	4140–4153
11. Shell 1 A.C. Gordon	CWLNE21, 21S, 10W	3386–3443
12. Midcontinent Marine 1 S. Hilger	W2SWSW9, 26S, 4W	4042–4050
13. Shell 4 P.A. Koehn	SWNENE16, 21S, 3W	3394–3412
14. Shell L. Lawrence	SWNENW35, 19S, 3W	3500–3530
15. Derby 1 Rainbow	NWNWSE33, 22S, 7W	3874–3935

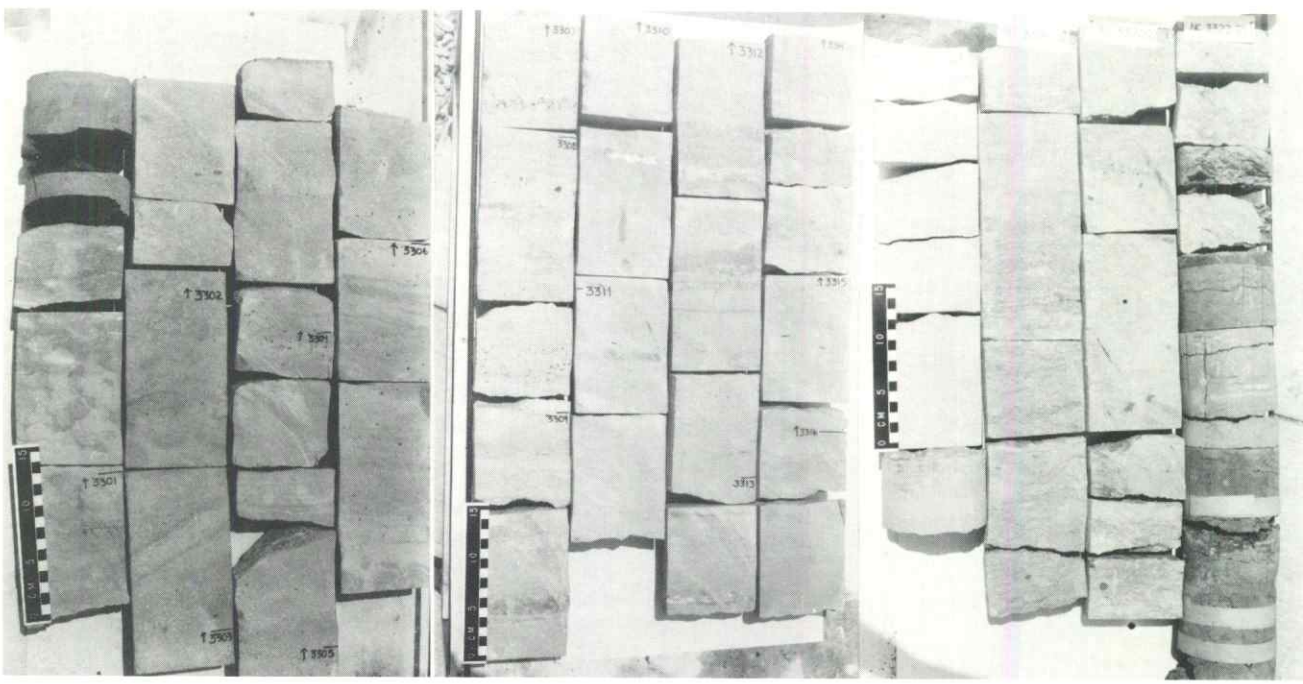

FIGURE 2—Northern Natural Gas No. 1 Caldwell core, 3,300–3,325 ft.

marily horizontal and gives the siltstone a mottled appearance. The burrows are 1–2 mm in diameter. Lithofacies 3 commonly overlies a burrowed greenish-gray sandy mudstone (lithofacies 4). In places it is overlain by a fine-grained quartz arenite (lithofacies 6) and may be part of a coarsening-upwards sequence. Lithofacies 3 makes up 2.3% of the thickness of all the sections.

LITHOFACIES 4—is composed of bioturbated greenish-gray, dark-greenish-gray, and olive-black mudstone containing white to tan, very fine grained quartz sand filling the burrows. No structure is observed in the mudstone. Burrows primarily are horizontal, with some short vertical burrows, and are probably of the ichnogenus *Planolites*. The grain size and abundance of the sand often increase upwards. This lithofacies commonly overlies the laminated mudshale (lithofacies 1), but it can be found throughout the section. Lithofacies 4 is the most abundant of all the lithofacies, constituting 41% of the thickness of all the sections.

LITHOFACIES 5—consists of thin laminations of alternating olive-black mudshale and white very fine grained quartz sand. The laminations are .5–1 mm in thickness. This lithofacies overlies a mudshale (lithofacies 1) and underlies a sandy unit (lithofacies 6). Lithofacies 5 makes up only .2% of the thickness of all the sections.

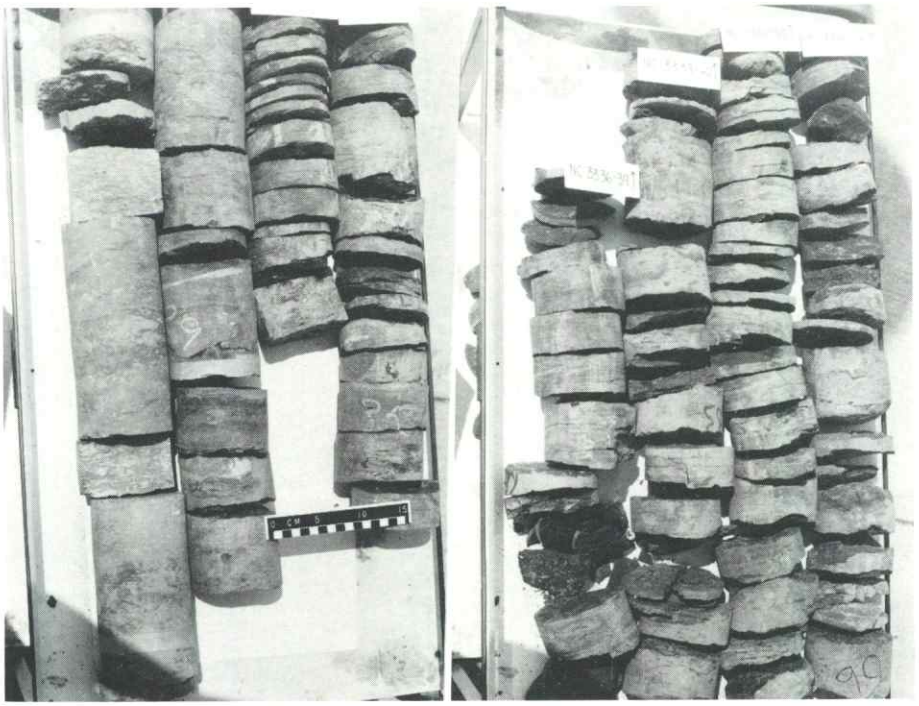

FIGURE 3—Northern Natural Gas No. 1 Caldwell core, 3,325- 3,348 ft.

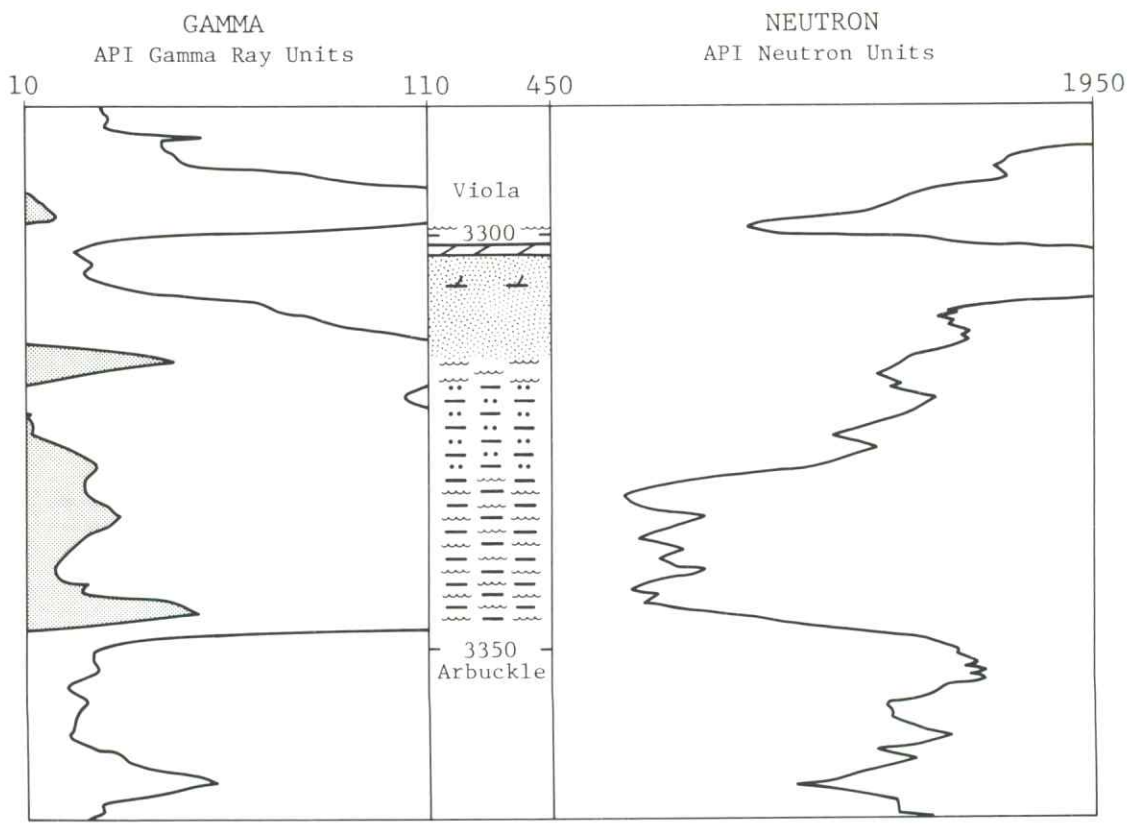

FIGURE 4—Gamma ray and neutron logs of Northern Natural Gas No. 1 Caldwell, Simpson Group interval.

LITHOFACIES 6—consists of structureless very fine to coarse, nearly pure quartz arenite with intraclasts. Greenish-gray shale partings are common.

LITHOFACIES 7—consists of plane-laminated, ripple-laminated, and cross-stratified very fine to coarse-grained quartz arenite with intraclasts and shale partings. Lithofacies 6 and 7 are very similar, but x-radiographs of lithofacies 6 show that bioturbation has destroyed any sedimentary structures that may have been present. Plane laminations in lithofacies 7 are 1 mm in thickness. Cross-stratification of lithofacies 7 is medium scale, and laminae dip a maximum angle of 25° from horizontal. These lithofacies usually are found in the middle or near the top of the section and commonly overlie the bioturbated sandy mudstones of lithofacies 4. The sedimentary structures indicate this unit was deposited by migration of dunes or sand waves in the upper part of the lower flow regime (Harms, 1982). Lithofacies 6 and 7 make up 27.5% of the total thickness of all the sections.

LITHOFACIES 8—consists of red and green mottled silty dolomite and limestone. This lithofacies usually is found near the top of the section and often caps the section. Lithofacies 8 makes up 3.7% of the measured sections.

Environment of deposition

Six of the Simpson facies can be recognized in the Northern Natural Gas 1 Caldwell core. The base of the core contains a dark-greenish-gray mudshale of lithofacies 1 and suggests deposition in a shelf or lagoonal environment, based on the fine grain size, fine laminations, and the predominance of *Lingula* brachiopods. The mudshale is overlain by a bioturbated mudstone and very fine sandstone that indicates deposition in a lower shoreface zone, transition zone, or washover sediment into a lagoon. The high level of bioturbation suggests low wave energy and relatively slow sedimentation rates, so the sediment emplaced during storms was reworked (Elliot, 1978). This bioturbated layer is overlain by a bioturbated greenish-gray siltstone of lithofacies 3. The siltstone could have been deposited on a shelf or in a lagoon. The siltstone of lithofacies 3 is overlain by a structureless very fine to medium-grained quartz arenite of lithofacies 6. Higher in the section one crossbed is observed in this core. The quartz arenite may represent a middle shoreface and upper shoreface environment. The core is capped by a recrystallized silty dolomite of lithofacies 8.

The sequence observed in the Northern Natural Gas 1 Caldwell core is a gradational coarsening-upward sequence, with sand increasing in both abundance and grain size upwards. This sequence could have been formed in several different environments. The coarsening-upwards sequence may represent progradation of shoreline deposits over shelf deposits. The sequence also could have formed as a barrier island transgressed over a lagoon, similar to a model proposed by Kraft and John (1979). In this model, the overwash process is the dominant mechanism. Esslinger (1983) suggests that the Simpson Group of Oklahoma was deposited in a progradational estuarine environment. He suggests that the lack of land vegetation in the Ordovician would allow less-confined, coalescing estuaries. Detailed well-log analysis of the area should delineate the size and shapes of the sand bodies of the Simpson Group and aid in pinning down the depositional environment, as well as help in any future oil and gas exploration within the Simpson Group.

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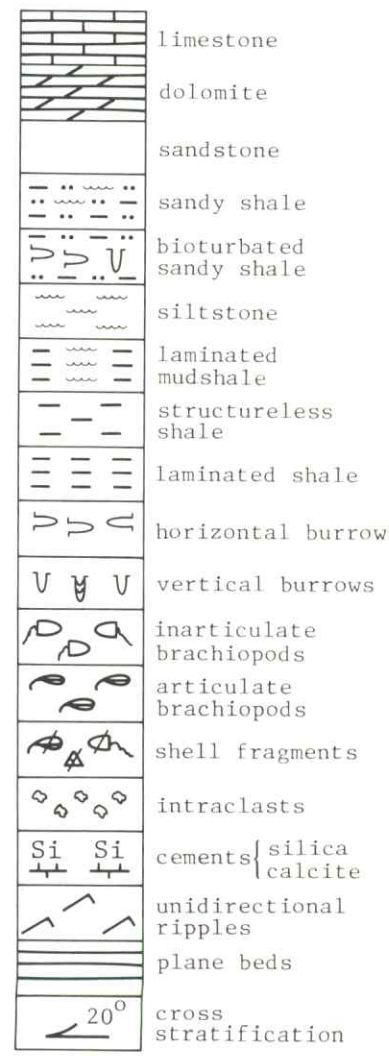
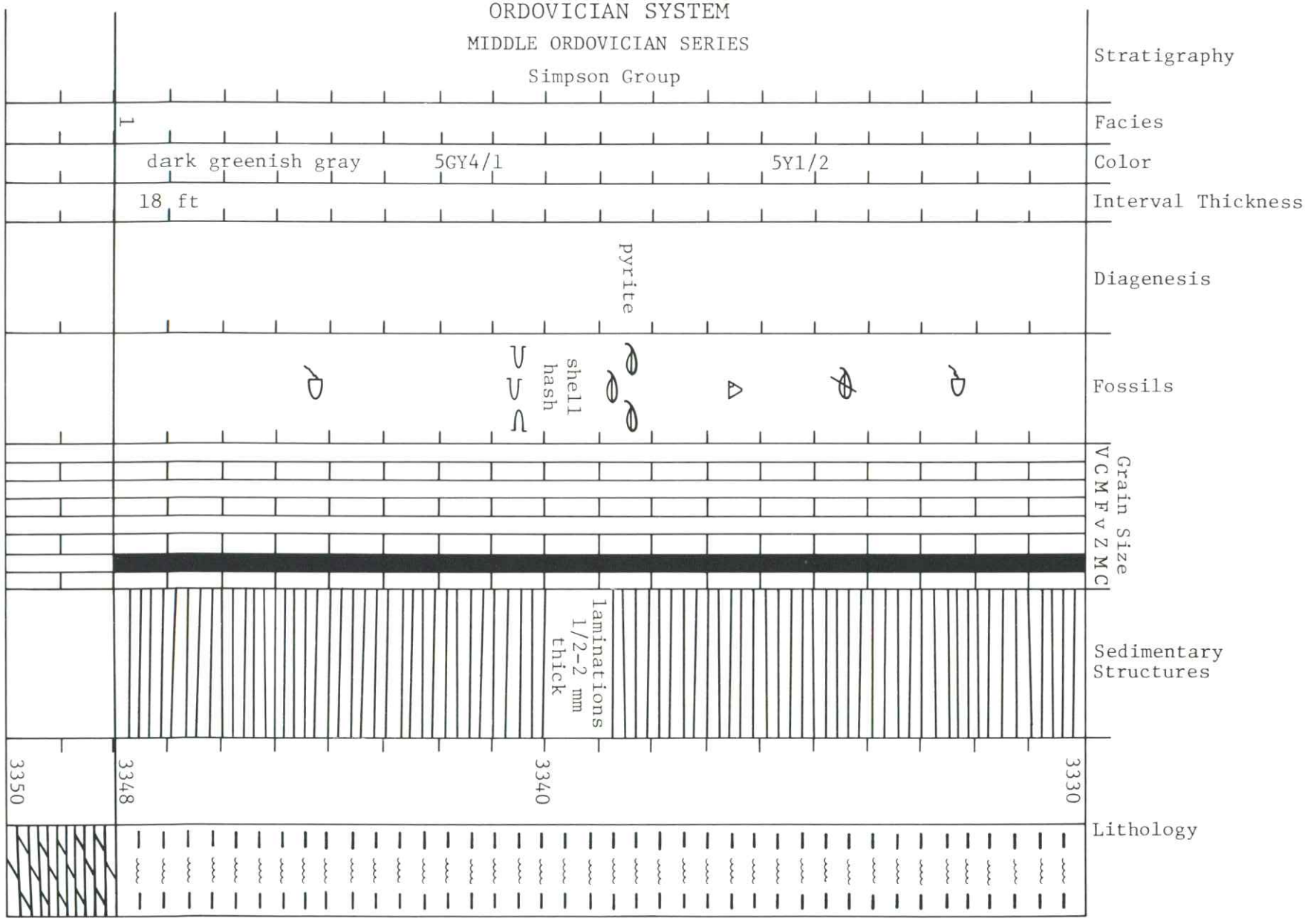
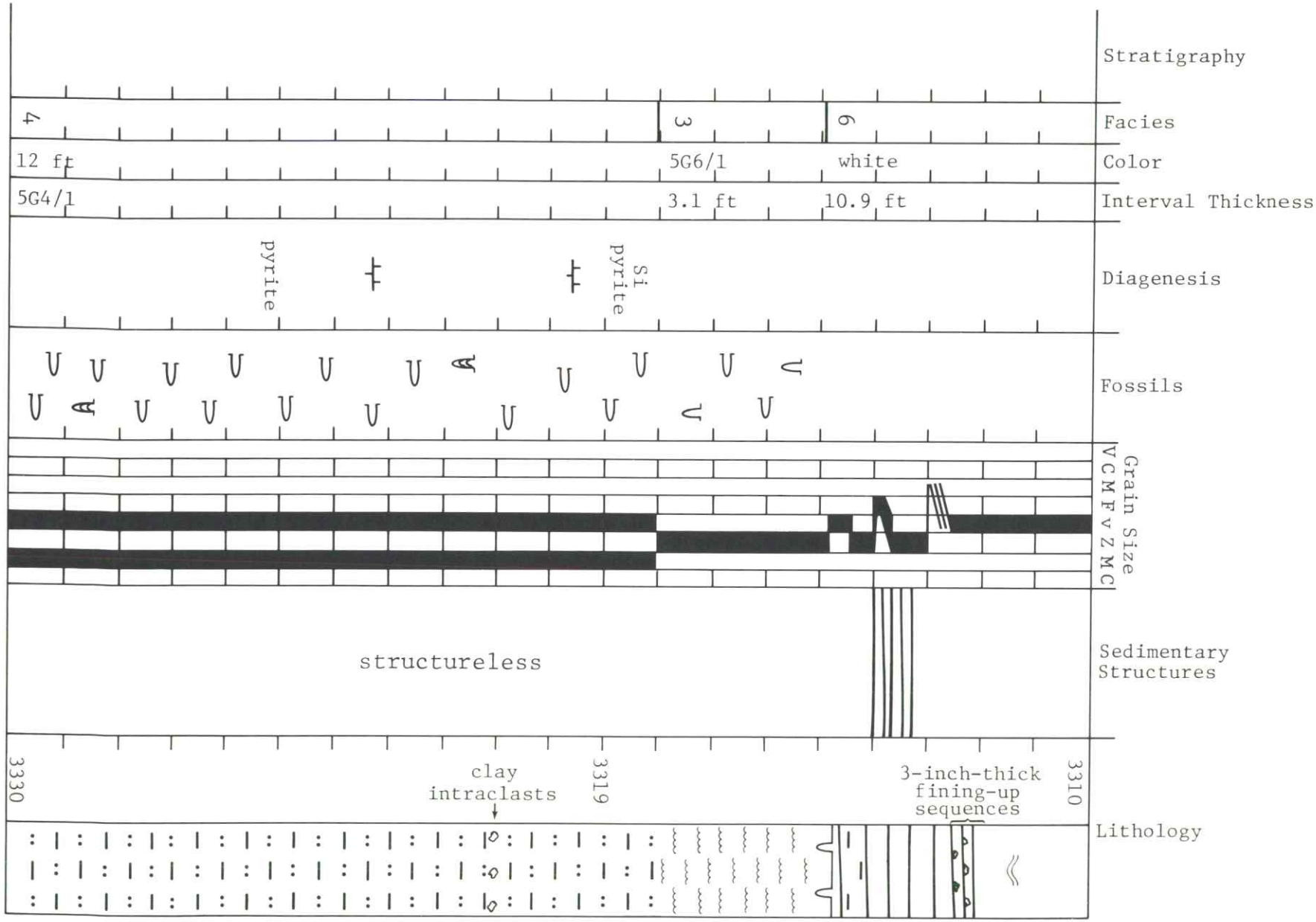


FIGURE 5—Graphic core description for Northern Natural Gas No. 1 Caldwell well (NENE sec. 2, T. 20 S., R. 8 W., Rice County, Kansas.


ORDOVICIAN SYSTEM
MIDDLE ORDOVICIAN SERIES
Simpson Group
Stratigraphy
1
Facies
dark greenish gray
5GY4/1
5Y1/2
Color
18 ft
Interval Thickness
pyrite
Diagenesis
shell hash
Fossils
Grain Size
V C M F v Z M C
laminations 1/2-2 mm thick
Sedimentary Structures
3350
3348
3340
3330
Lithology


Stratigraphy
4
3
9
Facies
12 ft
5G6/1
white
Color
5G4/1
3.1 ft
10.9 ft
Interval Thickness
pyrite
Si pyrite
Diagenesis
Fossils
Grain Size
V C M F v Z M C
structureless
Sedimentary Structures
3330
clay intraclasts
3319
3-inch-thick fining-up sequences
3310
Lithology

Stratigraphy
Facies
Color
Interval Thickness
Diagenesis
Fossils
Grain Size
V C M F v Z M C
Sedimentary Structures
Lithology
1
8
6
7
6
red and green mottled
white
1 ft
1 ft
1.5 ft
1 ft
barite
20°
structure-less
clay intraclasts
3300
3310
top

Core studies of the Viola limestone in Barber and Pratt counties, south-central Kansas

by *P. N. St. Clair,* Marathon Oil Company, Casper, Wyoming

Introduction

St. Clair (1981) made detailed examinations of slabbed Viola core and thin sections from ten wells in Barber and Pratt counties in a thesis study of petrography, lithofacies, and diagenesis. Locations of the cored wells are shown in fig. 1 and listed in table 1. Core from Sinclair–Prairie Degeer #1 NENWNE sec. 34, T. 32 S., R. 15 W. are presented in this workshop. The cores collectively sample all the major subdivisions of the Viola in this two-county area, with the exception of the residual chert facies. In the following text, descriptions and interpretations are based on the full set of ten cored wells. However, most of the features described can be observed in the core samples from the Degeer #1 well.

Stratigraphy

The Viola limestone of south-central Kansas consists of limestones, dolomites, and cherts. Although several geologists such as Taylor (1947) and Ver Wiebe (1948) subdivided the Viola into informal lithologic units, Lee (1943) concluded that the Viola could not be zoned on a regional basis. Adkison (1972) made a detailed study of the structure and stratigraphy of the Viola across the Sedgwick Basin and traced some individual units across limited areas. St. Clair (1981) concluded that the Viola in Barber and Pratt counties could be subdivided into four mappable units, which were informally named the basal limestone (unit 1), the lower cherty dolomitic limestone (unit 2), the upper limestone (unit 3), and the upper cherty dolomitic limestone (unit 4).

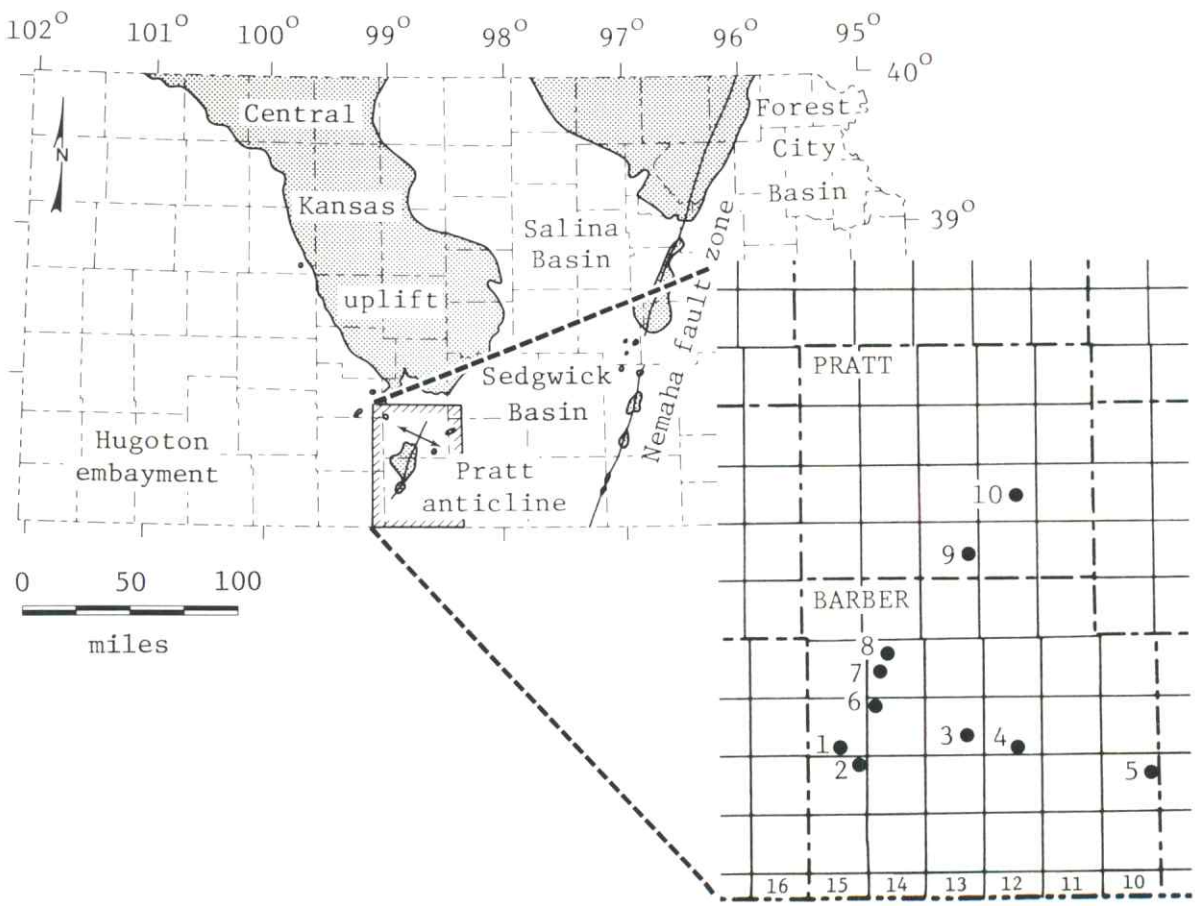
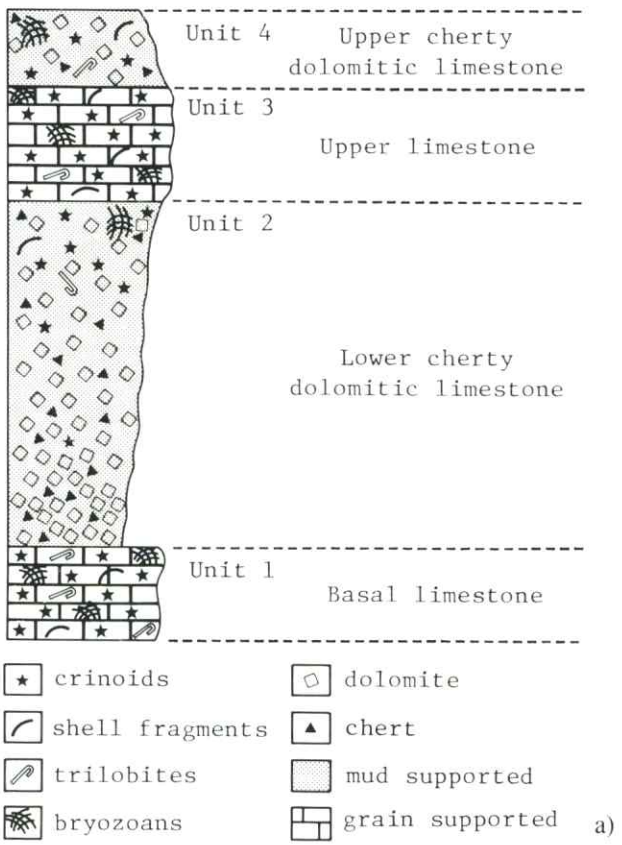


FIGURE 1—Map showing location of study area and wells listed in table 1.

TABLE 1—List of wells and locations shown in fig. 1.

Name	County	Location	Depth of cored interval
1. Sinclair-Prairie 1 Degeer	Barber	NENWNE34, 32S, 15W	1508-1551 (4948-5087)
2. Sinclair 1 Alice Gentry	Barber	NECNE1, 33S, 15W	1571-1594 (5106-5231)
3. Sinclair-Prairie 1 M. Binning	Barber	SESESW26, 32S, 13W	1454-1481 (4769-4860)
4. Lario 2 Randles	Barber	CNENE34, 32S, 12W	1417-1447 (4649-4746)
5. I.T.I.O. 1 George	Barber	CSESW12, 33S, 10W	1433-1458 (4702-4782)
6. Carter 1 Lytle	Barber	CNENW6, 32S, 14W	1435-1473 (4709-4832)
7. Sinclair-Prairie 1 A. Oldfather	Barber	NENESW18, 31S, 14W	1349-1389 (4426-4556)
8. Sinclair 4 G. Oldfather	Barber	SWNWSE7, 31S, 14W	1319-1357 (4328-4453)
9. Bridgeport 1-I Brown	Pratt	SESESW25, 29S, 13W	1361-1400 (4465-4592)
10. Sinclair-Prairie 1 Burton	Pratt	NESENW22, 28S, 12W	1309-1343 (4294-4407)



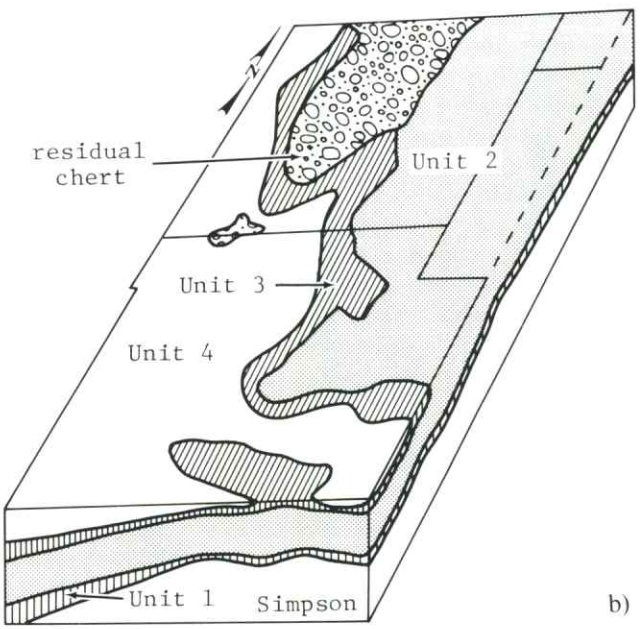


FIGURE 2—a) Generalized stratigraphic section of the Viola Limestone in south-central Kansas. b) Block diagram of the eastern half of the study area showing the present distribution of the Viola subdivisions. Basal limestone = 1; lower cherty dolomitic limestone = 2; upper limestone = 3; and upper cherty dolomitic limestone = 4.

The petrographic characteristics and fossil contents of these units are summarized graphically as a composite section in fig. 2, together with a block diagram to show their subsurface distribution, based on studies of both limited core and cuttings from an extensive well control.

Petrographic summaries and interpretations of lithofacies units

Basal limestone

The basal limestone forms an almost continuous sheet across the study area and has a characteristic "tight-lime" (low-porosity) log response that is useful for locating the boundary between the Viola and the underlying Simpson Group. The units can be summarized as a crinoid packstone-grainstone facies limestone. Fossil fragments other than crinoids most commonly include brachiopods, bryozoans, and trilobites, and less commonly mollusks, ostracodes, sponge spicules, and unidentified phosphatic fossils. Pellets and intraclasts are rare. The interparticle areas are largely filled with optically continuous calcite overgrowths on the crinoids, with minor amounts of bladed cement on the other fossil fragments. Lime mud is present, but only rarely does it occur in large enough quantities to prevent extensive cementation by syntaxial overgrowths on the crinoids. The fossil fragments have sufficient grain

contacts to form a supporting framework. In some cases, pressure solution has resulted in embayed and sutured grain contacts.

The fossils vary in their state of preservation. The crinoids, which are the best preserved, may be partially replaced by dolomite or silica and occasionally display peripheral micritization due to algal or fungal borings (Bathurst, 1966). The trilobites generally are slightly abraded and show the most extensive peripheral micritization. Brachiopods are usually highly fragmented and abraded and are most commonly silicified, while bryozoans show the least preservation and are often completely recrystallized or dolomitized.

Adkison (1972) reported crossbedding in the basal limestone, but none was recognized in samples in the study area. Green shale stringers occur in places, as do lenses of fine-grained dolomite. These dolomite lenses may be up to 1 cm thick and probably were originally lime mud. Large intraclasts, up to 2.5 cm long, which were ripped up from these lenses, may also occur.

Aside from the dolomitized mud lenses, dolomite also occurs as well-developed rhombs ranging in size from 0.08 to 0.26 mm. They are found replacing inter- and intraparticle lime mud and also may replace fossils. The amount of dolomite increases as the original amount of lime mud increases. This is probably due to the greater ease of dolomitization of original aragonitic or high-magnesium calcite mud (Cloud, 1962). Also, since the lime mud impedes the complete filling of interparticle areas by syntaxial overgrowths, the rocks with greater amounts of lime mud may have been more porous than those with little mud, thereby aiding dolomitization.

Chert nodules are rare in this facies. When they do occur, they are composed of a mixture of cryptocrystalline and microcrystalline quartz, chalcedony, and abundant calcite inclusions. Their long axis may be up to 5 cm and is oriented roughly parallel to bedding. The nodules contain numerous fossil ghosts of trilobites, brachiopods, bryozoans, crinoids, and ostracodes and have a mottled light-brown, gray, and white coloration. The contact between nodules and the carbonate matrix is abrupt. The chert nodules are found in those samples with the highest original lime-mud content and consequently the most extensive dolomitization.

Lower cherty dolomite limestone

This unit was originally present throughout the study area but has since been removed by erosion over areas on the Pratt anticline. It ranges in thickness from 0 to 104 ft and consists of dolomite mixed-skeletal wackestones and dolomitized mudstones.

The lower part consists of green to light-brown or gray, argillaceous, cherty dolomite mudstones, which are commonly laminated or mottled. The dolomite is very fine to medium grained and occurs as rhombs or subhedral crystals. Many of the dolomite crystals are multiple zoned with concentric outlines of alternating ferroan and nonferroan dolomite. Ferroan saddle dolomite (Radke and Mathis, 1979) occurs as a cement, partially filling the remaining voids. Ferroan saddle dolomite is a variety of dolomite that has a warped crystal lattice (Radke and Mathis, 1979).

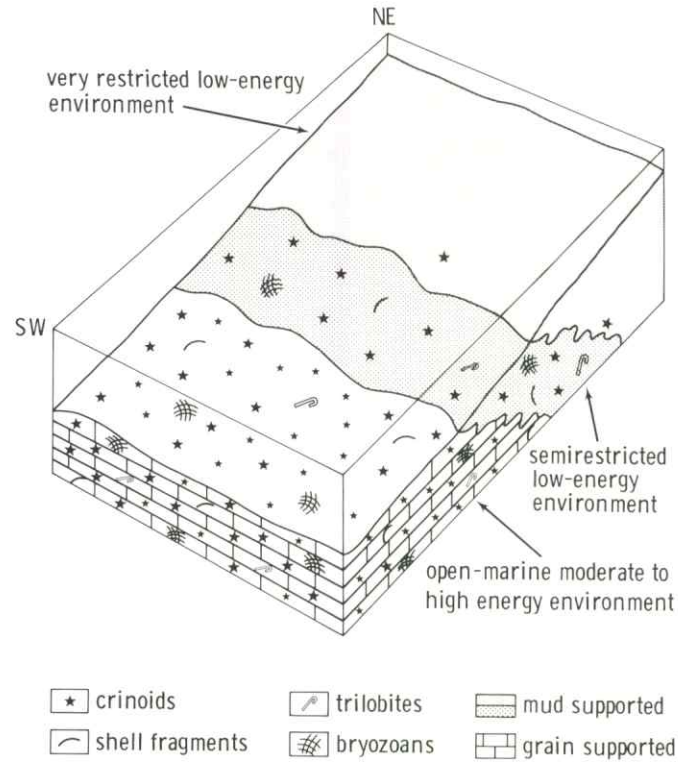


FIGURE 3—Generalized model for depositional environments in the Viola Limestone in south-central Kansas.

Crinoids, brachiopods, trilobites, bryozoans, and ostracodes rarely are present. Most of the crinoids are replaced by large single crystals of dolomite. The crinoids were recognized as "ghosts" within the dolomite crystals. The other fossils are associated with chert nodules and are either partially or totally silicified depending on how complete chert-nodule formation has been.

Laminations occur as alternating layers of medium- and fine-grained crystals, which may reflect original sediment-size differences. Burrows are common and may be filled by dolomite rhombs of a different size from those in the undisturbed sediment. Aside from these features, the size distribution of dolomite crystals is relatively uniform, implying recrystallization from a sediment with a relatively uniform grain size, such as lime mud.

The chert nodules are white or gray with white borders. They may be greater than 8.5 cm in length and are composed of cryptocrystalline quartz. Some chert nodules display ghosts of fossils that are not present in the dolomitized matrix. This may be interpreted as either preservation of the original texture and composition of the sediment in the chert nodule or preferential silicification around fossils. The uniform texture of the dolomite and the occurrence of partial silicification in the vicinity of fossils supports the latter theory. The fossils were probably washed in and created a localized environment favorable to silicification.

A pale-green or light-gray, argillaceous, cherty, dolomitic mixed-skeletal wackestone occurs at the top of this unit

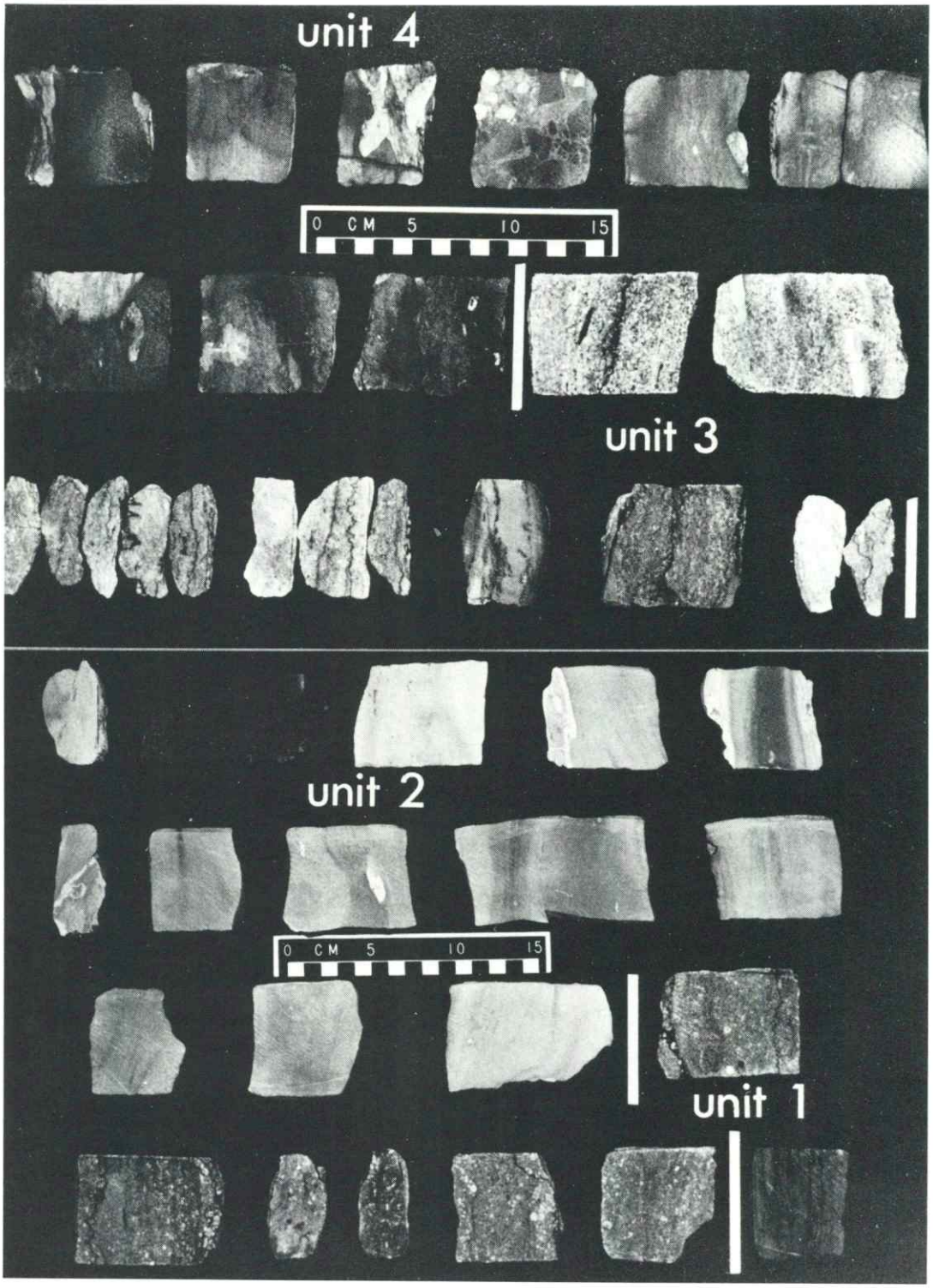


FIGURE 4—Slabbed core of Viola Limestone from Degeer No. 1 (sec. 34, T. 32 S., R. 15 W.). Basal limestone = 1; lower cherty dolomitic limestone = 2; upper limestone = 3; and upper cherty dolomitic limestone = 4. Stratigraphic depth increased from top to bottom and from left to right.

in some cores. The matrix, which was probably originally aragonitic and high-magnesium calcite mud by analogy to modern shallow-water carbonates (Cloud, 1962), has since been partially or completely dolomitized. The dolomite exists as well-formed rhombs from 0.08 to 0.26 mm in size and as very fine grained anhedral crystals. The dolomite rhombs may exhibit as many as five different stages of growth, illustrated by alternating layers of nonferroan and ferroan dolomite. Fine-grained neomorphic calcite spar may exist between the dolomite rhombs.

The fossils in this facies include crinoids, bryozoans, brachiopods, trilobites, phosphatic brachiopods, sponge

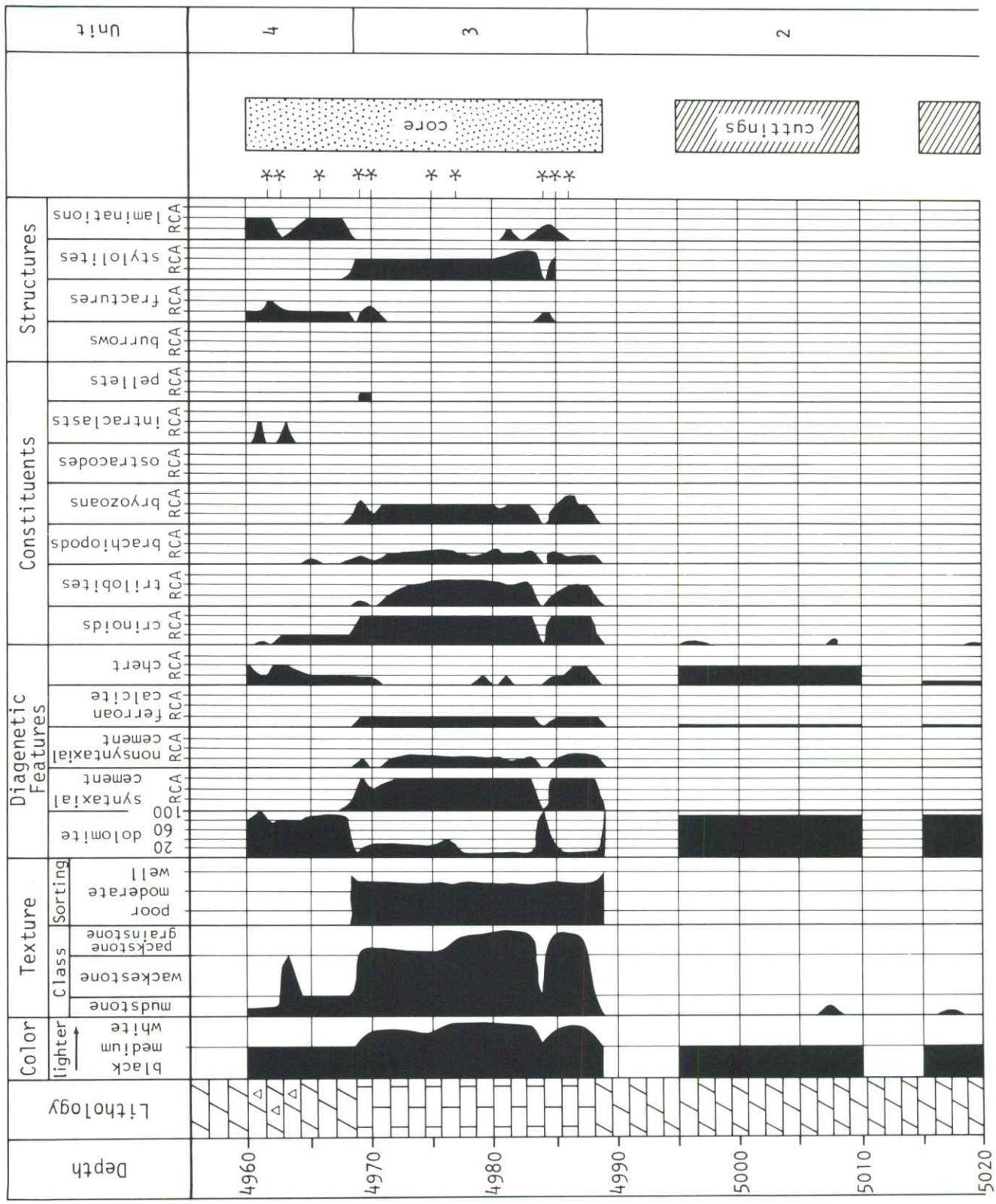


FIGURE 5—Core description of Viola Limestone in Sinclair–Prairie Degeer No. 1 well, NENWNE sec. 34, T. 32 S., R. 15 W., Barber County, Kansas.

2
1
core
* thin section
5020
5030
5040
5050
5060
5070
5080
5090

spicules, ostracodes, and unidentified phosphatic skeletal fragments. Only a few of these are present in a single sample. Other constituents include nonskeletal phosphatic material and peloids, which are probably recrystallized skeletal fragments. Originally calcareous fossils generally are still calcite, but they may be partially silicified to chalcedony or microcrystalline quartz. The brachiopods and crinoids are most commonly silicified. Some fossils are dolomitized, usually the crinoids, which may be replaced by a single crystal of dolomite or by many tiny rhombs. Bryozoans whose zooecia have been filled with mud also tend to be partially replaced by dolomite.

The chert nodules in the mixed skeletal wackestone may be up to 5.2 cm long. They are light gray or white and are composed of cryptocrystalline quartz. The contact between the nodules and the carbonate matrix usually is sharp.

Upper limestone

The upper limestone is only present today in the southwestern half of the study area, having been beveled by erosion in the northeast. It ranges in thickness from 0 to 32 ft and consists of crinoid packstones and grainstones. In almost all respects, the petrographic characteristics of the upper limestone are extremely similar to the basal limestone.

Upper cherty dolomitic limestone

This unit occurs only in the western and southern part of the area, having been beveled by erosion to the east and the north. It ranges in thickness from 0 to 48 ft and consists of mixed-skeletal wackestones with some dolomitic intraclast wackestones and dolomitic mudstones over the Pratt anticline.

Pale-green or light-gray, mixed-skeletal wackestones were deposited in the southern part of the study area. Their matrix probably was originally aragonitic and high-magnesium calcite mud, which has since either been completely replaced by dolomite or recrystallized to neomorphic calcite spar with minor replacement dolomite.

The dolomite matrix consists of micritic to very fine-grained anhedral crystals and fine-grained clear rhombic crystals. Ferroan dolomite occurs only as a very coarse grained, void-filling, saddle dolomite cement.

Where the matrix is neomorphic calcite spar, it may consist entirely of extremely fine grained crystals, or it may be fine- to medium-grained, subhedral crystals. Sometimes it has a texture similar to that of the dolomite matrix of the lower cherty dolomitic limestone, with extremely fine-grained anhedral crystals mixed with very fine to fine-grained calcite rhombs. In places clear, fine-grained, rhombic dolomite occurs in these samples.

Fossils in these mixed-skeletal wackestones include crinoids, brachiopods, trilobites, bryozoans, ostracodes, mollusks, and sponge spicules. Other constituents include peloids, which probably are fossils that have been micritized beyond recognition, and phosphatic material. Generally no more than three constituents are present at any given location, and usually only one or two varieties are present. Crinoids are the most common, followed by trilobites and ostracodes. Syntaxial overgrowths on the crinoids, when present, are poorly developed. The fossils usually are calcite but may be partially or completely replaced by cryptocrystalline quartz. The crinoids also are commonly replaced by single crystals of dolomite and appear as crinoid "ghosts" within the dolomite crystals.

In general, the degree of dolomitization of the original matrix increases as the number of fossils decreases. This could imply that the environment became more restricted, possibly by a sharp increase or decrease in salinity, which also may have promoted penecontemporaneous dolomitization.

Chert nodules in the skeletal wackestones are white or gray with white borders, are composed of cryptocrystalline quartz, and may be more than 6.5 cm in length. When formation of nodules is complete, nodules have abrupt contacts with the carbonate matrix. In a number of samples, incomplete chert-nodule formation is evidenced by curved bands of cryptocrystalline quartz, with the most intensive silicification occurring at the outer edges of the bands. If the silica replaced a calcite matrix, the calcite crystals often are rimmed with micritic dolomite. The amount of dolomite increases toward the center of the developing nodule. Quartz also occurs as a drusy, void-filling cement. It is very fine to fine-grained with the crystal size increasing away from the edge of the void.

North of the skeletal wackestones, along the edge of the Pratt anticline, this unit is represented by dolomitized intraclast wackestones and laminated dolomitized mudstones. These lithologies are green and gray or pale green and white.

The dolomite consists of very fine grained to coarse-grained subhedral to rhombic crystals. The larger rhombs display alternating layers of nonferroan and ferroan dolomite. The mudstones and wackestones may have laminations, with alternating layers of medium- and coarse-grained rhombs or very fine and fine-grained subhedral crystals. The intraclasts may be more than 2 cm in length and are composed of very fine grained dolomite. They tend to be more ferroan than their coarser-grained matrix. The difference in crystal size in the laminations and between the intraclasts and matrix may represent variation in original sediment size or, in the case of the intraclasts, different times of dolomitization. The intraclasts, which are very fine grained, may have been penecontemporaneously dolomitized, possibly before transport, whereas the matrix was dolomitized in a later diagenetic event.

Interpretation of Viola depositional environments

The crinoid packstone-grainstone facies of the basal limestone was unconformably deposited on the Simpson after a marine transgression. It represents deposition in a moderate- to high-energy, open-marine environment with normal salinity. The general thinning of this unit northeastward supports the idea of a gradual shallowing in this direction, which presumably continued throughout deposition of the Viola. Taylor (1947) proposed an unconformity at the top of the basal limestone in north-central Kansas, and although the possibility exists in the study area, this cannot be documented conclusively.

Shaw (1964) stated that vertical successions of environments displayed in autochthonous rocks deposited in epeiric seas are reflections of a lateral sequence that existed at any given time. Accordingly, the mudstones at the base of the lower cherty dolomitic limestone represent an environment that was laterally equivalent to the crinoid packstone-grainstone facies over which the mudstones were deposited. The environment of deposition of the mudstones was in the lee of the crinoid packstone-grainstone facies. Conceivably, the mudstones were separated from the packstones and grainstones by a less restricted environment such as that which produced the mixed-skeletal wackestones which occur at the top of this unit.

In cores, the transition from the open-marine environment of the crinoid packstone-grainstone facies to the very restricted environment of the mudstones is abrupt. The actual contact, however, is nowhere represented in the cores. The rapid transition may reflect an unconformity, marine regression, or seafloor uplift that occurred after the deposition of the crinoid packstone-grainstone facies. The semirestricted mixed-skeletal wackestone facies which separated the open-marine crinoid packstone-grainstone facies from the very restricted mudstone facies is absent in the transition of the basal limestone to the overlying unit. Therefore, the possibility that the transition represents progradation of the restricted facies over the open-marine facies is unlikely.

The depositional environment of the mudstone facies was characterized by abnormal salinity or the absence of life-sustaining nutrients. Shaw (1964) postulated that because of presumed shallow slopes in epeiric seas, friction would have dampened the effects of normal, diurnal tides. Shallowness of the sea would have prevented the development of great nutrient-laden currents like those in modern oceans (Belak, 1980). Under such conditions, lack of adequate circulation would have created areas of increasing restriction as the sea shallowed toward the Central Kansas arch. Excessive evaporation in this area, without replenishment with freshwaters, could result in the development of progressively higher salinities toward the arch, beyond the limits of tidal exchange. This model indicates an environment that is restricted through both a lack of life-sustaining nutrients and abnormally high salinities. Abnormally low salinities or a variable salinity also are conceivable if extensive rains provided enough freshwater to dilute the system or to cause seasonal fluctuations in salinity.

After the abrupt marine regression or sea-flow uplift that preceded deposition of the mudstones at the base of the lower cherty dolomitic limestone unit, a gradual marine transgression occurred, which resulted in the deposition of mixed-skeletal wackestones over the mudstones. The skeletal wackestones were deposited under semirestricted, low-energy conditions, probably between the depositional belt of the mudstone facies and that of the crinoid packstone-grainstone facies.

The marine transgression continued, culminating in the deposition of the crinoid packstone-grainstone facies of the upper limestone unit. During this period moderate- to high-energy, open-marine conditions again prevailed in the study area.

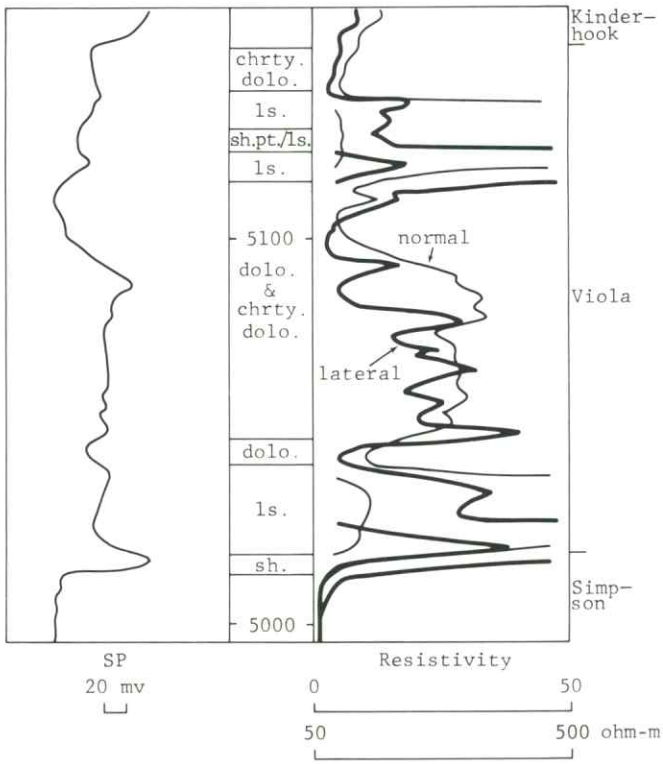


FIGURE 6—Spontaneous potential and resistivity logs for Degeer #1 core sample.

The deposition of the mixed-skeletal wackestones of the upper cherty dolomitic limestone unit over the crinoid packstone and grainstones of the upper limestone resulted from either progradation of facies belts seaward during a stillstand in sea level or development of the Pratt anticline, forcing the belts seaward. Whichever occurred, the depositional slope was probably steeper than it was during earlier deposition of the Viola, resulting in less restricted conditions behind the crinoid packstone-grainstone facies and narrower depositional belts. The semirestricted, low-energy environment of deposition of the mixed-skeletal wackestones shallowed toward the Pratt anticline, resulting in increased restriction and in the deposition of intraclast wackestone and laminated mudstones along the slopes of the anticline.

A generalized depositional model for the Viola in south-central Kansas is shown schematically in fig. 5 and summarizes the lateral relationships between the facies of the informal stratigraphic subdivisions. In this interpretation, the crinoid packstone-grainstone facies was deposited in an open-marine environment, the mixed-skeletal wackstones were deposited in a semirestricted environment, and the dolomitic mudstones were deposited in a very restricted, low-energy environment. The facies belts roughly paralleled the Central Kansas arch, which is located to the northeast of the model.

Following the deposition of the Viola, the area was subaerially exposed, resulting in an unconformable contact between the Viola and the Maquoketa Shale (Adkison, 1972).

Workshop core: Degeer #1

The preceding remarks summarize observations made on core drawn from ten wells in the two-county area. Core samples from Degeer #1 provide example specimens from all four Viola unit subdivisions (fig. 4). Graphic logs of texture, diagenetic features, constituents, and structures are shown in fig. 5. Since Degeer #1 is an older well (1947), the associated wireline-log suite is rather restrictive. However, the spontaneous potential and resistivity logs (fig. 6) are sensitive to porosity/permeability variations which are closely keyed with the lithofacies character of each unit. The relatively tight limestone divisions of units 1 and 3 are readily contrasted by their high resistivities with the more porous dolomites of units 2 and 4, which show lower resistivities.

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Wireline log zones and core description of upper part of the Middle Ordovician Viola Limestone, McClain and McClain SW fields, Nemaha County, Kansas

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Introduction

The Viola Limestone is productive in several fields in the Forest City Basin in northeast Kansas (e.g., the Davis Ranch, John Creek, McClain, McClain SW, Sebetha, and Straham). Core description of the Viola Limestone in the Forest City Basin has not, however, been available in the literature. In this study, cores of the upper part of the Middle Ordovician Viola Limestone from two wells in McClain field and one well in McClain SW field, Nemaha County, Kansas, are described and lithologic units are correlated with wireline log zones.

McClain and McClain SW fields are located on the western side of the Forest City Basin (fig. 1). Discovered in December 1981, McClain field is a structural trap (fig. 2) producing oil from the Viola Limestone and Middle Or-

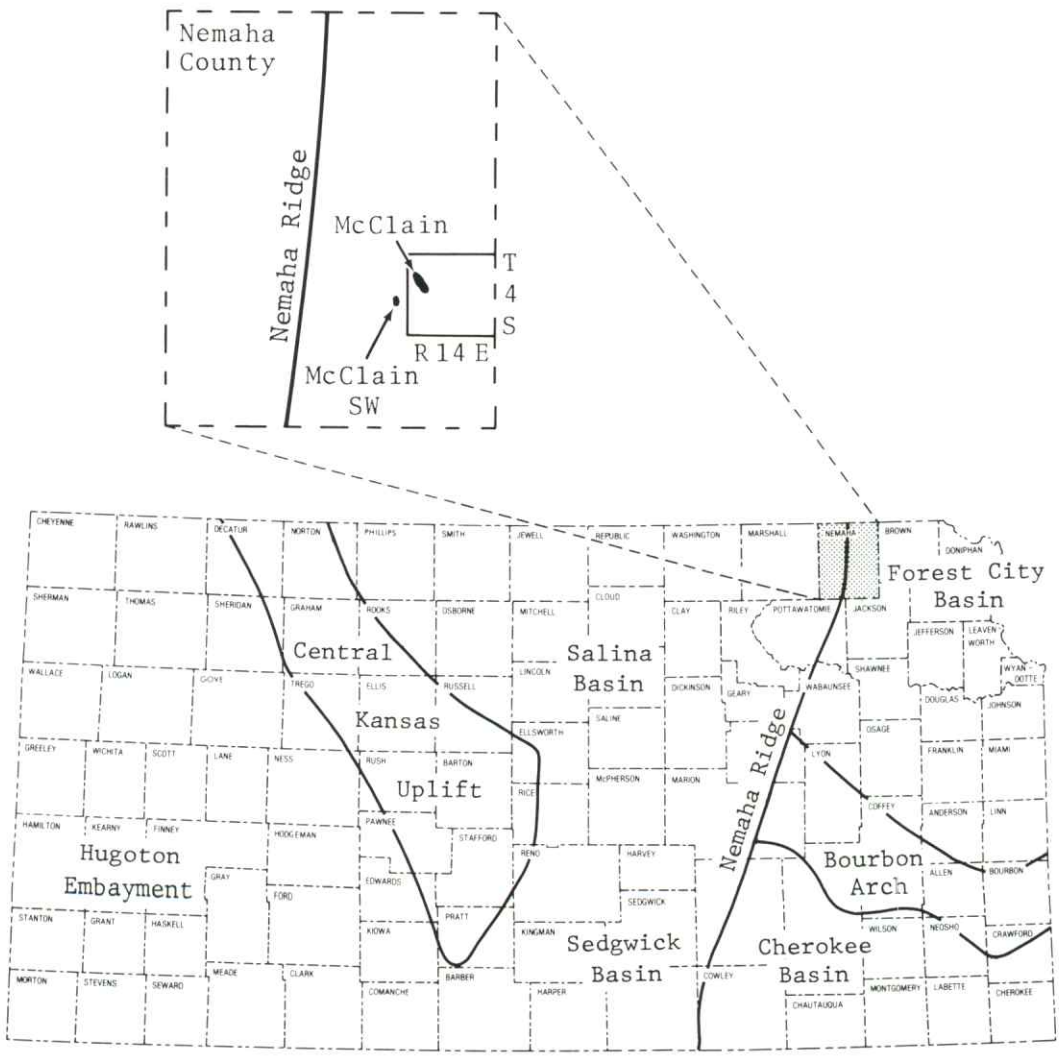
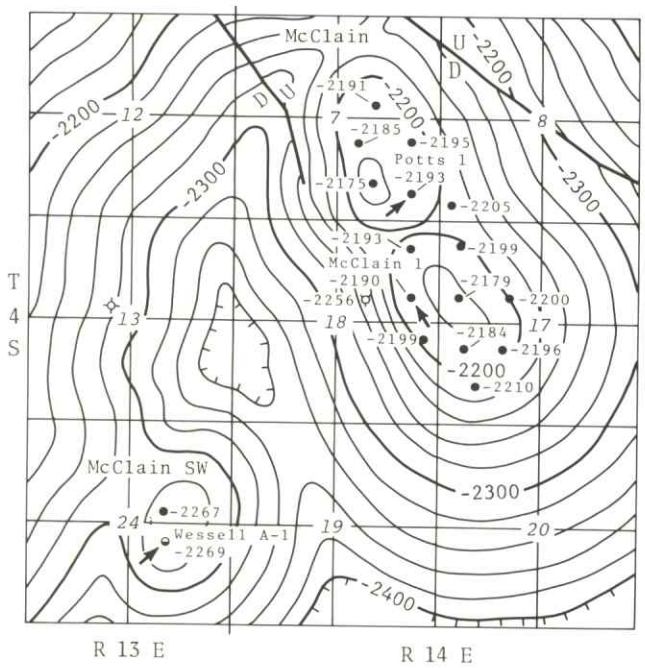


FIGURE 1—Location of McClain and McClain SW fields on the western side of the Forest City Basin, Nemaha County, Kansas.



contour interval = 20 feet

FIGURE 2—Viola structure McClain and McClain SW fields, Nemaha County, Kansas. Arrows indicate wells in which the upper part of the Viola Limestone was cored.

dovician, upper Simpson sandstone at depths of approximately 3,450 ft and 3,650 ft, respectively. As of June 1984, production was 290,453 BO from the Viola and 140,447 BO from the Simpson. June 1984 production was 8,127 BO from the Viola and 3,873 BO from the Simpson. McClain SW field has two wells, the Hermesen 1-24, which has produced 12,400 BO from the Viola with June production at 862 BO, and the Wessel "A" # 1, which is temporarily abandoned.

Wireline log zones and core description

Prior to core study, four wireline log zones were defined in the upper part of the Viola Limestone in McClain and McClain SW fields (fig. 3). In descending order, these zones are these: the "uppermost Viola" referring to the uppermost 10–12 ft of the Viola characterized by low log porosities, the "main porosity zone," which is the producing interval where it falls above the oil/water contact, the "tight streak," and the "lower porosity zone." The tight streak generally displays log porosities lower than those of the main or lower porosity area but is not uniformly tight in all wells. In places, the tight streak has fair log porosity. Core description of the wireline log zones is given below.

The uppermost Viola zone was cored only in the Cities Service Wessel "A" #1 where it corresponds to core unit VI (fig. 6). The zone is an argillaceous, medium to finely crystalline dolomite (echinoderm wackestone) with poor permeability and poor to negligible core porosity. Burrows are present throughout (plate I, A). Oil staining in the upper 4.5 ft of the zone suggests the uppermost Viola zone in the Wessel "A" #1, although having poor porosity and permeability, is in communication with the underlying, main porosity-zone reservoir.

The main porosity zone was cored, at least in part, in all three wells (figs. 4-6; see sheet 1 in back pocket). It is a medium to coarsely crystalline dolomite with fair to good core porosities including biomoldic, intergranular, fracture, and vuggy. In places the zone is mottled. Depositional textures are difficult to distinguish due to pervasive dolomite and in places strong oil staining. For the most part, however, the zone seems to have been an echinoderm packstone and grainstone (plates II and III).

The tight streak is a mottled (bioturbated), medium crystalline dolomite and was probably an echinoderm wackestone, packstone, and in places grainstone dolomite. Porosity in this zone is generally poor, but a few grainstone/packstone beds are present with fair porosity (plate IV and figs. 4–6). Types of porosity include biomoldic, intercrystalline, and less commonly, vuggy and fracture. Intergranular porosity is present in a few porous grainstone beds. This zone does not form a vertical permeability barrier separating the main and lower porosity zones.

The upper part of the lower porosity zone is a medium to coarsely crystalline dolomite and has fair to very good porosity including intergranular, biomoldic, and fracture (plate V, C). This part of the zone seems to have been an echinoderm grainstone and packstone. Planar and low-angle cross-stratification are generally mottled, medium crystalline dolomite (echinoderm wackestone/packstone; plate VI, A and B) with fair porosity including biomoldic, intercrystalline (plate VI, C), fracture, vuggy, and in places intergranular. Also present is finely crystalline dolomite mudstone (plate VI, D) with intercrystalline, fracture, and fine moldic porosities. Collapse breccia is present and fractures are locally common in the lower part of the lower porosity zone in the Petro Lewis Potts #1 core (plate VII, A and C).

Below the lower porosity zone the Viola is a mottled (bioturbated), medium crystalline dolomite, predominantly bioclast wackestone and mudstone, with poor to negligible porosity (plate VII, B and D, and figs. 4 and 5). Brachiopods, rare in the overlying zones, are common in some beds. Echinoderm debris occurs throughout.

Because the wireline log zones were defined solely on the basis of wireline log porosity they do not, in all cases, coincide with core units which are defined by a number of criteria including carbonate rock type, sedimentary structures, grain and porosity types, and argillaceous content (see figs. 4–6). Still, a general relationship exists between wireline log zones and lithology as described above and summarized in table 1.

Depositional environments

Bioturbation and biota (echinoderms, brachiopods, and bryozoans) in most of the upper part of the Viola in this study suggest deposition on a relatively shallow, open-marine shelf in waters a few meters to a few tens of meters deep. Burrow mottled, bioclast wackestone and packstone within and below the lower porosity zone and making up much of the tight streak reflect deposition below wave base

Wireline log zones	General core description
uppermost Viola	argillaceous, medium to coarsely crystalline dolomite (echninoderm wackestone) with poor porosity including biomoldic and rare vuggy
main porosity	medium to coarsely crystalline dolomite (echinoderm packstone and grainstone) with fair to good porosity including biomoldic, intergranular, fracture, and vuggy
tight streak	mottled (bioturbated), medium crystalline dolomite (echinoderm wackestone, packstone, and locally grainstone) with generally poor porosity including biomoldic and less commonly vuggy, intergranular, and fracture
lower porosity	fine to coarsely crystalline dolomite; upper part is low-angle cross stratified and planar laminated (echinoderm and ooid (?) grainstone) with fair to very good porosity including moldic, intergranular, and fracture. Lower part is mottled (echinoderm wackestone/packstone and dolomite mudstone) with fair porosity including biomoldic, fracture, vuggy, and intercrystalline
unnamed zone below lower porosity	mottled (bioturbated), medium crystalline dolomite (bioclast wackestone and mudstone) with poor to negligible porosity including biomoldic, vuggy, intercrystalline, and fracture

FIGURE 3—Wireline log zones recognized in the upper part of the Viola Limestone in the Cities Service Wessel "A" #1, Pendleton McClain #1, and Petro Lewis Potts #1. Wireline log zones: U.V.—uppermost Viola, M.P.—main porosity, T.S.—tight streak, and L.P.—lower porosity.

in relatively quiet marine waters. Deposition in shallow, more agitated, marine waters is suggested by planar and cross-stratified grainstone of the lower porosity zone and grainstone/packstone of the main and lower porosity zones. Mudstones of the lower part of the lower porosity zone, particularly those in the Petro Lewis Potts #1 core, may record very shallow, low-energy, restricted subtidal deposition.

The uppermost Viola zone in the Wessel "A" #1 records increased detrital influx, the upper 0.5 ft of the Viola becoming progressively more argillaceous upward toward an abrupt contact with overlying shale and fine sandstone of the Upper Ordovician Maquoketa Shale (fig. 6 and plate I, C). The upper 0.5 ft of the Viola has a disrupted (bioturbated?) appearance. Pyritized skeletal debris immediately above the Viola/Maquoketa contact reflects reducing conditions and perhaps slow deposition. Somewhat deeper water shelf deposition is suggested by parallel laminated fine sandstone and shale of the lowermost Maquoketa Shale (plate I, D).

Diagenesis

Fine to coarsely crystalline dolomite composes over 95% of the Viola in cores from this study. It replaces both micrite matrix and grains and occurs as void-filling intergranular cement. For the most part, this dolomite is thought to have formed relatively early, perhaps in the freshwater-marine phreatic mixing zone (fig. 7). Depositional textures (e.g., grains and types of porosity) are difficult to distinguish in many places due to pervasive dolomite.

Primary intergranular porosity is common in the main porosity zone (plate III) and upper part of the lower porosity zone (plate V, C) and occurs in scattered grainstone beds in the tight streak (plate IV, C). It is negligible in the uppermost Viola zone and in mudstones and wackestones of the tight streak, lower porosity zone, and interval below the lower porosity zone. Intergranular porosity in grainstones and packstones is partially filled in most beds by dolomite occurring as rhombs which have replaced echinoderm fragments and grown into the surrounding pore space (plates III, B, and V, C).

Biomoldic porosity occurs throughout the upper part of the Viola in all of the wireline log zones recognized in this study. Intercrystalline, vuggy, and fracture porosities, though significantly less important volumetrically, likewise occur throughout much of the upper part of the Viola. Biomoldic, intercrystalline, and vuggy porosities are thought to have formed shortly after the major phase of dolomite formation. These porosities record relatively early, freshwater dissolution of undolomitized grains (resulting in biomoldic porosity) and micrite matrix (resulting in intercrystalline porosity) in the freshwater phreatic zone. Collapse breccia and red stain in the lower porosity zone of the Petro Lewis Potts #1 core reflect freshwater diagenesis, perhaps relatively near the surface. Fractures in the cores are vertical, commonly hairline, and probably formed, for the most part, during structural deformation of the area. Fractures associated with collapse breccias and red-stained dolomite mudstones in the lower porosity zone of the Potts #1 core may, however, be related to early diagenesis.

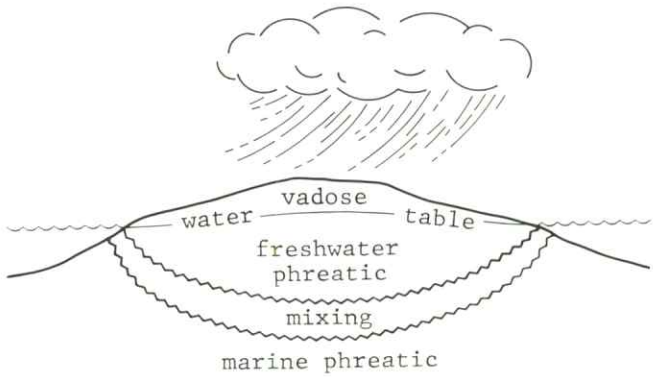


FIGURE 7—Idealized, shallow-subsurface, carbonate diagenetic environments, not to scale (after Longman, 1980).

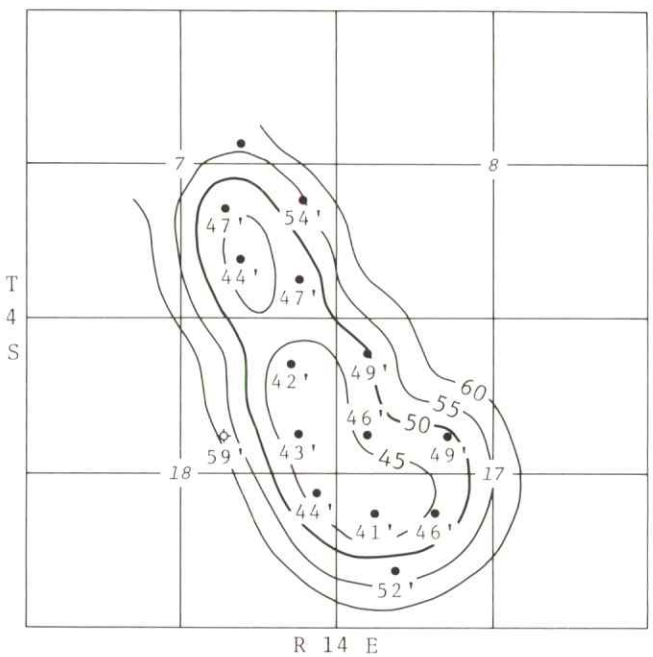


FIGURE 8—Lower Simpson Sandstone isopach, McClain field, Nemaha County, Kansas.

In the study area, higher porosities in the main porosity zone occur in the structurally higher wells. This may reflect greater freshwater dissolution of carbonate and/or better primary intergranular porosity on the upper part of an Ordovician high, the location of which approximates that of the present structure at McClain field. A Middle Ordovician high is suggested by thinning of the Lower Simpson sandstone over the crest of the present structure at McClain field (fig. 8, compare with fig. 2). The major period of structural deformation in the Forest City Basin is post-Mississippian (pre-Desmoinesian) and involves basement tectonic activity associated with uplift of the Nemaha Ridge.

References

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Plates I–VII follow

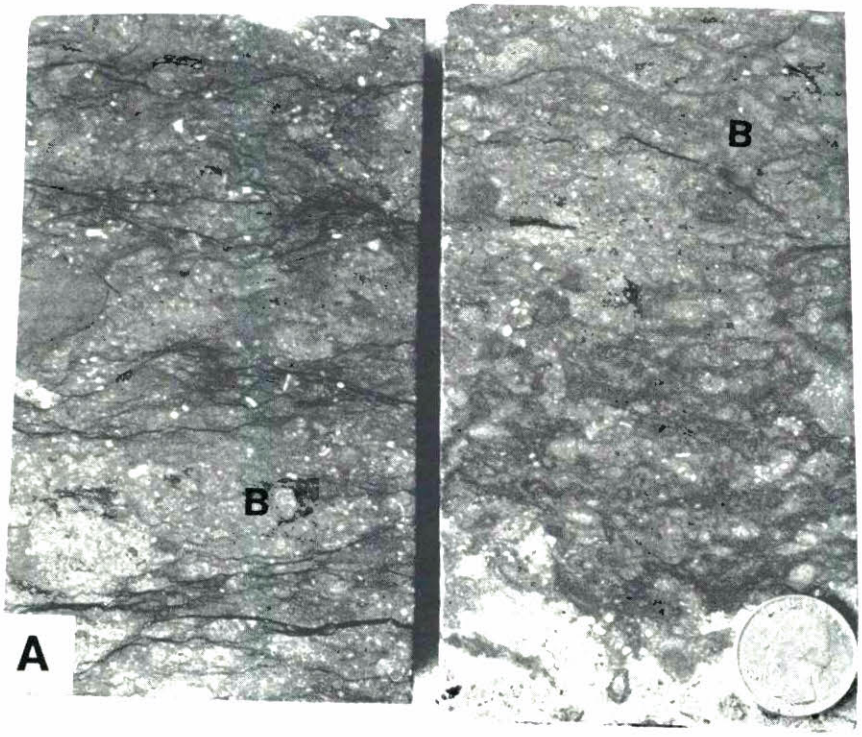
PLATE I. Uppermost Viola zone and Maquoketa Shale

A. Burrowed (B), argillaceous, medium to finely crystalline dolomite (echinoderm wackestone) of the uppermost Viola zone (Wessel "A" #1, left-3492.3 ft and right-3496.3 ft).

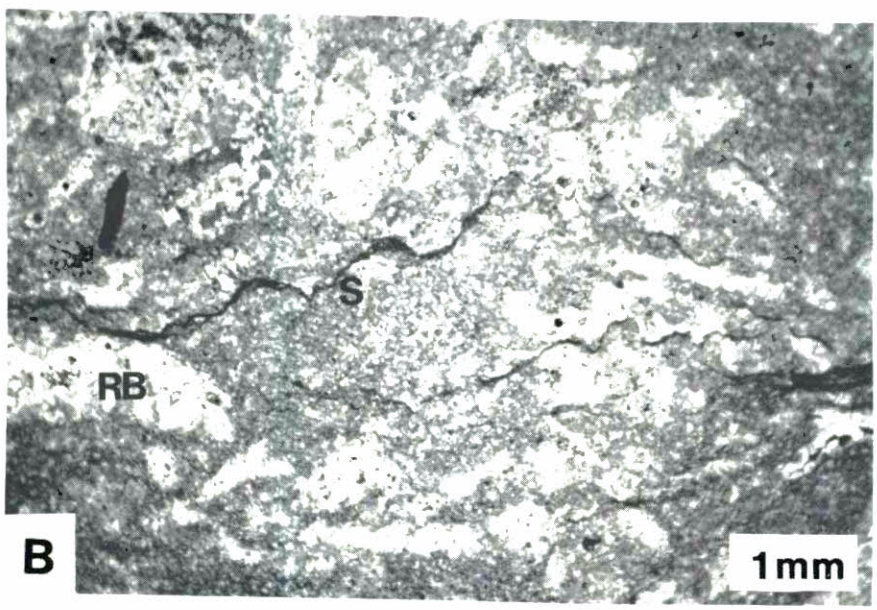
B. Finely crystalline dolomite (bioclast wackestone) of the uppermost Viola zone. Light-colored, medium crystalline dolomite areas are replaced bioclasts (RB). Microstylolites (S) are common (mag. 18.7x; Wessel "A" #1, 3492.6 ft).

C. Contact (C) of the Viola Limestone (uppermost Viola zone) and overlying Maquoketa Shale. The uppermost Viola has a disrupted appearance, and a thin layer of pyritized skeletal debris occurs just above the contact (Wessel "A" #1, 3486.5 ft).

D. Parallel laminated fine sandstone and shale of the lower part of the Maquoketa Shale (Wessel "A" #1, 3485.5 ft).


B
B
A

C


S
RB
B
1mm

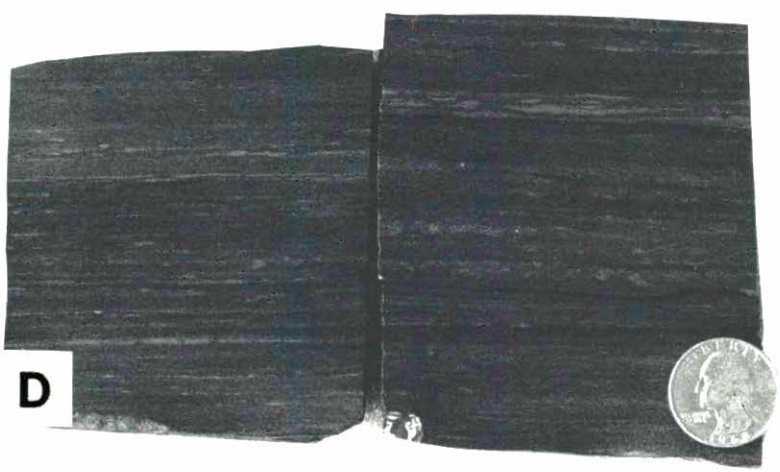

D

PLATE II. Main porosity zone

A–C. Oil stained, medium to coarsely crystalline dolomite (echinoderm grainstone, packstone, and in places wackestone) of the main porosity zone. Porosities include biomoldic (M), intergranular, vuggy (V), and fracture (F). A—Potts #1, 3457 ft; B—McClain #1, 3501.2 ft; and C—Wessel "A" #1, 3500 ft).

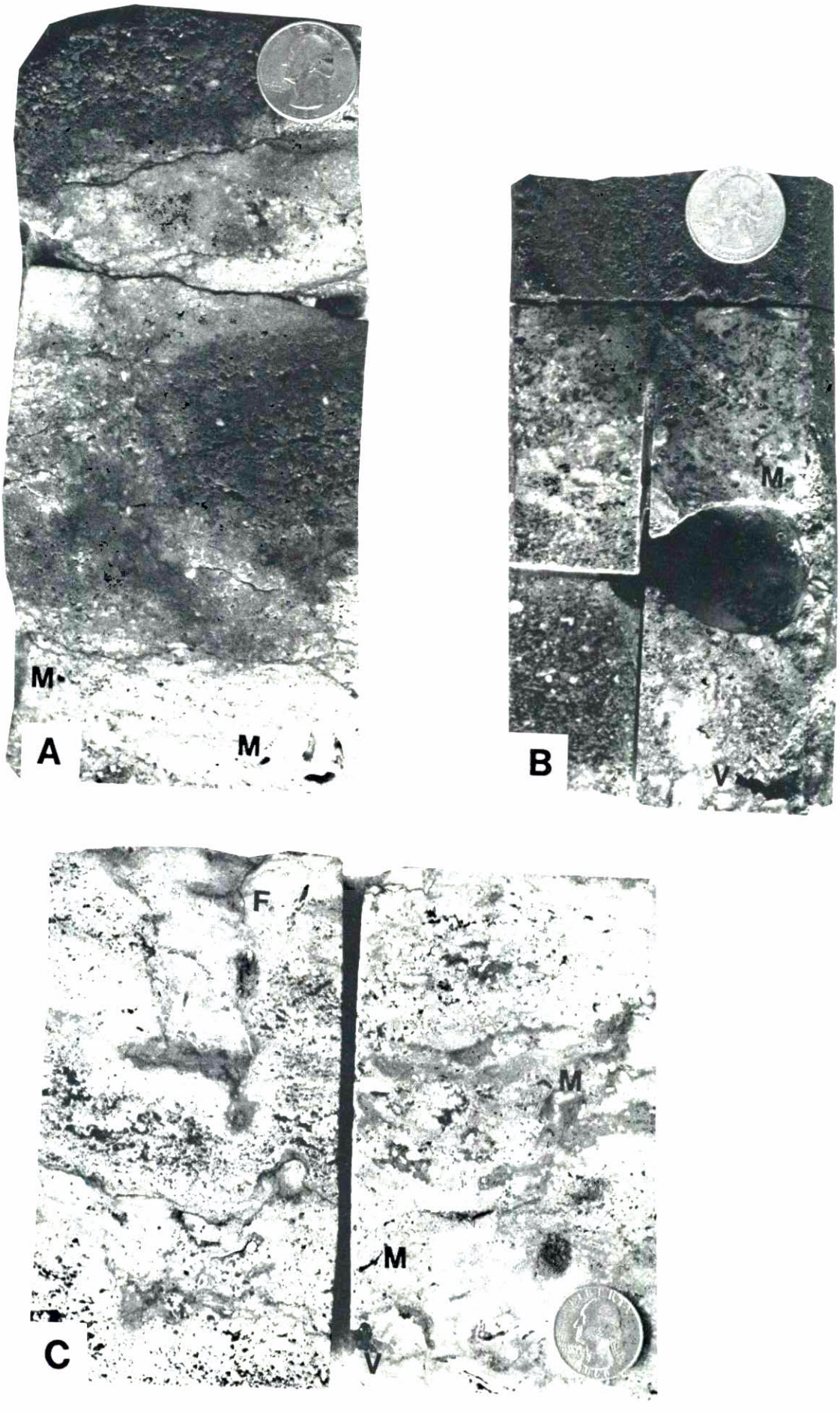
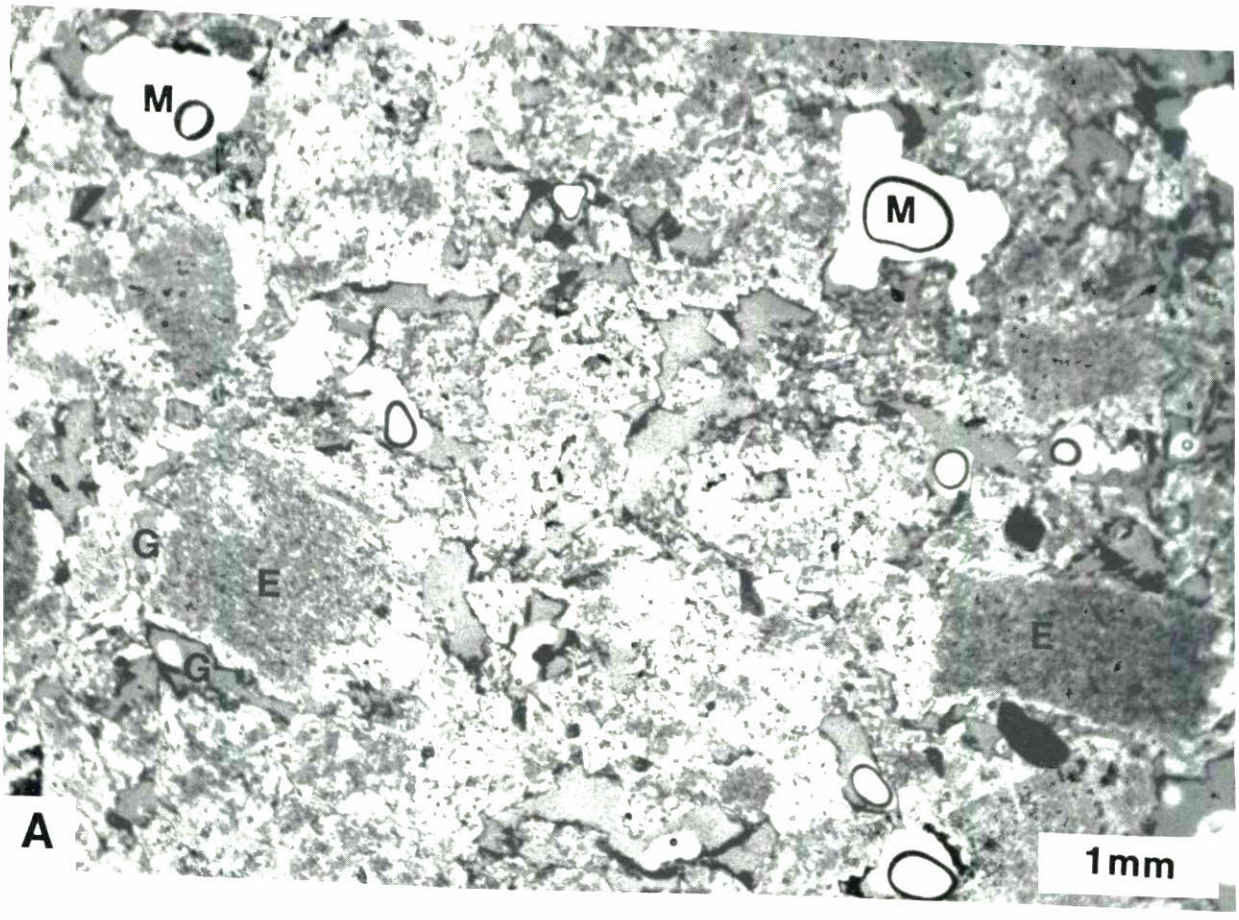

M
A
M
M
B
V
F
M
M
C
V

PLATE III. Main porosity zone

A and B. Coarsely crystalline dolomite (echinoderm (E) grainstone) of the main porosity zone. Both intergranular (G) and biomoldic (B) porosities are present, but it is often difficult to distinguish between the two (mag. 18.7x; A—McClain #1, 3501.8 ft, and B—Wessel "A" #1, 3502.4 ft).


