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REDUCTION OF RISK IN EXPLORATION AND PROSPECT GENERATION THROUGH A MULTIDISCIPLINARY BASIN-ANALYSIS PROGRAM IN THE SOUTH-CENTRAL MID-CONTINENT REGION

Final Report
October 1998

By
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April 1999

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ABSTRACT

There has been a substantial decline in both exploratory drilling and shallow-field workover activity in the United States over the last 15 years due primarily, to variability and ongoing uncertainties in the price of domestic oil. To reverse this trend and to preserve the entrepreneurial independent operator, the U.S. Department of Energy (DOE) is attempting to encourage hydrocarbon exploration activities in some of the under-exploited regions of the United States. This goal is being accomplished by conducting broad regional reviews of potentially prospective areas within the lower 48 states and by studying and developing ways to increase efficiency and lower exploration costs for domestic operations by independent operators, the backbone of drilling within the U.S.

These studies have been conducted on a scale generally unavailable to the smaller independents. The results of this work are being made available to industry and the public, to encourage more aggressive domestic operations in the U.S.

This report will discuss a series of regional studies that were undertaken within the South-Central Mid-Continent region of the U.S. Coverage is also provided about a series of innovative techniques that were used for this assessment.

ACKNOWLEDGMENTS

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1.0 INTRODUCTION

Following the decline of oil prices in the United States in the mid-80's, both exploratory drilling and field crews for seismic work dropped off in the US. The US Department of Energy has adopted a program aimed at reversing these trends. The objective is to encourage additional domestic activity and to preserve the entrepreneurial independent operator. To further this goal, broad regional reviews are being conducted of potentially productive areas within the lower 48 states.

The DOE Basin Analysis program was initiated in 1994. Reeves and Carroll, 1994a, and Reeves and Carroll, 1994b, describe the purpose of the work and the early stages of basin selection and prioritization. The first region to be studied was the Black Mesa basin, in northeastern Arizona. Results of this analysis have been presented in Reeves et al, 1996, and Sharma et al, 1996.

This assessment was followed by the work in the South-Central Mid-Continent that is described in this report. This work concentrated on Proterozoic sediments within and Paleozoic sediments overlying the southern end of the Mid-Continent Rift System (MRS). The most intense focus was on the deeper portions of the Forest City basin of Kansas, Nebraska, Missouri, and Iowa. This region has historically been productive in the shallow section; however, it is underexplored in the deep formations. A second target was the Salina basin of Kansas and Nebraska, which is almost unexplored, with very little production from any depth.

Work on the South-Central Mid-Continent began in the summer of 1996. The South-Central Mid-Continent was originally selected for study because USGS estimates for undiscovered recoverable resources in the lower 48 states (Takahashi, 1995, Gautier et. al., 1996) showed reasonably high values in this region. In addition, the area was not currently under study by other federal or state agencies, an important factor for consideration, since the Exploration and Drilling (E&D) Research Program was designed to avoid overlap with programs of these agencies or other federal or state research.

It was recognized that the study area lay at the southern end of the MRS that runs from the Great Lakes region south to Kansas. It has been known since the 1800s that the Nonesuch shale, along the southern margin of Lake Superior, contains live oil, which can be seen dripping from the walls of the White Pine copper mine, in Michigan. The organic content of dark portions of the rift sediments in the Great Lakes area is also quite high.

A series of Precambrian monadnocks that project up into the Paleozoic sequence in eastern Kansas produced economic quantities of oil during the decades of the 1930s–1950s (Walters 1946, 1953). It was felt that Precambrian sediments in this rift could have been the source of this oil.

Early analysis of the Precambrian potential of the MRS area was promising. Susan Landon (editor of AAPG Memoir 59, Interior Rift Basins), in personal communications with BDM staff cited estimates and predictions of 20 to 30 billion barrels in play in the rift system as a whole. Individual field sizes could range from 500 million to 3 billion barrels, based on the type of deposits involved. This type of information encouraged further study.

Several wells had been drilled along the MRS during the 1970s and 1980s. In addition, some earlier wells had taken samples of the shallowest portions of the rift. As work on the project progressed, it became obvious that data from this drilling demonstrated a pattern of steadily decreasing organic contents within the rift sediments from north to south. High organic content values were reported in Minnesota, while results in Iowa were lower. Values identified in Kansas were lower still, with some of the Kansas samples totally oxidized. The decrease was steady, progressing from north to south. Some of the Kansas samples had 0% organic content in what should be equivalents to the best potential source-bed shales, as identified in other wells to the north.

In addition, studies of the regional tectonics during the Late Proterozoic and Early Paleozoic failed to identify any major events which might have shattered any seals within the rift fill. Continental-interior rift sediments often include a large number of small pods of organic-rich sediments, representing lacustrine deposits with a rich bios. Fetid black shales frequently typify such sediments. These deposits can provide excellent source material, which can mature quickly, in geologic terms, in the rapid-deposition environment of a rift. Rapid, deep burial and heating from intrusives and extrusives can induce thermal maturity at a very early point in the history of the sediments. Volcanic activity along the rift margins tends to produce a complex, interlocking series of lava flow over and around lava flow, producing exceptionally effective seals.

Individual rift-lake pod sequences can be relatively small, although large numbers of pods can exist along a rift valley. Generally, the best commercial-scale hydrocarbon accumulations are formed when numerous of the rift lake sequences are ruptured, with the hydrocarbon accumulations migrating from the small source units into a single, large reservoir in younger, porous sediments.

The Mid-Continent region lacks the wide-spread rupturing events found in the southwestern portion of the Colorado plateau, like the Cretaceous—Post-Cretaceous volcanism throughout the Black Mesa region and southern Utah, which apparently allowed Chuar hydrocarbons to escape into Cambrian and Lower Paleozoic reservoirs (Reeves et al, 1996, and Uphoff, 1997). The combination of low organics to the south within the MRS and a lack of a large-scale penetrative or rupturing orogenic event in the region of the South-Central Mid-Continent has greatly reduced the chance of finding deeper, Precambrian-sourced hydrocarbons in the study area.

Despite these problems, it was recognized during the study that Ordovician-age oil has been found widely distributed to the east of the Nemaha uplift in Kansas and southeastern Nebraska. Alternative origins were sought for this oil, either a local source, or an eastern or southeastern source, in the Ozark trough area. Both alternatives were considered to be likely possibilities.

This Final Report describes the change of focus in the project, and describes the diversity of approaches that are being used in the multidisciplinary study.

2.0 REGIONAL GEOLOGIC ANALYSIS

The initial phases of this project focused on studies of the Mid-Continent Rift System (MRS).

2.1 Study of the Precambrian Section

Intracontinental rifts develop when the mantle beneath continental crust becomes overheated and expands. The expansion of the mantle leads to stretching and rupture of the crust, with mountains generally lining both sides of the rift, and a long valley through the center of the feature. Lakes are common within the rift, fed by mountain streams and rivers. Sedimentation can be quite rapid in this type of setting. As expansion of the mantle continues, the mountains continue to grow, through active faulting. Lakes abruptly jump from point to point as the crust continuously adjusts to tectonic movements.

Within a rift, organic-rich sediments tend to accumulate in a large number of small, very well sealed pockets within the overall sediment package. They generally mark the location of lake or inlet/estuary deposits, encapsulated within volcanic sequences. Tightly sealed lava flows and dikes tend to surround the best source beds.

The down-dropped portions of rifts are generally typified by long, narrow water bodies, a gulf, like the Gulf of Suez, in a marine or near-marine setting, or a string of lakes, if intracontinental. On the scale of a major rift, each individual lake is small, a very localized feature, and quite ephemeral. Over time, the rift, as a whole, is the site of lake after lake, each small and short-lived but, in total, omnipresent, widespread, and the site of significant sediment accumulations. The lakes are often deep along one margin near an active fault, but are rapidly filled by sediments generated during erosion along the uplifted margin of the rift. The total rift-fill sedimentary section can include many small isolated pockets, or pods, of potential source rock sediments.

Large volumes of coarse-grained potential reservoir-quality sediments generally fill extensive areas along the rift system complex. Fine-grained sediments are common in the shallow-water portions of the lake. The high-energy, well-lit lake waters generally teem with life. Even in Proterozoic lakes, single-celled life forms and stromatolites were common. Fossil stromatolite "reefs" have been discovered in the Precambrian in rift deposits on several continents. In Phanerozoic Rift lakes, many varieties of more advanced plants and animals are abundant.

Convective turnover, driven by hot springs deep within the lakes keeps the water well oxygenated, encouraging life forms at all depths within the water body. The organic-rich deposits frequently achieve significant thickness as the rifting proceeds. This mix of potential source rocks in close proximity to potential reservoirs, along with a hotter-than-normal environment, warmed by volcanism, is one reason hydrocarbons are so frequently generated along rifts.

Sedimentation in individual rift lakes is generally terminated by catastrophic events, as major crust-penetrative faults shift and the rift realigns and adjusts to new stress states. Most lakes are ultimately inundated by massive lava flows, as the crustal blocks move and sedimentation ends in an area. When a new series of mountains rises and a different section along the trend drops, the former lake valleys frequently fill with lavas. Volcanic activity overwhelms clastic sedimentation in these spots. As this happens, a new depression with interior drainage becomes the temporary low along the trend, abruptly producing a fresh series of lakes in the new lows.

Each pod tends to be isolated from its neighbors. Extensive associated volcanism produces a complex series of seals around the lake deposits. Numerous dikes generally flank the former lakebeds while repeated lava flows cover the sediments. The lava flows spread out, one after another often from multiple sources and many directions. The cumulative effect of this is to cover and cap the pods with a highly efficient complex series of seals. These caps can survive many types and degrees of tectonism. If one of the lava seals is shattered, there is usually a backup cap above it.

The rift system surrounding the western and southern margins of the Arabian peninsula and continuing southward into Africa is a good modern analog to the ancient MRS. It is an area where many reservoirs have formed and retained their tightly sealed integrity during a highly active tectonic history. A pattern of organic-rich source-bed shales can be found in the African rift lakes, closely associated with potential coarse-grained reservoirs, and surrounded by dikes and multiple layers of lava.

These associations tend to produce numerous isolated, tightly-encapsulated small reservoirs. Faulting has had relatively little effect on the sealed reservoir pods here. Individual faults are generally too small and restricted in extent to allow the escape of many hydrocarbons. Even regional fault zones have little effect on hydrocarbons away from the faults. Within the African continent, most of these units are too small to be of current economic interest. In the area of the Red Sea and Gulf of Aden, tectonics have allowed some of these hydrocarbons to migrate and accumulate in larger reservoirs, of greater commercial interest.

Contemporaneous volcanism produces the original seals and can play a role in the maturation of the sediments. It is a second, later period of tectonism and volcanism that, if sufficiently widespread, can cut through all the complex seals. Such widespread volcanism can punch small plugs and dikes upward over such a widespread area that many of the rift units are punctured and breached. This type of volcanism is present along the southwestern corner of the Colorado plateau. Dikes and volcanoes began to appear around the Four Corners area during the Cretaceous. Igneous activity has continued in the region into the historic period. Intrusives are widespread across the entire Four Corners area, having swept the region in repeated waves.

This pattern would explain the migration history found at the 1994 BHP (Broken Hill Proprietary Petroleum Co.) well in the Kaiparowits basin in southern Utah (Uphoff, 1997). BHP reported that oil migrated from the Precambrian Chuar Formation into the Cambrian Tapeats sandstone in the formations penetrated by the well during the Cretaceous, not earlier. During the late Mesozoic, volcanic plugs and dikes forced their way up through the Chuar section, punching holes in seal after seal. Ultimately, the intrusives ruptured the capsules that had contained the Chuar oil since Late Proterozoic time.

Volcanic activity continued in the region throughout the Tertiary period and into the Recent, potentially allowing additional oil to migrate from numerous smaller Chuar traps into larger pools along monoclines or other deep structures with porosity. This pattern should apply in Arizona as well as Utah.

The South-Central Mid-Continent region did not experience the same type of Phanerozoic volcanic activity seen during the Cretaceous—Post-Cretaceous on the southwest edge of the Colorado Plateau. This raises questions about the mechanism for breaking seals and migration from any Proterozoic compartments which may exist within the Proterozoic Mid-Continent Rift system sediments.

Vertical faulting alone is typically not sufficient to break open a significant number of these traps. Thus, fault zones like the Humboldt system and Nemaha uplift may have allowed limited quantities of oil to leak locally from a few reservoirs that were cut directly and breached, near the uplift. However, away from the Humboldt fault, most of any rift pods are presumably still intact, in many small compartments.

Both the Chuar and the Mid-Continent Rift sediments could have generated significant quantities of oil. If it was generated, this oil should have had a high potential for surviving the great erosion at the end of the Proterozoic. Rift oil is not likely to migrate or degrade unless the region is later reheated and over-cooked. The oil will not escape unless a specific oil-filled compartment is breached by erosion, or a complex system of interlocking and overlapping seals is cut by faulting or penetrated by igneous plugs. Small-scale, minor faulting, or minor volcanic activity will not breach many of the seals. Only widespread volcanism will cut through a large number of traps, allowing significant quantities of oil to migrate and accumulate in Phanerozoic reservoirs.

The environment along a rift can change abruptly, as witnessed by the short distance between deep Lake Victoria sediments (a potential future source of oil), the surrounding savanna, and the ringing volcanoes. When buried beneath several thousand feet of sediments, a slight misdirection of the drill bit could completely miss the fact that a lake (or oil pocket) existed in the vicinity. In a single compartment (an ancient lake, for example), reserves may be too limited to be of commercial interest, depending upon depth, cost of exploration, etc.

For the reasons described above, it will be logical in the South-Central Mid-Continent to prospect for areas where individual reservoirs in the Proterozoic Rift sequence are likely to have been breached, allowing the reserves from several pockets to combine into larger accumulations. The Mid-Continent region has been cut by localized faulting and volcanic activity, but it is questionable if there has been sufficient disturbance to breach many of the Proterozoic compartments along the rift zone.

2.2 Potential of the Precambrian Rift-Fill Sequence

Historical and recent drilling has produced a limited amount of data that suggests that the southern end of the MRS has much less potential than the northern section. While the Precambrian Nonesuch shale in the northern Mid-Continent, with live oil seeps in the White Pine mine, is famous for its high organic content and thermal maturity, the % organic content of the rift shales appears to decline steadily to the south.

The Chuar Formation in northeastern Arizona has tested as high as 10% Total Organic Carbon (TOC) with a 3% average (Chidsey et al, 1990; Palacas and Reynolds, 1989; Reeves et al, 1996, p. 16–20).

Samples of the Nonesuch Formation at the White Pine mine in Michigan have yielded readings ranging up to 2.8%, but no higher, even though live oil can be seen there (Mauk and Hieshima, 1992).

In Rice County, Minnesota, of 25 samples collected and tested from the Lonsdale well deep exploratory test, the richest sample contained only 1.77% TOC (Hatch and Moray, 1985). All of the other samples from this well ranked much lower.

Testing in Iowa, at the Amoco Eischeid rift well (Anderson, 1990), revealed a maximum of 1.4% TOC, from a single sample (Palacas et al. 1990).

Three deep basement wells in Kansas, including the Poersch well, drilled by Texaco (Berendsen et al., 1988), tested at 0.5% TOC or less (Hatch, 1988). Several of the Kansas samples were totally oxidized (Hatch, 1988).

These figures represent a marked trend, with decreasing values in TOC toward the southern end of the MRS (Table 2–1).

Table 2–1 Total Organic Carbon (TOC) Values for Selected Precambrian Samples

Location	TOC
Chuar	10% (maximum), 3% average
Nonesuch (W. Pine, Michigan)	2.8% maximum, 0.6 average (in laminae only)
Lonsdale (Rice Co., Minnesota)	1.77% (1 of 25 samples)
Eischeid (Iowa)	1.4% maximum
Finn (Kansas)	0.5%
Freiderich (Kansas)	none (oxidized?)
Poersch (Kansas)	oxidized

2.3 Study of the Lower Paleozoic Sequence

At the same time, while discouraging data was accumulating about the low TOC values and poor prospects for source bed potential within the rift units in the southern portion of the MRS, an understanding was also being gained about the importance of tectonics in the release and accumulation of hydrocarbons from rift sediments. Tectonic history plays an important role in moving hydrocarbons from small local pools into larger, economically-sized fields. The combination of the poor TOC data and a lack of the proper type of Phanerozoic tectonics greatly reduced interest in the in the Precambrian-sourced potential of the MRS.

As interest in the Proterozoic section was declining, data was being gathered on deep production in the Forest City basin. A more-careful look was then taken at the structural setting of the Paleozoic section across the study area. Early attention focused on the ancient North Kansas and Iowa Basins, structural sags that existed during the upper Ordovician, Silurian, and Devonian. Attention was also given to the earliest Paleozoic structural features and to the sedimentary sections that accumulated during the Cambrian and lower Ordovician.

Figure 2-1 is a greatly simplified regional isopach of the Mid-Continent. It shows that the South-Central Mid-Continent region was relatively featureless at this time. The surface slopped gradually from a high along the Trans-Continental Arch (running from the Four Corners region, through Colorado, to Lake Superior) down to the Ozark trough (following the general trend of the Reelfoot rift, an ancient sag that underlies the modern Mississippi valley). The Cambrian and lower Ordovician sedimentary sequences thicken from featheredges in Kansas or Oklahoma to the southeast, then begin to thicken dramatically into the Ozark trough.

Ozark trough sediments accumulated above an already thick rift sequence. The Reelfoot feature is generally believed to have opened and deepened during the interval between 600 and 500 Ma. It was most active during the Precambrian and earliest Cambrian, although the area continued to sink rapidly well into early Paleozoic time.

The Cambrian-lower Ordovician sediment column was accumulating so rapidly in the area of the Ozark trough that early generation of hydrocarbons in the rift area is highly likely. The setting resembled that in which the Chuar and MRS sediments were deposited, although lifeforms were more abundant and varied by Cambrian time than they had been during the Proterozoic. There is little evidence of late phase volcanism in this area.

Hydrocarbons that were generated along this rift during the latest Proterozoic/Cambrian may have been more mobile that those produced during the volcanic phases in the MRS or in the Chuar. If hydrocarbons did form in this region, and if they were free to migrate, the logical place for them to migrate to would be updip, to the northwest or to the east. Any migration to the northwest would have proceeded directly toward the study area, the Forest City-Salina Basin region.

Figure 2–1 is greatly simplified. In actuality, there were many local highs, small arches, sags and domes between the Reelfoot area and the Trans-Continental Arch. The details of updip migration patterns would have been highly complicated, but the overall trend would have been to the northwest.

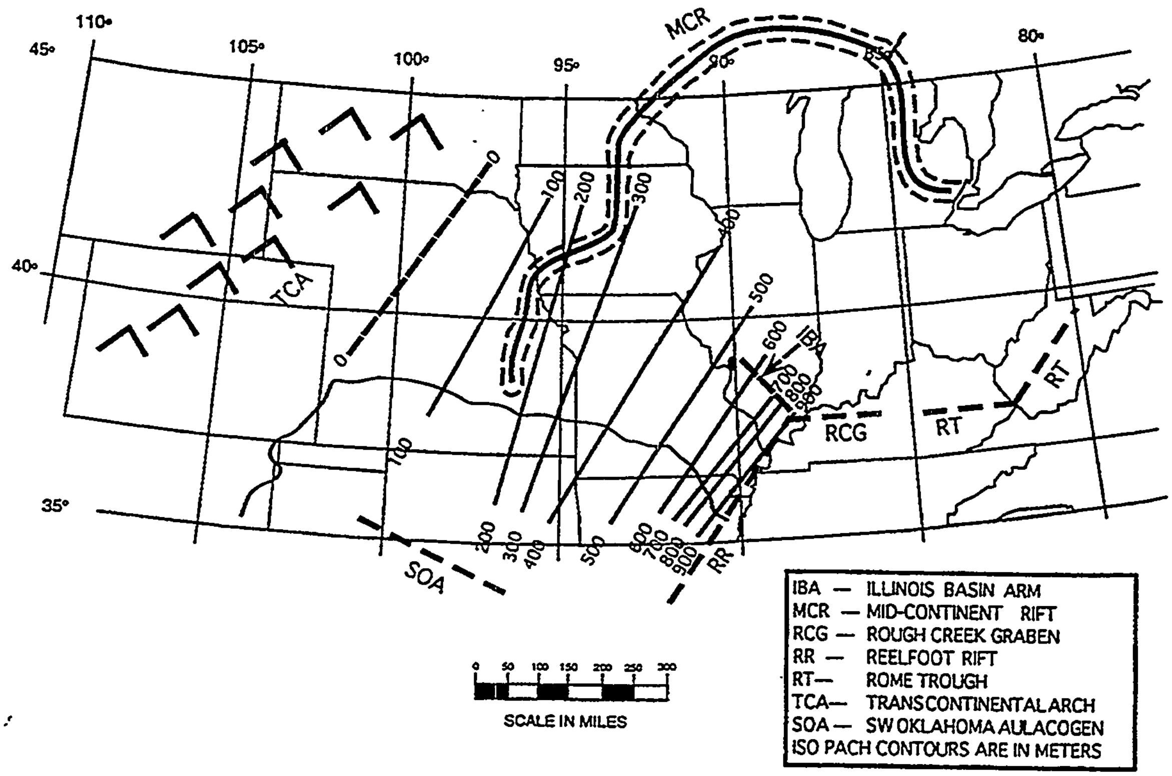

Figure 2–1 Cambrian-Ordovician Isopach Map of the Mid-Continent Region

This possibility of early sourceing, maturation and migration may account for some of the Ordovician oil that has been reported in the series of deep producing wells just to the east of the Nemaha uplift.

The regional framework of the South-Central Mid-Continent region changed significantly (see Fig. 2–2) during the upper Ordovician-Silurian, with the area of the southern end of the ancient MRS sinking, forming the North Kansas Basin. The Missouri - Arkansas region was relatively positive at this time, cutting off the quick, direct migration pathway from the Ozark trough to Kansas.

During the Devonian (see Fig. 2–3), the main depocenter migrated to the northeast, into Iowa. The area of greatest sag was still over the ancient MRS trend. The Missouri-Arkansas area remained relatively positive at this time. Again, there was no direct migration route from the Reelfoot area to Kansas.

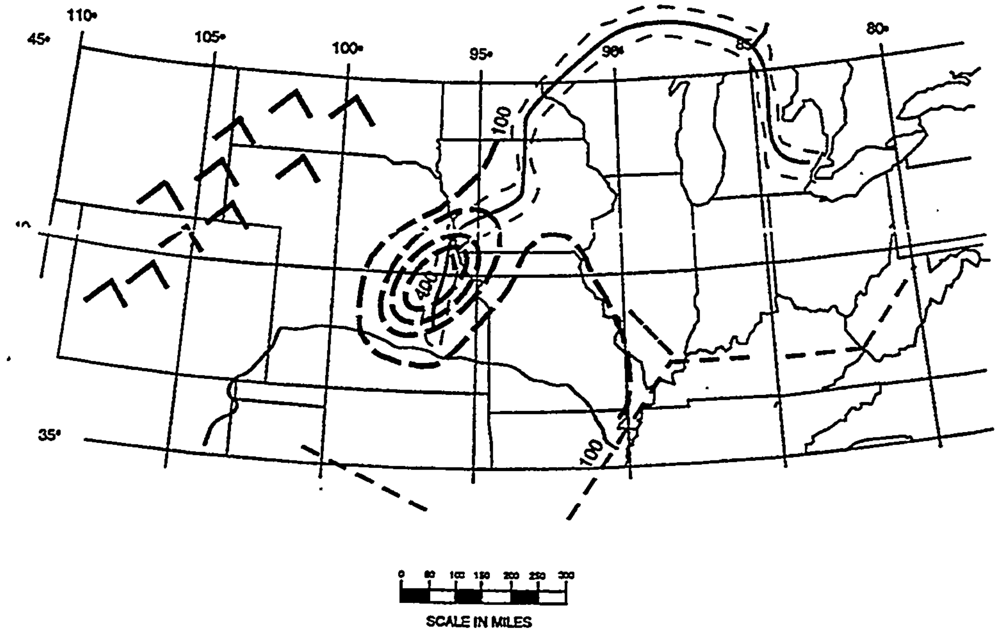

Figure 2–2 Ordovician-Silurian Isopach Map of the Mid-Continent Region.

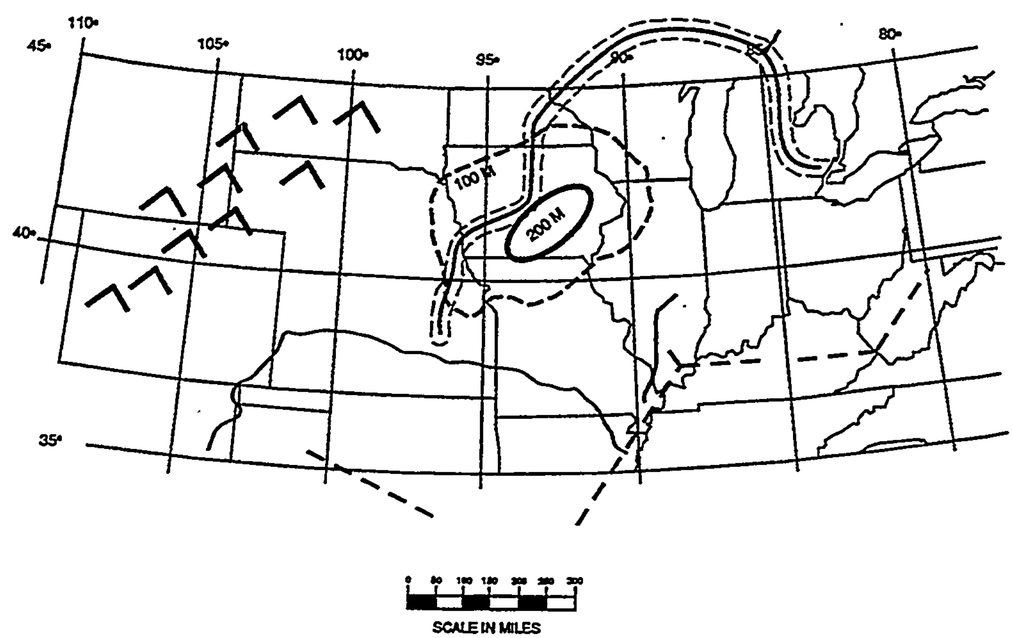

Figure 2–3 Devonian Isopach Map of the Mid-Continent Region

During Mississippian time, the entire Mid-Continent region experienced active tectonism. This fundamentally changed the structural picture, with uplifts beginning to form in the Ozark area and along the Nemaha trend.

Although prospects for large, commercial-sized accumulations of Precambrian-sourced hydrocarbons were now viewed as slim, it seemed that a large-scale migration could have brought hydrocarbons to the study area from the east and southeast during the earliest Paleozoic. Plans were made for detailed studies and modeling of the Paleozoic sediments of the South-Central Mid-Continent.

2.4 Computer Modeling of the South-Central Mid-Continent

Discussions were initiated with the Department of Geology and Geophysics at the University of Minnesota for a cooperative effort to model the sedimentary and tectonic history of the South-Central Mid-Continent. Dr. Mark Person of the Gibson Computational Hydrogeology Laboratory at the University of Minnesota has been developing a series of basin modeling programs for many years.

2.4.1 Program History

A program known as FHAMod had been developed at the University and was available in 1994. It was anticipated that the BDM team would play a significant role in further enhancement of this program, be granted training for its operation and subtleties, and be given unlimited access to the code. Unresolvable problems with the preprocessor prevented the system from being loaded and run on the BDM computers in 1995, so the plan and cooperation were not able to proceed at that time.

Dr. Person took a sabbatical year and made significant progress in upgrading and improving FHAMod in cooperation with the USGS during 1995 and 1996. The revised and improved, latest version of the program is now known as RIFT2D. The purpose of the program is to model basin history and fluid dynamics in rift-related sedimentary basins.

2.4.2 Project Description

With the program now updated and improved, the original proposal and arrangement was reconsidered in FY 1997. A license to test and use the updated version of the FHAMod/RIFT2D computer program was renegotiated with the University of Minnesota to see if the system could now be installed and made to run on BDM Petroleum Technologies computers. The new system worked, and a copy of the program code was sent to the BDM Petroleum Technologies Geosciences Computer Laboratory in Bartlesville, Oklahoma, and successfully loaded.

2.4.3 Project Methodology

According to the agreement with the University of Minnesota, the BDM Petroleum Technologies research team was responsible for providing extensive, multiple data sets. This information was required for cross-sectional basin modeling in the Mid-Continent region. Intensive data acquisition was undertaken. The sources used included published literature, Masters Theses and Ph.D. Dissertations, the Internet, personal communications with various local experts, and files and archives of Geological Surveys.

As will be discussed below, several trips were made; to collect samples of key potential source rocks in the field, and to state geologic surveys. A set of petrographic and geochemical data was generated from outcrop samples of Lower Paleozoic candidate source-rock sequences collected from a variety of Ozark Plateau exposures. The data sets were transferred to the University of Minnesota, where the data were entered into their computer. As the model was run, and problems were encountered, the University computer programmers adapted and further modified the RIFT2D code to increase efficiency and accuracy of results.

2.4.4 Results

BDM Petroleum Technologies and the University of Minnesota developed a cross-sectional model of the regional sedimentary history, along with details of compactional, structural, and erosional evolution. The model also included details on groundwater flow, heat transfer and possibilities for hydrocarbon generation.

Collection and organization of all data was done at BDM Petroleum Technologies. The data were run at the University, so that the experts on the program could handle glitches or program bugs. Trips were made to the University when a new run of the program was planned.

The model constructed a cross-section beginning in the Ozark area, and crossing the Salina Basin, the Nemaha uplift, the southern end of the Mid-Continent Rift System, the Forest City Basin, and the Great Plains, to the Front of the Rocky Mountains. The first run and sensitivity analysis of the model took place in September, 1997, at the University of Minnesota. The final runs of the model were made during mid 1998.

The details of the University of Minnesota work and their results are attached as Appendix 1.

2.5 Field Trips

A field party of BDM Petroleum Technologies geologists made a scouting trip to the Ozark Plateau region of Missouri during June, 1997. The lower Paleozoic stratigraphic section was investigated to determine the data collection potential for the southern Mid-Continent area. The data that were gathered were to be used in the University of Minnesota basin-modeling program.

The primary objective of the trip was a field evaluation and lithofacies investigation to attempt to identify possible source and reservoir rocks along the flanks of the Ozark Uplift. Samples were collected for petrographic and geochemical analysis in conjunction with the stratigraphic field assessment.

Figure 2–4 shows the sampling locations from the scouting trip. The intervals investigated focused predominantly on carbonate units. Most of these samples were taken from the upper Cambrian, the lower and upper Ordovician, and the lower Mississippian sequences. At each outcrop, depositional facies were determined, and organic-rich or potentially organic-rich rocks were collected.

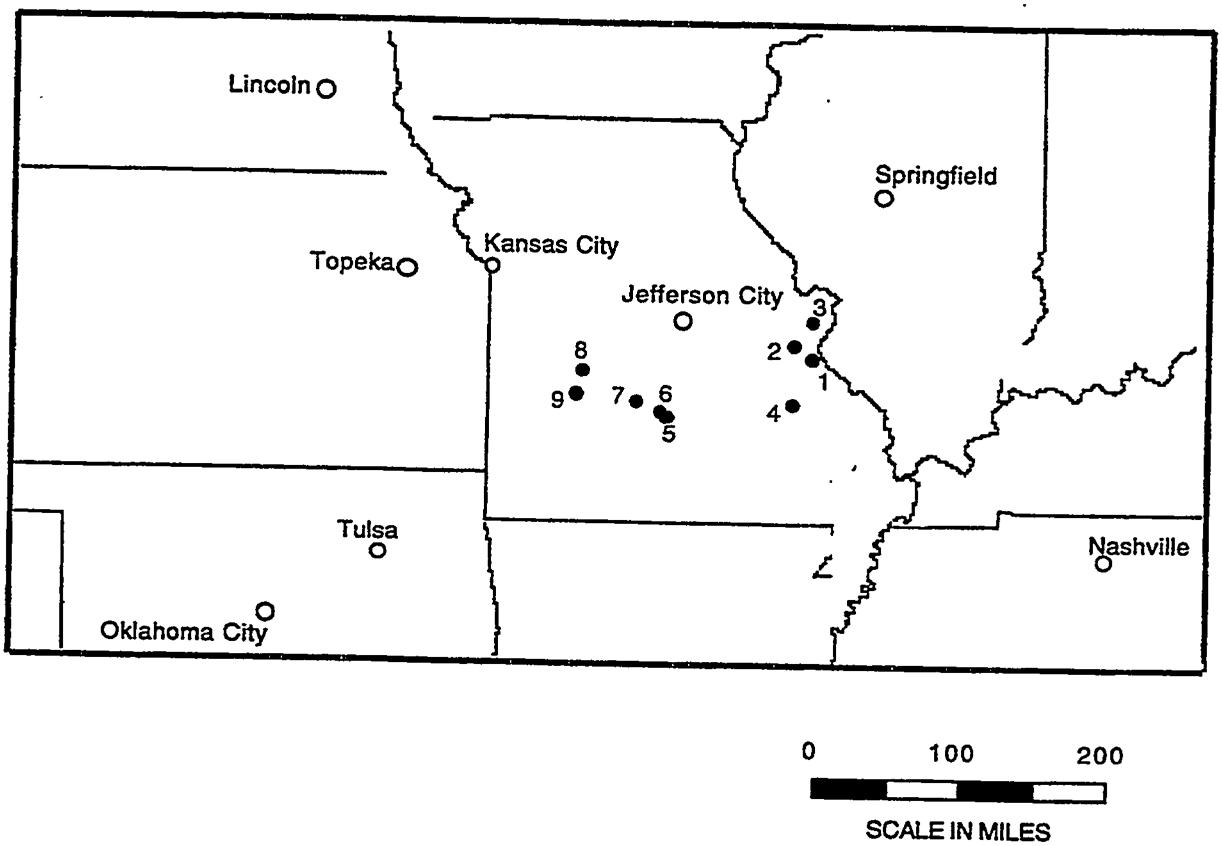

Figure 2–4 Field Sample Locations in the Ozark Uplift Region

The focus of the sampling was on fossiliferous and algal carbonates, as well as organic-rich shales. Twenty hand samples were collected from nine outcrops. The samples were described in detail, and thin sections were prepared for petrographic and geochemical analysis. Selected samples were used for geochemical analyses.

Following the scouting trip, a data-collection trip was made to the Missouri Geological Survey in Rolla, Missouri. Stratigraphic, well log, and geochemical data were collected for northwestern

Missouri. This information was compiled for use in the University of Minnesota basin-modeling program.

A trip was then made to the Kansas Geological Survey for the collection of stratigraphic, well log and geochemical data. Core samples were also collected for petrographic and geochemical analysis. The core sampling was done to build an information base that could be used to correlate geochemical signatures from outcrops around the Ozark Uplift into the subsurface.

The data were gathered to gain a better understanding of oil-generation potential and migration possibilities within the southern Mid-Continent.

2.6 Stratigraphy and Stratigraphic/Structural Traps in the Southern Mid-Continent Region

As data were gathered for the basin-modeling project, studies were undertaken to locate and identify the nature of stratigraphic and structural traps in the deep sediments within the South-Central Mid-Continent region.

Several cyclical carbonate accumulations can be seen across the study area. These cycles contain minor shale and sandstone sections within thick limestones and dolomites. They typify the lower Paleozoic stratigraphy of the southern Mid-Continent. These carbonate cycles are directly related to well-recognized large-scale cratonic sequences reported on by Sloss (1963).

In general, these "Sloss sequences" have widespread basal sands overlain by thick carbonate successions with minor shale and sandstone intervals. Potential stratigraphic and structural traps may exist within these sequences. These traps would be expected, based on the known stratigraphic relationships and structural morphologies found in this region and similar areas.

Four major potential stratigraphic and structural trap types have been identified that could be common within the South-Central Mid-Continent region. These trap types include:

- stratigraphic (depositional) traps,
- truncation and onlap traps,
- secondary porosity (erosional) traps, and
- secondary porosity (fracture) traps.

2.6.1 Stratigraphic (Depositional) Traps

Conventional stratigraphic (depositional) traps have considerable reservoir potential in the South-Central Mid-Continent. During lower Paleozoic time, carbonate organic and inorganic buildups formed at many locations across the low-relief, low-angle carbonate shelf.

Oolitic, coquinoidal, and localized accumulations of fragmentary calcareous sands are examples of inorganic buildups that can be found in the study area. Reef development, most commonly recognized in the Silurian, and bryozoan-mud-mounds, characteristic of the Mississippian, are common types of organic buildup that characterize the lower Paleozoic in the region.

Paleozoic reef development is known from the western portions of the Illinois Basin, along the fringes of the Ozark Uplift. Inorganic buildups and reef growth may flank many of the other paleotopographic highs in the South-Central Mid-Continent region.

2.6.2 Truncation and Onlap Traps

Onlap traps are associated with paleotopographic relief features. The Trans-Continental Arch, extending from the Four Corners region of Arizona and New Mexico to Minnesota and the Great Lakes, was a positive structural feature throughout the lower Paleozoic. It acted as the western limit for deposition across the Mid-Continent region. Formations successively onlapped the Trans-Continental Arch as sea level fluctuated during the lower Paleozoic. This structural high was only breached for short periods of time during the Paleozoic.

On a more local scale, the Precambrian basement has up to 2000 ft of relief in the study area (Bunker et al. 1988), and some topographic highs were not completely buried until the Silurian or later. Smaller-scale onlap is possible around these basement irregularities. Examples are present in Kansas, generally associated with magnetic anomalies, reflecting topographic highs. Magnetic anomalies or topographic basement highs are evident in the present-day Forest City Basin, in a narrow belt related to the Nemaha Uplift, along the Mid-Continent Rift System, and in the central Salina Basin.

Tectonic activity, sea level retreat and associated erosion, and major fault block movements generate widespread truncation traps. In general, the Mid-Continent region has had a low-lying basal surface where undulation or uplift would cause drastic erosion or depositional patterns reassessment. The Ozark Uplift (Late Ordovician into the Silurian and Devonian), the Central Kansas Uplift (episodes from the Ordovician to the Mississippian), and the Nemaha Uplift (Mississippian) are three major uplifts that dramatically altered the depositional configuration in the Mid-Continent region. Other minor uplifts in the study area include the southeast Nebraska Arch, the Chautauqua Arch, the Ellis Arch, the northeast Missouri Arch, the Lincoln Fold system and the Humboldt Fault system. Stratal relationships encompassing the erosional surface generated from uplifts and erosion has to be inspected for possible truncation traps.

2.6.3 Secondary Porosity (Erosional) Traps

Secondary, vuggy porosity is found as a common side effect in carbonate sequences around truncation features. This type of porosity readily forms in carbonate rocks during diagenesis. Vuggy porosity will form in limestones and dolomites as a result of subaerial exposure and dissolution.

Significant major and minor erosional episodes interrupted deposition during the lower Paleozoic. These periods produced extensive zones with well-developed secondary porosity in the region. A key element for exploration in the region will be the identification of regions and formations where secondary porosity may be a significant reservoir contributor.

Primary erosion intervals during the lower Paleozoic occurred at the end of the Cambrian (pre-Arbuckle), during multiple episodes within the Ordovician, at the end of the Silurian, and at the end of the Mississippian. Each of these erosive periods represents a time when extensive secondary porosity could have been developing across existing carbonate shelf deposits.

The Silurian Hunton Group of Oklahoma provides a major example of secondary porosity development. Within the Hunton, vuggy, karst features form major reservoir traps (Fritz and Medlock, 1995). Reservoir potential associated with secondary porosity generation can be isolated and local, or widespread and regional.

Exploration in the study area should focus on locations where the carbonate sequences have been exposed and subjected to diagenesis.

2.6.4 Secondary Porosity (Fracture) Traps

In the South-Central Mid-Continent region, extensive fracture patterns are common around structural uplifts. Specific fracture associations are found along the length of the Nemaha Uplift and above the area where the Humboldt Fault cuts the basement. Most of these fractures presumably developed during Mississippian to Pennsylvanian tectonic activity that formed the present-day configuration of uplifts and the Forest City and Salina Basins.

There are two main fracture systems, which have generated key migration pathways in the study area. This has allowed migration into producing areas and reservoirs. The Nemaha Uplift and associated Humboldt Fault system have producing fields along their margins. These remain prime targets for fracture migration studies to identify additional reservoirs.

2.7 Conclusions

Interest in the possibilities of ultra deep oil in the sediments within the Mid-Continent Rift System (MRS) declined as data were gathered on the organic content of the clastics that accumulated in the southern portion of the rift. In addition, it was noted that it is unlikely that deep-sourced Proterozoic hydrocarbons would have been released to accumulate in larger, more-shallow traps.

Shallow oil is common around the Forest City basin, but is almost unknown in the Salina basin, which was cut off from key migration pathways leading from the south. Chemical fingerprinting of shallow oil in the Pennsylvanian of the Forest City basin strongly suggests that this oil originated in southern Oklahoma, where the Pennsylvanian section is much deeper. This oil has apparently migrated updip across the state of Oklahoma, to pinchout traps and structures in southeastern Kansas and surrounding areas.

The Salina basin was cut off from these migration pathways by the Central Kansas arch and Nemaha uplift.

Studies of the lower Paleozoic section demonstrated that oil has been generated, at least on a local basis, within the Ordovician section. This oil contains a distinctive marker, typical of Ordovician-age oil, worldwide, so it can be dated as distinctively Ordovician. This oil has not migrated into the Ordovician beds from older or younger source rocks.

Studies were undertaken to determine if other hydrocarbons could have migrated updip from the Ozark trough during the early Paleozoic. Possible reservoir and source rocks were found to be consistently present across the region. Basin modeling and thermal-history studies (see the Appendices) have produced encouraging results.

As it was recognized that locally-sourced hydrocarbons do exist in the deep beds in the study area, additional encouraging information accumulated. Specific areas with good reservoir potential should become evident as more stratigraphic information becomes available for the South-Central Mid-Continent region.

Since the South-Central Mid-Continent region formed above a relatively flat surface during the early Paleozoic, any slight uplift or sag could dramatically alter the local depositional style or migration pathways through time. The focus of exploration work in the study area should concentrate on identifying the small-scale alterations in the South-Central Mid-Continent basin morphology, and the stratigraphic consequences of small, local structures and basement features.

Zones of secondary porosity, associated with karst features and vuggy porosity within local carbonates can be prime exploratory targets in the study area.

3.0 EXPLORATION METHODOLOGIES

The DOE program in the South-Central Mid-Continent was designed to focus on exploration techniques and methodologies, as well as to study the geology and hydrocarbon potential of the region itself. This section discusses several of the methodologies that were developed and used for this work.

3.1 Basin Modeling

A major element of the research in the South-Central Mid-Continent was the cooperative basin-modeling program with the University of Minnesota, using the RIFT2D software package.

3.1.1 Data Collection in the South-Central Mid-Continent

Data collection in this region focused on information required for the general analysis of the target basins, as well as data needed to run the RIFT2D basin-modeling software. A significant multidisciplinary investigation of the region was undertaken.

The goal was to characterize the regional structural and stratigraphic development. The identification and description of potential source rocks in the deeper section was a specific goal of the project. The research focused on characterization of various geochemical attributes and the identification of "hot" areas that might have been susceptible to hydrocarbon generation. In addition, emphasis was placed on furthering an understanding of the hydrogeologic characteristics (especially porosity and permeability) of both reservoir and source rocks throughout the region. These data were vital in order to put constraints on fluid-flow dynamics within the model system.

Special attention was applied to developing an understanding of the fine-scale stratigraphic relationships across the South-Central Mid-Continent region, with an emphasis on variations in thickness and the continuity of individual units.

The data obtained during this study included:

- stratigraphic,
- structural,
- hydrologic,
- temperature,

- pressure, and
- geochemical information.

The information was acquired through:

- field trips,
- sample studies,
- well reports,
- literature reviews,
- information retrieval services,
- inter-library loans, and from
- the Geological Surveys of Kansas, Oklahoma, and Missouri.

All data were compiled into the appropriate forms (e.g., maps, cross-sections, databases, tables, charts, and short reports) for use in the RIFT2D basin model and for regional basin assessment.

Data Collection

Data collection served two purposes in this study.

1. The initial use for the collected data was the overall basin analysis of the South-Central Mid-Continent. The large quantity of information that was gathered allowed the testing of various concepts on stratigraphic relationships throughout the Lower Paleozoic. The Lower Paleozoic stratigraphy of the South-Central Mid-Continent has been described previously, but most of this earlier work did not focus on such details as hydrocarbon generation potential, or possible regional migration and accumulation of hydrocarbons, specifically in the Ordovician and Silurian/Devonian formations.

   In this project, smaller-scale relationships were investigated. These included such items as:

   - stratigraphic relationships in the deep section associated with basement features, formation onlapping relationships,
   - development of smaller structures through time and the resulting stratigraphic associations,
   - carbonate build-up complexes.

   The overall history of the South-Central Mid-Continent was reconstructed from multiple sources of information.

2. Then, all data were applied to the RIFT2D basin model, a 2-D modeling package. This particular basin-modeling software package can produce accurate simulations of basin structure and history, but it requires a very large amount and wide range of information if it is to generate the most reliable, geologically-reasonable interpretation. As outlined by the University of Minnesota, the RIFT2D basin modeling software requires three main categories of data:

   - geologic,
   - hydrologic, and
   - thermal.

   The geologic data requirements included:

   - general stratigraphic identification,
   - detailed descriptions of lithofacies,
   - timing and rates of sedimentation,
   - sedimentary compressibility coefficients,
   - source rock identification, distribution, and potential,
   - reservoir identification, and distribution,
   - identification of structural features,
   - description of basin tectonic history, and
   - cross-sections.

   Hydrologic data requirements included:

   - identification of aquifers,
   - formation porosities,
   - permeabilities,
   - water table configuration, and
   - fluid chemistry.

   Thermal data requirements included:

   - down-hole and bottom-hole temperatures from multiple locations,
   - rock thermal-conductivity properties,
   - heat flow,
   - heat capacities, and
   - thermal maturity of organic matter.

Data collection was a joint effort performed by BDM Petroleum Technologies personnel, the University of Tulsa, and, in part, the University of Minnesota. The majority of the data collection and interpretation was performed by, and all work was overseen by BDM Petroleum Technologies. The reliability of the model results was directly dependent on obtaining the best quantity and quality data possible. Only top quality and abundant input to the software could produce an acceptable final basin model.

Data Collection Procedure

Multiple sources were used during the data-gathering stage of this product. These sources included:

- data service companies,
- well-log libraries,
- core repositories,
- field trips,
- state geological surveys,
- the published literature.

Along with the in-house research, several field trips were made during the course of the project. These trips included two visits to Missouri and two to Kansas. The two visits to Missouri were integral to the early stages of investigation into the geology of the region. The first Missouri trip was made to view outcrops and collect samples for analysis and laboratory study. The second trip involved a visit to the facilities of the Missouri Geological Survey.

In addition to the Missouri trips, two visits were made to the Kansas Geological Survey in Lawrence, Kansas, for data collection. These trips were undertaken to establish personal contacts and to collect:

- literature,
- maps,
- well logs
- scout tickets, and
- rock samples

from the Kansas portion of the Forest City basin. Access was also granted to the Kansas Geological Survey's extensive core library. Over 30 cores were viewed, described, and sampled in the library.

Missouri Outcrop and Missouri Geological Survey Trips

A scouting trip to the Ozark uplift region of Missouri was completed in June, 1997. The purpose of the trip was to observe and study the Lower Paleozoic stratigraphic section *in situ*, and to collect samples for further study and laboratory analysis. The target locations were areas where potential source rocks outcropped and were accessible for sampling. The first objective was a field evaluation and lithofacies investigation of possible source and reservoir rocks along the flanks of the Ozark uplift. Sample collection for thin section, petrographic, and geochemical analyses was performed in conjunction with the stratigraphic field assessment.

A regional map showing the sampled outcrop locations (1 through 9) is shown in Figure 3–1. Stratigraphic samples were taken from the Lower Paleozoic Arbuckle Group and from younger Ordovician formations, were collected in the Ozark uplift physiographic region.

Stratigraphic intervals investigated on this trip included:

- the Upper Cambrian,
- the Lower and Upper Ordovician, and
- the Lower Mississippian.

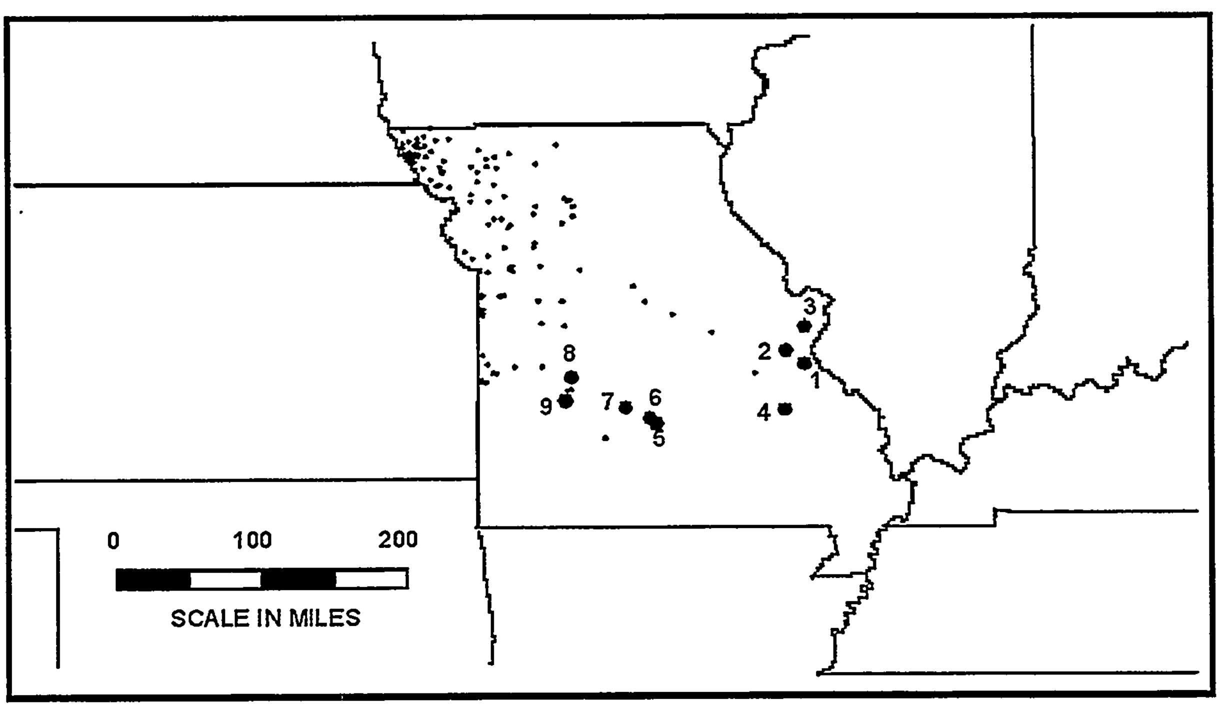

Figure 3–1 **Well location map of data collected from the Missouri Geological Survey, and numbered locations represent outcrop locations during the field examination of Lower Paleozoic strata flanking the Ozark Uplift.**

The focus for the collection of samples was on:

- fossiliferous limestones,
- algal carbonates, and
- organic-rich shales.

Upon return to the offices and laboratory, the samples were analyzed, and thin sections were prepared for petrographic and geochemical analysis. The intent of the investigations into these units was the gaining of a better understanding of the Lower Paleozoic source rock potential in the ancient Lowermost Paleozoic depositional basin that originally existed in the area of what is now the Ozark uplift.

A second data collection trip to Missouri was made to the Missouri Geological Survey at Rolla. Stratigraphic, well log, and geochemical information were collected, covering the northwestern Missouri region (see Fig. 3–1). This completed the first phase of data collection for the basin-analysis and basin-modeling project.

Kansas Geological Survey Data Collection Trips

Extensive data on Kansas are available and were gathered for this project via the Internet. The Kansas Geological Survey (KGS) has been a leader and excellent model of how to maximize the possibilities and potential for electronic data distribution via the World Wide Web. The home page for the survey is located at

http://www.kgs.ukans.edu/kgs.html

Numerous data files and maps are available from the Oil and Gas portion of the web site, at

http://www.kgs.ukans.edu/PRS/petroIndex.html

Many of these maps and other files have been incorporated into the South-Central Mid-Continent study. The variety of data from the web site includes:

- basin maps,
- structural-feature maps,
- gravity maps and data,
- magnetic maps and data, and
- well locations information and maps.

Information is also available on detailed field properties ranging from stratigraphic and structural descriptions to production histories.

The first trip to the KGS was undertaken for core description and sampling at the Survey's core library. To increase efficiency and decrease costs, the cores to be sampled were identified prior to the visit to the core library. All preliminary preparations and organization were handled with assistance of the University of Kansas and its graduate students.

During the trip, the BDM personnel were able to view, describe, and sample over 30 cores that included Lower Paleozoic strata of interest. Samples were taken from all identified potential source rocks, primarily:

- the Ordovician Maquoketa Shale and
- the Devonian Chattanooga Shale.

In addition to sample collection, all well files stored at KGS were made available to BDM for investigation. A large quantity of hydrogeologic data was obtained from these for future study and analysis of the hydrodynamic system in the South-Central Mid-Continent region.

A second trip was made to the KGS, this time focusing on regional stratigraphic relationships and to acquire additional hydrogeologic information. Plans were developed for this data-collection trip through the KGS Web site, along with correspondence with the survey. Again, the web site allowed for a pre-trip assessment of the data available at the survey that would be useful for basin analysis and the RIFT2D basin model.

Collection areas were prioritized. The Forest City basin formed the top priority. This was followed by the Salina basin, then the area of the east-west cross section through the center of the state that was used for the University of Minnesota RIFT2D basin model (see Fig. 3–2). Recognizing the needs of the basin-modeling project, well logs and strip logs (or *Davies* logs, as they are known in Kansas) became a primary goal of this second data-collection trip.

An attempt was made to match strip logs to electric logs, and to locate a production report for each of the wells of interest. Ultimately, 88 logs were collected from 49 different wells. Also, several maps and reports on the South-Central Mid-Continent and Forest City basin were purchased for the project.

3.1.2 Data Processing and Use

The collected data were organized and prepared in several different formats for better use and understanding and for loading into the University of Minnesota RIFT2D modeling program. The primary focus of the data organization and presentation was for the basin-modeling program. Data was input into a stratigraphic database, which included over 750 wells in Kansas, Nebraska and Missouri (see Fig. 3–3). This information was then used to satisfy the requirements of the RIFT2D software.

Sauk Sequence Subsidence and Accumulation Rates (m/my)

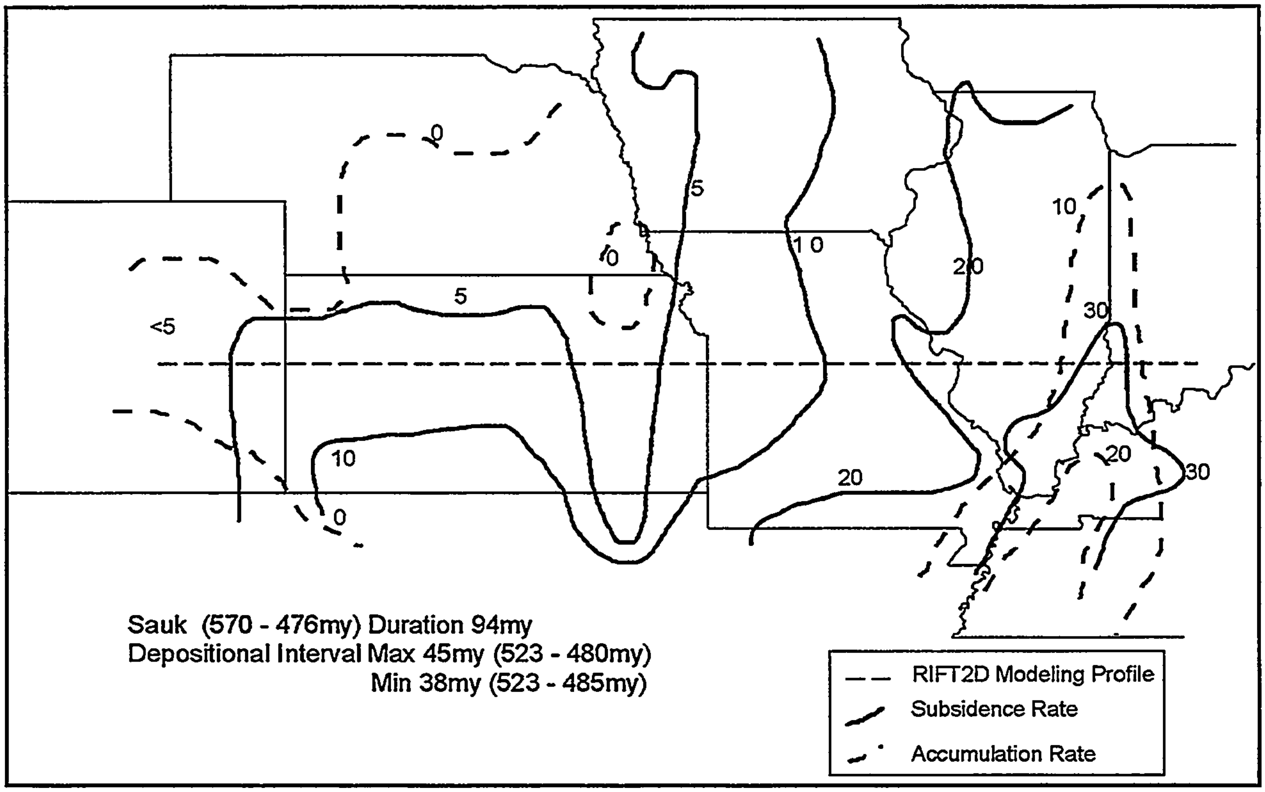

Figure 3–2 **Sauk sequence subsidence and accumulation rate map for the South-Central Mid-Continent region. Also shown is the east-west profile line from Colorado through Illinois used in the University of Minnesota basin modeling RIFT2D software.**

Numerous maps were generated for depositional sequences in the South-Central Mid-Continent. These maps attributes such as rates of:

- subsidence,
- sediment accumulation,
- uplift, and
- erosion.

Individual maps were prepared to show regional rate isopachs for each of the individual variables for specific time intervals (see Fig. 3–2). The time intervals selected for each of the individual maps were based on Sloss sequences or subsets of Sloss sequences. It was felt that these gave the most accurate representation of basin development through geologic time. Sloss sequences were used as the time framework for two reasons:

1. These sequences define large-scale intervals of deposition or non-deposition across the cratonic interior of the U.S.
2. Sloss sequences closely match the hydrostratigraphic units used in the RIFT2D basin model.

Cross-sections were produced along an east-west profile line to begin the initial phase of the modeling project. These lines followed a close approximation of the cross-section used in the RIFT2D basin model, and networked across the Nemaha Uplift area of northeastern Kansas. These cross-sections assisted in gaining an understanding of the present day stratigraphic relationships and of the historic development of these conditions. Other information has been summarized in the form of:

- charts,
- tables,
- graphs, and
- report write-ups

as a means to characterize the development of the South-Central Mid-Continent region in terms of:

- morphological development,
- hydrogeologic character,
- thermal maturation, and
- hydrocarbon generation and accumulation potential.

Regional Tectonic Setting of the South-Central Mid-Continent

During the Middle Proterozoic Keweenawan, at approximately 1.1 Ga, continental rifting began, forming a narrow rift basin, lined on both sides by volcanic highlands. This feature started in the Ohio - Michigan area, ran through the Great Lakes, and continued on into the South-Central Mid-Continent area. The structure is known as the Mid-Continent Rift System (MRS). It almost split the North American craton in two, before the activity ceased. Deep crustal seismic profiles in the area of Lake Superior show that this is the deepest failed rift known on the face of the planet.

The rift basin quickly filled with coarse clastic sediments and mafic volcanics. The MRS was the initial target of investigation, as numerous similarities exist between the MRS and the rifting that resulted in deposition of the organic-rich Precambrian Chuar sediments in the previously-studied Black Mesa area in Arizona. Late in the Proterozoic, the central area of the MRS was uplifted, in a structural inversion, creating a complex, fault-bounded horst system along its axis. This type of inversion is a common late-stage event in many continental rifts.

Total Wells from Database

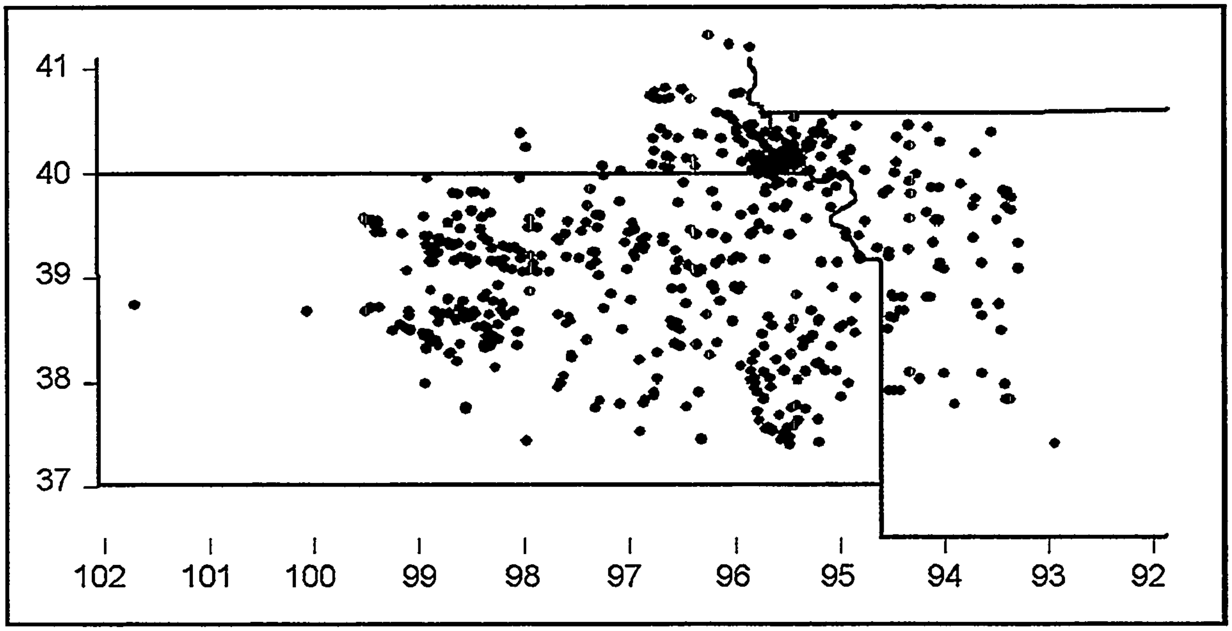

Figure 3–3 Location map illustrating well data collected, and included in the stratigraphic database for the South-Central Mid-Continent region.

Prior to the resumption of sedimentary deposition during the Cambrian, the area was subaerially exposed, and the Precambrian terrain was highly eroded, removing most topographic remnants of the volcanoes and flanking mountains that had lined the rift. This created a relatively low-relief surface upon which younger sedimients were deposited. The main variability in the Precambrian surface was isolated "hills" in Kansas and Oklahoma. These features show significant relief, up to several hundred feet, but are isolated in occurrence.

The Early Cambrian topography and deposurface across the South-Central Mid-Continent generally sloped gradually from the Transcontinental arch, a positive feature which extended from the Four Corners area to Minnesota, down to a deep depression, the Ozark trough, which occupied roughly the area along the modern-day Mississippi valley. Many Cambrian and Lower Ordovician sedimentary sequences are quite thick in Arkansas and Missouri. These same units then thin updip, to the northwest, until they pinch out in Oklahoma and Kansas. This structural configuration and the sedimentary wedge have great significance for the project, in that the deeper areas, to the southeast, were potential sites for the accumulation of large amounts of organic-rich sediments that were rapidly buried and susceptible to hydrocarbon generation.

A sag, known as the Ancestral North Kansas basin, formed and persisted throughout the Cambrian and Early to Middle Ordovician in the South-Central Mid-Continent. It was filled by deposition of Sauk 3 and Tippecanoe 1 sequences (see Fig. 3–4). The Lower Paleozoic section across the study area was dominated by carbonates and associated shales. There is very little sand included in this portion of the sedimentary column.

The North Kansas basin was bounded on the west by the ancestral Central Kansas uplift and on the south by the Chautauqua arch. The Early Paleozoic North Kansas basin opened to the east into Missouri, and was possibly in communication with the Ozark trough, a deep structural feature which received a much larger volume of sediments during most of the Early Paleozoic. Hydrocarbons that might have formed in the Ozark area could have migrated updip and into the deep section in Kansas at this time. The Lower Paleozoic section of the North Kansas basin is comprised mostly of carbonates and shales, with minimal sandstones. Some of the few coarser clastics in the region are the Lamotte Sandstone (Upper Cambrian), St. Peter Sandstone (Lower Ordovician), and Platteville Formation (Middle Ordovician).

The first uplift pulse in the area of the Chautauqua arch and the Ozark region occurred in the Upper Ordovician. The shift in tectonic configuration resulted in changing depositional patterns during latest Ordovician time and through the Silurian and Devonian. The basin in Kansas was cut off from the Ozark trough by these tectonic activities. Deposition from the Silurian to Mississippian was still dominated by carbonates, which were deposited in a warm subtropical setting (see Fig. 3–5). This deposition is represented by the Tippecanoe 2 through Kaskaskia 2 Sloss sequences.

During Late Mississippian time, the present-day geologic structures in the South-Central Mid-Continent region began to form. The first significant events were the initial pulses associated with the rise of the Nemaha uplift, which would ultimately divide the North Kansas basin into the modern day Salina and Forest City basins. The formation of the Forest City and Salina basins was completed during the Pennsylvanian with the final movements along the Nemaha uplift. Multiple rejuvenation episodes occurred along the structure well into the Pennsylvanian.

During the Pennsylvanian and Permian, deposition finally shifted from being dominated by carbonate sediments to being composed predominantly of clastic sediments, represented by the Absaroka 1 and 2 Sloss sequences. The Forest City basin started to receive clastic sediments during the Atokan (Early Pennsylvanian). The Bourbon arch formed an early boundary for the basin to the south, but this feature was no longer a barrier when Cherokee Group sedimentation started (see Fig. 3–6). Ultimately, most of the Lower Paleozoic sediments were eroded from the emergent Nemaha uplift.

