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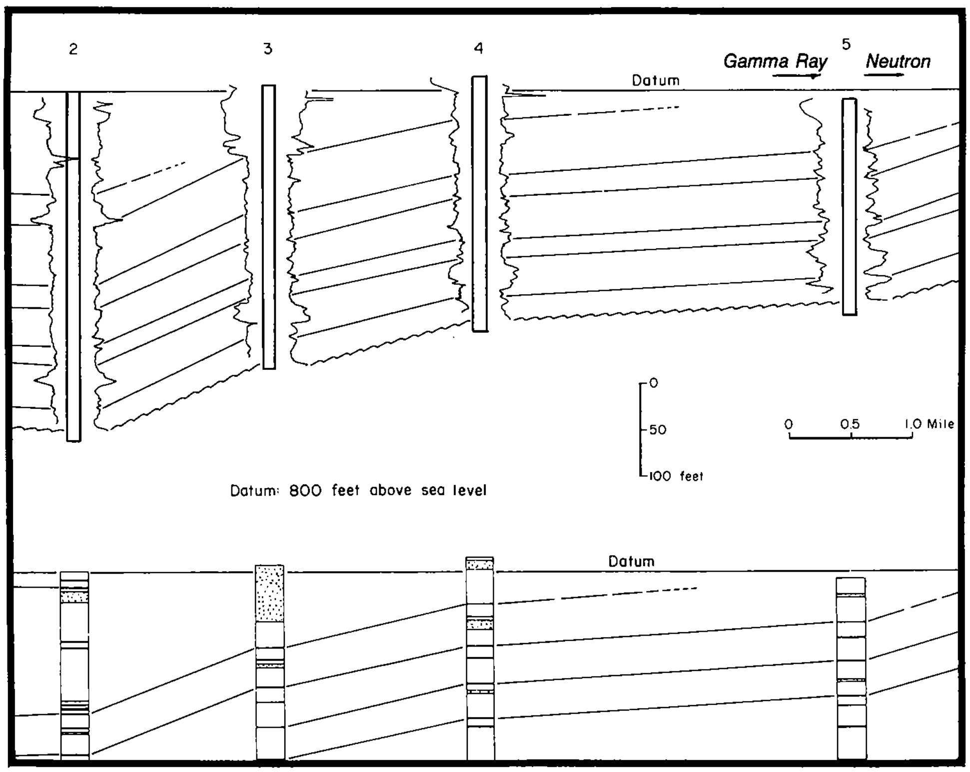
Evaluation of Heavy-Oil Potential of Northeastern Craig and Northwestern Ottawa Counties, Oklahoma

William E. Harrison, John F. Roberts, Larman J. Heath



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Evaluation of Heavy-Oil Potential of Northeastern Craig and Northwestern Ottawa Counties, Oklahoma

By

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FOREWORD

There is widespread interest within the petroleum industry and State and Federal Governments concerning the large heavy-crude-oil resource in the United States. This interest has been stimulated by several factors, among which are a decrease in the rate of growth of the Nation's proved crude-oil reserve, a forecast of increasing demand for domestically produced crude oil, and recent advancements in technology particularly as they relate to thermal methods of oil recovery. In western Missouri, eastern Kansas, and northeastern Oklahoma, heavy-oil deposits occur over an area roughly 8,000 square miles in size. This area extends for about 250 miles, basically along the Kansas-Missouri border but extending over into Oklahoma and reaching a width of about 80 miles. Heavy-oil deposits are found throughout the region.

A Federal research, development, and demonstration (RD&D) program was initiated to confirm the magnitude, location, and condition of the resource in the target area.

This project is one of three being conducted by geological or mineral resource organizations within the states of Kansas, Missouri, and Oklahoma. Its purpose is for better defining the heavy-oil deposits in the area contiguous to these three states.

Larman J. Heath
DOE Technical Project Officer

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ABSTRACT

This project was undertaken to evaluate the heavy-oil (oil less than 25° API) potential of northeastern Oklahoma--specifically, northwestern Ottawa and northeastern Craig Counties, the area considered to have the best possibility for shallow, heavy-oil accumulations. The investigation was partially funded by the U.S. Department of Energy as part of a three-state study covering northeastern Oklahoma and adjacent areas of Kansas and Missouri. Although previous reports indicated that potential resources of the entire region possibly amounted to billions of barrels of oil in place, a detailed subsurface investigation of the Oklahoma study area, including an 18-hole drilling and coring program, has shown that insignificant quantities of heavy oil are present in discontinuous Middle Pennsylvanian sandstones of varying permeability.

INTRODUCTION

Purpose of Study

This study was designed to help evaluate the heavy-oil (oil less than 25° API) potential of northeastern Oklahoma. Specifically, the project constitutes an effort to accurately assess the quantity of heavy oil in northwestern Ottawa and northeastern Craig Counties (Oklahoma). This investigation was partially funded by the U.S. Energy Research and Development Administration (ERDA), now the U.S. Department of Energy (DOE), as part of the overall effort to identify target areas that might lead to increased levels of domestic petroleum production. Similar studies have been conducted in adjacent areas of Kansas and Missouri. The combined results of these investigations will provide a better estimate of Tri-State heavy-oil potential than has been previously available.

Previous Investigations

Previous estimates of the heavy-oil potential of the Tri-State area have been made primarily on the basis of the geologic setting along the Kansas-Missouri border. In this area, oil saturations of up to 1,500 barrels/acre-foot and good reservoir conditions (up to 20% porosity and 200 md permeability) have been extrapolated for Bluejacket (Bartlesville) sands and have prompted estimates as high as 30 million barrels (Enright, 1964). Dietzman *et al.* (1965) indicated that estimates of many billions of barrels of oil in place have been made for southeastern Kansas, western Missouri, and northeastern Oklahoma.

Jordan (1964) compiled data on petroleum-impregnated and asphalt-bearing rocks in Oklahoma. This study identified 20 localities in Craig and Ottawa Counties which showed evidence of heavy-oil and other bituminous materials.

The reported occurrences consisted of outcrop samples and single-well fields which did not permit a volumetric appraisal.

Several workers have noted the presence of heavy-oil and asphaltic material in the Tri-State lead-zinc district (Siebenthal, 1908; Ireland, 1930; Weidman, 1932; Ball and Associates, 1965).

Area of Investigation

The area considered in this study is shown in figure 1. Reported occurrences of bituminous material in shallow wells and the presence of asphalt-bearing sandstone in mine shafts suggested that Craig and Ottawa Counties held the best potential for shallow, heavy-oil accumulations. Locations of wells drilled by the Oklahoma Geological Survey are shown in figure 2.

GEOLOGY

Regional Geology

The major geologic features of the region are shown in figure 3. The area encompassed by the Bourbon Arch, the Nemaha Ridge, the Arkoma Basin, and the Ozark Uplift has been called the Cherokee Petroleum Province (Baker, 1962) and has produced 1 1/2 billion barrels of oil in Oklahoma.

Rocks of the Cherokee Group (Middle Pennsylvanian) were considered to have the greatest potential for significant heavy-oil accumulations in the Tri-State area (Wells and Anderson, 1968; Ebanks and James, 1974; Ebanks *et al.*, 1977). The Krebs and Cabaniss Groups make up the Oklahoma equivalents of the Cherokee Group as used in other areas of the Midcontinent (Branson, 1962). In northeastern Oklahoma, the Krebs Group was deposited on a post-Mississippian erosional surface.

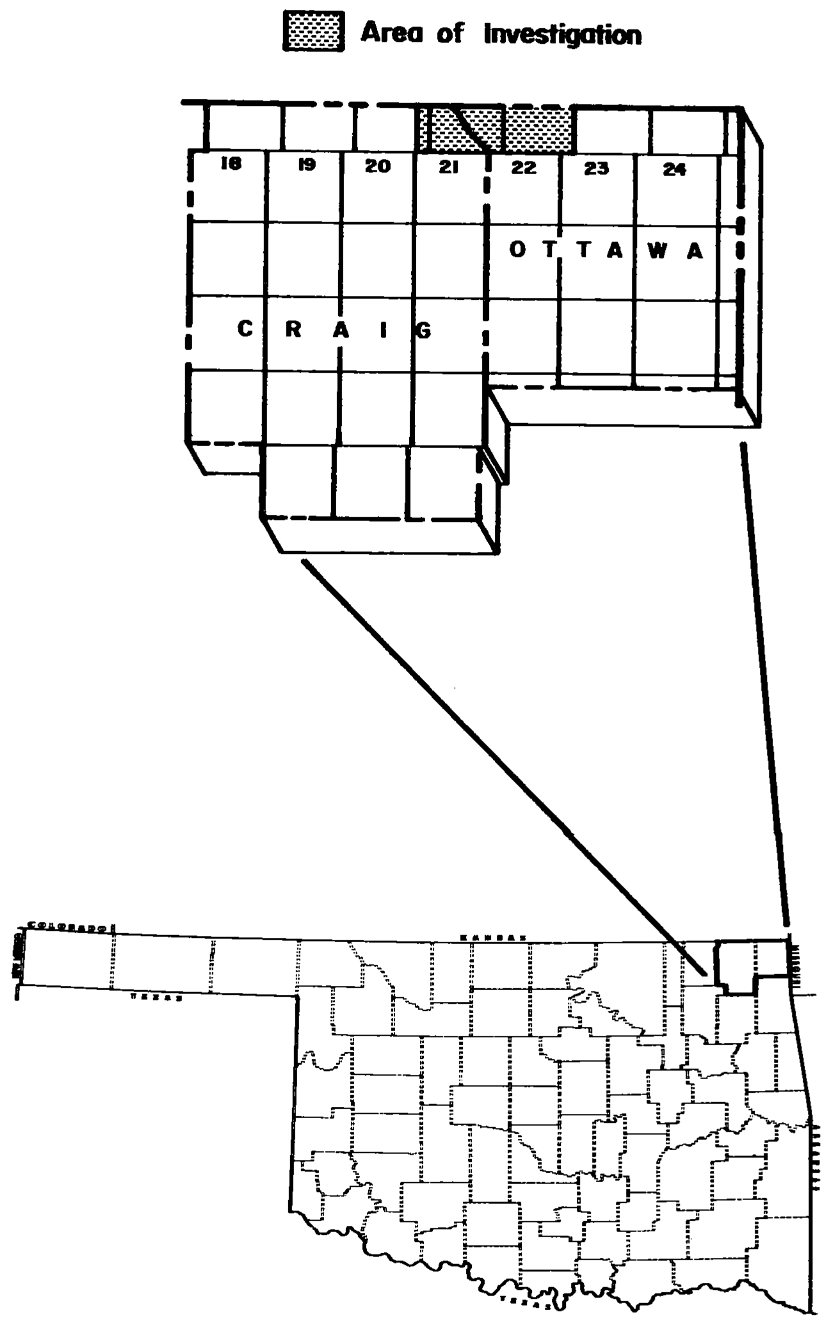

FIGURE 1.—Map showing area in Craig and Ottawa Counties which was investigated for heavy-oil potential.

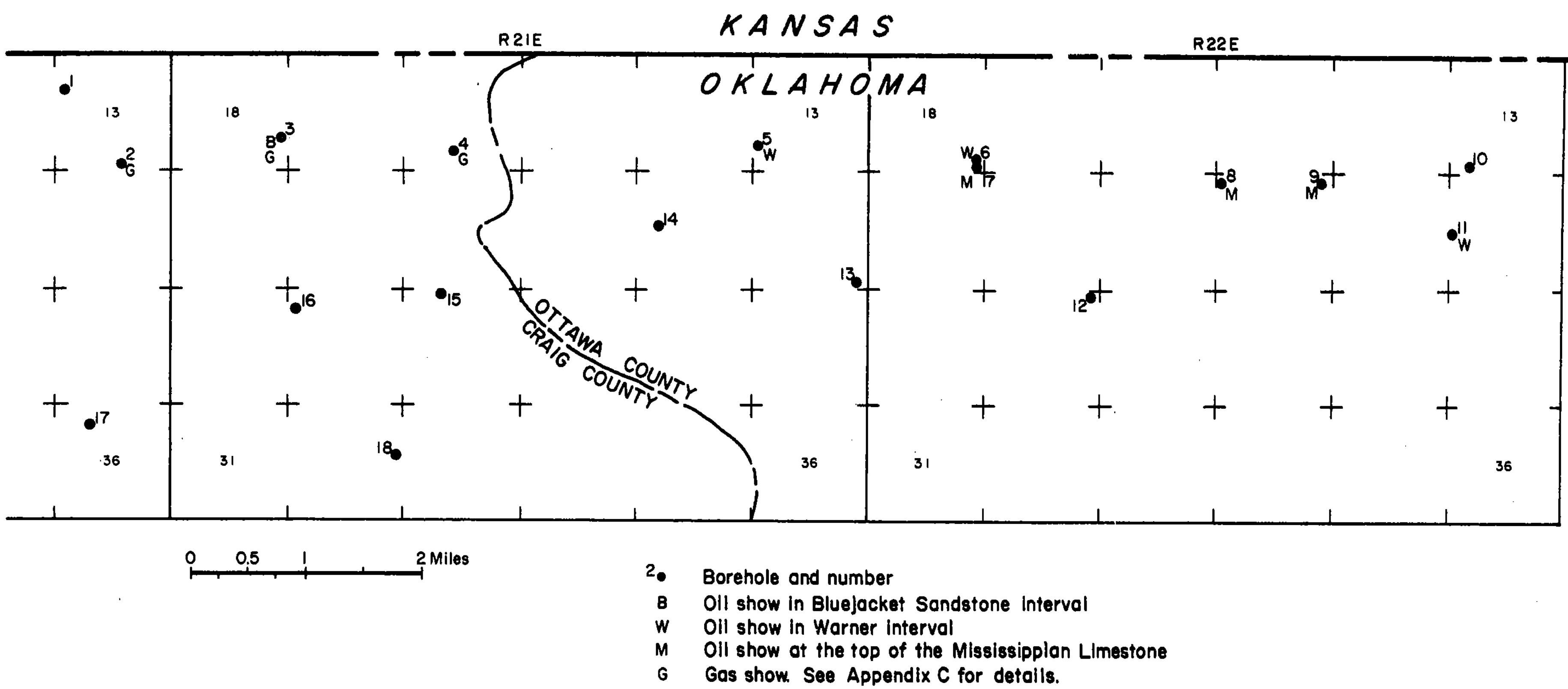

FIGURE 2.--Map showing boreholes and hydrocarbon shows in study area.