M
M
G
E
G
E
A
1mm

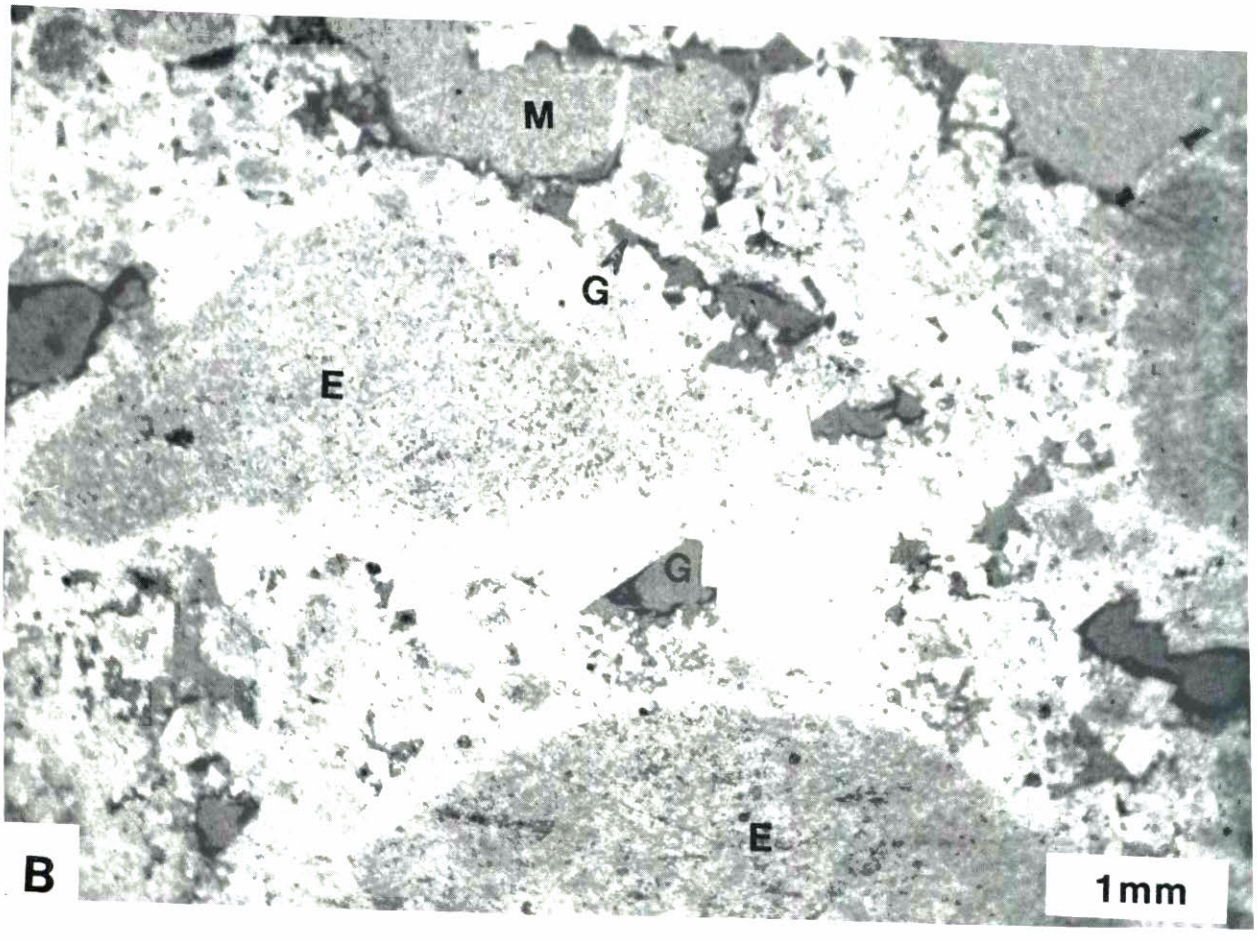
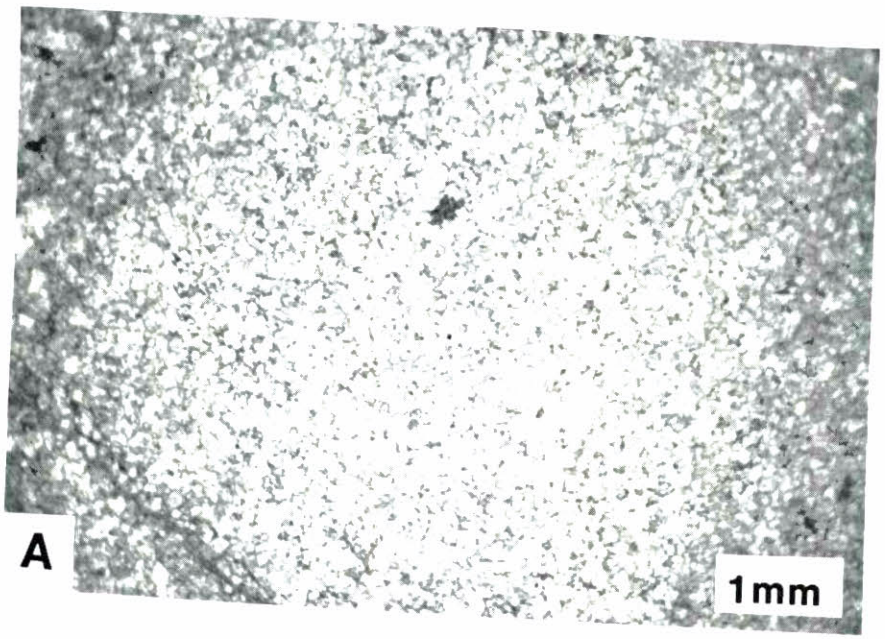

M
G
E
G
E
B
1mm

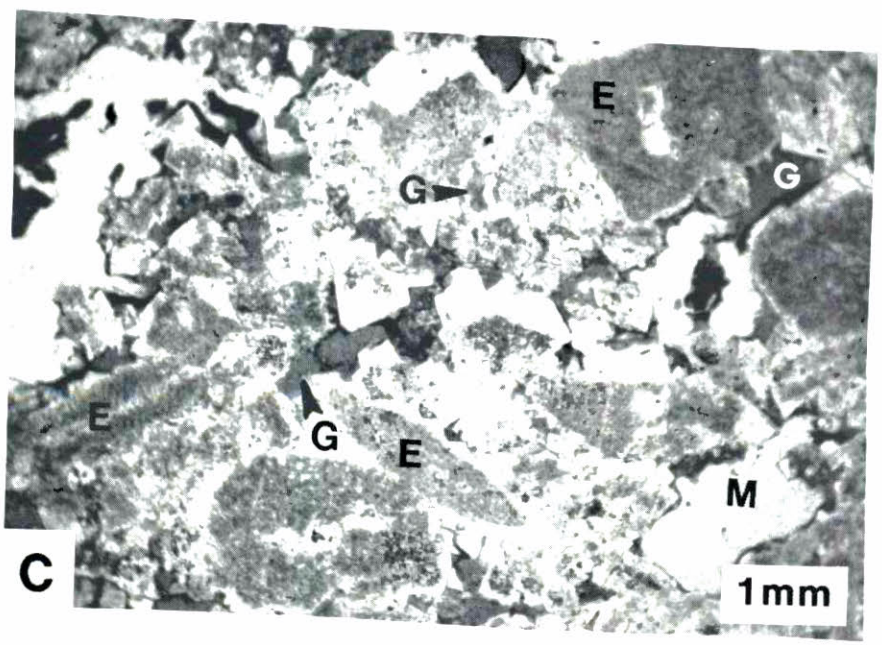
PLATE IV. Tight streak zone

A and B. Fine to medium crystalline dolomite of the tight streak. Porosity is negligible in dolomite mudstone of thin section photo A (mag. 18.7x) and negligible to poor in burrowed (B), echinoderm wackestone of photo B (A—McClain #1, 3507.6 ft, and B—Potts #1, 3463 ft).

C and D. Medium to coarsely crystalline dolomite (echinoderm (E) grainstone) of the tight streak. Thin section photo C (mag. 18.7x) shows intergranular (G) and biomoldic (M) porosities; photo D from the same bed shows oil staining in this grainstone (C and D—Potts #1, 3461.4 ft).


A
1mm

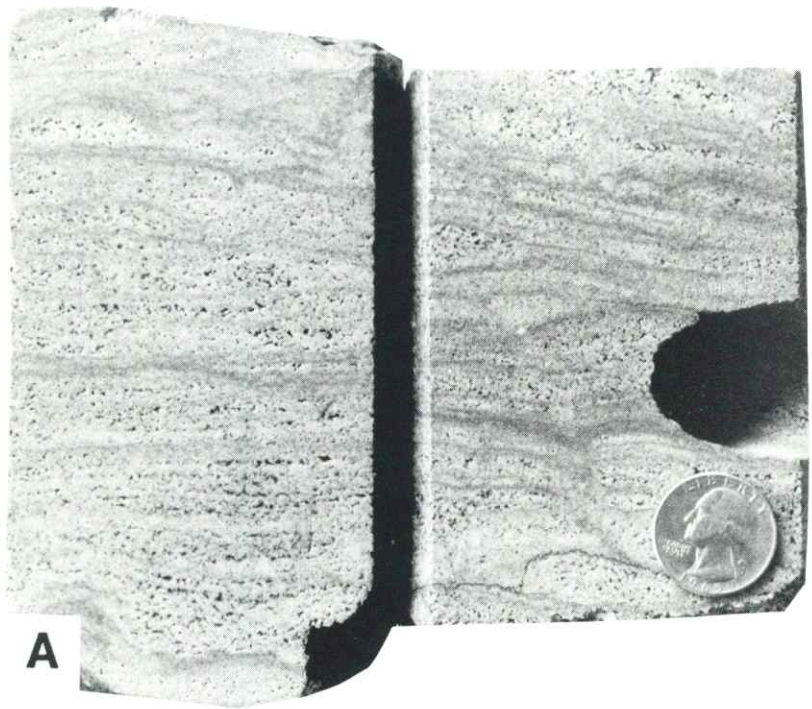
B
B

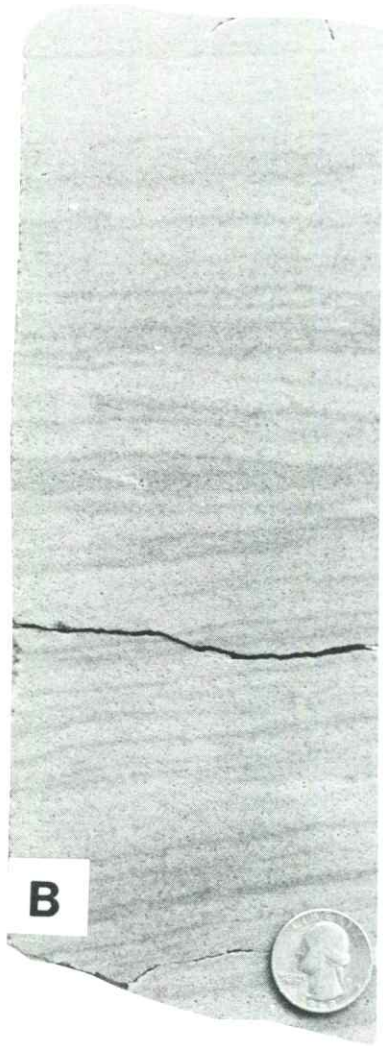

E
G
G
E
G
E
E
M
C
1mm

E
E
D

PLATE V. Lower porosity zone

A–C. Low-angle cross-stratified and planar-laminated, coarsely crystalline dolomite (echinoderm grainstone) of the upper and middle parts of the lower porosity zone. Intergranular (G) and biomoldic (M) porosities are indicated in thin section photo C (mag. 18.7x). As in the main porosity zone, it is often difficult to distinguish between intergranular and biomoldic porosities. Dolomite has replaced echinoderm debris (E) and grown into adjacent pore spaces (A—McClain #1, 3514.5 ft, B—Potts #1, 3481 ft, and C—Potts #1, 3470 ft).


A


B

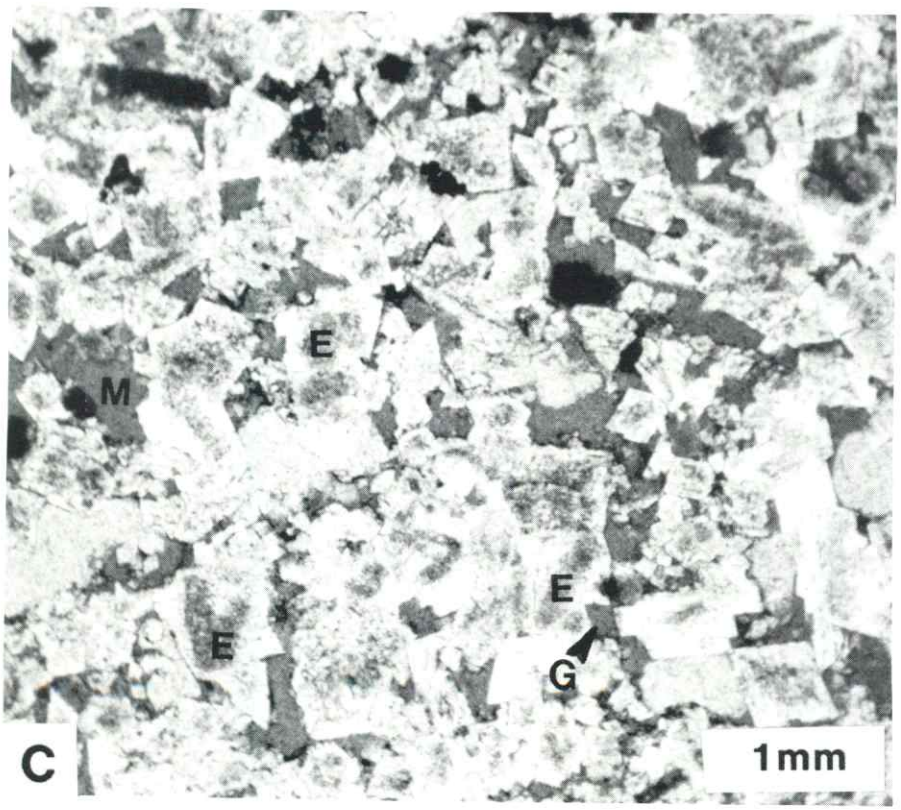
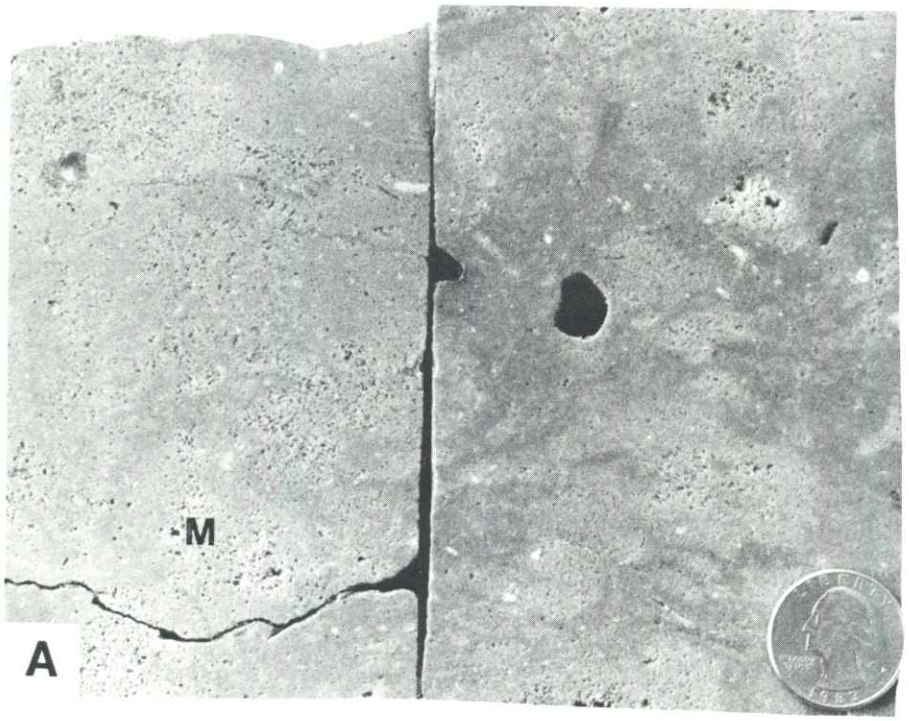
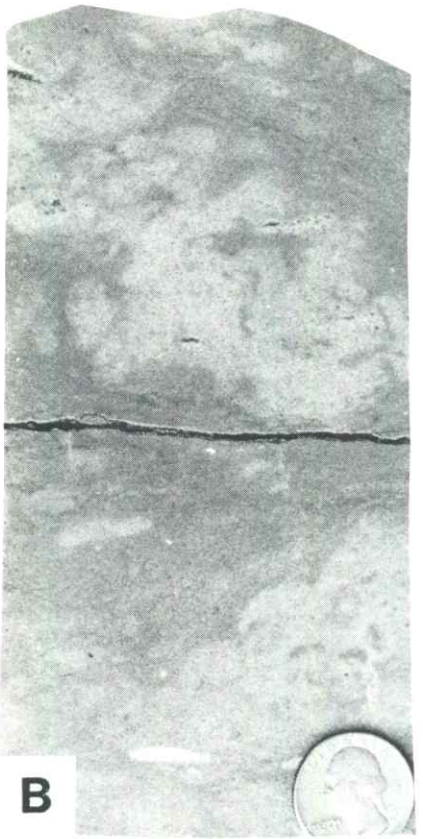
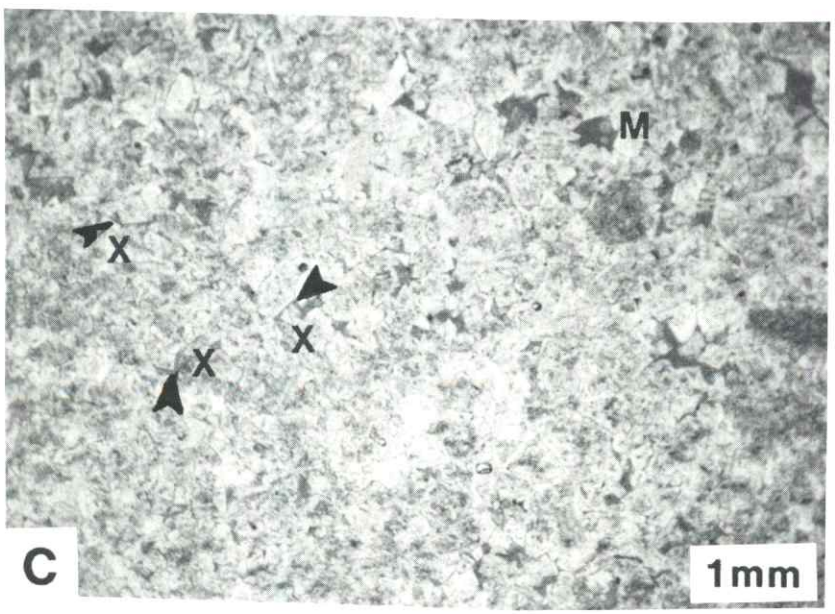

M
E
E
E
G
C
1mm

PLATE VI. Lower porosity zone

A–D. Fine to medium crystalline dolomite mudstone and wackestone of the lower part of the lower porosity zone. Photos A and B show burrow mottling, the light-colored areas being more coarsely crystalline and more porous. Fractures (F) are present in dolomite mudstone of photo D, and thin section photo C (mag. 18.7x) shows biomoldic (M) and intercrystalline (X) porosities. (A—McClain #1, left-3522 ft and right-3520.8 ft, B—Wessel "A" #1, 3529 ft, C—McClain #1, 3522.5 ft, and D—Potts #1, 3487.5 ft).


M
A


B


M
X
X
X
C
1mm

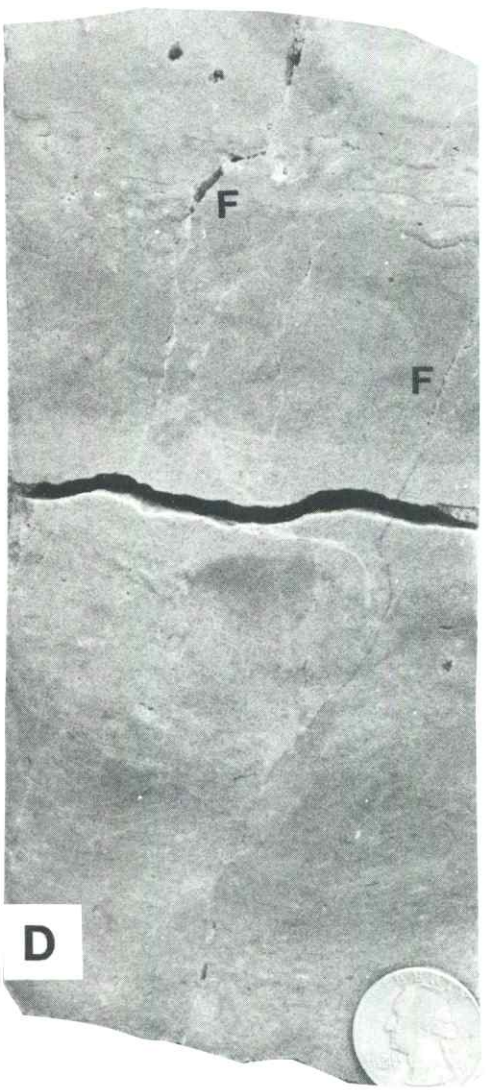
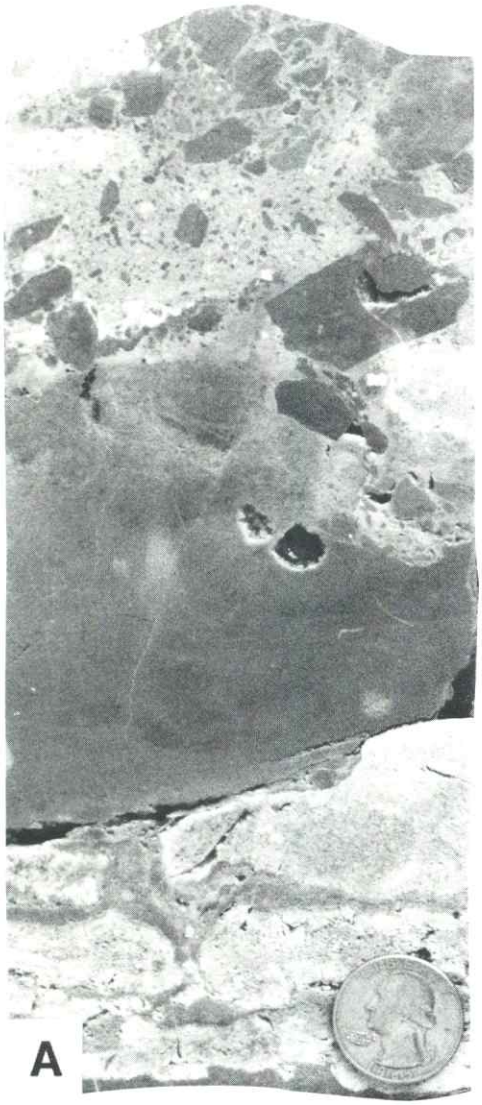
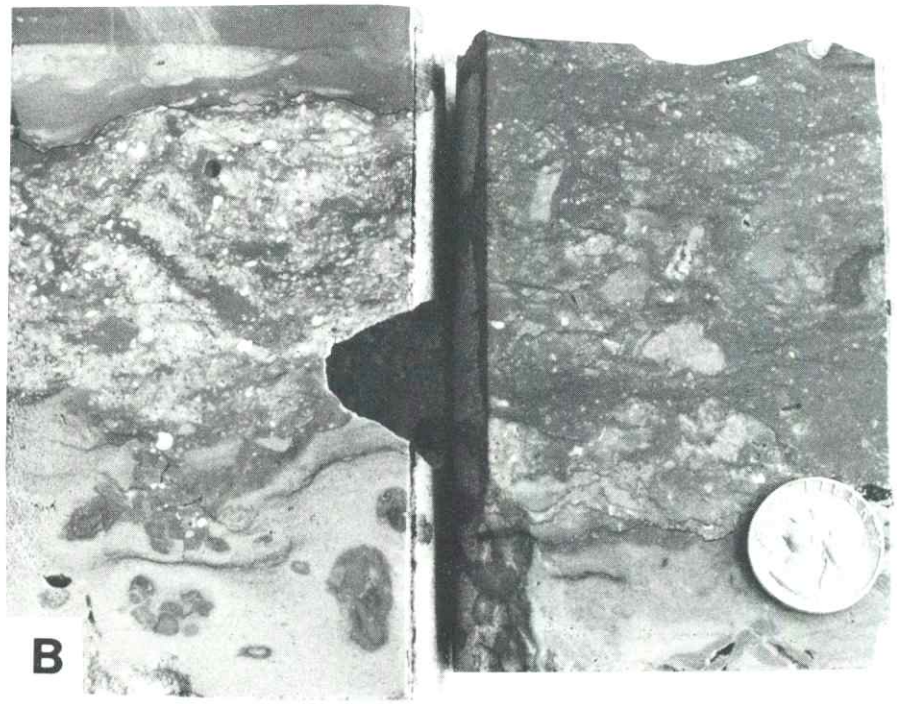

F
F
D

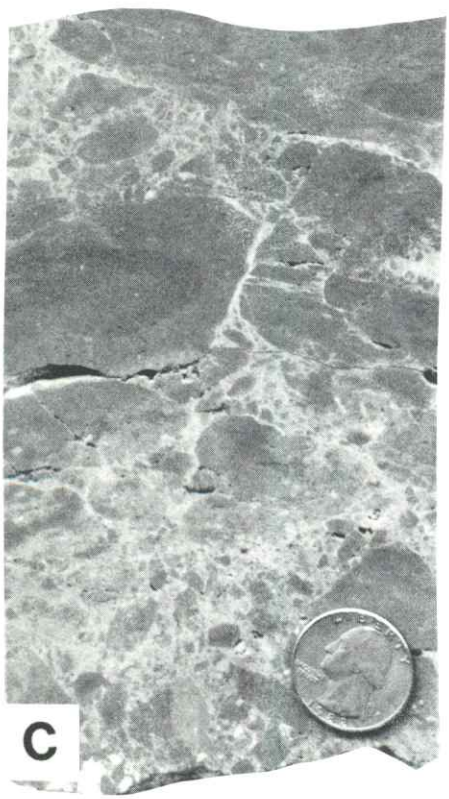
PLATE VII. Lower porosity zone and underlying interval

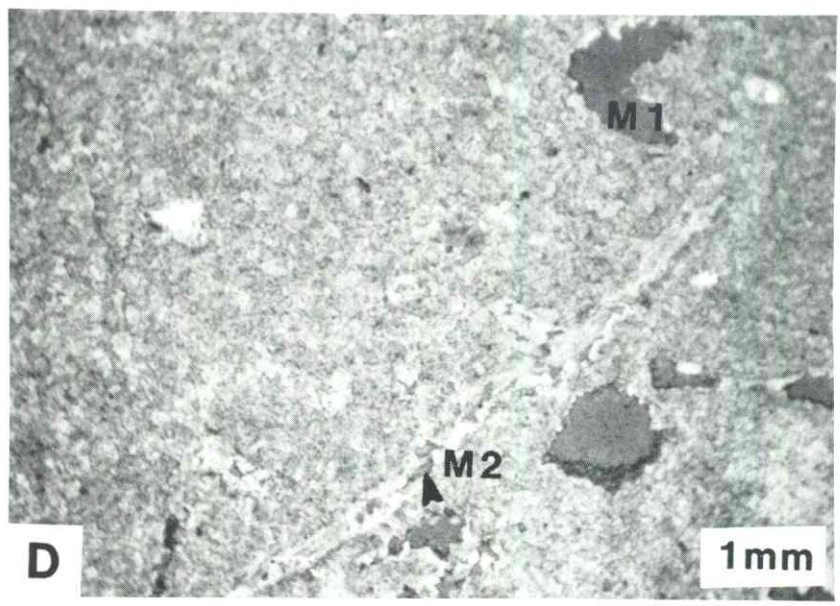
A and C. Collapse breccia of the lower part of the lower porosity zone. Red staining is common in these samples (A—Potts #1, 3491.5 ft, and C—Potts #1, 3491 ft).

B and D. Burrowed, fine to medium crystalline dolomite (bioclast wackestone) of the interval underlying the lower porosity zone. Thin section photo D (mag. 18.7x) shows biomoldic porosity; M1 is an echinoderm mold, and M2 is a partially leached brachiopod (B—McClain #1, 3543.5 ft, and D—Potts #1, 3494.1 ft).


A


B


C


M1
M2
D
1mm

Representative lithology of the Brandt–Sensenbaugh field, Butler County, Kansas

by *Bill Coffey,* TXO Production Corporation, Wichita, Kansas

A core representative of the Brandt–Sensenbaugh field was taken in order to provide more detailed information concerning the depositional environment and reservoir quality of the Mississippian pay. Because of the mature nature of the field, pertinent information such as electric logs, detailed geologic logs, and accurate production tests are either lacking or unavailable. This core provided the necessary data to form a more complete geologic setting of this field.

The Brandt–Sensenbaugh field was opened in June 1936, and by 1945, its productive limits were thought to have been reached. More recent infield drilling in the 1950's–1960's encountered new reserves, but in 1981, new production was discovered ½ mi from the northeast portion of the field, thus renewing interest in this Mississippian pay (fig. 1).

In order to perform accurate and descriptive facies studies, subsurface data including electric and geologic logs are a requirement. The recent field extensions prompted this need because of the potential for new reserves. As this field was initially developed during the 1930's and 1940's, most production was discovered with cable-tool drilling techniques. Further, electric logs were not utilized, and geologic logs either were not kept or were lost in the 40 yrs since their initial use. A core of the Mississippian pay helped to fill this lack of data.

To briefly summarize the result of this core analysis, figs. 2 and 3 are the respective graphic core description and porosity log of the subject well. The resulting general map of facies distribution is seen in fig. 4.

Lithologic description

The pay zone present in the Brandt–Sensenbaugh field is one of a high-energy, well-sorted biosparite. Secondary dolomite has selectively replaced portions of the sparry calcite cement. The above-mentioned diagenesis is limited, as primary intercrystalline porosity is preserved, accounting for the large majority of the total effective porosity.

The biohermal depositional environment suggested by the core analysis is lenticular and arcuate shaped. A cursory analysis of the underlying Arbuckle formation shows a pronounced structural high coincident with the Mississippian-producing trend. Hence, the underlying structure has controlled the geometry and development of the Mississippian porosity. This structural influence is evident as down-dip tests exhibit lower-energy facies consisting of mud-supported, poorly sorted biomicrites. There is a lack of deeper tests in the northern portions of the field, therefore the degree of Arbuckle-influenced structure is not known in the immediate core area. It is unclear as to why the Arbuckle structure is arcuate.

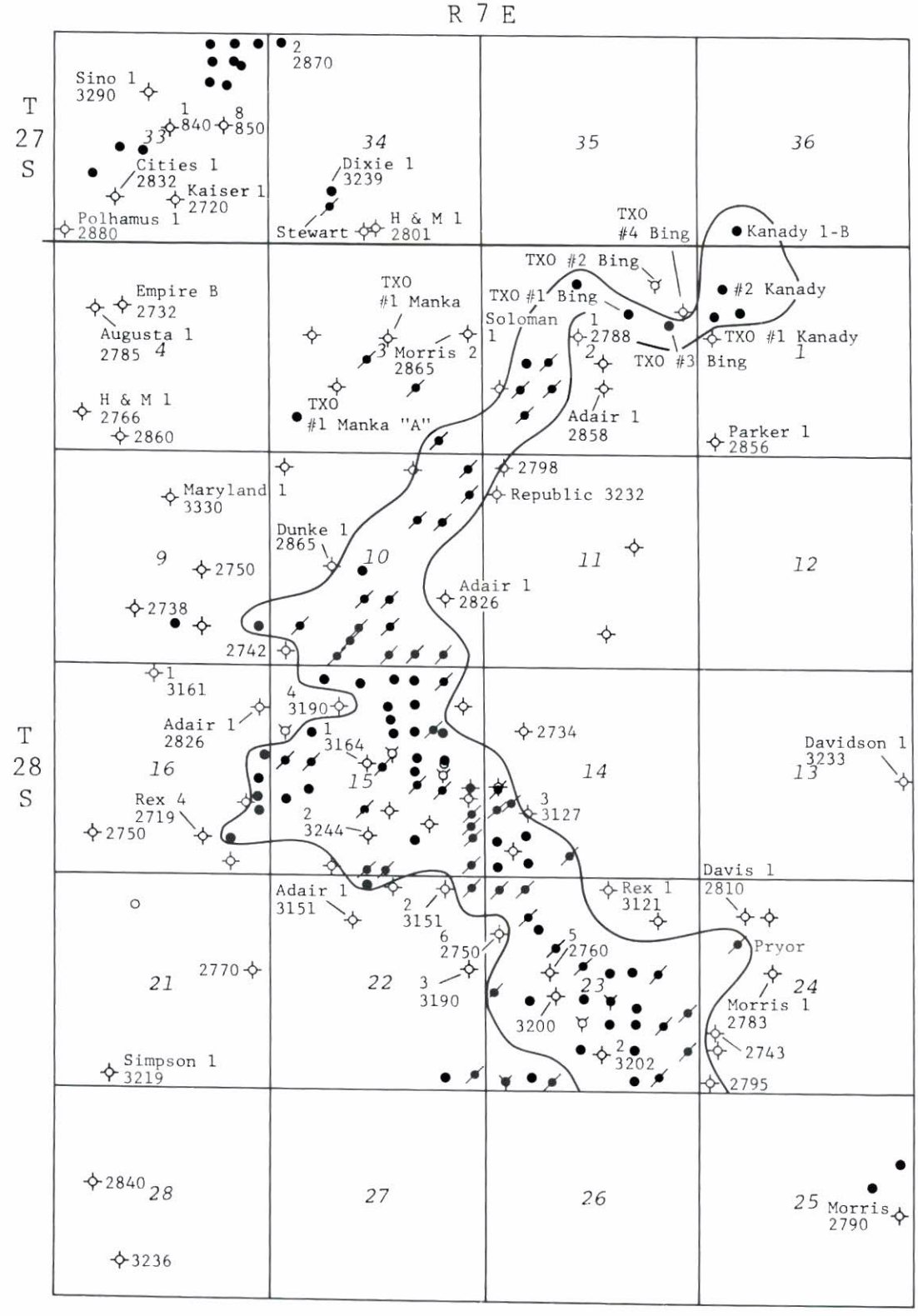


FIGURE 1—Location map of Brandt–Sensenbaugh field, Butler County, Kansas (courtesy TXO Production).

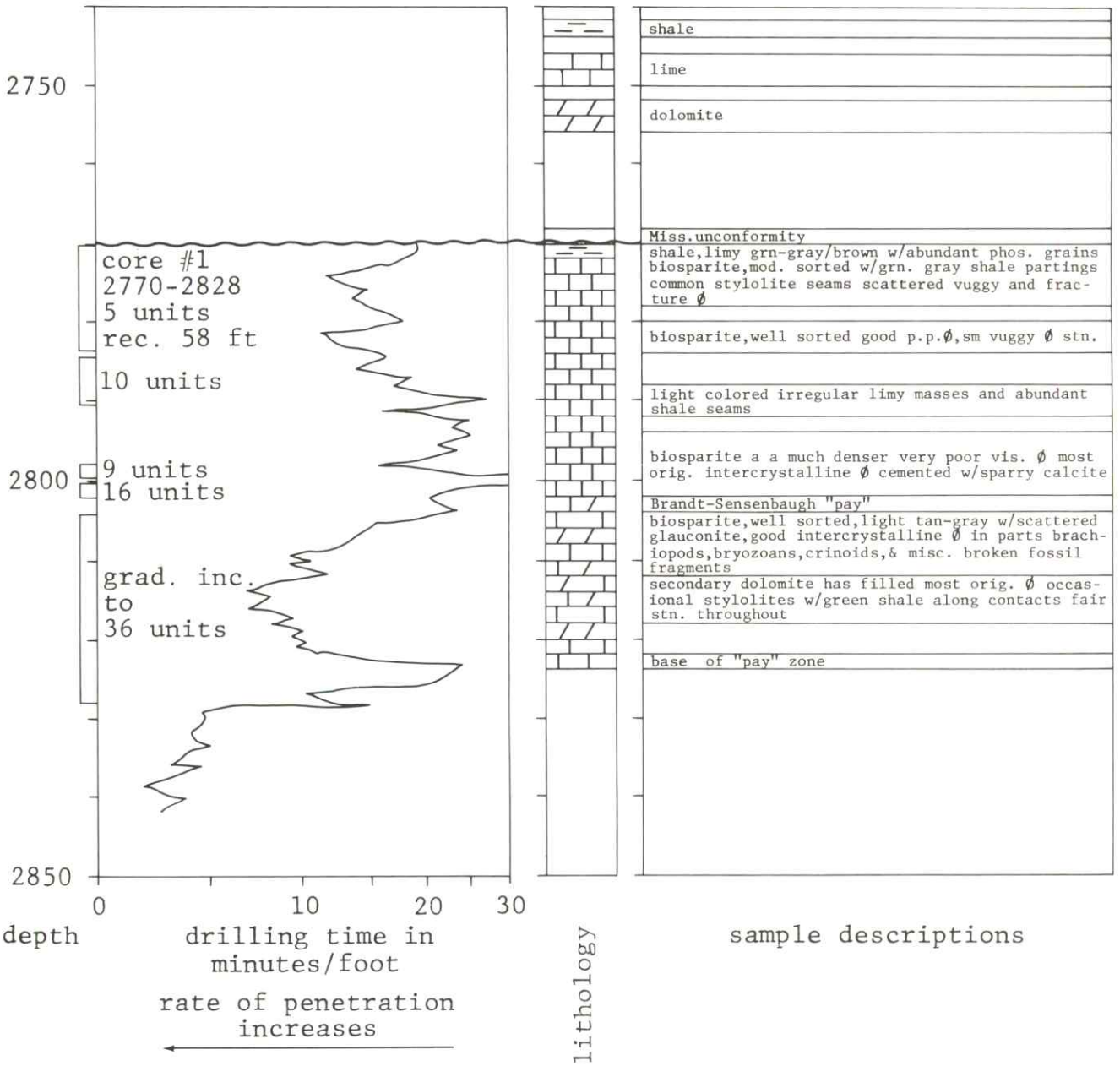


FIGURE 2—Core description of Bing #2, sec. 2, T. 28 S., R. 7 E., Butler County, Kansas (courtesy TXO Production).

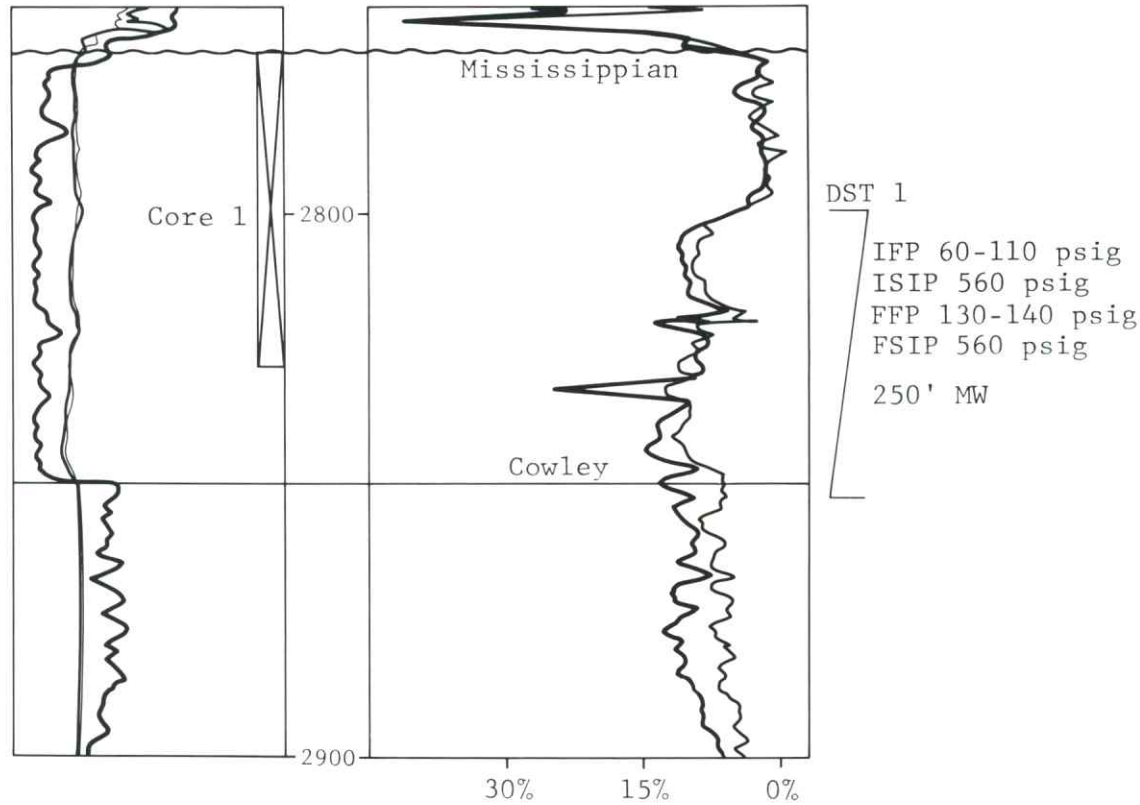


FIGURE 3—Gamma ray/neutron density log for Bing #2 well, Butler County, Kansas (courtesy TXO Production).

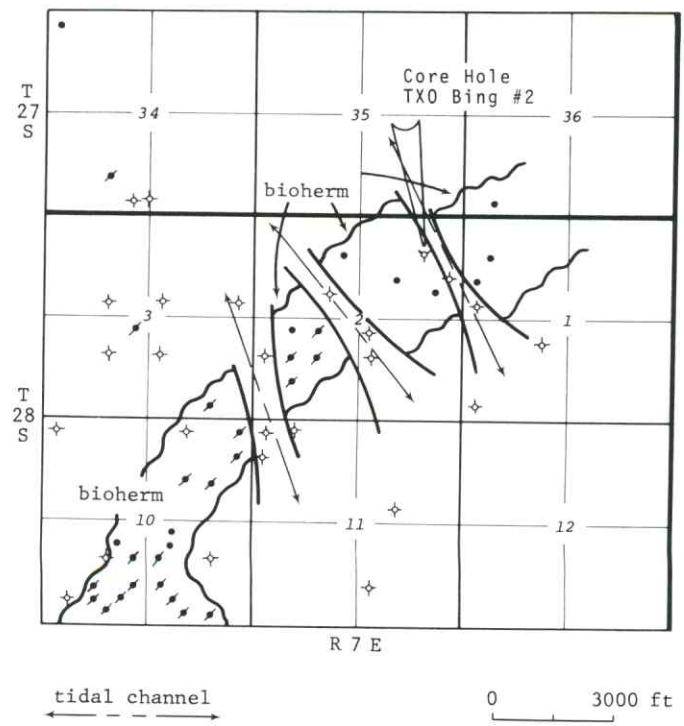


FIGURE 4—Facies distribution of Brandt–Sensenbaugh "pay," Butler County, Kansas.

"Pennsylvanian basal conglomerate," Ness County, Kansas

by *D. E. Nodine-Zeller,* Kansas Geological Survey, Lawrence, Kansas

"Pennsylvanian basal conglomerate" is a term widely used in Kansas to include reworked Mississippian or Ordovician beds that occur just beneath recognizable Pennsylvanian marine shales, limestones, or sandstones which range in age from Lower Desmoinesian (Cherokee Group) to Lower Missourian (Kansas City Group). The nature of these karst-derived deposits varies from hundreds of feet of heterogeneous rubble and riverine sediments such as those found in the Collins conglomerate to "Mississippi chat," which is essentially cherty residual debris resting on the surface of deeply weathered limestones. The unconformity represented by this unit is a very important one in the Midcontinent area because conditions conducive to the accumulation of oil and gas and to the emplacement of lead, zinc, and silver ores were created during this long post-Mississippian period of karst-type weathering in a tropical climate.

Introduction

A study of the Midcontinent Petroleum Company No. 1 J. G. Collins borehole was undertaken in order to determine the nature and age of the "Pennsylvanian basal conglomerate" and the stratigraphic units above and below it in a continuous core containing 125 ft of the conglomerate. The core was taken from 4,297 ft in rocks of the Marmaton Group (Desmoinesian Stage, Middle Pennsylvanian Series) to 4,555 ft reported as "Mississippi lime."

The Midcontinent Petroleum Company No. 1 J.G. Collins, CNWNW sec. 24, T. 20 S., R. 26 W., Ness County, Kansas (fig. 1), elevation 2461KB, was completed July 27, 1938, as a dry hole. No information on porosity, permeability, or drillstem tests is available. However, net porosity as well as thickness of the conglomerate is known to be highly variable. No wireline or lithology logs were made for this borehole. A graphic geologic section was constructed (fig. 2) showing the nature of beds represented by the core. This section was then correlated with several boreholes nearby that had wireline logs (fig. 5).

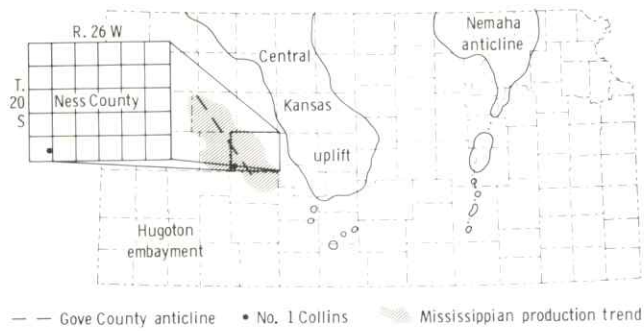


FIGURE 1—Location of Midcontinent No. 1 Collins borehole CNWNW sec. 24, T. 20 S., R. 26 W., Ness County, Kansas (Nodine-Zeller, 1981).

The No. 1 Collins borehole is situated 48 mi west-southwest of the western paleoerosional margin of the Central Kansas uplift on a buried anticline (fig. 1). Paleozoic rocks present in this area include the Arbuckle and Viola Limestones of Ordovician age, unconformably overlain by the "Kinderhook shale" or Chattanooga Shale of Devonian age. Mississippian beds include rocks of Kinderhookian, Osagean, and Meramecian age. Rocks of Penn-

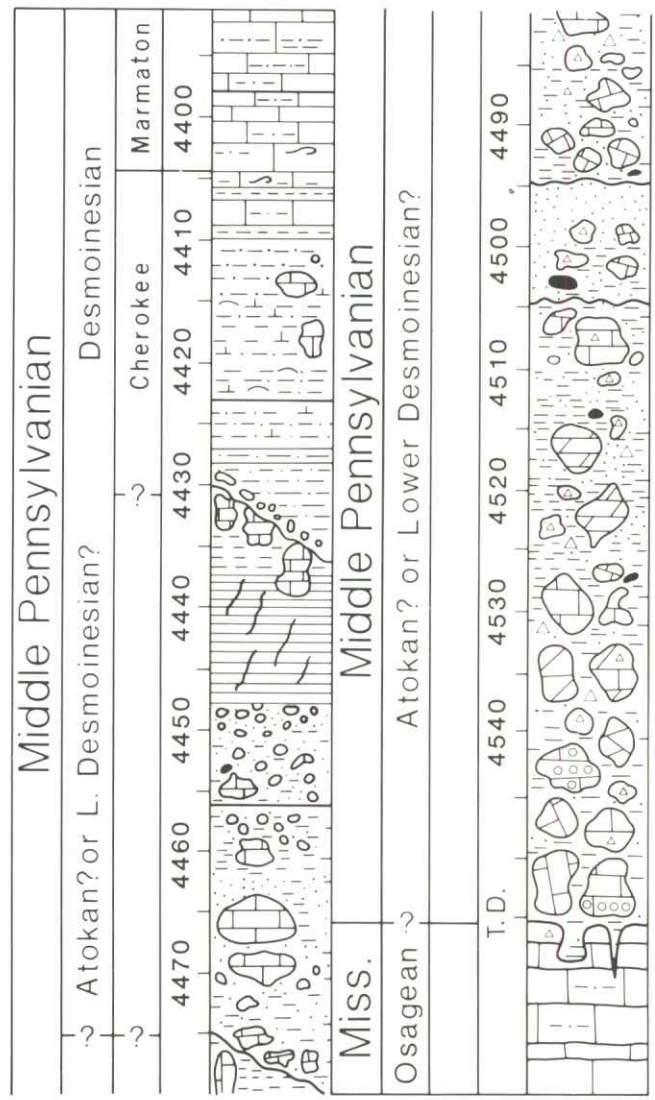


FIGURE 2—Graphic geologic section showing deposits in Midcontinent No. 1 Collins borehole. T.D. 4,555 ft. Top of paleosol is shown at 4430 ft, with superjacent basal Cherokee conglomerate (Nodine-Zeller, 1981).

sylvanian age (Desmoinesian, Missourian, and Virgilian Stages) unconformably overlie truncated Mississippian and older strata, with "Mississippi chat" or "Pennsylvanian basal conglomerate" intervening. Permian beds rest disconformably upon those of Pennsylvanian age. Toward the crest of the Central Kansas uplift, younger Pennsylvanian strata successively onlap the older, deeply eroded Paleozoic beds, and there Late Pennsylvanian rocks are in direct contact with Precambrian granites and quartz monzonites.

The "Pennsylvanian basal conglomerate" produces oil in scattered areas in Ness, Hodgeman, and Gove counties and elsewhere on the Central Kansas uplift. The Aldrich (sec. 7, T. 18 S., R. 25 W., Ness County) and Gorham (secs. 4 and 5, T. 14 S., R. 15 W., Russell County) fields produce from this horizon. The earliest report of production from the "Pennsylvanian basal conglomerate" was in 1927 in the Gorham field in Russell County, where the conglomerate is relatively thin and is almost wholly a sandstone unit referred to as the "Gorham sand" or "Gorham conglomerate" (McClellan, 1930). In 1928 the Stearns and Streator Company No. 1 Mermis, located in SWNWSW sec. 33, T. 13 S., R. 15 W., was completed for an initial production of 1,000 bbls of 36-gravity oil per day (Kesler, 1928). The production came from the top of the "Pennslylvanian basal conglomerate."

Description of core

Paleontological and physical evidence reveals that the deposits in the No. 1 Collins well represent the "Pennsylvanian basal conglomerate" of early Pennsylvanian (probably Atokan) age which incorporates pebbles, cobbles, and boulders of weathered Mississippian limestones and cherts in a silty, sandy, and shaly matrix that is largely derived from endstage weathering of Mississippian formations ranging in age from Osagean through Chesteran. Evidence also exists of highly weathered Morrowan limestones and shales occurring just beneath Cherokee rocks. The "Warsaw" limestone (figs. 11 and 15) previously reported to be present in the Collins borehole (Thompson and Goebel, 1963) upon closer examination turns out to be only cobbles, pebbles, or boulders of eroded Meramecian limestones incorporated in the "Pennsylvanian basal conglomerate" (Nodine-Zeller, 1981).

That the core interval designated "Pennsylvanian basal conglomerate" was indeed a conglomerate and not solidly bedded limestone was indicated by the following: 1) some cored limestones with a deeply weathered top and bottom, grading into fresh, unaltered fossiliferous limestone at the center of the piece, suggested that this was a cobble or

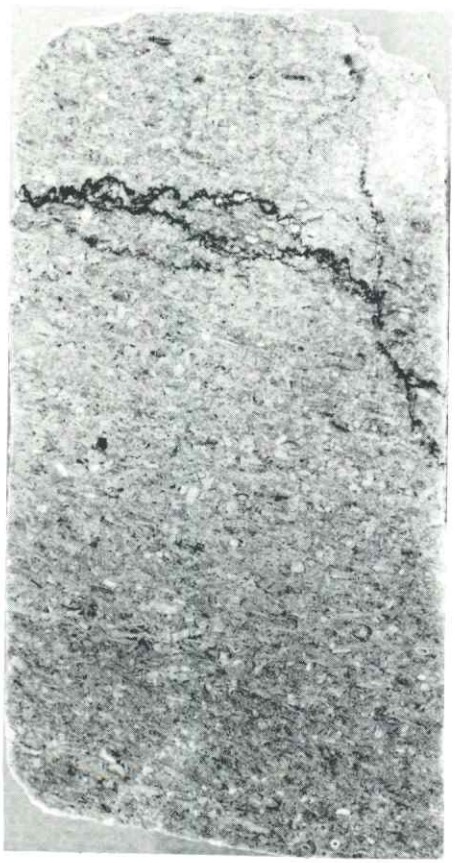


FIGURE 3—Weathered stylolitic, fossiliferous limestone cobble of Meramecian age; 4,494 ft. Scale in centimeters.

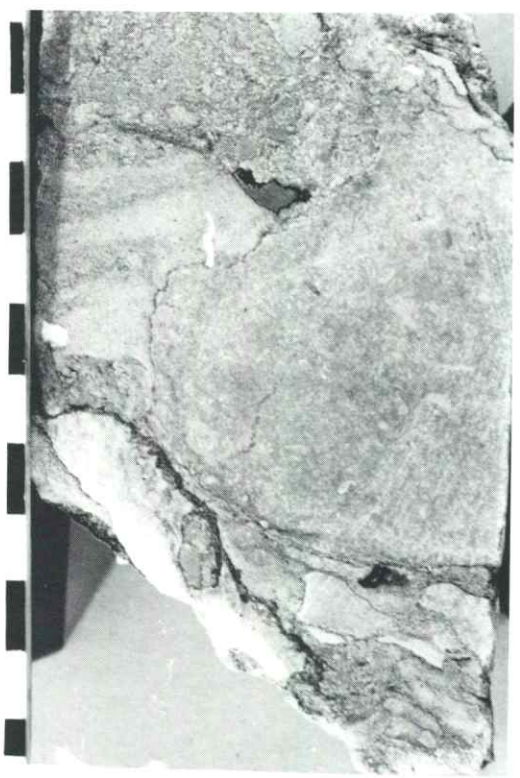


FIGURE 4—Transported, brecciated Mississippian limestone fragments infilled with sandstone and siltstone matrix beds containing irregular pieces of chalky white chert; 4,475 ft. Scale in centimeters.

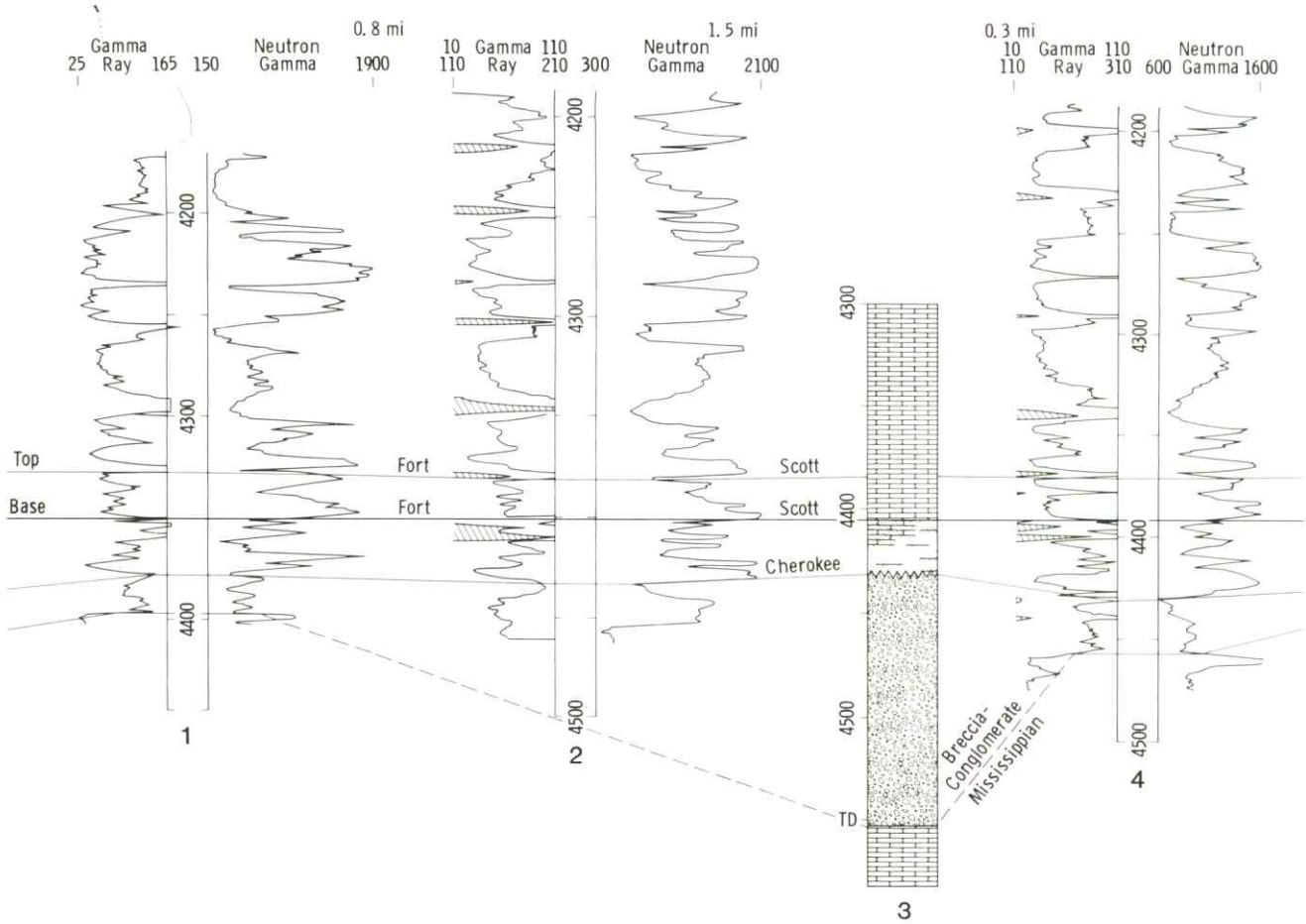


FIGURE 5—Correlation of Collins conglomerate with nearby wireline logs. 1) Mull Drilling Company No. 1 Goodman, CSENE sec. 35, T. 20 S., R. 26 W.; 2) O. A. Sutton No. 1 Goodman, CNESE sec. 26, T. 20 S., R. 26 W.; 3) graphic section of Collins conglomerate, CNWNW sec. 24, T. 20 S., R. 26 W.; 4) Rains and Williamson Oil Company No. 1 McVicker, CSENW sec. 24, T. 20 S., R. 26 W. (Adapted from Plate 4, Nodine-Zeller, 1981).

boulder subjected to peripheral weathering as it lay in the permeable matrix of the conglomerate; 2) random repetition of identical lithologies of Mississippian limestones in the core; 3) repeated, scattered occurrences of well-preserved Salem endothyrids in chert fragments ranging throughout the core; 4) several core pieces with bedding parallel to the length of the core; and 5) almost all cored limestones exhibit soft, green clay filling cracks and crevices (figs. 9 and 10) and penetrating even into microscopic interstices.

A detailed study of the composition of the "Pennsylvanian basal conglomerate" points to its derivation from solution-prone Mississippian carbonate strata exposed during a period of karst formation in early Pennsylvanian time (see p. 26–28 of Nodine-Zeller, 1981). During the karsting, dolomites and limestones were leached away leaving a thick mantle of residual chert, clay, sand, and silt. The insoluble residues obtained after dissolution of the pieces of Mississippian limestone from this core yield the same types of residues that are found in the matrix of the conglomerate (Nodine-Zeller, 1981). The karst debris, along with other weathered material, was later reworked by ancient streams crossing the Ness County area into channel deposits with thicknesses locally of 100–125 ft in some boreholes. A normal residual mantle is found in other areas with thicknesses on the order of 15–30 ft (fig. 5). No marine fossils are present in the enclosing matrix beds of the conglomerate, and the types of sedimentary structures are those one would expect from fluvial deposition by streams (fig. 17). An abundance of weathered white chert with smooth water-worn surfaces, some exhibiting solution fluting or rill marks, is evidence of long-term stillstand and weathering such as that encountered in karst regimes.

The cored section rests on the eroded top of a normal sequence of sponge spiculites of Osagean age as has been determined from observations of other cores taken in the Ness-Hodgeman County area (Ebanks, Euwer, and Nodine-Zeller, 1977). At the base of the core are cobbles, pebbles, and boulders of Mississippian limestones ranging in age from Osagean to Chesteran (4,555–4,475 ft). Above this, denoting a recognizable change in sedimentation, is a sandstone conglomerate (4,475–4,448 ft). On top of this is a highly weathered, unctuous, red clay shale containing highly weathered limestone cobbles and boulders (4,448–4,430 ft). It is in this unit (fig. 13) that a cobble was found that contained the lower Pennsylvanian conodont *Idiog-*

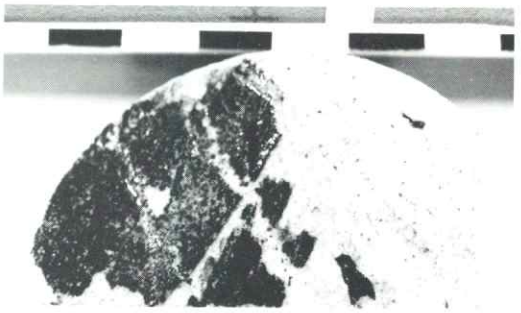


FIGURE 6—Large fragments of fossilized (coaly) wood in riverine sandstone; 4,499 ft. Scale in centimeters.

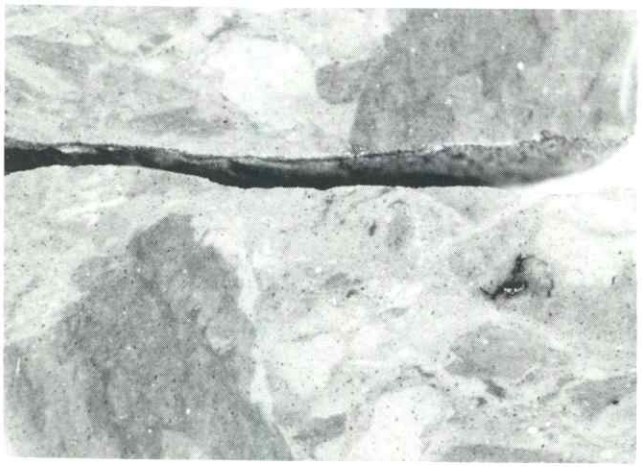


FIGURE 7—Burrow-mottled matrix sandstone from Collins conglomerate contains tiny fragments of white chert and Mississippian limestone; 4,455 ft. Scale in centimeters.

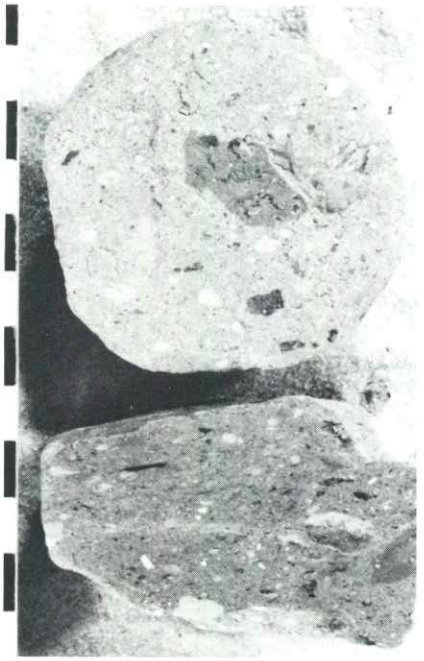


FIGURE 8—Matrix conglomerate bed of residual materials derived from eroded karsted Mississippian beds. Black material is subbituminous coal; white material is devitrified chert; 4,496 ft. Scale in centimeters.

nathodus. On top of the soil zone are red and green claystone and sandstone with small pieces of Mississippian (and Lower Pennsylvanian?) limestones and cherts in a thin basal conglomerate reworked by transgressing Cherokee seas (4,430–4,429 ft) and grading into marine limestones and shales of middle to late Cherokee age (4,429–4,404 ft) containing *Wedekindellina*. Above the Cherokee beds is the Fort Scott Limestone of the Marmaton Group (4,404–4,385 ft), whose top was used as a datum on the wireline logs in the cross section in fig. 5.

Beds from the bottom of the core T.D. 4,555 ft to 4,475 ft make up the main unit of the conglomerate, with pebbles, cobbles, and boulders of Mississippian limestone in a matrix of light- to dark-gray, gray-green, and green glauconitic shale, clay, or mudstone and gray, gray-green, and green siltstone, with interspersed beds of gray, gray-green, or greenish-buff, fine- to coarse-grained sandstone. The matrix beds are mostly friable, nonindurated, and noncalcareous (figs. 7, 8, 14, and 16–18). They contain scattered pyrite, sphalerite, chalcopyrite, geodes, mamillary quartz, doubly terminated quartz crystals, beekite rings, drusy quartz, glauconite grains, all types and sizes of quartz grains, aggregates of pyritized spicules, and coaly debris. Dolomitized sponge-spiculite siltstones of Osagean age (fig. 12), enclosed in gray and green clay shales of the conglomerate matrix, were recovered from the base of this interval. Coaly debris and plant fossils (fig. 6) occur in matrix beds throughout the core, and plant fragments were reported by the driller or geologist in matrix beds as low as 4,527 ft. The presence of reworked plant material and coal in these beds indicates a Pennsylvanian age for the matrix beds since the earliest known occurrence of plants and coal in Kansas is in terrestrial Morrowan rocks. The pebbles, cobbles, and boulders of Mississippian limestone are in varying stages of weathering from fresh, with well-preserved fossils, to slightly weathered to completely leached and decalcified with a "rotted" appearance. Large amounts of chert are found in this interval. Some chert fragments are fresh and contain well-preserved Meramecian endothyrid foraminifers, sponge spicules, or other fossils. However, most of the chert is moderately or severely weathered and devitrified to a chalky, white composition.

Beds from 4,475 to 4,448 ft make up a white conglomeratic sandstone and contrast sharply with beds below and above in color and composition. This sandstone is believed to represent a resorting and size-reduction of materials found in the conglomerate below. The color is white to light tan or pinkish-white and pale gray. The sandstone contains much more concentrated glauconite, pyrite, sphalerite, beekite rings, and silicified fossil debris. It is widely variable in composition and includes intraclasts of thinly laminated, angular, pale-greenish-gray and gray sandstone, short stringers and pods of glauconite and glauconitic silt, stringers of sandstone, and sandstone clasts. The quartz in the matrix grades from silt to sand

size. Most is frosted and rounded, but some is clear and angular. Throughout this unit are cobbles and pebbles and even smaller clasts of Mississippian limestones.

The interval from 4,448 to 4,430 ft represents a deeply weathered soil profile (fig.2). It contains at bottom a red to greenish-gray to deep-purple unctuous claystone, containing shrinkage cracks that have been recemented with green clay and calcite veins. Above that is a gray, noncalcareous, fossiliferous sandstone, with intraclasts of finer-grained, thinly laminated shaly sandstone with coaly debris, sphalerite, pockets of mud, and pieces of geodes with "dead" oil. On top of that are highly decomposed mudstones and siltstones and pieces of severely weathered limestone, stained yellow and red with limonite and hematite, and shot through with calcite veins (fig. 13).

Beds from 4,436 to 4,430 ft represent the paleosol. No core was recovered in this interval, so lithologic descriptions were obtained from the drillers' log and geologist's report. They recorded limestone with a slight oil show, green lumpy clay, sticky shale, and much sand.

Immediately above the paleosol is the transgressive marine basal Cherokee conglomerate derived from reworking of the soil rubble. It is a pebble conglomerate with coarse sand grains, glauconite, bright red iron stains, and gray-green silt (4,429–4,430 ft). The superjacent beds of Cherokee age are tan to brown, limy siltstones, burrow-mottled gray to gray-green mudstones, and tan to dark-gray biomicrites containing a normal-marine fauna of early Desmoinesian age. In the siltstones and mudstones are still-recognizable Mississippian limestone clasts. The siltstones and mudstones are interbedded with limestones that contain lumps of pyrite and disseminated pyrite, glauconite, and rip-up shale clasts. Several zones in this interval contain broken fusilinids and other fossil hash, along with reworked lithoclasts, and are interpreted as representing disturbed sedimentation due to transgressive-regressive episodes during early Cherokee time.

Establishment of normal-marine conditions is represented by the Fort Scott Limestone at 4,404 ft. Very tiny Mississippian limestone clasts are still to be seen in this silty algal limestone containing ostracodes, pelecypods, bryozoans, and a wide variety of foraminifers, including fusulinids.

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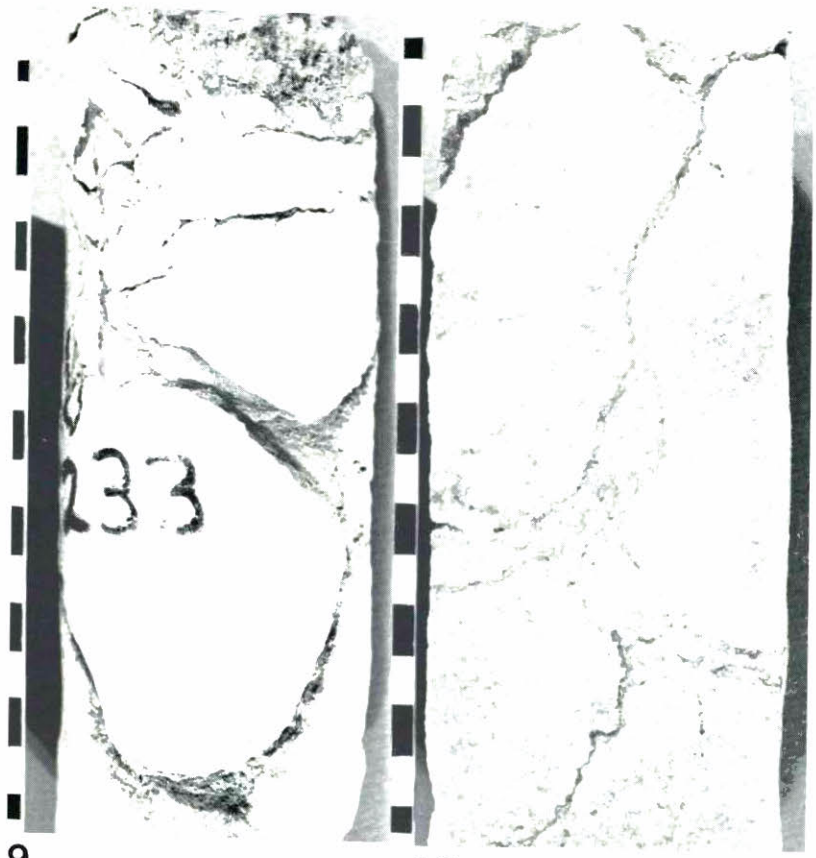
FIGURES 9–10—Brownish-gray Mississippian limestone cobble with fractures and crevices infilled with light-green clay residuum; 4,491 ft. Scale in centimeters.

FIGURE 11—Leached, dolomitized "Warsaw" cobble with oomoldic porosity. Typically occurring fenestellid bryozoan at top of photograph. Such cobbles are often identified as "Warsaw" Limestone because of the presence of fenestellid bryozoans of this type (see fig. 15 also); 4,520 ft. Scale in centimeters.

FIGURE 12—Argillaceous Osagean sponge-bed cobble or boulder containing dark sponge debris and white siliceous sponge spicules. Some cobbles and boulders are very well preserved and display irregular, wispy, high-angled bedding surfaces. Others are thoroughly weathered to a uniform light-tan color and are demineralized and dolomitized, with bedding structures obliterated; 4,549 ft. Scale in centimeters.

FIGURE 13—Extremely weathered argillaceous limestone from paleosol zone in Collins conglomerate, showing stylolites with iron oxide deposits, veins filled with calcite, tiny rounded blebs of iron oxide, and irregular patches in limestone that have been reduced to ochre-colored limonitic clay; 4,436 ft. Scale in centimeters.



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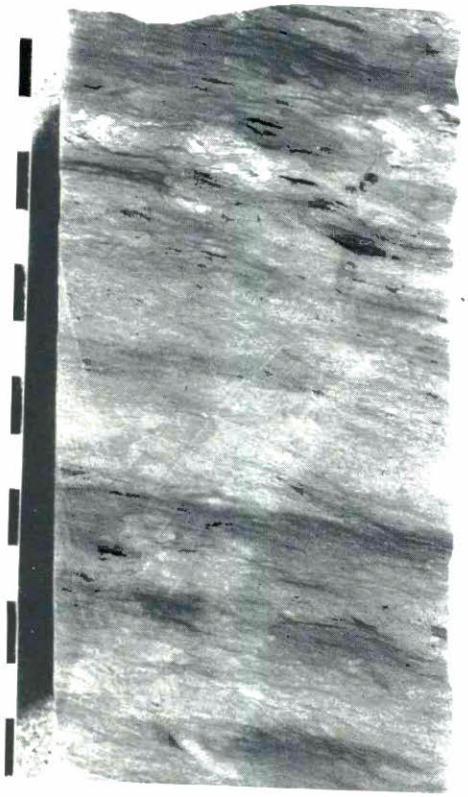

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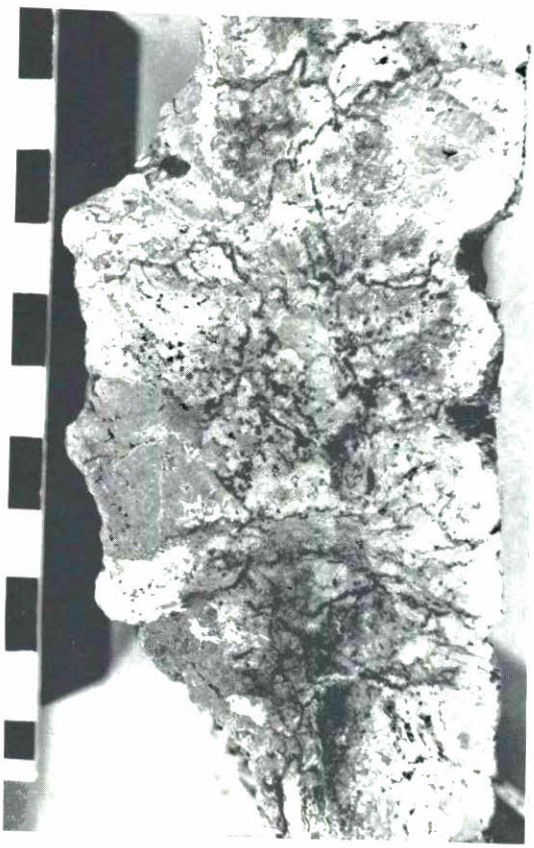

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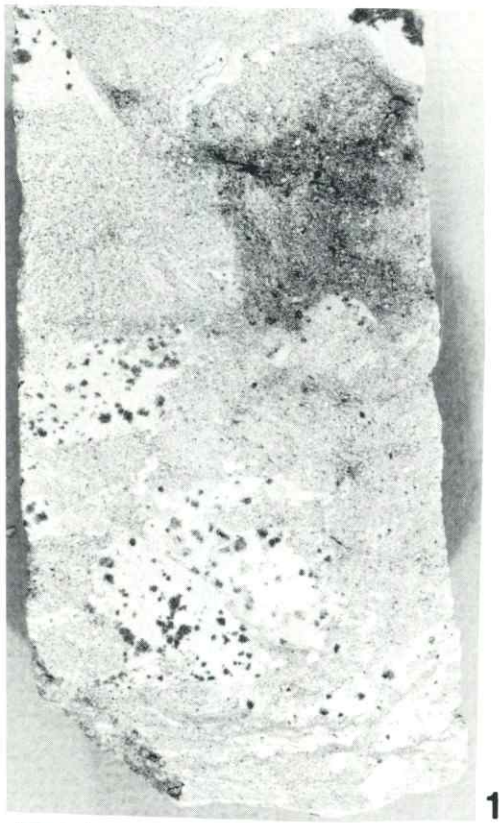
FIGURE 14—Conglomerate matrix bed of light-colored, fine-grained sandstone with iron stains, enclosed in coarse sand and silt containing particles of white chert, glauconite, black flecks of coaly debris, and minute gray claystone clasts; 4,456 ft. Scale in centimeters.

FIGURE 15—Highly leached, porous, dolomitized Meramecian (''Warsaw'') limestone cobbles, containing traces of fenestellid bryozoans; 4,520 ft. Scale in centimeters.

FIGURE 16—Heterogeneous mixture of sand and silt grains, flakes of shale, mudstone stringers, devitrified white chert, glauconitic stringers, and blebs of pyrite; 4,513 ft. Scale in centimeters.

FIGURE 17—Penecontemporaneous recumbent folds in trough cross stratification of matrix sandstones of Collins conglomerate formed in water-saturated sandstone beds, produced by current surges of high velocity; 4,509 ft. Scale in centimeters.

FIGURE 18—Debris-laden glauconitic sandstone matrix beds containing sand and silt stringers, tiny angular pieces of white tripolitic chert, and mixed Mississippian limestones, finely comminuted and stringers of coaly debris, and varicolored claystone clasts; 4,509 ft. Scale in centimeters.



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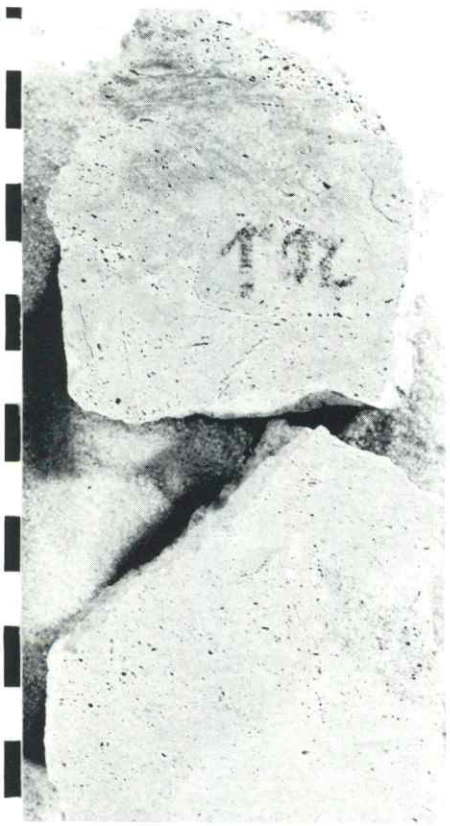

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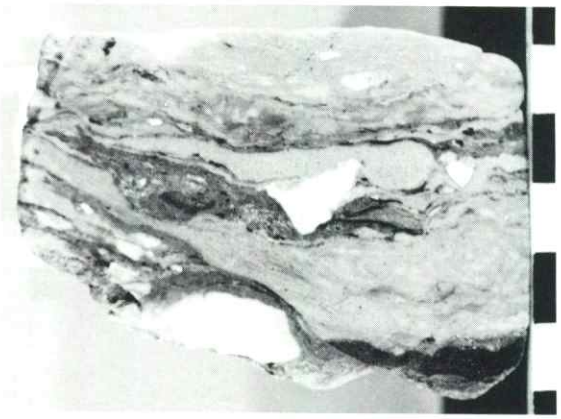

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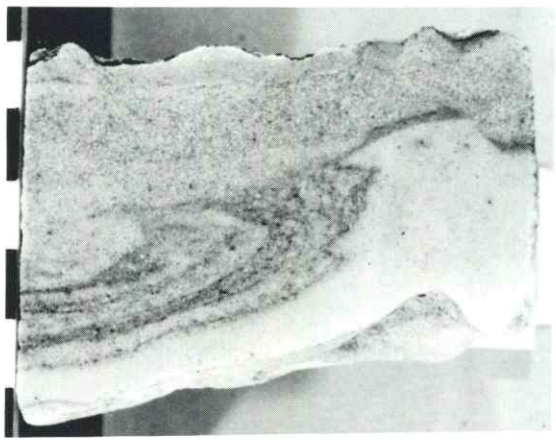

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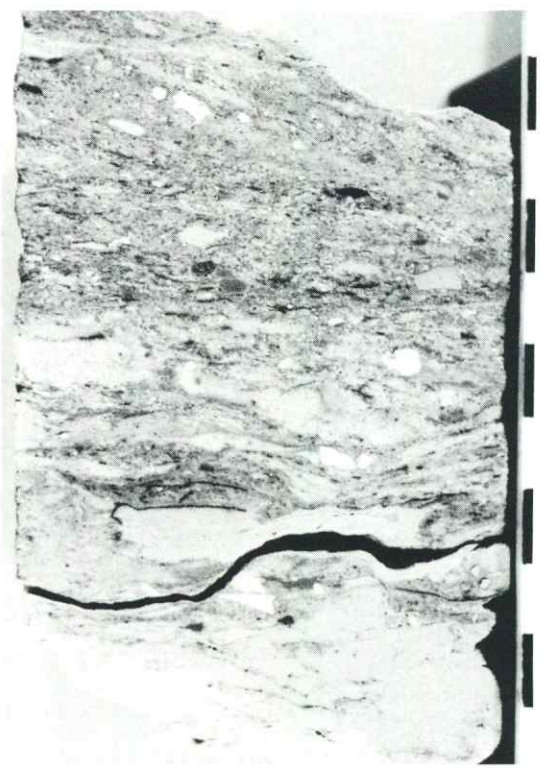

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Distribution of petrophysical properties in a lower Morrow sandstone (Keyes), southwest Kansas

by *Richard H. Franz,* Chevron U.S.A. Inc., Denver, Colorado

Summary

Core 5 low A (Anadarko Production Co., Kansas Geological Survey) sampled the Keyes sandstone from the lower Morrow from Morton County (sec. 8, T. 33 S., R. 40 W.), Kansas (fig. 1, core location 4). The well has produced a small amount of oil and is in the Cimarron Valley field where the Morrow produces both oil and gas. Core 5 Low A was incorporated in an M.S. thesis project largely funded by the Tertiary Oil Recovery Project (TORP) at the University of Kansas (Franz, 1984). The core was studied as part of an attempt to relate geological aspects and petrophysical properties of selected Morrowan rocks in southwestern Kansas. The study focused on petrographic and petrophysical properties and their interrelationships, for given general lithofacies types.

Glauconitic, crossbedded sandstone constitutes the major reservoir facies in this core. The lithofacies is significant because it exhibits a range in permeability (0.1–176.4 md), porosity (7.9–16.8%), and effective pore radii (2–17 microns). Sedimentologic and diagenetic factors are important as controls of petrophysical properties. The vertical distribution of permeability implies preferential fluid flow through the upper portion of the sand body. However, the chlorite and ferroan dolomite-ankerite cements may react with injected fluids. Knowledge of this type is important in the development of a field, for example, in the design of an enhanced-recovery project.

Stratigraphy

The type log (fig. 2) is a generally applicable subdivision of the Lower Pennsylvanian in the Anadarko Basin and the Hugoton Embayment. In western Kansas, rocks of Morrowan age have been defined as the Kearny Formation (fig. 3; Zeller, 1968; McManus, 1959). The Kearny Formation consists of those rocks present between the generally oolitic limestone of Mississippian age and the overlying dark limestones and shales of the Atoka. The upper contact of the Morrow with the Atoka is usually easily picked out on logs because of the distinctive Atokan "Thirteen Finger limestone." The Kearny occurs within a depth interval of 1,300–1,900 m and ranges up to 185 m in thickness. The formation thickens and occurs deeper southward across Kansas into the Anadarko Basin (Swanson, 1979).

The subdivision of the Kearny (Morrow) into lower and upper sections generally separates marine deposits of the lower Kearny from younger nonmarine deposits. The lower Kearny consists of black shales and discontinuous, glauconitic limestones, sandstones, and fossiliferous sandstones. The upper Kearny is characterized mainly by black shales, carbonaceous shales, and discontinuous, coarse-grained, arkosic sandstones. The Keyes sandstone, at the base of the lower Morrow, is a discontinuous band of glauconitic sandstones and sandy lime packstones.

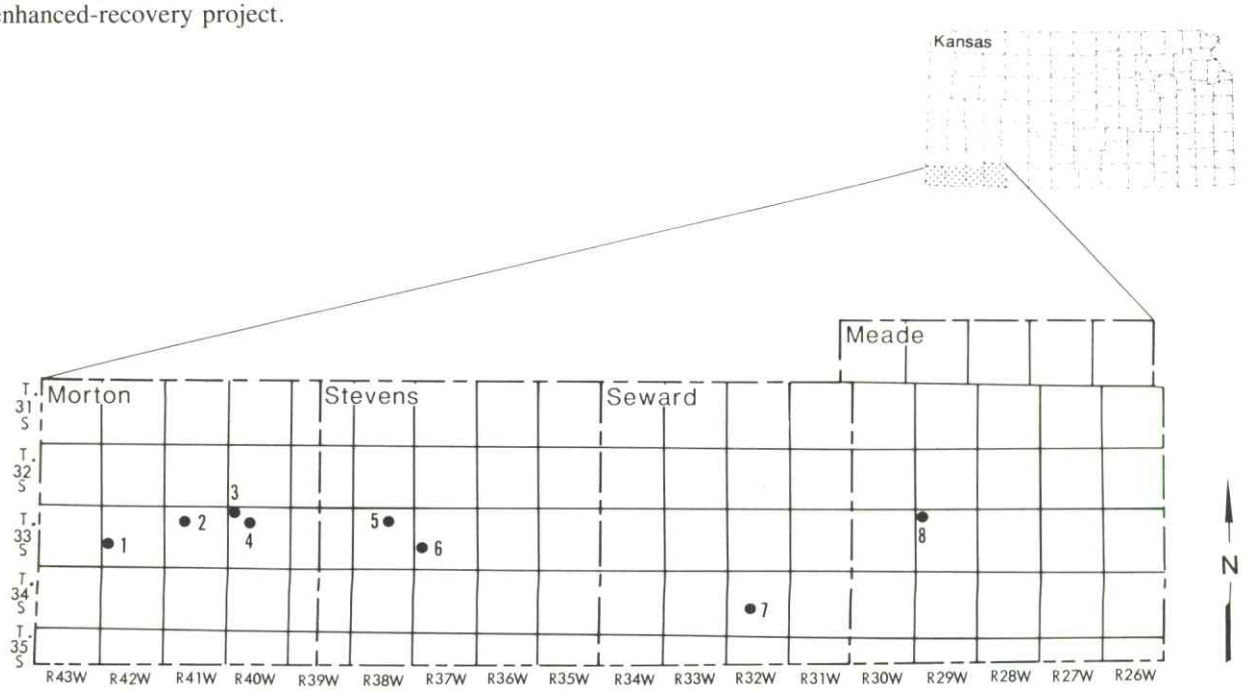


FIGURE 1—Location of cores used in this study.

Core 5 Low A was taken from a depth interval of about 1,740.7–1,753.6 m (5,615–5,657 ft; 5,624–5,666 ft by log) in Morton County (sec. 8, T. 33 S., R. 40 W.), Kansas (fig. 1, core location 4). The Kearny (Morrow) section and cored interval are indicated on the log for well 5 Low A shown in fig. 4. The cored interval corresponds most closely to the basal, marine Keyes sandstone of the lower Morrow (fig. 2).

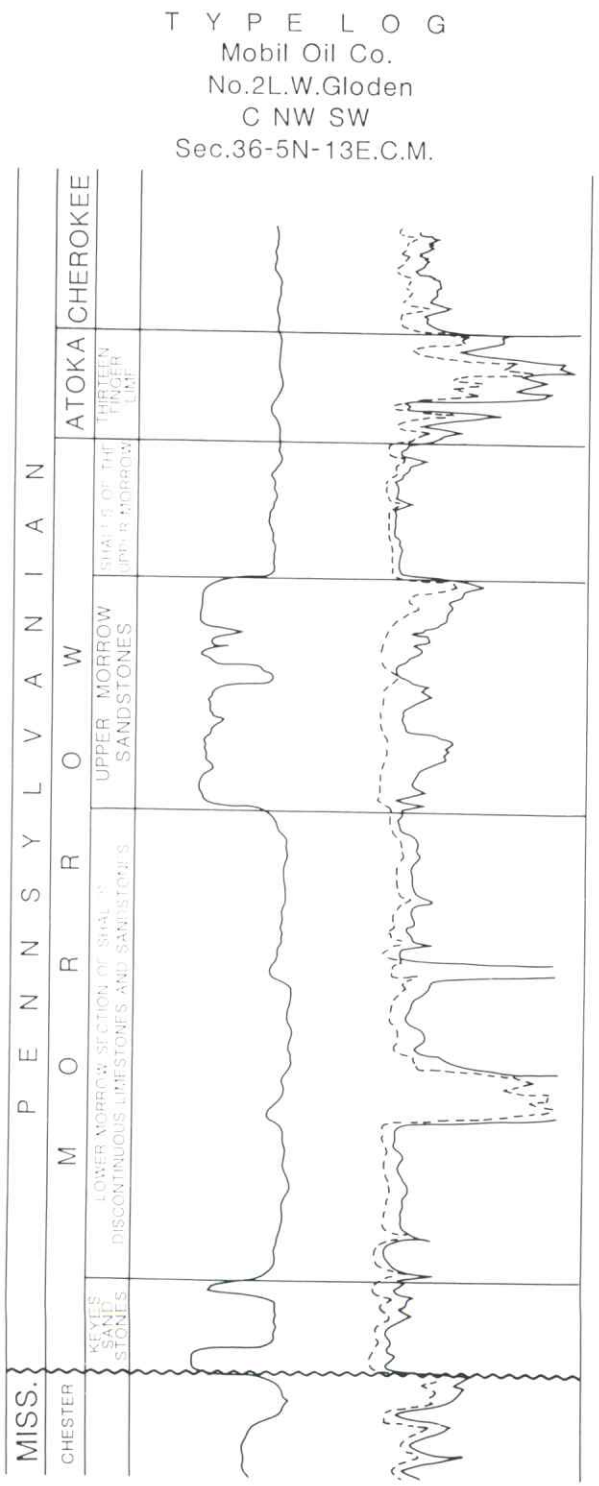


FIGURE 2—Typical electric log of Morrowan Stage and adjacent rocks in the Anadarko Basin (after Arro, 1965).

Structural and depositional setting

Major tectonic elements of the Midcontinent during the Pennsylvanian are shown in fig. 3. Deposition of lower Morrow sediments took place during a general transgression from the Anadarko Basin into the Hugoton embayment. This transgression was marked by a number of shoreline stands during which depositional environments included nearshore beach and barrier bar and shallow marine shelf (Busch, 1961; Khaiwka, 1968).

Extensive southeastward deltaic progradation characterized the paleogeography of southwestern Kansas during deposition of upper Morrow sediments (Swanson, 1979; Adler and Rascoe, 1983). Marginal marine and deltaic environments prevailed at this time. Sand, typically coarse grained, commonly was deposited in point bar sequences and distributary channels and as distributary mouth bars (Swanson, 1979).

Petroleum geology

Sandstones and conglomeratic sandstones of the upper Morrow are most important as reservoirs in the Anadarko Basin and Hugoton embayment (Swanson, 1979). Most production has been wet gas with distillate, although pools of fairly light (38–42 API) oil exist throughout the area (Swanson, 1979; Paul and Bahnmaier, 1981).

The Keyes sandstone interval in Core 5 Low A is productive in the Cimarron Valley field, located in Morton County, Kansas. Oil and gas production in this field comes from the St. Louis Limestone (Mississippian), the Morrow, and the Council Grove Group (Permian–Wolfcampian). Gas production has been much more significant than oil production, totaling 626,983 MCF. Cumulative oil production is 184,328 bbls through 1982. In 1982, 54,453 MCF of gas and no oil was produced. Well 5 Low A (Low 5A) has produced 1,072 bbls of oil. Sample production figures from other Keyes wells in this field include: 90 BOPD with 40% water (Low 3A), 70 BOPD with 20 BW (Low D5), 4,256 MCFPD (Low C4), and 9,980 MCFPD (Goddard A-1; Paul and Beene, 1983; W. L. Watney, personal communication, 1983).

Core description and interpretation

Two important lithofacies occur in Core 5 Low A: glauconitic, crossbedded sandstone and muddy, poorly sorted, glauconitic, bioturbated sandstone (figs. 5, 6, and 7). The former is more abundant and is the reservoir facies. It is generally medium- to coarse-grained and moderately well sorted (fig. 8). A coarser variation that contains shale clasts up to 1 cm long is present. Towards the top of the major interval of this lithofacies, grain size ranges down to fine grained, and sorting improves (well to very well sorted; fig. 9). The predominant sedimentary structure is relatively high-angle crossbedding. Thin laminae of black clay are abundant except in part of the upper half (3.5 m) of the core.