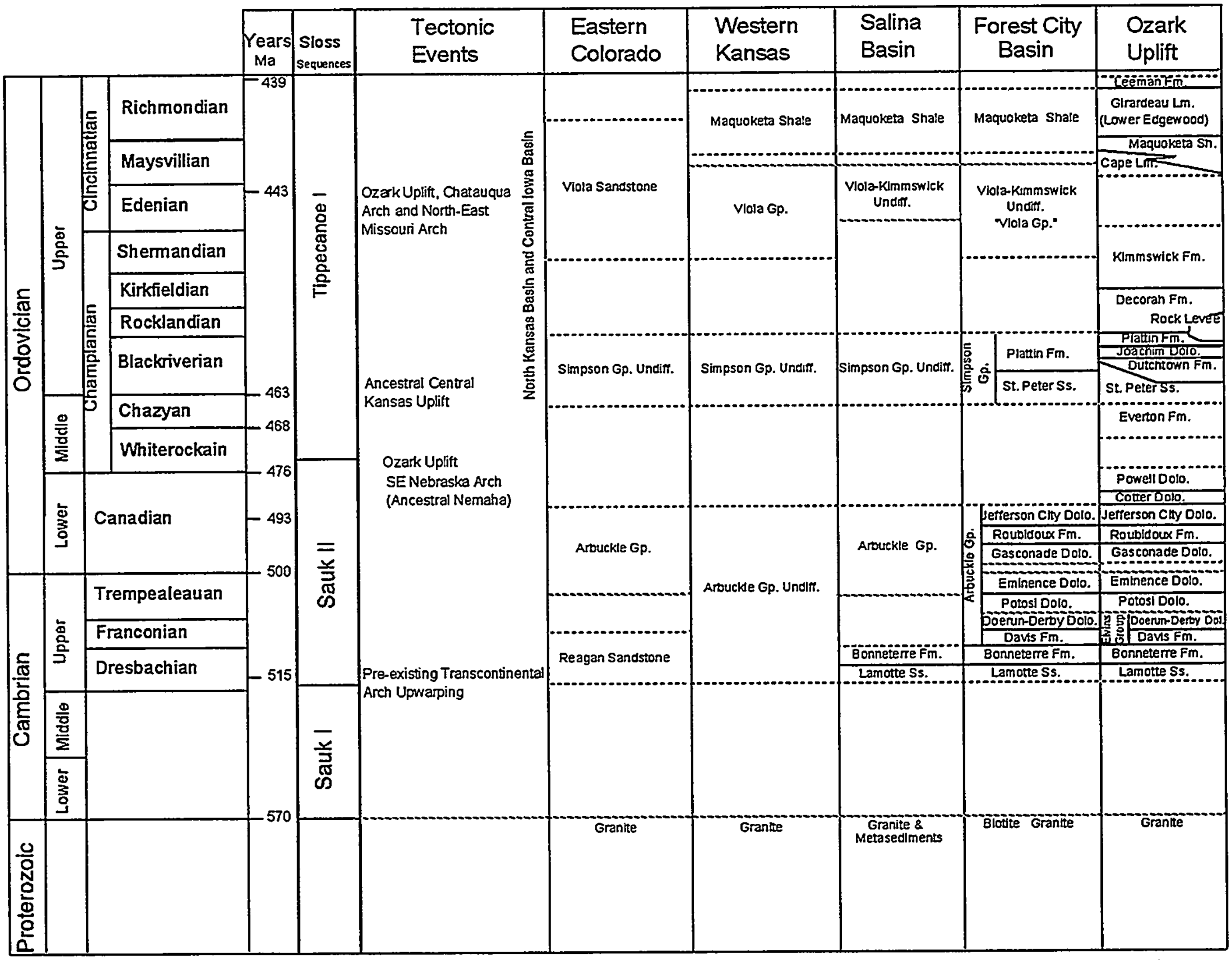

Figure 3–4 Stratigraphic correlation chart of the Cambrian through Ordovician periods for the South-Central Mid-Continent region.

Pennsylvanian sediments in the Forest City basin are dominated by "cyclic" clastic sediments with minor carbonate intervals in most of the cycles. Pennsylvanian reservoir rocks in the Forest City basin are predominantly found among the fluvial and deltaic sandstones. Pennsylvanian sediments in the Salina basin were still dominated by carbonates, with associated shales. Deposition in the Salina basin started with the deposition of the Cherokee Shale in the Late Desmoinesian. Carbonate deposition continued during much of Permian time with limestones dominating the section, although gypsum and salt beds formed locally in hypersaline environments and dolomitization was common. The Pennsylvanian sediments in the Salina area include relatively few, minor sandstones.

Post-Devonian Paleotectonic Features

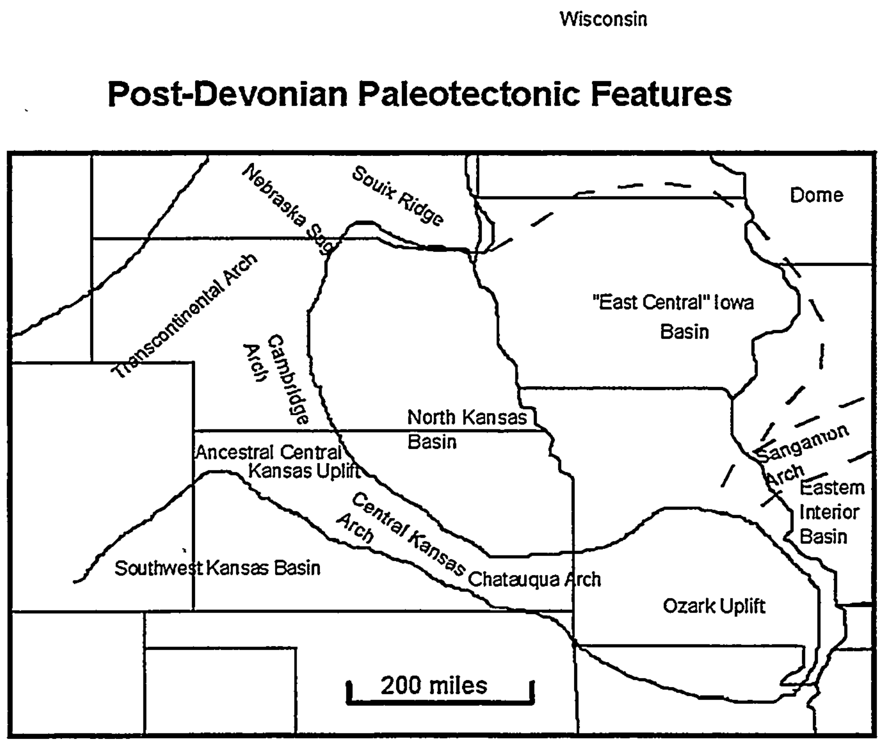

Figure 3–5 Paleotectonic setting at the end of the Devonian period.

Post-Mississippian Paleotectonic Features

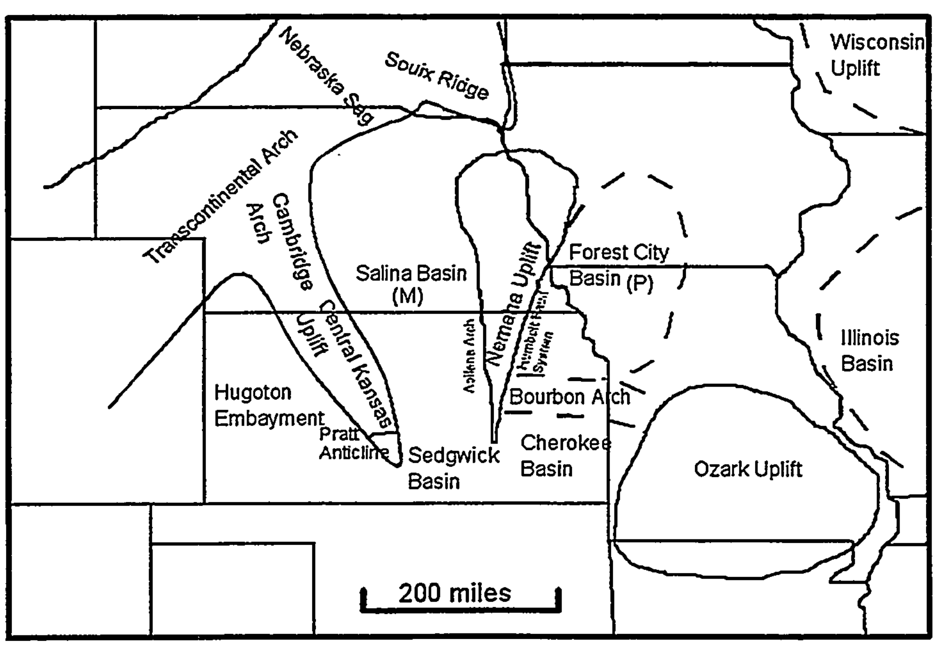

Figure 3–6 Post-Mississippian paleotectonic configuration for the South-Central Mid-Continent region.

Stratigraphic Studies

Stratigraphic correlation charts for the Upper Paleozoic, Mesozoic, Tertiary, and Quaternary sections of the South-Central Mid-Continent region were completed (see Figs. 3–4 and 3–7). Several long-term depositional cycles are recognized in these rocks, related to Sloss (1963) sequences. These cycles typically are composed of widespread basal sands overlain by thick carbonate successions with minor shale and secondary sandstone intervals. As shown in the correlation charts, carbonate deposition dominated the region from Cambrian to Pennsylvanian time.

There are 13 unconformities or disconformities in the Lower Paleozoic section in the Forest City basin. This includes the unconformity between Precambrian-age rocks and Upper Cambrian sediments. The only significant, widespread interruptions in the pattern of carbonate deposition in the Lower Paleozoic were the initial, basal sandstone deposits (e.g. the Lamotte Sandstone, Reagan Sandstone, and St. Peter Sandstone), and several series of deeper water shales (e.g. the Maquoketa Shale and Chattanooga Shale). These types of carbonate deposits are characteristic of sedimentation on a shallow-water shelf in a warm subtropical setting. The most important aspect of this type of carbonate deposit is the capacity to generate build-up deposits in the form of reefs or organic-rich mounds.

There was a significant shift in depositional patterns beginning during the Pennsylvanian period. This change was a direct result of the Ouachita orogenic event that was beginning to affect the region to the south of the study area at that time. The Pennsylvanian section is dominated by clastic material. These beds are mostly fluvial and fluvio-deltaic clastic wedges, all shed from the rising mountain belt. There was a distinction in deposition between the Salina and Forest City basins. The Salina basin maintained a dominantly carbonate to evaporitic depositional setting during the Pennsylvanian. The area was effectively cut off by the Central Kansas uplift on the south and west and the Nemaha uplift on the east, protecting the basin from the rivers and the massive quantities of clastic sediment that inundaten have led to conclusions about potential stratigraphic and structural traps. Potential stratigraphic and structural traps have been considered, based on the known stratigraphic and structural morphologies of the region through time. Four major stratigraphic and structural trap types have been considered for the South-Central Mid-Continent region. These include:

- onlap and truncation traps,
- stratigraphic (depositional facies) traps,
- secondary porosity (erosional) traps, and
- fracture-induced traps

Onlap twater carbonates, near-shore sandstones, and shales typify the Cretaceous sedimentary section. This stratigraphic succession is composed predominantly of clastics.

Tertiary sediments consist of silt, clay, and sand, while Quaternary sediments are much the same with the addition of glacial till, composed of sand and gravel.

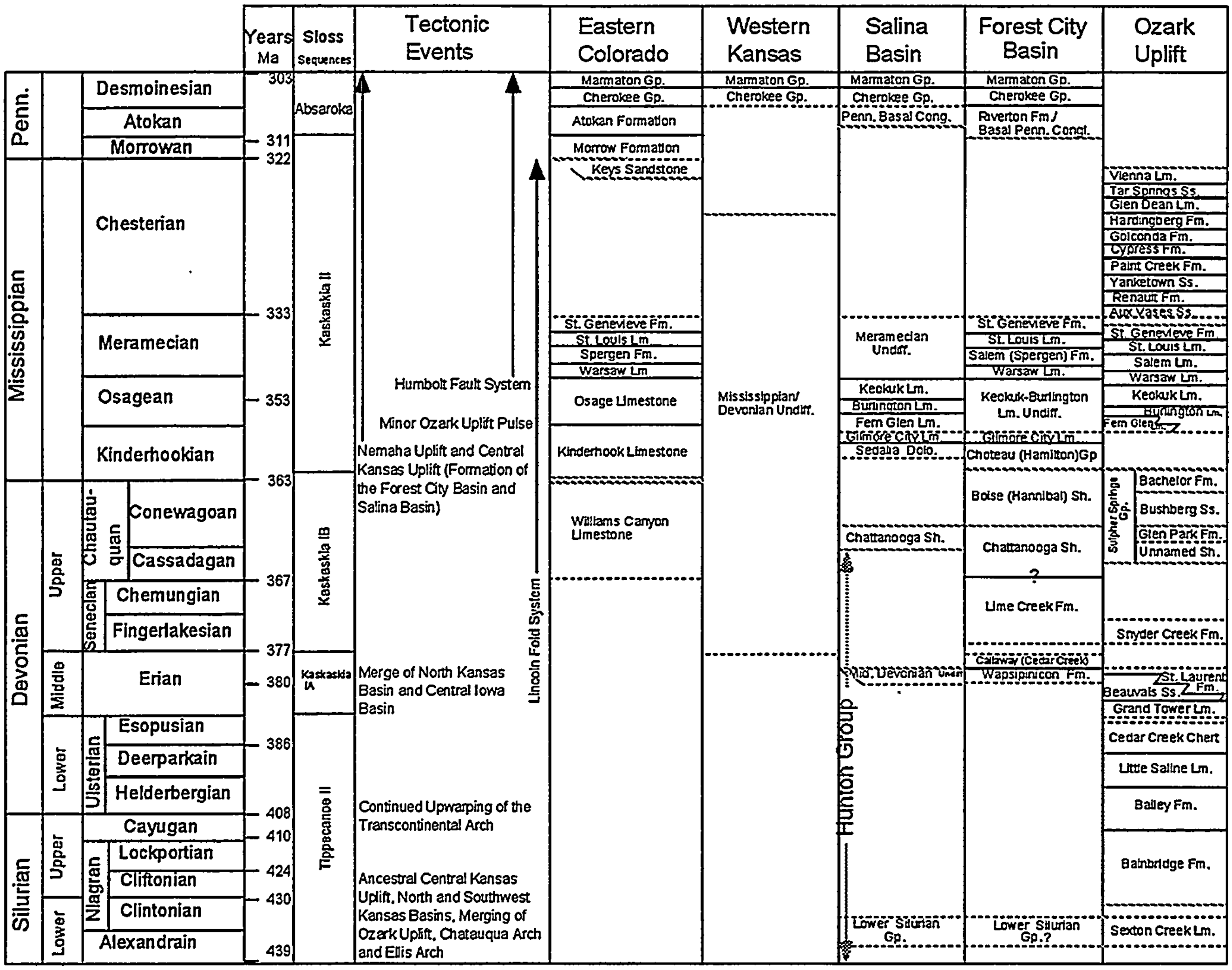

Figure 3–7 Silurian to Early Pennsylvanian stratigraphic correlation chart.

Stratigraphic and Structural Traps in the South-Central Mid-Continent Region

Detailed study of the stratigraphy and stratigraphic relationships in the South-Central Mid-Continent region have led to conclusions about potential stratigraphic and structural traps. Potential stratigraphic and structural traps have been considered, based on the known stratigraphic and structural morphologies of the region through time. Four major stratigraphic and structural trap types have been considered for the South-Central Mid-Continent region. These include:

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Onlap traps are associated with paleotopographic relief features. The Transcontinental arch, the southwest trending feature that runs from Minnesota to the Four Corners area, was a positive structural feature throughout the Lower Paleozoic. It acted as the western limit to the Mid-Continent region. Formations successively onlapped the Transcontinental arch as sea level fluctuated during the Lower Paleozoic.

The Precambrian basement has up to 2,000 ft of relief in the study area (Bunker et al. 1988), and some of these topographic highs were not completely buried until the Silurian or later. Smaller-scale onlap is possible around these basement irregularities. Examples of potential topographic highs are present in Kansas. These features are associated with magnetic anomalies (see Fig. 3–8). The magnetic anomalies and topographic basement highs are evident:

- in the Forest City basin,
- in the central Salina basin,
- as a narrow belt related to the Nemaha uplift, and
- along the pre-existing Mid-Continent Rift system.

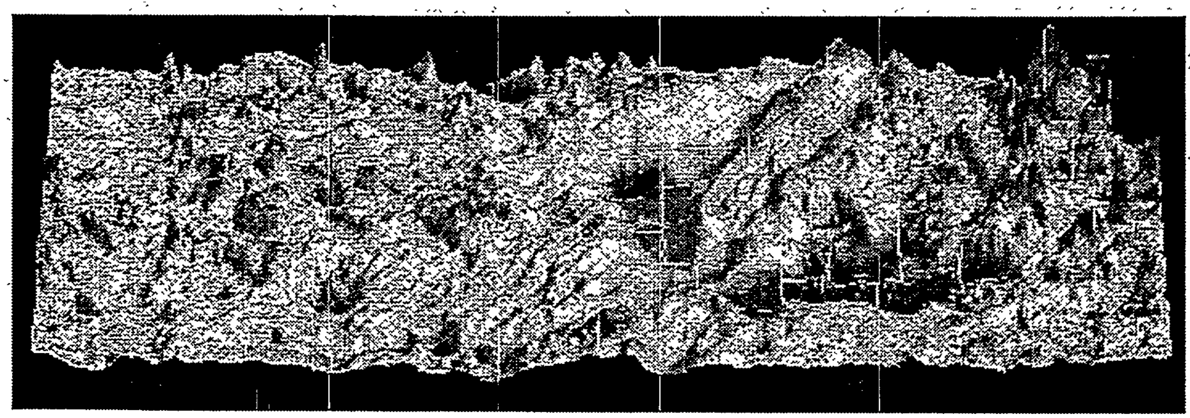


Figure 3–8 Magnetic perspective anomaly map of Kansas.

The magnetic features are areas that warrant further investigation, focusing specifically on depositional patterns in the deep, Lower Paleozoic section, with possible pinchout traps. Geophysical studies can be an extremely valuable tool for exploration in the study areas. The techniques to be used are discussed in greater detail in the next section of this report.

Figure 3–8 was downloaded from the Kansas Geological Survey (KGS) Web site. For a color version of these and other geophysical maps, refer to the KGS web page, at:

http://www.kgs.ukans.edu/PRS/PotenFld/index.html

Widespread truncation traps can be generated by

- regional tectonic activity and/or widespread erosion,
- sea level retreat and associated erosion, and
- major fault block movements.

In general, the South-Central Mid-Continent region formed a low-lying shallow-water shelf with a low-relief basal surface, where slight tectonic uplift or minor sea level changes could cause widespread erosion and drastic changes in depositional patterns. Uplifts

- in the Ozark area (Late Ordovician into the Silurian and Devonian),
- along the Central Kansas uplift (episodes from the Ordovician to the Mississippian), and
- of the Nemaha uplift (Mississippian and Pennsylvanian)

were three major events that dramatically altered the depositional configuration of the South-Central Mid-Continent region. Other minor structures that formed in the study area include:

- the southeast Nebraska arch,
- the Chautauqua arch,
- the Ellis arch,
- the northeast Missouri arch,
- the Lincoln fold system, and
- the Humboldt fault system.

Stratal relationships encompassing the erosional surface generated from uplifts and erosion should be inspected by explorationists for possible truncation traps.

Stratigraphic (depositional) traps have been recognized from detailed stratigraphic studies of fine-scale variability in sedimentation through the Lower Paleozoic section. Organic and inorganic carbonate buildups commonly formed on the low-angle carbonate shelf throughout the Lower Paleozoic.

- Oolitic,
- coquinoidal, and
- calcareous fragmentary sands

are examples of inorganic buildups that can be found in the limestone formations.

- Reef development, most commonly recognized in the Silurian/Devonian, and
- bryozoan-mud-mounds, characteristic of the Mississippian,

are examples of organic buildups.

Reef development is well known and widespread. Reefs are known to produce hydrocarbons:

- in the western Illinois basin, and
- along the fringes of the Ozark uplift.

Inorganic buildups and reef growth should be common on the flanks of many of the other paleotopographic highs in the South-Central Mid-Continent region. These make another major target for seismic surveys and drilling in the study area.

Secondary porosity is a diagenetic product commonly found in carbonate formations that have been subaerially exposed. Major Lower Paleozoic erosional episodes occurred repeatedly as sea level rose and fell and slight orogenic pulses affected the region. This provided an excellent series of opportunities for the development of secondary porosity. The large-scale, widespread erosion intervals that occurred during the Lower Paleozoic include

- the end of the Cambrian (pre-Arbuckle),
- multiple episodes within the Ordovician,
- the end of the Silurian and Devonian, and
- the end of the Mississippian

In addition to these major erosional episodes, there are many smaller, more localized cases of secondary porosity development in the study areas.

These erosive periods represent opportunities for secondary porosity development across the existing carbonate shelf deposits. The Silurian Hunton Group in Oklahoma is an example of a widespread reservoir unit with well-documented secondary porosity traps (Fritz and Medlock 1995). As sea level subsided, the carbonate shelf was exposed, facilitating dolomitization and dissolution. This was followed by erosional beveling and subsequent deposition of an overlying seal, the Woodford Shale. This process created excellent reservoirs within the diagenetically altered carbonates of the Hunton Group.

Reservoir potential associated with secondary porosity generation can be localized and isolated or widespread. Therefore, erosional surfaces and stratal relationships above and below require individual attention from the prudent, aggressive explorationist, and consideration as potential drilling targets.

Uplifts are frequently associated with extensive fracturing patterns in the South-Central Mid-Continent region. Especially well-developed fractures are associated with the Nemaha uplift / Humboldt fault system, the Mississippian- to Pennsylvanian-aged tectonic uplift that separates the Forest City and Salina Basins.

The results of fracturing are twofold. Fractures generate migration pathways, and they can also produce porosity for *in-situ* accumulation of hydrocarbons. The Nemaha uplift and associated

Humboldt fault system have bordering reservoirs that remain prime targets for future hydrocarbon discoveries.

Potential Lower Paleozoic Exploration Targets

Ordovician and Silurian/Devonian carbonate buildups should be recognized as important exploration targets in the Forest City and Salina basins. These carbonate successions generally have the following characteristics (Carlson 1988):

- Carbonate buildups generally follow regional structural trends (primarily oriented northwest-southeast or northeast-southwest) within the basin. Siluro-Devonian oil fields in Nebraska and Illinois have proven production along these trends from organic and non-organic build-up features.
- Ordovician and Siluro-Devonian carbonate fields frequently occur at the intersections of structural trends because domes or topographic highs, the precursory conditions for build-up growth, are concentrated in those areas.
- Carbonate buildups occur at the expense of the overlying shale facies. Identification of areas with unusually thin shales can assist in the location of thicker carbonate areas (Carlson, 1988).
- Production from the deep portion of the Upper Devonian section generally occurs where localized structures coincide with zones of facies change from shale to carbonates (Carlson, 1988).
- Basal sand deposits should receive further investigation, especially in the areas with many onlapping stratigraphic relationships. Two prime target areas in which these types of stratigraphic relationships should be considered are along the ancestral Nemaha uplift, and to the northwest, along the flanks of the Transcontinental arch.
- Northeastern Kansas contains numerous magnetic anomaly highs that, if proven to be paleotopographic high spots, could be areas with localized stratigraphic onlap. These anomalous features follow a north-northeast - south-southwest trend.
- An additional area for further investigation should be the thick shale packages in areas that have undergone substantial structural movements. Extensive fracturing of these shales, given sufficient rock competency, could create reservoirs within source rocks. Shale units can act as both a source- and reservoir-rock. Areas that possess an extensive fracture network (e.g. along the Humboldt fault system) should be studied in more detail, to determine the reservoir potential of the Lower Paleozoic shales.

Geochemistry and Source-Rock Evaluation

A solid understanding of the geochemical characteristics of the formations within the study area was crucial in identifying potential source rocks for hydrocarbon generation. Classification of the geochemical characteristics within the region was performed by analyzing all available sources of information. Geochemical data were obtained from:

- literature reviews,
- state Geological Surveys, and
- analysis of collected samples, from both outcrops and cores.

A trip to the Kansas Geological Survey in Lawrence, Kansas was completed in December 1997 for the description and sampling of well cores. The cores to be studied were selected prior to the trip. Preparations for the viewing of the cores were organized through the University of Kansas.

During the trip, 19 individual cores which included various Lower Paleozoic strata were described and sampled (see Fig. 3–9). Sample collection concentrated on rocks from:

- the Maquoketa Shale,
- the Chattanooga Shale, and
- the Kansas City/Pleasanton Groups.

A total of 29 core samples were collected:

- 24 Maquoketa Shale samples,
- 3 Chattanooga Shale samples, and
- 2 Kansas City/Pleasanton Groups samples.

All samples collected were sent for thin section preparation, and geochemical analysis, including:

- TOC,
- Rock-Eval Pyrolysis, and
- vitrinite reflectance.

Four Lower Paleozoic outcrop samples (from the Maquoketa shale and Mississippian section), collected in Missouri during the field investigation of Lower Paleozoic carbonates, were included in the geochemical sample suite.

Along with the core samples collected for analytical assessment, all well files pertaining to the core data were made available to BDM personnel to search for additional useful information. This led to the acquisition of additional geochemical data, including additional information on the parameters already listed:

- TOC,
- Rock-Eval Pyrolysis, and
- vitrinite reflectance, plus
- T_{max},

from 25 well locations in Kansas. These included data from Cambrian- to Pennsylvanian-aged formations (see Fig. 3–9).

Geochemical data collection and analysis were used to characterize the potential source rocks and non-source rocks within the South-Central Mid-Continent stratigraphic succession. The purpose of the data collection activities was to enhance the understanding of the geochemical characteristics of the study area, specifically for information required for the University of Minnesota RIFT2D basin-modeling program. More-reliable modeling results were gained by adding this information.

In addition, running the model with varying data quantities and qualities tested the sensitivity of the RIFT2D basin model. This sensitivity testing helped BDM Petroleum Technologies understand the key variables for this particular modeling package. This enabled the development of better strategies for data gathering for modeling in new areas.

Prior to these analyses, geochemical data collected from the Kansas Geological Survey were supplemented by adding published data from Kansas, Missouri, Nebraska, Iowa and Illinois collected during a literature review.

The geochemical evaluation focused on potential source rocks within the regional study area, including (See Fig. 3–10):

- the Ordovician Maquoketa Shale,
- the Guttenberg Shale Member of the Decorah Formation (part of the Simpson Group),
- the Glenwood Shale (the capping unit of the Simpson Sandstone),
- the Devonian Chattanooga Shale, and
- the Pennsylvanian Cherokee Shale

The most-important geochemical characteristics of the potential source rocks include:

- the presence of adequate quantities of organics, and
- the maturity of the organic matter present.

These can be evaluated through analysis of:

- total organic carbon (TOC),
- T_{max}, and
- the generation/production indices (GI/PI).

These two indices are an expression of the Rock-Eval Pyrolysis analysis,

$$S_1/(S_1 + S_2)$$

where S_1 is the measured amount of free hydrocarbon within the sample, and

S_2 is the measured amount of hydrocarbons formed by the breakdown of kerogen.

TOC values in the range of 0.5 – 1.0% are generally considered to be within the acceptable range for potential source rock material (Merrill, 1991).

Table 3–1 is a summary of all of the results from the TOC data acquired within the Mid-Continent region. The sample locations are shown in Figure 3–9.

Table 3–1 Geochemical summary results for selected formations in the South-Central Mid-Continent region, including results from Iowa

Formation	TOC Mean	T_{max} Mean	GI/PI
South-Central Mid-Continent			
Tarkio Limestone	0.20		
Topeka Limestone	0.40		
Heebner Shale	0.92	432	0.09
Lansing-Kansas City Groups	5.27	434	0.07
Marmaton Group	0.31	351	0.64
Cherokee Group	1.19	407	0.43
Morrowan Group	2.60		0.15
Mississippian Undifferentiated	0.53	313	0.90
Chattanooga Shale	2.54	429	0.19
Maquoketa Shale	0.96	429	0.10
Viola Limestone	0.42	423	0.45
Simpson Group	1.59	432	0.11
St. Peter Sandstone	0.21	437	0.07
Arbuckle Group	0.06	340	0.50
Iowa Formations			
New Albany Shale	4.65	422	
Maquoketa Shale	4.00	436	
Decorah Formation	0.61	437	
Guttenberg Member	21.80	448	
Platteville Formation	2.29	439	
Glenwood Shale	11.34	439	
St. Peter Sandstone	4.08	429	

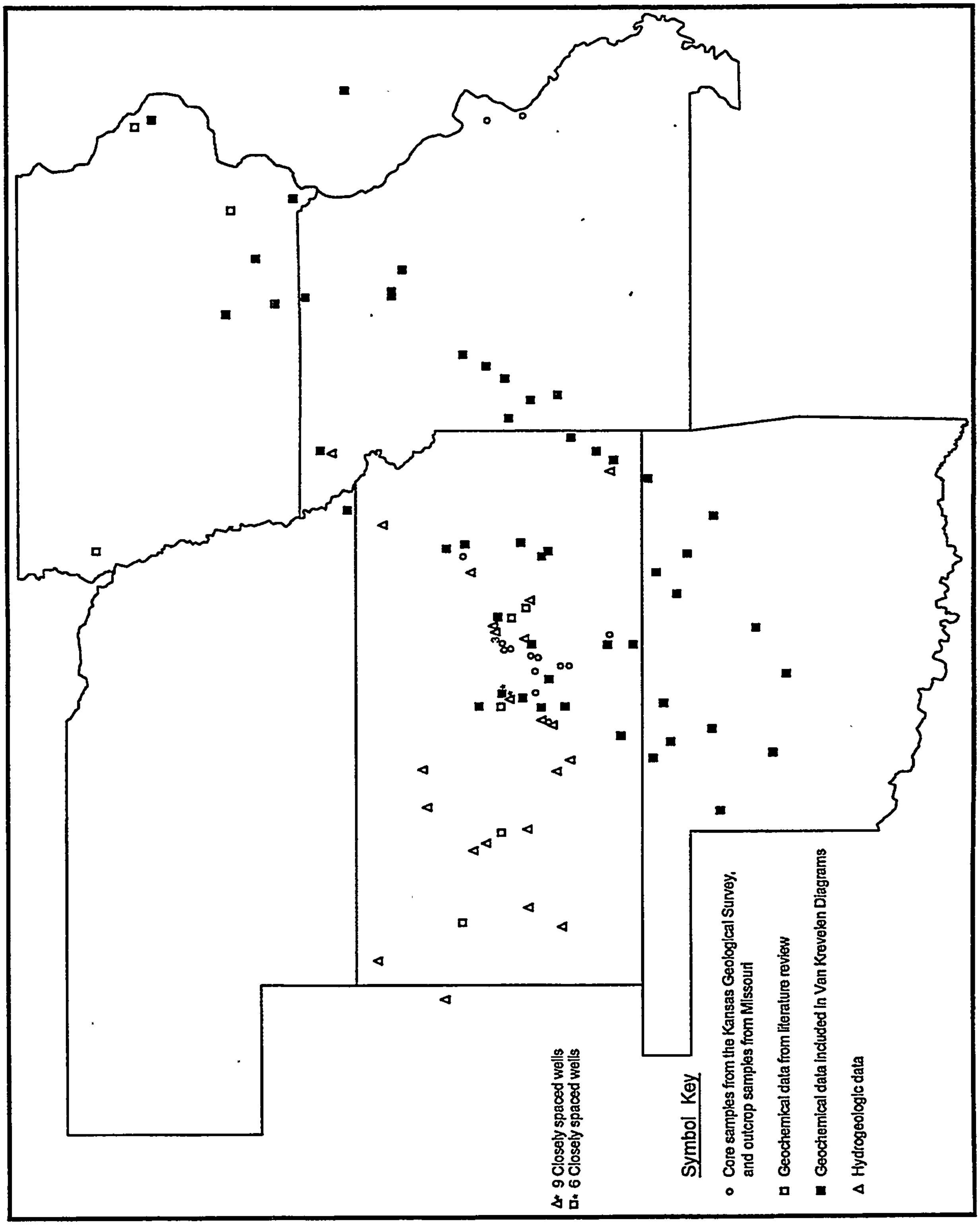


Figure 3–9 Data location map for all geochemical and hydrogeologic information. Data includes outcrop and core samples, core analyses, published geochemical results, and in-house geochemical results.

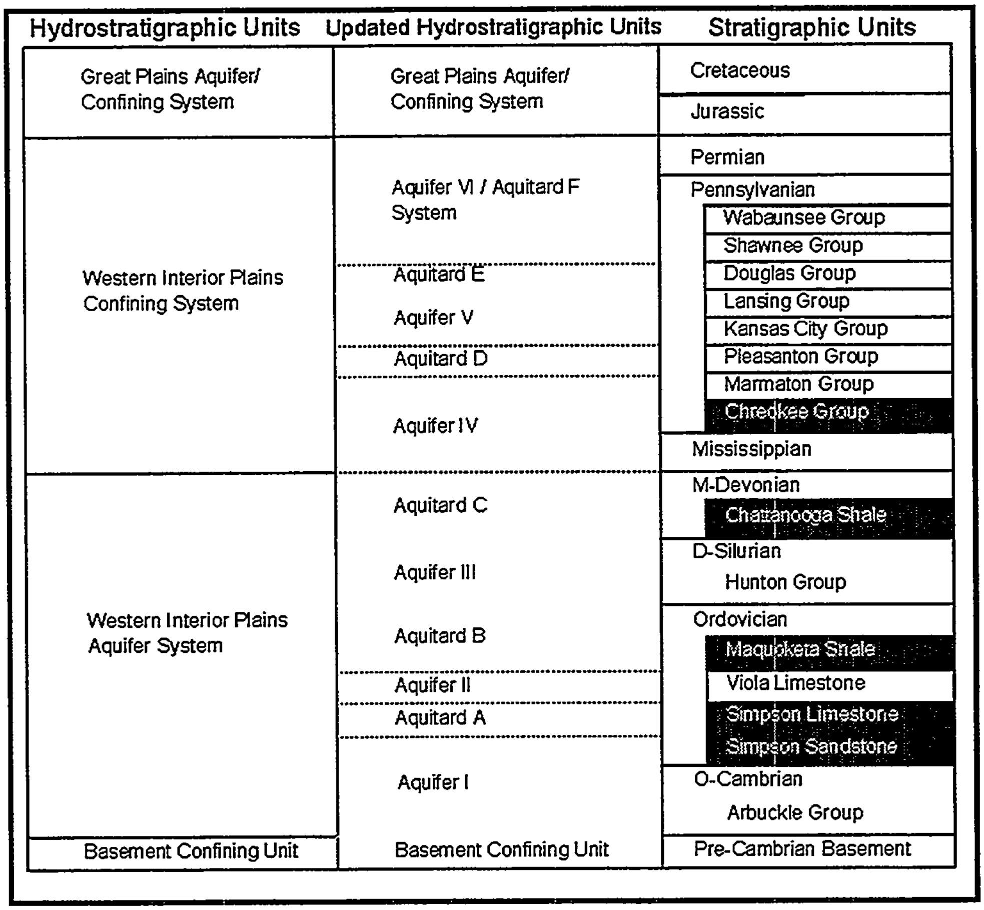


Figure 3–10 Chart indicating original hydrostratigraphic units used in the University of Minnesota RIFT basin model, and the updated/revised hydrostratigraphy. These are shown along with the stratigraphic column with source rocks shaded.

Based on the general rule regarding TOC quantities:

- the Simpson Group,
- the Maquoketa Shale,
- the Chattanooga Shale, and
- several formations within the Pennsylvanian
  - the Cherokee Shale,
  - the Morrowan Group,
  - the Lansing/Kansas City Groups, and
  - the Heebner Shale

should be considered to be potential source rock material within this region.

All of the listed Ordovician-age formations that were deposited in Iowa have become potential source rocks.

The results of this work indicate that there are several formations that should be considered to be potential source rocks in the study area, especially to the northeast, in Iowa.

TOC values within or above the 0.5 –1.0% range are only half of the source rock requirement. Only rocks that are high in TOC that have also reached thermal maturity should be considered to be potential source rocks.

The additional criteria for potential source rocks within the South-Central Mid-Continent were the analysis of T_{max} and the generation/production (GI/PI) indices (see Fig. 3–11). These parameters express the maturity of the potential source rock material. T_{max} and GI/PI are listed in Table 3–1.

Samples considered to be mature, which fall within the oil-generation window, have:

- GI/PI values of approximately 0.1, and
- T_{max} values within the range of 430 – 445°C.

As illustrated in Table 3–1, mature formations include:

- the Heebner Shale,
- the Morrowan Group,
- the Chattanooga Shale,
- the Maquoketa Shale, and
- the Simpson Group.

T_{max} and the GI/PI data assist in the characterization of the maturity of source rocks for the University of Minnesota RIFT2D basin modeling program.

- TOC,
- T_{max}, and
- GI/PI data analyses

indicate that the potential source rocks previously input to the University of Minnesota RIFT2D basin model:

- the Cherokee Shale,
- the Chattanooga Shale,
- the Maquoketa Shale,
- the Guttenberg Member, and
- the Glenwood Shale

were valid choices, and that there were additional formations that could be considered in a more-detailed modeling program of the South-Central Mid-Continent.

Generation Potential for Selected Formations within the South-Central Mid-Continent

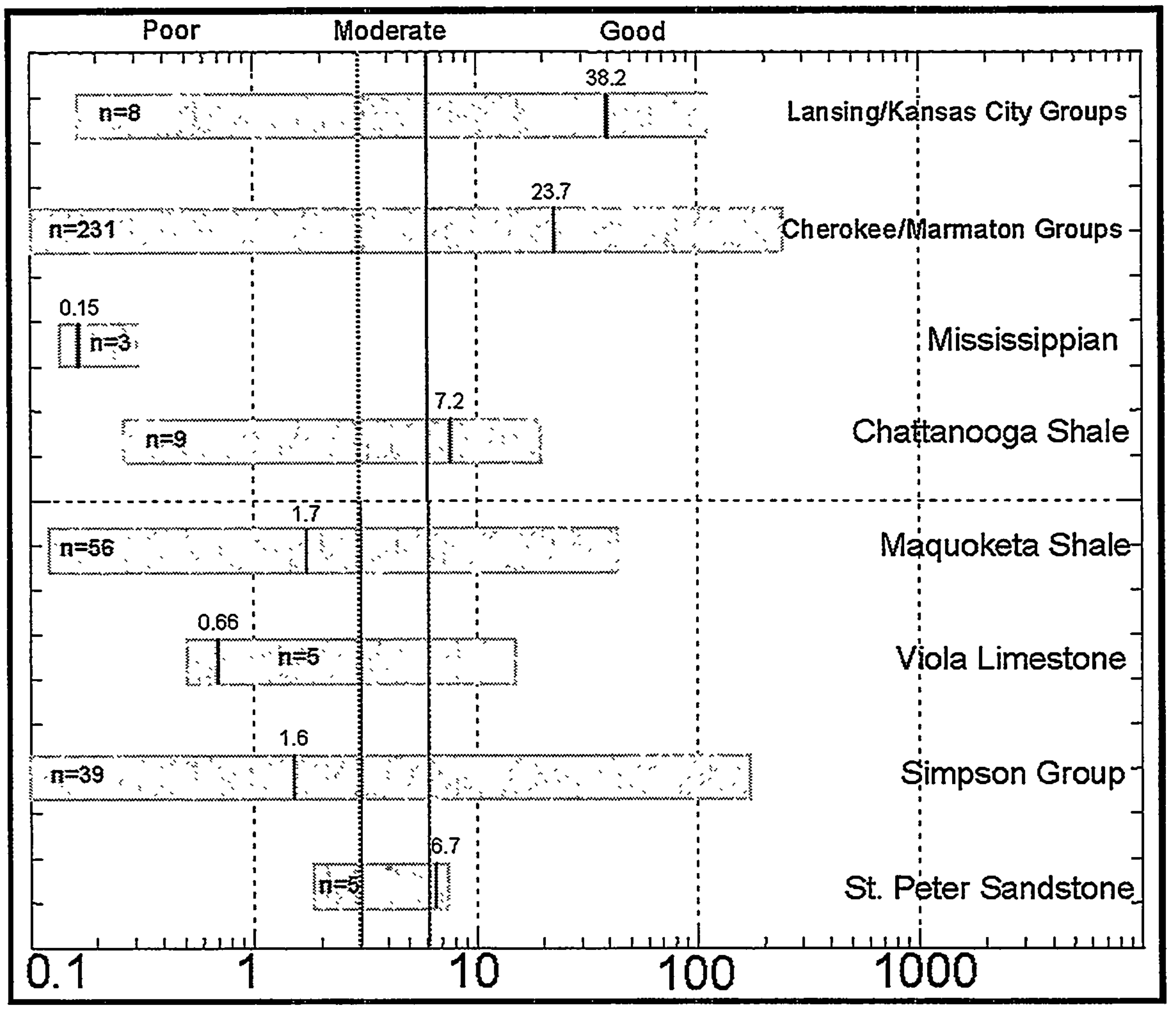


Figure 3–11 Generation potential for selected formations within the South-Central Mid-Continent region.

Kerogen type is an important variable for the University of Minnesota RIFT2D basin modeling software program. It provides major implications as to the quantity and quality of any hydrocarbons generated in the study area. Through the results of the geochemical data collection process, kerogen types were determined for the major potential source rocks within the South-Central Mid-Continent.

Kerogen types are categorized using Van Krevelen diagrams. These diagrams are based on a cross-plot between:

- the Hydrogen Index (HI) and
- the Oxygen Index (OI),

variables determined through Rock-Eval Pyrolysis.

Specific diagrams used in this analysis were modified from Hunt (1996). The HI and OI were plotted and classified for four types of kerogen.

Kerogen found within the samples included disseminated organic matter that was insoluble in non-oxidizing acids, bases and organic solvents (Merrill, 1991). The organic matter originally deposited was not kerogen, but was a precursor that was converted to kerogen through diagenesis.

Kerogen type can be used to determine the general depositional environment of the original organic matter, and the type of hydrocarbon that the kerogen is likely to form. There are four main types of kerogen, grouped into two divisions.

- Types I and II are generally considered to originate from marine source beds from organic debris of algal and bacterial origin, and are more oil prone than kerogen types III and IV.
- Types III and IV kerogens are typically considered to originate from terrestrial environments, including organic matter derived from plant and humic material. These two kerogen types are more prone to generate gas, but can also generate oil.

Results indicate that three types of kerogen predominate within the potential source rocks in the South-Central Mid-Continent. Figure 3–12 is a modified Van Krevelen diagram. It shows the four general types of kerogen and the specific data for Maquoketa Shale samples. The data analyses are from various wells in the South-Central Mid-Continent region (see Fig. 3–9).

The Pennsylvanian formations show a range of kerogen types. The Kansas City Group, Marmaton Group, and Heebner Shale all contain largely type IV kerogens, based upon the available data. The Lansing Group, on the other hand, contains largely type I kerogen, plotting distinctively apart from the data for the other Pennsylvanian formations.

The remaining Lower Paleozoic (Chattanooga Shale, Maquoketa Shale, and Simpson Group) formations contain either type I or II kerogens, as shown in Figure 3–12.

Geochemical results from:

- TOC,
- T_{max},
- GI/PI, and
- HI/OI

indicate that several formations have a high potential to be source rocks within the South-Central Mid-Continent. Most of these potential source rocks in the region contain a mix of type I and type II kerogens, suggesting a marine biological origin.

In terms of thermal maturity, the analyses show that the majority of the source rock material in the region is within oil-window conditions. Overall, these data demonstrate that it was valid to input the source rocks that were used in the RIFT2D basin model.

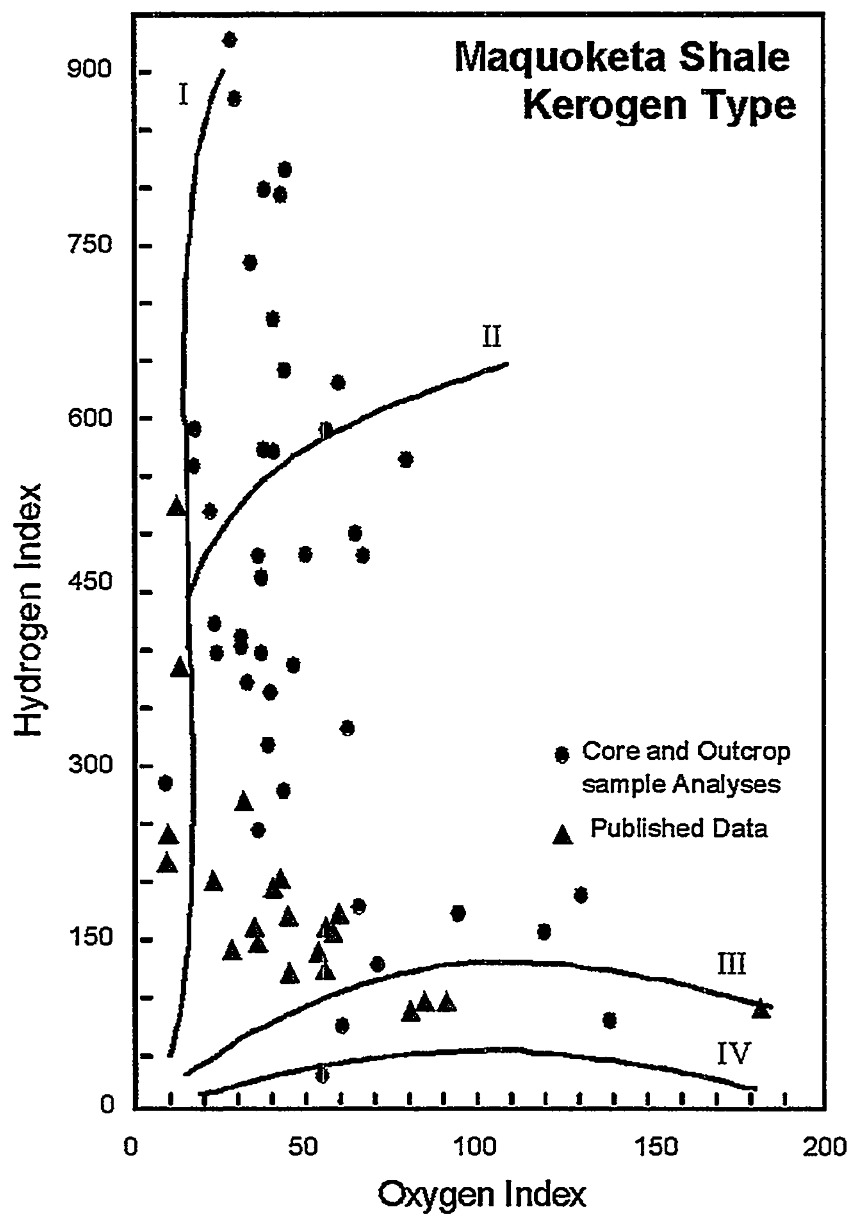


Figure 3–12 Modified Van Krevelen diagram for the Maquoketa Shale. Plotted information is used to determine the kerogen type for potential source rocks.

Hydrogeology

An understanding of the flow characteristics within the South-Central Mid-Continent region was vital for the modeling of the generation and migration of hydrocarbons in the region through time. The hydrogeology of the region was described after analysis of data from:

- literature reviews,
- core-analysis reports, and
- well-log studies.

Additionally, petrographic analysis was performed on the samples that had been collected in the field or from the surveys. These multiple data sources all contributed to the regional classification of the hydrogeology.

Core analyses were collected from the Kansas Geological Survey during the core-sampling trip of December 1997. The data input into the model included information from 30 wells in Kansas, eastern Colorado, and western Missouri (see Fig. 3–9). Lower Paleozoic core analyses from various formations within the Lower Paleozoic provided model input on:

- porosity,
- permeability,
- oil saturation, and
- lithologic characteristics (i.e., fracturing, vugularity, fissility, etc.).

These data were compiled, based on formation and lithology, and are summarized in Table 3–2.

Porosity Data

Steady progress was made on the modeling program, improving the quality of the results. This required the addition of more-precise porosity information. The earliest porosity data input for the model came from published information. They were calculated values based upon simple assumptions of an empirical relationship between assumed porosities and depth.

Much more realistic values were obtained from well log studies. The results from the well logs are summarized in Table 3–3. These values for porosity are averages for each group or formation across the area of interest. Table 3–3 indicates that there is a wide range of values, and that the porosity does not simply correlate with depth. A constant relationship can not be determined, and it is evident that the empirical relationship is a significant over-generalization about rock porosities.

Table 3–2 **Petrophysical properties (porosity and permeability) of formations within the South-Central Mid-Continent**

Formation	Permeability	Porosity	Oil Saturation	Lithologic Characteristics
Topeka Limestone	1.73	9.44	11.24	partially fractured
Lansing/Kansas City Groups	0.53	4.1	5.7	abundant vertical fractures
Morrowan Group	5.93	19.62	1.07	in part vugular
Mississippian Dolomite	21.87	12.39	12.88	vugular, some vertical fracturing
Mississippian Limestone	15.78	4.79	3.3	
Chattanooga Shale/Meisner Sandstone	33.88	11.28	8.46	partially vertically fractured
Hunton Dolomite	69.1	25.4	10.84	consistently vugular, in port vertically fractured
Hunton Limestone	49.55	15.02	26.54	
Viola Dolomite	53.33	9.55	8.93	locally vugular and vertically fractured
Viola Limestone	89.34	6.76	9.76	locally vugular and vertically fractured
Simpson Dolomite	5.84	8.12	2.2	
Simpson Limestone	0.15	4.52	3.07	
Simpson Sandstone	83.25	11.91	14.08	
Simpson Shale	0.15	10.38	11.76	
Arbuckle Dolomite	143.15	10.68	2.4	vugular, in places fissile
Arbuckle Limestone	105.53	8.55	23.44	

Because these values were obtained for modeling purposes, and only very general averages were needed, lithology was not considered. Therefore, the geologic Groups were not subdivided according to rock type. As a result, some of the units containing a high percentage of shale show what seem to be high porosities. These numbers were used in conjunction with permeability data in the modeling program.

An example of how information gained during study changed long-held concepts concerned the Cherokee Group, a stratigraphic unit that exhibits high porosity and permeability. The average porosity of the entire Cherokee Group across the east-west cross section is 21%. This indicates that the Cherokee should be treated as a potential aquifer rather than as an aquitard, the previous standard classification.

Table 3–3 Porosity averages for groups along east-west cross section

Group	Average Porosity, %	Group	Average Porosity
Arbuckle	9.6	Lansing	10.5
Simpson	12.9	Douglas	19.0
Decorah	8.9	Shawnee	13.8
Viola	7.0	Wabaunsee	16.9
Maquoketa	12.3	Admire	14.2
Hunton	12.1	Council Grove	14.5
Kinderhook	17.5	Sumner	12.3
Mississippian	13.3	Chase	16.0
Morrowan	11.6	Nippewalla	23.4
Cherokee	22.6	Morrison	26.0
Marmaton	14.3	Dakota	29.1
Pleasanton	19.2	U. Cretaceous	35.9
Kansas City	9.9		

Regional Diagenesis and Petrophysical Characterization

Three major diagenetic waves have been identified that significantly modified the petrographic properties of the Lower Paleozoic carbonate succession in the study area. The first two episodes were regional diagenetic events. The third was also widespread, but had a larger effect in some areas than in others. These processes modified strata across the Ozark uplift area, and on into the Forest City basin.

The effects of two major diagenetic episodes were seen in thin sections that were prepared for BDM studies of the Arbuckle Group. Figure 3–13 illustrates the effects of both silicification and dolomitization within a single thin section. The contrast between the two in terms of reservoir potential is dramatic. The left portion of this photomicrograph demonstrates the effects of silicification. Remnants of the fabric and texture of the original oolitic grainstone can still be seen. The right half of the photomicrograph shows thorough dolomitization, which has completely obliterated the original texture in that part of the rock.

This rock was originally deposited in an energetic, shallow-water environment. Ooids formed and were tossed about by the waves. The original limestone likely had very good porosity. The first wave of diagenesis occurred as a process of silicification (see Fig. 3–14). This process non-selectively replaced the original carbonate material with silica. Diagenetic events such as this have dramatic effects on the porosity of a formation and also, generally, alter its permeability characteristics.

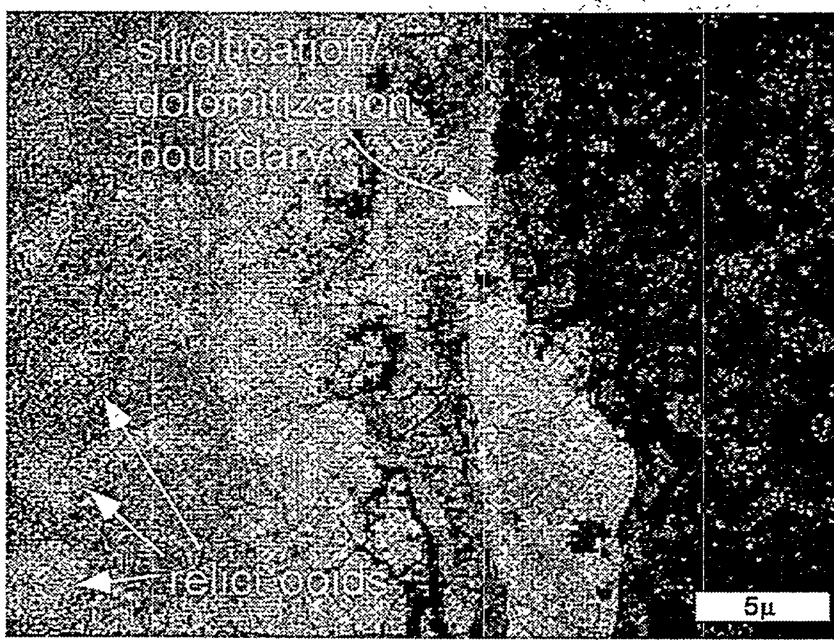


Figure 3–13 Photomicrograph of Arbuckle Group carbonate illustrating the two main phases of diagenesis present. Original textures can still be seen in the left side of the photo where only silicification has occurred. The right side of the photo shows dolomitization [xpl].

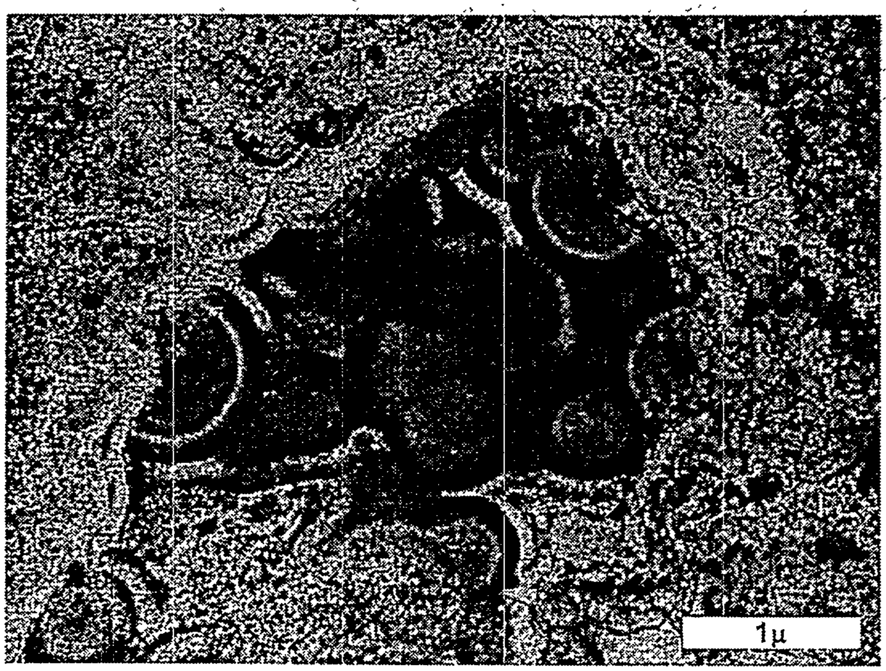


Figure 3–14 Photomicrograph of silicified "grapestone" surrounded by extensive dolomitization [xpl].

The second major diagenetic phase to affect the Lower Paleozoic strata within the study area was dolomitization. This process, in the areas where it occurred, completely destroyed the original texture of the carbonate units. Plain-polarized light (see Fig. 3–15) shows the effects of this process very well. In the example shown, relict pelloidal grains have acted as nucleation points for coarsely crystalline dolomite rhombs. The ghosts of the pelloidal grains are the only remaining clues as to the original compositions of the carbonates.

The final alteration event that affected the Lower Paleozoic carbonate strata in the study area was the creation of secondary, fracture porosity across the region. Fractures and associated, open porosity are present in many of the samples that were observed. Such porosity will have a significant effect on the hydrogeologic characteristics of a formation. Interconnected fracture networks greatly enhance the potential for fluid flow within a particular formation. On a local or regional scale, fracture networks can have significant effects on fluid-flow dynamics.

Results of the thin section analyses carried out by BDM Petroleum Technologies personnel indicate that the diagenetic modification observed in thin sections took place in multiple phases. Interpretation of the information available from the thin sections, such as:

- color,
- texture,
- grain size and shape, and
- optical properties

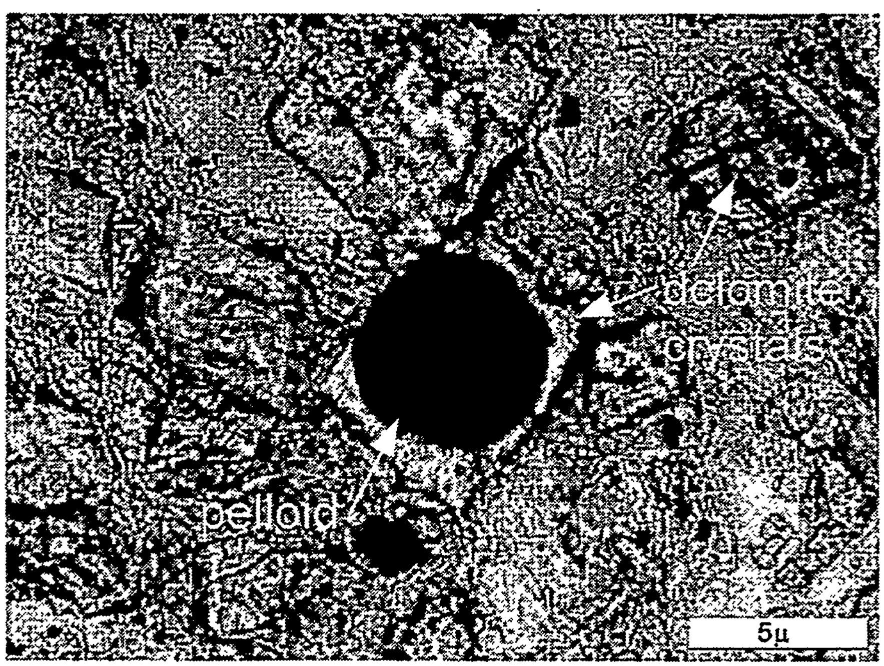


Figure 3–15 Photomicrograph in plan polarized light of coarsely crystalline dolomite nucleating on relict pelloids.

helped to give indications about paleo-basinal conditions, such as fluids and their compositions, and the rise of local structures.

Equally important for the hydrostratigraphic characterization of the Lower Paleozoic succession was the presence of secondary porosity in the target carbonates. Formations containing secondary (fracture) porosity have a greater capacity for fluid flow, and therefore warrant classification as potential aquifers if fracturing is sufficiently extensive in the formation.

The purpose of the porosity/permeability data collection effort was to better describe the hydrogeologic characteristics of the Lower Paleozoic formations within the South-Central Mid-Continent. The characterization process significantly improved the hydrogeologic parameters that were entered into the University of Minnesota RIFT2D basin modeling program.

It was found that the previously generally-recognized hydrostratigraphic units, the:

- aquifers, and
- aquitards

that had been described in the literature were over generalized (see Fig. 3–10), and in some cases, outright incorrectly classified. The inclusion of the new, revised data has greatly improved the output from the RIFT2D basin model.

Originally, the hydrostratigraphic units that generally were described in the literature and that were used in the initial runs of the RIFT2D Basin Model included:

- the Basement confining unit,
- the Western Interior Plains aquifer system,
- the Western Interior Plains confining unit (aquitard),
- the Great Plains aquifer system,
- the Great Plains aquitard, and
- the High Plains aquifer (a surficial unit and unimportant for hydrocarbon considerations).

The revised hydrostratigraphic units identified within the Western Interior aquifer system during the work for this project are illustrated in Figure 3–10. The refinements were based not only on literature reviews, but also on the lithological characteristics of the rock formations, and on the porosity and permeability data that were acquired. The fine-scale hydrostratigraphic units include alternating aquifers (porous sandstone units and fractured or vuggy limestone formations) and aquitards (continuous impermeable shales).

Instead of the simplicity of the former system, with only two major subsurface aquifers, the analysis of the porosity and permeability and other data a revised interpretation of great hydrogeologic complexity.

The revised classification includes 7 aquifers and 8 aquitards (see Fig. 3–10). The level of detail in the revised classification of hydrostratigraphic units drastically improved the RIFT2D basin model output because the new hydrostratigraphic unit classification system represents a much closer approximation of real-world conditions.

3.1.3 Results from 3-D Basin Modeling

The final objective of the BDM Petroleum Technologies data collection activities was to describe the volumetrics of both potential source rocks and reservoir rocks across the east-west profile line used for the RIFT2D basin model. Key factors for source and reservoir rock volumetric determinations are considerations of lateral continuity. Thickness variations across the region are also extremely important. A great deal of attention was paid to these issues.

This goal was accomplished by the generation of multiple cross-sections across the South-Central Mid-Continent. A total of five stratigraphic cross-sections were used to produce multiple data sources to show basinal development through time (see Fig. 3–16). Cross-section construction began with the correlation of individual well logs across Kansas and western Missouri. Four cross-sections were prepared in northeastern Kansas, the Forest City basin and Nemaha uplift areas.

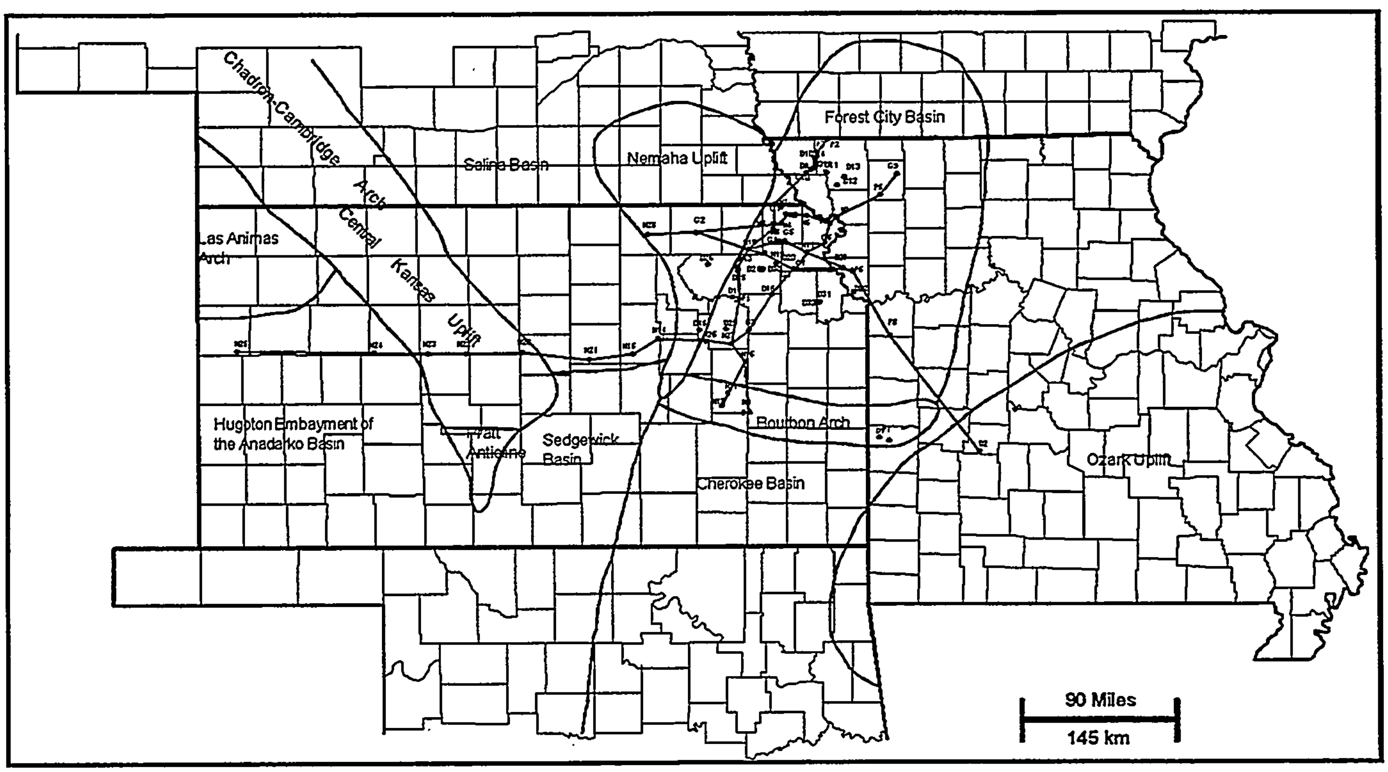


Figure 3–16 Map with present day physiographic provinces indicating the location of cross-section lines used in basinal analysis.

The same sets of cross-sections were used for gravity modeling in the South-Central Mid-Continent. For geophysical purposes, gravity anomalies associated with the Mid-Continent Rift system and the Nemaha uplift were specifically investigated. A single cross-section was generated that follows the east-west profile line used in the RIFT2D basin model (see Figs. 3–17 and 3–18). This east-west cross-section adds greater detail to the input parameters of the RIFT2D basin model. Additional information on the geophysical modeling is included in Section 3.2.

A highly significant finding from the basin modeling work was that reservoir and source rocks are consistently present across the region. These results are presented in Figure 3–10.

Two major stratigraphic trends can be observed in the east-west cross-section across Kansas. Pre-Pennsylvanian Lower Paleozoic strata thicken to the east across the study area, while Upper Paleozoic through Cretaceous strata thicken to the west. The only deviations from these general trends occur around the highly disturbed areas surrounding the Nemaha uplift and along the persistent Lower Paleozoic positive feature, the Central Kansas uplift. Many Lower Paleozoic strata lack continuity around these structural features, significantly influencing local and regional fluid flow, potential oil-migration pathways, and the possibilities for oil generation.

