THE WOODFORD SHALE IN PORTIONS OF LOGAN COUNTY, OKLAHOMA: FEASIBILITY OF DEFINING AN ALGORITHM FOR MAPPING AND EXPLORATION

By

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CHAPTER I

INTRODUCTION

Statement of the Problem

The Woodford Shale (Figure 1) is recognized as an important source rock within the Midcontinent (for example, see Kirkland et al., 1992, p. 38). The Woodford's extraordinary productivity of oil and gas is due to its distinctive lithology, diagenetic history and widespread distribution. These characteristics suggest that the Woodford could also be suspected to be a potentially significant reservoir—a proposition that leads to the conclusion that the reservoir-attributes of the Woodford merit study. The Woodford has produced economically significant amounts of oil and gas at numerous localities within Oklahoma, including the Hollrah Exploration Co. No. 1 York, in the study area (see Appendix A). More than 150 wells in Oklahoma have produced petroleum from the Woodford (PI/Dwights Production Data, 2004). At some localities the Woodford is porous and permeable, attributes shown jointly by microlog and porosity-log responses. Although the Woodford is commonly and abundantly fractured where it crops out, in the subsurface matrix porosity may be so extensive as to have made the Woodford a widespread commercial reservoir. The effects of fracturing of the subsurface Woodford are not well documented. (Of course, the word "commercial"

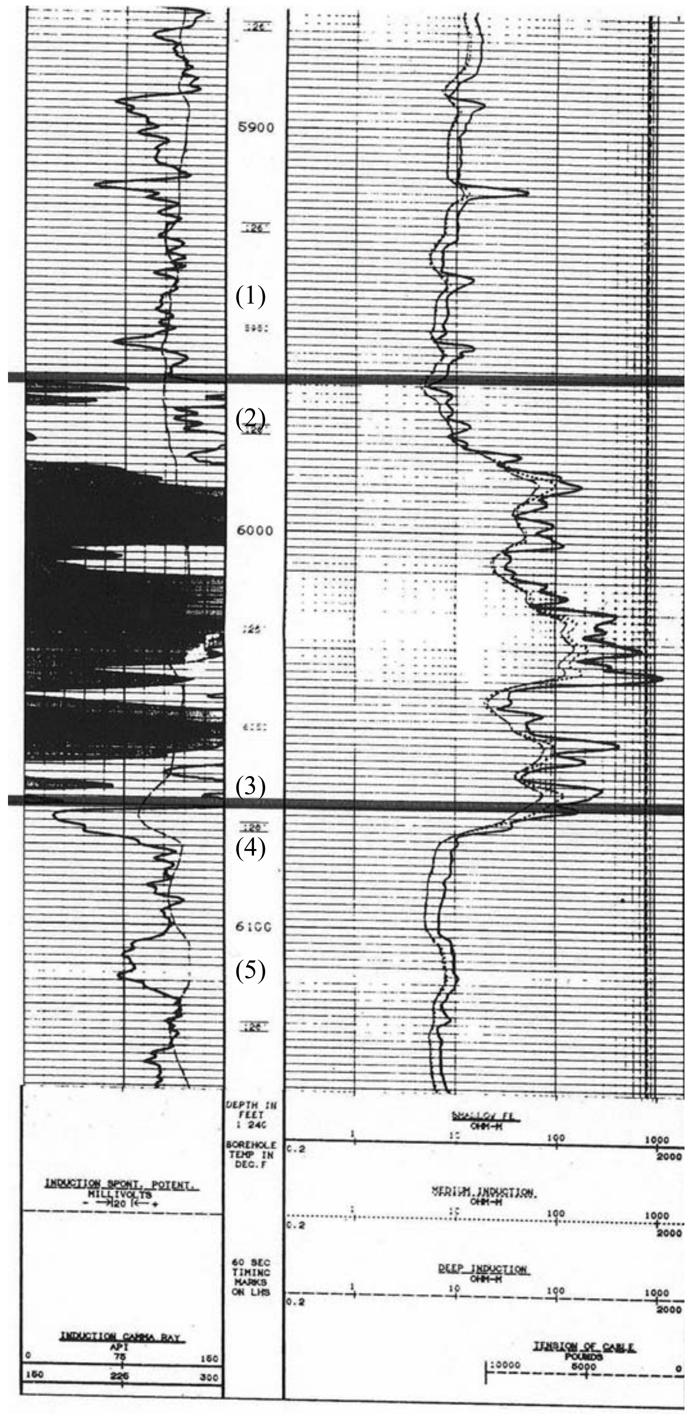


Figure 1. Log of the Woodford Shale interval in the Hollrah Exploration Company No.1-31 Davis Farms, Sec. 31, T16N, R3W. Symbols: (1) Pennsylvanian strata, (2) upper boundary of Woodford Shale, (3) lower boundary of Woodford Shale, (4) remnant of the Hunton Group, (5) Sylvan Shale.

implies that the Woodford's merit as a reservoir is dependent considerably on the prices of oil and gas.)

Little has been published about mapping potentially productive zones within the Woodford. The so-called "uniformity" of the Woodford provides the unique opportunity to examine lithic properties that vary detectably within the unit, and to create qualitatively a framework for their study. Documentable and utilitarian variations within the Woodford seem to be confined within a framework of observable log-signature attributes. Differences among these attributes are obvious in some instances but subtle in others. This study was intended to examine some of these attributes and to assess the feasibility of describing an algorithm for mapping the Woodford effectively.

Assessing the feasibility of a mapping algorithm for documentation of the Woodford allows a broad approach to be used. In definition of the problem, declaration that a solution would be true and operationally effective seemed to be presumptuous. Instead, the purpose of study was analyzed first through an assemblage of questions. I believed that by searching for the answers to several of these questions, the intrinsic value of information acquired could be evaluated, and could lead to a successful conclusion.

Several of the questions that were considered dealt with determination of what lithic and wireline-log properties comprise a "normal" stratigraphic section of the Woodford. In this document the log-character of variation within the Woodford is described, as well as differences in the upper and lower boundaries from locality to locality.

In the attempt to isolate an effective mapping technique, several questions were considered. (1) Can a basic understanding of the Woodford be gained that would prove useful throughout the study area, in localities where the strata are uncommonly folded or faulted, and in areas beyond the study area? (2) Would study of a six-township "pilot area" be adequate to build a working algorithm? (3) Would *any* single mapping technique be effective and practical for examining and describing attributes of the Woodford in a manner that would permit isolation of possible oil and gas traps? (4) Can the study results be reproduced by others?

General Method of Investigation

Well logs were the primary source of information about the subsurface; they were used to compile data for isopach and structural geologic maps of the Woodford Shale and Hunton Group. (Stratigraphic positions shown in Figure 2.) These maps were constructed to test hypotheses about geology, and about paleotopography of unconformities at the base of the Woodford and at the base of the Pennsylvanian System.

An attempt was made to correlate lithology with log-character. Bit cuttings from the Hollrah Exploration Co. No. 1 York were described. A complete set of samples is retained by both the author and by Gary F. Stewart of Oklahoma State University. Correlation of lithology and log-character reduced the ambiguity inherent in log analysis. By utilizing both log-character and evidence of lithology, the author's confidence in correlations among wells was increased.

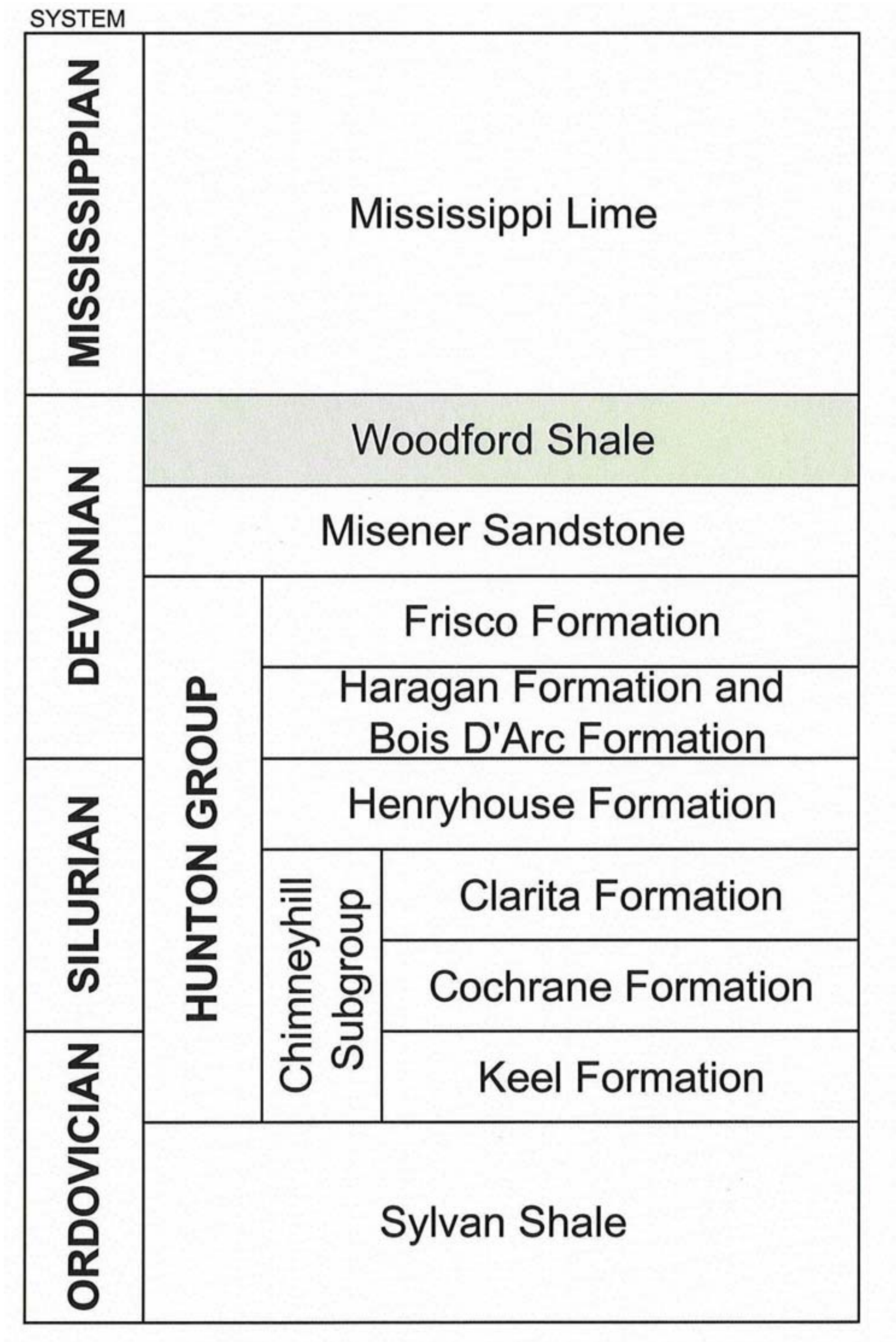


Figure 2. Stratigraphic sequence in the study area, from lowermost Mississippian rocks to the Sylvan Shale (modified from Amsden, 1989, p. 144).

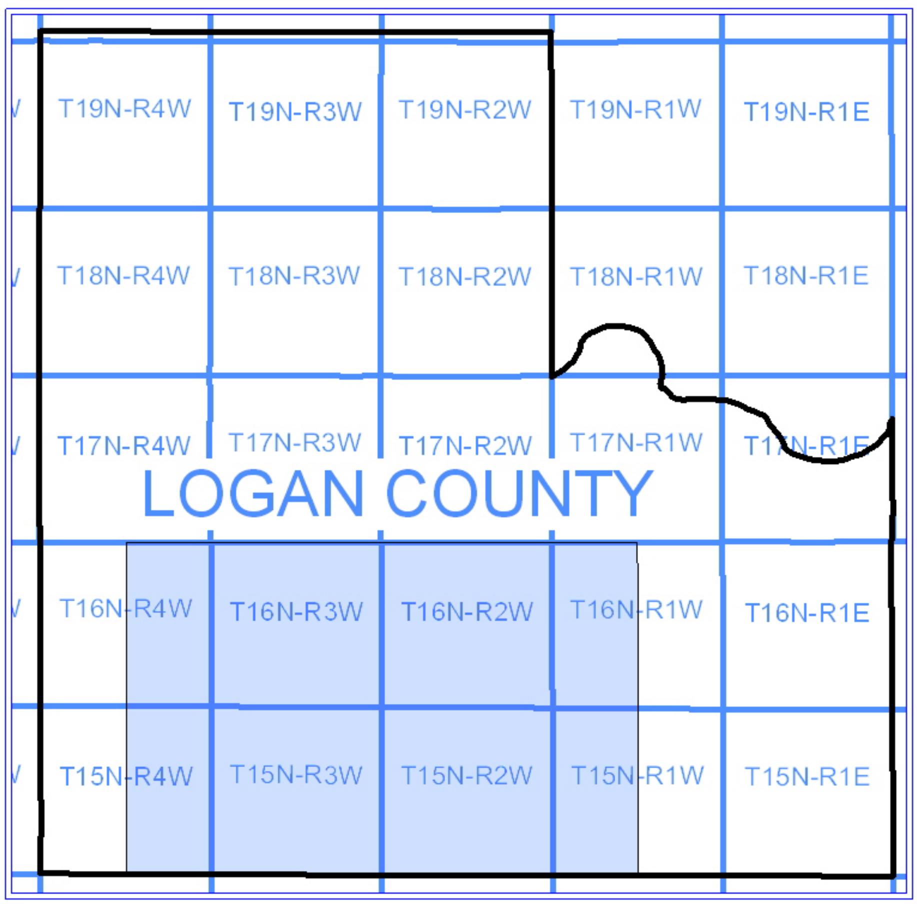
Location of the Study Area

Although portions of eight townships are described, the study area is equivalent to a six-township area. It is in Logan County, Oklahoma, near the town of Guthrie [Figure 3(a)]. Townships included in this study include the west half of T15N and T16N, R1W, all of townships 15N and 16N, ranges 2W and 3W, and the east half of T15N and T16N, R4W [Figure 3(b)]. This area is bounded by the Nemaha Uplift and the associated Central Oklahoma Fault Zone on the west, and is part of the Central Oklahoma Platform (the southern part of the Northern Shelf Areas) (Figure 4).