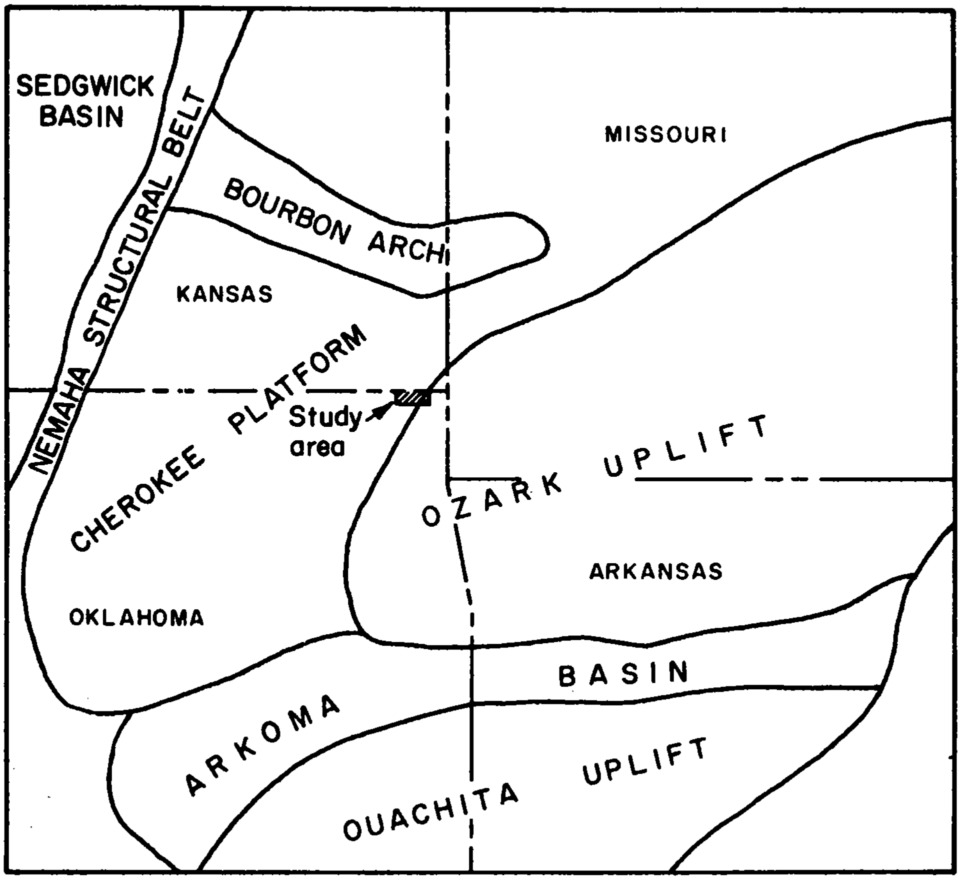

FIGURE 3.--Map of the regional geologic features in the Tri-State area.

This irregular surface, the top of the Mississippian limestone, dips westward at 20 to 30 feet per mile (see figure 4).

In addition to the major structures shown in figure 2, there are three additional structural features of regional interest. The Seneca Fault extends from Spurgeon, Missouri, to about three miles south of Pryor, Oklahoma, and can be traced through the southeastern corner of Ottawa County (Ireland, 1930; Reed et al., 1955). The throw of this fault varies from 90 to 140 feet (Siebenthal, 1908).

The Horse Creek Anticline is an asymmetrical fold which can be traced from northern Mayes County through the southeastern corner of Craig County and across Delaware County into Missouri (Ireland, 1930; Branson and Huffman, 1965). The southern limb of the fold has greater dip (5°-18°) than does the northern limb (approximately 2°)(Siebenthal, 1908).

Weidman (1932) described the Miami Syncline as a structural fold that extends from sec. 15, T. 24 N., R. 21 E., northeastward through Ottawa County and 15 miles into Kansas. The syncline is well exposed in a railroad cut southwest of Afton and in a mine shaft near Picher. Measurements in the latter show dips of 25° on the west flank of the syncline and 30° on the east flank (Weidman, 1932).

Stratigraphy

Baker (1962) compiled nomenclature of Desmoinesian rocks in northeastern Oklahoma and southeastern Kansas, and figure 5 is taken from his synthesis. The oldest rocks encountered in the 18-hole drilling and coring program conducted by the Oklahoma Geological Survey were Mississippian in age. See Appendix A for the field methods used in the drilling program. The Boone Formation makes

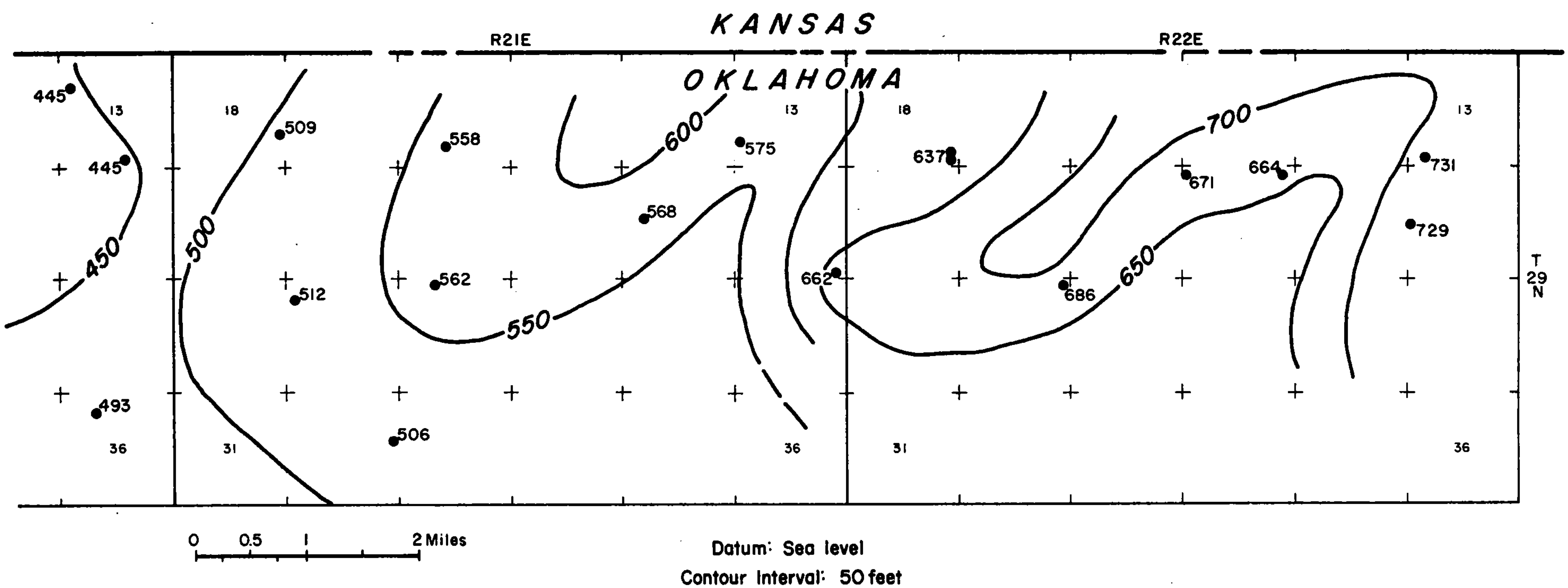

FIGURE 4.--Structure map on the top of the Mississippian limestone.

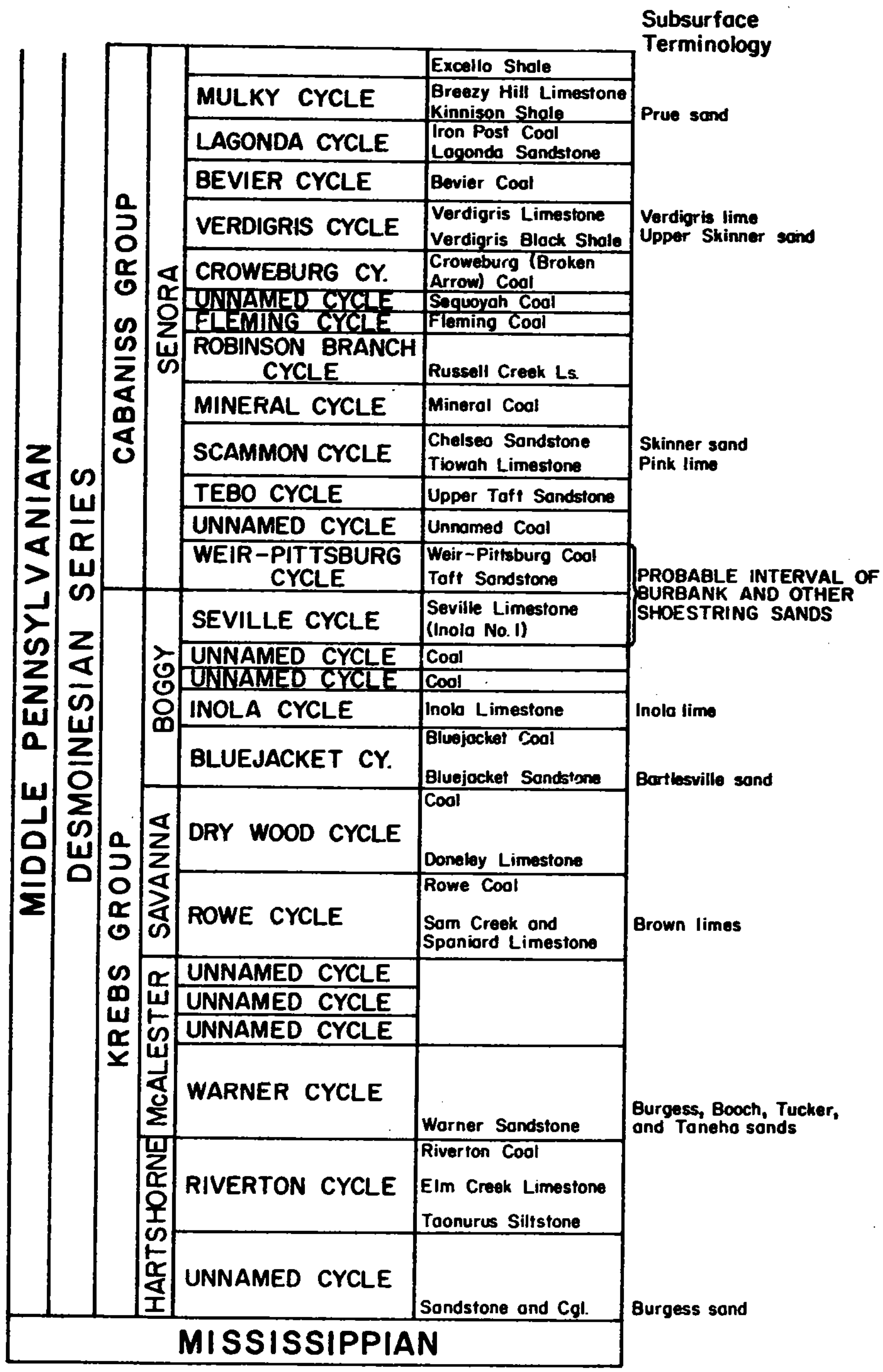

FIGURE 5.--Nomenclature of Middle Pennsylvanian rocks in the Tri-State area. Modified from Baker (1962).

up almost all of the Osagean and Meramecian Series of the Mississippian and, in the study area, is a cherty limestone that provides a convenient marker for sample- and wire-line-logging purposes. The Boone Formation has been mined for lead and zinc in the eastern part of the study area (McKnight and Fischer, 1970).

Formations of the Krebs Group overlie the Boone Formation and consist of alternating terrestrial sandstones, shales, and thin coal beds with attendant underclays. These sequences are cyclic deposits as indicated in figure 5, and the termination of each cycle is usually marked by a coal bed. The upper part of the Krebs Group contains a few thin beds of limestone in the western part of the study area (see detailed lithology, Appendix B). Discrete sandstone units are somewhat discontinuous and vary markedly in thickness in localities where they are laterally continuous.

The three holes located in the westernmost portion of the study area were the only ones that penetrated formations of the Cabaniss Group. These three boreholes were spudded in the Senora Formation, and each penetrated a coal-sandstone sequence in the approximate stratigraphic position of the Weir-Pittsburg coal and Taft Sandstone.

The Pennsylvanian sandstones of northeastern Oklahoma have been interpreted as being of deltaic origin by Visher et al. (1971). These workers used criteria established for modern delta systems and were able to identify interdistributary, distributary, and prodelta sequences in the Bluejacket (Bartlesville) Sandstone. Thus the deltaic nature of a major reservoir in the Krebs Group has been demonstrated.

Distribution of Sandstone in the Krebs Group

The Riverton coal indicated in figure 5 occurred in two logs (#15 and #16) from the study area below the first sandstone (Warner?) above the Mississippian-

Pennsylvanian unconformity. This interval is approximately equivalent to the "Interval of Lower Warner Sandstones" as described by Ebanks _et al_. (1977). The exact stratigraphic position of this particular sandstone interval can be resolved only by detailed study. Such a study is in progress for Craig County by the Oklahoma Geological Survey and, it is hoped, will help solve some of the stratigraphic problems in the area.

In portions of the study area, sand-rich facies change to a silt-shale facies within a very short distance. The discontinuous nature of sandstones in Desmoinesian rocks in northwestern Ottawa and northeastern Craig Counties limits the use of these sandstones in correlation. This characteristic also minimizes the possibility of economically recovering significant quantities of heavy oil that might be trapped in such sandstones.

Overlying the Warner interval are cyclic deposits of terrestrial sands, shales, and coals. The many thin coal beds in the central and western part of the study area suggest many transgressive-regressive cycles. Some of the coal beds are separated from each other by relatively thin intervals and indicate short-lived transgressive-regressive conditions. Some of the coals are restricted areally and suggest that individual cycles affected relatively small areas. Sandstones and siltstones in the shallow subsurface of Craig and Ottawa Counties are so variable, both laterally and vertically, that detailed stratigraphic correlation is difficult. Some of the thin coal beds appear to be laterally persistent for considerable distances and may provide a means for conducting more precise stratigraphic investigations. Appendix C contains additional correlation information.

In the western part of the study area, a few boreholes penetrated thin marine limestones in positions equivalent to formations in the upper Krebs and lower Cabaniss Groups. Thus the observation of Ebanks *et al*. (1977) that Middle and Upper Pennsylvanian sequences reflect more widespread marine invasion than do Lower Pennsylvanian rocks are supported by data from the present study.

Middle Pennsylvanian deposits on the Cherokee Platform are primarily the result of alluvial, fluvial, and deltaic sedimentation. Such sedimentary environments give rise to discrete sand bodies which are laterally discontinuous. Migrating depocenters produce the type of lobate sand bodies shown in figures 6 and 7. Reservoirs that result from such conditions do not hold as much potential for exploration and development as would laterally continuous, blanket-type sand bodies.