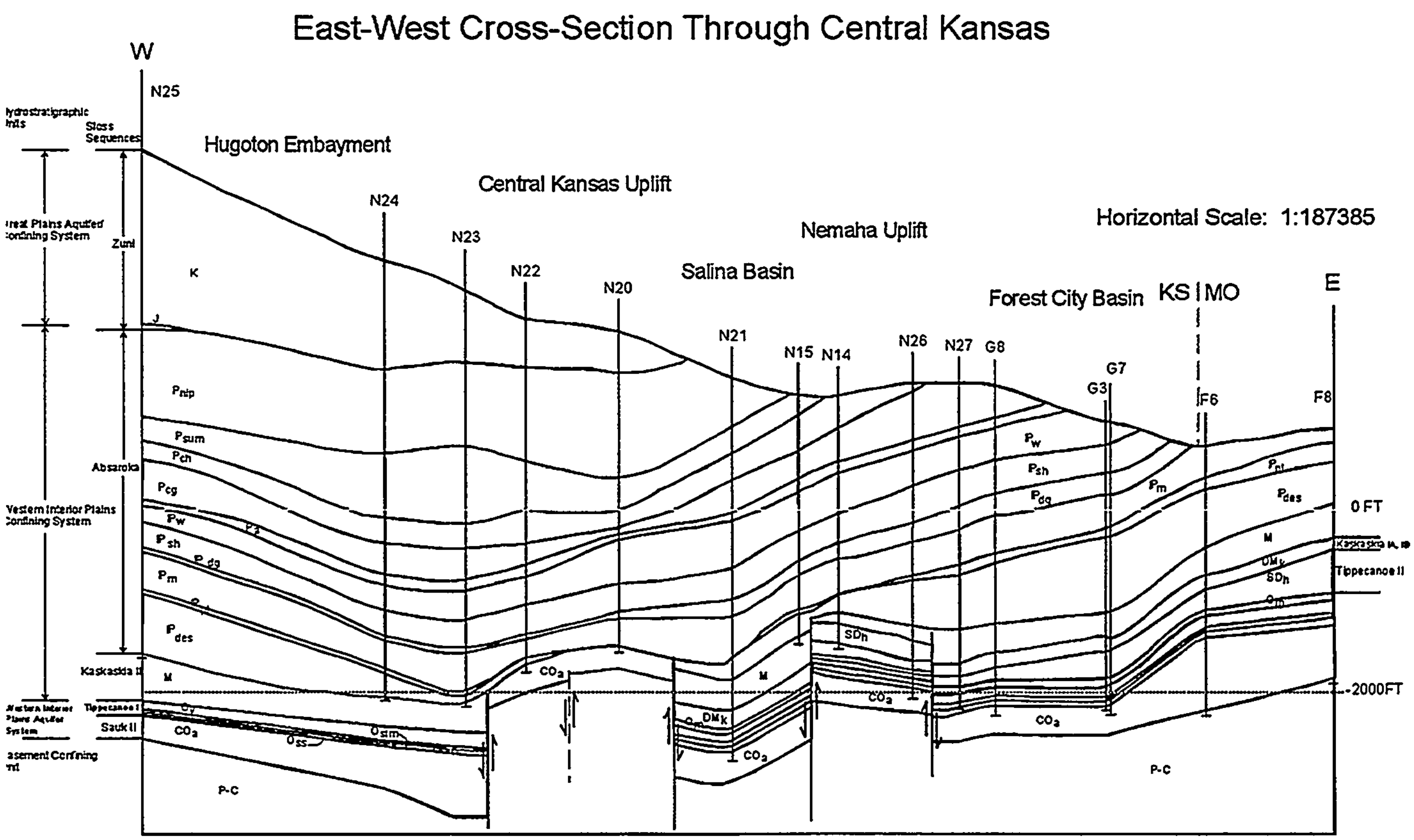


Figure 3–17 **East-west cross-section through central Kansas from the Colorado border into Missouri.**

The geologic development of the most important structural elements within the South-Central Mid-Continent can also be seen in these cross-sections. These key structural features include the Nemaha uplift and the Central Kansas uplift. Lower Paleozoic stratigraphic units truncate via original depositional thinning along the flanks of the Central Kansas uplift. Numerous beds pinch out to featheredges at this structure.

By way of contrast, thick sections of strata were removed by significant erosion during Mississippian-Pennsylvanian time along the trend of the Nemaha uplift. Depositional thinning on the flanks of the Central Kansas structure indicates that it was present and persisted throughout most of the Lower Paleozoic. By way of contrast, abrupt, post-depositional removal of pre-existing sediments along the Nemaha structure show that the Nemaha structure formed well after the area had been covered by a thick sedimentary section.

These two structural features were primary influences effecting fluid-flow within the South-Central Mid-Continent region. They created local barriers and truncated the regional aquifer systems. The earliest strata to blanket the Mississippian-/Pennsylvanian-aged Nemaha and the ancient Central Kansas uplifts were the Pennsylvanian-age Missourian Series. Post-Missourian strata demonstrate the normal regional westward-thickening trend that is seen through the Cretaceous.

A significant effort was initiated to graphically characterize the three-dimensional distribution of strata, particularly source and reservoir rocks, within the South-Central Mid-Continent region. The intent was to completely represent the structural and depositional history at the system- and formation-scale level. An extensive database, containing over 750 wells was constructed.

The acquisition of additional stratigraphic data focused on:

- the Forest City basin,
- the Salina basin,
- the north-eastern side of the Central Kansas uplift,
- the northern portion of the Sedgwick basin,
- the Pratt anticline,
- the northern portion of the Cherokee basin, and
- the Bourbon arch

structural provinces.

A series of structure and residual-thickness maps were generated covering the region. The objective was to characterize the development of the study area through geologic history in 3-dimensions (see Fig. 3–19). The structural and stratigraphic development of the South-Central Mid-Continent region was described. Numerous fine-scale structural features became evident once the cross-sections and 3-d basin analyses were completed. The following major tectonic features were also identified from this analysis:

- the Transcontinental arch in the Cambrian and Silurian,
- the Southeast Nebraska arch (Ancestral Nemaha uplift),
- the Northeast Missouri arch of the Ordovician, and
- the Abilene arch of the Devonian and Mississippian.

The data collection and interpretation greatly enhanced the results of the University of Minnesota RIFT2D basin modeling project. Early runs of the program, using limited data input and accepting many default values produced a highly unrealistic model of the region. The added data have dramatically improved the modeling results for the South-Central Mid-Continent.

Formation Symbol Key

Symbol	Formation or Group	Symbol	Formation or Group
K	Cretaceous Undiff.	$\mathbb{P}_{des}$	Desmoinesian (Marmaton and Cherokee Groups)
J	Jurassic Undiff.	M	Mississippian Undiff.
P_{nip}	Nippewalla Group	DM_{k}	Kinderhookian
P_{sum}	Sumner Group	SD_{h}	Hunton Group
P_{ch}	Chase Group	O_{m}	Maquoketa Shale
P_{cg}	Council Grove Group	O_{v}	Viola Limestone
P_{a}	Armire Group	O_{slm}	Simpson Limestone
$\mathbb{P}_{w}$	Wabaunsee Group	O_{ss}	Simpson Sandstone
$\mathbb{P}_{sh}$	Shawnee Group	CO_{a}	Arbuckle Group
$\mathbb{P}_{dg}$	Douglas Group	P-C	Pre-Cambrian Undiff.
$\mathbb{P}_{m}$	Missourian (Pedee, Lansing, Kansas City Groups)		
$\mathbb{P}_{pl}$	Pleasanton Group		

Figure 3–18 Formation symbol key for reference in the east-west cross-section.

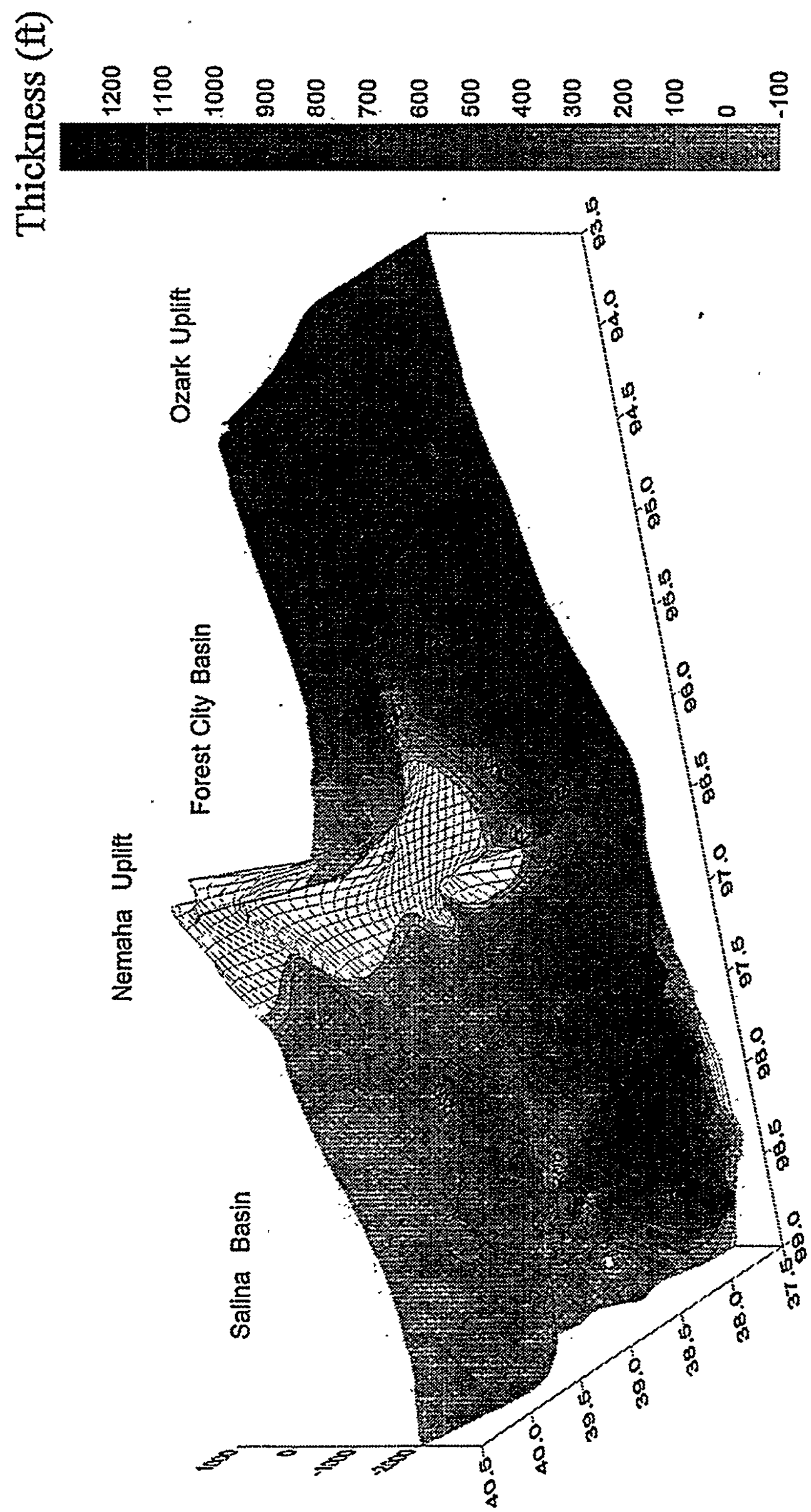


Figure 3–19 Example of the 3D basin analysis in the South-Central Mid-Continent region. Illustrated in the diagram is the present day topographic expression of the Precambrian basement, and a color map of the Arbuckle Group thickness.

3.2 Gravity and Magnetic Studies

As part of the DOE research on innovative exploration methodologies, detailed geophysical investigations were conducted in the South-Central Mid-Continent study area. These sophisticated studies were carried out to model the subsurface geology of the Salina and Forest City basins. The objective of these studies was to model the structure and lithology of the basement in these areas and predict possible areas of favorable hydrocarbon accumulation in the undrilled areas of the basin, particularly in older formations, closer to the basement.

Success in exploration for hydrocarbons in undrilled portions of a basin, where there is no well control, requires a good understanding of the basin framework along with tectonic and structural features which affected sedimentation in the basin. Much of this information may be obtained from relatively inexpensive and non-invasive techniques like gravity and aeromagnetic surveys.

While gravity and aeromagnetic data interpretations lead to non-unique solutions, integrated studies of these two methods can provide useful information about basement structure and type and thickness of sediments in an area. Much of this information can come from a regional interpretation of residual gravity and aeromagnetic maps. These maps will clearly demarcate the basin boundaries, in most cases, and identify major structural and tectonic features within the basin.

3.2.1 Basement Lithology And Structure

The basement rocks underlying the study area in the Mid-Continent consist of Precambrian granite, rhyolite, granite-schist, gabbro, basalt, and granodiorite, as well as meta-sediments, like quartzite (e.g. Van Schmus et al. 1993). The nature of the basement in the South-Central Mid-Continent is lithologically quite heterogeneous and structurally complex.

A pronounced gravity anomaly, generally referred to by geophysicists as the Mid-Continent Geophysical Anomaly (MGA) (King and Zeitz, 1971) cuts through the heart of the study area (see Fig. 3–20). The MGA, the geophysical expression of the Mid-Continent Rift System (MRS), extends from the Lake Superior region to near the Kansas-Oklahoma border. The middle Proterozoic (Keweenawan) Rift (Setzer et al., 1983) is characterized by gravity and aeromagnetic highs with flanking gravity lows.

Surface exposures and drilling data along the trend of the anomaly indicates that these distinctive features are probably caused by buried mafic volcanics and associated clastic sediments deposited in the narrow basin formed during continental rifting of Keweenawan (~1.1 Ga.) age (Setzer et al., 1983).

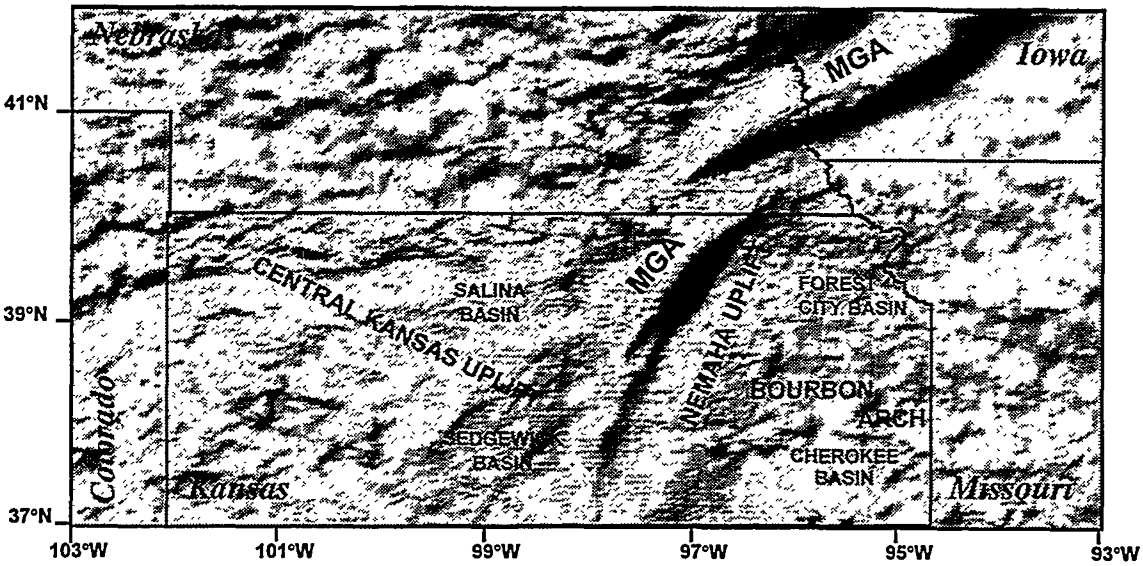


Figure 3–20 **Shaded relief map of gravity anomaly in the Mid-Continent region showing major tectonic features. The image is produced by artificial illumination at 135° azimuth and 45° inclination. [MGA - Mid-Continent Geophysical Anomaly].**

East of the MGA and forming the western boundary of the Forest City basin is the Nemaha uplift and the associated Humboldt fault system. The Nemaha Uplift, which separates the Forest City basin from the Salina basin, is part of a crystalline basement block that was uplifted during the Late Mississippian-Pennsylvanian (Steeples, 1982). Although the details of the origin of the Nemaha Uplift and the Humboldt fault are not clear, their lateral proximity and subparallel trend to the MGA suggest an association with the rift structure.

The uplift occupies an area that theoretically should have been part of a late rift-phase eastern flanking basin. This basin theoretically would have formed along the margin of the MRS during Keweenawan time. The flanking basins were zones of relatively thin, weak crust, cut by extensive faulting. They were originally buried under thick sedimentary columns, composed largely of volcanic detritus shed from volcanoes and ridges along the length of the MRS.

Apparently some of the ancient Keweenawan faults remained as zones of weakness that were reactivated with relative ease during the deformational stresses of Mississippian-Pennsylvanian time. As the basement was compressed, the Humboldt zone failed, and the Nemaha area popped up dramatically, leading to the erosion of Paleozoic cover and most of the Keweenawan sediment off the crest of the uplift.

Flanking basins can be found on the east and west sides of the rift from Lake Superior all the way to the southern end of the system, except in the Nemaha area. Complex faulting and extensive erosion of Lower Paleozoic sediments and large amounts of basement material on the crest of the uplift have made interpretation of original lithologies and structural relationships very difficult in that region. Yarger, 1981, has described the Humboldt and nearby fault systems as a reactivated rift structure.

According to Chenoweth (1987), the basement rocks in the central part of the study area basins are mostly granite, although there are also local high-magnetite-bearing granite and granodiorite intrusives of Late Proterozoic (1,380–1,450 Ma). In the eastern and northeastern portion of the Forest City basin, the basement is thought to be composed of early Proterozoic metamorphic rocks.

3.2.2 Data Sources

Gravity and magnetic data acquired in the field need to be processed so that they may reflect the effect of subsurface structures. This involves correcting and reducing the observed values for several parameters. For gravity data these involve several corrections, including:

- latitude,
- terrain,
- free air, and
- Bouguer

corrections.

Aeromagnetic data needs to be corrected for:

- terrain
- geomagnetic, and
- diurnal

variations. The data can then be interpreted and modeling studies carried out to deduce the subsurface lithology and basement features. The combined interpretation of gravity and magnetic data also indicate the type of igneous bodies likely to be encountered in a particular area.

Basic, ultrabasic, and intermediate igneous rocks, such as basalt, gabbro, or diorite, normally have high magnetic susceptibilities because they include large amounts of magnetite in their composition. Consequently, the rocks have large residual magnetic anomalies. These rocks also have high density values and, hence, higher residual gravity anomalies as compared to other rocks. Details about the modeling and analysis of gravity data have been presented in previous reports by the BDM Petroleum Technologies Basin Analysis team (NIPER/BDM–0302, pg. 126–132).

High-resolution gravity and aeromagnetic data were acquired from the National Geophysical Data Center (NGDC) in Boulder, Colorado. The gravity data, supplied on a CD ROM database format comes complete with a viewer software package (Geovu). Most of the gravity data for the Mid-Continent study came from the Defense Mapping Agency (DMA) and the National Geodetic Survey (NGS) databases.

The aeromagnetic data, also supplied on a CD-ROM, consisted of multiple files, with 40,000 to 75,000 records in each file. The data-file formats varied, and were dependent upon the agency responsible for carrying out the aerial survey. Due to these format variations, individual aeromagnetic data files required some reformatting before they could be analyzed.

Additional gravity and aeromagnetic information on Kansas is available on the Internet

www.kgs.ukans.edu/PRS/petroIndex.html

from the Kansas Geological Survey. Well-logs and core descriptions collected from various core and log libraries as well as from published literature were also used in modeling.

3.2.3 Gravity Modeling Procedure

As mentioned before, gravity and magnetic modeling provide a non-unique interpretation. However, the interpretation may be constrained by the application of hard information such as well-logs, cores and seismic data, if available. A practical approach to modeling gravity and magnetic data is to model the explored parts of the basin using as much information as possible to obtain a near-unique solution. Density data so obtained will provide the first good approximation of density variations in undrilled parts of the basin.

Modeling studies of gravity data involve computing total gravitational effects at a point on the surface of the earth due to the structural and stratigraphic features present in the subsurface and comparing the results with the observed gravity values. The details of the two-dimensional gravity modeling procedure used in the study are briefly discussed below:

- Well-log and drilling data were collected from various sources, and the tops of stratigraphic units were picked from each log. Transects were selected across the basin. Data from wells along the transect were used to correlate and construct structural cross-sections. These cross sections were used as the starting basis for the gravity modeling process. For this purpose, the formations were grouped into larger geologic units based upon lithologic similarity.

- The high-resolution gravity and aeromagnetic data for the study area were extracted from the respective databases. The extracted data files were gridded using a Kriging function. The observed gravity data was adjusted by subtracting a second-order surface, to eliminate effects due to regional crustal thickening (Xia et al 1996). Gravity and aeromagnetic anomaly profiles along the transects were extracted from the gridded data files.

- In the cross-sections, the topography of the basement was modified using data from various published sources as well as by initial interpretation of gravity- and magnetic-anomaly data.

- The stratigraphic cross-section was digitized, to obtain point coordinates outlining each geologic unit. The digitized data formed part of the input information for the modeling program. Also required were the total number of points outlining a geologic unit, the total number geologic units in a model, the density value for each unit, and the regional gravity-correction adjustments needed to compare computed and observed gravity values. The density values assigned to the different units were approximated from a density-porosity log by calculating the bulk-density values, using a limestone matrix value of 2.71.

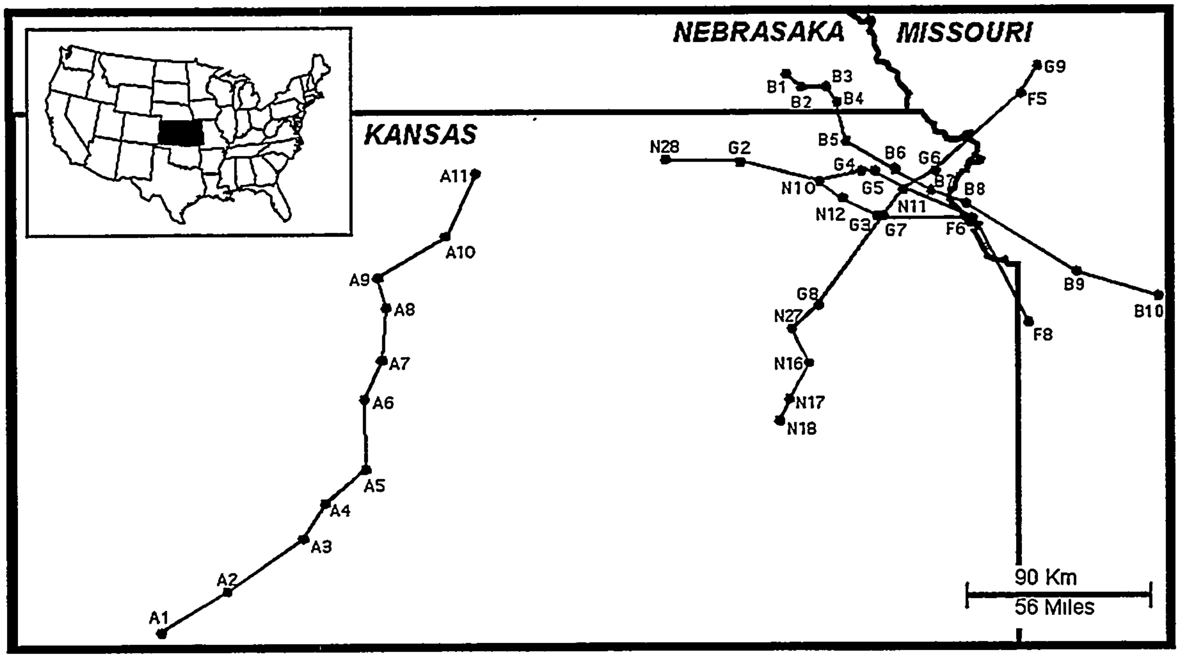
- The program BDM-developed software program, GRAVANOM, written in FORTRAN 77, was used in the modeling process. This program is capable of modeling multi-layered models with complex structures. This program has been rigorously tested and used in prior gravity modeling studies conducted in the Black Mesa basin in northeastern Arizona (Sharma et al, 1996). Details about GRAVANOM program are presented in Sharma, 1998.

- After each model run, the computed gravity results from the model were compared with measured gravity values, the objective being to obtain a good fit. An iterative process was carried out, during which adjustments were made to the theoretical geometry, structure and density of the subsurface features, constrained by available geologic information. The model was then run again. The density and structural configuration for which the computed gravity values matched most-closely with the observed values was considered to be a realistic potential interpretation of the subsurface structural and lithologic features.

3.2.4 Detailed Investigations

Gravity-modeling studies in the South-Central Mid-Continent area involved modeling of geologic structures along the following five profiles (Fig. 3–21):

- Profile SEC1: A 378-km. N-S trending profile, modified from Rascoe (1986). The profile covers parts of Western Kansas and extends across the Hugoton Embayment and over the Central Kansas Uplift. The maximum sediment thickness along the section is about 1.5 km.



Profile SEC1 - A1 - A11
Profile SEC2 - B1 - B10
Profile SEC3 - N28, G2, N10, G4, G5, N11, F6, F8
Profile SEC4 - N28, G2, N10, N12, G3, G7, F6, F8
Profile SEC5 - N18, N17, N16, N27, G8, G7, N11, G6, F5, G9

Figure 3–21 Base map with locations of cross-sections used in gravity modeling.

- Profile SEC2: A 270-km. NW-SE trending profile, modified from Wells (1986). The profile covers parts of southern Nebraska, northeastern Kansas, and western Missouri. It extends from the flanks of the MRS, across the Forest City Basin, with maximum sediment thickness of about 1 km.
- Profile SEC3 and SEC4: These are about 300-Km long, approximately east-west trending, arcuate profiles. They cover parts of northeastern Kansas and western Missouri and extend over the MGA/MRS, the Nemaha uplift-Humboldt Fault system, and across the Forest City basin, with maximum sediment thickness of about 1.2 km. The profiles join, and share the same well data at the ends, although they follow different courses in the middle. Although the profiles are very similar, each was modeled independently to get a better idea about the MGA/MRS and the Nemaha Uplift - Humboldt fault system.
- Profile SEC5: A 314-km southwest-northeast trending profile covering parts of northeastern Kansas and northwestern Missouri. This profile covers the central part of the Forest City basin, with maximum sediment thickness along the section being about 1.3 km.

3.2.5 Modeling Results and Interpretations

These cross-sections were modified and additional structural details were added from other published sources (Bennison 1986). The topography and composition of the basement were modified using data from various published sources (Sims 1986) as well as by using gravity and magnetic anomaly data. The density values assigned to the different lithounits were obtained from density logs, as well as from various published sources (Crain 1986; Dobrin and Savitt 1988). Table 3–4 shows the density values used in modeling these profiles.

Table 3–4 Density values used for different geologic units in gravity modeling.

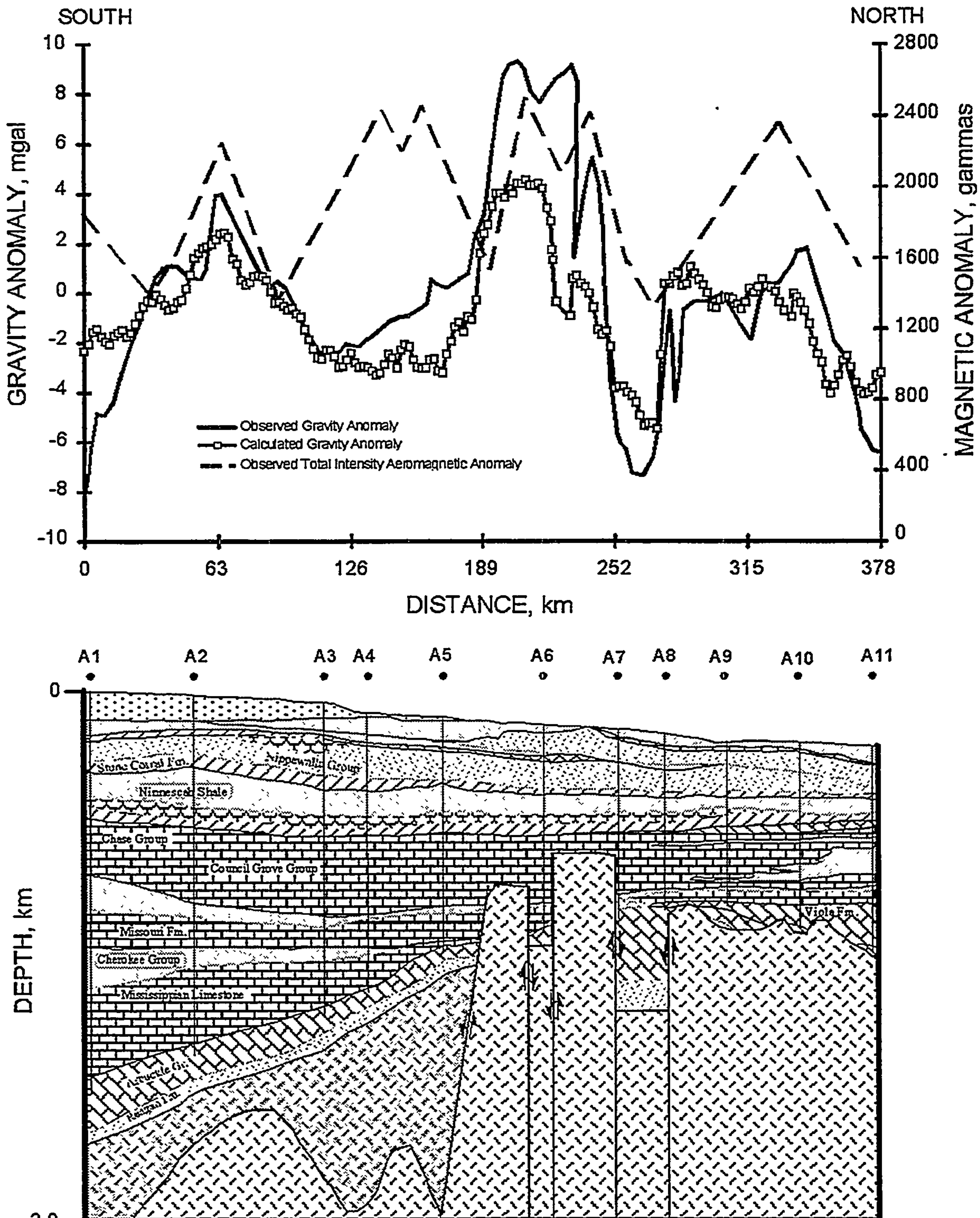
Units	Rock Types	Bulk Density, gm/cm3
Alluvium	soil, gravel	1.93
Salt	salt	2.164
Nippewalla Group	sandstone	2.3
Stone Corral Formation	anhydrite	2.32
Ninnescah Shale	shale	2.44
Chase Group	shale	2.44
Council Grove Group	shale, limestone	2.59
Admire Group	limestone, shale	2.6
Wabunsee Group	shale, limestone	2.59
Virgilian Shale	shale, limestone	2.59
Missouri Limestone	limestone	2.6
Pleasanton Group	shale, sandstone	2.35
Marmaton Group	shale, sandstone, limestone	2.44
Cherokee Group	sandstone, shale, limestone	2.6
Mississippian Limestone	limestone	2.6
Kinderhookian Shale	shale	2.44
Hunton Group	dolomite	2.77
Maquoketa Shale	shale, dolomite	2.77
Viola Formation	dolomite	2.77
Simpson Group	sandstone	2.44
Arbuckle Group	dolomite	2.77
Reagan Formation	arkose	2.3
(Precambrian) Arkose	arkose	2.3
Granite	granite	2.8
Granite Schist	granite schist	2.65
Granodiorite	granodiorite	2.9
Basalt	basalt	3.2

Along Profile SEC1, the basement is modeled to be heterogeneous. It is assumed to be a granitic basement intruded along old faults by large granodiorite batholiths, some of which have penetrated into the overlying Paleozoic sediments (see Figs. 3–22 and 3–23). Small graben-like features filled with Early Paleozoic sediments may be present along the crest of the Central Kansas Uplift, as indicated by abrupt changes in the gravity-anomaly values. This model of the basement lithology is in agreement with the basement lithology map for the Mid-Continent area compiled by Chenoweth (1987).

Along Profile SEC2, the basement is modeled as a heterogeneous complex (see Fig. 3–24). In the northwestern part of the section, the basement is inferred to be basalt/gabbro, part of the Mid-Continent Rift. This inference is supported by high values in the aeromagnetic anomaly profile. Further to the south, the basement is modeled as granite and granite schist, with granodiorite plugs. Supportive evidence for the presence of these intrusives comes from the corresponding aeromagnetic anomaly profile which shows the several sharp spikes, which are taken to indicate the presence of igneous intrusives with high magnetic susceptibilities.

Along SEC3 (see Fig. 3–25) and SEC4, the basement is modeled to be lithologically heterogeneous. The MGA, which appears as a sharp peak in the western part of both the gravity and aeromagnetic profiles, is modeled as a body of dense basalt with a specific gravity of 3.2. The gravity lows to either side of the MGA are modeled as representing substantial thicknesses of Precambrian arkosic rocks, part of the Rice Formation. This model generally agrees with the more detailed model of the MRS proposed by Woelk and Hinze (1991) and is supported by basement lithology data presented by Berendsen and Blair (1992). To the east of the MGA on this line, the Nemaha Ridge-Humboldt fault system is modeled as a series of fault-bounded basement blocks with varying amounts of relative displacement. The Nemaha Ridge, which was uplifted between Early - Late Mississippian (Steeples 1982) caused uplift and erosion of most of the Pre-Mississippian sedimentary rocks, although sections of Lower Paleozoic rocks may be preserved in small grabens within the complex fault system. Subsequent deformation and uplift of the Nemaha Ridge is thought to have taken place at a much slower rate. This is indicated by gentle drape folding of the younger sediments over the Ridge. In the central and eastern part of the profiles, the basement is modeled as granite with granodiorite intrusives. Supportive evidence for the presence of these intrusives comes from the corresponding aeromagnetic anomaly profile, which shows the presence of several sharp spikes. Again, these spikes are taken to indicate the presence of igneous intrusives with high magnetic susceptibilities.

Along SEC5, the basement is modeled as being less heterogeneous. In this region the model indicates partly granite and partly granodiorite, with granite schist found along the western part of the profile (see Fig. 3–26). This model of the basement lithology is in agreement with the basement lithology map for the Mid-Continent area compiled by Chenoweth (1987). The basement surface is modeled to show significant relief due to erosion. Small graben-like features filled with Early Paleozoic sediments may be present towards the western part of the section, as indicated by abrupt changes in the gravity anomaly values.



Cross-section based on Plate 32, *Petroleum Geology of the Mid-Continent*, Tulsa Geological Society Sp. Pub. no. 3

Figure 3–22 Gravity-magnetic profile along SEC1.

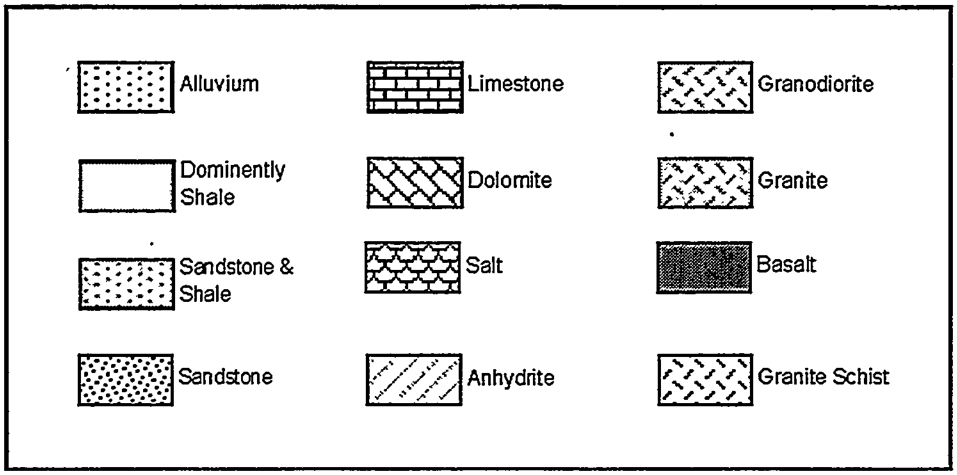


Figure 3–23 Lithologic symbols used in gravity-magnetic models.

3.2.6 Summary and Conclusions

Modeling studies indicate that the Precambrian basement in the study area is lithologically quite heterogeneous. It consists of granite, granodiorite and granite-schist. The basement surface in some areas indicates significant relief due to erosion.

The central part of the study area is cut by the Proterozoic, Keweenawan MRS, which is filled with high-density mafic rocks and associated sediments. This area is structurally quite complex. To the east of the MRS, the Nemaha Ridge-Humboldt Fault system is modeled as a series of fault-bounded basement blocks with differing amounts of relative displacement. Uplift and erosion has removed most of the Pre-Mississippian sedimentary rocks, including Keweenawan-aged rift-flank sediments, in this area, although sections of Lower Paleozoic rocks may be preserved within the grabens in the fault system.

Small graben-like features filled with Early Paleozoic sediments may also be present in the deeper parts of both the basins. These have the potential to hold yet unexplored reserves of oil and gas.

While the results of gravity-magnetic modeling studies in this area provided non-unique interpretations of the subsurface geology, none-the-less, they yielded important information about the basement structure and the composition of the basement rocks.

The modeling could be further constrained through the use of additional hard information such as core and seismic data, if it becomes available. A practical approach to further utilize the gravity-magnetic modeling process in this area would be to model the unexplored parts of the basin using the density values identified in the explored parts of the basins. However, these density values should be considered only as the first good approximation of actual density variations in undrilled parts of the basin, with a high potential for further refinement.

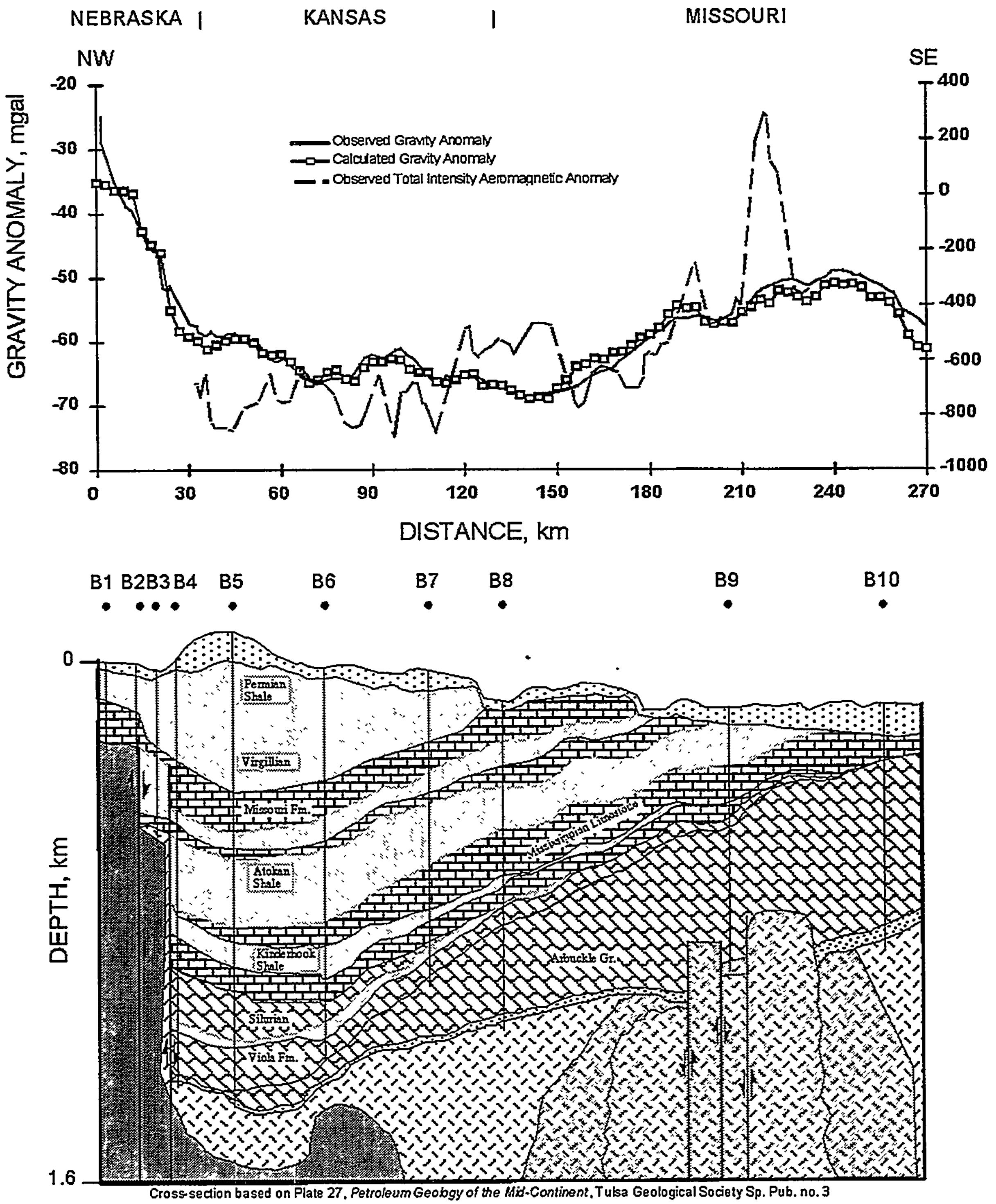


Figure 3–24 Gravity-magnetic profile along SEC2.

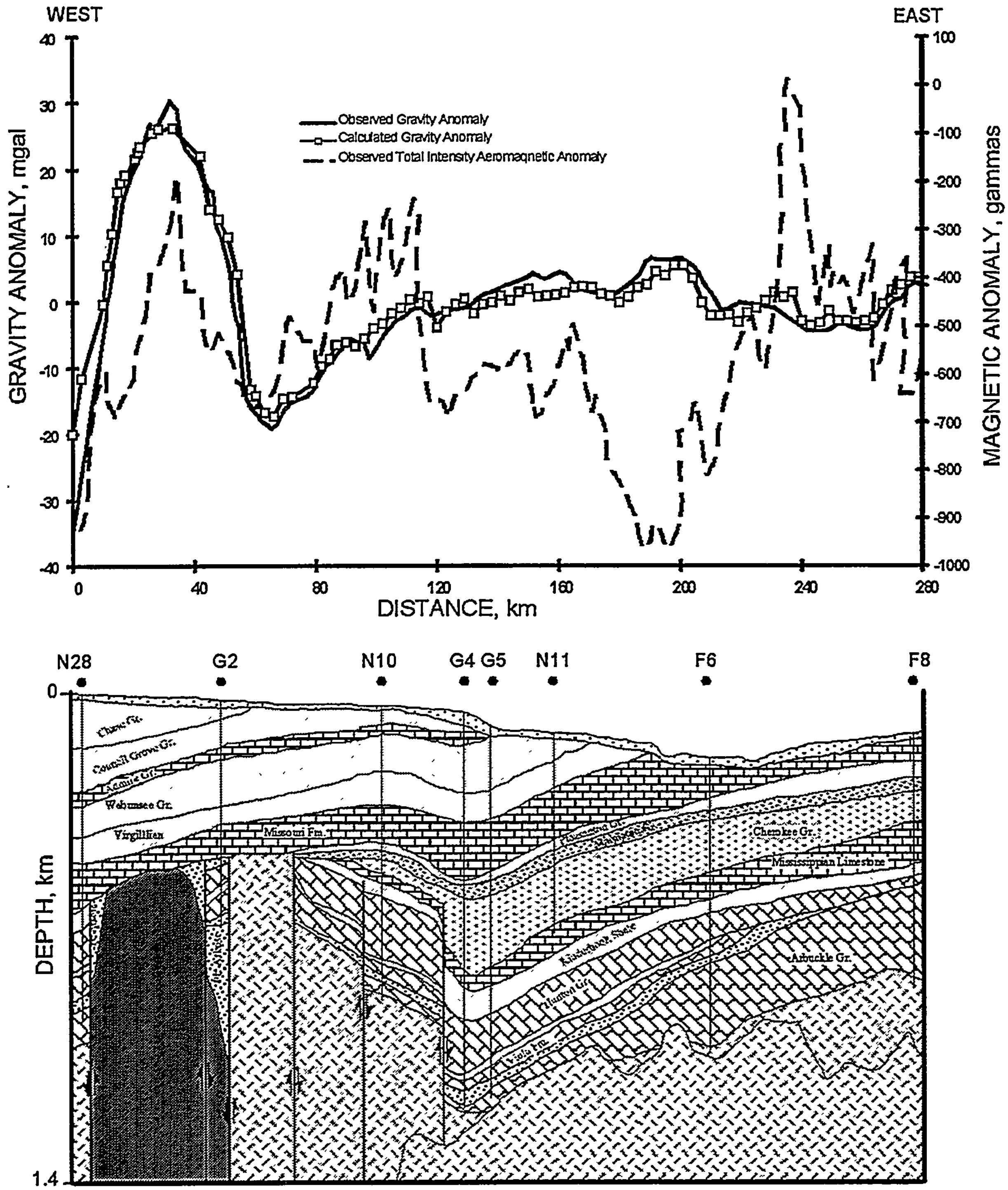


Figure 3–25 Gravity-magnetic profile along SEC3.

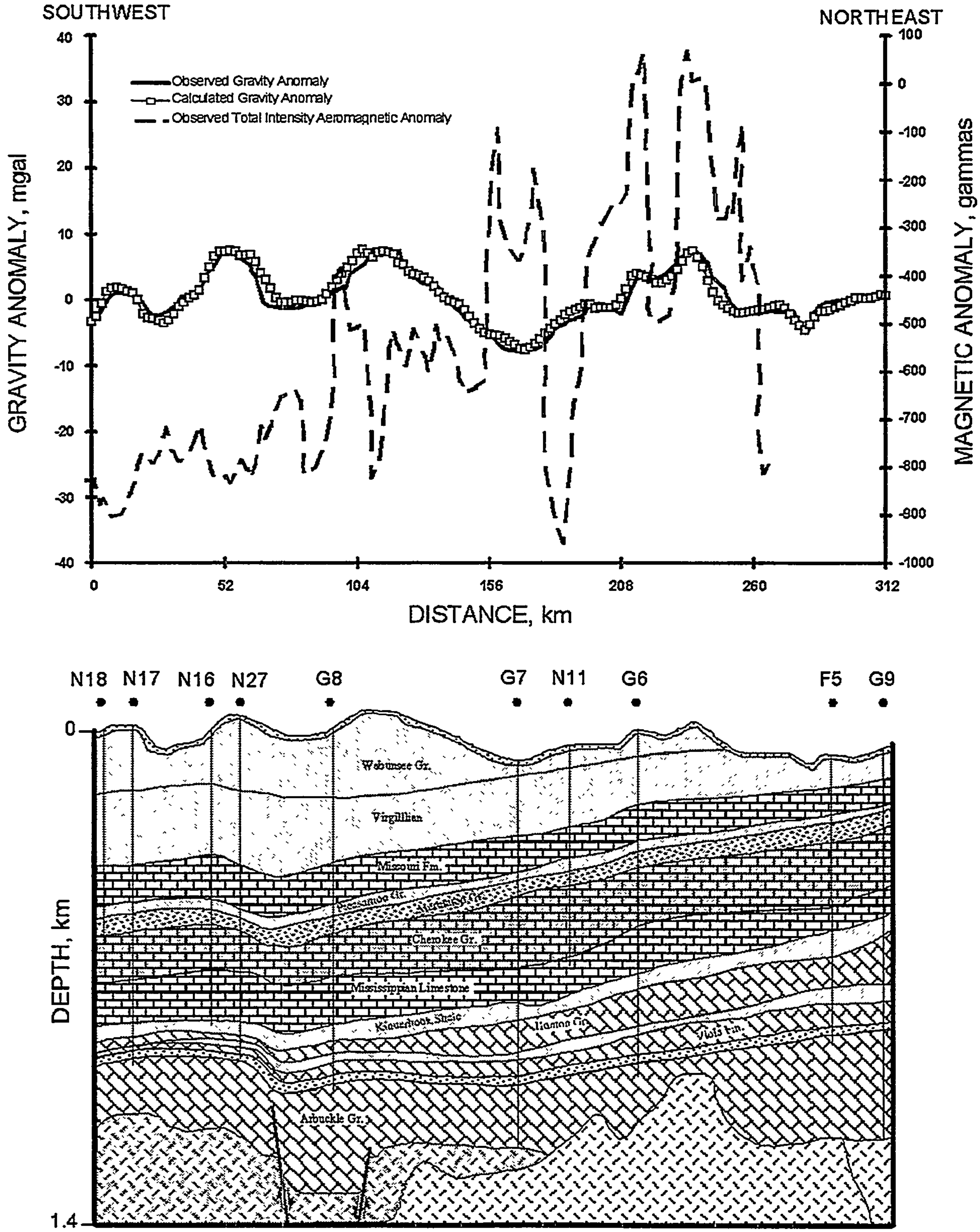


Figure 3–26 Gravity-magnetic profile along SEC 5.

3.3 High-Resolution 3-D Seismic Survey

Seismic surveys have been a key exploration technology within the US for decades. A primary element within the exploration technologies portion of the South-Central Mid-Continent program was research on high-tech, 3D, state-of-the-art, seismic survey design, parameter selection, and innovative approaches to interpretation.

A seismic field test program was planned for the South-Central Mid-Continent study region. A test area in Osage County, Oklahoma, was selected. This site was on tribal land, allowing the 3D-test program to combine with and further the goals of the President's Native American Initiative, advancing two goals with a single program.

3.3.1 Objective

The objective of this project was to demonstrate the newer capabilities of state-of-the-art 3D techniques for imaging small structures, thin reservoirs, stratigraphic pinchouts, and other subtle traps. The project goal included determining the cost-effectiveness of current survey techniques and procedures as a prospecting tool for the smaller independent geological/geophysical exploration company.

DOE had made the decision to determine the capabilities, costs and effectiveness of conducting 3D seismic surveys in a small operator setting and to examine in detail the economics of conducting such a survey. With these objectives in mind, it was initially decided to follow typical small operator practices in the 3D seismic field test. In keeping with this goal, the seismic interpretation was done using BDM personal computers, rather than using a large-company workstation approach. The hardware and software requirements for loading and interpretation of the data were designed and selected with the small independent operator in mind.

As has been mentioned, the Osage County location was chosen, in part, to further the goals of the President's Native American Initiative. This initiative is designed to encourage entrepreneurial activities on tribal reservations and other Native American lands. Osage County is largely Osage tribal land, and has had a long history of shallow oil production. Small independent companies are operating many of the wells in the area. An important aspect of the program was the strict adherence in the work to all Osage Tribal Council rules and local environmental regulations. While the 3D seismic survey was conducted to the south of the basin modeling cross section, which ran to the north, through Kansas, the added value of working on Native American lands and proximity to BDM offices outweighed considerations of working nearer to the Salina or Forest City basins.

The BDM Petroleum Technologies program for the 3D-field test was designed to develop and demonstrate new and innovative techniques for the smaller independent exploration or development company. The techniques could assist in the search for thin, shallow targets. The approach would use state-of-the-art data acquisition, processing and interpretation technologies, and identify areas of potential cost savings in the design and implementation of such a survey. Recent technological innovations in 3D seismic technology have made it possible to image subtle geological features in structurally and stratigraphically complex areas that may contain significant accumulations of hydrocarbons.

The 3D seismic field test was designed to accomplish the following seven specific tasks:

1. Design a model field test program using parameters and a scale appropriate for small operators or other independents, including Native American nations
2. Field-test the design
3. Test and evaluate the potential of the newest equipment and state-of-the-art parameters to image thin beds and subtle hydrocarbon traps
4. Develop new and innovative seismic interpretation technologies for use in identifying shallow exploration targets
5. Assess the efficiency, effectiveness, and economics of the survey design, processing, and interpretation from the point of view of a typical small operator
6. Transfer the results of the survey to Osage tribal representatives with the objective of encouraging additional energy development on Native American land
7. Transfer information on the innovations in the survey design technology, parameters, and interpretive methodologies to independent operators

3.3.2 Project Description

Details of the history, process, and results of the 3D seismic program can be found in Reeves et al, 1998.

A series of geologic studies was done of a series of areas within Osage county. This work was done prior to the start of the 3D seismic program. The goal was to identify good prospects with a high potential for oil or natural gas reserves. The effort included fracture and lineament studies, as outlined in Section 3.4 of this report.

The plan was to use one of the identified prospects as the study area and to shoot a conventional 3D seismic survey in the area, using parameters typical of a small, independent operator. This program was designed, in part, to increase interest in the region by independents, and to stimulate exploratory activity on Native American lands. The program was exceptionally successful in stimulating interest in the study area. The effectiveness of the publicity campaign almost ended up dooming the entire program.

Information on the potential prospects was conveyed to the Osage tribe, and the BDM publicity office and the Technology Transfer group released information on the program and its goals. Following this publicity, several operators, led by Chevron, moved into the county and began obtaining leases from the Osage tribe. They obtained permits for seismic operations covering the entire western half of the county, as well as several blocks in the eastern half. It turned out that all of the prospects developed during BDM-Oklahoma work were leased by the tribe to these other operators, bringing revenues to the Osage tribe and providing employment in the area.

Ultimately, three major surveys were conducted in the county, as well as several minor studies. All of the original potential prospects were taken by the time the DOE 3D program was ready to proceed, and several new sites that were quickly developed also were leased by the time BDM approached the tribe for permission to shoot in those areas.

Eventually, an arrangement was negotiated with DLB Oil and Gas, Inc., of Oklahoma City, one of the independent operators that followed Chevron into the county. This arrangement worked out to be a much better test and demonstration project for DOE than the simple, conventional 3D survey that had originally been planned.

DLB had planed to shoot a 16-mi^2 prospect in the Bigheart area, just northeast of Hominy, Osage County, Oklahoma, using a standard set of 3D parameters. BDM Petroleum Technologies personnel revised the original plans for a "conventional" 3D survey, and instead made arrangements with DLB to piggyback a redesigned, much more innovative high-resolution survey on top of the already-planned survey. The high-resolution work was to take place in a 6-mi^2 area in the northwest corner of the DLB prospect. The 3D-survey area (see Fig. 3–27) forms an irregularly shaped block in parts of Townships 22 and 23 North, and Ranges 9 and 10 East.

DLB was going to be using a "typical" set of parameters and layout for an independent operator, similar to those originally planned for the BDM DOE survey. The DLB design included 110-ft bin sizes (220-ft line spacing). The revised BDM Petroleum Technologies survey was designed to be shot at higher resolution, with a 55-ft bin size (110-ft line spacing). The two techniques were combined in the test area, with 55-ft bins superimposed on the 110-ft bins for the 6 mi^2 in the extreme northwest portion of the DLB lease area.

The objective of collecting data with 55 ft bin size was to see if the close scanning of the sub-surface could provide capabilities to image very subtle structural and stratigraphic features that are important for oil and gas exploration. Another important factor under consideration was the cost aspect of collecting data with different bin sizes keeping small independent operators in mind.

The new, innovative approach allowed a direct comparison of data quality for the two different bin sizes over precisely the same survey area. The objective became to determine if reducing the bin size from 110-ft to 55-ft, while keeping all remaining field and recording parameters the same, would provide sufficiently improved resolution to justify the extra cost. It was assumed that the high-resolution survey would allow the mapping of subtle geological features, but it was uncertain just how much the imaging capabilities would improve.

Extensive work was done for the survey design and to select field parameters, as well as the standards for the processing (Reeves et al, 1998, in press). The interpretation of the 3D data was initiated by investigating certain important characteristics of the data. Special attention was paid to evaluating the imaging capabilities of data collected with the 55-ft and 110 ft bin sizes. The high-resolution capabilities of the Osage 55′ bin 3D data were demonstrated in several ways.

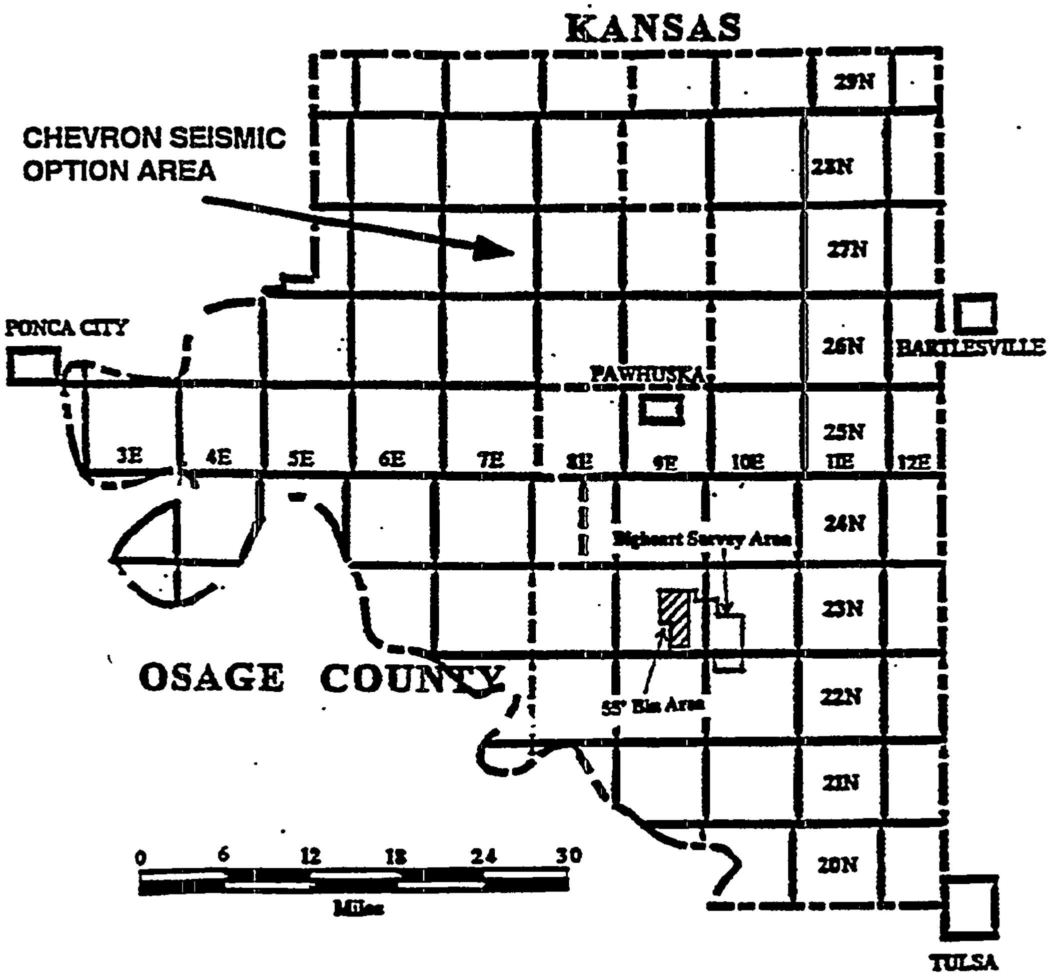


Figure 3–27 Map of the Survey Area in Osage County, Oklahoma.

The seismic data acquisition was completed using state-of-the-art equipment and a Vibroseis crew in February 1997 after vibrating a total of 5778 points. The field tapes were sent to Geo Trace Technologies Inc. of Dallas, Texas, for processing. The data from the field tapes were processed in the seismic data processing center to enhance the signal-to-noise ratio of the seismic data by the application of different data processing routines. All seismic reflections from within a certain area (called the 'bin') were averaged to represent the seismic data from the center of the bin. The final processed data were, therefore, represented by the averaged seismic traces from the various bins located throughout the seismic survey area. The 110-ft bin data involved averaging over an area four times the size or the 55-ft bin data.

The processed seismic data, ready for interpretation, were received during the last week of May and the first week of June 1997. The processed 3D data were prepared and shipped in a form that allowed the data to be loaded on BDM Petroleum Technologies desktop computers. 3Dpak software from Seismic Micro-Technology, Inc., of Houston, Texas was used for the interpretation process. This was a software package representative of what could be cost-effectively used by a small independent operator.

The last step before the actual interpretation of the 3D seismic data was the loading of the large volume of processed 3D data from the 55-ft bin and the 110-ft bin surveys onto the desktop computer. The data installation was fairly straightforward but precautions were taken to ensure that the computer had adequate disc storage space. For the two surveys in Osage County, about 600 MB of storage space was required for the data alone.

System requirements for the computer included at least 16 MB of RAM and a math processor. The actual desktop computer used at BDM Petroleum Technologies was a Pentium Pro with 6 GB of hard disc space and 64 MB of RAM.

3.3.3 Data Interpretation

The vital first step in the interpretation of seismic data is the identification of the various reflections on the seismic section. This correlation of seismic reflection with geology can best be done through the use of synthetic seismograms generated from sonic and density logs.

Generation of Synthetic Seismograms

Synthetics were generated at various well locations using sonic, density, gamma ray, neutron and resistivity/induction well logs obtained from the log library maintained by the Bureau of Indian Affairs at Pawhuska and the Oklahoma Well Log Library at Tulsa. Besides well logs, production data and well completion reports were also collected.

14 sonic logs from the study area were digitized. ProMAX seismic processing software, loaded on a BDM Petroleum Technologies Sun Workstation, was used to generate synthetic seismograms for these wells. The synthetic seismogram from the Millsap #1 well, which was extensively used in our studies, is shown in Fig. 3–89, NIPER/BDM–0338.

Various techniques were experimented with for the generation of synthetics. Note that the synthetic (Fig. 3–89, NIPER/BDM–0338) generated with a 100Hz Ricker wavelet (where 100 Hz is the central frequency of the Ricker wavelet) shows much finer stratigraphic detail than a synthetic generated using a 40 Hz signal (Fig. 3–90, NIPER/BDM–0338).

Several key producing formations (including the Bartlesville sandstone and Arbuckle dolomites) and distinctive marker beds (like the Woodford shale) were identified on the seismic sections from available synthetic seismograms. These seismic reflectors were mapped along inlines and crosslines, forming a closed loop to ensure that the starting and the ending reflectors matched.

Once the data were loaded, and the synthetics had been generated, a series of conventional and innovative approaches were taken in the interpretation phase of the work.

Identification of the Bartlesville Sandstone Reflector

In this part of Oklahoma, the Pennsylvanian-age Bartlesville Sandstone has been the most prolific producer of oil and natural gas in most areas. Figures 3–28 and 3–29 show the location of the Bartlesville sandstone within the stratigraphic column, along with the sonic and gamma-ray signatures of this reservoir for the Bobby Gray-136 well.

The trends identified on the Bartlesville map explain the locations of many of the old oil fields scattered across the study area. Most of the abandoned wells and still-active strippers were drilled in areas with good Bartlesville sand development.

Identification of the Layton Sandstone Reflector

A second common drilling target in the study area has been the Layton sandstone. This unit was also mapped from the seismic data. Figure 3–84, NIPER/BDM–0351 shows the geologic structure at the level of the Layton sandstone. The contours have been drawn at 2-m-sec intervals.

3.3.4 Detailed Investigations of the Seismic Data

The interpretation work by BDM Petroleum Technologies began with a "bottom up" approach, looking at the basement, including deep structure and faulting trends. The deep Lower Paleozoic sediments were then studied to identify how fundamental tectonics and relief on the initial Paleozoic depositional surface influenced sedimentary patterns and the stratigraphy in the region. This was done to identify new potential reservoirs, in the deep and shallow sections.

Basement Structure and Tectonics

The seismic data from the entire 16.75-mile^2 110′-bin survey area in Osage county were interpreted to generate a structure map for the top of the seismic basement reflector. The two-way reflection times to the top of the basement reflector were obtained by extrapolating the two-way times at one of the deeper wells (the Millsap #1) that penetrated the top of the Ordovician-aged Arbuckle formation. The reflector times were cross-checked against sonic logs from other wells in the survey area.

The identification and mapping of seismic basement was relatively simple in the north and central parts of the study area because the basement reflector in this area is generally quite strong, with relatively little tectonic activity. In the southern and southeastern parts of the study area, however, the identification and correlation for the seismic basement reflector is much more difficult, due to the much larger number of faults that cross that area.

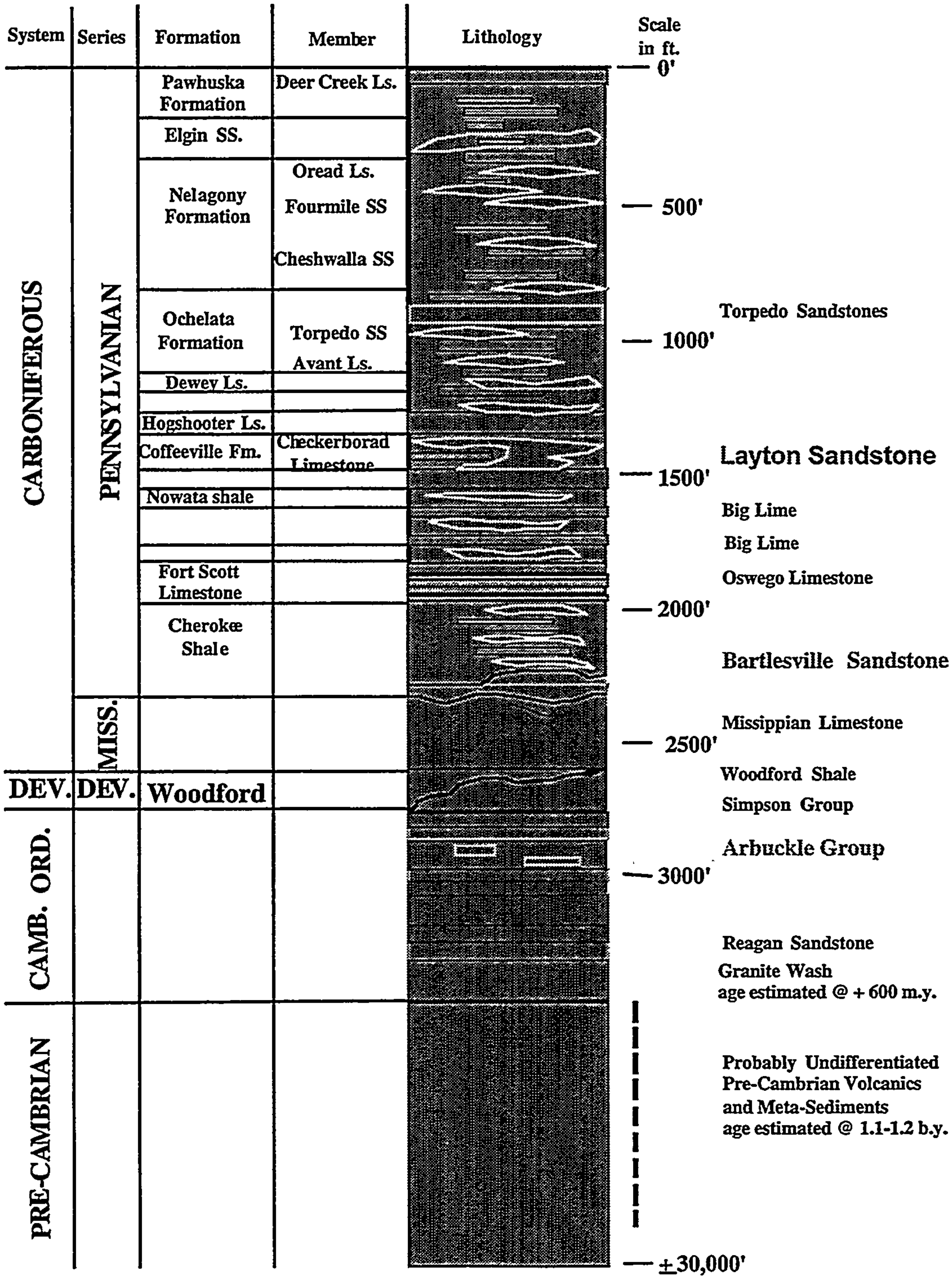


Figure 3–28 Representative Stratigraphic Column for Osage County.