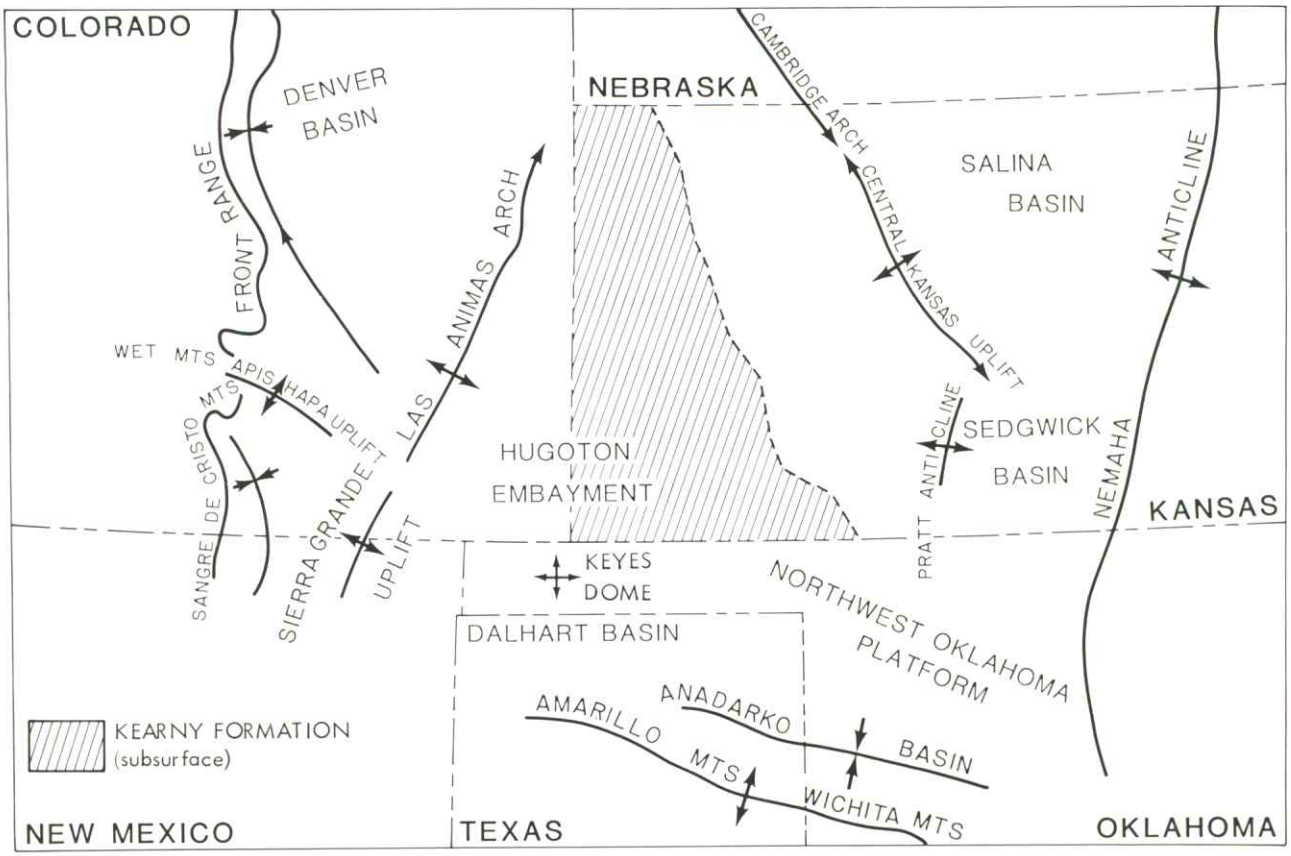


FIGURE 3—Occurrence of the Kearny Formation and tectonic features of the southern Midcontinent (after Merriam, 1955; McManus, 1959).

The vertical sequence present in Core 5 Low A is basal greenish limestone and shale (0.6 m); muddy, poorly sorted, bioturbated sandstone (0.5 m); crossbedded sandstone (1.6 m); bioturbated sandstone (1.9 m); then a thick (7.9 m) interval of crossbedded sandstone (fig. 7). Contacts between facies are fairly sharp. Overlying the cored interval is about 50 ft of shale. The greenish limestone and shale sequence is most likely Mississippian. The nature of the Mississippian–Pennsylvanian contact is unknown due to poor core recovery; however, the contact generally is believed to be a regional angular unconformity. The vertical sequence in this cored interval seems to represent an overall regressive transition from a lower energy (possibly interbar or bar flank) area on a shallow marine shelf to a higher energy area represented by the crossbedded sandstone lithofacies. The thick interval of crossbedded sandstone lithofacies becomes cleaner (fewer shale laminae and clasts) and better sorted in its upper half, suggesting more agitated energy conditions. The shoaling-upward sequence and the abundance of glauconite suggest the crossbedded sandstone of Core 5 Low A was deposited as an offshore bar (Franz, 1984). Offshore bars typically show characteristics reflecting an increase in energy conditions upwards, although this is usually seen as an upwards increase in grain size (Brenner and Davies, 1974; Spearing, 1975).

Petrography and diagenesis

The main lithofacies of Core 5 Low A, crossbedded sandstone, is assigned a general petrographic classification (Folk, 1980) as follows: moderately well to very well sorted medium to coarse sandstone, dolomite, and quartz-cemented submature to mature glauconitic subarkose. Detrital constituents include an average of about 7% feldspar, 3–25% glauconite, and less than 1% skeletal carbonate grains. Shale clasts average on the order of 3% and range up to nearly 12%. They are more abundant in the lower portions of lithofacies.

Diagenesis of the crossbedded sandstone lithofacies has led to formation of authigenic materials (chlorite, quartz, ferroan dolomite-ankerite) and to compaction. Chlorite grain coatings and quartz overgrowths are best developed in the upper half of the core (figs. 10 and 11). Late-stage ferroan dolomite-ankerite occurs largely as a replacement of detrital clays (laminae and clasts), but also as a pore-filling cement (fig. 12). This authigenic mineral is most notable in the lower "shaly" portions of the core. Compactional features (stylolites) associated with clay laminae also seem more significant in the lower portions of the core (fig. 13).

Petrophysical properties

Porosity, permeability, and effective pore-throat size in the crossbedded sandstone lithofacies range from 7.9 to 16.8%, 0.1 to 176.4 md, and from about 2 to 17 microns (figs. 14, 15, and 16), respectively. Porosity and permeability were determined by brine saturation and with a Ruska liquid permeameter. Pore-size distribution curves (figs. 14, 15, and 16) were derived from data obtained by

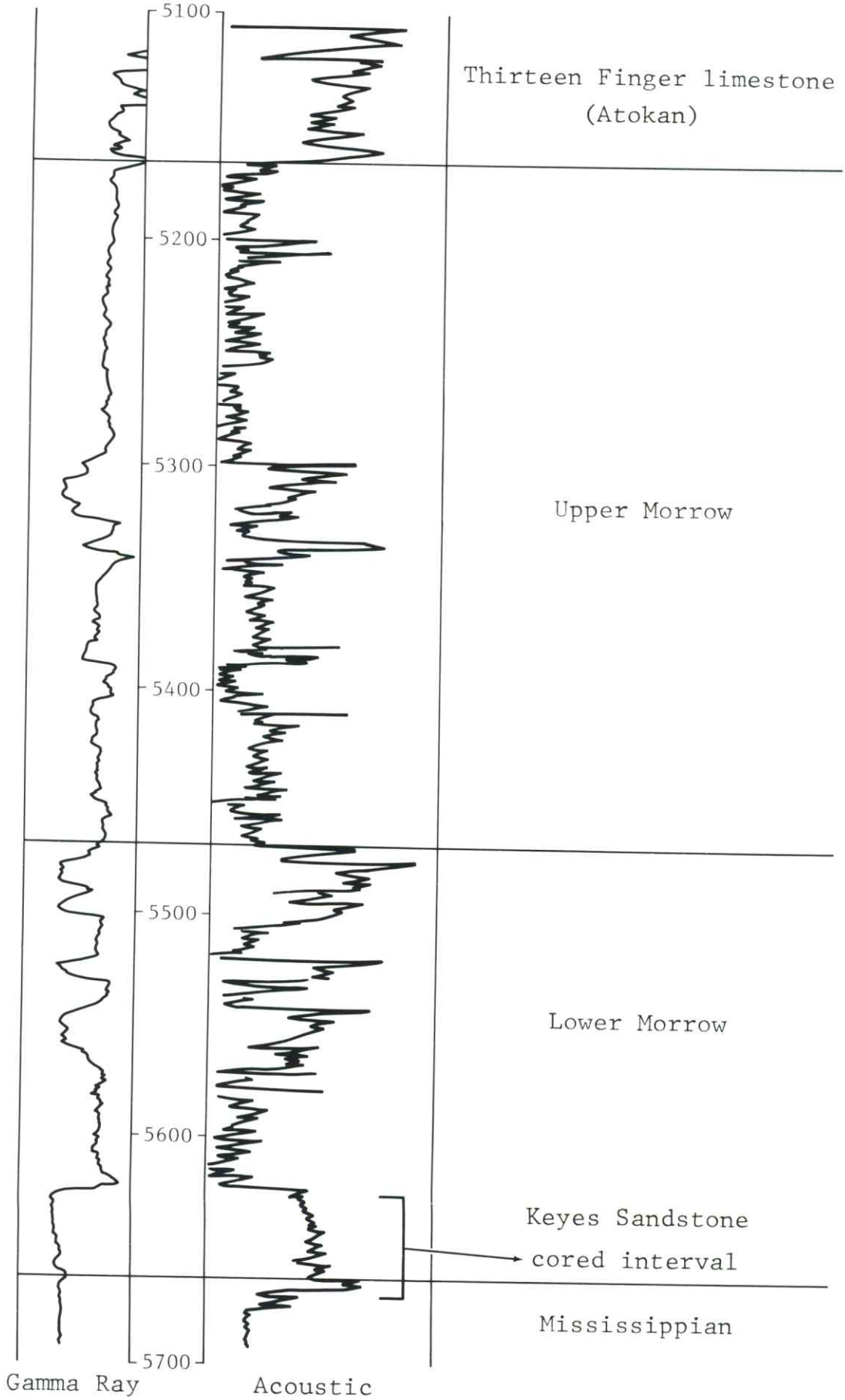


FIGURE 4—Gamma-ray/acoustic log for well Anadarko Low A #5, Cimarron Valley Keyes field, Morton County, Kansas.

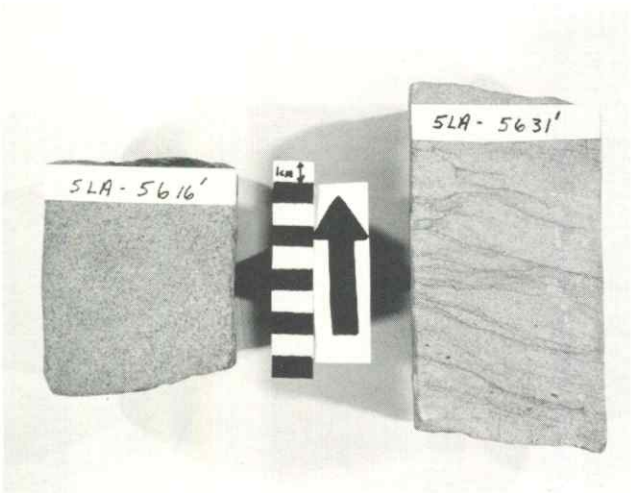


FIGURE 5—Glauconitic, crossbedded sandstone. Upper portion at 5616 ft (left), lower at 5631 ft (right). Note characteristic black clay laminae; scale = 10 cm.

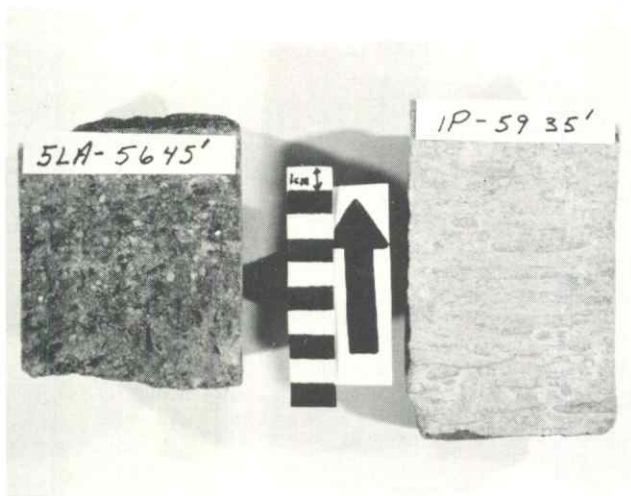


FIGURE 6—Muddy, poorly sorted, glauconitic, bioturbated sandstone (left). From lower part of core at 5645 ft; scale = 10 cm.

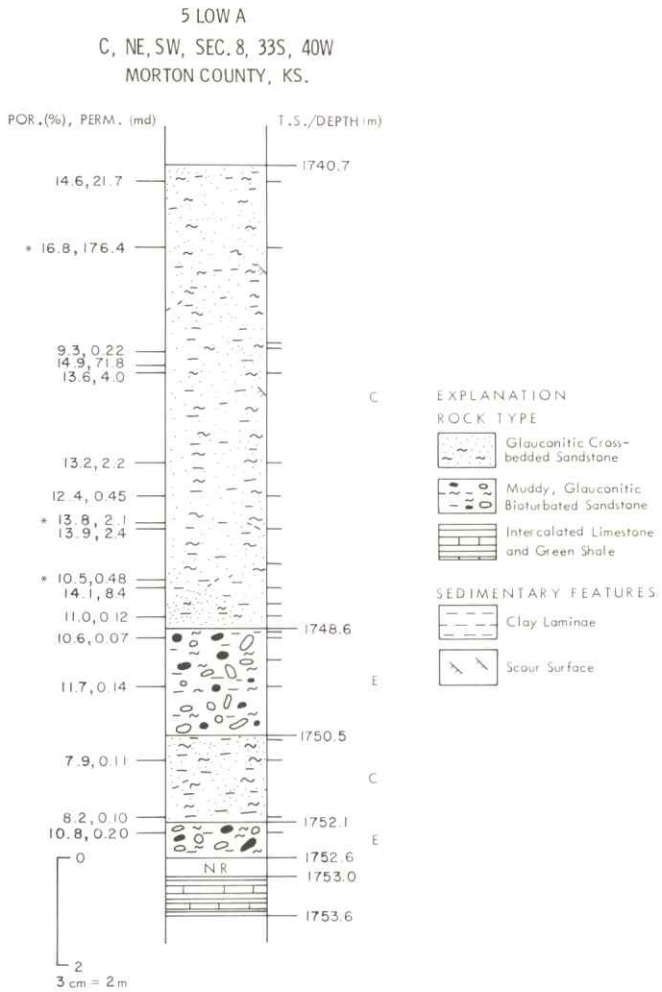


FIGURE 7—Core of well Low A #5 showing vertical distribution of permeability and porosity as well as rock type.

mercury injection tests performed by Core Labs, Inc. (Pittman, 1979).

The vertical distribution of these properties, particularly permeability (fig. 7), is important to note. The upper half of the major portion of crossbedded sandstone has the higher values of permeability, porosity, and pore-throat size. The locations of the samples for which a pore-size distribution curve is presented are indicated in fig. 7 by asterisks.

Relationships between sedimentology, diagenesis, and petrophysical properties

Higher permeability values in the upper half of the main interval of crossbedded sandstone can be associated with higher porosity and larger pores (figs. 7 and 14). Depositional and diagenetic factors are believed to be important controls of this vertical distribution of petrophysical properties. The upper part of the core tends to be somewhat better sorted and cleaner (less clay and fewer laminae and clasts) than the rest of the cored interval (figs. 8 and 9). Sorting is an important control of initial porosity and permeability; in general, better sorting favors higher porosity and permeability (Pettijohn and others, 1973, p. 525). A higher percentage of clays (including ductile shale clasts) would tend to promote compaction, thereby reducing pore-throat size, porosity, and permeability. Compactional features are more obvious in the lower part of the sequence, including the lower half of the main crossbedded sandstone

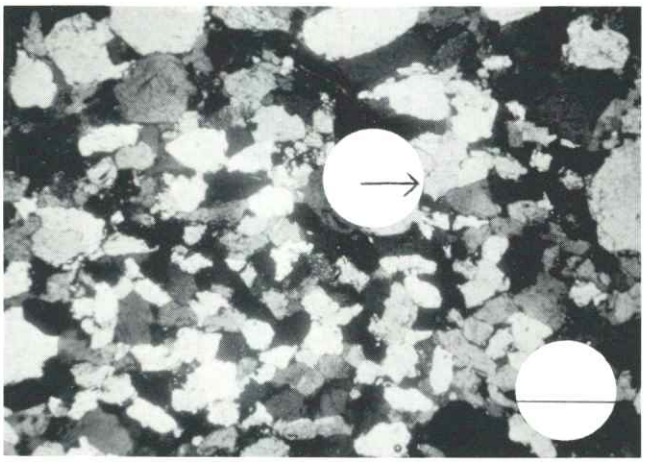


FIGURE 8—General textural character of crossbedded sandstone lithofacies—medium to coarse grained, moderately well sorted. Note ferroan dolomite-ankerite (arrow). Depth—5635 ft; bar = 0.7 mm XN.

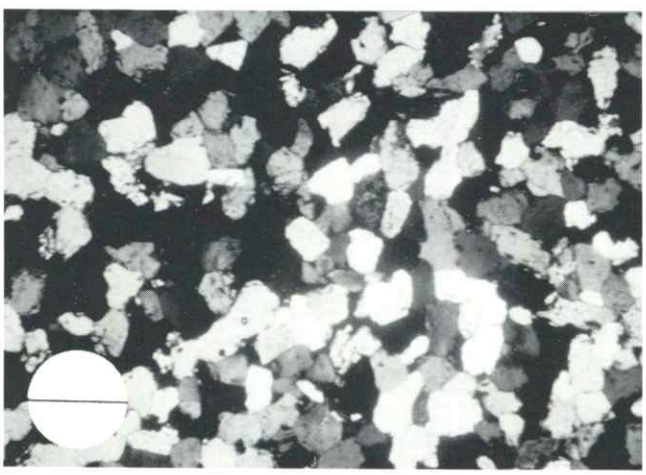


FIGURE 9—Upper portion of crossbedded lithofacies—fine to medium grained, well to very well sorted. Depth—5619 ft, bar = 0.7 mm XN.

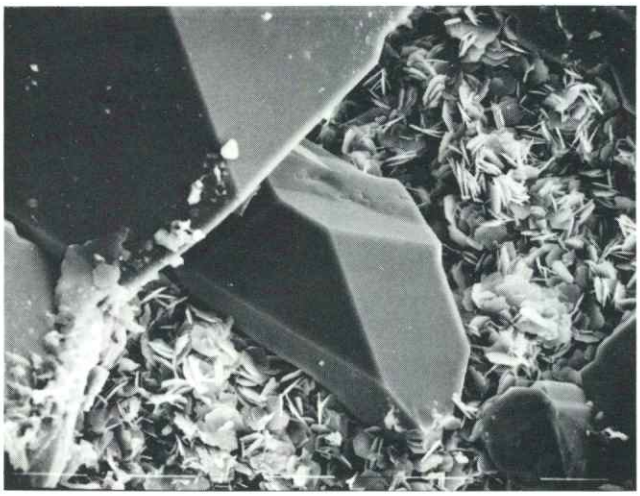


FIGURE 10—SEM photomicrograph of authigenic chlorite grain coating overgrown by quartz. Characteristic diagenetic features of the upper part of the crossbedded lithofacies. Depth—5619 ft; white bars = 10 microns.

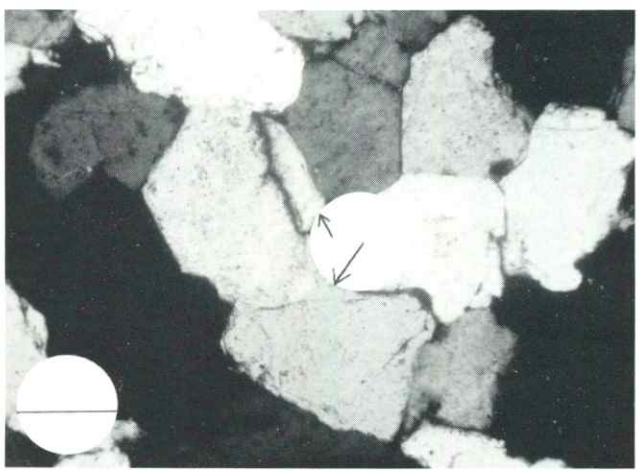


FIGURE 11—Quartz overgrowth cementation characteristic of upper part of crossbedded lithofacies (arrows). Depth—5619 ft; bar = 0.2 mm XN.

interval (fig. 13). Estimates of porosity reduction by compaction were made using the equation: porosity loss by compaction = porosity-initial (assumed) − [porosity-present (measured) + percent cement (measured)] (Jonas and McBride, 1977, p. 42). Compaction is somewhat greater in the lower part of the crossbedded lithofacies: sample 5LA5619.5—8.7% porosity reduction by compaction, 5LA5635.3—12.3%.

Pore type and authigenic mineralogy also are probably important controlling factors of permeability. A high percentage of intergranular pores favors high permeability in contrast to a high percentage of micropores (clays to pore-throat size less than 0.5 microns), which is associated with low permeability (Pittman, 1979). Point counts of pore types reveal that sample 5LA5619.5 (K = 176.4 md) has 71.1% intergranular pores and 6.0% micropores (22.9% secondary), as compared to sample 5LA5635.3 (K = 2.4 md), which has 48.6% intergranular and 40.6% micropores (10.8% secondary; fig. 17). In addition, ferroan dolomite-ankerite as a replacement and cement may reduce permeability in the lower part of the core. The well-developed quartz overgrowth cement in the upper portion of the core, if formed early, could have prevented or reduced compaction.

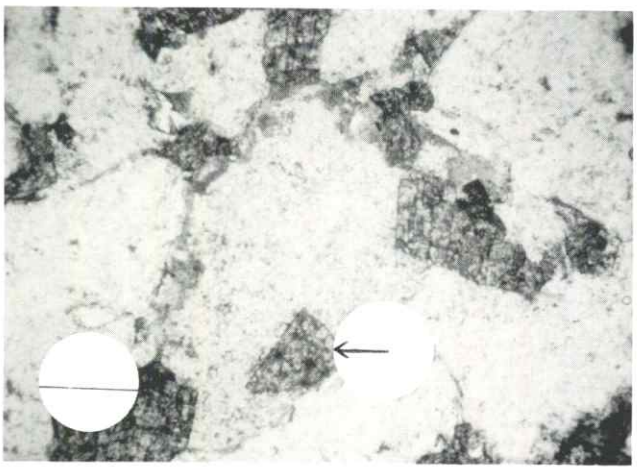


FIGURE 12—Ferroan dolomite-ankerite replacement of clays (arrow). Characteristic diagenetic feature of lower part of core. Depth—5648 ft; bar = 0.2 mm PPL.

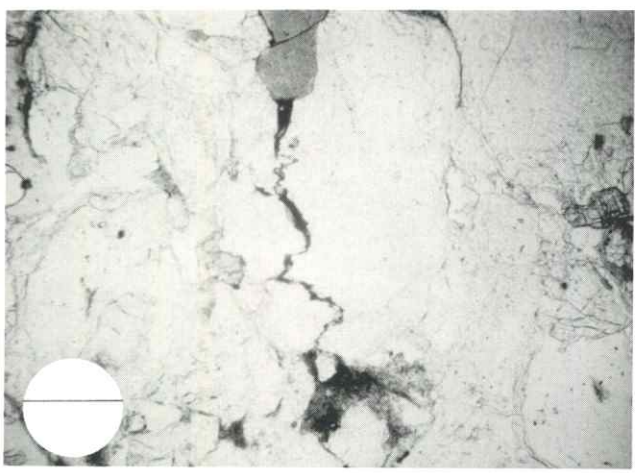
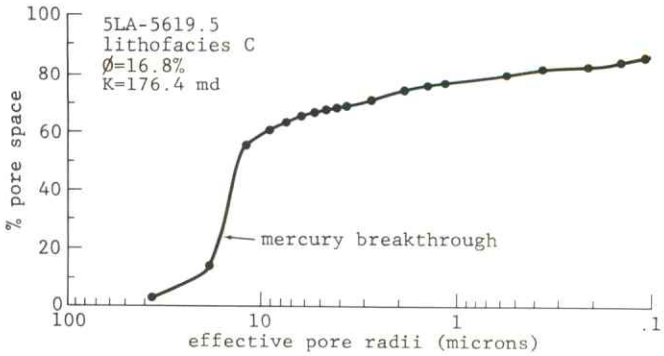


FIGURE 13—Stylolite. Depth—5638 ft; bar = 0.2 mm PPL.



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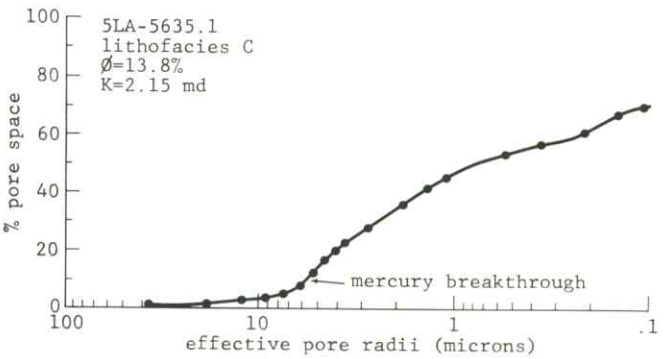

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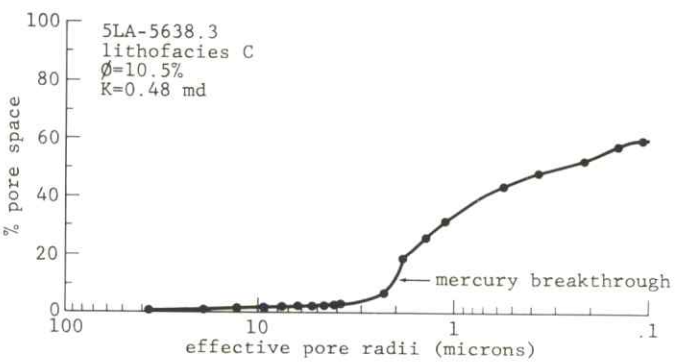

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FIGURES 14–16—Graphs showing porosity, permeability, and effective pore throat size in the crossbedded sandstone lithofacies of core 5 Low A.

Implications for enhanced oil recovery (EOR)

Zonation of permeability, exhibited by the main reservoir lithofacies in this lower Morrow Keyes interval, suggests that preferential fluid flow would occur through the upper portion of the sand body. This information will be important to those who may attempt development of a Keyes field. For example, a reservoir engineer attempting to model the sweep of injected EOR fluids through the reservoir would need to know about permeability distribution.

With respect to enhanced recovery efforts, considering the pore-lining minerals that will be contacted by EOR fluids also is necessary. In the case of Core 5 Low A, the upper, more permeable zone contains authigenic pore-lining chlorite (fig. 10). Chlorite is among the minerals that are sources of ferric ions, which are deleterious to poly-

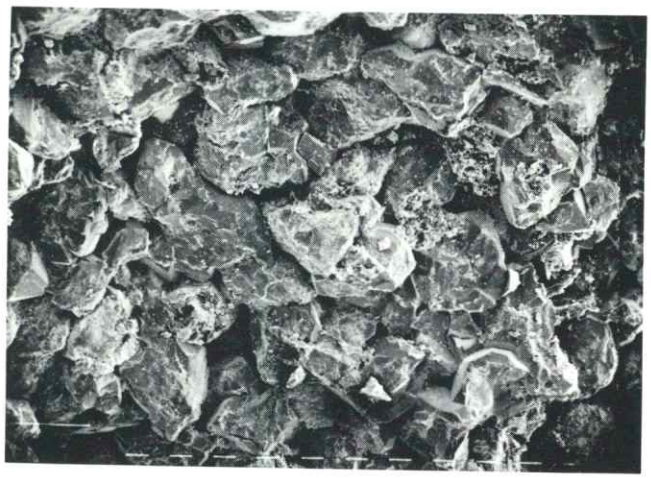

FIGURE 17—SEM photomicrograph of preserved primary intergranular porosity and quartz overgrowth cementation. Upper part of crossbedded lithofacies at 5619 ft; white bars = 100 microns.

mers and sulfonates (Peterson, 1982). Acid treatment would result in the dissolution of chlorite and the formation of $Fe(OH)_3$ as an unwanted precipitate. This problem may be avoided with the use of an oxygen scavenger and iron-chelating agent added to the acid (Almon and Davies, 1979, p. 390).

Conclusions

The Keyes Sandstone interval represented in Core 5 Low A exhibits a vertical zonation in petrophysical properties that can be related to depositional and diagenetic factors. Depositional environment (shallow marine shelf-offshore bar) influenced sorting and composition (clay content). The better-sorted, cleaner, upper part of the sequence exhibits the higher values of pore-throat size, porosity, and permeability. The higher clay content of much of the lower sequence resulted in a greater degree of compaction and a higher percentage of micropores (as opposed to intergranular and also secondary pores). The poorer sorting and greater degree of compaction and greater fraction of micropores resulted in lower values of pore-throat size, porosity, and permeability.

The zonation of petrophysical properties (particularly permeability) and the authigenic mineralogy present pose important considerations with regard to EOR efforts. Specifically of concern are: 1) the implication of a zone of preferential fluid flow, and 2) the potentially destructive effects of iron.

ACKNOWLEDGMENTS—Core 5 Low A is in the collection of the Kansas Geological Survey in Lawrence. This research was supported by the Tertiary Oil Recovery Project of the University of Kansas and the Kansas Geological Survey (Franz, 1984).

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Diagenesis of the Pennsylvanian Morrowan sandstone, Clark County, Kansas

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and
Lois M. Jones, Conoco Research Laboratory, Ponca City, Oklahoma

Introduction

Diagenetic processes exert major control on reservoir properties for the accumulation of economically recoverable hydrocarbons in coarse-grained siliciclastic rocks. Both reduction and increase of primary porosity may result from diagenetic processes. Although diagenetic increase in porosity is favorable to the accumulation of hydrocarbons, reduction in porosity may be desirable in some instances because the rock itself may serve as a trap for the hydrocarbon accumulation. Hydrocarbon exploration depends heavily on information from wireline geophysical logs. As diagenetically formed minerals in a reservoir affect both the physical and electrochemical properties of the rock, knowledge of the composition and distribution of diagenetic minerals is of major importance for a clear understanding of the geophysical data.

The purpose of this paper is to report the mineralogic composition, texture, and diagenetic history of the Pennsylvanian Morrowan sandstone from the Lexington oil field in Clark County, Kansas. The information can be of use in the exploitation of the Morrowan sandstone reservoirs and, in conjunction with wireline geophysical data, in the recognition of potential productive zones within the Morrowan sequence in other areas adjacent to the Lexington field. Samples analyzed in this study came from four cored wells in the Lexington field, Clark County, Kansas (fig. 1a and b).

Geologic setting

The sandstone of Morrowan Stage of the Pennsylvanian System occurs in the subsurface in Clark County and adjacent areas in Kansas. The overall thickness of Morrowan Stage rocks in the Clark County area ranges from 0 to about 150 ft. Rocks of the Morrowan Stage include sandstone and interbedded shale with minor amounts of conglomerate. The Morrowan rocks unconformably overlie the St. Louis Limestone of the Meramecian Stage and are unconformably overlain by rocks of the Atokan Stage (fig. 2). The Morrowan rocks generally are confined to paleotopographic lows on the underlying St. Louis Limestone. Following the interpretation by Mannhard and Bausch (1974), who studied the Morrowan rocks of the Harper Ranch field in Clark County, Kansas, the sandstone from the Lexington field is considered to have been deposited in a system of strike valleys developed on the truncated Mississippian strata and was related to northeastward marine transgression that was interrupted by several minor regressions.

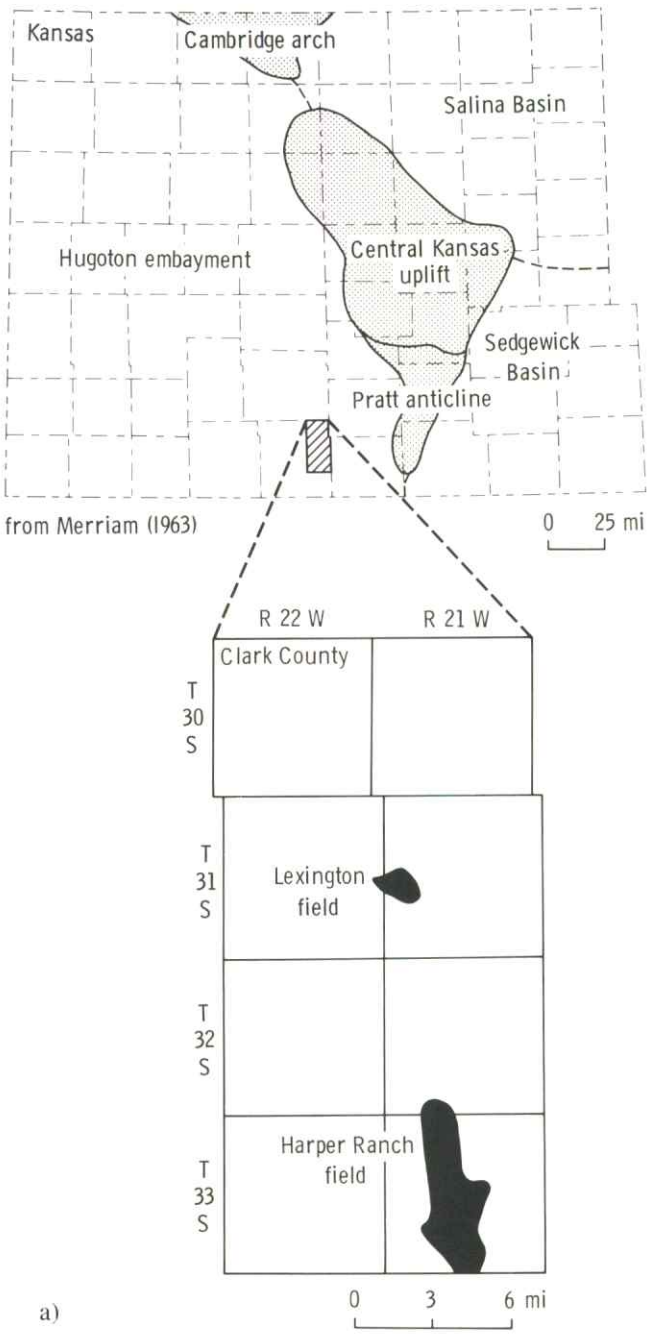


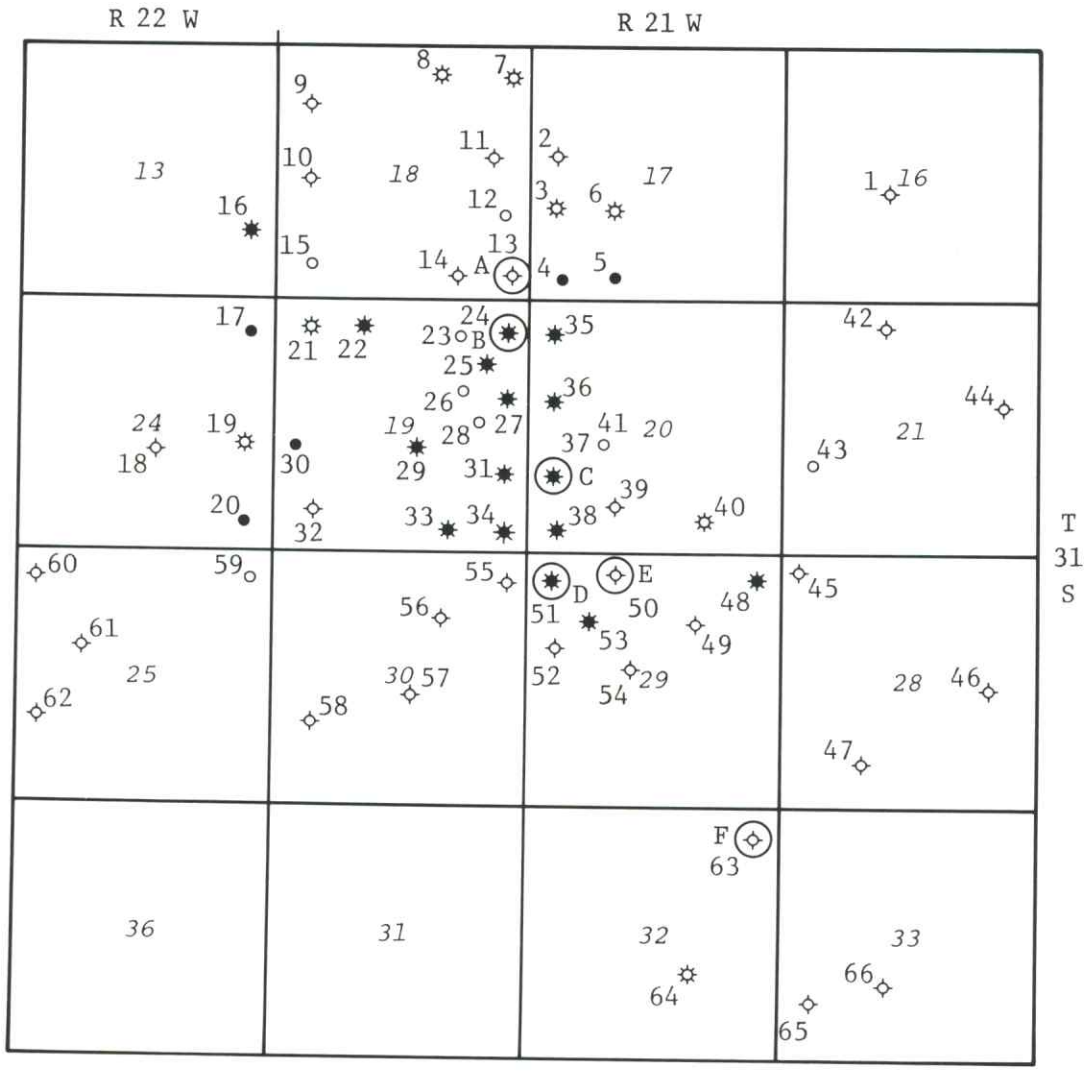
FIGURE 1—a) Location of Lexington field in relation to major pre-Desmoinesian post-Mississippian structural features of Kansas. b) Location of wells in the Lexington field area.

Petrography

Samples of the Morrowan sandstone and shale were taken from several stratigraphic intervals from four cored wells. The petrographic study included identification of constituent minerals, cements, and textures of the rocks. The grain size was determined by point count using 350 points per slide. At each point the smallest projecting diameter of the grain was measured. Roundness values of the grains were determined by comparison with roundness images proposed by Powers (1953). Sorting was determined using the Inclusive Standard Deviation as described in Folk and Ward (1957). Identification of clay minerals was based on x-ray diffraction data from different fractions of clays separated from shale and sandstone. Scanning electron microscopy was used to determine the distribution and morphology of different diagenetic minerals.

Framework grains

Morrowan Stage sandstone consists of 70–85% framework grains by volume. Quartz comprised over 90% of the



b)

framework minerals. Chert averaged 3%, whereas glauconite, orthoclase and plagioclase feldspar, and sedimentary rock fragments (shale clasts and carbonate rock fragments) averaged 1% or less of the total volume. Tourmaline, the predominant heavy mineral, occurred in trace amounts. Conglomeratic phases contained greater amounts of rock fragments, consisting of chert, carbonate rock fragments, and shale clasts.

Petrographic details of the Morrowan sandstone are given in tables 1 and 2. The median grain size ranged from 1.70 to 2.50 or medium to fine grained. Sorting averaged 0.60 0 or moderately well sorted. Quartz grains were rounded to subangular; the decrease in roundness was partially due to the effects of etching, replacement, and interpenetration that occurred during diagenesis.

Cements

The framework minerals are bonded together by ankerite, calcite, quartz, clay minerals, and pyrite, of which carbonate minerals and quartz are the most common. The proportion of quartz cements generally decreases with increasing amounts of carbonate cements.

SECONDARY QUARTZ—Interpenetration of quartz grains and secondary overgrowths are two forms of quartz cement of the sandstones (figs. 3 and 4). Many quartz grains show enlargements of secondary quartz that are in optical continuity with nucleus grain. Trace amounts of clay minerals coat the surface of the detrital quartz grains in some samples. Secondary overgrowths are an early diagenetic phenomenon. Pressure-solution effects that led to the for-

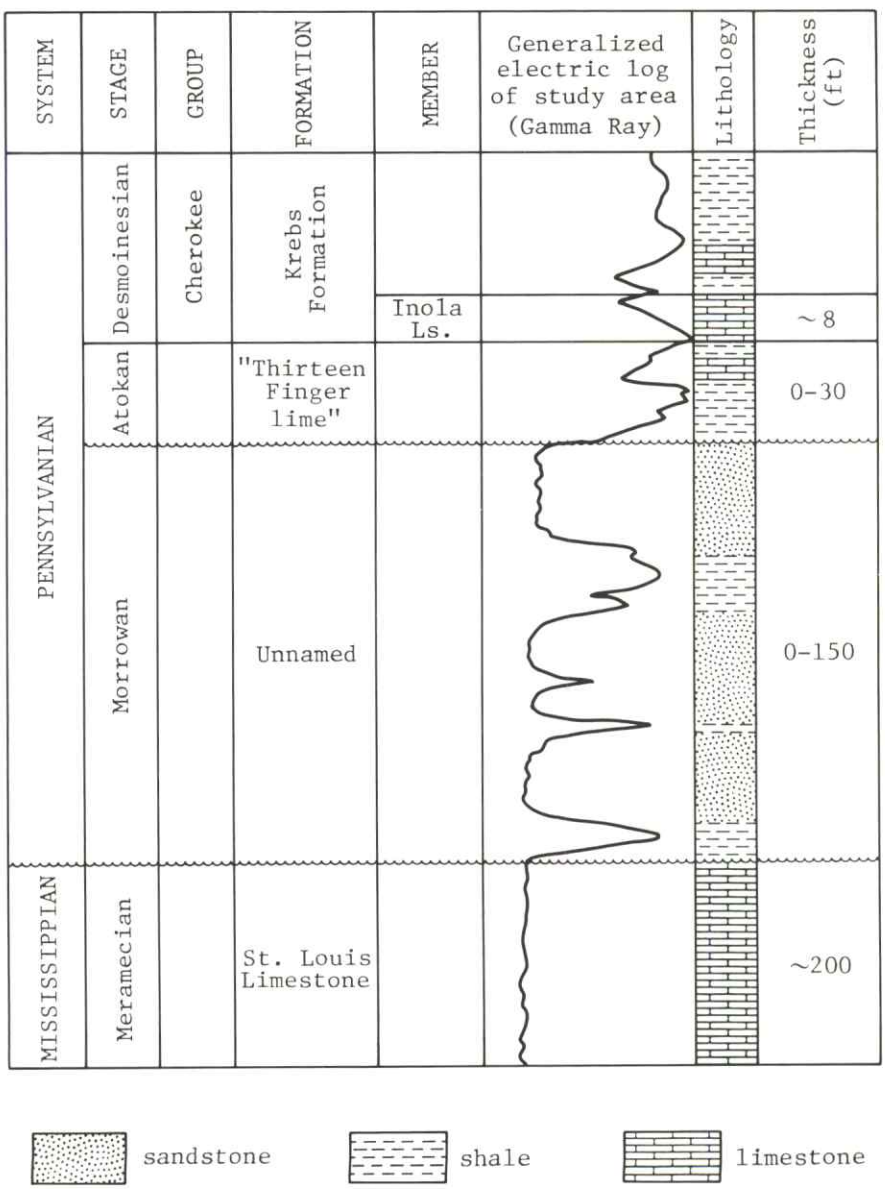


FIGURE 2—Stratigraphic column for the Lexington field, Clark County, Kansas (based on correlation from Zeller, 1968; type log for Clark County, Kansas).

mation of several concavo-convex boundaries among quartz grains destroyed features of earlier diagenetic events.

CARBONATE CEMENTS—Ankerite and less commonly calcite are the dominant types of carbonate cements. Ankerite was identified by x-ray diffraction scanning at ¼ degree per minute, indicating the (104) reflection at 2.90 0. The carbonate cements occur as discontinuous, irregular patches and lenses and as continuous groundmass of the quartz grains. Ankerite grains are commonly anhedral to subhedral but a few rhombohedral crystals of ankerite also occur. Carbonate minerals are the primary cement in nearly all sandstones comprising up to 32% of the total rock. In highly cemented rocks, the framework grains are almost completely separated from each other.

Two generations of carbonate cement occur, the earlier carbonate probably calcite and the later ankerite. The earlier cement seems to have been replaced by the ankerite leaving a "ghost" outine of the original grain (fig. 5).

CLAY MINERALS—Illite, randomly mixed-layer illite-smectite, and kaolinite are the major clay minerals in the Morrowan sandstone and shale. Both detrital and neoformed clay minerals occur in the sandstone. Detrital clay minerals occur as coatings on quartz grains and in some cases as a coating between the detrital quartz grain and the secondary overgrowth. Detrital clay minerals also occur as pore fillings between framework grains and the total is less than 1%. The majority of clay minerals are secondary in origin and kaolinite seems to be the dominant type among the neoformed clay minerals. Euhedral, hexagonal crystals of kaolinite often fill intergranular and secondarily enlarged pore spaces (fig. 6). Occasionally illite has grown over both kaolinite and quartz (fig. 7). Clay minerals in the sandstone account for less than 3% of the total rock.

The clay mineral composition of the sandstone is very similar to that of the interbedded shale. The composition of clay mineral is size dependent. Kaolinite is more abundant in the coarse fraction than in the fine fraction. For example, the 0.8–2.0 μm fraction of the clays consists of 54–84% of kaolinite, 13–38% of illite, 5–10% of randomly mixed-layer illite-smectite, and trace amounts of chlorite; whereas, the less than 0.2 μm fraction contains 55–79% of illite, 8–20% of randomly mixed-layer illite-smectite, and 12–35% of kaolinite.

PYRITE—Pyrite occurs as anhedral, irregular patches, and as cubic crystals. Pyrite seems to replace carbonate minerals and to occur also as pore-filling minerals. It is present in amounts of up to 2% of the total rock.

Porosity

Porosity of the sandstones, estimated from thin sections, ranged from 4% to 20%, with the low porosity sandstones having increased amounts of carbonate cement. In the sandstones with higher porosities (greater than 10%), porosity is predominantly secondary due to dissolution and replacement of carbonate minerals and framework grains.

Chemical and isotopic data

Carbonate cements from 16 core samples of Morrowan sandstone and two core samples of the St. Louis Limestone

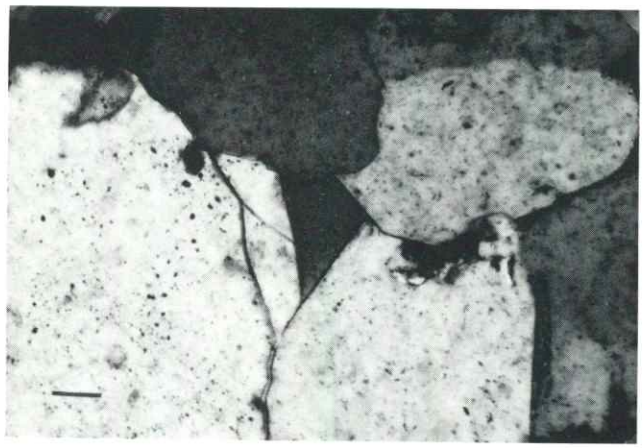


FIGURE 3—Photomicrograph of a Morrowan sandstone indicating pressure-solution effects on quartz grains.

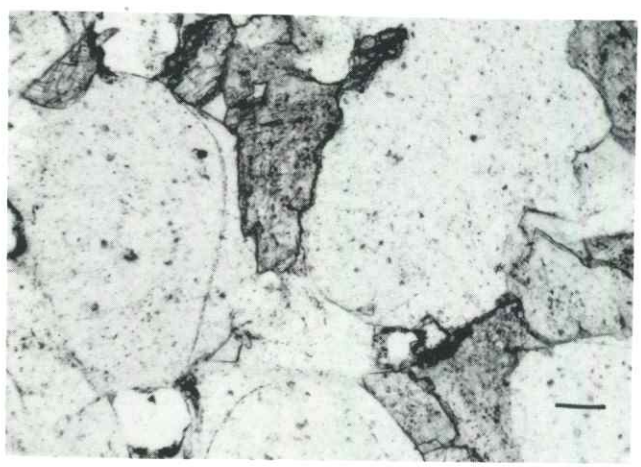


FIGURE 4—Photomicrograph of a Morrowan sandstone indicating quartz overgrowth on nucleus quartz grains; other grains are ankeritic cement.

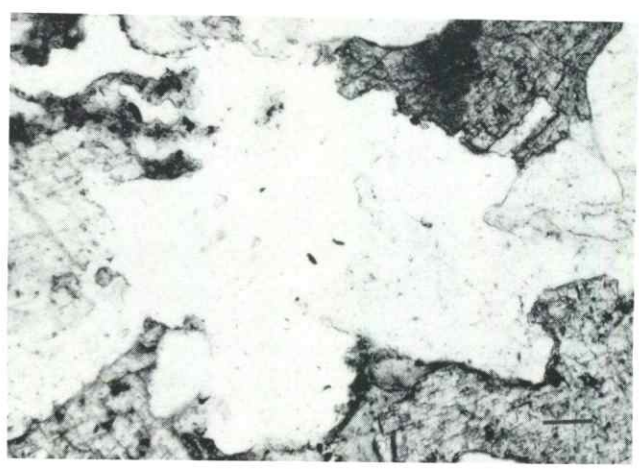


FIGURE 5—Photomicrograph of a Morrowan sandstone indicating "ghost" original carbonate cement (G) in a predominantly ankeritic cement.

TABLE 1—Grain-size analysis of Morrowan sandstone, Lexington field, Clark County, Kansas.

Sample		Grain size	Sorting	Roundness
Moore 2-20	5172 ft	1.89Ø	±0.65Ø	3.3
	5185 ft	2.33Ø	±0.52Ø	3.3
Moore 2-29	5134 ft	2.30Ø	±0.63Ø	3.1
	5151 ft	2.71Ø	±0.54Ø	3.1
Seacat 5-19	5245 ft	2.64Ø	±0.59Ø	3.0
	5257 ft	2.60Ø	±0.68Ø	3.0
McPhail 1-32	5172 ft	2.14Ø	±0.64Ø	3.3

TABLE 2—Point-count results of Morrowan-age sandstone, in percent by volume (Tr = trace amounts).

	Framework Grains						Cements					Pore Space
Sample	quartz	feldspar	chert	glauconite	shale clasts	total framework	clay minerals	carbonates	quartz cement	pyrite	total cement	
Moore 2-20												
5172 ft	71	Tr	4	Tr	Tr	75	3	4	Tr	Tr	7	18
5185 ft	61	1	2	Tr	Tr	63	1	32	Tr	Tr	33	4
Moore 2-29												
5134 ft	65	Tr	2	1	3	71	2	9	2	2	15	14
5151 ft	60	Tr	2	Tr	Tr	62	Tr	31	1	Tr	32	6
Seacat 5-19												
5245 ft	63	Tr	3	1	Tr	67	1	11	1	Tr	13	20
5257 ft	70	Tr	5	1	Tr	76	1	10	1	Tr	12	12
McPhail 1-32												
5172 ft	73	Tr	6	Tr	Tr	79	2	4	3	Tr	9	12

TABLE 3—Chemical analyses of carbonate cements of Morrowan sandstone and carbonate rock of St. Louis Limestone (in ppm).

Sample	Sr	Rb	Ca × 10^{-3}	Mg × 10^{-3}
		Carbonate cements		
Moore 2-20				
5161 ft	253	2.3	119	40
5172 ft	518	3.8	316	105
5180 ft	281	2.4	94	32
5185 ft	312	2.3	196	76
5195 ft	320	2.5	237	87
Moore 2-29				
5127 ft	369	2.6	152	52
5134 ft	320	2.4	172	58
5135 ft	269	2.0	136	34
5141 ft	371	3.0	151	53
Seacat 5-19				
5232 ft	287	2.5	389	102
5239 ft	321	2.8	182	62
5245 ft	352	2.8	201	69
5251 ft	281	2.7	160	56
5257 ft	239	1.8	208	66
McPhail 1-32				
5166 ft	547	4.8	294	2

TABLE 4—Strontium isotopic data of carbonate cements from Morrowan-age sandstone, St. Louis Limestone carbonate rocks and oil-field waters, from the Lexington field, Clark County, Kansas.

Sample	1/Sr, ppm^{-1}	$^{87}Sr/^{86}Sr$
	Carbonate cements of Morrowan-age sandstone	
Moore 2-20		
5161 ft	0.004	0.70871 ± 0.00010
5172 ft	0.002	0.70904 ± 0.00012
5180 ft	0.004	0.70916 ± 0.00009
5191 ft	0.003	0.70865 ± 0.00005
Moore 2-29		
5127 ft	0.003	0.70874 ± 0.00003
5135 ft	0.003	0.70877 ± 0.00002
5141 ft	0.003	0.70883 ± 0.00006
5151 ft	0.003	0.70890 ± 0.0005
Seacat 5-19		
5232 ft	0.004	0.70871 ± 0.0004
5239 ft	0.003	0.70860 ± 0.0002
5245 ft	0.003	0.70870 ± 0.0005
5251 ft	0.004	0.70841 ± 0.00003
McPhail 1-32		
5166 ft	0.002	0.70923 ± 0.00015
	St. Louis Limestone carbonate rocks	
Moore 2-29		
5155 ft	0.003	0.70856 ± 0.0004
5158 ft	0.002	0.70822 ± 0.0011

were analyzed for their Ca, Mg, Sr, and Rb contents. Atomic-absorption spectroscopy methods were used for the determination of Ca, Mg, and Sr using the method of standard addition. Solutions were analyzed using a Perkin–Elmer 305B Atomic Absorption Spectrophotometer. The instrumental parameters used for the listed elements are those recommended by Perkin–Elmer Corporation. Replicate analyses of some samples indicated maximum error of about 5% for each of the above elements.

Ca contents ranged from 9.4 to 38.9% and Mg contents from 0.2 to 10.5%. Sr contents were between 329 and 547 ppm, and Rb contents were between 1.3 and 5.3 ppm. The molar Sr/Ca ratios of the carbonate cements ranged between 1.61×10^{-3} and 6.85×10^{-3}. The chemical data of the carbonates are given in table 3.

Measured $^{87}Sr/^{86}Sr$ ratios for carbonate cements are indicated in table 4. The isotopic ratio measured for the Eimer and Amend $SrCO_3$ standard was 0.70804. The Rb/Sr ratios of the cements, ranging between 7×10^{-3} and 9×10^{-3}, indicate that the Sr isotopic ratios of the carbonate cements remained essentially unchanged from the decay of ^{87}Rb to ^{87}Sr. In samples of the Moore 2–20 core of the Morrowan sandstone, the Sr isotopic ratios of the carbonate cements ranged from 0.70865 to 0.70904. In the Moore 2–29 core, the Sr isotopic ratios of the carbonate cements had values between 0.70874 and 0.70890. In the Seacat 5–19 core, the cements had $^{87}Sr/^{86}Sr$ ratios ranging from 0.70841 and 0.70871. An analysis of a single sample from 1–32 McPhail core indicated the Sr isotopic ratio of 0.70923. In contrast, two samples of the Mississippian St. Louis Limestone had Sr isotopic ratios of 0.70822 and 0.70856. The $^{87}Sr/^{86}Sr$ ratios of the carbonate cements from sandstones of Morrowan age are plotted against depth in fig. 8. This figure illustrates that the isotopic data vary randomly in a vertical direction.

Discussion

Diagenetic sequence and probable time of hydrocarbon accumulation

The earliest diagenetic event in the cementation history of the sandstone of the Morrowan Stage was the formation of quartz overgrowths on quartz grains. This initial overgrowth probably was due to a lowering of the pH of the pore waters, possibly arising from oxidation of organic material at shallow depth. Compaction of sediments led to further reduction in porosity as is evident from the pressure-solution effects on quartz grains that resulted in the formation of several concavo-convex boundaries among neighboring quartz grains. With continued burial, quartz became unstable and was partly replaced by calcite. Upon deeper burial the increase in temperature could have caused the solubility of silica to increase. The temperature increase also can bring about precipitation of $CaCO_3$, provided that the partial pressure of CO_2 for the water remained constant and that the water composition is near that of $CaCO_3$ saturation (Siever, 1959). Following the deep burial and replacement of quartz by the calcite cement, a change in the hydrodynamic system must have occurred that led to the ankeritization of the previously formed calcite creating secondary porosity in the rock. Because "ghost" outline of original carbonate grain can be occasionally found in the ankeritic cements (fig. 5), the conservation of volume during ankeritization must have been nearly maintained. The dolomitization reaction without any volume change may be described as:

$$(2 - x)CaCO_3 + 0.8\ Mg^{2+} + 0.2\ Fe^{2+} + xCO_3^{2-} = CaMg_{0.8}Fe_{0.2}(CO_3)_2 + (1 - x)Ca^{2+}$$

where x is approximately equal to 0.25.

The dissolution of the ankeritic cement is the most important diagenetic event that created secondary porosity in the Morrowan sandstone. The creation of these secondary pores is a possible indication of introduction of acidic waters into the Morrowan sandstone. Data are insufficient to confidently establish whether or not the acidic water was introduced when the rocks were exposed to near-subaerial condition or when the rocks were deeply buried. Lack of evidence for any erosional unconformity at the top of the Morrowan sandstone suggests that subaerial condition was not an important factor for the introduction of acidic water. The reduction of pH of pore fluid under deep burial could have resulted either from introduction of acidic water expelled possibly from compacted mudstone interbedded with the sandstone units or from introduction of CO_2 from potential hydrocarbon source beds at depth prior to the hydrocarbon maturation.

The major diagenetic changes following the ankeritization are possibly concatenate events relating to the hydrocarbon accumulation in the Morrowan sandstone. These post-ankeritization diagenetic events include partial dissolution of the ankeritic cements and occlusion of the resultant secondary porosity primarily by deposition of kaolinite and, to a much less degree, by precipitation of illite, mixed-layer illite-smectite, and pyrite. One possible mechanism by which dissolution of the ankeritic cements could have occurred was introduction of CO_2 in the pore fluid of the Morrowan sandstone. Considerable amount of CO_2 is generated from degradation of organic matter in source beds before peak oil generation (Moper, 1972). The CO_2 generated in source beds will remain dissolved in the oil more than in the water until pathways become available for migration of the fluid from the source beds. The pressure decrease attendant with migration will facilitate release of some of the dissolved CO_2 from the fluid to a separate gas phase, which will migrate ahead of the hydrocarbons and waters. In this scenario, the dissolution of the ankeritic cements of the Morrowan sandstone can be explained by the introduction of exsolved CO_2 from potential hydrocarbon source beds to the pore fluids of the Morrowan sandstone.

Following the creation of the secondary porosity, precipitation of kaolinite became the major diagenetic reaction. Formation of kaolinite is favored in a slightly acid pH solution with low alkali/H^+ ratio. The formation of kaolinite can be described as:

$$2Al^{3+} + 2H_4SiO_4 + H_2O = Al_2Si_2O_5(OH)_4 + 6H^+$$

A possible source for the dissolved alumina and silica could be the CO_2-rich fluids that entered the Morrowan sandstone prior to the arrival of the hydrocarbons. Alternatively, the pore water was high in Al/Si before CO_2-rich fluid entered the Morrowan sandstone. Although the introduction of CO_2 caused the water to become slightly acidic, kaolinite precipitation did not occur possibly because of chemical kinetics. Attempts of synthesis of kaolinite from gel or amorphous material at low temperature have encountered considerable difficulties, yet successful syntheses have been made in the presence of organic compounds (Linares and Huertas, 1971; Hem and Lind, 1974). The formation of kaolinite in the Morrowan sandstone may have been similarly catalyzed by the presence of organic compounds that entered the pore system subsequent to the introduction of CO_2 in the pore fluid.

Additional reduction in the porosity occurred as a result of formation of small amounts of illite and mixed-layer illite-smectite. The growth of these minerals may be related to somewhat higher pH and higher alkali to hydrogen-ion activity ratio than that for kaolinite.

Pyrite was the last diagenetic mineral of the reservoir rock. Either bacterial reduction of sulfate in the pore water or introduction of H_2O into the pore water before peak migration of hydrocarbon or both could have provided the needed sulfur species for the formation of pyrite. The iron in the pyrite could have come from either anaerobic bacterial reduction of hydrated iron oxides that may have been associated with the Morrowan sandstone or dissolution of the ankeritic cement. The overall reactions for the pyrite formation can be expressed as:

$$2CH_2O + SO_4^{2-} = HCO_3^- + HS^- + 6H^+$$

$$CH_2O + 4FeO.OH + H_2O = 4Fe^{2+} + HCO_3^- + 7OH^-$$

$$Fe^{2+} + H_2S_{aq} = FeS_2 + 4H^+ + 2e$$

$$Fe^{2+} + 2HS^- = FeS_2 + 2H^+ + 2e$$

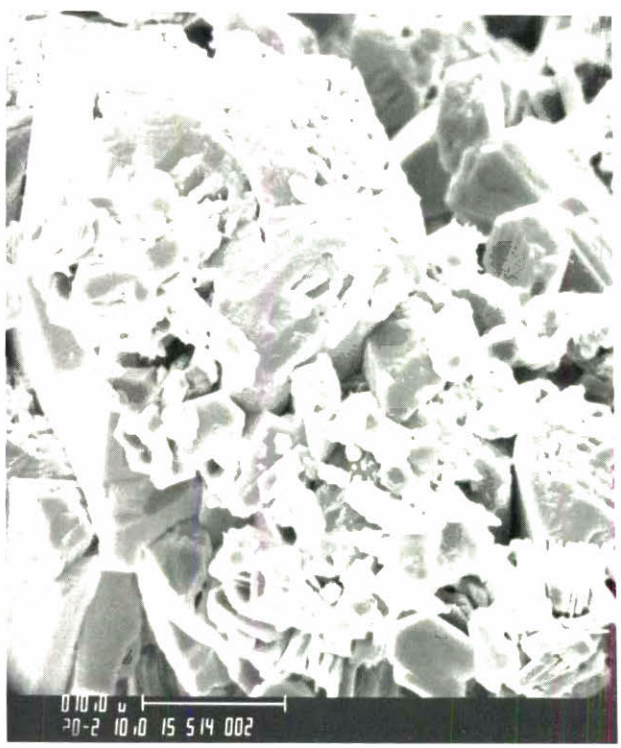


FIGURE 6—Scanning-electron microscope photograph of a Morrowan sandstone illustrating kaolinite filling a cavity in leached ankerite rhomb.

The carbonate cement-clay mineral-pyrite relationship in the Morrowan sandstone indicates that major diagenetic processes continued at least through the formations of illite, mixed-layer illite-smectite, and pyrite. As the inorganic reactions become minimal after accumulation of large quantities of hydrocarbon in the reservoir, the time of hydrocarbon accumulation must post-date the period of formation of the last major diagenetic minerals. In the case of the Morrowan sandstone, the formation of clay mineral assemblage of kaolinite, illite, and mixed-layer illite-smectite is the last major diagenetic event. Therefore, the accumulation of petroleum in the Morrowan sandstone occurred after the formation of these clay minerals. The peak accumulation could have possibly happened shortly after the formation of much of the pyrite.

Foscolos and Kodama (1974) summarized several commonly occurring mineralogic features of clay diagenesis. They noted that discrete expandable clays do not commonly occur below a burial depth of about 3,000 ft and that kaolinite often disappears below 9,000 ft. Furthermore, mixed-layer illite-smectite clays commonly persist at depths between 3,000 and 12,000 ft. Considering that kaolinite is the very abundant clay mineral and that mixed-layer illite-smectite is a common clay mineral in sandstone and interbedded shale of the Morrowan sequence, the burial of the sequence was probably no deeper than about 9,000 ft.

Sr/Ca ratios of cements and possible origin of dolomitizing fluids

Information on the Sr/Ca ratio of the carbonate minerals as cements for the Morrowan sandstone is very useful in determining the chemical history of the fluid that was involved in the precipitation of the cement. The molar Sr/Ca ratio of the liquid in equilibrium with dolomite is dependent on the molar Sr/Ca ratio of the initial fluid, the molar Sr/Ca ratio of the replaced carbonate mineral (calcite or aragonite), and the distribution coefficient of Sr between the dolomite and the associated liquid. Sass and Starinsky (1979) demonstrated quantitatively that during advanced dolomitization the Sr/Ca ratio in solution approaches a limiting value which is determined by the Sr/Ca ratio of the replaced carbonate and that the limiting value is about twice that of the replaced carbonate, because of the very low value of the distribution coefficient of Sr. Veizer (1983) recently discussed the uncertainties of the value of the distribution coefficient of Sr between dolomite and liquid. The recommended values range between 0.025 and 0.07. The distribution coefficient of Sr for iron-rich dolomite (ankerite) can be expected to be slightly higher than the proposed range of values for common dolomite.

FIGURE 7—Scanning-electron microscope photograph showing slight etching of well-crystallized kaolinite and growth of illite bridging kaolinite and quartz.

From consideration of the proposed range of values of the distribution coefficient of Sr between dolomite and liquid, the molar Sr/Ca ratios of the liquids in equilibrium with dolomitic (ankeritic) cements of the Morrowan sandstone was probably between 5.3×10^{-3} and 54.8×10^{-3}. These Sr/Ca ratios of the liquids in equilibrium with the dolomite cements were undoubtedly controlled by the Sr/Ca ratios of the initial liquids that caused dolomitization and the Sr/Ca ratio of the replaced carbonate mineral. General information can be obtained concerning possible source of the initial fluid that was involved in the dolomitization process, provided the molar Sr/Ca ratio of the replaced carbonate mineral is known. The precursor of dolomite cement of the Morrowan sandstone is considered to be calcite, because of the occasional presence of "ghost" calcite (?) in the dolomite cement and presence of calcite cement found in a nonproductive unit of Morrowan sandstone from the same locality as that of the productive unit. The molar Sr/Ca ratio of the calcite cement was found to be 0.8×10^{-3}, which is well within the range of 0.19×10^{-3} to 0.8×10^{-3} for commonly occuring natural calcite in sedimentary carbonate rocks (Sass and Starinsky, 1979). If the Sr/Ca molar ratio of the initial liquid was close to that of average sea water (8.6×10^{-3}) and the dolomitization of the Morrowan calcite cement occurred in presence of limited amount of the liquid, that is the low liquid to solid ratio, then the molar Sr/Ca ratio of the liquid that was in equilibrium with the dolomite might have attained a value of 1.6×10^{-3}, which is twice the molar Sr/Ca ratio of the original calcite in the Morrowan sandstone. However, the molar Sr/Ca ratio of the liquid in equilibrium with dolomite would increasingly become closer to that of the original dolomitizing liquid with increasing liquid to solid ratio. From the Sr/Ca values of the dolomite cements of the Morrowan sandstone, and taking into account Veizer's (1983) recommended values of the distribution coefficient of Sr between dolomite and associated liquid, the calculated molar Sr/Ca ratios of the liquids in equilibrium with the dolomite were found to be between 5.3×10^{-3} and 54.8×10^{-3}. Such high Sr/Ca ratios for presumed liquids in equilibrium with dolomite could not have been derived from the original calcite mineral with molar Sr/Ca ratio of about $0.8\triangle \times 10^{-3}$. The high ratios then must be a reflection of the molar Sr/Ca ratios of the original liquid that caused dolomitization of previously formed calcite cement of the Morrowan sandstone. Although some of the liquids in equilibrium with the dolomite cements had molar Sr/Ca ratios less than that of the average sea water with a

value of about 8.6×10^{-3}, many had molar Sr/Ca ratios that were considerably higher than that of the average sea water. The dolomitizing liquids with ratios as high as 54.8×10^{-3} is a minimum estimate of the molar Sr/Ca ratio of the original liquid, because of the reactions of the original liquid with low Sr/Ca ratio-bearing calcite. Possible natural liquids that could have such high molar Sr/Ca ratios include highly evaporated sea-water brine and liquid that was once involved in recrystallization of aragonite to calcite. Thus, in view of the very high molar Sr/Ca ratio needed for the initial liquid, cementation of the Morrowan sandstone was probably caused by a liquid that was either a highly evaporated sea-water brine or previously involved in recrystallization of aragonite to calcite.

A sample of sandstone (McPhail 1–32, 5172) from a nonproductive bed had nearly pure calcite cement. The molar Sr/Ca ratio of the cement was found to be 0.85×10^{-3}. Assuming a distribution coefficient of 0.058 for the Sr between calcite and liquid (Katz and others, 1972; Veizer, 1983), the molar Sr/Ca ratios of the liquid that precipitated the calcite probably had a molar Sr/Ca ratio of about 14.7×10^{-3}, which is higher than that of the average sea water. The high molar Sr/Ca ratio of the pore fluid during calcite cementation of the Morrowan sandstone suggests that at least some fraction of the pore water prior to calcite cementation was either linked to evaporation of sea water or involved in the recrystallization of aragonite to calcite.

Varied Sr/Ca ratios of the carbonate cements provide some clues as to the physical condition that governed the cementation of the Morrowan sandstone. The variation in the molar Sr/Ca ratios of the calcium-carbonate cements probably reflects that the carbonate cementation of the Morrowan sandstone proceeded progressively with varied Sr/Ca ratios of the pore fluids. Changes in the chemical character of the pore fluids are related to several pulses of fluids that were introduced into the reservoir during the formation of early carbonate cements.

Sr isotopic data and possible sources of Sr in carbonate cements

The $^{87}Sr/^{86}Sr$ ratio of calcite cement from one sample (McPhail 1–32 5166) of the Morrowan sandstone was found to be 0.70923. The calcite cement seems to be the earliest among the carbonate cements. The Sr isotopic composition of the calcite cement is nearly identical to that of contemporaneous Morrowan sea water, the value of which has been given by Peterman and others (1970). The source of the Sr for this early carbonate phase, therefore, could have been the contemporary sea water Sr.

The $^{87}Sr/^{86}Sr$ ratios of the ankeritic carbonate cements ranged between 0.70841 and 0.70904. The Sr isotopic composition of the ankerite cements is distinctly different from that of the contemporary sea water. Therefore, the fluids that produced ankeritization must have derived Sr, at least in part, from a source that had $^{87}Sr/^{86}Sr$ ratio as low as 0.70841 or lower. This ratio is well within the range of

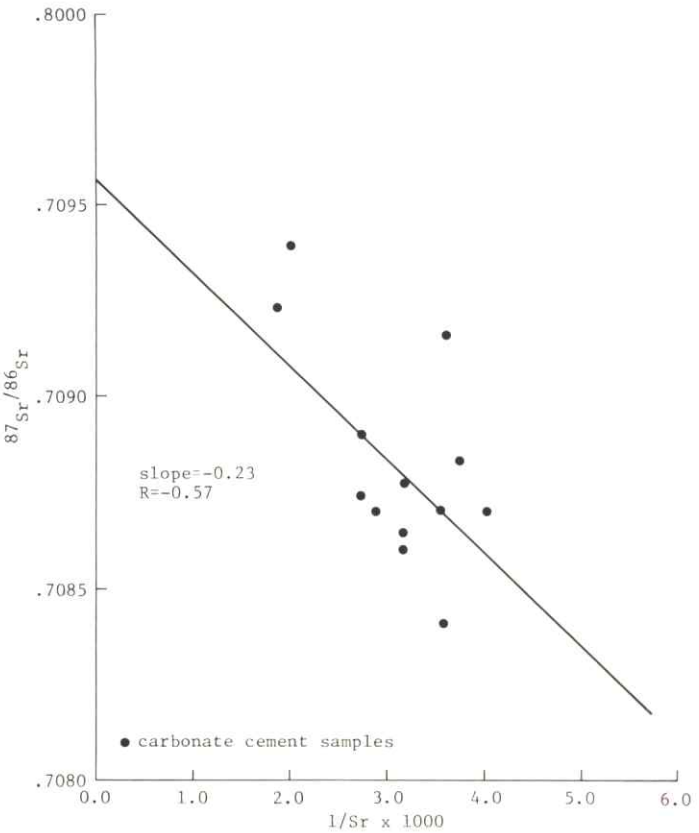


FIGURE 8—$^{87}Sr/^{86}Sr$ ratio vs. 1/Sr for the carbonate cements of the Morrowan-age sandstone of the Lexington field.

value for Paleozoic marine-carbonate rocks and hence a marine source for the Sr is very likely. Although the rock or rocks from which the Sr was derived could not be positively identified, the similarity in the Sr isotopic composition between the ankeritic cement with the lowest $^{87}Sr/^{86}Sr$ ratio and the limestone and dolomite of the underlying Mississippian St. Louis Limestone makes these older rocks a possible source of Sr for the dolomitizing fluids of the carbonate cement of the Morrowan sandstone.

The Sr isotopic composition of the ankeritic cements is varied. To determine whether or not the observed Sr isotopic variation of the carbonate cements could be explained by mixing Sr of two isotopically different sources, the $^{87}Sr/^{86}SR$ ratios of the cements were plotted against their corresponding 1/Sr values (fig. 8). The two sets of data are only very roughly linear ($r = -0.57$); hence, the trend is clearly suggestive of the existence of a chemical history of the cements that is more complex than derivation of Sr from two separate sources. The complex isotopic distribution is further illustrated in the vertical distribution of the Sr isotopic composition of the carbonate cements (fig. 9). As noted in the diagram, the isotopic differences can exist even among samples that are separated vertically by less than a meter. The observed vertical distribution of the Sr isotopic data indicates that diagenetic reactions that produced ankeritic cements probably proceeded in several discrete stages with randomly varied Sr isotopic composition of the pore fluids or of the replaced carbonate minerals.

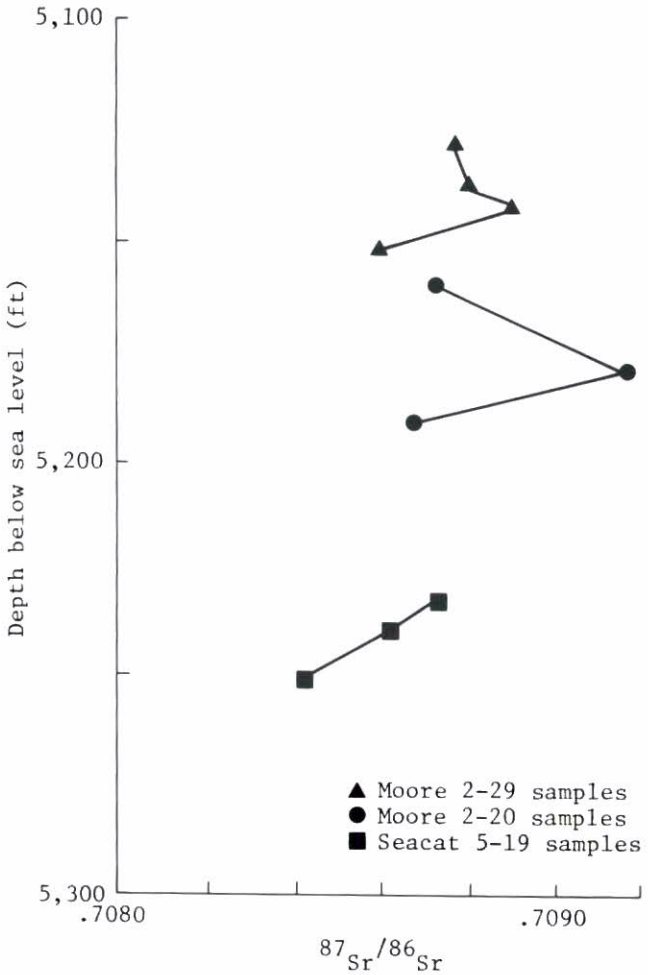


FIGURE 9—Relationship between depth of Morrowan sandstone sample and Sr isotopic ratio of carbonate cement of Morrowan sandstone, Lexington field, Clark County, Kansas.

ACKNOWLEDGMENTS—Core samples were obtained from the collection of Mesa Petroleum Company. This work was supported, in part, by National Science Foundation grant EAR-8019599.

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Stratigraphy of the Cherokee Group, southeastern Kansas

by *John W. Harris,* Kansas Geological Survey, Lawrence, Kansas

Abstract

The Cherokee Group of southeastern Kansas consists of interbedded shale, sandstone, coals, and thin limestone beds that were deposited in a variety of marginal-marine environments. The discontinuous nature of reservoir sandstones, patchy distribution of subsurface control, and problems in surface correlation of coal beds and other associated units make regional stratigraphic studies difficult. Descriptions of 24 continuous cores of the Cherokee Group from Cherokee and Crawford counties, Kansas, resulted in a detailed stratigraphic model that may be extended farther into the subsurface or to the outcrop belt. Several thin, unnamed, but laterally persistent coal beds were encountered. These coal beds and overlying radioactive shales are the most persistent units, are easily identified on gamma-ray/neutron-well logs, and thus may be used as subsurface stratigraphic marker beds.

Introduction

The Cherokee Group (Desmoinesian Stage, Middle Pennsylvanian Series) consists of interbedded sandstones, shales, coals, and thin lenticular limestones that represent the oldest deposits of Pennsylvanian age in eastern Kansas. Sandstones of the Cherokee Group are important reservoir rocks, and over a half billion barrels of oil have been produced mainly from stratigraphic traps (Ebanks and James, 1974). In addition, over 200 million tons of coal have been mined and over 285 million tons of demonstrated coal reserves have been identified within the Cherokee Group (Brady, Livingston, and Adams, 1974). The complex stratigraphy of the Cherokee Group results from deposition in marginal-marine and shallow-marine environments, and several previous workers have encountered difficulties with correlation of stratigraphic units (Pierce and Courtier, 1937; Moore, 1950; Howe, 1956; Searight and Howe, 1961; and Ebanks, James, and Livingston, 1977). The continuous cores used in this study allow correlation of thin units and permit the development of a detailed subsurface stratigraphic model.

The area of stratigraphic evaluation extends from the outcrop belt of the Cherokee Group, northwestward into the subsurface, and both outcrop and subsurface data were used in this study. A total of 24 continuous cores from Cherokee and Crawford counties, Kansas, formed the foundation for detailed stratigraphic correlations. The cores are "BX" cores, 1⅝ inches in diameter, and extend from bedrock to the top of the Mississippian limestone, providing continuous sections of the Cherokee Group. Twenty-two cores were donated to the Kansas Geological Survey by Gulf Mineral Resources Company, and two additional cores were provided by the U.S. Office of Surface Mining (OSM). Initial descriptions of these cores were completed at a scale of 1 inch equals 1 ft (8 cm = 1 m) using a checklist to ensure adequate detail and uniformity in the descriptions. A rock color chart (Goddard and others, 1963) was used to determine colors of dry samples of fine-grained rocks. Cores are stored and detailed descriptions are on file in the mineral resources section at the Kansas Geological Survey in Lawrence.

Geologic setting

The Cherokee Basin or shelf, including most of the study area, is an elongate extension of the northeast Oklahoma platform. The Cherokee Basin is bounded by the Nemaha ridge on the west, the Ozark uplift on the east, and is separated from the Forest City Basin to the north by the Bourbon arch, a small positive structural feature (Cole, 1969). Rocks of the Cherokee Group were deposited disconformably over a karst surface developed on Mississippian limestones in southeastern Kansas, southwestern Missouri, and northeastern Oklahoma. The upper contact of the Cherokee Group is the base of the Fort Scott Limestone Member of the Marmaton Group (Jewett, O'Connor, and Zeller, 1968). Thickness of the Cherokee Group ranges from less than 300 ft (90 m) in eastern Kansas to over 9,000 ft (2,750 m) in the Arkoma Basin near McAlester, Oklahoma (Oakes, 1953). The outcrop belt of the Cherokee Group in the study area is 12–20 mi (20–32 km) wide, trending northeast-southwest through western Missouri, southeastern Kansas, and eastern Oklahoma. Regional dip may vary locally due to minor structures or differential compaction but averages about 20–30 ft/mi (4–6 m/km) to the west-northwest (Ebanks, James, and Livingston, 1977). Strata of the Cherokee Group were deposited during a major transgressive phase containing minor progradational or regressive pulses. This is evidenced by the successive onlap of younger strata on to positive structural elements as well as the transition from predominantly terrigenous sediments at the base of the Desmoinesian Stage to carbonates at the top (Visher, Saitta, and Phares, 1971; Frezon and Dixon, 1975).

Stratigraphy

The Cherokee Group was named for exposures in Cherokee County, Kansas, and includes all rocks above the Mississippian limestone and below the Fort Scott Limestone formation. Formal stratigraphic nomenclature of the Cherokee Group in Kansas is summarized in fig. 1, which is a composite section resulting from observations made on 24 continuous cores used in this study. Coal beds and associated rock units described from these cores were named in accordance with the established stratigraphic nomenclature of Jewett, O'Connor, and Zeller (1968) to avoid confusion and addition of new names with the exception of several unnamed coal beds. The contact between the Krebs Formation and the Cabaniss Formation

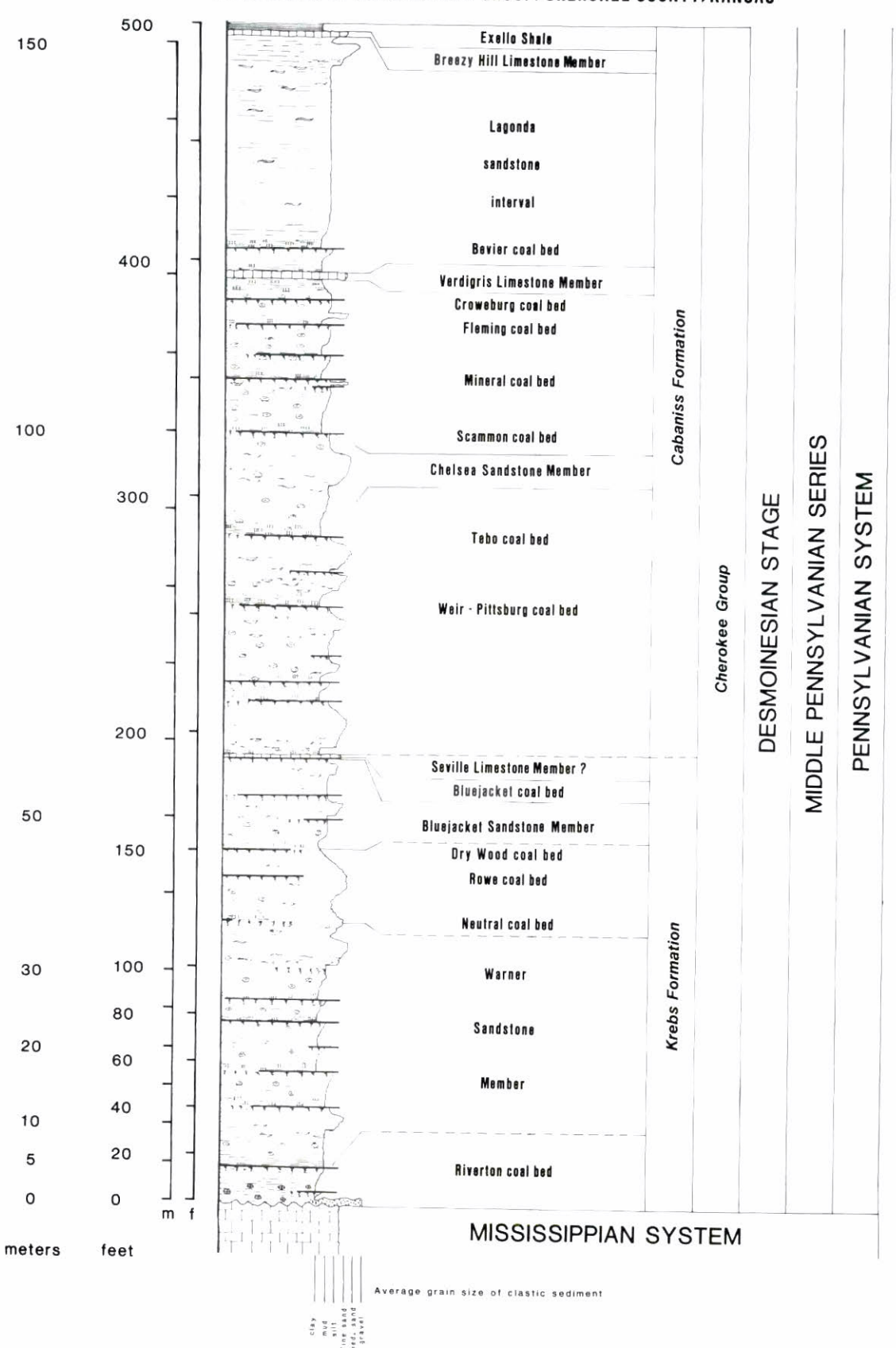

FIGURE 1—Composite section of the Cherokee Group resulting from description of 24 continuous cores in Cherokee and Crawford counties, Kansas.

in southeastern Kansas and southwestern Missouri is placed at the top of a thin but widespread argillaceous limestone unit (the Seville Limestone Member). Paleontologic evidence indicates that a significant time-stratigraphic break may exist between the Seville Limestone and overlying units (Howe, 1956). The Seville Limestone, or a limestone at about that stratigraphic position, is present in the cores examined, but this limestone is not easily traceable in the subsurface. Lateral continuity of the thin coal beds has been demonstrated through correlation between numerous surface and underground mines as well as within the cores examined in this study. Coal beds less than 1 ft (30 cm) thick commonly have an areal extent of tens of square miles, and in some cases, hundreds of square miles (Howe, 1956; Wanless, Baroffio, and Trescott, 1969; and Wright, 1975). Therefore, coal beds, associated seatrock horizons, and overlying dark-gray shales are the stratigraphic markers used in this study.

The longest continuous core used in this study, P & M # 20 (SENENE sec. 8, T. 32 S., R. 22 E.), starts in the Breezy Hill Limestone Member and extends to the top of the Mississippian limestone. This core is 486 ft (148 m) long and has 100% core recovery. The shortest core used in this study, OSM CH-1 (SW sec. 27, T. 31 S., R. 24 E.), started approximately 30 ft (9 m) above the Weir–Pittsburg coal bed, extends to about 8 ft (2.5 m) below the Neutral coal bed, and is 152 ft (46 m) long with 98% core recovery. The core displayed at this workshop, P & M # 4 (SWNWSW sec. 29, T. 32 S., R. 22 E.), has its top just above the Verdigris Limestone Member and extends to the top of the Mississippian limestone. This core is 411 ft (125 m) long with 96% core recovery. Two core descriptions that summarize the correlations and lateral variability observed in the cores are presented in figs. 2 and 3. Fig. 2 is a map showing the locations of cores and gamma-ray/neutron-well logs used for stratigraphic correlations in this study. Fig. 3 shows the stratigraphic relationships between P & M # 4 and JSC # 7 (NESENE sec. 30, T. 30 S., R. 25 E.). These cores are 22 mi (35 km) apart and the stratigraphic section observed in JSC # 7, near the Bourbon arch, is 50 ft (15 m) thinner than the section observed in P & M # 4. Most of the coal beds and other stratigraphic markers are present and are traceable in the subsurface for at least 22 mi (35 km) along the strike.

Stratigraphic relations in cores

The Riverton coal bed usually is the first well-developed coal bed above the Mississippian limestone surface. The Riverton is characterized by a thin but persistent clay parting just above the base of the coal bed. Above the Riverton coal bed and below the Neutral coal bed are four unnamed but laterally persistent coal beds (figs. 1 and 3). These coal beds range in thickness from 1.7 ft (52 cm) to a feather edge. The interval separating the lower two unnamed coal beds is quite variable in thickness, possibly because of a greater degree of localized solution and subsidence in the Mississippian limestones. The upper two of these unnamed coal beds generally are separated by 8–10 ft (2.4–3.0 m) of dark-gray or lenticularly bedded shale and seatrock. This couplet of unnamed coal beds is easily traceable in the subsurface and both coal beds have been used as stratigraphic markers in this study. The Warner Sandstone Member also occurs above the Riverton coal bed and below the Rowe coal bed (Jewett, O'Connor, and Zeller, 1968). At least three sandstone bodies, which may show either coarsening-upwards or fining-upwards sequences, are present in this interval. These various sandstone bodies have been referred to as the lower and upper Warner sandstones (Ebanks, James, and Livingston, 1977).

The Neutral, Rowe, and Dry Wood coal beds are present above the Warner sandstone interval. The Neutral coal bed is erratic in distribution and often is represented in these cores by a seatrock horizon and overlying dark-gray shale in the appropriate stratigraphic position (figs. 1 and 3). The Rowe coal bed occurs about 20 ft (6 m) above the Neutral coal horizon and the Dry Wood coal bed is present about 15–20 ft (4.5–6 m) above the Rowe. The Dry Wood coal bed (and an overlying radioactive shale) are important stratigraphic marker beds used in this study.

Above the Dry Wood coal bed are four thin but laterally persistent coal beds. Overlying the second unnamed coal bed above the Dry Wood is an argillaceous limestone about 1 ft (30 cm) thick that is here considered to be the Seville Limestone Member (Jewett, O'Connor, and Zeller, 1968; figs. 1 and 3). The third unnamed coal bed above the Dry Wood coal bed is commonly overlain by a radioactive shale and has been used as a stratigraphic marker in this study. Several sandstones (with both coarsening- and fining-upwards sequences) encountered in this stratigraphic interval have been called informally the lower and upper Bluejacket sandstones (Ebanks, James, and Livingston, 1977).