Previous Investigations of Special Significance

Among the many worthy studies of the Woodford Shale are some that have no direct bearing on the research considered here. Some of these documents give good regional descriptions of the Woodford Shale and describe facies variation within the unit; others touch on related topics of interest in more detail than was necessary for the purposes of this paper. Many of these documents are listed in the "Selected References" at the end of this paper; a list of some papers of special note follows. Valuable information about geochemistry of the Woodford was set out by Cardott (1985, 1989), Schmoker and Hester (1989), and Mear (1993). Comer (1991), Kuykendall et al. (1993), and Lambert (1993) are excellent sources of information concerning stratigraphy of the Woodford interval. This list is not a complete record of the amount of information currently available on the Woodford Shale, but it does allow an interested reader the opportunity to explore this topic further.

(a)



(b)

Figure 3. Location of the study area.

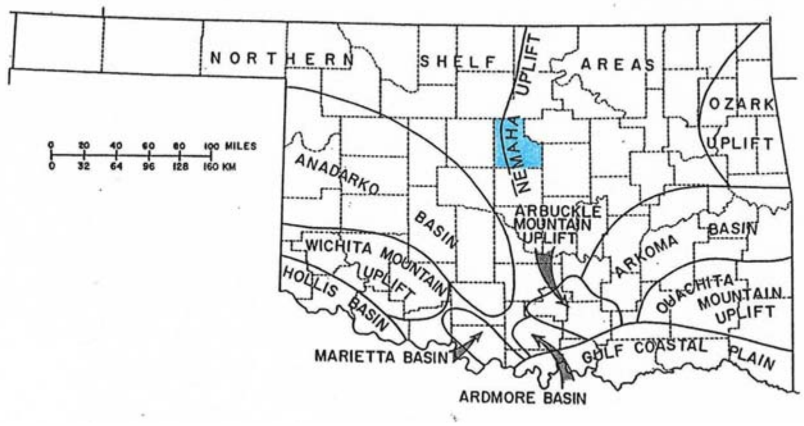


Figure 4. Map showing major geologic provinces of Oklahoma (after Johnson and Cardott, 1992).

Kurt Rottman compiled a study worthy of special mention. Rottman (2000) contends that for exploration of the underlying Hunton Group, the present thickness of the Woodford Shale should be modified to account for the effects of differential compaction; doing so aids in recognition of petroleum traps. Although this method seems to have been tested and shown to be effective for the intended purpose, I chose to use unaugmented records of thickness. This study deals specifically with the present state of the Woodford Shale, with the aim of mapping it effectively, as it is.

CHAPTER II

STRATIGRAPHY OF STRATA THAT UNDERLIE AND OVERLIE THE WOODFORD SHALE IN THE STUDY AREA

Hunton Group

The Hunton Group is a sequence of limestone and dolomite of Late Ordovician to Early Devonian age (Amsden, 1975). In the study area it overlies the Ordovician Sylvan Shale (Figure 2). Carbonate rocks of the Hunton are relatively shallow marine deposits (Al-Shaieb, 1993) that thicken southward from the study area into the deep portion of the Anadarko Basin (Amsden, 1975). In the type area, the group is composed of seven formations (Figure 2). Within the study area, four formations of the Hunton Group are absent: the Henryhouse, Haragan, Bois d'Arc, and Frisco. These rock-stratigraphic units were removed by erosion before deposition of the Woodford Shale. At many locations within the study area, only the Chimneyhill Subgroup is present. It comprises three formations, the Keel, Cochrane, and Clarita (Figure 2). Thinned northward chiefly by erosion, the Hunton extends to within a relatively short distance from Kansas (Amsden, 1989, p. 146; Figure 5.) Structural configuration of the Woodford Shale is similar to that of the Hunton Group (for example, see Appendix B, Figure B1.). However, just east of the Nemaha Uplift (Figure 4), the Hunton seems to have been deeply dissected by erosion (Figure 5).

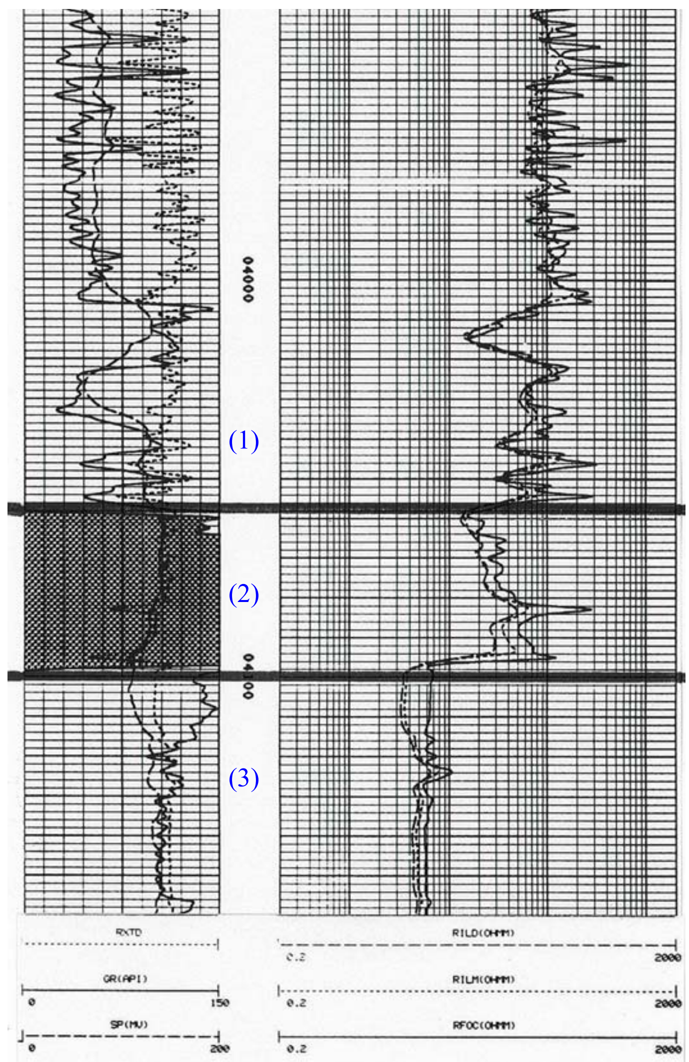


Figure 5. Log of the Woodford Shale interval upon rocks of the Ordovician Sylvan Shale, showing the depth of the erosion of the Hunton Group in the Statex Petroleum Incorporated No. 1-23 Ollie, Sec. 23, T17N, R4E, Lincoln County, Oklahoma. Symbols: (1) Mississippi Lime, (2) Woodford Shale, and (3) Sylvan Shale.

Woodford Shale

The first recorded use of the name Woodford Shale was by Taff (1902). The Woodford is defined as being Late Devonian and Early Mississippian (Amsden, 1975). Although mostly shale, at some localities in Oklahoma, the formation includes substantial portions of chert, sandstone, siltstone, and limestone (Sullivan, 1985). The dark gray to black shale commonly is highly radioactive. The Woodford is divisible vertically into three mappable units, as based on wireline-log attributes (see also Sullivan, 1985). The upper and lower units are similar in lithology as made evident by log character and by inspection of bit cuttings. These units consist chiefly of dark gray shale. They are separated by a darker gray to black, more radioactive stratum (Figure 6).

The Woodford Shale of the study area was deposited during transgression of anoxic waters from the deep-water Ouachita depositional basin (Kirkland et al., 1992, p. 40). In the study area, the formation was deposited on an erosional landscape, on rocks of Silurian to Late Devonian age. (For evidence see Northcutt et al., 2001; p. 5, Figure 5.) At some localities in northern Oklahoma, rocks as old as those of the Arbuckle Group (Cambrian-Ordovician) underlie the Woodford (Figure 7). The Woodford is the initial record of transition from predominantly carbonate rocks of the Early Paleozoic to predominantly clastic rocks of the Middle and Late Paleozoic (Ham, 1969, p. 7-8).

Mississippian System

At most places in the study area, the Woodford is overlain conformably by Mississippian strata. The Mississippian rocks primarily are light-colored, shallow-water limestones, dolomites, cherts and shales. Mississippian rocks of Oklahoma primarily are of four series; in ascending order these are Kinderhook, Osage, Meramec, and Chester (Frezon and Jordan, 1979). In north-central Oklahoma, Mississippian rocks include strata of only Kinderhookian and Osagean age (Davis, 1985, p. 147).

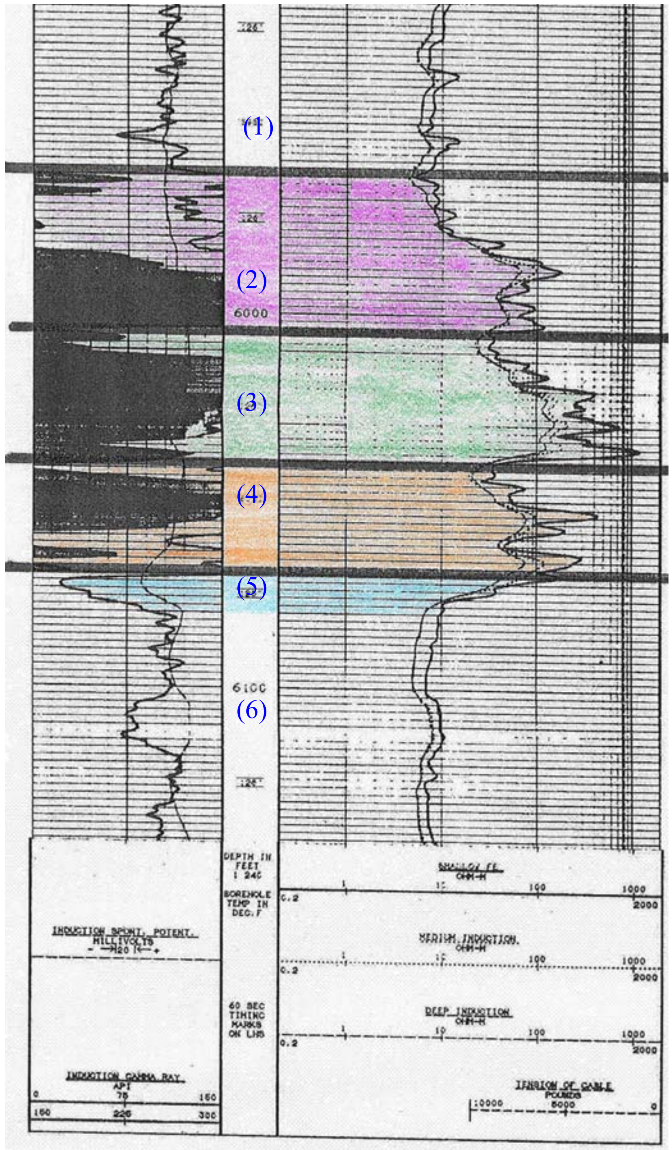
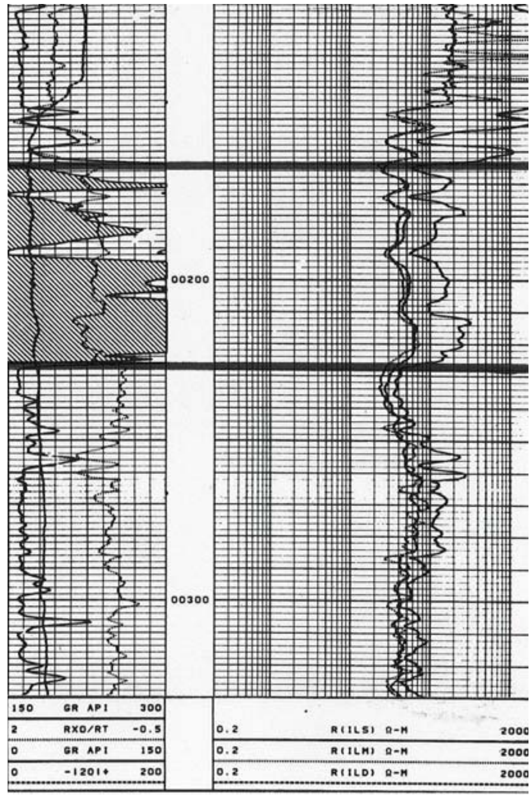
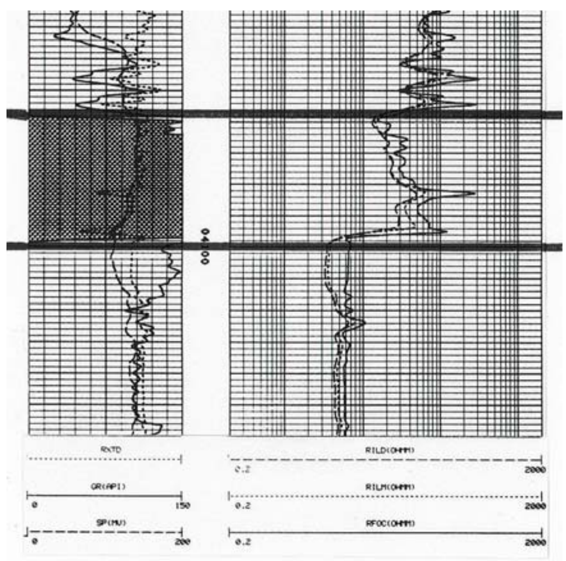


Figure 6. Log of the Woodford Shale interval in the Hollrah Exploration Company No.1-31 Davis Farms, Sec. 31, T16N, R3W. Symbols: (1) Pennsylvanian strata, (2) upper-transitional member, (3) middle member, (4) lower-transitional member, (5) remnant of the Hunton Group, and (6) Sylvan Shale.



(a)



(b)

Figure 7. Examples of localities where Woodford Shale overlies Paleozoic rocks older than the Hunton Group. (a) Woodford Shale overlies rocks of the Arbuckle Group. Contact is at 226 ft., in the Hold Oil Corporation No. 1 Alvin Pierce, Sec. 18, T20N, R20E, Mayes County, Oklahoma. (b) Woodford Shale overlies rocks of the Sylvan Shale. Contact is at 4096 ft., in the Statex Petroleum Incorporated No. 1-23 Ollie, Sec. 23, T17N, R4E, Lincoln County, Oklahoma.

Pennsylvanian System

In north-central Oklahoma, deposition of Pennsylvanian strata was preceded by regional and local structural deformation of Mississippian and pre-Mississippian strata, and by extensive erosion of Lower Paleozoic rocks. (For a detailed account, see Northcutt, 2001.) Within the study area Mississippian rocks are absent locally, but at some places are more than 100 feet thick. Strata of the Desmoinesian Cherokee Group overlie Mississippian strata, and locally, they overlie the Woodford. (For a more detailed treatment of the topic see Hawthorne,1982.)