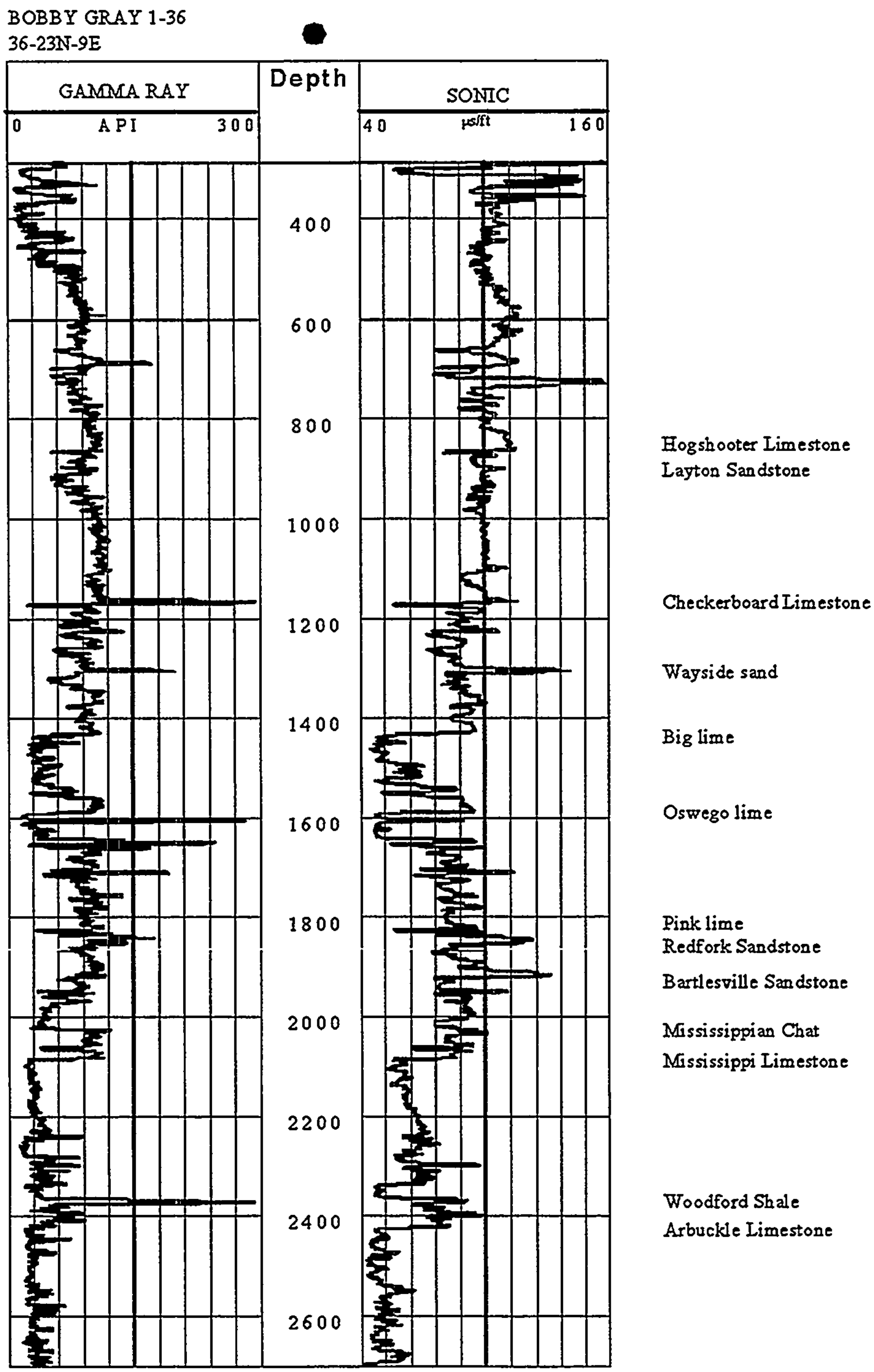


Figure 3–29 Representative Sonic and Gamma Ray Logs Showing the Tops of the Important Reflectors.

Figure 3–30 shows the faults that affected the basement surface in that region. The fault traces have been superimposed on the structure map. As can be seen on this map, two directions of faulting predominate in the study area:

- one trending northwest-southeast,
- the other trending northeast-southwest.

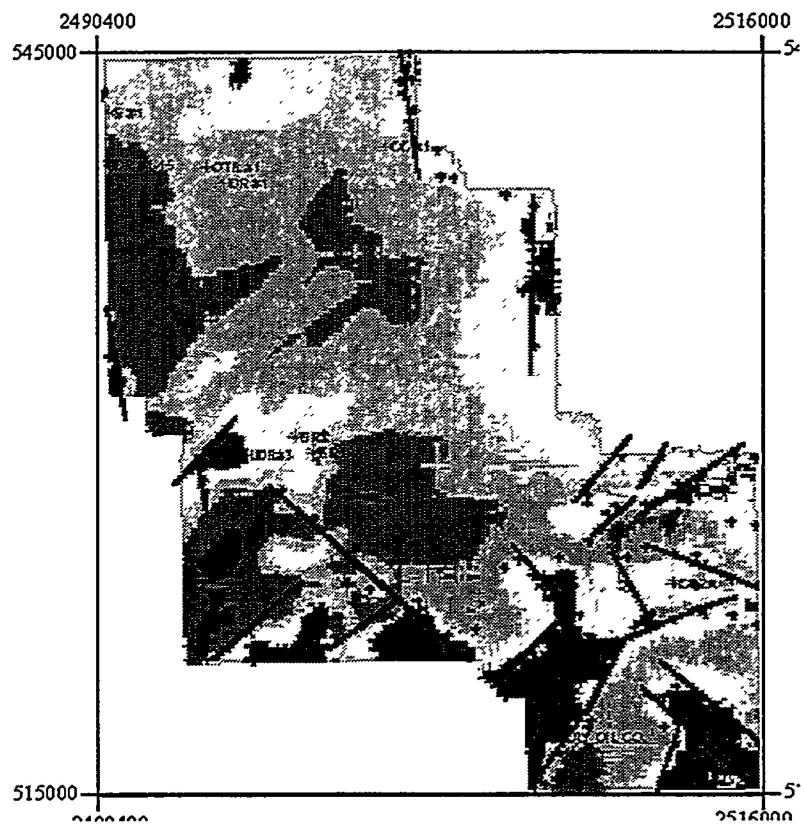


Figure 3–30 Interpreted Seismic Basement Time Map, with Overlay of Faulting.

Fracture and Lineament Studies

Information on surface and subsurface lineaments and fractures was interpreted by BDM Petroleum Technologies personnel, using satellite images and aerial photographs of the Osage County study area, as will be discussed in the following section, 3.4. The results from this work were carefully integrated with the seismic interpretation studies, in a multi-disciplinary, synergistic approach.

This evidence strongly supports initial observations (NIPER/BDM–0223, March 1995), by BDM Petroleum Technologies personnel, of a strong association between shallow/surface linear features and subsurface oil and gas traps in northeastern Oklahoma. Similar associations were found in the Oklahoma Panhandle, and the Denver and Forest City Basins. It has been postulated that the fault systems have acted as loci for the development of oil and natural gas reservoirs in areas with good seal development. The accumulations apparently form in secondary porosity traps.

Observations on Structural Control of Hydrocarbon Accumulations

As has been mentioned above, the Layton sandstone was an early target for conventional seismic mapping. It soon became a favorite target for more-sophisticated, specialized studies. Figure 3–84, NIPER/BDM–0351 shows the geologic structure at the level of the Layton sandstone.

Regional structure contours indicate that the formation is generally monoclinal in the northern part of the study area, where several commercial-sized hydrocarbon accumulations have been identified. Field 1, Figure 3–31 , is typical of one of these Layton fields. There is a general, gentle easterly dip of about 70 ft/mi. across the northern portion of the study area. However, a close examination of the contours around the areas where gas accumulations have been encountered (see Figure 3–32) indicates that a series of minor disturbances or irregularities exists in the area. This pattern suggests the possibility that there may be minor structural influence on some of the stratigraphic accumulations.

Mapping of a Layton Sandstone Channel

Results of attempts to map meandering Layton sandstone channels, using the 55′- and 110′-data, respectively, are shown in Figures 3–33 and 3–34, respectively. The results from this work included some of the most dramatic results from this project. The original work was done using a color display on a computer monitor. A wide range of color options and varying cutoff values were available. For publication purposes, gray scale displays had to be used.

The 110′-data shows very little of interest. Some generalized, formless areas of higher amplitude could be distinguished, but there was no single feature that jumped of the screen, or geologic sense to be made from the display. It was expected that the 55′-bin data would provide a much better resolution. This is due to the fact that the 110′ survey averages data over an area four times as large as the 55′ survey.

The change from the 110′- to the 55′-display was dramatic, a key finding of the research. When the 55′-bin data was initially displayed, the change was startling. With the higher resolution, the course of a meandering channel could be delineated. Varying the cutoff levels on the color display made it possible to increase the resolution still further. Ultimately, meanders and an overbank-splay deposit were identified. The shape of the splay stood out. Comparison of this 55′ plot and results from the Geo-Microbial Technologies microbial survey (see Chapter 6.0) show an extremely interesting correlation, suggesting that the splay, and part of the adjacent channel sand may be natural gas-saturated.

Seismic amplitudes appear to provide an excellent indicator of petrophysical properties within the Layton sandstone on the 55′-bin size data. Clean sand development can be identified in the area of the gas-productive Drummond 1–15 well. The reflector on the 55′-data there clearly shows high-amplitude seismic responses, compared to those seen in the area of the dry wells Osage Tribal Council #1 and Drummond #1, where the Layton is clayey and has much poorer petrophysical properties, in terms of reservoir quality.

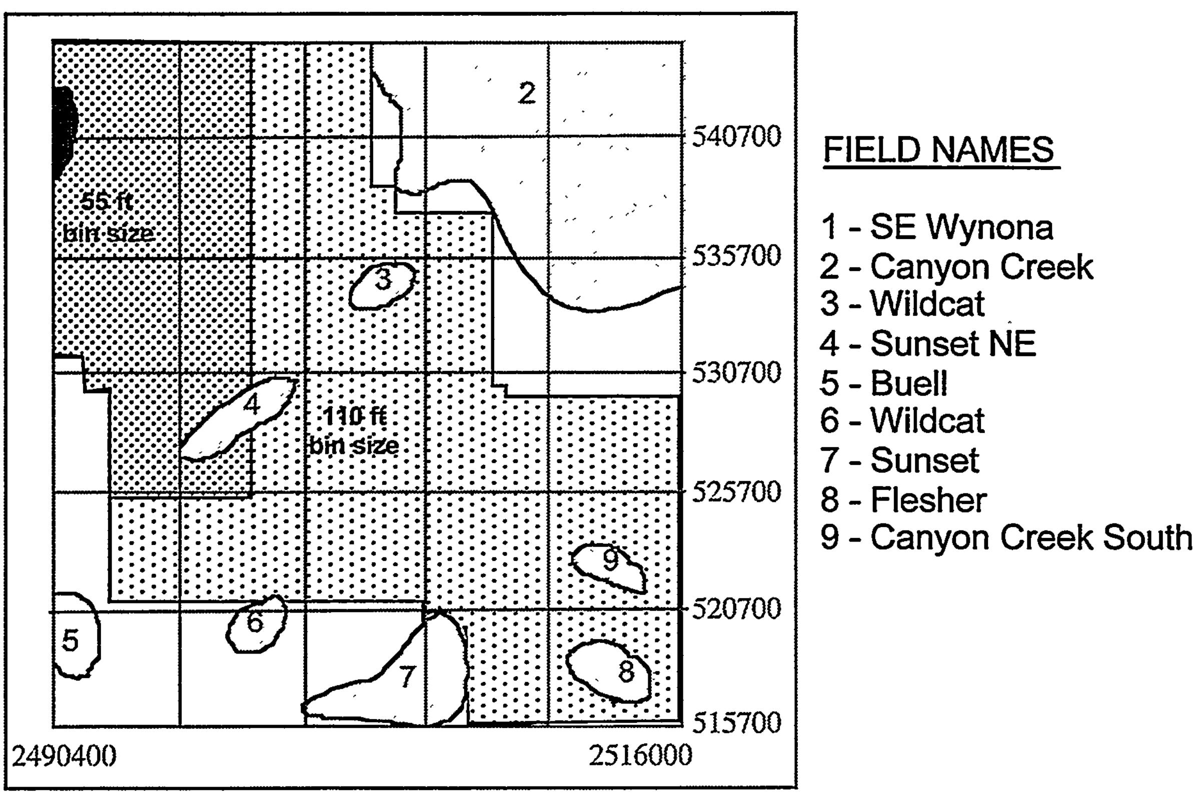


Figure 3–31 Oil and Gas Fields in the Osage County 3D Survey Area.

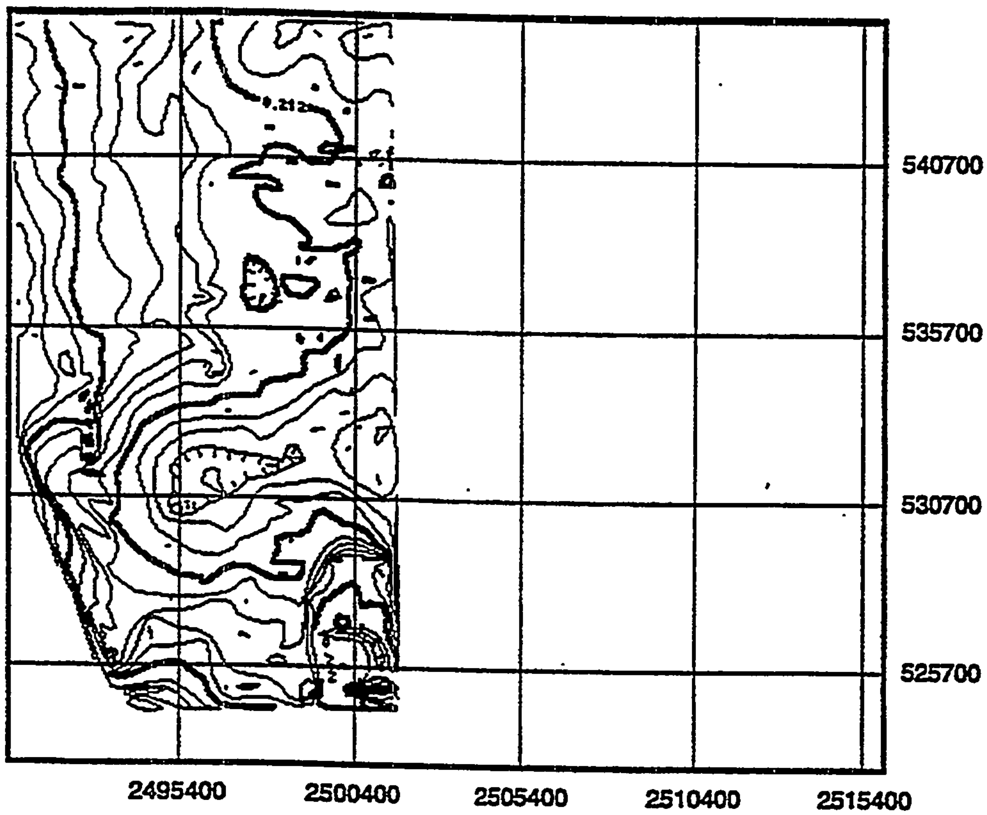


Figure 3–32 Structural Contours on the Top of the Layton Sandstone.

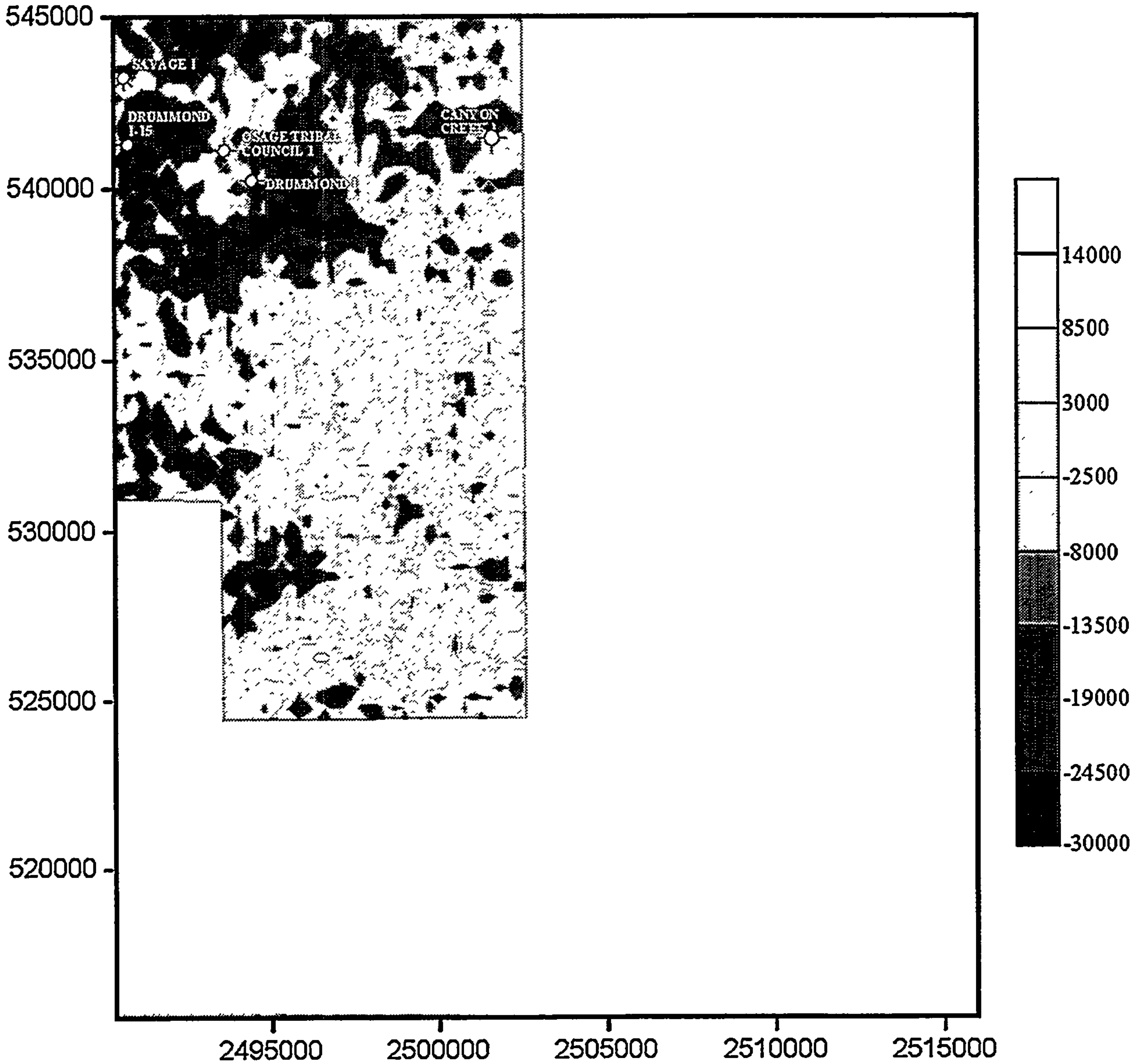


Figure 3–33 Seismic Amplitude of Layton Sandstone ,using 55-ft bin data.

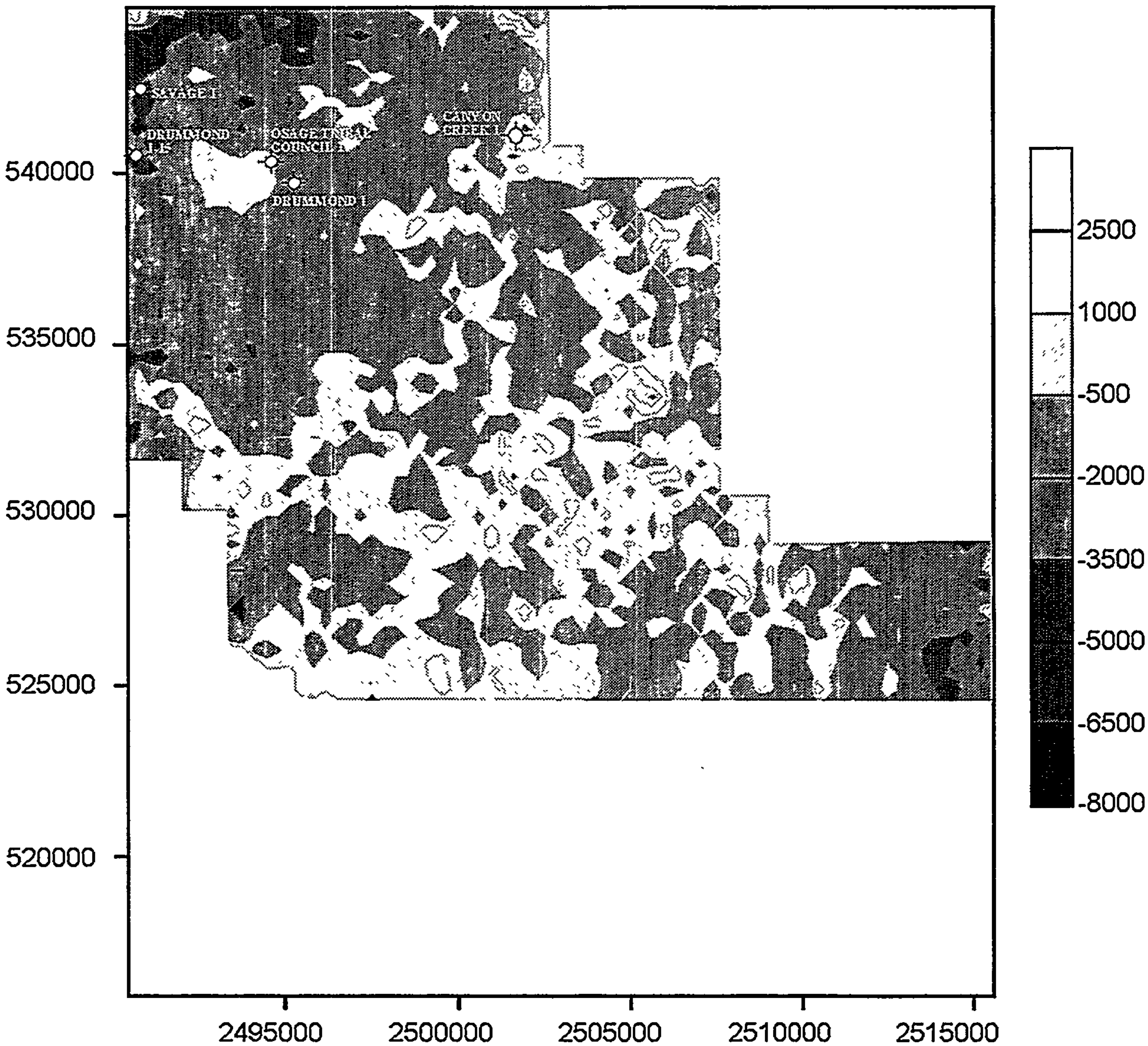


Figure 3–34 Seismic Amplitude of Layton Sandstone, using 110-ft bin data.

3.3.5 Innovative 3D Seismic Interpretation Techniques

Several innovative approaches were taken to the interpretation of the Bigheart survey.

Methodologies for the Detection of Lateral Variations in Fluid Saturation

Multiple innovative, sophisticated studies were undertaken of the characteristics of the seismic waves from this survey, as part of this study.

Innovative Studies to Track a Thin Gas Sand in Osage County

The value and potential of using high-resolution seismic data as an exploration tool was tested by tracking a thin gas-saturated sand in Osage County from a productive to an unproductive area. The sand under investigation was the Pennsylvanian-age Layton sand, encountered at a depth of approximately 1100′. The Layton has widespread distribution in Osage county, and produces oil and gas in various parts of the county. The objective of this investigation was to determine if there was a systematic way that could be developed to explore for the type of subtle stratigraphic features that are known to occur within units like the Layton. Small pools within units like the Layton contain significant quantities of oil and natural gas at shallow depths.

The density/neutron log for the Drummond #1–15 well clearly shows a "gas effect" crossover through the gas-saturated portion of this sand. In this zone, the density curve gives very low readings, and crosses the neutron curve. The density curve shows these low-density values because the effective density of a gas-saturated sandstone is very low, compared to the same sandstone when the rock is solid or is filled with a denser liquid, like water or oil.

About a mile to the east of the Drummond #1–15 well, the Layton sandstone becomes shaley. In that area, the sandstone no longer shows the gas effect, because the open porosity has become clogged, filled with clay or shale. With the porosity filled, the sandstone has a relatively high density.

Figure 3–35 shows a series of density-log-derived porosities along an east-west section from the Drummond #1–15, where the Layton sandstone is clean, with good porosity development, to the Drummond #1 and Canyon Creek #1, where the Layton pore spaces are clogged with clay. The gamma ray logs from the Drummond #1 and Osage Tribal Council #1 show a "dirty" sandstone, clearly indicating that the Layton, which is clean in the Drummond #1–15, has become much more shaley to the east.

The 3D seismic program became, in part, an exercise to determine if the saturation change in the thin Layton sandstone could be detected from lateral variations in the character of the seismic reflector. Such changes might include a consistent amplitude change across the gas sand, from a reservoir area to a "dirty" area.

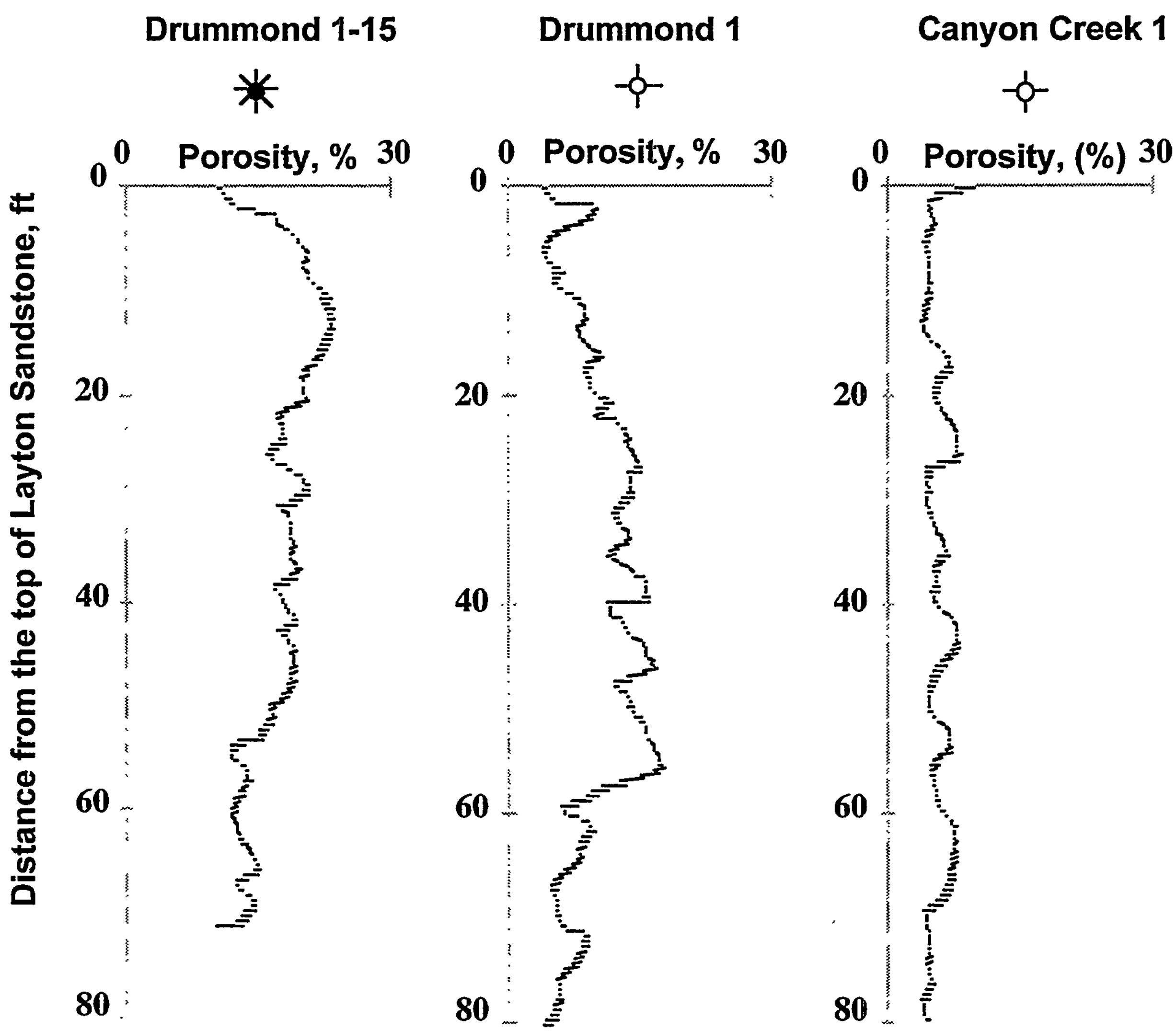


Figure 3–35 Log-Derived Porosity Profiles for Gas-Saturated and Dry Areas.

Amplitude Studies of the Layton Sandstone

The Layton sandstone varied from gas-filled and productive to clay-filled at various points across the study area.

Figure 3–36 shows a portion of Line 452 of the survey, from SP 1 to SP 78, between Times 0.19 sec and 0.35 sec. The traces shown include the reflector for the Layton sandstone (at Time approximately 0.225), as it passes from the gas-saturated portions of the reservoir to clayey parts. To the west (the left side of the figure, Traces 1–22), gas saturations are high in the Layton. The section clearly demonstrates high amplitudes in areas where the saturation of gas is high.

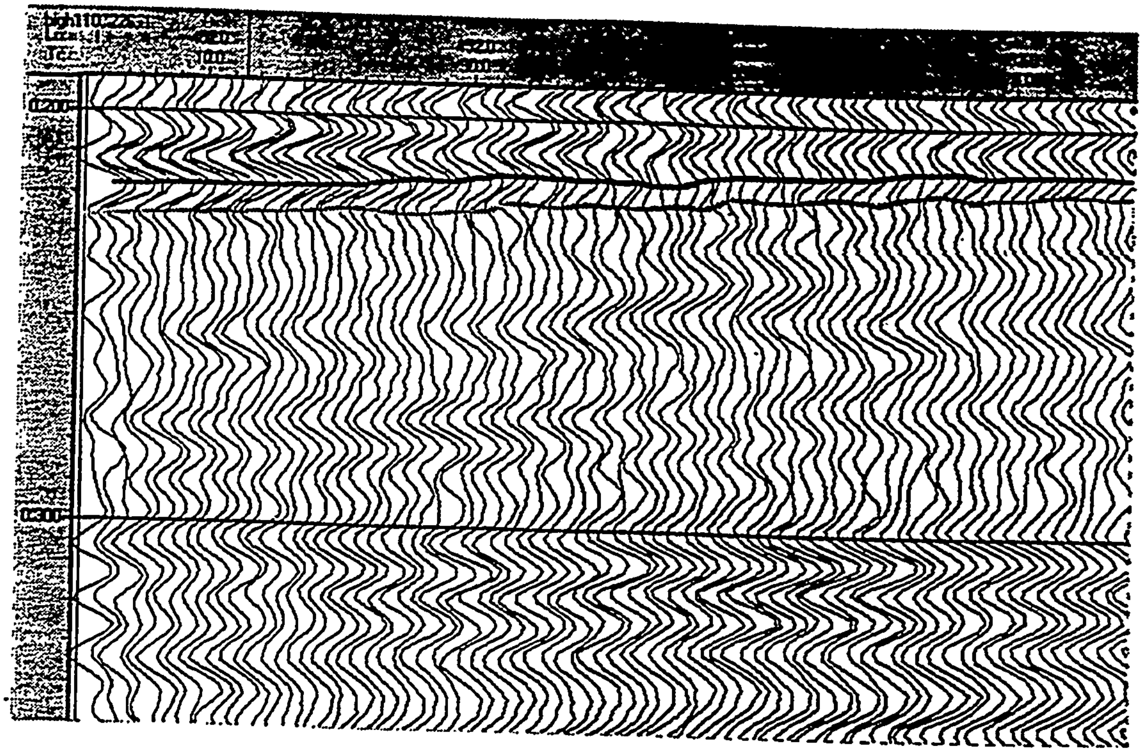


Figure 3–36 Wiggle Trace Display of the Western Portion of the Seismic Section along Line 452.

In other areas, (beginning around Trace 42, and extending to the east [right] to Trace 78) the amplitude is much lower. In areas where wells did not encounter any significant gas-saturation values or accumulations the seismic reflector amplitude values are quite low.

It was concluded that amplitude analyses could be one of the best tools described in this study.

It should be noted that because the Layton is such a thin sandstone unit (the zone with clean, high-porosity sands is only about 16′ thick), the top and the bottom of the formation will not be resolvable by a seismic reflected pulse. Nevertheless, it will be possible to identify a distinct negative excursion in the seismic wavelet from the target zone, due to the impedance contrast at the Hogshooter-Layton interface.

The amplitude of the negative reflection will be an indicator of the decrease in the velocity within the Layton sandstone. The velocity will decrease as gas saturations increase. Good petrophysical properties of the reservoir (a combination of high porosities and/or high saturation of the reservoir pore space with a low-velocity fluid, like gas) will contribute to an increased negative amplitude.

Statistical Time-Series Analysis of Amplitude Data

The characteristics of the entire seismic wave shape were studied, in addition to the studies of amplitudes at isolated points, already described. The powerful technique of Time Series Analysis was applied to the Osage County data.

Time Series and Spectra. All observed data can be classified as either deterministic or random. Deterministic data are those that can be described by an explicit mathematical relationship. Random data can be described only in terms of probability statements and statistical averages. The theory of time-series analysis deals with the measurement of products and properties of stochastic or random processes.

The yield from 70 consecutive batches (see Fig. 3–37) is a stochastic process because it fluctuates in a manner that makes it impossible to predict exactly the value of the next batch. Although future values for the batches cannot be predicted exactly, a forecast can be made of these future values, based on certain specific average properties of the Time Series. These are derived from statistical laws and models.

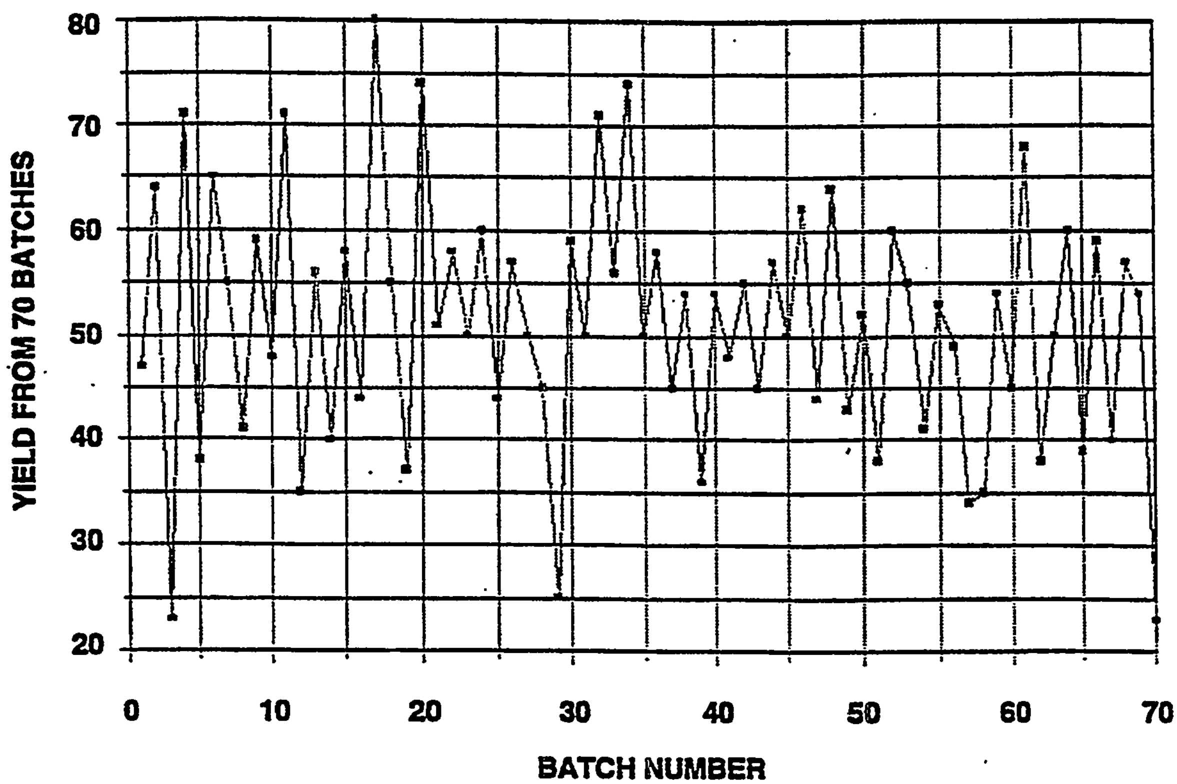


Figure 3–37 Fluctuating Yields from 70 Consecutive Batches.

A stochastic process may be adequately described by the lower moments (mean variance and covariance function, along with the Fourier Transform of the covariance function, the power spectrum) of its probability distribution functions. In other words, the stochastic process may be adequately described by means of a model containing a few parameters that may be estimated from the data.

Spectral Analysis of a Time Series. Spectral analysis brings together two very important theoretical approaches:

- the statistical analysis of Time Series, and
- the method of Fourier analysis.

Of the many branches of science and engineering where this powerful data analysis technique has found applications, its use in the development of information technology is, probably, the most significant.

The mathematical techniques of Fourier series analysis have found widespread applications because of the ease with which most periodic and aperiodic functions may be represented for further analysis by Fourier series.

Development of the Computer Program, SPECBDM, for Spectral Analysis of Geophysical Data. Time Series Analysis decomposes each reflected pulse into its Fourier components and then allows study of the character of the pulse as a function of its frequency content. A computer program called "SPECBDM" was developed at BDM Petroleum Technologies. This program can be used for spectral analysis of a Time Series, and for the computation of various statistical parameters in the frequency domain from the Time Series. The parameters include the Power Spectrum. The Power Spectrum is essentially the frequency distribution of the square of the Fourier amplitudes.

SPECBDM uses a filter to remove any trends from the data so that the Time Series will be truly stationary. It then proceeds to calculate the power spectra of the gravity and the magnetic series. It also computes a few other statistical parameters (such as the phase spectra) which may be useful for interpretation of gravity and magnetic data.

Application of SPECBDM in Osage County. Several Time Series were generated for data from Osage County by digitizing the seismic reflected waveforms at regular increments of time in gas-saturated and clayey portions of the subject Layton sandstone reservoir. The porosity profile across the Layton sand in the gas-saturated portion of the reservoir (see Fig. 3–35) was also digitized to generate a Time Series of the log profile.

The spectrum of the log profile has very similar characteristics to the reflected pulse spectra, indicating that the porosity in the reservoir is, at least partially, influencing the reflected pulse shape. In the unproductive, dry parts of the field, (Fig.3–38) the spectra for pulses 1 and 2 appear to be very similar to each other, but the spectrum of the third pulse is quite distinctive, and is probably an aberration, representing a highly-localized anomalous area. Alternatively, it could be a result of noisy traces.

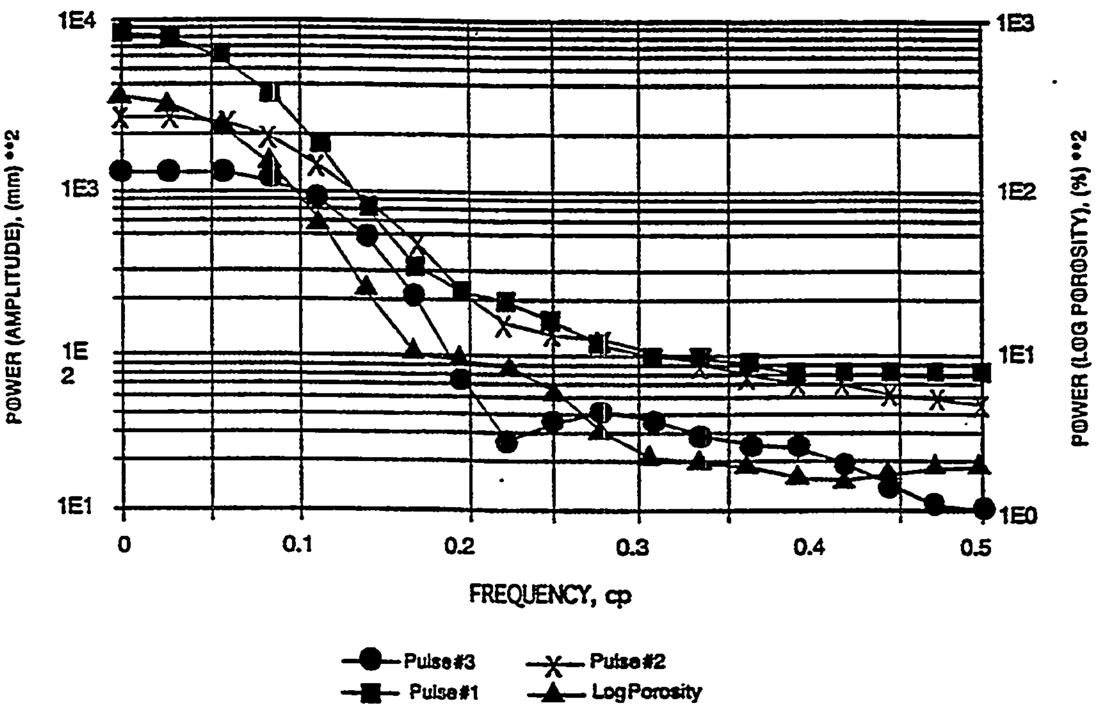


Figure 3–38 Power Spectra of Seismic Amplitudes of Three Seismic Pulses vs. Log Porosity from the Clayey, Non-productive Part of the Layton Sandstone.

A sharp drop in power at lower frequencies seems to be characteristic of clean, gas-filled portions of a reservoir. As the relative gas-saturation of a reservoir unit increases, the sharpness of the power attenuation theoretically should increase, because the impedance contrast across the interface between the reservoir unit and the enclosing units should also increase.

A careful examination of the waveform of the reflected signals across the region where the Layton gas sand is productive was quite instructive. Studies around locations where the sand is clayey and non-productive (to the east [right] of Traces 48 in Figure 3–36), already had indicated that there was a variation in amplitude over the gas-bearing portion of the sandstone. In addition, it was found that there was a change in the wave shape. This change was apparently due to a damping of the reflected pulse. This damping was probably caused by a reduction in porosity and attendant increase in velocity (see Fig. 3–39).

An increase in clay content (and an associated decrease in porosity) can be detected on the gamma ray logs in the Osage Tribal Council #1 and Drummond #1 wells (for the well locations, see Fig. 3–33) in the non-productive portions of the reservoir. Filling of the pore spaces with clay and a reduction in gas content will also increase sonic velocities in the sand, and, hence, will affect the shape of the reflected pulse. Density-log-derived porosities for the productive, gas-saturated; and the clayey, non-productive parts of the Layton reservoir are shown in Figure 3–35.

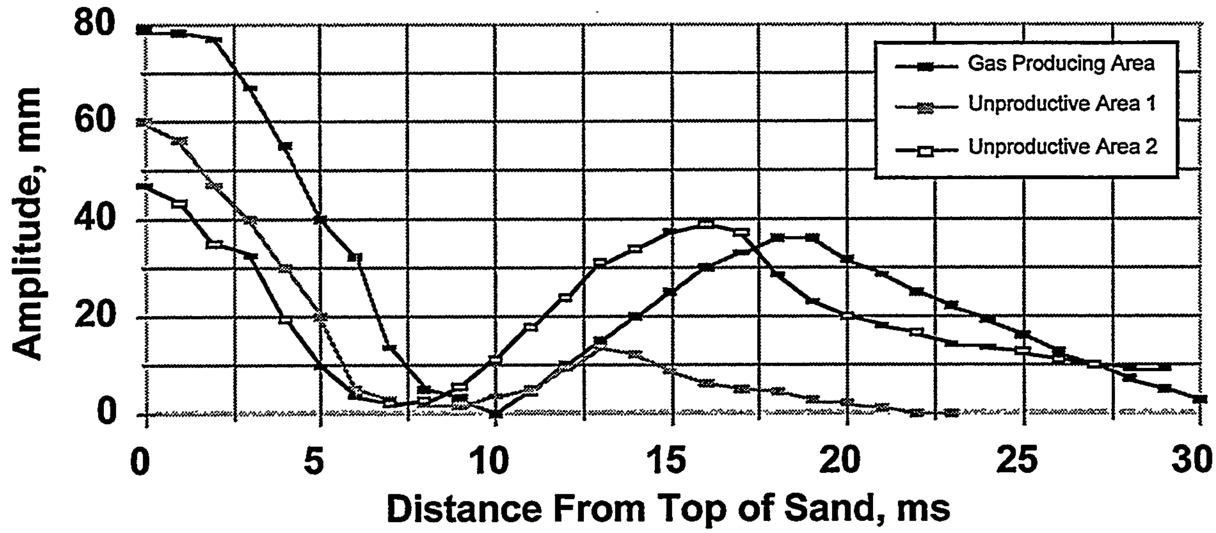


Figure 3–39 Wave Shapes of the Layton Reflector in the Gas-Saturated and Non-Productive Areas.

Utilization of the Display of Color to Emphasize Seismic Amplitude for the Identification of Subtle Features. While interpreting the Osage County 3D seismic data, it was found that the 3D seismic interpretation software provided powerful display and data manipulation tools. Techniques made available with the seismic-data interpretation software can greatly help in the investigation of subtle variations of structure and stratigraphy.

One example comes from the ability to adjust the color range of the display, to emphasize and analyze amplitude information contained in the seismic data. Key aspects of color include:

- amplitude variations represented by color gradations may be very useful in studying stratigraphic changes,
- adjusting the screen display of the seismic section by boosting or reducing the amplitude level can help significantly in the mapping of subtle geological features.

Boosting the amplitudes on a seismic section quite often helped in the identification and reliable mapping of fault traces.

Identification of small faults. The 55′-bin data clearly show two small faults along Line 516 at Time 0.44-seconds, Traces 128 and 132 (Fig. 3–40). A 40-foot displacement of the topmost bed can be seen, and the faults can be traced down to the basement. A third, westward-dipping fault can be mapped, at Trace 86, Time 0.50 seconds.

The 110′ line shown in Fig. 3–41 does not distinguish the two separate faults along the right half of the line. Because of the averaging effect on the 110′ line, the displacements are not indicated by sharp breaks, as they are in the 55′-bin data. The fault on the left half of the line also has a very different aspect on the 110′ line.

The 55′-data has a sharper imaging capability not only because of the effect of averaging, but also because it appears to contain a larger percentage of higher frequencies.

3.3.6 Results

A more detailed version of these results, conclusions, and recommendations can be found in Reeves et al, 1998 (in press).

Results from the 3D seismic survey ranged from analysis of survey costs and recommendations for cost reduction, to conclusions about the Osage County study area, to observations about the value of 3D data and higher resolution, and ideas for new approaches to interpretation.

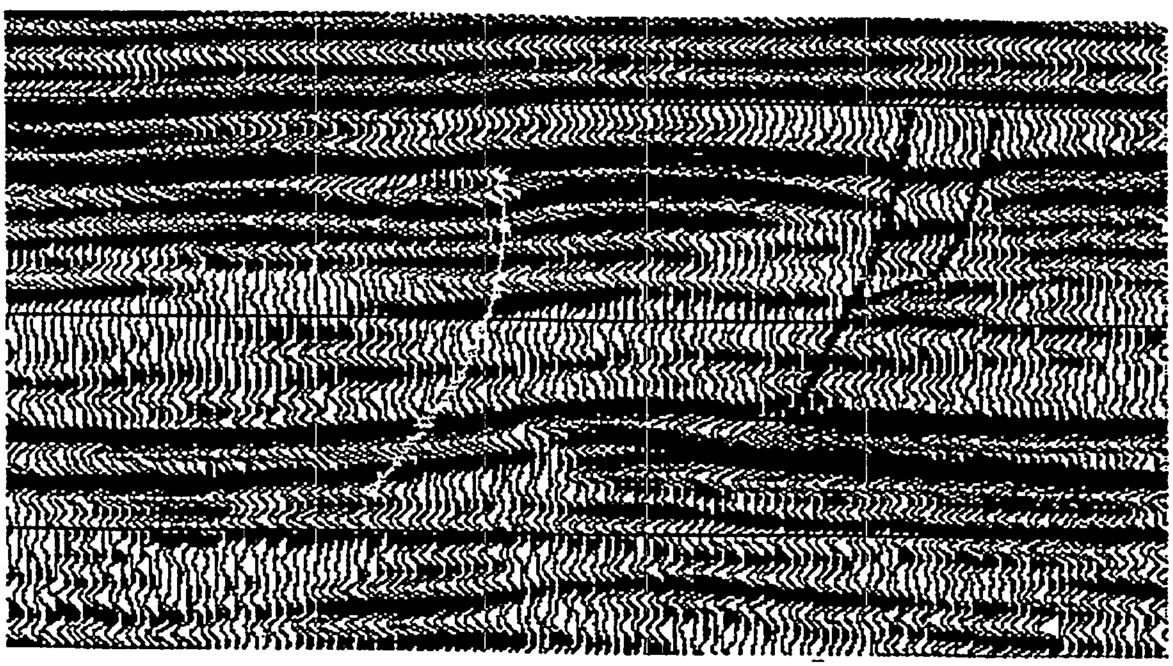


Figure 3–40 The Higher Resolution of the 55-ft-Bin Data is Demonstrated by the Mapability of Three Small Faults.

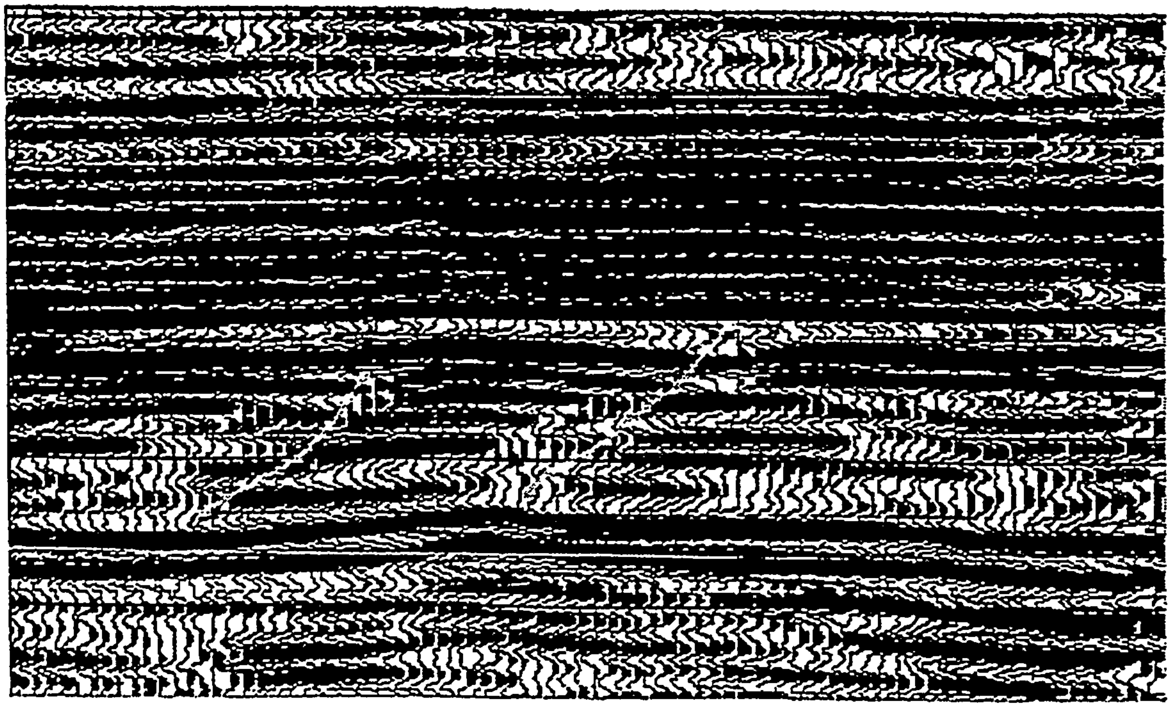


Figure 3–41 The Lower Resolution of the 110-ft Bin Data is Demonstrated by the Mapability of Only Two of the Three Small Faults Seen in Figure 3-40.

Analysis of the 3D Seismic Survey Costs

The cost of the Bigheart survey proved to be higher than anticipated. There were several reasons for this. These included:

- October and November, 1996 stood out for a series of highly unusual, inclement weather conditions that hit Oklahoma during those months. This may have been an early side effect of a building record El Niño. The weather problems resulted in the crew sitting idle for 24 days at a rate of $10,000 per day.
- Following the weather shutdown, work resumed. At this point, several measures were adopted to make up for the lost work period. A large amount of time was recouped by requisitioning a helicopter crew for transport, to improve maneuverability in muddy conditions. The helicopter both sped up field movement and was environmentally friendly, ultimately reducing damage costs and restoration fees. However, the rental costs were substantial.

3D Survey Cost Reduction Measures

Possible measures to reduce costs in future surveys would include the following:

- Careful selection of the fieldwork season, to avoid predictable potential bad weather conditions. Consulting regional climatic tables and long-term weather forecasts can help to ensure that the fieldwork is being planned for a time period with a reasonable prospect for satisfactory weather conditions. The prudent operator should also ensure that there is a reasonable opportunity to complete the survey before seasonal changes will predictably bring work to a halt.
- Conducting a detailed assessment of the terrain conditions during the initial elevation survey to evaluate the accessibility of the Vibroseis trucks to the various survey locations. This can reduce data acquisition time by increasing the total number of points vibrated per day.
- When possible, complete the roughest part of the survey terrain first, if there are high chances that the weather will be deteriorating later in the survey season.

The Relationship between Structure, Tectonics, and Oil and Gas Accumulations

The known locations of commercial accumulations of oil and gas in the study area in Osage County are shown in Figure 3–31. A comparison of the basement structure map (see Fig. 3–30) with the map of hydrocarbon accumulations reveals the following:

- A strong correlation exists between the areas with major oil and natural gas accumulations and prominent basement highs. The locations of hydrocarbon accumulations in the study area appear to have been largely influenced or controlled by basement structure.
- Major oil and gas accumulations in the region appear to occur along fault trends, with the dominant orientations of these faults being southeast-northwest or southwest-northeast.
- Although depositional patterns and thicknesses of the deeper formations appear to be strongly influenced by basement structures, shallow sedimentary units (including the Layton sandstone) do not appear to be strongly influenced by basement structure.

A Comparative Study of the Imaging Capabilities of 55′- and 110′-Bin Size Data

110′-bins involve data covering an area four times the size of 55′-bins. The larger bin-size involves the averaging of information over a larger area, so it is obvious that the 110′-bin data will be "smoother," compared to the 55′-bin data, and lacking in detail.

Key observations on the relative usefulness of the 55′- and 110′-data sets are discussed below, using seismic sections from several different areas.

Boosting the relative amplitudes of the seismic data may help in mapping fault traces. Fault interpretation benefits from boosted amplitude data.

The versatility of the 3D seismic interpretation package allows viewing of seismic data emphasizing different attributes of the data. Vertical and horizontal sections can be obtained directly from the 3D seismic data cube, for very detailed interpretation and integration with geology.

Subtle structural and stratigraphic features can be imaged better in the 55′-bin data, compared to the 110′-bin data, since the 55′-bin data appear to contain higher frequencies.

Pseudo 110′-bin data can be artificially generated from 55′ bin information by averaging data over a larger area, but the inverse, that is, obtaining 55′-bin resolution from data acquired with a 110′-bin, is not possible.

High-resolution 55′-data will be much more useful than 110′-data for the imaging of subtle geological features in depositional environments such as the platform deposits in Osage County, where there are rapid changes in lithology and facies.

In other geologic circumstances, involving the imaging of larger-scale features, 110′-bin data may be adequate. 110′-data may even prove to be more useful in certain instances where the objective is to map the dominant structural trends without being affected by "noise" from small geological features.

Comparison of Features Identified with the Seismic Survey and Results from other Project Surveys

Finally, once the seismic interpretation was completed, maps prepared from the seismic data were compared with results obtained from the fracture studies, a surface geochemical, and a microbial survey of the study area. These studies are described in Sections 3.4, 3.6, and 3.7, and in Reeves et al, 1998, in press.

The coincidence between the structural patterns described in the seismic work and orientations detected in the fracture analysis and the correspondence in location and shape of a large anomaly identified by the microbial survey and a channel sand identified on the 55′-bin size data are striking.

3.4 Regional Fracture Studies

A new software package, FRAC-EXPLORE, was developed by BDM Petroleum Technologies personnel as one of the innovative exploration techniques included in this DOE project. The program can be used for very rapid regional fracture analysis of large areas, or for detailed studies of air photos of a single lease.

3.4.1 Objective

The objectives of this task were to review, recommend, and/or develop cost-effective methodologies, techniques, and tools for oil and gas exploration. Specifically, for rapid, low-cost preliminary assessment of large regions, it was decided to develop a software package that would allow the evaluation of remote sensing data and surface lineament and fracture analysis for oil and gas exploration at a reasonable cost.

The techniques used by FRAC-EXPLORE for delineating subsurface hydrocarbon traps are based on five structural indicators:

- surface lineaments,
- surface-fracture orientations,
- local residual surface-fracture frequencies,
- local residual surface-fracture densities, and
- surface circular and arcuate anomalies.

The integration of each of the indicators can be used to prioritize prospective areas for additional geological and geophysical analyses in exploratory areas. In producing areas, with established fields, the technique can assist in the identification of areas for infill drilling.

3.4.2 Project Description

BDM-Oklahoma personnel initially developed FRAC-EXPLORE, starting in 1994. The program was available for beta testing and outside use during 1995, but was still being actively expanded and refined, at that time. A much-improved version, which included a user's manual, was released during July 1996.

The software was extensively tested internally. Version 1.0 of the product was used successfully for the identification of regional fault/fracture/lineament packages in the Four Corners area by BDM researchers for the analysis of the Black Mesa basin (Reeves et al, 1996). Results from FRAC-EXPLORE studies of the region were checked against the geologic assessment of the basin, and a close association was found between the fracture characteristics interpreted by FRAC-EXPLORE and those observed in the field.

The high degree of coincidence between the locations and orientations of basement structures and surface fracture/lineament trends in northeastern Arizona strongly suggested that the basement faults had been reactivated repeatedly throughout geologic time. The propagation of basement faults to the surface indicated the applicability of lineament and fracture analysis for hydrocarbon exploration in northeastern Arizona.

The software package was then used to evaluate the area in Osage County, Oklahoma, where the 3D seismic program, geochemical survey, and microbial survey were conducted. This area was then expanded, with analysis first of 13 counties in eastern Kansas, then a regional evaluation, ranging from Colorado to Iowa.

BDM Petroleum Technologies continued to reprogram and further improve the software as it was applied to the Basin Analysis task in the South-Central Mid-Continent. Version 2.0 has been refined to be much more user-friendly, with a greatly improved manual, on-line help assistance, and additional modules for expanded capabilities.

3.4.3 Study of Lineaments and Fractures

A regional study was conducted to investigate the structural style, oil and gas trapping mechanism, and exploration strategy for the general Mid-Continent region through an analysis of surface and subsurface lineaments and fractures. A more detailed, in-depth analysis focused on thirteen counties in east central Kansas.

The regional study of surface and subsurface linear features involved three primary phases:

1. collection and digitization of a large number of surface lineaments and fractures, gravity and magnetic lineaments, and basement fault systems in the general Mid-Continent region,
2. orientation and analysis of these linear features to identify the structural style and trapping mechanism in the region, and
3. correlation analysis of surface linear features and subsurface oil and gas traps (Guo et al. 1996c).

The work was conducted in three regions.

Southeastern Kansas

Four hundred high altitude black and white aerial photographs, taken in 1981 from an altitude of 40,000 feet, have been studied for the southeastern Kansas region. Each photograph covered an area of 11 square miles (scale 1:80,000). The fracture-lineation data were transferred to 1:100,000 scale topographic maps. Recognition of fracturing on the aerial photos was based on visual identification of actual rock displacement, on straight drainage segments, alignment of vegetation growing along fractures, tonal or color changes in surface soils and rocks, and cliff edges or faces.

A high-resolution image, taken with the French SPOT satellite, covering portions of the 13 counties in eastern Kansas, was purchased and used to map medium-scale surface linear features in the area. The image was interpreted using ER-Mapper, a commercially available computer software package useful for enhancing satellite images. All the identified surface linear features were digitized and integrated with those from aerial photograph interpretation.

Regional-Scale Photographic Studies

Thirty-six sets of surface lineament and fracture orientations were mapped from satellite images and/or aerial photos covering significant portions of the Mid-Continent and Colorado Plateau regions. Data were:

- collected from published literature,
- digitized, and
- statistically analyzed

in order to obtain the probability-distribution functions of natural fractures for characterizing subsurface fault systems.

The orientations and lengths of identified surface linear features were calculated using the digitized coordinates of the two end points of each individual linear. The lengths and spacing data for the surface linear features within each individual set were obtained using an analytical sampling technique.

Statistical analyses of each data set were then performed to find the best-fit probability-distribution functions for the

- orientation,
- length, and
- spacing.

Twenty-five hypothesized probability distribution functions were used to fit each data set. A chi-square goodness-of-fit test was used to rank the significance of each fit. A distribution that provided the lowest chi-square goodness-of-fit value was considered the best-fit distribution.

The following procedures were performed for the statistical analysis of surface-lineament and fracture characteristics:

- A rose diagram analysis for identifying the number of subsets in each surface lineament and/or fracture system.
- A filtering-analysis for partitioning surface-fracture systems into subsets.
- A sampling-analysis for the collection of surface-fracture spacing data using a new analytical technique.
- A best-fit analysis to obtain distribution functions for surface-lineament and fracture orientations, lengths, and spacing.

Osage County, Oklahoma

The objective of the remote-sensing and lineament analysis in Osage County was to review and test the ease-of-use and effectiveness of the FRAC-EXPLORE Version 2.0 software package (Guo et al. 1996a), in connection with a real world exercise, the DOE 3D seismic survey, already described.

Calculated fracture lineation orientation frequency and density distributions for the entire area of Osage County were interpreted, in an attempt to identify key structural trends and to identify prospects with a good potential for hydrocarbon reservoirs. Simultaneously, conventional geologic mapping and prospect generation were being undertaken.

When the results of both techniques were compared, it was found that FRAC-EXPLORE had identified many of the same best structures and potential drilling areas as the much more tedious and expensive geologic mapping approach.

3.4.4 FRAC-EXPLORE Upgrade

FRAC-EXPLORE Version 2.0 is based on a quantitative methodology developed at BDM-Oklahoma during 1995 (Guo et al. 1995). The first version of FRAC-EXPLORE was completed in July 1996 (Guo et al. 1996a). To increase the calculation efficiency of and to add new capabilities to the software, BDM Petroleum Technologies personnel completed the second version of FRAC-EXPLORE in December 1997.

Enhancements

Many significant improvements were made over the first version. The following enhancements have been included in the 2.0 version:

- The Graphical User Interface (GUI) was improved for consistency and clarity
- All variables have been explicitly defined. This allows a significant reduction in memory usage requirements
- The "Save Graphics" menu from the first version has been modified to make it more user-friendly
- Color legends were added to most graphic output screens to assist in the interpretations of anomalies
- A screen-display capability was added to allow for combining and overlaying maps where mixed types of structural anomaly indicators exist
- The software was recompiled using Visual Basic 5.0
- As a result of these improvements, FRAC-EXPLORE Version 2.0 runs at least 21 times faster than FRAC-EXPLORE 1.0.

Potential Data Input Types

Potential sources of image data for mapping surface lineaments and fractures include Landsat, SPOT, and high and low altitude aerial photographs. For mapping large-scale surface lineaments, Landsat data provides the best coverage. For mapping surface fractures in more detail, SPOT data and aerial photographs are recommended. FRAC-EXPLORE 2.0 requires all input data to be in ASCII format. Fracture data can be digitized using a standalone program, such as DIGITIZE, or a digitizer that is part of a multifunctional program, such as Corel Draw, GeoGraphix, or Logic Group.

Modules

FRAC-EXPLORE 2.0 uses a sequential analysis process consisting of six major modules. It is recommended that the user performs the modules in order, but the user can jump from one module to another.

1. The first module graphically displays surface lineaments, fractures, and/or circular and arcuate features. It is used to check and validate input data for subsequent quantitative analyses.

2. The second module provides a set of tools for generating rose diagrams of surface linear features. It can be used to produce a single rose diagram for a whole region or to generate a rose diagram for a selected township or section. An area with a diversity of orientations signifies localized fracture orientations that differ from the regional trend. Adjacent townships with lineaments whose orientations are dramatically different suggest subsurface structures, and possible trapped hydrocarbons.
3. The third module is designed for analyzing the density of surface linear features. Density is defined as the total fracture length per unit area. The default is a 100 by 100-foot area. The calculated values per area are then averaged for each section. This module consists of three tools: numerical calculation of density values by section in a region, calculation and display of density values for a given township, and statistical and graphical display of density values used to identify anomalous areas of potential subsurface structures.
4. The fourth module analyzes the frequency of surface linear features. Frequency is defined as the total number of fractures or lineaments per unit area. Areas that have a high density, may or may not also have a high frequency. This module consists of three tools: numerical calculation of frequency values by section in a region, calculation and display of frequency values for a given township, and statistical and graphical display of frequency values in order to identify anomalous areas.
5. The fifth module provides tools for analyzing the orientation of surface linear features. Orientation complication is defined as the degree that surface linear features diverge in orientation. An orientation complication factor is calculated as the percentage of the total orientation classes in which surface linear features are found. The larger the diversity in orientations, the larger the complication factor. This module consists of the same three calculations and display features as density and frequency.
6. The sixth module provides tools to integrate density, frequency, and orientation analysis with major lineaments and circular and arcuate anomalies. Only by integrating the various tools together can the optimum areas for potential subsurface structures be identified. It provides a statistical analysis tool for selecting density, frequency, and orientation cutoff values for identifying anomalous areas. The graphics tool displays the relative significance of the anomalous areas, as well as their relationship to surface lineaments, circular, and arcuate features.

Manual

In addition to the software, a detailed user manual provides instructions and examples on how to use FRAC-EXPLORE 2.0. Ten chapters cover software installation, input data preparation, graphic display of surface features, geological and mathematical analysis of fracture characteristics, and anomaly integration and ranking. Minimal expertise in geology or petroleum engineering is required to run the software; however, the independent operator is expected to have some background in geology and/or petroleum engineering to effectively analyze the graphical output in order to prioritize prospective areas.

Internet Posting of the Software

To ensure the greatest possible distribution of the FRAC-EXPLORE program to potential users, the program has been posted on the Internet at

www.npto.doe.gov/Software/compindx.html

where FRAC-EXPLORE is item 18 on the list.