The Weir–Pittsburg coal bed occurs 60–70 ft above the Seville Limestone Member. The Weir–Pittsburg coal bed is economically the most important coal bed in the Cherokee Group, and two cores used in this study encountered voids due to underground mining of this coal bed. The Tebo coal bed occurs about 35 ft (10 m) above the Weir–Pittsburg coal bed. A split ranging up to 12 ft (3.5 m) is commonly observed in the Tebo coal bed. The Chelsea Sandstone Member is found between the Tebo coal bed and the Scammon coal bed. The Chelsea Sandstone generally consists of a coarsening-upwards sequence of wavy-bedded siltstone or flaser-bedded sandstone. Above the Chelsea Sandstone Member are found, in stratigraphic order, the Scammon, Mineral, Robinson Branch, Fleming, and Croweburg coal beds. This interval commonly consists of dark-gray shale or lenticular-bedded shale with small amounts of sandstone. The Verdigris Limestone Member is a thin but widespread marine limestone unit found about 8 ft (2.5 m) above the Croweburg coal bed. The Verdigris and the underlying dark-gray shale are easily recognized on gamma-ray/neutron-well logs and are widely used as marker beds in the subsurface. The Bevier coal bed occurs about 5–10 ft (2–3 m) above the Verdigris Limestone Member; above the Bevier coal bed is the Lagonda sandstone interval. The Lagonda interval consists of medium-gray shale, lenticular-bedded shale, and minor amounts of sandstone. This interval ranges in thickness from less than 20 ft (6 m) to over 100 ft (30 m) in the study area. The Breezy Hill Limestone Member occurs above the Lagonda interval. Above the Breezy Hill is a dark-gray, platy shale

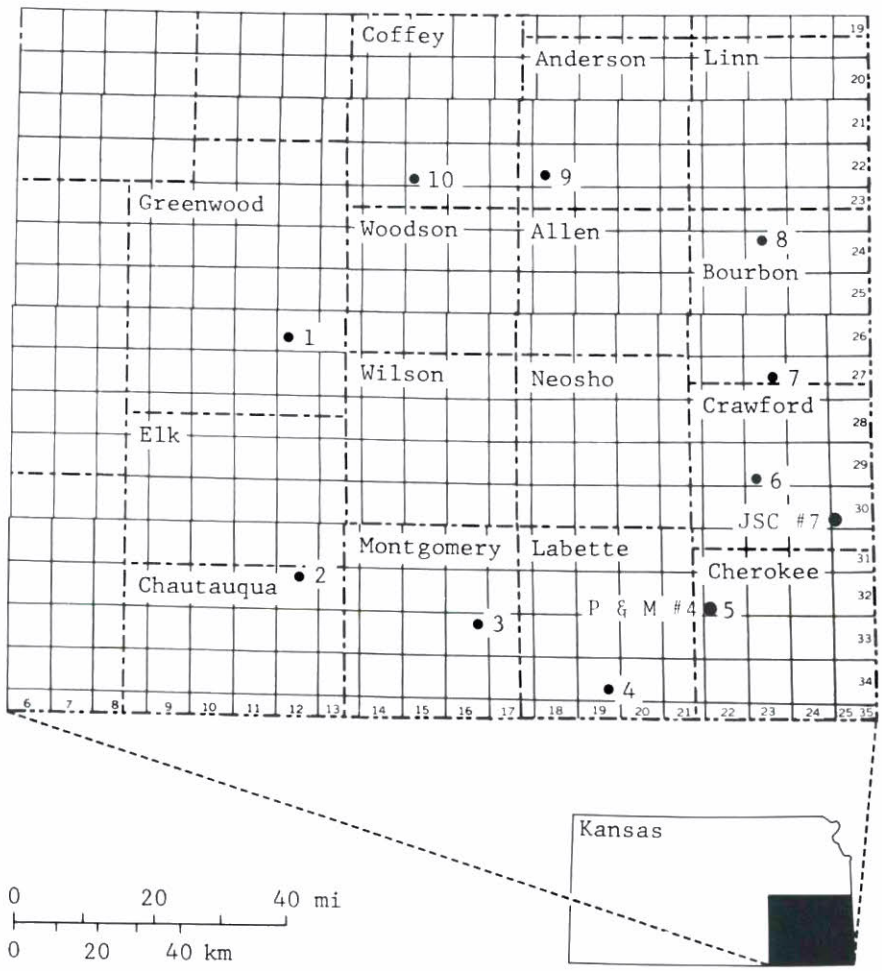

FIGURE 2—Location of cores and well logs used in stratigraphic cross sections.

containing small phosphatic nodules that correlates with the Excello Shale of Missouri and Oklahoma.

Relationship of cores to gamma-ray/neutron-well logs

Coal beds, seatrock zones, and dark-gray shales are the most laterally persistent lithologic units encountered in the cores used in this study. Coal beds are identified by a low reading on the neutron log and usually a low reading on the gamma-ray log, and often the shales overlying coal beds are highly radioactive. Following comparison between cores and well logs, gamma-ray/neutron logs were used to construct a stratigraphic cross section covering several counties in southeastern Kansas. Over 150 core descriptions and well logs from Kansas, Missouri, and Oklahoma were utilized in this study and the resulting correlations are summarized in figs. 2, 4A, and 4B (figs. 4A and 4B on sheet 2 in back pocket). Several coal beds encountered in this study, some unnamed, have proved to be widespread, are easily identified on gamma-ray/neutron logs, and are suitable for subsurface marker beds. Radioactive shales overlying some coal beds also have been used as stratigraphic markers.

The base of the Verdigris Limestone Member is the most reliable marker in the Cherokee Group and has been used as a datum for stratigraphic cross sections shown in figs. 4A and 4B. The Mississippian limestone surface, although irregular, is another reliable marker in the subsurface. The Riverton coal bed and the third and fourth unnamed coal beds above the Riverton are good stratigraphic markers. The Dry Wood coal bed, the third unnamed coal bed above the Dry Wood, the Weir–Pittsburg coal bed, and especially the Tebo coal bed seem to be overlain by radioactive shales that can be traced over much of the study area. The Scammon, Mineral, and Fleming coal beds often are overlain by radioactive shales and have proved to be good marker beds in the Cabaniss Formation. A dark-gray shale below the Verdigris Limestone Member is highly radioactive and has been widely used as a marker bed. Marker beds above the Verdigris Limestone Member include the Bevier coal bed and the base of the Fort Scott Limestone Formation. Several thin coal beds have been encountered in the Lagonda sandstone interval and could be used as marker beds in certain areas.

Lithofacies descriptions

Shales

DARK-GRAY SHALES—Shales that range from dark gray (N2) to medium dark gray (N4) are the most abundant lithofacies. These shales range in thickness from over 25 ft (8 m) to less than 1 ft (30 cm), are hard, and break with a hackly or splintery fracture. Grain size may be either clayshale or mudshale with minor amounts of quartz silt present. Fossils include brachiopod shells and spines, mollusks, gastropods, crinoid columnals, ostracodes, fish scales, and plant fossils (Dr. Doris Zeller, personal communication, 1982). A few small horizontal burrows are present in some layers. Diagenetic features include calcareous cement as well as pyrite, clay ironstone, phosphate, and calcareous concretions. The dark-gray shales are found most commonly overlying coal beds or seatrock zones with sharp lower contacts and generally have gradational upper contacts. The fine grain size of this lithofacies and the abundant pyritization of fossils indicate that deposition occurred under low-energy conditions in a disaerobic or anoxic environment.

MEDIUM- TO LIGHT-GRAY SHALES—Shales ranging from medium gray (N5) to very light gray (N8) on the color chart also are present in the cores. This lithofacies may be up to 75 ft (25 m) thick in the upper part of the Cherokee Group. Medium- to light-gray shales are hard and break with a hackly fracture. Mudshale is most common, and minor amounts of dispersed quartz silt and mica are present. Fossils include plant fragments, brachiopods, mollusks, crinoid columnals, and other marine forms, but fossils usually are not as abundant as in the dark-gray shales. Clay ironstone and pyrite concretions as well as carbonate cement are common. Medium- to light-gray shales often overlie dark-gray shales with gradational lower contacts and often grade upwards into lenticular-bedded shale or seatrock.

LENTICULAR-BEDDED SHALES—Lenticular-bedded shales (Reineck and Wunderlich, 1968) commonly are encountered below or stratigraphically adjacent to sandstone bodies. They generally consist of dark- to medium-gray (N3–N5) mudshale interlaminated with thin (> 1 cm), light-gray (N7) lenses of silt to fine-grained quartz sand. Thickness of this lithofacies generally is less than 20 ft (6.5 m). Lenticular-bedded shales contain plant fragments and both vertical and horizontal burrows, but body fossils are rare. Calcareous cement, pyrite concretions, and clay ironstone concretions are common diagenetic features. Lower contacts generally are gradational with dark- to medium-gray shales, and the abundance of thin sand lenses generally increases upwards within each unit. Upper contacts generally are gradational with siltstone or sandstone.

CLAYSTONE AND MUDSTONE—Claystone and mudstone range in color from medium gray (N5) to very light gray (N8), are soft, lack fissility, and break with a blocky fracture. Thicknesses generally are less than 10 ft (3 m). Mudstones commonly contain quartz, silt, and abundant plant fragments. Mudstones and claystones generally exhibit gradational lower contacts with the underlying shale or siltstone, and upper contacts generally are gradational with seatrock or shale.

Siltstones

WAVY-BEDDED SILTSTONES—The wavy-bedded (Reineck and Wunderlich, 1968) siltstone facies contains approximately equal amounts of light-gray (N7) rippled siltstone interlaminated with dark- to medium-gray (N3–N5) mudshales. Thickness of this lithofacies may range from over 30 ft (10 m) to less then 3 ft (1 m). Ripples and convolute bedding are common sedimentary structures. Plant fossils, as well as various types of burrows, also are present in the siltstones. Diagenetic features include clay-ironstone spherulites and concretions and zones of calcareous cement. Wavy-bedded siltstones generally have gradational or intercalating lower contacts with either a shale or sandstone. Occasionally a sharp but nonscoured contact is observed below this facies, indicating rapid lateral progradation of a sedimentary environment. Upper contacts with the overlying siltstone or sandstone may be either sharp or gradational.

RIPPLED SILTSTONE—The rippled siltstone facies usually is light gray (N7) in color, is less than 10 ft (3 m) thick, and is composed primarily of quartz silt. Ripples are the most common bedforms. Plant fossils are common, and most rippled siltstone facies are burrowed. Lower contacts are usually gradational with the underlying wavy-bedded siltstone or sandstone.

STRUCTURELESS SILTSTONES—Structureless siltstones range from medium gray (N5) to light gray (N7) in color and are composed of quartz silt with various amounts of mud matrix. Massive siltstone facies may differ from the other types of siltstones by having a greater degree of bioturbation that has destroyed primary sedimentary structures, or by exposure and leaching.

Sandstones

MUD-CLAST CONGLOMERATE—Mud-clast conglomerates generally contain locally derived mud clasts, coal clasts, lime-mud clasts, plant fossils, and broken and abraded fragments of marine fossils. Clasts may be up to 2 inches (5 cm) in diameter and usually are set in a matrix of fine quartz sand. This facies usually is massive and has no visible sedimentary structures. A sharp, scoured lower contact generally is present between the conglomeratic facies and the underlying lithology, and upper contacts may be either sharp or gradational with the overlying sandstone.

LARGE-SCALE CROSSBEDDED SANDSTONE—These sandstones generally are light gray (N7) in color and are composed mainly of very fine to fine-grained quartz sand. High-angle sets of crossbeds up to 1 ft (30 cm) in height are the most common sedimentary structure. Plant fragments are the most common fossils. This facies generally has a sharp, scoured lower contact with the underlying lithology and commonly is observed overlying mud-clast conglomerates.

RIPPLED SANDSTONE—Rippled sandstones generally are the most abundant sandstone type. This facies is generally light gray (N7) and is made up of very fine to fine-grained quartz sand. Thickness of units is usually less than 10 ft (3 m). Unidirectional current ripples up to 1 inch (2.5 cm) in height are the most common primary sedimentary structures. Plant fossils and a few burrows may be present.

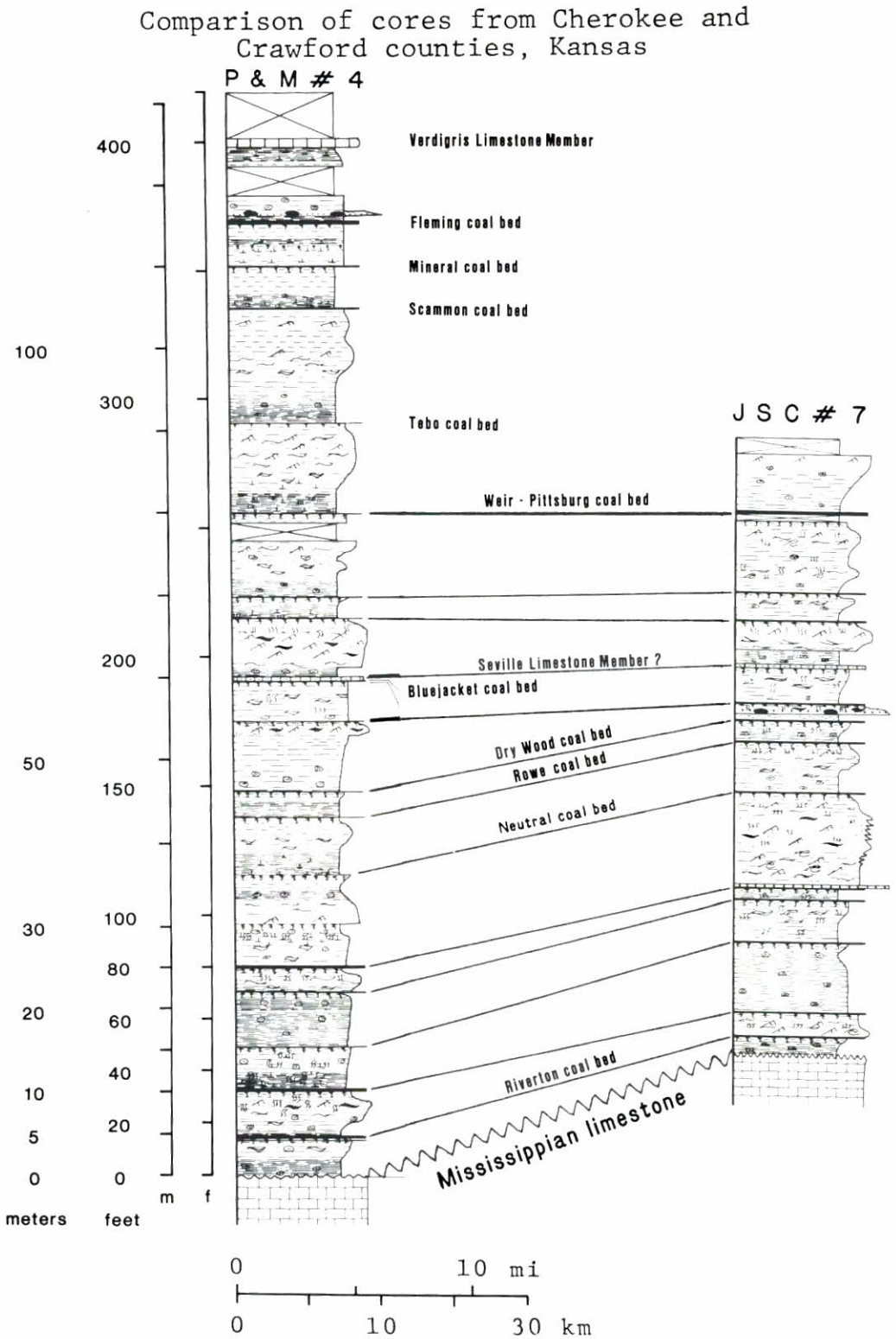

FIGURE 3—Summary of stratigraphic correlations observed in 24 continuous cores in Cherokee and Crawford counties, Kansas.

Rippled sandstones commonly have gradational or abruptly gradational lower contacts with flaser-bedded sandstone or siltstone. Upper contacts generally are gradational with a siltstone.

FLASER-BEDDED SANDSTONES—Flaser-bedded (Reineck and Wunderlich, 1968) sandstones are characterized by the presence of thin (< 1 cm), dark-gray mudstone lenses interlaminated with light-gray rippled sandstone. Ripples are the most common bedforms, and mud flasers are preserved in ripple troughs. Plant fossils and burrows are common. Flaser-bedded sandstones generally have gradational lower contacts with a wavy-bedded siltstone or sandstone and commonly are overlain by rippled or large-scale crossbedded sandstone.

STRUCTURELESS SANDSTONE—This sandstone facies ranges in color from medium gray (N5) to light gray (N7) and is composed of fine-grained quartz sand in a mud matrix. No sedimentary structures are apparent, and this facies could also be the result of increased bioturbation or exposure and leaching.

Limestones

MUDSTONE TO WACKESTONE—Limestones of the Cherokee Group, although thin, may be laterally widespread and are important because of their use as marker beds and in stratigraphic subdivision. The Verdigris Limestone Member is generally a light-gray (N7) lime mudstone to wackestone, containing brachiopods, bivalves, crinoids, bryozoans, and carbonate mud. Such units generally show no sign of bedding features. Both upper and lower contacts either are gradational or abruptly gradational with the surrounding shale. Some large cone-in-cone structures as well as elongate calcareous nodules have been observed in both cores and outcrops. Therefore, distinguishing between such diagenetic features and true carbonate sediments is important.

ARGILLACEOUS LIMESTONE—Argillaceous limestones commonly are found within dark-gray shales overlying coal beds. These limestones range from dark gray (N3) to medium gray (N5) in color and are usually less than 1 ft (30 cm) in thickness. Fossils include brachiopods, mollusks, gastropods, bryozoans, and crinoid columnals. These fossils are set in a matrix of dark-gray clay or mud, perhaps introduced by burrowing. These argillaceous limestones have sharp or abruptly gradational contacts with the surrounding lithology.

Coal

Coal beds encountered in the cores examined ranged from 2.5 ft (0.75 m) to less than 1 inch (2.5 cm) in thickness. Coal beds are bituminous in rank, black in color, bright to moderately bright banded, and have a blocky fracture. Calcareous cement and sulfate minerals are present in cleats and fractures. Coal beds have sharp upper and lower contacts. These thin coal beds, the associated seatrock zones, and the overlying dark-gray shales seem to be laterally persistent and are used for stratigraphic correlations.

Seatrock

Seatrock, also known as "underclay," "fireclay," and "seatearth," commonly is found below coal beds but also can be found where no coal bed is present. Seatrock is usually a lighter gray color than the surrounding units, and thicknesses are generally less than 6 ft (2 m). Seatrock zones contain clay, silt, sand, or thin argillaceous limestone beds, and abundant plant and root fragments are nearly always present. Seatrock is soft to moderately hard, breaks with a blocky or conchoidal fracture, and may have a soapy feel. Some claystone or mudstone seatrock units contain slickensides. Iron carbonate and altered pyrite concretions are common and are often concentrated in the lower portion of the unit. The lower contact of a seatrock unit is usually gradational with the underlying lithology. Seatrock generally has a sharp upper contact with the overlying coal bed or dark-gray shale, indicating a break in sedimentation. Seatrock units are believed to represent ancient soil horizons on top of which coal swamps developed. Explanation of lithofacies symbols used in stratigraphic sections is given in fig. 5.

ACKNOWLEDGMENTS—Research for this project was supported in part by the U.S. Geological Survey, Department of the Interior, under USGS Agreement No. 14-08-0001-G704. Special thanks are extended to Dr. Lawrence Brady of the Kansas Geological Survey for his critique of the manuscript as well as his support throughout the course of this study and to Dr. Anthony W. Walton, Department of Geology, The University of Kansas, for reviewing the manuscript and providing many valuable suggestions incorporated into this report. I also appreciate the assistance of Dave B. Killen who helped with core preparation and drafting.

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Depositional environment and reservoir geometry of the Bronson–Xenia field, Allen County, Kansas

by *Douglas H. Rofheart,* Mobil Exploration and Producing Services, Inc., Dallas, Texas

M. C. Colt 26AO Johnson (fig. 1) exhibits features indicative of multistoried sand bodies deposited by meandering fluvial channels. The cored interval shows an erosional base, planar tabular cross-stratified sand that decreases in grain size vertically from medium to fine sand, and an erosional surface at midcore. This erosional surface is the contact between an older fluvial point-bar deposit and a similar younger deposit. The upper sand also shows a vertical decrease in grain size and is overlain by fine-grained overbank deposits. The overbank deposits are composed of interbedded sand and shale and show unidirectional current ripples. The multistoried sand-body geometry exhibited in Colt 26AO Johnson can be used to generate predictive models of reservoir characteristics. This model can then be used to develop an enhanced oil-recovery program.

Introduction

The Bronson–Xenia field in Allen County, Kansas, produces from the Bluejacket Sandstone of the Middle Pennsylvanian (Desmoinesian) Cherokee Group (fig. 2). A geologic study of this field was conducted using data acquired from 167 wells in order to gain an understanding of the reservoir characteristics. Data consisted of geophysical gamma-ray logs and nine full-diameter drill cores from the core repository of the Kansas Geological Survey. The purpose of the study was to three-dimensionally model the reservoir based on depositional environment, diagenesis, petrophysics, and reservoir geometry. A model of this nature can be used as an outline when devising an enhanced-recovery project. The Bronson–Xenia field is particularly well suited for a study of this type because of an unusually close well spacing (1.5 acres).

Stratigraphy and geologic setting

The Bluejacket Sandstone occurs in the surface and subsurface of southeastern Kansas, southwestern Missouri, and northeastern Oklahoma. The Cherokee Basin, a shelf-like extension of the Arkoma Basin of Oklahoma, is bordered on the west by the Nemaha uplift and on the east by the Ozark uplift (fig. 3). The Bourbon arch, a low-relief topographic feature of the pre-Pennsylvanian surface, separates the Cherokee Basin from the Forest City Basin to the north. The thickness of the Desmoinesian stratigraphic section in the Cherokee Basin ranges from 110 m to 275 m and dips to the west-northwest (Ebanks and James, 1974).

Middle Pennsylvanian sediments accumulated during an overall transgression as evidenced by the change from predominantly clastics in the Cherokee Group to carbonates in the Marmaton Group (Weirich, 1953; Visher et al., 1971; Ebanks and James, 1974). This transgression was interrupted by several regressive periods, which resulted in the deposition of lenticular "shoestring" sandstones, shale, and coal. Deposition of Cherokee Group sediments occurred in a diversity of environments that included shifting and prograding alluvial and deltaic plains, beaches, shallow seas, and tidal delta complexes (Rick, 1923; Visher et al., 1971; Ebanks and James, 1974).

Depositional environment

The reservoir sands of the Bronson–Xenia field were deposited by highly sinuous, low-gradient meandering fluvial channels in an overall fluvio-deltaic setting. The fluvial channels migrated through highly vegetated swamps and marshes as evidenced by the thin Dry Wood coal bed that directly underlies the Bluejacket Sandstone. The Colt 26AO Johnson core (fig. 1) shows lithologies, sedimentary structures, and textural features characteristic of deposits of this type. A gradual upward decrease in sand-grain size and scale of sedimentary structure is indicative of point-bar deposition in a meandering fluvial system (Visher, 1965). The Bluejacket Sandstone core from 26AO Johnson also exhibits unidirectional cross stratification, an erosional base (?), rare bioturbation, and complete absence of marine fossils. The basal sands of the Bluejacket are not composed of well-developed lag deposits but generally show minor shale clasts, wood fragments, and iron-claystone nodules. Overbank deposits consist of unidirectionally rippled very fine sand, siltstone, and interbedded sand and shale commonly showing lenticular bedding.

Reservoir geometry

Gamma-ray logs were used to construct net-sand isopach maps in order to delineate the geometry of the Bronson–Xenia reservoir (fig. 4 on sheet 2 in back pocket). The overall geometry of the reservoir is that of a blanketlike sand with irregular, highly variable thickness. Previous studies reported an elongate, lenticular geometry for Cherokee Group sandstones deposited in similarly interpreted depositional environments (Hulse, 1978; Maderak, 1960). A fence diagram of the Bronson–Xenia field was constructed in an attempt to determine if the resultant sand geometry was actually multilateral sand bodies. Four "shoestring" sand bodies were outlined based on nine core descriptions and 167 gamma-ray logs that commonly showed two or more distinct sand units. The gamma-ray logs were supported by 100 core descriptions conducted by Daniel A. Busch, the consulting geologist for Mack C.

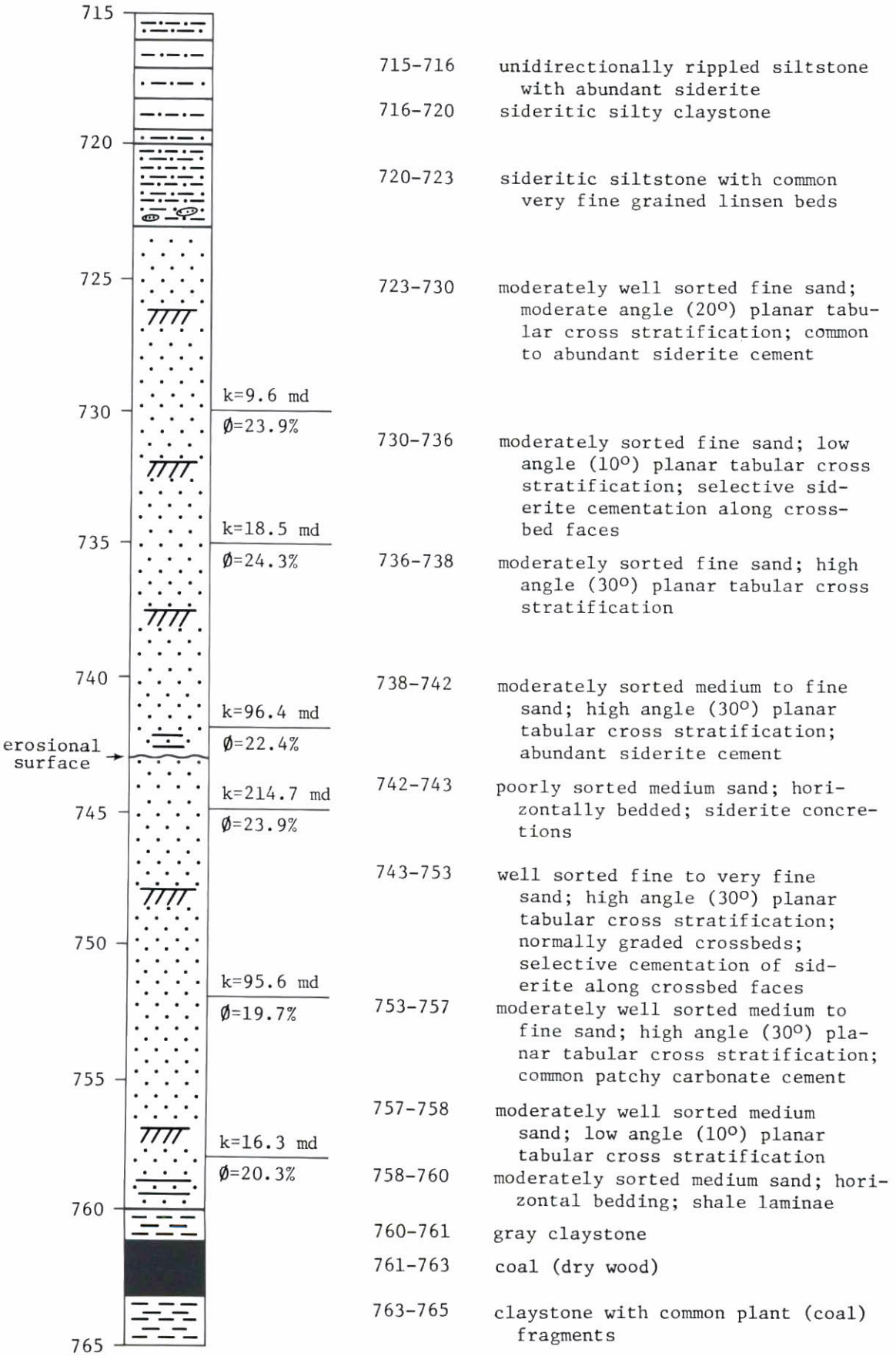

FIGURE 1—Stratigraphic section of M. C. Colt 26AO Johnson, sec. 33, T. 24 S., R. 21 E., Allen County, Kansas.

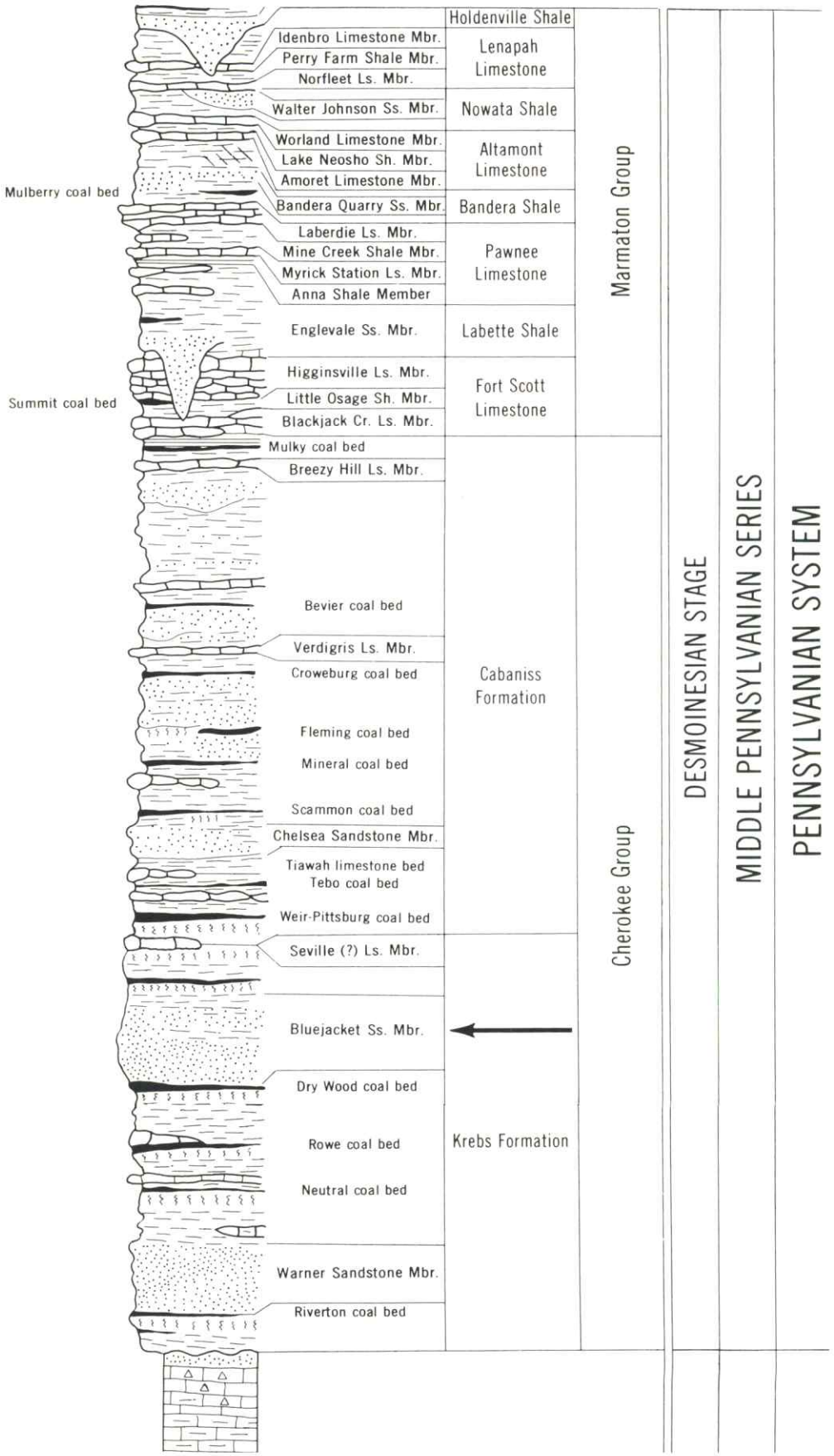

FIGURE 2—Stratigraphic section of southeast Kansas (after Zeller, 1968).

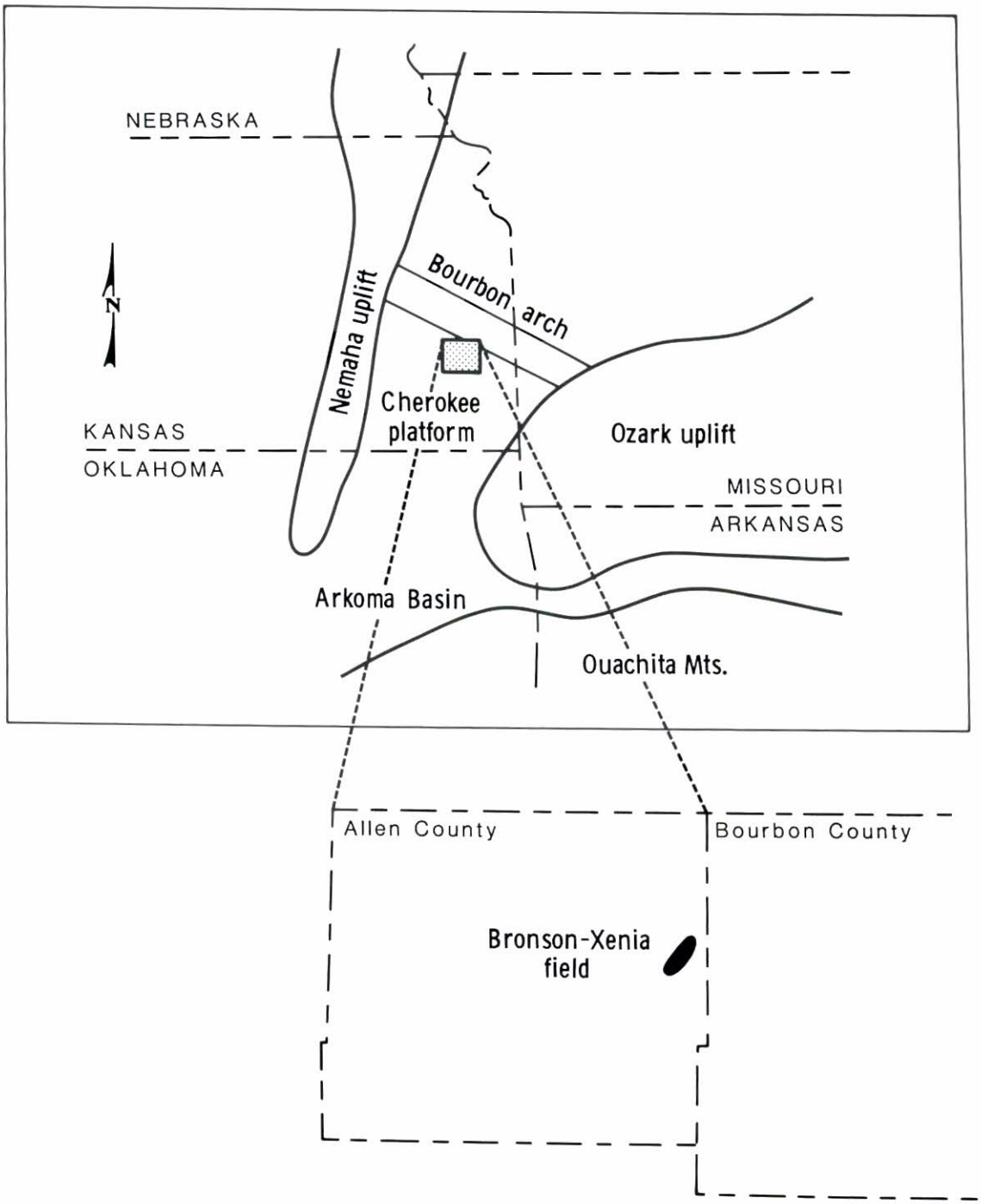

FIGURE 3—Structural setting and field location of M. H. Colt 26AO Johnson.

Colt, Inc. The contact between sand bodies commonly showed erosional features such as truncation of crossbeds, common shale clasts or wood fragments, and an increase in sand-grain size. Colt 26AO Johnson has an erosional surface at 743 ft that truncates crossbedding and shows an increase in grain size from fine to medium sand across the contact. Colt 26AO Johnson is anomalous because it does not contain shale clasts or wood fragments above this contact. Above the erosional surface, the vertical sequence of sedimentary structures and decreasing grain sizes represents a second generation of point-bar deposition.

Applications to enhanced oil recovery

In order to develop an efficient and effective enhanced oil-recovery (EOR) project, a three-dimensional model of the reservoir must be constructed. This model, which is based on reservoir geometry, depositional environment, diagenesis, and petrophysics, can be utilized to delineate high permeability zones in the reservoir. A successful EOR project will result from maximum areal sweep of the

reservoir. Portions of the reservoir that have lower permeabilities and higher residual oil saturations can be swept by adopting a suitable fluid-injection pattern. A clear understanding of fluid-migration patterns in the reservoir can assure that residual oil is contacted by the displacing fluid and that expensive injection fluids will not be lost.

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Kansas-type cyclothems and porosity development in the Middle Pennsylvanian Marmaton Group, Dirks field, Logan County, Kansas

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Abstract

Seven facies are recognized in core from the upper part of the Middle Pennsylvanian (Desmoinesian) Marmaton Group, Texaco Dirks # 2 well, Dirks field, Logan County, Kansas. These facies make up two Kansas-type cyclothems, the Altamont and Lenapah, and record deposition in response to fluctuating sea level and varying terrigenous influx on the broad, epeiric shelf that was the northern extension of the Hugoton embayment. The facies correspond to Heckel's (1977) basic, Kansas-type, cyclothem members, i.e., (transgressive) middle limestone, (transgressive) core shale, (regressive) upper limestone, and (regressive) outside shale. The Altamont cyclothem lacks the core shale and perhaps the middle limestone. The overlying Lenapah cyclothem contains all of the basic members of Heckel's Kansas-type cyclothem.

Porosity development in the Altamont and Lenapah cyclothems of the Dirks # 2 is restricted to the upper limestone members. The upper limestone of the Lenapah cyclothem, the Idenbro Limestone Member, contains intergranular and moldic (principally oomoldic) porosity. Portions of this regressive limestone are weakly oil stained, and porosity is poor to locally fair. The upper limestone member of the Altamont cyclothem, the Worland Limestone Member, is strongly oil stained and is a pay in this well and in the study area. The Worland Limestone displays intergranular, moldic, solution-enlarged moldic, vuggy, and fracture porosity. Porosity and permeability are fair to locally good and are thought to be primarily the result of meteoric diagenesis perhaps associated with a subtle topographic high on the seafloor during deposition of the Altamont Limestone. A cross section through the study area indicates a slight thinning of strata overlying the Altamont Limestone in wells where porosity in the Worland is well developed and the Worland Limestone is a producing oil reservoir. This thinning may indicate an ancient Altamont high.

Introduction

Core 4 of the Texaco Dirks # 2, Dirks field, Logan County, Kansas, is 45.5 ft (13.9 m) in length (subsurface depth 4,374–4,419.5 ft) and from the upper part of the Middle Pennsylvanian (Desmoinesian) Marmaton Group. The core primarily is composed of cyclically deposited limestone, shale, and dolomitic limestone of the Bandera Shale, Altamont Limestone, Nowata Shale, Lenapah Limestone, and Holdenville Shale (fig. 1). Detailed core study and subsurface mapping using wireline logs provide information about the depositional environments and porosity development in the Altamont Limestone, the reservoir in the Dirks and adjoining Miller fields. These fields are situated on a northern extension of the Hugoton embayment (fig. 2). The first production from these fields was in May 1981. Combined lifetime production from the five producing wells in the two fields was 35,085 bbls of oil as of May 1983, with production for May 1983 being 898 bbls of oil and 1,887 bbls of water (1,457 bbls of water were from a single well).

Pennsylvanian cyclic sedimentation of the Midcontinent

Much of the Pennsylvanian and Permian of Kansas is characterized by an alternation of laterally persistent shale, sandy shale, and limestone, reflecting cyclic sedimentation on a broad, epeiric shelf. Moore (1929, 1936, 1949) was one of the first to apply cyclical sedimentation patterns to understanding these sequences. He regarded couplets of successive shale and limestone members as cyclothems.

Heckel (1977) defined the basic, vertical, cyclic pattern which characterizes the Missourian part of the Upper Pennsylvanian in eastern Kansas. In ascending order it is: outside shale member, middle limestone member, core shale member, upper limestone member, and outside shale member (fig. 3). This basic sequence he termed a Kansas-type cyclothem. Moore's (1936, 1949) restricted usage of the term cyclothem to a shale-limestone couplet was abandoned by Heckel, as it is here. Watney (1980), in his study of the Upper Pennsylvanian Lansing–Kansas City Groups in northwestern Kansas and southwestern Nebraska, referred to these units respectively as: upper shale, lower carbonate, lower shale, upper carbonate, and upper shale (table 1).

The vertical pattern or sequence defined by Heckel and Watney is explained most simply, they suggested, by a single transgression and regression of the sea with deepest water (maximum transgression) during deposition of the core shale (fig. 3). The middle limestone was deposited during the transgressive phase. The upper limestone and most of the outside shale were deposited during the regressive phase. The upper part of the outside shale can be transgressive recording the initial stages of deposition of the overlying cyclothem. Heckel stated that the sedimentary record of the marine transgression is typically very thin

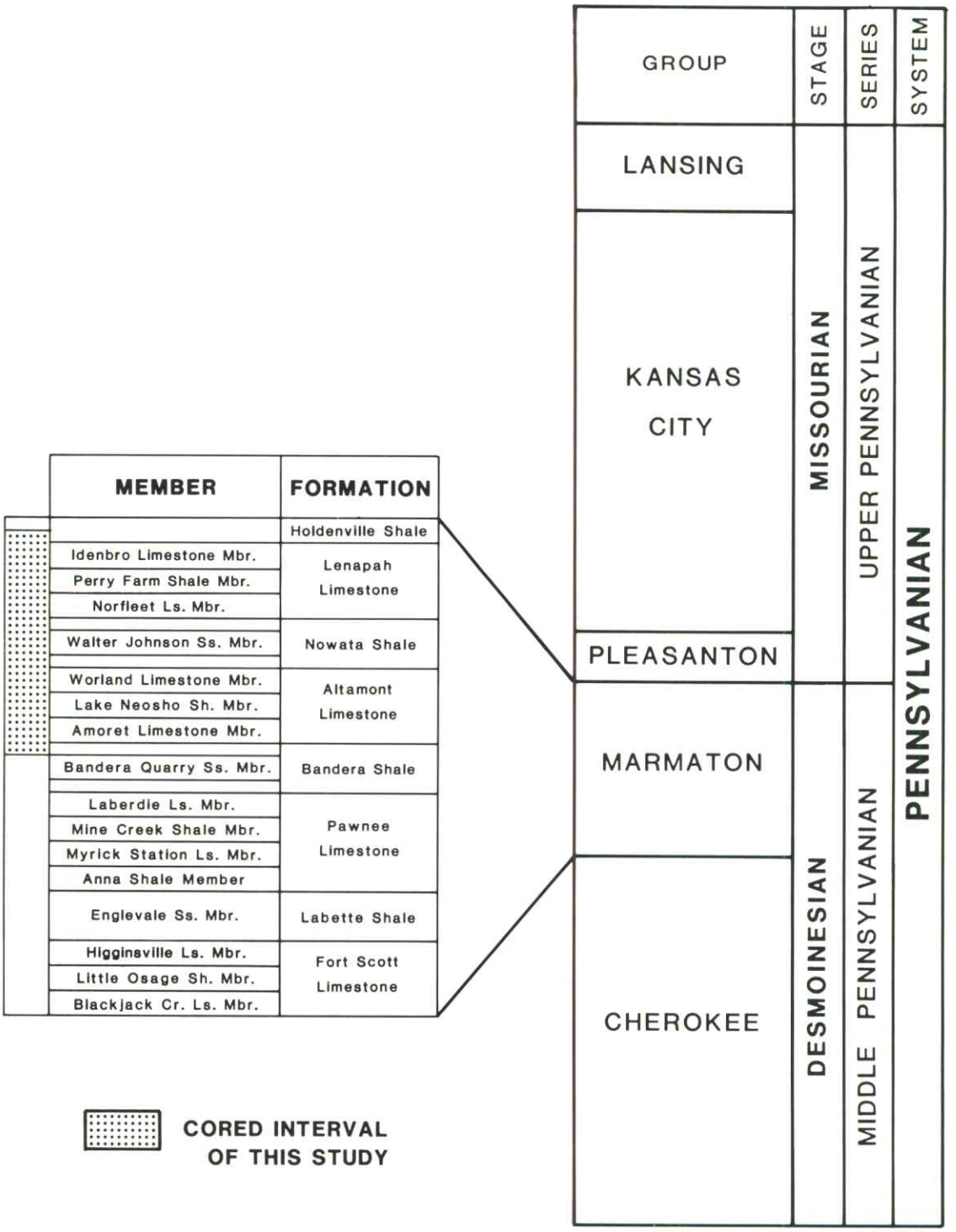

FIGURE 1—Pennsylvanian/Desmoinesian–Missourian stratigraphy of Kansas (from Zeller, 1968).

because of the progressive stranding of detrital influx farther away at the shoreline (in the case of northwestern Kansas to the north [Watney, 1980]) and the difficulty of generating carbonate material during rapidly deepening water.

Depositional facies of the Dirks # 2 core

Twenty-one lithologic units, organized into seven depositional facies, have been recognized in core from the Dirks

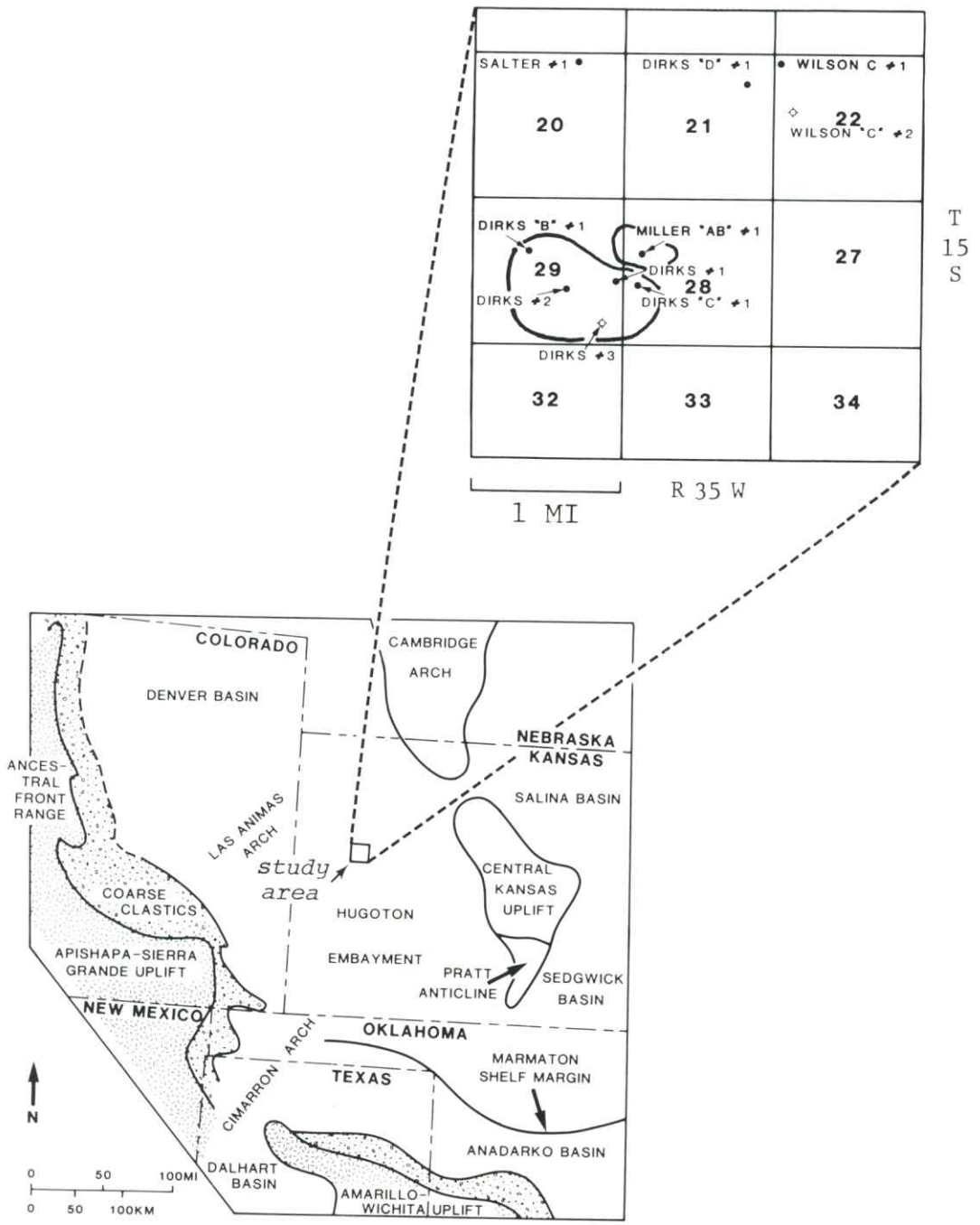

FIGURE 2—Desmoinesian–Missourian paleogeographic map of western Kansas and adjacent areas (after Watney, 1980) and detailed inset of study area (Dirks and Miller fields outlined). Marmaton shelf margin, defining the northern limit of the Anadarko Basin, is based on a gross change in lithology from a shelf limestone facies (> 2/3 limestone) to a basin shale facies (< 1/3 limestone) as mapped by Rascoe (1962).

2 (fig. 4; on sheet 3 in back pocket). Each of these facies corresponds to a member of Heckel's basic Kansas-type cyclothem. Description of these facies is given below, followed by a discussion of the position of each facies in the cyclothem model. Unless specified, Heckel's terminology will be used in this report.

Facies I

Facies I (units 1–3) includes greenish-gray, unfossiliferous siltstone (units 1 and 2) and olive-gray, sparsely fossiliferous shale (unit 3). The massive to mottled nature of the siltstone may indicate burrowing or plant-root action (plate 1A). The siltstone, with local carbonate nodules, suggests deposition in a shallow nearshore/marginal-marine or terrestrial (e.g., brackish marsh) environment. The shale records deposition in quieter, slightly deeper, marine waters. Olive-gray shale of the upper 0.5 ft (0.15 m) of this facies grades upward into interbedded shale and limestone of facies II.

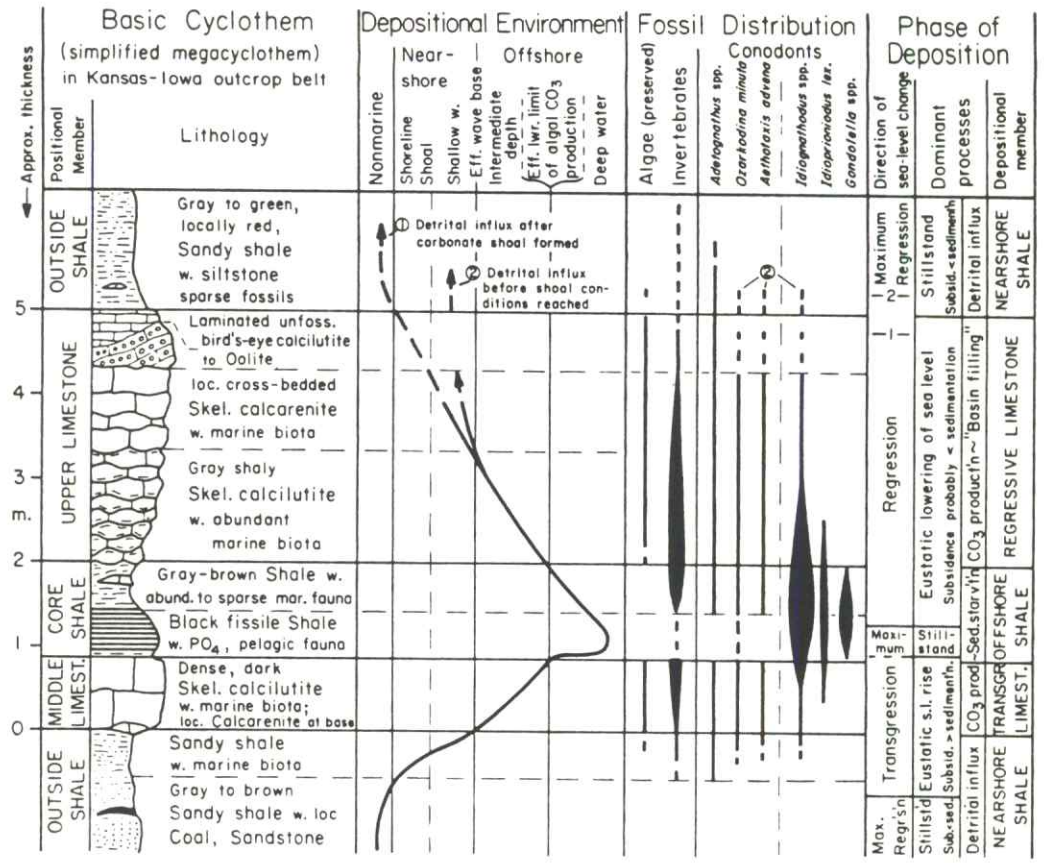

FIGURE 3—Basic Upper Pennsylvanian Kansas-type cyclothem sequence (from Heckel, 1977).

TABLE 1—Lithologies, diagenesis, and depositional environments of Kansas-type cyclothem facies, Lansing and Kansas City Groups, northwest Kansas (from Watney, 1980). S—sharp contact G—gradational contact

Heckel's members	Watney's facies	Thickness (ft)	Lithology	Diagenetic alternation	Facies contacts	Genetic facies	Depositional environment
outside shale	upper shale	<5–30	red-brown, unbedded silty shale	intense		regressive shale	oxidized, continental clastics
					S		
upper limestone	upper carbonate	<1–15 (upper)	lime-mudstone to grainstone common; occasionally dolomitic; sparse to very fossiliferous	moderate to intense		regressive carbonate	shallow, clear-water carbonate; tidal flat, lagoon, and open marine; high and low energy
		(lower)	lime-mudstone or wackestone, argillaceous at bottom; fossiliferous				subtidal, low energy, clear-water, open-marine carbonate grading downward to mixed turbid argillaceous carbonate
					G		
core shale	lower shale	2–20	fossiliferous, gray-green; occasionally black	minimal		marine shale	subtidal, low energy, marine; restricted, anoxic conditions prevalent to south and to north locally shallow water
					G		
middle limestone	lower carbonate	0–15 (upper)	lime-mudstone to wackestone, fossiliferous	minimal to locally moderate		transgressive carbonate	subtidal, low energy, open marine; clear to turbid water conditions
		0–8 (lower)	silty grainstone to packstone; occasionally base rich in quartz sand or silt				sandy or silty reworked shoal water, intermittent restricted to open marine
					S		

Facies II

Facies II contains four units: interbedded olive-gray shale and crinoid-brachiopod wackestone characterized by undulose bedding (unit 4; plate 1B), bioclast wackestone and minor *Tubiphytes* boundstone (unit 5; plate 1C, D, and E), *Chaetetid* bafflestone (unit 6; plate 2B, C, D, and E), and limy dolomite and dolomite (unit 7; plate 3). *Chaetetid* bafflestone and the underlying wackestone of unit 5 are heavily oil stained.

Unit 4 and the lower and middle parts of unit 5 record subtidal deposition in quiet, marine waters which decreased in turbidity with time. Deposition was below wave base but in the photic zone in water probably a few meters to a few tens of meters deep. Relatively diverse biota of unit 4 and the lower and middle parts of unit 5 (fig. 4) are interpreted to represent normal-marine conditions with phylloid algae recording clear, relatively shallow water deposition. A sharp decline in fossil diversity and abundance in the upper part of unit 5 (fig. 4), indicates a shift to more restricted conditions related to decreasing water depths. Bioclasts in the uppermost 0.5 ft (0.15 m) of this unit are restricted essentially to brachiopods. The contact of units 5 and 6 is abrupt and irregular (plate 2A), and the upper 1 ft (0.3 m) of unit 5 is strongly dolomitized. These features suggest that the upper surface of unit 5 may record subaerial or very shallow marine erosion.

Coated-grain packstone, making up the lowermost few inches of unit 6, abruptly overlies unit 5 (plate 2A). Overlying this is *Chaetetid* bafflestone. The environmental significance of *Chaetetes* was reviewed by Wilson (1975, p. 209) in his discussion of Pennsylvanian–Early Permian microfacies of the Midcontinent. Wilson stated that the *Caninia–Chaetetes* microfacies is characterized by massive, micritic limestone beds with corals, not necessarily in growth position nor attached to each other, forming a bafflestone. This microfacies, Wilson suggested, represents coral-rich banks and shoals in clear, very shallow, relatively quiet, open-marine waters. A similar environment is visualized for *Chaetetid* bafflestone of unit 6.

Unit 7 is characterized by features suggesting subaerial exposure and meteoric diagenesis. Planar algal stromatolites in the lower part of unit 7 (plate 3A) and a low-diversity fossil assemblage, composed predominantly of ostracods, brachiopods, and gastropods, represent intertidal to supratidal deposition. Desiccation and dissolution features include clay-filled fractures and fissures, hardened clasts, and irregular-shaped vugs (plate 3). The contact between units 7 (facies II) and 8 (facies III) is sharp, and the upper surface of unit 7 is irregular with relief of approximately 1 inch (2.5 cm; plate 3B). This surface was probably subaerially exposed and perhaps eroded. The rock immediately underlying the contact may be a caliche. Dolomitization of unit 7 is pervasive below this contact as it was below the irregular contact between units 5 and 6 (fig. 4).

Thus, facies II is an upward-shoaling carbonate sequence terminating in subaerial exposure and erosion. The environment changed from shallow-marine shelf to supratidal.

Facies III

Olive-gray shale of unit 8 (facies III) abruptly overlies facies II. The lower 0.5 ft (0.15 m) of shale (plate 4A) is unfossiliferous, contains minor carbonaceous material, and is generally lighter in color and less fissile than the remainder of the facies. Bryozoans and crinoids are rare and brachiopods are locally common in the middle and upper parts of facies III. The fossiliferous shale was deposited in a quiet-water, subtidal, marine environment perhaps a few meters to a few tens of meters deep. Unfossiliferous shale of the lower part of the facies records nearshore, perhaps slightly shallower, marine deposition. The relatively sparse, low-diversity fauna of this facies is attributed to detrital influx.

Facies IV

Olive-gray shale of facies III grades upward into olive-gray, locally bioturbated, bioclast wackestone of facies IV (plate 4B, C). Limestone of facies IV becomes less argillaceous upward. The relatively diverse fauna (e.g., brachiopods, encrusting forams, fusulinids, green algae, bryozoans, and crinoids), micrite matrix, and lack of current structures suggest deposition generally below wave base in normal-marine waters a few meters to perhaps a few tens of meters deep. *Osagia* (blue-green algae and encrusting foram)-coated bioclasts (plate 4B), possibly analogous to modern oncolites (Crowley, 1969), suggest occasional, moderate wave or current energies.

Facies V

Facies V is composed of calcareous, olive-gray to olive-black, fissile shale. Thin-shelled brachiopods are locally common and crinoids are present in the upper part of the facies (plate 4D). Phosphorite (?) nodules are rare. This shale displays a gradational contact with overlying limestone of facies VI. Deposition of this shale probably was below wave base in quiet, marine waters.

Facies VI

The lower part of facies VI (unit 11) is lime mudstone and argillaceous, crinoid wackestone and packstone (plate 5A). These rocks grade upward into locally oil-stained and cross-stratified bioclast grainstone and packstone (plate 5B, C, and D) which make up the middle part of this facies (units 12-14). In places, the matrix of these rocks was selectively dolomitized. Elsewhere, medium-crystalline dolomite cement fills intergranular areas. Crinoids and bryozoans generally are the most common bioclasts in these rocks with calcispheres (?) common in unit 13 (plate 5C). A relatively thin interval of interbedded limestone, shale, and conglomerate (unit 15; plate 5F) overlies the bioclast grainstone and packstone. The conglomerate contains lime mudstone and pale-green siltstone clasts. Overlying this and comprising the upper part of facies VI (unit 16) is burrowed, bioclast wackestone and packstone grading upward into cross-stratified ooid grainstone (plate 6A).

Facies VI contains two shoaling-upward sequences, units 11–15 and unit 16. Both begin with subtidal, marine wackestone and packstone and grade upward into high-energy, shallow-water grainstone.

Facies VII

Greenish-gray, unfossiliferous shale and nodular, unfossiliferous lime mudstone of facies VII, units 17–19 (plate 6B and C), record tidal-flat or perhaps shallow-

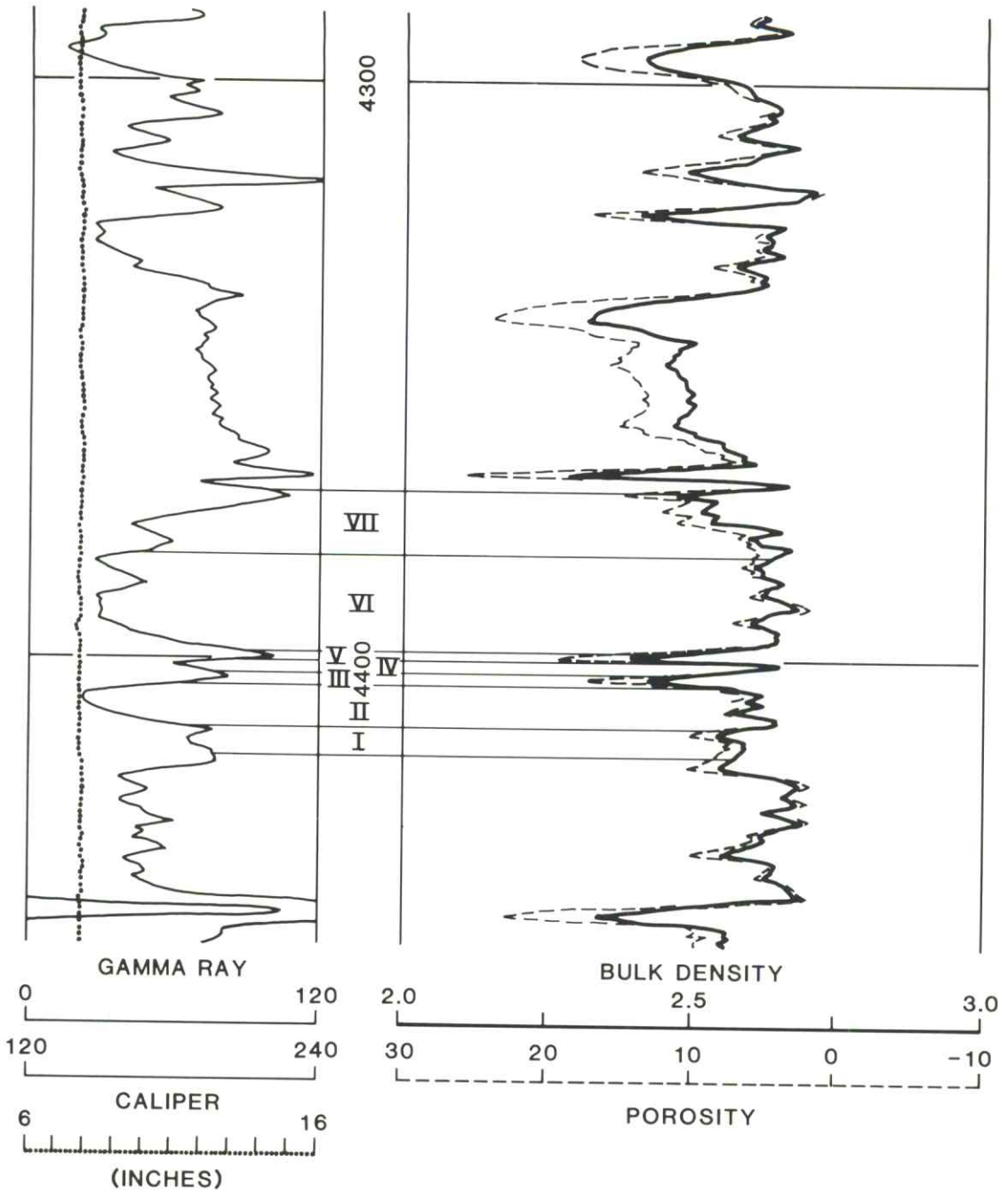

FIGURE 5—Gamma ray/neutron-density well log signatures of the depositional facies of the Dirks #2 core.

lagoon to nonmarine deposition. Irregular-shaped limestone nodules residing in greenish-gray shale in the lower part of unit 19 may be due in part to early solution of carbonate mud by waters undersaturated with respect to calcium carbonate (plate 6B). Limestone nodules in the middle and upper parts of unit 19 may have precipitated from meteoric waters in the soil zone and may be caliche. Calcite-filled fractures in some nodules (plate 6C) indicate desiccation or perhaps dissolution. Brownish-gray and grayish-brown, unfossiliferous mudstone (plate 6D) of the upper part of facies VII (unit 20) may reflect nonmarine deposition, with a possible return to marine conditions recorded by olive-gray shale which makes up the uppermost 0.5 ft (0.15 m) of the facies.

Similar rocks have been described by Watney (1980) from the Upper Pennsylvanian (Missourian) of northwestern Kansas and southwestern Nebraska. Watney stated that nodular carbonates (some with shrinkage fractures), the absence of fossils, and the oxidized appearance of sediment, including a typical red-brown color, reflect continental deposition and in some cases development of a paleosol.

Log signature

Fig. 5 shows the gamma ray/neutron-density log signatures of the depositional facies of the Dirks # 2 core. Log responses of Kansas-type cyclothems were discussed in detail by Watney (1980) and will not be reviewed here. A figure from Watney's study is, however, included to show the typical responses of several cyclothems in the Kansas City Group (fig. 6). Note the similarities with cyclothems of the cored interval of this study.

Depositional cycles

The vertical sequence of the Dirks # 2 core fits, with some irregularities, Heckel's Kansas-type cyclothem model. The core contains two cyclothems represented by facies I-III, a partial cyclothem, and III-VII, a complete Kansas-type cyclothem.

Siltstone and shale of facies I suggest continental (?) and shallow-marine deposition and correspond to Heckel's outside shale. Olive-gray shale of the upper part of this facies signals the initiation of a marine transgression. The overlying, upward-shoaling carbonates of facies II record an overall marine regression culminating in subaerial exposure. This facies corresponds to Heckel's upper limestone. Completing the partial cyclothem is olive-gray shale of facies III, equivalent to Heckel's outside shale. The core shale member is absent in this sequence and in the equivalent interval in nearby wells. The transgressive, middle limestone member, likewise, seems to be absent. This member may, however, be represented by the lowermost 2–3 ft (0.6–0.9 m) of facies II. In any case, this sequence (facies I–III) suggests that only a relatively minor transgression occurred in the area during deposition of the lower cyclothem.

The overlying cyclothem begins with olive-gray shale of the upper part of facies III (outside shale) recording a marine transgression. Facies IV is Heckel's middle limestone, i.e. a relatively thin, bioclast wackestone and packstone that contains a diverse and relatively abundant marine biota recording deposition in an open-marine environment generally below effective wave base but in the photic zone. Facies V corresponds to the core shale. Absence of a black shale in facies V suggests water depths were too shallow for the establishment of a thermocline which would inhibit good bottom oxygenation (Heckel, 1977). This relatively thin shale is, however, darker and less silty than those interpreted as outside shales (e.g., facies I, III, and VII). Facies VI is the upper limestone. Like Heckel's upper limestone member, facies VI consists of shale-parted, bioclast wackestone and packstone which grade upward into bioclast packstone and grainstone and finally into cross-stratified, ooid grainstone. Facies VII, representing tidal flat and nonmarine deposition, is an outside shale.

Diagenesis

Pennsylvanian cyclothems of the Midcontinent display diagenetic patterns which can be related to the cyclic depositional model described earlier in this report (fig. 3). These patterns, discussed by Watney (1980; table 1, this report) and summarized by Heckel (1982, 1983), are reviewed here with respect to the Dirks # 2 core. A generalized model showing shallow-subsurface, diagenetic environments is presented in fig. 7.

Heckel stated that the middle limestone and core shale were deposited during continued transgression and pass directly from the marine phreatic diagenetic environment into the low-oxygen, connate environment with little or no evidence of meteoric diagenesis. Core shales may show some discoloration (mottled yellow red), dissolution of fossils, and occasional fracturing due to percolating meteoric waters. This shale acted as a seal, however, above the middle limestone, and mineralogically unstable grains in the middle limestone were not leached but, instead, underwent slow neomorphism. The result is good preservation of original depositional textures. Cements generally are ferroan calcite and dolomite in the middle limestone and may postdate considerable compaction. Calcarenites when present in the core shale also display ferroan-carbonate cements and overpacking of grains.

In the Dirks # 2 core no discoloration or fracturing of the core shale (facies V) is present. The middle limestone (facies IV) shows good preservation of original depositional textures with no secondary meteoric or primary porosity. These rocks are muddy, and overcompaction is not present.

Generally, diagenetic alteration of the upper limestone and outside shale is more striking and displays a greater variety of features. Heckel stated that the upper limestone displays features indicative of its passage through a number of diagenetic environments beginning with the marine phreatic and passing through the meteoric, mixing zone, and deeper connate. Mineralogically unstable grains are leached and blocky calcite cement precipitated in the meteoric environment under conditions that become increasingly oxygen depleted as mixing zone and deeper connate water move into the rock during and after the succeeding transgression.

Upper limestone members of the Dirks # 2 core (facies II and VI) show a variety of porosity and cement types. Fracture, moldic (primarily leached bioclasts), solution-enlarged moldic, and vuggy porosity in facies II record freshwater diagenesis in the meteoric environment (plates 1D, and E; 3B, C, and E). In addition, *Chaetetid* corals display intragranular porosity in this facies (plate 2D). Porosity in the lower part of facies VI (units 12 and 13) generally is primary and includes intergranular and intragranular. In ooid grainstone of the upper part of facies VI (unit 16), bladed, isopachous, calcite cement records early, marine phreatic cementation. This stage of cementation was arrested prior to complete filling of intergranular areas, resulting in the retention of some primary intergranular porosity (plate 5E). In places, this intergranular porosity is filled by poikilitic, echinoderm overgrowths and/or a finely crystalline, equant calcite cement. Moldic and oomoldic porosities in unit 16 developed due to dissolution of mineralogically unstable grains in the meteoric environment (plate 5E).

Microcrystalline replacement dolomite and medium-crystalline dolomite cement of facies II, concentrated immediately beneath two irregular surfaces thought to record subaerial exposure (fig. 4), may have formed soon after deposition. This dolomite may have resulted from mixing of marine pore fluids with freshwater during subaerial

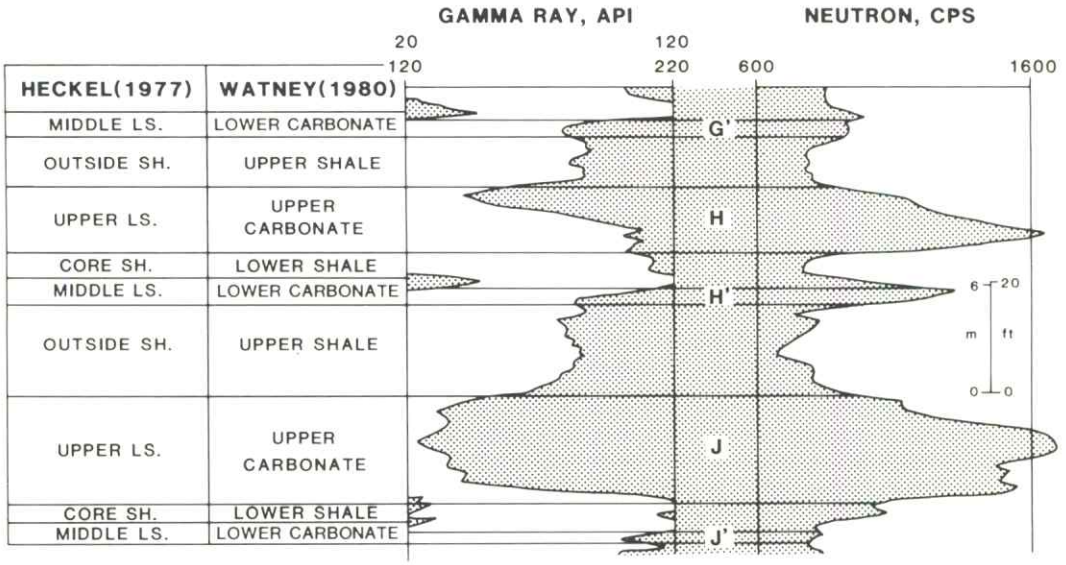

FIGURE 6—Typical gamma ray/neutron well log signatures of Kansas-type cyclothems from an interval in the Kansas City Group, northwestern Kansas (from Watney,1980).

CORE FACIES	POSITION IN KANSAS-TYPE CYCLOTHEM (Heckel, 1977)	STRATIGRAPHIC UNITS		CYCLOTHEM
		Member	Formation	
VII	OUTSIDE SHALE		Holdenville Shale	LENAPAH CYCLOTHEM
VI	UPPER LIMESTONE	Idenbro Limestone	Lenapah Limestone	
V	CORE SHALE	Perry Farm Shale		
IV	MIDDLE LIMESTONE	Norfleet Limestone		
III	OUTSIDE SHALE		Nowata Shale	
II	UPPER LIMESTONE CORE SHALE(ABSENT) MIDDLE LIMESTONE(?)	Worland Limestone Lake Neosho Shale Amoret Limestone	Altamont Limestone	ALTAMONT CYCLOTHEM
I	OUTSIDE SHALE		Bandera Shale	

FIGURE 7—Correlation of core facies with formations and members of the Altamont and Lenapah cyclothems.

exposure. Microcrystalline replacement dolomite and dolomite cement in units 12 and 13 of facies VI may have precipitated at shallow burial depths in a hydrologic system of mixed meteoric and marine waters.

Heckel stated that diagenetic processes that affected the outside shale member were closely related to the depositional environment of the shale and were an extension of those that affected the underlying upper limestone member. These processes often were associated with subaerial exposure and included soil formation and freshwater phreatic and vadose diagenesis. Watney (1980) suggested that carbonate nodules, closely resembling caliche, and tubule structures, interpreted as recording plant-root action, attest to the presence of soil-forming processes in the outside shale.

The typical red-brown color of mudstone in the upper part of facies VII may be post-depositional in part, and, in places, irregular-shaped, lime-mudstone nodules in this facies may have resulted from early solution of lime mud by percolating meteoric waters (plate 6B). Tubular structures and carbonate nodules in the upper part of unit 19 (plate 6C) resemble those described by Watney, which he suggested were associated with soil-forming processes of the outside shale.

Stratigraphy

Four Kansas-type cyclothems make up the Marmaton Group. In ascending order, they are the Fort Scott, Pawnee, Altamont, and Lenapah. These cyclothems, previously termed megacyclothems, were described by Jewett (1945) and Moore (1949). Two of these cyclothems, the Altamont (facies I–III) and the Lenapah (facies III–VII), occur in core 4 from the Dirks # 2. Correlation of the seven core facies of the Dirks # 2 with formations and members of these cyclothems is shown in fig. 8.

Schenk (1967) described the Altamont Limestone, of the cyclothem of the same name, where it crops out along a northeast-southwest trend stretching from Iowa to northeastern Oklahoma. In outcrop the Altamont Limestone is divided into three members, the older Amoret and younger Worland Limestones and the intervening Lake Neosho Shale. Schenk stated that the Amoret and Worland Limestones are transgressive and regressive, marine carbonates, respectively, and the Lake Neosho Shale is a black, phosphoritic shale recording maximum marine transgression. He further stated that the Bandera Shale and Nowata Shale which underlie and overlie the Altamont Limestone, respectively, contain variegated, terrigenous detritus, often with coal, and record deltaic deposition. These units make up Schenk's Altamont megacyclothem and correspond to the members of Heckel's Kansas-type cyclothem. Core study of the Altamont cyclothem in the Dirks # 2 and subsequent log correlations indicate that the Lake Neosho Shale (core shale member) and possibly the Amoret Limestone (middle limestone member), described in outcrop, are absent in the study area (fig. 8). In contrast, all of the formations and members of the Lenapah cyclothem are present in the core.

Exploration methods

Watney (1980) detailed exploration techniques for the Lansing–Kansas City Groups in northwestern Kansas and southwestern Nebraska. Depositional environment and diagenesis were critical to reservoir development in this region. The regressive, upper limestone members afforded the best opportunity for hydrocarbon accumulation. Upper limestone reservoirs include grainstones and mud-supported rocks. Critical to reservoir development in the upper limestones was the creation of secondary porosity by brackish or freshwater dissolution of carbonate. In general, the effects of meteoric diagenesis become increasingly pronounced northward (landward) and over local topographic highs (Watney, 1980). In the Dirks # 2 core, porous intervals are likewise restricted to the regressive, upper limestone members (fig. 9), occur in grainstones (facies VI) and mud-supported rocks (facies II), and are characterized by secondary porosity produced by meteoric diagenesis.

Mapping by Watney showed that structure alone can not account for all Lansing–Kansas City production in this area. In fact, a major problem in the exploration for Pennsylvanian hydrocarbon accumulations in this region has been the lack of correspondence between present-day structure and distribution of reservoir facies. Production is on structure in some areas, but elsewhere it occurs on the flanks of structural highs or in lows. This lack of correspondence seems to be the case in the study area, where the producing interval is the Altamont Limestone (Worland Limestone Member). Here, the Texaco Dirks # 1 and # 2 are producing from a structural closure as mapped on the top of the Altamont Limestone, while the Texaco Dirks "B" # 1 production is from the flanks of that structure (fig. 10; on sheet 3 in back pocket). Thus, additional maps, e.g., lithofacies, isopachs, and porosity, are needed to define the play.

In Watney's work, porosity development is not necessarily related to present structure but may be controlled by lithofacies distribution or paleotopography. As seen in fig. 10, Altamont porosity shows a general correlation with present structure. In detail, however, this relationship does not hold (e.g., compare Dirks "B" # 1 and Dirks # 3 in sec. 29).

Lansing–Kansas City production in this region is commonly associated with subtle highs on the Pennsylvanian seafloor that were favorable to the development of reservoir-quality porosity. Higher energy conditions associated with these topographic highs may have resulted in the deposition of carbonate sands with good, primary intergranular porosity. In addition, these elevated areas would more likely undergo meteoric diagenesis and the formation of secondary porosity. An east-west cross section through Dirks and Miller fields (fig. 11) shows that the stratigraphic interval immediately overlying the Altamont Limestone is relatively thick in the Dirks # 2 dry hole, the southernmost well on the cross section. This thickening suggests a position just off a subtle Altamont high. The lack of porosity in the Altamont in the Dirks # 2 (fig. 10) may indicate the absence of significant meteoric diagenesis in this setting. Thus, porosity and permeability development in the Worland Limestone Member of the Altamont Limestone (facies II), the reservoir in the Dirks and Miller fields, seems to have depended primarily on meteoric diagenesis associated with a local Altamont high on the seafloor.

Conclusions

Core 4 of the Texaco Dirks # 2, Logan County, Kansas, records deposition of a broad, epeiric shelf, a northern extension of the Hugoton embayment, in response to fluctuating sea level and varying terrigenous influx. The core includes two Kansas-type cyclothems (facies I–III and III–VII), Marmaton in age. Regressive carbonate units in the cyclothems, termed upper limestone members in Heckel's (1977) model, afford the best opportunities for hydrocarbon reservoirs. The regressive carbonate of the upper part of the core, facies VI (Idenbro Limestone Member of the Lenapah Limestone), displays primary intergranular and secondary moldic, primarily oomoldic, porosity. Porosity is poor to locally fair. The regressive carbonate which makes up facies II (Worland Limestone Member of the Altamont Limestone) is heavily oil-stained and is the pay in the study area. Primary intragranular and secondary porosities, including moldic, solution-enlarged moldic, vuggy, and fracture, characterize this carbonate. Porosity here is fair to locally good and permeability in the fractured portion of the facies is good. Porosity development in facies II was primarily the result of meteoric

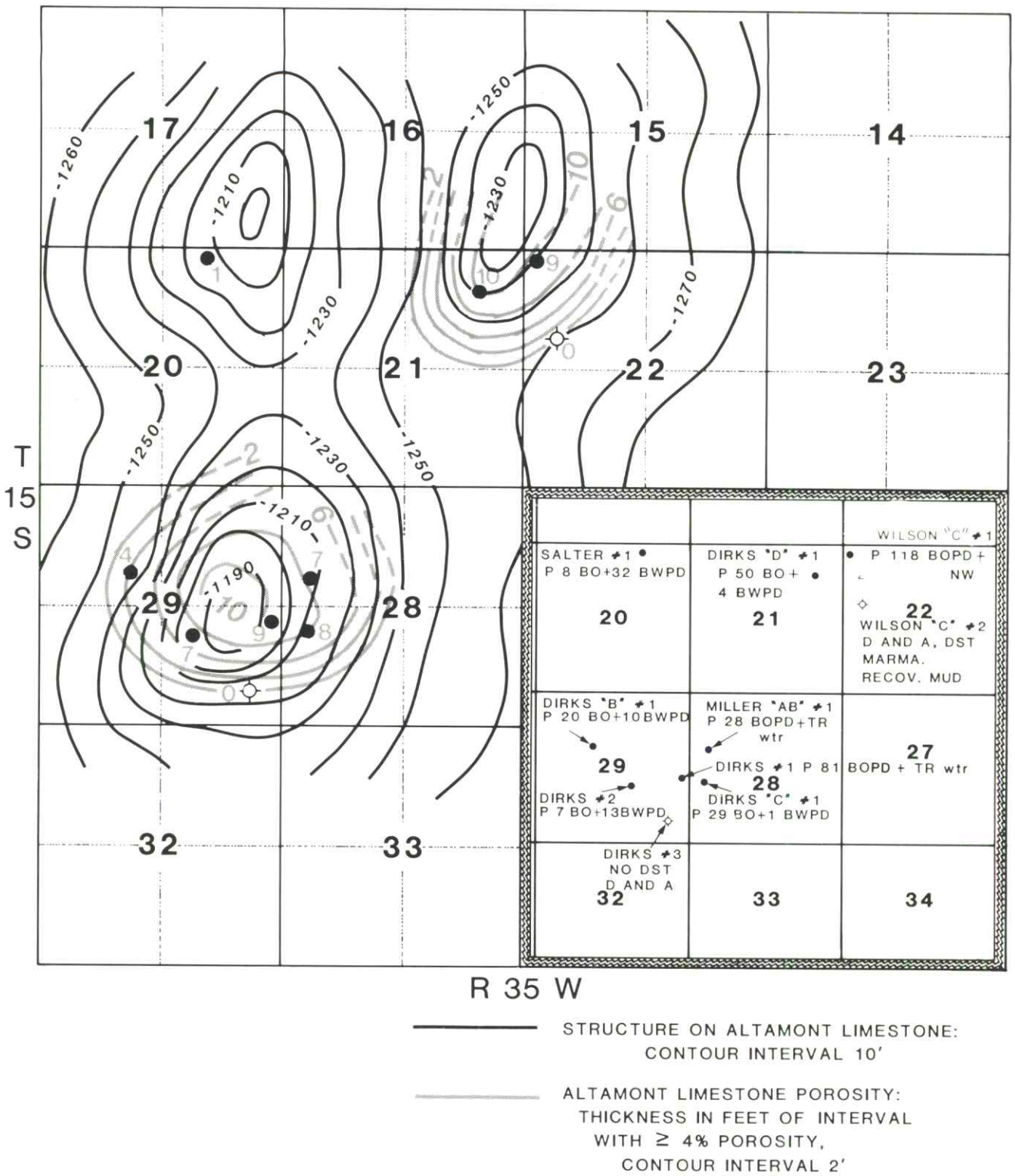

FIGURE 8—Map showing relationship of Altamont porosity, determined from compensated neutron-formation density log, to present-day structure mapped on the Altamont, T. 15 S., R. 35 W., Logan County, Kansas. Inset shows well names and initial productions.

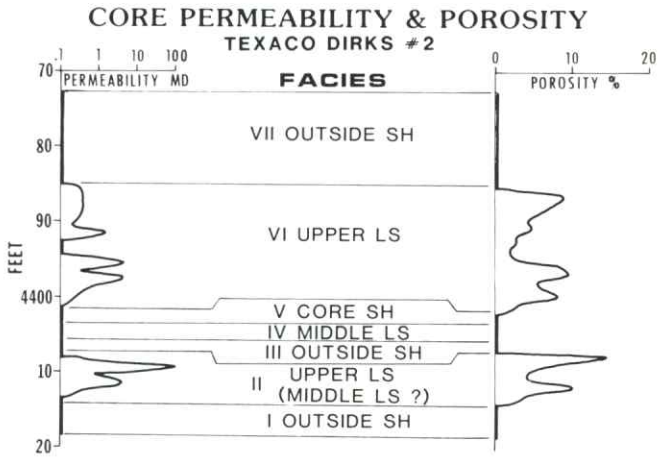

FIGURE 10—Core permeability and porosity of Texaco Dirks #2.

diagenesis which was related to subaerial exposure on an Altamont high on the seafloor.

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Plates 1–6 follow

PLATE 1—Facies I and II.

A) Mottled, greenish-gray siltstone of facies I (units 1 and 2). Mottling is due to plant-root action (p) or perhaps burrowing.

B) Interbedded shale and crinoid wackestone of the lower part of facies II (unit 4).

C) Bioclast wackestone facies II (unit 5) showing green algae plates (a) and *Tubiphytes* (T).

D and E) Secondary porosity in bioclast wackestone of facies II (unit 5). Photomicrograph E (crossed nicols) shows moldic (leached bioclasts) porosity (m). Photo D shows moldic (m) and solution-enlarged moldic (?) porosity in dolomitized wackestone. Some bioclasts (green algae plates) have been leached and the resulting pore space infilled by medium-crystalline, dolomite cement (dc).

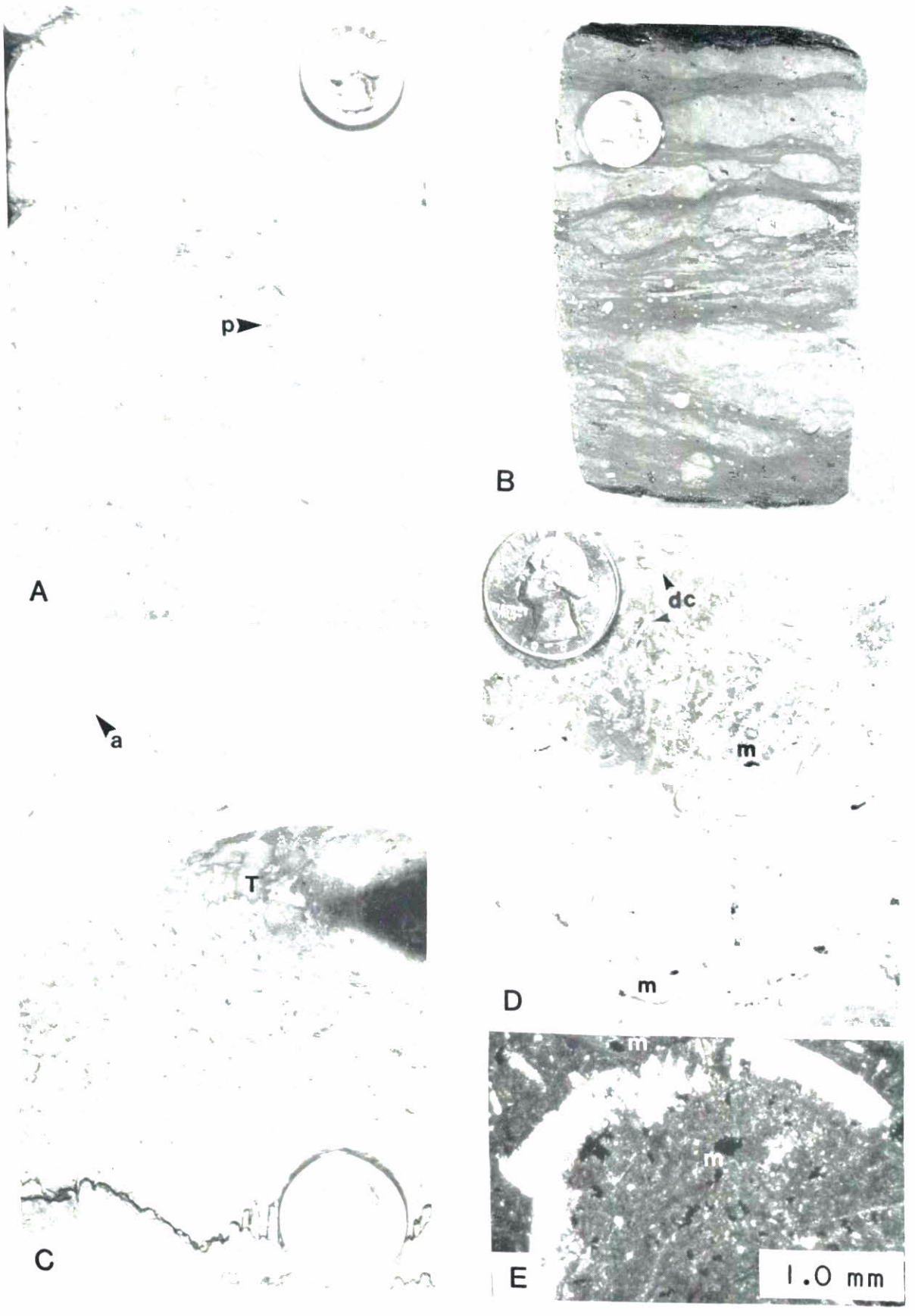
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PLATE 2—Facies II.

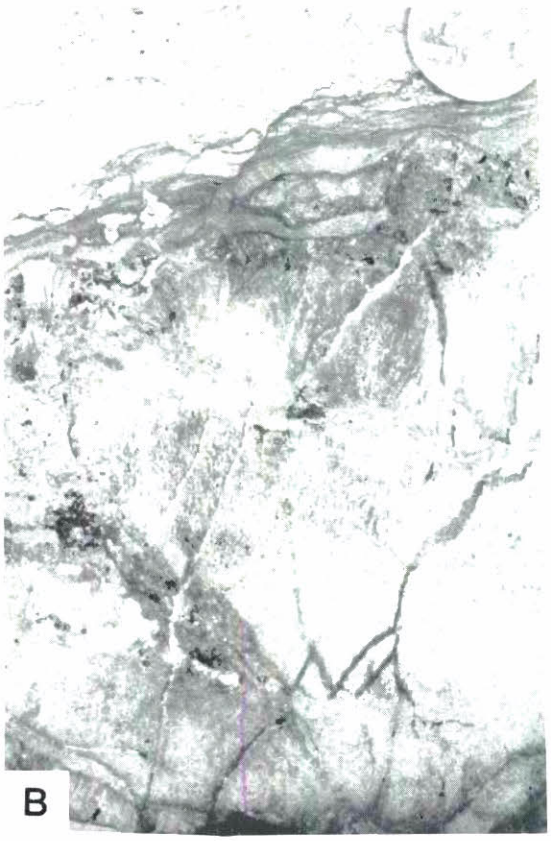
A) Sharp, irregular contact between sparsely fossiliferous, light-gray dolomite of the upper part of unit 5, facies II, and coated-grain packstone of the lowermost part of unit 6, facies II.

B) Fractured, *Chaetetes* bafflestone (unit 6) and abruptly overlying dolomite (unit 7).

C) *Chaetetes* coral chambers filled by dolomite (light-colored) and minor calcite cements (unit 6).

D and E) Photomicrographs showing chambers of the tabulate coral *Chaetetes* (unit 6). Chambers are open (o) or are filled or partially filled with micrite (m), calcite cement, dolomite cement, or residual hydrocarbons (h). Note diagonal band of collapsed chambers in photo D. Both photos under plane light.

