DISTRIBUTION, DEPOSITIONAL ENVIRONMENT, AND RESERVOIR PROPERTIES OF THE PENNSYLVANIAN COTTAGE GROVE SANDSTONE, SOUTH GAGE FIELD, OKLAHOMA

By

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PREFACE

This study deals with the depositional environment and reservoir properties of the Upper Pennsylvanian Cottage Grove Sandstone of the Ochelata Group of the Missourian Series. Determination of environment was accomplished through preparation of correlation sections, isopach and structural contour maps, and core analyses. Reservoir characteristics were studied, utilizing thin-section microscopy, X-ray diffraction techniques, and scanning electron microscopy.

Appreciation is extended to Professor John W. Shelton, thesis adviser, whose enthusiasm and constructive guidance throughout this study proved invaluable. Equal appreciation is extended to Mr. Herbert G. Davis, who suggested the study, provided cores and electric logs for examination, and generously provided tangible and intangible support. His sharing of knowledge of the study area and the Anadarko basin were particularly helpful. Professor Zuhair Al-Shaieb, who also served on the thesis committee, provided valuable assistance in examination of reservoir properties. Thanks are due to Dr. Paul Basan, Dr. Edward Pittman, and Dr. Richard Larese, Amoco Production Company, Tulsa, for aid in trace-fossil examination and scanning electron microscopy. Amoco Production Company, Denver, and Shenandoah Oil Corporation, Oklahoma City, aided in environmental interpretation, as well as providing electric logs and arranging for examination of cores. Thanks are due to Mr. Dale Boyle and Mr. Mike Edwards, Core

Laboratories, for providing data and assistance in reservoir analysis. The Oklahoma City Geological Society provided financial support through a Grant-in-Aid award, and their Well Log Library provided subsurface information. Appreciation is expressed to Dr. D. E. Simon and Halliburton Services for preparation of thin sections. Numerous companies in Tulsa, Oklahoma City, and Denver were very cooperative in providing electric logs which were necessary in completing the field study. Mr. Edward Byrne is complimented for his aid in drafting and preparation of various figures. Mr. Harold Hanke, Professor John Naff, and fellow graduate students made helpful comments and offered encouragement during the course of the study. Gratitude is extended to the Oklahoma State Department of Geology for providing two years of financial assistance.

Finally, the writer would like to express special thanks to his parents for their continued encouragement and support which made it possible to achieve an education.

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CHAPTER I

ABSTRACT

The Pennsylvanian Cottage Grove Sandstone of the Ochelata Group of the Missourian Series produces oil and gas in the South Gage field, a stratigraphic trap in central Ellis County, Oklahoma. The Cottage Grove Sandstone is interpreted as an offshore shallow-marine bar.

Sandstone development occurred as a convex-upward sand buildup. The body is enclosed within marine shale; lower and lateral contacts are quite sharp, whereas the upper contact is rather gradational. The sandstone body extends for more than 11 miles and averages approximately 2 miles in width. Maximum sandstone thickness exceeds 100 feet.

Sedimentary structures within the unit include (1) a lower zone of small-scale cross-stratification, (2) an intensely burrowed zone, and (3) an upper zone of siltstone-shale interstratification. Due to its coarser grain size (very fine sand), the small-scale cross-stratified zone is the only oil-productive zone in the Cottage Grove. Massive bedding is present in thin, carbonate-cemented layers.

Regional correlation of the Cottage Grove northward indicates that a sharp break in the depositional slope did not exist between limestone deposition to the north and terrigenous clastic deposition to the south. Correspondingly, it is thought that fairly shallow water conditions existed at South Gage during Cottage Grove deposition. Carbonate constituents probably were derived from this northern carbonate

region, but terrigenous clastics of the Cottage Grove were transported into the area from the east; they probably were derived to a large extent from the Ouachita uplift. The South Gage field was more than 20 miles west of the eastern coast and 40 miles south of carbonate deposition.

Fine grain size and abundance of various types of diagenetic clays (illite, kaolinite, and chlorite) are responsible for high water saturations measured in core analyses and calculated from log analyses. They also may create problems in well completion and development of the field. Oil recovery depends primarily upon pore-throat and average pore sizes, which relate both to the grain size and diagenetic products. The thin, carbonate-cemented layers may serve as barriers to fluid migration.

CHAPTER II

INTRODUCTION

The Pennsylvanian Cottage Grove Sandstone produces oil and gas in the South Gage field, a stratigraphic trap in Ellis County, Oklahoma (Fig. 1). The area of investigation includes 50 sections in T20-21N, R23-25W. Subsea elevations to the top of the Cottage Grove Sandstone range from 4875 feet in the northwestern part of the area to 5285 feet in the southeast. Cumulative oil production to January 1, 1978, was slightly over 1,000,000 barrels.

Objectives and Methods

The principal objectives of this study are to determine the depositional environment of the Upper Pennsylvanian Cottage Grove Sandstone of the Ochelata Group of the Missourian Series and to achieve an understanding of various properties of the South Gage reservoir.

Subsurface information sources, including dual induction laterologs, induction electrologs, compensated neutron - formation density logs, sonic logs, and gamma ray logs, were utilized in preparation and interpretation of various correlation sections, structural maps, and isopach maps. These were used to determine structural and stratigraphic relationships, in particular those responsible for trap formation at South Gage field.

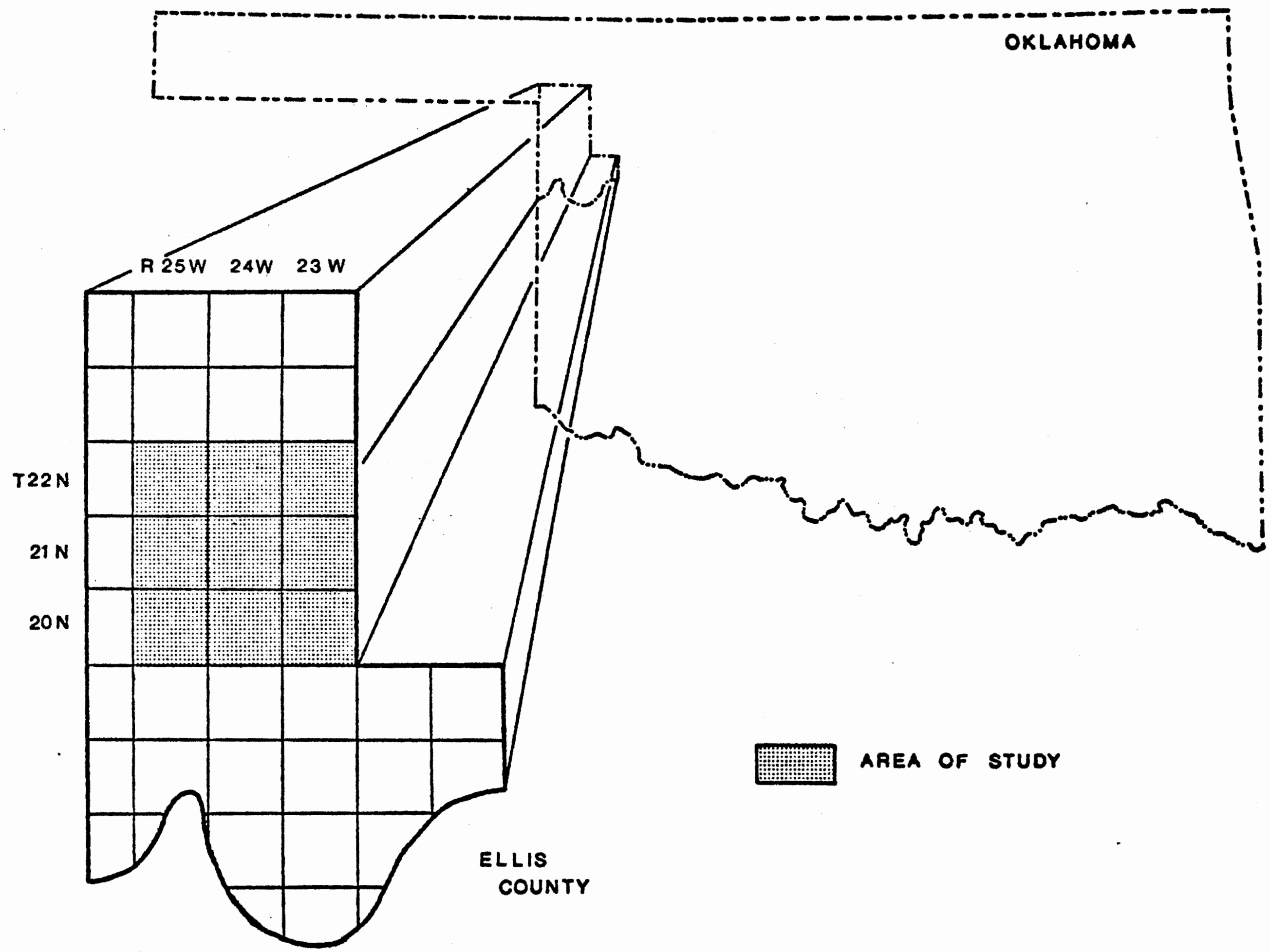


Fig. 1.-Location map of study area.

Internal features of the Cottage Grove were determined through a detailed examination of four cores, including petrography (thin-section, X-ray diffraction, and scanning electron microscopy). An estimate of depositional environment was made from the integration of internal features, structural framework, stratigraphic framework, and geometry.

Reservoir properties were studied by the different petrographic techniques. These were combined with porosity and permeability data from core analysis.

Previous Investigations

The Cottage Grove Sandstone was named by Newell for Cottage Grove Township in Allen County, Kansas (Moore, 1932). Oakes (1940) described the Cottage Grove on outcrop in Washington County, Oklahoma, as "massive to thin bedded, fine-grained, micaceous, and buff colored."

Pate (1959) included the Cottage Grove in a study of stratigraphic traps in northwestern Oklahoma, and delineated areas within which future exploration should be considered. Capps (1959) analyzed Missourian and Virgilian rocks in northwestern Oklahoma and described the Cottage Grove lithologically from subsurface samples. He suggested a clastic source to the south and deposition in a neritic, low-energy environment on a shelf which varied in its degree of stability. Gibbons (1960) also described the Cottage Grove lithologically from subsurface samples in northwestern Oklahoma and concluded that the sandstone was a western extension of an equivalent unit east of the Nemaha uplift.

Rascoe (1962), from the distribution of the Cottage Grove in the Anadarko basin, considered its development to be related to the formation of an east-west sedimentary trough across Oklahoma during the Missourian. Holmes (1966) concluded that the Cottage Grove Sandstone of the Cedardale Field, Woodward and Major Counties, Oklahoma, was deposited as a series of bars trending northeast-southwest. Swanson (1967) reported that in the northern hinge zone of the Anadarko basin oil and gas accumulations commonly occur in areas of marked facies changes (such as those exhibited by the Cottage Grove), sediment onlap, and sediment truncation.

More recently, Lalla (1975) reported that the Cottage Grove in northern Oklahoma, east of the Nemaha uplift, is a deltaic complex. He also concluded a source area existed to the southeast. Rascoe (1978) indicates that the major source of the Cottage Grove Sandstone was the Ouachita Mountains. He proposes that Missourian sandstones in central Oklahoma represent fluvial-deltaic conditions, whereas the sandstones in western Oklahoma formed in marine environments.

CHAPTER III

HISTORY OF DEVELOPMENT

Pan American Petroleum Corporation (Amoco) completed the Sherrill No. 1 in Section 36, T21N, R25W (well 1, Fig. 2), as a Morrow gas discovery in December, 1959, marking the first major well completion in the immediate area of the South Gage field. Shenandoah Oil completed the Peer No. 1, a Morrow test in Section 23, T21N, R24W (well 21, Fig. 2), as a Cottage Grove oil producer in February, 1975. An extensive development period is currently continuing; over 50 wells have produced from the Cottage Grove since that date. During the fifteen years that separate these two tests, nineteen wells were drilled through the Cottage Grove and completed in the Morrow.

The first well drilled by Huber Corporation, in Section 25, T21N, R24W, encountered a fairly thick section of Cottage Grove Sandstone. The Cottage Grove, which was cored in Huber's second well, the Schoenhals No. 1, consists of dark gray, fossiliferous shale, thin, light gray, finely crystalline limestone, and thick, dark gray, dense and brittle shale. This well is located directly southeast of the field in Section 31, T21N, R23W (well 6, Fig. 2). Huber Elledge No. 1, drilled in Section 26, T21N, R24W (well 8, Fig. 2), was a dual completion in the Morrow and Cottage Grove. It was the original Cottage Grove discovery of the field. The five wells Pan American completed before this discovery did not test the Cottage Grove. Tests through

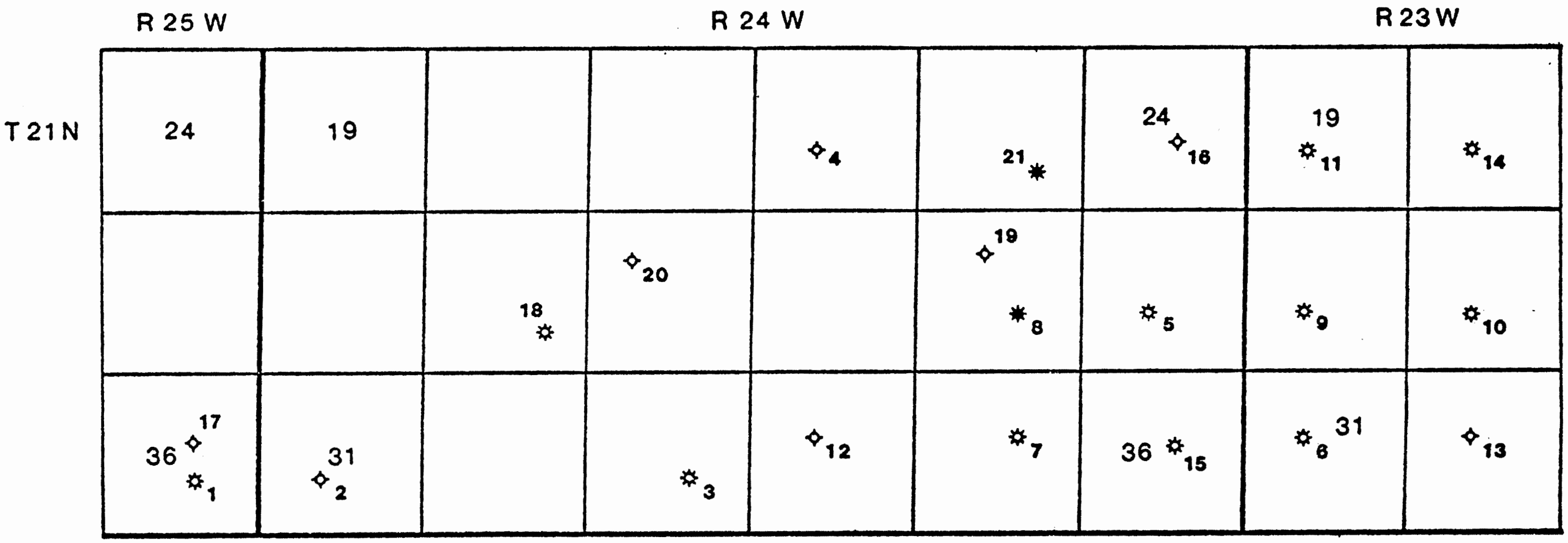


Fig. 2.-Well location map, South Gage field, showing history of development.

perforations opposite the Cottage Grove section in two of four succeeding wells drilled in 1964 indicated water with slight oil shows.

After the initial Cottage Grove discovery in 1963, only four of twelve wells tested the Cottage Grove; no further completions were attempted until the Shenandoah discovery in February, 1975. Activity then expanded rapidly, with Shenandoah controlling the central part of the field, May Petroleum the western part, and more recently, Amoco Production the eastern segment.

CHAPTER IV

STRUCTURAL FRAMEWORK

South Gage field is located on the north flank of the Anadarko basin (Fig. 3). The present asymmetric, west-northwest-trending basin formed during Late Paleozoic, when subsidence and clastic sedimentation were greatest. The basin is both structural and depositional (Swanson, 1967). The basin is bounded on the north by a broad cratonic shelf, on the south by the Frontal Wichita fault system (Harlton, 1972), and on the west beyond the shelf by the Sierra Grande uplift. The Nemaha uplift separates the basin from the Central Oklahoma platform to the east, whereas the basin extends into the Ardmore basin to the southeast. The Anadarko basin contains a maximum of approximately 45,000 feet of strata immediately north of the Amarillo-Wichita uplift (Rowland, 1974). Major oil and gas fields are located in anticlines and stratigraphic traps near the basinal edges, suggesting updip migration of hydrocarbons (Swanson, 1967).

Many of the Cottage Grove fields in the Anadarko basin trending east-west are located along north-south lineaments. Although supporting evidence apparently was masked by post-Missourian basinal subsidence, this feature is perhaps due to Middle-Late Pennsylvanian paleotopography or to structural control which might be related to the north-trending Nemaha uplift to the east (Jones, 1964; Lyons, 1964).

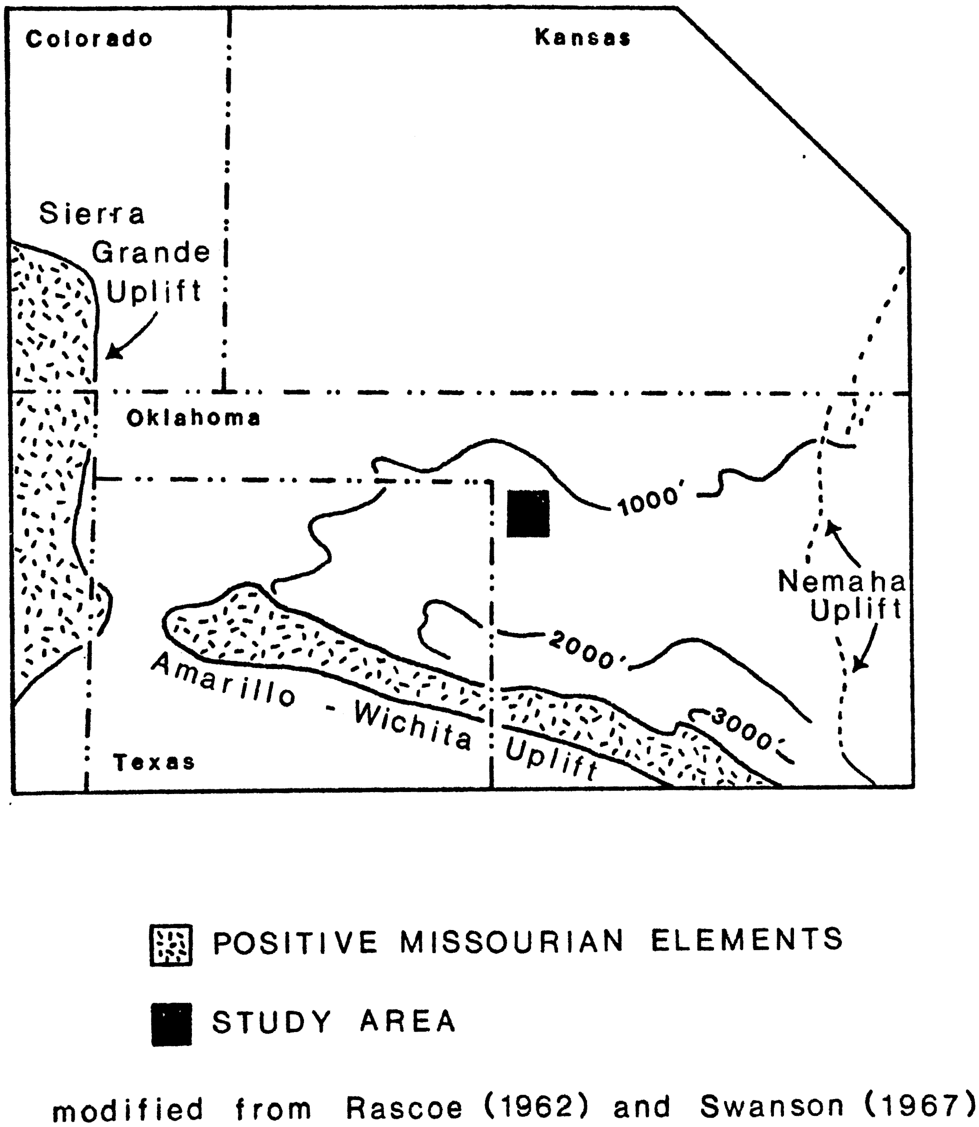


Fig. 3.-Regional tectonic map of Anadarko basin, showing isopach of Missourian Series.

Regional structural maps of the study area, prepared on Pennsylvanian horizions, indicate no major structural irregularities or faults in the South Gage area, but rather a fairly constant southerly dip into the deeper part of the basin. Structural mapping on the top of the Cottage Grove shows structural closure corresponding to maximum sandstone development.

Regional Structure on the Base of the Hogshooter Limestone

The base of the Hogshooter Limestone below the Cottage Grove shows a subregional east-northeast trend, with a homoclinal dip of approximately 60 feet per mile to the south-southeast. The surface is only slightly undulatory; noses and saddles are present as broad features (Fig. 4).

Regional Structure on the "Hot Shale" Marker

The subregional trend of the "Hot Shale" marker above the Cottage Grove is essentially the same as that shown by the base of the Hogshooter Limestone. Dip is south-southeast at slightly less than 60 feet per mile. In general, noses and saddles are broadly defined (Fig. 5). Structural closure is present in T21N, R24W, over the center of the South Gage field.

Local Structure on the "Hot Shale" Marker

Local to subregional structure of the "Hot Shale" marker over the South Gage area shows some variability. Strike is east-northeast (Fig. 6). Overall dip is to the south-southeast; dip north-northwest

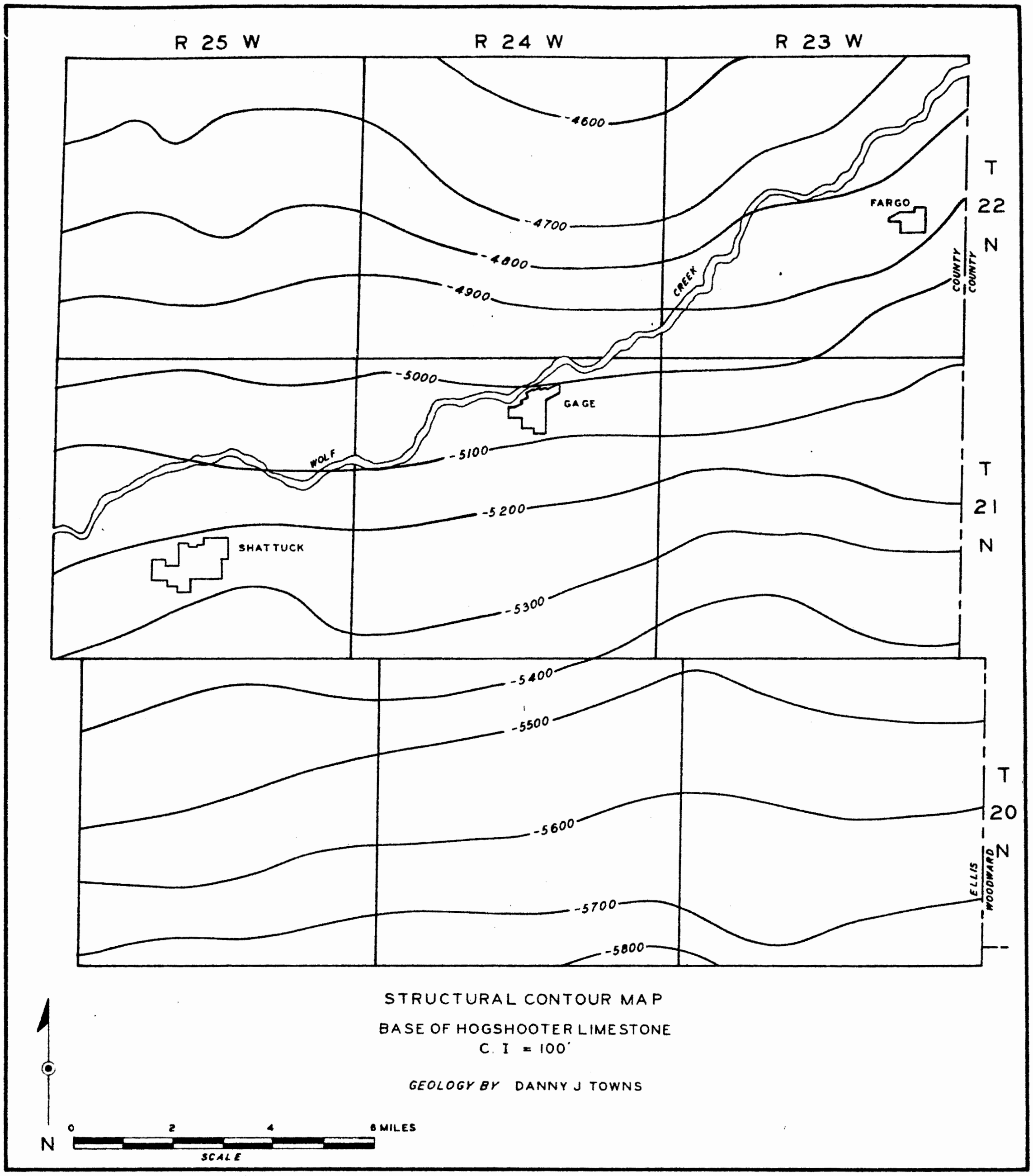


Fig. 4.-Regional structural contour map, with base of Hogshooter as reference surface.