The program can be directly downloaded from:

www.npto.doe.gov/Software/frac_v2.zip

3.4.5 Presentations at Professional Meetings

The following presentations were made at various professional meetings and workshops to transfer the new methodologies, techniques, and the software developed for oil and gas exploration using remote sensing data and surface fracture analysis:

- Safley, L. E.: Demonstration of FRAC-EXPLORE 2.0 at a one-day workshop sponsored by the National Petroleum Technology Office, in Tulsa, Oklahoma, February 24, 1998.
- Guo, G.: Demonstration of the capabilities and applications of FRAC-EXPLORE 2.0 during the 1998 Rocky Mountain Association of Geologists (RMAG) Fractured Reservoir Symposium, in Denver, Colorado, January 19–20, 1998.
- Guo, G.: "FRAC-EXPLORE, a New Computer Software for Locating Oil and Gas Reservoirs Using Remote Sensing Data and Surface Fracture Analysis," a poster, presented at the Twelfth International Conference and Workshops on Applied Geologic Remote Sensing, Denver, Colorado, 17–19 November 1997.
- Guo, G.: "Analysis of Surface Lineaments and Fractures for Hydrocarbon Exploration and Production Optimization in the Mid-Continent Region," presented at the 1997 SPE 72nd Annual Technical Conference & Exhibition, San Antonio, Texas, 5–8 October.
- Guo, G.: "A New Methodology and Computer Software for Delineating Oil and Gas Reservoirs Using Surface Lineament and Fracture Analysis," SPE 38125 presented at the 1997 SPE Petroleum Computer Conference, Dallas, Texas, 8–11 June.
- Guo, G., Reeves, T. K., George, S. A., and Lindsey, R. P.: "Using Remote Sensing Data and Surface Lineament and Fracture Analysis for Hydrocarbon Exploration in Northeastern Arizona," presented at the 1997 AAPG Annual Meeting, Dallas, Texas, 6–9 April.

- Guo, G., Carroll, H. B., Johnson, W. I., George, S. A., Falls, A. H. and Lindsey, R. P.: "Using Surface Lineament and Fracture Analysis to Delineate Additional Reserves in a Mature Field: A Case Study in Osage County, Oklahoma," SPE 37414 presented at the 1997 SPE Production Operations Symposium, Oklahoma City, Oklahoma, 9–11 March.
- Guo, G., George, S. A., and Lindsey, R. P.: "Statistical Analysis of Surface Lineaments and Fractures for Characterizing Naturally Fractured Reservoirs," 4RC–052 presented at the 4th International Reservoir Characterization Conference, Houston, Texas, 2–4 March 1997.
- Guo, G., George, S. A., and Lindsey, R. P.: "Applications of Surface Lineaments and Fractures for Optimal Horizontal Well Drilling and Production Potential Estimation," SPE 37150 presented in the 1996 SPE International Conference on Horizontal Well Technology, Calgary, Alberta, Canada, 18–20 November.

These tech transfer activities included examples and case studies of successful use of surface lineament and fracture analysis for oil and gas exploration.

3.4.6 Conclusions

The following mathematical/statistical observations and conclusions were obtained from the extensive remote-sensing statistical analysis:

- Natural fracture orientations are best described by triangular and normal distributions, followed by logistic, chi-square, and PearsonV distributions. Triangular and normal distributions are, by far, the most significant distributions for characterizing natural fracture orientation data.
- Natural fracture lengths are best described by PearsonVI and PearsonV distributions. Other favorable distribution functions for characterizing natural fracture length data include extreme-value, lognormal2, lognormal, loglogistic, logistic, and triangular distributions.
- Natural-fracture spacing data are best described statistically by lognormal2 and PearsonVI distributions followed by lognormal, inverse Gaussian, Weibull, exponential, and PearsonV distributions.
- Probability-distribution functions utilized to identify and characterize natural fracture systems, based on analysis of surface lineaments and fractures, can also be used for stochastic simulations of subsurface fault systems. This allows delineation and quantification of basement-fault-controlled oil and gas traps, based on studies of satellite images and aerial photos.

The following geologic conclusions were reached concerning the Mid-Continent study area:

- All the surface and subsurface linear features belong to one of two major sets, trending either northeast or northwest. Gravity and magnetic linear features in the basement and surface features also display a minor set trending east or north. This means the basic structural grain of the Mid-Continent region includes two major fracture sets trending northeast and northwest, with a minor set trending north or east.
- The strong consistency in orientation between surface and subsurface linear features strongly suggests that there have been repeated reactivations of the major fault systems within the basement in the Mid-Continent region. These faults have apparently been remobilized many times and have propagated upward all the way to the surface. The movements on these faults may have been quite small. The reactivation may represent diurnal shifts due to the effects of earth tides. Such tides do not produce significant motion; rather they tend to shatter overlying shallow rock beds due to incessant movement, twice daily adjustments.
- The ultimate conclusion was that the structural style of the Mid-Continent region is basement-influenced. The basement fault systems in the region may have controlled the loci for the development of other geological structures in the shallow section, including oil and gas traps in the Mid-Continent area.

The close association both in orientation and position between surface linear features and subsurface oil and gas traps was observed in northeastern Oklahoma, in the Oklahoma Panhandle, the northern Denver Basin, and the Forest City Basin.

This led to the conclusion that these types of relationships should be common in other parts of the Mid-Continent region, which are underlain by basement rocks of similar lithologies and deformation histories. Therefore, surface lineament and fracture analysis can be employed as a cost-effective tool for hydrocarbon exploration in the Mid-Continent region.

The close agreement between the results from conventional geologic analysis and the application of FRAC-EXPLORE in Osage County demonstrated how the program can be a valuable tool for the independent. The early application of FRAC-EXPLORE can have real value during the first phases of field development, once a new lease has been obtained, or when an operator is considering entering a new frontier region.

The completion and widespread distribution of FRAC-EXPLORE Version 2.0 and its user's manual, including the posting through DOE on the Internet at

www.npto.doe.gov Software/compindx.html

(where it is item 18 on the list) has provided a comprehensive, user-friendly computer software package for the small, independent operator. Explorationists and development geologists will be able to apply remote-sensing data and surface lineament and fracture analyses in the search for secondary fracture porosity, increasing the potential for successful, commercial-levels of oil and natural gas production.

3.5 Thermal Assessment of Possible Petroleum Source Rocks

The University of Tulsa participated in the investigation of the Forest City and Salina Basins under two successive contracts. The first contract began on May 8th, 1996, and was concluded with the submission of a final report in February, 1997. This report is included as Appendix Two to this report.

Work under the second contract began on April 29, 1997, and was completed with the submission of a final report, received on August 4th, 1998. A copy of the August final report by the University of Tulsa personnel is attached as Appendix Three to this report.

3.5.1 Project Description

The early phases of the University of Tulsa work are described in the February, 1997, Final Report "Thermal Assessment of Possible Petroleum Source Rocks, and Petroleum Generation and Occurrence, in Parts of the Salina and Forest City Basins Adjacent to the Nemaha Ridge," by Colin Barker and Richard J. Erickson. This report is included as Appendix Two.

The second contract between BDM and TU Geoscience Department focused on the potential for petroleum generation and the identification of relevant geochemical characteristics from a variety of sources. Petroleum in the Forest City Basin could have been generated within as many as three main source rock sequences:

- Pennsylvanian,
- upper Devonian to lower Mississippian, and
- Ordovician.

A comparison of gas chromatograms of oils derived from Pennsylvanian source rock and from Ordovician source rock clearly indicates major geochemical differences in their composition (Quarterly Technical Progress Report, NIPER/BDM–0311, April 1, 1997–June 30, 1997, p. 144–146).

Trips were made to the Minnesota Geological Survey core repository in Hibbing, Minnesota, and the Iowa Geological Survey Bureau core repository in Iowa City, Iowa, to gather samples for detailed analysis. The availability of other no-cost or low-cost geographic data from the Iowa State Geological Survey Bureau or the US Geological Survey was also investigated.

The following well cores supplied samples or data for the study:

Sample 1 -	Hollandale Core, section 7-T103N-R19W, Freeborn County, Minnesota; McGregor Member, Platteville Formation; quarter slab of core from 447.5′ to 448.0′
Sample 2 -	Hollandale Core, section 7-T103N-R19W, Freeborn County, Minnesota; Decorah Shale; core piece from 429′
Sample 3 -	Hollandale Core, section 7-T103N-R19W, Freeborn County, Minnesota Decorah Shale; core piece from 430′
Sample 4 -	NGPCA M. M. Flynn #2 (W14380), section 19-T76N-R9W, Washington County, Iowa; Glenwood Shale; half slab of core from about 1115.4′ to 1116.4′
Sample 5 -	NGPCA W. F. Flynn #2, section 20-T76N-R9W, Washington County, Iowa; Guttenberg Member, Decorah Formation; core piece from 976′
Sample 6 -	NGPCA W. F. Flynn #2, section 20-T76N-R9W, Washington County, Iowa; Guttenberg Member, Decorah Formation; core piece from 977′
Sample 7 -	Cominco SS-3, Jackson County, Iowa; Guttenberg Member, Decorah Formation; 1 5/8" long half slab of core from 675′
Sample 8 -	Cominco SS-3, Jackson County, Iowa; Guttenberg Member; Decorah Formation
Sample 9 -	Iowa Geological Survey Bureau BS-4, section 20-T95N-6W, Clayton County, Iowa; Guttenberg Member, Decorah Formation; core piece from 481.0′ to 481.7′
Sample 10 -	Core 91708-A B3A, section 22-T29N-R24W, Hennepin County, Minnesota; Glenwood Shale; core chips from 33.2′
Sample 11-	Core 91708-A B7A, 22-T29N-R24W, Hennepin County, Minnesota; Glenwood Shale; core chips from 51.6′

All new-well drilling in Kansas was monitored to identify wildcat wells in the Forest City and Salina Basins. Operators of such wells were contacted and arrangements were made to receive portions of any samples that were taken. Interest focused specifically on rock samples from intervals that had been identified as potential source rocks, or intervals that could be expected to contain shows of oil or gas, and crude oil samples from any oil recovered during drill-stem tests.

The source-rock samples were prepared and analyzed for total organic carbon (TOC) and Rock-Eval pyrolysis. Samples containing oil had the oil extracted and analyzed by gas chromatography. Thin sections were made for key samples.

A database of published geochemical information was compiled and combined with the new data.

The data were used to run a series of models, as discussed in Appendix Two.

3.5.2 Conclusions

Models based upon wells from the southern Salina Basin (i.e., Kyler #1), the southwestern Forest City Basin (Davidson #1), and the northwestern Forest City Basin (Coddington #3–24) suggest that Ordovician source rocks in these areas have generally reached the early mature stage, minimum.

The Palen #1 well in the central Salina Basin shows that source rocks as shallow in the column as the Cretaceous have reached at least the early mature stage. The deeper strata in the central Salina Basin should have reached even higher levels of maturity.

In all of the areas where wells were modeled, it was found that the rapid deposition of thick Pennsylvanian strata resulted in quick, relatively-deep burial of potential source rocks in the Lower Paleozoic section. The Pennsylvanian burial history pattern seems to be the key element in the thermal maturation of the source rocks in the Forest City and eastern Salina basins. Most of the structural traps within these basins were formed during or before the Pennsylvanian, so any hydrocarbons generated during or after the Pennsylvanian could have been captured in these structural traps.

In the area toward the Rocky Mountain Front, in the central and western portions of the Salina basin, the effects of Cretaceous burial begin to overwhelm those of Pennsylvanian burial. The rise of the Rocky Mountains supplied large amounts of material during the Cretaceous.

The amount and rate of burial of deeper sediments by Permian strata is difficult to determine, as is the amount of section lost to erosion between the end of Permian deposition and the start of the Cretaceous. Over much of the study area, the reconstruction of Cretaceous deposition is even more difficult to estimate.

The close match between the surface vitrinite reflectance values predicted by the BasinMod model of the Palen #1 well and the vitrinite reflectance value actually measured in the lignite sample from the Wilson indicates that the model has correctly accounted for Cretaceous deposition and post-Cretaceous erosion.

The modeling work completed by the University of Tulsa staff has provided valuable, encouraging information on the potential generation of hydrocarbons in the South-Central Mid-Continent study area, including in the Salina basin.

3.6 Surface Geochemical Survey

BDM Petroleum Technologies also conducted a geochemical survey in the Osage County study area as part of the exploration methodologies program. Samples were collected of surface soils and tested for a series of marker chemicals.

The surface geochemical survey was conducted at the Bigheart site in Osage County. The work was designed to coordinate with and complement the high-resolution seismic survey previously described and the microbial survey discussed in the following section.

3.6.1 Objectives

The objective of the geochemical work was to examine several surface geochemical techniques that could be used for locating oil or gas seeps. The methodology applied was one that could be employed by independents with limited budgets and personnel. To this end, both the sample collection and analytical techniques had to be inexpensive, fast and easy to conduct, and should not require extensive training for the survey personnel.

Common surface geochemical methods requiring sampling at depths of 5–25 ft were deemed too costly. The plan to collect extremely shallow samples also eliminated integrated soil-gas methods in which a gas absorber would be placed in the ground for a period of time and then collected at a later date. Furthermore, these methods could not require extensive expertise in soil science since many independents do not have formal training in this area nor the funds to acquire this type of training.

An advantage of the survey methodologies used in Osage County was that they were essentially non-invasive. This makes them useful in environmentally sensitive areas or in other regions where disturbance of the ground is undesirable.

3.6.2 Survey Location

Figure 3–42 is a map of the survey area, located approximately 8 mi. northeast of Hominy, Oklahoma.

Although the high-resolution 3D seismic study area was originally designed to cover 6 mi^2, the seismic lines actually extended over approximately 7.25 mi^2. The extra coverage was necessary to provide adequate fold at the edges for the seismic program. The surface geochemical survey covered the entire area.

The seismic survey was designed to collect data using orthogonal grid lines at a 440-ft spacing, with survey points located every 110-ft along these lines. Each of the survey points was located using a global positioning system (GPS) system. Survey points are accurate to within 15 cm when multiple benchmarks and satellites are used.

Figure 3–43 shows the layout that was planned for the seismic grid. East-west lines (the rows with Xs on the map) are numbered R-1, R-3, R-5, etc., beginning with the northernmost line. The easternmost point on each line is numbered 100, with the sequence increasing to the west. The westernmost point on each row is 257. The row at the top of the figure is R-17.

Geochemical samples were taken at the intersection of the grid lines, giving 12 sample points per mile.

The layout of the actual survey differed somewhat from the planned survey because of dense woods (trees block satellite reception), gullies, creeks, ponds, and the occasional near-coincidence of a close-by fence line.

Figure 3–44 shows the deviation from the planned grid.

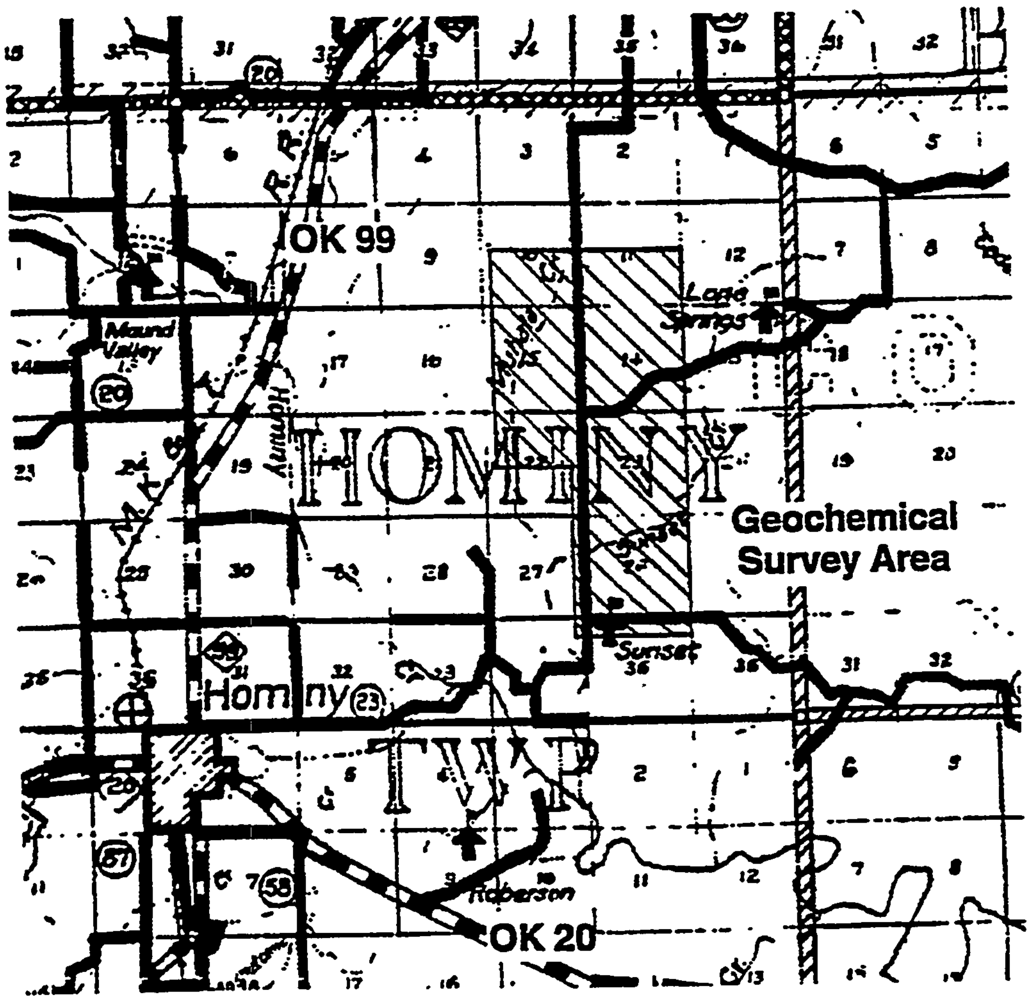


Figure 3–42 Location of Surface Geochemical and High-Resolution 3D Seismic Surveys.

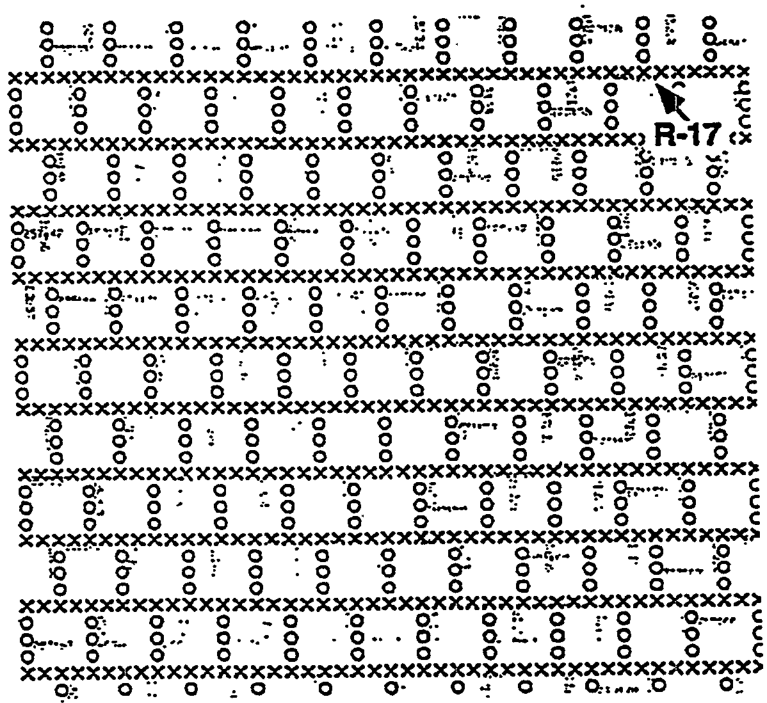


Figure 3–43 Survey Area Showing Planned 440′ Grid and 110′ Intermediate SPs.

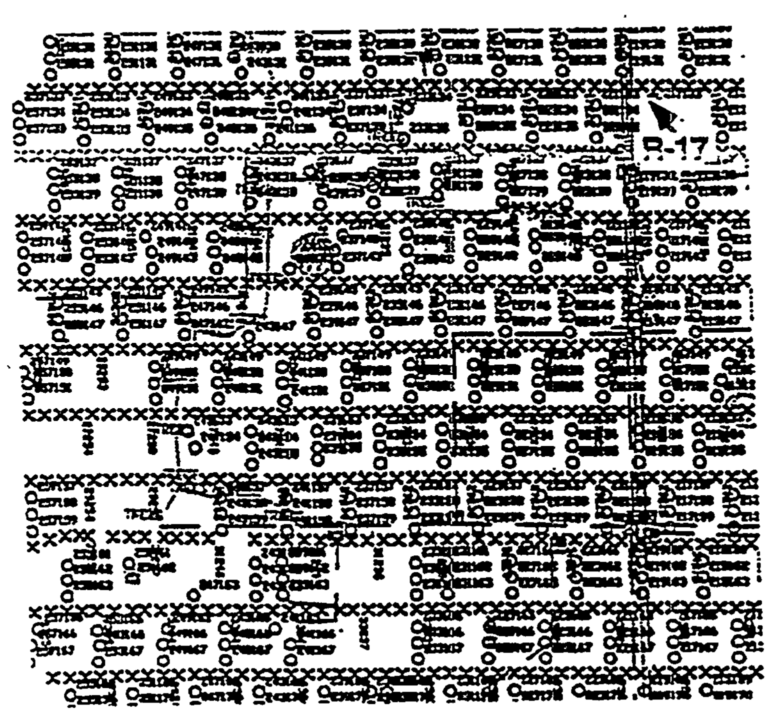


Figure 3–44 Actual Survey, Showing the Same Area as Figure 3-27.

3.6.3 Sampling Procedure

Three types of samples were collected at each grid point:

1. Approximately one-half of a 1-quart polyethylene storage bag of soil was collected from within the top 1–1.5 inches of the surface using a small (Army-style) trenching shovel. Reasonable attempts were made to exclude organic matter, such as large roots and grass (in its natural or cow-digested forms). This sample was collected for iodine and magnetic susceptibility analysis.
2. A 6-inch long ↔ 0.75-inch diameter soil plug was taken with a standard soil sampler. The bottom 4 inches were placed in a 1-inch-diameter ↔ 4-inch-long polyethylene vial with a snap cap. The lids were taped after a few unsnapped. These samples were collected for pH analysis.
3. After the first 6 inches of sample were taken with the soil sampler, each hole was reentered and a second 6-inch sample was retrieved (6–12 inches below the ground surface). This second soil plug was placed in a 1-inch-diameter ↔ 8-inch-long Pyrex test tube. The test tube was sealed with a Neoprene stopper, which was taped to the test tube to prevent accidental removal or loss. These stoppers had been predrilled with a 0.25-inch hole and sealed with a 0.25-inch diameter glass bead. This sample was intended for soil gas analysis.

Occasionally, the deeper plug or sometimes both soil plugs could not be collected because of rock or hardpan. Under those conditions, a composite sample was sometimes taken (for example, two samples were collected between 6 and 9 inch depth in place of a single sample from 6 to 12 inches). A duplicate sample set was collected at about every 30th sample site to check for reproducibility.

3.6.4 Sampling Rate

The sampling rate varied depending on field conditions and occasional obstacles encountered. Once the sampling technique was established, an experienced team of two could collect the standard three samples at a site and walk to the next site in 8 min., under ideal conditions. This represents a minimum sampling time.

If the sample locations had not been pre-surveyed and marked, the sample-collection rate would have decreased markedly, with considerable time being added for the identification of sample location. Rough terrain slowed work substantially.

In addition to the primary batch of 3,000 samples collected over the survey area, the geochemical survey team collected a small series of additional samples to evaluate the local reproducibility, time dependence, spatial consistency, and temperature dependence of the data.

3.6.5 Premise for the Test

The entrapment within soils of many surface geochemical indicators, or markers, for hydrocarbon seeps are dependent upon the presence of clays in the shallow subsurface dirt.

This is due to the high surface area of the clays and to their affinity for certain ions and organic compounds.

Key geochemical markers that can interact with these clays are iodine-hydrocarbon complexes, the radiometric elements (potassium-40, uranium-, and thorium-daughter products), and, potentially, soil gas itself. If these materials are interacting in these ways, the amount of these indicators may be dependent on the amount of clay present. If so, then clay variations within a survey area could cause or mask indications of a seep.

Experts in the field of surface geochemistry acknowledge that the absolute amount of an indicating geochemical species will be dependent upon the geographic location.

A minimum of three scenarios has been suggested:

1. *Limited quantity of clay present.* Clay adsorbs the indicating species, and limits the ultimate amount of the species retained. Since the soil has many chemical species that will be competing for these adsorption sites, the more clay, the greater the amount of a geochemical marker, GM.

   $$GM + A + B + C + \ldots + Clay \Rightarrow (GM, A, B, C, \ldots)Clay$$

   where A, B, C, etc., are other chemical species in the soil that are in competition with the GM for the limited absorption sites on the clay.
2. *Limited quantity of the geochemical marker.* In this scenario, the geochemical marker is present in very small quantities. Even in the presence of small amounts of surface-active material (clays, silts), there will always be an abundance of absorption sites, and the markers will always be able to compete very favorably with other soil components in the absorption process.
3. *Independent of amount of clay present.* Chemical (or microbial) processes unrelated to the adsorption process reduce the mobility of the geochemical marker, producing an elevated concentration in the hydrocarbon plume.

If process (1) correctly describes the interaction, then there will be a strong correlation between seep plumes, geochemical markers, and the amount of clay present in the near-surface soils.

To evaluate the importance of process (1), one must have a relative measure of the surface area of the particles making up the soil. Since clays contain the vast majority of the active surface area in a soil, and since soil science considers the clay fraction to be the particulate material smaller than 2 μm; the researcher needs a method to measure the number of particles smaller than 2 μm in the local soil.

Material smaller than 50 μm but larger than 2 μm is classified in soil work as "silt." Geologically, true silt consists primarily of fine silicon dioxide, or sand.

According to Stokes' law, the time, t, required for a particle of radius, r, to settle a distance, x, can be described by

$$t = x\frac{9\eta}{2gr^2(\rho - \rho_0)}$$

where η is the viscosity of the water,

ρ is the density of the particle, and

ρ_o is the density of water.

Strictly speaking, Stokes' law applies to spherical particles sufficiently separated so that they do not interact with each other. Since this research program is interested only in a relative value for correlation purposes, these restrictions are not important.

The settling time of a soil suspension determines the maximum particle size remaining in the suspension. The intensity of scattered light will be proportional to the cumulative surface area of the particles remaining in suspension. Thus, a scattered-light measurement system can estimate the relative amount of material remaining in suspension.

For the geometry of the BDM Petroleum Technologies light-scattering equipment, only particles smaller than 50 µm remain in suspension after 2–1/2 minutes, and only particles smaller than 2 µm will be present after 27 hr.

To test the validity of process (1) for the Bigheart survey area, 109 soil samples from Osage County were randomly selected. Iodine analyses were performed on these samples. Based on the scattered light test results, the amount of clay (surface area) in the soil varied 27-fold across the survey area.

3.6.6 Results of Geochemical Surveys

Detailed analyses were conducted on all of the samples that were collected. Tests were run for three things:

- Iodine,
- pH, and
- Magnetic Susceptibility.

Each of these surveys is discussed in detail below.

Iodine Survey

The correlation between clay surface area and the amount of iodine present in the samples was very weak, with a correlation coefficient of -0.324. Due to the similarity of the depositional environment for the clay and silt, the correlation between these two was quite high (0.869), meaning that the correlation between the silt and iodine was also very low (0.068). These results indicate that process (1) in Section 3.6.5 occurred only to a minor extent, if at all. Therefore, variations in the amount of clay present in the soil samples should have minimal influence on the iodine survey.

A strong iodine anomaly existed in the southern end of the project area in the vicinity of some abandon oil wells. A second strong anomaly existed to the west of the center of the project area as a classic halo. A third, less-well-defined anomaly also appeared in the northeastern quadrant of the project.

In general, these anomalies were seen as areas with normal levels of iodine at the center and a ring, or partial ring (arcs), of unusually high values surrounding this center. The iodine values in these rings are more than 1.5 standard deviations above background levels. In addition, if one considers only those locations where the iodine values have a standard deviation greater than –1.0 (low values), there are conspicuous "holes" in the iodine map where anomalies exist.

The mean iodine value for the field was 2.82 ppm with a standard deviation of 1.90 ppm.

pH Survey

The raw pH data did not readily reveal any anomalous areas. However, upon using a mild 2D smoothing routine, anomalies could easily be seen. These appeared as areas of low pH, with a surrounding ring of high pH. This ring of high pH was in turn surrounded by still another zone of low pH values.

The pH anomalies were generally centered on the same areas as the iodine anomalies. The weakest iodine anomalous feature became much more evident, and stood out better on the pH survey.

The average pH of the survey area was 5.00 with a standard deviation of 0.68.

Magnetic Susceptibility Survey

The data revealed several areas of elevated magnetic susceptibility. The southern-most anomaly had scattered high readings within the abandoned oil field.

In the area to the west of the center of the project area where the pH and iodine surveys had identifiable anomalies, the magnetic susceptibility map showed a feature, although it was not directly on top of the pH and iodine anomalies.

The anomaly identified by the other methodologies in the northeast quadrant of the project area was also difficult to identify using magnetic susceptibility.

In general, magnetic susceptibility anomalies were more diffuse and less easily recognizable than those that showed up the other two surveys. The magnetic susceptibility values averaged 163 with a standard deviation of 70.

3.6.7 Interferences

In general, cultural features seemed to create little interference with the geochemical levels.

Cultivated fields of winter wheat, maize, and Bermuda grass did not seem to correlate with any anomalous iodine or pH values. There was also no observed correlation with streambeds.

The only apparent interference occurred along a gravel road adjacent to row R-85. pH values along this road were unusually high, possibly because of lime applied to the road.

A few abandoned oil wells exist within one anomaly. Although several dry holes exist within the survey area, none are within any of the anomalies identified here.

3.6.8 Conclusions

The conclusion from this field experiment is that the clay content is not an important factor, at least for iodine, and probably for other markers as well. This simplifies the search for hydrocarbon anomalies.

Based on the tests performed in Osage County, it was not possible to distinguish between the importance of processes (2) or (3), or some other unidentified processes. Indeed, if process (3) is the correct, locally applicable mechanism controlling results in this region, then there may be other geochemical markers that may depend on the soil surface area.

Two easily identifiable iodine anomalies were identified, along with a third, possibly anomalous weaker feature. The same three features show up and appear to be anomalous on the pH survey. The weak iodine anomaly in the northwestern quadrant is better developed on the pH map.

The magnetic susceptibility survey revealed anomalies that were more diffuse and less distinct than those seen with the other two methodologies.

3.7 Soil Microbial Survey

Geo-Microbial Technologies (GMT), of Ochelata, Oklahoma, was sub-contracted by BDM to conduct an independent microbial survey over the same Osage county study area that was used for the 3D seismic survey and the geochemical study. This was considered to be another promising, low-cost exploration methodology that could be used effectively by the small, independent operator.

The GMT microbial survey used the common GPS stations and collected their samples at the same identical points as the seismic and geochemical studies. GMT collected their samples in a rapid, efficient manner, during a period of good weather.

3.7.1 Survey Procedures

The detailed description of the procedures used by GMT is contained in an appendix of a report by Reeves et al., 1998 (NIPER/BDM-376). This appendix includes complete information on the process and results of the survey, so they are not repeated here.

GMT sample collection procedure, laboratory work, and interpretation were totally isolated from all work performed by BDM Petroleum Technologies personnel, and the results were held as separate, confidential data until the seismic and geochemical surveys had been completed.

3.7.2 Conclusions

The results of the GMT work proved to be quite interesting. Sample collection over an old oil field showed little of interest. This is what microbial experts would expect if the old fields had been efficiently and relatively-thoroughly depleted by years of production.

The most distinctive anomaly identified by GMT was large in amplitude and had a distinctive shape. It was located in the northern portion of the study area, and generally coincided with a possible channel sand that showed up on the 55'-bin size seismic data. This feature could not be distinguished on the 110' data.

The results of the GMT survey nicely compliment the high-resolution seismic survey, demonstrating the synergistic value of using multiple techniques in a lease or prospect area.

Several features of possible interest can be seen on the 55-foot seismic survey. The GMT survey also shows more than one relative "high." However, when the two studies are combined, only one area stands out as a prime target. Not only do the seismic and GMT techniques concur as to a potential target, but they appear to agree on the general overall configuration of the possible prospect area.

It should be recognized that this study has only been conducted in one lease area. Additional tests need to be conducted if industry is to confirm and rely upon the combination of high-resolution seismic and microbial techniques.

4.0 CONCLUSIONS

The South-Central Mid-Continent was studied through conventional geologic and geophysical approaches, and with several innovative techniques, described in this report.

The initial premise of the study was that there should be a high potential for hydrocarbon generation within the Mid-Continent Rift System (MRS). However, organic contents in the southern portion of the MRS proved to be disappointingly low. In addition, the region had not experienced sufficient tectonic disturbances during the Phanerozoic to release many hydrocarbons into shallow reservoirs.

The study then shifted to a focus on the Lower Paleozoic stratigraphic sequence and the locations and tectonic evolution of important structures in the region. Innovative, multi-disciplinary techniques were used for the study. The conclusions from these projects all agreed that the Lower Paleozoic section had a good potential for both in-migration and local sourceing of hydrocarbons in the Lower Paleozoic sediments of the study area.

Conclusions from or about the various techniques that were used are described below.

The Basin-Modeling Study, using the RIFT2D software developed by the University of Minnesota, demonstrated the possibility of hydrocarbon generation within the deeper portion of the Paleozoic section. It also showed that there had been possible migration of hydrocarbons from the southeast, into and across the study area during Cambrian and Lower Ordovician time.

In addition, this work, along with the Thermal Modeling results, discussed below, suggested strongly that there could have been locally-derived hydrocarbons generated within the deep section of the Study area basins. All of the unbiased computer approaches arrived at similar, positive conclusions concerning the potential for the historic generations of hydrocarbons in the South-Central Mid-Continent.

Gravity and Magnetic Modeling proved to be a very low-cost technique for mapping basement structures and configuration. It can be used to identify possible mini-rift structures in the basement, as well as local basement uplifts, monadnocks, or buried volcanic piercement structures. These types of features may produce drape features in the shallow sediments, and are often the sites of stratigraphic pinchouts and feather-edges in deeper sediments. Any of these can be subtle traps, but good-quality reservoirs.

The 3D Seismic Survey was extremely effective in drawing attention to and increasing survey and drilling activity in the survey region, Osage County, Oklahoma. A major, Chevron, and several smaller independents moved into the county following announcement of the program by BDM. Three separate, large seismic surveys were completed and several wells were drilled. Employment in the county increased substantially during this period of activity, and the tribe is now benefiting from ongoing royalties, while the domestic oil supply has been increased.

The technical results of this survey are covered in much greater detail in Reeves et al, 1998. Highlights include several well-documented examples as to how 55'-bin size data can benefit the exploration geophysicist, plus dramatic examples of how amplitude analyses and wave-form studies can shed important light on reservoir parameters, and identify hydrocarbon-saturated reservoirs vs. portions of the same formations that are clay-filled.

The Remote-Sensing Fracture Analysis studies assisted in identifying areas of interest in the South-Central Mid-Continent, on a regional basis, and, in Osage County, Oklahoma, were a key ingredient in the selection process for seismic prospects.

A major benefit of the program was the development and delivery to DOE of a software package, FRAC-EXPLORE 2.0, which has been posted on the DOE NPTO web site, making it available, for free, to any interested company or consultant.

The Thermal Modeling work completed by the University of Tulsa staff has provided valuable, encouraging information for the explorationist. Their data demonstrated potential generation of hydrocarbons in the South-Central Mid-Continent study area, including in the Salina basin.

The Pennsylvanian burial history pattern seemed to be the key element in the thermal maturation of the source rocks in the Forest City and eastern Salina basins. In all of the areas where wells were modeled, it was found that the rapid deposition of thick Pennsylvanian strata resulted in quick, relatively-deep burial of potential source rocks in the Lower Paleozoic section, accompanied by significant heating of the units.

Data from the southern Salina Basin (the Kyler #1) and western Forest City Basin (the Davidson #1 and the Coddington #3–24) suggest that Ordovician source rocks in these areas have generally reached the early mature stage.

Data from the central Salina Basin (the Palen #1) suggest that shallow Cretaceous source rocks have reached at least the early mature stage.

In the area toward the Rocky Mountain Front, in the central and western portions of the Salina basin, the effects of Cretaceous burial begin to overwhelm those of Pennsylvanian burial. The rise of the Rocky Mountains supplied large amounts of material during the Cretaceous.

The shallow surface Geochemical Survey identified several anomalies. The iodine and pH surveys tended strongly to coincide with each other, while the magnetic susceptibility survey tended to pinpoint different areas, as being of interest.

All three types of surveys tended to identify circular or arcuate anomalies, without much detail.

The results of the Microbial Survey were extremely interesting, in that they coincided to a remarkable degree with the seismic interpretation of a channel in the Layton sandstone that was identified through the 55'-bin size seismic survey.

However, the microbial survey was done by a subcontractor, and does not exactly fit the goal of being a technique that a small independent could undertake on its own, at low cost, and with little training. Despite the fact that the work would probably have to be contracted out, the survey was completed in an extremely quick and efficient manner, and the results were so impressive in their correspondence with the location and details of configuration of the Layton, as imaged on the seismic maps, that the technique merits serious consideration.

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APPENDIX 1
COMPUTER MODELING OF HYDROCARBON GENERATION IN SEDIMENTARY BASINS ADJACENT TO THE SOUTHERN MID-CONTINENT RIFT (UNIVERSITY OF MINNESOTA JULY 1998 REPORT)

COMPUTER MODELING OF HYDROCARBON GENERATION IN SEDIMENTARY BASINS ADJACENT TO THE SOUTHERN MIDCONTINENT RIFT

A final report to:

The United States Department of Energy

and

BDM Petroleum Technologies
P.O. Box 2543
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July 1, 1998

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PROJECT STATUS

In the third and final phase of the collaborative effort between the United States Department of Energy, BDM Petroleum Technologies, and the University of Minnesota's Gibson Computational Hydrogeology Laboratory (hereafter DOE, BDM, and UMN, respectively) a sensitivity analysis was performed to ascertain the role of permeability in petroleum generation and migration within the Midcontinent region throughout the Paleozoic. The results of the sensitivity analysis are detailed below. The analysis required extensive modification of the transient RIFT2D data deck developed in the second trimester of the collaborative effort and detailed in the previous status report. Additional permeability and porosity data for Paleozoic reservoirs in Kansas were provided by BDM personnel and incorporated into the transient data deck. With the assistance of Dr. M. Szpakiewicz and other BDM personnel, the model representation of the Midcontinent region's tectonic evolution was refined. With the completion of this phase of paleohydrologic modeling in the Midcontinent region, UMN has satisfied all requirements of the original contract with the exception of the presentation of a workshop for BDM personnel on the use of RIFT2D software.

SUMMARY OF FIRST AND SECOND-TRIMESTER RESULTS

This final report begins with a brief summary and synthesis of the first and second-trimester progress reports. The first trimester of the joint DOE-BDM-UMN project was devoted to the acquisition of preliminary geologic data and the construction of a steady-state model of the present-day groundwater flow regime along a cross-section originating in the Front Range of the Rocky Mountains and extending eastward across Colorado, Kansas, and terminating in central Missouri atop the Ozark Uplift. The steady state model was used to constrain the present-day permeability distribution and delineate hydrologic boundary conditions for the transient model. The following conclusions were drawn from the steady-state modeling effort. (1) Modern groundwater flow is restricted to the Tertiary and lower Cretaceous (Dakota Sandstone) aquifers. The Cambro-Ordovician aquifer system, while presently stagnant, may have served as a conduit for warm, metalliferous brines (e.g. Garven et al., 1995). (2) Basins to the east of the Central Kansas uplift were insulated from topography-driven groundwater flow originating in the Rocky Mountains. The presence of this structural feature suggests that long-distance petroleum migration from the Denver basin to the Salina and Forest City basins was unlikely. (3) The Ozark uplift forms an approximate groundwater divide and can thus be taken as the eastern boundary of the model domain. In addition, the Front Range of the Rocky Mountains forms a logical western boundary to the model domain.

The second trimester of the joint DOE-BDM-UMN project was devoted to the development of a data deck for transient cross-sectional modeling of petroleum generation and migration along an identical transect through the Midcontinent region. This data deck served as the input for the transient RIFT2D model of coupled fluid flow and heat transfer in evolving sedimentary basins. The transient data deck used seven hydrostratigraphic units to represent the Paleozoic rocks of the Midcontinent basins; an eighth hydrostratigraphic unit was included to represent the Middle Proterozoic flanking sedimentary basins of the deeply buried Midcontinent Rift System (hereafter MRS). The 1250 km cross section was discretized with 70 nodal columns, each of which consisted of between 3-30 nodal rows (see Figure 3 from second trimester progress report). The 600 Ma simulation period consisted of 10 tectonic stages and 12,000 time steps of 50 ka duration. Model results suggest that the thermal history of Paleozoic basins in the Midcontinent region was dominated by conductive heat transfer, despite the development of relatively strong topography-driven flow systems associated with the Ozark, Nemaha, Central Kansas, and post-Cretaceous uplift events. The transient model indicated that Paleozoic source rocks in the Midcontinent region attained thermal maturity in portions of Colorado, where they were buried to depths in excess of 3 km during Cretaceous subsidence and sedimentation; elsewhere, burial depths were insufficient to generate significant amounts of petroleum. It was concluded that the eastward-directed topography-driven flow system associated with post-Cretaceous uplift may have enhanced long-range petroleum migration into Paleozoic basins of western Kansas. However, the presence of the Central Kansas uplift likely inhibited the efficacy of this flow system and thus limited the charging of basins east of the uplift. Finally, the transient model indicated that, due to their insufficient volume, source rocks in flanking basins of the MRS were an unlikely source for petroleum in the overlying Salina and Forest City basins. In this final report, a senstivity study is presented using the transient version of RIFT2D to investigate the role of permeability variations in overpressuring, basin thermal history, and long range oil migration.

DESCRIPTION OF SENSITIVITY STUDY

The results of the sensitivity analysis are discussed below in terms of the effects of variations in permeability on various hydrologic and thermal field variables. Recall that three permeability distributions were investigated: (1) a homogeneous permeability distribution that is characteristic of a fine-grained sandstone; (2) the distribution of Garven et al. (1995), which is characterized by high-permeability Cambro-Ordovician and Lower Cretaceous (Dakota Sandstone) aquifers surrounded by undifferentiated Paleozoic aquitards; and (3) the distribution of Macfarlane (1996), which is characterized by two aquifers, the high-permeability Dakota Sandstone and the moderate-permeability Cambro-Ordovician carbonates, and the surrounding undifferentiated aquitards of very low permeability.

The bedding-parallel permeabilities (κ_{xx}) of all Midcontinent strata were assumed to display a linear dependence on porosity (ϕ):

$$\log[\kappa_{xx}(\phi)] = c_o + c_1\phi \tag{1}$$

where c_o and c_1 are empirically determined coefficients and κ_{xx} carries units of m^2. The preferred transport of pore fluids parallel to bedding rather than across bedding in sedimentary rocks is represented by the permeability anisotropy χ_κ, where

$$\chi_\kappa = \frac{\kappa_{xx}}{\kappa_{zz}} \tag{2}$$

Unfractured sedimentary rocks are characterized by $\chi_\kappa >> 1$. All hydrostratigraphic units are characterized by $\chi_\kappa \sim 100$ in the sensitivity study. The porosities of Midcontinent strata are assumed to obey an "Athy-type" relation, whereby the porosity varies exponentially with effective stress (σ_e):

$$\phi(\sigma_e) = \phi_o \exp(-\beta\sigma_e) \tag{3}$$

The coefficient β is the matrix (rock) compressibility. The effective stress is defined as the difference between total stress (σ_t ;overburden pressure) and fluid pressure (P):

$$\sigma_e = \sigma_t - P \tag{4}$$

It is these material properties (c_o, c_1, χ_κ, and β) that are varied in the sensitivity study of paleohydrology in the Midcontinent region. The material properties that characterize the aforementioned permeability distributions are displayed in Table 1.

Table 1. Material properties employed in sensitivity study of Midcontinent-region paleohydrology. Note: 1 = Crystalline bedrock; 2 = Lower-Cretaceous Dakota Sandstone; 3 = Maquoketa Shale; 4 = Middle Proterozoic (Keweenawan) sandstone and shale (undifferentiated); 5 = Cambro-Ordovician Dolomite; 6 = Cretaceous shale; 7 = Lower Mississippian Dolomite; 8 = Pennsylvanian -- Permian shale and limestone (undifferentiated); and 9 = Chattanooga Shale. All hydrostratigraphic units are characterized by $\chi_K \sim 100$.

			Homogeneous		Garven		Macfarlane	
Unit	ϕ_o	β(km^{-1})	c_o	c_1	c_o	c_1	c_o	c_1
1	0.10	0.0	-20	0	-20	0	-20	0
2	0.40	0.4	-16	10	-16	8	-16	8
3	0.60	0.8	-16	10	-18	6	-20	6
4	0.40	0.2	-16	10	-18	6	-20	6
5	0.30	0.5	-16	10	-16	8	-16	8
6	0.50	0.8	-16	10	-18	6	-20	6
7	0.30	0.5	-16	10	-18	6	-20	6
8	0.30	0.8	-16	10	-18	6	-20	6
9	0.60	0.8	-16	10	-18	6	-20	6

RESULTS OF SENSITIVITY STUDY

Summary

The predominance of fine-grained sedimentary rocks, the presence of structural features, and the disconnected nature of aquifers within the Paleozoic strata of the Midcontinent region limit the efficacy of paleogroundwater flow to modify subsurface temperatures throughout basin history. The thermal history of the Midcontinent region was conduction dominated, despite the development of topography-driven flow systems associated with the Kansas City, Nemaha, Ozark, and post-Cretaceous uplift events. The presence of large volumes of low permeability rock within the Paleozoic basins and the discontinuity of deep aquifers together limited the potential for advective perturbation of the temperature field by these topography-driven flow systems. Therefore, the thermal history of any Paleozoic basin within the Midcontinent region is reasonably approximated by its burial history. A minor advective overprint, attributable to a topography-driven flow system attributable to post-Cretaceous uplift, may be discernible in the basin fill immediately to the west of the Central Kansas uplift. The above results hold independent of the assigned permeability distribution. The ramifications of this sensitivity analysis with regard to petroleum generation and migration are important. Owing to their shallow burial, petroleum generation within Paleozoic source rocks was insignificant everywhere except that area immediately to the east of the Front Range of the Rocky Mountains, where burial during the Cretaceous was sufficient to place source rocks within the oil window. In addition, the limited range of topography-driven flow systems severely attenuated the potential for long-distance migration of petroleum. In particular, the topography-driven flow system attributable to post-Cretaceous uplift was incapable of inducing long-distance petroleum migration into basins east of the Central Kansas uplift.

Field Variables

A suite of contour plots of relevant field variables (*e.g.*, hydraulic head, oil head, temperature, porosity, etc.) for the various permeability distributions is presented in Figures 1-6. The plots depict the field-variable values at (1) the time of maximum burial during Cretaceous sedimentation (~520 Ma) and (2) near the completion of post-Cretaceous uplift (~550 Ma). Note that all times are measured with respect to the onset of the transient simulation of Paleozoic basin evolution. These times were selected for visualization of transient model results because they correspond to (1) a period of maximum overpressuring and petroleum generation (due to deep burial) of Midcontinent basins and (2) a period when the hydraulic gradient across the entire Midcontinent region was a maximum and the resultant flow field was most likely to perturb the temperature field and induce long-distance petroleum migration. As such, these two stages of basin evolution are most relevant to the joint DOE-BDM-UMN project. In contrast, the topography-driven flow systems associated with the Ozark uplift and the smaller-scale Nemaha and Central Kansas uplifts were restricted to sub-basins of the Midcontinent region. Therefore, they were incapable of significantly perturbing the conductive thermal structure or inducing long-distance petroleum migration between sub-basins. The flow systems associated with these events are thus considered subordinate, and, in the interest of conserving space, are not discussed in this report. These results are, however, readily available upon request.

Homogeneous permeability distribution

The hydraulic-head distributions at the aforementioned times for the homogeneous permeability field are displayed in Figures 1a and 3a. The relatively high permeability that characterizes the homogeneous basin severely attenuates the generation of excess hydraulic head within the deepest section of the basin (note the hydraulic-head-contour scale). This, in combination with the absence of appreciable surface topography, renders the Midcontinent region basins nearly stagnant throughout Cretaceous sedimentation. The temperature field during this phase of basin evolution (Fig 2a) reflects the weak groundwater flow system: heat transfer within the Midcontinent region is dominated by conduction, and, consequently, the isotherms are nearly horizontal regardless of which permeability distribution is used.

The surface topography generated by post-Cretaceous uplift (~550 Ma) induces a relatively vigorous eastward-directed flow system within the homogeneous basin (Fig. 3a). The homogeneous basin is characterized by nearly vertical lines of equal head, which are a manifestation of the dominant horizontal flow component across the majority of the basin. Although not visible due to vertical exaggeration, the hydraulic head contours depart from vertical near the western and eastern model boundaries, where the vertical component of groundwater discharge dominates. Adjacent to the Front Range of the Rocky Mountains, the vertical flow component is relatively intense and directed downward, which is indicative of a recharge zone. Here, the downward flux of cool groundwater is of sufficient magnitude to perturb the conductive thermal profile within the basin such that the isotherms are deflected downward (Fig. 4a). The absence of water table relief west of the Central Kansas uplift during this phase of basin evolution inhibits the formation of a strong discharge zone adjacent to the Ozark uplift, which for ms the eastern model boundary. Therefore, with the exception of the region proximal to the Front Range, heat transfer within the Midcontinent region during this phase of maximum regional groundwater relief (~550 Ma) remains conduction dominated, as is indicated by the horizontal isotherms. Note that the apparent slope of isotherms west of the Central Kansas uplift in Figure 4a is an artifact of the extreme vertical exaggeration present in the plot. If the basin's true aspect ratio were preserved in the figure, the isotherms would appear horizontal and the head contours vertical.

Permeability distribution of Garven et al. (1993)

The distribution of hydraulic head within Midcontinent-region basins characterized by a permeability field similar to that of Garven et al. (1993) displays a considerable amount of structure (Figs. 1b and 3b) relative to that of a homogenous permeability field (Figs. 1a and 3a). The assignment of a more realistic (lower) permeability to the fine-grained sediments that dominate the thick Cretaceous section allows the generation of non-trivial (~300 m) excess hydraulic head (i.e. overpressure) and the generation of a relatively vigorous compaction-driven flow system throughout Cretaceous sedimentation. Relaxation of this excess head occurs via discharge within the basal Cambro-Ordovician aquifer complex, which is assigned a permeability several orders of magnitude greater than that of the overlying sedimentary package. Compaction-driven flow within the basal aquifer is of sufficient magnitude to slightly perturb the conductive thermal structure of the basin (Fig. 2b). However, paleothermometers within the rock record would be incapable of preserving this minor advective overprint.

As was the case in the homogeneous basin, a topography-driven flow system was established across the western half of the Midcontinent region throughout post-Cretaceous uplift. The hydraulic-head structure during this phase of basin evolution (Fig. 3b) reflects the permeability contrast between the Cambro-Ordovician and Dakota-Sandstone aquifer complexes and the surrounding aquitards. The curvature of head contours within the Cretaceous aquitard reflects the vertical leakage of groundwater into the Dakota-Sandstone aquifer complex; similar, albeit weaker, curvature within underlying aquitards is indicative of downward leakage into the basal Cambro-Ordovician aquifer complex. Within the Dakota-Sandstone and Cambro-Ordovician aquifer complexes, the head contours are nearly vertical, which is indicative of dominantly horizontal flow within these conduit-like permeable structures. A similar hydraulic-head structure was observed in the steady-state modeling and described in the first-trimester status report. However, transient modeling has revealed that the actual magnitude of horizontal discharge within these conduit-like aquifers was, in fact, significantly weaker than indicated by the steady-state modeling. Clear evidence of this conclusion is embodied in the modeled thermal structure of the basin during this phase of basin evolution (Fig. 4b). Apparently, flow within the Dakota-Sandstone and Cambro-Ordovician aquifer complexes was of insufficient magnitude to perturb the conductive thermal profile. Close inspection of the contoured thermal profile (Fig. 4b) reveals a nearly indiscernible advective perturbation of the conductive temperature field. Again,. paleothermometers within the rock record would be incapable of preserving this overprint.

Permeability distribution of Macfarlane (1996)

The permeability distribution of Macfarlane (1996), which assumes the existence of a permeable Dakota-Sandstone aquifer complex encapsulated within thick aquitards and bounded by a basal Cambro-Ordovician complex of intermediate permeability, generates an impressive compaction-driven flow system during Cretaceous sedimentation (Fig. 1c). Nearly 3 km of excess hydraulic head is generated at the completion of Cretaceous sedimentation, and this head is primarily dissipated via horizontal flow within the Dakota-Sandstone aquifer complex. Despite the amount of overpressuring and the intensity of the compaction-driven flow system within the Dakota-Sandstone aquifer complex, the thermal structure during this phase of basin evolution remains conduction dominated (Fig. 2c).

The low thermal diffusivity that characterizes the aquitards of Macfarlane's (1996) permeability distribution retards the rate at which excess head can be dissipated. As such, the lower aquitard complex, which separates the Dakota-Sandstone aquifer complex from the Cambro-Ordovician strata, and a portion of the Cretaceous aquitard remain overpressured throughout the early stages of post-Cretaceous uplift. The distribution of hydraulic head (Fig. 3c) thus reflects the coexistence and interaction of a topography-driven flow system and a compaction-driven flow system. Near the Front Range, the downward migration of meteoric recharge is hindered by the continued expulsion of pore fluids from the overpressured Cretaceous aquitard. Further to the east, away from the region of maximum overpressuring in the Cretaceous aquitard, the downward leakage of meteoric recharge into the Dakota-Sandstone aquifer complex is more pronounced. The Dakota-Sandstone aquifer complex is also fed by upwardly-directed pore fluids driven from the overpressured underlying aquitard. Again, despite the complexity of this hydraulic head distribution, the corresponding flow rates are of insufficient magnitude to perturb the conductive thermal profile (Fig. 3c). The flow rate within the Dakota-Sandstone aquifer complex is dependent on the rate of leakage, both compaction and topography driven, within the surrounding aquitards. The permeability distributions of both Garven et al. (1993) and Macfarlane (1996) assign sufficiently low permeabilities to the aquitards so as to limit the discharge within the conduit-like aquifers to levels for which the thermal Peclet number is much less than unity and the advective effects of groundwater flow are negligible.

Petroleum Generation

Despite the interesting hydraulic-head structures that characterize the various assigned distributions of Midcontinent-region permeability, the thermal evolution of the Midcontinent region is dominated by conductive heat transfer. Therefore, the petroleum generation within Paleozoic source rocks is not strongly dependent of permeability and is largely governed primarily by their maximum burial depth and duration of burial. Contour plots of present-day vitrinite reflectance and generated oil-mass are provided in Figures 5a and 5b, respectively. Both vitrinite reflectance and generated oil-mass attain maximum values within Cambro-Ordovician source beds proximal to the Front Range of the Rocky Mountains, where the burial depth of Paleozoic basins was greatest.

CONCLUSIONS

This final report summarizes the work completed in the DOE-BDM-UMN collaborative effort to model hydrocarbon generation and migration in sedimentary basins of the Midcontinent region. The first trimester of research was devoted to steady-state modeling of the Midcontinent region with the objective of constraining the present-day permeability distribution and delineating hydrologic boundaries for the transient hydrodynamic model. The second trimester was devoted to the construction and testing of a transient data deck for the RIFT2D software package. This data deck was used to obtain preliminary model results for the hydrodynamic and thermal evolution of the Midcontinent region throughout the Paleozoic. The final trimester of research was devoted to the refinement of this transient data deck and its use in a sensitivity study that analyzed the role of permeability in the generation and migration of petroleum within the Paleozoic basins of the Midcontinent region. On the basis of steady-state and transient model results, the following conclusions are drawn regarding the hydrodynamic and thermal evolution of Midcontinent region basins and petroleum generation and migration within these basins:

1. The thermal histories of Paleozoic basins within the Midcontinent region are conduction dominated. The topography and compaction-driven flow systems that were established with various sub-basins throughout the Paleozoic were incapable of significantly perturbing the conductive thermal structure.

2. The majority of modern groundwater flow is restricted to the Tertiary and lower Cretaceous (Dakota Sandstone) aquifers. The basal Cambro-Ordovician aquifer is presently stagnant; however, it may have served as a locus of groundwater discharge in the past (Garven et al., 1993).

3. The Central Kansas uplift formed a structural impediment to groundwater migration that insulated basins to the east from topography-driven groundwater flow originating in the Rocky Mountains. This conclusion argues against hydrodynamically-driven, long-distance petroleum migration from the Denver basin to the Salina and Forest City basins.

4. Petroleum generation within the Midcontinent region was restricted to the Cambro-Ordovician source beds within sub-basins adjacent to the Front Range of the Rocky Mountains, where deep burial during Cretaceous sedimentation exposed these rocks to temperatures sufficient for petroleum generation. During the Paleozoic, source rocks within the flanking sedimentary basins of the Middle Proterozoic MRS were buried (or re-buried) to sufficient depths to induce petroleum generation; however, the volume of this source material was likely insufficient to render it a viable source for oil trapped in overlying Paleozoic basins.

5. Long-distance migration of petroleum within the Midcontinent region, particularly migration east of the Central Kansas uplift, cannot be ascribed to topography or compaction-driven groundwater flow in the modeled cross section.

FUTURE RESEARCH

The results of the DOE-BDM-UMN collaborative effort to model hydrocarbon generation and migration in sedimentary basins of the Midcontinent region leave the source of petroleum in the Salina and Forest City basins, which are situated to the east of the Central Kansas uplift, enigmatic. At the onset of this project, the most favorable hypothesis for both source and migration of petroleum invoked oil generation in deeply buried Paleozoic basins adjacent to the Front Range of the Rocky Mountains and subsequent migration via the large-scale eastward-directed topography-driven groundwater flow system developed during post-Cretaceous uplift. However, the steady-state and transient modeling of the paleoflow system suggests that (1) the post-Cretaceous topography-driven flow system was of insufficient strength to induce petroleum migration into the Salina and Forest City basins and (2) the Central Kansas uplift formed a structural impediment to this flow system that severely attenuated eastward-directed groundwater migration. Therefore, it appears unlikely that groundwater migration within the modeled cross section was capable of transporting petroleum long distances to the Salina and Forest City basins.

An alternative hypothesis invokes petroleum generation within deeply buried source rocks of the Anadarko basin, followed by long-distance northward-directed migration via a topography-driven groundwater flow system that developed during the Ouchita orogeny. The validity of this hypothesis could be tested using steady-state and transient (RIFT2D) groundwater modeling techniques similar to those reported here.

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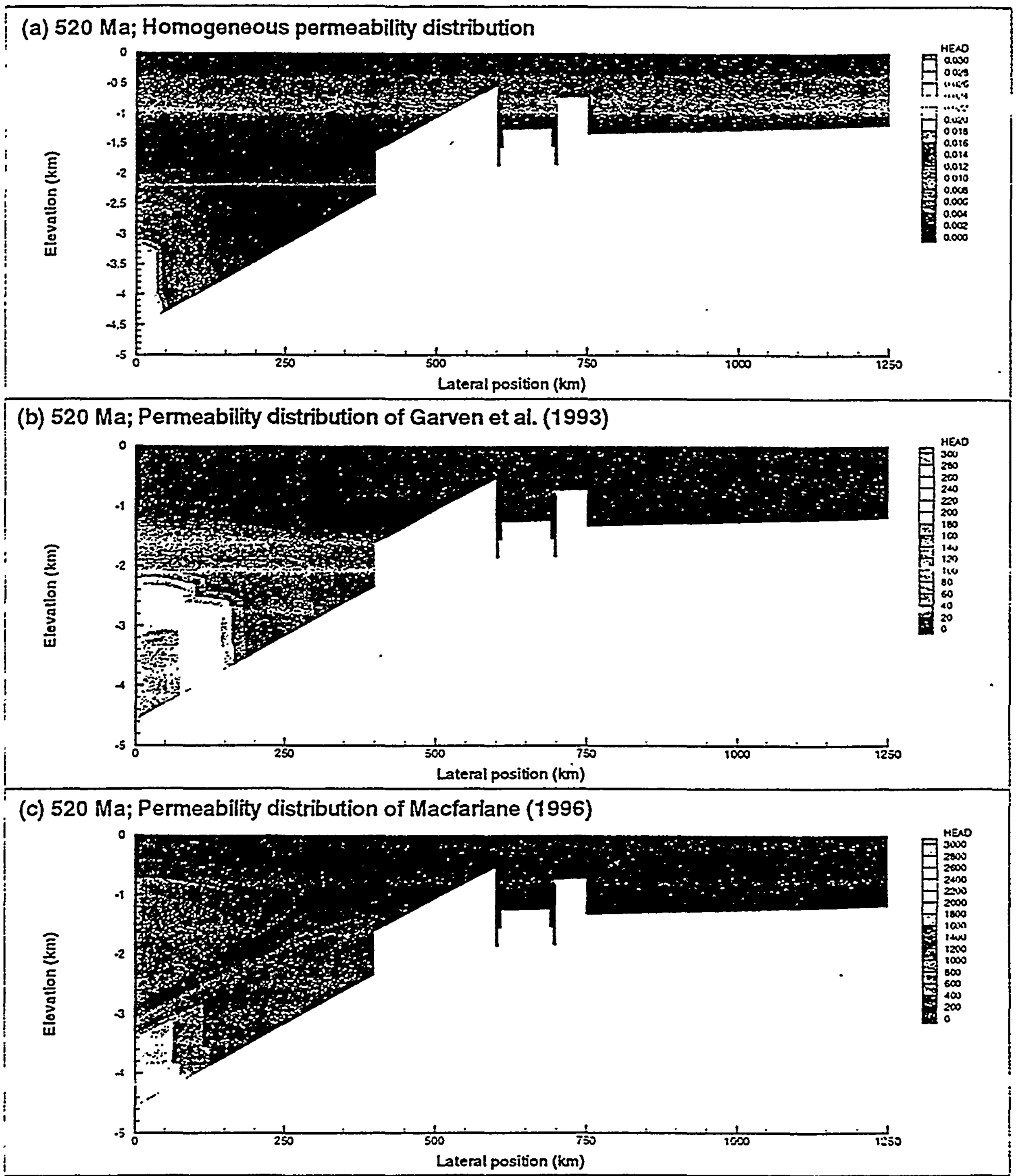

Figure 1. Cretaceous hydraulic head as a function of permeability distribution.

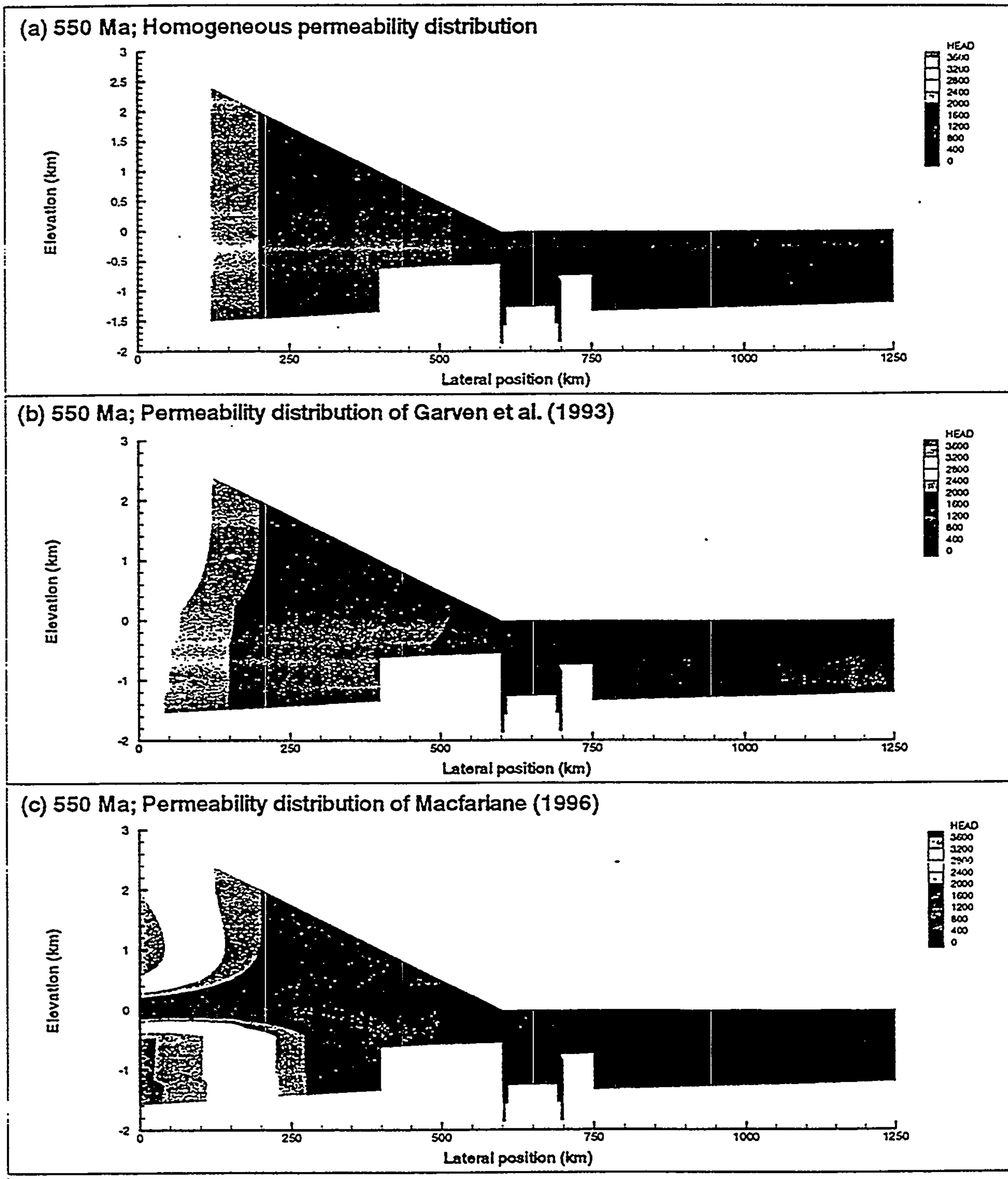

Figure 3. Post-Cretaceous hydraulic head as a function of permeability distribution.