A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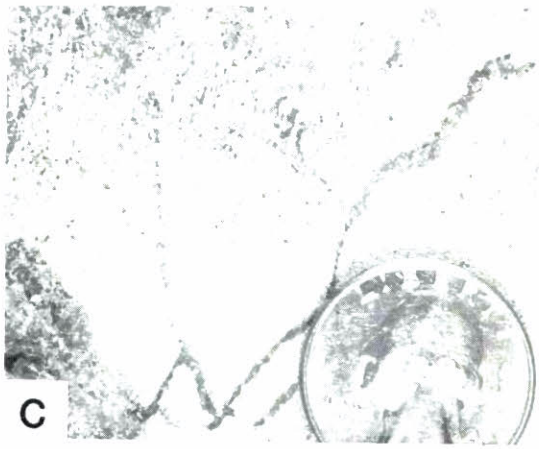
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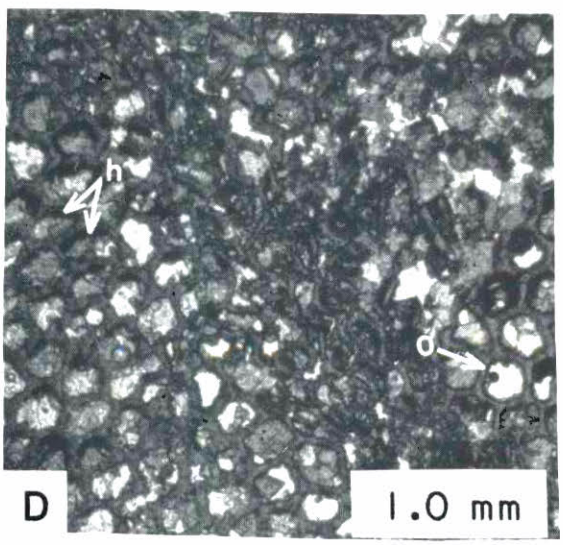
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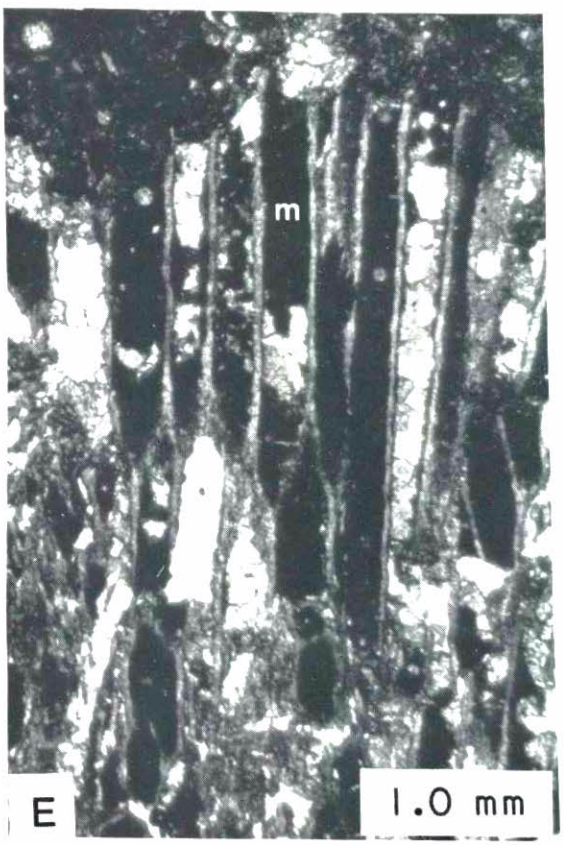
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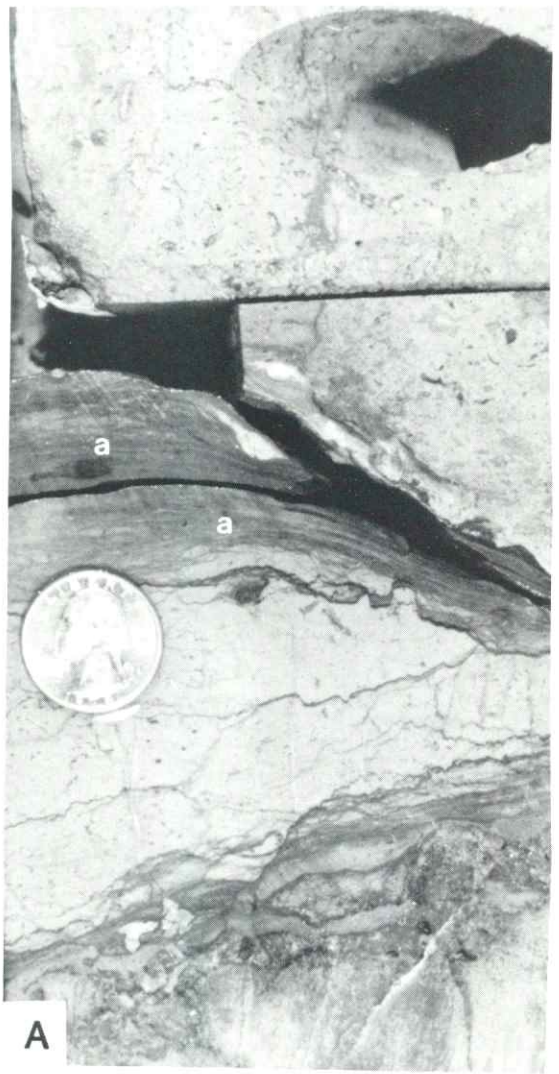
PLATE 3—Facies II.

A, B, and C) Dolomite and dolomitic limestone of facies II (unit 7). Photos show planar algal stromatolites (a), clasts (c), moldic (m) and fracture (f) porosity, clay-filled fractures or fissures (fr), and the irregular upper surface of facies II (S). Dolomite at top of unit may be a caliche (photo B).

D) Photomicrograph of clasts in dolomitic limestone of facies II (unit 7).

E) Solution-enlarged moldic (em) and moldic porosity in finely crystalline dolomite of facies II (unit 7), light-colored clasts (c). Photo taken under crossed nicols.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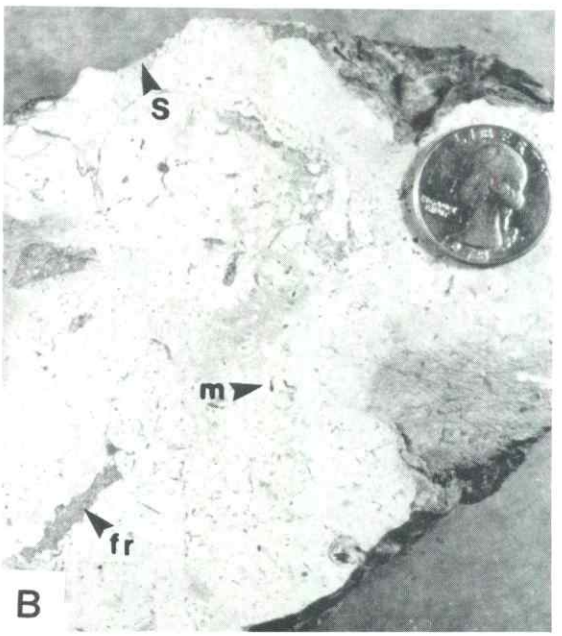
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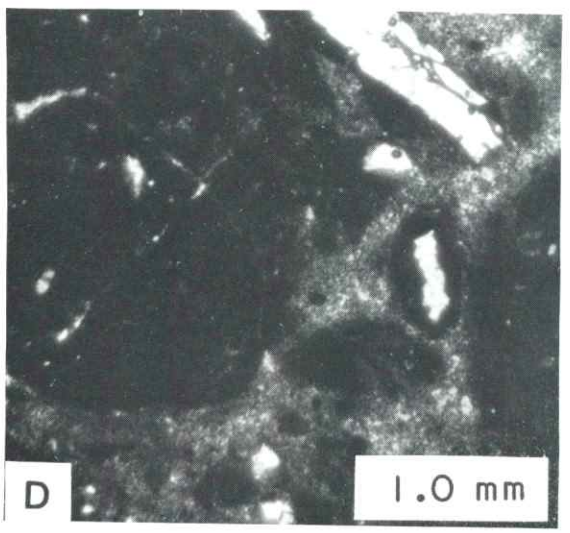
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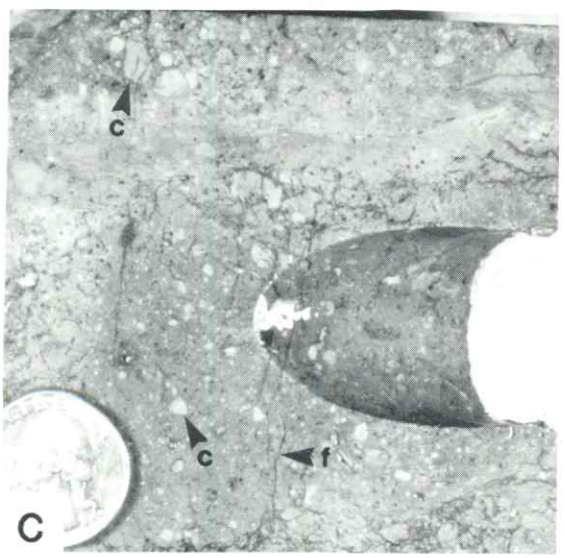
c
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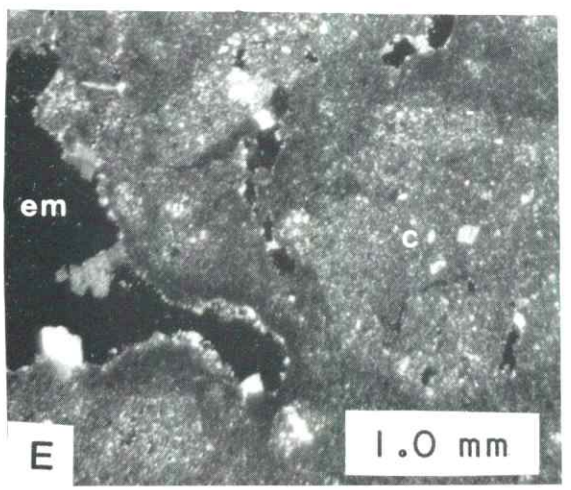
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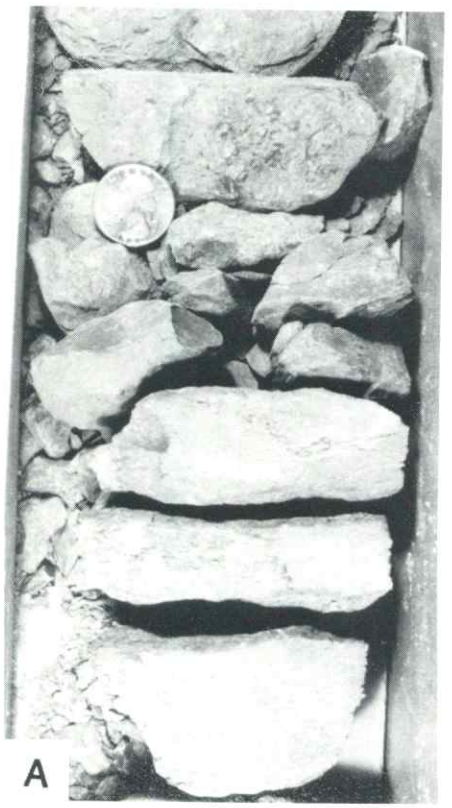
PLATE 4—Facies III, IV, and V.

A) Olive-gray shale of the lower part of facies III (unit 8).

B and C) Bioclast wackestone of facies IV (unit 9). Note *Osagia* grains (o) and crinoids (c) in photo B and burrow mottled character of limestone in photo C.

D) Olive-black, fissile shale of facies V (unit 10). Band of thin-shelled brachiopods and phosphorite (?) nodules (pn) in middle part of photo.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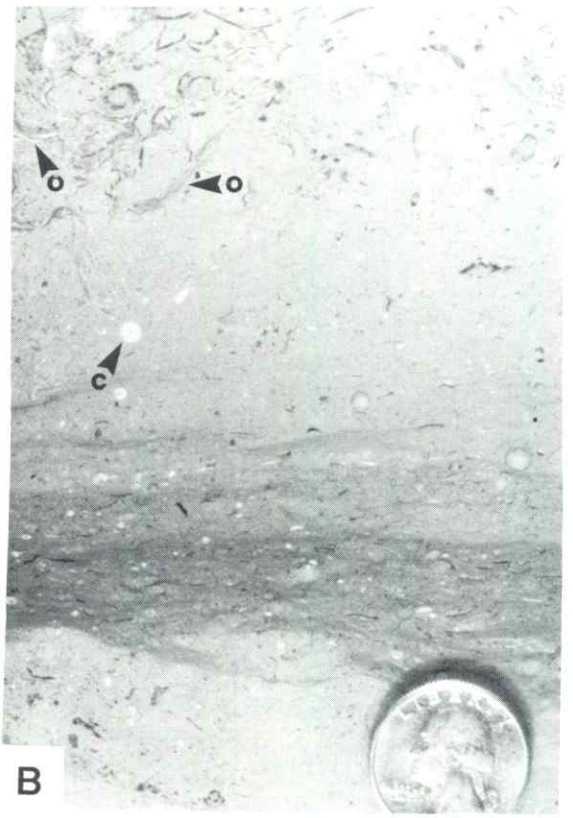
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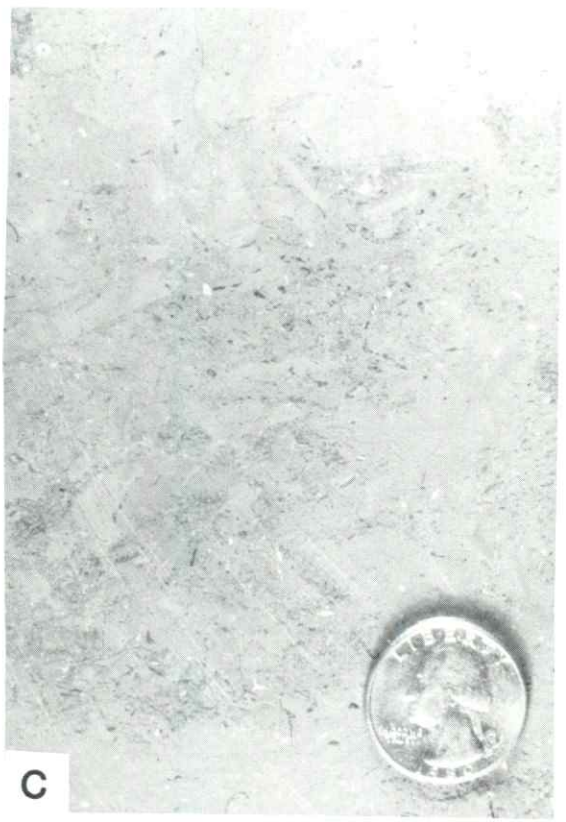
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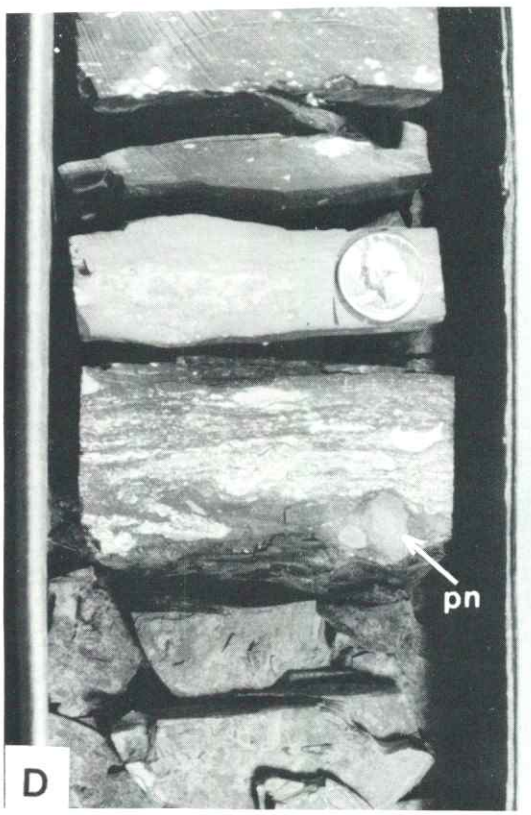

pn
D

PLATE 5—Facies VI.

A) Argillaceous, crinoid wackestone of the lowermost part of facies VI (unit 11).

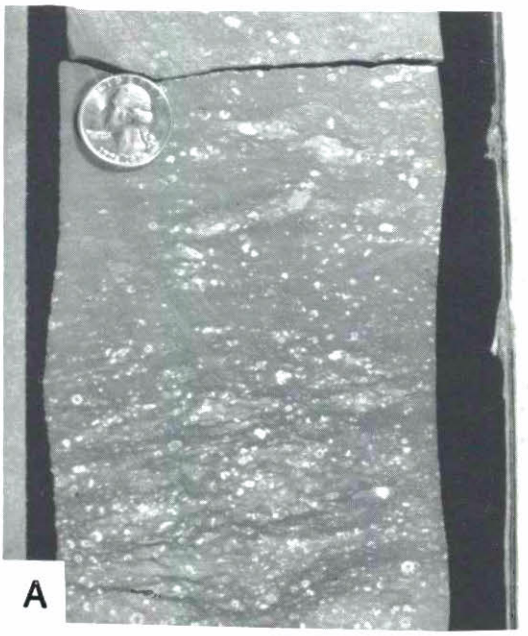
B) Bioclast packstone of the lower part of facies VI (unit 12); crinoid (c) and bryozoan (b).

C) Bioclast grainstone, facies VI (unit 13) containing crinoids (cr), calcispheres (?) (c), bryozoans (b), and small mobile forams (f). Plane light.

D) Overcompacted crinoid grainstone/packstone, crinoid fragments commonly with syntaxial, calcite overgrowths (unit 12).

E) Ooid-bioclast grainstone of facies VI (unit 16) showing early, marine isopachous cement (e), a later, finely crystalline, equant calcite cement (b), poikilitic, echinoderm overgrowths (o), primary intergranular porosity (p), and secondary oomoldic porosity (s). Photo under crossed nicols.

F) Peloidal limestone, facies VI (unit 15), displaying mudcracks (?) (mc) and overlain by siltstone-lime mudstone conglomerate and above that interbedded shale and crinoid-bryozoan wackestone (b = bryozoans).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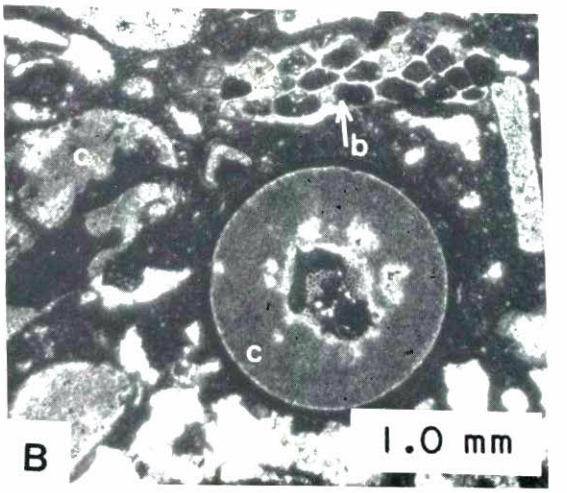
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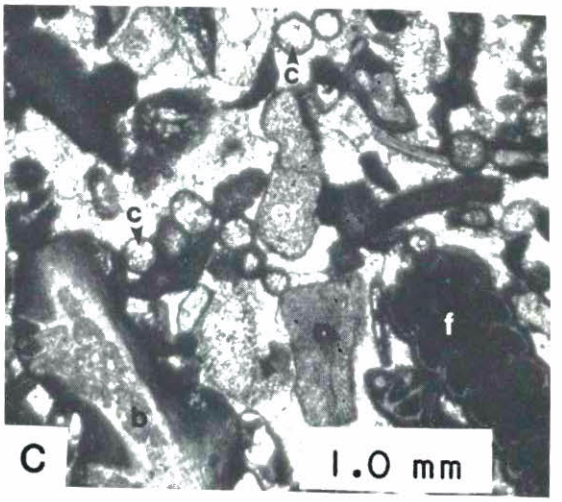
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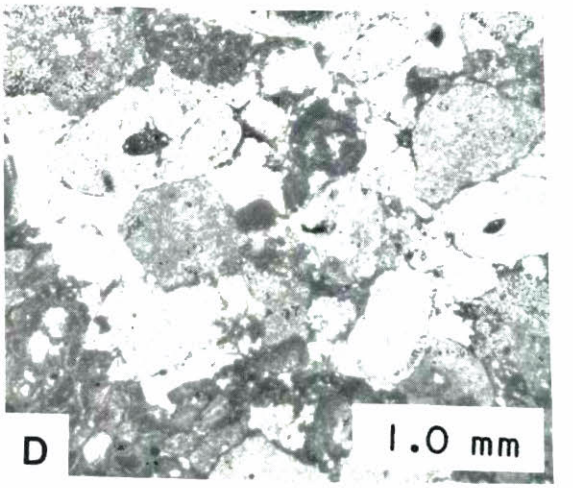
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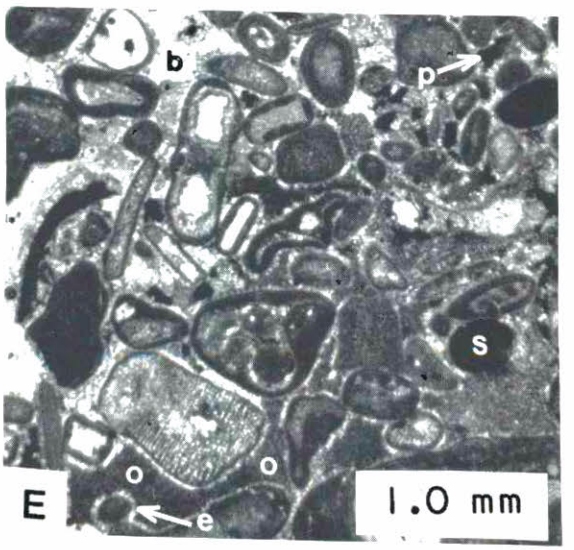
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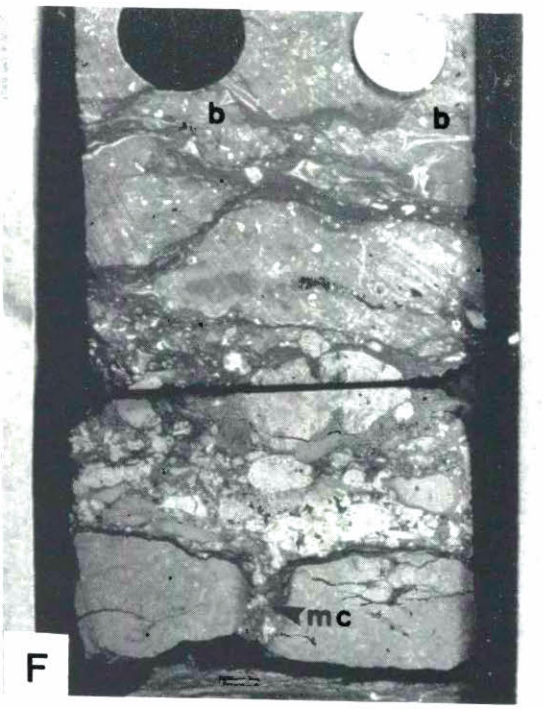
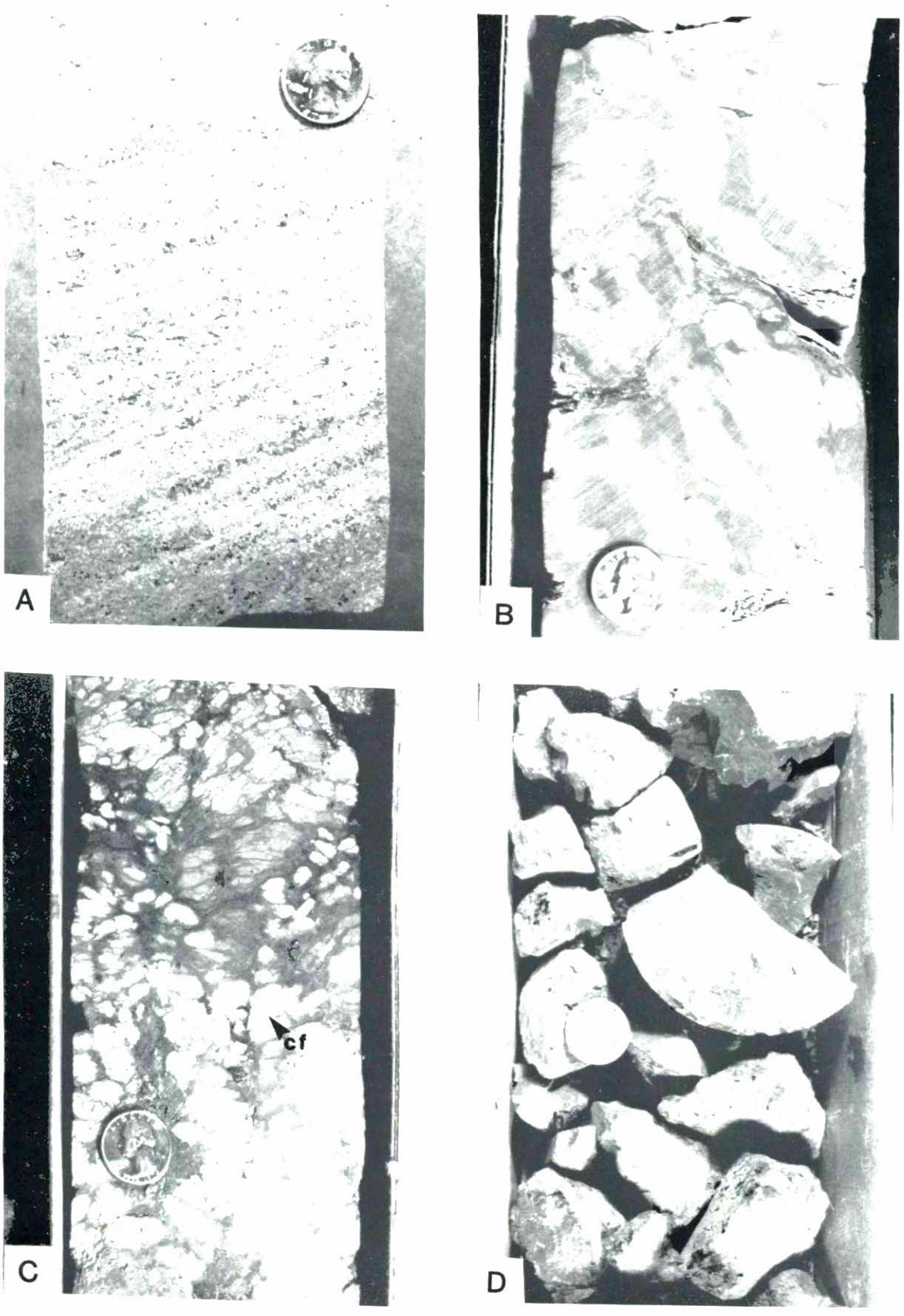

b
b
mc
F

PLATE 6—Facies VI and VII.
A) Cross stratified, ooid grainstone of the uppermost part of facies VI (unit 16).
B) Nodular, lime mudstone and shale of facies VII (unit 19).
C) Shale and nodular limestone with calcite-filled fractures (cf) resembling caliche, facies VII (unit 19).
D) Brownish-gray, unfossiliferous mudstone, facies VII (unit 20).


A
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Swope Limestone (K-Zone) in central and southwestern Kansas, the role of core in understanding reservoir development and mechanisms responsible for cyclic sedimentation

by *W. Lynn Watney*, Kansas Geological Survey, Lawrence, Kansas

Introduction

The Lansing–Kansas City has been an important oil-producing interval in Kansas for many years. Oil produced from this interval represents a significant portion of the 5.75 billion bbls estimated to have been in place in Pennsylvanian reservoirs in Kansas (Watney and Paul, 1983). Much of this oil reservoired in Lansing–Kansas City units has been found on the Central Kansas uplift (fig. 1) where oil was first discovered in 1923.

During 1981 and 1982 the Lansing–Kansas City was the leading pay zone in discovery wells while the Mississippian strata maintained second place. Comparisons such as net reserves added by new discoveries may show a completely different picture, but these figures are not available. On the contrary, the Lansing–Kansas City reservoirs are are well known to be discontinuous, and geological factors besides structure are usually important parameters that must be considered early in developing a successful exploration strategy in the search for these reservoirs.

Key ingredients in understanding and exploring for petroleum reservoirs in Lansing–Kansas City carbonates are core data and a suite of logs that accurately resolve the variation of the stratigraphic succession. Rig time is costly and cores are difficult to justify for every hole, but logs and core contain essential geologic information that permits the recognition and correlation of lithofacies. This information also provides geologists with an opportunity to understand more about the type, origin, and distribution of porosity necessary in evaluating prospects in these strata.

The objectives of this paper are as follows: 1) to provide an overview of cyclic stratigraphy and geologic setting of western Kansas; 2) to compare and contrast the observations in the cores chosen in central and southern Kansas (complementing other papers on the Lansing–Kansas City presented in this compilation); and 3) to integrate the observations made from the cores into a regional depositional setting, relating the results to exploration strategy.

Cyclic stratigraphy and geologic setting for the Lansing–Kansas City in western Kansas

The Lansing and Kansas City Groups are an Upper Pennsylvanian (Missourian) age succession of some dozen repetitions each composed of a transgressive carbonate, a marine shale, and several regressive lithofacies. These cycles are dominated by the regressive carbonate, generally the site of the petroleum reservoir. The component lithofacies are as follows, listed from top to bottom:

1) regressive shale
2) regressive carbonate
3) marine shale
4) transgressive carbonate;

or in cyclothem nomenclature—originating with R. C. Moore (1929) and later modified by Heckel and Baesemann (1975):

1) outside shale
2) upper limestone
3) core shale
4) middle limestone.

The transgressive carbonate and marine shale are typically thin in all cycles in western Kansas. Furthermore, the marine shale can be a strong emitter of natural gamma radiation and thus provide a striking response on a gamma-ray log.

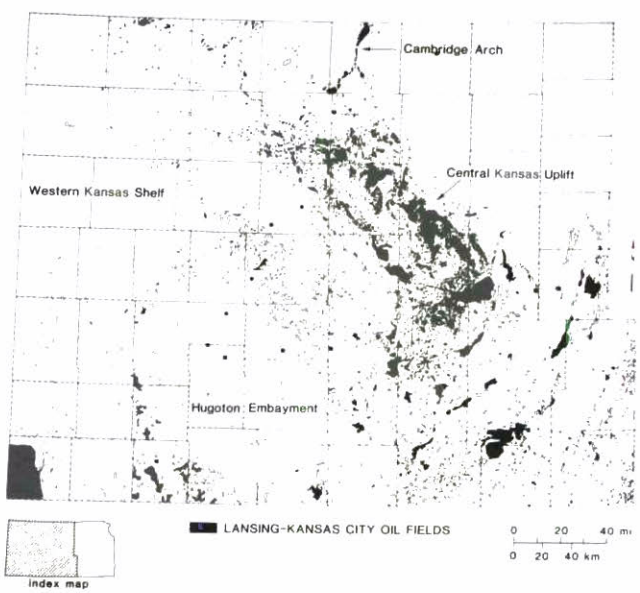

FIGURE 1—Producing oil fields from Lansing and Kansas City Groups in western and central Kansas. Fields producing from this interval are solid black, while other fields with other pay zones are only outlined. Locations of five cores shown; Stegman, Litsey 4, and Lemon 6 denote locations of core described in this paper. Symbol reflects production status in Lansing–Kansas City interval (dot represents oil producing).

The Swope Limestone, the focus of this paper, hereafter referred to as the K-Zone, contains the excellent subsurface marker bed, the generally black Hushpuckney (marine) shale. The correlation is particularly clear in combination with another marker in the overlying J-Zone (the Stark Shale Member of the Dennis Limestone described by M. K. Dubois in this volume). The letter nomenclature is in common use in the subsurface of western Kansas, originating from Morgan (1952). Parkhurst (1959) established the correlation between this subsurface nomenclature and the formal outcrop names.

The vertical heterogeneity of lithofacies in the Lansing–Kansas City does fit a cyclic template dominated by regression, i.e., shallowing-upward succession. A simple model of sediment progradation and aggradation does not adequately explain the generation of the K-Zone cycle, but rather other regionally significant mechanisms such as eustatic sea-level change have been proposed (Moore, 1929; Wanless and Shepherd, 1936; Heckel, 1977, 1980).

The major conclusions reached by Watney (1983) concerning mechanisms of cycle development include: 1) the major mechanism producing the cycle is an oscillating change in eustatic sea level on the order of a minimum of 200 ft—first the sea rapidly inundating the shelf, then sea level more slowly falling until essentially all of the shelf in western Kansas is emergent, permitting flushing by freshwater and resulting early diagenesis, and 2) time-variant episodic changes of relief of the depositional surface across western Kansas producing second-order changes in facies distribution in each of the lithofacies components.

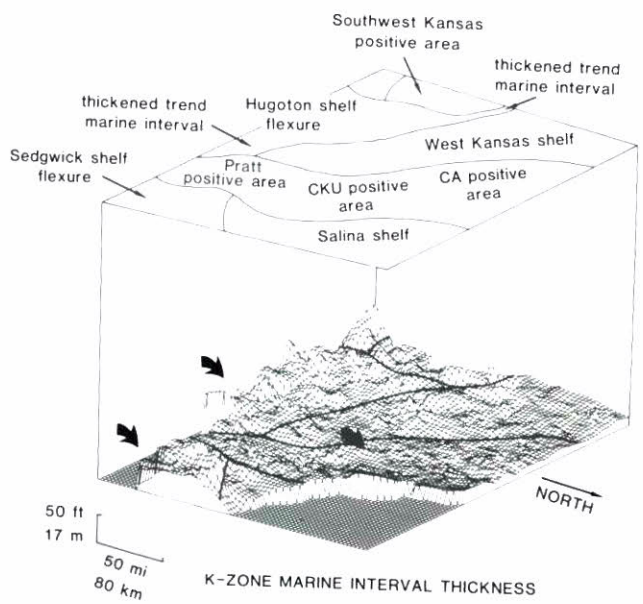

FIGURE 2—Perspective diagram of the marine-interval thickness of the K-Zone looking southwest over the study area in western Kansas. Above the perspective diagram are the various subdivisions of the depositional platform based on core and isopach information. Areas of flexure represent regions of rapid thickening and marine interval of K-Zone; areas of flexure border the Anadarko Basin immediately south, a basin which was subsiding rapidly during the Missourian. The approximate locations of the cores are located by the arrows: Stegman on the Central Kansas uplift (CKU) positive area, Litsey on the flanks of the Pratt positive area, and Lemon on the Hugoton flexure area.

The cores of the K-Zone described below were chosen specifically to illustrate evidence for subaerial exposure of the K-Zone regressive carbonate all which preceded the next shelf-wide inundative event (J-Zone). Secondly, the choice of three cores distributed across central and southwestern Kansas, representing only portions of the K-Zone in the two southernmost examples, was done to compare and to contrast the late regressive processes of the K-Zone on the Central Kansas uplift, on the flanks of the Pratt anticline, and on the southwestern shelf during K-Zone deposition (fig. 1). Several maps are shown to assist in obtaining this perspective. Details of the shelf setting in western Kansas are available in Watney (1984). A general diagenetic model for the Upper Pennsylvanian cyclothem is described by Heckel (1983). Nollsch (1983) evaluated this model for the Swope Limestone along the outcrop area in eastern Kansas to southwestern Iowa.

Western Kansas was the location of a broad stable platform during the Late Pennsylvanian. The Lansing-Kansas City was deposited some 20 m.y. after the major tectonic movement of the Central Kansas uplift (CKU) and the Cambridge arch (CA) during the Late Mississippian and earliest Pennsylvanian. The positive residual relief on the CKU and CA were finally covered with Pennsylvanian sediments by the time of K-Zone (Swope) deposition. Locally the K-Zone lies directly on the Precambrian surface over local positive elements on the crest of the CKU. Isopach and lithofacies maps of Pennsylvanian strata reveal the positive nature of these features (figs. 2–4).

The region south and west of the CKU–CA during Missourian time represented a stable carbonate-dominated shelf setting at least as far south as the Oklahoma–Kansas border. South of this area a constructive carbonate shelf margin has been described (Rascoe, 1962; Lane, 1977; Kumar and Slatt, 1982) beyond which the Missourian carbonate succession rapidly diminishes in thickness into the Anadarko Basin.

Format and keys for core descriptions

Three sets of illustrations are used to describe the three cores chosen in this study. Figs. 7, 8, and 9 are descriptions of each core providing a graphic log keyed to the legend for lithology and particle and fossil types shown in fig. 6. A column marked "facies" in figs. 7, 8, and 9 is coded according to fig. 5. Another column labeled "diag. overpr." (diagenetic over-printing) is keyed also to fig. 5. A brief description of the lithologies is included for each core. While the entire 17 ft of the K-Zone in the Stegman core is displayed in fig. 7, only the very upper, cored portions of the K-Zone are illustrated in the other two cores, only 19 ft of the 43-ft-thick K-Zone in the 4 Litsey well (fig. 8) and 16 ft of the 50-ft-total thickness in the 6 Lemon well (fig. 9).

Fig. 10 illustrates the combined graphic core and wireline logs for each cored well. The box along the right side of each illustration in fig. 10 represents an environmental interpretation described in the figure caption. Notice that

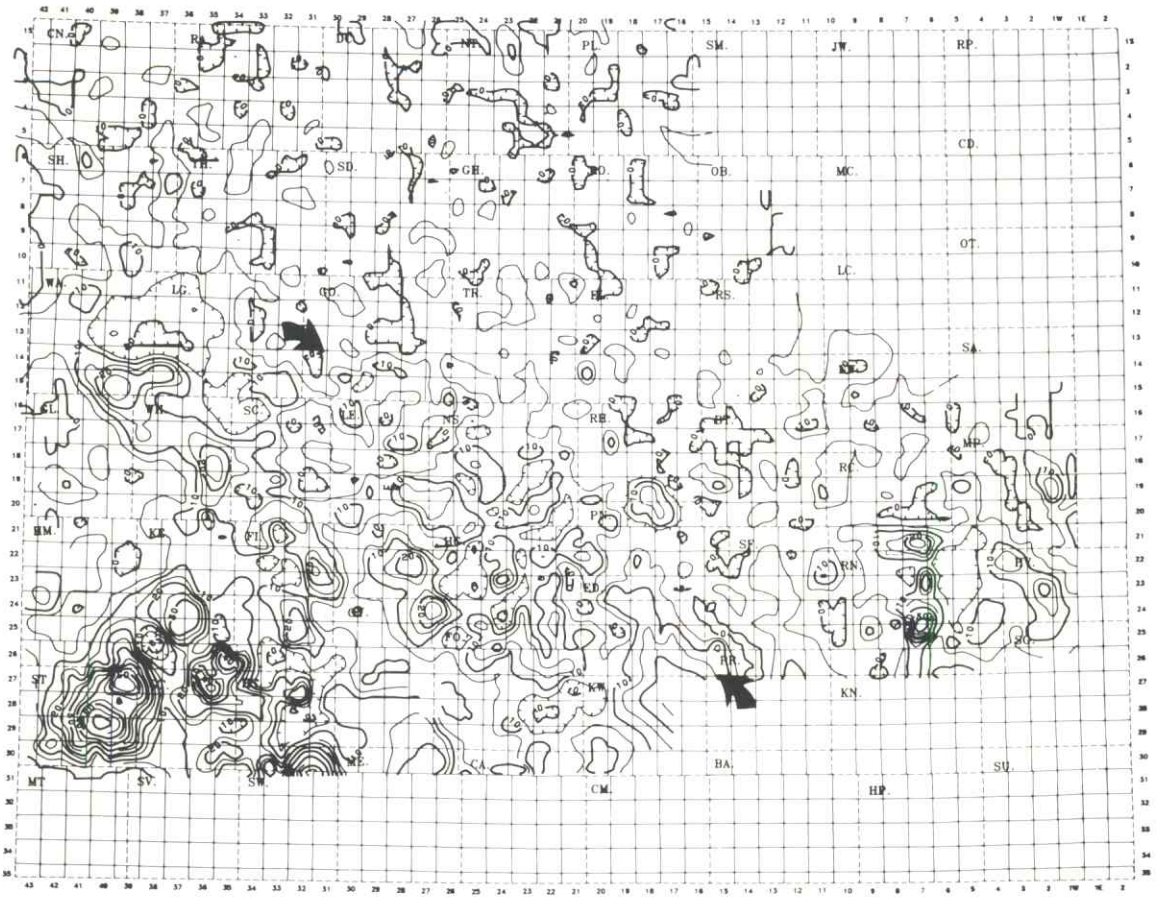

FIGURE 3—Contour map of total thickness of porous carbonate in the K-Zone regressive carbonate reflecting 2,300 points of control; contour interval is 5 ft. Labels include township numbers around the edge of the diagram and county outlines (dashed) and their abbreviations. Note the township-sized porous lobes that terminate northward in the vicinity of Lane (LE), Hodgeman (HG), and Edwards (ED) Counties in the south-central portion of the study area indicated here between the two arrows. This porosity trend coincides with the northern edge of the Hugoton shelf flexure (fig. 2). The dominant porous carbonate facies here is oolite. The Lemon core is representative of this trend.

the entire K-Zone is identified in the graphic, even though it was not entirely cored. Selected illustrations of core slabs and photomicrographs follow in figs. 11–13.

Clinton 2–D Stegman SENWNE sec. 11, T. 16 S., R. 17 W., Rush County

The 2–D Stegman core (sec. 11, T. 16 S., R. 17 W.) is located on the crestal area of the CKU and the northern edge of a local northwest-trending Precambrian high called the Rush rib (Merriam, 1963; fig. 1). The Rush rib is also the location of a Pennsylvanian isopach thin and structural high. The cored interval in the Stegman well cut the I- and J-Zones as well as the K-Zone (figs. 7, 10, and 11). The topmost surfaces of each of the regressive carbonates in the J, K, and L contain well-developed subaerial crusts indicating that this area became emergent immediately following the accumulation of carbonate sediment. The regressive shale in the J-Zone is a red-brown shale with caliche mottling, representing a well-developed soil zone typical of that seen in most cycles in northern Kansas. Furthermore, the upper surface of the underlying J-Zone carbonate is strewn with corroded, blackened, pitted clasts of dense, brown micrite lying on the subaerial crust. In the K-Zone, which is of interest here, the very thin (centimeters thick) regressive shale is green and unfossiliferous. The shale contains dark-brown solution-pitted fitted clasts of grainstone that again rest on top of a subaerial crust. This shale may actually be an infilling between in situ particles at the weathered top of the K-Zone regressive carbonate. The overlying fossiliferous shale of the next transgression (J-Zone) sharply overlies this shale. This contact very likely may be erosional in origin.

The dark-brown, laminated, micritic crust in the upper K-Zone consists of multiple surfaces, each well developed and distinct. Literature on characterizing and interpreting other ancient subaerial crusts is abundant. These surfaces are referred to as caliche crusts, carbonate crusts (James, 1972), calcrete (Klappa, 1979), laminated soil stone crusts (Robbin and Stipp, 1979), desert stromatolites (Krumbien

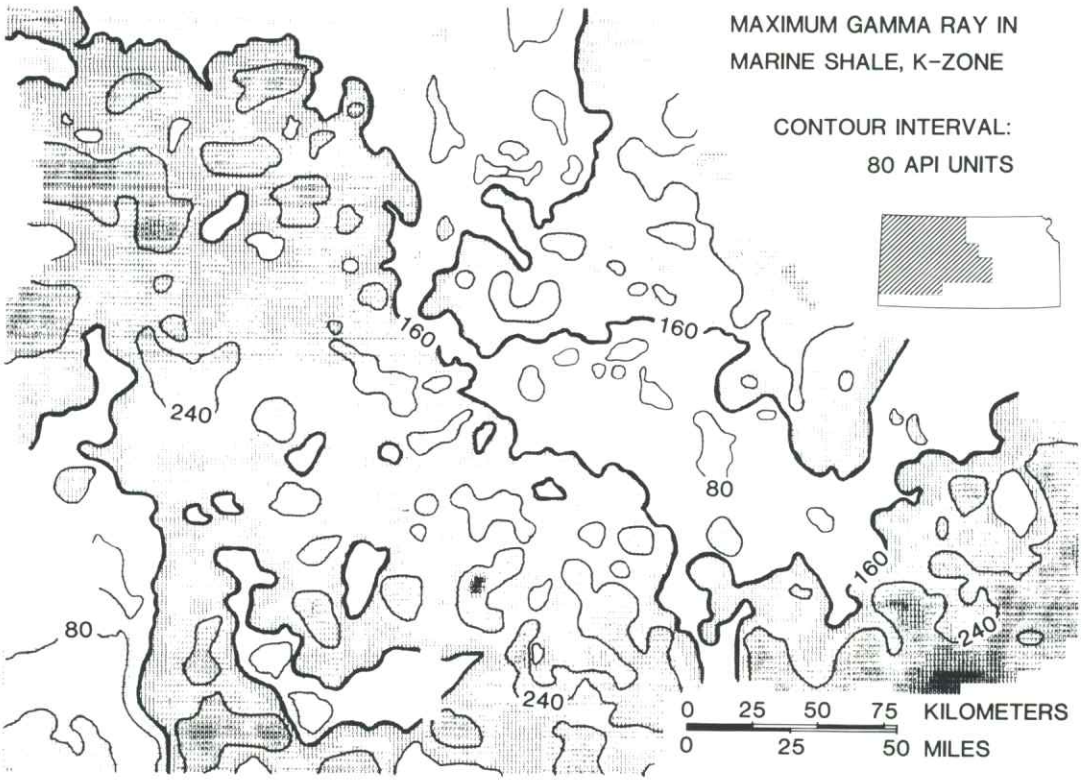

FIGURE 4—Variable-density contour map of the maximum natural gamma radiation recorded in the marine shale of the K-Zone; contour interval is 80 API units. Note that 160 API contour is heavier and essentially outlines the regions of the Central Kansas uplift, Cambridge arch, and the southwest Kansas positive area previously identified as isopach thins (fig. 2).

and Giele, 1979), cornstone (Steel, 1974), and subaerial laminated crusts (Multer and Hofmeister, 1968). Undoubtedly as more varieties are recognized and distinguished from hardgrounds, blue-green algal stromatolites, and other discontinuities, more credibility will be given to this thin, but very diagnostic, evidence for subaerial exposure.

Other related diagenesis within the grainstone in the upper K-Zone include the enhancement of intergranular pores to form a reticulated pore system coated by the same micritic carbonate that forms the subaerial crusts (Watney, 1984). Root casts, millimeter sized and lined again by the dense micritic carbonate, pepper the upper K-Zone. Also the upper carbonate is broken by sheet cracks (Dunham, 1969). Uppermost portions of the K-Zone carbonate are almost entirely composed of this early diagenetic, freshwater carbonate. Lower in the unit other related freshwater alteration is present including molds, vugs, and patchy recrystallization of micritic to microgranular (porous) calcite spar.

Below the upper grainstone, which is classified as a high-energy restricted (shallow-water) shelf facies, the regressive carbonate is mainly an open-marine wackestone, but near the base this carbonate is interrupted by 2 ft of tubular foram, blue-green algal-coated (*Osagia*) packstone perhaps representing a slightly restricted, marine environment. The agitation of the bottom is conjectural, but the particles are rounded and coated on all sides. While the general environment was low energy, the bottom may have been periodically agitated by storms with large waves with a particularly deep fetch. Lime mud could be removed while grains could be rotated to again continue to be encrusted after these storms. The unusual occurrence of this accumulation of coated grains suggests shallower waters at this site than in most other locations on the shelf. However, foraminifera-bryozoan-worm algal nodules are noted at a depth of approximately 125 ft off the Florida reef tract (Enos, personal communication, 1984). If the osagid facies is analogous to this modern example, deep, quiet, and open-marine conditions would still be the dominant environment at this position. Bottom agitation occurred early at this site shortly after the regressive carbonate began to accumulate.

The base of the K-Zone in the Stegman core is a thin, green, very fossiliferous shale covered by a thin, diversely fossiliferous packstone that contains probable phosphatic peloids and corroded clasts of carbonate rock. This is the transgressive unit, sharply overlying the thin, regressive shale of the underlying cycle. The overlying wackestone of the regressive carbonate rests on the packstone without the intervening Hushpuckney marine shale. Immediately off the crestal area of the CKU, the same unit was deposited and is black and dense. A hiatus must have existed at the top of the transgressive packstone as suggested by the accumulation of phosphate peloids. In any case, the bottom-water conditions were different over the uplift than over areas on either side during the accumulation of marine shale. From the regional examination of four Kansas City cycles in western Kansas (Watney, 1984), the site of the

Clastic facies

B	black shale with conodonts, fish scales, phosphate
DG	dark-gray shale--restricted fauna, orbiculoid brachiopods
GGR	green to gray shale, normal marine fauna including crinoids, brachiopods, bryozoa
GRQ	green quartz siltstone to claystone, lacks normal marine fossils
RB	red-brown, maroon shale or siltstone
CON	mixed pebble carbonate conglomerate

Diagenetic overprinting

M	molds
V	vugs
CSP	microgranular calcite spar
DSP	dolospar
S	silification
F	fractures
SC	solution channels
IB	in situ breccia
SHC	sheet cracks
CIRC	circumgranular cracks
RC	root casts
///	noticeable recrystallization
ᔓ	fissures--solution-enlarged vugs

Carbonate facies

1-O	brachiopod
2-O	crinoid-brachiopod
3-O	bryozoan
4-O	fusulinid-crinoid
5-SR	tubular (encrusting) foram + O (Osagia) + B (brach-crinoid) + G (gastropod-bivalve) restricted to slightly restricted marine
6-O-SR	phylloid algal, tubular foram, brachiopod, crinoid
67-SR	gastropod - bivalve (mollusk) - ostracod
8-R	silty, argillaceous micrite (mudstone)
9-VR	peloidal, laminated, fenestral micrite, very restricted
10-H	diverse skeletal packstone-grainstone, open marine
11-H	oolite
12-H	pellet, peloid, restricted skeletal packstone-grainstone, restricted marine
13-H	Osagia grainstone-packstone
14-S	subaerial crust
15-S	caliche
16-O	hardground
STR	stromatolite

FIGURE 5—Legends providing code and descriptions of depositional facies and diagenesis for figs. 7, 8, and 9.

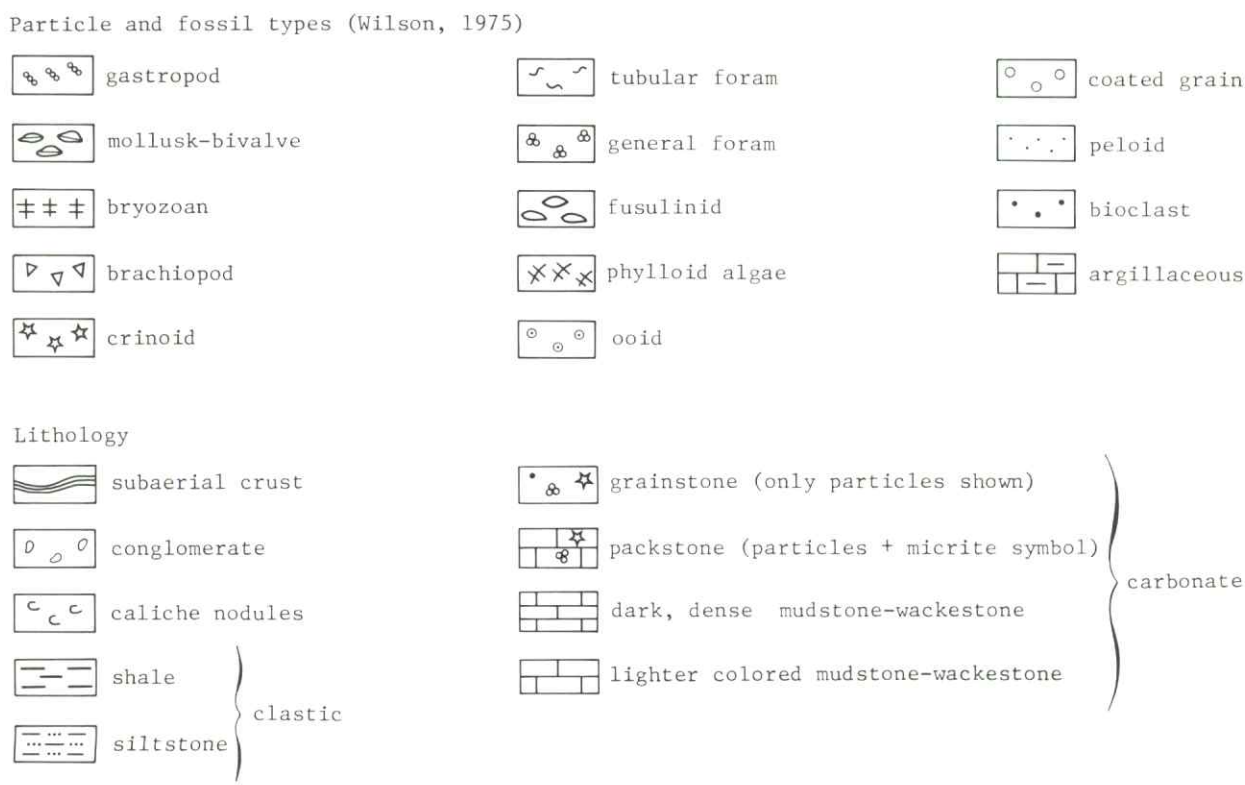

FIGURE 6—Additional legends providing symbols for particles, fossils, and lithologies used in graphic columns of figs. 7-12.

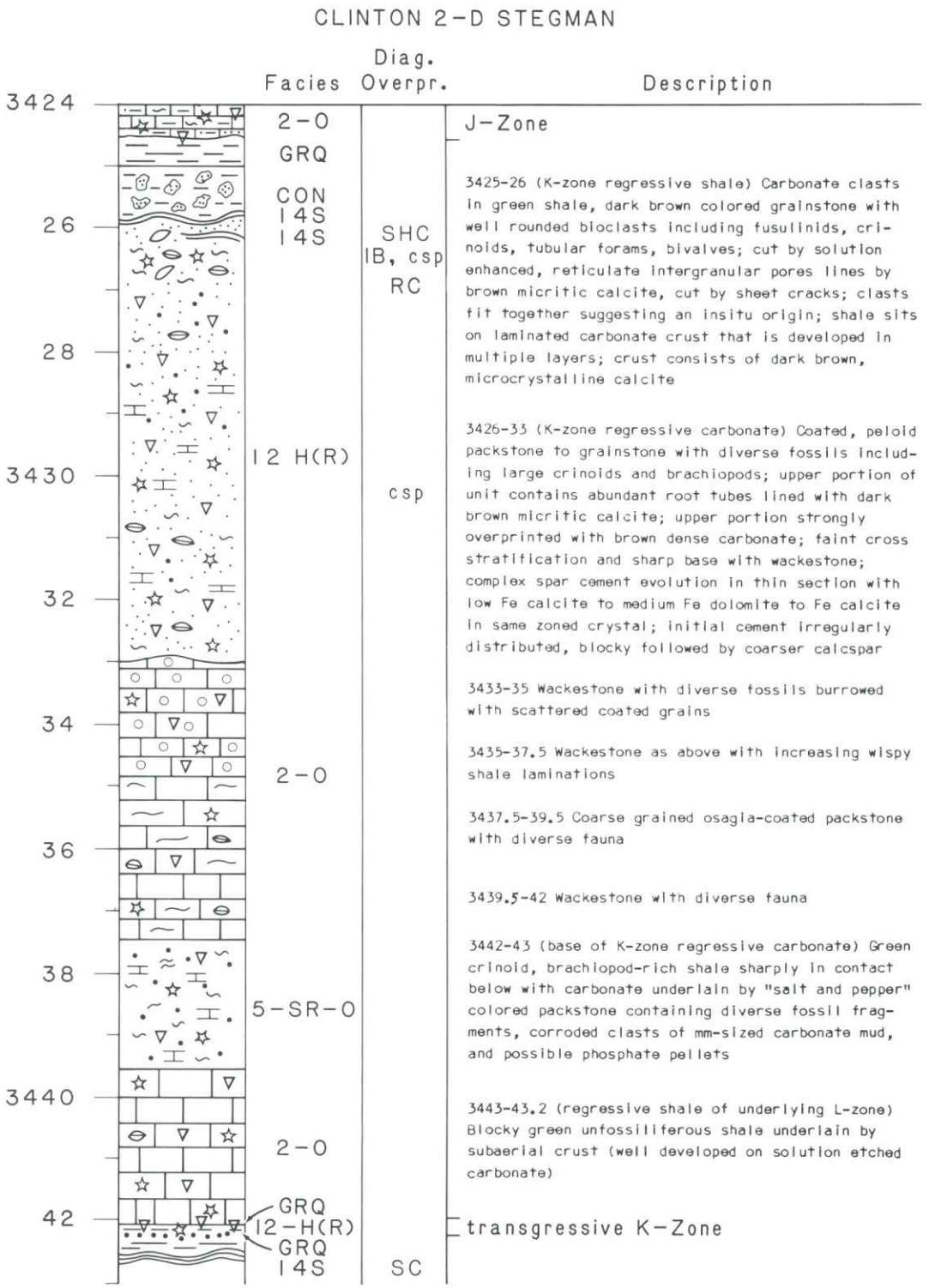

FIGURE 7—Core description of Clinton #2-D Stegman located in the SENWNE sec. 11, T. 16 S., R. 17 W., Rush County. Depths along left margin in feet, graphic column with symbols described in fig. 6, and facies and diagenetic overprinting symbols described in fig. 5. Cores described with the use of Dunham's (1962) classification of carbonates.

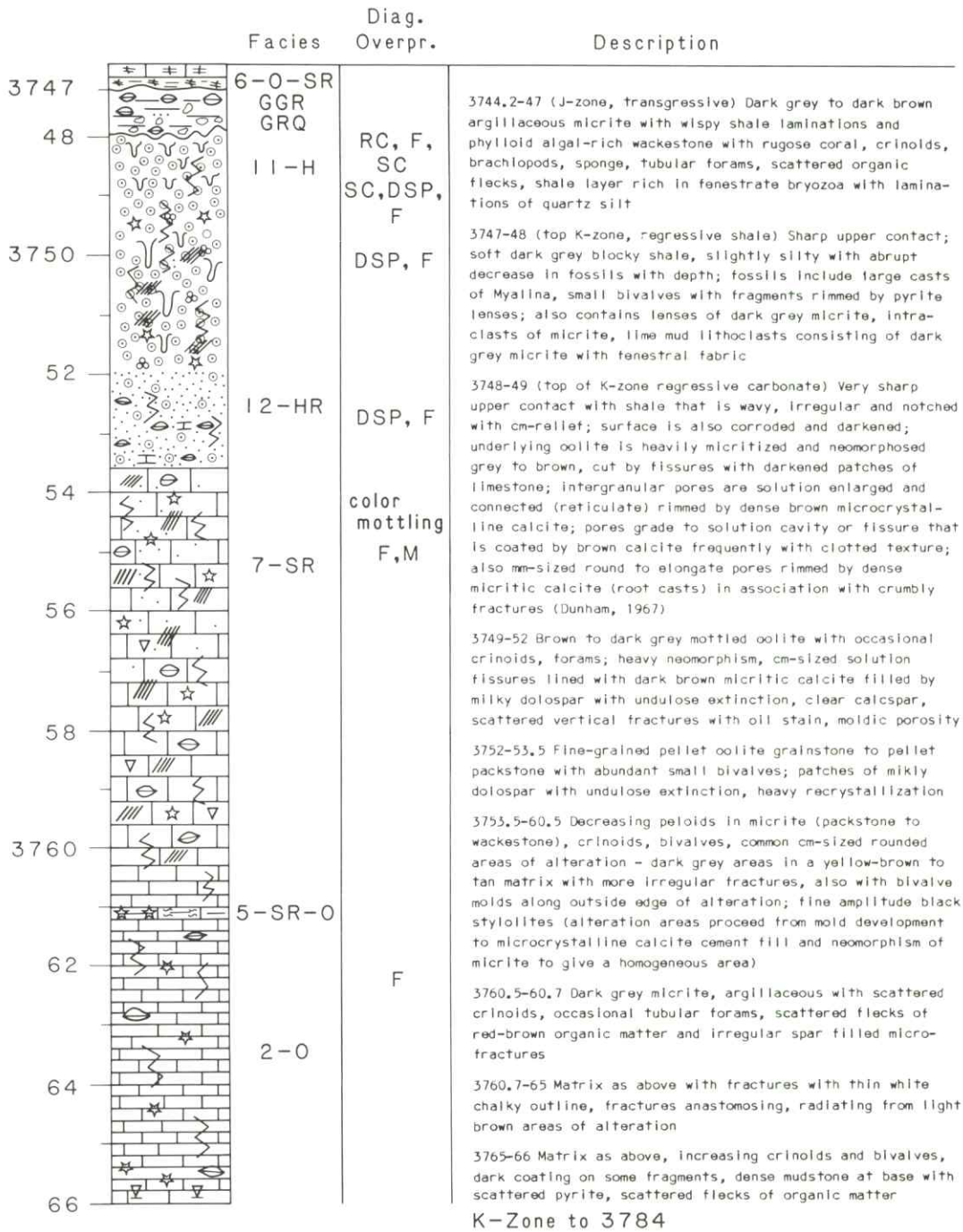

FIGURE 8—Core description of Texaco #4 Litsey located NENENW, sec. 25, T. 31 S., R. 6 W., Harper County.

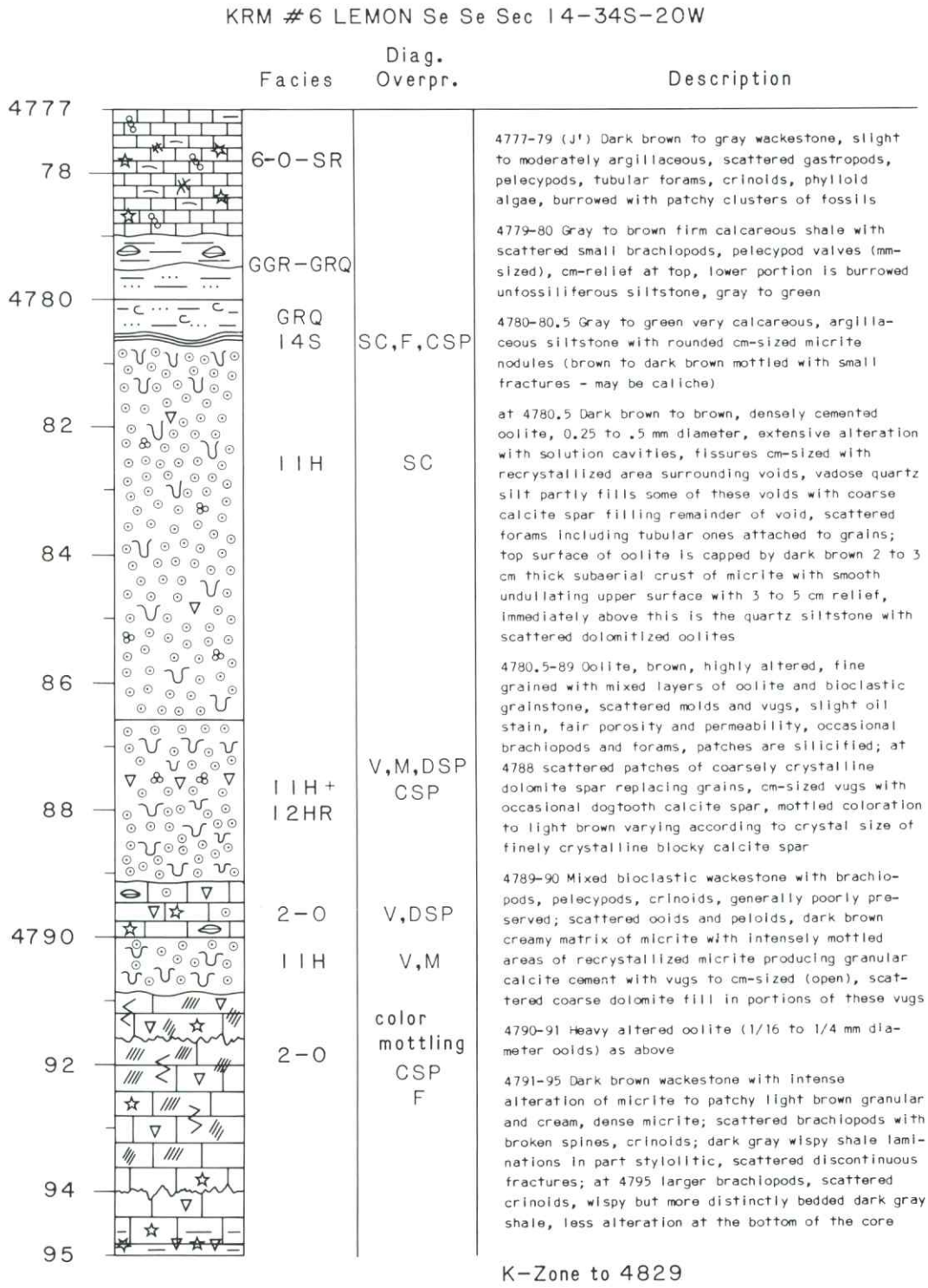

FIGURE 9—Core description of KRM Petroleum Corporation, #6 Lemon located in SESE sec. 14, T. 34 S., R. 20 W., Comanche County.

Stegman core was consistently the location for: 1) a condensed succession of lithofacies; 2) missing marine shale or low gamma-ray-emitting facies of the marine shale; 3) a transgressive, thin, lag conglomerate consisting of eroded particles and marine skeletal debris; 4) thin or missing regressive shale; 5) distinctive and abundant evidence for subaerial exposure and rather extensive (intense) levels of freshwater diagenesis of the carbonates; and 6) shallow-water and slightly restricted to restricted marine-carbonate facies occupying a large portion of the regressive carbonate.

Pronounced subaerial exposure and freshwater diagenesis are recorded in other cores that are located on the CKU. Frequently, the development of secondary porosity associated with subaerial exposure such as solution vugs, fissures, fractures, and recrystallization of micrite have resulted in abundant, sometimes spectacular, reservoir development, almost independent of the original depositional facies. Previous experience of the author (Watney, 1980) and that of other workers in these sedimentary rocks (Brown, 1963; Dubois, 1979; Prather, 1981) has recognized the importance of grain-rich (generally higher-energy) carbonate rock in reservoir development. Grainstones directed the flow of undersaturated (fresh), dissolving waters into underlying mudstones and wackestones, perhaps creating secondary porosity, and were commonly stabilized under new diagenetic conditions with both the partial cementation of primary porosity and also the creation of new, secondary porosity.

What about the development of the cycle that was prevalent over regions flanking the CKU during the K-Zone? While the K-Zone is an important producing zone on the CKU, it also is one in areas west and south of the CKU. Not all areas are porous and permeable though, so what can account for the variation and how does this variation affect exploration strategy?

Texaco 4 Litsey NENENW sec. 25, T. 31 S., R. 6 W., Harper County, Kansas

The 4 Litsey core of the K-Zone (the second core described here) is located on the flanks of the Pratt anticline. The regional maps indicate that the location during the deposition of the K-Zone was a positive spine that extended southward off the CKU, coinciding very closely with the present-day structural configuration (fig. 2).

Fig. 8 only includes the upper 19 ft of the K-Zone. The contact with the overlying transgressive portion of the J-Zone is present indicating a marked change in depositional environment from that of the latest stage K-Zone (figs. 8, 10, and 12). The very top of the K-Zone is extensively altered by freshwater diagenesis though less apparent than in the Stegman well. However, definitive evidence for subaerial exposure also exists at this site. For example, the dense, brown, micritic calcite cement rims solution voids and root tubules (RC). This cement is essentially the same cement that composed the subaerial crusts in the 2–D Stegman core.

Clasts of what seem to be early lithified, micritic calcite from the upper corroded surface of the K-Zone regressive carbonate are now emplaced in a matrix of unfossiliferous silty shale. The reworking and scattering of particles preceded the overlying transgression and are likely related to the weathering and exposure of the K-Zone also suggested by other evidence. Solution cavities, fractures, crumbly fractures, collapsed ooids, and heavy, patchy, neomorphosed micrite further substantiate the importance and intensity of freshwater diagenesis at this location on the shelf. What is different between the Litsey and Stegman cores is described in fig. 10 and summarized as follows: 1) the cycle in the Litsey well is markedly thicker, although for a southerly shelf location it is actually only of intermediate thickness (see wirelog, fig. 10); 2) the Hushpuckney shale is highly radioactive in the Litsey well; 3) the facies succession is open marine to almost the very top of the cycle in the Litsey well; and 4) the lower cored interval of the regressive carbonate is low-energy, dense, darker carbonate in the Litsey well, a facies which is not common to the upper (northern) shelf.

The prominent differences that exist between the 6 Lemon and the 4 Litsey cores and that of the 2–D Stegman well are their greater thickness, thin restricted-marine facies compared to the Stegman core, and oolite vs. uncoated or only lightly coated bioclasts in the Stegman core. Note that although core is not available from the lower regressive carbonate, this interval has a higher gamma ray than in comparable positions in the regressive carbonates generally seen in the north. The portion logged in the J-Zone above the K-Zone in the 6 Lemon well also is similar. Cores from other wells from the southern area suggest that this lower carbonate is slightly to moderately argillaceous, dark colored, and contains flecks of organic matter. Previous work (Watney, 1979) suggests that the gamma ray alone is not a good measure of shale content in the lower regressive carbonates because of this organic matter (OM) and associated adsorbed uranium.

The oolite facies is leached and cemented, locally with solution of cement and collapsed oomolds and shards of cement. Coarse cements, blocky and scalenohedral calcite, abundant neomorphism of ooid cortices, and patchy recrystallization and discoloration of the wackestone that underlies the oolite are very prominent evidence of early diagenesis. Most of these observations are seen in thin section and are not readily apparent from the slab itself.

The alteration of the wackestone is analogous to a leopard pattern with irregular centimeter-sized patches of darkened micrite. Petrographic analysis indicated darkening is due to the presence of semi-opaque microcrystalline material, perhaps clay. This material is associated with microspar, pinpoint-sized vugs, and irregular, discontinuous fracturing. Similar patterns also are observed in micrite-rich sections beneath other oolitic grainstones from zones other than the K-Zone. The 6 Lemon core also shown here has this same alteration pattern in the wackestone beneath the oolite. Furthermore, the Swope limestone in a US–69 roadcut near LaCyne, Kansas, has this same alteration and duplicates these textural relationships.

The porous interval in the K-Zone of the 4 Litsey well coincides with the oolitic grainstone as indicated by the density-porosity curve in fig. 10. This oolitic zone also is

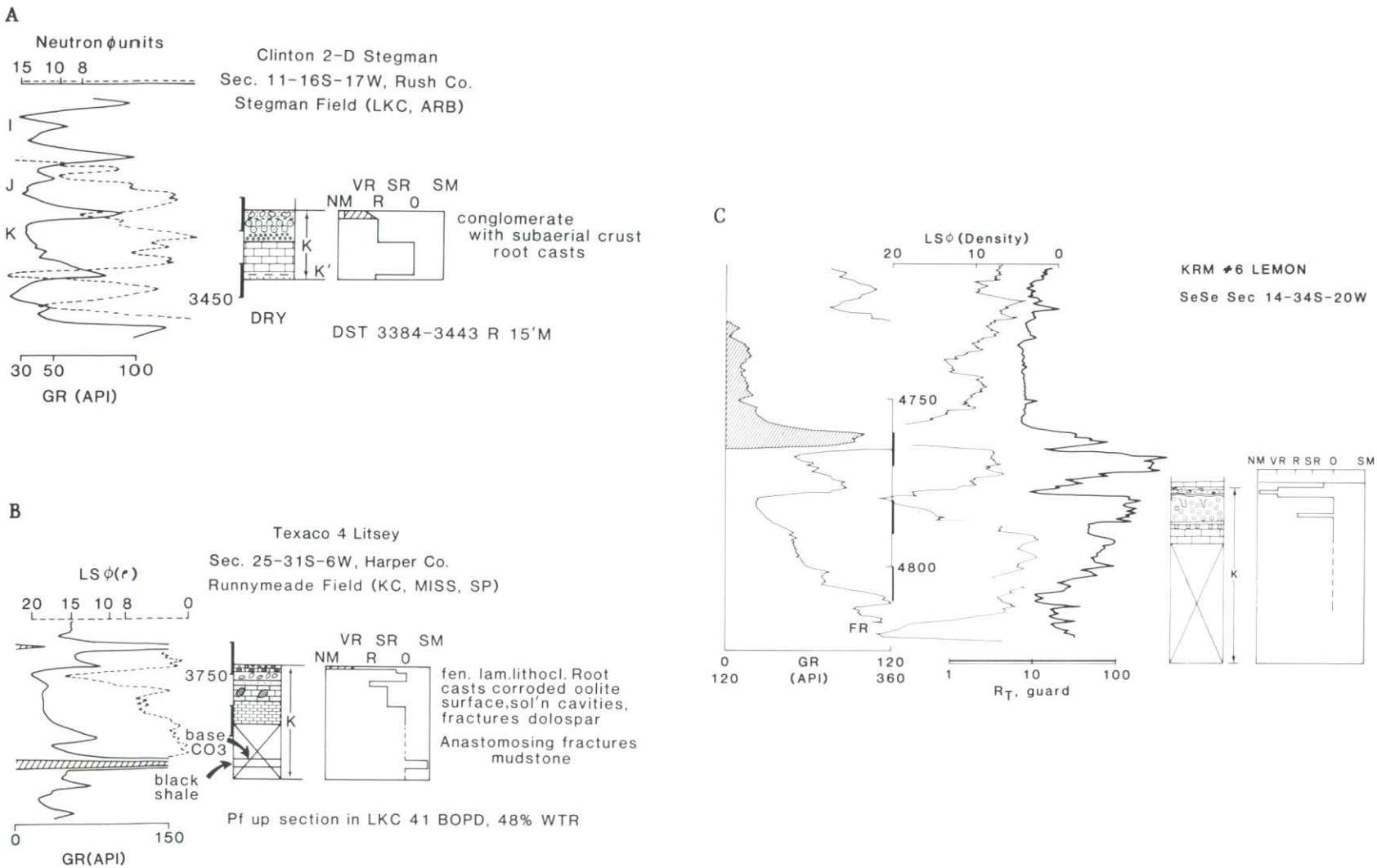

FIGURE 10—Combined wireline log and graphic core descriptions of (A) #2-D Stegman, (B) #4 Litsey, and (C) #6 Lemon. Note that entire K-Zone interval is denoted as well as other lithofacies not cored but suggested by wireline logs. Box to right of each description indicates depositional environment interpreted from core (dashed in area not cored). Abbreviations are as follows: NM–nonmarine, VR–very restricted, R–restricted, SR–slightly restricted, O–open marine, and SM–stagnant marine; scale in ft immediately to the right of the wireline curves in (A) and (B) and between gamma-ray and density curves in (C). Note that vertical scale is the same in (A), (B), and (C). Hatched patches in (B) represent noticeable recrystallization. FR in (C) means first recording of gamma ray. The zones producing in the fields associated with the core are abbreviated in the headings except for the #6 Lemon which is part of the Lemon Ranch-Collier Flats field with Toronto, Kansas City, and Mississippian pays.

the most shale-free (cleanest) carbonate interval of the K-Zone according to the gamma-ray log. Eight percent porosity normally is considered the lower limit of effective (permeable) pore space but is only a rule of thumb for reconnaissance mapping. Combination porosity tools with consideration of lithology provide a better evaluation of the type and expected distribution of porosity, e.g., primary and secondary. Oomoldic porosity, which is common in this core, is notorious for high porosity values that are not effective. Tortuosity of the complex pore systems when this porosity is effective increases the formation factor in the Archie water-saturation equation. This increase in turn lowers the water saturation determined by log analysis, making the zone seem to contain a greater hydrocarbon concentration than it probably has. Cores allow visual examination of oil saturation and pore structure and together with analysis of porosity and permeability of the core provide information necessary to calibrate the wireline logs.

The 4 Litsey core is from the Runneymede field which contains four separate pay zones including Lansing–Kansas City, Marmaton, Mississippian, and Simpson. Since its discovery in 1953, the field has produced 705,000 bbls through the end of 1982, now including 12 wells. The field lies on the crest of a southerly plunging anticline at the horizon of the K-Zone. Regional dip is to the southwest. Structural closure at the horizon is less than 10 ft.

KRM Petroleum Corporation 6 Lemon SESE sec. 14, T. 34 S., R. 20 W. Comanche

The last example of the K-Zone described here is from the 6 Lemon well (sec. 14, T. 34 S., R. 20 W.) located in the Collier Flats–Lemon Ranch field complex in Comanche County in southwestern Kansas (fig. 1). This area is off the major structural uplifts, sitting on the east flank of the Hugoton embayment. The field is situated on and near the crest of a south-southwesterly plunging anticline. Updip well locations on the northeastern reaches of this structure are not productive. Pay zones include Douglas, Lansing–Kansas City, and Mississippian.

The Lemon Ranch field discovered in 1979 has produced over 400,000 bbls from 22 wells, most of the oil coming from the Swope or K-Zone. The 32 wells of the Collier Flats field have produced in excess of 600,000 bbls of oil again primarily from the K-Zone.

The 6 Lemon core of the K-Zone contains a subaerial crust capping the oolitic grainstone (fig. 13). Clasts of dense, laminated micrite overlie this surface, apparently remnants of a weathered and eroded crust now incorporated into the overlying unfossiliferous siltstone. As in the 4 Litsey core, the reworking process associated with the next transgression is marked by a thin fossiliferous shale with a sharp basal contact separating it from the unfossiliferous siltstone. Evidence of freshwater diagenesis is again abundant.

Again the cleanest interval of the regressive carbonate is the oolite according to the gamma-ray log (fig. 10). The oolite facies is a modest 6 ft thick, but locally exceeds 20 ft in thickness. Apparent porosity in excess of 8% coincides with the oolite. High porosity and high resistivity together with clean carbonate rock with interconnected pores strongly suggest a productive interval. Pipe was in fact run in this hole and the zone was perforated for production. Since the field's discovery in January 1979, 10 wells have been drilled on the Lemon lease. The lease had produced 243,000 bbls of oil at the end of 1982.

A useful aid in evaluation of facies is a map of the thickness of porous carbonate that exceeds 8% porosity. Thicknesses of porous carbonate in the vicinity of the Lemon core are comparable to the values along the trend of thick porous carbonate indicated in fig. 3 between the arrows.

The lower open-marine, crinoid-brachiopod wackestone in cores on the southern shelf as previously mentioned generally are dark colored and contain flecks of organic matter. These units may be transitional to the underlying marine shale deposited when bottom conditions were stagnant and euxinic with slow sedimentation rates. As sea level fell, the circulation was re-established and normal bottom oxygenating conditions gradually were restored. The maximum gamma radiation recorded by the marine shale is low and is comparable to that of the regressive shale over the positive areas of the CKU, CA, and the northern shelf (fig. 4). Bottom stagnation apparently was not established over these areas. Shallower water conditions were not conducive for preservation of organic matter along the northern shelf perhaps due to more oxygenated conditions where higher rates of sedimentation may also have led to the dilution of the organic matter.

These variations in facies in the lower regressive carbonate of the 6 Lemon core suggest a more basinward, downslope setting where thicker carbonate accumulated, the base of which was more transitional to the once-stagnant bottom conditions prevalent during the marine shale deposition. The oolite facies also is the dominant shallow-water facies along this southerly shelf also recognized in the 4 Litsey core.

Discussion

Previous results (Watney, 1984) conclude that the oolite belt is very significant indeed. It is not developed on the upper shelf or common to some cycles (e. g., H-Zone) with the exception of the extreme southern shelf where oolites seem to be main facies reflecting carbonate buildup as the carbonate shelf breaks into the Anadarko Basin. The Anadarko Basin apparently was rapidly subsiding, where deep water was maintained during Late Pennsylvanian (Kuman and Slatt, 1982; Moore, 1979; Galloway et al., 1977; Rascoe, 1962).

Subsidence along the southern margin of the Hugoton embayment was greater than in the northern region of western Kansas. A zone of abrupt thickening trending west-northwest across west-central to south-central Kansas is the location south of which oolite becomes the dominant shallow-water facies. Even though differential subsidence was likely a factor in the development of oolite, a fall in sea level to a position where the strand line coincided with this "hinge or flexure zone" finally provided conditions where

wave and current energy focused on the break in slope and oolitic shoals developed.

The area to the north was emergent by this time as the strandline made its southerly migration. In fact, lobe-shaped bodies of oolitic grainstone tens of feet thick and miles in length point northward onto the upper shelf following along the line of flexure, resembling the spillover lobes developing today in the Bahamas. Tidal currents moved the ooids locally, but storms were probably the dominant force in moving the oolite northward onto the shallower platform to form the extending fingers.

Oolite complexes are not part of the upper shelf facies because of the distance from the southern shelf edge. A more gradual regional slope dissipated much of the tidal energy necessary to agitate the grains and develop the thick oolitic cortices. Nevertheless, storm currents and even lesser currents more normal to the northern shelf over paleohighs worked the carbonate sediment, removing mud (winnowing) and very locally transporting and sorting grains. Typically though grains on the northern shelf are micritized or darkened because of sitting on the sea floor being attacked by endolithic algae, are encrusted by forams and/or algae, and/or have superficial oolitic coatings (e.g., 2-D Stegman core).

The marine waters that inundated the western Kansas shelf from the south did slowly shallow. Moderate-high energy facies tracts moved progressively across the shelf, focusing on paleohighs and along breaks in slope oriented parallel to the strike of the bathymetric slope. Porosity developed in the upper regressive carbonates commonly is a reflection of these grain-rich facies as substantiated by the cores. Mapping thickness of porosity and relating this to the interval isopachs and gamma-ray mapping of the marine shale have outlined favorable trends related to the configuration of the shelf and the change in sea level. The evidence of subaerial exposure in all three cores shown here including the southern shelf document that the sea did for a short time leave the shelf high and dry, allowing early freshwater diagenesis to take over and modify these carbonates. The magnitude of sea-level change is availed by the isopach and facies data. The paleoslope from the isopachs is roughly 0.5 ft/mi over the 2.0-mi-wide shelf across Kansas that makes the total relief approximately 100 ft less than that filled in by sediment aggradation estimated to be around 30 ft based on facies and interval isopachs. On the northern shelf, Dubois (1979) shows evidence of substantial erosional downcutting and red-shale-filled fissures in the J-Zone. Watney (1980) documents the progressive, northward increase in intensity and duration of exposure in the G-Zone to where the top has been eroded to form a conglomerate. The paleorelief, the facies, and the diagenesis suggest sea-level fall and withdrawal rather than simply sediment fill to sea level.

Either the platform moved upward and downward periodically or a dynamic sea level existed where rates of rise and fall produced these cycles (cycling every 250,000–400,000 yrs). The resulting hiatus between cycles is subtle and even more so on the southern shelf because of the shortness of time, but the effect on the fabric of the carbonates including pore distribution is substantial indeed.

The mechanism causing the sea-level fluctuation has been suggested to be Gondwannan continental glaciation (Wanless and Shepherd, 1936; Heckel, 1977; Crowell, 1979; Watney, 1984). The broad shelf in western Kansas and over the continental interior was near sea level. Undisputable evidence for large glacial advances in Gondwanna could easily account for sea-level changes of 100 ft or even 300 ft and could have been the major force behind the cyclic phenomenon observed in these sediments in Kansas.

Secondly, the periodicity of glacial advance and retreat corresponding with sea-level fall and sea-level rise necessary to fit the cyclicity of the sedimentary record is no problem if this Pennsylvanian waxing and waning of glaciers was anything like the Pleistocene. Furthermore, evidence from the Pleistocene glacial stages suggests rapid glacier retreat, i. e., rapid sea-level rise, followed by a slower glacier advance, i. e., sea-level fall that takes a longer time. Also sea-level inundation on the shelf would tend to accelerate with the steady subsidence on the shelf.

How does all of this relate to exploration strategy? First, it is essential to be able to identify the cyclic succession in the zone of interest. Core data are the only way to recognize this including subtle diagenetic features that illustrate the processes that have affected the cycle. What is the porosity type and is it possible to identify trends of similar porosity development on a map? Secondly, it is necessary to tie the core data to the available wireline logs, transferring key information such as facies relation to porosity development. Other factors such as thickening or thinning of the regressive carbonate or the patterns of maximum gamma radiation in the marine shale extablish collaborating evidence for the recognition of reservoir trends.

Structural interpretation done concurrently with the stratigraphic study will help to focus on acreage where the two are in a favorable development. Moreover, most likely in western Kansas the stratigraphic-reservoir maps will identify trends that are more wide ranging than the small structural closures identified by the available subsurface control. Unless seismic profiles or potential-field geophysical surveys are available to identify the structural highs, stratigraphic reservoir mapping may be the only way that acreage is picked up to be evaluated further for prospects.

The crux of the whole exploration program is to have core described and analyzed to provide the stratigraphic framework that allows the geologic calibration of the wireline tools and to optimize the integration of existing subsurface information.

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FIGURE 11—Core slab photos and photomicrographs from the Clinton #2-D Stegman (sec. 11, T. 16 S., R. 17 W.), Rush County. Bar scale in all photomicrographs is 1 mm.

A: 3425 ft, slab photo of upper contact of regressive carbonate and regressive shale (K-Zone). Subaerial crust (darker carbonate) at arrow capping irregular surface of limestone unit; note rounded lithoclasts of carbonate in overlying shale.

B: 3,440 ft, slab photo of clear-tan to light-gray mollusk, crinoid-, brachiopod-bearing wackestone with burrow mottling typical of the lower regressive carbonate (shallow water possibly slightly restricted). Light-gray less-fossiliferous micrite between stylolites.

C: 3,425 ft, photomicrograph of multigeneration subaerial crust shown in A with laminated and clotted, dense, dark micritic carbonate cement, fractured after it formed. Overlying grains and fracture surface also coated with dense dark micrite.

D: 3,425.1 ft, photomicrograph of interval immediately beneath subaerial crust. Irregularly distributed, dense, dark micritic cement partially coating rounded, poorly preserved bioclasts. Note some of this cement concentrated at grain contacts which hang beneath grains, probably analogous to meniscus and pendant (vadose) cements.

E: 3,425.1 ft, photomicrograph from pellet grainstone containing elongated patches rimmed by dark micritic carbonate. Patches contain more micritized grains, more closely packed together than surrounding spar-cemented grainstone. Patch shown is interpreted as solution cavity rimmed by calichelike calcite filled by corroded, altered bioclasts.

F: 3,433 ft, slab photo of upper contact of regressive carbonate of L-Zone underlying K. Another subaerial crust with cm-sized relief directly overlain by reworked transgressive portion of K-Zone. Note patches and coatings of darkened carbonate beneath crust.

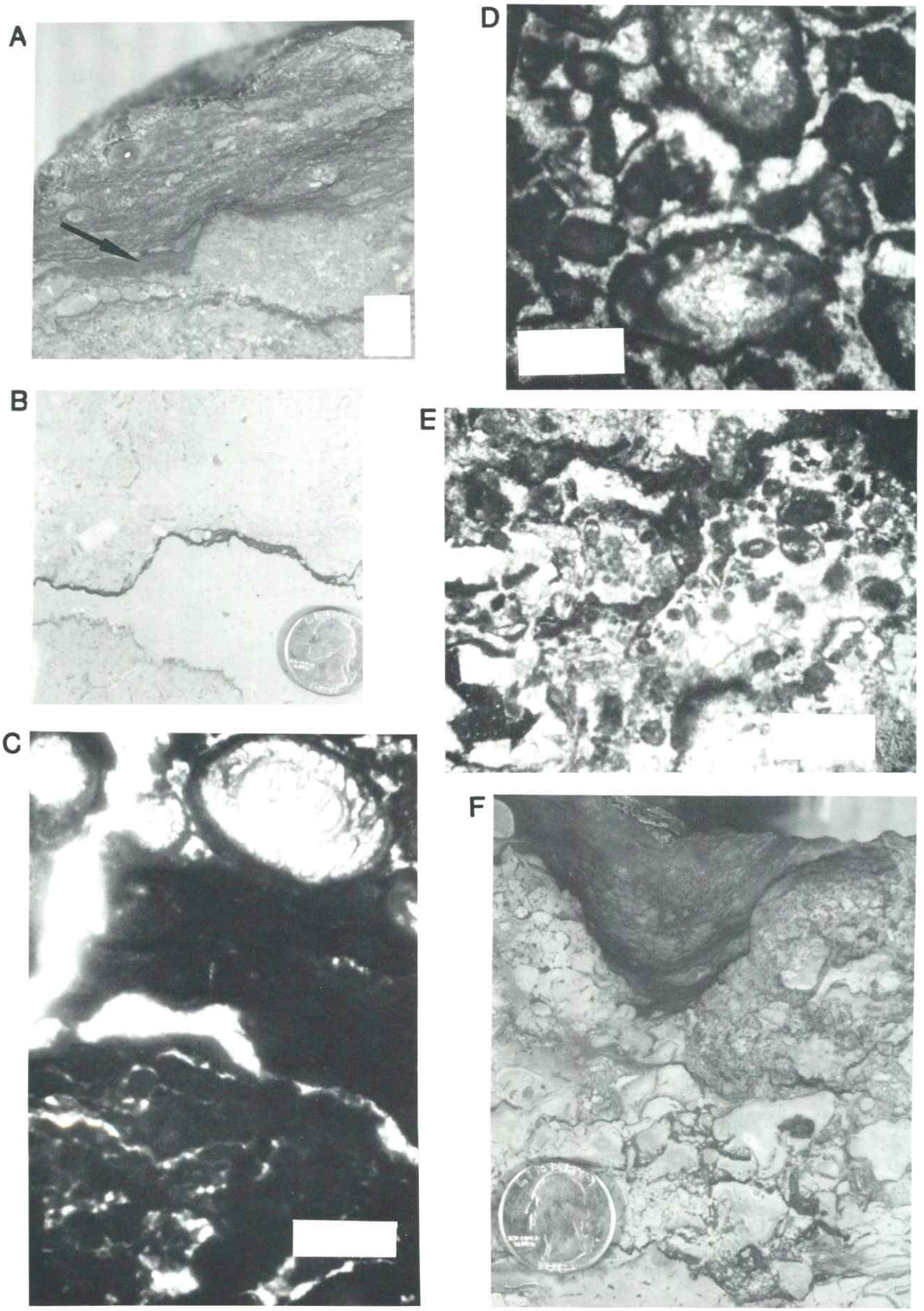
A
B
C
D
E
F

FIGURE 12—Core slab photos and photomicrographs from the Texaco #4 Litsey (sec. 25, T. 31 S., R. 6 W.), Harper County; bar scale in photomicrographs is 1 mm.

A: 3,745 ft, slab photo of dark, argillaceous, diversely fossiliferous, transgressive limestone of J-Zone.

B: 3,750.5 ft, slab photo of crinoid, tubular-foram-oolitic grainstone with abundant oomolds and vertically oriented patches of darker-colored oolite, containing poorly preserved ooids; irregular areas of coarse milky dolospar.

C: 3,754 ft, slab photo of fine peloid-rich mudstone, cm-sized dark-gray mottling with moldic and fracture porosity and recrystallized lime mud.

D: 3,748.2 ft, photomicrograph in plane light of poorly sorted bioclastic packstone with solution-enhanced intergranular porosity forming reticulated open network of pores (appreciable interconnection even in dimensions of thin section). Note dark micritic carbonate that coats most of this void space; grains again poorly preserved.

E: 3,748 ft, photomicrograph in plane light taken immediately above (D) containing solution cavity lined with very dark carbonate followed by a clotted dark micritic carbonate. Cement that lines void attributed to calicification and suggests subaerial exposure.

F: 3,748.5 ft, photomicrograph in plane light of oomoldic grainstone intensely recrystallized. Original voids filled by blocky to druzy calcite cement. Blue epoxy as black areas only fill some pores (effective porosity).