Hydrocarbon Shows

Seven of the boreholes drilled during this project indicated the presence of liquid hydrocarbons (fig. 2). There were three shows in the Warner Sandstone, three shows at the top of the Mississippian limestone, and a single oil show in the Bluejacket (Bartlesville) Sandstone.

The shows in the Warner Sandstone occurred in boreholes 5, 6, 7, and 11, which were drilled in an east-west transect that is 6 miles in length (fig. 5). The two wells drilled in 1978 (boreholes 8 and 9, fig. 5) were positioned to determine the lateral continuity of the sand and if any sands present were impregnated with oil. Boreholes 8 and 9 demonstrated a lack of continuity of the Warner Sandstone and an absence of oil in hole 9, which did have a sandstone in the Warner interval.

Holes 6, 8, and 9 had oil shows in the upper Mississippian limestone. These shows were mainly in fractures and in large voids connected by fractures. Borehole 3 had a show of oil in the Bluejacket Sandstone; however, wells 1.5 miles east and west of this hole showed no evidence of oil.

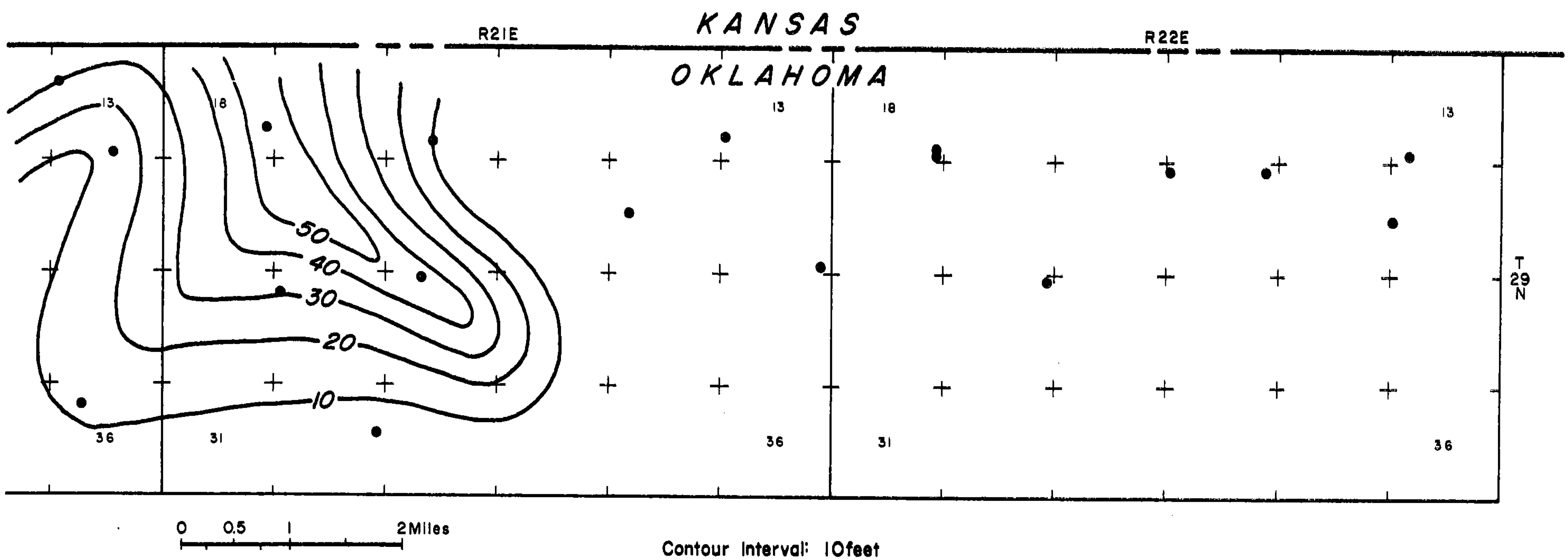

FIGURE 6.--Isopach of sandstone in the Bluejacket interval. The lobate geometry of the Bluejacket and Warner sand-rich facies (figure 7) is consistent with previous interpretations of fluvial and deltaic sedimentation.

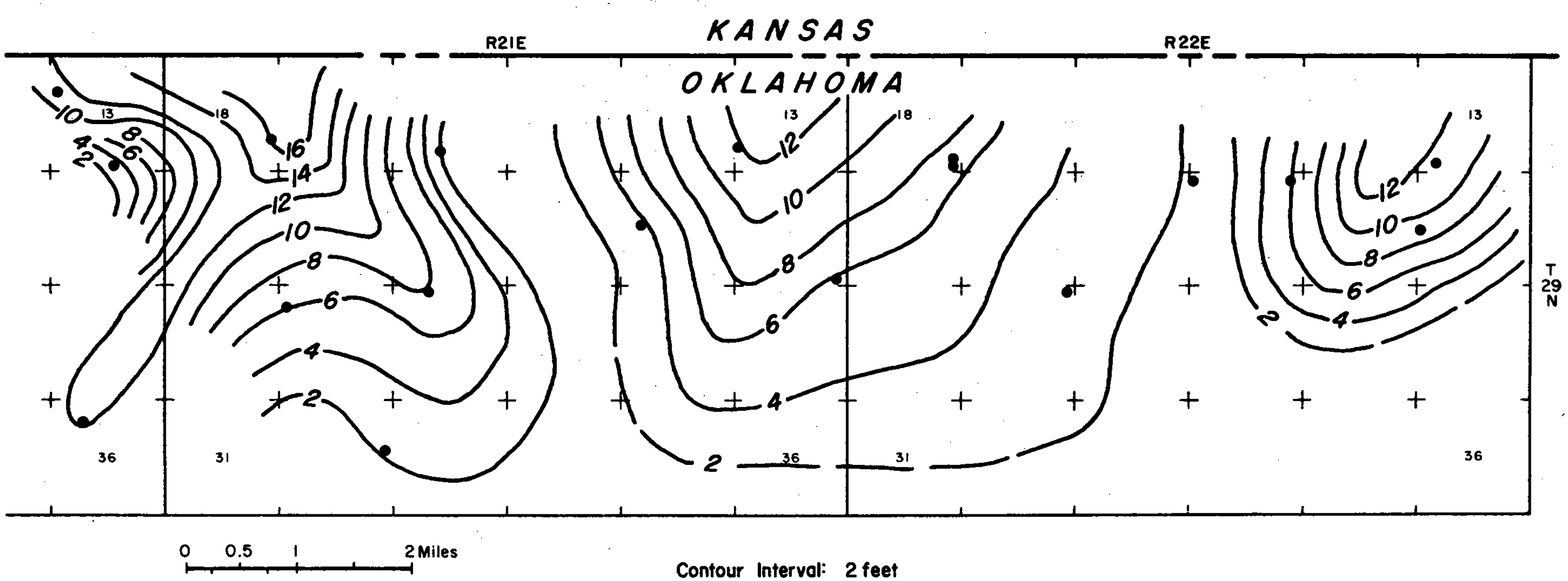

FIGURE 7.--Isopach of sandstone in the Warner interval. See caption for figure 6.

Some of the holes in Craig County had very slight shows of gas. These boreholes (2, 3, and 4; fig. 2) bubbled gas at various rates. The owners of the property on which these wells were drilled had a service company run temperature survey logs. The service company picked several zones interpreted as providing gas to the borehole. Flow rates determined by a representative of DOE were about 10-20 cubic feet of gas per day. Additional details on the gas shows encountered during this project can be found in Appendix D.

Core Analysis

Table 1 shows data obtained from core material taken from five wells. The oil-bearing sandstones for boreholes 6 and 11 are very fine- to medium-grained sandstones with minor amounts of feldspar, chert, and clay. Within a predominantly sandy section, there are often distinct stringers of clay that vary from 1/8 to 3/4 of an inch in thickness. The clay layers would serve as effective seals within a single sandstone and thus constitute a significant reservoir problem. The influence of such lithology is shown by core samples from wells 6 and 11, which have porosity and varying degrees of saturation but are either impermeable or have very low permeabilities. Individual borehole lithology and logs are shown in Appendix E.

Selected thin-section descriptions of sandstones and siltstones in the Warner interval can be found in Appendix B. No other sandstones were subjected to core analysis or petrographic examination.

Distribution of Warner and Bluejacket Sandstones

Isopach maps of sandstones in the Warner and Bluejacket intervals are shown in figures 6 and 7. Both isopachs are characterized by highly localized sand-rich lobes. The major sandstone in the Bluejacket interval is restricted to the western portion of the study area and attains a maximum thickness of nearly 60 feet (fig. 6).

The Warner Sandstone has three major lobes in the study area (fig. 7). Two lobes are approximately 11-12 feet thick, while the westernmost lobe has a maximum thickness of 16 feet. The areal distribution of the sand bodies is consistent with previous interpretations summarized by Ebanks et al. (1977).

Summary

The results of this study indicate that significant quantities of heavy oil are unlikely in northern Craig and Ottawa Counties. Middle Pennsylvanian sandstones in this area are discontinuous and vary considerably in reservoir quality, especially permeability (table 1). Wells drilled 1 mile from each other (for example, wells 1 and 2 in Craig County; wells 8 and 9 in Ottawa County) can be correlated with each other on the basis of coal beds; however, sandstones present in one well may not be present in the other.

The lack of oil in sandstones that do have good reservoir characteristics suggests that heavy-oil potential of the study area is low. Table 1 shows that hole 1 had the highest permeability of any sample measured. The same sample, however, did not have any oil saturation. Thus the heavy-oil resources of the study area are virtually nil, and future resource estimates of the Tri-State area must consider the results of this project.

GEOCHEMISTRY

Four sandstones in the Warner interval and two cores of Mississippian limestone were selected for detailed bitumen study. Bituminous material was

TABLE 1. -- Results of porosity, permeability, and saturation measurements.

Well	Depth feet	Porosity (percent)	Saturation Oil	Saturation Water	Saturation Total	Permeability (millidarcies)
1	23.5	17.0				37.0
1	26.5	19.7				7.8
6	131.5	18.7	31	50	81	5.3
6	132.5	15.6	41	38	79	8.1
6	133.5	20.6	42	46	88	4.7
6	153.5	12.8	3	40	43	0.33
9	124.7	17.4				Imp.
9	126.9	24.9				0.26
9	127.2	23.6				Imp.
11	41.5	12.8	3	23	26	Imp.
11	42.5	13.5	10	19	29	Imp.
11	43.5	22.7	20	10	30	7.2
11	44.5	12.1	55	15	70	16.0
16	265.5	8.9				Imp.
16	267.5	8.9				Imp.
16	272.5	11.7				0.13
18	210.5	15.4				Imp.
18	211.5	6.7				Imp.

extracted from these samples by soxhlet techniques and separated by adsorption chromatographic methods into hydrocarbon and non-hydrocarbon fractions. Procedures used in this portion of the study are essentially the same as those used by Ebanks et al. (1977).

Only three of the 18 samples had total bitumen concentrations greater than 2 percent, and 13 samples had bitumen yields of less than 1 percent (table 2). These yields are considerably lower than those reported by Ebanks et al. (1977) for Pennsylvanian sands in southeastern Kansas. Samples with bitumen yields greater than 0.3 to 0.4 percent provide the best data on class distribution because of the error involved in working with very small quantities. Samples in table 2 that have bitumen yields of 0.3 percent and greater average over 60 percent total hydrocarbons. Asphaltenes and nitrogen-, sulfur-, and oxygen-containing compounds are somewhat low in quantity when compared to tar sands and other heavy oils.

The chemical characteristics of the heavy oil in the Tri-State area indicate some type of degradation. The undegraded original oil probably had an API gravity similar to other oils on the Cherokee platform such as Avant (34° API), Glenn Pool (37° API) and Burbank (37° API) Fields. The extent of degradation, however, is open to question. Evans et al. (1971) found that Mississippian oils in Saskatchewan which had experienced the greatest alteration or degradation were depleted in saturated hydrocarbons and enriched (relative to saturates) in aromatics. The concentrations of saturated hydrocarbons in Tri-State heavy oils suggest that perhaps degradation of liquid petroleum has not been too severe. Degradation has, however, resulted in sufficient alteration so that Tri-State heavy oil has chemical characteristics which are quite distinct from other Pennsylvanian oils in the area.

TABLE 2. --Rock type and chemical characteristics of extracted oils (bitumen).

Hole	Interval, (ft.)	Lithology	Bitumen, Percent	Asphaltenes, Percent	Sat. Hydrocarbons, Percent	Arom. Hydrocarbons, Percent	NSO's, Percent
6	105.0-106.0	sandstone	0.4	5	11	30	54
6	106.2-106.9	sandstone	0.1	*			
6	106.9-107.2	sandstone	0.3	11	4	28	56
6	131.5-132.0	sandstone	1.9	17	34	26	24
6	132.5-133.0	sandstone	2.2	9	40	27	24
6	133.5-134.0	sandstone	3.2	14	38	33	15
8	164.3-164.4	limestone	0.1	14	32	29	25
9	126.0-126.2	sandstone	0.1	*			
9	126.8-127.1	sandstone	0.1	*			
9	128.0-128.2	sandstone	0.1	*			
9	128.4-128.6	sandstone	0.1	20	5	23	52
9	165.7-166.1	limestone	0.3	12	42	34	12
9	166.3-166.5	limestone	0.3	9	46	36	9
9	166.7-167.0	limestone	0.1	*			
9	168.5-168.7	limestone	0.2	36	22	20	22
9	169.2-169.5	limestone	0.4	39	32	22	6
11	43.5-44.0	sandstone	1.7	6	33	35	26
11	44.0-45.0	sandstone	2.2	10	32	33	26

*yields too low for column chromatography

ACKNOWLEDGMENTS

Many individuals assisted in various phases of this project. John Webb collected and interpreted many of the existing records for northeastern Oklahoma. Jack S. Wells, W. J. Ebanks, Jr., and Boyd R. Haley provided much information and valuable assistance while the project was being conducted. Appreciation is extended to Grant D. Zimbrick and Gary S. Steffens, who contributed to the laboratory and field work associated with this investigation. Robert O. Fay supervised the drilling activity. Joseph A. Curiale performed the geochemical analyses.

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APPENDIX A

FIELD METHODS

A total of 18 wells were drilled by the Oklahoma Geological Survey during 1977 and 1978. The 16 sites drilled in 1977 were selected on the basis of regional subsurface study. The two holes drilled in 1978 were determined by results of the first 16 holes. Personnel of the Oklahoma Geological Survey contacted landowners for permission to drill and also filed appropriate information with the Oklahoma Corporation Commission. Drill sites were inspected by representatives of the Oklahoma Corporation Commission after the project was completed. Drill sites were usually in pastures near section-line roads or at the edges of soybean fields. Elevations were determined from the nearest section corners.