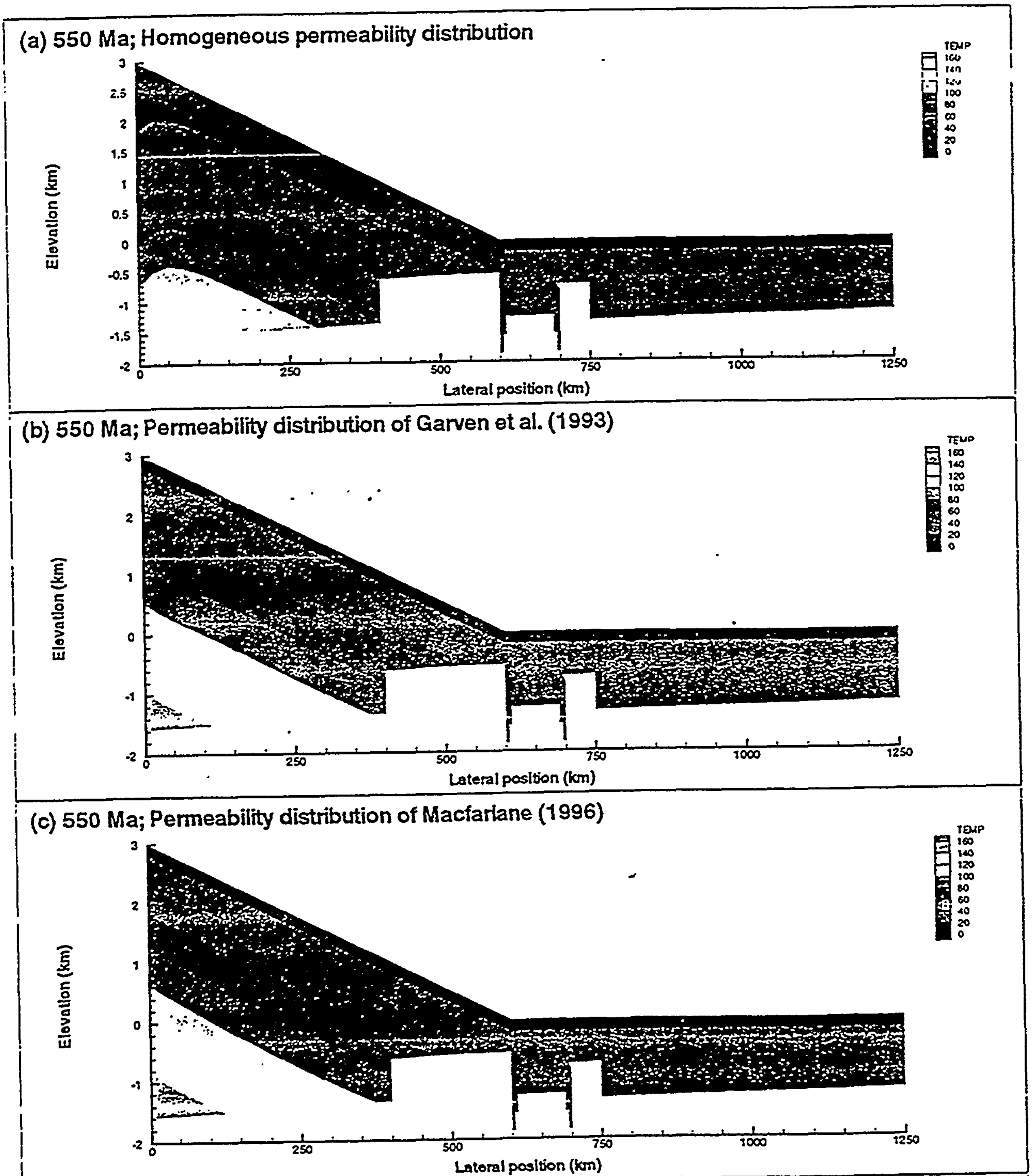

Figure 4. Post-Cretaceous thermal structure as a function of permeability distribution.

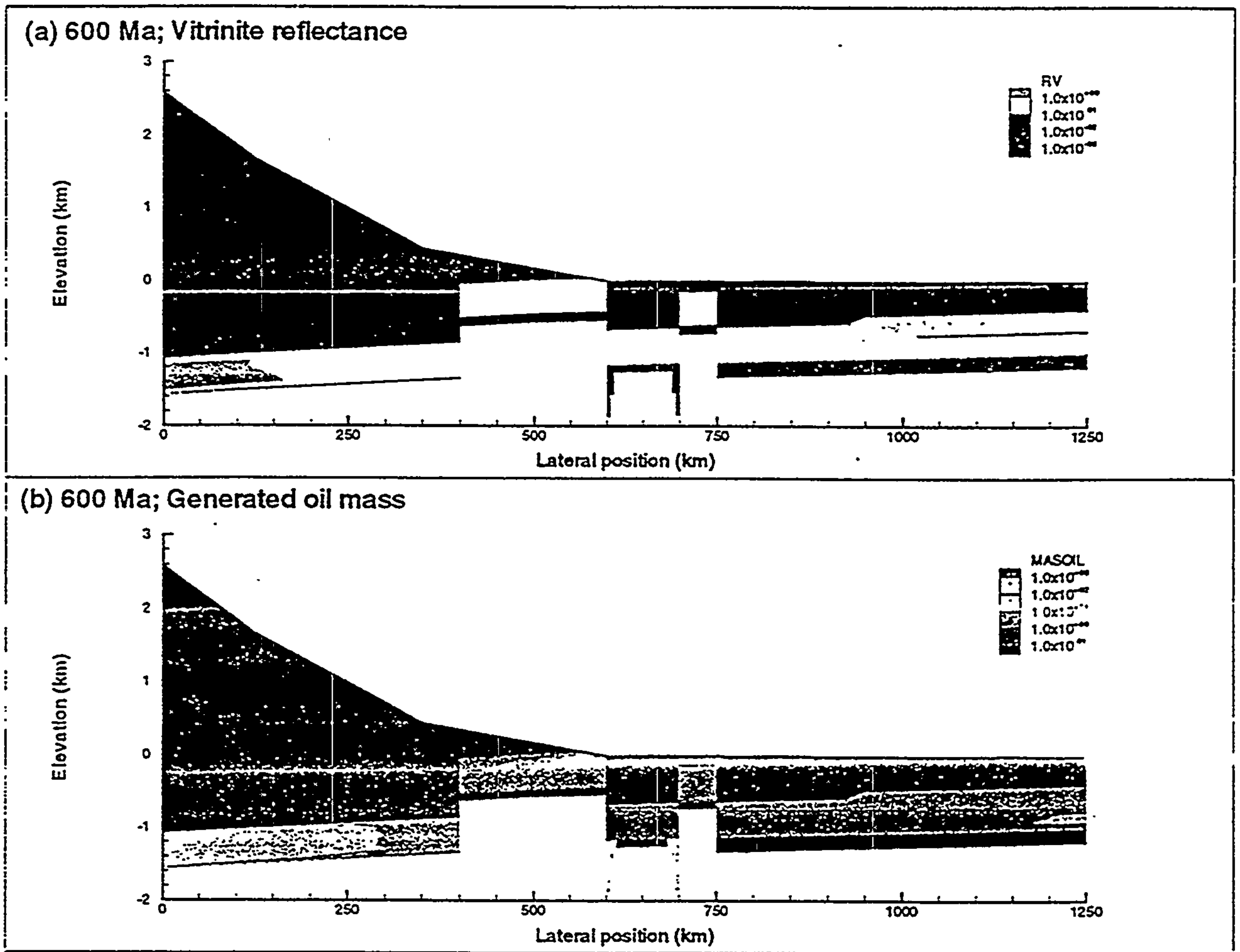

Figure 5. Computed vitrinite reflectance and oil generation within Midcontinent basins.

APPENDIX 2
THERMAL ASSESSMENT OF POSSIBLE SOURCE ROCKS, AND PETROLEUM GENERATION AND OCCURRENCE, IN PARTS OF THE SALINA AND FOREST CITY BASINS ADJACENT TO THE NEMAHA RIDGE
(UNIVERSITY OF TULSA FEBRUARY 1997 REPORT)

Final Report / February 1997

Thermal Assessment of Possible Petroleum Source Rocks, and Petroleum Generation and Occurrence, in Parts of the Salina and Forest City Basins Adjacent to the Nemaha Ridge.

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The Forest City Basin and Adjacent Areas

A. Geological history

The Forest City Basin is a Paleozoic basin extending from northeastern Kansas into adjacent parts of Missouri, Nebraska, and Iowa. The eastern boundary of the basin is formed by the Ozark Uplift of central Missouri. The northern and northeastern boundary is less well defined, and is the updip limit of Middle and Upper Paleozoic strata in Iowa and Nebraska. The southern boundary of the basin is the Bourbon Arch, a roughly east-west subsurface feature. The western boundary of the basin is the Nemaha Uplift.

The Forest City Basin is part of a larger Paleozoic basin that extended from Missouri to the Central Kansas Uplift. Precambrian basement includes igneous rocks as well as sedimentary and metasedimentary rock (Merriam, Cole, and Hambleton, 1961). The Precambrian Midcontinent Rift formed a narrow trench trending north-northeast to south-southwest, and the sedimentary strata filling this trench are unusually thick. The Amoco #1 Eischeid drilled in Carrol County, Iowa, penetrated 14,898 feet of Precambrian clastics in the Midcontinent Rift (Anderson, 1990). An unconformity at the top of the Precambrian indicates that erosion and lack of deposition occurred from the late Precambrian through the Late Cambrian.

Seas covered the area of the present Forest City Basin during the Late Cambrian through the Early Ordovician. In Kansas and northwestern Missouri, most of the Upper Cambrian and Lower Ordovician is dolostone of the Arbuckle Group (see Table 1) (Merriam, 1963; McCracken and McCracken, 1965). This dolostone was deposited in a large carbonate bank in a sea that extended over much of what is now the central United States. In surface exposures in northeastern Iowa, Cambrian strata tend to be sandstones that were probably deposited on the margin of the sea (Anderson, 1983). Deposition ended with the withdrawal of the seas from much of the midcontinent region at the end of the Early Ordovician.

Clastics of the Simpson Group and carbonates of the overlying Viola Formation were deposited in Middle Ordovician seas that covered almost the entire U.S.A. These two formations are separated by an unconformity. In Iowa, the Viola is replaced by the mixed shales and carbonates of the Decorah Formation and the predominantly carbonate Galena Formation (Anderson, 1983; Hatch et al., 1987). The Upper Ordovician Maquoketa Shale (equivalent to the Sylvan Shale) is separated from the underlying Middle Ordovician strata by an unconformity.

Following a depositional hiatus at the close of the Ordovician and beginning of the Silurian, marine carbonates were deposited in the Forest City Basin and over much of North America. Hunton Group strata were deposited over most of Kansas, Nebraska, Missouri and Oklahoma, and stratigraphically equivalent strata were deposited in Iowa. An unconformity at or near the top of the Silurian is present from Oklahoma (Amsden, 1975) through Kansas (Merriam, 1963) into Iowa (Anderson, 1983). During the Late Silurian, shale deposition replaced carbonate deposition in northern Iowa. Following an interruption of deposition and a period of erosion in the Late Devonian, deposition again resumed with deposition of the Chattanooga Shale (equivalent to Woodford Shale).

During the Mississippian, extensive carbonate banks extended from Oklahoma to Iowa, although deposition was not continuous and several unconformities are recognized within the Mississippian section. Deposition continued until the end of the Mississippian in Kansas (Merriam, 1963) but ended in Iowa at the end of Meramecian deposition (Anderson, 1983). An unconformity separates the Mississippian from the overlying Pennsylvanian throughout the United States.

A thick section of clastics and carbonates was deposited in the Forest City Basin during the Pennsylvanian. About 2600 feet of Pennsylvanian strata are present in the Carter #1 Davidson well, which was used in our model (see Below). This thickness far exceeds the combined thickness of the other Paleozoic strata in the Forest City Basin, so deposition during the Pennsylvanian is the most significant event in the burial history of Paleozoic rocks in the Forest City Basin.

Surface outcrops of Permian rocks are present in the western part of the Forest City Basin in Kansas and Nebraska, but the original extent and thickness of Permian rocks is not known.

No Mesozoic strata are known from the Forest City Basin, however in western and central Kansas and northwestern Iowa, Upper Cretaceous strata are known from surface outcrops adjacent to the Forest City Basin.

B. Tectonic history

Two major tectonic events are significant in the history of the Forest City Basin. Uplift of the Chautauqua Arch during the Ordovician through Devonian (Snyder, 1968) caused complete erosional removal of the Simpson Group, Viola and Maquoketa formations, and Hunton Group from the southern edge the basin. Formation of this arch separated the Forest City Basin from the Cherokee Platform to the south.

Prior to the Pennsylvanian, the Forest City Basin was just part of a larger basin that extended from western Kansas and western Nebraska into Missouri and Iowa. During the Early Pennsylvanian, the rise of the Nemaha Uplift separated this larger basin into the Salina Basin on the western side of the Nemaha Uplift and the Forest City Basin on the eastern side.

Oil production

Most of the oil and gas production within the Forest City Basin is from two major trends. Other minor producing trends have been mentioned in Newell et al. (1987), but these will not be reviewed here.

A. Oil production: eastern trend

The eastern trend extends from Miami and Franklin counties in Kansas into Cass and Jackson counties in Missouri (i.e., near Kansas City). Oil production in this area is from Pennsylvanian reservoirs at depths generally less than 1000 feet.

The earliest oil and gas development in Kansas occurred in Miami County near the southern end of the eastern production trend. In 1854, George W. Brown had moved from Pennsylvania to Lawrence, Kansas, where he was a newspaper editor. In 1857, he was sent a sample of petroleum from a surface seep in Miami County. In 1860, Brown visited his former home in Pennsylvania and learned of the interest in the Drake oil discovery near Titusville. In June, 1860, a company formed by Brown drilled three wells in Miami County near the town of Paola. The first two were abandoned at about 100 feet, but the third had oil shows at 275 feet (Schruben, 1972). The Civil War ended further oil and gas exploration in Kansas until 1865.

From 1865 until about 1900, numerous oil and gas wells were drilled in the eastern production trend of the Forest City Basin, but most had marginal production. Moore (1927) reported that for eastern Kansas wells 50 barrels a day was considered a good well and 1 to 2 barrels a day was more typical, although production rates of as much as 500 barrels per day had been reported. By 1886 production was sufficient to support a refinery at Paola (Schruben, 1972).

The gravity of oils in the eastern Forest City Basin tends to be low. Moore (1927) reported an average API gravity of 31°. Schruben (1972) reported that in 1905 when Standard Oil stopped buying oil with API gravity lower than 30°, this eliminated the market for 30% of Kansas crude.

B. Oil production: western trend

The second producing trend runs roughly north-northeast to south-southwest along the western edge of the Forest City Basin. This trend follows the eastern side of the Nemaha Uplift from Morris and Lyon counties in Kansas, through Richardson County, Nebraska (i.e., the southeastern-most county in Nebraska), and into Atchison and Holt counties in the northwestern corner of Missouri (Burchett et al., 1983; Leighner and Irwin, 1969).

Along this trend, traps are commonly small anticlinal closures formed during regional uplift of the Nemaha. The reservoirs include Viola, Hunton, and Pennsylvanian strata. Examples of such fields are Davis Ranch field in Wabaunsee County (Curtis, 1960a), John Creek field in Morris County (Curtis, 1960b), and Strahm Field in Nemaha County (Elster, 1960). These oils also tend to have low API gravities. In the Davis Ranch field, API gravities are 29.5° (Viola reservoir), 19.3° (Hunton reservoir) and 31° (Pennsylvanian reservoir) (Curtis, 1960a). Oils from the other two fields mentioned have comparably low API gravities (Curtis, 1960b; Elster, 1960).

Discoveries on the western side of the Forest City Basin began in 1939 with the discovery of the Falls City Field in northwestern Missouri (Brandt, 1960; Newell et al. 1987), but most of the fields along this production trend were discovered in the late 1940's or 1950's.

C. Oil potential

The eastern trend has been extensively drilled and probably holds little potential for significant new oil and gas discoveries. Production along the western trend is limited to about 30 isolated, generally small fields, so additional fields could be found along this trend. The area between the eastern and western trends has been sparsely drilled and might have the best potential for discovery of new oil and gas fields. The area on the western slope of the Nemaha Uplift on the western production trend has also been very lightly drilled (i.e., commonly about 0 to 8 wells per township), and probably has considerable potential for new field discoveries.

Potential source rocks

The Chattanooga Shale (commonly referred to simply as "Kinderhook" on sample logs and drillers' reports) is the stratigraphic equivalent of the Woodford Shale, which is widely recognized as a major source rock in Oklahoma. In wells along the western production trend, the Chattanooga is commonly 20 to 40 feet thick. Its organic carbon contents in the Forest City Basin are not known.

Maquoketa Shale might have sufficient organic carbon to be a potential source rock, although Hatch (personal communication, 1997) expressed some doubt about the possibility that the Maquoketa is a source rock in the Forest City Basin.

Hatch et al. (1983) reported organic carbon concentrations as high as 41 wt. % from a core of the Gutenberg Member of the Decorah Formation taken from the Natural Gas Pipeline #1 E.M. Greene well in Washington County, southeastern Iowa. The Gutenberg is interbedded organic-rich shales and fossiliferous carbonates in this core. The subsurface distribution of the Gutenberg is not well known, but it was not present in the Amoco #1 Eischeid well in northwestern Iowa.

Pennsylvanian strata might have sufficient organic contents to be potential source rocks, but preliminary modeling of the Pennsylvanian strata in the Carter #1 Davidson well indicates that the Pennsylvanian section is thermally immature and would not have generated hydrocarbons.

Original scope of research

The original scope of this research was to sample and analyze source rocks and crude oils from eastern Kansas. The source rocks were to provide data on organic carbon richness (TOC) and degree of thermal maturity (as vitrinite reflectance, R_o). The oils were to be analyzed by gas chromatography to attempt to link crude oils to their source rocks.

During the initial stages of planning this research, we were aware that a team of Kansas Geological Survey and USGS researchers had already carried out similar sampling, but they had only published one short summary paper (Newell et al., 1987) and ended further work on the project in about 1987. In July, 1996, Lynn Watney, a co-author of the Newell et al. paper, indicated that the amount of sampling done by the Kansas Geological Survey group was much more extensive that what had been published, and that most of the sampling we had planned would simply duplicate their work. Watney offered to allow us to use the Kansas Geological Survey data. However, when he offered the data, Watney was unaware that Joseph Hatch, another co-author, intended to prepare a more comprehensive paper using the data. Hatch offered to allow us to use the data and review his research paper after he completed his paper. Hatch confirmed that our planned sampling and analyses would duplicate the work that had already been done. Hatch originally intended to complete his paper in October, 1996. This would have allowed us to incorporate the Kansas Geological Survey data into our research with only a short extension in the time of our contract with BDM. Unfortunately, Hatch's paper was not written until December, 1996, and in February, 1997, was being revised by the co-authors. We have still not seen the manuscript. The need to complete our work in a timely manner has prevented our research from using any of the Kansas Geological Survey's data that have not been published.

Revised research plan

Gathering the source-rock and crude-oil data was intended to support basin modeling of the Forest City Basin. After consulting with BDM and DOE technical monitors, our original contract was modified to focus on just the basin-modeling phase of our research. Lacking data, we would need to make some simplifying assumptions about basin history, but a preliminary basin model could be developed for revision and improvement in a later phase of the research. This paper presents the findings of this preliminary modeling.

Results of basin modeling

We modeled the Forest City Basin along an east-west line following Township 15 South across the southern part of the Forest City Basin. This is shown in Figure1. An east-west line crossing the basin farther north might have encountered a deeper part of the basin where potential source rocks could be more mature, but well control is poorer farther north and the southern line was selected more for the availability of data than for an optimum location within the basin.

Carter #1 Davidson
Section 29-T15S-R11E
Lyon County, Kansas

Of the three wells used in the model, the Carter #1 Davidson is the center well (Location B, Figure 1). It is located just east of the Nemaha Uplift and is in the deepest part of the Forest City Basin along the east-west line of our model. Samples were described by the Kansas Sample Log Service (their log number 2358), and their formation boundaries and lithologic descriptions form the basis for modeling the well. Total depth of this well is 3470 feet.

The burial history curve for this well follows potential Middle Ordovician through Lower Mississippian source rocks. The plot of depth through time with superimposed isotherms is shown in Figure 2, while Figure 3 shows lithologies and the oil generation window (stippled). Prior to the Pennsylvanian, burial of these potential source rocks was less than about 2000 feet, and heating was insufficient to generate hydrocarbons. Rapid deposition of the thick Pennsylvanian strata buried potential source rocks at about 4000 feet. Deposition was so rapid that heat flow was insufficient to keep the new sediments at thermal equilibrium. Significant deposition ended after the Pennsylvanian, but the potential source rocks did not reach temperatures adequate to generate hydrocarbons until the Mesozoic. Source rocks in the Simpson Group, Maquoketa Shale, and Chattanooga Shale are marginally mature with R_o values of 0.5 to 0.6 %. On the burial history plot, strata with R_o values of 0.5% or greater are shaded gray.

Corbin E. Robison #1 Knoche

Section 24-T15S-R22E

Miami County, Kansas

The eastern-most well on the line is the #1 Knoche drilled in 1965 by Corbin E. Robison (Location C, Figure 1). Total depth of this well was 1590 feet. Formation tops are taken from the Ira Rinehart scout card RH-184 dated 12/22/65. This well was completed as a dry hole.

The Knoche well is on the eastern edge of the Forest City Basin, and the Paleozoic section is not as thick as that of the Davidson well. As a result, the total thickness of the potential source rocks is less, and the burial and associated heating is not as great. As in the Davidson well, the only significant burial occurred during the Pennsylvanian and the greatest amount of heating occurred after the start of the Mesozoic. Modeling the burial history for the Knoche well shows that the potential source rocks only reached a thermal maturity equivalent to an R_o of about 0.4 % (Figure 4). Source rocks in this part of the Forest City Basin probably did not generate hydrocarbons.

S.K.D. #1 Kyler

Section 5-T15S-R7W

Ellsworth County, Kansas

S.K.D. drilled the Kyler well to a total depth of 3600 feet in 1973 and completed the well as a dry hole. Drill-stem tests recovered minor shows of gas in the Upper Pennsylvanian and Permian section. Formation tops are from the Petroleum Information scout card issued 4/16/73. This well is the western-most well in the east-west line of our model (Location A, Figure 1), and the well is actually west of the Forest City Basin and in the Salina Basin. It was necessary to extend the line far to the west of the Davidson well, because wells between the Kyler and Davidson wells have a stratigraphic column and burial history that is essentially the same as the Davidson well. Even the Kyler well, which is approximately 100 miles east of the Davidson well, has a very similar burial history to that of the Davidson well. The top of the Arbuckle in the Kyler well is only about 200 feet deeper than it is in the Davidson well.

The burial history of the source rocks in the Kyler well are very similar to that for the Davidson well (Figure 5). This indicates that mature source rocks probably extended westward from the Forest City Basin into the Salina Basin. This would be expected because prior to uplift of the Nemaha during the Early Pennsylvanian, the Forest City and Salina basins were combined into a single large basin. The model for the Kyler well indicates that mature source rocks are probably present in the Salina Basin.

Discussion of basin modeling results

Our models show that lower Paleozoic source rocks in the Forest City Basin are probably mature enough to have generated oil. The maximum thermal maturity reached corresponds only to an R_o value of 0.5 to 0.6 %, so the source rocks have just reached the lower end of the oil-generation range. This means that potential source rocks shallower in the section will be immature. This, of course, then eliminates oil generation from the Mesozioc part of the Forest City Basin. Within the Forest City Basin, mature source rocks would be expected along the western production trend and perhaps into the central region between the eastern and western production trends. Source rocks along the eastern production trend are probably immature.

We could have selected a well on the Nemaha Uplift for the western-most well in our cross section, but the complexity of modeling both the movement of the Nemaha and the more extensive erosional losses on the uplift prevented modeling such a well during the limited time available for this study. Uplift and probable erosion of the source rocks makes it unlikely that a well on the Nemaha Uplift encountered mature source rocks. The Kyler well established that source rocks west of the Nemaha Uplift have a burial history and thermal maturity similar to source rock in the vicinity of the Davidson well in the western production trend of the Forest City Basin. For this reason, it is probably better to consider the Nemaha Uplift as a small interruption in an otherwise continuous layer of marginally mature source rock that extended west of the Forest City Basin rather than consider the Nemaha Uplift as the western limit of source rock. Prior to the Early Pennsylvanian rise of the Nemaha Uplift, oil generated in the eastern Salina Basin could have migrated into the Forest City Basin.

Refining the models and future research

The burial histories and thermal-maturity models presented in this report require additional refining before they can give final conclusions about the oil and gas potential of the Forest City Basin. In preparing our burial histories, we have had to make some rough estimates of erosional losses, and these are shown in Table 2. Additional stratigraphic correlation and incorporation of R_o data should improve the accuracy of these estimates.

We have also used very general lithologic characterizations of the stratigraphic units in our model. The lithology of each unit determines the amount of compaction of that unit during burial and, hence, the overall burial history for all source rocks in the geologic column. Further refining of our models will require more detailed lithologic description for each stratigraphic unit.

The activation energy for the transformation of kerogen into oil or gas is also important for accurate modeling. Hatch (personal communication, 1997) indicated that he thought that the activation energy for certain Ordovician kerogens is much lower than what is generally recognized. If Hatch's opinion can be verified by laboratory measurement of the activation energy of Ordovician kerogen, then Ordovician source rocks would have reached thermal maturity at temperatures lower than anticipated from our current modeling. We expect to measure the activation energy of Ordovician kerogen in the next phase of our research. The activation energy value we get will not only help improve the Forest City Basin models, but it would also be significant for any other basin that holds Ordovician source rocks.

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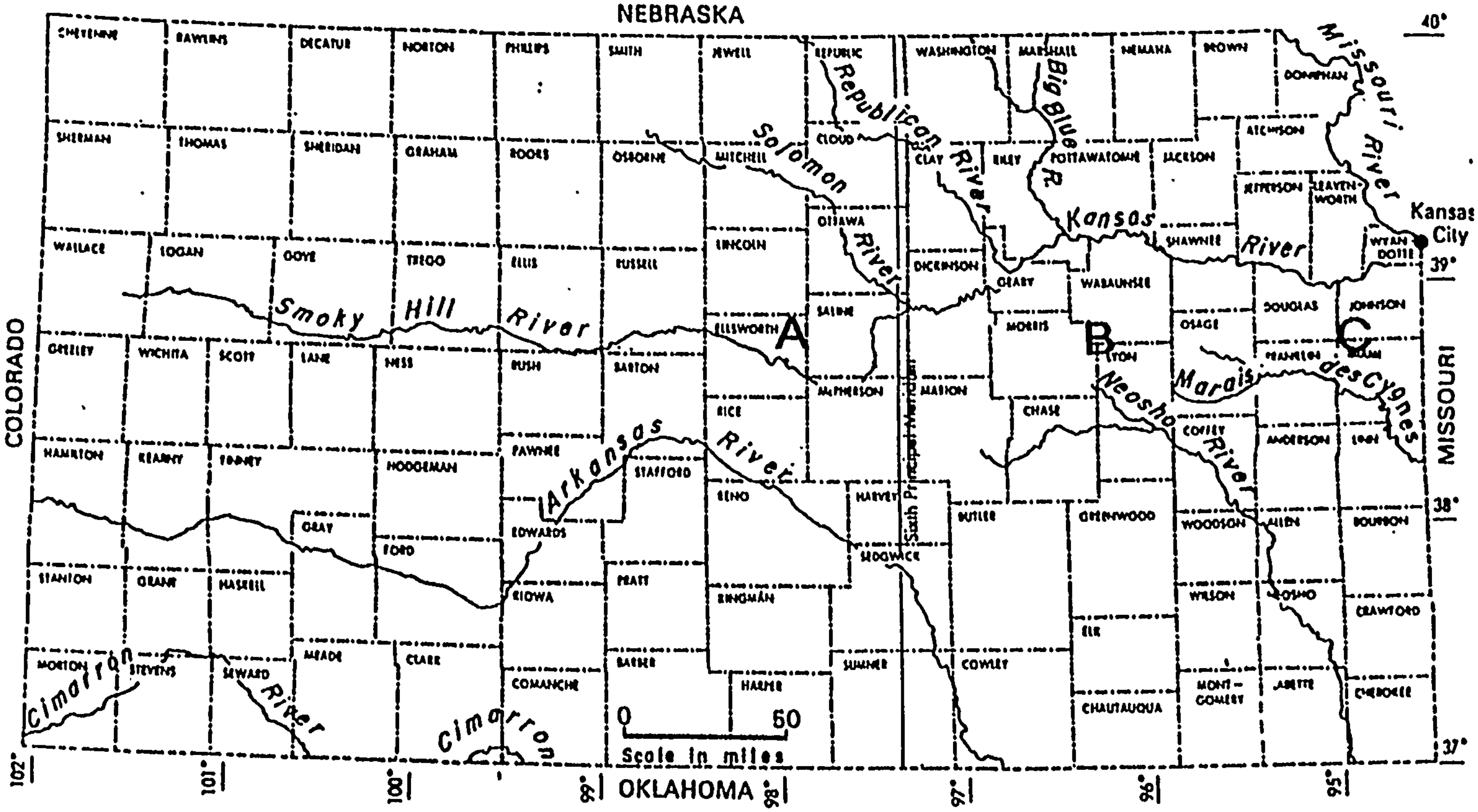
System		Stage	Group	Formation	
Pennsylvanian		**Virgilian**			
		Missourian			
		Desmoinesian			
		Atokan			
		Morrowan			
Mississippian		Chesterian			
		Meramecian			
		Osagian			
		Kinderhookian		**Chattanooga Shale** (= Woodford Shale)	
Devonian			**Hunton**		
Silurian					
Ordovician	Up.			**Maquoketa Shale** (= Sylvan Shale)	
				Viola Limestone	Galena Fm. Decorah Fm. (includes **Gutenberg Shale** Member)
	Mid.		**Simpson**	Platteville Limestone	
				St. Peter Sandstone	
	Low.		**Arbuckle**		
Cambrian					

Table 1 Simplified stratigraphic units of Forest City Basin and adjacent Iowa. Names used in the models or in the text of this paper are shown in **bold face**

Time of erosion	Thickness of strata lost (in feet)
From end of the Pennsylvanian to present	1000
From end of Atokan deposition to start of Desmoinesian deposition (middle Pennsylvanian)	500
From end of Mississippian deposition to first Pennsylvanian deposition	500
From end of Hunton deposition to start of Chattanooga deposition (Middle and Late Devonian)	300
From end of Maquoketa deposition to start of Hunton Group deposition (Late Ordovician to Early Silurian)	400
From end of Viola deposition to start of Maquoketa deposition (Middle and Late Ordovician)	300
From end of Arbuckle deposition to start of Simpson Group deposition (Early Cambrian)	800

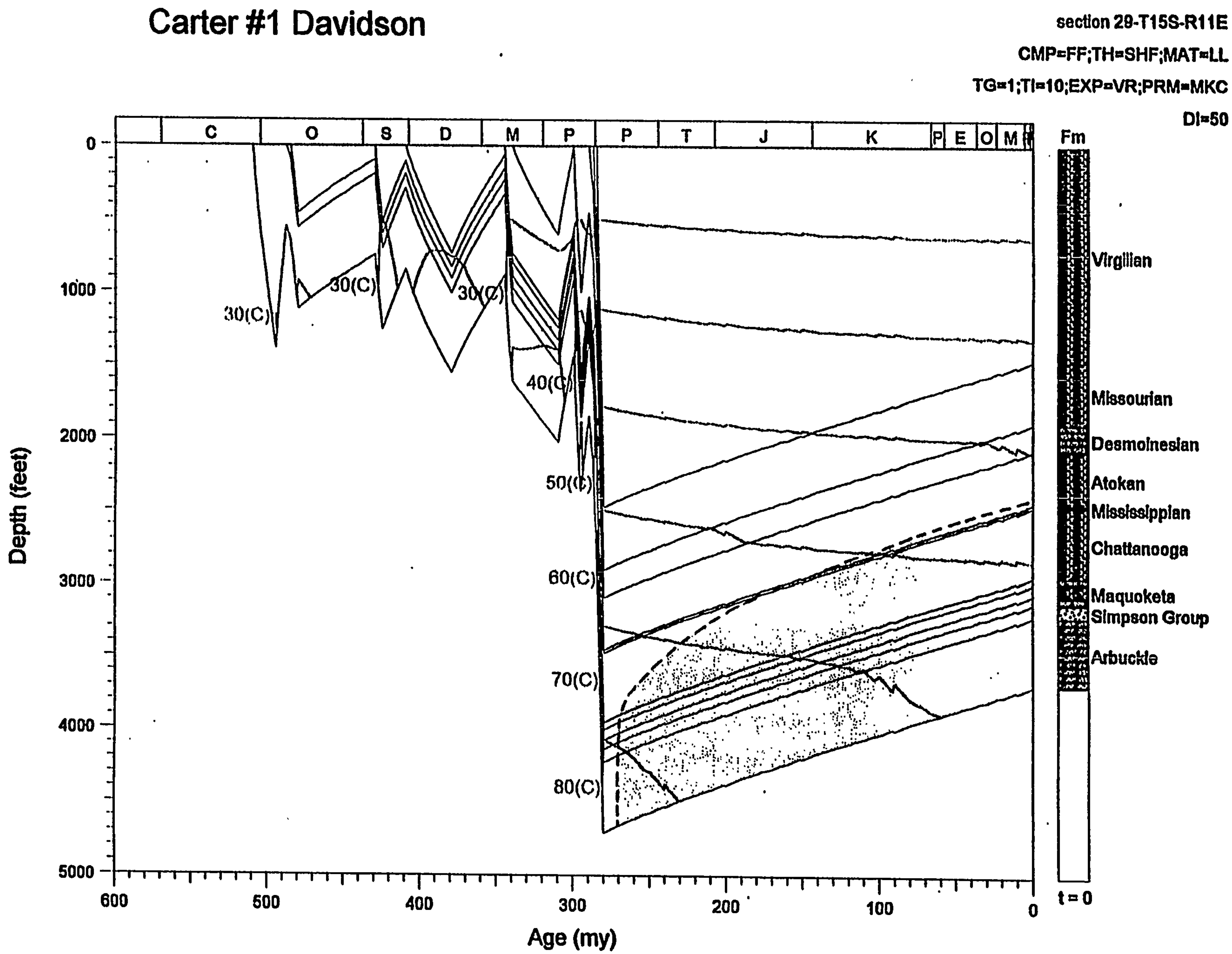
Table 2 Estimates of erosional losses used in the burial histories presented in this report.



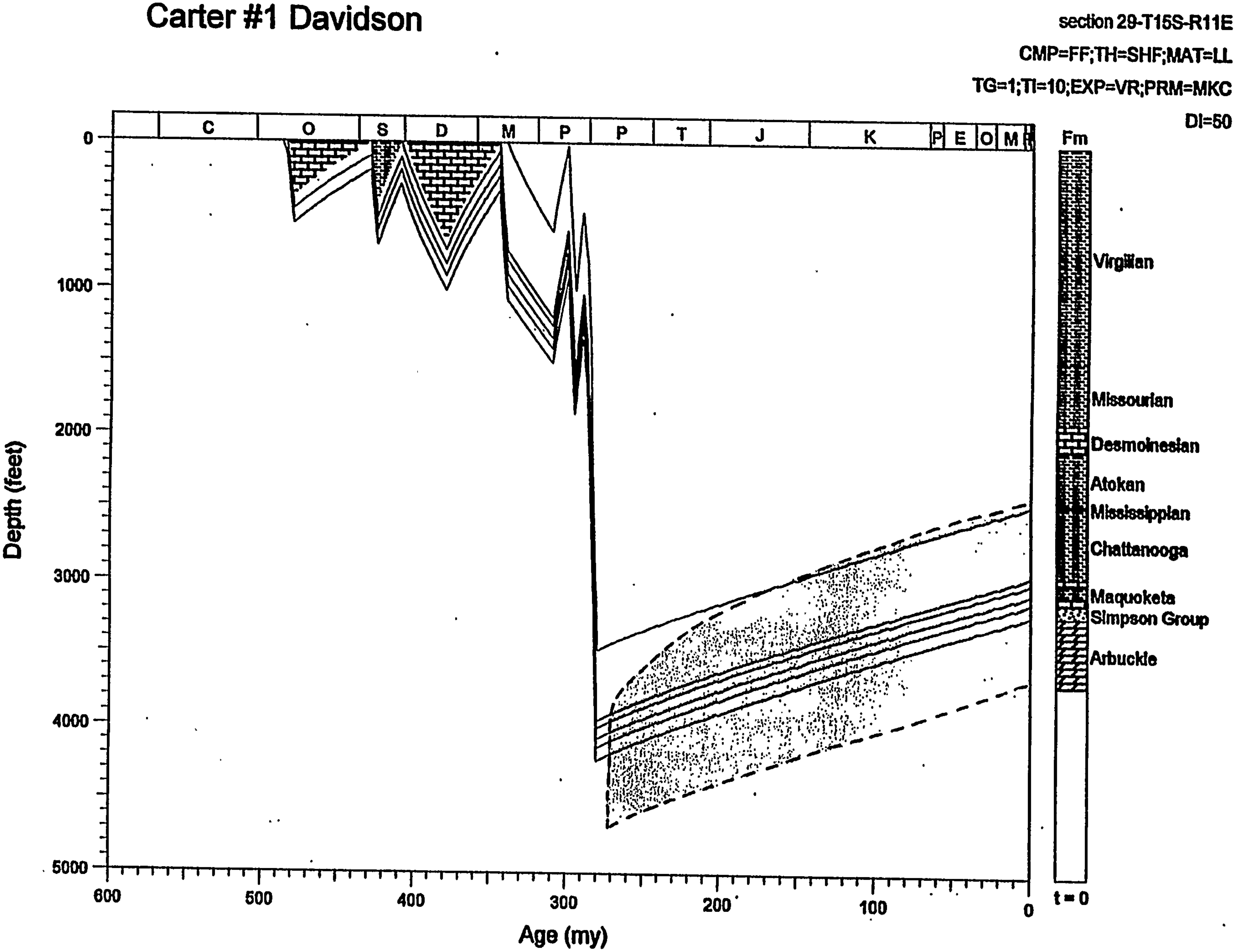
Map of Kansas wells used in basin modeling:

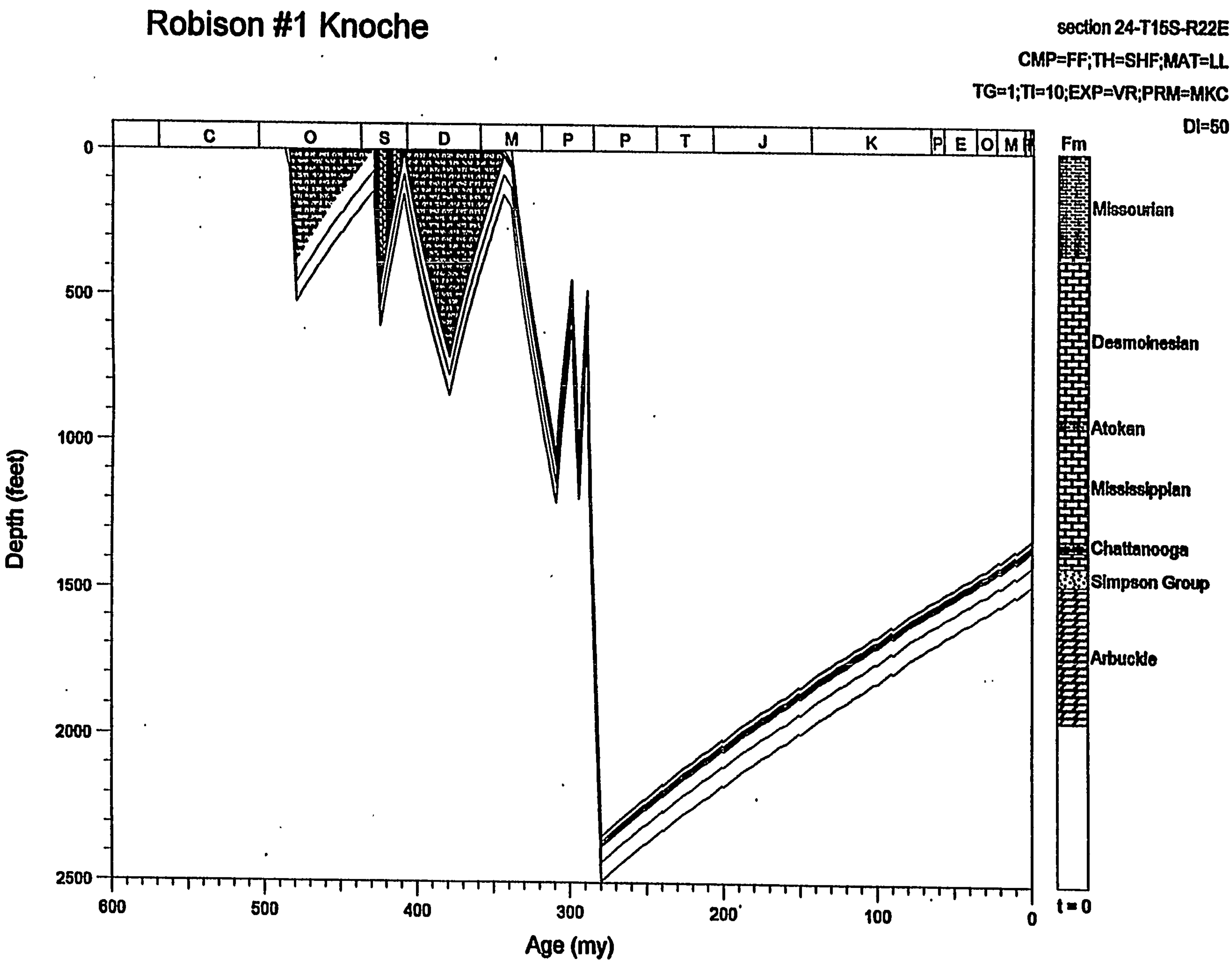
- **A** S.K.D. #1 Kyler, Section 5-T15S-R7W, Ellsworth County
- **B** Carter #1 Davidson, Section 29-T15S-R11E, Lyon County
- **C** Corbin E. Robison #1 Knoche, Section 24-T15S-R22E, Miami County

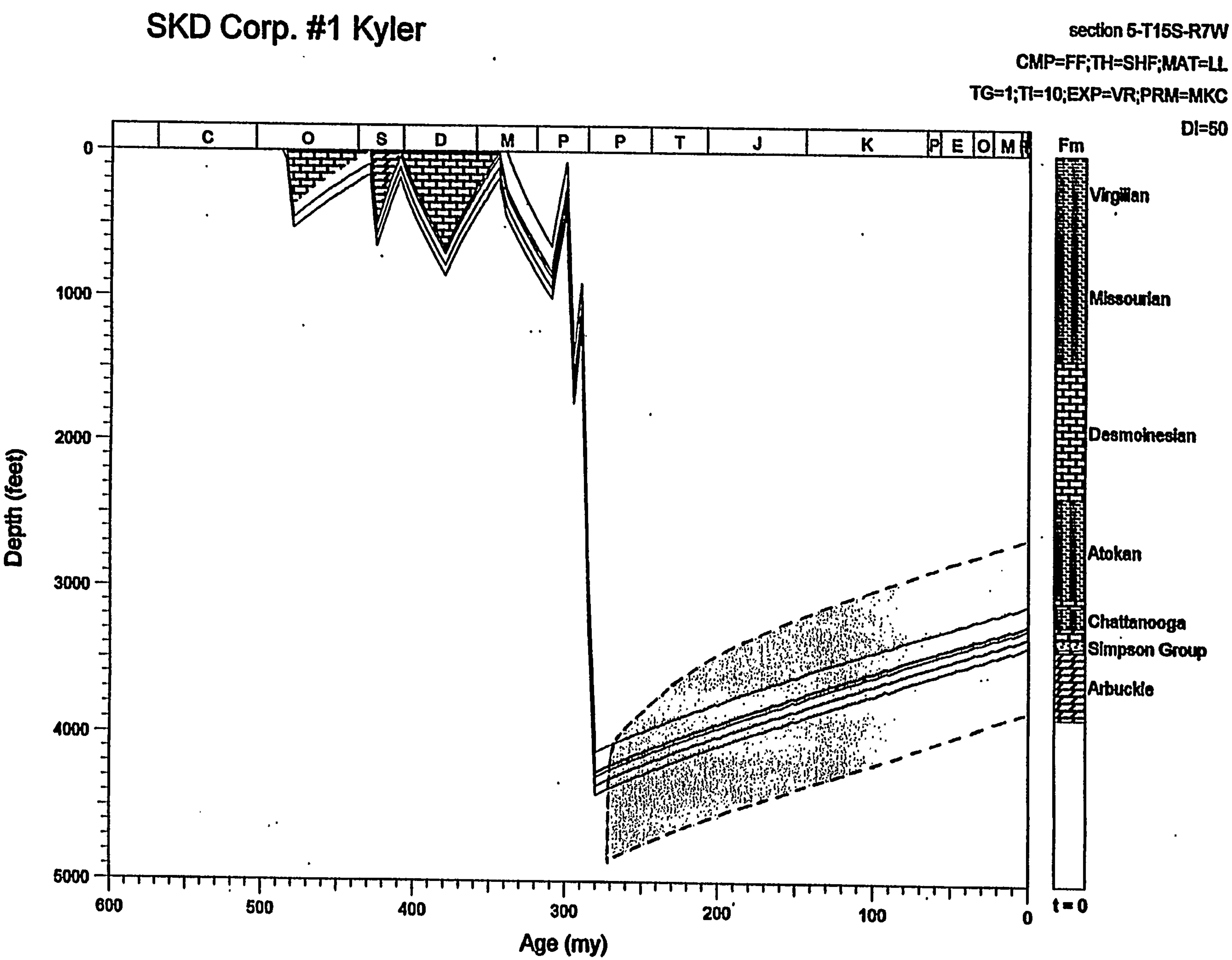
Figure 1.


Carter #1 Davidson
section 29-T15S-R11E
CMP=FF;TH=SHF;MAT=LL
TG=1;TI=10;EXP=VR;PRM=MKC
DI=50
C
O
S
D
M
P
P
T
J
K
P
E
O
M
Fm
30(C)
30(C)
30(C)
40(C)
50(C)
60(C)
70(C)
80(C)
Virgilian
Missourian
Desmoinesian
Atokan
Mississippian
Chattanooga
Maquoketa
Simpson Group
Arbuckle
t = 0
Depth (feet)
Age (my)
0
1000
2000
3000
4000
5000
600
500
400
300
200
100
0

Carter #1 Davidson




Robison #1 Knoche
section 24-T15S-R22E
CMP=FF;TH=SHF;MAT=LL
TG=1;TI=10;EXP=VR;PRM=MKC
DI=50
C
O
S
D
M
P
P
T
J
K
P
E
O
M
Fm
Missourian
Desmoinesian
Atokan
Mississippian
Chattanooga
Simpson Group
Arbuckle
t = 0
Depth (feet)
0
500
1000
1500
2000
2500
600
500
400
300
200
100
0
Age (my)



SKD Corp. #1 Kyler
section 5-T15S-R7W
CMP=FF;TH=SHF;MAT=LL
TG=1;TI=10;EXP=VR;PRM=MKC
DI=50
C
O
S
D
M
P
P
T
J
K
P
E
O
M
Fm
Virgilian
Missourian
Desmoinesian
Atokan
Chattanooga
Simpson Group
Arbuckle
t = 0
Depth (feet)
0
1000
2000
3000
4000
5000
600
500
400
300
200
100
0
Age (my)

APPENDIX 3
POSSIBLE PETROLEUM GENERATION AND OCCURRENCE IN THE PRE-MESOZOIC PARTS OF THE FOREST CITY BASIN (FINAL REPORT AND DATABASE SUPPLEMENT)

University of Tulsa

Possible Petroleum Generation And Occurrence in the pre-Mesozoic Parts of the Forest City Basin

Final Report

July 31, 1998

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1.0 INTRODUCTION

1.1 Forest City Basin: A stratigraphic definition

The Forest City Basin extends from central Iowa through the northwestern corner of Missouri and the southeastern corner of Nebraska into eastern Kansas. As this term is generally used (e.g. Jewett, 1951; Lee, 1943; and others), it refers to the Pennsylvanian sedimentary basin that developed by subsidence of the peneplain formed at the upper surface of Mississippian strata. The basin is named for Forest City, Holt County, northwestern Missouri.

The term "Forest City Basin" probably came into usage in about the 1920's, although the first published use of the term was not until 1932 when Holl (1932) used the term in a map title. Hinds and Greene (1915) published the first structural maps of the basin, but they did not refer to the basin by any name. Their Plate XXV, a structural map contoured on the base of the Pennsylvanian, shows the basin outline and the deepest part of the basin near Forest City. This map, published by the Missouri Bureau of Geology and Mines, shows only the Missouri part of the basin and omits the deeper part of the basin in Kansas (cf. Burchett et al., 1983). Hinds and Greene (1915) also included the description of cores taken from a "diamond drill hole on the W.F. Davis farm near Forest City, Missouri" which had been drilled in 1901. This hole penetrated Pennsylvanian, Mississippian, Devonian, and about 100' of Silurian dolomite, and it reached a total depth of 2500'. A 2500' cored well in 1901 would have been a remarkable scientific and engineering accomplishment; this well and the maps of Hinds and Greene (1915) are probably why the basin was named for a location in Missouri rather than one in Kansas, where the basin had been explored for oil since the 1860's.

The Forest City Basin may be defined as an area of Pennsylvanian deposition bounded by the Nemaha Uplift on the west and the Bourbon Arch (Moore and Jewett, 1942) on the south. The eastern limit of the basin is the surface truncation of Pennsylvanian strata against the western and northern flanks of the Ozark Uplift. The northeastern and northern limits of the basin are not as clear, but could be defined by the distribution of Pennsylvanian strata in Iowa (cf. Anderson, 1983, his Figure 8.7).

1.2 Salina Basin: A stratigraphic definition

The term "Salina Basin" was proposed by Barwick (1928) for "the pre-Pennsylvanian syncline bounded on the east by the Nemaha granite ridge, and on the southwest by the

Barton arch, and on the south by the saddle between the Chautauqua arch and the Barton arch. The basin continues northward into Nebraska..." As originally defined, the Salina Basin was a topographic low which received sediments during the Pennsylvanian, although Lee, Leatherock, and Botinelly (1948), Lee et al.(1956), and others have used the term for a geographic region through a longer period of geological time.

1.3 Sedimentary basins older than Pennsylvanian

As narrowly defined above, the Forest City and Salina basins received sediments only during the Pennsylvanian. Prior to the Pennsylvanian, other sedimentary basins were present in Missouri, northern Kansas, southeastern Nebraska, and Iowa. Rich (1933) recognized the "North Kansas Basin" (pre-Mississippian). Lee (1946) recognized the "ancestral North Kansas Basin" (pre-Devonian) and the "ancestral Forest City Basin" (Mississippian).

1.4 Forest City and Salina basins: A working definition

Our research involves source rocks deposited during the Ordovician and during the Late Devonian and Early Mississippian, time intervals before the development of the Forest City and Salina basins. Because these source rocks were deposited in precursor basins, it might seem inappropriate to link these source rocks to the Forest City and Salina basins. However, our models show that deposition of thick clastic sequences during the Pennsylvanian controlled the maturation of the underlying source rocks. These clastic sequences were thickest in or near the centers of the Forest City and Salina basins. It is therefore practical for us to consider the Forest City and Salina basins to be the geographic areas within the boundaries described above. The stratigraphic column within these basins includes not only the Pennsylvanian section, but also strata above and below the Pennsylvanian.

2.0 SOURCE ROCKS

Our early modeling indicated that Ordovician shales and the Devonian to Lower Mississippian Kinderhook and Chattanooga shales (Figure 1) are potential source rocks that might have sufficient thermal maturity to have generated hydrocarbons. However, thermal modeling of potential source rocks would be meaningless if these rocks have insufficient organic carbon for the generation of hydrocarbons. Using cores and cuttings obtained from the Kansas Geological Survey's Wichita Well Sample Library and from the Iowa Geological Survey Bureau's Oakdale research laboratory, R. Erickson selected material for measurement of total organic carbon (TOC) and Rock-Eval pyrolysis. Table 1 contains TOC and Rock-Eval data as well as locality and stratigraphic information. Locations of source-rock samples and wells modeled are shown in Figures 2,3, and 4.

2.1 Lower Simpson Shales

Several shale layers occur between the top of the Lower Ordovician Arbuckle Group (or the stratigraphically equivalent Prairie du Chien Group in the northern Forest City Basin) and the top of the St. Peter Sandstone. These shales are generally not named, although the Kress Member, a shaley and conglomeratic unit with little or no source-rock potential, has been named; it occurs at the base of the St. Peter and is present in outcrops in Illinois, Minnesota, Missouri, and Wisconsin (Templeton and Willman, 1963). Shale intervals that are potential source rocks in the lower part of the Simpson Group lack formal names, and we have simply called them lower Simpson shales.

Sample 45 is a lower Simpson shale from the Palen #1 (Mitchell County, Kansas) located in the west-central part of the Salina Basin. This sample consists of hand-picked black shale pieces from 4140' to 4160', an interval about 70' below the top of the Simpson Group and about 10' above the top of the Arbuckle Group. This shale has a TOC of 2.28 wt.%.

Samples 43 and 44 from the Blair #1 in northeastern Kansas are also lower Simpson shales from just below the Simpson sandstone (equivalent to St. Peter Sandstone). The sample log on file at the Wichita Well Sample Library indicates the top of the Simpson sandstone at about 2850'. Drilling records for this well indicate that the driller stopped drilling and circulated the mud for 4 hours before drilling through the intervals of sample 43 (2865' to 2870') and sample 44 (2870' to 2875'), so these hand-picked samples of black shale (sample 43) and greenish-gray shale (sample 44) are probably from the indicated depth intervals and are not samples from some overlying shale. The black shale sample has a TOC of 2.18 wt.% and is certainly rich enough to be considered a potential source rock. The adjacent greenish-gray shale has TOC of 0.40 wt.% and would probably not be a source rock. Although probably not a source rock, sample 44 is very significant because it contains an important quantity of hydrocarbons in a kerogen-poor shale. This occurrence of hydrocarbons in discussed in the section on hydrocarbon shows.

The Coddington #3-24 in southwestern Iowa has a minor amount of shale between the base of the St. Peter and top of the Prairie du Chien Group. The gamma-ray – induction log (run by BPB, April 2, 1984) shows the top of the St. Peter at 3124′. Going downward from the base of the St. Peter Sandstone at 3143′, the gamma-ray log shows an gradual increase in shale to 3154′, where a sharp decrease in gamma ray response and abrupt increase in resistivity indicate the top of the underlying Prairie du Chien Group. Some of the lower Simpson interval might contain potential source rocks, and cuttings from 3150′ to 3160′ contain reddish-brown, green and black shales. The black-shale pieces are small and might be recirculated cuttings or cavings from shales farther uphole. The 11′ shale zone from 3143′ to 3154′ seems to have too little potential source rock to produce a clear increase in black or dark-brown shale in the cuttings. This shale interval was not sampled for TOC.

The St. Peter Sandstone interval is typically a white sandstone of nearly pure quartz sand, and this interval would not be expected to contain potential source rocks. However, the TOC and Rock-Eval data published by Jacobson et al. (1988, their Table 1) for the cores from the Iowa Geological Survey Bureau borehole at Camp Quest (Plymouth County, northwestern Iowa) contain three samples that seem to be from the St. Peter. The depths and TOC values of these samples are: 2.9 wt.% at 762.2′, 9.3 wt.% at 762.8′, and 1.2 wt.% at 776.2′. Because the stratigraphic interval and lithology associated with these samples is not entirely clear in Jacobson et al. (1988), R. Erickson examined the Camp Quest cores at the Iowa Geological Survey's Oakdale core repository. All three samples are from brown shales lying within the St. Peter Sandstone. The samples from 762.2′ and 762.8′ are from a shale layer about 4′ thick. The base of this layer is a fairly sharp contact of chocolate-colored shale over white sand; the 762.8′ sample is from just above this contact. Within this layer, sand content gradually increases upward until typical St. Peter Sandstone is encountered at about 759′; the 762.2′ sample is from this transition zone. The 776.2′ sample is from a separate brown shale layer about 1.5′ thick.

2.2 Glenwood Shale and other upper Simpson shales

The Glenwood Shale underlies much of the Forest City Basin, extending from outcrops near Minneapolis, Minnesota, and northeastern Iowa into the subsurface of most of Iowa (Anderson, 1983). The Glenwood is about 15 feet thick at outcrops in southeastern Minnesota (Ojakangas and Matsch, 1982) and about 50 feet thick at outcrops in northeastern Iowa (Anderson, 1983). In Crawford County, west-central Iowa, the Glenwood is only about 6 feet thick (Upland Leasing Augustine #1 well, section 35-T85N-R39W, Crawford County, Iowa) and is absent in the Coddington #3-24 well (Mills County, Iowa)and adjacent parts of southwestern Iowa (Agnew, 1955).

The Glenwood dips into the Forest City Basin, ranging from an elevation of about 750' above sea level in the vicinity of Minneapolis, Minnesota (Minnesota Geological Survey Core 91708-A, Hennepin County, Minnesota) to about 416' below sea level in the Augustine #1 well in west-central Iowa. In the deepest part of the Forest City Basin in southwestern Iowa, stratigraphically equivalent strata are about 1900' below sea level Coddington #3-24.

Total organic carbon was measured in three samples of Glenwood shale (Table 1). The two Glenwood samples from Minnesota (samples 10a and 11a) had very little TOC and could not be considered potential source rocks. However, the Glenwood sample (sample 4a) from southeastern Iowa has over 12 wt.% TOC which is sufficient to be a source rock.

Although the Glenwood Shale is absent in southwestern Iowa (Agnew, 1955) and Kansas (Zeller, 1968), stratigraphically equivalent shales are present in parts of Kansas. Shales in the interval between the top of the St. Peter Sandstone and the base of the either the Viola or the Galena Formation are generally not given formal stratigraphic names and are refered to here as upper Simpson shales. The Davidson #1 (Lyon County, Kansas) penetrated a black shale in this interval (samples 28 and 29). These samples had TOC of 2.23 wt.% and 2.11 wt.%. No other potential source rocks were found in the upper Simpson interval of the wells examined for this study.

The gamma-ray – induction log of the Coddington #3-24 well shows that the Platteville interval is mostly limestone or dolostone with a few 2' to 3' thick shale layers. None of these layers was thick enough to sample in the cuttings of this well. In this well, upper Simpson shales are too thin to be significant source rocks.

2.3 Guttenberg Member, Decorah Shale

The Guttenberg Member of the Decorah Shale is primarily a limestone (Anderson, 1983), but it contains numerous layers of brown, organic-rich shale. A 22 cm-long (8¾") piece of core from Washington County, Iowa (sample 6) contains three layers of brownish-gray, organic-rich shale, each of which is approximately 3 to 5 cm thick. Separating the shale layers are two layers of white to bluish-gray limestone containing a few brachiopod shells and shell fragments. The larger brachiopod shells have their convex sides upward, suggesting the presence of tidal or wave currents. The shale layers have irregular top and bottom surfaces, and at least one appears to contain a small disconformity within the layer. Sample 6a from the organic-rich shale and contains 14.02 wt.% TOC; sample 6b is from the limestone layer and contains 1.45 wt.% TOC.

Sample 7 (Jackson County, Iowa) of the Guttenberg is a chocolate-brown shale without any limestone layers. This sample is particularly rich in organic carbon, having 41.23 wt.% TOC. Table 2 shows the mineral composition of sample 7b as determined by X-ray diffraction; the x-ray analysis was done by Mineralogy, Inc. of Tulsa, Oklahoma.

The source rock database contains 24 samples of the Guttenberg with TOC ranging from 1.45 wt.% to 43.3 wt.%. Of these 24 samples, 11 have TOC greater than 20 wt.%. All published TOC values for the Guttenberg are based on samples from eastern Iowa; the western-most samples in the database are from the Flynn wells in Washington County. How far such potential source rocks extend into western Iowa is problematic. Witzke (1983, his Figure 5) shows the Guttenberg extending from southeastern Iowa completely across the southern part of Iowa into the area around the Coddington #3-24 well. However, the gamma-ray – induction log of the Decorah interval in this well is similar to the Platteville section described above. The Decorah interval is mostly limestone or dolostone with only a few thin shale layers; any organic-rich shales are too thin to sample in cuttings and are probably too thin to be significant source rocks in the area around the Coddington #3-24.

2.4 Maquoketa Formation

In eastern Iowa, the basal part of the Maquoketa contains two members that contain sufficient TOC to be source rocks. The Elgin Member is a shale with dolostone intervals is present in east-central Iowa, and the stratigraphically equivalent Scales Member is a brown shale present in eastern Iowa near the Illinois border (Witzke, 1983). Other Maquoketa members, the Brainard and Clermont, also contain minor intervals with elevated TOC.

Guthrie (1994, 1996) has done extensive work on the Maquoketa of the Illinois Basin and eastern Iowa. Guthrie (1994, 1996) measured TOC of 25 samples of the Scales Member over an interval of approximately 143′ in the Cominco SS-4A (Jackson County, Iowa). Samples from the upper 102′ had TOC values of less than 0.5 wt.%, but samples from the lower 36′ had TOC values above 0.5 wt.%. Near the bottom of Guthrie's sampled interval was about 5′ of shale with TOC ranging from 7.69 wt.% to 9.68 wt.%. (Guthrie called this borehole the Saunders SS-4A.)

In the Fenix and Scisson Mid-America Pipeline #4 (Johnson County, Iowa), Guthrie (1994) measured TOC of 11 samples of the Brainard Member and 4 samples of the Elgin Member; the total sampled interval was about 225′. The most of the Brainard samples had TOC values less than 0.5 wt.%, but Guthrie's bottom Brainard sample had 0.75 wt.% TOC. The Elgin samples had TOC values ranging from 0.61 wt.% to 1.05 wt.%. (Guthrie called this well the I.C. Terminal #4. This well was operated by Fenix and Scisson of Tulsa, Oklahoma, and it was drilled on the Mid-America Pipeline Company Iowa City Terminal.)

Guthrie (1994) also measured TOC on 7 Clermont Member samples and 4 Elgin Member samples from the New Jersey Zinc H-33 (Des Moines County, Iowa). Only two samples from near the base of the Clermont had TOC values greater than 0.5 wt.%, but these values were 0.97 wt.% and 1.49 wt.%. The four Elgin samples had TOC values from 3.51 wt.% to 4.30 wt.%. (Guthrie called this well the Anderson #1.)

The lithologic character of the Maquoketa changes across southern Iowa. The shale facies that are dominant in southeastern Iowa are replaced by carbonate facies in southwestern Iowa (Witzke, 1983, his Figure 10). The gamma-ray – induction log of the Coddington #3-24 well in southerwestern Iowa shows Maquoketa from 2639' to 2950'. The top 7' of this interval is shale, but the rest of the Maquoketa is limestone or dolostone with a few thin shale layers. Sample 51 contains black shales from the top of the Maquoketa. The TOC of this sample is 3.01 wt.% which is sufficient for the upper Maquoketa black shale to be considered a source rock. Unlike the Maquoketa in southeastern Iowa, the potential source rock encountered in the Coddington #3-24 well is at the top of the Maquoketa rather than at or near its base.

The Maquoketa of northeastern Kansas characteristically consists of greenish-gray, silty dolomitic shale or cherty silty dolomite (Zeller, 1968). The Maquoketa section in the USGS Douglas County Livestock and Fair Association #1 well (northeastern Kansas) includes some black shales. The cuttings from 2190' to 2200' contain pieces of sandstone and some black shale; sample 17 consists of black shale pieces picked from this interval. The TOC of this black shale is 2.45 wt.%, so the Maquoketa interval in this well contains at least some potential source rock.

In the southwestern Forest City Basin, the Shoffner #1 well (Saline County, Kansas) also has Maquoketa shale with sufficient TOC to be potential source rock. Sample 34 from 3305' to 3310' contained shales with 1.23 wt.% TOC.

2.5 Kinderhook and Chattanooga Shales

The Kinderhookian Series includes the Chattanooga Shale and other shales overlying the Chattanooga. In many places is is difficult to distinguish Chattanooga Shale from other, overlying Kinderhook shales. In many places, the Chattanooga Shale is characterized by the presence of *Sporangites huronensis* spores, and where such spores are present we have called the shale Chattanooga. Devonian to Lower Mississippian shales lacking these spores are simply called Kinderhook shale in this report.

Several wells in northeastern Kansas had Kinderhook shale or Chattanooga shale with sufficient TOC to be potential source rocks. The Blair #1 well (Jackson County) has about 135' of Kinderhook section overlying about 15' of Chattanooga Shale. Two samples of Kinderhook black shales (samples 13 and 14) have 1.12 wt.% and 1.52 wt.% TOC; sample 15 of the underlying Chattanooga has 1.33 wt.% TOC in a gray (not black) shale interval. East of the Blair well, the Wormer #1 well had 81' of Kinderhook overlying 17' of Chattanooga Shale. In the Wormer #1, no Kinderhook shales above the Chattanooga were analyzed for TOC, but the Chattanooga sample (sample 20) has 0.92 wt.% TOC. Southeast of the Blair well, the Douglas County Livestock and Fair Association #1 well has black Chattanooga Shale with 1.55 wt.% TOC (sample 19). Southeast of the Douglas County well, the UGSG Watson #1 well has 14.05 wt.% TOC.(sample 44). Sample 44 is a dark-gray shale with numerous *Sporangites huronensis* spores; these abundance of these rather large spores is probably responsible for the high TOC value.

2.6 Pennsylvanian source rocks

Our early modeling work in the Forest City and Salina basins indicated that the Pennsylvanian section (Table 3) was probably not thermally mature enough to have generated hydrocarbons. For this reason, we specifically ignored most of the numerous Pennsylvanian black shales present in these basins. For our models of individual wells, the samples we analyzed for TOC came from cuttings rather than cores. In these wells several Pennsylvanian black shales are present above the Kinderhook and Ordovician shales in which we were interested. Pennsylvanian shale pieces might have caved into the drilling mud or been recirculated in the mud, and these might have been mistaken for the shales we wanted to study. To reduce doubt about the source of the TOC and Rock-Eval data attributed to the Kinderhook and Ordovician shales, we sampled about five Pennsylvanian shales in the Davidson #1 well (samples 21, 22, 23, 24, 25, 28, 29, and 48), one Pennsylvanian shale in the Shoffner #1 (sample 31), and one Pennsylvanian shale in the Coddington #3-24 (sample 50). In the Davidson #1, all but one of the Pennsylvanian shales had TOC much higher than the lower Simpson black shale, leaving little doubt that the material in samples 28 and 29 was from the lower Simpson. The Pennsylvanian black shales in the Davidson #1 included three samples with TOC values between 10 wt.% and 20.5 wt.%, some of the highest TOC values found in our research. The Marmaton black shale in the Coddington #3-24 has 16.67 wt.% TOC, which is much higher than the 3.01 wt.% TOC found in the Maquoketa sample (sample 51) from the same well. In the Shoffner #1, the Heebner Shale had less TOC than the TOC found in the Ordovician shales (samples 33 and 34). In all but one case, the TOC and Rock-Eval values of the Pennsylvanian black shales are sufficiently different than those of the underlying shales to allow distinguishing between Pennsylvanian shales and older shales.

Table 1: TOC and Rock-Eval data from Forest City Basin and Salina Basin Samples. Locations of samples are shown in Figures 2,3, and 4.