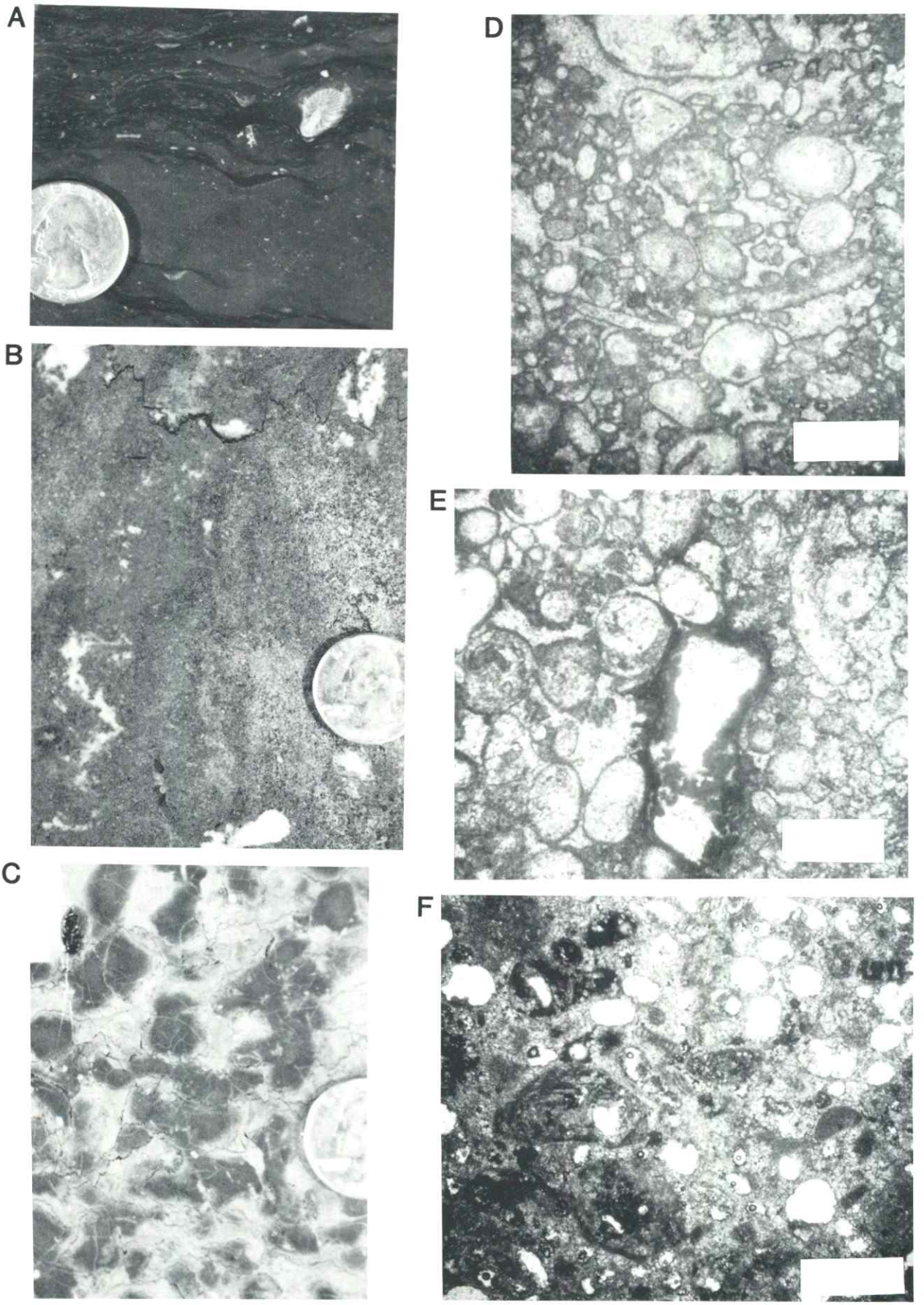
A
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FIGURE 13—Core slab photos and photomicrographs from the KRM -6 Lemon (sec. 14, T. 34 S., R. 20 W.), Comanche County; bar scale in photomicrographs is 1 mm.

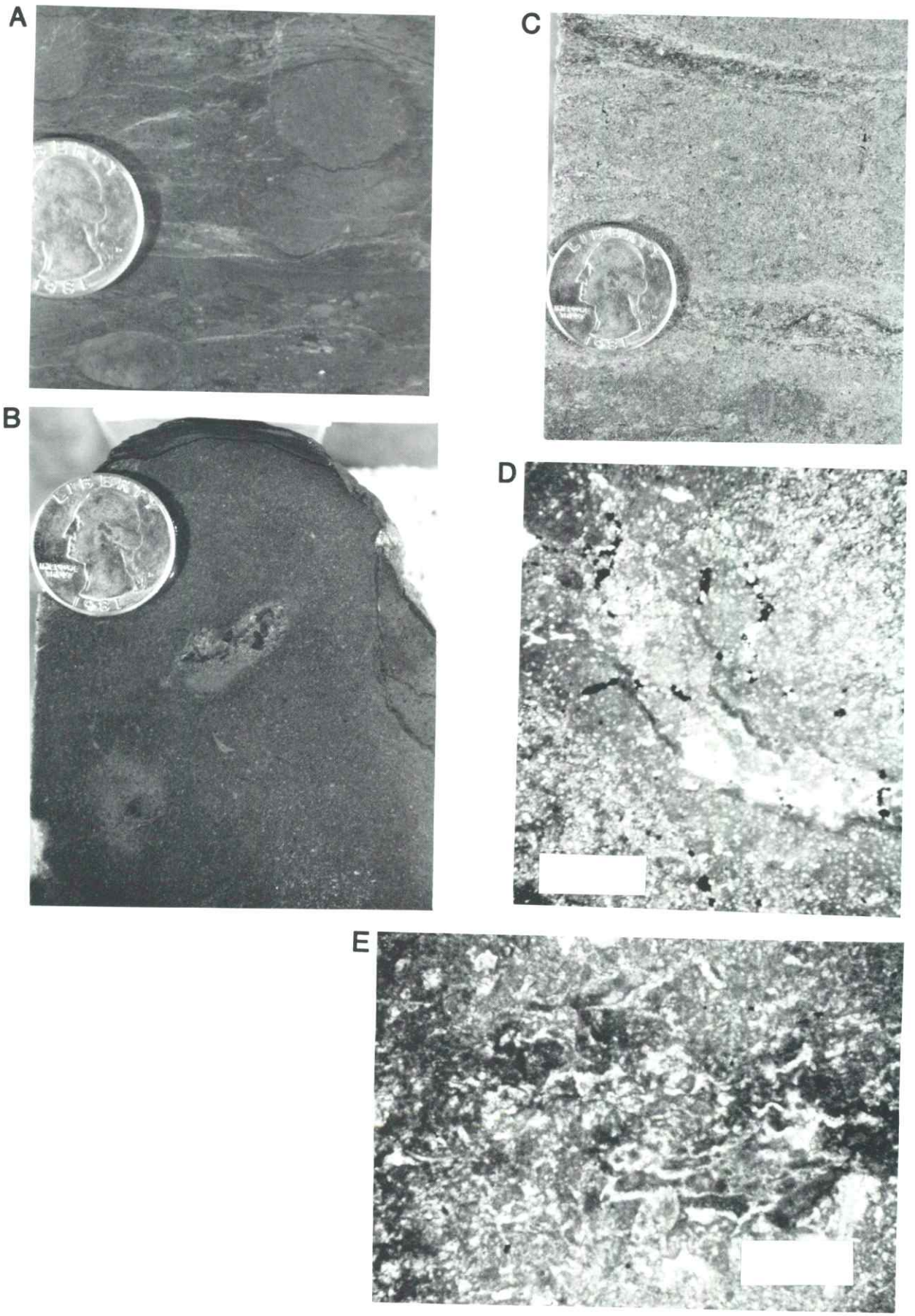
A: 4,780 ft, slab photo of gray-green siltstone containing rounded cm-sized dark mottled lime mudstone clasts with anastomosing fractures and circular-sized mm-sized voids (root casts). Probably eroded remnants of underlying carbonate transported from nearby, containing evidence for subaerial exposure.

B: 4,780.5 ft, slab photo of brown to dark-brown oolite solidly cemented yet cut by solution voids. Note cm-sized cavity partly filled by a layer of lighter-colored quartz silt and ooids resting at the bottom of the cavity. Furthermore, the upper surface of the slab is the top of the K-Zone regressive carbonate. This surface is a subaerial crust (2–3-mm-thick darkened micritic calcite); note the relief.

C: 4,785 ft, slab photo of oolitic grainstone with abundant oomolds and vuggy porosity.

D: 4,780 ft, photomicrograph in plane light of argillaceous siltstone cut by void lined by micritic calcite that is densest adjacent to the void wall. Interpreted as a longitudinal cut through root cast.

E: 4,780 ft, photomicrograph in plane light of clotted, poorly laminated dense micritic calcite alternating with calcspar located in nodular calcareous area in quartz siltstone or regressive shale of K-Zone; resembles caliche carbonate.


A
B
C
D
E

Application of cores in development of an exploration strategy for the Lansing–Kansas City "E" Zone, Hitchcock County, Nebraska

by *Martin K. Dubois,* Consulting Geologist, Winfield, Kansas

Abstract

Cores from the Lansing–Kansas City "E" Zone are particularly useful in the development and application of exploration strategy in areas without core control by aiding in the recognition and correlation of key units in the "E" Zone on available mechanical well logs. A core on the "E" Zone from the Theodore Gore Company # 1 Williamson "B" well illustrates the complexity of one particular Upper Pennsylvanian sedimentary cycle. At least one and possibly two minor transgressions interrupted the overall regressive portion of the sequence of the "E"-Zone cycle. Oil is produced from carbonate packstones and grainstones that were deposited during two episodes of shoaling within a complex marine-nonmarine sedimentary cycle. Packstones and grainstones are best developed on ancient positive areas of the seafloor, areas where nonmarine sediments overlying these regressive carbonates are thin. After documentation of this relationship, the thickness of nonmarine rock can be mapped in areas without core control by using mechanical well logs. Isopach maps of the nonmarine sediments identify areas with potential for "E"-Zone production.

Introduction

A core of the Lansing–Kansas City "E" Zone from the Theodore Gore Company # 1 Williamson "B" well, Meeker Canal field, Hitchcock County, Nebraska, was originally studied by the author in Dubois (1979), an unpublished master's thesis. Many of the figures and ideas in this paper are from the earlier work.

Geologic setting

Hitchcock County is located along the Nebraska–Kansas state line in southwest Nebraska near the junction of two major, yet low-relief, structural features, the Las Animas arch and the Cambridge arch. Most of the uplift along the Cambridge arch, a northwest to southeast feature that plunges to the southeast, occurred after Mississippian time but prior to deposition of Pennsylvanian sediment (Lee and Merriam, 1954). The Las Animas arch, a southwest to northeast trending structure that currently plunges to the northeast, is a more subtle feature, yet its geologic history is complex. Rascoe (1978) showed that during the late Paleozoic (post-Mississippian) the Las Animas arch

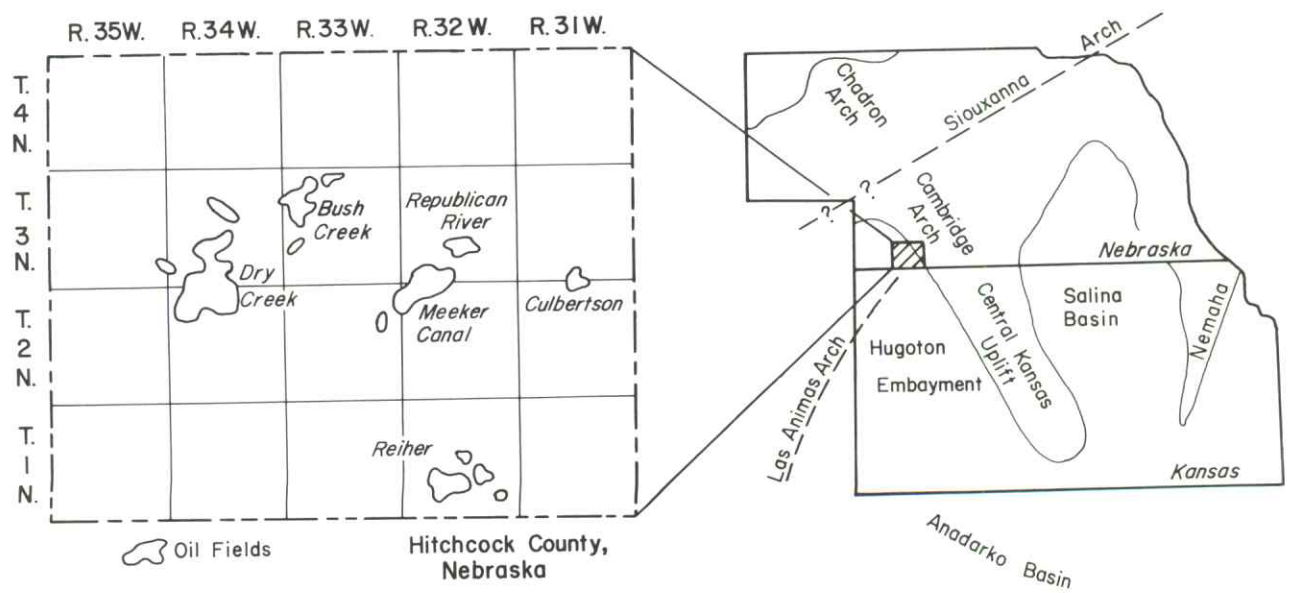


FIGURE 1—Index map showing location of Hitchcock County, Nebraska, in relation to major tectonic features (after Dubois, 1979).

plunged to the southwest away from the Cambridge arch, whereas arching in the southwestern portion of the Las Animas during the Mesozoic and Cenozoic resulted in the present-day configuration with the Las Animas arch plunging to the northeast towards the Cambridge arch. The ancestral Las Animas arch may have influenced regional sedimentation in the study area during Upper Pennsylvanian Lansing–Kansas City time.

Lansing and Kansas City sediments were deposited on the northern, shoreward portion of an extensive, low-relief, gently southward-dipping platform. The platform's margin was near the Kansas–Oklahoma border (Rascoe, 1962) and the platform had paleoslopes as little as 0.1 m/km (0.5 ft/mi) in Hitchcock County (Watney and Ebanks, 1978). The paleogeographic position of Hitchcock County corresponds to Heckel's (1977) northern shoreward-facies belt. During deposition of the Lansing–Kansas City "E" Zone, Hitchcock County probably had a relatively flat to mildly undulating surface with maximum relief on the order of 30–60 ft (9–18 m). Local positive features having a relief of 15–30 ft (4.5–9 m) dotted the landscape (Dubois, 1979). The best "E"-Zone porosity is found on these local positive features.

Stratigraphy

Lansing and Kansas City Groups are of the Missourian Stage of the Upper Pennsylvanian System (fig. 2). Several schemes of informal classification have been applied to the limestones of the Lansing and Kansas City Groups, herein called Lansing–Kansas City, in Nebraska and Kansas. Letter classification systems are used by most oil operators because they are more convenient than the formal rock formation and member names that have been assigned to these rocks where they crop out in eastern Kansas. Six letters (A–F) were assigned by Kincaid, Trimble, and Larson (in Parker, 1961) to the six uppermost limestone units of the Lansing–Kansas City (fig. 3). I have added a seventh letter, G, for the unassigned interval just above the base of the Kansas City. The six- or seven-letter classification system is used by most oil operators in southwestern Nebraska, and the seven-letter classification system will be used here.

Production and reserves

Nearly all the oil produced in Hitchcock County comes from the Lansing–Kansas City. Production in a field may be from any one of seven zones, and most produce oil from two or more zones. The Meeker Canal field produces from the "E" and "F" Zones and to a lesser extent from the "D" Zone. The "D" and "E" Zones remain behind pipe in many wells and will be perforated as the "F" Zone is depleted (Rakaskas, 1982). Ultimate recovery by both primary and secondary methods will average 40–50 thousand bbls of oil per well when developed on 40-acre tracts (J. E. Rakaskas, personal communication, 1979).

Production from the # 1 Williamson "B" well, NWSW sec. 5, T. 2 N., R. 32 W., completed in 1977, is a typical well in the 50-well Meeker Canal field (fig. 4). On a drill-stem test from 3,758 to 3,812 ft, covering the "E" Zone, 280 ft of gas and 270 ft of mud-cut oil were recovered. Shut-in pressures were 989–969 lbs and flow pressures were 40–142 lbs. This zone was perforated from 3,779–3,796 ft overall and treated with 3,750 gal of acid. Initial production was 55 bbls of oil and 2 bbls of water per day. Shows in the "D" and "F" Zones were noncommercial due to lack of porosity. Two other wells on the Williamson "B" lease were later drilled. The # 2 well located in the NESW sec. 5, T. 2 N., R. 32 W., was completed in the "E" Zone in 1979 for 50 bbls of oil and 1 bbl of water per day. The # 3 well, located in the SWSW sec. 5, T. 2 N., R. 32 W., was completed in 1980 for 25 bbls of oil and 8 bbls of water per day from the "F" Zone. By the end of 1982, the three wells had produced 59,955 bbls of oil from the

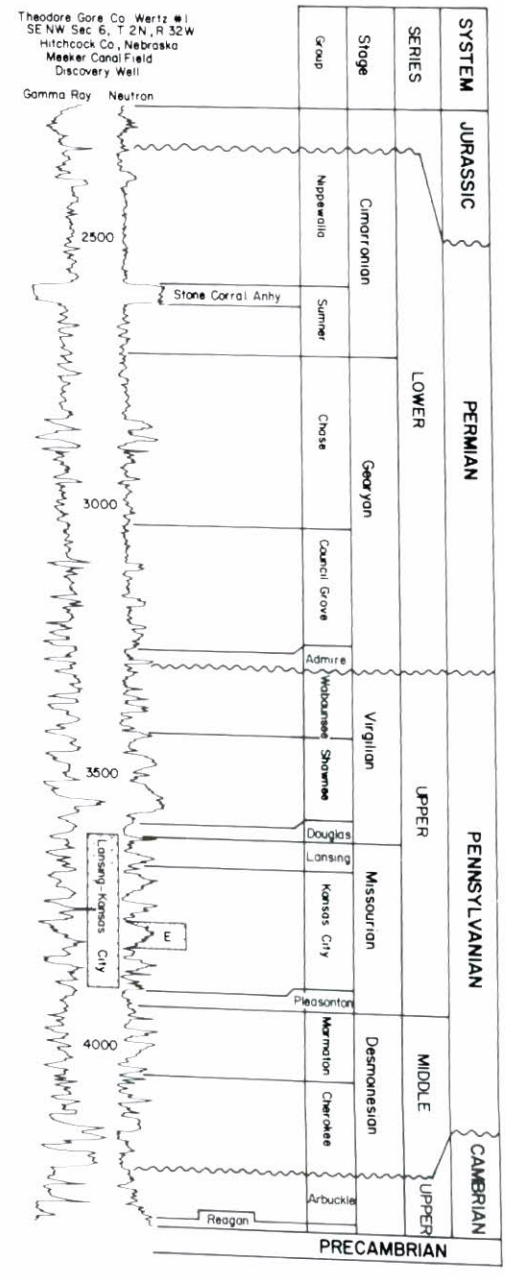


FIGURE 2—Stratigraphic section in Hitchcock County, Nebraska, correlated with the Rawlins County Type Log (Kansas Geological Society, 1966; after Dubois, 1979).

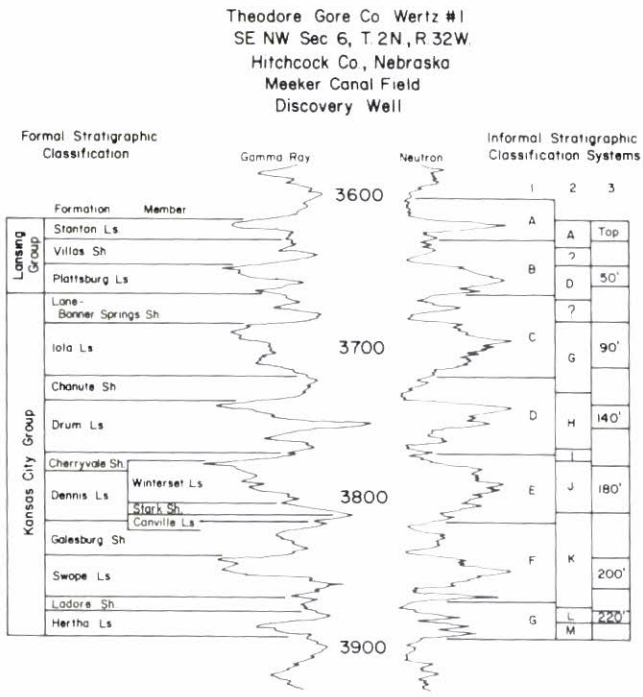


FIGURE 3—Stratigraphic classification schemes for the Lansing–Kansas City Groups. Informal classification systems: 1) letter designations commonly used in southwest Nebraska, modified after Kincaid, Trimble, and Larson (in J. M. Parker, ed., 1961); 2) Morgan's (1952) classification system, based on correlations with Watney's (1977) work in northwest Kansas; 3) system based upon depths below the top of the Lansing, used by some operators in central Kansas (W. L. Watney and M. J. Brady, personal communication, 1979). The formal stratigraphic classification is based on Parkhurst's (1961) work. He traced the Lansing–Kansas City into the subsurface from the outcrop and correlated the formation and members with Morgan's (1952) letter designations. The thicker carbonate of the "E" zone is also Morgan's "J" zone, the "180 foot" zone, and the Winterset Limestone (after Dubois, 1979).

original zones (Rakaskas, personal communication, 1983). The # 1 Williamson "B" well has produced a total of approximately 38,000 bbls and is still making 11 bbls of oil per day and a trace of water after 6 yrs of production (Rakaskas, personal communication, 1983). Production for the Meeker Canal field was 650,276 bbls of oil at the close of 1982.

Complex "E"-Zone cycle

A vast amount of literature deals with Pennsylvanian cyclothems of the Midcontinent. Early workers recognized the transgressive-regressive nature of Pennsylvanian rock sequences (Moore, 1936; Elias, 1937; Weller, 1958). Later work on the Lansing–Kansas City along the outcrop belt in eastern Kansas by Harbaugh (1959), Harbaugh and others (1965), Crowley (1969), Frost (1975), and Heckel (1975a, b, 1977) supported and refined the basic cyclothem theory applied to these rocks by Moore (1936). Watney (1977, 1980) and Watney and Ebanks (1978) applied the principles of cyclothemic theory in their work on the subsurface Lansing–Kansas City rocks in northwestern Kansas and southwestern Nebraska.

The "E" Zone in Hitchcock County is not a simple transgressive-regressive cycle typically recognized in Lansing–Kansas City rocks. At least one and possibly two minor transgressions interrupted the overall regressive sequence (fig. 5). Two pay zones are in the "E" Zone, rock units 3 and 6 in figs. 5, 6, 7, and 8. Both are shallow-water, relatively high-energy packstones and grainstones separated by approximately 10 ft (3 m) of deeper-water, low-energy rocks.

To facilitate discussion of the "E"-Zone sedimentary cycle, numbers were assigned to specific rock units (lithofacies) that were correlatable both in cores and on mechanical well logs. Rock units 9, 10, and 11 were not cored in the # 1 Williamson "B" well but were observed in other cores in Hitchcock County and are included in the discussion below. The following is a summary of depositional events and resultant rock types of the "E"-Zone cycle.

1. A relatively rapid marine transgression initiated the "E"-Zone cycle and resulted in deposition of a thin transgressive limestone (unit 11), barely detectable on the # 1 Williamson "B" electric log. The limestone is very similar to unit 1, the "D"-Zone transgressive limestone, with the dominant grain types being foram-algal (*Osagia*)-coated grains, and caliche lithoclasts. Terrigenous clastic influx initiated during further transgression resulted in the accumulation of a maroon-gray to maroon-brown shale with locally abundant bryozoan, crinoids, and brachiopods (unit 10). Unit 10 is stratigraphically equivalent to Heckel's (1977) black, phosphatic core shales of eastern Kansas also recognized further south covering much of western Kansas. This black-shale facies can be recognized on well logs by its characteristic high natural gamma-ray radiation as recorded by the gamma-ray log.
2. A minor regression interrupted the transgression and resulted in deposition of unit 9, consisting of mixed skeletal wackestones and packstones abruptly overlying a mudstone. The unit has considerable lateral variations (phylloid-algal wackestone facies and more grain-supported rocks) northeast of the Meeker Canal field where shallower water most likely existed.
3. Terrigenous clastic influx followed another relatively rapid transgression and the dark shale of unit 8 was deposited. This predominantly dark gray-maroon silty shale has a sparse, but normal, marine faunal assemblage and contains carbonate-enriched nodules and burrows. The carbonate content increases upwards giving the first hints of a relatively slow regression.
4. The slow regression was accompanied by diminished terrigenous clastic influx, clearing of the water, and carbonate-mud production resulting in deposition of a marlstone (unit 7). The marlstone (or shaly and silty carbonate mudstone) consists of a mixture of carbonate mud and terrigenous silt and clay. The silt and clay are concentrated in discrete laminae as well as disseminated throughout the matrix. The carbonate mud is concentrated in nodulelike masses (5–20

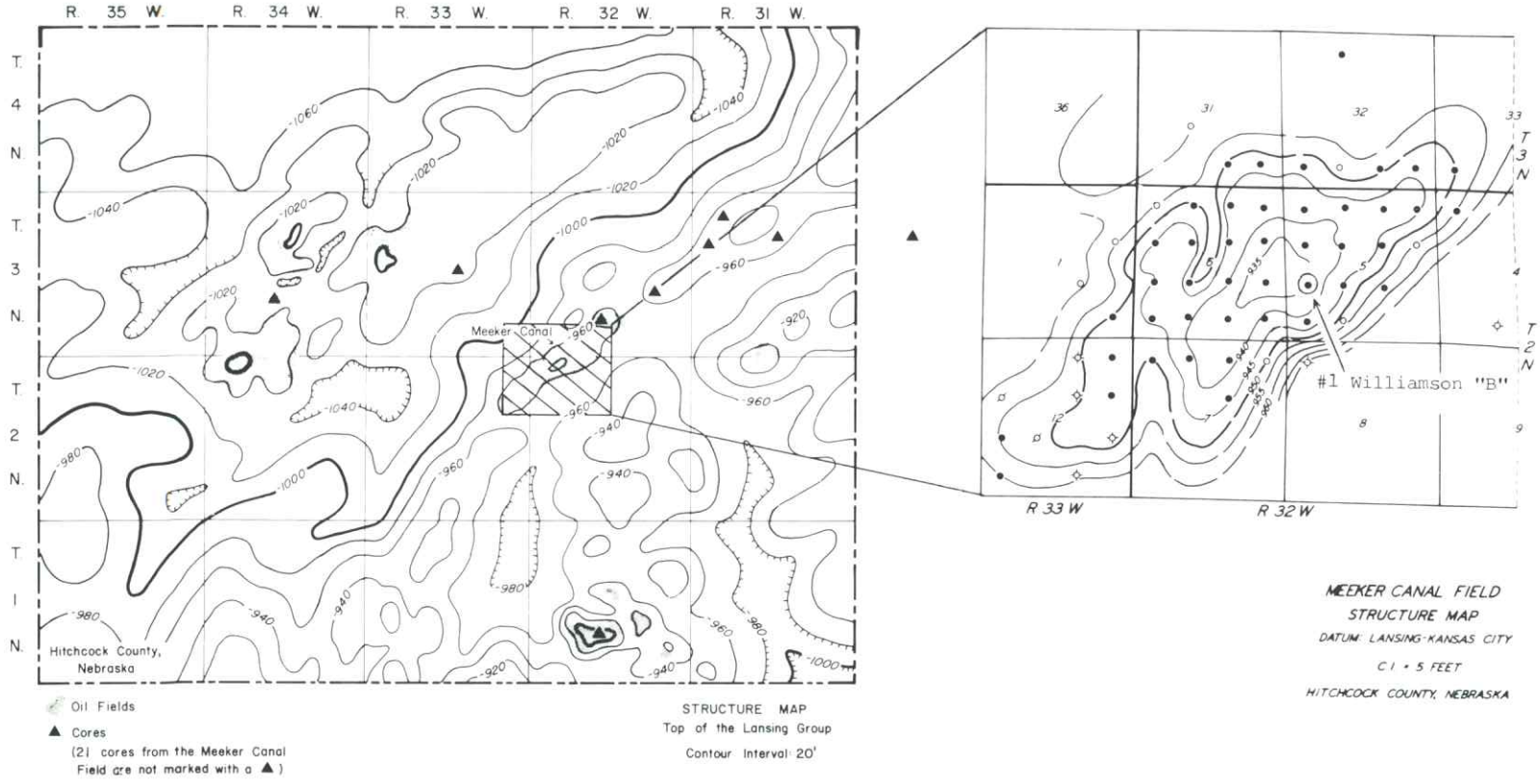


FIGURE 4—Lansing structure maps. Tops from approximately 475 wells were used in preparation of the map on the left; the small scale map on the left is after Dubois (1979), and the larger scale map on the right is modified after Rakaskas (1982).

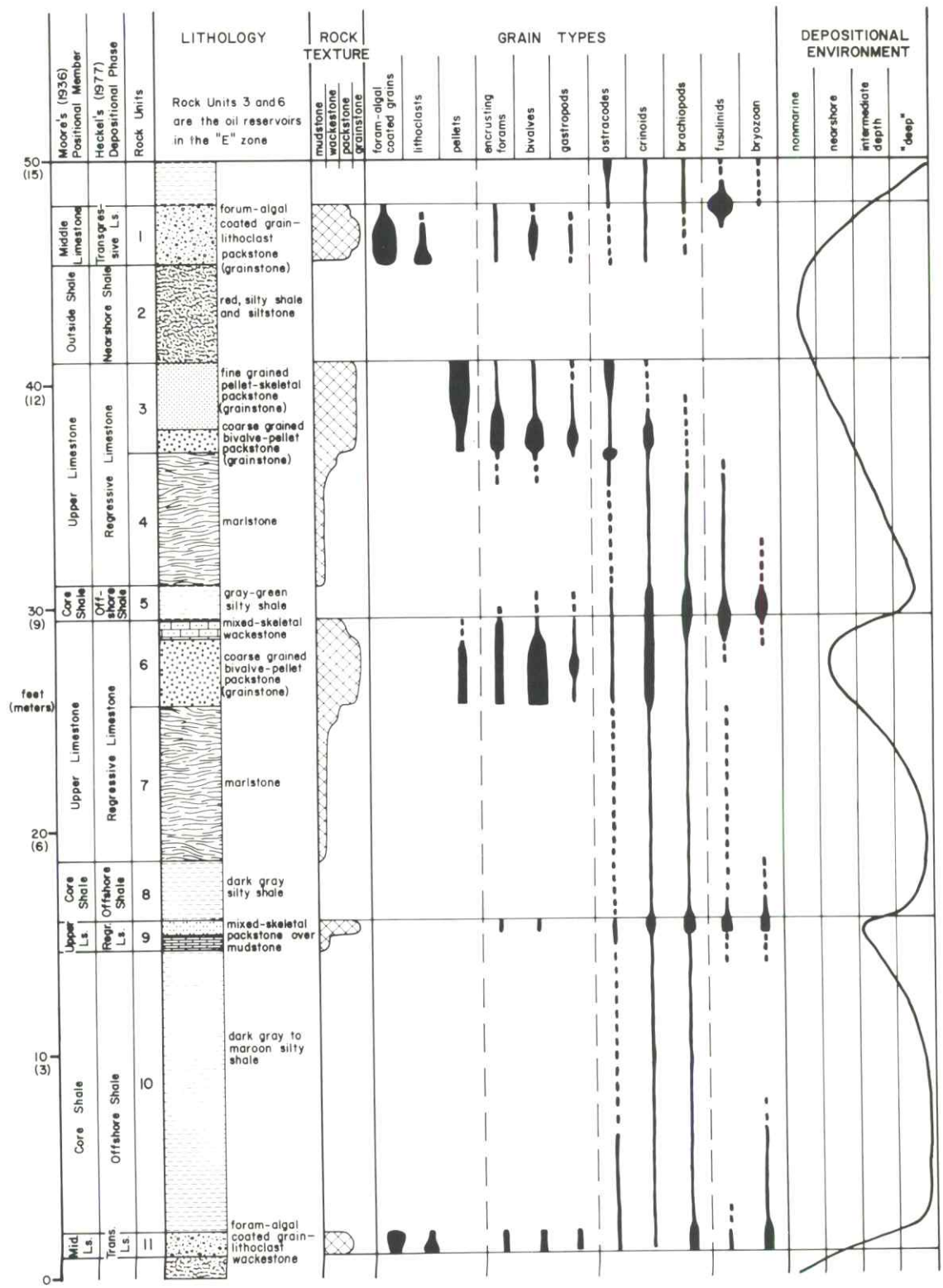


FIGURE 5—"E" zone cycle of the Meeker Canal field (after Dubois, 1979).

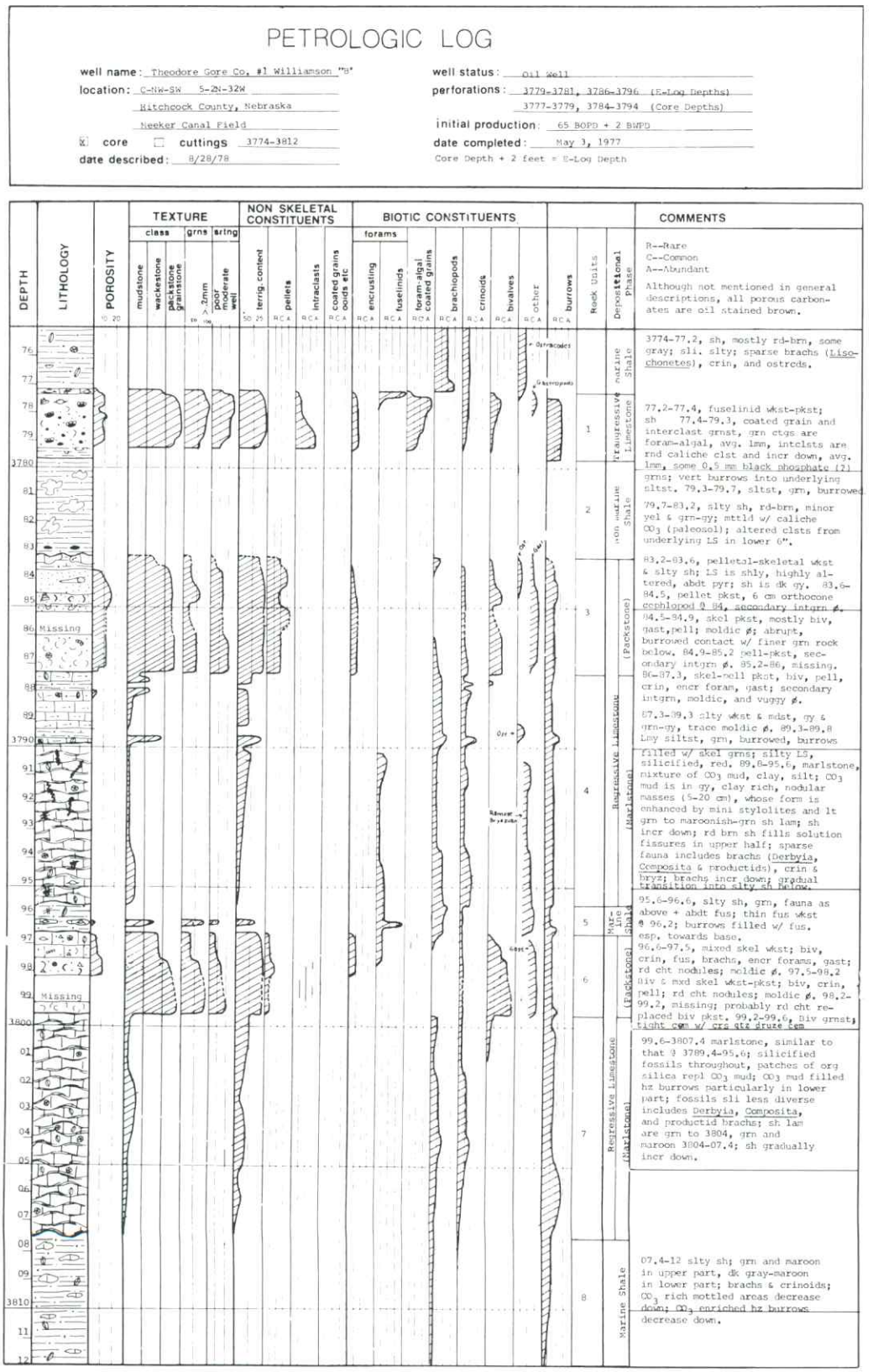


FIGURE 6—Core description of #1 Williamson "B" well, Hitchcock County, Nebraska. Dunham's (1962) textural classification of carbonate rocks was used.

cm) or in carbonate-enriched horizontal burrows 1–2 cm in diameter (fig. 9A). Intervals rich in carbonate mud are typically light gray while silt- and clay-rich laminae are light green to maroonish gray.

5. Further regression and cessation of terrigenous influx resulted in more prolific production of carbonate grains in a shallow, moderately agitated environment producing the packstones and grainstones of unit 6 (fig. 9B, C). Two distinct rock types with a gradational boundary make up this interval. The lower one is a coarse-grained bivalve packstone and grainstone, nearly identical to that in the lower part of unit 3, having a slightly restricted faunal assemblage. The upper part of unit 6 is a mixed-skeletal wackestone with a normal marine faunal assemblage similar to that of unit 5. This is the first evidence of another minor transgression. The base of unit 6 is generally an abrupt, scoured, erosional surface.

   The neutron-porosity log in the # 1 Williamson "B" well reads only 5–8% and the unit was not perforated. Much of the porosity was occluded by red chert, silica, and calcite cement. The chert apparently is "hot," is associated with abnormally high gamma radiation, and has a distinct signature on the gamma-ray log (fig. 7). This will be discussed later in the text. In parts of the Meeker Canal field, unit 6 is an excellent reservoir with average porosity of 10–15%, but single values are as great as 25%. As is the case in the # 1 Williamson "B" well, porosity is secondary, predominately moldic, and resulted from dissolution of bivalve-shell fragments.

6. The "deeper" water wackestones at the top of unit 6 and the silty shale of unit 5 are evidence of another minor, yet relatively rapid, transgression. The greatest faunal diversity in the entire "E"-Zone cycle is found in this shale interval and includes ramose bryozoan, several genera of brachiopods, fusulinids, crinoids, ostracodes, and bivalves.
7. The marlstone of unit 4 (fig. 10A) signifies another relatively slow regression. It is remarkably similar to unit 7 and undoubtedly deposited in a very similar environment. Differences are primarily diagenetic. Portions of carbonate mud have been replaced with orange or red silica and narrow (cm), near-vertical, solution fissures have been filled mostly with nonmarine red-brown silt and clay from unit 2 throughout unit 4 in the # 1 Williamson "B" core.
8. As regression continued and terrigenous influx ceased, more prolific carbonate-grain production in a shallow moderately agitated environment resulted in the deposition of packstones and grainstones of unit 3 (fig. 10B, C). In the # 1 Williamson "B" well, two distinct facies are separated by a gradational boundary. At the base is a coarse-grained bivalve grainstone with moldic and vuggy porosity, while the upper part is a fine-grained pellet packstone with predominately secondary intergranular porosity and a more restricted faunal assemblage. Continued regression resulted in subaerial exposure of the "E"-Zone carbonate. The top 0.4 ft of this unit is a shaly pelletal-skeletal wackestone and silty shale. The limestone is weathered and contains abundant pyrite.

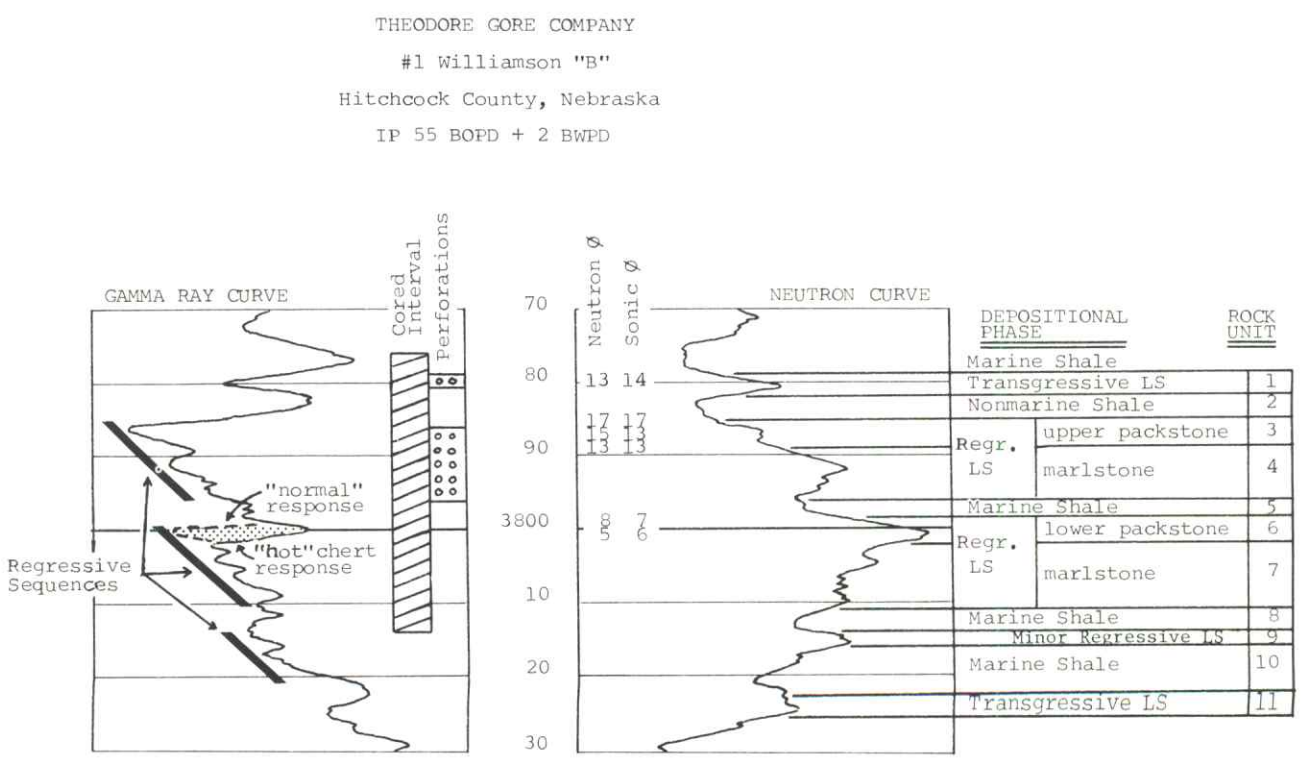


FIGURE 7—Gamma ray-neutron log from the Theodore Gore #1 Williamson "B" well, Hitchcock County, Nebraska.

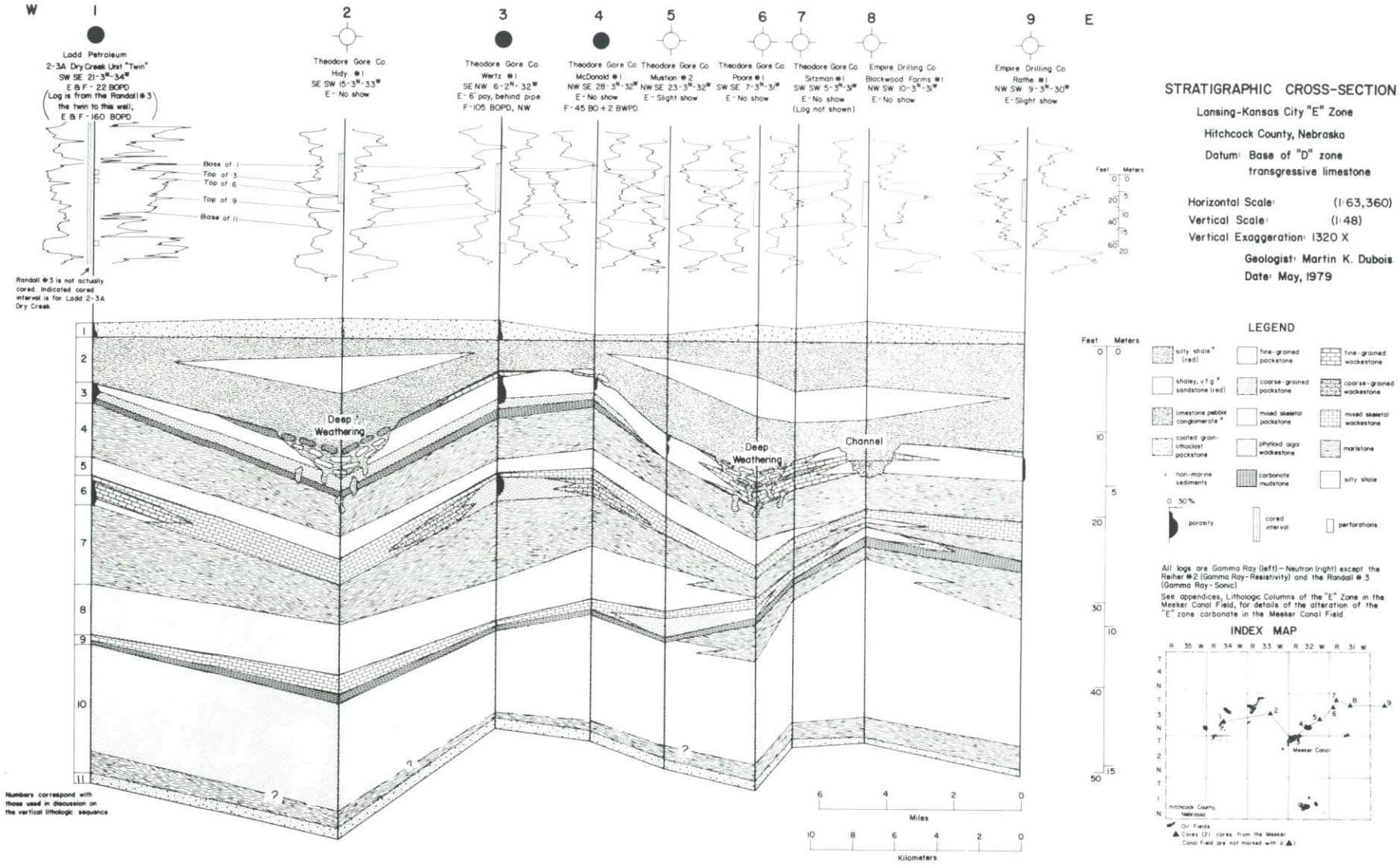


FIGURE 8—West to east stratigraphic cross section of the "E" zone cycle, Hitchcock County, Nebraska, modified after Dubois (1979).

Most of the silt and shale in this interval is derived from the overlying nonmarine silty shale.

9. During subaerial exposure, porosity in units 3 and 6 was enhanced by freshwater leaching while eolian-derived red silt and clay of unit 2 (Fig. 11A) blanketed the region. This silt and clay was redistributed by sheetwash, more wind, and intermittent streams into topographic lows resulting in a much thicker accumulation of nonmarine sediment in the paleolows than on the paleohighs (Dubois, 1979, 1980). Caliche in unit 2 in the cores from the # 1 Williamson "B" well and cores from nearby wells and calcite-filled pedotubules observed in other cores from unit 2 is evidence of soil development in the nonmarine sediment. The caliche occurs as small isolated nodules or may replace nearly 100% of the matrix. This occurence fits the description of a K-soil horizon, typical of semiarid environments described by Gile and others (1965), where the soil has been indurated with calcite (caliche).
10. Nonmarine conditions ended abruptly with a rapid marine transgression and deposition of unit 1, the transgressive limestone of the "D" Zone (fig. 11B, C). The unit is predominantly a coarse-grained grainstone with most grains being coated grains and caliche interclasts. Grain coatings are an encrusting-foram, blue-green algal consortium (*Osagia*). At the base is a burrowed green siltstone that was probably deposited in an intertidal environment. A fusulinid wackestone found at the top of unit 1 was most likely deposited in deeper water than the rest of unit 1. Continued transgression resulted in a reduction of carbonate-grain production and an influx of terrigenous clay and silt that comprises the marine shale (fig. 11D) that overlies unit 1.

FIGURE 9A—Core slab of marlstone (unit 7) at 3,802 ft in the #1 Williamson "B" well. Light areas are carbonate mud-enriched horizontal burrows. Dark areas are gray silty shale laminae (scale is 2 cm).

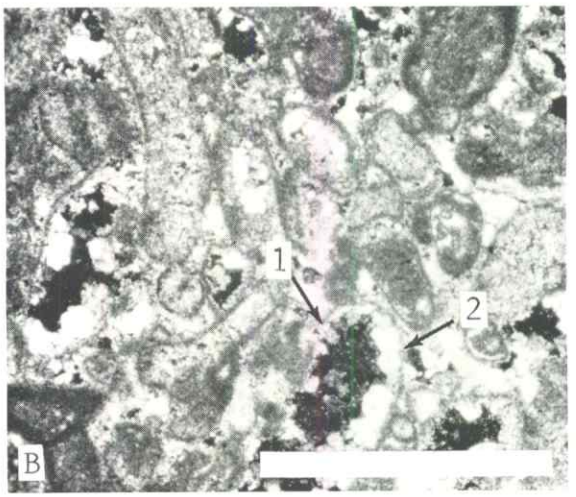


FIGURE 9B—Thin section photomicrograph of a bivalve grainstone (base of unit 6) at 3,800 ft in the #1 Williamson "B" well. Rounded grains are predominately bivalves. Most porosity is moldic (arrow at 1). Clear quartz druze cement (arrow at 2) fills much of the porosity; scale is 1 mm, cross-polarized light.

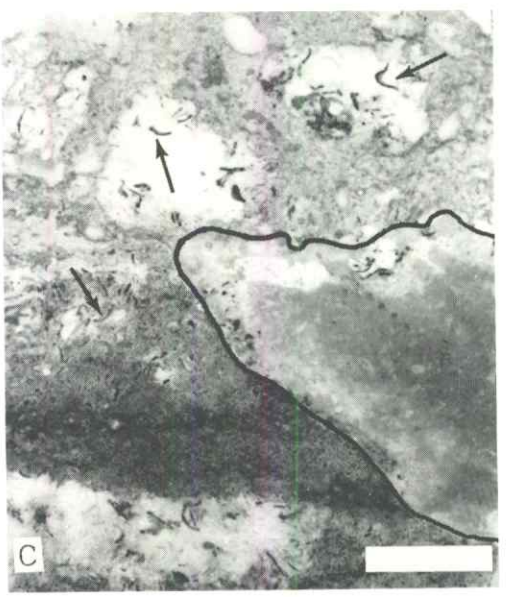


FIGURE 9C—Oil-stained core slab of a bivalve-mixed skeletal packstone (middle of unit 6) at 3,800 ft in the #1 Williamson "B" well. Lighter areas are cemented with calcite or quartz druze. A red chert nodule that has replaced both grains and matrix is outlined. Examples of bivalve molds, the dominate porosity type, are indicated with arrows (scale is 2 cm).

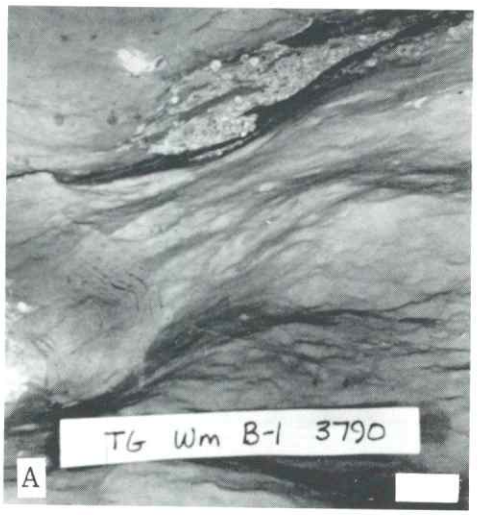


FIGURE 10A—Core slab of marlstone (unit 4) at 3,790 ft in the #1 Williamson "B" well. Lighter areas are carbonate mud rich and darker areas are green silty shale laminae. The marlstone is very similar to that of unit 7 in figure 9A (scale is 1 cm).

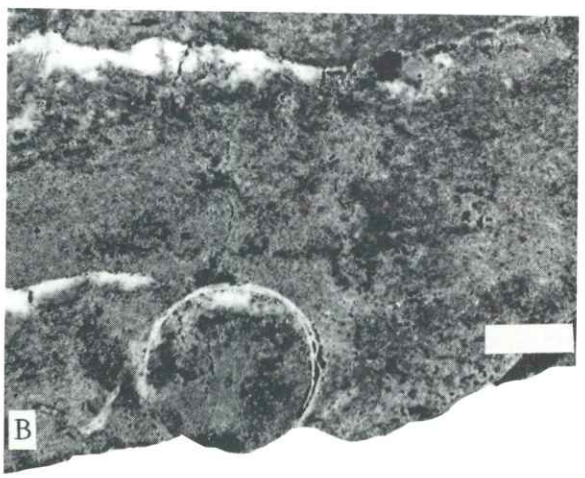


FIGURE 10B—Uniformly oil-stained core slab of a fine-grained pellet grainstone-packstone (unit 3) at 3,784 ft in the #1 Williamson "B" well. Light areas are tightly cemented with calcite. The circular feature is an orthocone cephalopod, one of the rare macrofossils in unit 3 (scale is 1 cm).

Summary of the complexities of the "E"-Zone cycle

The existence of three shoaling-upward sequences within one cycle is evidence that three distinct regressions took place. The upper two regressive sequences (rock units 3, 4, and 5 and rock units 6, 7, and 8) are nearly identical. At the base of each is a silty shale which grades upward into a low-energy marlstone. The content of carbonate mud increases upward in the marlstone unit and is truncated by shoal-water packstones and grainstones.

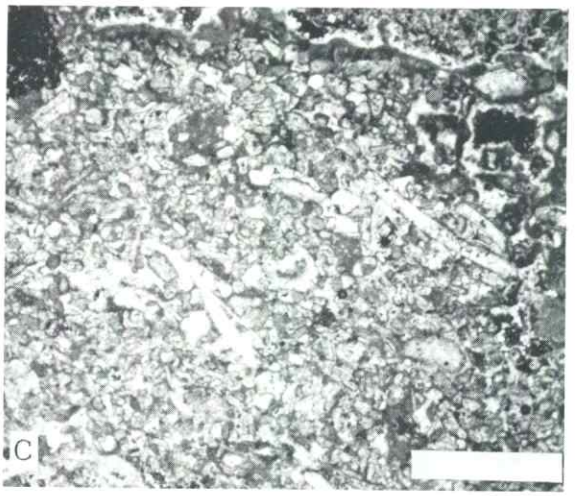


FIGURE 10C—Photomicrograph of one of the tightly cemented portions of fig. 10B. Most smaller grains are pellets and most larger grains are bivalve fragments (scale is 1 mm, cross-polarized light).

Faunal changes that accompany the vertical lithologic changes further support invoking a fluctuating sealevel in order to explain the complexities in the "E" Zone. Rock units 3 and 6 are dominated by a shallow-water, slightly restricted faunal assemblage consisting of bivalves, gastropods, and tubular-encrusting forams. They also contain substantial amounts of pellets commonly found in shallow-water carbonate sediments. Deeper-water, normal-marine fauna, including numerous genera of brachiopods, crinoids, bryozoans, and fusulinids, are found in the marlstones and silty shales.

Paleotopography and its effect on facies and diagenesis

The nonmarine rocks of unit 2 vary in thickness more so than any other rock unit in the "E"-Zone cycle, varying from a few feet to more than 30 ft (fig. 12). The difference in thickness over a short distance up to a few miles is presumed to be an estimate of the minimum relief on the exposed "E"-Zone carbonate surface (Dubois, 1980). The datum for the cross section in fig. 8, the base of the "D"-Zone transgressive limestone, unit 1, was chosen so that the top of the "E"-Zone regressive carbonate illustrates this minimum topography. Unit 2 in the # 1 Williamson "B" well is only 3.5 ft thick. This thickness as well as the core on the cycle itself is nearly identical to well number 3 in the cross section (fig. 8), the # 1 Wertz, located 3/4 mi to the northwest and also in the Meeker Canal field. Most oil production from the "E" Zone is located where the nonmarine rocks are less than 5 ft thick. Moreover, all significant production is where these rocks are less than 10 ft thick (Dubois, 1979, 1980). Nevertheless, not all thin areas are productive in the "E" Zone. The Republican

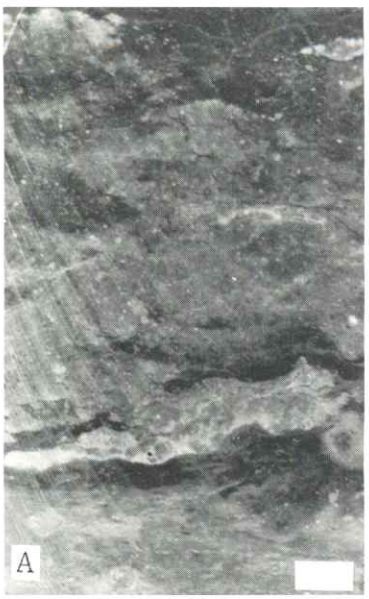


FIGURE 11A—Core slab of red-brown nonmarine silty shale (unit 2) at 3,782.5 ft in the #1 Williamson "B" well. Much of the matrix has been replaced with caliche. Darkest areas contain the least caliche (scale is 1 cm).

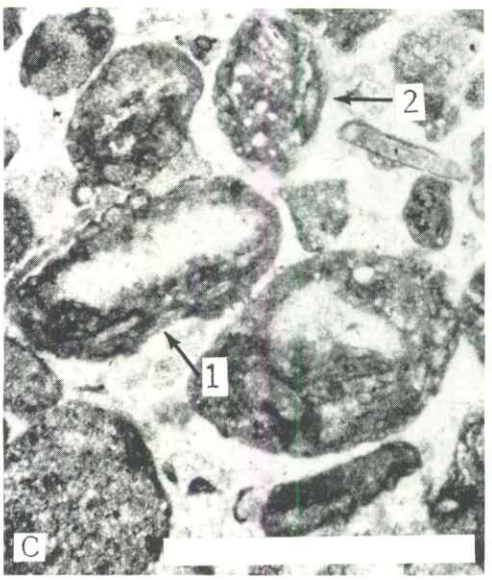


FIGURE 11C—Photomicrograph of fig. 11B. Tubular-encrusting forams and algae, possibly the blue-green algae *Girvanella*, coat rounded bivalve (arrow at 1) and caliche lithoclast (arrow at 2) grains (scale is 1 mm).

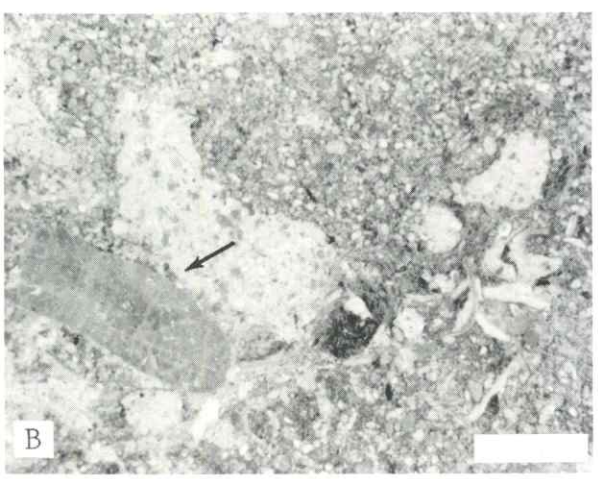


FIGURE 11B—Oil-stained core slab of encrusting foram-algal coated-grain grainstone (unit 1) at 3,778 ft in the #1 Williamson well. A large caliche lithoclast (arrow) was derived from the underlying paleosol (scale is 1 cm).

FIGURE 11D—Core slab of red-brown marine shale overlying unit 1 at 3,776 ft in the #1 Williamson "B" well contains numerous genera of brachiopods (light arcuate grains; scale is 1 cm).

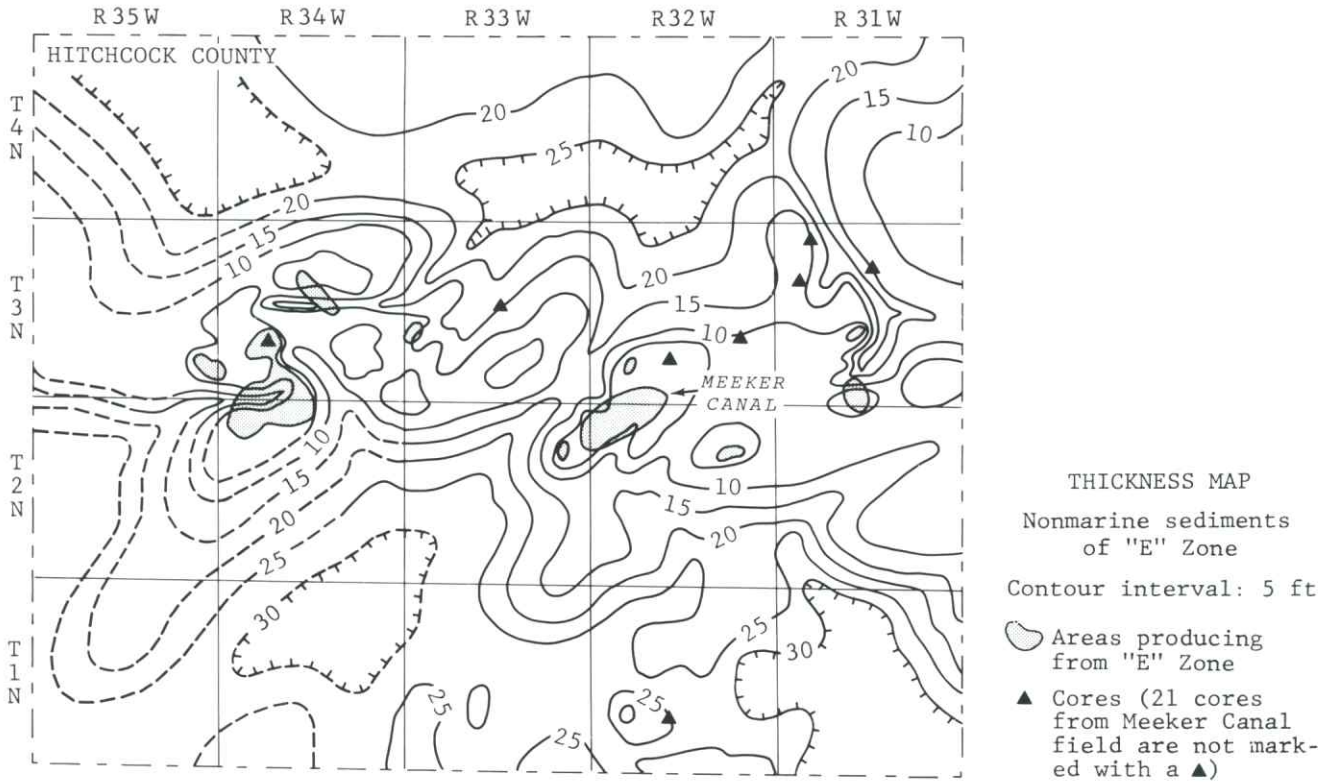


FIGURE 12—Thickness map of nonmarine sediments of "E" Zone in Hitchcock County, Nebraska.

River field, which produces primarily from the "F" Zone, is an example.

The relative abundance of grain-supported textures versus mud-supported textures and the presence of subaerial diagenetic patterns corresponds well with the change in thickness of nonmarine rocks. The two producing intervals of the "E" Zone, rock units 3 and 6, show considerably more facies changes, as illustrated in fig. 8, than "deeper"-water carbonates in the cycle. On positive seafloor features (areas having thin nonmarine rocks), both pay zones have grain-supported rock textures and shallow-water, restricted faunal assemblages. Whereas, in paleolows, laterally equivalent rocks generally have mud-supported textures and deeper-water, more normal-marine faunal assemblages.

Freshwater diagenesis during subaerial exposure of the "E"-Zone carbonates and original rock textures was important in generating porous reservoir rocks. Most porosity is secondary, a result of leaching of aragonitic skeletal grains and carbonate mud in packstones and grainstones in the vadose zone on topographic highs. In lows, deep weathering, accompanied by large-scale dissolution formed vertical fissures infiltrated by silt and clay. This completely destroyed any reservoir potential the original rocks may have had.

Mechanical well-log signature of "E"-Zone rocks

In areas without core data, abundant radioactivity logs (gamma ray-neutron-guard) may be correlated with logs from cored wells in order to identify rock units and map those areas that seem to have some potential for new production in the "E" Zone. Fig. 8 illustrates that correlation of rock units using gamma ray-neutron logs of cored wells. The most obvious and fruitful application is mapping of the nonmarine rock-interval thickness. Without some core control, identification of the "D"-Zone transgressive limestone (unit 1) on mechanical well logs would be difficult. This correlation was easily made to 220 well logs from other wells with the aid of 21 cores from the Meeker Canal field and 9 cores from other areas to produce the map in fig. 12.

The three distinct regressive sequences are recognizable on the gamma-ray curves of well logs (fig. 7). Carbonate content increases upwards in each regressive sequence. This is reflected in three definite sequences of upward-decreasing intensities on the gamma-ray curve of the "E"-Zone cycle.

"Hot" (radioactive) limestones common in the "E" Zone have created some interpretation problems when no cores are available. The source of the radioactivity is red chert like that in the # 1 Williamson "B" well in rock unit 6, at 3,800 ft on the well log (fig. 7). Without a core of the interval and with only a Radiation Guard Log, a pay zone can be easily mistaken for a shale or shaly limestone when this chert is present, particularly when it has good porosity. High porosity causes the neutron curve to move towards the center of the log. Taken with a high gamma-ray reading, the lithology anticipated without core would be shale. Other "hot" limestones shown on the well logs in fig. 8 include unit 6 of well 2, unit 9 of well 4, and units 6 and 9 of well 5.

Summary

It was on highs of the ancient seafloor that porosity was formed and later oil was trapped in the "E" Zone. Here, grain-supported textures prevailed and vadose leaching enhanced the porosity. In surrounding lows, rock textures are generally mud supported, and intense weathering destroyed any reservoir potential the original rock may have had. Other potentially productive paleohighs can be detected by mapping the nonmarine interval that overlies the "E"-Zone regressive limestone using available mechanical well logs in conjunction with core data.

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Depositional facies and diagenetic fabrics of the D-Zone cyclothem, Lansing–Kansas City Groups, Hitchcock County, Nebraska

by *B. E. Prather,* Shell Oil Company, New Orleans, Louisiana

Introduction

The D-Zone of the Lansing–Kansas City Groups in Hitchcock County, Nebraska (fig. 1), was deposited during one cycle of eustatic rise and fall of sea level during the Late Pennsylvanian (Missourian). The cyclothem is composed of four lithofacies common to most cyclic deposits of this age in the western Midcontinent: 1) a lower carbonate unit (transgressive limestone), 2) a lower shale unit, 3) an upper carbonate unit (regressive limestone), and 4) an upper shale unit (after Watney, 1980; fig. 2).

The lower carbonate and upper carbonate units of the D Zone are commonly porous and, therefore, serve as reservoir rocks. The lower shale and upper shale units serve as seals for oil that has accumulated in the carbonate units. The interbedded low-relief carbonate/shale stratigraphy is ideal for trapping hydrocarbons in low-relief structural closures, yet many of the present-day structures tested are not productive because of the lack of porous rock. For this reason alone, understanding controls on distribution of porosity in this and similar zones is important.

The core from the Theodore Gore Poindexter No. 1 contains most of the facies typically found in the D Zone throughout the study area (fig. 3). Examination of it has provided an understanding of the depositional and diagenetic factors controlling the distribution of porosity in this zone. Integration with other cores has extended this interpretation regionally.

Tectonic setting

The study area in Hitchcock County is located in the northernmost limit of the Hugoton embayment, a broad

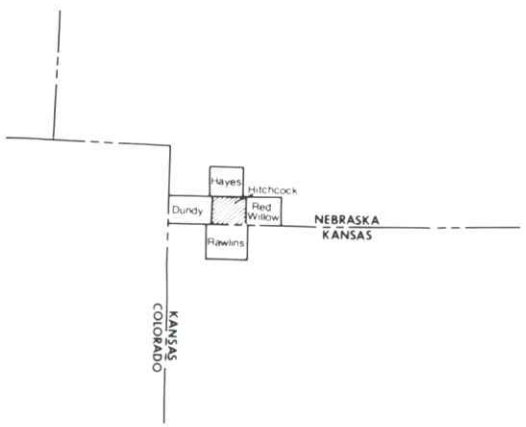


FIGURE 1—Map showing Hitchcock County, Nebraska, and surrounding counties in Nebraska and Kansas.

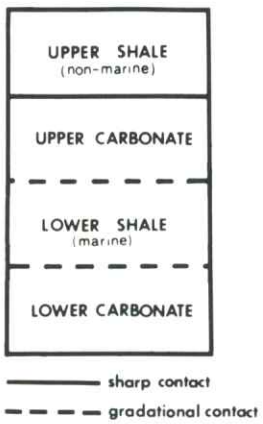


FIGURE 2—The typical sequence of lithologies common to most cyclic deposits in the Lansing–Kansas City groups of the western Midcontinent (after Watney, 1979).

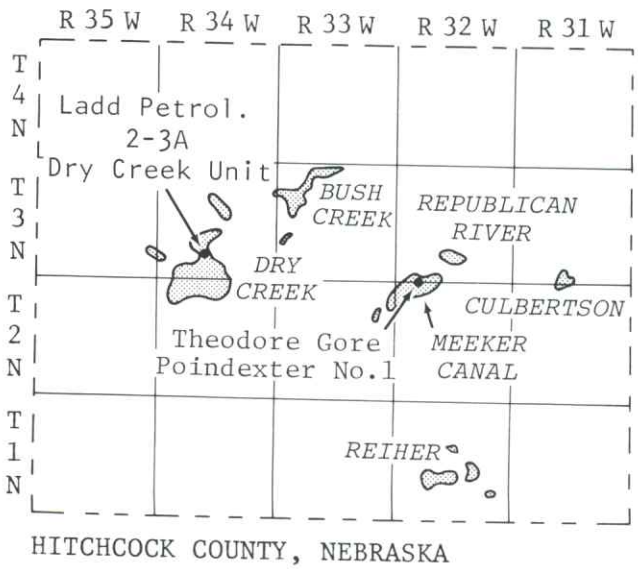


FIGURE 3—The larger oil fields in Hitchcock County, Nebraska, occur in upper carbonate units (regressive limestones) of the Lansing–Kansas City Groups. The cores examined in this workshop are from the wells indicated by arrows.

"shelflike" extension of the Anadarko Basin in western Kansas (fig. 4). The Hugoton embayment was the site of marine deposition throughout the Paleozoic (Merriam, 1954). In the Late Paleozoic, eustatic rise and fall of sea level led to periods of marine deposition and periods of erosion and continental deposition (Merriam, 1954).

The Cambridge arch, a large anticline plunging southeastward from the Transcontinental arch, lies to the northeast of the study area. It is positioned on the same structural axis as the Chadron arch of Nebraska, the Central Kansas uplift, and possibly the Black Hills uplift. This feature is believed to have been tectonically inactive during Lansing–Kansas City deposition (Merriam and Atkinson, 1955). Still it was a location of positive topographic relief onlapped by Late Pennsylvanian sediments.

The Las Animas arch presently is a broad anticline plunging northwestward away from the Apishapa uplift in southeastern Colorado. Isopachous and facies maps of Pennsylvanian and Permian rocks, however, reveal that an ancestral Las Animas arch dipped southwestward away from the Cambridge arch (Rascoe, 1978). Movement on this feature during deposition of the D Zone may have subtly affected the distribution of facies, particularly the lime grainstones, in the study area.

Stratigraphic setting

The Lansing–Kansas City Groups are the upper two groups of the Missourian Stage of the Upper Pennsylvanian Series. In the western Midcontinent, they have been subdivided by Parkhurst (1959) into formations and members believed to be correlative to their equivalent units in the outcrop belt in eastern Kansas (fig. 5). Recent work done by Burchett (1983) at the Nebraska Geological Survey suggests some modification of Parkhurst's work may be necessary.

Operators in southwestern Nebraska and western Kansas commonly employ informal classification schemes to divide the Lansing–Kansas City Groups. These classification schemes can vary from operator to operator. At least five such classifications are in current use and all of these vary in applicability and utility. The classification used here is modified from Kincaid, Trimble, and Larson (in Parker, 1961) and illustrated in Dubois (1979, fig. 5). This classification most closely approximates the division of the Lansing–Kansas City in separate sedimentary cycles.

The utilization of this classification scheme necessitates examination of conventional core to locate the positions of the upper and lower unconformities that bound each cyclothem. The unconformities are generally overlain by a thin transgressive carbonate bed (lower carbonate unit) which is easily recognized in cores and on wireline logs. Locally, however, particularly in updip regions, the lower carbonate may be absent due to nondeposition or it is unrecognizable on wireline logs due to thinning below resolution of logs or incorporation of terrigenous clastic material diminishing the contrast with the adjacent shale. Even in these areas, the position of the unconformities is generally obvious in cores and thereby capable of being calibrated to log character and mapped.

Despite the difficulties in identifying the bounding unconformities, every attempt should be made to divide the

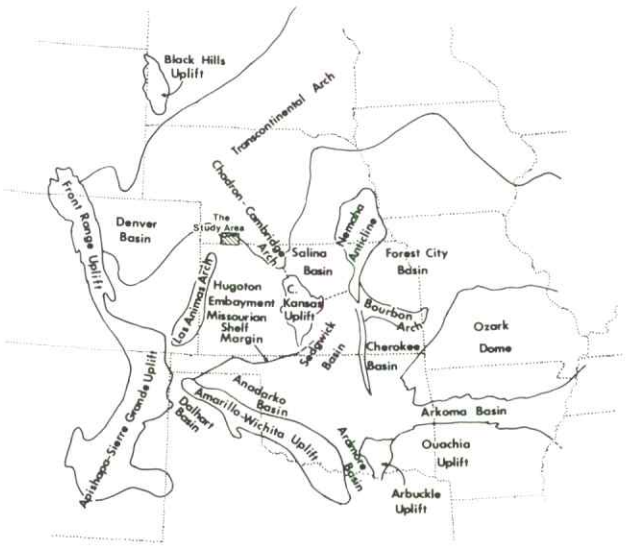


FIGURE 4—The structural and tectonic elements that controlled regional patterns of sedimentation in the Midcontinent during the Late Pennsylvanian (compiled from Moore, 1929; Branson, 1961; Rascoe, 1962; Heckel, 1980; and Watney, 1980).

Lansing–Kansas City Group into these sedimentologically significant zones. This will aid in discussion and understanding of sedimentary processes responsible for their deposition.

Depositional facies

Lower carbonate

The lower carbonate unit unconformably overlies the E-Zone upper shale within the area of investigation. This thin limestone bed, in the Poindexter No. 1 core, is a yellowish-brown, silty, pelletoid, *Osagia*-oncoid, skeletal lime packstone to grainstone with scattered rounded shale clasts (fig. 6). The shale clasts were presumably reworked from the underlying E-Zone upper shale during transgression (fig. 7). These rocks grade upward through locally developed pellet, fusulinid, lime grainstone to very shaly fusulinid lime wackestone near the gradational contact with the overlying lower shale (fig. 8).

The pellet *Osagia* grainstone facies represents initial deposition of the lower carbonate in slightly agitated, restricted shallow-marine waters. The overlying pellet fusulinid grainstone facies is a higher-energy, unrestricted marine deposit which accumulated in the study area as the sea level rose. Finally, lime and terrigenous muds containing scattered fusulinids were deposited. This vertical distribution of facies is characteristic of carbonates deposited in epeiric seas during transgression (Elias, 1962; Laporte and Imbre, 1964; Irwin, 1965; Laporte, 1969; Watney, 1979; Heckel et al., 1979; Heckel, 1980; fig. 9).

The lower carbonate can be readily distinguishable on most wireline log suites. It is characterized by intermediate gamma-ray counts and high neutron counts or low-density values (fig. 10). Locally, where the lower carbonate contains higher percentages of terrigenous clastic material, it has a diminished but usually recognizable log response.

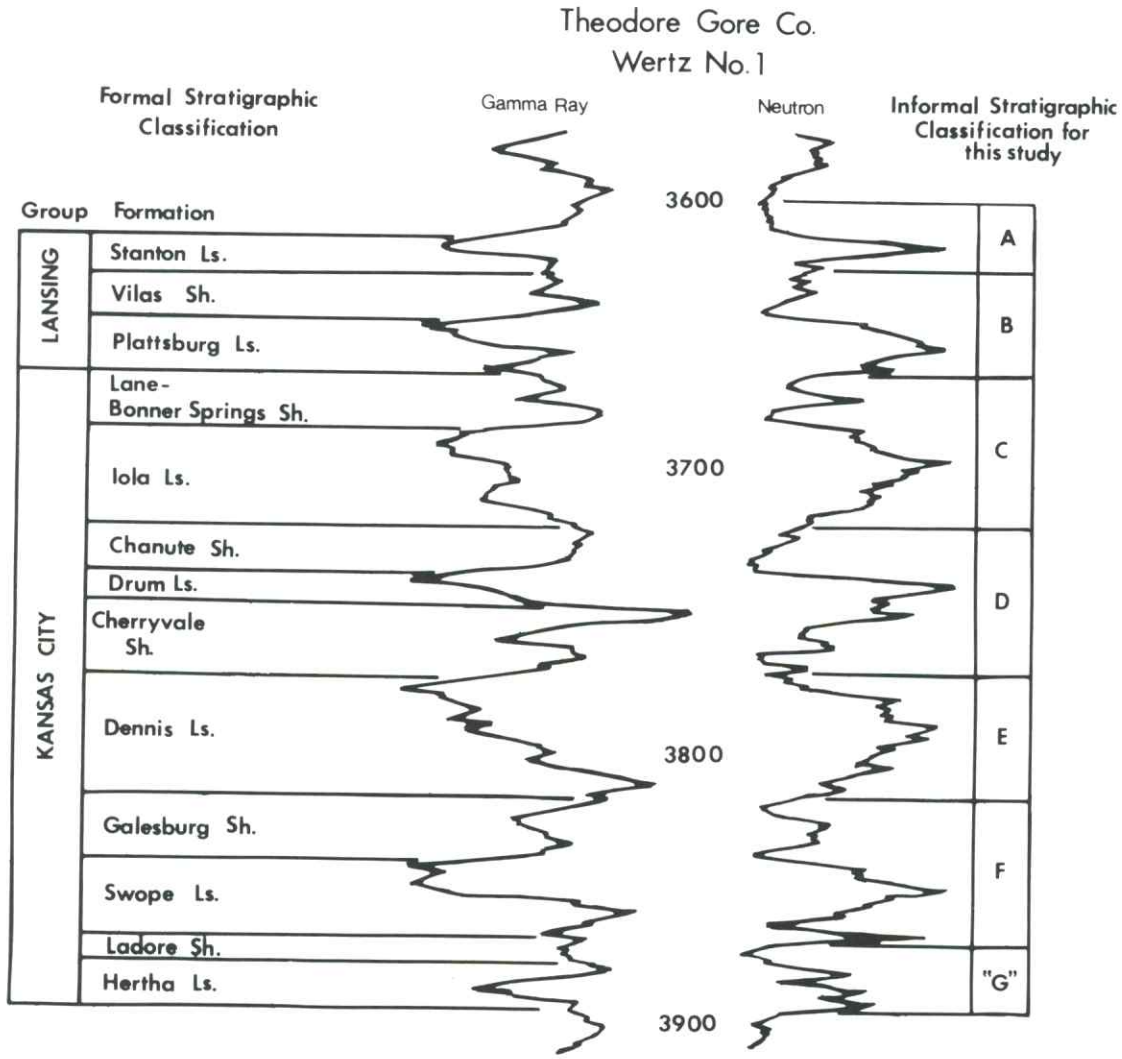


FIGURE 5—Stratigraphic outcrop nomenclature related to the wireline log signatures of the Lansing–Kansas City groups using correlations of Parkhurst (1959). The informal classification scheme used in this study appears at the right of the log trace.

Core may be necessary in these areas in order to distinguish log deflections of the lower carbonate from those of similar appearance produced by siltstone beds which occur in the underlying E-Zone upper shale.

Lower shale

The lower shale conformably overlies the lower carbonate. It can be divided into two units: 1) a basal greenish-gray fissile shale (unit 2A) and 2) an overlying dark-reddish-brown fossiliferous calcareous claystone (unit 2B; fig. 6).

The greenish-gray shale maintains a uniform thickness of 4–6 ft throughout the study area. In the Poindexter No. 1, it contains a limited faunal assemblage of rare brachiopods, echinoderms, and ostracodes. This shale is laterally equivalent to thinner shales with very high gamma-ray "kicks" in southwestern Hitchcock County. This log response is usually associated with black shales. Heckel (1980) noted that gray shale facies of this type may be updip equivalents to more basinal black phosphatic shale facies and probably represent deposition in oxygen-poor environments on the margins of a large anoxic water mass during maximum transgression of sea level in "Kansas-type" cyclothems (fig. 11).

The gray shale beds can be recognized on gamma-ray/neutron logs by their intermediate-level gamma-ray, low neutron-density deflections. These log responses should be located directly over the log responses of the lower carbonate bed.

The overlying reddish-brown claystone in the lower shale (fig. 8) thickens northward at the expense of time-equivalent, downdip (southward), massive carbonates to about 18 ft. The claystone must have been deposited very rapidly in order to preserve its red color, in what must have been at least a mildly reducing environment. The dumping of large quantities of detritus on the periphery of the basin probably caused local sea-level regression.

This subfacies can be distinguished from the gray shale facies using gamma-ray/neutron and density logs. It is characterized by lower deflections of the gamma-ray and higher neutron-density deflections (fig. 10).

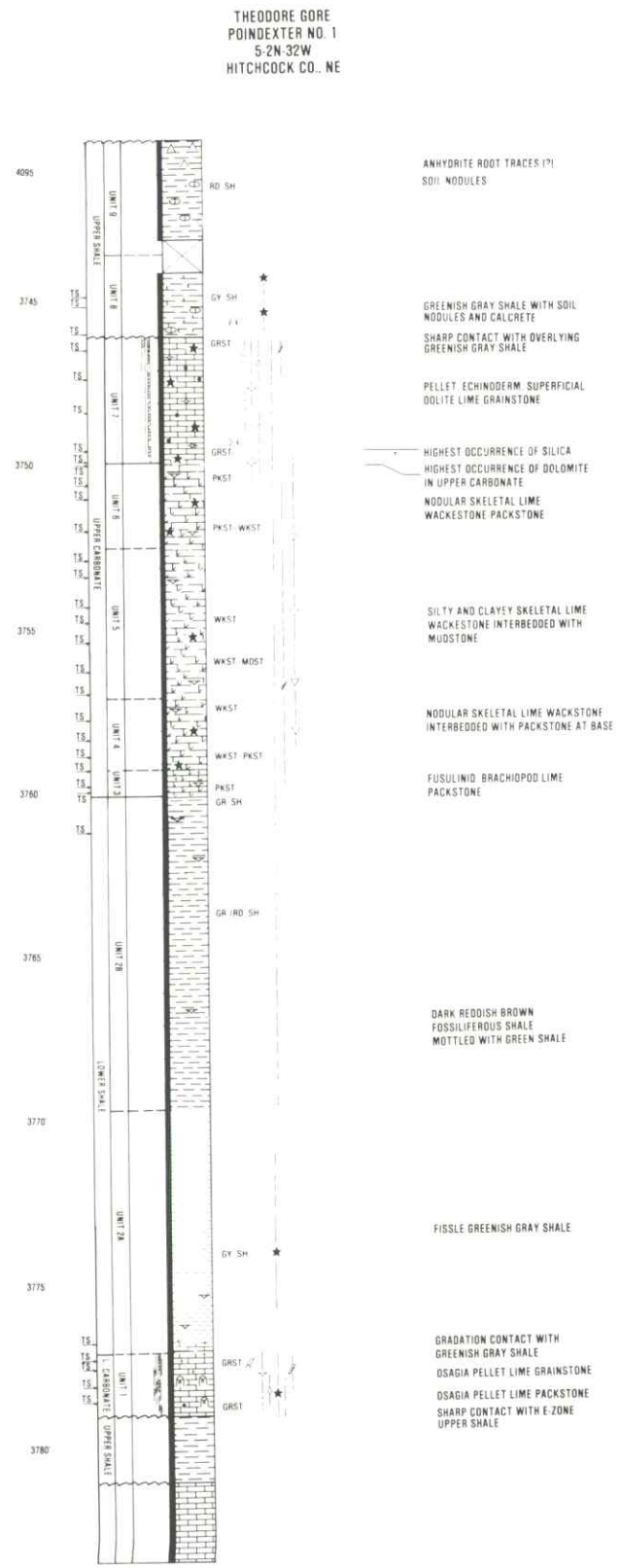


FIGURE 6—Core description of the D Zone from the Theodore Gore Poindexter No. 1 oil well in Meeker Canal oil field. The symbology used is from Swanson (1981).

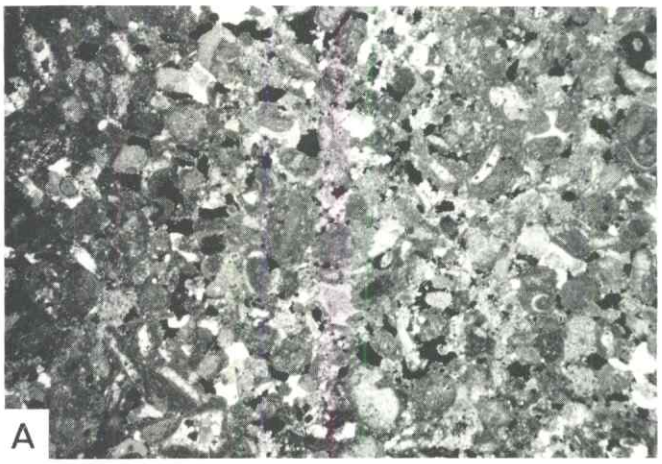
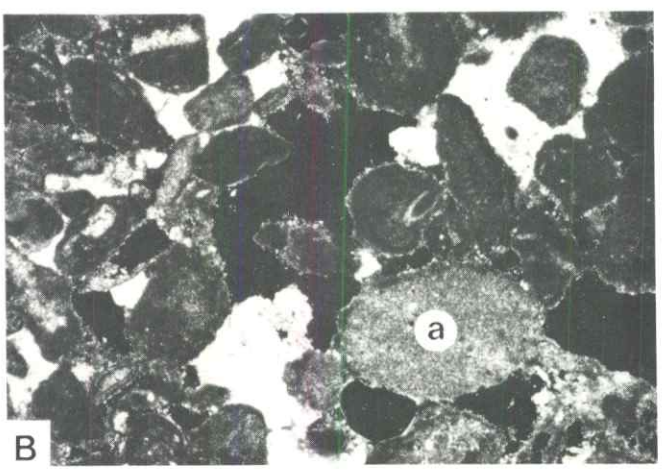
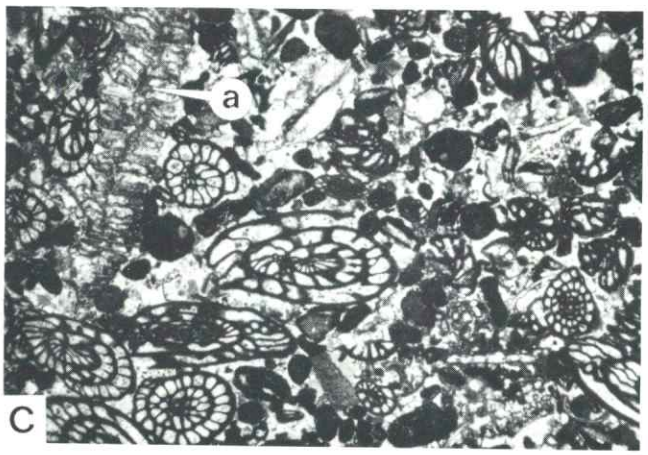


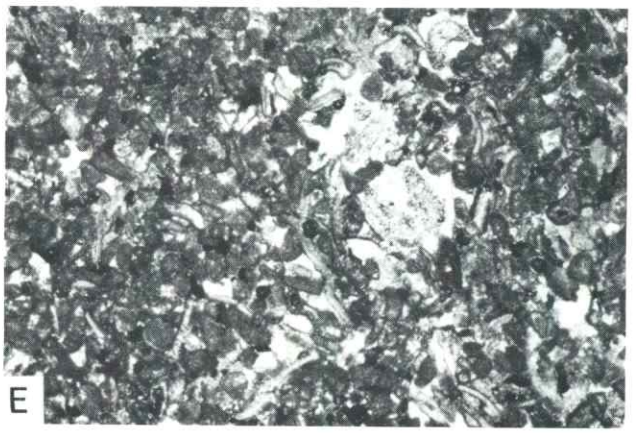
FIGURE 7—Photomicrographs from selected facies of the D-Zone cyclothem in Poindexter No. 1 core.
A) *Osagia*, pellet grainstone facies from the lower carbonate, 3,778.5 ft.



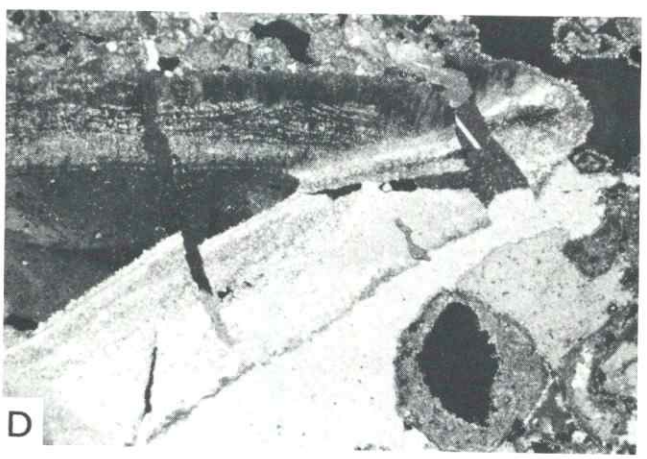
B) Portion of *Osagia*, pellet grainstone with rounded shale clast (a). Note the larger solution-enhanced pores and corroded blocky calcspar cement, 3,777.2 ft.



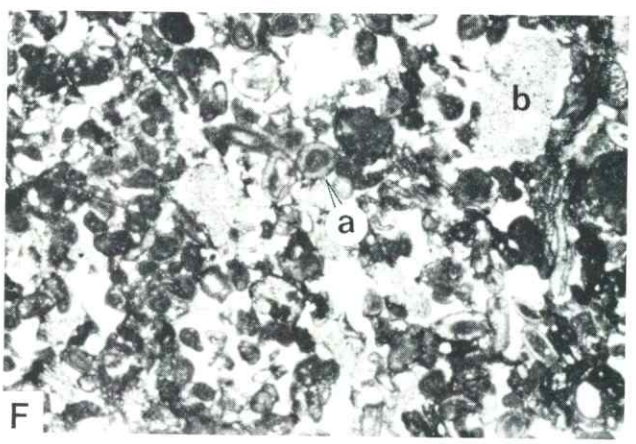
C) Fusulinid grainstone facies in upper portion of the lower carbonate. Note the large green algae (*Epimastrapora*) fragment (a), 3,776.7 ft.