CHAPTER III

LOWER AND UPPER BOUNDARIES OF THE WOODFORD SHALE

Because the study included examination of published information, well logs, bit cuttings, maps, and cross-sections, many types of data were available. By defining the basic types of data collected and processed, one can begin to organize that information so as to address an orderly working knowledge of methods for solving the problem at hand.

Interpretation of Well-logs

In some parts of the study area, only “ancient” electric logs are available. Spontaneous potential logs, conductivity logs, and dual induction resistivity logs were abundant. “Micrologs” and strip logs were utilized, but they were available only locally. Because the “black” shales of the Woodford Shale are intensely radioactive, gamma-ray logs were especially useful for correlation. The objective of examining and cataloguing well logs was to formulate some consistent basis for determination of the lithologic and rock-stratigraphic boundaries recorded by these logs, despite the rather large variation in density of coverage (number of logs per unit area), ages of logs, kinds of logs, and general qualities of logs (calibration, registry of curves, clarity of images, and so forth).

Upper Boundary of the Woodford Shale

Within the study area, the Woodford Shale is overlain by rocks of Mississippian or Pennsylvanian age. Where Mississippian rocks overlie the Woodford, the contact almost certainly is conformable (Sullivan, 1985). In the case of the study area, the boundary seems to be gradational upward from Woodford shales (that are dark gray and black) into Mississippian limestones (that are brown) (Figure 8). Where the Woodford has been truncated and is overlain by Pennsylvanian shales, the contact normally is abrupt (Figure 9). [However, some caution is in order, because at some places the upper boundary of the Woodford is obscured by material presumed to have been eroded and redeposited above the unconformity (for example, see Figure 10).]

<u>Woodford Bounded Above by Mississippian Strata</u>

Where the Woodford is overlain by Mississippian strata, identification of the upper boundary of the Woodford by log signatures generally is straightforward. A moderately negative SP (spontaneous potential) response is common of Mississippian limestones, but the SP is suppressed abruptly within the upper portions of the Woodford. This kind of stratigraphic contact also is characterized by strata of comparatively low resistivity at the boundary, underlain next by beds that show “spiking” resistivity. An example of this kind of relationship is illustrated in Figure 8.

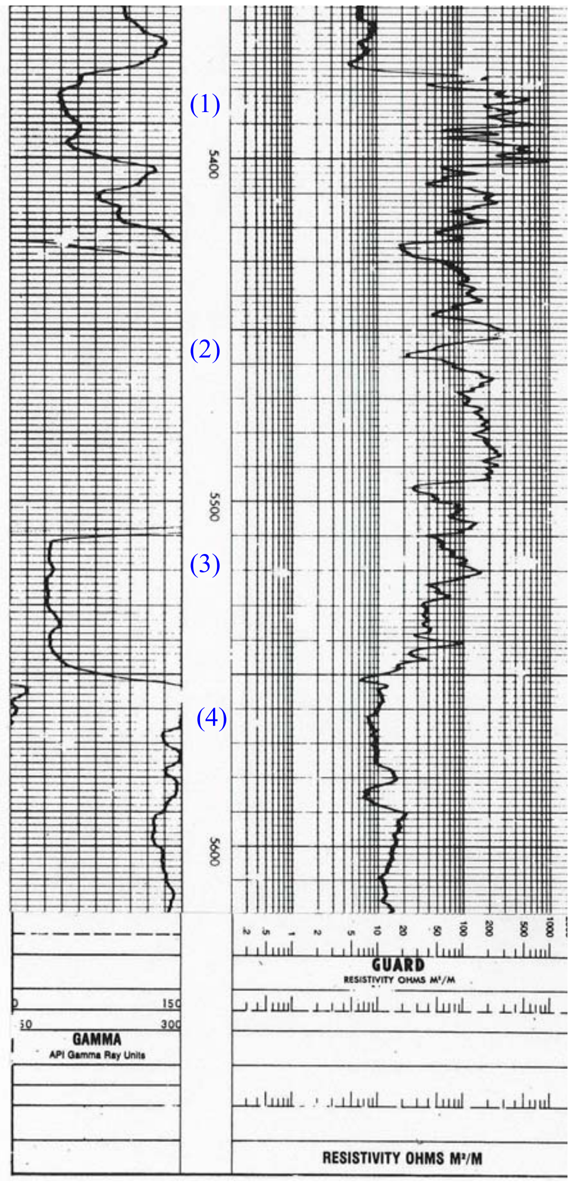


Figure 8. Example of a conformable upper boundary between the Woodford Shale and overlying Mississippian strata in the Ferguson Oil and Gas Company Incorporated No. 1 Tyler, Sec. 7, T16N, R1W. The contact is at 5424 ft. No spontaneous potential curve is shown on this log. (The curve in track 1 is a gamma ray log.) Symbols: (1) Mississippi Lime, (2) Woodford Shale, (3) strata of the Hunton Group, and (4) Sylvan Shale.

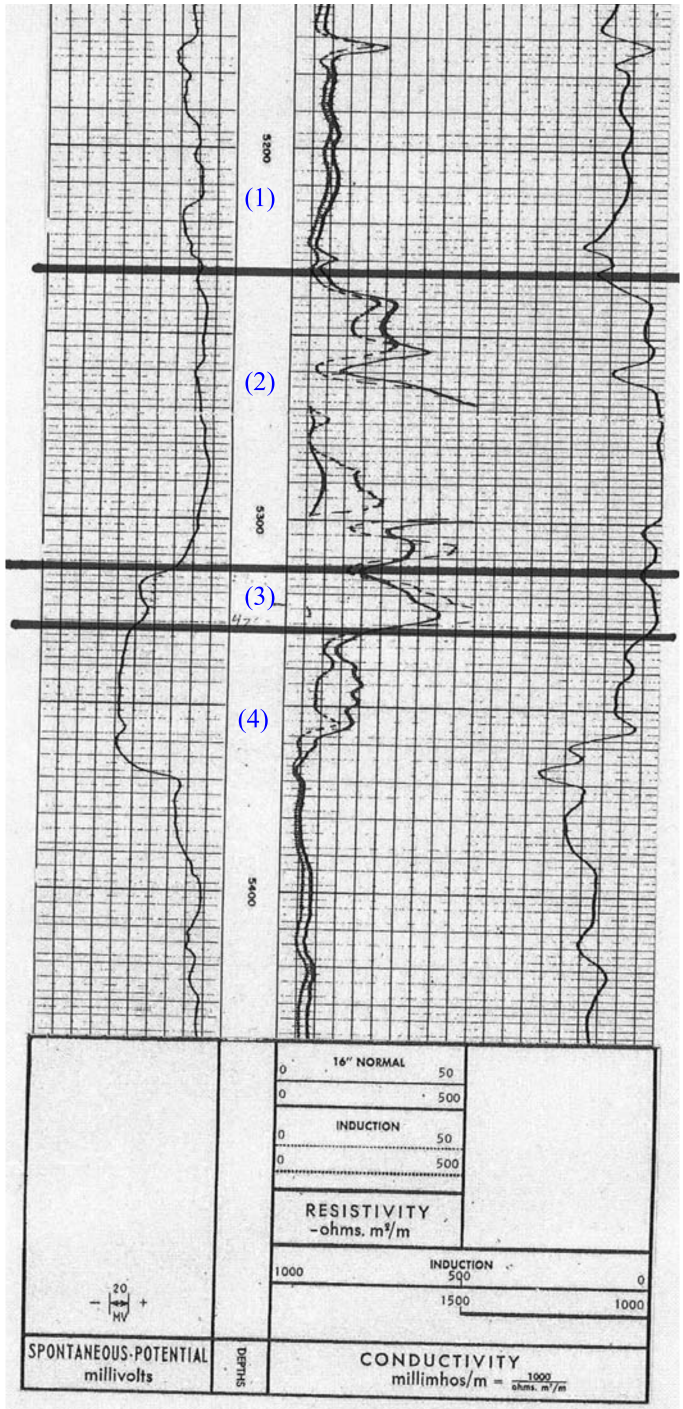


Figure 9. Example of an abrupt, erosional contact of Woodford Shale and Pennsylvanian strata in the H. J. Porter No. 1 School Land, Sec. 16, T16N, R1W. Contact is at 5234 ft. Symbols: (1) Pennsylvanian strata, (2) Woodford Shale, (3) probable Misener Sandstone, and (4) strata of the Hunton Group.

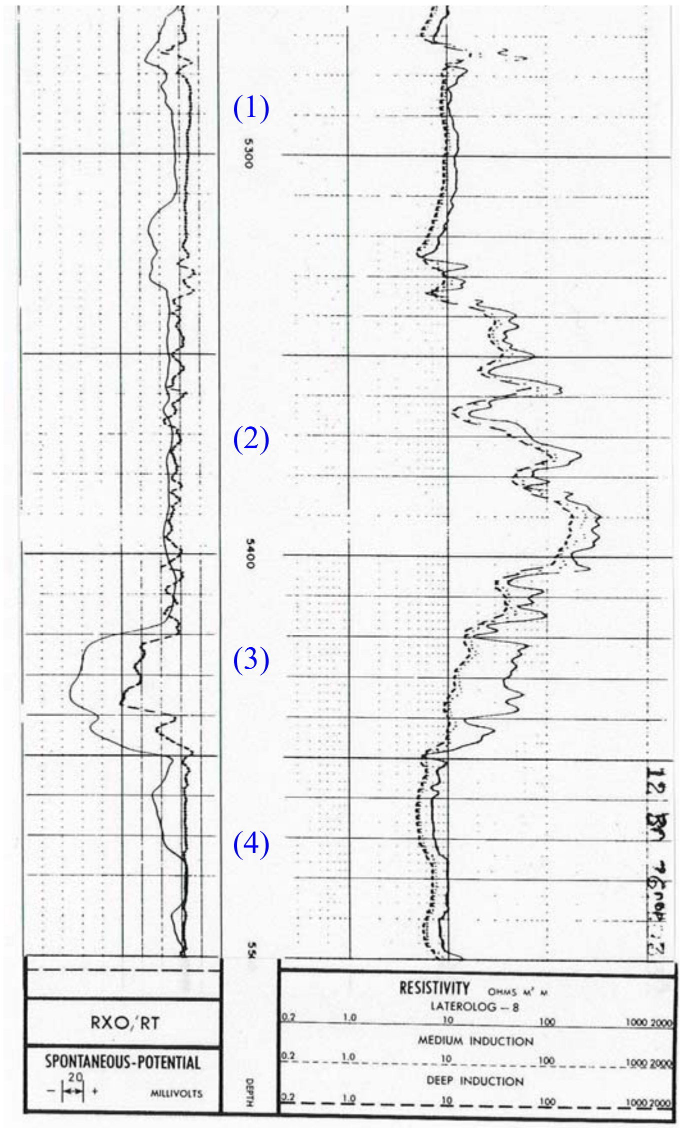


Figure 10. Example showing the response of the spontaneous potential log, possibly indicating reworked material at the erosional contact between the Woodford Shale and Pennsylvanian strata. Contact between Pennsylvanian strata and Woodford Shale is at 5325 ft. The well is the Nelson Petroleum Company No. 1 Rosa Gilbert, Sec. 17, T16N, R1W. Symbols: (1) Pennsylvanian Strata, (2) Woodford Shale, (3) strata of the Hunton Group, and (4) Sylvan Shale.

Woodford Bounded Above by Pennsylvanian Strata

Near the Pennsylvanian-Woodford boundary, resistivities of beds commonly are similar to that of Woodford under Mississippian rock, but minimal negative deflection of the SP curve is common in Pennsylvanian strata, especially where the calcareous gray Pennsylvanian shales overlie shales of the Woodford. At such localities, almost no difference in deflection of the SP can be noted between rocks of the Pennsylvanian and those of the Woodford (Figure 9). However, in some places thick strata of sandstone are close above the Woodford (for example, in Sec. 3, T15N, R3W; Figure 11). Log signatures of these sandstones are distinctive: sandstones are recorded by highly negative SP response, and transition to the Woodford below is recorded as a direct migration of the curve to the shale base line. In either case, gamma-ray logs are quite effective in determining the location of the uppermost portions of the Woodford. The top of the Woodford commonly is identifiable as the position of the highest significant (off-scale) divergence of the gamma-ray signature (Figures 1 and 11, for example).

Significance of Stratigraphic Sequences of the Woodford Shale Near the Upper Boundary

Knowing or closely approximating the types of depositional or erosional features near the upper boundary of the Woodford would aid in identification of areas where the upper portions of the Woodford are intact. In the search for and explanation of porous and permeable beds in the upper part of the Woodford, it is important to understand the relationship between the upper boundary and the permeable interval under

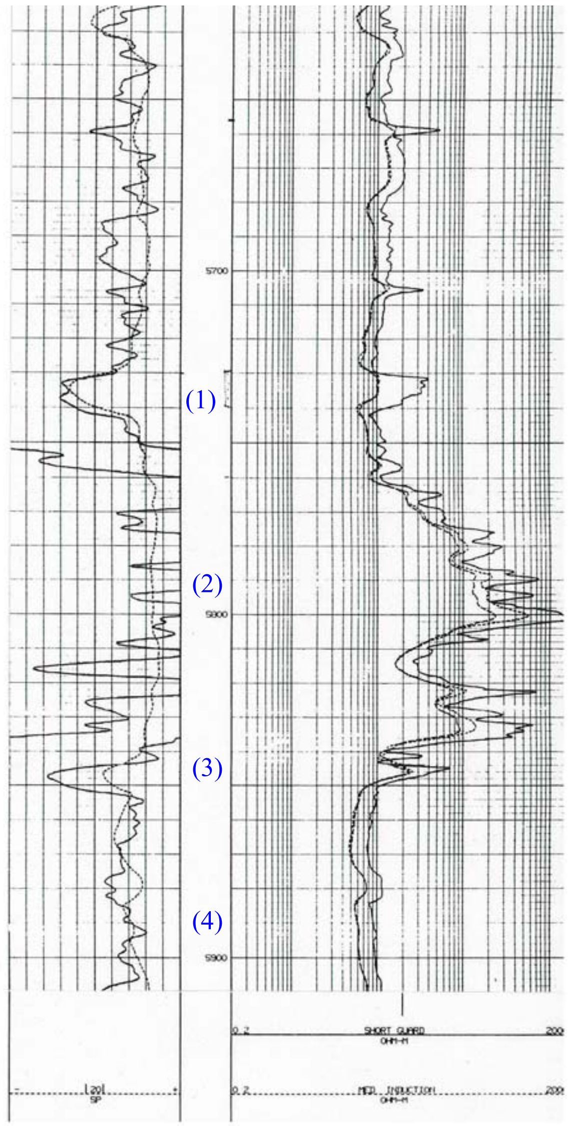


Figure 11. Strata of the Desmoinesian Skinner Sandstone interval overlying the Woodford Shale. Contact is at 5752 ft., in Clements Energy No. 1 Dreessen, Sec. 3, T15N, R3W. Symbols: (1) Strata of the Skinner Sandstone interval, (2) Woodford Shale, (3) remnant of the Hunton Group, and (4) Sylvan Shale.