Holes were drilled using both air and conventional rotary techniques. Well-site geologists supervised the drilling activity and collected and bagged cuttings and 4- and 5-foot intervals. All wells were drilled a few feet into the Mississippian limestone for correlation purposes. Coring points were determined by a combination of (1) projection from previous holes and (2) shows in the cuttings. All cored intervals were laid out, marked, examined, and described at the well site. Sandstones selected for petrophysical measurements were sealed in small metal cans and shipped to a service company for determination of porosity, permeability, and oil-water saturation.

Gamma-ray--neutron logs were run by a commercial service company. Both types of logs were useful in correlation, but detailed petrophysical information could not be obtained.

Representative samples of sandstone in the Warner interval were selected for thin-sectioning and petrographic study. Minerals that could not be identified by optical methods were subjected to X-ray diffraction techniques for positive identification. The results of thin-section examinations are presented in Appendix B.

APPENDIX B

THIN-SECTION DESCRIPTIONS OF SANDSTONES AND SILTSTONES IN THE WARNER INTERVAL

Stratigraphic Test Hole 6

130 feet — Fine-grained sandstone: immature quartz arenite cemented primarily by clay material

60-65%	subangular to subrounded fine quartz sand
10%	clay and clay altered to sericite (cement)
10%	opaque material (probably tar)
5%	trace minerals including chert, muscovite, orthoclase, ilmenite, and zircon
10-15%	porosity (est.)

131 feet — Fine-grained sandstone: immature quartz arenite cemented by calcite and clay

60%	subangular quartz sand
10%	minor minerals including chert, altered feldspar, muscovite, and zircon
15%	limonite-stained clay (cement)
5-10%	quartz overgrowths
5%	patchy calcite (cement)

132 feet — Fine-grained sandstone: mature quartz aernite cemented by calcite and quartz

60%	subrounded quartz sand
10%	minor minerals including chert, weathered feldspar, muscovite, and zircon
15%	quartz overgrowths (cement)

10% calcite (cement)

5% heavy oil or tar

133 feet Fine-grained sandstone: immature quartz arenite cemented by calcite and limonite

- 65% subangular fine quartz sand
- 15% limonite (cement)
- 10% patchy calcite (cement)
- 5% quartz overgrowths (cement)
- 5% trace minerals including chert, muscovite, zircon, and clay clasts

Stratigraphic Test Hole 11

41 feet Fine- to medium-grained sandstone: immature quartz arenite cemented by quartz and clay

- 65% subangular fine to medium quartz sand
- 15% clay and clay altered to sericite (cement)
- 5-10% quartz overgrowth (cement)
- 5% weathered feldspar and clay clasts
- 5% heavy oil or tar

42 feet Very fine-grained sandstone: immature quartz arenite cemented by clay

- 65% subangular very fine to medium quartz sand
- 15% clay and clay altered to sericite (cement)
- 10% siderite (cement)
- 10% minor minerals including weathered feldspar, chert, muscovite, and zircon

43 feet Medium-grained sandstone: mature arenite cemented by calcite and clay

65% medium quartz sand grains

20% limonite-stained clay (cement)

10% patchy calcite (cement)

5% heavy oil or tar

44 feet Very fine-grained sandstone: immature quartz arenite cemented by calcite and clay

60% subangular very fine to medium quartz sand

20% clay (cement)

10% calcite (cement)

5% trace minerals including muscovite, plagioclase, and zircon

5% heavy oil or tar

Stratigraphic Test Hole 16

274 feet Siltstone: mature quartz arenite cemented by calcite

60% subangular quartz silt

35% calcite (cement)

5% trace minerals including magnetite, muscovite, zircon, and plagioclase

APPENDIX C

CORRELATIONS AND CROSS SECTIONS

Correlation of individual sandstone units proved to be impossible over long distances due to the discontinuous nature of these beds. Thin coal beds provided the best means of correlation throughout the study area, and Section B (fig. C-1) demonstrates the lateral continuity of some of these beds. Some of the coals, however, are the result of highly localized transgressive-regressive cycles and are not useful for correlation. Two such coals are present in the 120- to 140-foot interval in borehole 9.

The gamma ray-neutron logs also provided a means of correlation. Section A (fig. C-1) indicates the similarity in gamma ray-neutron response for several intervals penetrated in the study area. Coals and sandstones noted on the sample logs can be correlated with characteristic patterns on both gamma-ray and neutron curves.

Stratigraphic units identified on B are the result of a separate Oklahoma Geological Survey project being conducted for Craig County and are tentative.

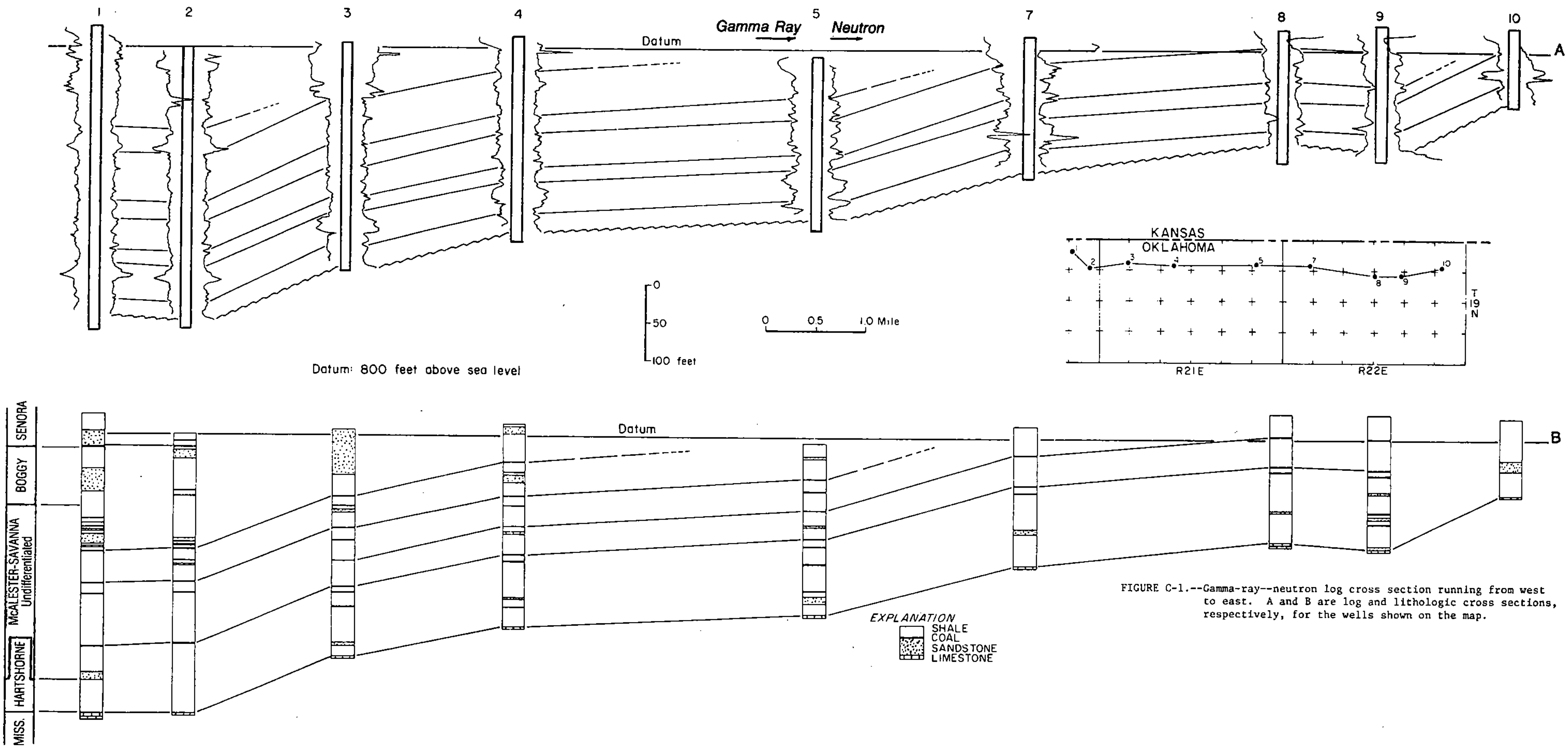


FIGURE C-1.--Gamma-ray--neutron log cross section running from west to east. A and B are log and lithologic cross sections, respectively, for the wells shown on the map.

APPENDIX D

GASEOUS HYDROCARBON SHOWS

Figure D-1 shows the relation between lithology and the temperature surveys that some of the landowners obtained from a service company. The service company identified specific intervals that were contributing gas to the borehole. Flow rates were determined by DOE personnel from the Bartlesville Energy Research Center to be about 10-20 cubic feet of gas per day. The landowners did not attempt to complete any of the OGS stratigraphic tests as gas wells.

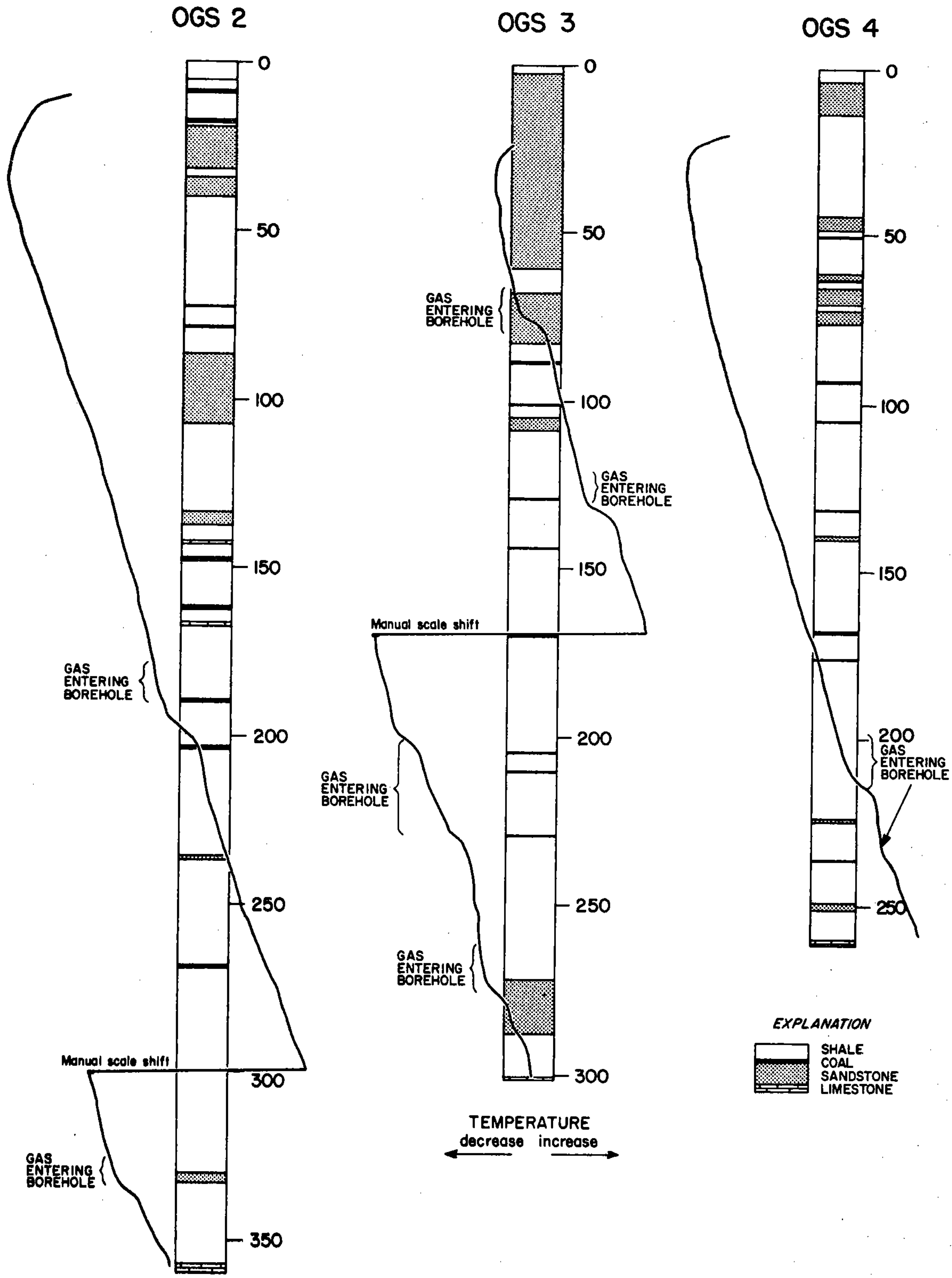
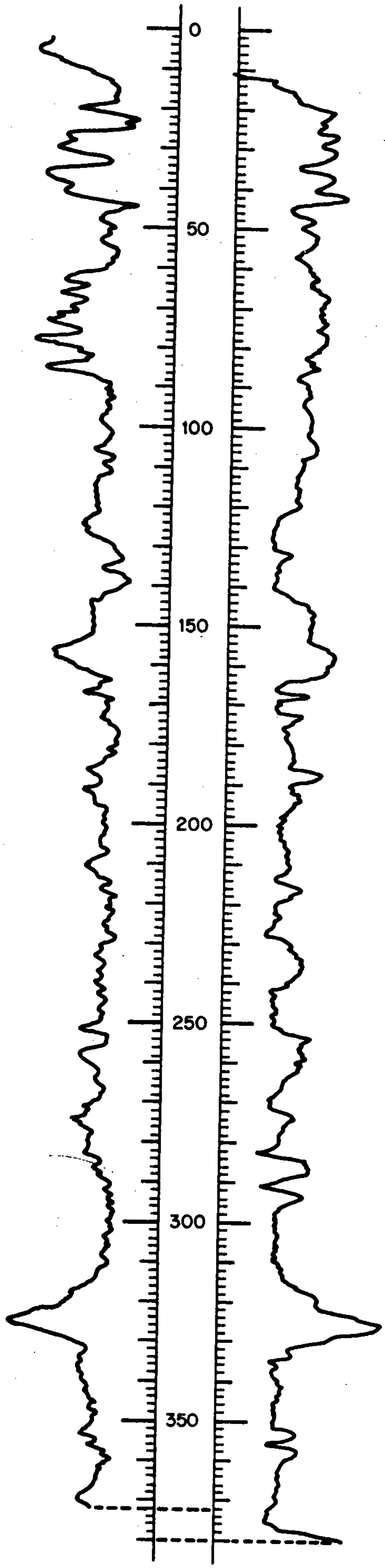


FIGURE D-1.--Relation between lithology and zones where gas entered borehole.