E) Pellet, molluscan, crinoid grainstone of the upper interval. Note the syntaxial overgrowths on the crinoid fragments, 3,749.5 ft.



D) Broken calcite-healed trilobite fragment from the upper carbonate unit. Note that the calcspar is occluding secondary porosity. The presence of calcspar can greatly reduce porosity locally in the upper interval of the D-Zone 3,748 ft.



F) Pellet, superficial-oolite grainstone is characterized by oolites with single radial calcite coatings surrounding fine-grained nuclei (a) and crinoid fragments (b), 3,647.3 ft. All bar scales are 1 mm.

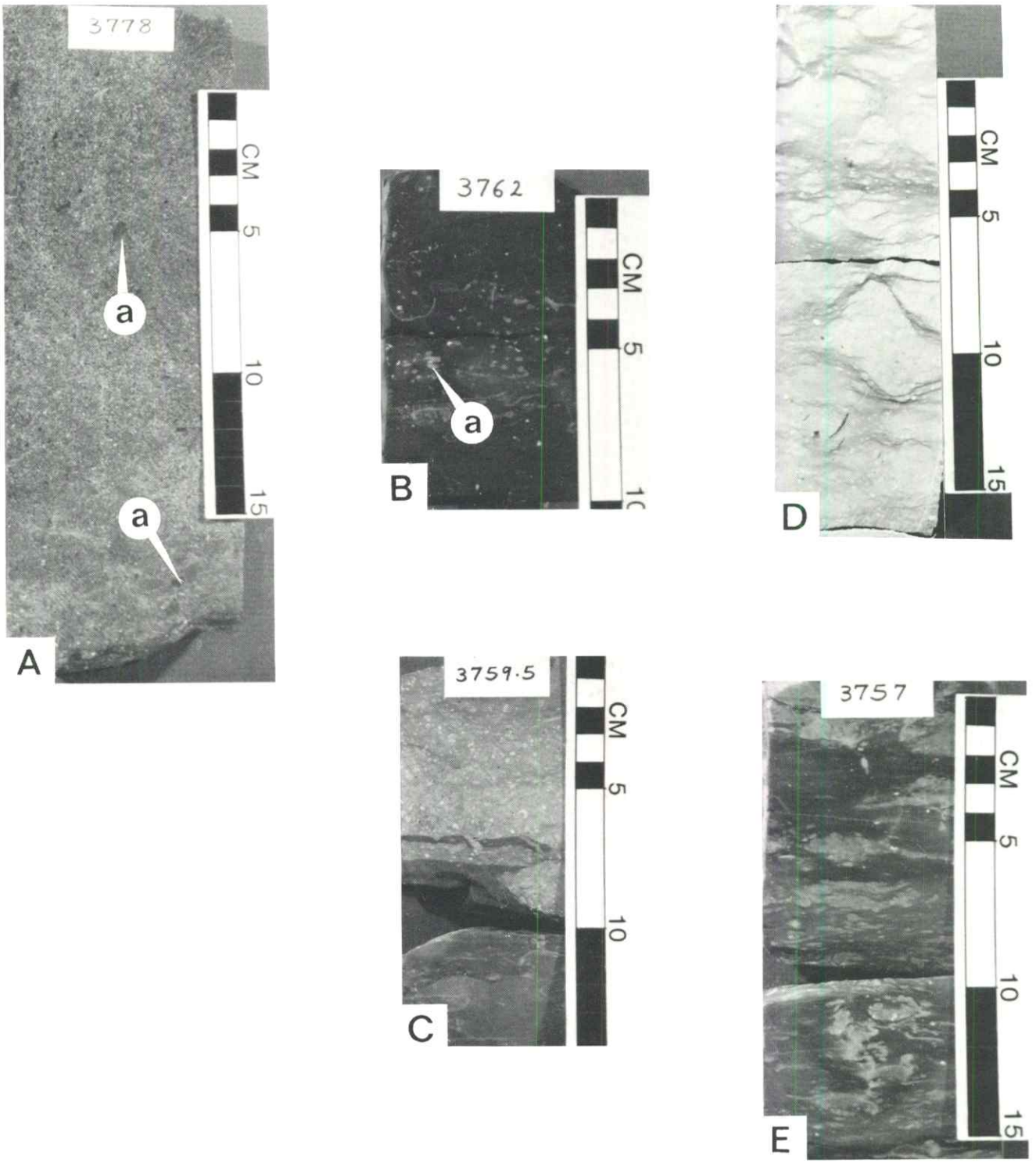


FIGURE 8—Core slabs from the Poindexter No. 1 D-Zone.
A) Large shale clasts (a) reworked from the E-Zone upper shale are easily recognized in core slabs of the D-Zone lower carbonate.
B) The lower shale unit is characterized by its dark-red color and scattered fossil fragments such as *Rhombopora* bryozoan fragments (a).
C) Unit 3 at the base of the upper carbonate is a very dense skeletal packstone.
D) Overlying unit 3 are the nodular skeletal packstones and wackestones of unit 4.
E) Unit 5 is characterized by this very argillaceous dusky-red skeletal wackestone and mudstone.

Upper carbonate

The upper carbonate is divided into a predominantly mud-supported lower interval and a predominantly grain-supported upper interval.

In the Poindexter No. 1 core, the upper carbonate-lower shale contact is overlain by a clean, thin (6 inches), very dense skeletal packstone (unit 3). This facies is laterally equivalent to skeletal grainstones elsewhere in the study area. Unit 3 was deposited above wave base where the sediments were effectively sorted.

Overlying unit 3 is a nodular skeletal lime packstone-wackestone with numerous wavy laminae (microstylolite swarms) of green clay (unit 4, fig. 8) and dusky-red argillaceous skeletal lime wackestone and mudstone (unit 5, fig. 12). The nodular appearance of these rocks may have been produced through a combination of bioturbation and pressure solution. The presence of an increased percentage of argillaceous material in these facies suggests water turbidity may have increased during their deposition. The turbid water conditions probably resulted in decreased rates of carbonate grain production so that with continued subsidence, lower energy facies of units 4 and 5 migrated into the study area. Solution breccias, although not evident in the Poindexter No. 1 core, are known to commonly occur elsewhere in this interval. The breccias apparently formed during periods of freshwater influx which resulted in dissolution of the limestone. The resulting cavities were later infilled with fragments of the host limestone and red clay and silt deposited by downward-percolating ground water.

The terrigenous influx responsible for deposition of unit 5 eventually waned, allowing for improved water clarity resulting in increased carbonate-grain production. A typical shoaling-upwards sequence resulted as the carbonates built to sea level. This phase of deposition is represented by the packstones and wackestones of unit 6 and the grainstones of unit 7.

The sharp contact between unit 7 and unit 6 in the Poindexter No. 1 core suggests submarine scouring may have taken place prior to deposition of the pellet, superficial-oolite grainstones in unit 7 (fig. 6). The pellet, superficial oolites were deposited within a shoal-water sand bar which was present in the vicinity of Meeker Canal oil field. The position of this sand bar and others in the study area are revealed as thins on the isopachous map of the upper shale unit of the D-Zone (fig. 13).

The base of the upper carbonate is easily recognizable on gamma-ray/neutron logs because units 3 and 4 combine to produce the high neutron-density deflection at the base of the upper carbonate. Thickness of the two units as measured in cores corresponds well with the thickness indicated by logs.

The top of the upper carbonate is not always easily distinguished from the upper shale by gamma-ray/neutron/guard or sonic log character. Watney (1980) pointed out that in landward, clastic-dominated areas of the Hugoton embayment, log character contrasts generally become diminished as a result of freshwater diagenesis and in situ brecciation accompanied by clay infiltration within carbonate units. This factor may have an effect on logs from the Poindexter No. 1, where thickness of unit 7 as measured in cores varies slightly with the thickness indicated by the corresponding log traces.

Subfacies of the upper carbonate, other than units 3, 4, and 7, cannot be readily distinguished on wireline logs. However, these rocks can be grouped into a carbonate and terrigenous mud-rich subfacies represented by a slightly greater gamma-ray and reduced neutron-density deflection located between the base of unit 7 and the top of unit 4.

Upper shale

The upper shale in the Poindexter No. 1 was only partially cored. Therefore, the upper portion of the upper shale cored in the Ladd Petroleum Dry Creek Unit 2–3A has been added in order to give complete representation of all typical rock types known to occur in the D Zone.

The upper shale of the D Zone in the study area unconformably overlies the upper carbonate. The thickness of the upper shale ranges from 6 to 15 ft and is thought to reflect predepositional topography (fig. 13). It can be divided into a basal unit (unit 8) of calcareous, pyritic, greenish-gray claystone which forms a matrix that surrounds rounded limestone clasts, calcrete beds, caliche

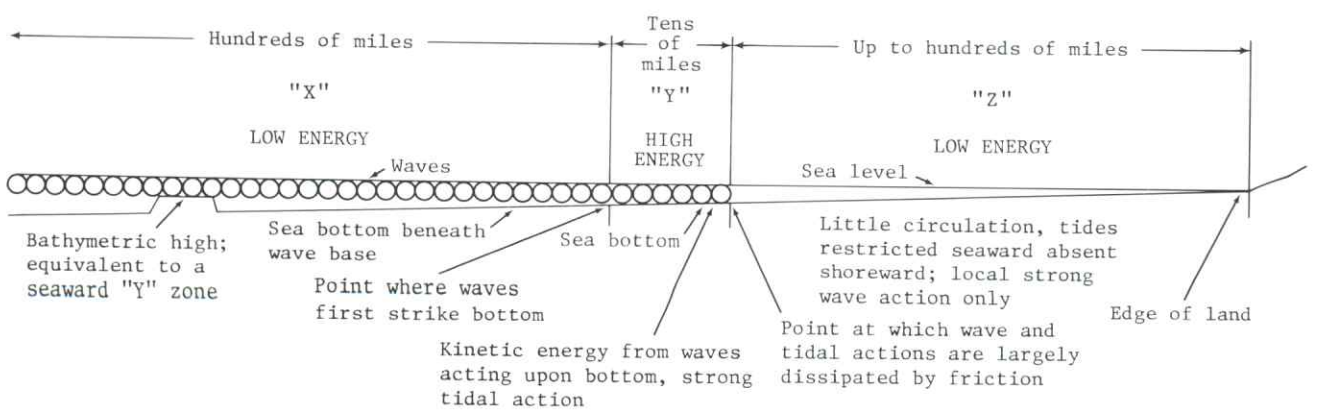


FIGURE 9—Irwin's (1965) model for epieric clear-water sedimentation divides the epeiric sea into three energy zones as indicated. The vertical sequence of lithologies in the lower carbonate are interpreted to represent progressive landward migration of these environments during transgression.

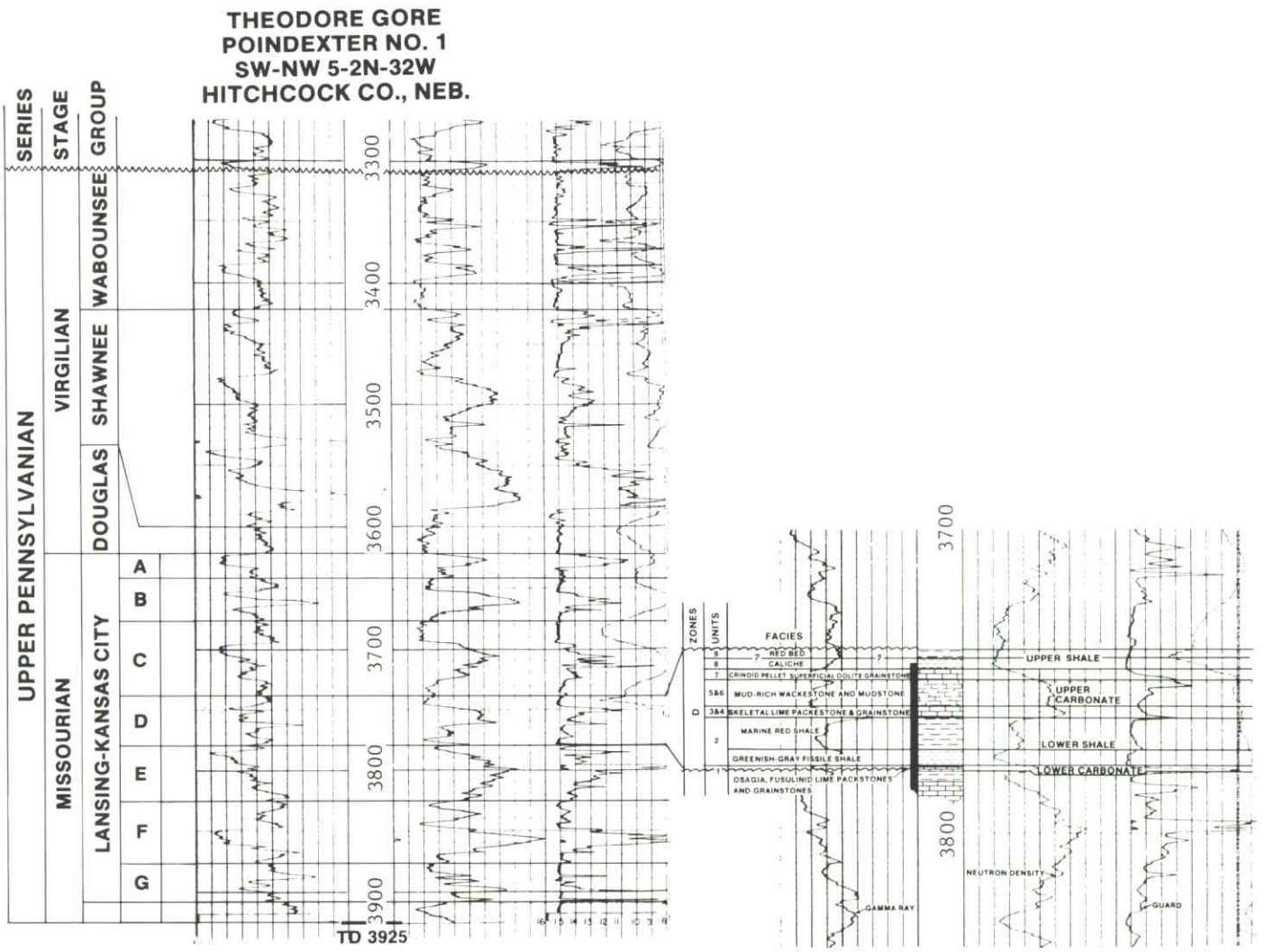


FIGURE 10—Gamma-ray/neutron-density/guard log from the Poindexter No. 1 showing division of Lansing–Kansas City Groups into individual sedimentary cycles. Detailed subdivisions of the D-Zone is shown to the right.

nodules, and soil nodules. In the Poindexter No. 1 core, however, this unit lacks the limestone clasts and calcrete beds. The claystone matrix is composed of interlocking finely crystalline subhedral calcite and dolomite crystals which produce a crystic plasmic fabric (after Brewer, 1964, p. 37). The presence of this rock type and the other characteristics described above indicate that this unit represents a subsoil caliche similar to those found in many recent and ancient soil weathering profiles (Allen, 1974; Leeder, 1975; Reeves, 1970; Hubert, 1977).

The upper unit (unit 9) is a reddish-brown silty claystone with scattered soil nodules, slickensides, and an uppermost gypsiferous rooted horizon. These characteristics suggest that the upper shale is a paleosol (Hubert, 1977; McPherson, 1979; Wright, 1982; Weider and Yaalon, 1974; Boul et al., 1973).

Both units are easily recognized in core as distinct red and gray units. Nevertheless, the interpretation of these units should not be based solely on their color. Locally, the basal unit which is normally greenish-gray has been reddened. At these locations, remnants of nonreddened greenish-gray crystic plasmic fabric are commonly preserved on undersides of the regolith limestone clasts. Also, remnants of calcareous and dolomite caliche nodules are present, which suggests this bed may previously have been part of the caliche horizon. The reddening that has taken place at these locations is indicative of secondary oxidation and formation of iron oxides, a process that may have occurred throughout the overlying red-bed unit. The source of the iron oxides probably resulted from intrastratial alteration of iron silicates such as biotite, hornblende, and chlorite similar to that proposed by Walker (1967). This type of reddening is believed to occur in semi-arid to arid climates. Additionally, the preservation of gypsum-filled root molds in the uppermost upper shale is indicative of aridity during soil formation.

The thickness of the upper shale generally corresponds well with the thickness represented on the wireline logs by the distance between the top of the D Zone (base of C-Zone cyclothem) and the top of the upper carbonate. Resolution of unit 8 within the upper shale on logs generally is not possible. The upper shale is commonly characterized by enlarged borehole conditions as indicated by caliper logs.

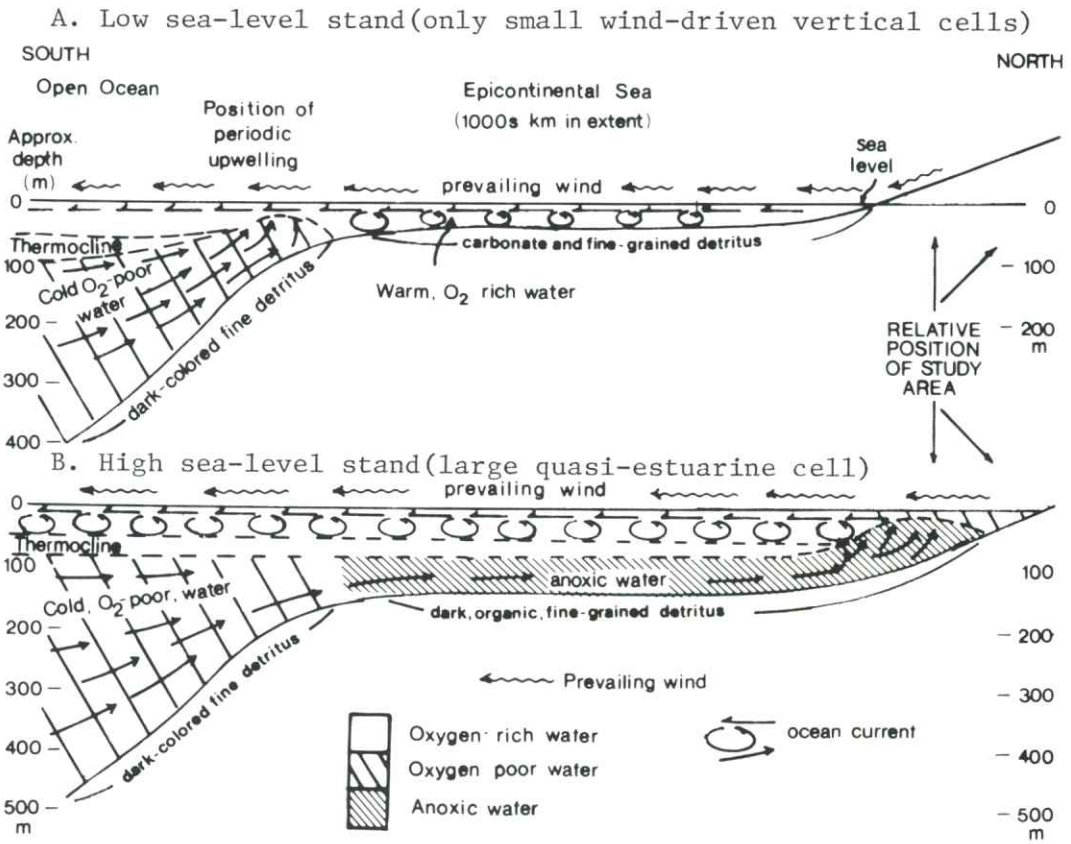


FIGURE 11—The depositional setting for the black shale facies common in "Kansas-type" cyclothems as proposed by Heckel (1977). The relative position of Hitchcock County on these sections during the accumulation of the D-Zone is indicated.

Diagenetic fabrics

Diagenetic features indicative of subaerial exposure abound in the rock of the cyclothem while those indicative of burial and marine diagenesis are considerably less common. Diagenetic fabrics most easily recognized in the core from the Poindexter No. 1 are 1) secondary porosity, 2) silica replacement of skeletal fragments by red chalcedony, and 3) stylolitization.

Secondary porosity

Porosity in both the upper carbonate and lower carbonate is predominantly secondary, solution enhanced, interparticle, vuggy, and moldic. This porosity was produced by leaching of carbonate grains and cement by freshwater during establishment of freshwater phreatic and vadose environments resulting from subaerial exposure of the carbonate units.

The distribution of the porosity in the D-Zone upper carbonate though is related to the occurrence of shoal-water sand bars. These bars are expressed as thickening of the upper carbonate and relief on its upper surface. Therefore, the isopachous maps of the occurrence of upper-shale thins can be used in the study area to indicate the position of the sand bars. Porosity in the lower carbonate formed as a result of dissolution by freshwater. Controls on the porosity distribution in the lower carbonate are probably related to the flow of freshwater through grain-supported microfacies, lithifying and preserving the porosity in the unit prior to burial.

Dolomite

Limpid rhombic dolomite in the upper carbonate of the Poindexter No. 1 core is scattered throughout the matrix of the lower interval. Although not visible in cores because of its small crystal size, the distribution of this mineral may be an indicator of an important diagenetic event. The characteristics of this dolomite and dolomite cements in the grainstones from nearby wells indicate it probably formed in a mixing zone. A plot of the highest stratigraphic occurrence of the dolomite on a cross section produces a remarkably flat line that transects facies boundaries. This line therefore may represent the highest position of the water table that existed as the mixing zone migrated through the area as sea level fell early in the diagenetic history of the cyclothem. Mixing zones can be indicators of diagenetic environments within which dissolution and porosity development can take place because the ground water in mixing zones is undersaturated with respect to calcite and saturated with respect to dolomite (Plummer, 1975) and its mixing zones are juxtaposed next to undersaturated meteoric freshwaters. Therefore the presence of mixing-zone

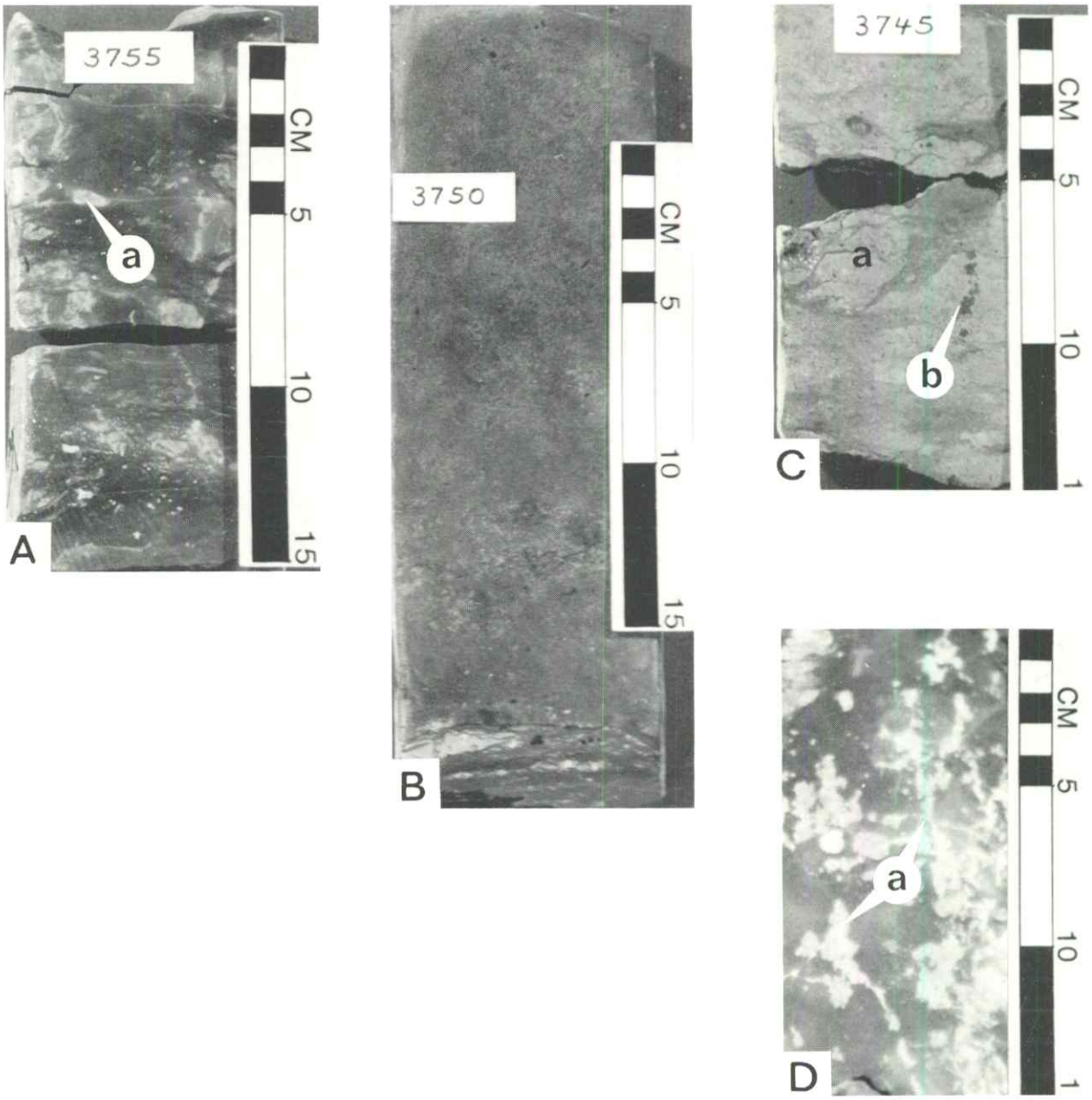


FIGURE 12—Core slabs from the Poindexter No. 1 D-Zone.
A) Argillaceous lime mudstone of unit 5. The white areas (a) may be burrows.
B) The basal contact of the upper interval of the upper carbonate is sharp in the Poindexter No. 1. Vuggy and moldic porosity in the overlying upper carbonate is easily recognized in the core slab.
C) The basal soil caliche in the upper shale is characterized by caliche nodules (a) and pyrite (b). The uppermost portions of the upper shale locally contain gypsum-filled root molds as illustrated in (D); Ladd Petroleum 2–3A Dry Creek Unit, 4,094–4,095 ft.

dolomite, even in nonporous rock, may be a clue that suitable diagenesis has occurred and that porosity may be present elsewhere.

Silica replacement

The presence of red, silicified, carbonate skeletal fragments in the D-Zone carbonate units is an important indicator for subaerial exposure. Silica becomes soluble in alkaline soil solutions when the pH rises above 9. Under these conditions, quartz silt and clays can be leached releasing SiO_2 in the form of silicic acid or as a colloid (Smale, 1973). Precipitation of the silica takes place at the water table where the downward-percolating silica-laden meteoric water mixes with less-alkaline continental ground waters reducing the pH to below 9. The highest stratigraphic occurrence of red silica in the D Zone may denote the highest position of the water table during which time grainstones were undergoing vadose leaching. Much of the

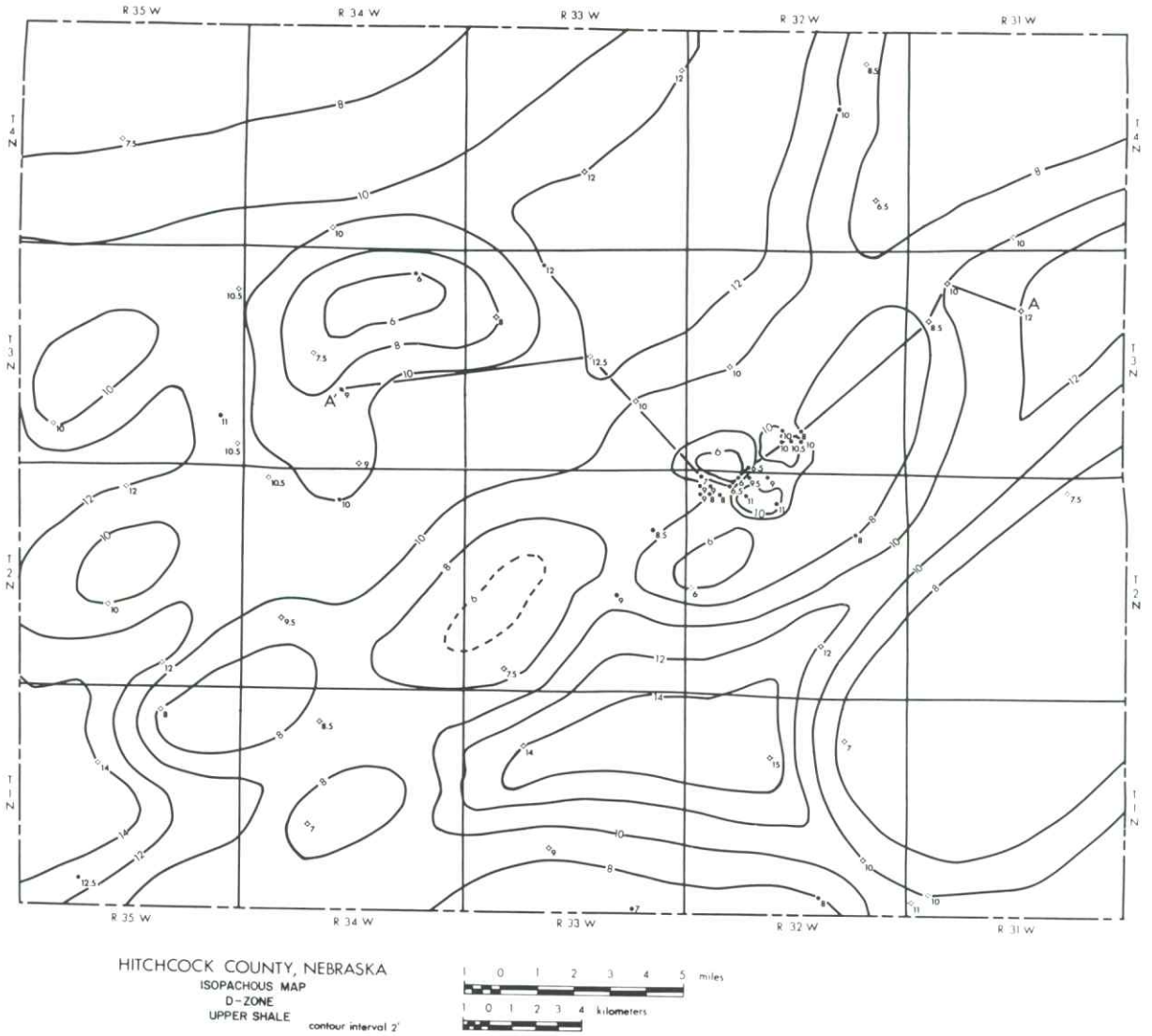


FIGURE 13—Thinning of the upper shale in the D-Zone coincides with localized shoal-water sand bars of the upper carbonate composed of pellet, superficial-oolite grainstones. These sand bars by virtue of their initial porosity were selectively leached during subaerial exposure as undersaturated meteoric water passsed through this sediment.

silica in the D-Zone is in the form of length-slow chalcedony. Length-slow chalcedony may be indicative of silica replacement associated with sulfate enrichment of subsurface waters (Folk and Pittman, 1979), suggesting that ground water during this phase of diagenesis was hypersaline.

Stylolitization

During burial, pressure solution in the more terrigenous mud-rich facies combined with earlier bioturbation to produce the common nodular appearance of those rocks. Recognition of the origin of the nodular limestones is important in classification of the upper carbonate subfacies.

Conclusions

Detailed examination of core aids in understanding depositional processes that were operating in the Late Pennsylvanian seas of the western Midcontinent. Understanding these processes allows for development of depositional models which can aid in predicting the distribution of the grain-supported rock necessary to form reservoir rocks.

Recognition of certain diagenetic features such as solution breccias, red silica-replaced skeletal fragments, and mixing-zone dolomites in nonporous upper carbonate sections aids in documenting and characterizing the diagenetic environments which resulted in the development of secondary porosity affecting the zone of interest.

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Deltaic deposition in the Tonganoxie or "Stalnaker" Sandstone (Stranger Formation, Virgilian): TXO Robinson C–1, Harper County, Kansas

by *Anthony W. Walton*, Department of Geology, University of Kansas, Lawrence, Kansas, and *Gary Griffith*, TXO Production Co., Wichita, Kansas

Introduction

N. W. Bass (1929) pointed out that in the subsurface of Kansas, oil occurs in long, narrow "shoestring" sandstones, such as those in the Cherokee of the Cherokee Basin, and sheetlike bodies, of which he gave the "Stalnaker" of the Sedgwick Basin as an example. Over the years, many geologists have debated the origin of these types of sand, especially the famous shoestrings. Recent opinion seems to be settling on a fluvial or delta distributary origin for shoestrings, which are especially characteristic of the Pennsylvanian here.

Few examples of the sheetlike type have been documented, and less is known of their origin. Recent exploration by TXO Production in Harper County led to gas discoveries in the "Stalnaker" interval. In the course of development activities, TXO took a 60-ft core of "Stalnaker" in their Robinson C–1 well, sec. 20, T. 37 S., R. 8 W. in the Sullivan field in Harper County (figs. 1, 2, and 3). Careful examination of this core indicates that the sandstones it sampled accumulated in a deltaic environment.

In the Robinson C–1 core, various environments of deltas are represented, especially the distributary mouth bar and the splays and bays of the delta platform. This core includes very good examples of the sedimentary structures and the episodic bedding characteristic of delta-front environments where river floods, marine storms, and day-to-day processes create a complexly variable environment. Superimposed upon this variability are larger cycles reflecting prograding and foundering delta lobes, or perhaps changes of sea level. Structures and sequences in this core are remarkably similar to those described for the modern Mississippi Delta (Coleman and Prior, 1980).

Cores such as this one are our best source of data for interpreting environments of deposition of sandstones. Information on environments of deposition is useful in many aspects of the petroleum industry. Reconstruction of

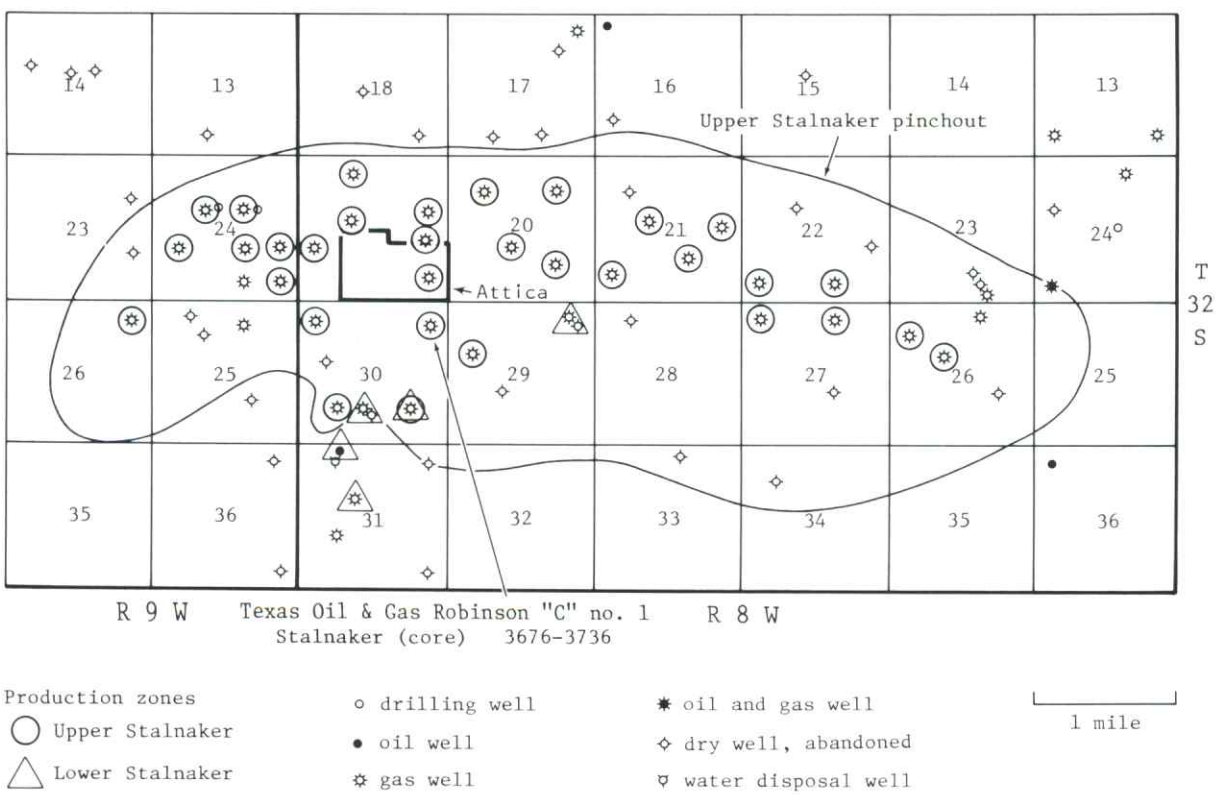


FIGURE 1—Location map of Robinson C–1 well.

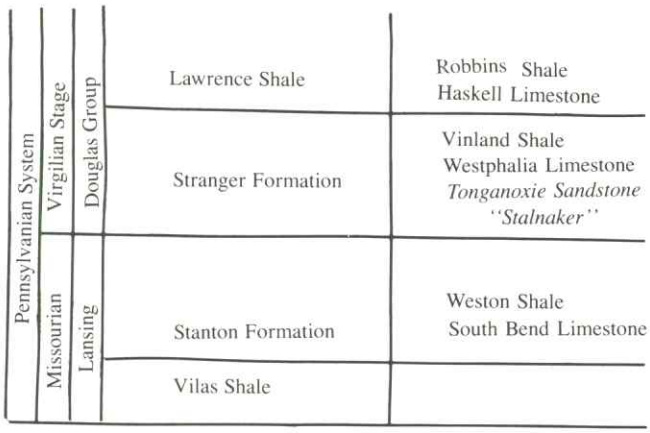


FIGURE 2—Stratigraphic subdivision of upper Missourian and lower Virgilian rocks in Kansas.

paleogeography points to areas where porous rock may have accumulated. Offsets to discovery wells are best planned with knowledge of how the reservoir rocks formed. Mapping of reservoirs is guided by interpretation of environments. Estimates of reserves should be tempered by knowledge of likely size range of sand bodies of various origin. Finally, effectiveness of secondary and tertiary recovery efforts is controlled by continuity, orientation and mineral content (both primary and diagenetic) of the reservoir rock. These are controlled by depositional environment. Using information from cores for calibration, it is possible to use well logs, and sometimes even cuttings, to map sand types in the subsurface.

ACKNOWLEDGMENTS—The authors thank Hal Brown of TXO Production, Wichita, for permission to present results of this investigation.

Stratigraphy

Sandstone was first encountered in the Stranger Formation in south-central Kansas in 1914, when gas was discovered on the Stalnaker farm in Sumner County (Winchell, 1957). Further exploration led to discovery of oil nearby, and the formation has been productive since.

Winchell (1957), in a subsurface study, found that the "Stalnaker" sandstone occurs in the same interval as the Tonganoxie Sandstone of the outcropping Stranger Formation of the Douglas Group (Virgilian;Late Pennsylvanian) in southeastern Kansas (fig. 3). Ball (1964), in his exhaustive treatise on the Douglas, confirmed Winchell's correlation, which had been originally suggested by Lukert (1949). Sanders (1960) and Lins (1950) examined surface and subsurface distribution of sandstone of the Stranger Formation in northeastern Kansas. Griffith (1981) filled a gap between the area Sanders mapped and that which Winchell mapped, so that the distribution of sand in the Stranger over the entire area from the outcrop to the Nemaha uplift, and beyond into Harper and Kingman counties is known. These studies, especially Winchell (1957) and Ball (1964), point out that the limestone above the "Stalnaker" in south-central Kansas, sometimes called "Iatan," is in fact the Haskell Limestone at the base of the Lawrence Shale of the Douglas Group.

The Tonganoxie (or "Stalnaker") Sandstone of south-central Kansas grades into shale along a line running from southwesternmost Montgomery County northwestward across Chautauqua and Greenwood counties, then westward into Sedgwick County (fig. 4). North of that line, in southern and central Greenwood County and central Butler County, only isolated patches of sandstone in the Tonganoxie, perhaps channels, were found in shale by Winchell (1957) and Griffith (1981). To the west in northwestern Harper County and Barber County, the interval between the older Lansing Group and the Haskell Limestone decreases sharply (fig. 4). Winchell (1957) believed that the Tonganoxie overlies the Lansing unconformably. Ball (1964) convincingly argued, for the eastern part of Winchell's area, from Elk County to Sedgwick County, that the Stanton Limestone of the Lansing Group undergoes a southward facies change to terrigenous sandstone and shale, but no section has been removed by erosion from its top. Winchell's (1957) and Griffith's (1981) cross sections, however, show the rapid thinning of the Tonganoxie in Harper and Kingman counties and the complementary thickening of the Lansing.

In northeastern Kansas, sandstones in the Tonganoxie make a long, linear pattern running southwest or south-southwest from their outcrop in central Douglas County and southern Leavenworth County into the subsurface as far as southeastern Lyons County. The sandstone body is lens shaped in cross section. Its lower boundary lies on different units in different places, cutting as low as the Stoner Limestone Member of the Stanton Formation in places (Lins, 1950; Sanders, 1959). Sanders (1959) also shows another band of sandstone in the Tonganoxie, in the subsurface 30–50 mi west of the first band, but merging with it in southeastern Lyons County. In northern Greenwood County, the pattern of isopach thicks and thins of the Tonganoxie in both Sanders' (1959) and Griffith's (1981) maps is irregular and complex. A possible interpretation of the subsurface data of Sanders and Griffith is a set of fluvial channels feeding a delta in northern Greenwood County, north of the area where little sand was deposited (fig. 4).

The overall pattern of deltaic sandstone in south-central Kansas and adjacent Oklahoma (the "Stalnaker") and fluvial and deltaic sandstone in northeastern and east-central Kansas with an area of marine sedimentation between and to the west has been described by Rascoe (1978) and Moore (1979) for the Midcontinent area in the early Virgilian (fig. 4). Sources of terrigenous sediment lay both to the northeast and north and to the south or southeast.

Core description

TXO Robinson C–1 core, S½NENE sec. 30, T. 32 S., R. 8 W., Harper County, Kansas. Parts of the upper and lower "Stalnaker" (i.e., Tonganoxie) Sandstone. This core is in the collection of the Kansas Geological Survey at Lawrence, Kansas.

INTERVAL 1. LOWER "STALNAKER" (3,736–3,726.4 FT)—Rippled sandstone with mud interbeds. Sand beds 0.1–10 cm thick, mud beds up to 0.5 cm thick. Thicker sands may be laminated (fig. 5a).

This interval shows evidence of frequent changes of current conditions. It contains several fining-upward inter-

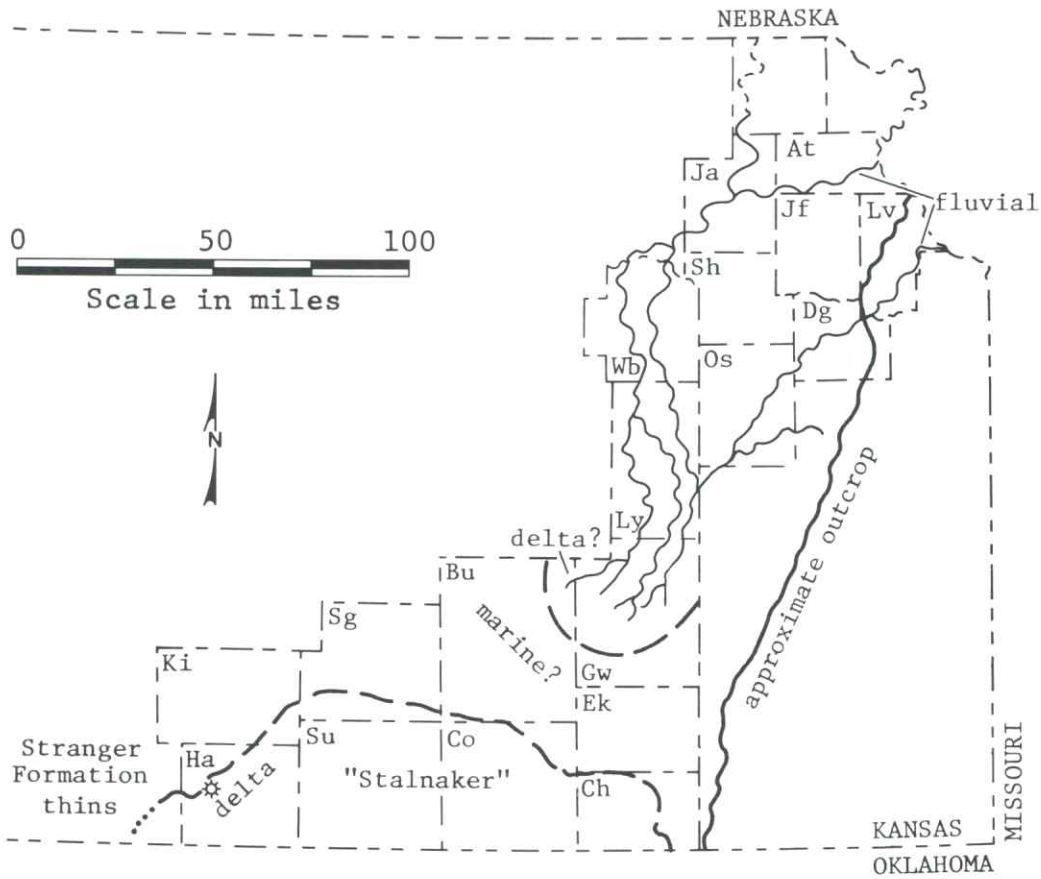


FIGURE 3—Environments of sand deposition in the Tonganoxie Sandstone Member of the Stranger Formation.

vals about 5 cm thick that show decrease of current velocity: the intervals begin with a scour surface, pass upward into laminated fine sandstone, then into rippled very fine sandstone and wavy-bedded sandstone and mudstone interbeds. Where these sequences are not present, the rock consists of wavy-bedded sandstone and mudstone interbeds. Ripples in both situations may be bidirectional.

This sequence can be attributed to an environment where waves were the dominant process of sorting and depositing sediment. Fining-upward sequences represent storms, the interbeds represent either normal conditions or weaker storms. Lack of burrowing suggests either rapid sedimentation or conditions toxic to organisms. Sands are seldom deposited in toxic marine environments, so rapid sedimentation is the more likely explanation. Association of this interval with overlying rocks (intervals 2 and 3) that imply more agitated conditions and rapid sedimentation are consistent with the interval 1 being delta-front deposits within an overall delta sequence.

INTERVAL 2. LOWER "STALNAKER" (3,726.4–3,725.4 FT)—Fining-upward sequences of scour surface—laminated fine sandstone—rippled very fine sandstones—flaser-bedded sandstone. Very similar to storm sequences of interval 1, but no associated lenticular beds. This could represent a slightly shallower part of the delta front than does interval 1.

INTERVAL 3. LOWER "STALNAKER" (3,725.4–3,718.7 FT)—Mostly laminated fine sandstone, but interbeds of mud or very fine, rippled sandstone separate the interval into upward-fining sequences 2–60 cm thick (fig. 5b). Sequences begin with a scour surface. All have laminated lower parts; some have rip-up clasts within their lower parts. The laminated interval makes up nearly all of the sequence. At the top of each sequence is a relatively thin layer of rippled very fine sandstone or lenticular-bedded sandstone and mudstone.

These beds indicate episodic sedimentation, short bursts of activity (erosion, followed by deposition as current decreased) alternating with periods of little or no sedimentation. Ripples seem to be wave-influenced current ripples. This type of deposition could occur in proximal parts of delta fronts where storms rework sediment deposited by fluvial activity.

INTERVAL 4. LOWER "STALNAKER" (3,718.7–3,717.2 FT)—Laminated fine sandstone with interbeds of mudstone (fig. 5c). Sparse burrowing in mudstones.

This interval represents a transition to less-agitated conditions. Within a delta, such a transition could occur between the proximal delta front and delta plain bays, lagoons, and marshes. It could also represent subsidence or transgression and a return to more distal conditions. Overlying intervals suggest a delta plain environment.

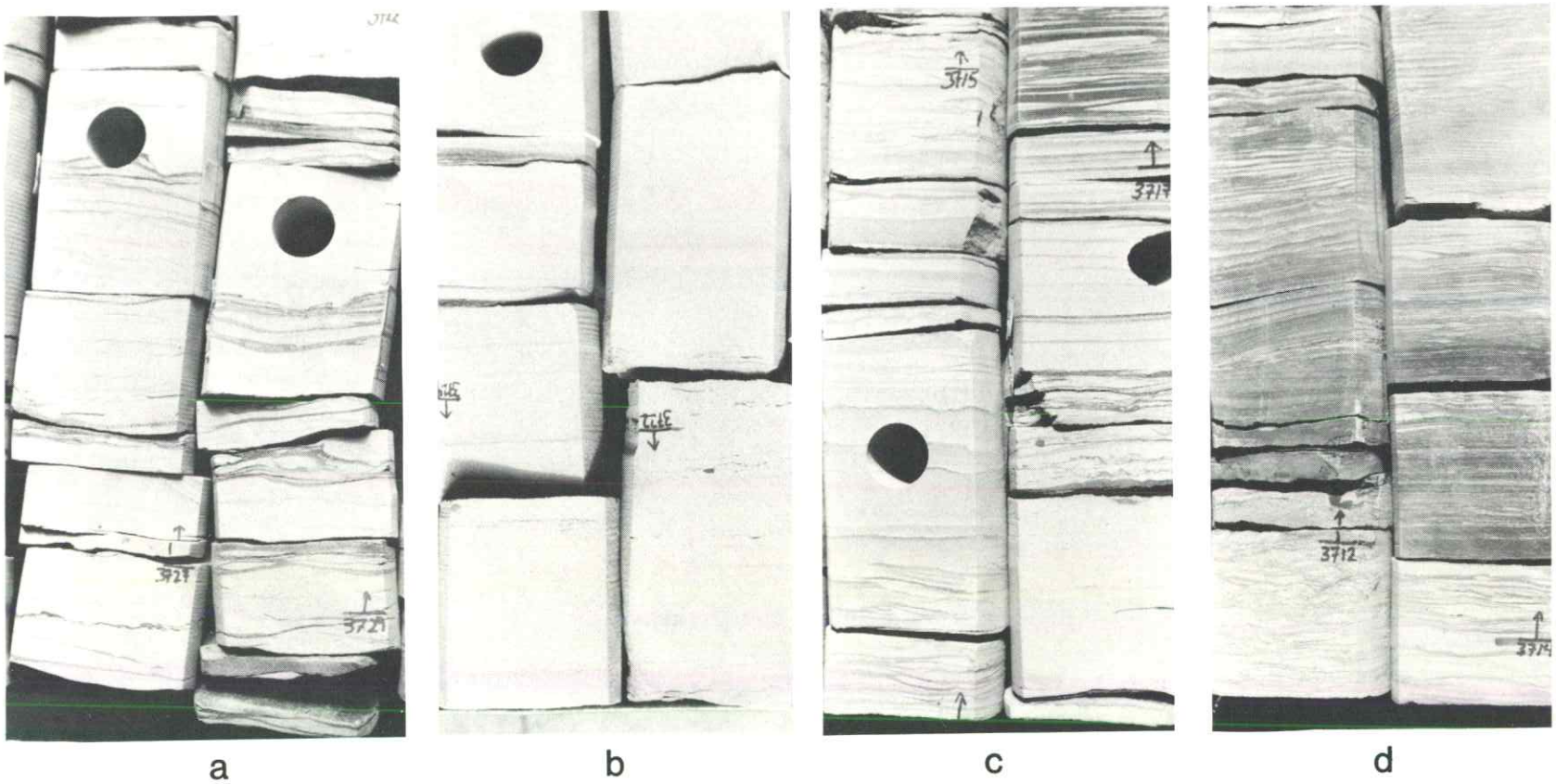


FIGURE 4—Photographs of the Robinson C–1 core; cores are marked with depth in ft. a) Interval 1—showing rippled or laminated sandstones and wavy or lenticular-bedded sandstone and mudstone. Sands have sharp bases and some have gradational tops. b) Interval 3—episodically deposited sandstones showing laminae, some ripples, and rare mudstone interbeds. Sands have scour surface at base, laminated lower parts, and rippled tops, and may grade into mudrock. c) Intervals 4, 5, and 6—interval 4 resembles interval 1 or 2. Interval 5 is an upward-coarsening cycle from lenticular-bedded mudstones to rippled sandstones. Interval 6 contains peculiar, varvelike siltstones a few cm thick (beginning at 3,715.7). d) Intervals 6, 7, and 8—interval 7 is another upward-coarsening sequence, but it is thinner than the ones above and below. It contains varvelike laminae at about 3,713.5 and a mottled interval just below 3,712.

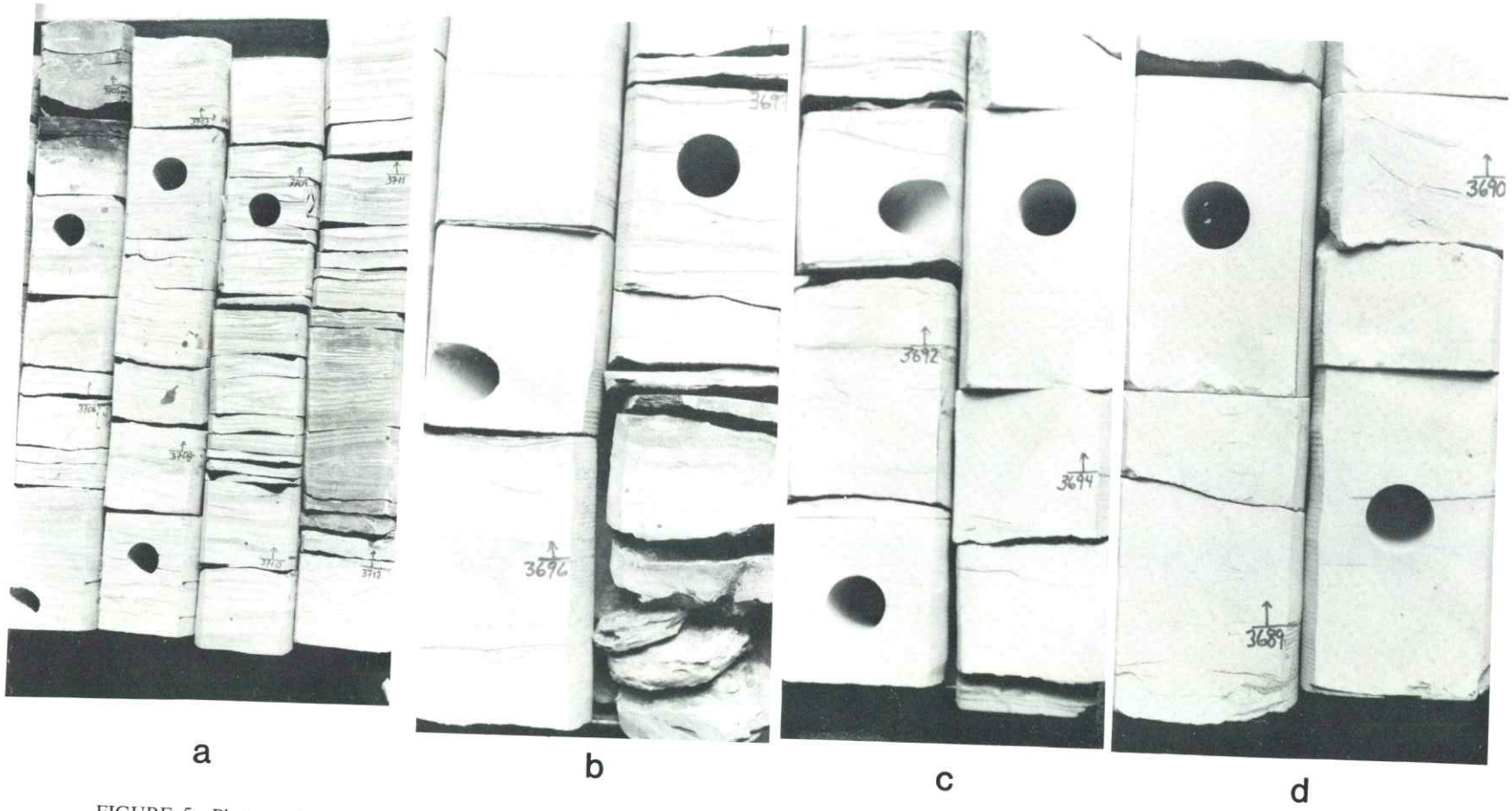


FIGURE 5—Photographs of the Robinson C–1 core; marks give core depths in ft. a) Intervals 8 and 9—a complete upward-coarsening cycle, interpreted as a levee splay, occurs between 3,712 and 3,705.2. Some streaked shales of interval 10 appear above the coal at 3,705.2. b) Intervals 10 (very top) and 11—shales with large plant fragments are in interval 10. Interval 11 is rippled (especially at 3,696 and below) or laminated, similar to intervals 1 through 4, but contains no wave ripples. c) Interval 11—rippled sandstones. d) Interval 12—contortions (3,690.3) and small-scale crossbeds (3,688.2).

INTERVAL 5. LOWER "STALNAKER" (3,717.2–3,715.8 FT)—Linsen-bedded mudstone and very fine sandstone, sparse burrowing (fig. 5c).

Interval 5 is the lowest member of the first of three upward-coarsening sequences. The other two (interval 7 and intervals 8 and 9) are capped by thin coal beds. These sequences represent small splays built into bays or lagoons on the delta plain. Probably, they are levee splays that developed along a distributary channel (Coleman and Prior, 1980).

INTERVAL 6. LOWER "STALNAKER" (3,715.8–3,713.9 FT)—Laminated to thinly bedded sandstone, siltstone, and mudstone (fig. 5d). Some beds or laminae of sandstone are rippled. This interval is dominated by peculiar thin beds or laminae that begin with scour surfaces overlain by rippled very fine sand, structureless very fine sand, or gray siltstone, pass up into structureless gray siltstone, then into mudstone (fig. 5c, d). These sequences as a whole give the interval its thin-bedded or laminated appearance, in contrast to interval 3, where the laminae are upper-flow-regime bed forms. The laminae or thin beds in interval 6 show ripples in some cases, but otherwise could be products of deposition from suspension.

Interval 6 overlies interval 5 gradationally; together they form an upward-coarsening sequence, representing a levee splay built into a bay or lagoon or a subdelta. Ripples in this interval, as in intervals 7, 8, and 9, are all unidirectional within each block of core. This suggests current deposition without significant wave influence. Interval 6 is abruptly overlain by interval 7.

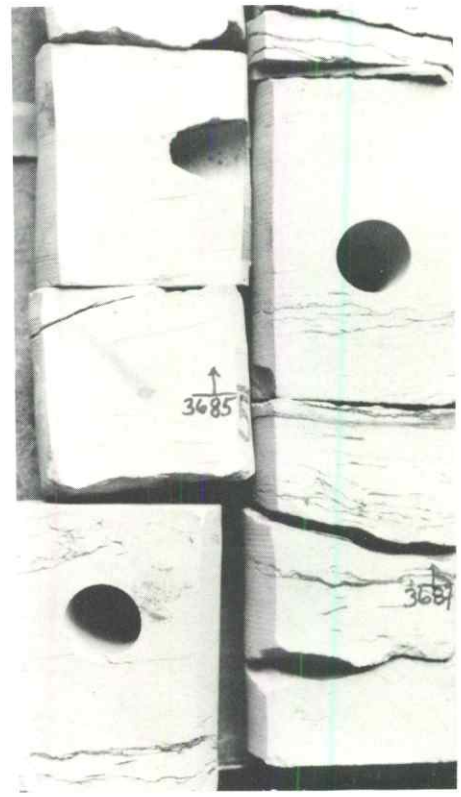
INTERVAL 7. LOWER "STALNAKER" (3,713.9–3,712 FT)—An upward-coarsening sequence beginning with streaked muds that pass upward into lenticular-bedded muds and sands, then into laminae of the kind described in interval 6, but thinner. Above these are lenticular beds, with a higher proportion of sand and thicker beds than the sequence just below. The top is root-marked very fine sandstone and seat earth with a very thin (0.5-cm) coal (fig. 5d).

This interval probably can be assigned to the same environments as intervals 5 and 6, a splay of levee material built into a delta-plain lagoon.

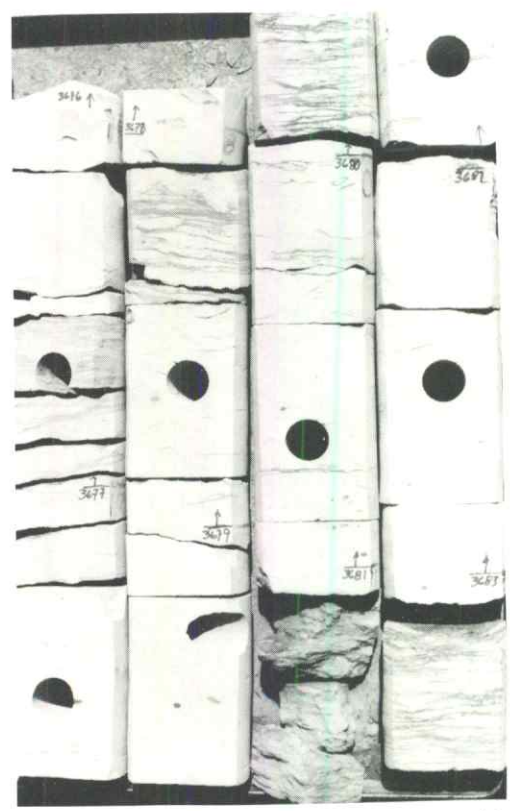
INTERVAL 8. LOWER "STALNAKER" (3,712–3,709 FT)—Coarsening-upward sequence, beginning with streaked muds, passing into peculiar laminae like those in intervals 6 and 7, then into rippled very fine sandstone and siltstone (fig. 6a). Some deformation of ripple sets has occurred. Interval 8 passes gradationally into interval 9.

INTERVAL 9. LOWER "STALNAKER" (3,709–3,705.1 FT)—Rippled sandstone and siltstone, grading upward into a root-marked zone and capped with a coal (fig. 6a). Intervals 8 and 9 together could represent a levee splay building into a bay or lagoon on a delta plain, adjacent to a delta distributary.

INTERVAL 10. LOWER "STALNAKER" (3,705.1–3,697.7 FT)—Major shale break separating lower and upper "Stalnaker" sands (fig. 6a, b). Lower part of this interval is sparsely burrowed, streaked shales. Upper part is mostly claystone with some streaks of silt. Large fragments of plants are common on bedding planes; these are far larger than the fragments in any other interval. This interval could



a)



b)

FIGURE 6—Photographs of the Robinson C–1 core; marks give core depths in ft. a) Interval 13—rippled beds indicating episodic deposition. b) Interval 14 (and very top of interval 13)—episodic beds of rippled sandstone (above a sharp or scoured base) grading into lenticularly bedded sandy mudstones.

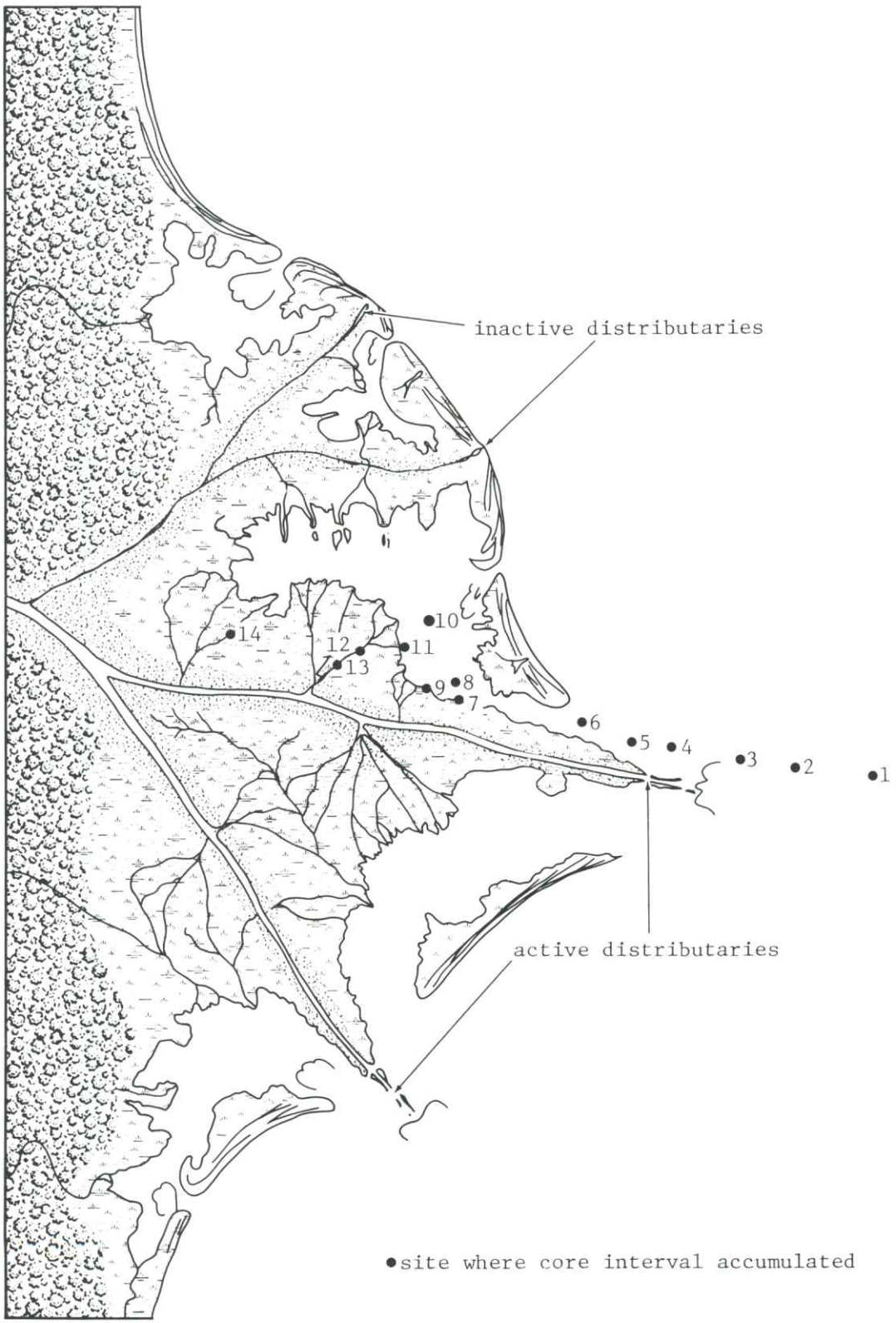


FIGURE 7—Idealized delta showing possible location of environments in which core intervals accumulated; not to scale, but deltas are tens to hundreds of miles across.

be interpreted within the delta model as having formed in a delta-plain environment where conditions permitted preservation of large plants, but not of shells of animals. The large size of the plant debris argues against assigning this facies to a more distal environment, such as a marine shelf. Probably this sediment accumulated in an open bay on the delta plain.

INTERVAL 11. UPPER "STALNAKER" (3,697.7–3,691 FT)—Rippled very fine to fine sandstone, some interbeds of siltstone at base (fig. 6c). Some laminated fine sandstone at 3,697 ft. No overall grain size change, except upward-coarsening at very base, and no obvious development of grain-size sequences within the interval.

This interval is difficult to interpret. It could be a distributary mouth bar developed into the lagoon or bay represented by interval 10 or part of the channel represented by intervals 12 through 14. The bar interpretation is more likely because the general flow regime was lower than that in interval 12, which is unlikely in normal channel situations. Interval 11 differs from delta-front deposits in the lower Stalnaker because of the lack here of important wave influences on the ripples. Hence this unit probably represents progradation of a crevasse splay into a bay or lagoon on the delta plain.

INTERVAL 12. UPPER "STALNAKER" (3,691–3,687.1 FT)—Laminated to low-angle crossbedded fine sandstone (fig. 6d). Some interbeds of silt, some of convoluted fine sandstone, and some rippled intervals.

Crossbedded and laminated sandstones in this interval imply sustained high-flow velocities. Large-scale crossbedding develops under unidirectional currents, but not under wave conditions in fine or very fine sands (Harms and others, 1982). These conclusions together with the nature of intervals 13 and 14 suggest a channel, perhaps a

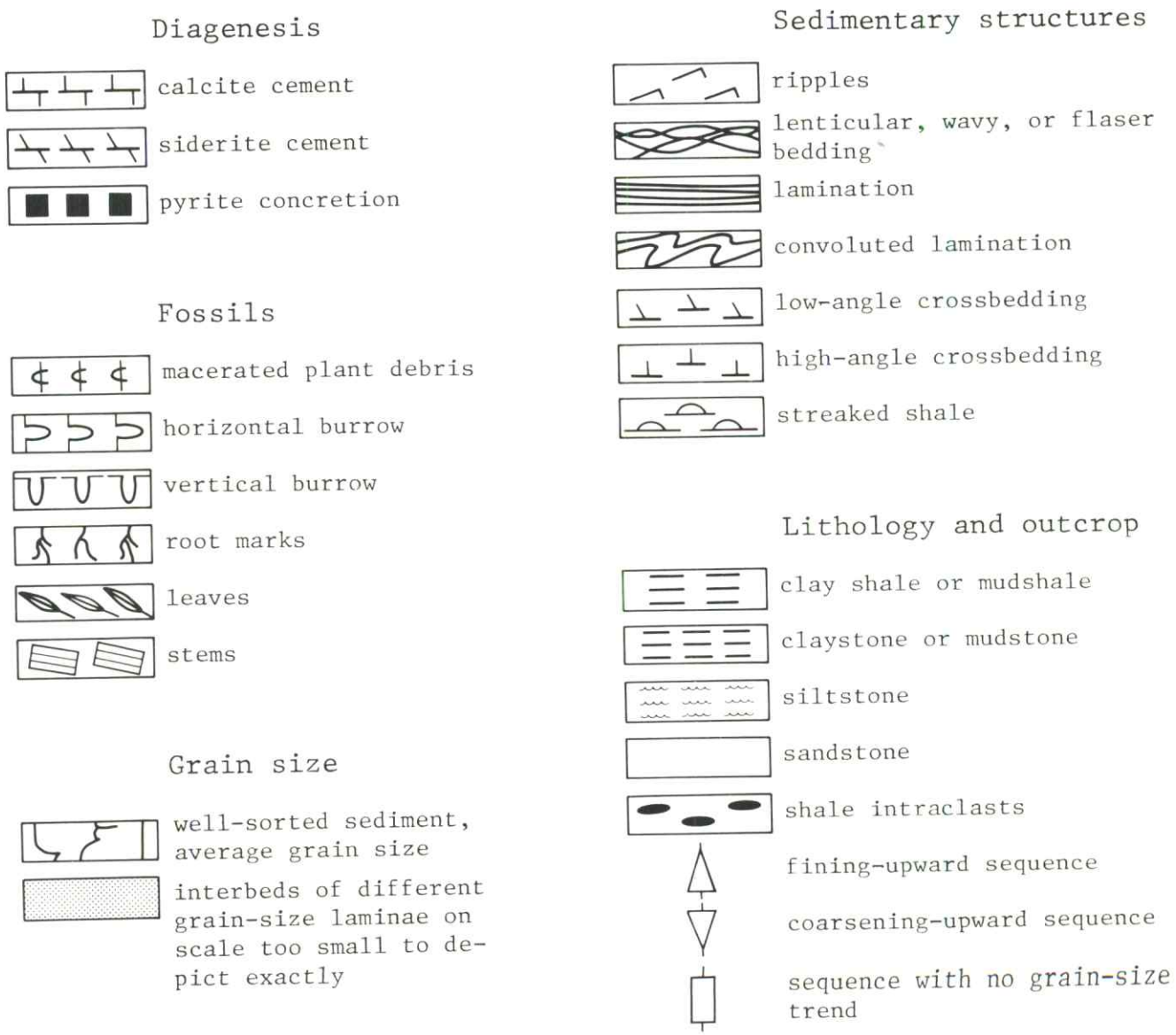
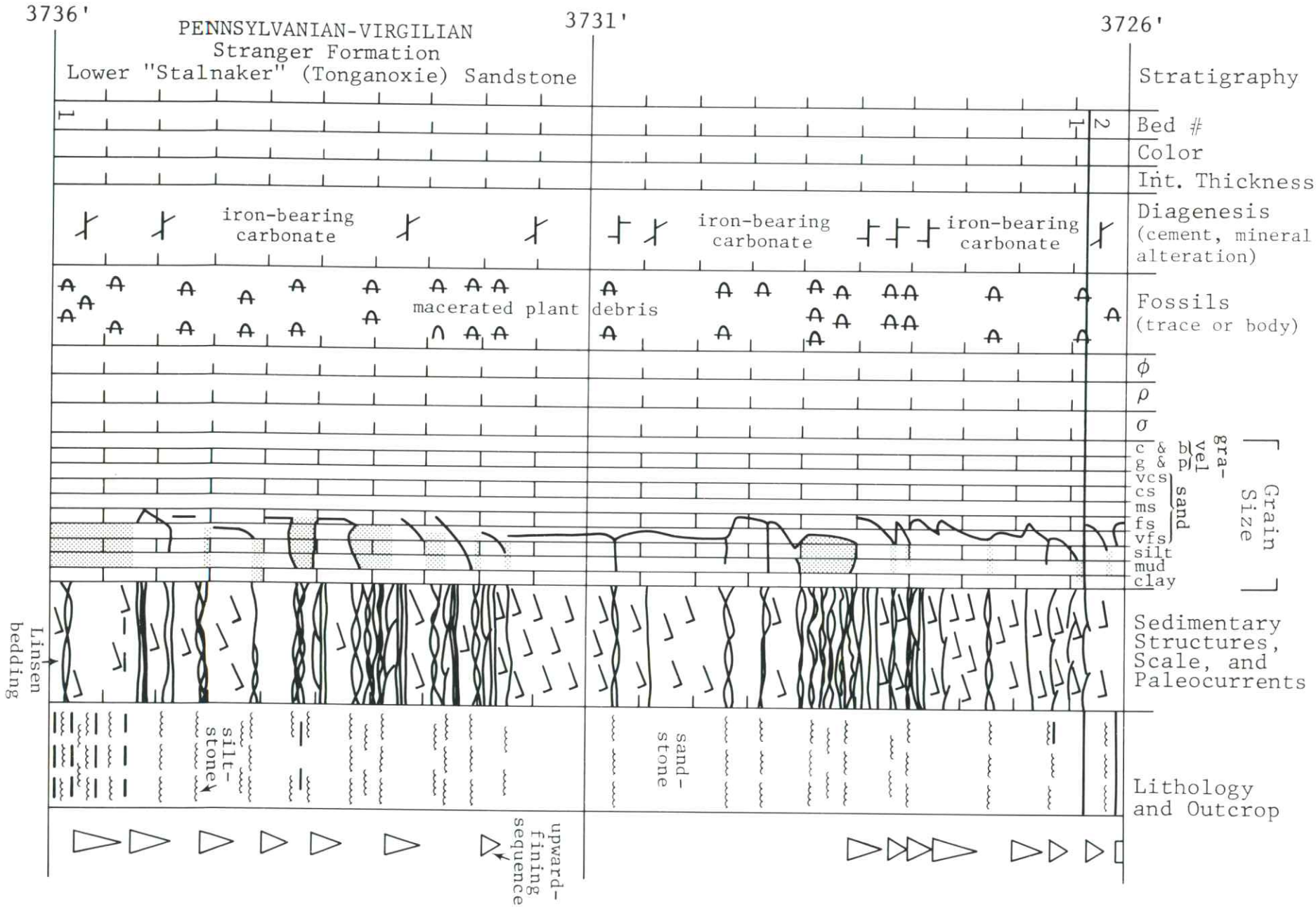
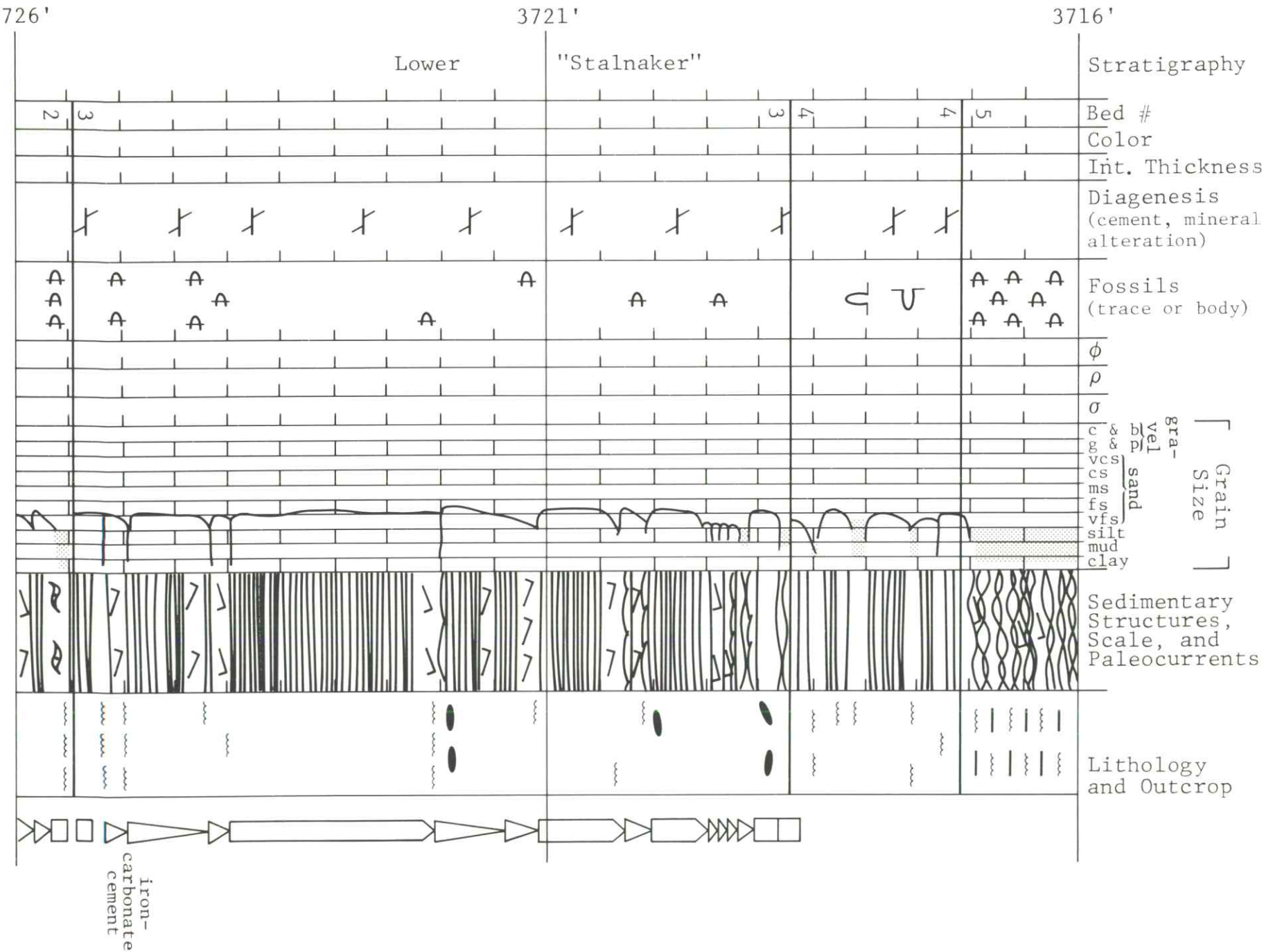
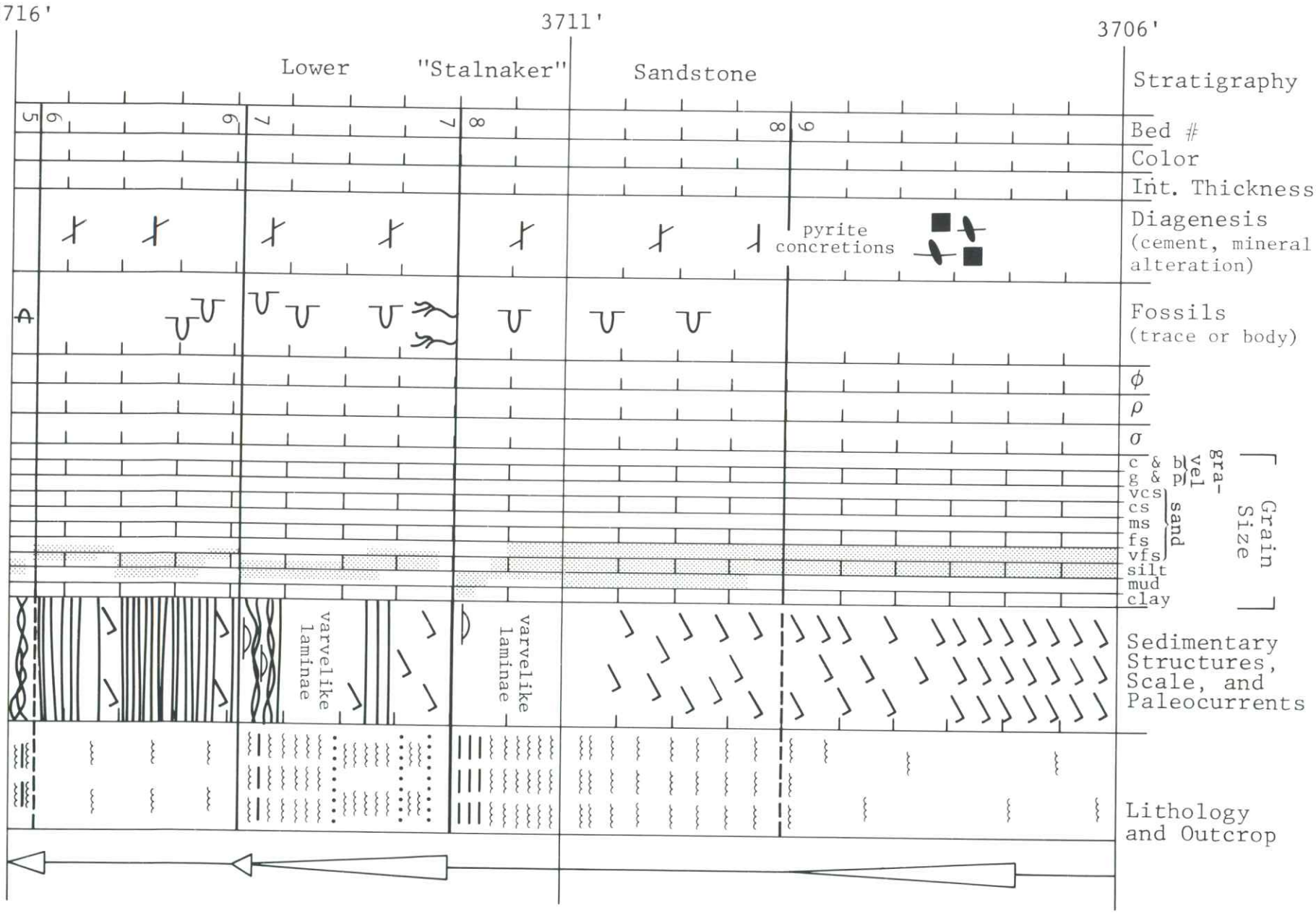


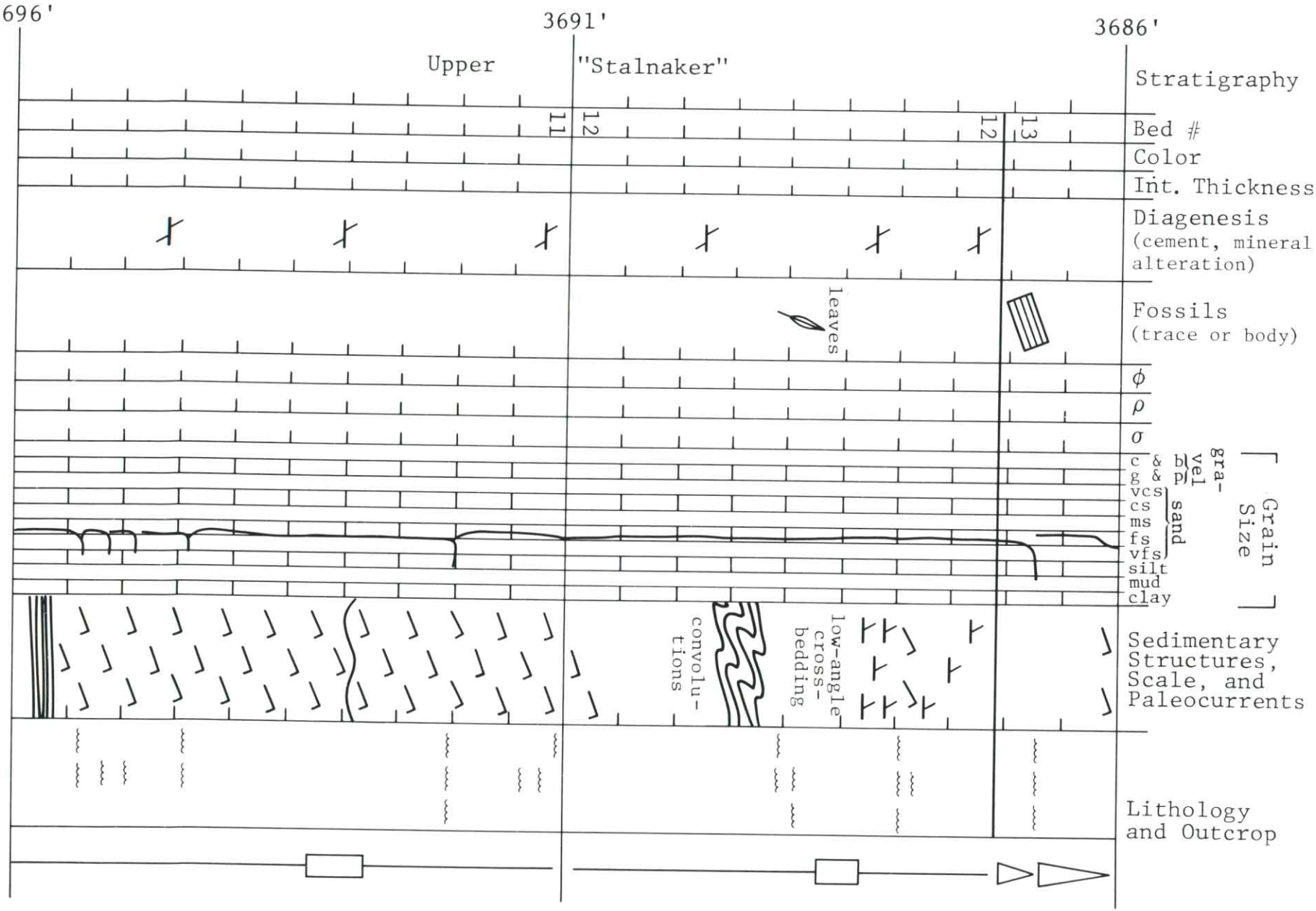
FIGURE 8—Stratigraphic section from TXO Robinson C–1, S1/2NENE sec. 30, T. 32 S., R. 8 W., Harper County, Kansas. Measured by A. W. Walton, October 1982.