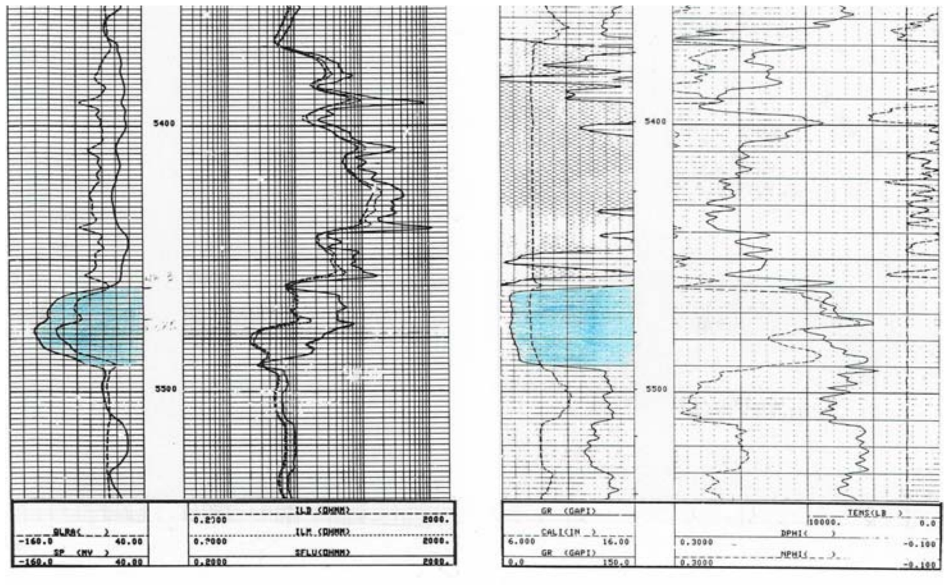
scrutiny. Questions as to the possibility and probability of erosional truncation or depositional lapout of important formation members then become timely.

Lower Boundary of the Woodford Shale

The lower boundary of the Woodford Shale overlies a regional unconformity (Amsden, 1975, p. 9). Because of this, extraordinary variations in log-character at this boundary are to be expected. At most localities within the study area, the Woodford overlies eroded strata of the Hunton Group. Where Hunton rock was removed before deposition of the Woodford, beds of the Woodford overlie Sylvan Shale [for example, see Figure 7(b)].

Log-signature Characteristics: Hunton Group Overlain by Woodford Shale

Where Woodford strata overlie the Hunton Group, some patterns of log-signature are characteristic. At most places, spontaneous potential of the Hunton carbonate limestones and dolomites is distinctly negative, unlike the suppressed SP of the Woodford shales [Figure 12(a)]. Most resistivity logs show slight decreases in resistivity near the boundary [Figure 12(a)], but large resistivity in the dolomitic Hunton carbonates beneath. Gamma-ray logs are effective in identification of this boundary. Radioactivity of the Woodford contrasts greatly with that of Hunton strata (Figure 12). Rocks of the Hunton show gamma-ray deflection in the range of 10 to 60 API units, whereas shale of the Woodford commonly is in the range of 90 to 200+ API units [Figure 12(b)]. The lower boundary of the Woodford is expectedly abrupt, but locally is obscured by material



(a) (b)

Figure 12. Examples of Woodford Shale overlying Hunton strata. Comparison of spontaneous potential and gamma-ray log responses at the contact in the Downey Oil Company No. 1A Lesh, Sec. 19, T16N, R1W. Contact at 5460 ft.

that was reworked and deposited upon the unconformity; a notable rock-stratigraphic unit of this kind is the Misener Sandstone (Figure 9).

The Misener Sandstone Problem

Within the lowermost 20 to 30 feet of the Woodford certain "electrofacies" are recordable. These "electrofacies" may be interpreted as Misener Sandstone (for example, see Figure 13), but are herein considered to be portions of the "lower transitional

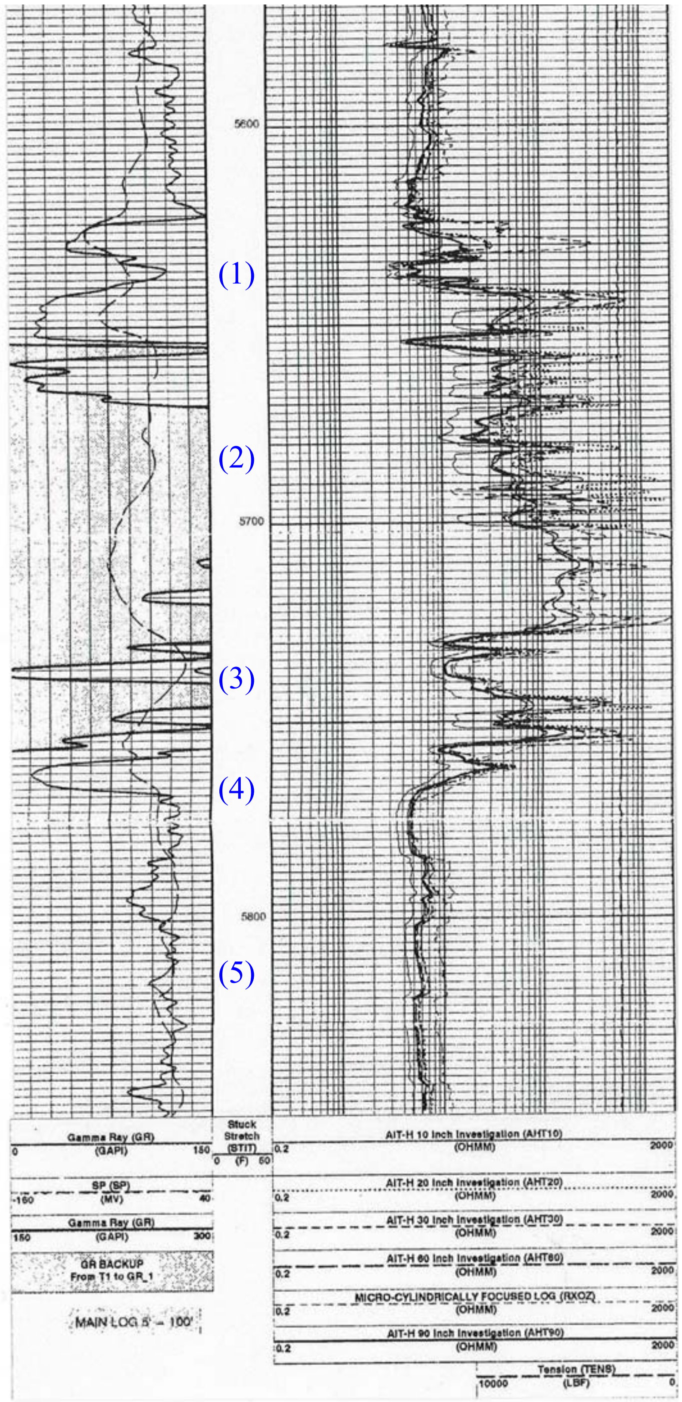


Figure 13. Log of the Woodford Shale interval in the Hill Oil Company No. 1-16 Sierra Madre, Sec. 16, T15N, R2W. Notice the subtle negative shift of the spontaneous potential log across the lower portions of the lower-transitional Woodford interval. Contact between Woodford Shale and Hunton at 5756 ft. Symbols: (1) Mississippi Lime, (2) Woodford Shale, (3) lower-transitional Woodford interval, (4) remnant of the Hunton Group, and (5) Sylvan Shale.

Woodford." Whereas this provisional name is sufficient for mapping in most of the study area, there are certain instances where the proper name "Misener" is the appropriate term. This nomenclature (i.e. Misener) is used herein only (a) in instances where data were derived directly from scout cards, completion reports, mudlogs, or sample-identification logs, and where reference to the Misener seemed to be reliable, or (b) to describe strata that are in a position-in-sequence stratigraphically equivalent to that of the Misener, that show log-responses markedly distinctive from those of the Woodford and Hunton.

Misener sandstone is within certain portions of the study area (for example, see Figure 9). It underlies the Woodford and overlies the sub-Woodford unconformity. Some geologists regard the Misener as being contemporaneous with the lower portions of the Woodford (Kuykendall et al., 1993). In some areas, the Misener is dolomitic; at such places the SP response is strongly similar to that of the Hunton (Figure 9). Locally parts of the Misener are uncommonly radioactive, thereby giving the log-signature appearance of Woodford strata. In this study, strata difficult to identify either as Misener or as sections of thin Hunton were denoted as Hunton, due to the perceived balance of probability. Maps show this accordingly, namely Plates I and II.

<u>Other Rock-stratigraphic Units That Underlie the Woodford</u>

As illustrated by Figure 7, the lower part of the Woodford overlies formations other than the Hunton. In those localities where comparatively thick sections of rock were removed by erosion during development of the sub-Woodford unconformity, the Woodford is upon rocks as old as the Arbuckle Group. However, within the study area, the oldest rocks beneath the Woodford are beds of the Sylvan Shale. (For an example, see Figure 14.)

Significance of the Lower Boundary of the Woodford Shale

To varying degrees, variation in thickness of the Woodford is correlated with paleotopographic and structural configuration of the underlying strata. Where Woodford overlies productive strata, such as the Hunton or Arbuckle, and where these strata are folded, migration of petroleum was probable to some degree. Assessment of regional and local paleotopography and structural configuration of the underlying strata would allow more effective exploration for petroleum.

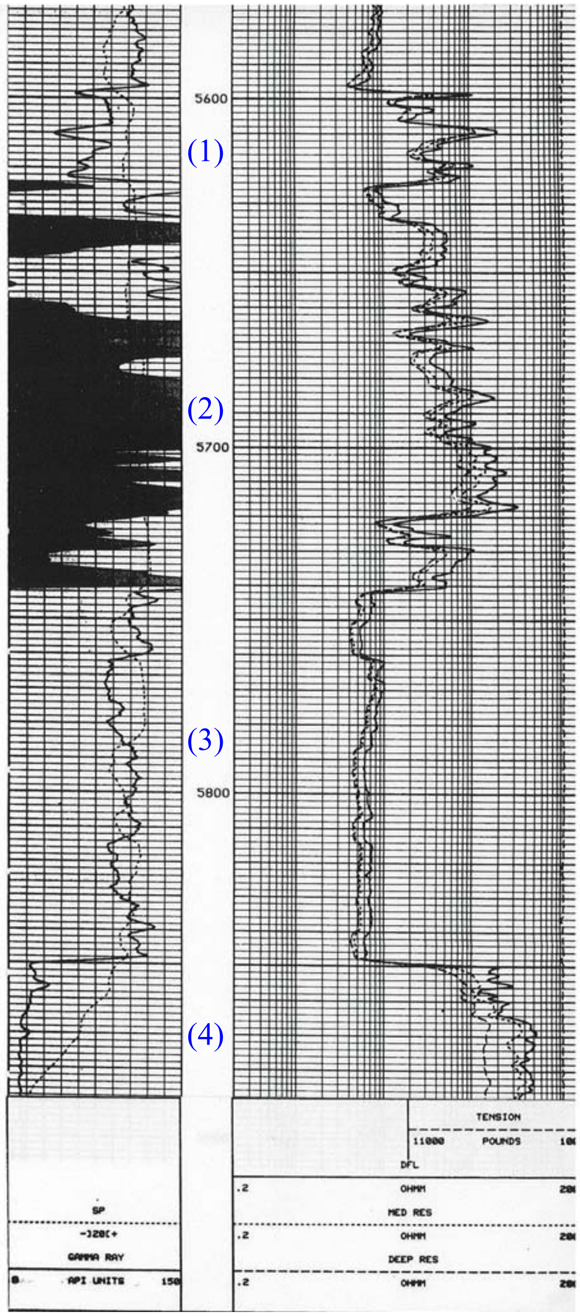


Figure 14. Log of the Woodford Shale interval overlying strata of the Ordovician Sylvan Shale in the Rox Exploration No. 2 Garrison, Sec. 20, T15N, R1W. Contact is at 5741 ft. Symbols: (1) Mississippi Lime, (2) Woodford Shale, (3) Sylvan Shale, and (4) Viola Group.

CHAPTER IV

MAPS OF THE WOODFORD SHALE

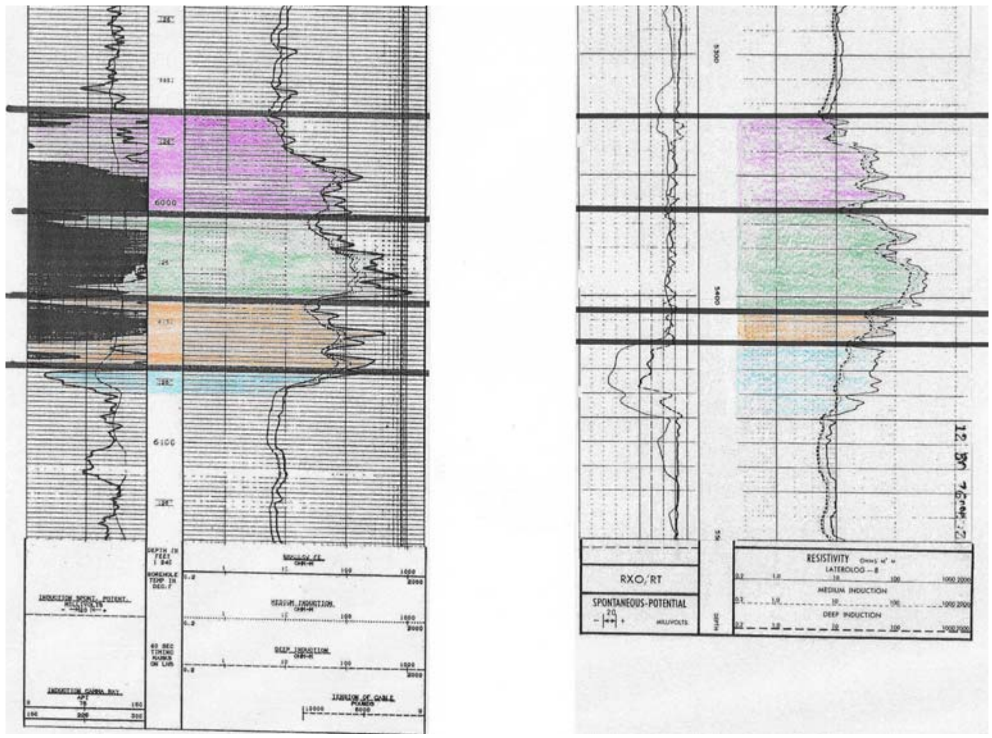
Division of the Woodford Shale

The Woodford Shale or one of its equivalents is widespread, a fact that is commonly recognized (for example, see Figure 15). Comparatively small variation in lithology across vast expanses seems to be typical. However, subtle variation provides information regarding the paleotopography and the structural configuration of bounding units.