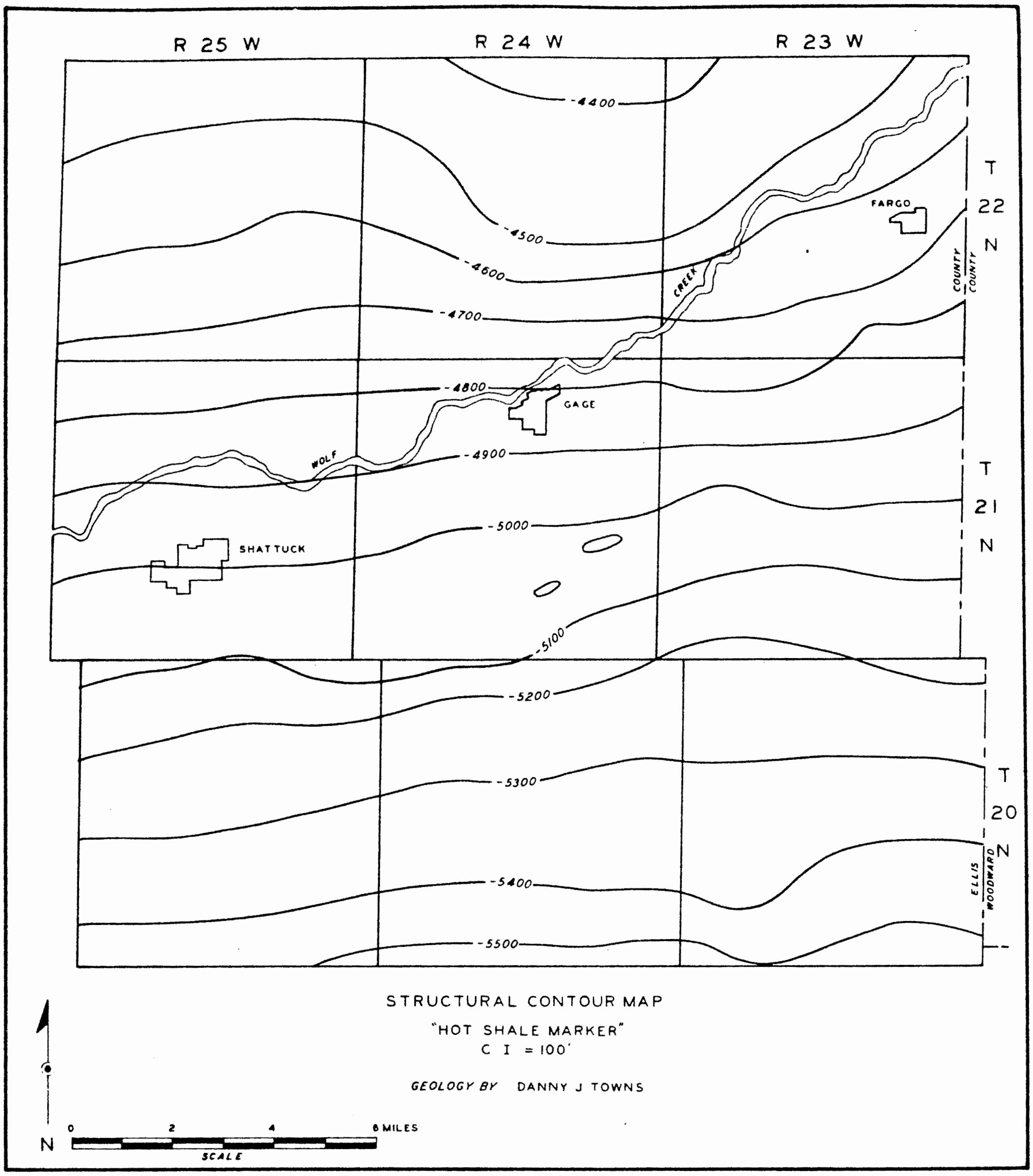


Fig. 5.-Regional structural contour map, with "Hot Shale" as reference surface.

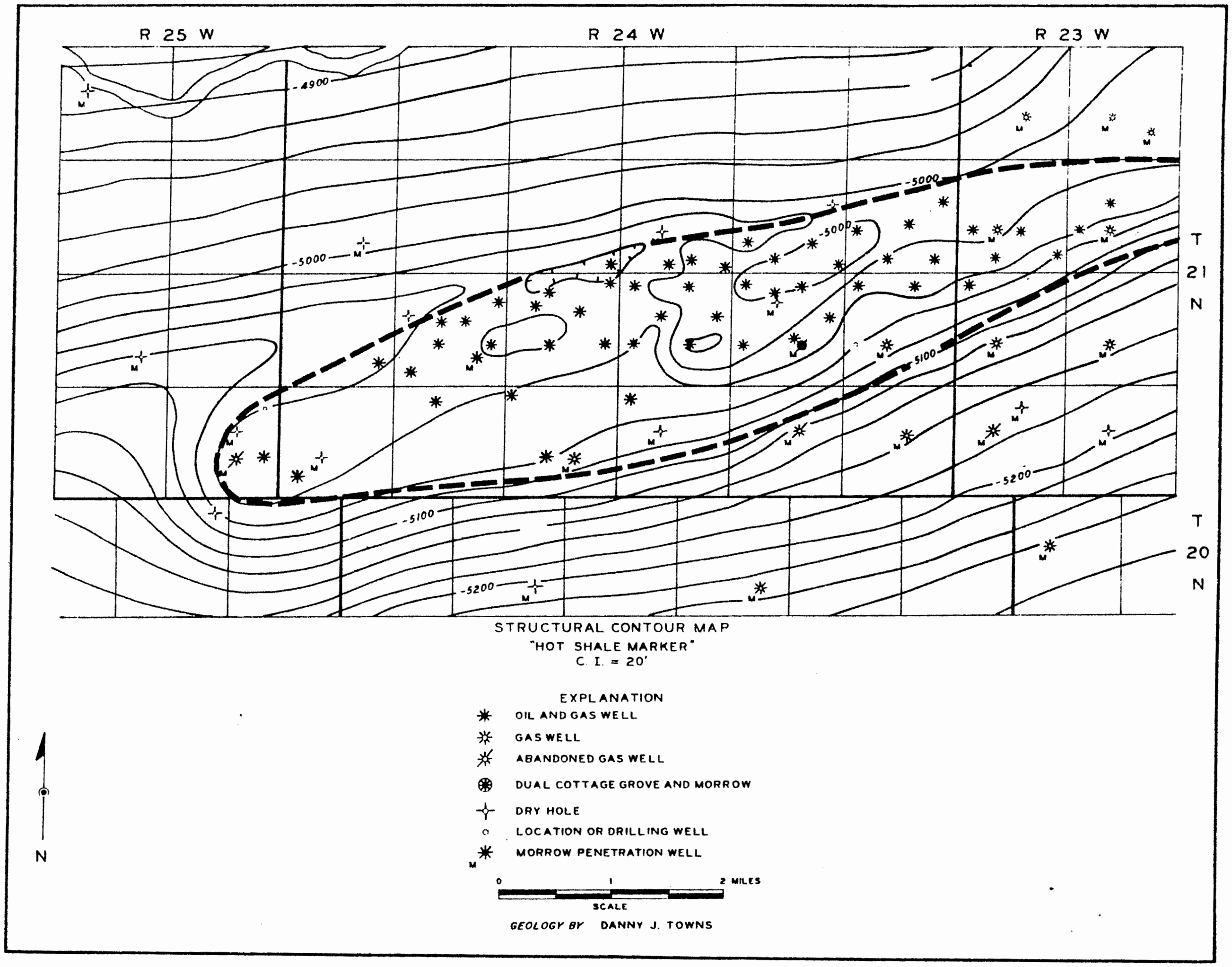


Fig. 6.-Local structural contour map, with "Hot Shale" as reference surface. Oil production is confined to area within dashed lines.

of the field is approximately 70 feet per mile, whereas it is about 80 feet per mile east-southeast of the field. However, three anomalous areas are present directly over the field. An east-northeast-trending trough lies along the north-northwest edge of the field where the dip changes from south-southeast to north-northwest. In Section 21, 22, 23, 28, 29, and 30, T21N, R24W, and Sections 25 and 35, T21N, R25W, saddles, with overall plunge to the west-southwest, portray quite clearly the change in dip direction (Fig. 6). Along the central part of the field there are approximately 30 feet of structural closure; dip is gentle in this crestal part of the structure. Along the south-southeast edge of the field dip is a maximum of 150 feet per mile; to the south-southeast beyond the field dip is regional.

CHAPTER V

STRATIGRAPHIC FRAMEWORK

The Cottage Grove Sandstone is in the lower part of the Ochelata Group of the Missourian Series. "Osage-Layton," "Mussellem," "Layton," "Peoples-Layton," and "Lower Tonkawa" are all names which have been applied to the Cottage Grove (Jordan, 1957). Marine shale separates the Cottage Grove from both the Tonkawa Sandstone above and the Hogshooter Limestone below. The Morrow Sandstone, a primary exploratory objective in the area, is approximately 2500 feet below the Cottage Grove (Fig. 7).

The Cottage Grove Sandstone is present throughout northern Oklahoma and part of southern Kansas as a fairly uniform sand blanket (Rascoe, 1962). The South Gage field is located near the westernmost limit of this blanket, where sandstone is less continuous. Siltstone, shale, and carbonate units dominate the Cottage Grove interval in this part of the basin. Limestones of the Kansas City Group are the Cottage Grove equivalent on the stable shelf region north of the study area.

Correlation

Regional and local stratigraphic correlation sections were prepared to show characteristics of the Cottage Grove and its relationships with adjacent units (Figs. 8-15). Markers used for correlation of regional sections include (1) the base of the Hogshooter Limestone,

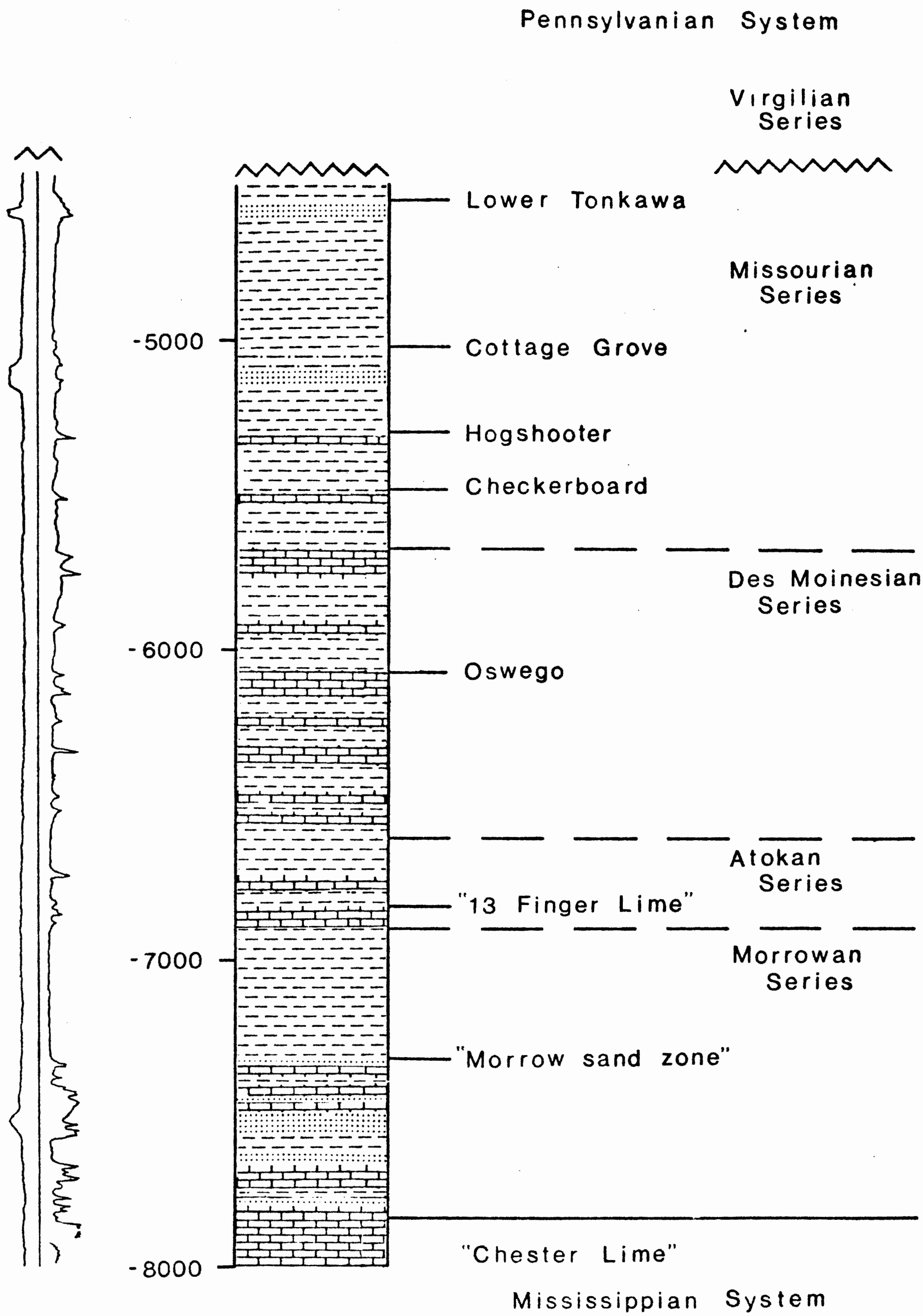


Fig. 7.-Stratigraphic column at South Gage field.

(2) a persistent resistivity marker approximately 100 feet above the Hogshooter, (3) the base of the Cottage Grove (referred to as BGG), (4) two sharp gamma ray deflections, the lowermost defining the top of the Cottage Grove interval (referred to as the "Hot Shale" marker), and (5) an upper persistent resistivity marker. Markers used for correlation of local sections include (1) a persistent resistivity deflection (carbonate bed) approximately 35 feet below the base of the Cottage Grove, (2) the base of the Cottage Grove, and (3) the gamma ray deflections previously described. The base of the Cottage Grove was determined from correlation which combined data from gamma ray, density, self-potential (SP), and resistivity logs. Where coarser clastics (siltstone and/or sandstone) are present, there is little difficulty involved with this procedure; however, where these clastics are absent and a gamma ray log is not available, the level of confidence in selection of this horizon decreases. The other markers are consistent and can be correlated from adequate subsurface data with high reliability. The Cottage Grove interval is defined as the stratigraphic section above the base of the Cottage Grove and below the "Hot Shale" marker. The Cottage Grove Sandstone is defined as only that portion of the Cottage Grove interval characterized by coarse clastics, which are commonly recognized, if present, by an SP deflection distinctive from the shales both above and below the unit. Figure 8 illustrates the vertical variability accompanying changes in sandstone development. In well no. 2 of Figure 8, Cottage Grove Sandstone thickness is 65 feet, as compared to zero thickness in well no. 1, less than one mile from well no. 2. Total interval thicknesses are 80 feet and 30 feet, respectively. Where coarse clastics are absent, the Cottage Grove

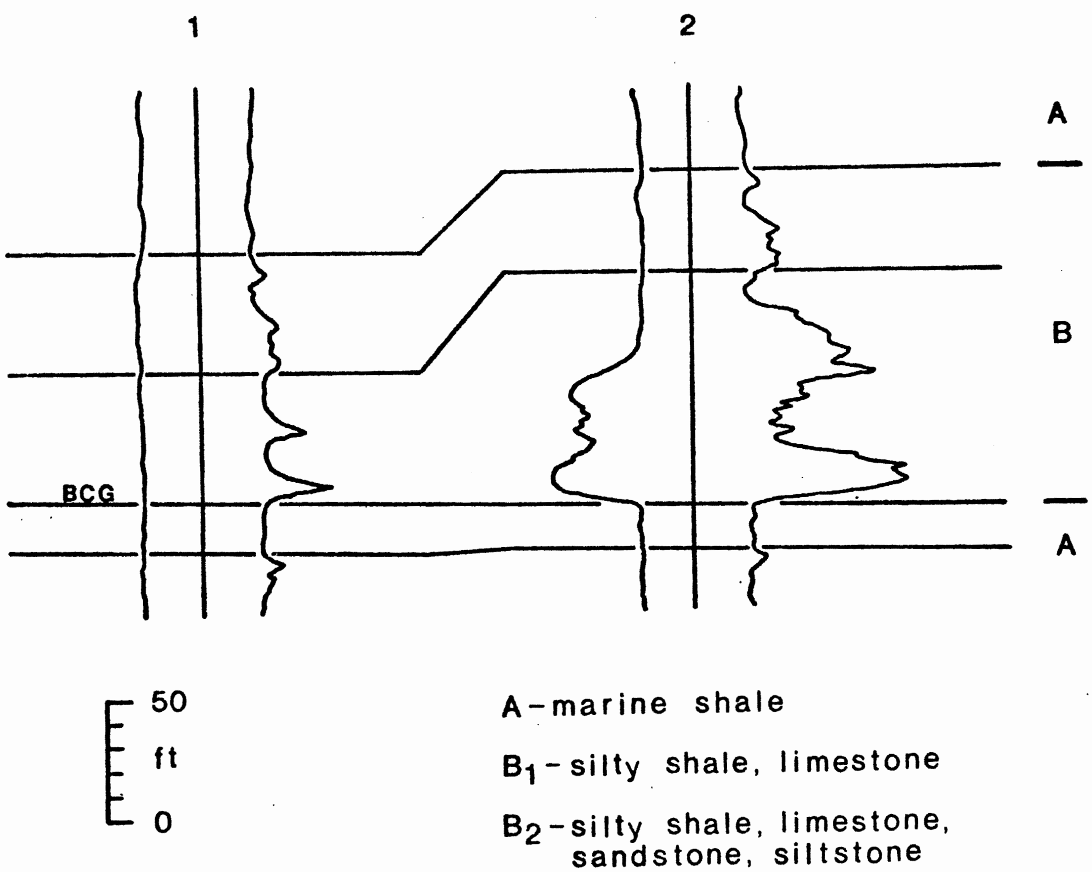


Fig. 8.-Local correlation section, South Gage field.

interval is characterized by silty calcareous shales interbedded with thin, dense, fossiliferous limestones. Where sandstones and/or siltstones are present, silty shales and thin limestones also are developed, commonly interbedded with the coarser material. In a vertical sequence, the formation is a persistent but variable layer between sequences of marine shale. Presumably, overall transgression was occurring during deposition of this part of the Missourian Series, with deposition of the Cottage Grove representing a brief regressive period characterized by an increase in the sedimentation rate.

On a regional correlation section (Figs. 9 and 10) the Cottage Grove interval in the South Gage field (well No. 5, section A-A') shows thickening of the overall section due to sandstone accumulation and thinning of the interval directly above the Cottage Grove. Similar features are shown by well No. 3, north of South Gage field. Elsewhere along the section, sandstone is absent, with the exception of well No. 9, which contains a calcareous sandstone in the Cottage Grove interval. Section B-B', located more than 20 miles east of the South Gage field (Fig. 11), is characterized by sparsity of sandstone, with well developed sandstone occurring only in the northern part of the section. In this northern area, 25 feet of carbonate section, probably representing a southern extension of the carbonate province to the north, underlies the Cottage Grove. Local sandstone units to the south are highly calcareous and may be considered as limestones. East of section B-B', the Cottage Grove Sandstone becomes more continuous and sheetlike (Rascoe, 1962).

Local correlation sections prepared perpendicular to depositional strike indicate that sandstone development is restricted to the South

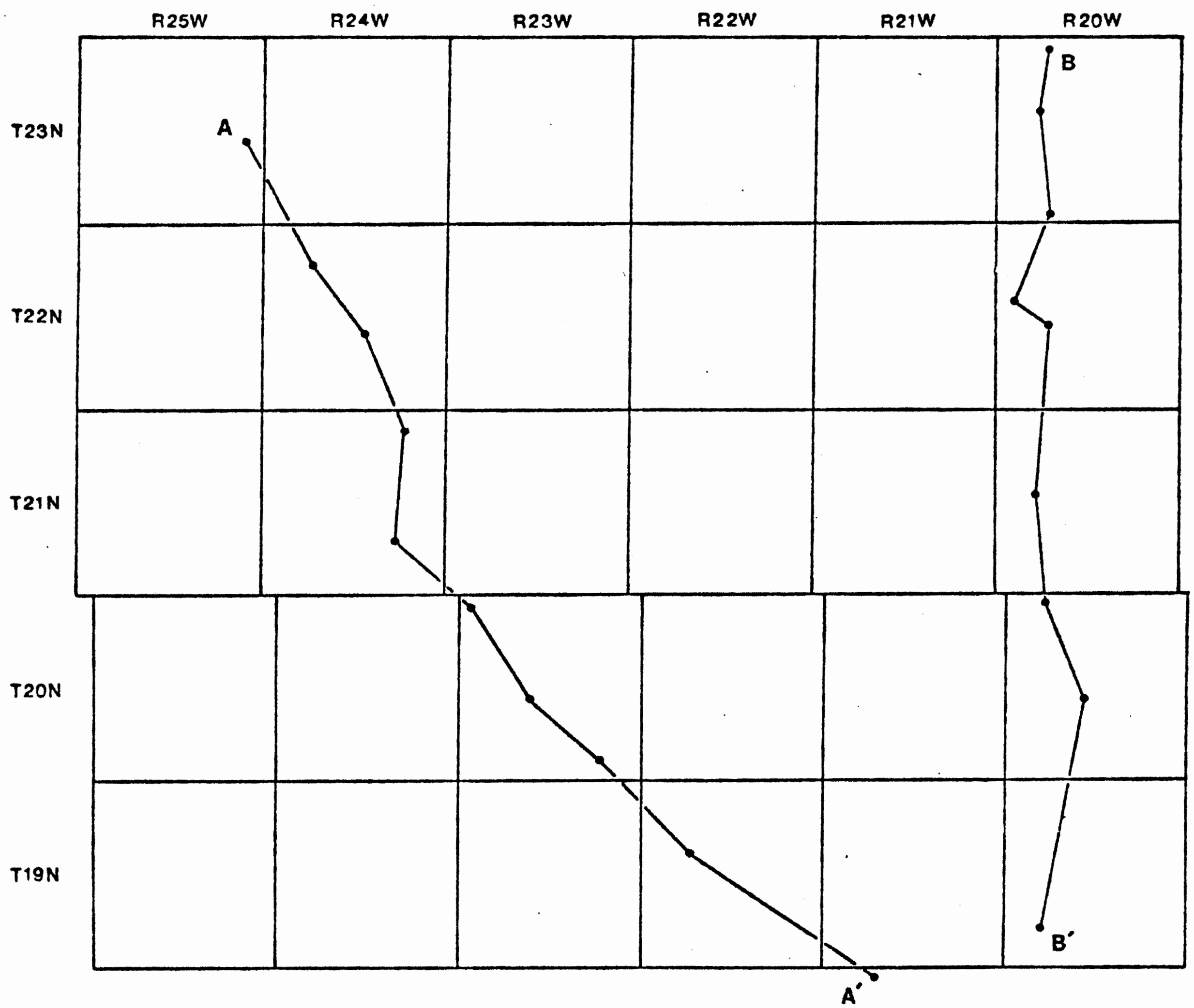


Fig. 9.-Index map for regional correlation sections shown in Figures 10 and 11.