Location	Sample Number	Formation	Depth (feet)	TOC (wt.%)	S1	S2	S3	Tmax (°C)	HI	OI	PI
Hollandale core Section 7-T103N-R19W Freeborn County, Minnesota	2a	Decorah Formation	429	0.20	0.01	.013	0.08	NR	65	40	0.07
NGPCA M.M. Flynn #2 Section 19-T76N-R9W Washington County, Iowa	4a	Glenwood Formation	1115.4*	12.31	2.36	125.39	0.45	443	1019	4	0.02
NGPCA W.M. Flynn #2 Section 20-T76N-R9W Washington County, Iowa	6a	Guttenberg Member Decorah Formation	977	14.02	9.04	157.97	0.53	444	1127	4	0.05
	6b		977	1.45	0.46	8.43	0.15	444	581	10	0.05
Cominco SS-3 Section 14-T84N-R3E Jackson County, Iowa	7a	Guttenberg Member Decorah Formation	675	41.23	11.47	434.77	1.29	450	1054	3	0.03
Iowa Geol. Survey Bureau BS-4 Section 20-T95N-R6W Clayton County, Iowa	9a	Guttenberg Member Decorah Formation	481.0*	5.90	0.49	57.74	0.85	435	979	14	0.01
Minnesota Geological Survey Core 91708-A Section 22-T29N-R24W Hennepin County, Minnesota	10a	Glenwood Formation	33.2	0.38	0.07	0.96	0.16	430	253	42	0.07
	11a		51.6	0.31	0.05	0.80	0.28	427	258	90	0.06
USGS Watson #1 Section 18-T18S-R23E Miami County, Kansas	12	Chattanooga	1205*	14.05	2.38	87.93	1.48	439	626	11	0.03
Phillips Petroleum Blair #1 Section 24-T7S-R16E Jackson County, Kansas	13	Kinderhook	2170*	1.52	0.68	2.15	0.50	439	141	33	0.24
	14	Kinderhook	2180*	1.12	0.34	0.73	0.27	439	65	24	0.32
	15	Chattanooga	2310*	1.33	0.41	1.56	0.45	443	117	34	0.21
	43	lower Simpson black shale	2865*	2.18	0.66	1.30	0.67	431	60	31	0.34
	44	lower Simpson greenish-gray shale	2870*	0.40	1.15	0.82	0.69	340	205	173	0.58

Location	Sample Number	Formation	Depth (feet)	TOC (wt.%)	S1	S2	S3	Tmax (°C)	HI	OI	PI
USGS & Kansas Geol. Survey Douglas County Livestock and Fair Association #1 Section 13-T12S-R17E Douglas County, Kansas	19	Chattanooga Shale	2020*	1.55	0.16	0.81	0.33	433	52	21	0.16
	17	Maquoketa	2190*	2.45	1.35	10.64	0.41	435	434	17	0.11
Anschutz Wormer #1 Section 19-T7S-R17E Atchison County, Kansas	20	Chattanooga Shale	2350*	0.92	0.70	1.68	0.65	440	183	71	0.29
Carter Oil Company Davidson #1 Section 29-T15S-R11E Lyon County, Kansas	21	Shawnee Group	270*	2.72	0.46	2.13	2.81	430	78	103	0.18
	22	black shales	1040*	10.89	1.70	31.66	5.75	421	291	53	0.05
	48	Heebner	1260*								
	23	Lansing Group in/near Eudora Shale	1595*	12.54	1.76	30.90	3.86	425	246	31	0.05
	24	Marmaton Group	2130*	1.44	0.40	1.26	1.76	424	88	122	0.24
	25	black shale	2135*	20.46	3.07	53.84	4.13	427	263	20	0.05
	28	lower Simpson	3300*	2.23	0.27	1.90	1.38	437	85	62	0.12
	29	black shales	3340*	2.11	0.19	0.56	1.37	427	27	65	0.25
Ohio Oil Company Shoffner #1 Section 19-T15S-R1W Saline County, Kansas	31	Heebner Shale	1900*	0.52	0.32	0.47	0.83	341	90	160	0.41
	33	Kinderhook	3060*	0.95	0.37	0.72	0.80	428	76	84	0.34
	34	Maquoketa	3305*	1.23	0.43	0.91	0.55	434	74	45	0.32
Diversified Resources Anna Coddington #3-24 Section 24-T71N-R41W Mills County, Iowa	50	Pennsylvanian black shale	1050*	16.67	2.23	53.14	3.63	426	319	22	0.04
	51	Maquoketa	2660*	3.01	0.14	0.78	1.27	430	26	42	0.15
Olson Drilling Palen #1 Section 26-T8S-R10W Mitchell County, Kansas	45	lower Simpson black shale	4140*	2.28	0.38	0.70	1.07	366	31	47	0.35

Rock-Eval units: S1 and S2 = mg hydrocarbon/g rock $S3 = mg\ CO_2/g$ rock
Hydrogen Index: HI = (S2 x 100)/TOC Oxygen Index: OI = (S3 x 100)/TOC Production Index: PI = S1/(S1 + S2)
* Depth is top of a sample interval, typically 5′ to 10′ thick.

Table 2: Mineral composition of Guttenberg Member, Decorah Shale, Sample 7b, Jackson County, Iowa

Mineral constituent	Relative abundance (%)
Quartz	9
K-feldspar	3
Calcite	17
Dolomite	9
Siderite	trace
Pyrite	3
Carbonate apatite	2
Kaolinite	trace
Illite/mica	9
Mixed layer illite/smectite (70-79% illite layers in mixed layer clays)	3
Amorphous	45
Total	100%

Table 3 Pennsylvanian strata of Kansas and Iowa

Stage	Group	Black Shales
Virgilian	Wabaunsee	
	Shawnee	Heebner
	Douglas	
Missourian	Lansing	Eudora
	Kansas City	
	Bronson	
	Pleasanton (Kansas only)	
Desmoinesian	Marmaton	
	Cherokee	
Atokan	Caseyville (Iowa only)	

3.0 ACTIVATION ENERGIES OF SOURCE ROCKS

Chemical reactions that convert kerogens into hydrocarbons follow thermodynamic and kinetic laws that govern all chemical reactions. A source rock can contain an array of many different and complex kerogen molecules, and conversion of these into hydrocarbons follows can follow numerous reaction pathways. Fortunately, the composition of each kerogen molecule and the equation for each reaction are not needed to model kerogen conversion. If we know the activation energies for the kerogen mixture of any source rock, the conversion of that kerogen mixture into hydrocarbons can be modeled mathematically and the maturity of the source rock can be determined.

At the start of this project, activation energies for Glenwood, Guttenberg, Maquoketa, and Chattanooga source rocks were unavailable. Early models relied on default activation energy suites available in the BasinMod program. To check the validity of the default energy values, we obtained samples of these source rocks and had Humble Geochemical Services determine the activation energies, which are reported in Table 4. A sample used for measurement of activation energy should be selected from source rock that has never started kerogen conversion. This requirement made it necessary to select samples from locations where the source rocks were not deeply buried.

The Glenwood sample (sample 4a) is from a core taken in M.M. Flynn #2 (Washington County, Iowa) at a depth of 1115.4′ to 1116.4′. The layer sampled is a dark-brown, hard, laminated, noncalcareous shale. The Guttenberg sample (sample 7a) is a dark-brown shale from the Cominco SS-3 core (Jackson County, Iowa) at depth of 675′. The Elgin Member of the Maquoketa (sample 55) was sampled in a core of black shale taken in the New Jersey Zinc H-33 borehole (Des Moines County, Iowa) at 463′ deep. The Saverton Member of the Maple Mill Formation is a black shale that is stratigraphically equivalent to the Chattanooga Shale; the Saverton sample is from the New Jersey Zinc H-28 borehole (Lee County, Iowa) and is from 521′ deep. All four source-rock samples used to measure activation energies are from eastern Iowa, and applying activation energies from the eastern margin of the Forest City Basin across both the Forest City and Salina basins might seem questionable. However, in the central Forest City Basin of southwestern Iowa and northeastern Kansas as well as in the Salina Basin of central Kansas, potential source rocks have been subjected to deeper burial and would probably not be suitable for activation energy measurements.

The results of our fluid inclusions studies (discussed below) suggest that source rocks might have been heated by hot fluids moving through nearby beds, thus challenging this assumption of a low temperature. However, the Rock-Eval Production Index values for the Glenwood (sample 4a) and Guttenberg (sample 7a) are 0.02 and 0.03, respectively; suggesting that nearly all the organic material in these samples is still kerogen and had not been converted into hydrocarbons. Rock-Eval data are not available for the Maquoketa and Saverton samples.

The activation energies of the Glenwood and Guttenberg kerogens are rather high and correspond to energy values associated with Type I kerogen. [Kerogen types II and III tend to have lower activation energies than Type I (Tissot and Welte, 1984).] What is particularly striking about the Glenwood and Guttenberg kerogens is the narrow range of their activation energies. All the Guttenberg kerogen is converted at a single activation energy, and Glenwood kerogen is converted at two activation energies. This suggests that Guttenberg and Glenwood kerogens have less variation in the types of kerogen molecules and fewer conversion reactions than other Type I kerogens. Most or all the Guttenberg and Glenwood kerogens were probably derived from a simple, unicellular organism, *Gloeocapsamorpha prisca*, so a limited number of different kerogen molecules and a narrow range of activation energies is not surprising.

The range of activation energies for the Maquoketa Formation is slightly wider than the ranges for the Glenwood and Guttenberg. However, 92% of the Maquoketa kerogen is converted between 55 and 57 kcal/mole, a range comparable to those of the Glenwood and Guttenberg.

The Saverton sample has the widest range of activation energies of the four ranges reported here, but most of the conversion occurs within a narrow range that is similar to the narrow ranges seen for the other source rocks. Although some kerogen is converted between 48 and 50 kcal/mole, the total amount converted within this range is only 0.6%. Over 94% of the kerogen conversion occurs between 56 and 58 kcal/mole.

The BasinMod program uses default values for Type I kerogen activation energies that are quite different than the activation energies found in our study. The BasinMod default starts kerogen conversion at 49 kcal/mole with 7% conversion at that energy level. None of the samples we measured had more than 1% conversion at energies of 49 kcal/mole. In the BasinMod default, all kerogen has been converted by 54 kcal/mole. In all four of the activation energy ranges we measured, over 99% of the conversion occurs at energies of 55 kcal/mole or greater.

Table 4: Range of Activation Energies and Percent of Kerogen Conversion. Locations of samples are shown in Figure 3.

Activation Energy (kcal/mole)	Glenwood Formation sample 4a (Middle Ordovician)	Guttenberg Member Decorah Formation sample 7a - shaley layer (Middle Ordovician)	Elgin Member Maquoketa Formation sample 55 (Upper Ordovician)	Saverton Member Maple Mill Formation sample 54 (Upper Devonian)
43				
44				
45			0.03	
46				
47				0.14
48			0.73	0.11
49				0.23
50				0.12
51				
52				
53				
54				
55			75.83	
56	91.60	100.00		84.74
57			16.89	
58			2.12	9.40
59			0.44	3.23
60				
61				
62	8.40			
63			4.17	
64				
65				2.29
Arrhenius Factor	2.6255E+14	1.9212E+14	1.6381E+14	3.1670E+14

3.0 REPORTS OF OIL AND GAS

3.1 Hydrocarbon shows

Reports of noncommercial oil and gas occurrences (i.e., "shows") in sparsely drilled parts of the Forest City and Salina basins have been compiled. These shows are significant because they indicate the presence of mature source rocks, although whether the hydrocarbons were generated in nearby mature source rocks or migrated from a distant source is not necessarily known. Table 5 is a summary of all reported oil and gas shows in Iowa. Newell et al. (1985, 1988) published a summary of hydrocarbon shows in the Salina Basin of Kansas.

3.2 New evaluations of oil shows in Kansas

Oil production in the eastern Forest City Basin of Kansas began in the 1800's, and oil production on the Nemaha Uplift on the western side of the Forest City Basin is also well established. However, efforts to establish significant commercial oil or gas production in the central part of the basin have generally not been successful. One key question is whether the oil and gas on the eastern and western edges of the basin formed within the central Forest City Basin and migrated to the basin margins or if it migrated northward into the basin margins from mature source rocks to the south.

A comprehensive review of all shows within the central Forest City Basin is beyond the scope of this study, however new data from the Blair #1 (Figure 2) well strongly suggests that oil has been formed in the central Forest City Basin in Kansas. The Blair #1 lies in the center of the basin, about 20 miles east of the Leach Field on the Nemaha Uplift and about 30 miles west-northwest of the nearest fields of the eastern basin margin in northern Leavenworth County and eastern Jefferson County. The northeastern Kansas oil-field map of Carr et al. (1993a) shows only three small fields in approximately 50 townships (1800 square miles) that lie within the central Forest City Basin. These three fields have produced oil from Pennsylvanian and Mississippian reservoirs but not from deeper zones. The Blair #1 is immediately west of the abandoned Wormer Field.

The Blair #1 encountered potential source rocks in the Kinderhook, Chattanooga, and lower Simpson, and these have been discussed earlier. A greenish-gray lower Simpson shale sample (sample 44) contains little TOC, but it is significant because it contains hydrocarbons, as indicated by Rock-Eval pyrolysis. In Rock-Eval pyrolysis, the S1 value indicates the amount of hydrocarbons present in a sample and the S2 value indicates the amount of hydrocarbons formed by thermal cracking of kerogens in the rock; both values are expressed in mg of hydrocarbons per gram of rock. The S1 value for sample 44 is unusually high relative to the S2 value. The production index (PI) is defined as S1/(S1+S2), and the PI for sample 44 is 0.58, which the highest PI of all the samples in listed in Table 1. A relatively high PI is commonly interpreted to indicate a very thermally mature source rock in which most of the kerogen has already been cracked to hydrocarbons, but this is probably not the case with sample 44. Sample 43 was taken from the five-foot interval directly above the interval sampled in sample 44, yet sample 43 has a PI only slightly more than half that of sample 44. This suggests that the layer from which samples 43 and 44 were taken had not reached a high level of thermal maturity. The Tmax for sample 44 is 340°C, which is surprising when compared to the 430°C Tmax value for sample 43. Paul Walker (Humble Geochemical Services, personal communication, 1998) explained that the low Tmax for sample 44 is due to S1 carryover. Rock-Eval pyrolysis holds the sample at 300°C to release the hydrocarbons that make up the S1 value before gradually increasing the temperature to 600°C. Some high molecular-weight hydrocarbons might not be released during the initial S1 time but are released during the subsequent heating period. Sample 44 released sufficient quantity of such hydrocarbons that the temperature of maximum hydrocarbon release (i.e., apparent Tmax) was lower than the Tmax that would have been produced by cracking of kerogens. The TOC, PI, and Tmax of sample 44 indicate the presence of hydrocarbons in a kerogen-poor rock. Such hydrocarbons were probably formed in a source rock with a higher TOC than that of sample 44, and they were probably expelled and migrated into the greenish-gray shale layer represented by sample 44. It is possible that the oil found in the Pennsylvanian reservoirs in the Wormer Field migrated to the field from nearby Ordovician source rocks.

The Salina Basin of central Kansas is surrounded to the west, east, and south by oil-producing regions, but the central and northern parts of the basin have only a few, small, isolated fields between the Central Kansas Uplift to the west and the field of the Nemaha Uplift on the east (Carr et al., 1993b, 1993c). The numerous hydrocarbon shows in the Salina Basin have been listed and mapped by Newell et al. (1985, 1988), and a comprehensive list of shows is not repeated here.

Newell et al. (1988) noted "dead oil stain?" in the Maquoketa of the Mallard Petroleum Broeckelman #1, which was drilled in northwestern Jewell County near the Nebrasksa state line. This well is about 60 miles west of the nearest production on the Central Kansas Uplift, and about 100 miles from the nearest production to the south or southeast. This oil show occurs in Maquoketa carbonates in the interval from 3770′ to 3780′ and is our sample 49a. The amount of hydrocarbons in this sample is tiny, but Humble Geochemical Services extracted enough to analyze by gas chromatography. The chromatogram of this sample (Figure 5) shows distinct peaks for normal alkanes from C_{13} through about C_{24} and a large hump corresponding to numerous polyaromatics. Normal alkanes with even numbers of carbon atoms are slightly more abundant than those with odd numbers of alkanes, and significant amounts of normal alkanes above C_{19} as well as pristane and phytane are present. If this were a crude oil derived from a *G. prisca* source rock, we would expect to see dominance of alkanes with odd numbers of carbon atoms, very low relative amounts of normal alkanes above C_{19}, and little or no pristane or phytane (Jacobson et al., 1988). The oil show from the Broeckelman well is not derived from a *G. prisca* source rock.

3.3 Oil production in Iowa

A small amount of oil has been produced from the Keota Dome in southeastern Iowa (Washington and Keokuk Counties). Parker (1971) and Witzke et al. (1990) reviewed the history and oil production of this small field. The two wells completed in this field, the Natural Gas Pipeline Company of America W.F. Flynn #P-1 and the CST Leonard Bombei #1, are included in Table 5. Both wells were completed in the Pecatonica Member of the Platteville Formation. Total production from these wells is less than 500 barrels (Witzke et al., 1990). Initial production from the W.F. Flynn #P-1 well was 15 barrels per day, but production dropped to 1.5 barrels a day before the well was abandoned in 1963 (Witzke et al., 1990). The Petroleum Information scout card for the Leonard Bombei #1 well indicates that this well made 23 barrels of oil and 660 barrels of water in 14 days; total production for this well was 71 barrels in five months (Witzke et al., 1990).

The Pecatonica reservoir in these wells is only about 1000 to 1100 feet deep, and the low cost of drilling these wells might make them economically viable for a small oil-producing company despite the low daily rate of oil production. In addition to low production rates, four problems probably prevented the development of a commercial oil field at Keota Dome:

- Iowa has no oil refinery, and the oil from the W.F. Flynn #P-1 well had to be transported to Northwestern Refining Company in St. Paul, Minnesota (Larry L. Wilson, Director, Iowa Dept. of Natural Resources, personal communication, 1997). Lack of a local crude-oil purchaser and pipelines connecting the producing area with a refinery is an important barrier to the development of small oil fields.

- The reported API gravity of the Keota Dome oil is rather low. The Petroleum Information scout card for the Leonard Bombei #1 well reports an API gravity of 28°. No other oil gravities are reported at Keota Dome. Low gravity decreases the price paid for crude oil. At the shallow depth from which this oil is produced, it would not be surprising to find bacterial degradation of the oil, a process that lowers the API gravity.

- The two producing wells required between 600′ and 750′ of surface casing, the cost of which is a significant part of the total drilling cost of a shallow well.

- Large amounts of water produced with the oil increased the operating expense. The top of the oil-producing interval in the Leonard Bombei #1 well was at 372′ below sea level, and the well had a significant amount of water production. The Petroleum Information scout card for the W.F. Flynn #P-1 well does not report any water production; the reservoir in this well was 160′ higher than in the Leonard Bombei #1, so the Flynn well might have had no water production. Water production increases the cost of pumping the oil from the well. Produced salt water must be reinjected into the subsurface, and this requires drilling and operating a separate disposal well. Although production from several economically marginal oil wells might justify the operation of a disposal well, the single Bombei well would not.

Although the Keota Dome oil production was not commercial, it clearly demonstrates the presence of oil in southeastern Iowa. Of the 19 Iowa oil shows in Table 5, six are from the Keota Dome (shows 8 and 14-18).

Sample 4a is from the Keota Dome, the location of Iowa's only oil production. The oil production here is from the Pecatonica Member of the Platteville Formation, which immediately overlies the Glenwood. The Rock-Eval pyrolysis data derived from sample 4a (Table 1) indicate that the Glenwood is not mature at the Keota Dome. The S1 value indicates the number of milligrams of hydrocarbons that had formed naturally (i.e., prior to the artificial kerogen maturation that occurred during pyrolysis), and the S2 value is the number of milligrams of hydrocarbon that formed during pyrolysis. The 2.36 mg of hydrocarbons prior to pyrolysis is a tiny part of the 125.39 mg of hydrocarbons formed during pyrolysis, indicating an immature source rock in which very little kerogen had been converted to hydrocarbons. This suggests that the oil found at Keota Dome was formed elsewhere and migrated to the dome.

3.4 Hydrocarbon reports from the Hollandale Embayment, southeastern Minnesota

Austin (1970) and Morey (1984) reported oil shows in Freeborn County, Minnesota, just north of the Minnesota-Iowa state line. This area lies in the northern extension of the Forest City Basin named the Hollandale Embayment by Austin (1969). The embayment follows a depression in the surface of Precambrian rocks (Austin, 1970), and Paleozoic strata within the embayment are updip to Forest City Basin strata in Iowa. None of the Paleozoic beds within the Minnesota part of the embayment are known to have sufficient TOC to be source rocks (samples 10a and 11a, Table 1), and their current depth of about 600 feet deep is probably too shallow to have permitted hydrocarbon generation. The western, northern, and eastern sides of the embayment are encircled by Cambrian and Precambrian rocks, and the current geometry (and presumably the past geometry) of the embayment is such that oil in southeastern Minnesota could have only migrated northward from source rocks in Iowa. Therefore, the presence of oil in Ordovician strata in southeastern Minnesota would indicate mature source rocks in the Forest City Basin of Iowa.

Austin's (1970) report of oil from a borehole in southeastern Minnesota seemed significant and worth verifiying. In 1967 and 1968, Northern Natural Gas drilled two stratigraphic tests in section 7-T103N-R19W, Freeborn County, Minnesota; the location is about 2 miles east of Hollandale, Minnesota. These boreholes were not drilled to test an oil or gas prospect, but were drilled to evaluate lower Paleozoic strata for use in underground gas storage. The first borehole, the H-1, reached the Willow River Dolomite Member of the Shakopee Formation (Lower Ordovician) at a depth of 725' when a drill bit was lost and the hole was abandoned. The second borehole, the H-1A, was located 20' from the H-1 and had penetrated about 300' of Precambrian clastic rocks at its total depth of 1905' (Austin, 1970). The combination of these two boreholes is collectively referred to as the Hollandale core (Figure 4). Much of the rock column in these two wells was cored, and cuttings were collected from the uncored parts. The cores are preserved in the Minnesota Department of Natural Resources core repository in Hibbing, Minnesota. They are stored in aluminum trays with aluminum dividers; although the trays have waxed cardboard lids, the cores are not in contact with the wax and there is little chance of hydrocarbon contamination from the containers. Austin (1970) described the cores and cuttings from the Hollandale core, and for the Decorah Shale core at 428.0 to 443.0' stated, "core has dark surface color due to oil staining." The elevation of this stained section is about 770' above sea level. Austin reported no other oil shows in the Hollandale cores.

In July, 1997, R. Erickson visited the Minnesota core repository, examined the Decorah Shale and adjacent parts of the Hollandale core, and borrowed samples of the Decorah Shale (samples 2 and 3) and Platteville Limestone (sample 1). Sample 2 is a piece of whole core, approximately 2 inches in diameter and 0.5 inches thick, showing a black stain on the outer surface of the core; this core is from the interval described by Austin (1970) as having oil staining. The black stain does not fluoresce under ultraviolet light. The core piece was sawed in half using a water-lubricated saw, and one half (sample 2a) was sent to Humble Geochemical Services for TOC measurement and to attempt thermal extraction of trace hydrocarbons for gas chromatographic analysis. This sample had only 0.20 wt.% TOC, a value too low for the rock to contain even a thin surface stain of oil (Dan Jarvie, Humble Geochemical Services, personal communication, 1997). This measurement strongly suggests that Austin's (1970) report of oil staining is incorrect.

Morey (1984) compiled all known reports of oil or gas shows in Minnesota (although he overlooked Austin's reported oil show from the Hollandale core). Morey included a summary of a well drilled by the Minnesota Geological and Natural History Survey in 1887 in northeastern Freeborn County. An employee of the drilling company, H.C. Day, reported a small show of oil in Ordovician limestone, but no trace of this oil was found by N.H. Winchell of the Minnesota survey when he visited the site. Morey also reported one other possible oil show in southeastern Minnesota, a show of oil from the Platteville-Glenwood interval of a water well in surburban St. Paul. Morey (1984, p. 19) commented that such occurrences of "oil" (Morey's quotation marks) in the Platteville and Glenwood are fairly common throughout southeastern Minnesota. Analysis of Austin's reported oil show in the Hollandale core suggests that these other reports of oil are also incorrect.

Table 5: Oil and gas shows and completed wells in Iowa

ID	Operator	Well name	County	Sec - Twn - Rng	Type	Zone	Depth (feet)
1	Soap Creek Devel. Corp.	L.Strunk #1	Appanose	22-T70N-R16W	oil show oil show	Hunton (Devonian) Viola (Ordovician)	974 1223
2	Genie Petroleum	Ashley #1	Chickasaw	29-T96N-R14W	gas show	Solon Member Cedar Valley Fm. (Upper Devonian)	240
3	Upland Leasing	Ullrich #1	Crawford	36-T85N-R39W	completion attempt, hydrocarbon type not reported	Devonian	perforated 982 - 986 1182 - 1185
4	Fremont Oil	Schroeder #1	Fremont	28-T70N-R43W	oil and gas show	unknown	1000
5	Fremont Oil	Schroeder #1A	Fremont	28-T70N-R43W	oil show oil show	Shawnee (Pennsylv.) Marmaton (Pennsylv.)	235 655
6	F.E. Hunt	Fee/Connell #1	Guthrie	11-78N-R30W	gas show	unknown	1500
7	M.P. Hall Co.	Johnson #1	Harrison	17-T81N-R44W	oil show	St. Peter Sandstone (Middle Ordovician)	1709
8	Kent Kimball	Weiss #1	Keokuk	6-T76N-R12W	oil show	Pectonica Member Platteville Limestone (Middle Ordovician)	1414
9	Blazer Corp.	Kenworthy #1	Montgomery	11-T73N-R36W	oil show	McGregor Ls. Member Platteville Limestone (Middle Ordovician)	3045
10	Milo Ditterline	M. Josephson #1	Montgomery	30-T71N-R38W	gas show	lower Mississippian	1884 - 1896
11	H & L Oil	Van Dyck #1	Polk	3-78N-R25W	oil show	Demoinesian coal (Pennsylvanian)	39 - 255

12	Pryor & Lockhart	Marr Estate #1	Taylor	32-T68N-R33W	oil show	Lansing-Kansas City (Pennsylvanian)	340 - 360
13	Cline Oil	Long #1	Taylor	20-T68N-R34W	oil show	Rapid Member Cedar Valley Fm. (Middle Devonian)	2046 - 2060
14	Armato & Hollenkamp	E.R. Reece #1-A	Washington	4-74N-R6W	oil show	Galena Formation (Middle Ordovician)	875
15	Wolb & Bowers & Hill	Flynn Bros. #1	Washington	5-T76N-R9W	reported as oil well, no production	Pectonica Member Platteville Limestone (Middle Ordovician)	1230
16	Natural Gas Pipeline Co. of America	W.F. Flynn #P-1	Washington	20-T76N-R9W	oil well	Pectonica Member Platteville Limestone (Middle Ordovician)	993
17	Northern Drlg.	Herr #1	Washington	31-T77N-R9W	oil show	Pectonica Member Platteville Limestone (Middle Ordovician)	1120
18	CST Oil & Gas	Leonard Bombei #1	Washington	23-T77N-R9W	oil well	"Trenton" (Ordovician)	1185
19	Keosaugua Oil & Gas	Anderson #1	Wayne	25-T68N-R26W	oil show	unknown	980 - 985

4.0 FLUID INCLUSIONS STUDIES

4.1 Fluid inclusions

Fluid inclusions form as growth defects in minerals and can trap samples of the gases and liquids present at the time the mineral was growing (Roedder, 1984). Thus, the compositions of fluid inclusions have the potential to provide information about the nature of past migrating fluids. In this study it was particularly important to know whether hydrocarbons were present, and to see whether their occurrence is consistent with predictions from the thermal modeling.

4.2 Mass spectrometry of fluid inclusions

Some years ago we demonstrated the possibility of analyzing gases in *individual* fluid inclusions using a computer-controlled, fast-scanning mass spectrometer (Barker and Underwood, 1992; Underwood and Barker, 1995). A single mass spectrometer with faster signal analog to digital conversion (ADAC 16-bit, 200kHz) was used in the present study. The effective scan rate of 18 msec per mass spectrum produces 17 data points per atomic mass unit ("amu") over the range from 1 amu to 60 amu. The data are transmitted directly to the hard disk of the controlling PC and are subsequently transferred to a CD for offline processing with a Pentium PC. This approach provides essentially unlimited processing time that is not constrained by the high mass spectrometer scan speed during data acquisition.

The analytical procedure involves heating minerals containing fluid inclusions in a vacuum system that forms the inlet to the mass spectrometer system. As temperature rises, phase relationships in the inclusions may change in such a way that the pressure for the contents increases rapidly, ruptures the host mineral, and releases the gases for analysis. The release of an individual volatile component as a function of rising temperature can be monitored with a mass spectrometer by tuning it to a single amu value (Figure 6). The detailed shape of a burst shows that the full peak width at 95% of maximum response is slightly greater than 25 msec. Thus the problem of analyzing the volatile contents of each inclusion reduces to one of getting a complete analysis within the 25-msec time constraint imposed by an individual burst. Most commercial quadrupole mass spectrometers require about 100 msec/mass spectrum. Since the UTI 100C instrument used in our system can scan from mass 1 to mass 300 in 75 msec, a mass range from 1-60 amu can be scanned in under 20 msec. This mass range is scanned repeatedly during sample heating and inclusion rupture and provides compositional data for individual inclusion bursts that can be corrected for instrument background by subtracting the preceding mass spectrum. Quantitative analysis by mass spectrometry requires calibration data for both cracking patterns and relative sensitivities of the gases being analyzed. Pure gases and gas mixtures of known composition were obtained from a stainless steel calibration line that could be attached to the vacuum system. It had cylinders of pure gases attached to the stainless steel manifold by double valves, and a capacitance manometer that gave the pressure as each additional gas component was added to a mixture.

Twelve samples from wells in the study area were selected for fluid inclusion analysis (Table 6). Cores provide the best study materials, but unfortunately were not available. Because the analytical procedure only requires 10 - 30 mg samples, cuttings can be used, and careful selection provided suitable crystalline material. Six of the samples analyzed had no detectable fluid inclusions. In the other samples the number of individual fluid inclusions analyzed ranged from 2 to 814. In all cases the inclusion fluids were water dominated and had at most very minor traces of methane and no indication of higher hydrocarbons.

A useful initial check on the quality of a particular analysis is to plot amu 17 values against those for amu 18. These two masses are dominated by water and the 17/18 ratio is well known from calibration. Figure 7 gives the trend obtained from the 39 inclusions analyzed in the Coddington well (sample 52). There is very little scatter in the measured ratios showing that reliable data are produced by the mass spectrometer even at the high scan speeds used. When these data are plotted on a water (18) - carbon dioxide (44) - hydrogen sulfide (34) ternary diagram (Figure 8) they show that water dominates, but also show that CO_2/H_2S ratios remain constant with varying water content. In contrast, the 192 inclusions in the Davidson (sample 37) do not show this trend and are water rich with variable amounts of carbon dioxide (up to about 25 percent).

Unfortunately, the cuttings available were not suitable for microthermometry on the fluid inclusions and it was not possible to establish homogenization temperatures or measure salinities.

4.2 Fluid inclusions in the Cominco SS-3 well

The presence of a calcite-filled vug in sample 8 (Guttenberg Member, Cominco SS-3 well core, Jackson County, Iowa, 675′ deep) provided an opportunity to examine fluid inclusions. Within the population of inclusions measured, homogenization temperatures ranged from 78 to 91°C. Freezing point depressions varied from -1.6 to -23.0°C, which, for NaCl solutions, covers the range from near saturation to almost fresh water (2.73%). The corresponding changes in density should have an important influence on past water flow in the basin. Each inclusion has a salinity value and a homogenization temperature. Interestingly, inclusions with lower salinities also had lower homogenization temperatures.

If the paleogeothermal gradient were about 30°C/km and past surface temperature near 20°C, the fluid inclusion temperatures imply that at least 2 km of rock has been removed by erosion. Removal of this much rock in northeastern Iowa seems unlikely, but an alternative explanation of the fluid-inclusion data is possible. Hot fluids of about 80°C to 90°C might have flowed through the Ordovician rocks and been trapped in fluid inclusions as they formed in the calcite.

Table 6: Samples analyzed for fluid inclusions. Depths are in feet.

WELL NAME	DEPTH RANGE FEET	SAMPLE NO. (TYPE)	NUMBER OF INCLUSIONS
Davidson #1	1595 – 1600	38 (calcite, Lansing)	17
Davidson #1	2130 – 2135	37 (lmst, Marmaton)	814
Davidson #1	3290 – 3295	26 (lmst, Viola)	n.d.*
Davidson #1	3295 – 3300	27 (calcite cryst, Viola)	17
Davidson #1	3300 – 3305	39 (lmst/dolo, Simpson)	n.d.
Davidson #1	3340 – 3345	40 (dolo, Simpson)	n.d.
Watson #1	1210 – 1215	16 (lmst, Chattanooga)	n.d.
Broeckelman #1	3940 – 3950	30 (calcite cryst, Viola)	2
Shoffner #1	1900 – 1905	41 (lmst, Pennsylvanian)	n.d.
Shoffner #1	3060 – 3065	42 (lmst, Kinderhook)	7
Palen #1	4200 – 4205	46 (dolo, Arbuckle)	n..d.
Coddington #3-24	2660 – 2670	52 (calcite, Maquoketa)	41

* n.d. none detected

5.0 MODELS

We modeled four wells along an east-west line crossing the southern Forest City and Salina Basins of Kansas, the Palen #1 well in the central Salina Basin of Kansas, and the Coddington #3-24 well in the Forest City Basin of southwestern Iowa. Locations of wells are shown in Figures 2 and 3. Appendix 1 contains formation tops, unconformity data, and lithologies used in modeling these six wells.

The BasinMod computer program allows modeling the burial history of source rocks and other strata using current depths and thicknesses of formations, estimates of erosional loss of strata, lithologies of existing and eroded strata, and other data; much of this data is typically derived from oil well information. The program then calculates compaction, thermal history, the timing and extent of source-rock maturation, and other information using various user-selected calculation methods. One product of the model is a burial-history chart in which depth is plotted on the vertical axis and time is plotted on the horizontal axis. Levels of source-rock maturity are shown by shaded areas on the plot. Source rocks lying within these shaded zones would be expected to have generated hydrocarbons. The extent of source-rock maturation is shown as early mature, mid mature, or late mature; these levels correspond to heating equivalent to vitrinite reflectance levels (R_o) of 0.5% to 0.7%, 0.7% to 1.0%, and 1.0% to 1.3%.

5.1 Wells along east-west line in southern Forest City and Salina basins of Kansas

We modeled four wells (Table 7) along a line following Township 15 South and extending from Miami County in eastern Kansas to Ellsworth County in west-central Kansas (Figure 2).

This line extends across the southern Forest City Basin, the Nemaha Uplift, and the southern Salina Basin. The Knoche #1 is the easternmost well of this group. Although this well was completed as a dry hole, it lies within the northern part of the Paola-Rantoul Field, which is the largest of the oil fields that lie along the eastern margin of the Forest City Basin. Farther west, the Davidson #1 lies near the deepest part of the southern Forest City Basin. Six miles west of the Davidson #1 lies the Humbolt Fault, which forms the eastern boundary of the Nemaha Uplift and the western edge of the Forest City Basin. The John Creek Field lies on the upthrown side of the Humbolt Fault and is directly west of the Davidson #1 along the line following Township 15 South. The John Creek Field is a doubly-plunging anticline with a north-south axis; the Humbolt Fault cuts through this anticline just east of its crest (Curtis, 1960). The throw of the Humbolt fault is less than 100′ at the John Creek Field; the structural map and logs in Curtis (1960) indicate that the Arbuckle top is only about 60′ higher on the crest of the John Creek anticline than it is in the Davidson #1 well. The western side of the Nemaha Uplift drops gradually toward the Shoffner #1 well. The westernmost well of the four is the Kyler #1, which is just east of the Central Kansas Uplift and near the western edge of the Salina Basin.

BasinMod permits the user to select from a variety of calculation options, allowing the models to fit the thermal, geochemical, and physical conditions of a specific geologic setting. To compare all four wells, all were modeled with the same set of calculation options and parameters. Source-rock maturity can be calculated by one of three methods: Lawrence Livermore National Laboratory (LLNL), Lopatin, and simple R_o. Our modeling used the LLNL method for all four of the Kansas wells. (For comparison, the Lopatin and simple R_o methods were also used for the Davidson #1 well.) All our models used a steady-state heat flow with a present-day heat flow of 70 mW/m^2. This value is slightly higher than the 63 mW/m^2 used as a default value by BasinMod but still a reasonable value for the continental interior of the U.S. Kerogen conversion calculations used our measured value for the Guttenberg Type I kerogen (i.e., 100% of reaction occurring at 58 kcal/mole). Other values and options selected are shown in Table 8.

5.1.1 Knoche #1

The Knoche #1 lies near the eastern edge of the Forest City Basin. The BasinMod burial history (Figure 9) shows that none of the Ordovician and younger source rocks have reached even early stages of maturity. Any source rocks present in the Arbuckle Formation below the total depth (TD) of this well would probably also be thermally immature, and no source rocks are known to occur in the Arbuckle. No samples of well cuttings for this well are available at the Wichita Well Sample Library.

5.1.2 Davidson #1

The Davidson #1 lies in the deeper, western part of the Forest City Basin. The BasinMod burial history calculated using the Lawrence-Livermore method (Figure 10) shows that Ordovician rocks up to and including the Maquoketa Formation reached the early mature level. R. Erickson examined well cuttings and logs of this well at the Wichita Well Sample Library; in the Ordovician section of this well only the lower Simpson black shales had the black or dark-brown color that is typical of Ordovician source rocks and these were the only samples for which TOC was measured. These lower Simpson black shales (samples 28 and 29) had sufficient TOC to be considered potential source rocks. Six Pennsylvanian shale samples (samples 21, 22, 23, 24, 25, and 48) also had sufficient organic richness to be potential source rocks, but the Lawrence-Livermore model of the Davidson #1 shows that these shales would not have generated hydrocarbons.

Previous work by Newell et al. (1987) used the Lopatin method to evaluate maturity of Ordovician through Pennsylvanian source rocks from two wells in the Forest City Basin. One of these wells was in Nemaha County and would have had a burial history similar to that of the Davidson #1 at least through the start of the Cretaceous, however Newell et al. (1987) assumed 2000' of additional burial during the Cretaceous. Their second well was in Leavenworth County, and its burial history was nearly identical to that of the Knoche #1 well. For both wells, Newell's group calculated that Ordovician through Mississippian source rocks became more mature than what is shown by our models and showed maturation beginning in the Mesozoic. Although the additional Cretaceous deposition makes it difficult to compare the Newell group's Nemaha well with the Davidson #1, their Leavenworth County well should show maturity comparable to the Knoche #1 well. However, the Knoche #1 model showed that no source rocks mature, and the Newell group's Leavenworth County well had mature source rocks as high as the Mississippian. How closely does the Lopatin method duplicate results of the Lawrence-Livermore method? To answer this question, we used BasinMod to calculate a basin history diagram using the Lopatin method; results are shown in Figure 11. Comparing Figure 10 with Figure 11, we see that the Lopatin method gives much higher maturities for Ordovician source rocks and shows marginal maturities for source rocks as high as the Pennsylvanian. Tissot and Welte (1984, pages 584-585) discussed problems with use of the Lopatin method. In particular, they point out that the Lopatin method is suitable only for reactions having activation energies of 10 to 25 kcal/mole; the Glenwood and Guttenberg strata have activation energies of at least 56 kcal/mole (Table 4). Apparently, the Lopatin-derived maturity levels are unrealistically high.

We also modeled the Davidson #1 using BasinMod's simple R_o method (Figure 12). Hatch and Newell (in press) measured vitrinite reflectance on a Chattanooga sample from the Heller Stice #1 well (NW/4 section 11-T14S-R8E, Wabaunsee County, Kansas), which is about 20 miles northwest of the Davidson #1. Their R_o value of 0.6% was inserted into the present-day Chattanooga section of the Davidson #1, and the BasinMod program adjusted the thermal history to fit this R_o value. The resulting model shows that source rocks as high as the middle Missourian are in the early mature stage. If this were the case, some of the Pennsylvanian organic-rich shales would also have reached the early mature stage. However, Hatch and Newell also measured the vitrinite reflectance of 0.7% in a Cherokee Group sample from the Stice #1 well. Although the Cherokee Group sample was from about 200' above the Chattanooga sample, its vitrinite reflectance was higher. Clearly at least one of these vitrinite values does not fit the thermal history of either the Stice or Davidson well. Until this vitrinite problem is resolved, we are reluctant to accept the thermal history presented by the Davidson #1 simple R_o model.

5.1.3 Shoffner #1

The burial history for the Shoffner #1 well (Figure 13) shows no mature source rocks in this well. This seems surprising because its history is similar to that of the Davidson #1 well. The thickness of the Desmoinesian and Atokan section is greater in the Davidson than in the Shoffner, and this difference is probably just enough to cause the different thermal histories.

[Note that the thickness of the Desmoinesian and Atokan sections in the Davidson #1 (Figure 10) is about the same as the thickness of the early mature section.]

Although our model does not show any thermal maturity for source rocks in the Shoffner #1, three samples of potential source rocks (samples 31, 33, and 34) show that organic rich shales are present in the Upper Ordovician and Upper Devonian. If our model underestimates the thickness of section lost due to erosion after the Permian, these source rocks could be mature in the Shoffner well.

Some of our earlier Shoffner models using other BasinMod calculation methods showed that some of the Ordovician source rocks reached the early mature stage, but this early maturity disappears when the Shoffner is modeled using the same calculation methods that are used for all the other models on the east-west line.

5.1.4 Kyler #1

The Kyler #1 lies in the southwestern part of the Salina Basin. Our models of the Kyler #1 and the Palen #1 show that the original thickness of the Permian and Cretaceous sections and the amount of these sections lost to erosion are probably more important in the western Salina Basin than in the eastern Salina Basin and Forest City Basin. The amount of missing Permian section is difficult to determine, but the amount of Cretaceous section that has been lost can be estimated using vitrinite reflectance of Dakota Formation (Lower Cretaceous) lignite. R. Erickson collected a surface sample of Dakota lignite from a locality on the south side of the Smoky Hill River (sample 56, SW/4 NW/4 NE/4 section 6-T15S-R10W, Ellsworth County, Kansas) just south of the town of Wilson; this locality is shown as the Wilson lignite locality on Figure 2 and is about 19 miles west of the Kyler #1. The vitrinite of this sample is 0.41% and was measured by Wallace Dow (DGSI, The Woodlands, Texas). This reflectance level at the surface corresponds to 2000′ to 4000′ of overburden removal, and we have used the midpoint of 3000′ for our estimate of the amount of post-Cretaceous erosion.

The Kyler #1 burial history plot (Figure 14) shows that potential source rocks from the Arbuckle to the lower Desmoinesian have reached early maturity. Ideally, the early mature area should extend higher in the section so that the R_o of the upper part of the well closely matches the R_o of the surface lignite sample. Our Kyler model might underestimate the amount of pre-Cretaceous erosional loss.

No samples from this well are available in the Wichita Well Sample Library, so we are unable to determine what strata have sufficient organic carbon to be source rocks.

5.2 West Central Salina Basin Model - The Palen #1

The Palen #1 burial history (Figure 15) is quite different those for the other Kansas wells. The Palen #1 model shows that the entire geologic column has reached some level of thermal maturity. The section from the Arbuckle to the Cherokee Group has reached late maturity; of all the wells modeled for this study, this is the only well to show source rocks in the late maturity stage. Based of the vitrinite reflectance of the Dakota lignite from the Wilson locality, we estimated 3000' of erosional loss at the top of the Cretaceous. We did not force the BasinMod program to honor the R_o of the lignite. Even without this vitrinite data in the calculations, the burial history generated by BasinMod places the top of the early mature range at the surface of the Palen #1 well. The top of this maturity range coincides with vitrinite reflectance of 0.5%; this closely matches the 0.41% R_o of the lignite. The close match between the predicted surface maturity and the surface maturity measured from a surface lignite sample gives credibility to this model.

The lower Simpson black shale (sample 45) from the Palen #1 well is 2.28 wt.% TOC. The Palen #1 burial history indicates that this shale would be in the late mature stage and that it should have generated hydrocarbons. Oil generated in the vicinity of the Palen would have migrated updip, moving to the west or southwest toward the Central Kansas Uplift. Using this model, one would predict the existence of oil fields between the Palen and the Central Kansas Uplift. In 1997, Castle Resources announced the discovery of a new field 13 miles due west of the Palen #1 and 16 miles northeast of the nearest production at the Kill Creek Field in T8S-R14W. The Castle Resources Schweitzer #1 produced oil from a Simpson reservoir. The Schweitzer well is in the northeastern corner of Osborne County, and oil from this well was certainly derived from source rocks within the central Salina Basin.

5.3 Iowa Model – The Coddington #3-24

The Coddington #3-24 in southwestern Iowa is the deeper part of the northern Forest City Basin. Its burial history diagram (Figure 16) shows that Ordovician strata and the Devonian Wapsipinicon have reached early maturity. The Coddington model used the Sclater and Christie method to calculate compaction rather than the fluid flow method used in the other models. This method might result in a slightly higher level of maturity than what would have resulted from the fluid flow method.

The Maquoketa shale sample from the Coddington well (sample 51) had 3.01 wt.% TOC. If our model is correct, the Maquoketa would be a source rock in southwestern Iowa. The Marmaton black shale from this well (sample 50) has 16.67 wt.% TOC, but our model does not show that this part of the section is mature.

5.3 General conclusions from models

The models from the southern Salina Basin (i.e., Kyler #1), the southwestern Forest City Basin (Davidson #1), and the northwestern Forest City Basin (Coddington #3-24) suggest that Ordovician source rocks in these areas are at least in the early mature stage. The Palen #1 well in the central Salina Basin shows that source rocks as high as the Cretaceous can be at least in the early mature stage, and deeper strata can reach higher levels of maturity in the central Salina Basin.

For all the wells modeled, the deposition of thick Pennsylvanian strata resulted in rapid and fairly deep burial of Lower Paleozoic potential source rocks. The Pennsylvanian burial seems to be the key event in the thermal maturation of the source rocks in the Forest City Basin and eastern Salina Basin, and this maturation started shortly after the Pennsylvanian deposition. Most of the structural traps were formed during or before the Pennsylvanian, so any hydrocarbons generated after the Pennsylvanian could have been captured in these structural traps.

In the central and western Salina Basin, the effect of Cretaceous burial becomes as important if not more important than the that of Pennsylvanian burial. The amount of burial by Permian strata is difficult to determine, and the amount of section lost by erosion between the end of Permian deposition and the start of Cretaceous deposition is even more difficult to estimate. The close match of the surface vitrinite reflectance predicted by the BasinMod model of the Palen #1 and the vitrinite reflectance measured in the Wilson lignite sample indicates that the model has correctly accounted for Cretaceous deposition and post-Cretaceous erosion. If Permian deposition and post-Permian erosion produced burial and erosional loss that were no greater than Cretaceous burial and post-Cretaceous erosion, the Permian deposition and erosion would duplicate what has occurred since the start of the Cretaceous. If this were the case, the maturation of source rocks would have started earlier than what is shown in our model, but the levels of thermal maturity would be no higher than those of our model. Only if previous deposition resulted in much deeper burial than that produced by the Cretaceous would our Palen model underestimate the levels of thermal maturity.

Table 7: Four wells modeled in southern Forest City and Salina basins

Well name Operator	Year drilled	Location Section-Township- Range County	Total depth (feet)	Subsea depth of top of Arbuckle (feet)
Knoche #1 Corbin Robison	1965	Section 24-T15S-R22E Miami County	1590	-478
Davidson #1 Carter Oil Co.	1951	Section 29-T15S-R11E Lyon County	3470	-1877
Shoffner #1 Ohio Oil Co.	1958	Section 19-T15S-R1W Saline County	3616	-2217
Kyler #1 S.K.D. Corporation	1973	Section 5-T15S-R7W Ellsworth County	3600	-1864

Table 8: Options and values used in modeling

Property	Selected method or value
Time interval	10 million years
Depth interval	50′
Present-day surface temperature	20°C
Permeability calculation method	modified Kozeny-Carman
Thermal conductivity method	Deming-Chapman
Heat capacity correction, Δ heat, radiogenic heat, and basement heat flow options	Not used

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7.0 APPENDIX 1: DATA USED IN MODELING

7.1 Kansas wells

7.1.1 Lithology mixes used for compaction and thermal conductivity calculations for Kansas wells

Lithology mix	% sandstone	% shale	% limestone	% dolomite
Virgilian mix	10	50	40	0
Missourian mix	10	20	70	0
Desmoinesian mix	10	80	10	0
Mississippian mix	0	0	50	50
Hunton mix	0	0	30	70
Viola mix	0	0	70	30
Simpson mix	80	10	0	10

7.1.2 Knoche #1 Burial History

Formation or event	Type	Beginning age (Ma)	Well top (feet)	Present thickness (feet)	Missing thickness (feet)	Lithology
post-Pennsylvanian erosion	E	280			-1000	
Missourian	F	287	0	370		Missourian mix
Desmoinesian	F	290	370	610		Desmoinesian mix
post-Atokan erosion	E	295				
Atokan	F	300	980	29		Atokan mix
post-Mississippian erosion	E	310			-500	
Mississippian	F	340	1009	410		Mississippian mix
Chattanooga	F	345	1419	21		Shale
post-Middle Devonian erosion	E	380			-600	
Hunton	F	410	1440	10		Hunton mix
post-Ordovician erosion	E	425			-400	
Maquoketa	F	430	1450	9		Shale
post-Middle Ordovician erosion	E	480			-300	
Viola Limestone	F	485	1459	57		Viola mix
Simpson Group	F	488	1516	66		Simpson mix
post-Early Ordovician erosion	E	495			-800	
Arbuckle	F	510	1582	500		Dolomite

Key to Type: E - Erosion
F – Formation

7.1.3 Davidson #1 Burial History

Formation or event	Type	Beginning age (Ma)	Well top (feet)	Present thickness (feet)	Missing thickness (feet)	Lithology
post-Pennsylvanian erosion	E	280			-1000	
Virgilian	F	285	0	1553		Virgilian mix
Missourian	F	287	1553	447		Missourian mix
Desmoinesian	F	290	2000	200		Desmoinesian mix
post-Atokan erosion	E	295			-500	
Atokan	F	300	2200	380		Atokan mix
post-Mississippian erosion	E	310			-500	
Mississippian	F	340	2580	378		Mississippian mix
Chattanooga	F	345	2958	138		Shale
post-Middle Devonian erosion	E	380			-600	
Hunton	F	410	3096	52		Hunton mix
post-Ordovician erosion	E	425			-400	
Maquoketa	F	430	3148	77		Shale
post-Middle Ordovician erosion	E	480			-300	
Viola Limestone	F	485	3225	67		Viola mix
Simpson Group	F	488	3295	92		Simpson mix
post-Early Ordovician erosion	E	495			-800	
Arbuckle	F	510	3384	500		Dolomite

Key to Type: E - Erosion
F – Formation

7.1.4 Shoffner #1 Burial History

Formation or event	Type	Beginning age (Ma)	Well top (feet)	Present thickness (feet)	Missing thickness (feet)	Lithology
post-Permian erosion	E	270			-1000	
Wolfcampian	F	290	0	1400		50% limestone 50% shale
Virgilian	F	295	1400	720		Virgilian mix
Missourian	F	300	2120	659		Missourian mix
post-Mississippian erosion	E	323			-200	
Mississippian	F	340	2779	277		Limestone
Post-Early Mississippian erosion	E	350			-200	
Kinderhook	F	355	3056	117		Shale
Misener	F	358	3173	11		Sandstone
Post-middle Devonian erosion	E	380			-600	
Hunton	F	410	3184	120		Hunton mix
post-Ordovician erosion	E	425			-400	
Maquoketa	F	430	3304	99		Shale
post-Middle Ordovician erosion	E	480			-300	
Viola Limestone	F	485	3403	106		Viola mix
Simpson Group	F	488	3509	60		Simpson mix
post-Early Ordovician erosion	E	495			-800	
Arbuckle	F	510	3569	47		Dolomite

Key to Type: E - Erosion
F – Formation

7.1.5 Kyler #1 Burial History

Formation or event	Type	Beginning age (Ma)	Well top (feet)	Present thickness (feet)	Missing thickness (feet)	Lithology
post-Pennsylvanian erosion	E	280			-3000	
Virgilian	F	285	0	500		Virgilian mix
Missourian	F	287	500	1000		Missourian mix
Desmoinesian	F	290	1500	1000		Desmoinesian mix
post-Atokan erosion	E	295			-500	
Atokan	F	300	2500	712		Atokan mix
post-Mississippian erosion	E	310			-500	
Mississippian	F	340	3212	60		Mississippian mix
Chattanooga	F	345	3272	143		Shale
post-Middle Devonian erosion	E	380			-600	
Hunton	F	410	3415	5		Hunton mix
post-Ordovician erosion	E	425			-400	
Maquoketa	F	430	3420	25		Shale
post-Middle Ordovician erosion	E	480			-300	
Viola Limestone	F	485	3445	64		Viola mix
Simpson Group	F	488	3509	66		Simpson mix
post-Early Ordovician erosion	E	495			-800	
Arbuckle	F	510	3575	500		Dolomite

Key to Type: E - Erosion
F – Formation

7.1.6 Palen #1 Burial History

Formation or event	Type	Beginning age (Ma)	Well top (feet)	Present thickness (feet)	Missing thickness (feet)	Lithology
post-Cretaceous erosion	E	98			-3000	
Cretaceous	F	115	0	1445		Shale
Post-Permian erosion	E	250			-500	
Hollenberg	F	270	1445	165		Permian mix
Fort Riley	F	272	1610	368		Permian mix
Neva	F	276	1978	687		Permian mix
Post-Pennsylvanian erosion	E	280			-300	
Topeka (Virgilian)	F	285	2665	395		Limestone
Lansing	F	287	3060	245		Limestone
Marmaton	F	290	3305	210		Shale
Cherokee	F	292	3515	85		Shale
Post-Mississippian erosion	E	310			-750	
Mississippian	F	340	3600	140		Limestone
Kinderhook	F	350	3740	48		Shale
Misener	F	360	3788	3		Sandstone
Post-Middle Devonian erosion	E	380			-600	
Hunton	F	410	3791	14		Limestone
Post-Ordovician erosion	E	425			-400	
Maquoketa	F	430	3805	28		Shale
Post-Middle Ordovician erosion	E	480			-300	
Viola	F	485	3833	247		Limestone
Simpson	F	488	4080	120		Sandstone
Post-Early Ordovician erosion		495			-800	
Arbuckle	F	510	4200	500		Dolomite

Key to Type: E - Erosion
F – Formation

7.2 Iowa well

7.2.1 Lithology mixes used for compaction and thermal conductivity calculations for southwestern Iowa (SWI) wells

Lithology mix	% sandstone	% siltstone	% shale	% limestone	% dolomite
Virgilian mix (SWI)	0	10	80	10	0
Missourian mix (SWI)	5	0	75	20	0
Desmoinesian mix (SWI)	10	5	75	10	0
Wapsipincon mix (SWI)	0	0	40	10	50

7.2.2 Coddington #3-24 Burial history

Formation or event	Type	Beginning age (Ma)	Well top (feet)	Present thickness (feet)	Missing thickness (feet)	Lithology
post-Pennsylvanian erosion	E	280			-300	
Virgilian	F	285	0	200		Virgilian mix (SWI)
Missourian	F	287	200	300		Missourian mix (SWI)
Desmoinesian	F	290	500	1100		Desmoinesian mix (SWI)
post-Mississippian erosion	E	350			-500	
Burlington	F	360	1610	60		Limestone
post-Middle Devonian erosions	E				-300	
Lime Creek	F	377	1670	330		Shale
Cedar Valley	F	382	2000	300		Limestone
Wapsipicon	F	387	2300	339		Wapsipincon mix (SWI)
post-Middle Devonian erosion	E	450			-400	
Maquoketa	F	458	2639	311		Shale
post-Middle Ordovician erosion	E	475			-200	
Galena	F	478	2950	77		Dolomite
Decorah/Platteville	F	482	3027	93		Shale
Middle Ordovician erosion	E	490			-300	
St. Peter Sandstone	F	495	3120	30		Sandstone
post-Early Ordovician erosion	E	500			-600	
Prairie du Chien	F	505	3150	200		Sandstone
Jordan Sandstone	F	510	3350	230		Sandstone
Mt. Simon Sandstone	F	520	3580	210		Sandstone
post-Precambrian erosion	E	550			-1500	
Keweenawan	F	900	3790	100		Igneous rock

Key to Type: E - Erosion
F – Formation

FIGURE CAPTIONS

Figure 1

Upper Cambrian through Lower Mississippian stratigraphic units of Kansas and Iowa. Bold type indicates potential source rocks.

Figure 2

Map of Kansas showing wells used for models and locations of samples.

Figure 3

Map of Iowa showing location of Coddington #3-24 well and locations of samples.

Figure 4

Map of Minnesota showing locations of Hollandale core and Minnesota Geological Survey core from which Glenwood Shale samples (samples 10a and 11a) were taken.

Figure 5

Gas chromatogram of oil extracted from oil-stained Maquoketa carbonate (sample 49a) from 3770' to 3780', Mallard Petroleum Broeckelman #1 well, section 15-T1S-R10W, Jewell County, Kansas.

Figure 6

Release of water [top curve] and carbon dioxide [bottom curve] from Sample 52, Coddington #3-24 as a function of rising temperature (400 to 550 °C). Sharp "spikes" are produced by individual fluid inclusions rupturing. At temperature much above 550 °C carbonates begin to thermally decompose and generate large quantities of carbon dioxide.

Figure 7

Atomic mass units 17 and 18 plotted to show the constant ratios for the 39 fluid inclusions analyzed. Both 17 amu and 18 amu are formed from water in the mass spectrometer, and the straight line shows that even at the high scan speeds used the mass spectrometer is producing reliable data.

Figure 8

Water [18] - carbon dioxide [44] - hydrogen sulfide [34] ternary diagram showing data for 39 inclusions from Sample 52 in the Coddington 3-24 Well. The points define a trend with variable water but constant CO_2/H_2S ratio.

Figure 9

Burial history diagram for the Knoche #1

BasinMod cryptic code for all burial history diagrams (Figures 9-16):
CMP - compaction calculation method: FF - fluid flow method; SC - Sclater and Christie method
TH - thermal history calculation method: SHF Steady State Heat Flow
MAT - maturity calculation method: LL - Lawrence Livermore National Laboratory method; TTI - Lopatin TTI method; SIM - simple R_o method
TG - Thermal gain
TI - time interval in millions of years
EXP - expulsion calculation method: VR – efficiency method based on vitrinite reflectance
PRM – permeability calculation method: MKC – modified Kozeny-Carman
DI - depth interval for depth integration, in feet
CNV – conversion method for Lopatin calculations; Tab – conversion table

Figure 10

Burial history diagram for the Davidson #1 well using Lawrence Livermore National Laboratory method. For abbreviation codes see Figure 9 caption.

Figure 11

Burial history diagram for the Davidson #1 well with Chattanooga Shale fit to R_o of 0.6%. For abbreviation codes see Figure 9 caption.

Figure 12

Burial history diagram for the Davidson #1 well using Lopatin TTI method. For abbreviation codes see Figure 9 caption.

Figure 13

Burial history diagram for the Shoffner #1 well. For abbreviation codes see Figure 9 caption.

Figure 14

Burial history diagram for the Kyler #1 well. For abbreviation codes see Figure 9 caption

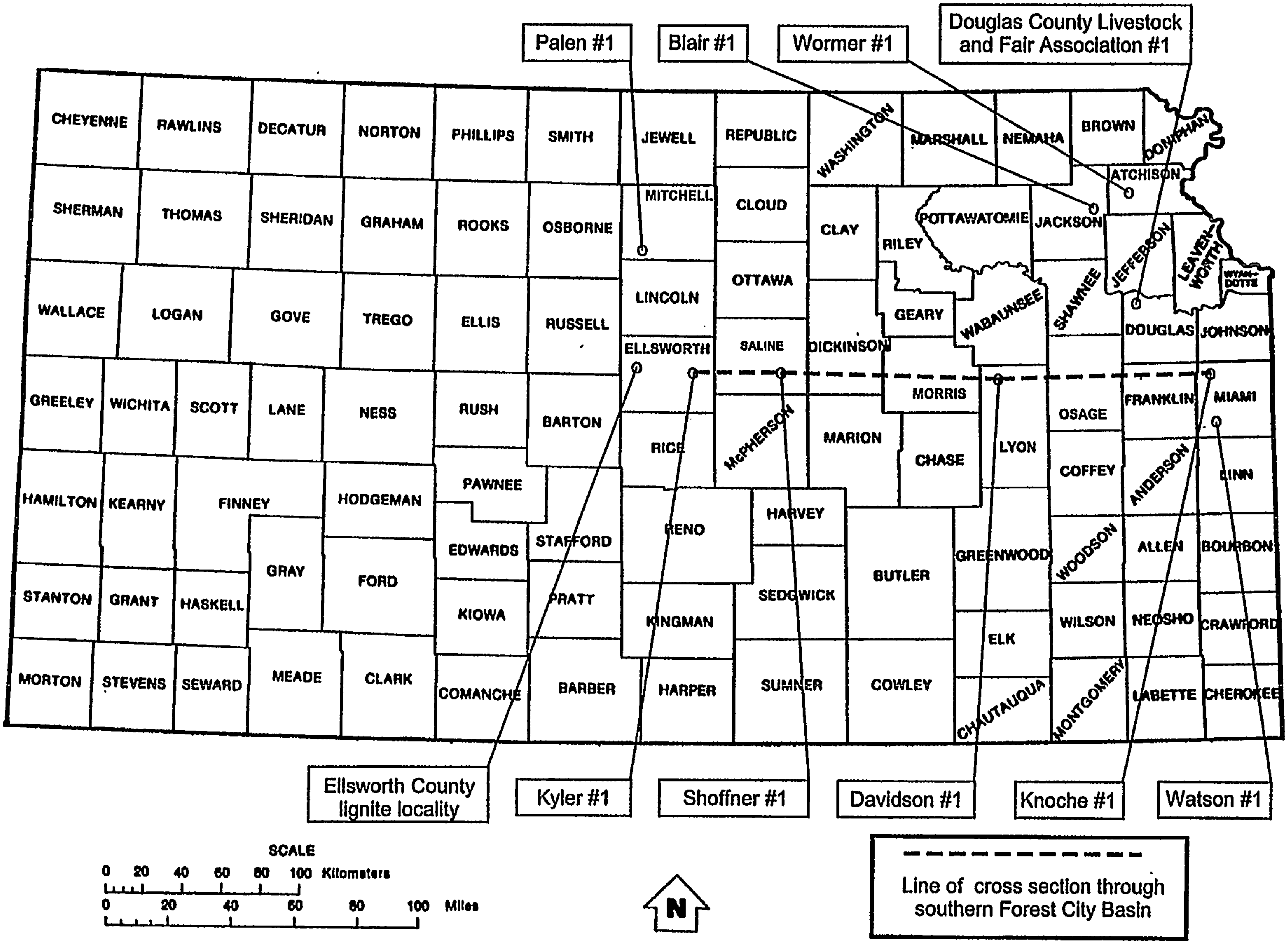
Figure 15

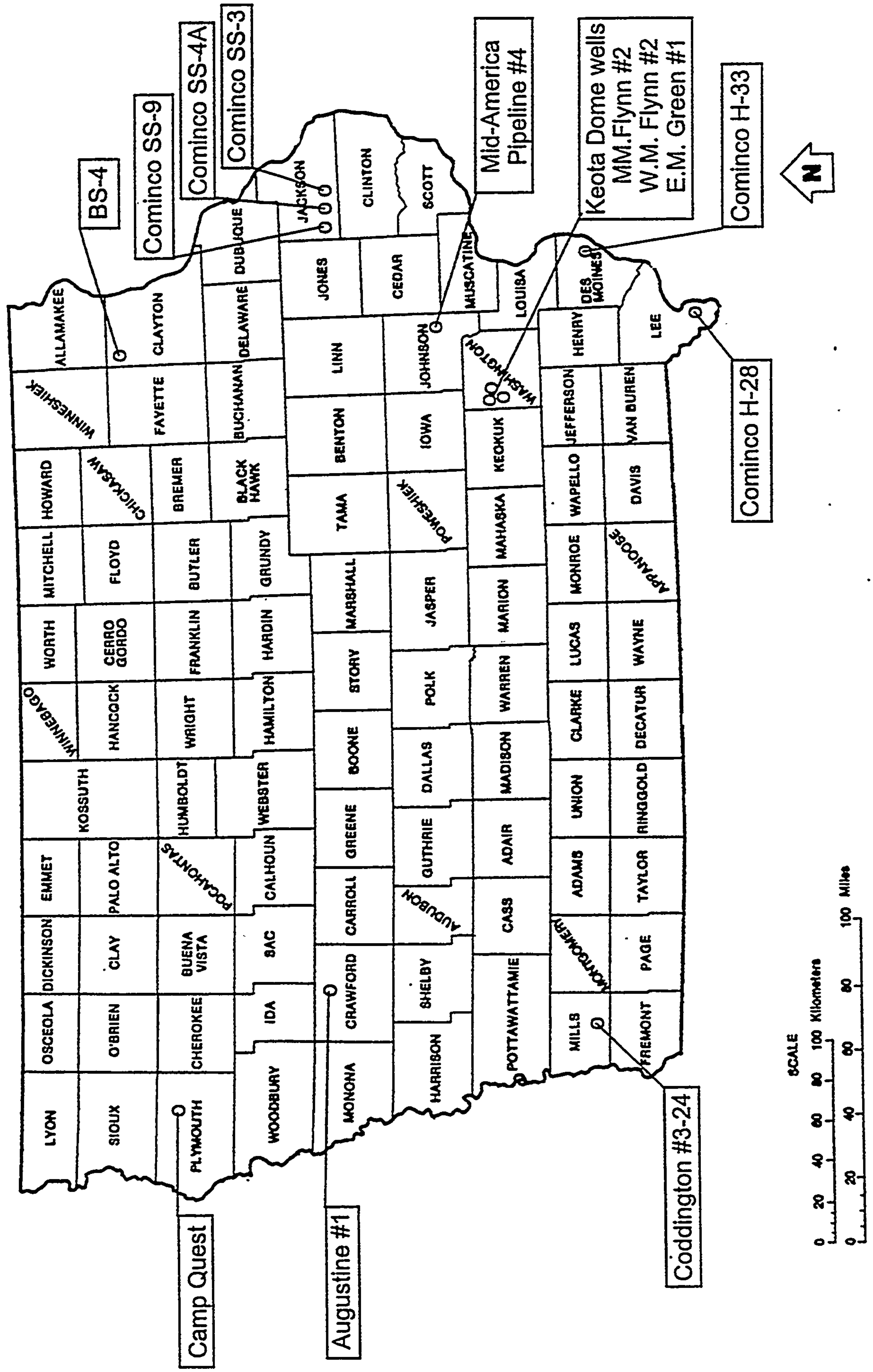
Burial history diagram for the Palen #1 well. For abbreviation codes see Figure 9 caption.