In the study area, the Woodford generally is divisible into three basic members, but careful study of log-character makes subdivision of these members a practical matter. In shales of the Woodford the SP is at the shale base line or weakly negative [Figure 16(b)]. Therefore, correlation or partitioning of the Woodford by use of the SP curve is difficult and impractical. Gamma-ray logs are quite useful—in fact, they are the best source of information about vertical variation in the Woodford. Resistivity logs are the most abundant; therefore combination of information from gamma-ray and resistivity

Woodford Shale	Oklahoma, Texas
Noel Shale	S.W. Missouri; N.W. Arkansas
New Albany Shale	Indiana; N-cent. Kentucky
Chattanooga Shale	Tennessee; E. Kentucky; N.W. Georgia; N. Alabama; N.E. Mississippi; W. Kentucky; Illinois; Missouri; Arkansas; Oklahoma
Ohio Shale	Ohio; N-cent. Kentucky
Arkansas Novaculite	S.W. Arkansas; S.E. Oklahoma
Hannibal Shale	N.E. Missouri; S.E. Iowa; W. Illinois
Hardin Sandstone	Tennessee; Alabama
Saverton Shale	N.E. Missouri; S.E. Iowa; W. Illinois
Grassy Creek Shale	N. E. Missouri; S.E. Iowa; W. Illinois
Louisiana Limestone	E. Missouri; S.W. Illinois, Iowa
McCraney Limestone	Iowa
Glen Park Formation	C-East. Missouri; SW Illinois
Sylamore Sandstone Member	N. Arkansas; S.W. Missouri; E. Oklahoma
Caballos Novaculite	S.W. Texas
Ouray Limestone	S.W. Colorado
Bakken Formation	N.W. South Dakota: W. North Dakota; E., N.W., and N-cent. Montana
Engelwood Limestone	W. South Dakota; N.E. Wyoming
Exshaw Formation	N.W. Montana

Figure 15. Variation of nomenclature of the Woodford Shale and equivalent or partly equivalent stratigraphic units, region to region and within regions. (From the USGS National Geologic Lexicon Database "Geolex")



(a) (b)

Figure 16. Diagram (a) shows the Hollrah Exploration Company No. 1-31 Davis Farms, Sec. 31, T16N, R3W. Diagram (b) shows the Nelson Petroleum Company No. 1 Rosa Gilbert, Sec. 17, T16N, R1W. (a) Correlation of divisions of the Woodford, as defined by gamma ray logs, with resistivity-log profiles. (b) Description of divisions of the Woodford, based on resistivity-log signatures, only. Observe that the lowermost unit of the Woodford is thinner in well (b) than in well (a), but the Hunton is thicker.

logs is the optimal case: the pool of useful data is maximized by correlation of gamma-ray and resistivity-log signatures. Of the population of resistivity logs, induction logs are the more useful for correlation and mapping.

Figure 16(a) illustrates the usefulness of information derived from a gamma-ray log. This "type log" is compared to a log with no gamma ray curve, but correlations are based on the resistivity profile [Figure 16(b)]. The quality of such correlations is affected significantly by the ages and qualities of the well-logs used.

Overall Variation of Thickness of Woodford Shale

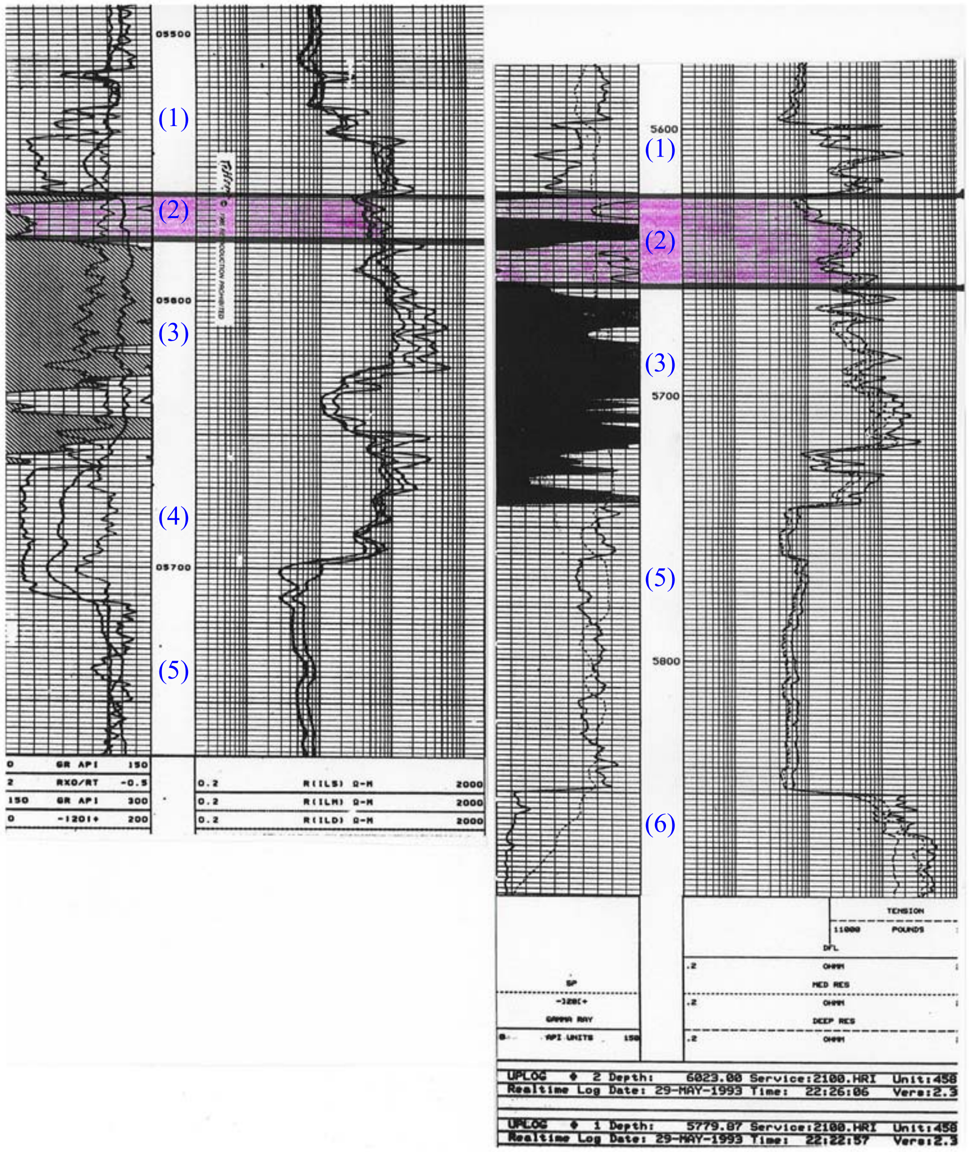
Thickness of the Woodford Shale is an important factor in the examination of practical mapping techniques. Although the Woodford is regarded loosely to be of "uniform" character and thickness, variation is common, and partially due to the effect of the pre-Pennsylvanian unconformity (Plates III and IV). In northern portions of T16N, R1W, subtle thinning of the Woodford almost certainly is due to post-Mississippian, pre-Pennsylvanian erosion. Upper submembers of the Woodford are missing, and the Woodford is overlain by Pennsylvanian rocks (Plate V).

By comparing thickness of the Hunton Group with thickness of the Woodford Shale, some paleostructural relationships can be inferred validly. It would seem that thicknesses are interdependent to some degree, and probably then reflect the accommodation space available during deposition of the Woodford. However, within T15N, R4W and T16N, R3W, thicknesses of the Woodford and of the underlying Hunton seem to have very little interdependency. (For example, see Sec. 35, T16N, R3W; Plates II and IV). The ARW Exploration Corporation No. 1-35 Bender contains a relatively thick Woodford interval (thickness of more than 100 feet) upon relatively thick Hunton strata (see the West-to-East stratigraphic cross section, Plates VI and VII). This type of relationship seems not to reflect the effects of accommodation space. Based on this information, the inference is drawn that local structural deformation had a greater effect on Woodford thickness than the regional and general effect of accommodation space.

Variation of Thickness within the Woodford Shale

Understanding the variation of thickness of *ad hoc* rock-stratigraphic units within the Woodford allows inferences to be made about configuration of the sub-Woodford unconformity surface and configuration of the uppermost surface of the Woodford. If one accepts the premise that the three primary "members" of the Woodford are distinguishably different in lithology, color, and organic content, then variation within one of these members could be considered independent of variation in the others. In this case, differences in thickness of the lower- and upper-transitional Woodford (Figure 16) should give information about paleostructural and/or paleotopographic configuration of the upper and lower boundaries of the formation. If this premise is accepted, then one can postulate that the lowest "member," having onlapped the sub-Woodford unconformity, should therefore show the greatest effect of paleotopography. Likewise, thickness of the upper-transitional Woodford (Figure 17) should indicate the presence or absence of "submembers," and truncation by or lap-out of Mississippian or Pennsylvanian strata could be identifiable.

Porous and permeable beds in the upper Woodford (Figure 18) lead one to question whether the Woodford would have produced oil and gas at numerous localities. (For examples, see Sec. 1, T15N, R3W; Secs. 7, 17, and 19, T16N, R1W.) Such strata can be identified by positive separation on micrologs and by porosity logs. Most such rocks are within the middle to upper portions of the upper Woodford member. Of course, variation in thickness of the upper-transitional interval becomes more important when mapping of possible reservoir rock is the objective.



(a) (b)

Figure 17. Comparison of thickness of the "upper-transitional member" of the Woodford interval. Logs hung from the top of the Woodford Shale. (a) The Rivondale Oil Company No. 3-5 Elliot, Sec. 5, T15N, R2W contains a thin "upper-transitional member", whereas the (b) Rox Exploration No. 2 Garrison, Sec. 20, T15N, R1W has a significantly thicker "upper-transitional member." Observe the thickening in (b) coupled with the addition of a submember near the lower boundary. The interval in both wells is bounded above by Mississippian strata. Symbols: (1) Mississippi strata, (2) "upper-transitional member" (3) Woodford Shale, (4) Hunton Group strata, (5) Sylvan Shale, and (6) Viola Group.

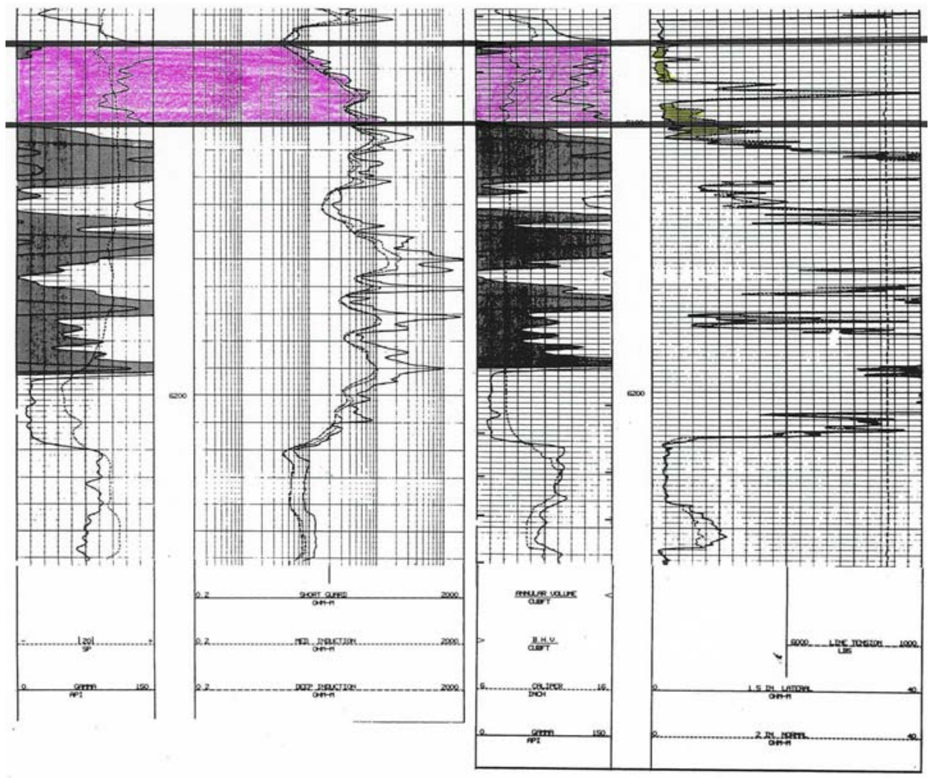


Figure 18. Logs of the Woodford Shale interval in the Bobby J. Darnell No. 1 Cavanaugh, Sec. 1, T15N, R4W. Top of the Woodford is at 6071 ft., top of the Hunton is at 6194 ft. Observe the evidence of microlog permeability (yellow) in the "upper-transitional member."

Variation of Thickness of Hunton Group

Thickness of the Hunton Group in the study area seems to vary due to effects of both structural and erosional forces. As discussed in Chapter II, the Hunton Group thins regionally to the north-northeast, and thickens regionally to the south-southwest. Locally within the study area thickness varies by as much as 100 feet. (See Plates VI and VIII, North-to-South stratigraphic cross section.) Rocks of the Hunton Group were removed by erosion in some areas, as shown by Plate II. This localized absence of Hunton strata, probably can be attributed to localized faulting, and faulting almost certainly accounts for the locally thick sections of Hunton strata (Plate II).