APPENDIX E

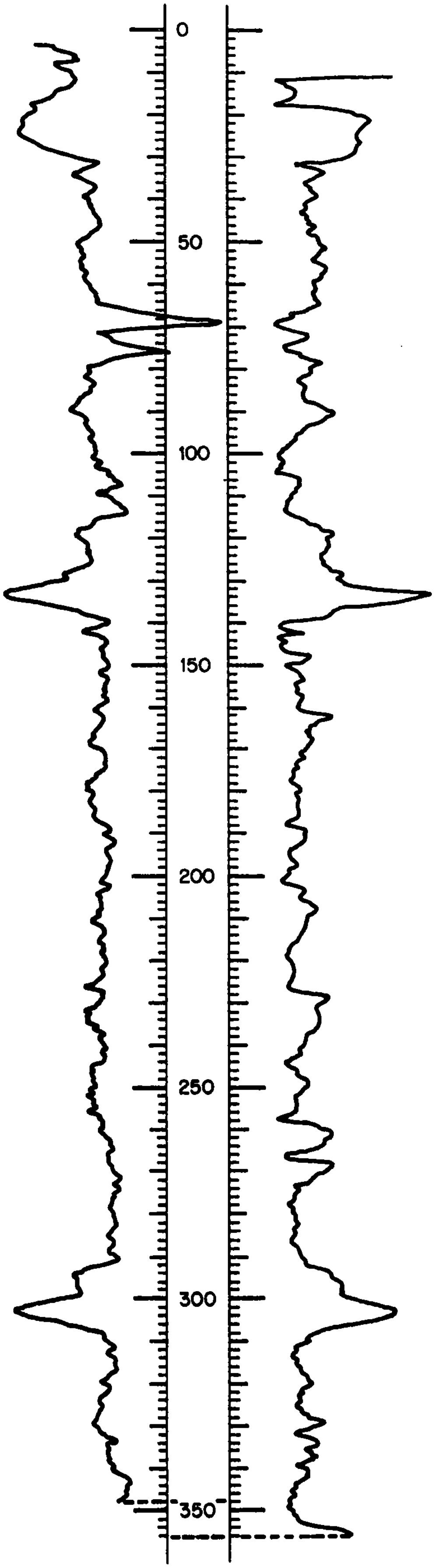
INDIVIDUAL BOREHOLE LITHOLOGY AND LOGS

Individual gamma-ray--neutron logs and lithologic descriptions for the 18 boreholes drilled for this project are shown at reduced scales. The original logs at a vertical scale of 5 inches per 100 feet are on file at the Oklahoma Geological Survey. Gamma-ray (on the left) and neutron (on the right) values are relative measurements only. Both values increase from left to right. Lithology is based on dominant rock type in given intervals.



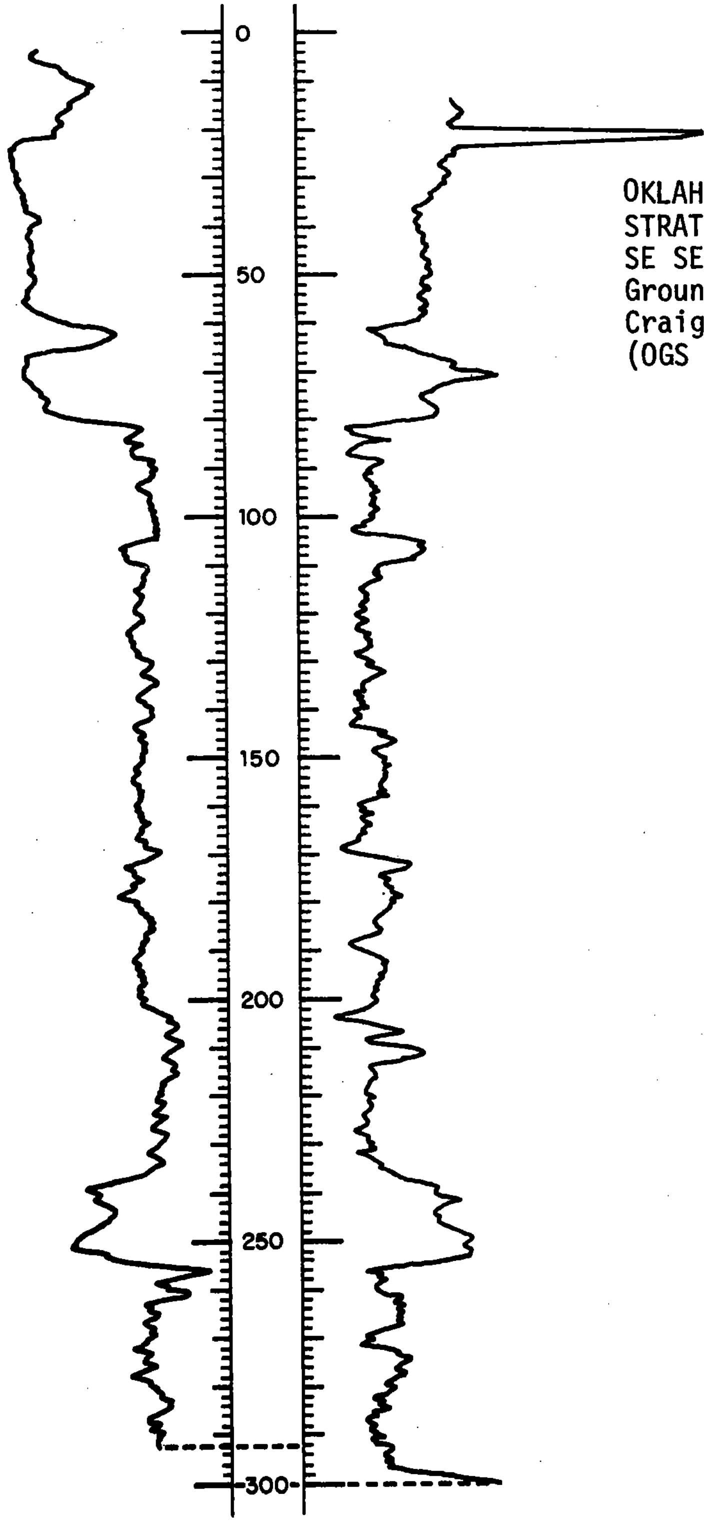
OKLAHOMA GEOLOGICAL SURVEY
STRATIGRAPHIC TEST HOLE 1
C NW SW NW Sec. 13 T. 29 N., R. 20 E.
Ground Elevation 825 feet
Craig County, Oklahoma
(OGS - Don Stewart no. 1)

Footage			Lithology
0	-	6.0	Soil
6.0	-	12.0	Shale
12.0	-	14.0	Shale
14.0	-	17.5	shale
17.5	-	28.0	Sandstone
28.0	-	41.0	Shale
41.0	-	42.0	Coal
42.0	-	43.0	Clay
43.0	-	68.0	Shale
68.0	-	97.5	Sandstone
97.5	-	131.0	Shale
131.0	-	131.4	Coal
131.4	-	132.4	Clay
132.4	-	137.0	Shale
137.0	-	137.4	Coal
137.4	-	138.4	Clay
138.4	-	142.0	Shale
142.0	-	143.0	Coal
143.0	-	146.0	Clay
146.0	-	148.0	Sandstone
148.0	-	152.0	Shale
152.0	-	164.4	Sandstone
164.4	-	167.5	Shale
167.5	-	168.0	Limestone
168.0	-	172.3	Shale
172.3	-	172.5	Coal
172.5	-	174.0	Underclay
174.0	-	214.5	Shale
214.5	-	214.8	Coal
214.8	-	217.0	Clay
217.0	-	227.8	Shale
227.8	-	228.2	Coal
228.2	-	232.0	Clay
232.0	-	294.0	Shale
294.0	-	294.2	Coal
294.2	-	295.2	Clay
295.2	-	327.0	Shale
327.0	-	338.0	Sandstone
338.0	-	372.0	Shale
372.0	-	380.0	Clay
380.0	-	388.0	Limestone



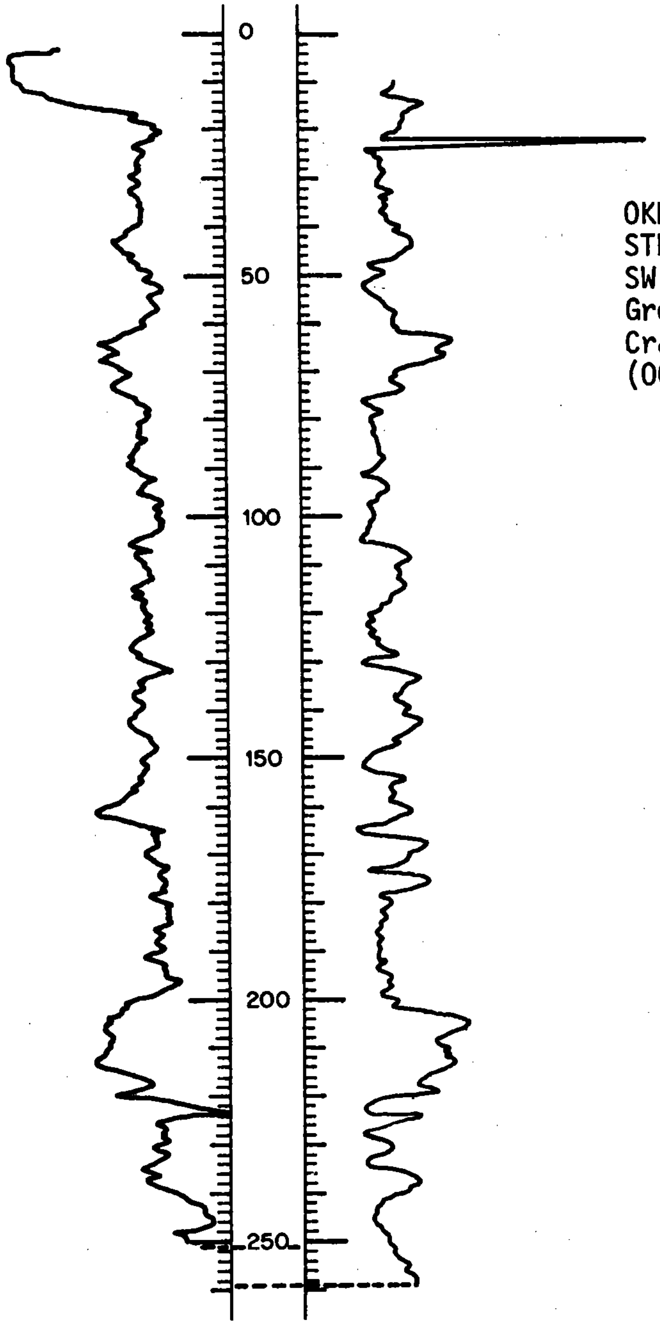
OKLAHOMA GEOLOGICAL SURVEY
STRATIGRAPHIC TEST HOLE 2
SE NE SW SW SE Sec. 13 T. 29 N., R. 20 E.
Ground Elevation 801 feet
Craig County, Oklahoma
(OGS - Charles Rickman no. 1)

Footage			Lithology
0	-	5	Soil
5.0	-	8.5	Shale
8.5	-	8.6	Coal
8.6	-	18.0	Shale
18.0	-	19.0	Coal
19.0	-	31.9	Clay
31.9	-	32.0	Sandstone
32.0	-	33.0	Shale
33.0	-	72.0	Clay
72.0	-	72.2	Coal
72.2	-	74.0	Clay
74.0	-	78.0	Shale
78.0	-	78.2	Coal
78.2	-	80.0	Clay
80.0	-	107.0	Shale
107.0	-	109.0	Clay
109.0	-	133.0	Shale
133.0	-	137.0	Sandstone
137.0	-	142.0	Shale
142.0	-	142.5	Limestone
142.5	-	147.0	Shale
147.0	-	147.5	Coal
147.5	-	148.5	Clay
148.5	-	161.8	Shale
161.8	-	162.0	Coal
162.0	-	164.0	Clay
164.0	-	166.0	Shale
166.0	-	166.5	Limestone
166.5	-	188.5	Shale
188.5	-	189.0	Coal
189.0	-	191.5	Clay
191.5	-	203.0	Shale
203.0	-	203.2	Coal
203.2	-	205.0	Clay
205.0	-	242.5	Shale
242.5	-	245.0	Clay
245.0	-	259.0	Shale
259.0	-	263.0	Clay
263.0	-	267.8	Shale
267.8	-	268.0	Coal
268.0	-	270.0	Clay
270.0	-	288.0	Shale
288.0	-	289.0	Clay
289.0	-	307.5	Shale
307.5	-	309.0	Clay
309.0	-	329.0	Shale
329.0	-	332.0	Sandstone
332.0	-	333.0	Shale
333.0	-	334.0	Clay
334.0	-	343.0	Shale
343.0	-	344.0	Clay
344.0	-	356.0	Shale
356.0	-	358.5	Limestone



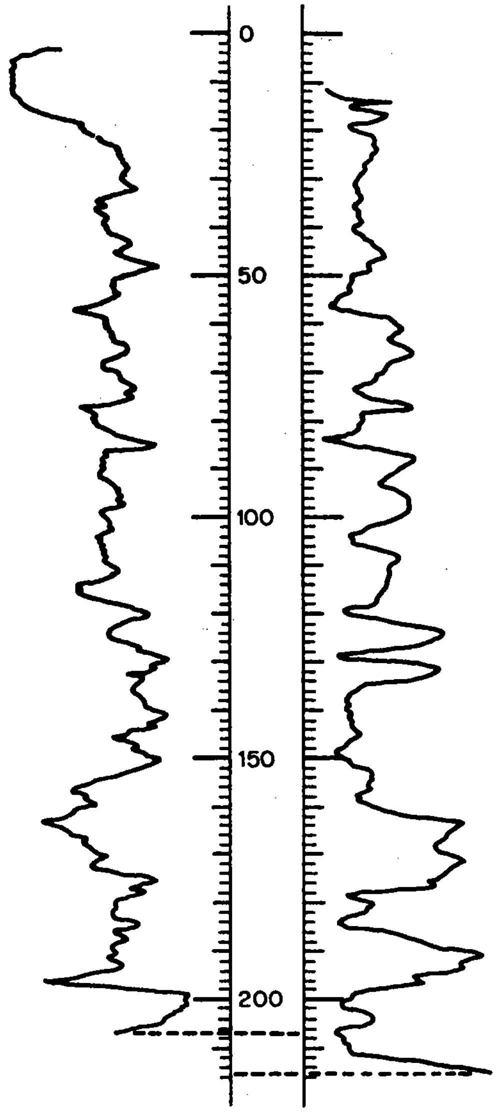
OKLAHOMA GEOLOGICAL SURVEY
STRATIGRAPHIC TEST HOLE 3
SE SE NE SE Sec. 18 T. 29 N., R. 21 E.
Ground Elevation 812 feet
Craig County, Oklahoma
(OGS - Walter Goddard no. 1)