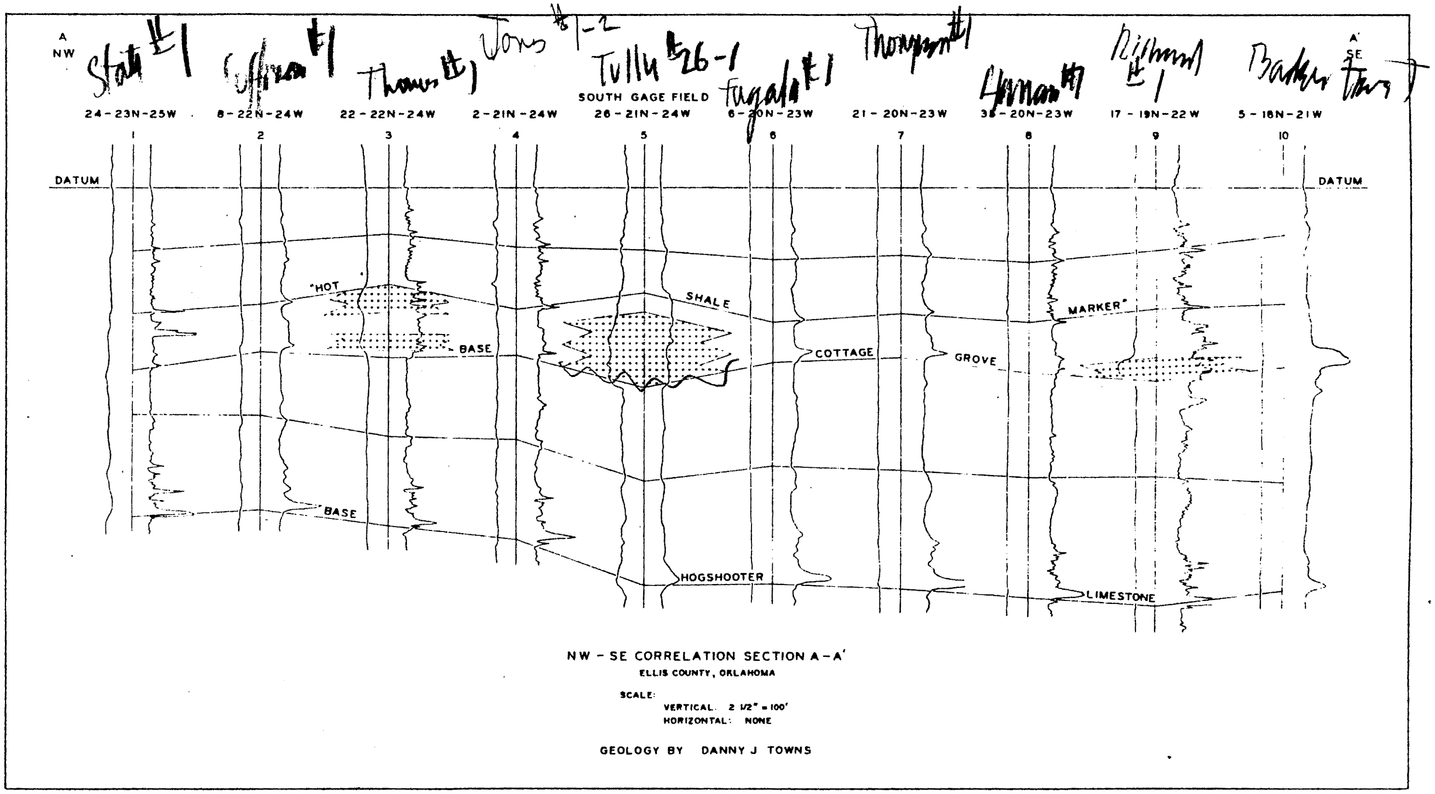


Fig. 10.-Regional correlation section of the Gage area. Line of section A-A' shown in Figure 9.

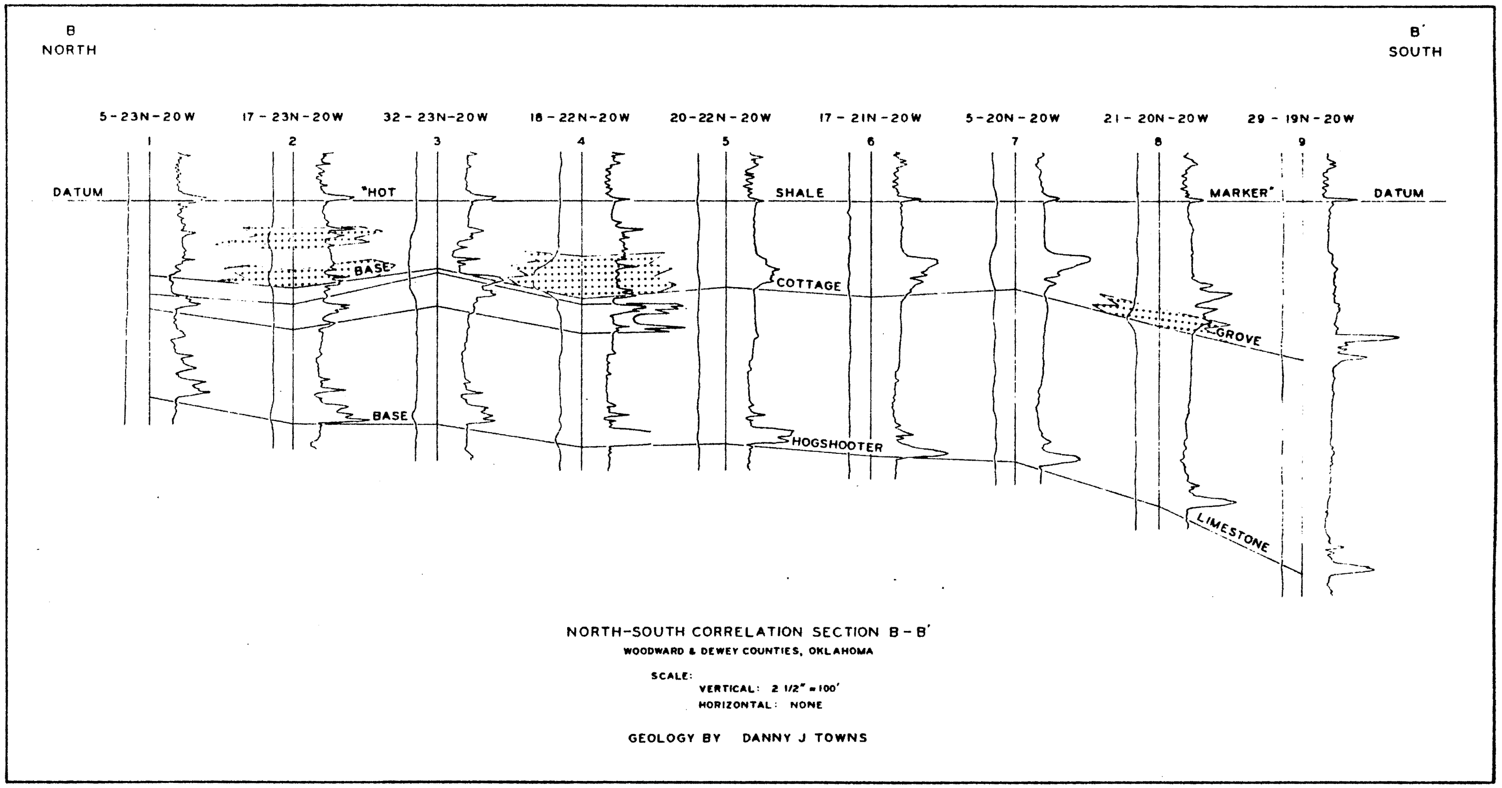


Fig. 11.-Regional correlation section east of the Gage area.
Line of section B-B' shown in Figure 9.

Gage field, where sandstone thicknesses commonly exceed 80 feet (Figs. 12-14). Markers directly below the Cottage Grove interval are separated by a fairly constant increment of strata. Variation in thickness from well to well is slight. Although minor scouring may have caused this variation in thickness, major channeling was not an important mechanism involved in the deposition of any unit directly overlying this increment of strata below the Cottage Grove.

Strata between two gamma ray markers above the Cottage Grove interval show modest but distinctive thinning directly over the field, where sandstone is thickest. Presumably, deposition of mud in topographically low areas compensated for the relief of the adjacent and subjacent sand body.

The Cottage Grove interval between these pairs of markers shows variability in thickness which corresponds to changes in sandstone. Interval thicknesses are generally less than 50 feet outside the field but more than 100 feet where sandstone development is greatest. Because of the persistence of the "Hot Shale" directly overlying the Cottage Grove, the differences in interval thickness probably reflect differences in mud deposition after sand deposition and subsequent differential compaction.

Parallel to local depositional strike, the Cottage Grove shows fairly uniform development and thickness (Fig. 15). The coarsest grained and best sorted sandstone occurs in the lower part of the interval, whereas the upper part is characterized by a gradual decrease in grain size, with silty, calcareous shale at or near the top. In the extreme eastern part of the field, this sequence is altered by the occurrence of a thin upper sandstone which resembles the coarser

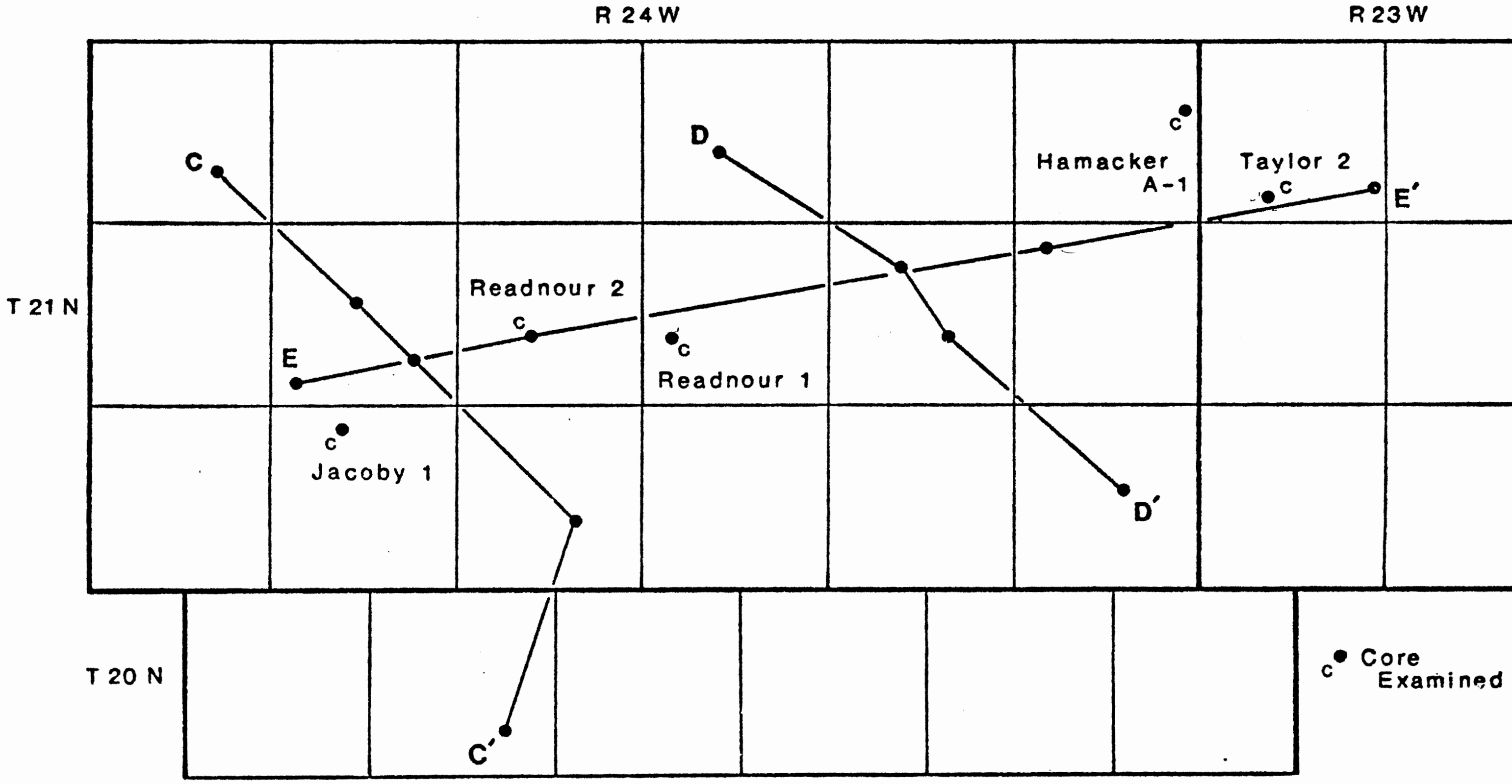


Fig. 12.-Index map of South Gage field correlation sections.

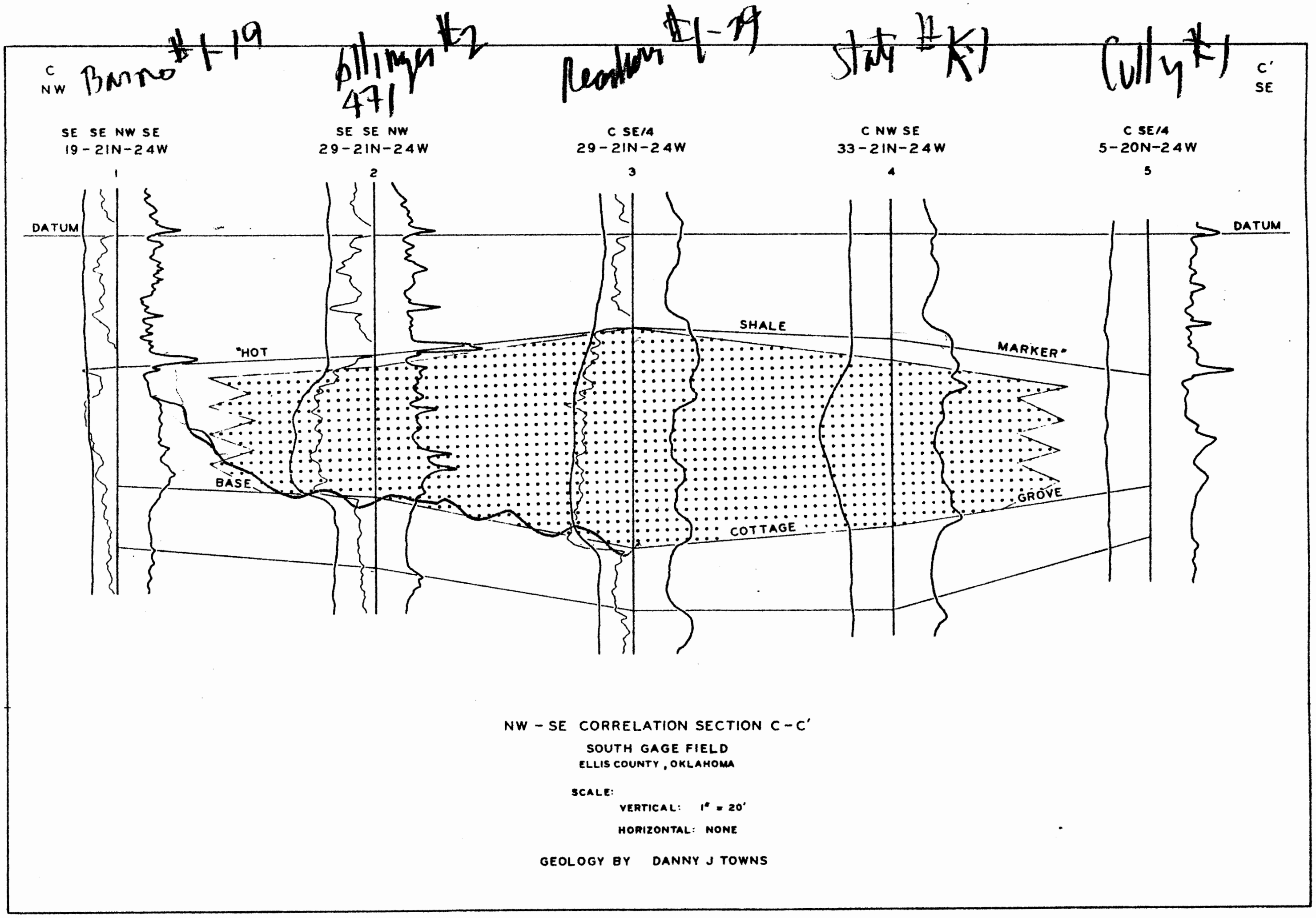


Fig. 13.-Local correlation section in dip direction in the western part of South Gage field. Line of section C-C' shown in Figure 12.

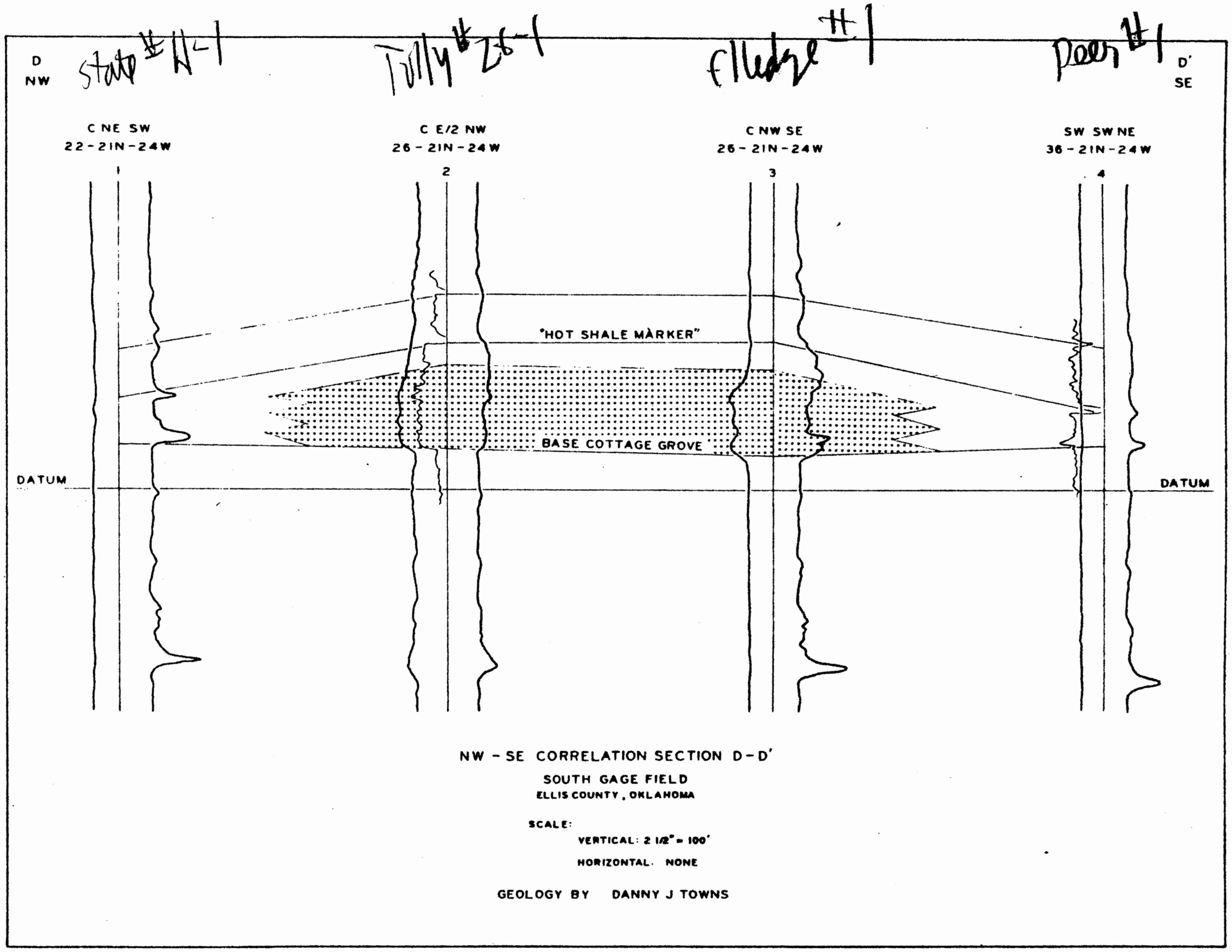


Fig. 14.-Local correlation section in dip direction in the eastern part of South Gage field. Line of section D-D' shown in Figure 12.

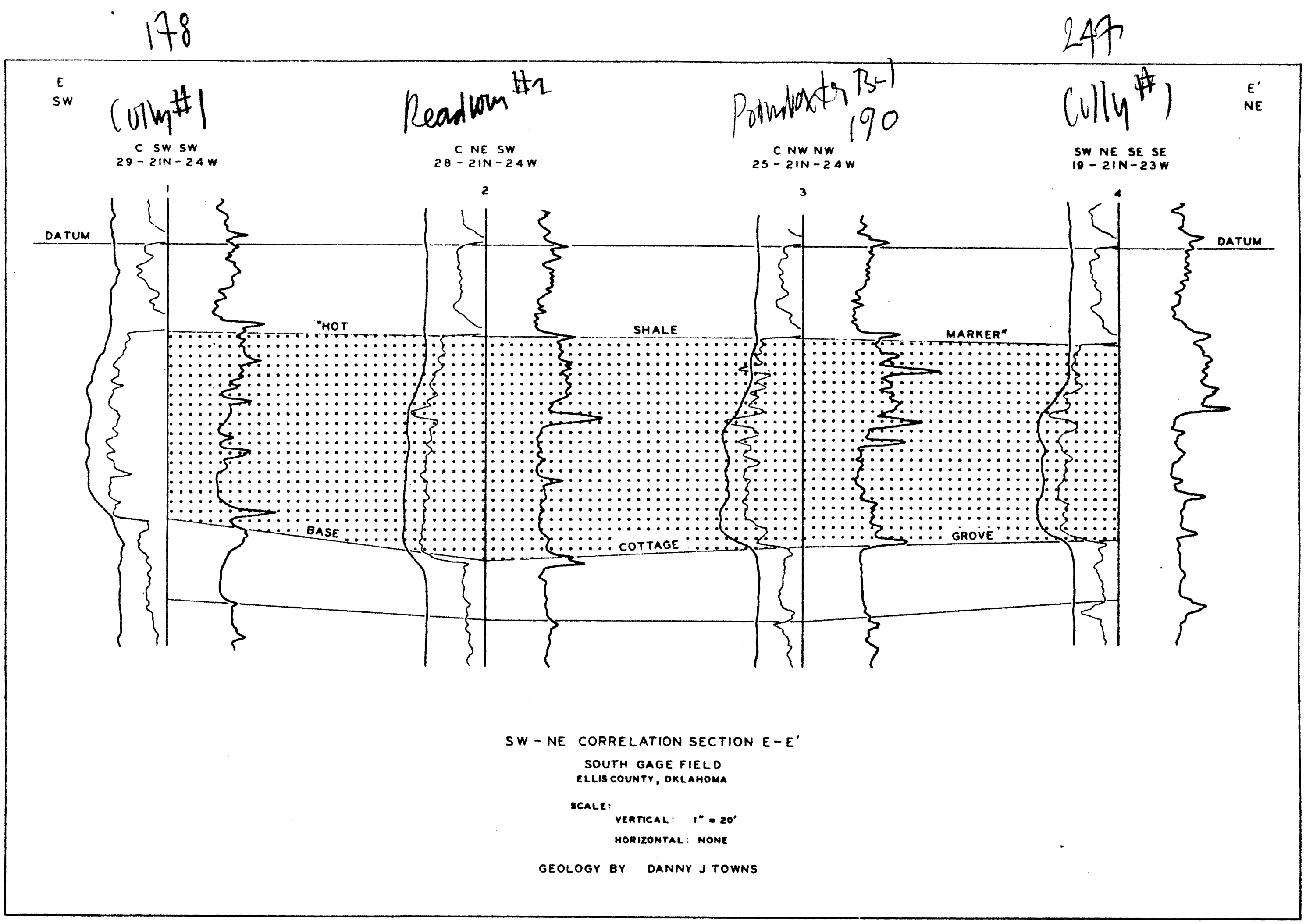


Fig. 15.-Local correlation parallel to strike direction in South Gage field. Line of section E-E' shown in Figure 12.

grained sandstone typically occurring near the base of the Cottage Grove Sandstone.

The areal variations in interval and gross sandstone thicknesses are portrayed by isopach maps (Figs. 16 and 17). Interval thickness, which varies from less than 50 feet outside the field to more than 110 feet in the west-southwest part of the field, is quite similar in trend to sandstone thickness, which ranges from zero to approximately 100 feet. However, thickness of gross sandstone does not necessarily correspond to thickness of net porous sandstone.