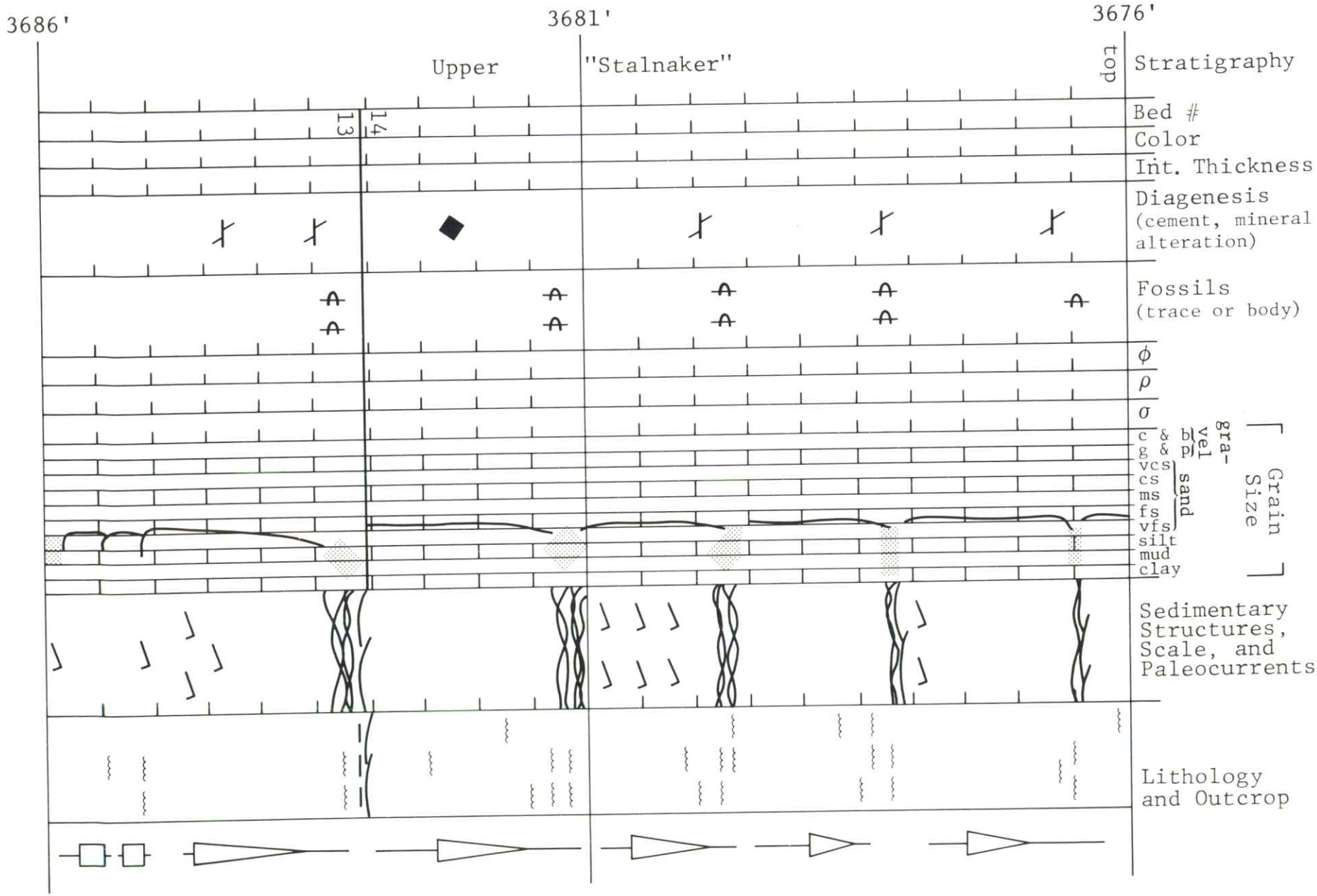

3736'
PENNSYLVANIAN-VIRGILIAN
Stranger Formation
Lower "Stalnaker" (Tonganoxie) Sandstone
3731'
3726'
Stratigraphy
Bed #
Color
Int. Thickness
Diagenesis (cement, mineral alteration)
iron-bearing carbonate
iron-bearing carbonate
iron-bearing carbonate
Fossils (trace or body)
macerated plant debris
ϕ
ρ
σ
Grain Size
c & b
g & p
gra-vel
vcs
cs
ms
fs
vfs
sand
silt
mud
clay
Sedimentary Structures, Scale, and Paleocurrents
Linsen bedding
Lithology and Outcrop
silt-stone
sand-stone
upward-fining sequence


3726'
3721'
3716'
Lower
"Stalnaker"
Stratigraphy
Bed #
Color
Int. Thickness
Diagenesis
(cement, mineral alteration)
Fossils
(trace or body)
ϕ
ρ
σ
c
g
vcs
cs
ms
fs
vfs
silt
mud
clay
gra-
vel
&
b
p
sand
Grain Size
Sedimentary Structures, Scale, and Paleocurrents
Lithology and Outcrop
iron-carbonate cement


3716'
3711'
3706'
Lower "Stalnaker" Sandstone
Stratigraphy
Bed #
Color
Int. Thickness
Diagenesis (cement, mineral alteration)
pyrite concretions
Fossils (trace or body)
ϕ
ρ
σ
Grain Size
c
g
vcs
cs
ms
fs
vfs
silt
mud
clay
sand
gra-vel
& & b
p
varvelike laminae
varvelike laminae
Sedimentary Structures, Scale, and Paleocurrents
Lithology and Outcrop

3706'
3701'
3696'
Lower "Stalnaker"
Upper "Stalnaker"
Stratigraphy
Bed #
Color
Int. Thickness
Diagenesis (cement, mineral alteration)
Fossils (trace or body)
coarse plant fragments
φ
ρ
σ
Grain Size
c & b
g & p
gra-vel
vcs
cs
ms
sand
fs
vfs
silt
mud
clay
Sedimentary Structures, Scale, and Paleocurrents
Lithology and Outcrop
9
10
10
11
streaked shales
coal


3696'
3691'
3686'
Upper
"Stalnaker"
Stratigraphy
11
12
12
13
Bed #
Color
Int. Thickness
Diagenesis
(cement, mineral
alteration)
leaves
Fossils
(trace or body)
ϕ
ρ
σ
c
g
vcs
cs
ms
fs
vfs
silt
mud
clay
gra-
vel
&
sand
Grain
Size
convolu-
tions
low-angle
cross-
bedding
Sedimentary
Structures,
Scale, and
Paleocurrents
Lithology
and Outcrop


3686'
3681'
3676'
Upper
"Stalnaker"
top
13
14
Stratigraphy
Bed #
Color
Int. Thickness
Diagenesis
(cement, mineral
alteration)
Fossils
(trace or body)
ϕ
ρ
σ
c
g
vcs
cs
ms
fs
vfs
silt
mud
clay
gra-
vel
&
pb
sand
Grain
Size
Sedimentary
Structures,
Scale, and
Paleocurrents
Lithology
and Outcrop

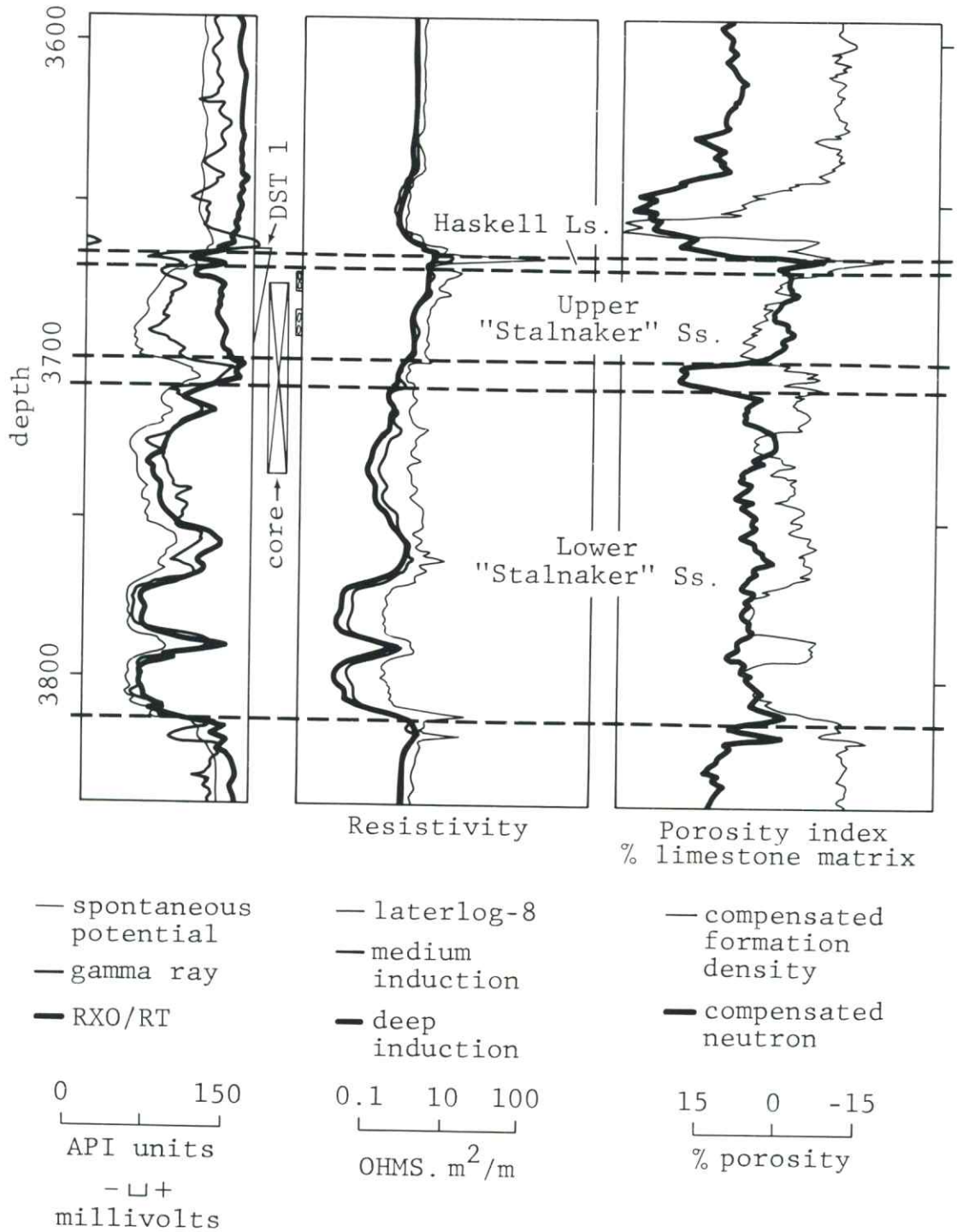


FIGURE 9—Spontaneous potential/gamma ray, resistivity, and porosity index log for upper and lower "Stalnaker" from TXO Robinson C-1.

distributary in a crevasse splay in which burrowing organisms could dwell at times of low flow.

INTERVAL 13. UPPER "STALNAKER" (3,687.1–3,683.1 FT)—Rippled fine sandstone with silt interbeds that separate the interval into units 10–45 cm thick (fig. 7a). Uppermost parts of these intervals are finer grained than lower parts. Ripples not very obvious but are unidirectional. Uppermost part of interval is lenticular-bedded sandstone and shale with burrows.

Unit 13 can be interpreted as part of a channel sequence, perhaps lower to middle point bar in a sinuous or meandering channel. It has evidence of marine influence (the burrows) and of episodic deposition, but with episodes depositing thicker layers than did those of the lower Stalnaker, perhaps a channel in a crevasse splay.

INTERVAL 14. UPPER "STALNAKER" (3,683.1–3,676 FT)—Fining-upward sequences of rippled sand grading into

burrowed lenticular-bedded mudstone and sandstone (fig. 7b). Sequences about 60 cm thick. Four whole sequences and the base of another are present.

These fining-upward sequences closely resemble the episodic beds within meandering channel sequences that express themselves as epsilon cross strata or accretion bedding of point bars. They do, however, display burrows, which imply at least brackish water during periods of low flow. Episodic unidirectional flow and burrowing suggest this interval represents farther deposition in the channel recognized in unit 13. The sequence in units 12, 13, and 14 represent progressive abandonment of a crevasse channel.

Overview

The features of the Robinson C–1 core suggest delta deposition. Lithologically distinct intervals in the core can be interpreted as results of deposition within a particular delta subenvironment. The lower and upper "Stalnaker" sands should be viewed as part of a single large system, a delta plain built by lower Stalnaker streams and marine sedimentation, followed by development of subdeltas and lobes of sediment assigned to either the lower or upper Stalnaker. The interpreted crevasse splay in the upper Stalnaker (intervals 11–14) represents a period of progradation into an area bypassed by major delta activity while the shales of interval 10 formed.

Summary

The "Stalnaker" in the Robinson C–1 core has several outstanding attributes that are useful in assigning it to a depositional environment. One is the intimate interbedding of features indicating proximity of continental environment (coal, plant fragments) and those indicating marine deposition (burrows, wave-formed sedimentary structures, upward-coarsening sequences). The rocks in the core can easily be broken into intervals that represent activity of one process or a set of processes. These are marine and fluvial processes that are known to act in delta regions, by comparison with modern environments. Furthermore, the sequence in which the processes acted is consistent with a prograding delta. Other features also suggest deltaic deposition. Clearly, much of the sediment was deposited in a fashion that precluded extensive reworking by burrowers. In sandstones, this normally suggests rapid deposition, rather than toxicity of the environment. Finally, sedimentation was episodic on several scales. At the smallest scale, upward-fining, decreasing energy (scour-planebeds-ripples-lenticular bedding) packets range from a few cm to 60 cm thick. These can be grouped into overall upward-coarsening sequences up to 5 m or so thick. Repetition of these sequences suggests the environments were adjacent to each other and controlled by water depth and rate of sediment input. In those sequences, both thickness of the sand-rich part of the packets increases and that of the mud-rich decreases upwards, so that mud interbeds are absent in the top of the sequence. All in all, this core suggests deposition of the Stalnaker in an area that was marginal to a marine environment, where conditions changed rapidly (both in time and laterally) but progressively, and accumulation was rapid. These conditions are best met in a delta. The environments in which the described intervals were deposited are placed on an imaginary delta in fig. 8.

Many previous workers have suggested that delta environments were important in forming terrigenous deposits in Kansas, beginning with Wanless (1963) and Wanless and others (1970). Deltaic sand bodies, especially distributary mouth bar or delta front sand bodies, have definite features that affect petroleum accumulation and production. Knowledge of reservoir sand type will guide development drilling and enhanced recovery operations. Deltaic sandstones may be more sheetlike than the fluvial shoestring sands for which eastern Kansas is so famous, but they may have thinner productive intervals. The coarsest grain size will occur at the top of the deltaic sandy units, not the bottom as in many fluvial sandstones. Diagenetic patterns and the degree of continuity of sand beds may also differ, though no one has examined these features of deltaic sandstones in Kansas.

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Depositional facies in the Funston cycle (Lower Permian) of southwestern Kansas

by *Talat Y. Abdullah*, Kansas Geological Survey, Lawrence, Kansas

Introduction

The Council Grove Group (Lower Permian) of southwestern Kansas consists of alternating strata of shale and limestone. The Funston Formation, lying under the Speiser Shale (fig. 1), is one of the major gas-producing zones in the Panoma gas area of the Hugoton embayment.

The principle objective of this paper is to interpret the depositional environments of the lithofacies that comprise the Funston cycle in the subsurface of southwestern Kansas.

Structure and tectonic history

The study area is located in the Hugoton embayment of southwestern Kansas (fig. 2). The embayment, described by Merriam (1963) as a northern shelflike extension of Oklahoma's Anadarko Basin, covers parts of Kansas, Colorado, Oklahoma, and Texas. The eastern side of the embayment is formed by the Pratt anticline, the Central Kansas uplift, and the Cambridge arch (fig. 3). The western limit is formed by the Las Animas arch of Colorado. The Hugoton embayment plunges southward, and sedimentary strata thicken both toward the axis of the embayment and southward into the Anadarko Basin of southwestern Oklahoma (Merriam and Goebel, 1968).

Downwarping in the general area of the embayment began during the Precambrian and continued through much of the Paleozoic. This was interrupted periodically by broad epeirogenic uplift. Deposits during the Cambrian were formed by transgressing seas initiating a long history of sediment accumulation. In the Late Paleozoic regional transgressions and regressions caused accumulation of cyclic marine and nonmarine strata (Merriam, 1956). Most of the structural features that originated during the Pennsylvanian remained active during the Permian. Prominent features such as the Nemaha anticline, the Central Kansas uplift, the Las Animas arch, and the Hugoton embayment existed during the deposition of Early Permian deposits (Mudge, 1967). Post-Paleozoic deposits mask the structure of the underlying Paleozoic strata. Structural development of the embayment was concluded by the close of the Permian, and the structure of the Late Paleozoic strata is, therefore, not reflected in the overlying younger strata (Merriam, 1963).

Currently, the structure of the top of the Council Grove Group in the study area is monoclinal (fig. 4). The dip is east-southeast with a magnitude of 20 ft/mi (3.75 m/km).

Stratigraphy

The Wolfcampian (Lower Permian) in southwestern Kansas consists of the Chase, Council Grove, and Admire groups (fig. 1). These groups mainly are composed of alternating shale and limestone units that are traceable for long distances to the outcrop area in eastern Kansas (Mason, 1968). The units exhibit cyclic patterns similar to those in Upper Pennsylvanian deposits (Jewett, 1933, in Merriam, 1963). Mason (1968) remarked that westward toward the Las Animas arch (fig. 3), the limestone and dolomite beds of the Chase Group grade laterally into red sandstones and siltstones.

The Lower Permian strata are conformably overlain by a sequence of shale, siltstone, and sandstone, most of which is red and interbedded locally with thick deposits of evaporites and dolomite (Merriam, 1963).

Depositional lithofacies

Based on detailed examinations of cores and thin sections from 11 wells from the study area (fig. 2), in a study made by Abdullah (1983), major lithofacies that comprised the

FORMATION	GROUP	STAGE	SERIES
Nolans Limestone	Chase	Gearyan	Lower Permian (Wolfcampian)
Odell Shale			
Winfield Limestone			
Doyle Shale			
Barneston Limestone			
Matfield Shale			
Wreford Limestone			
Speiser Shale	Council Grove		
FUNSTON LIMESTONE			
Blue Rapids Shale			
Crouse Limestone			
Easly Creek Shale			
Bader Limestone			
Stearns Shale			
Beattie Limestone			
Eskridge Shale			
Grenola Limestone			
Roca Shale			
Red Eagle Limestone			
Johnson Shale			
Foraker Limestone			
Janesville Shale	Admire		
Falls City Limestone			
Onaga Shale			

FIGURE 1—Stratigraphic position of rocks of the Lower Permian (Wolfcampian) Series in Kansas (Zeller, 1968).

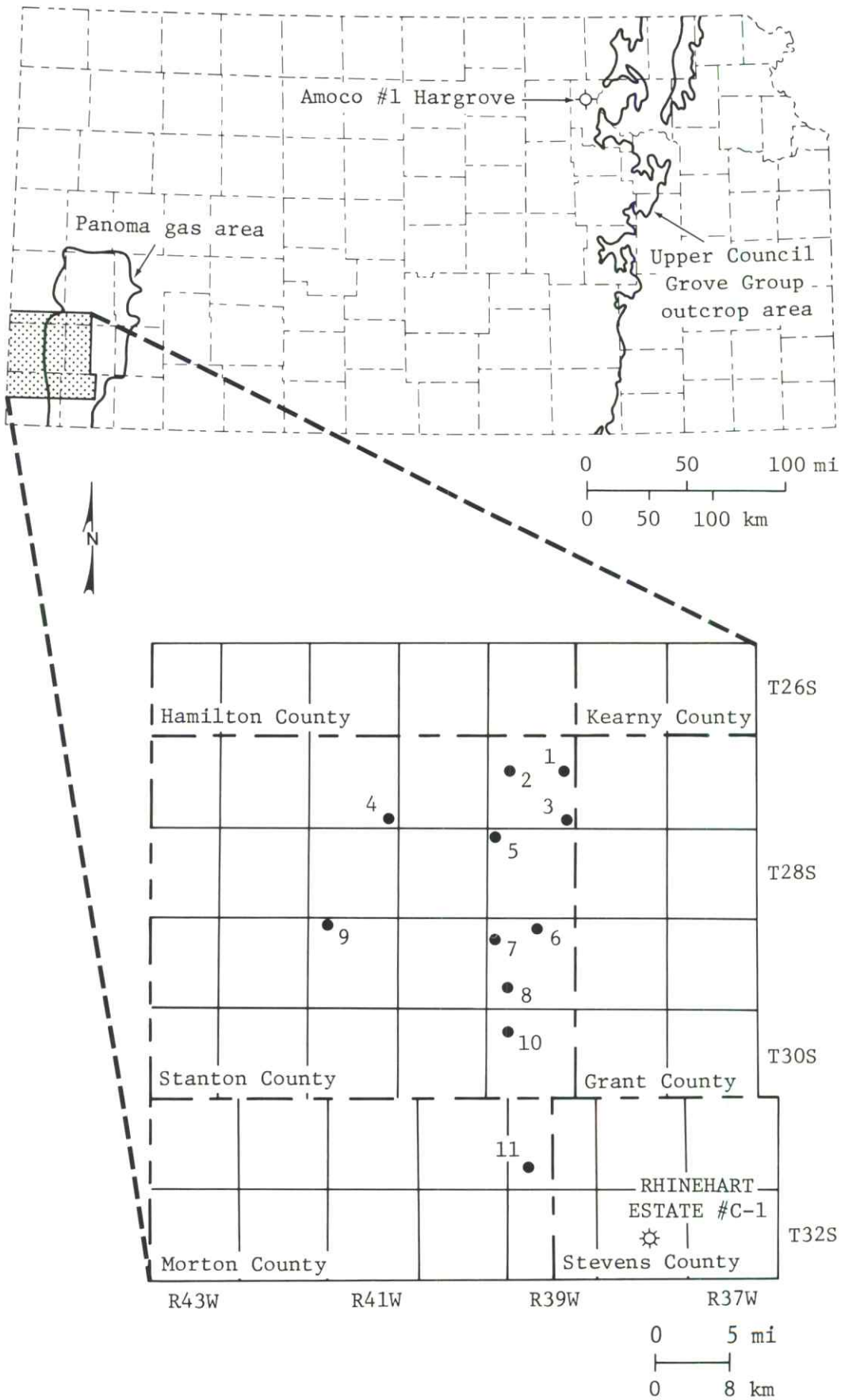

FIGURE 2—Study area (top) in southwestern Kansas shows locations of the cored wells used in thesis study (Abdullah, 1983), as well as the Anadarko #C-1 Rhinehart Estate of Stevens County. The Kansas map (bottom) shows relation of the study area to the Panoma gas area and the outcrop belt of upper Council Grove Group rocks in eastern Kansas.

Funston cycle were recognized, and their depositional environments were interpreted. Most of the features described in the thesis study can be observed in the core samples from the Anadarko # C–1 Rhinehart Estate, NESESW, sec. 22, T. 32 S., R. 38 W., Stevens County, Kansas. The various lithofacies are summarized in fig. 5 and are described below.

LITHOFACIES 1—Lithofacies 1 is the lowermost carbonate unit in the cycle. It is dark gray and is usually a wackestone (fig. 6). The thickness is 4 ft (1.2 m; 2,918–2,922 ft on the slabbed core). The wackestone is composed of fine- to coarse-grained, subrounded bioclasts of crinoids, brachiopods, mollusks, and ostracodes. Algal-coated grains and intraclasts also are abundant. The skeletal wackestone is interbedded with nonfossiliferous siltstone in the lower part of the unit. The upper contact of lithofacies 1 is gradational, whereas the lower contact is erosional and marks the regional transgression in the Funston cycle.

The upper interval of the unit is shaly and grades upward into dark-gray to black shale. Little diagenesis has occurred so that the original texture is generally well preserved. Porosity in the unit is usually very low.

Lithofacies 1 probably was deposited during the initial stages of transgression in a shallow, restricted intertidal environment that was interrupted by deposition of terrigenous clastic siltstones. The remaining part of the unit (upper interval) was formed in a low-energy, subtidal-marine environment.

LITHOFACIES 2—Lithofacies 2 consists largely of dark-gray to black shale beds with siltstone and carbonate intervals in the lower half of the unit. Total thickness of the unit is 20 ft (6.5 m; 2,898–2,918 ft on the slabbed core). The shale is massive, calcareous, fractured, and fossiliferous. Fossils are diverse and include brachiopods, crinoids, bryozoans, and ostracodes. Most of the fossil fragments either are completely or partially silicified. The

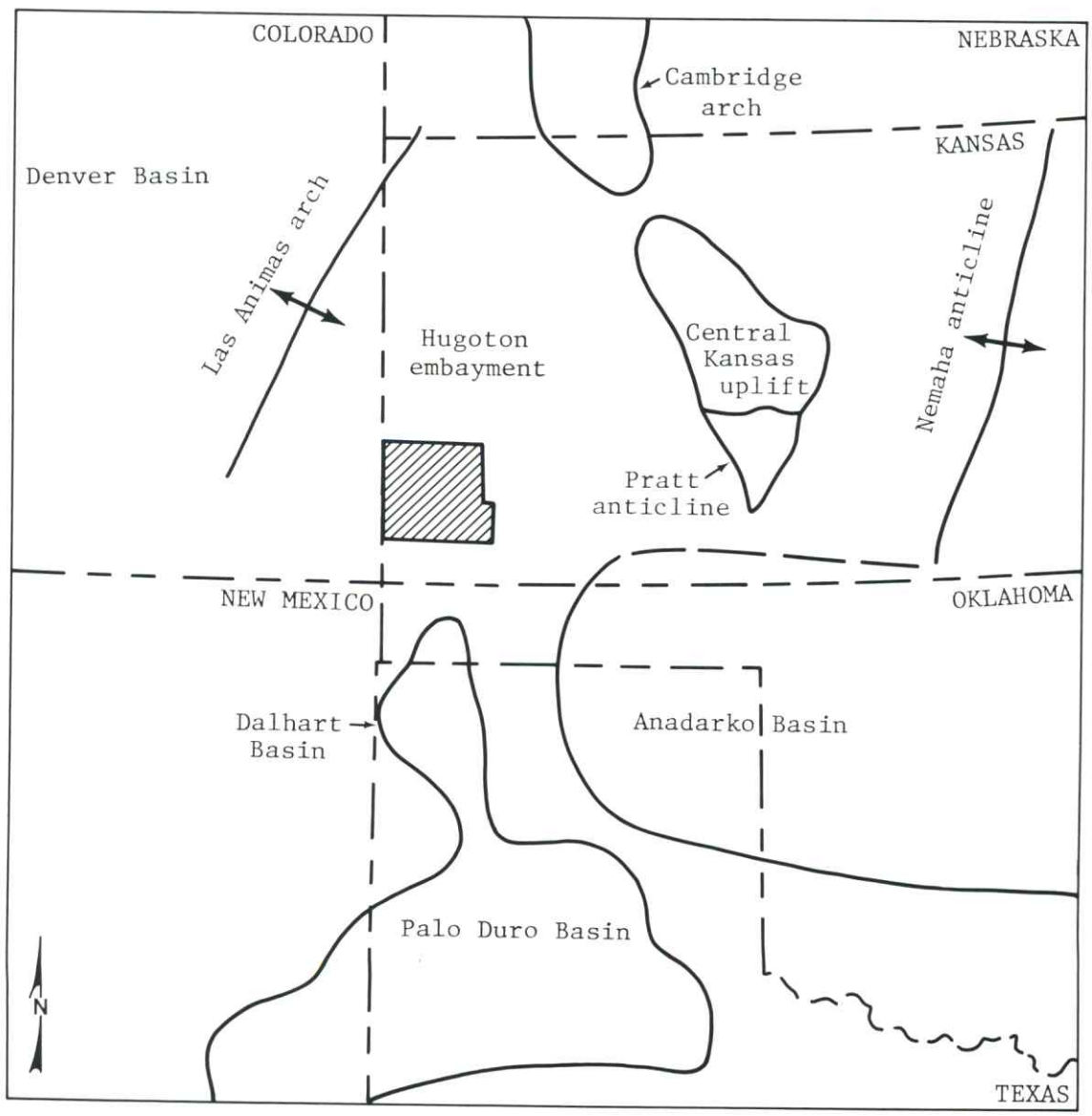

FIGURE 3—Major tectonic elements of Kansas and adjacent areas in Late Pennsylvanian and Early Permian time. Data for map are from Merriam (1963), Dixon (1967), and Mudge (1967).

upper contact is sharp, whereas the lower contact is gradational.

The limestone interval is about 1.5 ft (0.5 m) thick (2,909.5–2,911 ft on the slabbed core). It is a dark-gray, shaly, burrowed, skeletal wackestone. Fossils include brachiopods, crinoids, and bryozoans. Most of the fossil fragments are silicified.

The siltstone bed interval is about 3 ft (1 m) thick (2,911–2,914 ft on the slabbed core). The siltstones are shaly and exhibit ripple laminations (fig. 7).

Beds of lithofacies 2 were formed during an influx of terrigenous sediments (except for a less turbid period marked by the deposition of the skeletal wackestone bed) into a subtidal-marine environment.

LITHOFACIES 3—This carbonate unit is dark, mottled-gray mixed skeletal wackestone (fig. 8). It is 1 ft (0.3 m) thick (2,897-2,898 ft on the slabbed core). The lower part of the lithofacies consists of *Osagia* wackestone with fossil fragments such as crinoids and bivalves. The upper part is a burrowed, argillaceous skeletal wackestone. The upper contact is gradational, whereas the lower contact is erosional and probably marks a minor transgression.

The basal part of lithofacies 3 was deposited in a moderate-energy, shallow-water subtidal to lower intertidal marine environment. The remaining part of the unit was

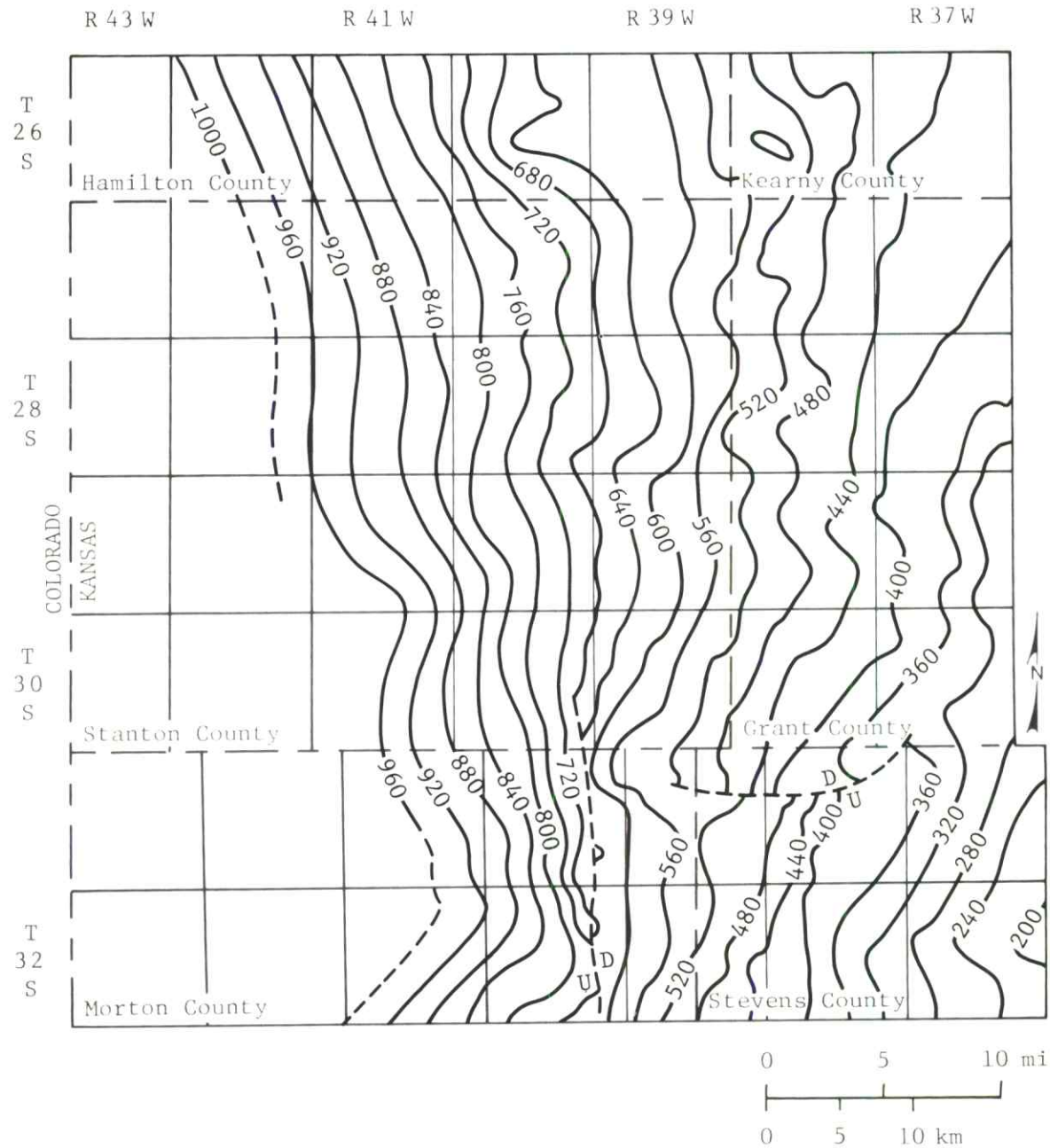

FIGURE 4—Structural contour map, top of Council Grove Group; contour interval = 40 ft.

formed in a turbid, low-energy subtidal-marine environment.

LITHOFACIES 4—Lithofacies 4 is a green to greenish-gray, massive, calcareous shale unit. It is 3 ft (1 m) thick (2,894–2,897 ft on the slabbed core). The shale is silty and fossiliferous. Brachiopods, crinoids, and ostracodes dominate the fossil assemblages in the unit. Chert nodules and silicified fossil fragments are common. The upper and lower contacts are gradational.

Lithofacies 4 was formed in a low-energy, turbid, subtidal-marine environment. The high-silt proportion and generally lighter color that characterize this unit indicate a shallower subtidal environment than that of the underlying shale beds of lithofacies 2.

LITHOFACIES 5—Lithofacies 5 is a gray, argillaceous mixed-skeletal wackestone. The thickness is about 2.25 ft (0.7 m; 2,891.75–2,894 ft on the slabbed core). Fossils include crinoids, brachiopods, bryozoans, and ostracodes. Most of the fossil fragments either are partially or completely replaced by silica. Chert blebs and burrows are common in this unit.

This unit was deposited primarily in a low-energy, shallow-water, subtidal environment. Abundance of quartz silt and clay suggests turbidity at the site of sedimentation.

LITHOFACIES 6—This lithofacies consists of green to greenish-gray shale beds. Its thickness is about 5.75 ft (1.75 m; 2,886–2,891.75 ft on the slabbed core). The shale is silty and fossiliferous with abundant chert nodules (fig. 9). Both the lower and upper contacts are gradational. The unit probably was formed in an environment similar to that of rocks of lithofacies 4.

LITHOFACIES 7—Lithofacies 7 consists of carbonate rocks that occupy the uppermost part of the Funston Formation. The color varies from light gray to tan. Its thickness is 4 ft (1.2 m; 2,882–2,886 ft on the slabbed core). The lower contact is gradational, whereas the upper contact is erosional and marks the regional regression.

The lower interval of the unit (2,885–2,886 ft) is a light-gray, argillaceous, mollusk wackestone. Color becomes lighter and terrigenous clay and silt content decrease upward in the interval (2,883.5–2,885 ft). Fossils and fossil fragments are abundant and include brachiopods, crinoids, echinoids, mollusks, bryozoans, and ostracodes. The texture is generally wackestone.

Diversity of fossils decreases upward in the interval (2,882–2,883.5 ft). The texture is a packstone (fig. 10).

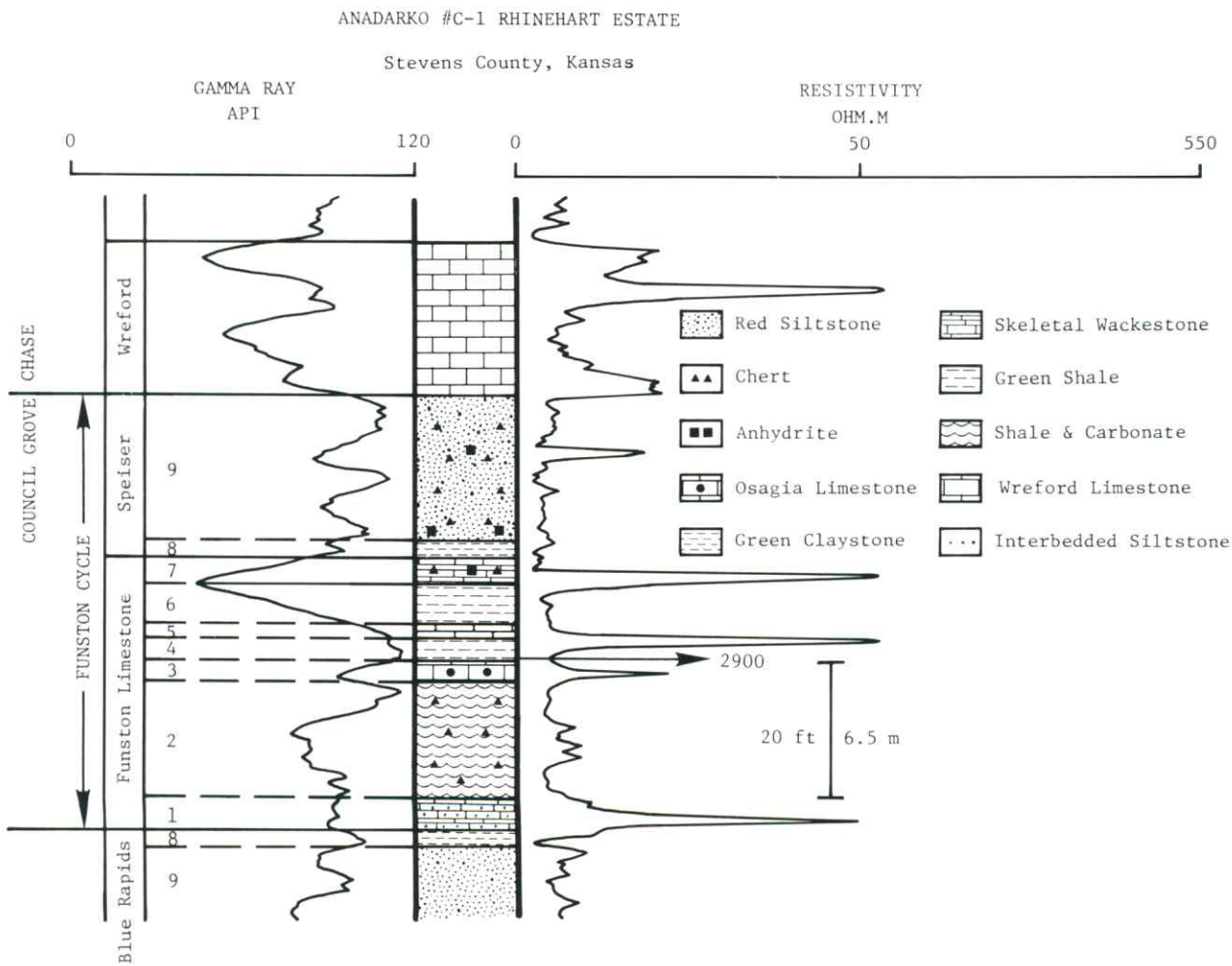

FIGURE 5—Gamma ray-resistivity well-log signature of the Anadarko #C-1 Rhinehart Estate, NESESW, sec. 22, T32S, R38W, Stevens County, Kansas. Depositional facies comprising the Funston cycle are indicated.

This upper interval consists largely of algal-coated grains with crinoid and echinoid fragments. Anhydrite and silica replacements are common. The uppermost part of lithofacies 7 (1.5 inches thick) is a dolomudstone interbedded with terrigenous red siltstone.

Rocks of the lower interval (2,883.5–2,886 ft) were deposited in a low-energy, shallow, subtidal-marine environment, whereas those of the upper interval (2,882–2,883.5 ft), except the dolomudstones, were formed in a restricted intertidal environment. The uppermost dolomudstone bed probably was formed on a supratidal flat.

LITHOFACIES 8—Lithofacies 8 is a green, structureless, nonfossiliferous claystone. Its thickness is about 2 ft (0.6 m; 2,880.2–2,882 ft). The unit is characterized by an erosional upper contact and a gradational lower contact where it underlies the Funston Formation, whereas its lower contact is erosional and the upper contact is gradational where it caps the Funston Formation. Anhydrite and chert nodules are common in this lithofacies.

Claystones of this unit probably are fluvial deposits. Hanford and Fredericks (1980) described similar rocks in the Palo Duro Basin of the Texas panhandle and suggested that the claystones were formed in a mud-rich coastal sabkha. Terrigenous sediments were transported by rivers into the sabkha flat.

LITHOFACIES 9—Lithofacies 9 consists of reddish-brown, very fine-grained sandstones and siltstones interbedded with green siltstones (fig. 11). The thickness is about 22 ft (8 m; 2,858–2,880.2 ft). Generally the thickness is greater in the northwestern and southwestern parts of the study area (figs. 12, 13, and 14). Arrows on fig. 14 indicate the probable direction of sediment transportation.

Lithofacies 9 overlies the Funston Formation and is located between two beds of lithofacies 8. Chaotic fractures and lath-shaped crystals of anhydrite are common in this unit, particularly in the lower interval. Gypsum probably was precipitated first and later was replaced by anhydrite. Similar events were reported from the modern sabkhas of the Trucial coast (Bathurst, 1975).

The siltstones of the Speiser Formation are similar to those of the Red Cave Formation of the Palo Duro Basin. Hanford and Fredericks (1980) suggested that the sandstones and siltstones of the Red Cave are fluvial or fluvial deposits reworked by the wind.

Terrigenous sediments in the upper half of the Council Grove Group and in the Chase Group along the Las Animas arch probably were derived from south-central Colorado (Mudge, 1967).

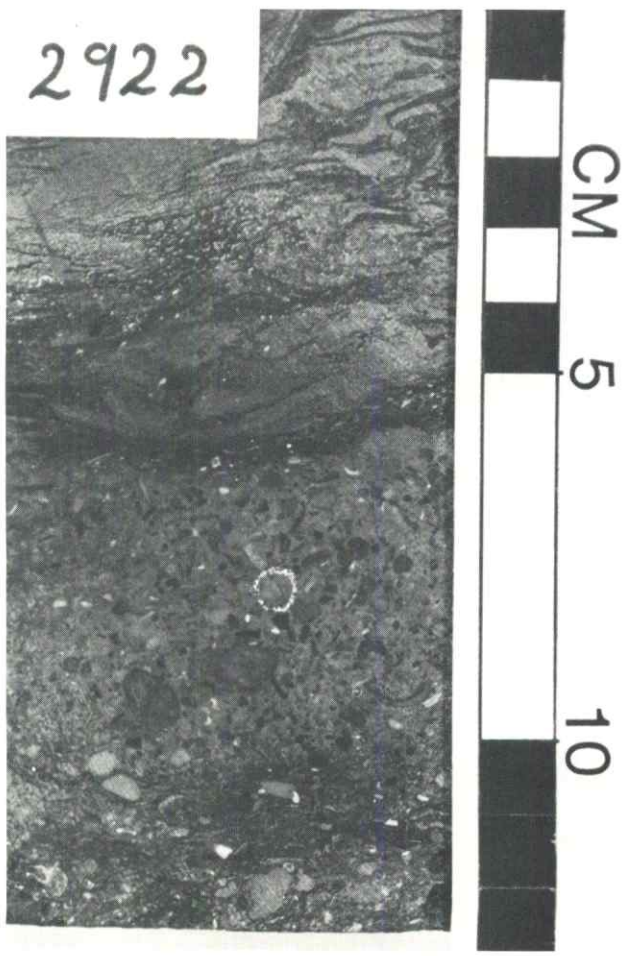

FIGURE 6—Core slab of base of lithofacies 1 (2,922 ft; Anadarko #C–1 Rhinehart Estate). Silty mixed-skeletal wackestone; black areas probably are algal-coated grains. Scale is in centimeters.

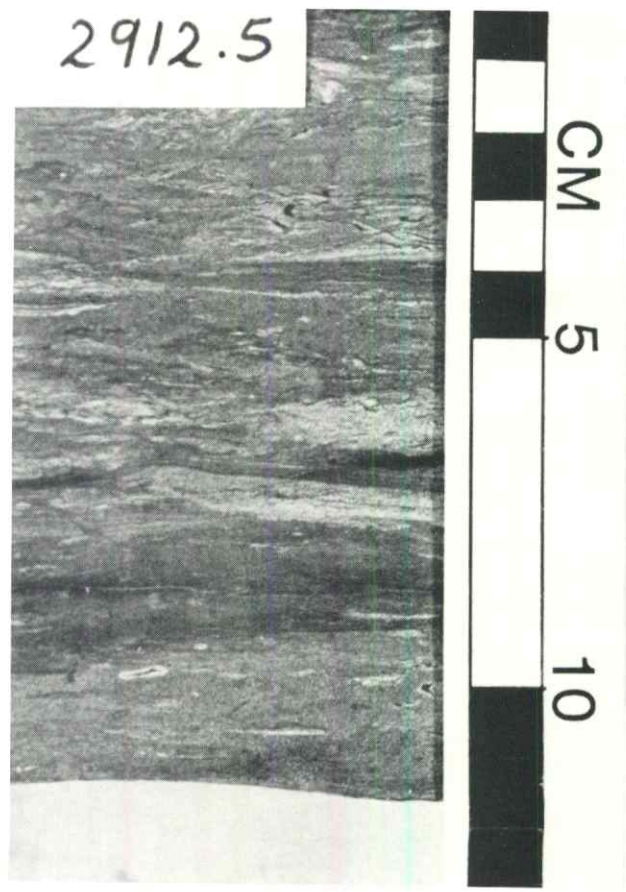

FIGURE 7—Core slab of lower interval of lithofacies 2 (2,912.5 ft; Anadarko #C–1 Rhinehart Estate). Ripple-laminated siltstone. Scale is in centimeters.

Interpretation of the Funston cycle

The various lithofacies comprising the Funston cycle were formed in a wide range of environments that included shelf lagoons with open circulation, restricted lagoons, tidal flats, and sabkhas. A summary of the events that occurred in southwestern Kansas during deposition of the Funston sediments are listed below.

1. A rapid regional transgression from the southeast accompanied by an influx of terrigenous clastics resulted in the deposition of lithofacies 1. Environments of deposition ranged from shallow-water, restricted tidal flats to a protected subtidal zone. Because of the rapid rise in sea level, little tidal-flat sediments accumulated.
2. As the regional transgression proceeded, turbidity increased and dark-gray to black, calcareous, fossiliferous shales and siltstones and carbonates were deposited (lithofacies 2). This stage probably represents the culmination of the regional transgression.
3. Decreasing turbidity allowed the deposition of carbonate sediments (lithofacies 3). Environments ranged from a shallow-water protected subtidal zone to restricted intertidal areas.
4. Increased turbidity that accompanied a minor transgression resulted in the formation of silty calcareous fossiliferous shales (lithofacies 4).
5. As the water began to clear following a minor regression, carbonate sediments accumulated in moderately agitated shallow waters. The carbonates (lithofacies 5) are rich in fragments from diverse fossil assemblages. Depositional environments are similar to those of moderately restricted subtidal zones.
6. Carbonate sedimentation was interrupted by high influx of terrigenous clastics and a rise of the sea level. This event represents the last marine transgression within the Funston cycle that resulted in the deposition of silty calcareous shales (lithofacies 6).
7. As the turbidity decreased, a major but slow regres-

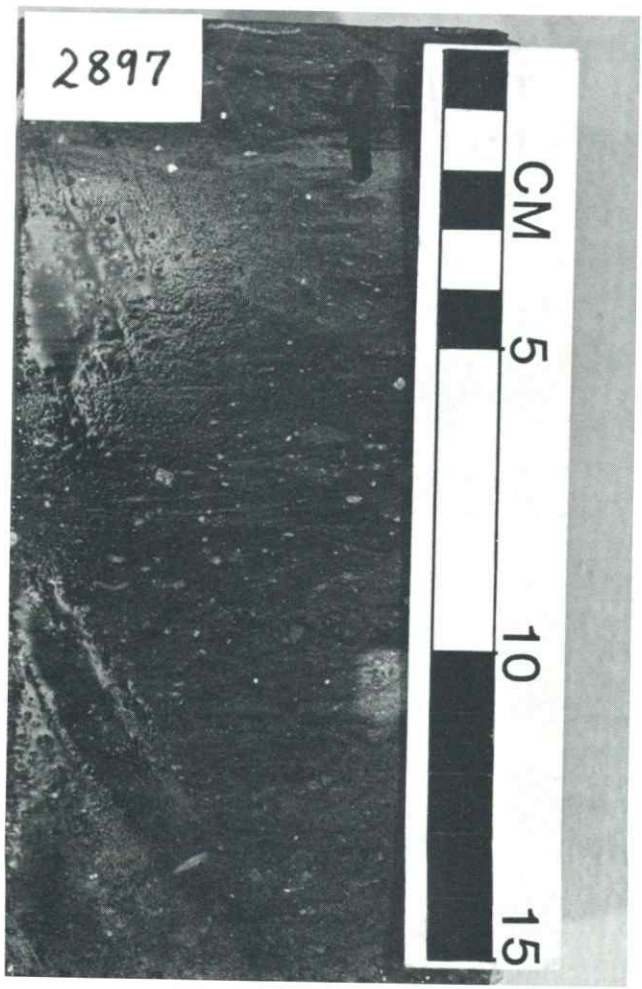

FIGURE 8—Core slab of upper interval of lithofacies 3 (2,897 ft; Anadarko #C–1 Rhinehart Estate). Argillaceous mixed-skeletal wackestone. Scale is in centimeters.

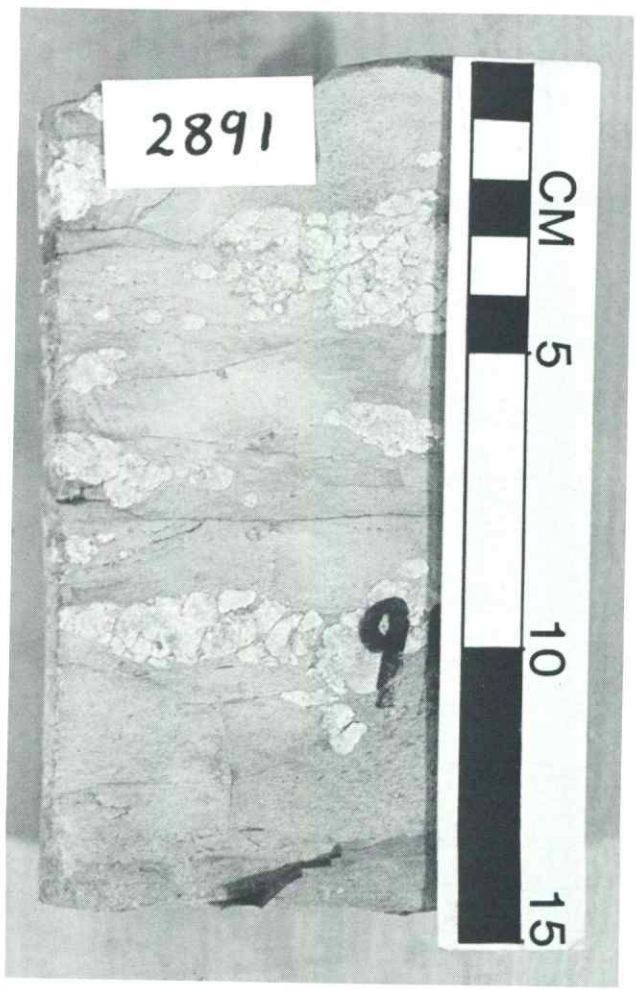

FIGURE 9—Core slab of lithofacies 6 (2,891 ft; Anadarko #C–1 Rhinehart Estate). Silty fossiliferous shale with chert nodules. Scale is in centimeters.

sion started. Carbonate sediments began to accumulate on the sea floor. The regression proceeded without any apparent interruption by influx of clastics. The resulting rocks (lithofacies 7) were formed in a variety of environments ranging from open-shelf lagoons to extremely restricted areas on tidal flats. Beds of the lower part of these rocks show great diversity of fossils indicating deposition in a relatively open shelf lagoon with moderate circulation. Upward in the unit, decreased faunal diversity and vertical lithologic changes suggest a landward shift in the depositional environments. In response to accumulation of carbonate sediments on the tidal flats with the continuing fall of sea level, facies prograded seaward on the tidal flats. The resulting facies are diachronous and become younger in a seaward direction.

With the continuing fall of sea level, terrigenous sediments were deposited near the shoreline. The top of lithofacies 7 is capped by green unfossiliferous claystones of lithofacies 8. Upward the claystones grade into red beds. The red beds might have formed either by fluvial processes or by eolian reworking of fluvial deposits. Thick accumulations of the terrigenous rocks commonly overlie thin beds that belong to the regressive carbonate unit (see fig. 12). This suggests that environments of deposition were shifted east-southeastward (seaward) during the regional regression. The poor development of evaporites at the top of lithofacies 7 is attributed to the lack of interruption in sedimentation of the prograding red beds. Anhydrite and caliche nodules are common in the red beds, however, suggesting semi-arid climate similar to that of recent sabkhas along the Abu Dhabi coast of the Arabian Gulf.

The Pennsylvanian cyclic strata of the Lansing and Kansas City Groups in western Kansas were probably deposited during periods of semi-arid climatic conditions

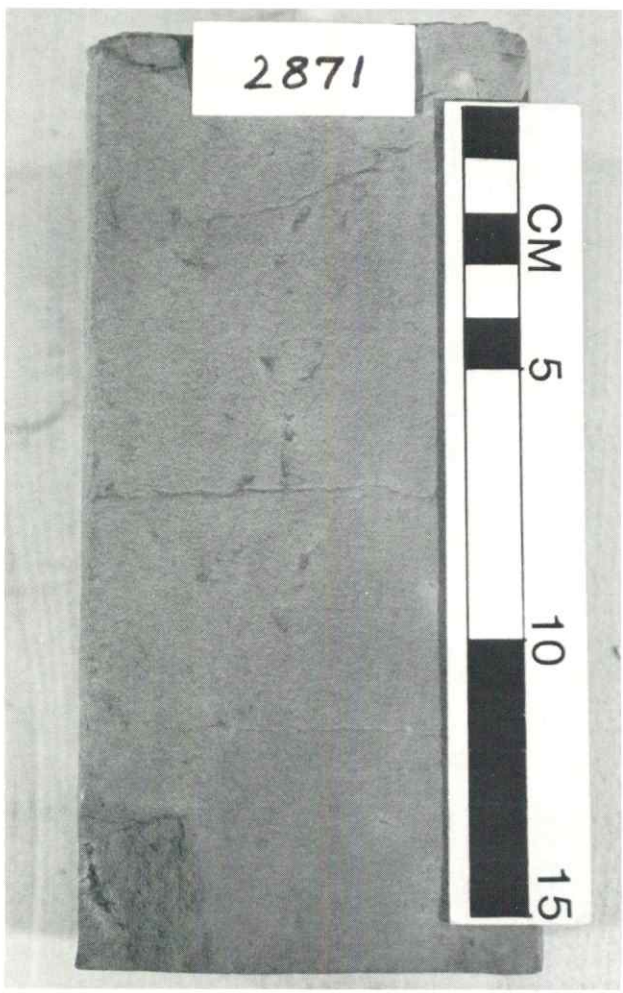

FIGURE 10—Core slab of upper interval of lithofacies 7 (2,882 ft; Anadarko #C-1 Rhinehart Estate). Crinoid, coated-grain packstone. Scale is in centimeters.

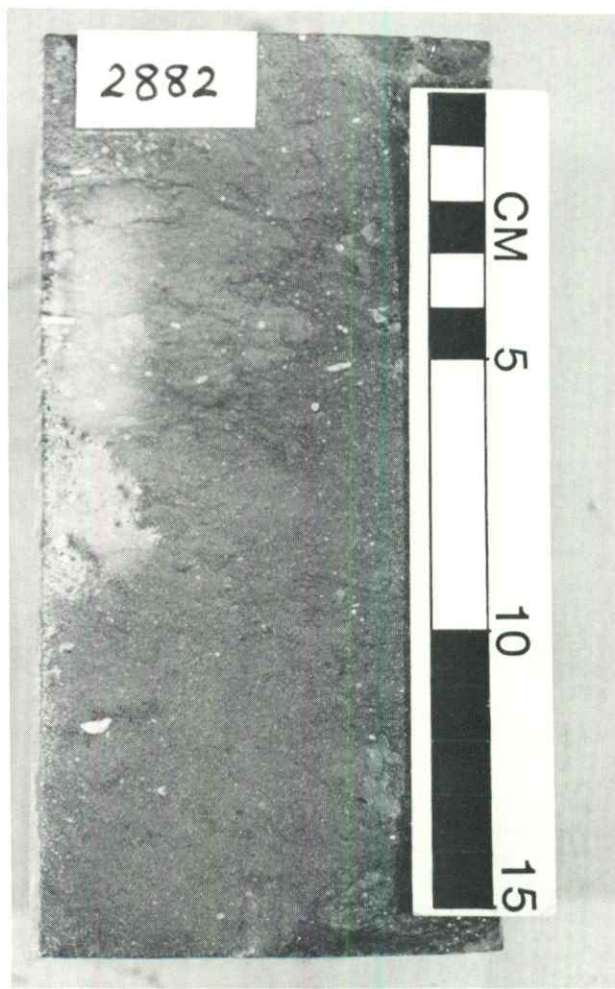

FIGURE 11—Core slab of siltstones of lithofacies 9 (2,871 ft; Anadarko #C-1 Rhinehart Estate). Fractured red, calcareous siltstone. Scale is in centimeters.

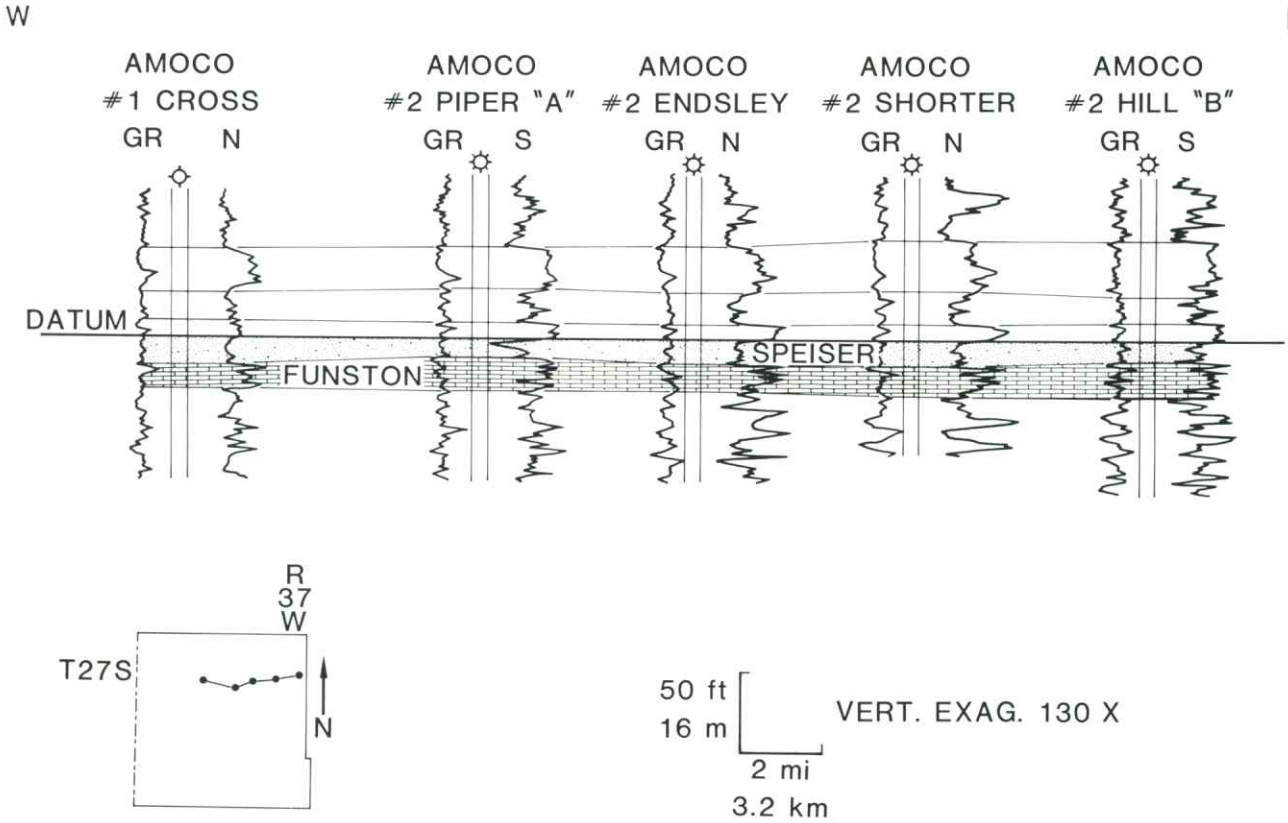

FIGURE 12—West-east subsurface stratigraphic cross section in southwestern Kansas; datum is top of the Council Grove Group. Inset map shows location of cross section line.

(Watney, 1980). Anhydrite development in the regressive carbonate strata of these groups has not been documented. However, Prather (1981) reported the presence of nodular anhydrite in a later-stage regressive shale in the D-Zone cyclothem (Lansing-Kansas City Groups) from southwestern Nebraska. This indicates that arid climatic conditions prevailed in areas north of the Hugoton embayment during the deposition of the Pennsylvanian cyclothems. On the other hand, bedded anhydrite in the younger Nolans Limestone (Upper Wolfcampian) was reported by Glossa (1982). Mudge (1967) indicated that climate became more arid at the close of the Wolfcampian. The Funston Limestone, therefore, probably was deposited during a transitional period from semi-arid to arid climatic conditions.

In summary, a rapid regional transgression followed by a slow, continuous regression was responsible for the deposition of the Funston-cycle sediments. Interbedded carbonate and shale beds can be explained by the occurrence of both minor transgressions and regressions within the cycle. Faunal and lithologic variations within the shoaling lithofacies 7 further support the idea of sea-level fluctuation.

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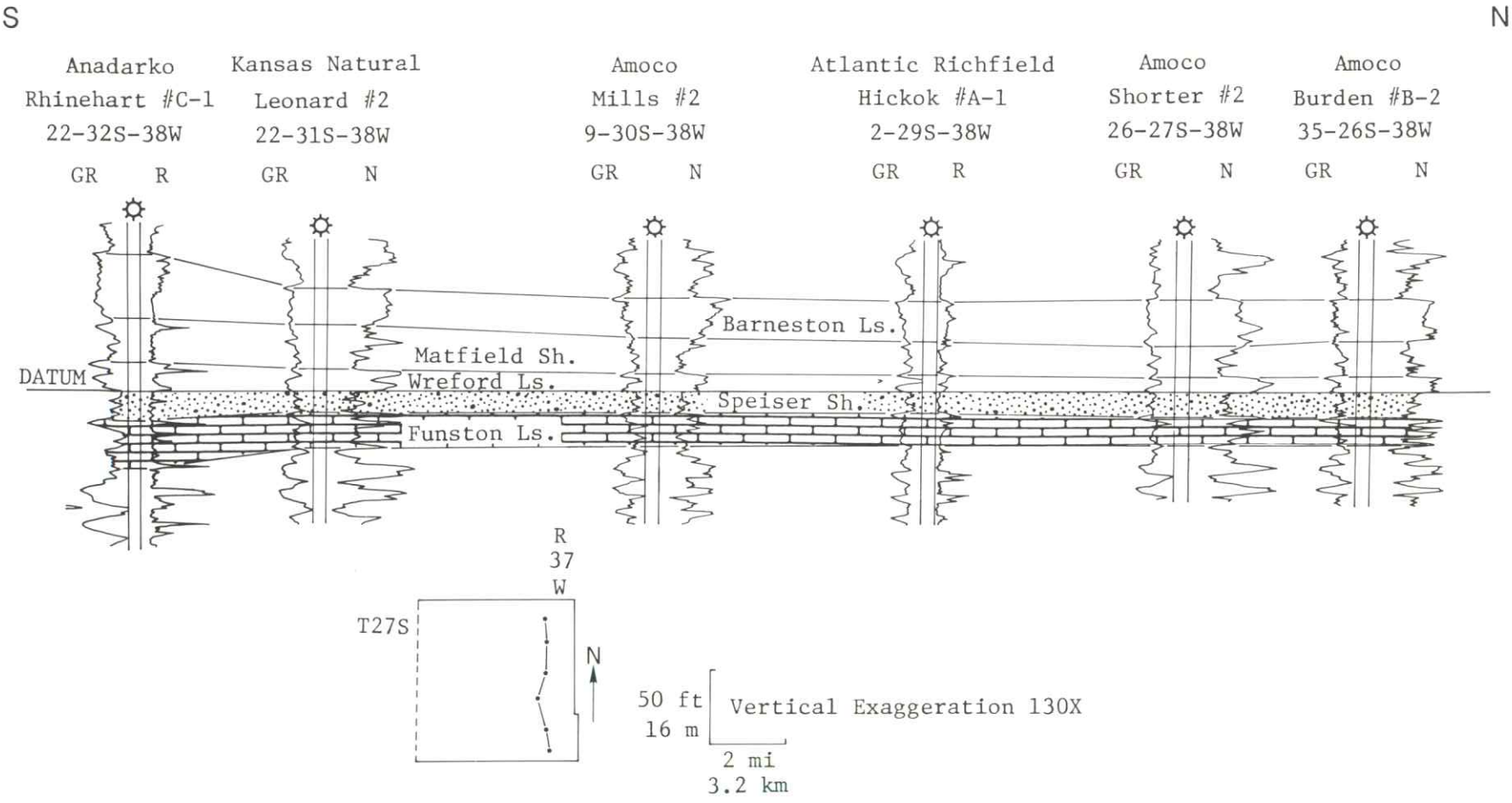

FIGURE 13—South-north subsurface stratigraphic cross section in southwestern Kansas; datum is top of the Council Grove Group. Inset map shows location of cross section line.

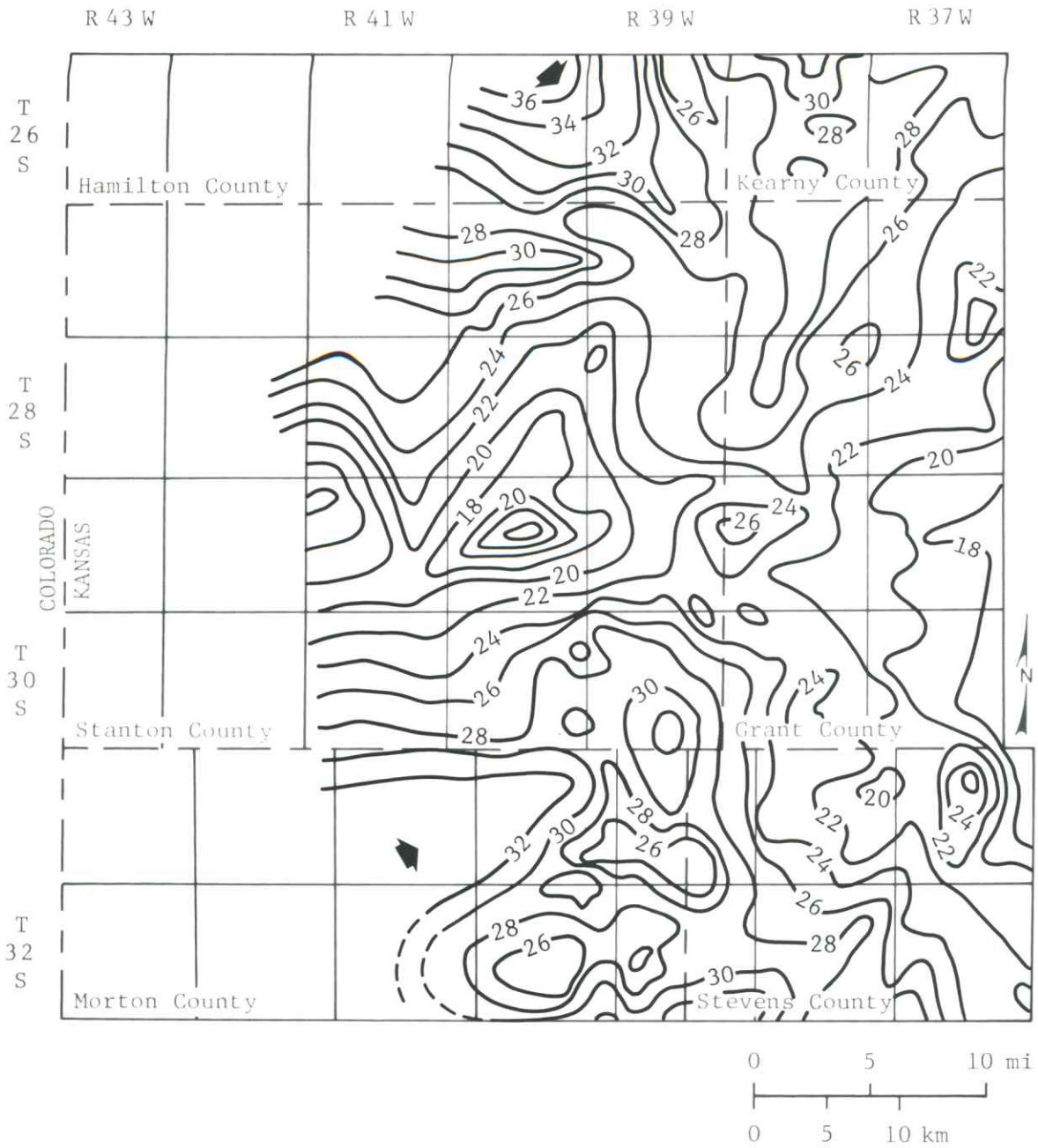

FIGURE 14—Isopach of the Speiser Formation; contour interval = 2 ft.

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Contents of envelope

Sheets 1–3

Kansas Geological Survey
A Division of The University of Kansas

Core studies in Kansas—sedimentology and diagenesis of economically important rock strata in Kansas

Wireline log zones and core description of upper part of the Middle Ordovician Viola Limestone, McClain and McClain SW fields, Nemaha County, Kansas

by Craig D. Caldwell, Cities Service Oil and Gas Co., Tulsa, and Roger Boeken, Cities Service Oil and Gas Co., Oklahoma City

Subsurface Geology Series 6
Sheet 1

PENDLETON LAND AND EXPLORATION, McCLAIN #1, McCLAIN FIELD, NEMAHA CO., KANSAS

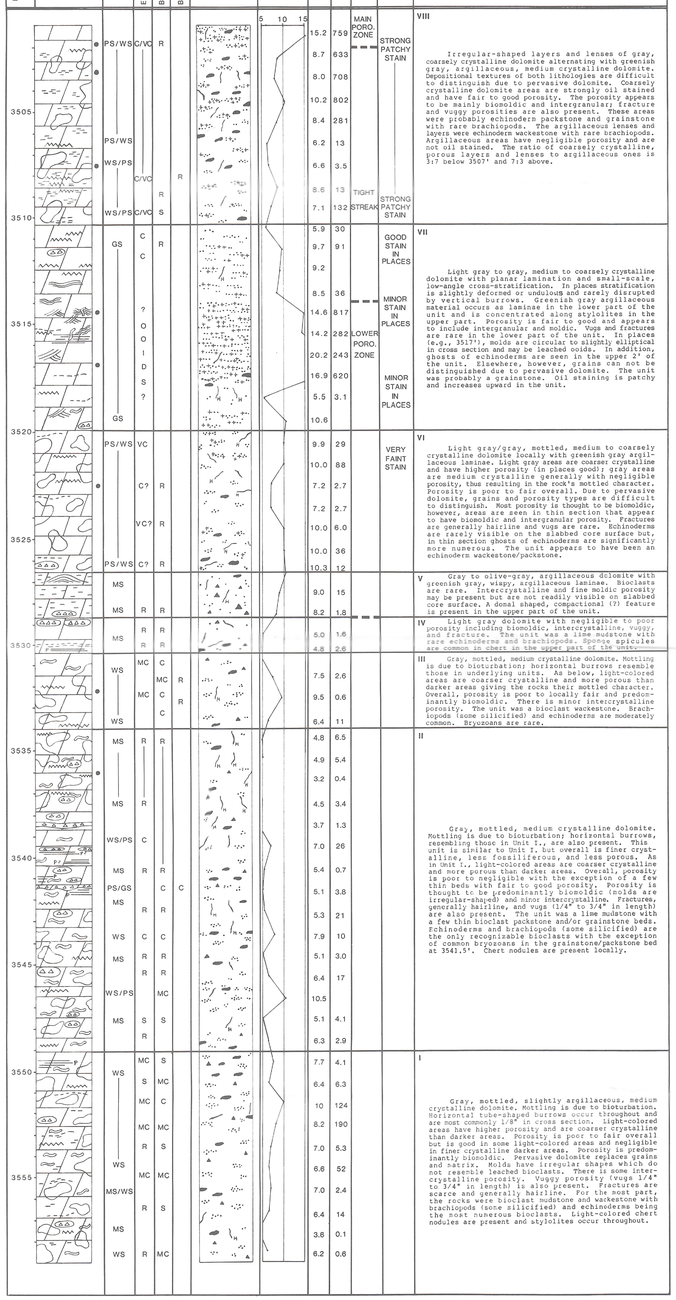


FIGURE 4—Schematic drawing and description of the Pendleton McClain #1, McClain field, Nemaha County, Kansas.

PETRO LEWIS, POTTS #1, McCLAIN FIELD, NEMAHA CO., KANSAS

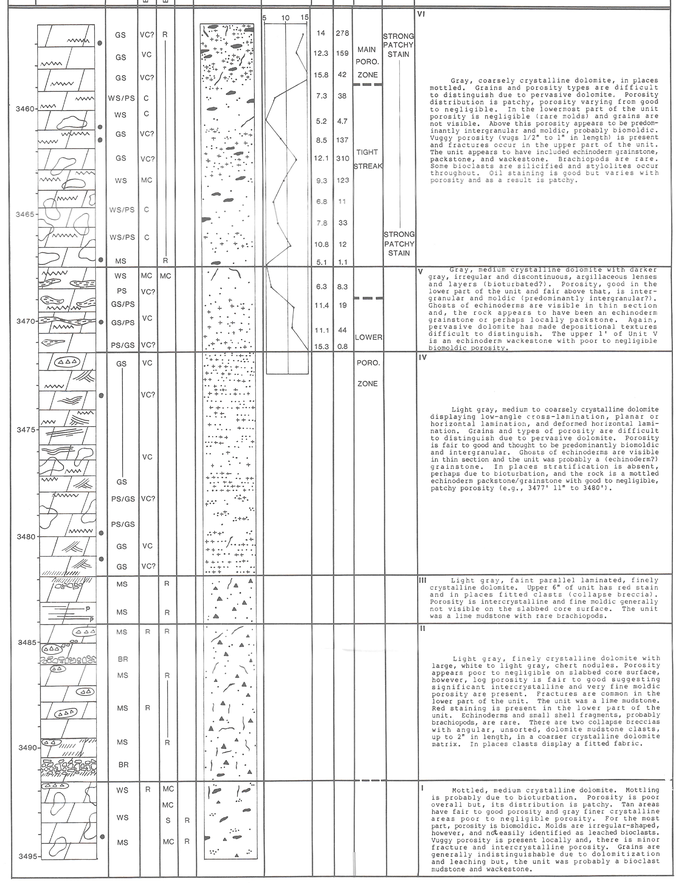
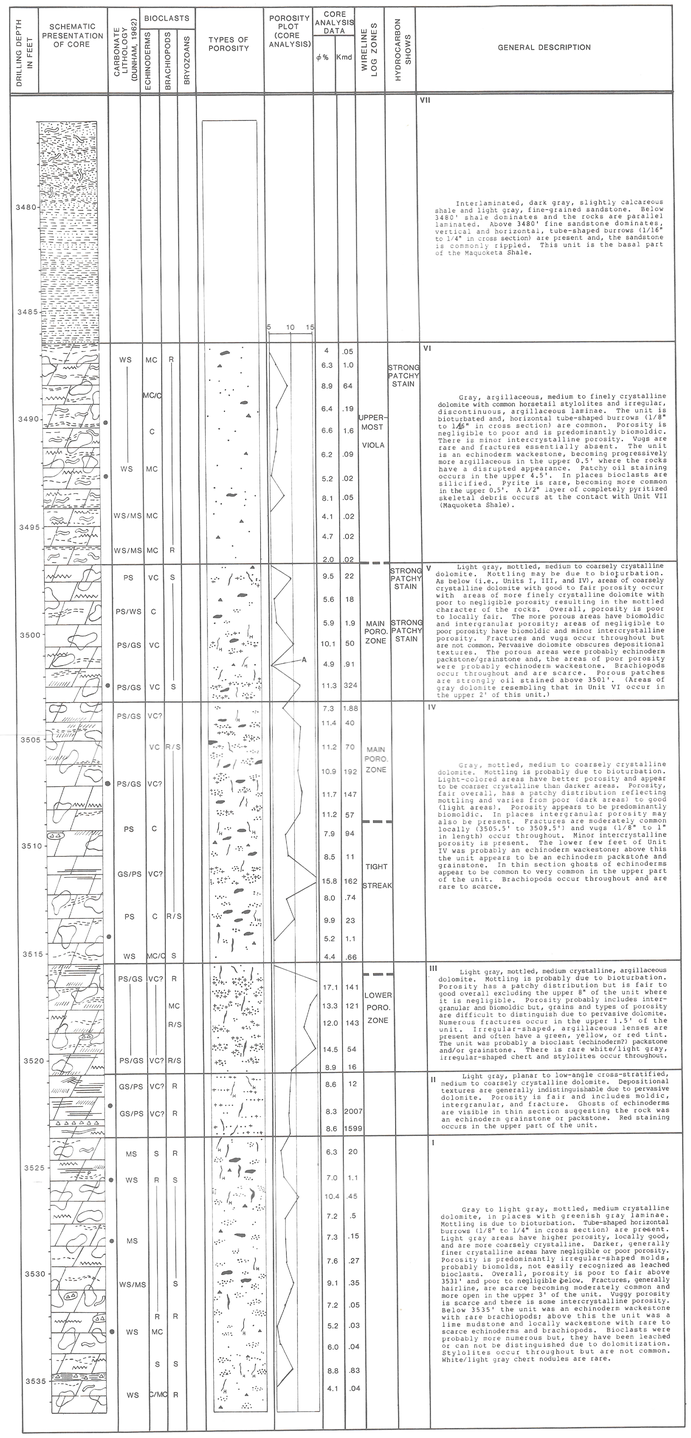


FIGURE 5—Schematic drawing and description of the Petro Lewis Potts #1, McClain field, Nemaha County, Kansas.

CITIES SERVICE, WESSEL "A" #1, McCLAIN SW FIELD, NEMAHA CO., KANSAS


DRILLING DEPTH IN FEET
SCHEMATIC PRESENTATION OF CORE
CARBONATE LITHOLOGY (DUNHAM, 1962)
BIOCLASTS
ECHINODERMS
BRACHIOPODS
BRYOZOANS
TYPES OF POROSITY
POROSITY PLOT (CORE ANALYSIS)
CORE ANALYSIS DATA
Ø %
Kmd
WIRELINE LOG ZONES
HYDROCARBON SHOWS
GENERAL DESCRIPTION
3480
3485
3490
3495
3500
3505
3510
3515
3520
3525
3530
3535
UPPER-MOST VIOLA
MAIN PORO. ZONE
TIGHT STREAK
LOWER PORO. ZONE
STRONG PATCHY STAIN
STRONG PATCHY STAIN
VII
Interlaminated, dark gray, slightly calcareous shale and light gray, fine-grained sandstone. Below 3480' shale dominates and the rocks are parallel laminated. Above 3480' fine sandstone dominates, laminated. Above 3480' fine sandstone dominates, laminated. Above 3480' fine sandstone dominates,

Stratigraphy of the Cherokee Group, southeastern Kansas

by John W. Harris, Kansas Geological Survey, Lawrence, Kansas

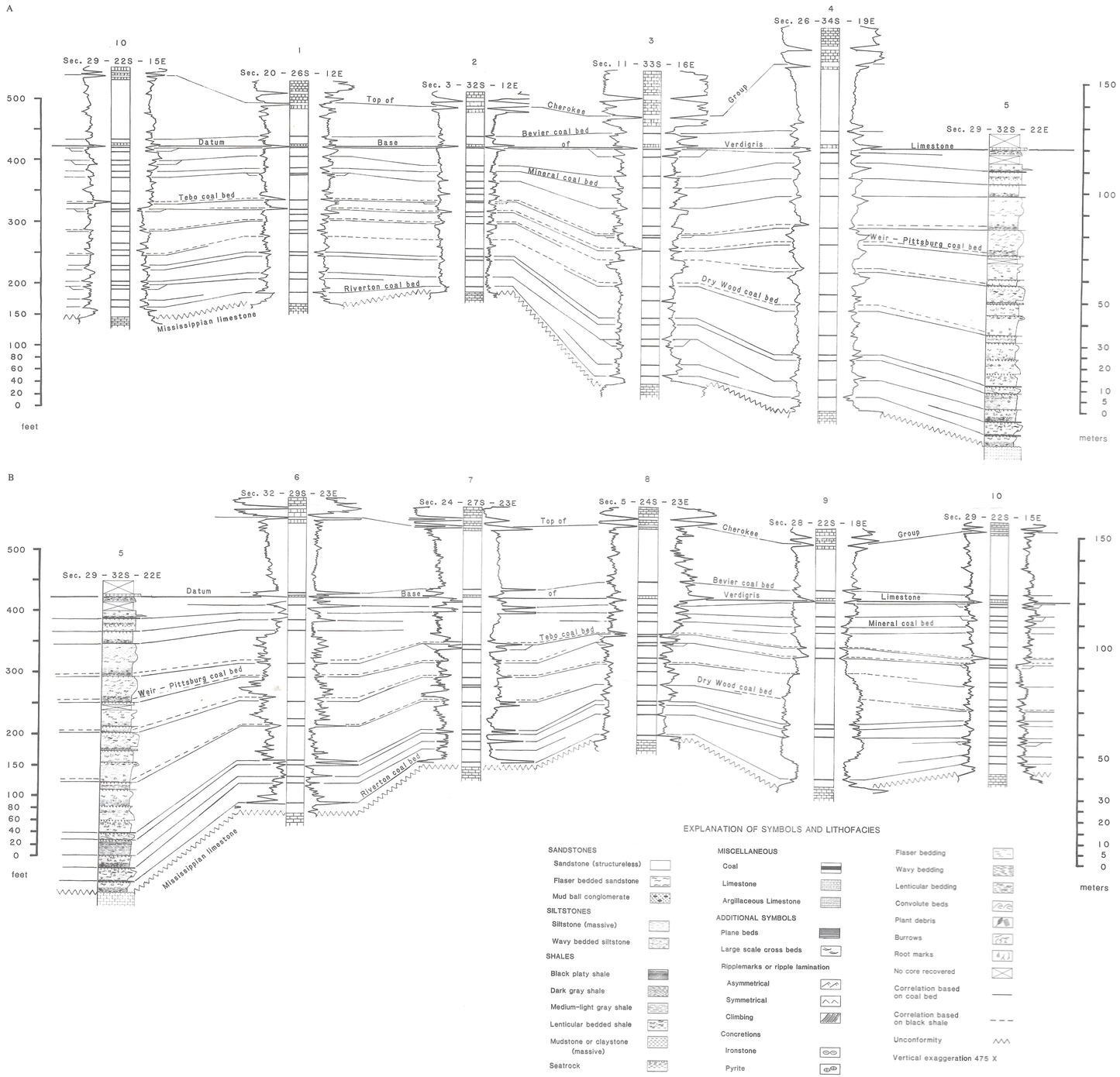


FIGURE 4—(A and B) Stratigraphic cross section of the Cherokee Group, southeastern Kansas (Harris, 1983).

Depositional environment and reservoir geometry of the Bronson–Xenia field, Allen County, Kansas

by Douglas H. Rofheart, Mobil Exploration and Producing Services, Inc., Dallas, Texas

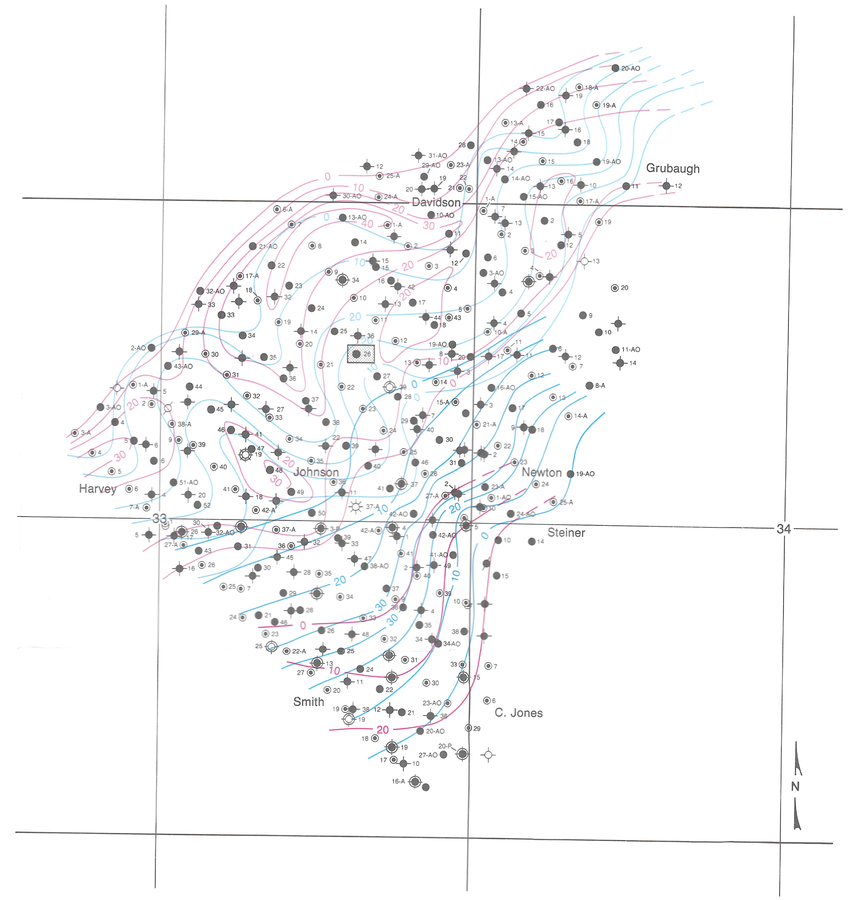


FIGURE 4—Multi-layered isopach map showing distribution of different sands in the "KB" field, T. 24 S., R. 21 E., Allen County, Kansas.

Kansas-type cyclothems and porosity development in the Middle Pennsylvanian Marmaton Group, Dirks field, Logan County, Kansas

by Craig D. Caldwell, Cities Service Co., Tulsa, Oklahoma

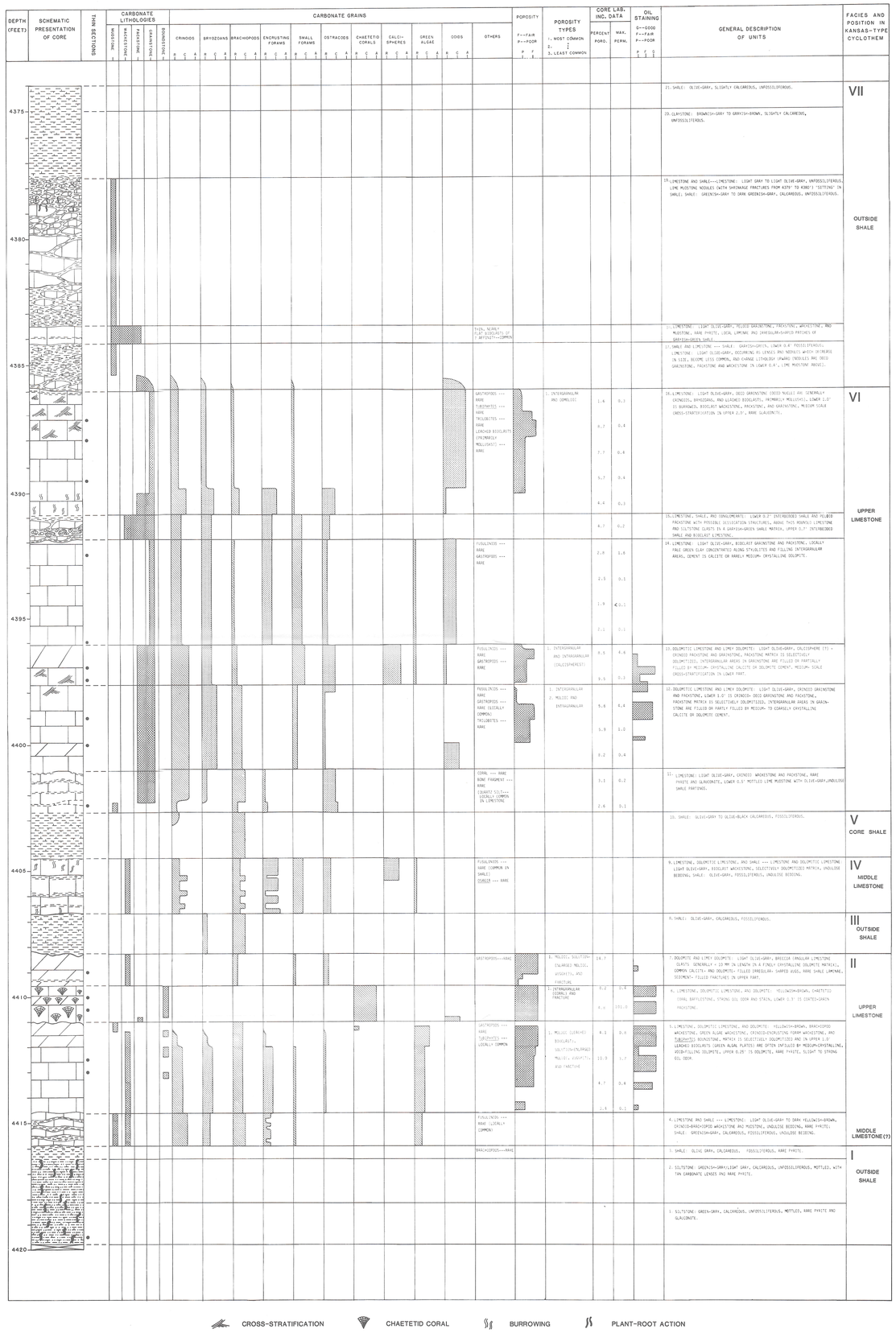


FIGURE 4—Schematic drawing and description of core 4, Texaco Dirks 2, Logan County, Kansas.

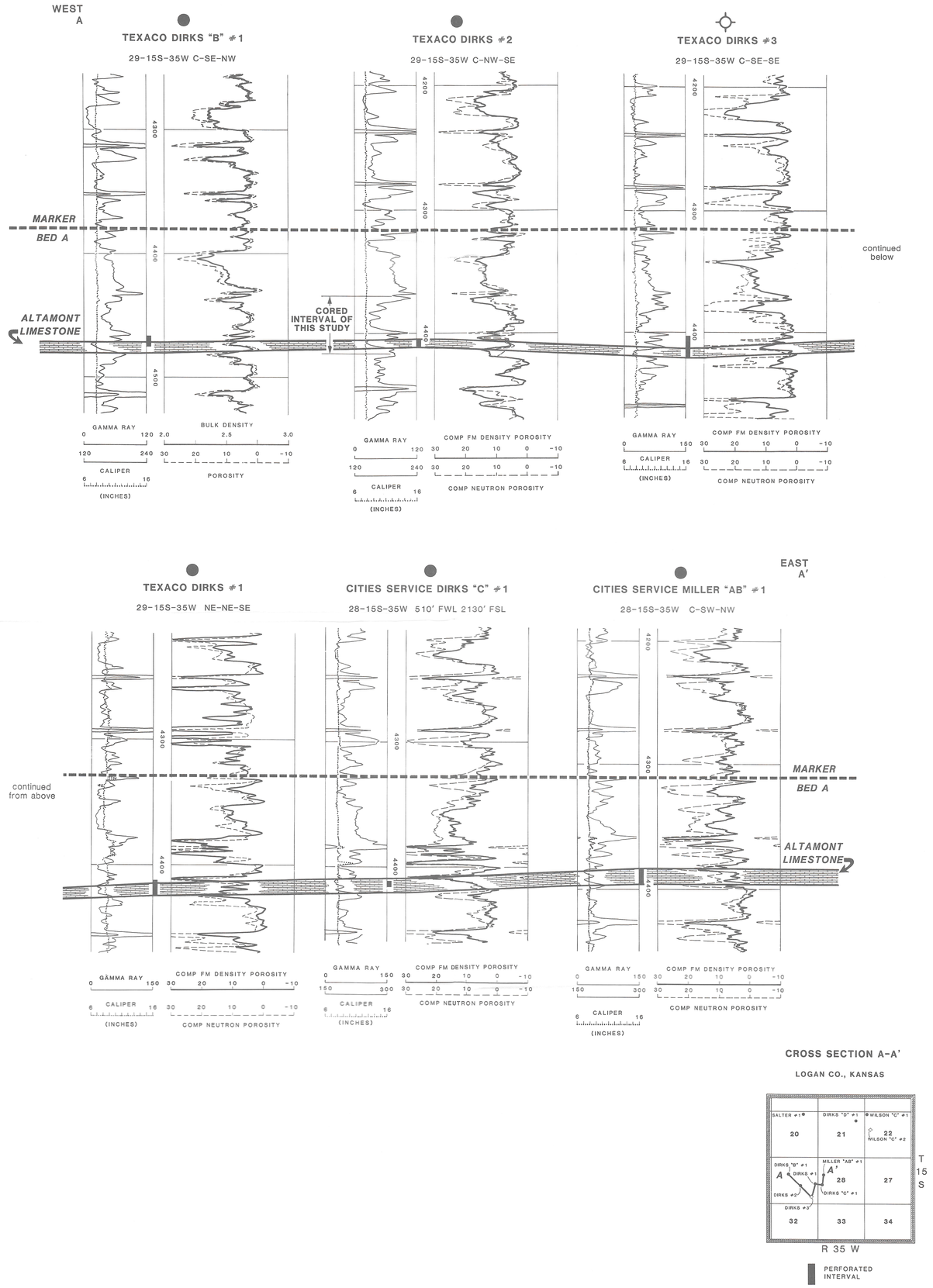


FIGURE 9—East- west stratigraphic cross section showing overall eastward thinning of section between Altamont Limestone and marker bed A (no horizontal scale).