Thickness of "Lower Woodford Member" Compared With Variation in Thickness of the Hunton

By comparing the thickness of the "lower transitional member" of the Woodford Shale to the thickness of the underlying Hunton strata, one observes a predictable inverse relationship in much of the study area. The "lower transitional member" thickens where the Hunton is thin, and thins where the Hunton is thick (for example see Figure 16). This relationship is due to the constraint of the available accommodation space upon low- and high-standing topography at the post-Hunton, pre-Woodford boundary. Thinning and thickening of this member are noticibly more indicative of Hunton paleotopography than are differences in thickness of the gross Woodford interval. However, exceptions to this noted relationship are present within the study area; possibly they indicate areas of structural deformation during deposition of the Woodford Shale. For example, see Sec. 35, T16N, R3W, on Plates II and IV.

CHAPTER V

ALGORITHM FOR MAPPING AND EXPLORATION

Evidence set out above shows that properties of the Woodford vary significantly, both regionally and locally. Of course, specific physical attributes of the Woodford control this variation. Stratigraphic differentiation within the Woodford indicates that the formation's physical attributes were modified by structural and paleotopographic influences. A functional understanding of the paleotopographic and structural configuration of unconformities that underlie and overlie the Woodford would provide information of benefit in exploration for petroleum.

Derived Methodology for Mapping

The concept of mapping distinguishable variation within the Woodford over great expanses seems burdened by imprecision, yet one can gain information about the Woodford that proves to be useful for mapping. Determining the boundary-types of the Woodford locally and generating maps defined by those characteristics, (assuming that successful correlations are made) results in a logically defined methodology for mapping the unit. Primarily the methodology derived from this study relies on the association between the types of upper and lower boundaries of the Woodford and variation of thickness within the upper- and lower-transitional Woodford.

Four fundamental procedures in gathering information are necessary to examine the mappable qualities of the Woodford: (1) Determine the stratigraphic/lithologic top and base of the Woodford Shale. (2) Interpret the type of boundary (erosional, or conformable) at the top of the unit. (See PlateV: Where Woodford Shale is overlain by Mississippian strata, a conformable boundary is inferred.) (3) Identify the bounding stratigraphic units, determine their thicknesses and the thickness of Woodford. (4) Identify the positions and thicknesses of "submembers" of the Woodford Shale. Some questions to consider: (1) Are submembers of the upper-transitional Woodford noticeably thin or missing? If so, does pinchout or does truncation seem to be the cause? (2) Is the lower-transitional Woodford noticeably thin? If so, then could the thinness be attributed to deposition across a high-standing paleolandform?

Because regionally the reservoir potential of the Woodford probably is greatest in the upper portions of the formation, and because the local record of oil and gas production shows evidence of reservoirs in the upper-transitional Woodford, the study of reservoir potential was confined to examination of the upper-transitional Woodford. Steps in the procedure were (1) Determine the stratigraphic/lithologic top and base of the Woodford Shale. (2) Infer the type of boundary (erosional, or conformable) at the top of the unit. If Mississippian strata overlie the Woodford, then the probable reservoir is of maximal thickness. (3) Check for available micrologs or porosity logs, or any other log that would lead to valid inferences about porous, permeable strata, and from these records compile information that permits the mapping of extents and thicknesses of permeable strata.

Applicability of Methodology Beyond Study Area

Because the Woodford has log characteristics that seem essentially "uniform" over great expanses, the derived method for mapping of reservoir strata should be applicable beyond the study area. When assessing the applicability of this procedure, two basic attributes of the Woodford are to be considered: (a) The Woodford varies locally, and (b) division of the Woodford into submembers is functional and beneficial.

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

The Woodford Shale is straightforward to delineate and it can be mapped over exceptional distances. It is divisible into three discrete parts or "members," each with distinct log character, derived at least partially by lithology. In localities where Mississippian rocks overlie the Woodford Shale, each member varies in thickness, but the "lower-transitional member" varies the most, and the "middle member" varies the least (see PlateV). Within the study area, the "lower-transitional" member can range from approximately 5 feet to over 30 feet thick. This variation is informative because the unit seems to be everywhere. It should be the most sensitive indicator, permitting inferences about the configuration of paleotopography or of paleostructure at the lower boundary, during transgression of the Woodford onto the eroded Hunton. At some localities, thinning of the "lower-transitional member" of the Woodford is almost certainly indicative of high-standing topography on Hunton rocks (for example, see Plate IV, Section 17, T16N, R1W). At other localities, reasons for thinning of the lower member of the Woodford are difficult to assign. However, if information is used judiciously, then with supportive evidence certain assumptions can be made confidently concerning Hunton structure and paleotopography. Probably the most useful map one could make to estimate the relationship between thickness of the Woodford and structure/topography of the Hunton would be an isopach map of the lower member. This map should indicate areas of anomalous thickening and thinning, thereby illustrating areas where further study may be quite useful. (See Appendix E for an example.)

Reservoir potential of the Woodford Shale seems to be concentrated most in the upper-transitional unit. These strata generally contain more chert than the lower two members, as made evident by examination of bit cuttings from the Hollrah Exploration Company No.1 York (Appendix C). These “hard” portions of the shale seem to be extraordinarily susceptible to fracturing. Because lithology of the Woodford allows for minimal development of primary porosity, it is highly probable that fracturing developed the porosity and permeability recorded by the log signature across these strata. Micrologs and porosity logs are beneficial in identifying these porous reservoirs.

In order to better understand the intricacies of the Woodford-Hunton relationship and the Woodford Shale as a potentially commercial (i.e., profitable) reservoir, more information must be gathered in the routine of logging wells. I suggest that this unit be logged by micrologs, gamma-ray, neutron, density, acoustic logs. Micrologs seem to be especially effective. Core samples and detailed bit-cutting descriptions of the Woodford should be very useful. Many of the newer imaging tools could also be of great value for evaluating the abundance of fractures and the directions of fracturing within the Woodford.

Although based on local variation of the Woodford, the methodology described in this document is not strictly reliant on particular variation. The concepts set forth in this study should be considered guidelines. The principal value of this study is illustration of evidence to support the following assertion. Close examination of lithic and spatial variation of the Woodford should lead to description of parameters under which the formation locally would be a commercial reservoir. I realize that the suggestions expressed here are guidelines, rather than prescriptions for success. I suggest that close scrutiny of the Woodford and an increase in prices of oil and gas (relative to inflation) would result in the deliberate search for traps in the Woodford Shale.

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APPENDICES

APPENDIX A

HOLLRAH EXPLORATION COMPANY
NO. 1 YORK
Sec. 6, T15N, R3W

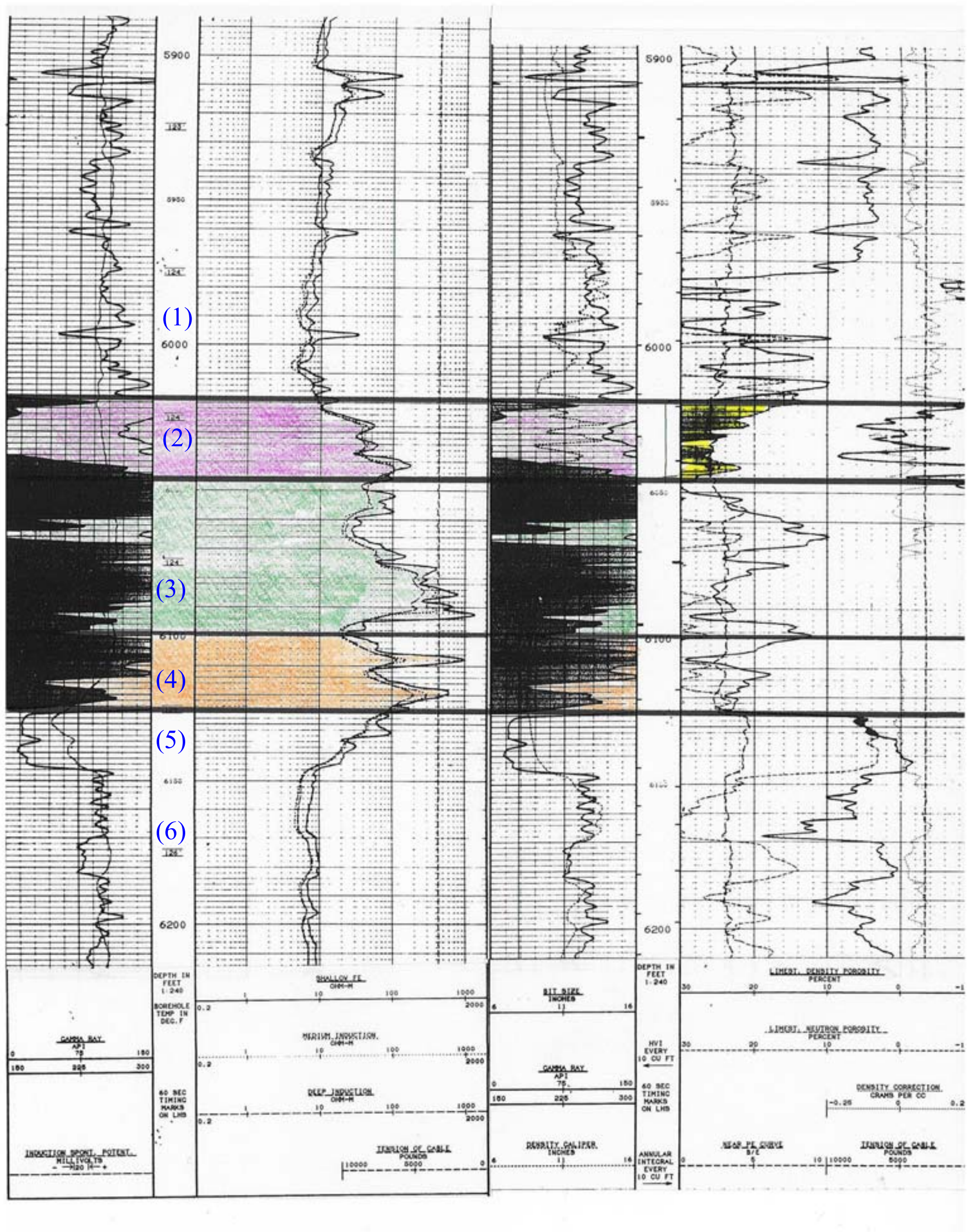


Figure A1. Log of the Woodford interval in the Hollrah Exploration Company No. 1 York, Sec. 6, T15N, R3W. Observe that the “upper-transitional member” is porous and permeable. This well produced oil from the Woodford Shale. Symbols: (1) Pennsylvanian strata, (2) “upper-transitional member,” (3) “middle member,” (4) “lower-transitional member,” (5) strata of the Hunton Group, and (6) Sylvan Shale.

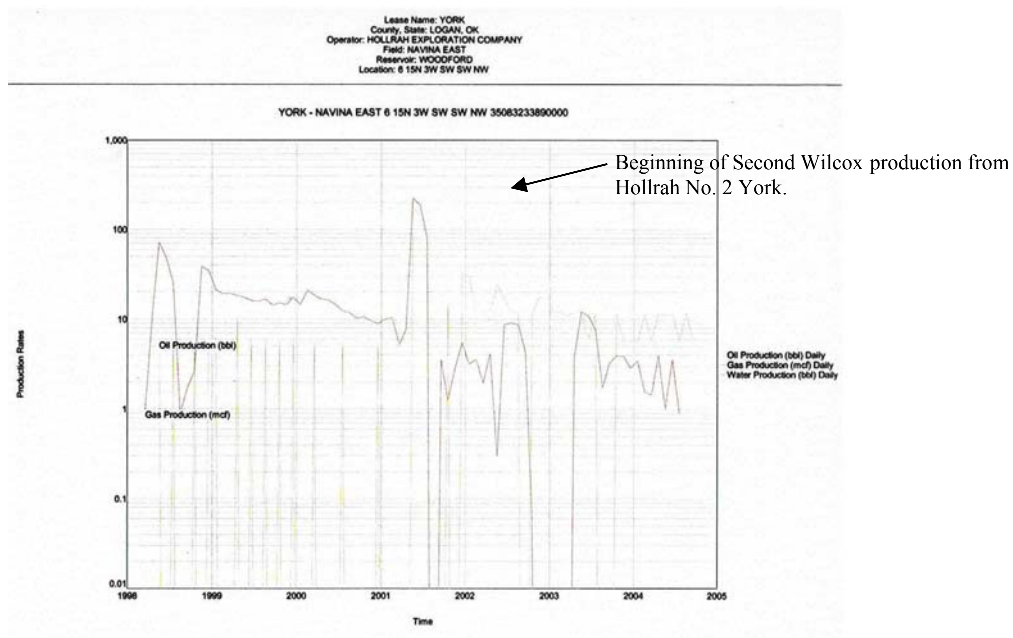


Figure A2. Plot of daily production of the No. 1 York versus time. In the current price environment, production from this well probably would have paid for the experiment of testing the Woodford Shale. Cumulative production from the Woodford was approximately 2700 barrels of oil. This production ceased in April, 2001; the “spike” in June, 2001 is correlated with production from the Second Wilcox in the Hollrah Exploration Company No. 2 York. (Production Data from IHS—PI/Dwights, 2004)

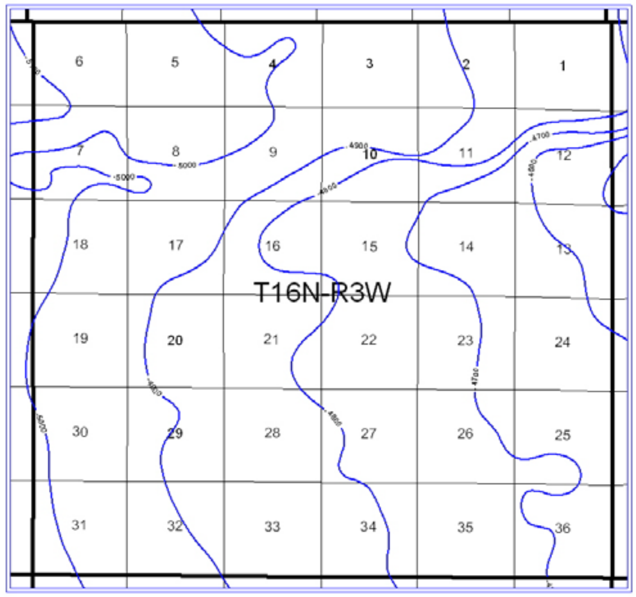
APPENDIX B

ANALYSIS OF LOCAL ISOPACH THICKNESSES

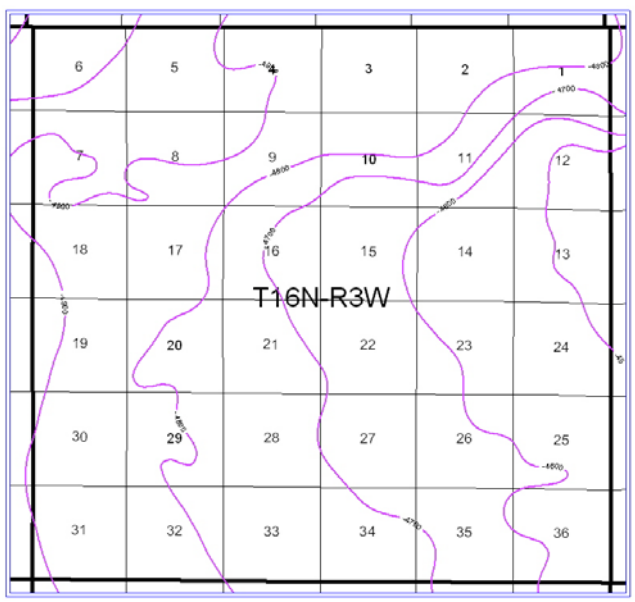
Hunton/Woodford Thickness Comparison: Analysis

Isopach maps created for this study show evidence of correlation between thickness of the Hunton Group and of the Woodford Shale. Structural configuration at the top of both of these rock stratigraphic units is similar, as shown in Figure B1. These supposed correlations would seem to illustrate some useful relationships. In order to test the hypothesis of positive correlation, three scatterplots were constructed.