Footage			Lithology
0	-	2.0	Soil
2.0	-	60.0	Sandstone
60.0	-	67.0	Clay
67.0	-	87.5	Shale
87.5	-	88.0	Coal
88.0	-	89.0	Clay
89.0	-	100.0	Shale
100.0	-	100.2	Coal
100.2	-	102.0	Clay
102.0	-	128.0	Shale
128.0	-	128.2	Coal
128.2	-	131.0	Clay
131.0	-	142.5	Shale
142.5	-	142.7	Coal
142.7	-	144.0	Clay
144.0	-	168.8	Shale
168.8	-	169.0	Coal
169.0	-	170.0	Clay
170.0	-	185.0	Shale
185.0	-	186.0	Clay
186.0	-	203.5	Shale
203.5	-	204.0	Coal
204.0	-	205.0	Clay
205.0	-	209.0	Shale
209.0	-	209.5	Coal
209.5	-	210.0	Clay
210.0	-	228.0	Shale
228.0	-	228.2	Coal
228.2	-	229.0	Clay
229.0	-	284.0	Shale
284.0	-	288.0	Sandstone
288.0	-	303.0	Shale
303.0	-	304.0	Limestone



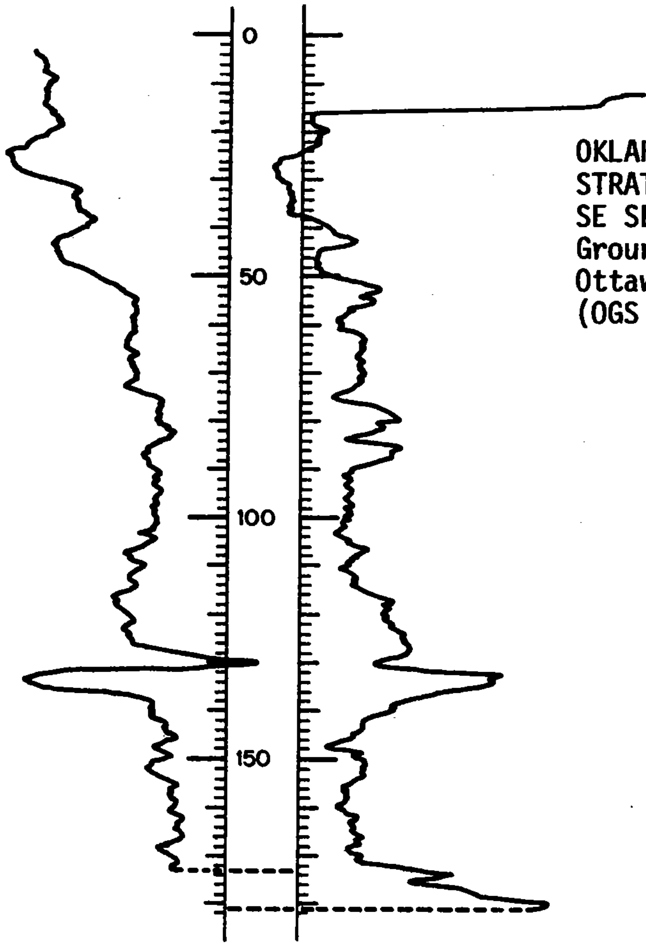
OKLAHOMA GEOLOGICAL SURVEY
STRATIGRAPHIC TEST HOLE 4
SW NE SE SW Sec. 16 T. 29 N., R. 21 E.
Ground Elevation 817 feet
Craig County, Oklahoma
(OGS - Walter Gray no. 1)

Footage			Lithology
0	-	4.0	Soil
4.0	-	14.0	Sandstone
14.0	-	22.0	Clay
22.0	-	50.0	Shale
50.0	-	50.2	Coal
50.2	-	53.0	Clay
53.0	-	61.0	Shale
61.0	-	63.0	Sandstone
63.0	-	63.3	Coal
63.3	-	65.0	Clay
65.0	-	70.0	Sandstone
70.0	-	72.0	Clay
72.0	-	76.0	Sandstone
76.0	-	92.6	Shale
92.6	-	93.3	Coal
93.3	-	98.0	Clay
98.0	-	105.0	Shale
105.0	-	105.3	Coal
105.3	-	107.0	Clay
107.0	-	131.0	Shale
131.0	-	131.3	Coal
131.3	-	132.3	Clay
132.3	-	139.0	Shale
139.0	-	139.5	Sandstone
139.5	-	167.6	Shale
167.6	-	168.0	Coal
168.0	-	169.5	Clay
169.5	-	175.8	Shale
175.8	-	176.0	Coal
176.0	-	223.0	Shale
223.0	-	224.0	Sandstone
224.0	-	235.0	Shale
235.0	-	235.1	Coal
235.1	-	236.0	Clay
236.0	-	259.0	Shale
259.0	-	260.0	Limestone



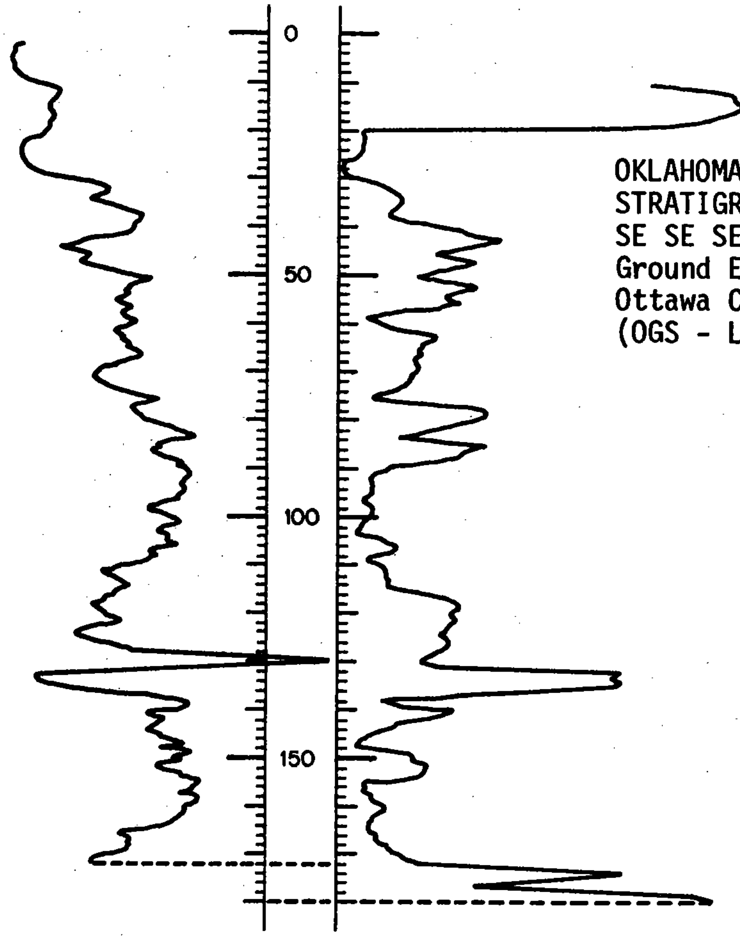
OKLAHOMA GEOLOGICAL SURVEY
STRATIGRAPHIC TEST HOLE 5
NW NW SW SW Sec. 13 T. 29 N., R. 21 E.
Ground Elevation 791 feet
Ottawa County, Oklahoma
(OGS - Richard Boyd no. 1)

Footage			Lithology
0	-	6.0	Soil
6.0	-	10.0	Clay
10.0	-	16.0	Gravel
16.0	-	18.0	Sandstone
18.0	-	40.5	Shale
40.5	-	40.7	Coal
40.7	-	43.2	Clay
43.2	-	56.0	Shale
56.0	-	56.2	Coal
56.2	-	59.0	Clay
59.0	-	84.0	Shale
84.0	-	84.7	Coal
84.7	-	85.7	Clay
85.7	-	102.0	Shale
102.0	-	104.0	Siltstone
104.0	-	119.5	Shale
119.5	-	120.0	Coal
120.0	-	121.5	Clay
121.5	-	129.0	Shale
129.0	-	129.4	Coal
129.4	-	130.0	Clay
130.0	-	150.0	Shale
150.0	-	150.5	Coal
150.5	-	151.5	Clay
151.5	-	184.0	Shale
184.0	-	184.5	Coal
184.5	-	186.0	Clay
186.0	-	193.0	Shale
193.0	-	198.0	Sandstone
198.0	-	216.0	Shale
216.0	-	218.0	Limestone



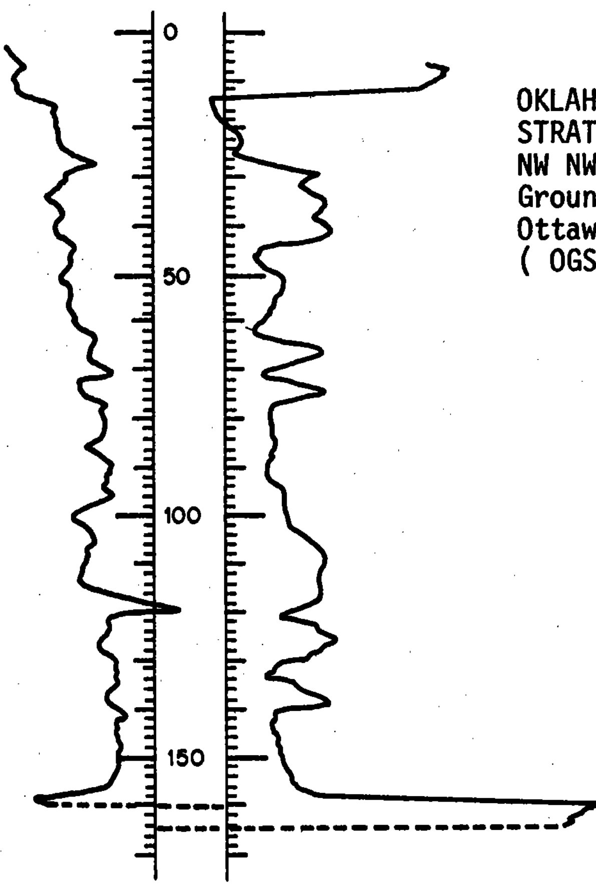
OKLAHOMA GEOLOGICAL SURVEY
STRATIGRAPHIC TEST HOLE 6
SE SE SE SE Sec. 18 T. 29 N., R. 22 E.
Ground Elevation 819 feet
Ottawa County, Oklahoma
(OGS - Leo Alsbaugh no. 1-A)

Footage			Lithology
0	-	92.0	See # 7
92.0	-	101.1	Shale
101.1	-	101.4	Coal
101.4	-	104.5	Shale
104.5	-	122.0	Sandstone
122.0	-	128.9	Shale
128.9	-	134.2	Sandstone
134.2	-	152.0	Shale
152.0	-	153.3	Sandstone
153.3	-	182.0	Shale
182.0	-	183.0	Limestone



OKLAHOMA GEOLOGICAL SURVEY
STRATIGRAPHIC TEST HOLE 7
SE SE SE SE Sec. 18 T. 29 N., R. 22 E.
Ground Elevation 819 feet
Ottawa County, Oklahoma
(OGS - Leo Alsbaugh no. 1)

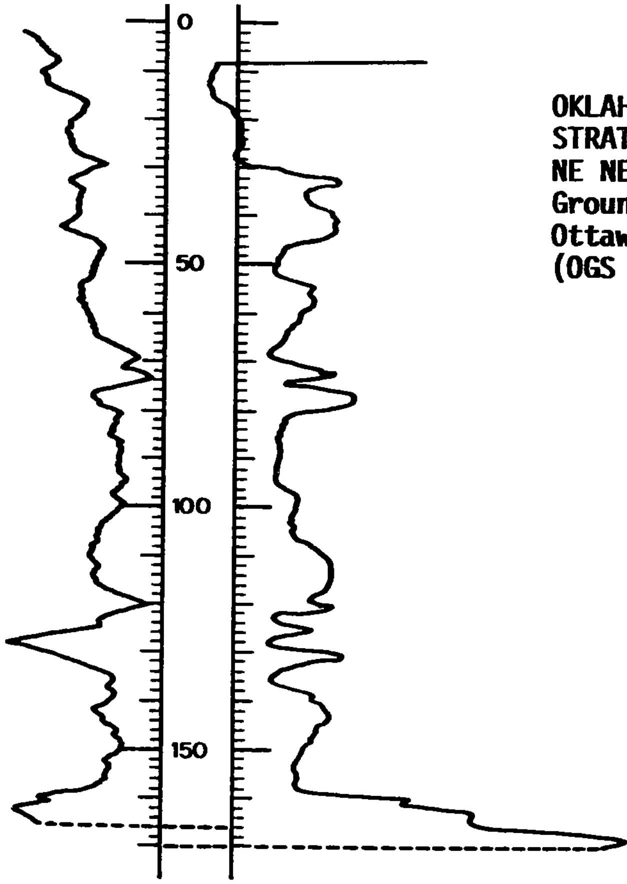
Footage			Lithology
0	-	3.0	Soil
3.0	-	18.0	Clay
18.0	-	33.0	Gravel
33.0	-	40.0	Shale
40.0	-	40.2	Coal
40.2	-	41.5	Clay
41.5	-	49.0	Shale
49.0	-	53.0	Sandstone
53.0	-	78.5	Shale
78.5	-	79.0	Coal
79.0	-	79.5	Clay
79.5	-	86.5	Shale
86.5	-	87.5	Coal
87.5	-	88.5	Clay
88.5	-	135.0	Shale
135.0	-	142.0	Sandstone
142.0	-	182.0	Shale
182.0	-	184.0	Limestone



OKLAHOMA GEOLOGICAL SURVEY
STRATIGRAPHIC TEST HOLE 8
NW NW NW NW Sec. 22 T. 29 N. R. 22 E.
Ground Elevation 831 feet
Ottawa County, Oklahoma
(OGS - M. B. Darnell no. 1)