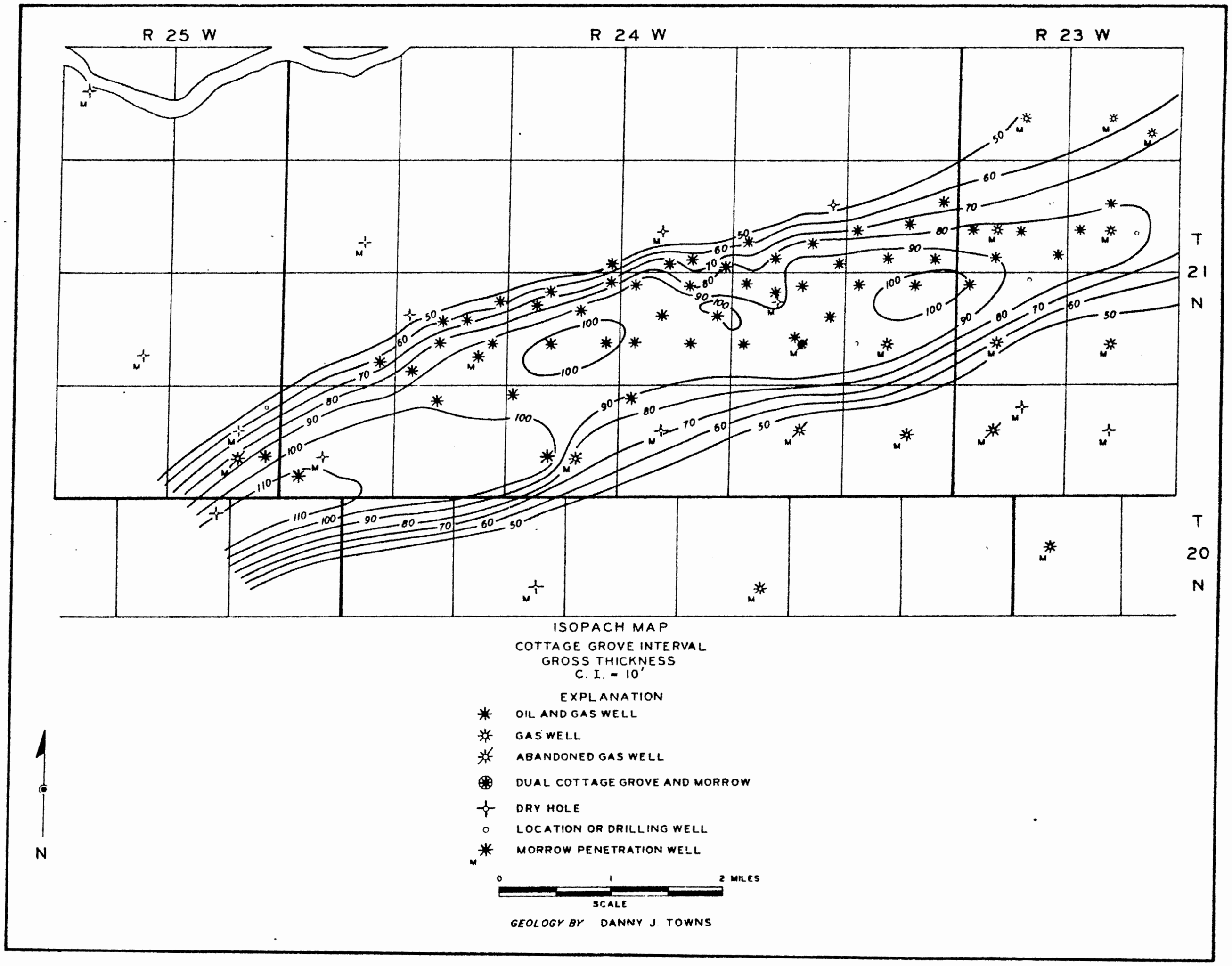


Fig. 16.-Isopach map of Cottage Grove interval, showing an increase in thickness corresponding to South Gage field.

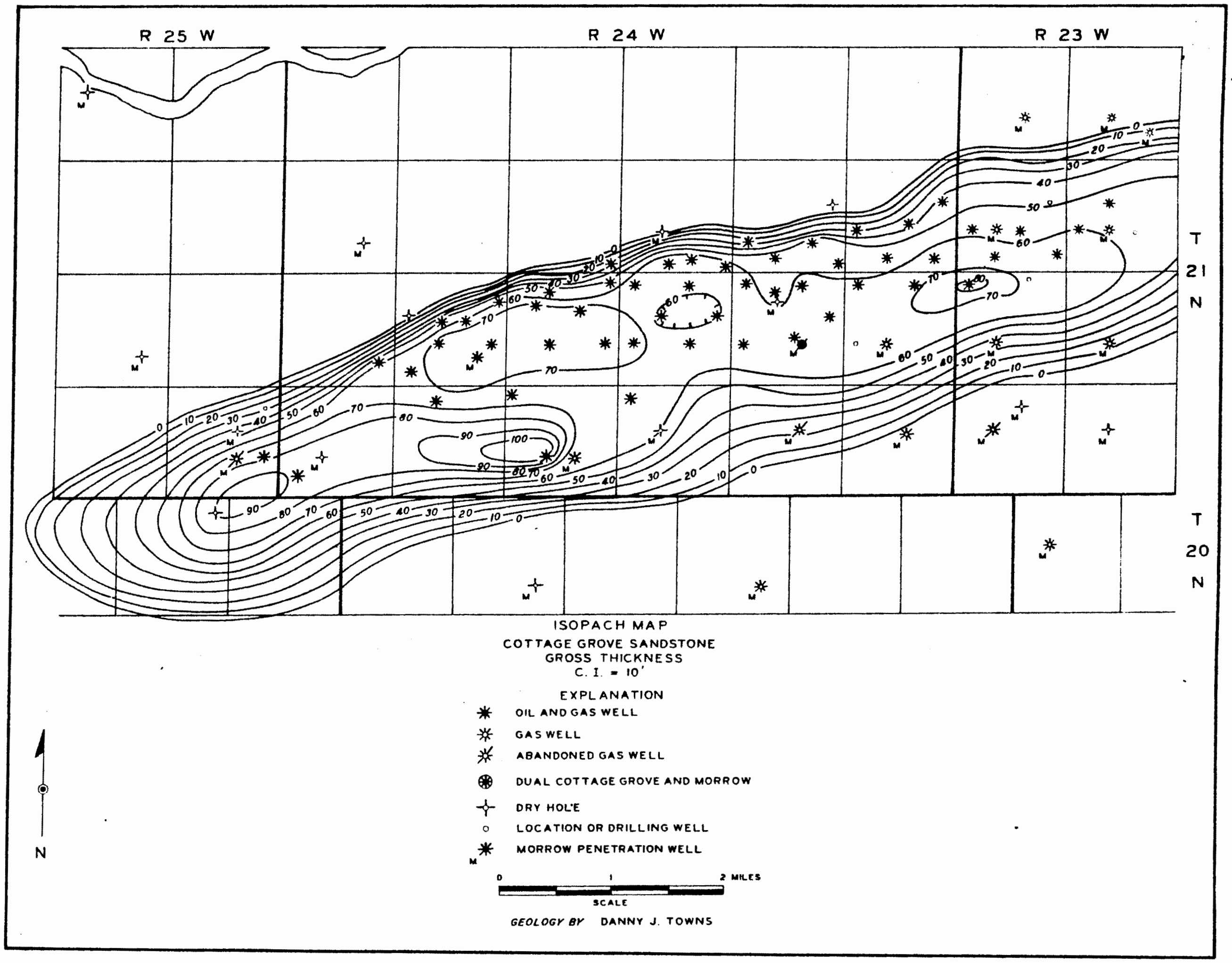


Fig. 17.-Isopach map of gross sandstone, showing area distribution, thickness, and trend of Cottage Grove Sandstone.

CHAPTER VI

GEOMETRY OF COTTAGE GROVE SANDSTONE

Length and Width

Although the Cottage Grove interval is present throughout the regional area, the development of sandstone at South Gage field is confined to an elongated band extending east-northeast-west-southwest. Although the eastern termination of this sandstone body is not defined within the study area, its western edge is located in the extreme southwest, in Section 3, T20N, R25W (Fig. 17). A minimum length for the sandstone body, therefore, exceeds 11 miles. Maximum width in the area does not exceed 2½ miles; the ratio of minimum length to maximum width is approximately 4.5:1.

Thickness

Thickness of gross sandstone varies from zero outside the field to a maximum of slightly over 100 feet in Section 33, T21N, R24W (Fig. 17). Sandstone accumulation is greatest in the west-southwest part of the body and along the long axis of development. Due to the grain size (very fine sand and silt), interstitial clay, and interlaminated shale within the Cottage Grove, it is not practical to map net sandstone. The sandstone body, which is without significant shale breaks, is thought to represent a fairly continuous depositional event rather than a series of different events. Ratio of width to maximum thickness is 100:1.

Boundaries

Local correlation sections (Figs. 12-15) indicate that the Cottage Grove Sandstone represents a buildup of sandstone and/or siltstone. If it is assumed that the uppermost marker was horizontal at the time of deposition and that differential compaction has not significantly altered shale thicknesses, the body was convex upward when it developed. The convexity of the upper surface is better portrayed with the same set of assumptions related to the underlying Hogshooter Limestone. The base of the sandstone exhibits a rather sharp contact with underlying marine shale, whereas the upper boundary is fairly gradational with overlying silty calcareous shale, although log character, especially that of the gamma-ray log, suggests a rather sharp contrast. Based on changes in sandstone thickness the lateral contacts are sharp. The change is more marked along the north-northwest edge of the body than on the south-southeast.

CHAPTER VII

INTERNAL FEATURES

Sedimentary Structures

Detailed analyses of four cores and data from two other cores indicate that three major zones of sedimentary structures occur in vertical sequence where the Cottage Grove Sandstone is well developed in the South Gage field. These include a lower zone of small-scale cross-stratification (cross-lamination), an intensely burrowed zone, and an upper zone of interstratified siltstone and shale. In addition to small-scale cross-stratification, burrows, and interstratification, other sedimentary structures in the cores include flowage features, massive bedding, and medium-scale crossbedding (Figs. 18-21).

Small-Scale Cross-Stratification

All cores of the Cottage Grove contain small-scale cross-stratification. Although most pronounced in the lower part of the sandstone, where it is the dominant sedimentary structure, it occurs throughout the sequence (Fig. 22). Types of ripple bedding in the lower zone include climbing-ripple lamination, complex ripple bedding, and ripple bedding with shale flasers. Festoon cross-lamination and herringbone cross-lamination are also present in this zone, in which very fine-grained sandstone and coarse siltstone with clay laminae are

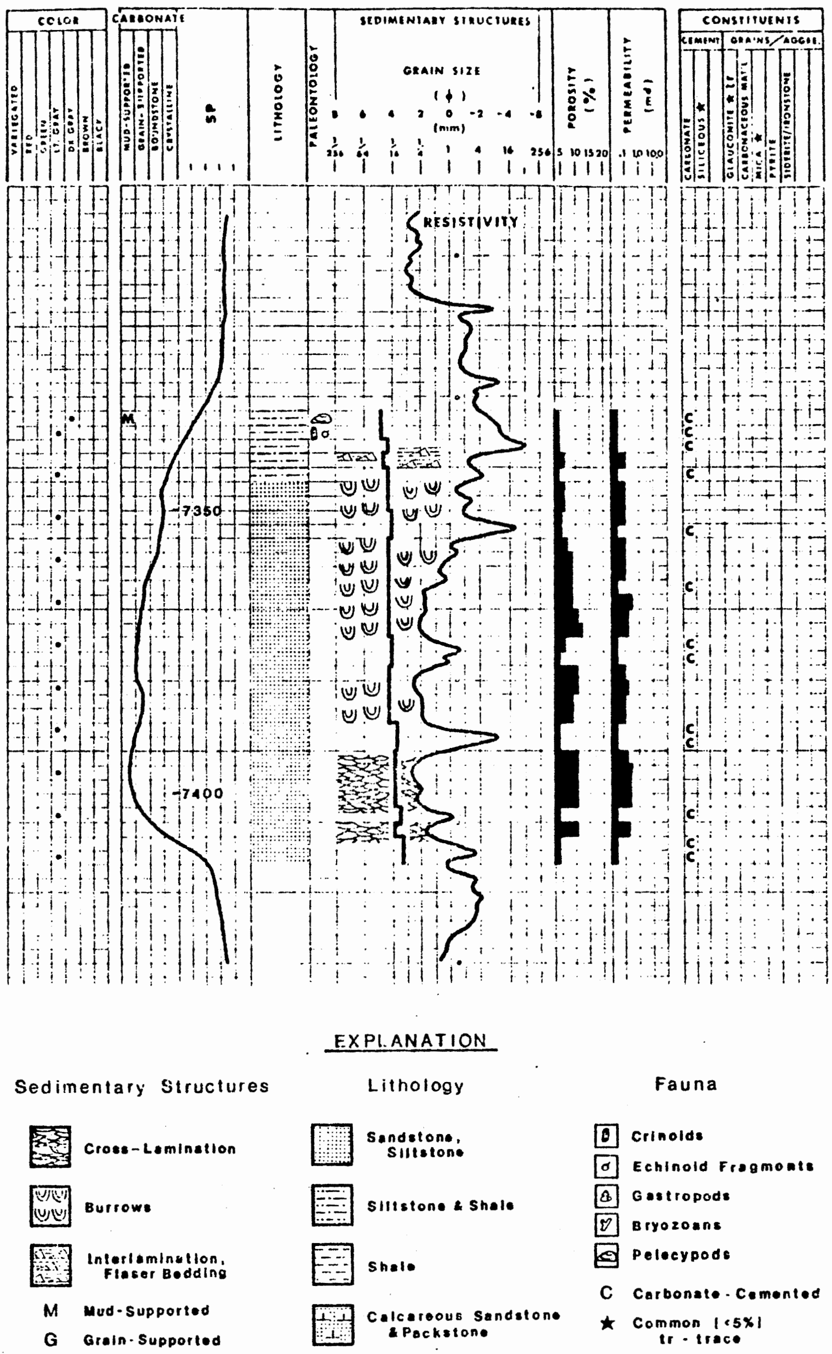


Fig. 18.-Core description of May Jacoby No. 1.

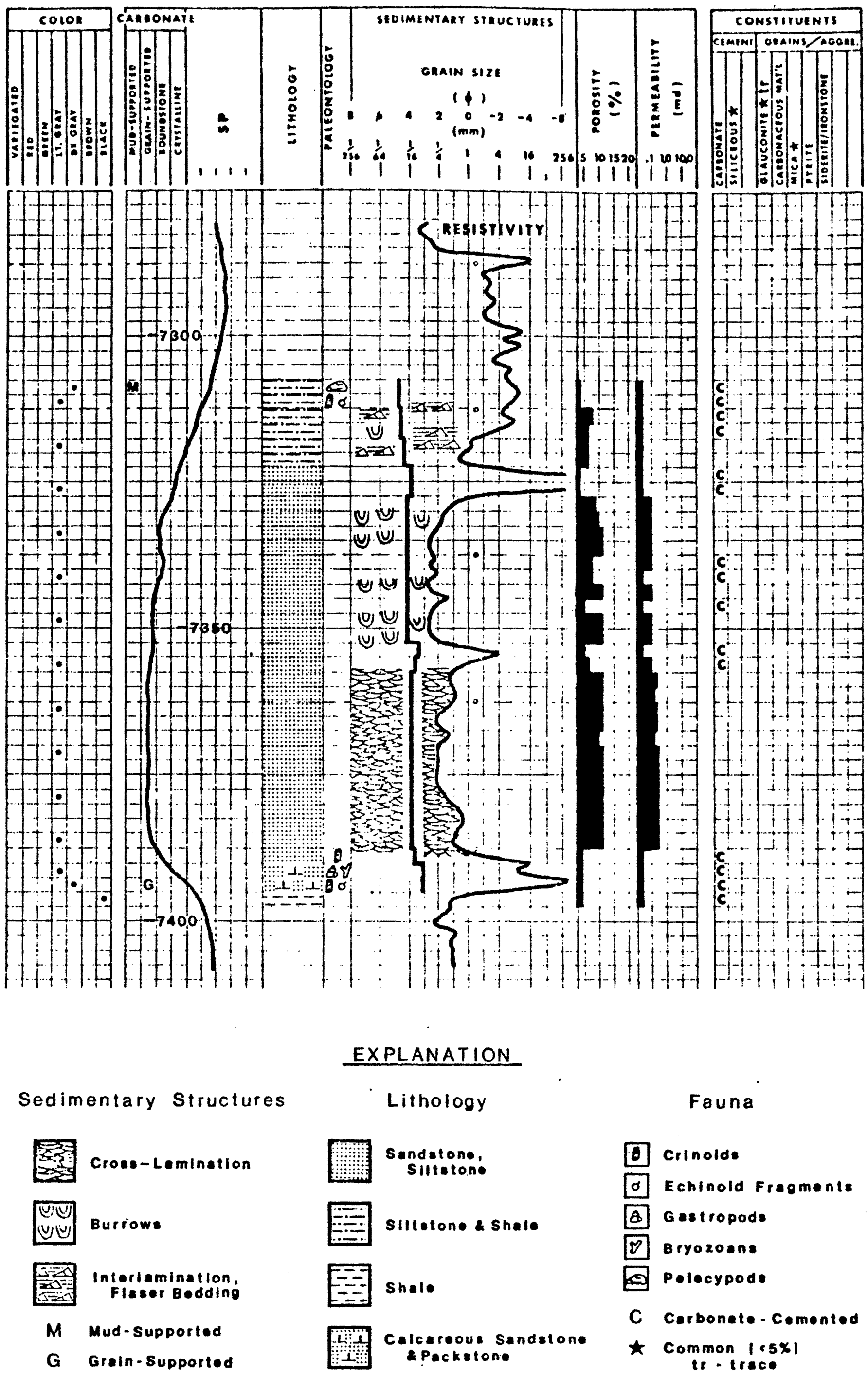


Fig. 19.-Core description of May Readnour No. 2.

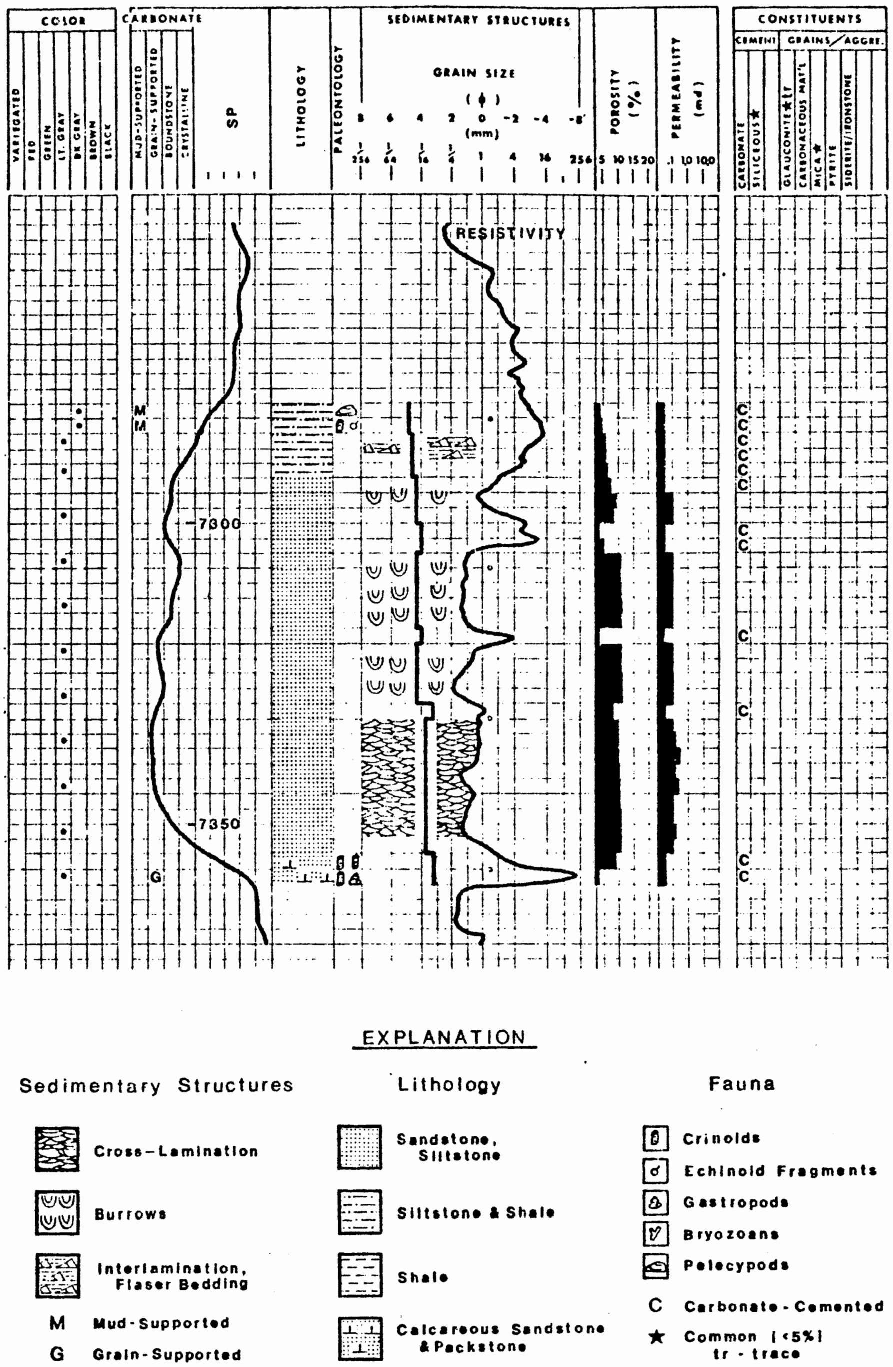


Fig. 20.-Core description of Shenandoah Readnour No. 1.

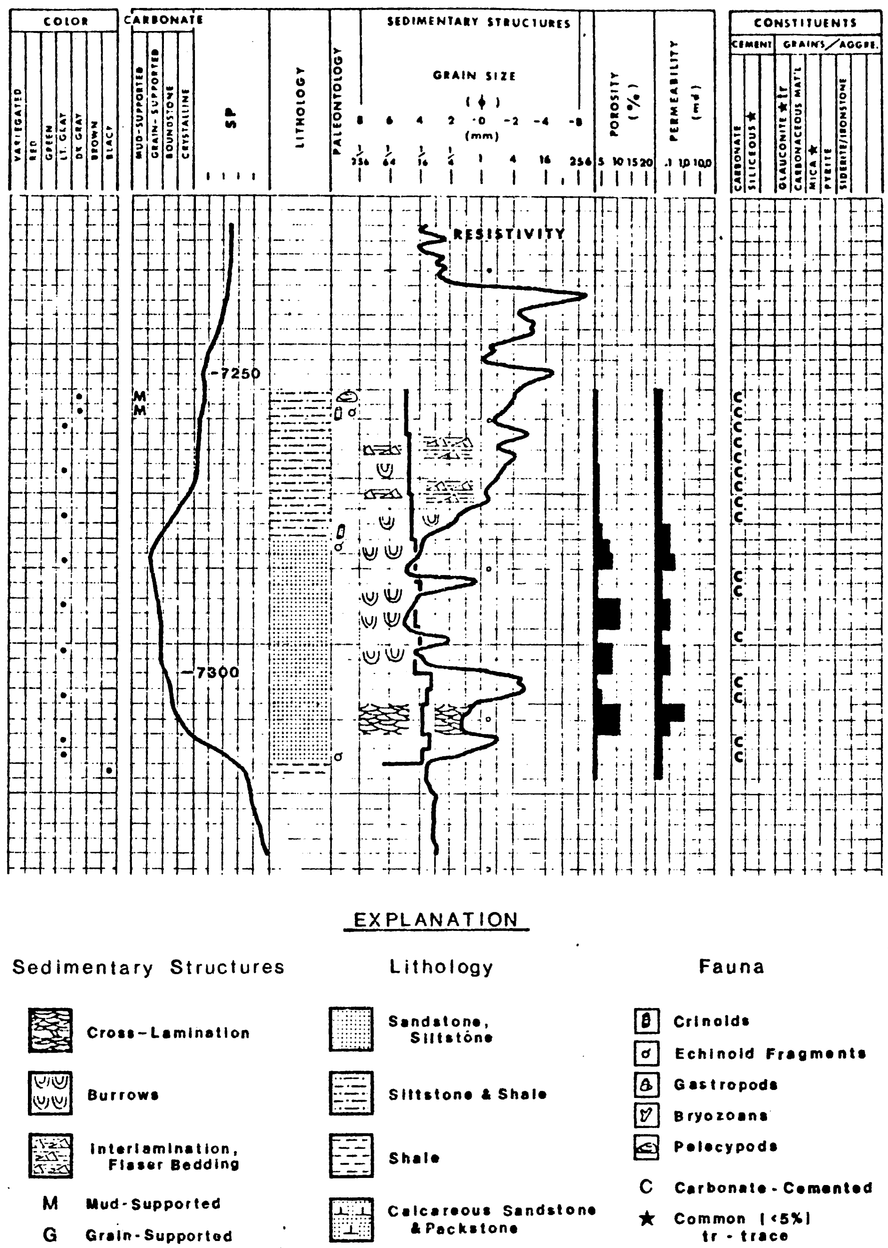


Fig. 21.-Core description of Shenandoah Hamacker No. A-1.