A scatterplot was constructed for wells within T15N and T16N, R3W (Figure B2). This scatterplot shows thickness of the Woodford Shale along the x-axis, in comparison to thickness of the Hunton Group along the y-axis. Thicknesses were calculated through information recorded in EXCEL spreadsheets. Figure B2 shows a broad scatter of points. The population was decomposed on an arbitrary, nongeological, but convenient basis—township and range. Figures B3 and B4 suggest that relations of thickness of the Hunton and Woodford are indeed different in these townships. Perhaps the explanation basically is as follows: The northern part of T15N, R3W and the southern part of T16N, R3W are transitional between the "shelf break" (into the Anadarko Basin) to the south, and the Central Oklahoma Platform to the north.



(a)



(b)

Figure B1. Illustration showing the similarities between the configuration at the top of the Hunton (a) and the configuration at the top of the Woodford Shale (b).

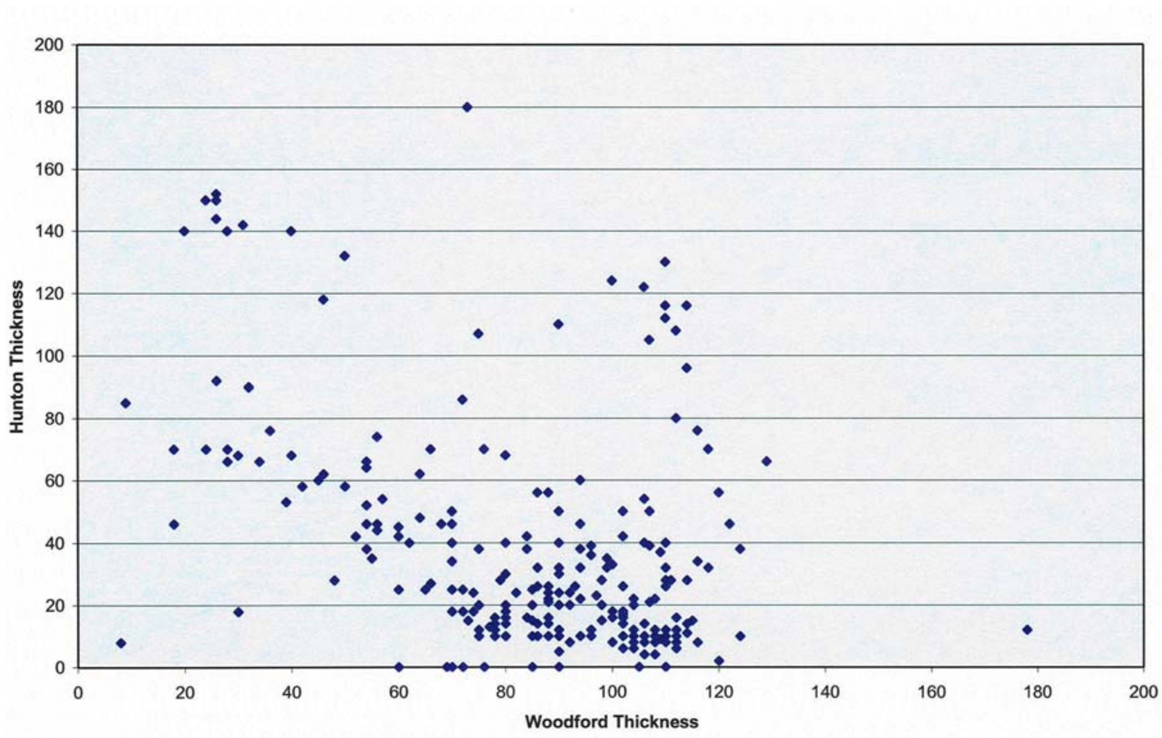


Figure B2. Scatter plot showing the relationship between thicknesses of the Woodford Shale and Hunton Group in Townships 15 and 16 North, Range 3 West. All thicknesses are plotted in feet.

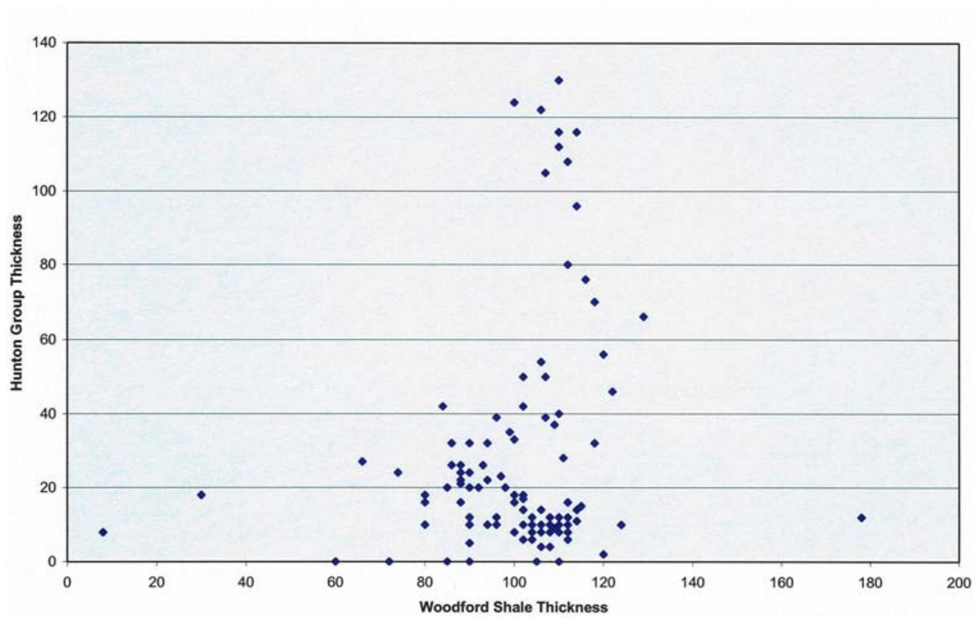


Figure B3. Scatter plot showing the relationship between thicknesses of the Woodford Shale and Hunton Group in T16N, R3W. All thicknesses are plotted in feet.

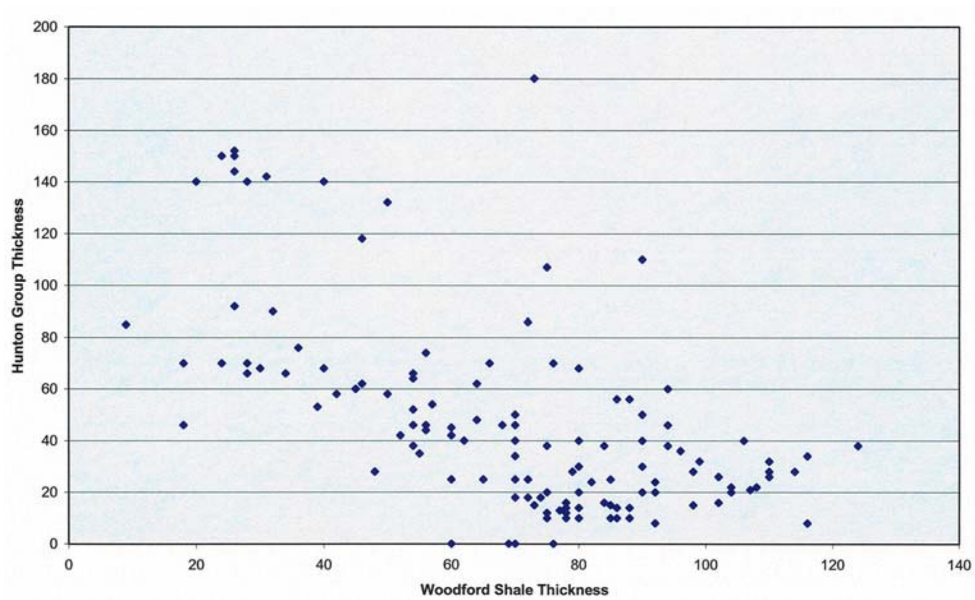


Figure B4. Scatter plot showing the relationship between thicknesses of the Woodford Shale and Hunton Group in T15N, R3W. All thicknesses are plotted in feet.

APPENDIX C

DESCRIPTION OF BIT CUTTINGS

Hollrah Exploration Company
Davis Farms No. 1-31
Sec. 31, T16N, R3W

Hollrah Exploration Company
Davis Farms No. 1-31
Sec. 31, T16N, R3W

Description of Bit Cuttings Across the Woodford Shale Interval

6030-35'
Dark gray to black, fine grained. Micaceous, dark brown to black chert. Possible concentration of fossiliferous material. Trace pyrite.

6035-45'
Dark grayish brown to black, fine grained. Micaceous, cherty (light tan). Some tan carbonate rock. Few, isolated quartz grains. Rare pyrite; possibly some material is fossiliferous.

6045-50'
Dark gray to black, fine grained. Limited lighter gray shale cavings with glauconitic material. Limited pyrite, fossil spores. Rare chert (light gray to grayish-brown). Some carbonate material.

6055-60'
Dark gray to black. Some pyrite and pinkish crystalline carbonate rock.

6060-65'
Dark brown to black. Some pyrite; little to no chert.

6065-70'
Dark gray shale, some fractures noted (possibly bit-related). Pyrite cubes and veining; grains of milky quartz.

6070-75'
Dark gray to nearly black, with some pyrite. Light brown to medium gray chert with noted conchoidal fracture; also dark gray to black chert. Some pinkish crystalline carbonate rock.

APPENDIX D

PRODUCTION STATISTICS

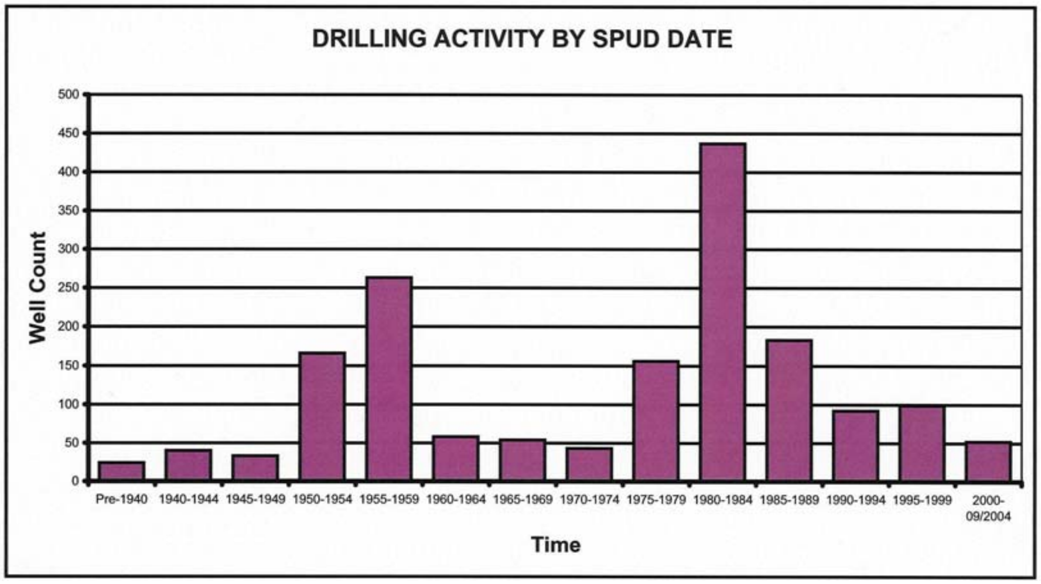
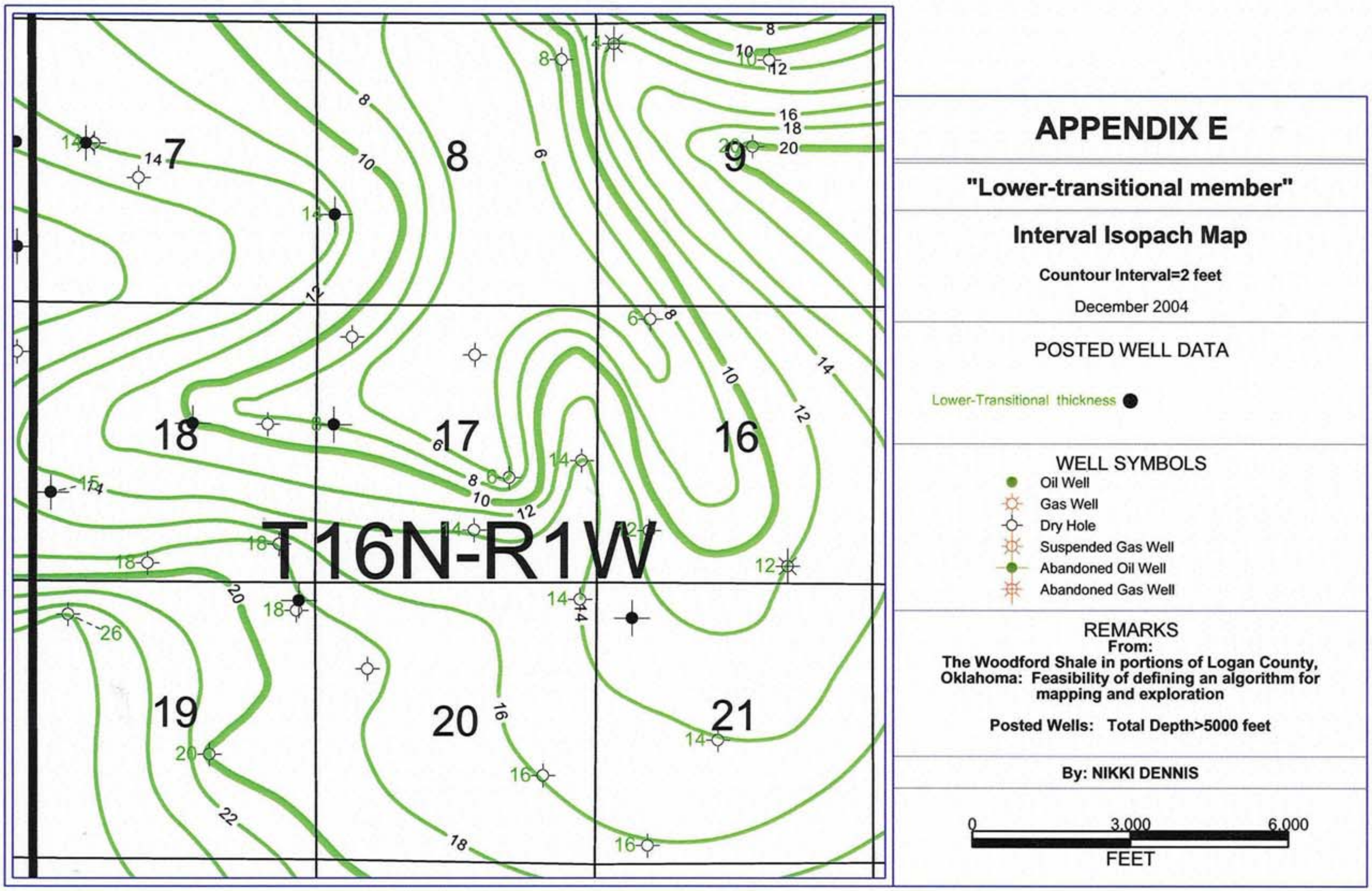