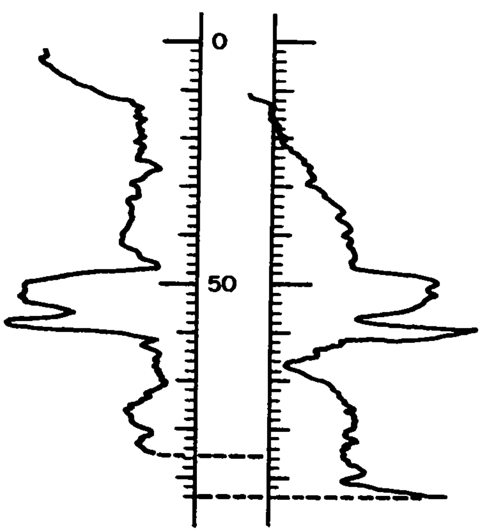
Footage			Lithology
0	-	8.0	Clay
8.0	-	8.5	Gravel
8.5	-	27.0	Clay
27.0	-	27.5	Coal
27.5	-	30.0	Clay
30.0	-	63.8	Shale
63.8	-	64.5	Coal
64.5	-	69.8	Clay
69.8	-	71.5	Shale
71.5	-	71.8	Coal
71.8	-	75.5	Clay
75.5	-	120.0	Shale
120.0	-	121.0	Siltstone
121.0	-	124.0	Shale
124.0	-	124.1	Sandstone
124.1	-	131.0	Siltstone
131.0	-	160.0	Shale
160.0	-	165.4	Limestone

OKLAHOMA GEOLOGICAL SURVEY
STRATIGRAPHIC TEST HOLE 9
NE NE NE NE Sec. 22 T. 29 N., R. 22 E.
Ground Elevation 830 feet
Ottawa County, Oklahoma
(OGS - Paul Darnell no. 1)

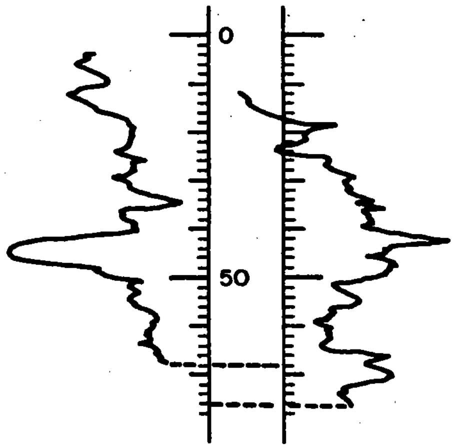


Footage			Lithology
0	-	22.0	Clay
22.0	-	28.0	Shale
28.0	-	28.8	Coal
28.8	-	30.0	Clay
30.0	-	67.7	Shale
67.7	-	68.1	Coal
68.1	-	73.0	Clay
73.0	-	73.7	Shale
73.7	-	74.3	Coal
74.3	-	80.0	Clay
80.0	-	90.0	Shale
90.0	-	94.2	Clay
94.2	-	96.2	Sandstone
96.2	-	121.5	Shale
121.5	-	122.0	Coal
122.0	-	124.7	Shale
124.7	-	124.8	Conglomerate
124.8	-	128.7	Sandstone
128.7	-	131.0	Siltstone
131.0	-	134.5	Shale
134.5	-	135.0	Coal
135.0	-	163.0	Shale
163.0	-	165.7	Sandstone
165.7	-	171.7	Limestone

OKLAHOMA GEOLOGICAL SURVEY
STRATIGRAPHIC TEST HOLE 10
NW SE SW SW Sec. 13 T. 29 N., R 22 E.
Ground Elevation 826 feet
Ottawa County, Oklahoma
(OGS - Berl Garrett no. 1)

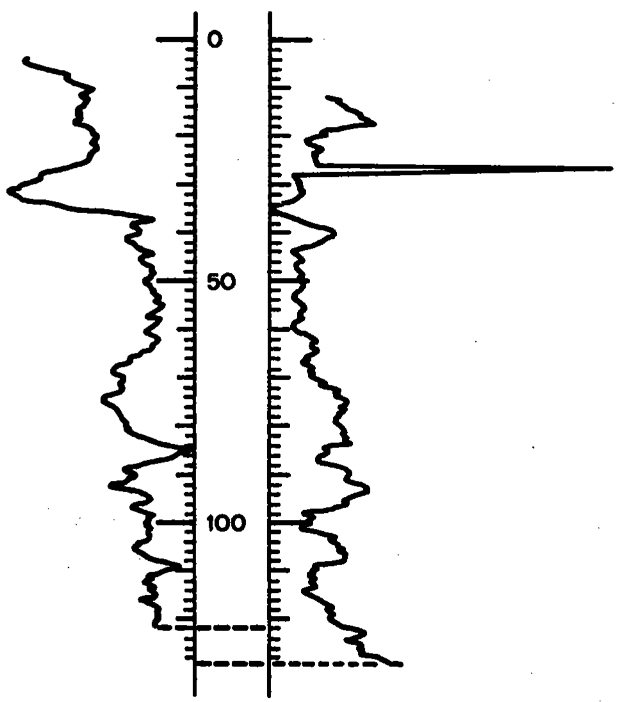


Footage			Lithology
0	-	2.0	Soil
2.0	-	10.0	Clay
10.0	-	51.0	Shale
51.0	-	59.0	Sandstone
59.0	-	60.0	Shale
60.0	-	63.0	Sandstone
63.0	-	95.0	Shale
95.0	-	96.0	Limestone



OKLAHOMA GEOLOGICAL SURVEY
STRATIGRAPHIC TEST HOLE 11
NW NW NW SW Sec. 24 T. 29 N., R. 22 E.
Ground Elevation 817 feet
Ottawa County, Oklahoma
(OGS - Berl Garrett no. 2)

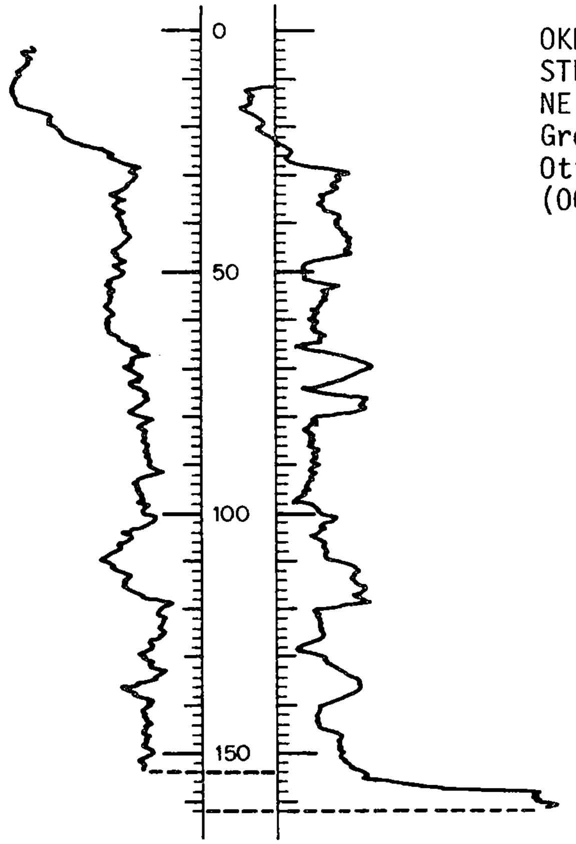
Footage			Lithology
0	-	4.0	Soil
4.0	-	15.0	Clay
15.0	-	21.0	Gravel
21.0	-	26.0	Clay
26.0	-	26.3	Coal
26.3	-	28.0	Clay
28.0	-	42.0	Shale
42.0	-	51.0	Sandstone
51.0	-	72.0	Shale
72.0	-	72.2	Coal
72.2	-	88.0	Shale
88.0	-	88.5	Limestone



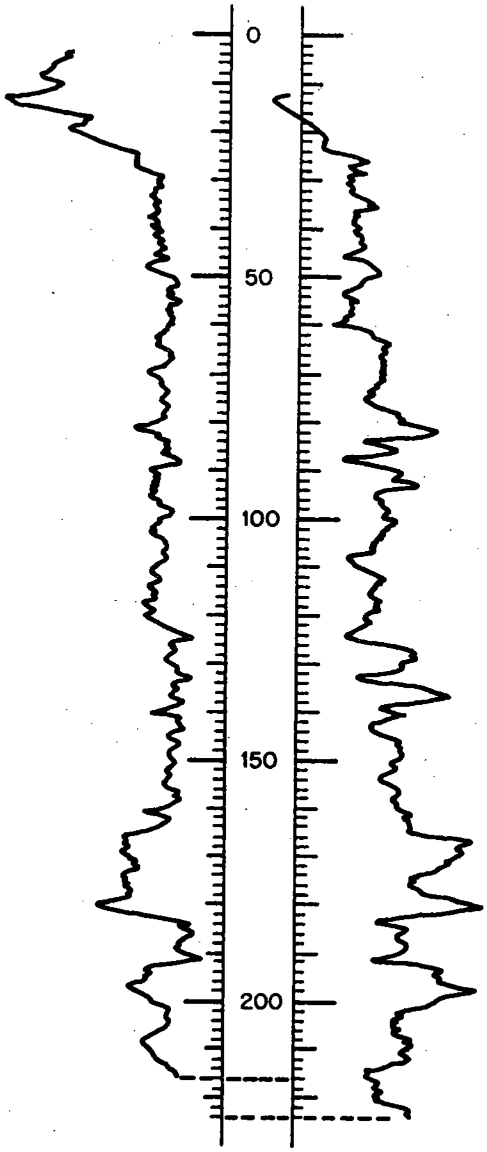
OKLAHOMA GEOLOGICAL SURVEY
STRATIGRAPHIC TEST HOLE 12
NE NE NE NE Sec. 29 T. 29 N., R. 22 E.
Ground Elevation 818 feet
Ottawa County, Oklahoma
(OGS - Clyde Bachman no. 1)

Footage			Lithology
0	-	3.0	Soil
3.0	-	34.4	Clay
34.4	-	37.0	Gravel
37.0	-	38.0	Shale
38.0	-	38.4	Coal
38.4	-	40.0	Clay
40.0	-	89.6	Shale
89.6	-	90.0	Coal
90.0	-	91.0	Clay
91.0	-	103.0	Shale
103.0	-	103.4	Coal
103.4	-	105.0	Clay
105.0	-	132.0	Shale
132.0	-	134.0	Limestone

OKLAHOMA GEOLOGICAL SURVEY
STRATIGRAPHIC TEST HOLE 13
NE SE SE SE Sec. 24 T. 29 N., R. 21 E.
Ground Elevation 782 feet
Ottawa County, Oklahoma
(OGS - John Sullivan no. 1)

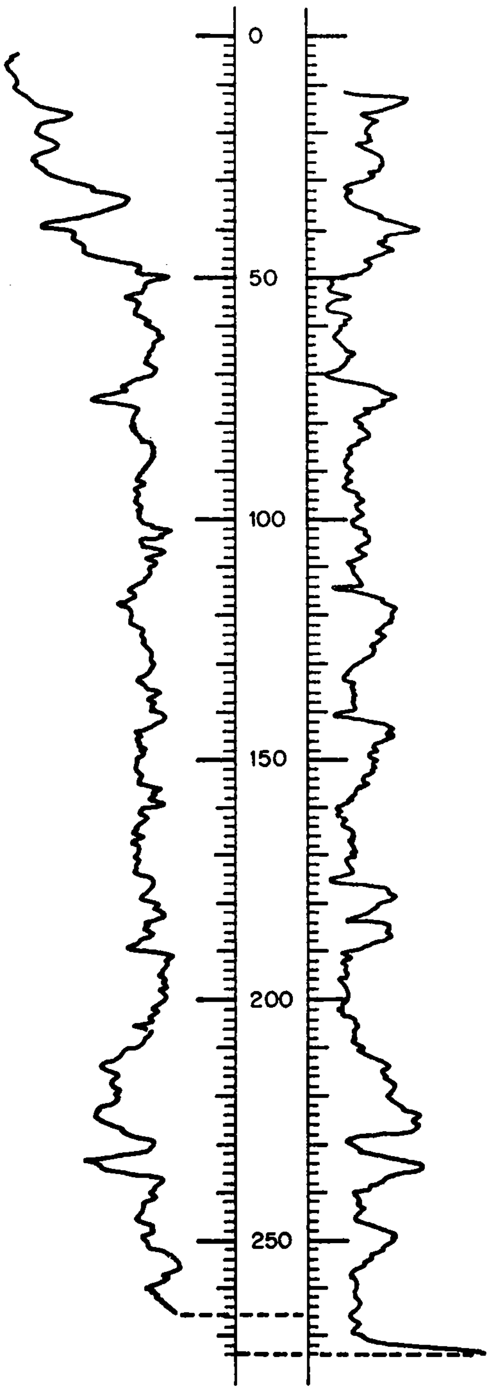


Footage			Lithology
0	-	4.0	Soil
4.0	-	20.0	Clay
20.0	-	27.0	Shale
27.0	-	27.3	Coal
27.3	-	30.0	Clay
30.0	-	41.0	Shale
41.0	-	44.0	Sandstone
44.0	-	50.0	Shale
50.0	-	53.0	Sandstone
53.0	-	65.6	Shale
65.6	-	66.0	Coal
66.0	-	67.5	Clay
67.5	-	74.0	Shale
74.0	-	74.5	Coal
74.5	-	76.0	Clay
76.0	-	98.0	Shale
98.0	-	98.3	Coal
98.3	-	101.0	Clay
101.0	-	120.0	Shale
120.0	-	124.0	Sandstone
124.0	-	128.0	Shale
128.0	-	128.4	Coal
128.4	-	130.0	Clay
130.0	-	160.0	Shale
160.0	-	164.0	Limestone