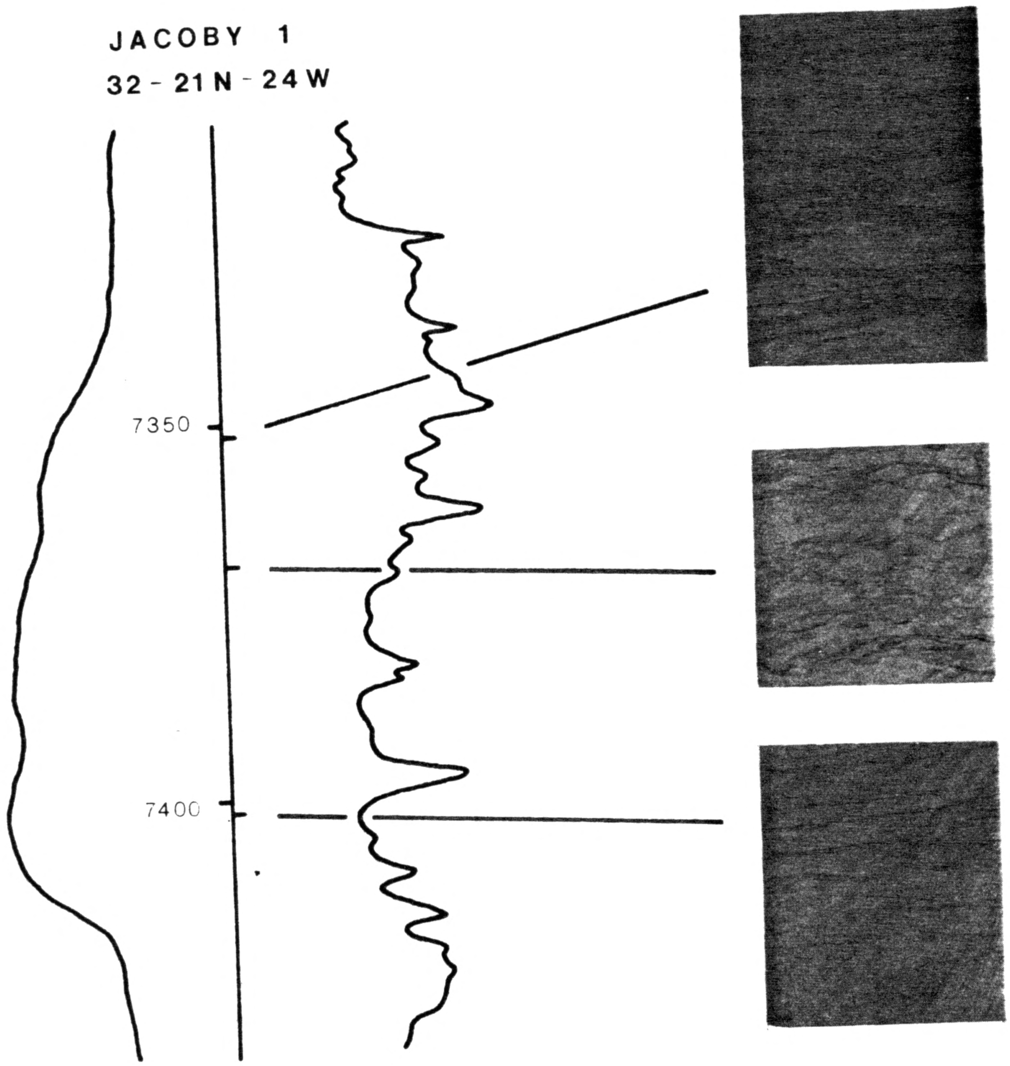


Fig. 22.-Major sedimentary structure zones in the Cottage Grove Sandstone.

very common. The lower small-scale cross-stratified zone is thickest in the central part of the field. For example, in May Readnour No. 2 near the center of the field it is 32 feet thick, whereas it is only 5 feet thick in Shenandoah Hamacker No. A-1 along the northern edge. Amoco Taylor No. 2 in the eastern part of the field has a lower zone of 14 feet and a similar upper zone of 12 feet; the latter is not present in cores to the west. Small-scale cross-stratified zones are generally oil productive in the South Gage field.

Bioturbation and Burrows

The zone characterized by dominantly horizontal burrows (Fig. 22) is somewhat thicker than the underlying zone of small-scale cross-stratification. Although high levels of bioturbation are present in thin intervals within this zone, traces of previously developed small-scale cross-stratification are evident. Coarse siltstone with micaceous bio-emplaced claystone is the dominant lithology in this zone. Thicknesses of this zone vary from approximately 40 feet in the May Jacoby No. 1 in the center part of the field to 25 feet in the Hamacker No. A-1.

Burrows are also present to a lesser extent in both the upper interbedded zone and the lower cross-stratified zone in association with clay-rich beds or laminae. Burrows are absent or very rare where sandstone units are well developed and lack significant detrital clay.

Interstratification

An upper zone of siltstone and shale interstratification is present in all of the cores as a transitional interval to the overlying silty shale (Fig. 22). Parallel interstratification, flaser bedding, and minor lenticular bedding are present in this zone, in which small-scale cross-stratification and burrowing also occur. Maximum grain size is coarse silt. Thickness of the upper interstratified zone is typically less than 15 feet.

Interstratification is also present at the base of the Cottage Grove Sandstone where thin beds of shale, sandstone, and conglomeratic skeletal packstone (fossiliferous calcarenacous sandstone and arenaceous limestone) are interbedded in an interval which is 1.5 feet to 2.5 feet thick (Fig. 23). Load structures occur in a 1.5 foot zone of interstratified sandstone and shale at the base of the unit in the Hamacker No. A-1. Because the interstratified interval is very thin, the base of the sandstone forms a rather sharp contact with the underlying marine shale.

Flowage Features

Flowage-type bedding is a common feature within the upper zone of interstratification. Micro-faulting, although uncommon, is the other type of deformed bedding. Flowage features are best illustrated from the upper zone of the Jacoby No. 1 (Fig. 24).

Massive Bedding

As many as 6 thin layers of highly carbonate-cemented sandstone are present, and they normally have the appearance of massive bedding. However, medium-scale crossbedding and small-scale cross-stratification characterize two samples (Fig. 25). It is thought that these structures were typical of these coarser grained, better sorted layers at

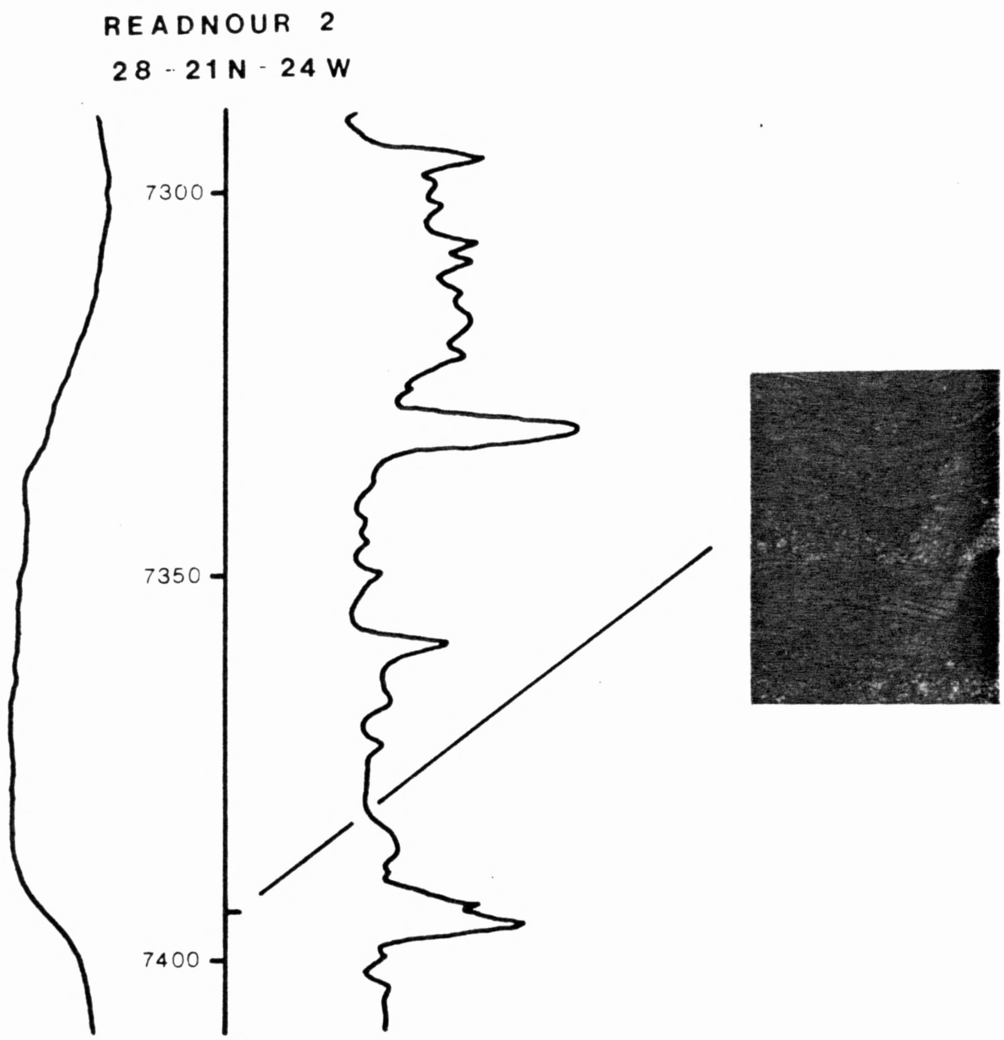


Fig. 23.-Interstratification in the basal part of the Cottage Grove Sandstone.

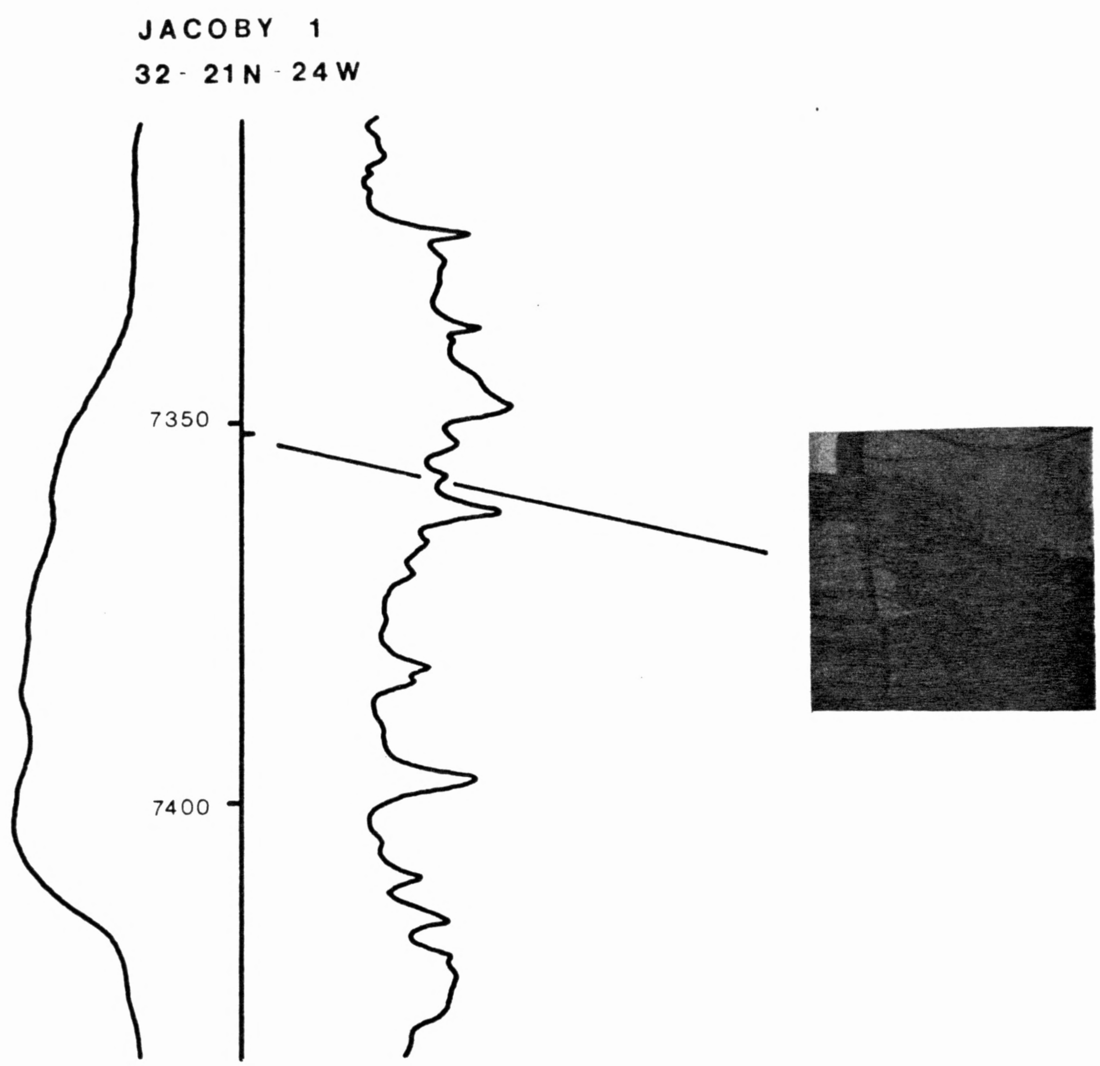


Fig. 24.-Flowage features in the upper interlaminated zone.

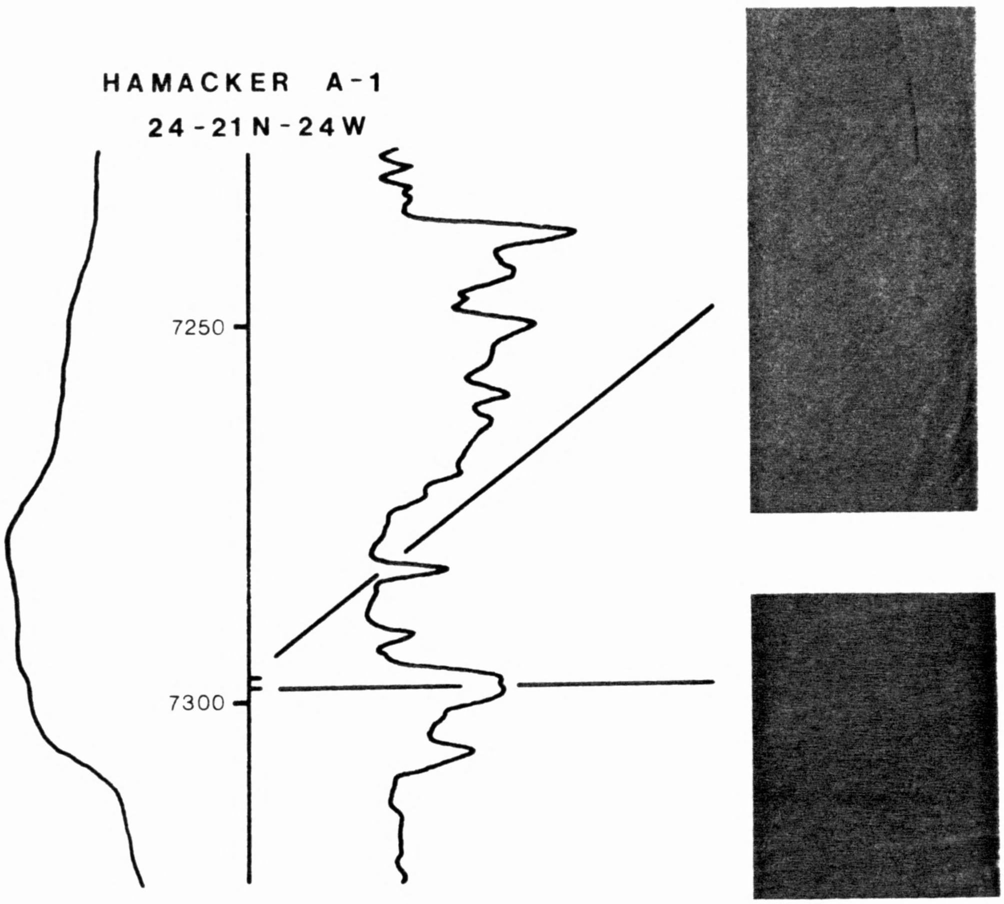


Fig. 25.-Massive bedding (a) and medium-scale crossbedding (b) in a carbonate cemented layer.

the time of deposition and that these bedding types are obscured by introduction of carbonate cement, recrystallization of carbonate grains which were abundant constituents, and partial replacement of quartz by carbonate.

Medium-Scale Crossbedding

Medium-scale crossbedding is a very uncommon structure which occurs only in a highly carbonate cemented zone separating the thick burrowed zone from the lower zone of small-scale cross-stratification. It is present in the Hamacker No. A-1 (Fig. 25).

Fossils

Abundant fragments of marine fossils are present at or near the base and top of the Cottage Grove Sandstone. Fragments are also scattered through the sandstone unit. Crinoid stems and echinoderm debris are the dominant body-fossil constituents, although pelecypods, bryozoans, brachiopods, and gastropods are present.

Trace fossils are abundant throughout the Cottage Grove Sandstone. Because these features, commonly considered as primary sedimentary structures, indicate behavioral activity of organisms in response to surrounding environments, they can be very useful as an additional tool in defining depositional environment. Trace fossils occurring in cores of the Cottage Grove Sandstone appear to be limited to the genus Planolites, small, dominantly horizontal burrows resulting from the activities of worms (P. B. Basan, 1977). The worms apparently survived only in areas where the sedimentation rate of coarse clastics was fairly slow. Locally and periodically sand deposition ceased, and organic-rich muds were deposited on the sandy sea floor. These muds represented a food source for the worms which immediately began to establish themselves at the location and rework the mud (Fig. 26).

Planolites, which are quite common in the geologic column, do not represent a specific environment. They have been reported in strata apparently deposited in lagoons, shoreface to nearshore shallow marine areas, and abyssal basins (Chamberlain, 1978). Burrow abundance and high state of preservation indicate that low-energy conditions were generally present during their formation.

Texture

The Cottage Grove Sandstone is composed of sandstone, siltstone, thin interbeds of shale, and thin grain-supported carbonate units. Average grain size of the sandstone, excluding clays and fossil fragments, varies from 0.10 mm (very fine sand) near the base of the unit, to 0.032 mm (medium to coarse silt) near the top. Although variations exist between successive beds, grain size is relatively uniform within each sedimentary structural zone. An overall fining-upward sequence reflects characteristic grain sizes of the different zones (Fig. 27). Thin carbonate-cemented layers are typically composed of very fine-grained sand which is coarser than units both above and below it. Maximum size of fossil fragments in grain-supported carbonates is 4-5 mm; coarsest size of terrigenous sand grains is 0.5 mm (medium sand). Overall, the Cottage Grove Sandstone is moderately sorted, although well developed sandstone units may be well sorted where only minor amounts of interstital clay are present. The basal fossiliferous unit is very poorly sorted. Sand grain shape is dominantly subangular;

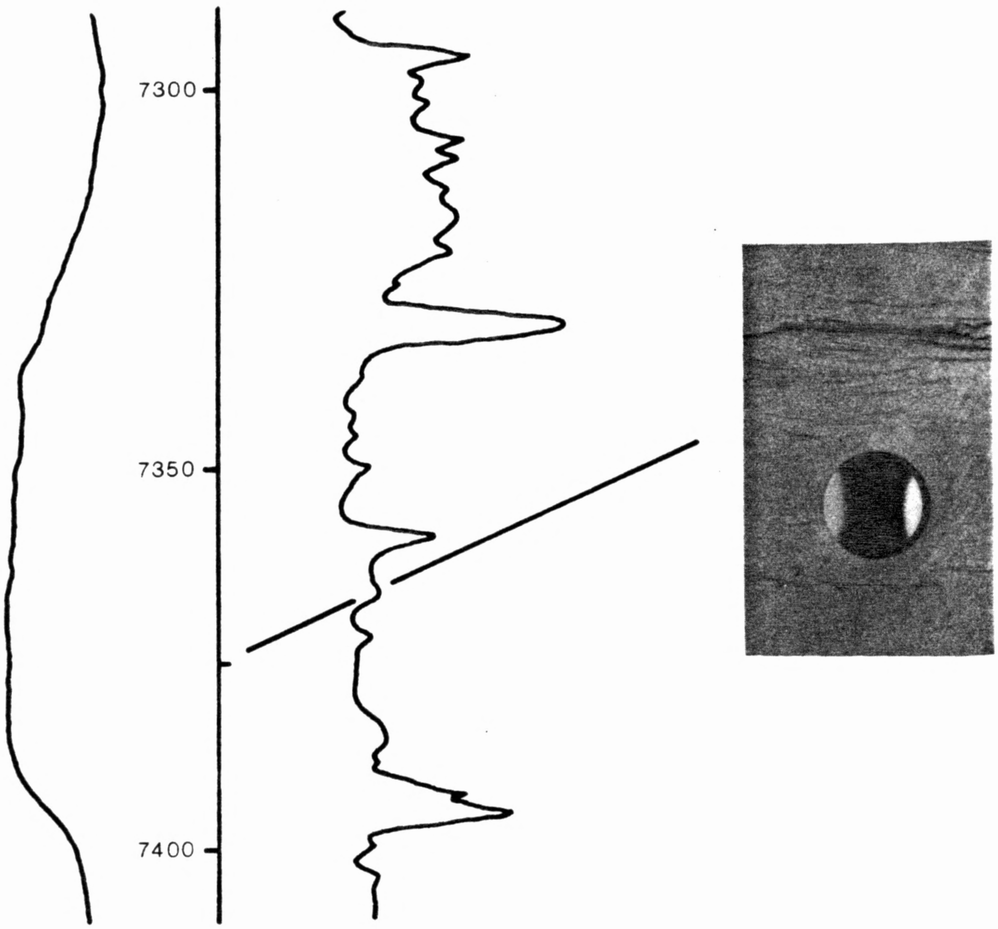
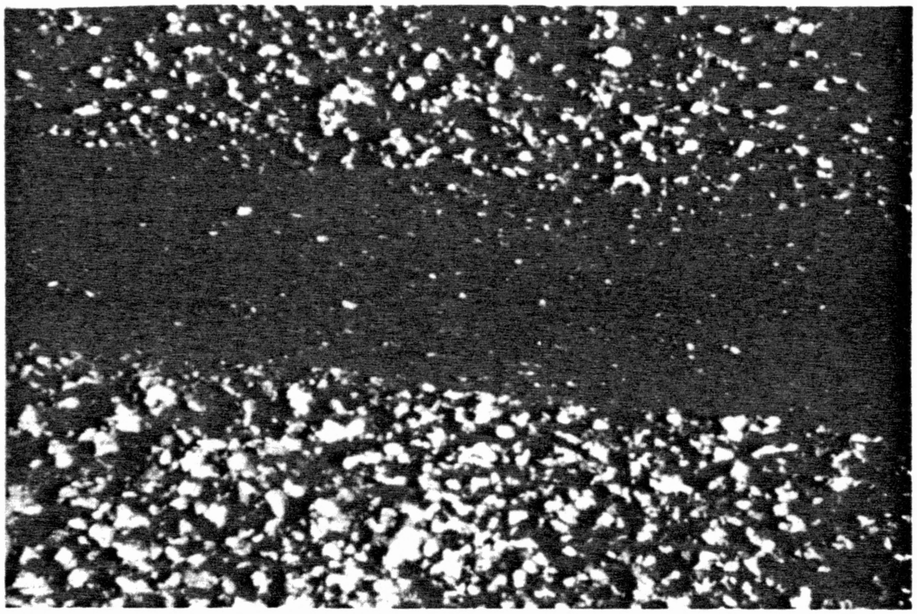
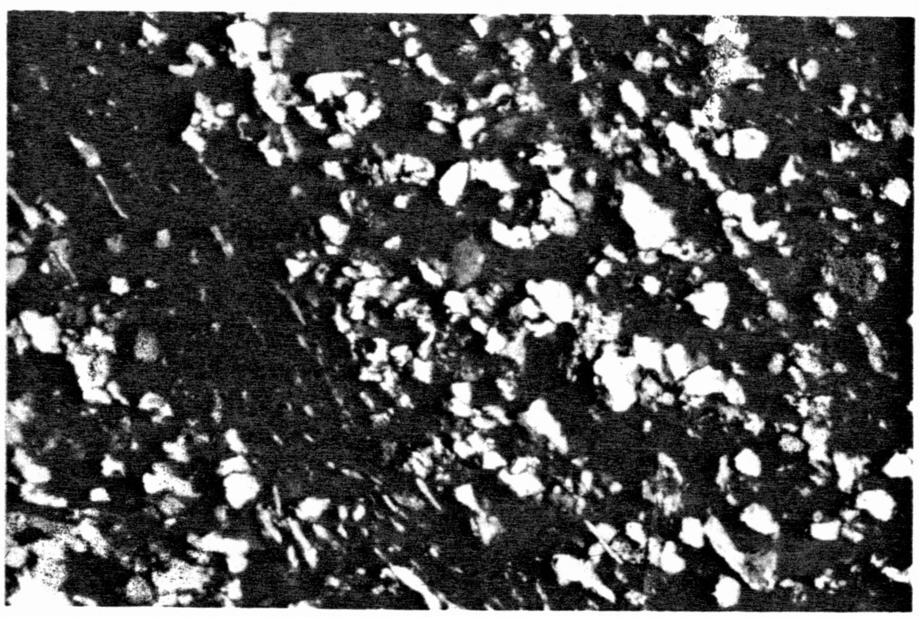


Fig. 26.-Burrows located along clay lamina in lower cross-laminated zone.