Figure D1. Graph showing the number of wells spudded within the study area during each five-year interval since January 1, 1940. The spike in drilling activity during the 1955-1959 interval can be attributed to the Suez Crisis (1956). The increase during the 1975-1979 and 1980-1984 intervals can be attributed to the oil price "boom." This was followed by a decline in 1985-1989 due to the oil price "bust". For more information on the socio-political explanation for drilling trends, see "The Prize: The epic quest for Oil, Money and Power" by David Yergin.

APPENDIX E

"LOWER-TRANSITIONAL MEMBER"
INTERVAL ISOPACH MAP


APPENDIX E
"Lower-transitional member"
Interval Isopach Map
Countour Interval=2 feet
December 2004
POSTED WELL DATA
Lower-Transitional thickness
WELL SYMBOLS
Oil Well
Gas Well
Dry Hole
Suspended Gas Well
Abandoned Oil Well
Abandoned Gas Well
REMARKS
From:
The Woodford Shale in portions of Logan County, Oklahoma: Feasibility of defining an algorithm for mapping and exploration
Posted Wells: Total Depth>5000 feet
By: NIKKI DENNIS
0
3,000
6,000
FEET
T16N-R1W
7
8
9
16
17
18
19
20
21

PLATES


T16N-R4W
T16N-R3W
T16N-R2W
T16N-R1W
T15N-R4W
T15N-R3W
T15N-R2W
T15N-R1W
PLATE I
Configuration of the Top of the Hunton
Countour Interval=100 feet
Wells spotted have TD>5000 feet
December 2004
POSTED WELL DATA
HUNTON (SS)
WELL SYMBOLS
Oil Well
Gas Well
Oil & Gas Well
Dry Hole
Injection Well
Service Well
Junked Oil and Gas
Temporarily Abandoned
Suspended Gas Well
Abandoned Oil Well
Abandoned Gas Well
Suspended Oil Well
REMARKS
From:
The Woodford Shale in portions of Logan County, Oklahoma: Feasibility of defining an algorithm for mapping and exploration
By: NIKKI DENNIS
0
3,000
6,000
FEET


Area of Sparse Control
T16N-R4W
T16N-R3W
T16N-R2W
T16N-R1W
T15N-R4W
T15N-R3W
T15N-R2W
T15N-R1W
THICK
Thin
Thick
THIN
PLATE II
Isopach Map of Hunton Thickness
Countour Interval=10 feet
Wells Spotted have TD>5000 feet
December 2004
POSTED WELL DATA
Hunton Thickness
WELL SYMBOLS
Oil Well
Gas Well
Oil & Gas Well
Dry Hole
Injection Well
Service Well
Junked Oil and Gas
Temporarily Abandoned
Suspended Gas Well
Abandoned Oil Well
Abandoned Gas Well
Suspended Oil Well
REMARKS
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6,000
FEET


T16N-R4W
T16N-R3W
T16N-R2W
T16N-R1W
T15N-R4W
T15N-R3W
T15N-R2W
T15N-R1W
PLATE III
Configuration of the Top of the Woodford
Countour Interval=100 feet
Wells Spotted have TD>5000 feet
December 2004
POSTED WELL DATA
Woodford (SS)
WELL SYMBOLS
Oil Well
Gas Well
Oil & Gas Well
Dry Hole
Injection Well
Service Well
Junked Oil and Gas
Temporarily Abandoned
Suspended Gas Well
Abandoned Oil Well
Abandoned Gas Well
Suspended Oil Well
REMARKS
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0
3,000
6,000
FEET


T16N-R4W
T16N-R3W
T16N-R2W
T16N-R1W
T15N-R4W
T15N-R3W
T15N-R2W
T15N-R1W
Thin
Thick
PLATE IV
Isopach Map of Woodford Thickness
Countour Interval=20 feet
Posted Wells: Total Depth>5000 feet
December 2004
POSTED WELL DATA
Woodford Thickness
WELL SYMBOLS
Oil Well
Gas Well
Oil & Gas Well
Dry Hole
Injection Well
Service Well
Junked Oil and Gas
Temporarily Abandoned
Suspended Gas Well
Abandoned Oil Well
Abandoned Gas Well
Suspended Oil Well
REMARKS
From:
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6,000
FEET


T16N-R4W
T16N-R3W
T16N-R2W
T16N-R1W
T15N-R4W
T15N-R3W
T15N-R2W
T15N-R1W
PLATE V
Worm's Eye View:
Map showing the stratigraphic units overlying the Woodford Shale
December 2004
ATTRIBUTE MAP
Pennsylvanian(inspected)
Mississippian(inspected)
Pennsylvanian (not inspected/scout card only)
Mississippian (not inspected/scout card only)
WELL SYMBOLS
Oil Well
Gas Well
Oil & Gas Well
Dry Hole
Injection Well
Service Well
Junked Oil and Gas
Temporarily Abandoned
Suspended Gas Well
Abandoned Oil Well
Abandoned Gas Well
Suspended Oil Well
REMARKS
From:
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T16N-R4W
T16N-R3W
T16N-R2W
T16N-R1W
T15N-R4W
T15N-R3W
T15N-R2W
T15N-R1W
N
S
W
E
PLATE VI
Cross Section Location Map
WELL SYMBOLS
Location Only
Oil Well
Gas Well
Oil & Gas Well
Dry Hole
Injection Well
Service Well
Junked Oil and Gas
Temporarily Abandoned
Suspended Gas Well
Abandoned Oil Well
Abandoned Gas Well
Suspended Oil Well
REMARKS
From:
The Woodford Shale in portions of Logan County, Oklahoma: Feasibility of defining an algorithm for mapping and exploration
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3,000
6,000
FEET

PLATE VII

Stratigraphic Cross Section

West to East

Datum: Top Woodford Shale

December 2004

REMARKS

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The Woodford Shale in portions of Logan County, Oklahoma: Feasibility of creating an algorithm for mapping and exploration.

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PLATE VIII

Stratigraphic Cross Section

North to South

Datum: Top Woodford Shale

December 2004

REMARKS

From:
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By: Nikki Dennis

T16N-R4W
T16N-R3W
T16N-R2W
T16N-R1W
T15N-R4W
T15N-R3W
T15N-R2W
T15N-R1W
Guthrie West
Guthrie East
Guthrie Townsite
Evansville
Guthrie Lake East
Navina East
Seward
Pleasant Valley
Waterloo
PLATE IX
Map Showing Depth of Penetration
Of All Wells Within the Study Area
ATTRIBUTE MAP
Wells penetrating rocks Mississippian age or younger
Sub-Mississippian Penetrations, not reaching the base of Woodford Shal
Wells Penetrating the entire Woodford Shale Interval
WELL SYMBOLS
Location Only
Oil Well
Gas Well
Oil & Gas Well
Dry Hole
Injection Well
Service Well
Junked Oil and Gas
Temporarily Abandoned
Suspended Gas Well
Abandoned Oil Well
Abandoned Gas Well
Suspended Oil Well
REMARKS
From:
The Woodford Shale in portions of Logan County, Oklahoma: Feasibility of defining an algorithm for mapping and exploration
December 2004
By: NIKKI DENNIS
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6,000
FEET

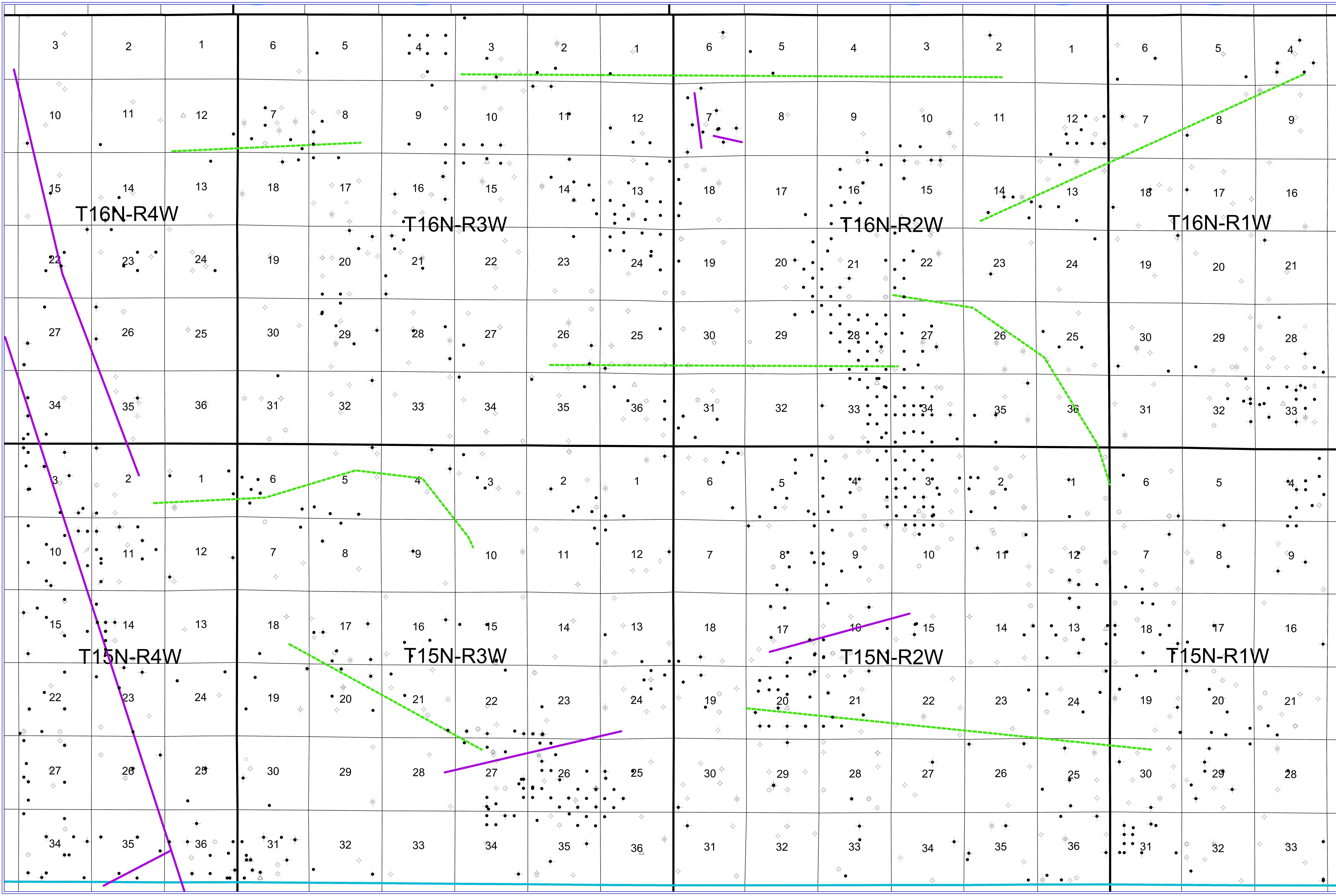

PLATE X

Map of Structural Fabric

of the Study Area

December 2004

WELL SYMBOLS

- Location Only
- Oil Well
- Gas Well
- Oil & Gas Well
- Dry Hole
- Injection Well
- Service Well
- Junked Oil and Gas
- Temporarily Abandoned
- Suspended Gas Well
- Abandoned Oil Well
- Abandoned Gas Well
- Suspended Oil Well

REMARKS

From:
The Woodford Shale in portions of Logan County, Oklahoma: Feasibility of defining an algorithm for mapping and exploration

Purple lines represent faults described by Ford (1954). Green lines represent inferred faults or inferred structural axes.

By: NIKKI DENNIS

0 3,000 6,000
FEET

VITA

Nikki Lyn Floyd Dennis

Candidate for the Degree of

Master of Science

Thesis: THE WOODFORD SHALE IN PORTIONS OF LOGAN COUNTY, OKLAHOMA: FEASIBILITY OF DEFINING AN ALGORITHM FOR MAPPING AND EXPLORATION.

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Personal Data: Born in Pryor, Oklahoma, on December 13, 1974, the daughter of Harry and Teresa Floyd.

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Experience: Interned for TEXACO in New Orleans, Louisiana, summer of 1998; employed as a teaching assistant for two years by Oklahoma State University, teaching laboratories for introductory geology, geomorphology and environmental geology; employed by Nadel and Gussman, L.L.C. as a geologist.

Professional Memberships: American Association for Petroleum Geologists.