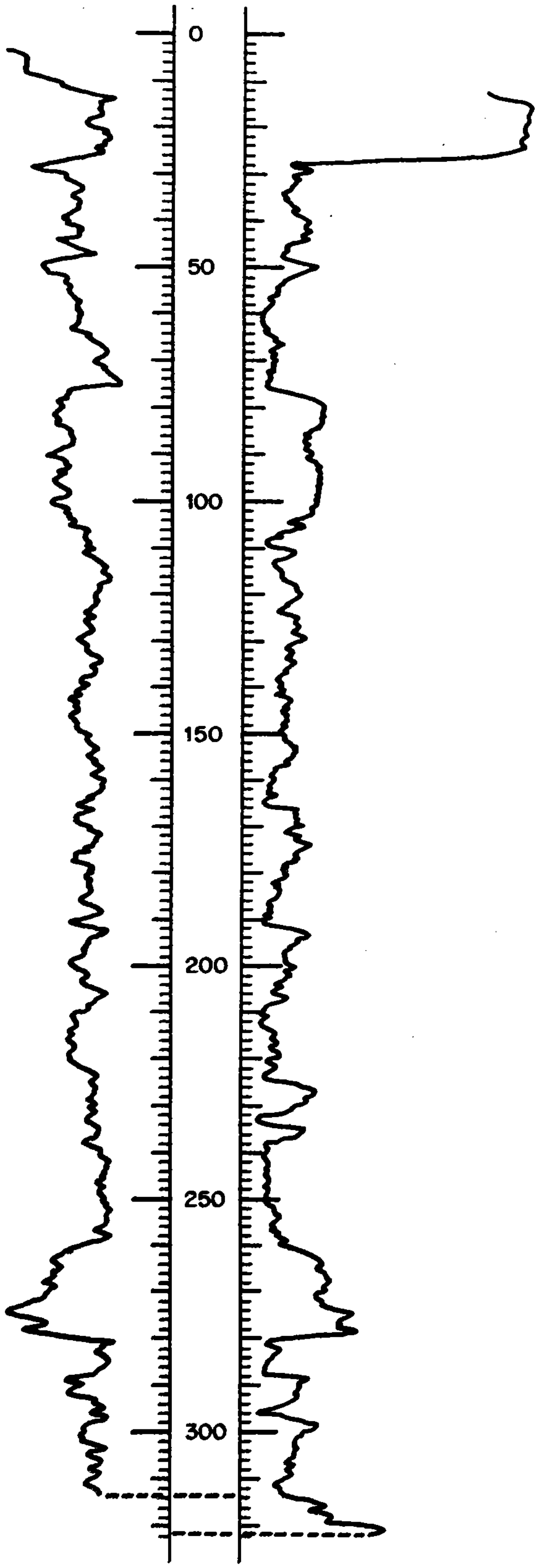
OKLAHOMA GEOLOGICAL SURVEY
STRATIGRAPHIC TEST HOLE 14
SE SE SW NW Sec. 23 T. 29 N., R. 21 E.
Ground Elevation 790 feet
Ottawa County, Oklahoma
(OGS - Gale Bachman no. 1)

Footage			Lithology
0	-	4.0	Soil
4.0	-	12.0	Clay
12.0	-	20.0	Sandstone
20.0	-	61.0	Shale
61.0	-	61.3	Coal
61.3	-	63.0	Clay
63.0	-	83.0	Shale
83.0	-	84.5	Coal
84.5	-	85.0	Clay
85.0	-	125.0	Shale
125.0	-	125.3	Coal
125.3	-	127.0	Clay
127.0	-	133.5	Shale
133.5	-	134.0	Coal
134.0	-	315.6	Clay
135.6	-	156.0	Shale
156.0	-	156.8	Coal
156.8	-	160.0	Clay
160.0	-	191.6	Shale
191.6	-	192.0	Coal
192.0	-	193.6	Clay
193.6	-	222.0	Shale
222.0	-	223.0	Limestone



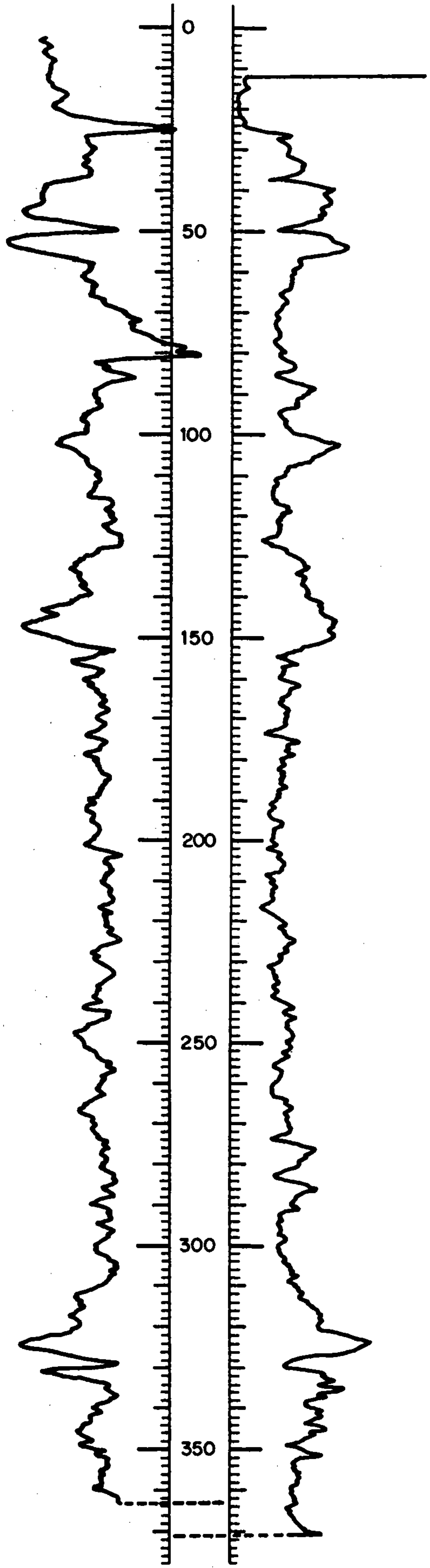
OKLAHOMA GEOLOGICAL SURVEY
STRATIGRAPHIC TEST HOLE 15
NE NW NE NW Sec. 28 T. 29 N., R. 21 E.
Ground Elevation 831 feet
Craig County, Oklahoma
(OGS - Willard Lester no. 1)

Footage			Lithology
0	-	1.0	Soil
1.0	-	30.0	Sandstone
30.0	-	37.0	Shale
37.0	-	48.0	Sandstone
48.0	-	58.0	Shale
58.0	-	58.2	Coal
58.2	-	60.0	Clay
60.0	-	72.0	Shale
72.0	-	72.2	Coal
72.2	-	75.0	Clay
75.0	-	77.0	Sandstone
77.0	-	103.0	Shale
103.0	-	103.3	Coal
103.3	-	104.0	Clay
104.0	-	117.0	Shale
117.0	-	117.2	Coal
117.2	-	118.0	Clay
118.0	-	142.5	Shale
142.5	-	142.7	Coal
142.7	-	144.0	Clay
144.0	-	174.0	Shale
174.0	-	174.5	Coal
174.5	-	177.0	Clay
177.0	-	183.0	Shale
183.0	-	183.5	Coal
183.5	-	186.0	Clay
186.0	-	188.0	Shale
188.0	-	190.0	Sandstone
190.0	-	229.8	Shale
229.8	-	230.0	Coal
230.0	-	238.0	Sandstone
238.0	-	247.0	Shale
247.0	-	247.5	Coal
247.5	-	269.0	Shale
269.0	-	270.0	Limestone



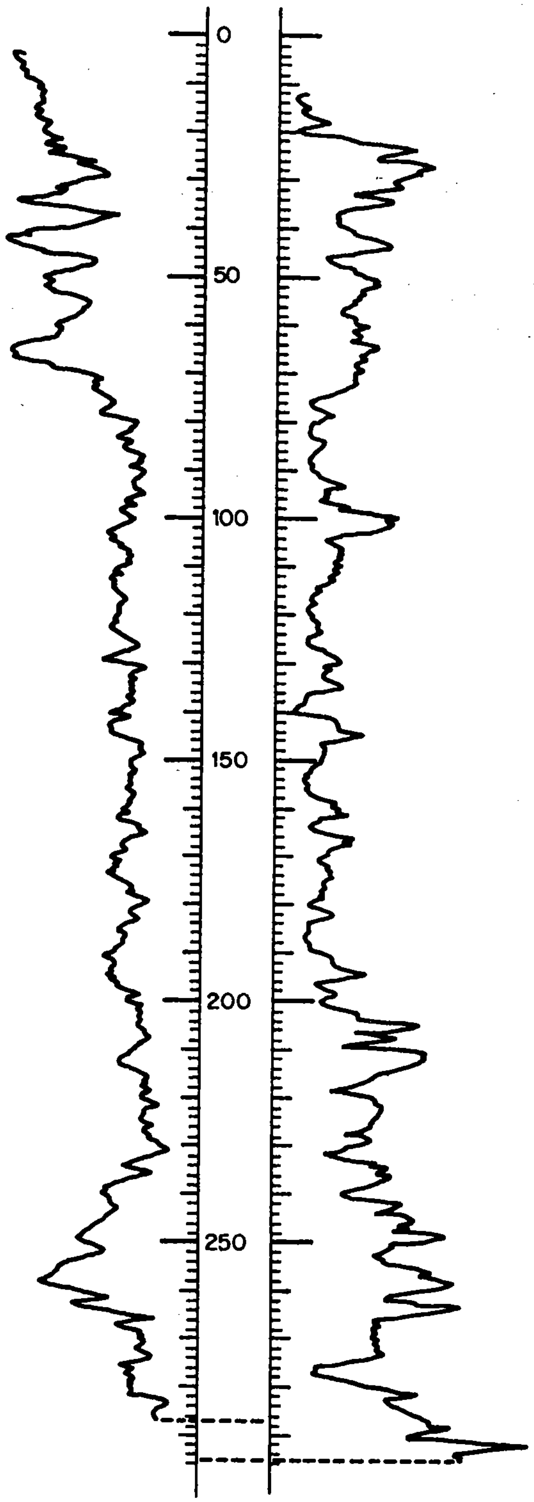
OKLAHOMA GEOLOGICAL SURVEY
STRATIGRAPHIC TEST HOLE 16
NE SW NW NW Sec. 29 T. 29 N., R. 21 E.
Ground Elevation 829 feet
Craig County, Oklahoma
(OGS - Calvin Brady no. 1)

Footage			Lithology
0	-	1.0	Soil
1.0	-	28.0	Sandstone
28.0	-	46.0	Shale
46.0	-	46.8	Coal
46.8	-	49.0	Clay
49.0	-	76.5	Shale
76.5	-	76.7	Coal
76.7	-	79.0	Clay
79.0	-	107.0	Shale
107.0	-	108.0	Sandstone
108.0	-	118.0	Shale
118.0	-	125.0	Sandstone
125.0	-	126.0	Shale
126.0	-	126.4	Coal
126.4	-	129.0	Clay
129.0	-	166.0	Shale
166.0	-	166.4	Coal
166.4	-	168.0	Clay
168.0	-	223.0	Shale
223.0	-	223.5	Coal
223.5	-	224.5	Clay
224.4	-	231.5	Shale
231.5	-	231.7	Coal
231.7	-	234.0	Clay
234.0	-	260.0	Shale
260.0	-	261.0	Sandstone
261.0	-	274.5	Shale
274.5	-	275.0	Sandstone
275.0	-	284.0	Shale
284.0	-	284.2	Coal
284.2	-	285.0	Clay
285.0	-	291.0	Sandstone
291.0	-	313.0	Shale
313.0	-	313.2	Coal
313.2	-	317.0	Shale
317.0	-	322.0	Limestone



OKLAHOMA GEOLOGICAL SURVEY
STRATIGRAPHIC TEST HOLE 17
SE SW NE NW Sec. 36 T. 29 N., R. 20 E.
Ground Elevation 858 feet
Craig County, Oklahoma
(OGS - Dale Tullis no. 1)

Footage			Lithology
0	-	2.0	Soil
2.0	-	5.0	Shale
5.0	-	20.0	Sandstone
20.0	-	24.8	Shale
24.8	-	25.0	Coal
25.0	-	26.0	Clay
26.0	-	36.0	Shale
36.0	-	37.5	Coal
37.5	-	43.0	Clay
43.0	-	52.0	Sandstone
52.0	-	52.5	Coal
52.5	-	55.0	Clay
55.0	-	56.0	Shale
56.0	-	59.0	Sandstone
59.0	-	82.0	Shale
82.0	-	82.5	Coal
82.5	-	87.0	Clay
87.0	-	117.5	Shale
117.5	-	118.0	Coal
118.0	-	120.0	Clay
120.0	-	125.0	Shale
125.0	-	125.5	Coal
125.5	-	129.0	Clay
129.0	-	140.0	Shale
140.0	-	152.0	Sandstone
152.0	-	157.0	Shale
157.0	-	157.5	Coal
157.5	-	159.0	Clay
159.0	-	171.0	Shale
171.0	-	171.2	Coal
171.2	-	174.0	Clay
174.0	-	176.0	Shale
176.0	-	178.0	Clay
178.0	-	200.0	Shale
200.0	-	200.5	Coal
200.5	-	201.0	Underclay
201.0	-	214.8	Shale
214.8	-	215.0	Coal
215.0	-	218.0	Underclay
218.0	-	239.0	Shale
239.0	-	239.5	Coal
239.5	-	240.0	Clay
240.0	-	273.0	Shale
273.0	-	279.0	Sandstone
279.0	-	280.0	Shale
280.0	-	280.2	Coal
280.2	-	281.0	Clay
281.0	-	309.0	Shale
309.0	-	322.0	Sandstone
322.0	-	326.0	Shale
326.0	-	332.0	Sandstone
332.0	-	365.0	Shale
365.0	-	366.0	Limestone



OKLAHOMA GEOLOGICAL SURVEY
STRATIGRAPHIC TEST HOLE 18
SW SE SE NE Sec. 32 T. 29 N., R. 21 E.
Ground elevation 796 feet
Craig County, Oklahoma
(OGS - Carl Kelsey no. 1)

Footage	Lithology
0 - 2.0	Soil
2.0 - 24.0	Clay
24.0 - 26.0	Sandstone
26.0 - 32.0	Shale
32.0 - 39.0	Sandstone
39.0 - 43.0	Shale
43.0 - 48.0	Sandstone
48.0 - 50.0	Coal
50.0 - 53.0	Shale
53.0 - 58.0	Sandstone
58.0 - 62.0	Shale
62.0 - 71.0	Sandstone
71.0 - 84.0	Shale
84.0 - 85.0	Coal
85.0 - 98.0	Shale
98.0 - 99.0	Coal
99.0 - 127.0	Shale
127.0 - 128.0	Coal
128.0 - 141.0	Shale
141.0 - 142.0	Coal
142.0 - 164.0	Shale
164.0 - 165.0	Coal
165.0 - 169.0	Clay
169.0 - 179.0	Shale
179.0 - 180.0	Coal
180.0 - 200.0	Shale
200.0 - 201.0	Coal
201.0 - 209.0	Shale
209.0 - 210.0	Coal
210.0 - 212.5	Sandstone
212.5 - 228.0	Shale
228.0 - 228.2	Coal
228.2 - 274.0	Shale
274.0 - 275.0	Coal
275.0 - 279.0	Clay
279.0 - 288.0	Shale
288.0 - 289.0	Coal
289.0 - 290.0	Clay
290.0 - 290.5	Limestone

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