(a)



(b)

Fig. 27.-Typical grain sizes of interlaminated zone (a) and cross-laminated zone (b). Crossed nicols, X40.

texturally the sediments are submature to immature.

Constituents

Based on analyses of 10 thin sections of the Cottage Grove Sandstone, quartz, feldspar, muscovite, and carbonate are the major framework constituents (Table I; Figs. 28-30). Including silica overgrowths, quartz composes an average 50 percent of the total rock. Potassium feldspar averages 4 percent, and muscovite averages 3 percent. Considering only framework constituents, quartz composes an average 81 percent of the sandstone, feldspar composes 6 percent, and muscovite 5 percent. Although calcite grains occur as framework constituents, they are included as carbonate cement because of problems in distinguishing grain boundaries due to recrystallization. Fossil fragments normally are absent, but they compose 71 percent of a packstone at the base of the Cottage Grove Sandstone. Accessory minerals include biotite, plagioclase, and ilmenite, in quantities less than 1 percent, and zircon, pyrite, tourmalline, apatite, and sphene in trace amounts. Siderite nodules are uncommonly present near the base of the sandstone in some sections.

Various clays, which compose an average of 18 percent of the rock, are important matrix constituents of the Cottage Grove Sandstone. Carbonate, which occurs as both micrite and spar, acts as a cementing agent; it averages 17 percent. Silica in the form of quarts overgrowths is generally an important cementing agent in well-sorted, quartz-rich units. Glauconite and iron oxides occur as trace components of the matrix in all samples. Clays, carbonate, and silica overgrowths show significant variability in relative abundance (Table I).

TABLE I

CONSTITUENTS IN COTTAGE GROVE SANDSTONE

Sample	Framework Constituents					Matrix and Cement		
	Quartz	Feldspar	Calcite**	Muscovite	Others	Clays	Carbonate	Silica
MJ 37b	56(81)	6 (9)	2 (3)	3 (4)	2 (3)	31	sli	X
MJ 58r	56 (79)	7 (10)	4 (6)	3 (4)	1 (1)	29	sli	X
MR 3i	24 (69)	1 (3)	4 (11)	4 (11)	2 (6)	65	sli	sli
MR 31b	71 (85)	3 (4)	3 (4)	3 (4)	3 (4)	17	sli	X
MR 79r	47 (85)	6 (11)	cem	1 (2)	1 (2)	6	39	X
SR 64r	62 (79)	5 (6)	6 (8)	3 (4)	2 (3)	22	sli	X
SR 70p	7 (8)	4 (5)	cem	1 (1)	71-ff (86)	1	16	sli
SH 5i	42 (84)	2 (4)	cem	3 (6)	3 (6)	31	19	X
SH 38b	72 (78)	4 (4)	5 (5)	7 (8)	3 (4)	9	sli	X
SH 51m	24 (86)	2 (7)	cem	1 (4)	1 (4)	-	72	sli
Average	50 (81)	4 (6)		3 (5)	3 (3)	21		

* - includes chert and cement in part
** - includes cement in part
b - burrowed zone
i - interlaminated zone

r - small-scale cross-stratified zone
p - packstone
m - carbonate-cemented layer
ff - fossil fragments

sli - 5% or less
X - important, included quartz
(70) - % of framework constituents

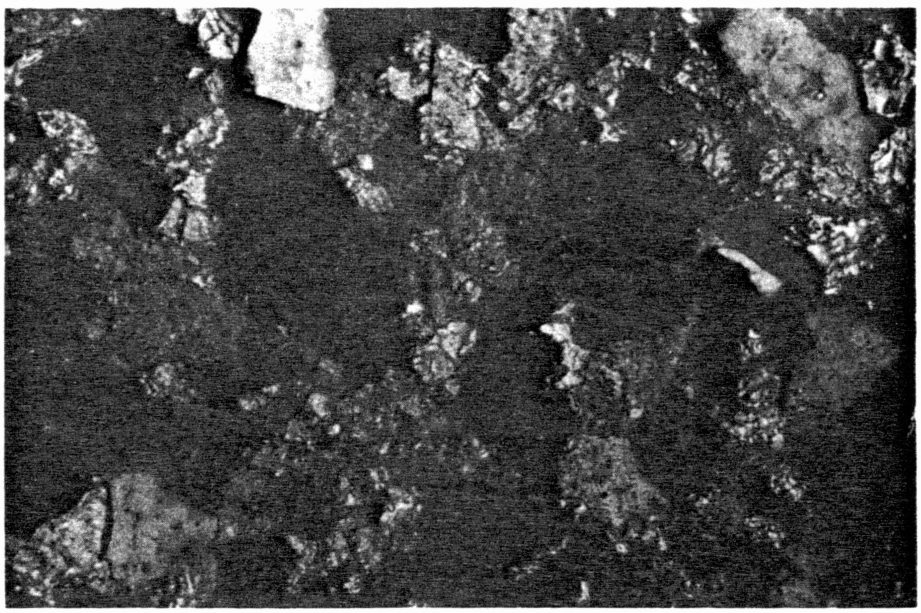


Fig. 28.-Carbonate, quartz, and plagioclase in massively bedded layer. Crossed nicols, X100.

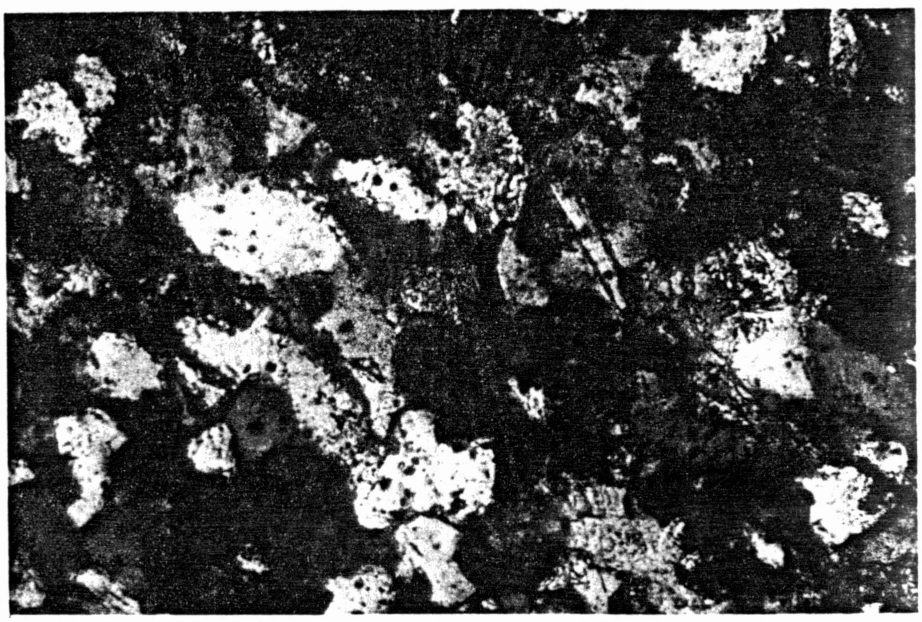


Fig. 29.-Quartz, clay, and muscovite in cross-laminated zone. Crossed nicols, X100.

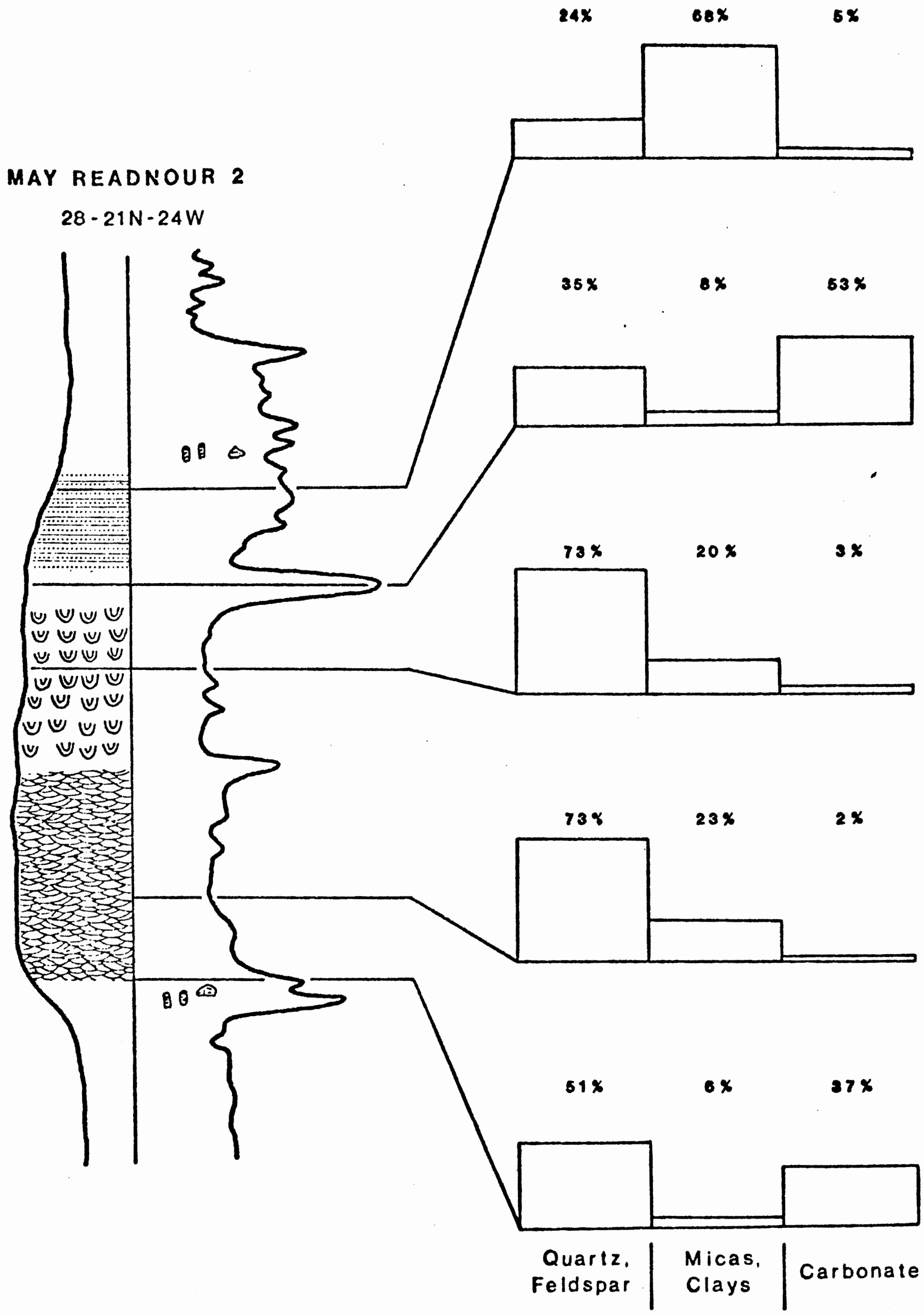


Fig. 30.-Electric log and major constituents, May Readnour No. 2.

Illite, kaolinite, and chlorite are the dominant clay minerals in the Cottage Grove Sandstone, based on X-ray diffraction analyses. Due to the common occurrence of detrital mica, complete removal of muscovite and sericite from the samples may not have been accomplished, and they possibly influence illite percentages. Illite dominates clay interbeds, whereas in well developed, well-sorted sandstones kaolinite is the dominant clay mineral. Chlorite composes approximately 5 percent of the clay fraction, except in Shenandoah Readnour No. 2, where it composes 9 to 13 percent of the total clay fraction. Illite ranges from 30 to 79 percent; kaolinite is also quite variable, ranging from 16 to 63 percent. Dark gray shale underlying the Cottage Grove contains approximately 84 percent illite and 16 percent kaolinite (Table II).

The Cottage Grove Sandstone can be classified as a subarkosic wacke to subarkosic arenite (Pettijohn, 1975), or as a quartz wacke (Krumbein and Sloss, 1963). Considering framework constituents alone, the sandstone is a subarkose (McBride, 1963).

TABLE II

CLAY MINERALS IN COTTAGE GROVE SANDSTONE

Sample	Zone	Illite*	Kaolinite	Chlorite
MJ 15	Interbedded	46	48	6
MR 7	Interbedded	57	39	3
MR 12	Interbedded	52	41	7
SR 14	Interbedded	54	37	9
SH 11	Interbedded	51	42	7
Average	Interbedded	52	41	6
MJ 37	Burrowed	44	51	5
MR 23	Burrowed	67	29	4
MR 40	Burrowed	39	56	5
SR 22	Burrowed	54	36	10
SR 29	Burrowed	50	40	10
SR 44	Burrowed	42	46	12
SH 33	Burrowed	79	16	5
SH 42	Burrowed	59	38	3
Average	Burrowed	54	39	7
MJ 58	Rippled	45	49	6
MJ 68	Rippled	37	57	6
MR 55	Rippled	30	63	7
MR 70	Rippled	47	48	5
SR 64	Rippled	34	53	13
Average	Rippled	39	54	7
Sandstone Average		49	44	7
Underlying Shale		84	16	-

* - includes illite and disordered illite

CHAPTER VIII

DEPOSITIONAL ENVIRONMENT

The Cottage Grove Sandstone in the South Gage field was deposited as a shallow marine offshore bar. Enclosure of the sandstone within marine shale, occurrence of marine fauna throughout the interval, presence of glauconite, and abundance of burrows and small-scale cross-stratification point to a marine environment, and an elongate to elliptical, convex-upward sand buildup is characteristic of bar geometry.

The Cottage Grove Sandstone east of South Gage field is a blanket sandstone extending beyond the Nemaha uplift to the east (Rascoe, 1962). In the study area the interval consists of a rather thin sheet of silty, calcareous shale with discontinuous patches of siltstone and/or sandstone. Distribution of the Cottage Grove, together with an increase in grain size of sandstone to the east, indicate that the Cottage Grove was derived from a source area in that direction, probably the Ouachita uplift to the southeast (Rascoe, 1978). The low feldspar content of the Cottage Grove Sandstone and the scarcity of coarse clastic material in the basin to the south apparently eliminates the Wichita uplift as a source area. Likewise, the extensive shelf carbonates to the north probably supplied the study area only with carbonate constituents to the Cottage Grove rather than any significant volume of quartz sand or silt.

The basal contact of the Cottage Grove Sandstone is quite sharp with underlying marine shale. Commonly packstone and wackestone, interbedded with sandstones, form the lowermost part of the Cottage Grove. It can be correlated most readily in the areas north and south of the South Gage field, a feature which suggests derivation from the northern carbonate shelf. The sharp contact between the Cottage Grove and the underlying marine shale probably represents a short period of nondeposition before influx of sand-size sediments.

After initial Cottage Grove deposition, available grain size decreased slightly. The bar began to form as marine currents deposited rippled sand beds with micaceous clay laminae. The entire lower zone of small-scale cross-stratification apparently formed without major shift of sand deposition.

Thin zones characterized by well sorted, fine-grained sandstone in the Cottage Grove section are commonly highly cemented by carbonate. Detrital mica and clay matrix, characteristic of other zones, are essentially absent in these thin layers, which contain sharp bases and tops. Medium-scale crossbedding in the carbonate-rich zones, together with the grain size, indicate that the sand was deposited by currents with higher velocities than the ripple-laminated units. These zones may possibly correspond to storm-related events.

Burrowing, which is common above the zone of small-scale cross-stratification, is most common where grain size is coarse silt and where clay is dispersed throughout the unit due to the biogenic activity. Because a vestige of lamination is preserved, it is assumed that depositional processes remained essentially the same but the depositional rate decreased. This change allowed worms to become established and rework sediment as it was deposited.

A further decrease in depositional rate accompanied a distinct increase in clay content characteristic of the upper interstratified zone. Small-scale cross-stratification is present in medium to coarse siltstone interbeds; the intervening clay layers are much thicker than the laminae of the lower cross-laminated zone. Near the end of Cottage Grove deposition, only mud with interspersed silt was being supplied to South Gage field from the east. Fossiliferous carbonate muds and clay formed the wackestone at the top of the Cottage Grove Sandstone. Deposition of the widespread "Hot Shale" on this wackestone apparently was a major transgressive event marking the end of coarse clastic (silt) deposition in the South Gage area. Although the change from sandstone to silty shale is gradual within the Cottage Grove interval, a rather sharp break on gamma ray logs suggests that the interval is in sharp contact with the overlying normal marine shale.

Water depth during deposition of the Cottage Grove Sandstone was apparently fairly shallow. The vertical sequence of sedimentary structures in the Cottage Grove is common in marine environments but is not unique to water of a specific depth. Fossils present in the unit are characteristic of a shallow marine fauna, but each grain has experienced transport. Planolites burrows are common in various marine environments. The Cottage Grove interval of the South Gage field is characteristically a silty calcareous shale. Although this unit becomes more calcareous northward, it is distinctive in character and is faily uniform in thickness. The facies change to carbonate near the Oklahoma-Kansas line is not associated with a change in interval thickness. Therefore, no sharp break in slope existed between the area of limestone deposition and the depositional area of terrigenous clastics (Cottage Grove). There is no indication that the Cottage Grove was subaerially exposed at any time.

No shorelines appear to have existed in close proximity to the South Gage field during Missourian time. The area of carbonate deposition to the north may have been exposed intermittently; the nearest terrestrial region was probably the low-lying delta to the east or the Wichita Mountains to the south. A deltaic complex lay more than 20 miles east of South Gage field (Rascoe, 1978). Sandstone development in the study area occurred a significant distance offshore, and the sand body possibly formed as a tidal bar. The depositional setting may have been similar to those during development of some Upper Cretaceous sandstones in the Powder River Basin (Berg, 1975b; Spearing, 1976; Brenner, 1978).

CHAPTER IX

RESERVOIR PROPERTIES

Between February, 1975, and January, 1978, the Cottage Grove Sandstone in South Gage field produced 1,000,000 barrels of oil and 65.0 million cubic feet of gas. Although the reservoir had been penetrated by a number of wells before 1975, the Cottage Grove was tested in only 5 wells, presumably because electric-log features were interpreted as representing an uneconomical reservoir.

Textural Features

Petrographic analyses indicate that the Cottage Grove texturally is atypical of sandstone reservoirs in the Anadarko basin, a factor which, by affecting water saturation and distribution, complicates log interpretation. Although grain size of the productive interval in the unit averages 0.073 mm, it varies from very fine sand to coarse silt. The sandstone is characterized by close packing, with pore space commonly small and difficult to distinguish. Long grain contacts are especially common; many contacts are concavo-convex, but virtually no tangential contacts are present, indicating moderate post-depositional compaction. Another effect of post-depositional pressure adjustment is distorted muscovite flakes around quartz grains. This feature is most common in the cross-stratified zone (Fig. 31), which contains less clay.

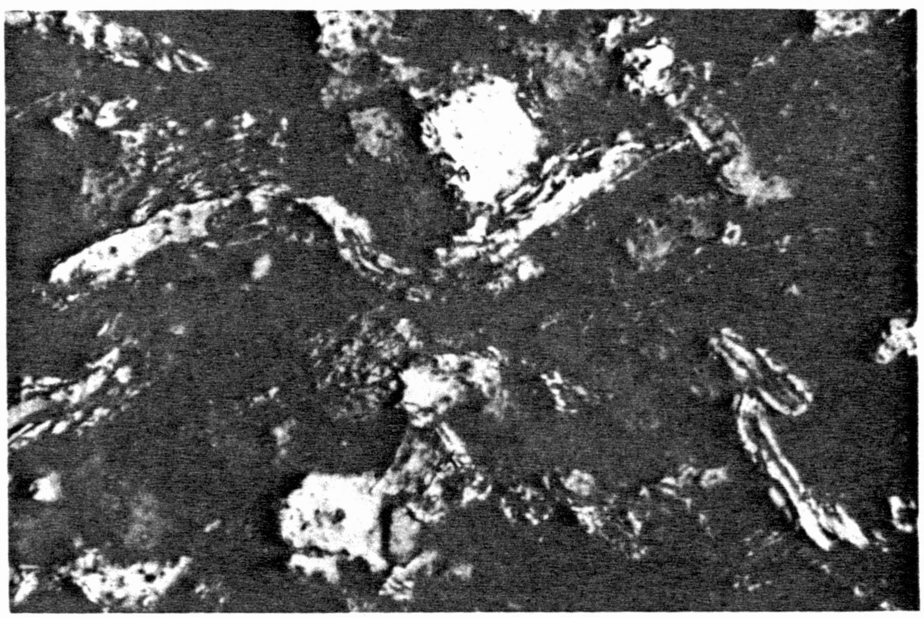


Fig. 31.-Distorted muscovite flake with quartz and clay. Crossed nicols, X128.

Diagenetic Overprints

Secondary cements and clays are common features which can seriously affect the quality of Cottage Grove reservoirs. Silica and carbonate are the most common cements in the Cottage Grove Sandstone. Quartz overgrowths are present most commonly where grains are not coated with clay, a feature characteristic of the cross-laminated zone (Fig. 32). Quartz grains with rims of clay rather than quartz overgrowths are typical of the interbedded zone. Secondary quartz is not extensively developed and apparently does not cause major production problems.

Although calcite is typically present as scattered patches throughout the rock, it completely fills pore space in some layers within the sandstone. Carbonate in these layers composes more than 70 percent of the total volume, forming barriers to vertical fluid migration. Presumably, carbonate grains which were originally deposited with terrigenous sand have been altered significantly by recrystallization (Fig. 33). Relict carbonate grains are recognized in a groundmass of carbonate cement, with "floating" fine sand grains (Fig. 34). Carbonate in contact with quartz grains has corroded the grain surfaces (Fig. 33). Euhedral dolomite rhombs are a common diagenetic product (Fig. 35). Silica cementation is partial, as opposed to nearly complete cementation by carbonate.

Secondary clays of the Cottage Grove Sandstone, based on X-ray diffraction studies, are illite, kaolinite, and chlorite. Scanning-electron microscopy (SEM) shows illite as flakes possessing delicate, fibrous-appearing, lath-like projections, which line pores and coat

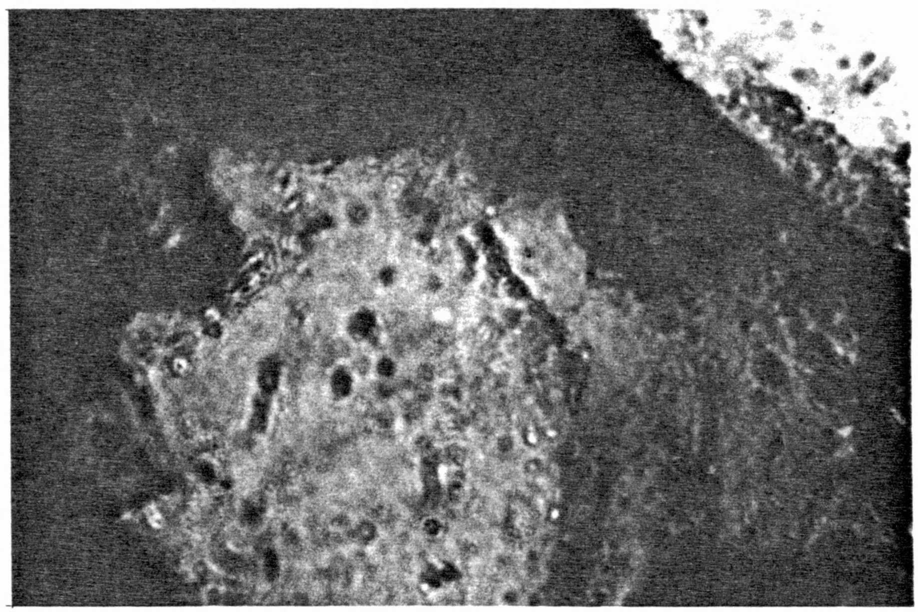


Fig. 32.-Secondary quartz overgrowths in cross-laminated zone. Crossed nicols, X512.

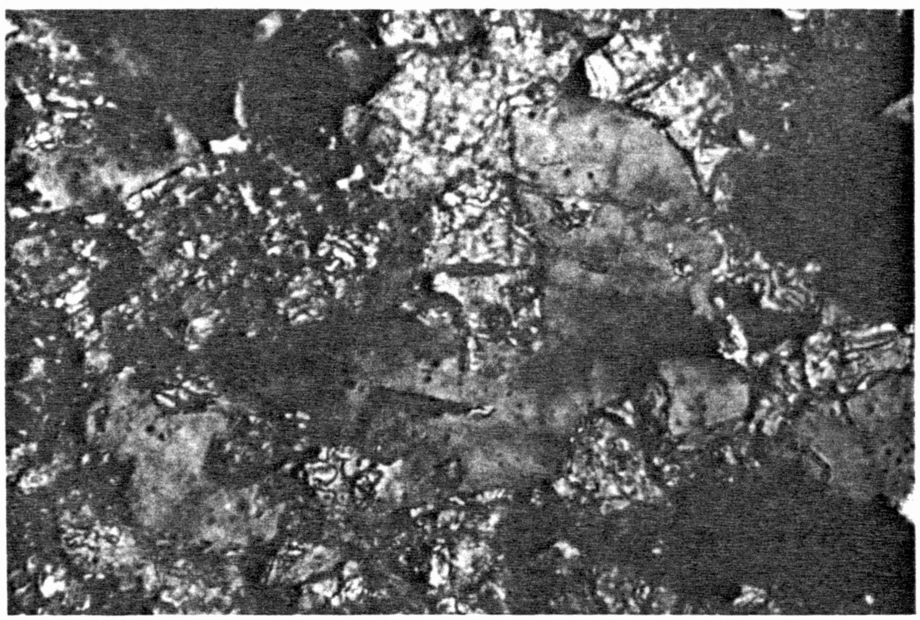


Fig. 33.-Recrystallized carbonate and corrosion of quartz in massively bedded layer. Crossed nicols, X400.

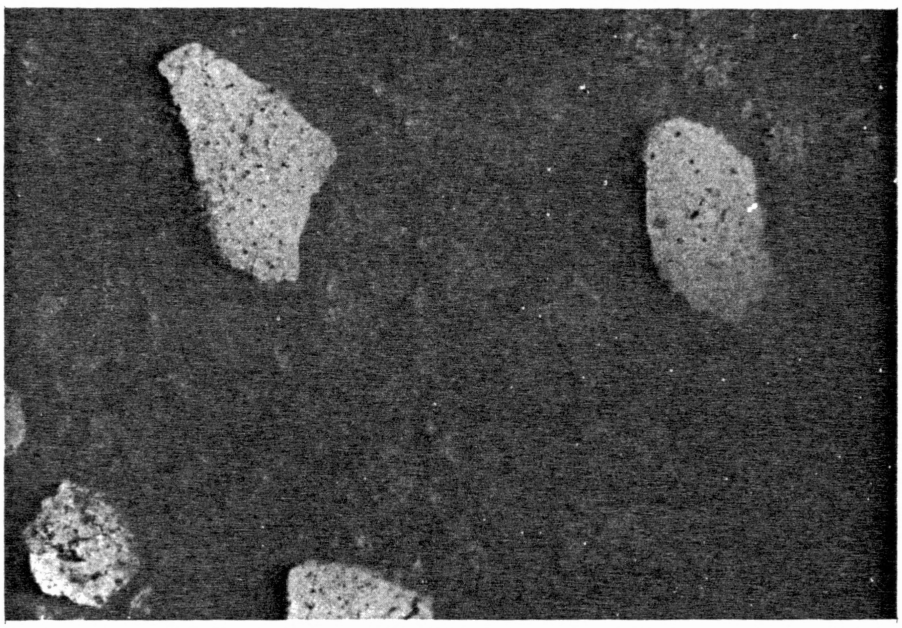


Fig. 34.-Floating quartz grains in carbonate-rich layer. Crossed nicols, X160.

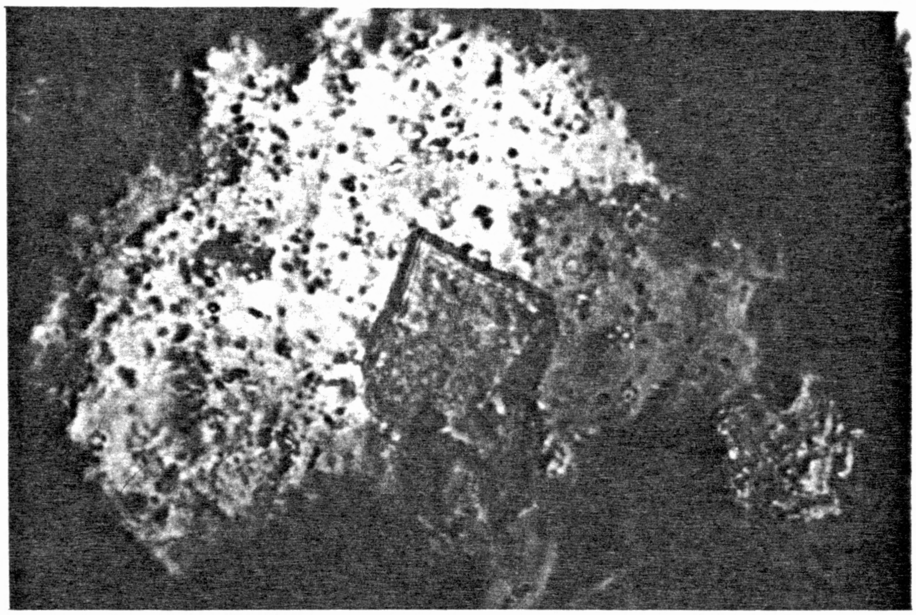


Fig. 35.-Dolomite rhomb and quartz grain in carbonate-rich layer. Crossed nicols, X512.

grain surfaces (Figs. 36-37). Chlorite usually occurs as plates, with face-to-edge cardhouse orientation, attached by edges to detrital sand grains. Forms include densely stacked plates and rosette habits (Figs. 38-41). They are present as pore linings, which partially fill pores. In thin section kaolinite is present as aggregates or books. Partial infilling of pores by formation of diagenetic clays, quartz overgrowths, and carbonate recrystallization reflect textural and compositional features of the host rocks. It is thought that hydrocarbons were introduced after these diagenetic products formed.

Porosity and Permeability

Whereas the values of porosity and permeability of the Cottage Grove primarily indicate diagenetic changes, they reflect to some extent the zones of sedimentary structures. Average porosity is commonly more than 10 percent in the burrowed and cross-laminated zones and less than 10 percent in the upper interbedded zone, with an increase in shale percentage. Porosity of less than 5 percent corresponds to thin, carbonate-cemented layers in the burrowed and cross-laminated zones (Fig. 42). Average porosity in the oil-bearing, cross-laminated zones, from available data, is 10.7 percent. An average of over 12 percent is reported for the eastern part of the field. Although porosity does not vary distinctively between the productive cross-laminated zone and the nonproductive burrowed zone, the average permeability is 0.3 md for the former and 0.12 md for the latter. This difference is due to variation in grain size (0.073 mm in the cross-laminated zone and 0.043 mm in the burrowed zone) and, to some extent, the biogenic dispersal of clays throughout the burrowed

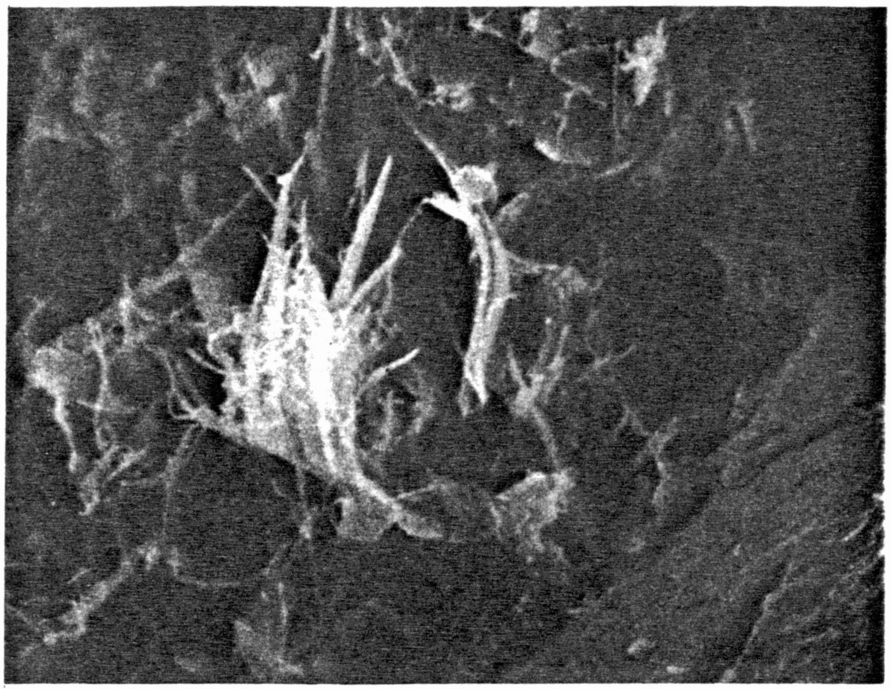


Fig. 36.-SEM photograph of delicate laths of illite in burrowed zone. X1950.

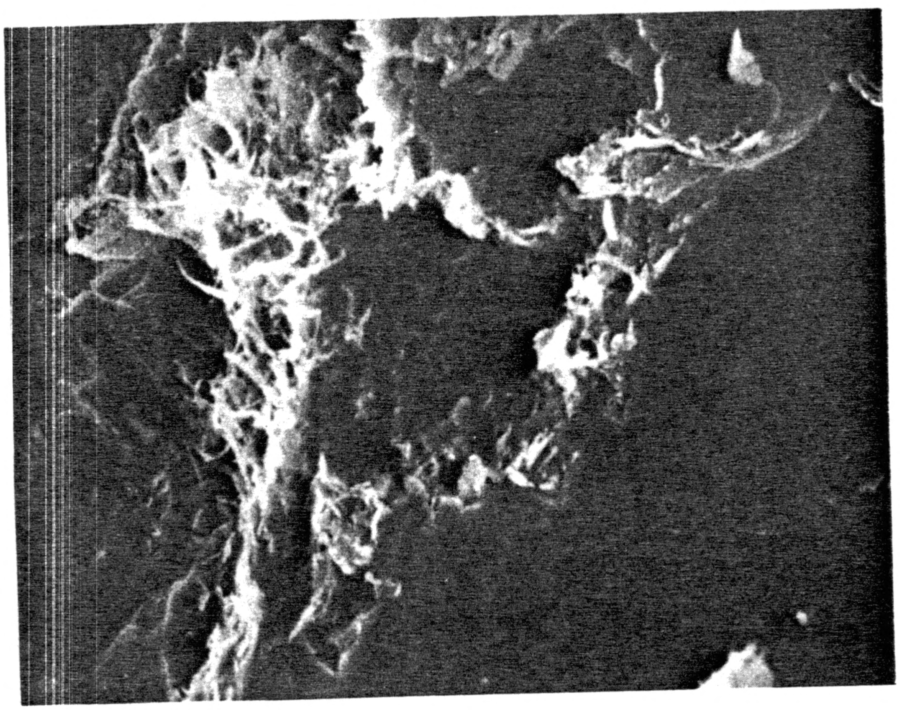


Fig. 37.-SEM photograph of pore-lining illite in burrowed zone. X1950.

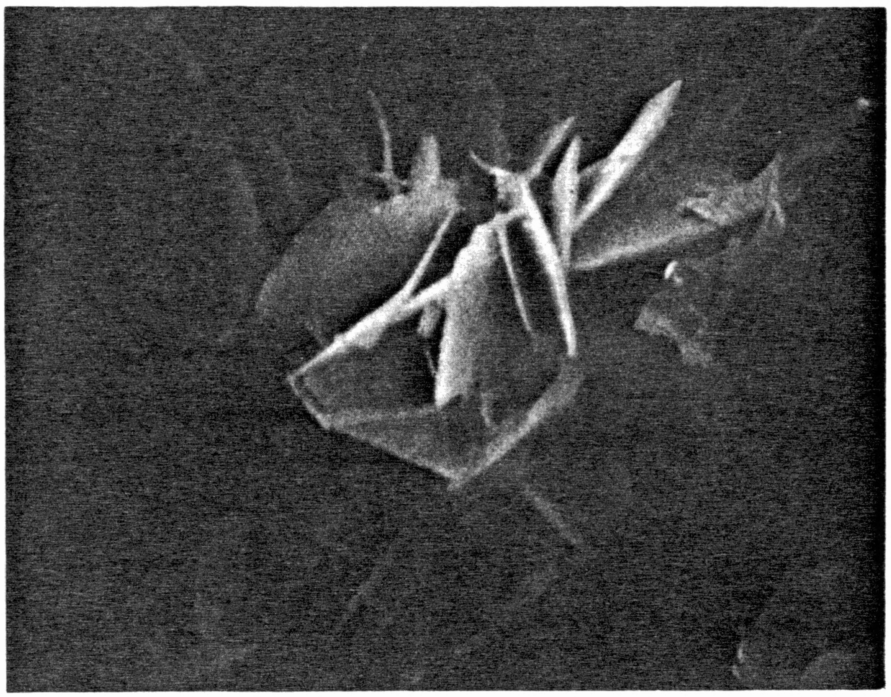


Fig. 38.-SEM photograph of rosette-like chlorite in cross-laminated zone. X6200.

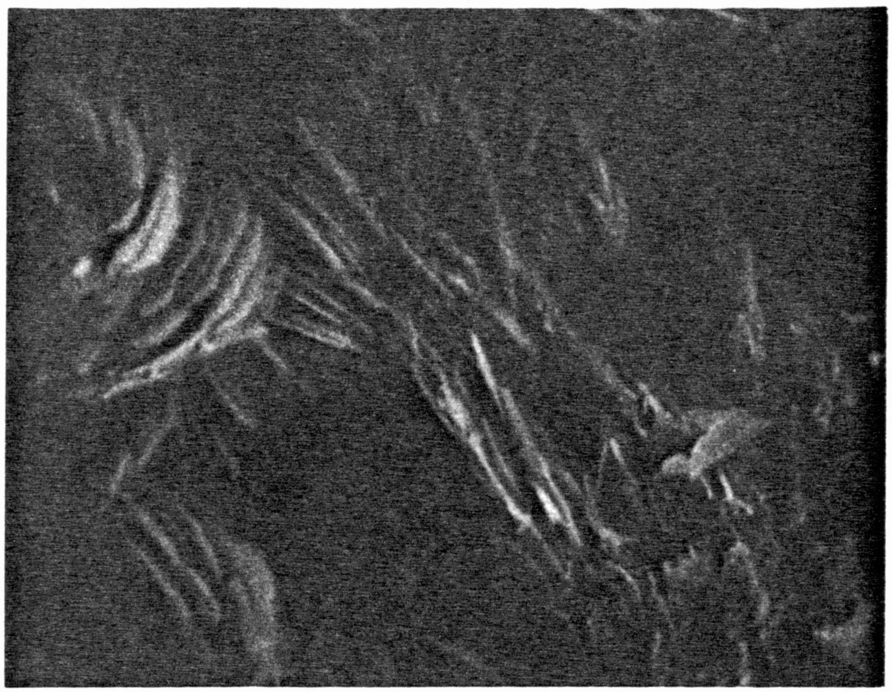


Fig. 39.-SEM photograph of chlorite in stacked plates in cross-laminated zone. X4340.

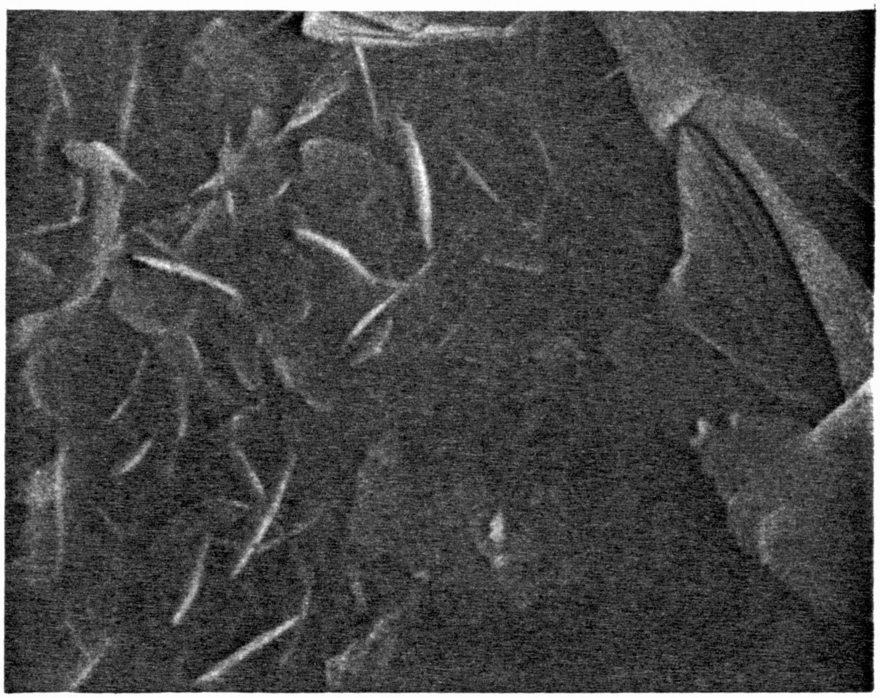


Fig. 40.-SEM photograph of chlorite with cardhouse arrangement of plates and plate-edge to grain relationships in the cross-laminated zone. X4235.

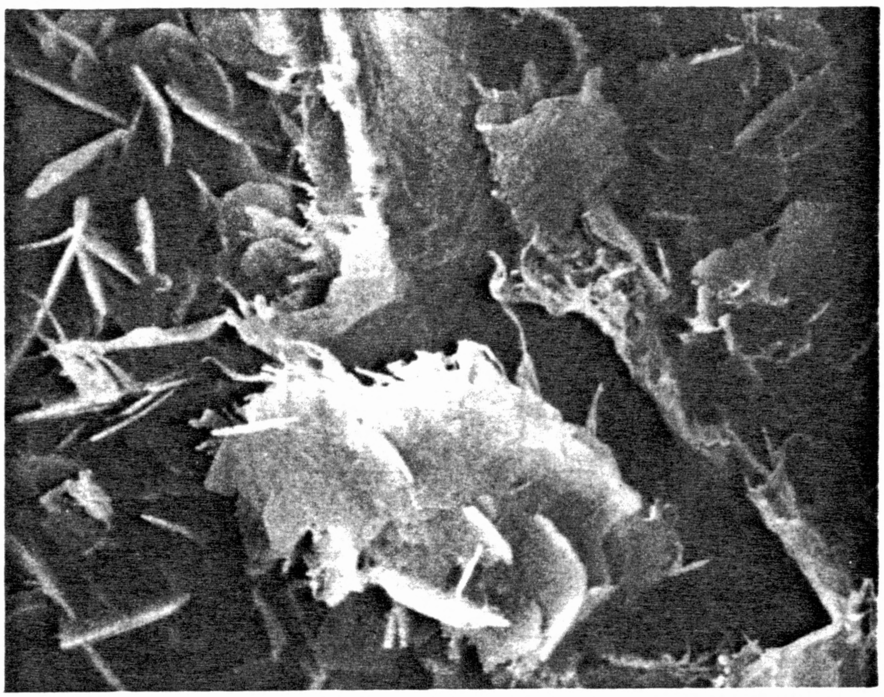


Fig. 41.-SEM photograph of cardhouse arrangement of chlorite plates and partially encrusting laths of illite. X5500.

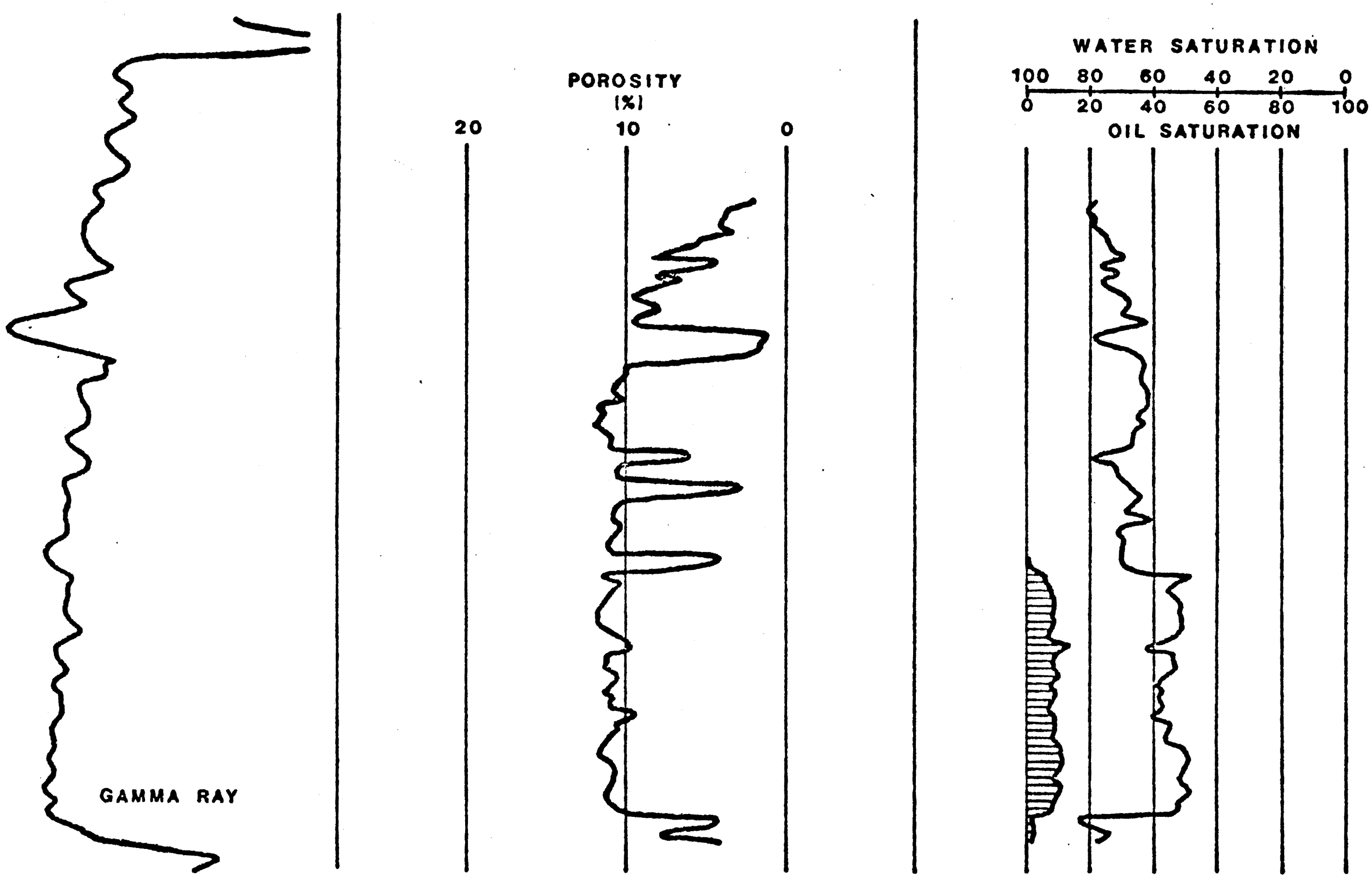


Fig. 42.-Gamma ray log, porosity, and water saturation, May Readnour No. 2.

zone. The upper interbedded zone is characterized by permeabilities less than 0.10 md.

Horizontal permeability is greater than 1.0 md in some parts of the oil-bearing zone. Maximum permeability measured in the laboratory of 1800 md is where the core is fractured. Additional porosity and permeability data are presented in Appendix B.

If porosity (n) and permeability (k) values are known, effective grain size (De), pore radii (rp), and pore throat radii (rt) can be calculated. Berg (1975a) has shown that

$De = (1.89\ k/n^{5.1})^{\frac{1}{2}}$,

$rp = \frac{1}{2}(0.414\ De)$, and

$rt = \frac{1}{2}(0.154\ De)$

where De = mean effective grain size in cm, rp = pore radius for reservoir, rt = pore throat radius for barrier, k = permeability in md, and n = porosity in percent.

In May Readnour No. 2, with an average oil-zone porosity of 11 percent and average permeability 0.3 md,

De = 16.64 μm,

rp = 3.44 μm, and

rt = 1.28 μm

In Amoco H. H. Taylor No 2, with an average oil-zone porosity of 12.3 percent, average horizontal permeability of 1.2 md,

De = 25.04 μm,

rp = 5.18 μm, and

rt = 1.93 μm

Pore radii (rp) measured in SEM photographs are 4.1 μm, 3.8 μm, 4.1 μm, and 8.1 μm. Mercury-injection analyses indicate that with an average porosity of 12 percent 30 percent of pore throat radii exceed 0.43 μm, a value approximately ¼ the calculated values. For comparison, pore radii in Morrow reservoirs, with an average permeability of 50 md and porosity of 12 percent, average 35 to 40 microns.

With pore sizes 5 μm or smaller and pore throats of 2 μm or smaller, special considerations must be given to completion and production procedures which are most likely to preserve or improve virgin permeability. Extreme care must be taken to prevent expansion and/or migration of delicate secondary clays into pore throats, where they act as permeability barriers.

One effective method used in treating the Cottage Grove is to inject a 1 percent KCl-gelled water solution during completion. This system prevents expansion of disordered illite layers, which are fresh-water sensitive and prone to migrate and clog pores. Strong acidization is not recommended, for authigenic chlorite reacts with the acid to form iron precipitates, which clog pores. The extensive occurrence of illite tends naturally to stabilize the kaolinite, but addition of a clay-stabilization system would ensure that kaolinite-rich areas do not migrate (Almon and Davies, 1977).

Water Saturation

A major problem in estimating reservoir performance from log interpretation of very fine-grained reservoirs is the high water saturation. For example, the average water saturation of the oil-productive zone in May Readnour No. 2 is more than 50 percent and oil saturation is less than 15 percent. During the initial production test, however, this well yielded 229 barrels of oil with only 19 barrels of water during an 8-hour period. The apparent contradiction between core analyses and performance is due to at least two major factors: (1) increase in percentage of adsorbed water with decrease in grain size (and increase in surface area), and (2) additional adsorbed and/or solid water associated with secondary clays, which give rise to microporosity and associated nonrecoverable water. Therefore, a high percentage of water is expected to be retained within the sandstone, and any significantly permeable unit with water saturations less than 60 percent should be oil productive. The oil-water contact is apparently present in the Jacoby No. 1, where the lower 4 feet of the cross-laminated zone have water saturation of 80 percent. Directly above this section are 13 feet of oil-productive sandstone with water saturation averaging 59 percent. Porosity and permeability values in the entire 17 feet are virtually the same.

CHAPTER X

DISTRIBUTION OF FLUIDS, RESERVOIR DELINEATION, AND WELL POTENTIAL

Because oil production in the Cottage Grove is apparently restricted to zones of small-scale cross-stratification, which contain the coarsest grain sizes and largest pore throats, distribution of oil may occur in any part of the interval where that sedimentary structure is dominant. However, oil does exist in the upper zones in association with fractures. May Jacoby No. 1, which is the most highly fractured of the four cores examined, contains an oil saturation of approximately 3.5 percent in most of the upper two zones. The correlation of oil production to sedimentary structure is demonstrated in the eastern part of the field, where the nonproductive burrowed zone separates upper and lower cross-stratified zones. Presumably, the burrowed and interbedded zones have pore-throat radii too small for oil to enter pores; in other words they are effectively impermeable to oil migration. However, the pores apparently are large enough for entry of gas condensate, for it is reported from the upper zones.

Figure 43 shows net sandstone with porosity values greater than 9.5 percent, a value which represents minimum porosity of oil-productive intervals (within the cross-stratified zone). Although somewhat similar in trend, a direct correlation does not exist between areas of thickest Cottage Grove sandstone and areas of thickest reservoir. In

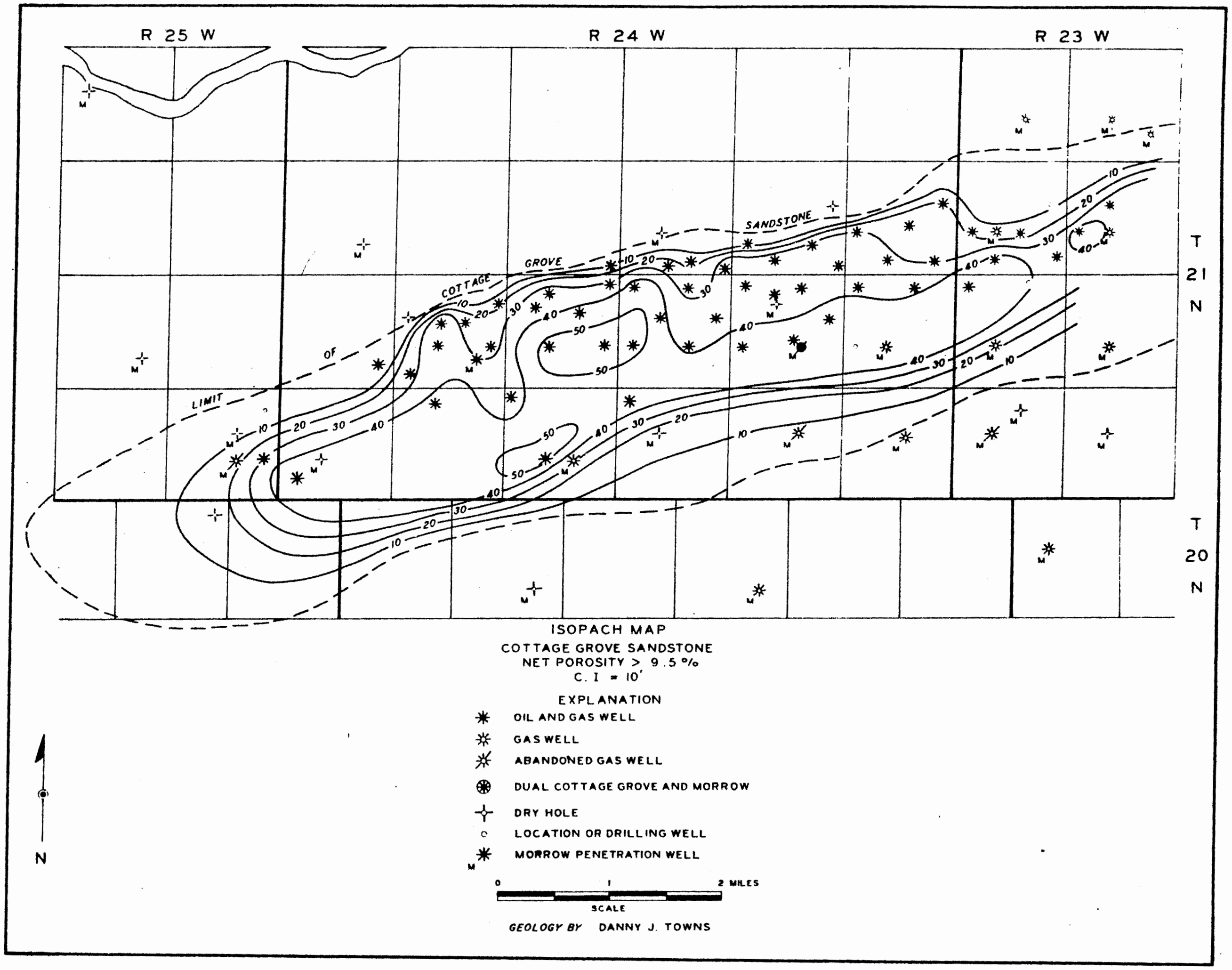


Fig. 43.-Map of net porous sand, with porosity greater than 9.5 percent.

general, more than 40 feet of porous sandstone from the cross-stratified and burrowed zones are present in the area 0.75 miles inward from the edges.

The thin, carbonate-rich layers, which are continuous between closely-spaced wells, are also barriers to fluid migration. Except for communication by means of fractures, they would be effective in dividing the Cottage Grove into a series of individual reservoirs (Fig. 44).

Reserves are overestimated if in completion the reservoir is treated as one bulk volumetric body. It should not be assumed that flow from one part of the cross-laminated zone will induce flow from the entire zone. Therefore, completion of the entire cross-stratified zone should be attempted.

Limited production data indicate that initial water production is lowest in updip wells toward the northern edge of the field. The oil-water contact is known only from the Jacoby No. 1, in which it was encountered near the base of the cross-stratified zone at 5126 feet subsea. Delineation of the contact apparently cannot be made from log interpretation alone. Furthermore, more than one contact most likely exists, for water production is expected from sections of the burrowed and interbedded zones. Maximum oil/water production is probably achieved by well completions in only the cross-laminated interval or intervals and with treatment specifically designed to stabilize the clays.

Data from 30 wells in the South Gage field show an average initial daily production of 185 barrels of oil and 85 barrels of water. A typical production curve (Fig. 45) indicates that initial production

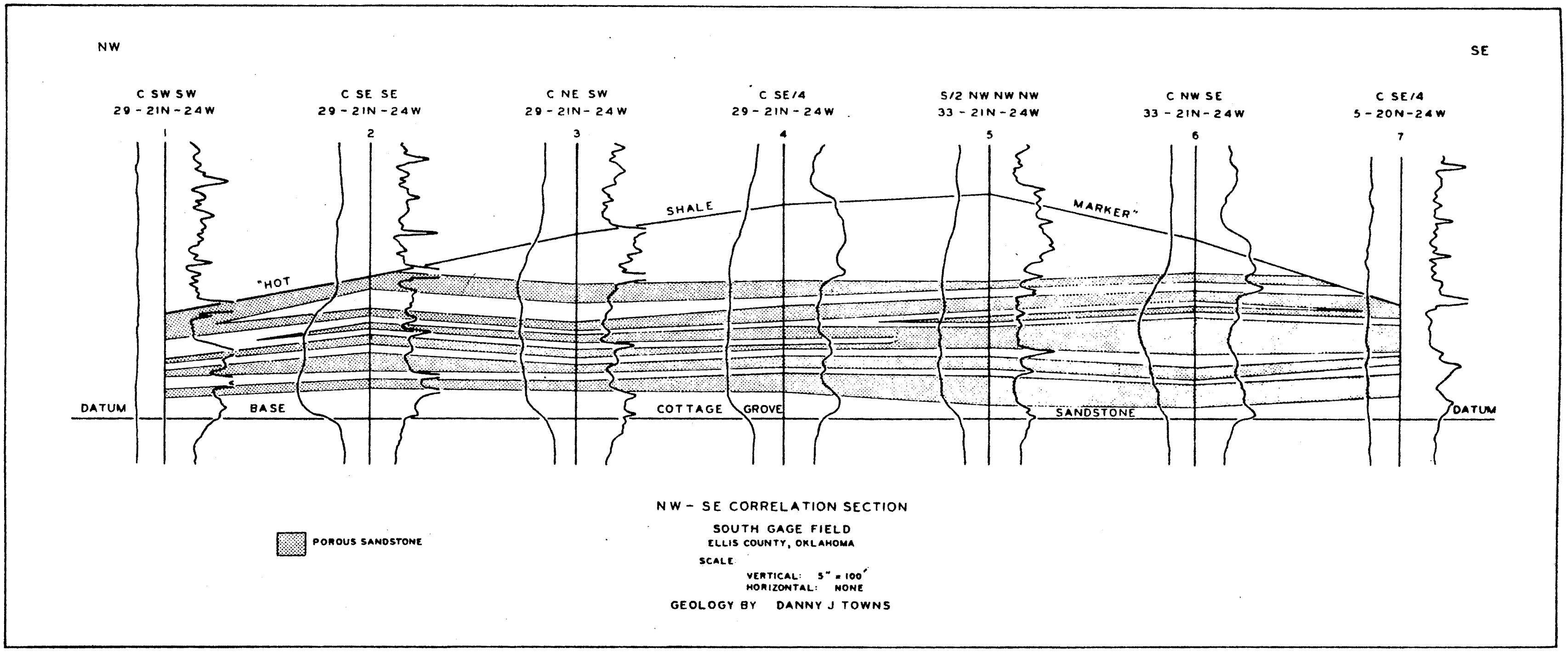


Fig. 44.-Correlation section in the western part of South Gage field showing carbonate cemented layers.

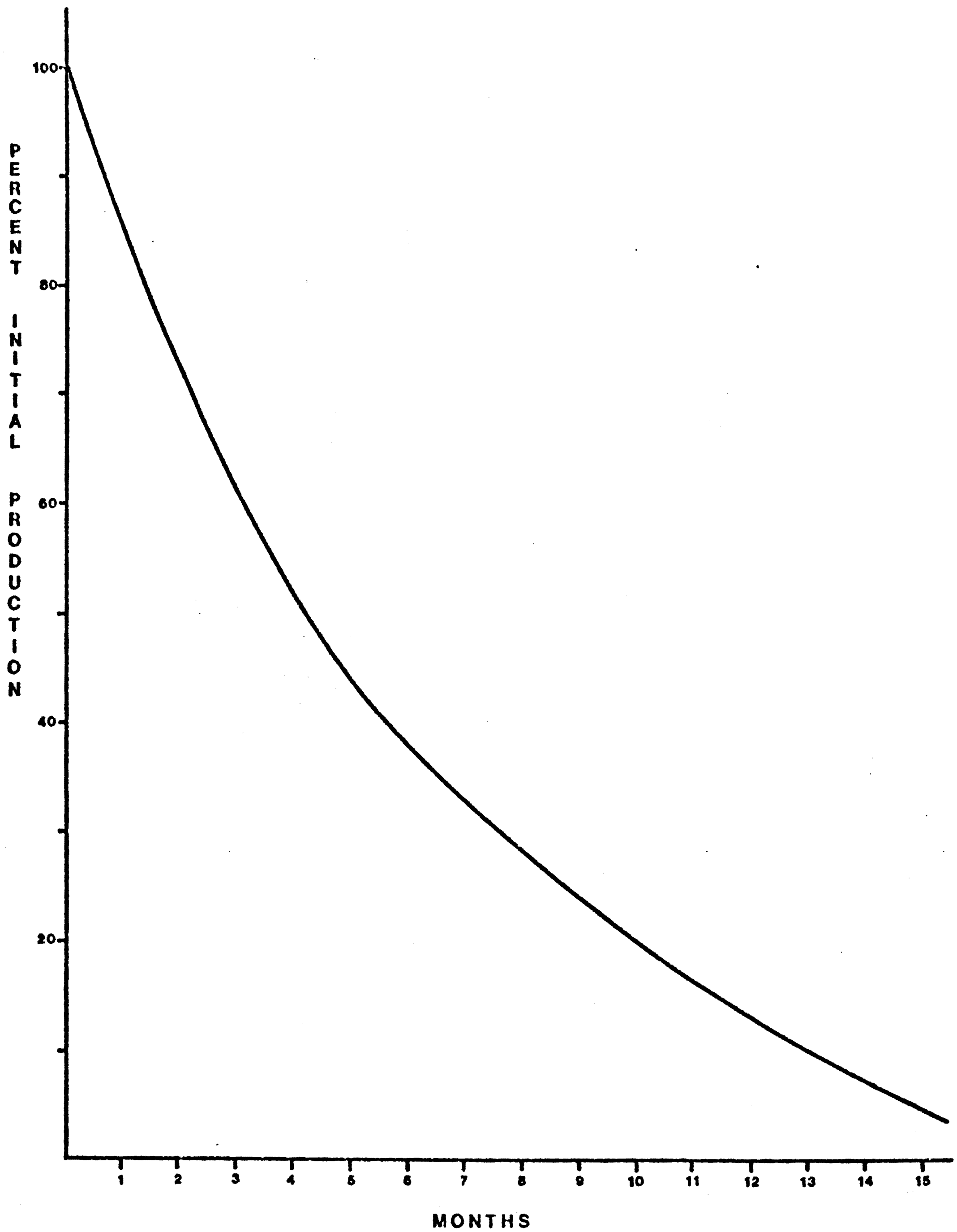


Fig. 45.-Typical oil-production, showing decline of 62 percent in the first 6 months of production.

rapidly decreases during the first few months of operation. In 6 months, monthly production can be expected to drop approximately 62 percent from initial rates, and after the first year of operation, production will be approximately 14 percent of the original value.

CHAPTER XI

SUMMARY

The principal conclusions of this study are as follows:

1. South Gage field is a stratigraphic trap which yields oil and gas from the Cottage Grove Sandstone on the north flank of the Anadarko basin.

2. Other than homoclinal dip into the deeper Anadarko basin, the only obvious structure in the South Gage area is a structural high in the area of maximum sandstone development in the field.

3. The Cottage Grove interval throughout the area is characterized by silty calcareous shale with local sandstone and/or siltstone.

4. The Cottage Grove Sandstone in the South Gage field represents a buildup of sand, with no apparent channeling, enclosed in marine shale. Maximum sandstone thickness exceeds 100 feet, and sandstone is developed in an area which is more than 11 miles long and up to 2.5 miles wide.

5. The sandstone body is convex upward; it has fairly sharp lower and lateral contacts and a rather gradational upper boundary.

6. Three major zones of sedimentary structures present in the Cottage Grove Sandstone are a lower zone of small-scale cross-stratification, an intensely burrowed zone, and an upper zone siltstone-shale interstratification.

7. Marine body fossils are common at or near the top and base of the sandstone, whereas Planolites burrows are common throughout the sandstone section.

8. A distinct fining-upward sequence is present from the base to the top of the Cottage Grove; thin, coarser grained, carbonate-cemented units are minor exceptions to this pattern.

9. Distribution of the Cottage Grove with respect to equivalent carbonates and shales and an increase in grain size of terrigenous sandstone in an eastward direction indicate that the Cottage Grove was derived from a source area in that overall direction, probably the Ouachita uplift.

10. Fossiliferous carbonate constituents present within the Cottage Grove probably were derived from northern shelf carbonates and deposited simultaneously with terrigenous clastics from the east.

11. Depositional processes may have remained quite constant throughout sandstone development, but depositional rate was varied, based on the more common occurrence of micaceous shales in the upper part of the interval and the carbonate-cemented sandstone.

12. Although overall transgression occurred during Missourian time, the Cottage Grove Sandstone represents a brief regressive period, particularly affecting the northern part of the Anadarko Basin and area to the east.

13. Although the Cottage Grove interval shows a marked facies change to carbonate near the Kansas-Oklahoma state line, there is no evidence of a sharp break between the area of limestone deposition to the north and terrigenous clastic deposition to the south.

14. The Cottage Grove Sandstone in the South Gage field possibly formed as a tidal bar in fairly shallow water more than 20 miles from the eastern coast and 40 miles south of the carbonate province.

15. Production of oil from the Cottage Grove is apparently restricted to very fine-grained sandstone zones characterized by small-scale cross-stratification. Production of gas is apparently from the burrowed and interstratified zones.

16. The thin, carbonate-cemented layers, which serve as local correlation markers, may act as barriers to oil migration within the lower zone of cross-stratification.

17. Water-saturation percentages are atypically high due to the extremely small grain size and abundant diagenetic clay.

18. Treatment of Cottage Grove reservoirs should consider the possible effects on these clays, such as chemical reactions and/or physical migration which may plug pore throats.

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APPENDIX A

NAMES AND LOCATIONS OF WELLS USED IN CORRELATION SECTIONS

No.	Operator and Well Number	Location
	Northwest-Southeast Correlation Section A-A'	
1.	Sohio, State #1	C SE NW Sec. 24-23N-25W
2.	Tidewater, Coffman #1	C SW NE Sec. 8-22N-24W
3.	Duncan - Midwest Oil, Thomas #1	C NE SW Sec. 22-22N-24W
4.	Arkla, Jones #1-2	SW SE NW SE Sec. 2-21N-24W
5.	Magness, Tully #26-1	C E/2 NW Sec. 26-21N-24W
6.	Pan Am, Fagala #1	C SE NW Sec. 6-20N-23W
7.	Pan Am, Thompson #1	C SE NW Sec. 21-20N-23W
8.	Clark Canadian, Hanan #1	C SW NE Sec. 35-20N-23W
9.	Hamon, Richard #1	C SW NE Sec. 17-19N-22W
10.	Enserch, Badger Trust #1	C NE Sec. 5-18N-21W
	North-South Correlation Section B-B'	
1.	Shamrock, Harrison Etal #1	C SW NE Sec. 5-23N-20W
2.	Sohio, Day #1	C SE NW Sec. 17-23N-20W
3.	Zoller & Danneberg, Ford #D-003	C SE Sec. 32-23N-20W
4.	Lloyd H. Smith, Johns #1-18	NW NW SE Sec. 18-22N-20W
5.	Helmerich & Payne, Betzen #1	W/2 E/2 SW NE Sec. 20-22N-20W
6.	Basin, Root #17-1	C SW Sec. 17-21N-20W
7.	Oklahoma Natural Gas, Campbell #1	C NW Sec. 5-20N-20W
8.	Superior, Bruce #1	SW NE Sec. 21-20N-20W
9.	Monsanto, Jeffery #1	C SW Sec. 29-19N-20W
	Northwest-Southeast Correlation Section C-C'	
1.	Arkla, Barnes #1-19	SE SE NW SE Sec. 19-21N-24W
2.	May, Allinger #2	SE SE NW Sec. 29-21N-24W
3.	Arkla, Readnour #1-29	C SE Sec. 29-21N-24W
4.	Pan Am, State #K-1	C NW SE Sec. 33-21N-24W
5.	Wessely, Cully #1	C SE Sec. 5-20N-24W
	Northwest-Southeast Correlation Section D-D'	
1.	Pan Am, State #H-1	C NE SW Sec. 22-21N-24W
2.	Magness, Tully #26-1	C E/2 NW Sec. 26-21N-24W
3.	Huber, Elledge #1	C NW SE Sec. 26-21N-24W
4.	Huber, Peer #1	SW SW NE Sec. 36-21N-24W
	Southwest-Northeast Correlation Section E-E'	
X 1.	May, Cully #1	C SW SW Sec. 29-21N-24W
2.	May, Readnour #2	C NE SW Sec. 28-21N-24W
3.	Huber, Poindexter #B-1	C NW NW Sec. 25-21N-24W
4.	Amoco, Cully #1	SW NE SE SE Sec. 19-21N-23W

No.	Operator and Well Number	Location
	Carbonate-Layer Correlation Section	
1.	May, Berry #1	C SW NW Sec. 29-21N-24W
2.	May, Allinger #2	SE SE NW Sec. 29-21N-24W
3.	May, Allinger #1	C NE SW Sec. 29-21N-24W
4.	Arkla, Readnour #1-29	C SE Sec. 29-21N-24W
5.	Filon, State #1-33	S/2 NW NW NW Sec. 33-21N-24W
6.	Pan Am, State #K-1	C NW SE Sec. 33-21N-24W
7.	Wessely, Cully #1	C SE Sec. 5-20N-24W

APPENDIX B

CORE ANALYSIS DATA

Core analyses data of the Shenandoah Readnour No. 1 are provided by Shenandoah Oil Corporation, Oklahoma City, Oklahoma.

Depth (ft)	Horizontal Permeability (md)	Porosity (%)	Water Saturation (%)
7285-86	<0.1	4.8	89.3
86-87	<0.1	3.3	86.1
87-88	<0.1	5.6	82.1
88-89	<0.1	6.9	83.2
89-90	<0.1	7.3	84.9
90-91	<0.1	5.9	81.1
91-92	<0.1	8.6	82.6
92-93	<0.1	7.7	80.4
93-94	<0.1	7.6	81.5
94-95	<0.1	5.4	83.9
95-96	0.1	10.4	65.0
96-97	0.1	10.7	64.7
97-98	0.1	10.5	63.9
98-99	0.1	9.9	64.6
99-7300	0.1	9.0	54.1
7300-01	0.1	9.0	54.5
01-02	<0.1	7.7	62.5
02-03	<0.1	2.5	68.3
03-04	<0.1	3.5	58.5
04-05	0.1	11.2	62.0
05-06	0.1	11.4	63.6
06-07	0.1	11.6	68.1
07-08	0.1	11.1	69.2
08-09	0.1	11.4	67.5
09-10	0.1	11.0	64.9
10-11	0.2	11.1	69.8
11-12	0.1	11.1	69.8
12-13	0.1	10.8	71.8
13-14	0.1	10.1	80.8
14-15	0.2	10.0	80.0
15-16	0.1	10.1	78.4
16-17	0.1	10.7	78.8
17-18	<0.1	3.6	75.0
18-19	<0.1	5.6	77.9
19-20	0.1	11.1	54.1
20-21	0.1	11.3	49.1
21-22	0.2	11.6	50.3
22-23	0.1	11.5	52.1
23-24	0.3	11.9	57.8
24-25	0.1	11.6	71.7
25-26	0.1	10.6	78.3
26-27	0.1	11.0	74.1
27-28	0.1	10.5	78.5
28-29	<0.1	3.3	69.3
29-30	0.1	9.8	67.7

Depth (ft)	Horizontal Permeability (md)	Porosity (%)	Water Saturation (%)
7330-31	0.1	9.0	55.5
31-32	0.2	10.9	56.1
32-33	0.3	11.0	55.5
33-34	0.1	10.3	50.0
34-35	0.1	11.0	53.6
35-36	0.2	11.4	50.7
36-37	0.4	11.6	50.6
37-38	0.3	11.8	53.2
38-39	0.1	11.6	53.0
39-40	0.1	10.4	59.5
40-41	0.1	10.8	58.6
41-42	0.1	11.1	52.9
42-43	0.3	11.2	53.5
43-44	0.2	11.1	51.0
44-45	0.1	11.0	51.7
45-46	0.1	10.5	51.9
46-47	0.1	11.0	62.2
47-48	0.1	9.3	76.5
48-49	0.1	10.7	76.7
49-50	0.1	10.5	50.9
50-51	0.2	10-4	48.2
51-52	0.2	10.3	51.9
52-53	0.1	9.7	56.3
53-54	<0.1	3.4	75.0
54-55	<0.1	2.3	61.0

Depth	Productivity
7285-7302	Gas
7302-7304	-
7304-7317	Gas
7317-7319	-
7319-7328	Gas
7328-7329	-
7329-7353	Oil
7353-7355	-

VITA

Danny Joe Towns

Candidate for the Degree of

Master of Science

Thesis: DISTRIBUTION, DEPOSITIONAL ENVIRONMENT, AND RESERVOIR PROPERTIES OF THE PENNSYLVANIAN COTTAGE GROVE SANDSTONE, SOUTH GAGE FIELD, OKLAHOMA

Major Field: Geology

Biographical:

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