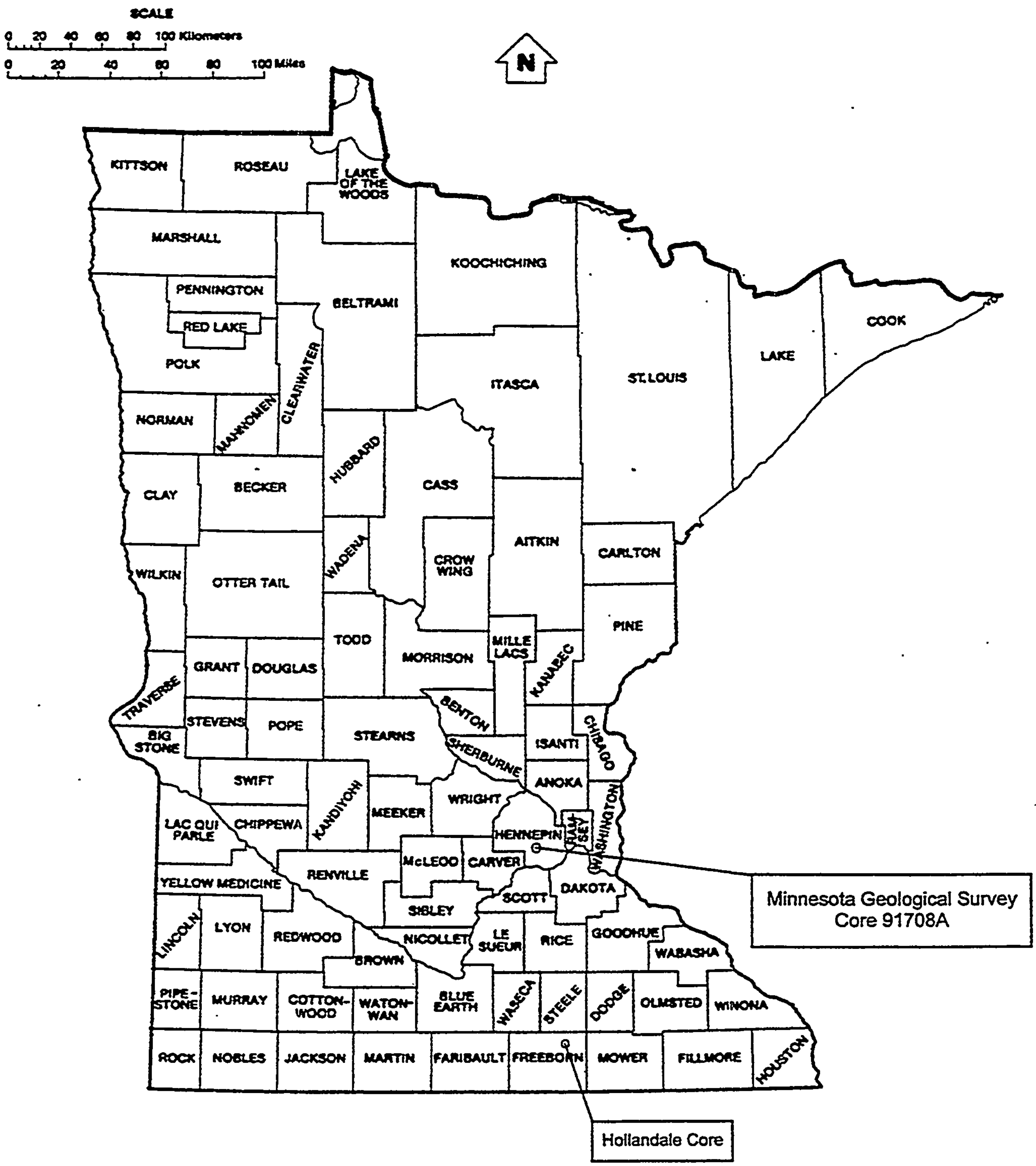
Figure 16

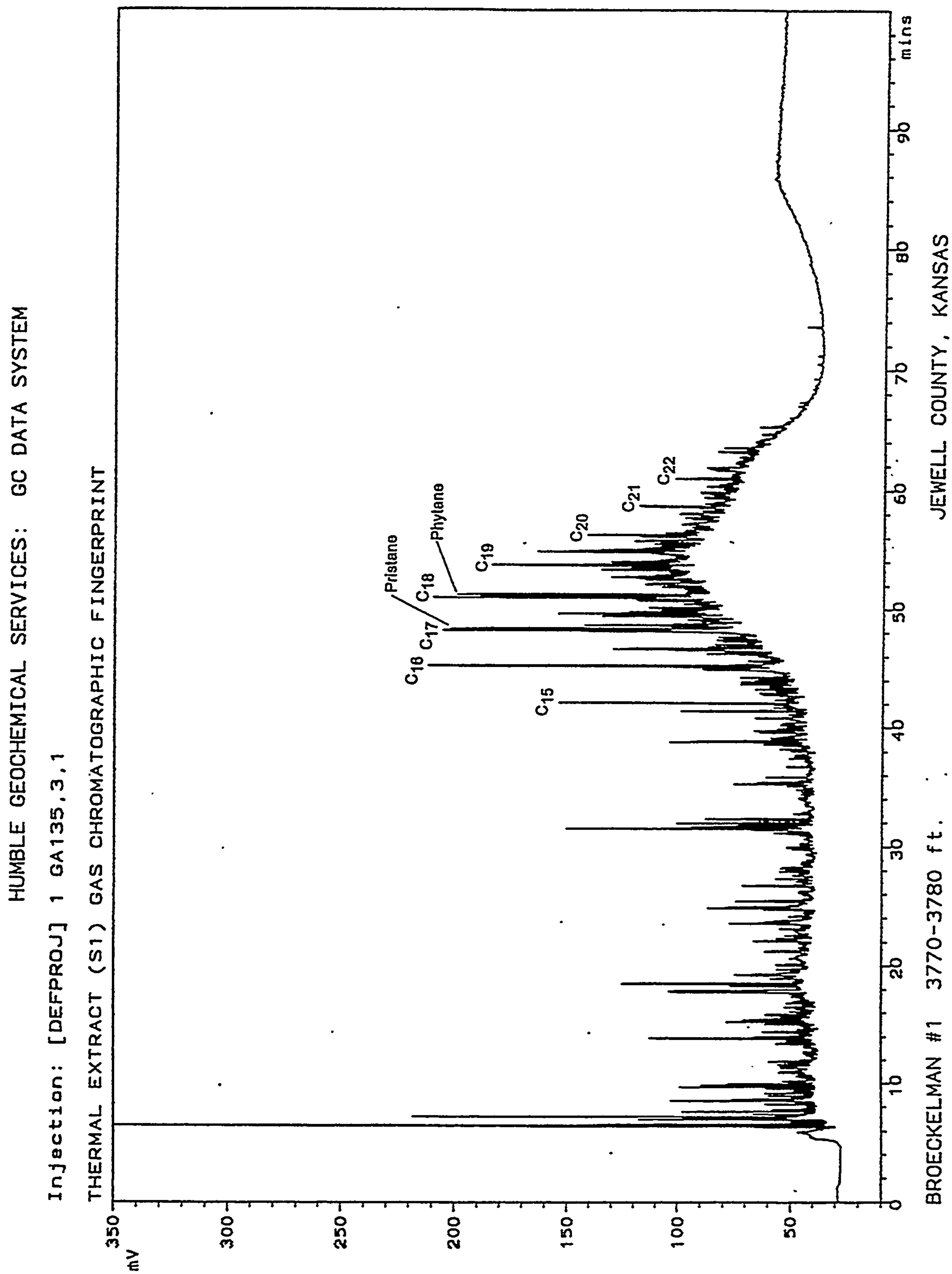
Burial history diagram for the Coddington #3-24 well. For abbreviation codes see Figure 9 caption.

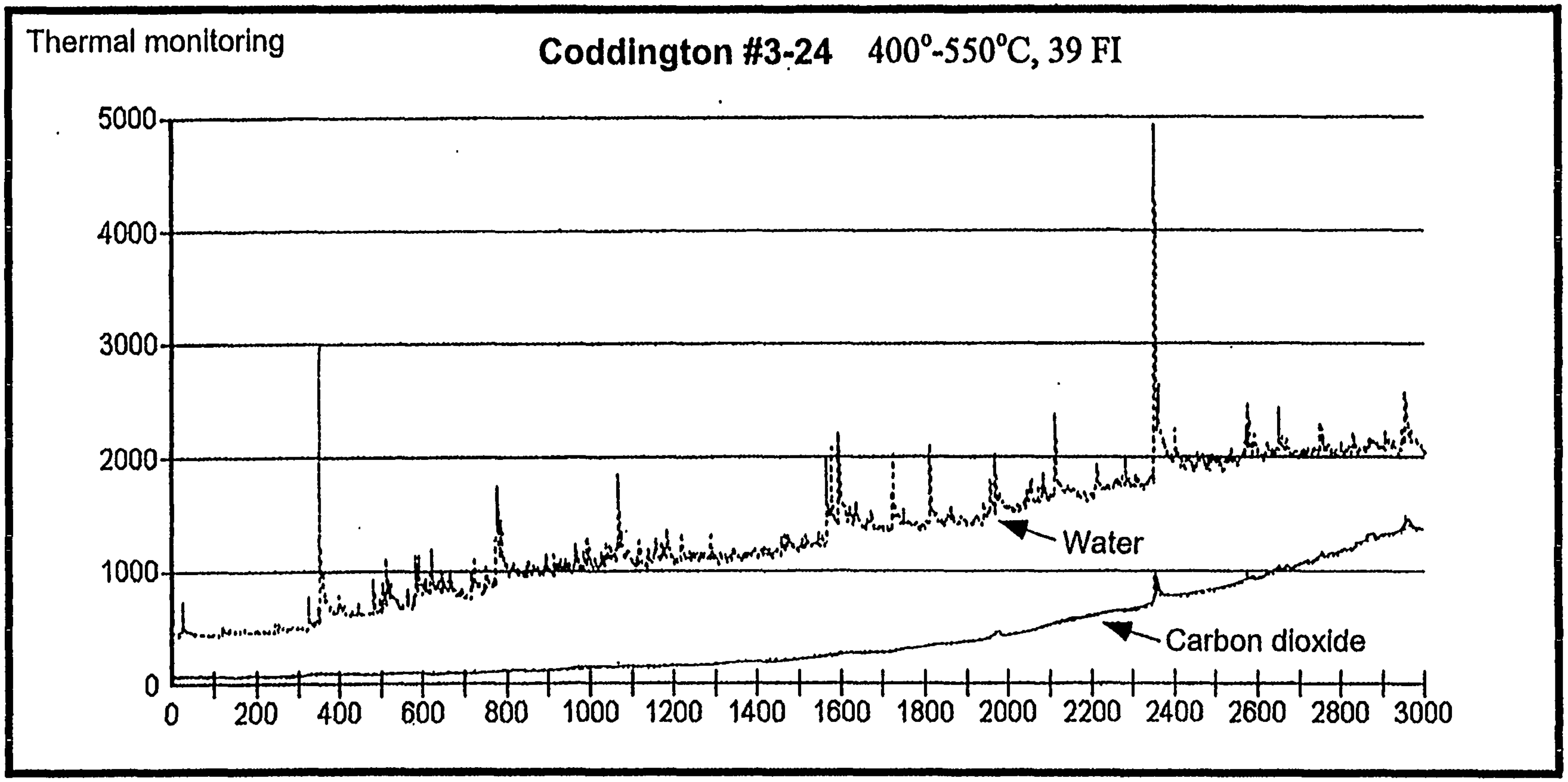
	Kansas		Iowa		
System	Series/Group/Formation		Series/Group/Formation		Member
Lower Mississippian	Kinderhookian Series	**Chattanooga Shale**			
Devonian				**Maple Mill**	**Saverton**
				Lime Creek Cedar Valley Wapsipinicon	
Silurian		Hunton Group		Gower Scotch Grove Hopkinton Blanding	
Upper Ordovician		Maquoketa		Maquoketa	Neda Brainard Ft. Atkinson Clermont **Elgin**/**Scales**
		Viola	Galena Group	Dubuque Wise Lake Dunleith	
Middle Ordovician				Decorah	Ion **Guttenberg** Spechts Ferry
	Simpson Group	Platteville		Platteville	McGregor Pecatonica
		upper Simpson shales St PeterSandstone **lower Simpson shales**		**Glenwood** St. Peter Sandstone	
Lower Ordovician		Arbuckle Group		Prairie du Chien Group	

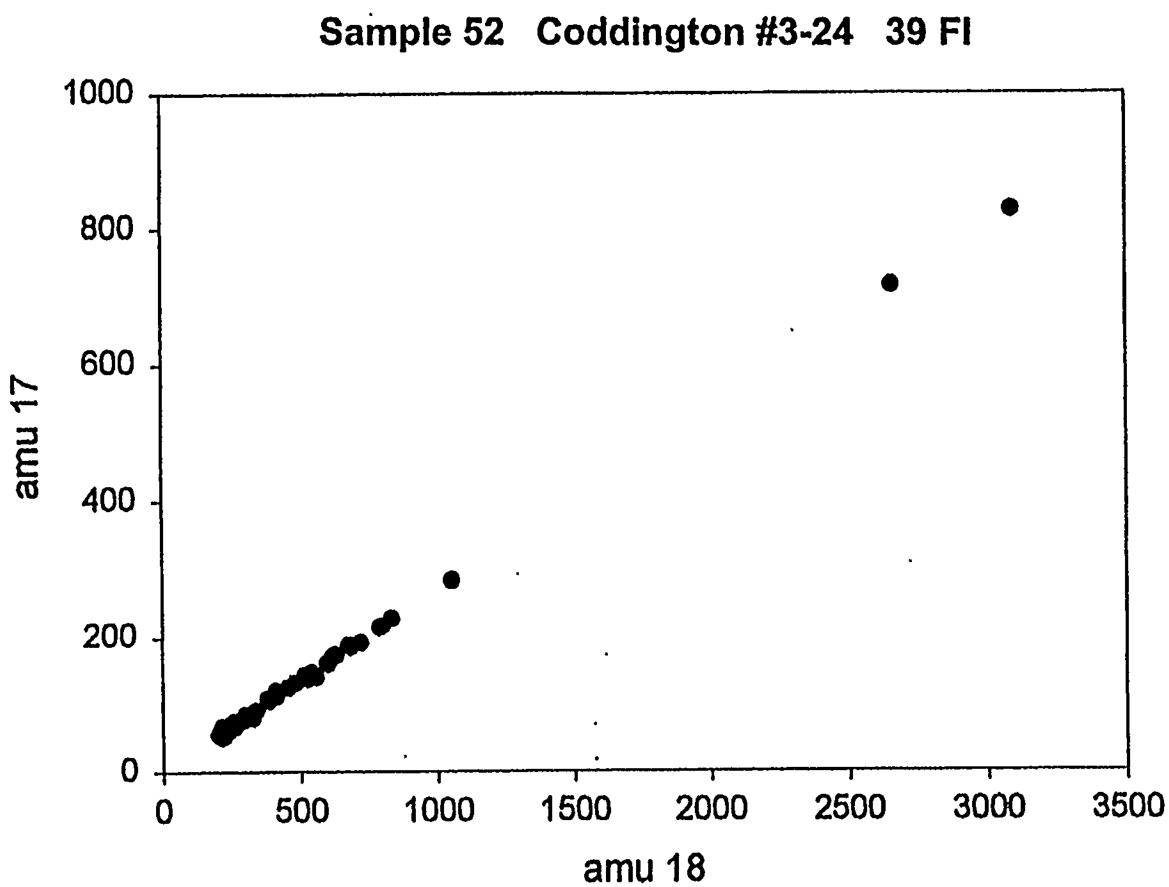

Palen #1
Blair #1
Wormer #1
Douglas County Livestock and Fair Association #1
CHEYENNE
RAWLINS
DECATUR
NORTON
PHILLIPS
SMITH
JEWELL
REPUBLIC
WASHINGTON
MARSHALL
NEMAHA
BROWN
DONIPHAN
ATCHISON
SHERMAN
THOMAS
SHERIDAN
GRAHAM
ROOKS
OSBORNE
MITCHELL
CLOUD
CLAY
RILEY
POTTAWATOMIE
JACKSON
JEFFERSON
LEAVEN-WORTH
WYAN-DOTTE
WALLACE
LOGAN
GOVE
TREGO
ELLIS
RUSSELL
LINCOLN
OTTAWA
GEARY
WABAUNSEE
SHAWNEE
DOUGLAS
JOHNSON
ELLSWORTH
SALINE
DICKINSON
GREELEY
WICHITA
SCOTT
LANE
NESS
RUSH
BARTON
RICE
McPHERSON
MARION
MORRIS
CHASE
LYON
OSAGE
FRANKLIN
MIAMI
HAMILTON
KEARNY
FINNEY
HODGEMAN
PAWNEE
COFFEY
ANDERSON
LINN
EDWARDS
STAFFORD
RENO
HARVEY
GREENWOOD
WOODSON
ALLEN
BOURBON
STANTON
GRANT
HASKELL
GRAY
FORD
KIOWA
PRATT
KINGMAN
SEDGWICK
BUTLER
ELK
WILSON
NEOSHO
CRAWFORD
MORTON
STEVENS
SEWARD
MEADE
CLARK
COMANCHE
BARBER
HARPER
SUMNER
COWLEY
CHAUTAUQUA
MONTGOMERY
LABETTE
CHEROKEE
Ellsworth County lignite locality
Kyler #1
Shoffner #1
Davidson #1
Knoche #1
Watson #1
SCALE
0 20 40 60 80 100 Kilometers
0 20 40 60 80 100 Miles
N
Line of cross section through southern Forest City Basin


BS-4
Cominco SS-9
Cominco SS-4A
Cominco SS-3
Mid-America Pipeline #4
Keota Dome wells
MM.Flynn #2
W.M. Flynn #2
E.M. Green #1
Cominco H-33
Cominco H-28
Coddington #3-24
Augustine #1
Camp Quest
N
SCALE
0 20 40 60 80 100 Kilometers
0 20 40 60 80 100 Miles
LYON
OSCEOLA
DICKINSON
EMMET
KOSSUTH
WINNEBAGO
WORTH
MITCHELL
HOWARD
WINNESHIEK
ALLAMAKEE
SIOUX
O'BRIEN
CLAY
PALO ALTO
HANCOCK
CERRO GORDO
FLOYD
CHICKASAW
FAYETTE
CLAYTON
PLYMOUTH
CHEROKEE
BUENA VISTA
POCAHONTAS
HUMBOLDT
WRIGHT
FRANKLIN
BUTLER
BREMER
BUCHANAN
DELAWARE
DUBUQUE
WOODBURY
IDA
SAC
CALHOUN
WEBSTER
HAMILTON
HARDIN
GRUNDY
BLACK HAWK
MONONA
CRAWFORD
CARROLL
GREENE
BOONE
STORY
MARSHALL
TAMA
BENTON
LINN
JONES
JACKSON
CLINTON
HARRISON
SHELBY
AUDUBON
GUTHRIE
DALLAS
POLK
JASPER
POWESHIEK
IOWA
JOHNSON
CEDAR
SCOTT
MUSCATINE
POTTAWATTAMIE
CASS
ADAIR
MADISON
WARREN
MARION
MAHASKA
KEOKUK
WASHINGTON
LOUISA
MILLS
MONTGOMERY
ADAMS
UNION
CLARKE
LUCAS
MONROE
WAPELLO
JEFFERSON
HENRY
DES MOINES
FREMONT
PAGE
TAYLOR
RINGGOLD
DECATUR
WAYNE
APPANOOSE
DAVIS
VAN BUREN
LEE

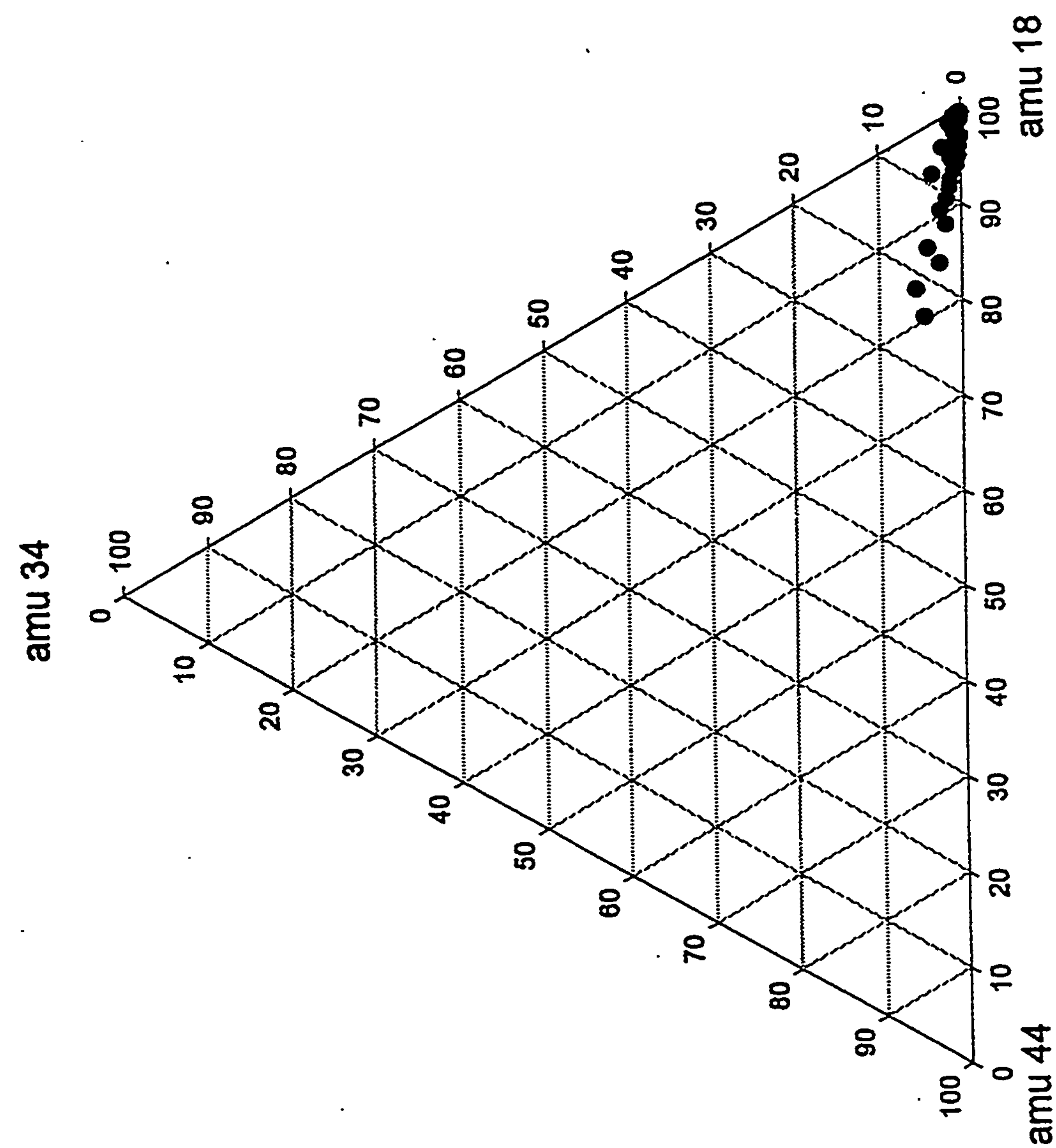

SCALE
0 20 40 60 80 100 Kilometers
0 20 40 60 80 100 Miles
N
KITTSON
ROSEAU
LAKE OF THE WOODS
MARSHALL
KOOCHICHING
PENNINGTON
BELTRAMI
RED LAKE
POLK
CLEARWATER
ITASCA
ST. LOUIS
LAKE
COOK
NORMAN
MAHNOMEN
HUBBARD
CASS
CLAY
BECKER
WADENA
CROW WING
AITKIN
CARLTON
WILKIN
OTTER TAIL
TODD
MORRISON
MILLE LACS
KANABEC
PINE
GRANT
DOUGLAS
TRAVERSE
STEVENS
POPE
STEARNS
BENTON
ISANTI
CHISAGO
BIG STONE
SHERBURNE
SWIFT
ANOKA
KANDIYOHI
MEEKER
WRIGHT
LAC QUI PARLE
CHIPPEWA
HENNEPIN
RAMSEY
WASHINGTON
McLEOD
CARVER
RENVILLE
YELLOW MEDICINE
SCOTT
DAKOTA
SIBLEY
Minnesota Geological Survey Core 91708A
LINCOLN
LYON
REDWOOD
NICOLLET
LE SUEUR
RICE
GOODHUE
WABASHA
BROWN
PIPESTONE
MURRAY
COTTONWOOD
WATONWAN
BLUE EARTH
WASECA
STEELE
DODGE
OLMSTED
WINONA
ROCK
NOBLES
JACKSON
MARTIN
FARIBAULT
FREEBORN
MOWER
FILLMORE
HOUSTON
Hollandale Core


HUMBLE GEOCHEMICAL SERVICES: GC DATA SYSTEM
Injection: [DEFPROJ] 1 GA135,3,1
THERMAL EXTRACT (S1) GAS CHROMATOGRAPHIC FINGERPRINT
mV
350
300
250
200
150
100
50
0
10
20
30
40
50
60
70
80
90
mins
C15
C16
C17
Pristane
C18
Phytane
C19
C20
C21
C22
BROECKELMAN #1 3770-3780 ft.
JEWELL COUNTY, KANSAS


Thermal monitoring
Coddington #3-24 400°-550°C, 39 FI
5000
4000
3000
2000
1000
0
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
3000
Water
Carbon dioxide


Sample 52 Coddington #3-24 39 FI
1000
800
600
400
200
0
amu 17
0
500
1000
1500
2000
2500
3000
3500
amu 18

Sample 52 Coddington #3-24 39FI



Knoche #1

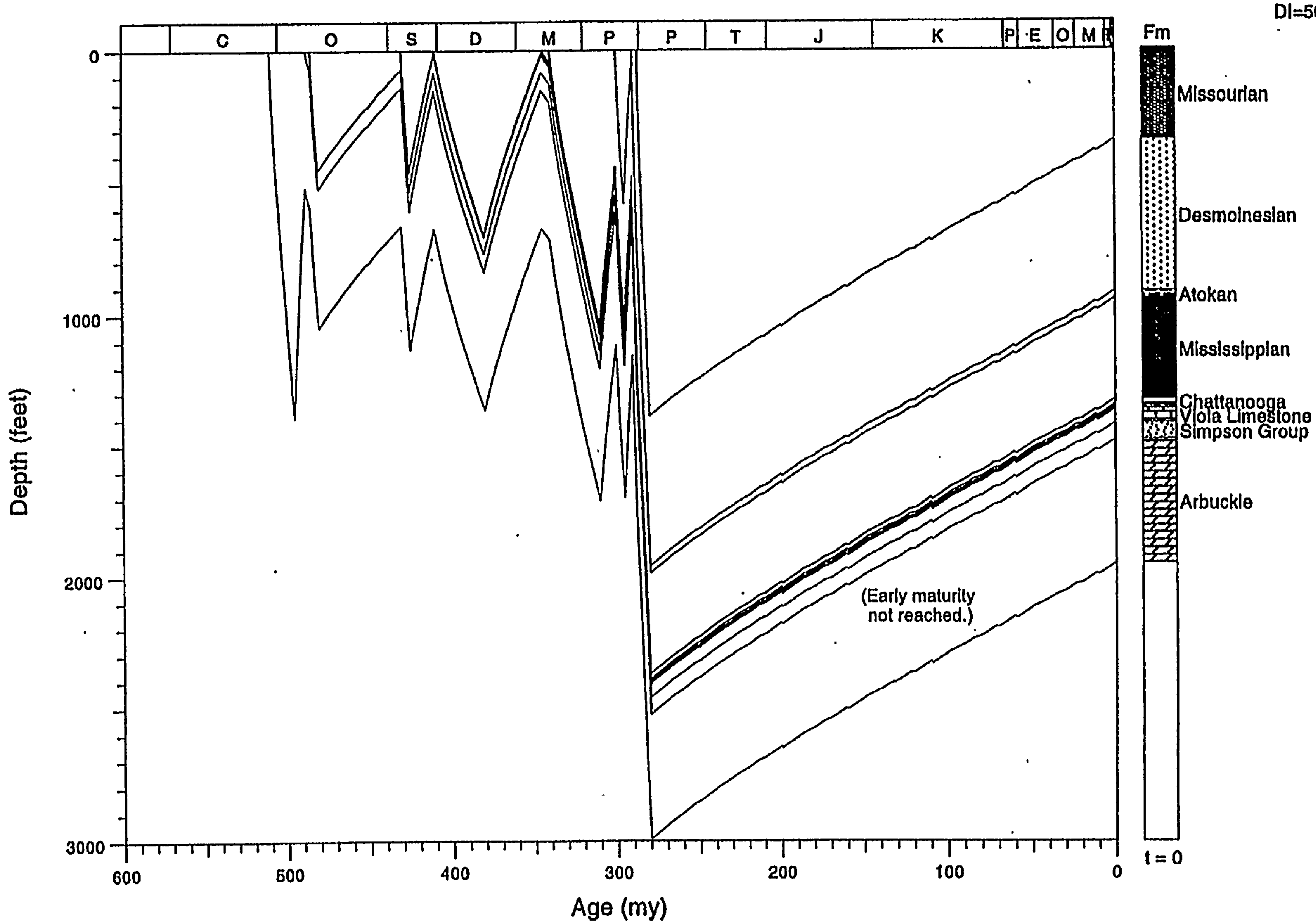
Miami Co., Kansas

Section 24-T15S-R22E

CMP=FF;TH=SHF;MAT=LL

TG=1;TI=10;EXP=VR;PRM=MKC

DI=50



Davidson #1

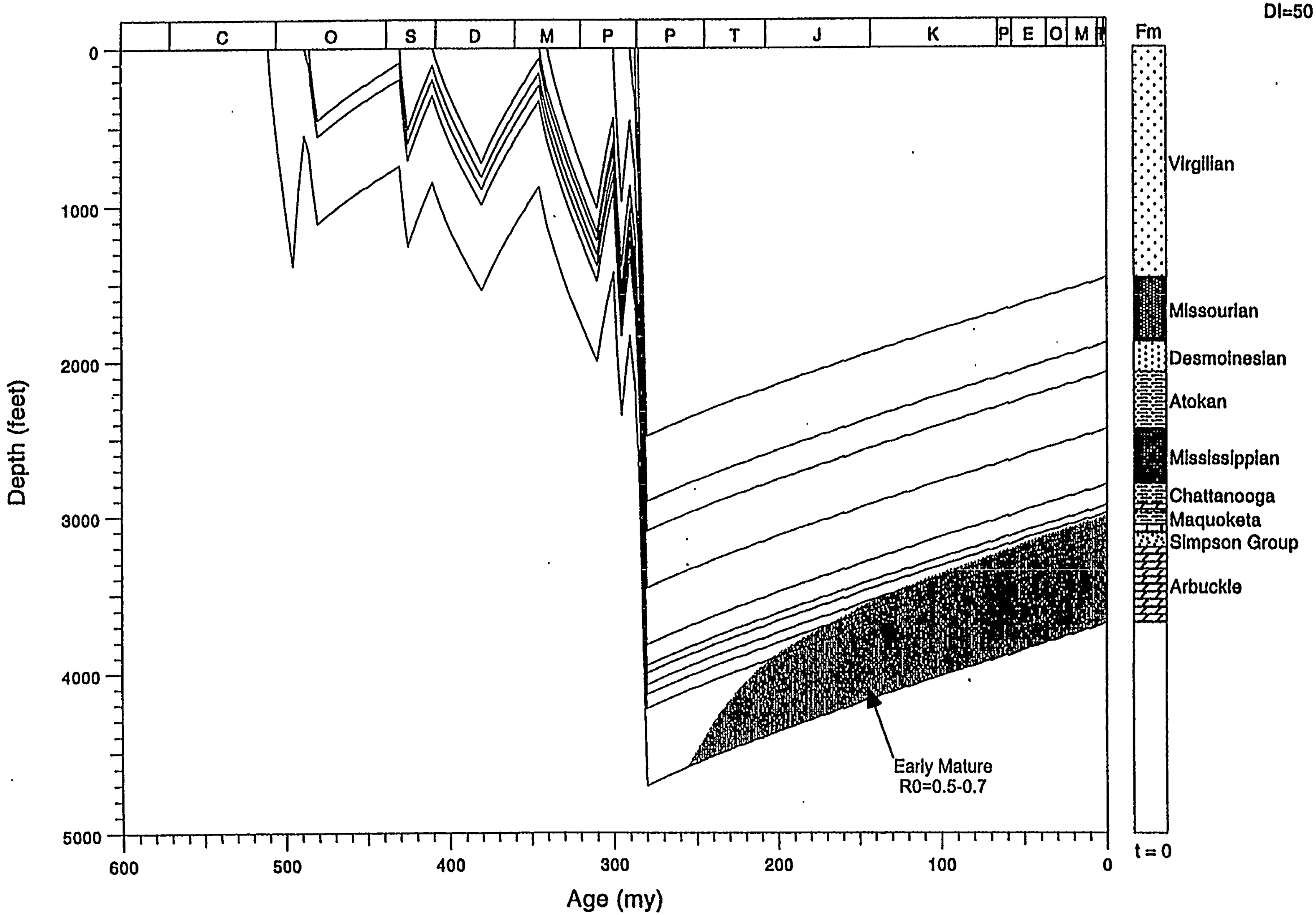
Lyon Co., Kansas

Section 29-T15S-R11E

CMP=FF;TH=SHF;MAT=LL

TG=1;TI=10;EXP=VR;PRM=MKC

DI=50



Davidson #1

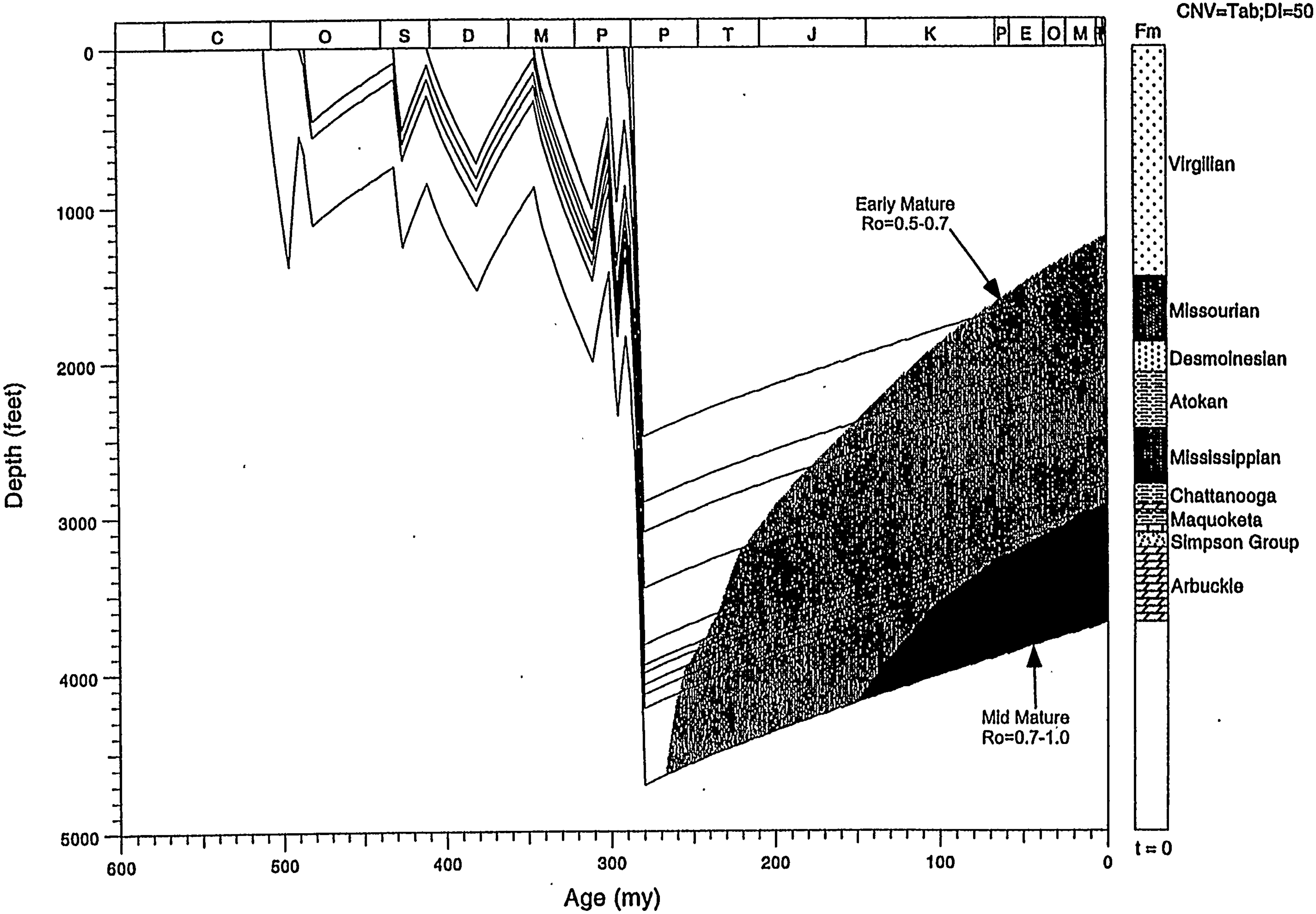
Lyon Co., Kansas

Section 29-T15S-R11E

CMP=FF;TH=SHF;MAT=TTI

TG=1;TI=10;EXP=VR;PRM=MKC

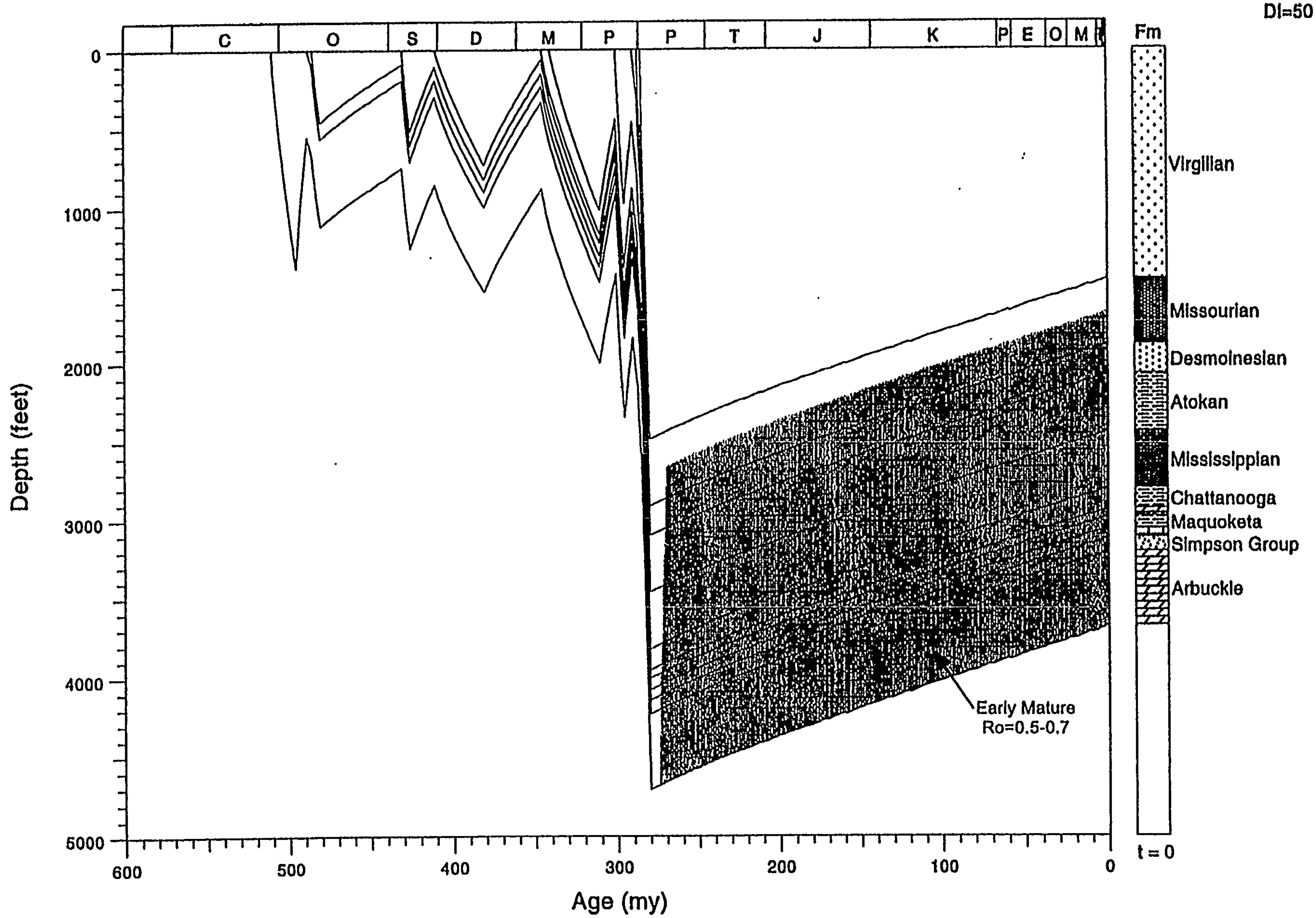
CNV=Tab;DI=50



Davidson #1

Lyon Co., Kansas

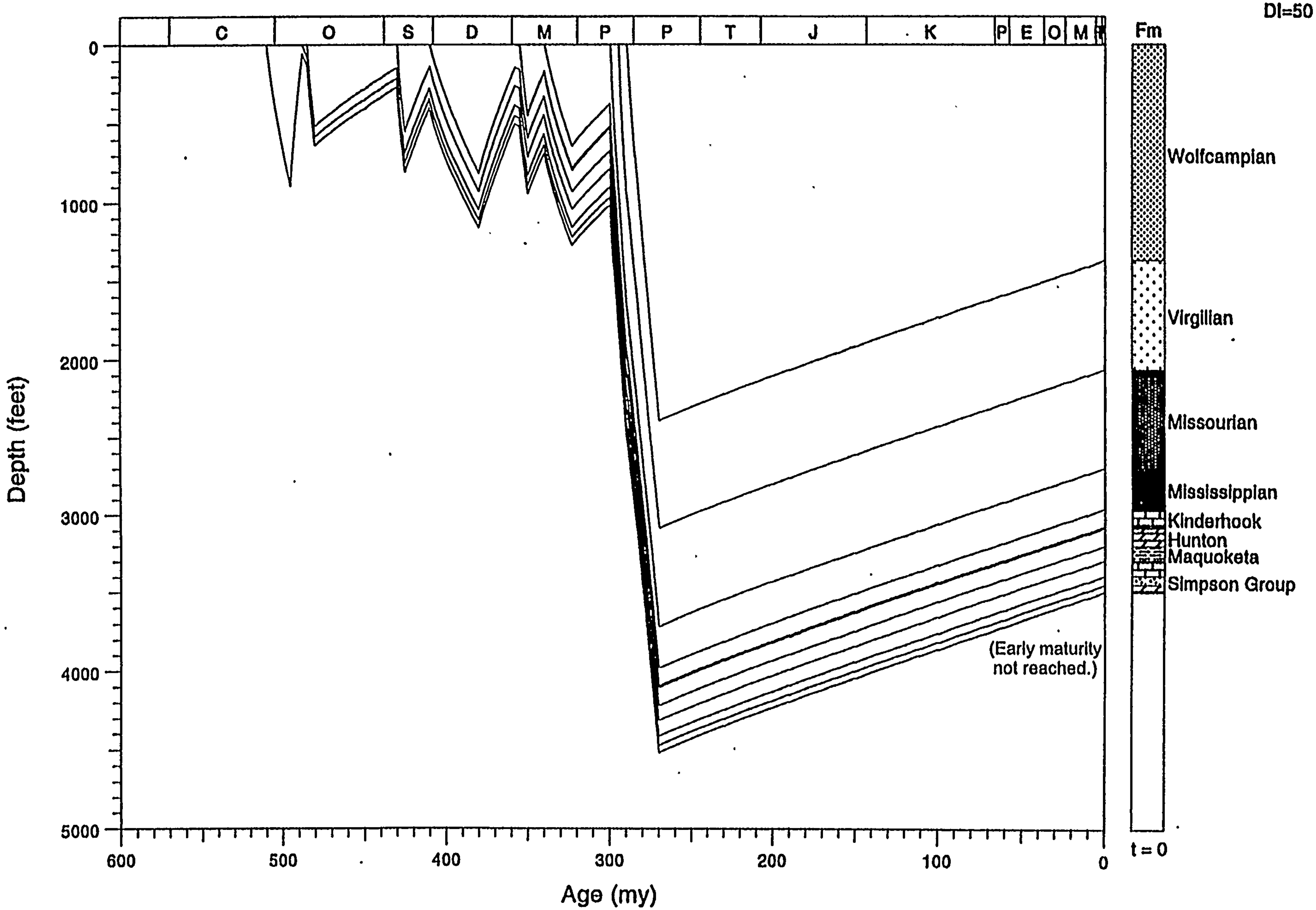
Section 29-T15S-R11E
CMP=FF;TH=SHF;MAT=SIM
TG=1;TI=10;EXP=VR;PRM=MKC
DI=50

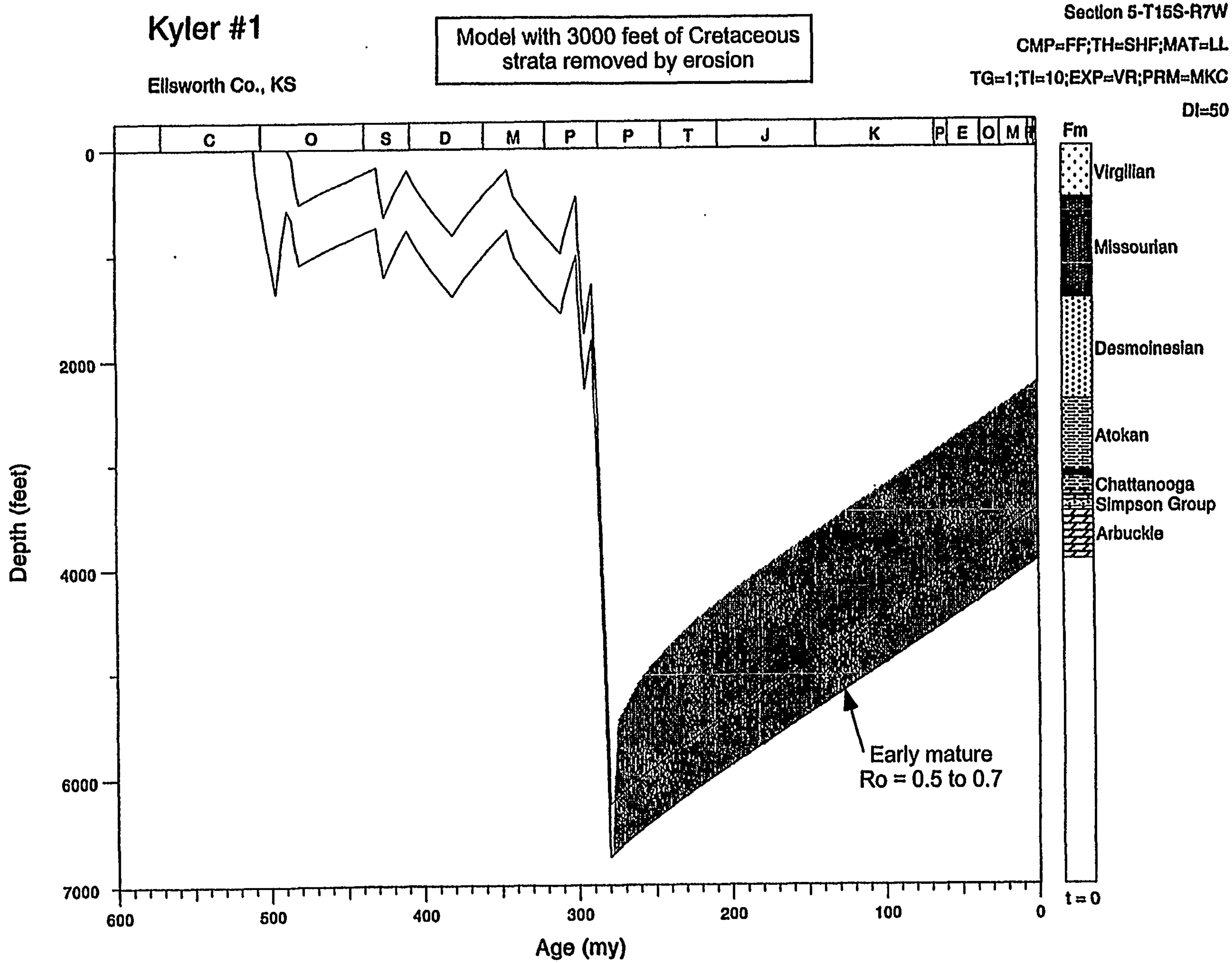


Shoffner #1

Saline Co., Kansas

Section 19-T15S-R1W
CMP=FF;TH=SHF;MAT=LL
TG=1;TI=10;EXP=VR;PRM=MKC
DI=50





Kyler #1
Ellsworth Co., KS
Model with 3000 feet of Cretaceous strata removed by erosion
Section 5-T15S-R7W
CMP=FF;TH=SHF;MAT=LL
TG=1;TI=10;EXP=VR;PRM=MKC
DI=50
C
O
S
D
M
P
P
T
J
K
P
E
O
M
Fm
Virgilian
Missourian
Desmoinesian
Atokan
Chattanooga
Simpson Group
Arbuckle
Early mature
Ro = 0.5 to 0.7
Depth (feet)
0
2000
4000
6000
7000
600
500
400
300
200
100
0
t = 0
Age (my)

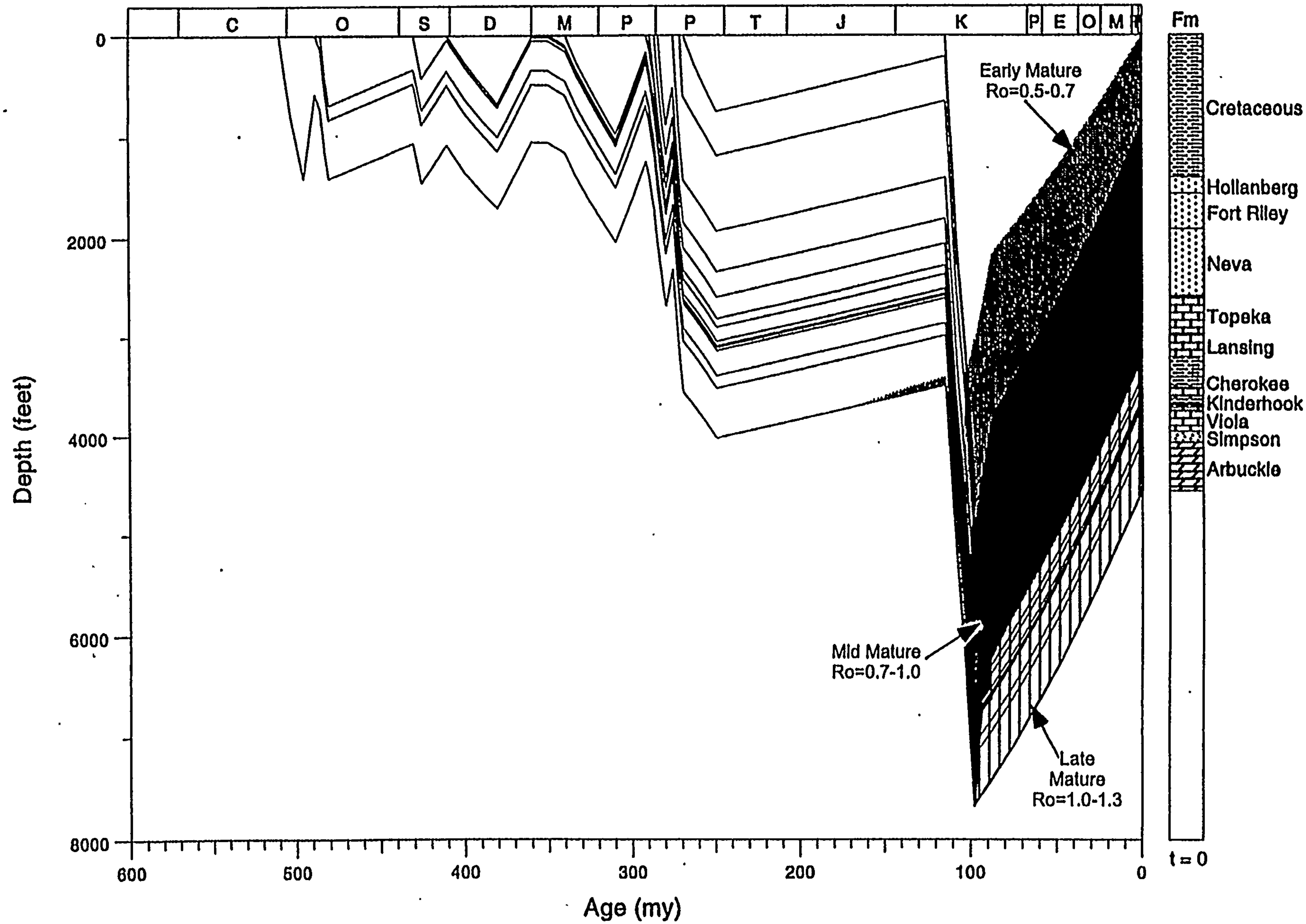
Palen #1

Mitchell Co., Kansas

CMP=FF;TH=SHF;MAT=LL

TG=1;TI=10;EXP=VR;PRM=MKC

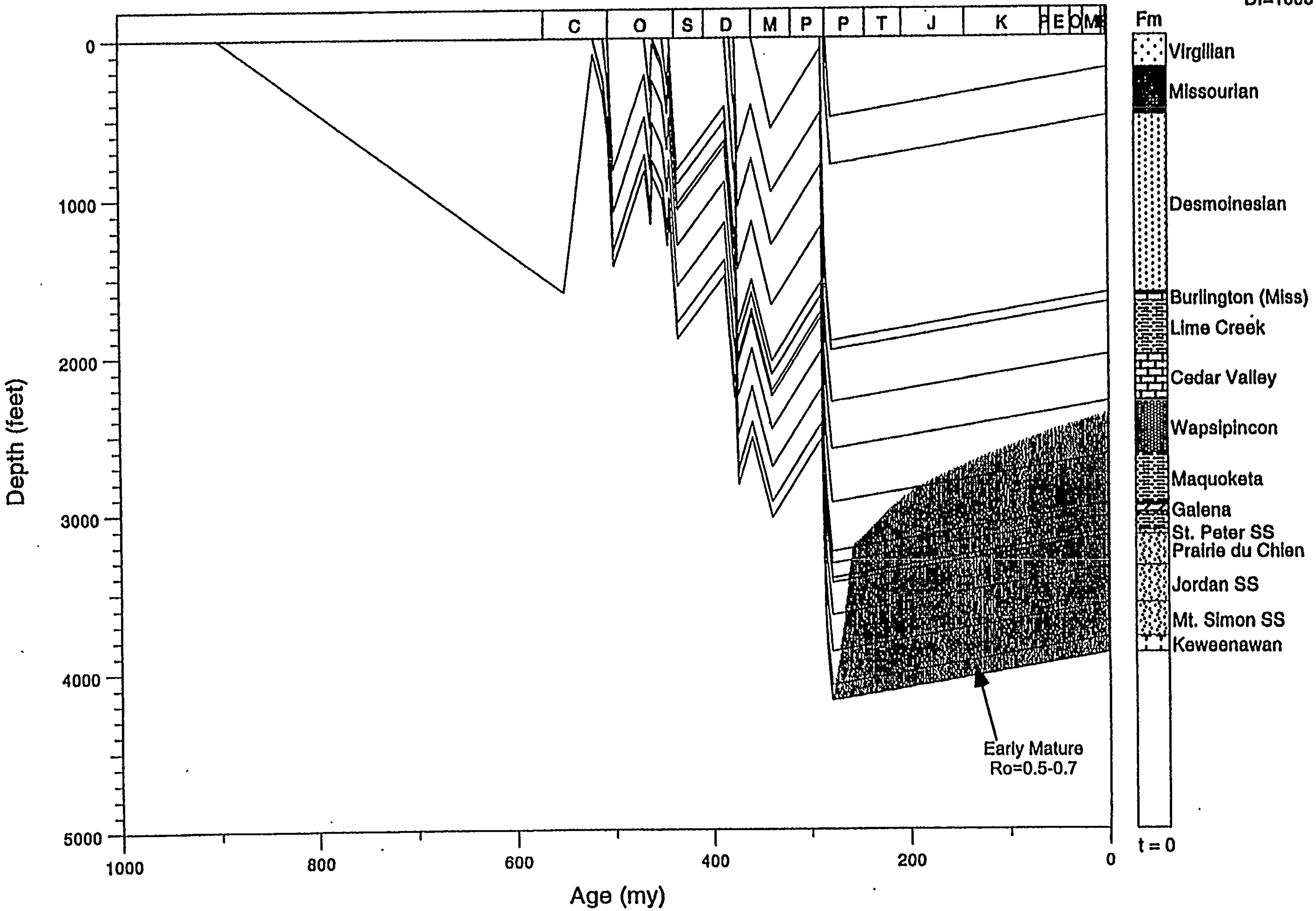
DI=3280.8



Coddington #3-24

Mills County, Iowa

Section 24-T71N-R41W
CMP=SC;TH=SHF;MAT=LL
TG=1;TI=22.5;EXP=None;PRM=PP
DI=1000



University of Tulsa

Possible Petroleum Generation And Occurrence in the pre-Mesozoic Parts of the Forest City Basin

<u>Database Supplement</u>

Final Report

July 31, 1998

Dr. Colin Barker
Richard J. Erickson

Geosciences Department
University of Tulsa

Phone: 918-631-3014
Fax: 918-631-2091
e-mail: geos_cgb@centum.utula.edu

Database supplement

New and previously published source-rock data have been compiled into a database containing source-rock total organic carbon (TOC) data. Each TOC entry is linked to locality and stratigraphic data, and previously published data are linked to the literature citation used as the source of the data.

The data are in a Microsoft Access database program; this is entered under the file name FCSal.MDB on the enclosed 3.5 inch disk. The principle data tables are the *Source Rock Data* table, the *Locality* table, and *References* table. The database also contains an *Oil Data* table and a *Field and Field Group Catalog* table, but these were not used. Each of the data tables has at least one data entry form within the Forms section. *The Source Rock Data, Locality,* and *References* tables have been linked in a crosstab query called *Source Rock Data.* The *General Summary* report is derived from the *Source Rock Data* query. A complete list of all data in the database is printed as the *General Summary* report that accompanies this database description.

The *Source Rock Data* table contains the type of sample (i.e., core, cuttings, or surface sample), stratigraphic data for each TOC value, depth of the sample, and locality number and reference number that link to entries in the *Locality* and *References* tables. RockEval data are not listed in the database, but for each TOC value, a box indicates whether RockEval data were published with the TOC information.

The *Locality* table includes state, county, section, township, and range information. All the TOC values in the database are from subsurface samples, and well operator and well name are included. The Iowa Geological Survey Bureau maintains a catalog of all wells and other boreholes for which the survey has samples or other information; the Iowa catalog number, beginning with the prefix "W", is given for all Iowa samples. Where available, the API number is given.

The *References* table gives author(s), publication date, and other standard literature citation information. The appropriate reference is linked to TOC data by a reference number.

General summary report Source rock catalog number 1

Locality Data

Locality number 1

State Iowa

County Washington

Section 20 Township 76N Range 9W

Operator Natural Gas Pipeline

Well name and number E.M. Green #1

Depth 950.3 Feet core

Stratigraphic Data

System Ordovician

Formation Decorah

Member Guttenberg

TOC and RockEval Data

TOC: 3.7 wt.%

☑ RockEval (Check mark indicates published RockEval data.)

Reference

Publication date 1987

Reference number 1

Author 1 last name Hatch

Author 1 initials J.R.

Author 2 last name Jacobson

Author 2 initials S.R.

Other authors B.J. Witzke, J.B. Risatti, D.E. Anders, W.L. Watney, K.D. Newell, and A.K. Vuletich

Citation Possible late Middle Ordovician Organic Carbon Isotope Excursion: Evidence from Ordovician oils and hydrocarbon source rocks, Mid-Continent and east-central United States, AAPG Bulletin, v. 71, p. 1342-1354

General summary report Source rock catalog number 2

Locality Data

Locality number 1

State Iowa

County Washington

Section 20 Township 76N Range 9W

Operator Natural Gas Pipeline

Well name and number E.M. Green #1

Depth 950.6 Feet core

Stratigraphic Data

System Ordovician

Formation Decorah

Member Guttenberg

TOC and RockEval Data

TOC: 41.4 wt.%

☑ RockEval (Check mark indicates published RockEval data.)

Reference

Publication date 1987 Reference number 1

Author 1 last name Hatch Author 1 initials J.R.

Author 2 last name Jacobson Author 2 initials S.R.

Other authors B.J. Witzke, J.B. Risatti, D.E. Anders, W.L. Watney, K.D. Newell, and A.K. Vuletich

Citation Possible late Middle Ordovician Organic Carbon Isotope Excursion: Evidence from Ordovician oils and hydrocarbon source rocks, Mid-Continent and east-central United States, AAPG Bulletin, v. 71, p. 1342-1354

General summary report Source rock catalog number 3

Locality Data

Locality number 1

State Iowa

County Washington

Section 20 Township 76N Range 9W

Operator Natural Gas Pipeline

Well name and number E.M. Green #1

Depth 951.3 Feet core

Stratigraphic Data

System Ordovician

Formation Decorah

Member Guttenberg

TOC and RockEval Data

TOC: 3 wt.%

☑ RockEval (Check mark indicates published RockEval data.)

Reference

Publication date 1987 Reference number 1

Author 1 last name Hatch Author 1 initials J.R.

Author 2 last name Jacobson Author 2 initials S.R.

Other authors B.J. Witzke, J.B. Risatti, D.E. Anders, W.L. Watney, K.D. Newell, and A.K. Vuletich

Citation Possible late Middle Ordovician Organic Carbon Isotope Excursion: Evidence from Ordovician oils and hydrocarbon source rocks, Mid-Continent and east-central United States, AAPG Bulletin, v. 71, p. 1342-1354

General summary report Source rock catalog number 4

Locality Data

Locality number 1

State Iowa

County Washington

Section 20 Township 76N Range 9W

Operator Natural Gas Pipeline

Well name and number E.M. Green #1

Depth 951.6 Feet core

Stratigraphic Data

System Ordovician

Formation Decorah

Member Guttenberg

TOC and RockEval Data

TOC: 33.9 wt.%

☑ RockEval (Check mark indicates published RockEval data.)

Reference

Publication date 1987

Reference number 1

Author 1 last name Hatch

Author 1 initials J.R.

Author 2 last name Jacobson

Author 2 initials S.R.

Other authors B.J. Witzke, J.B. Risatti, D.E. Anders, W.L. Watney, K.D. Newell, and A.K. Vuletich

Citation Possible late Middle Ordovician Organic Carbon Isotope Excursion: Evidence from Ordovician oils and hydrocarbon source rocks, Mid-Continent and east-central United States, AAPG Bulletin, v. 71, p. 1342-1354

General summary report Source rock catalog number 5

Locality Data

Locality number 1

State Iowa County Washington

Section 20 Township 76N Range 9W

Operator Natural Gas Pipeline

Well name and number E.M. Green #1

Depth 952.3 Feet core

Stratigraphic Data

System Ordovician

Formation Decorah

Member Guttenberg

TOC and RockEval Data

TOC: 23.3 wt.%

☑ RockEval (Check mark indicates published RockEval data.)

Reference

Publication date 1987 Reference number 1

Author 1 last name Hatch Author 1 initials J.R.

Author 2 last name Jacobson Author 2 initials S.R.

Other authors B.J. Witzke, J.B. Risatti, D.E. Anders, W.L. Watney, K.D. Newell, and A.K. Vuletich

Citation Possible late Middle Ordovician Organic Carbon Isotope Excursion: Evidence from Ordovician oils and hydrocarbon source rocks, Mid-Continent and east-central United States, AAPG Bulletin, v. 71, p. 1342-1354

General summary report Source rock catalog number 6

Locality Data

Locality number 1

State Iowa

County Washington

Section 20 Township 76N Range 9W

Operator Natural Gas Pipeline

Well name and number E.M. Green #1

Depth 952.8 Feet core

Stratigraphic Data

System Ordovician

Formation Decorah

Member Guttenberg

TOC and RockEval Data

TOC: 22.1 wt.%

☑ RockEval (Check mark indicates published RockEval data.)

Reference

Publication date 1987 Reference number 1

Author 1 last name Hatch Author 1 initials J.R.

Author 2 last name Jacobson Author 2 initials S.R.

Other authors B.J. Witzke, J.B. Risatti, D.E. Anders, W.L. Watney, K.D. Newell, and A.K. Vuletich

Citation Possible late Middle Ordovician Organic Carbon Isotope Excursion: Evidence from Ordovician oils and hydrocarbon source rocks, Mid-Continent and east-central United States, AAPG Bulletin, v. 71, p. 1342-1354

General summary report Source rock catalog number 7

Locality Data

Locality number 1

State Iowa County Washington

Section 20 Township 76N Range 9W

Operator Natural Gas Pipeline

Well name and number E.M. Green #1

Depth 954.1 Feet core

Stratigraphic Data

System Ordovician

Formation Decorah

Member Guttenberg

TOC and RockEval Data

TOC: 15.7 wt.%

☑ RockEval (Check mark indicates published RockEval data.)

Reference

Publication date 1987 Reference number 1

Author 1 last name Hatch Author 1 initials J.R.

Author 2 last name Jacobson Author 2 initials S.R.

Other authors B.J. Witzke, J.B. Risatti, D.E. Anders, W.L. Watney, K.D. Newell, and A.K. Vuletich

Citation Possible late Middle Ordovician Organic Carbon Isotope Excursion: Evidence from Ordovician oils and hydrocarbon source rocks, Mid-Continent and east-central United States, AAPG Bulletin, v. 71, p. 1342-1354

General summary report Source rock catalog number 8

Locality Data

Locality number 1

State Iowa

County Washington

Section 20 Township 76N Range 9W

Operator Natural Gas Pipeline

Well name and number E.M. Green #1

Depth 956.6 Feet core

Stratigraphic Data

System Ordovician

Formation Decorah

Member Spechts Ferry

TOC and RockEval Data

TOC: 0.71 wt.%

☑ RockEval (Check mark indicates published RockEval data.)

Reference

Publication date 1987

Reference number 1

Author 1 last name Hatch

Author 1 initials J.R.

Author 2 last name Jacobson

Author 2 initials S.R.

Other authors B.J. Witzke, J.B. Risatti, D.E. Anders, W.L. Watney, K.D. Newell, and A.K. Vuletich

Citation Possible late Middle Ordovician Organic Carbon Isotope Excursion: Evidence from Ordovician oils and hydrocarbon source rocks, Mid-Continent and east-central United States, AAPG Bulletin, v. 71, p. 1342-1354

General summary report Source rock catalog number 9

Locality Data

Locality number 1

State Iowa County Washington

Section 20 Township 76N Range 9W

Operator Natural Gas Pipeline

Well name and number E.M. Green #1

Depth 959 Feet core

Stratigraphic Data

System Ordovician

Formation Decorah

Member Spechts Ferry

TOC and RockEval Data

TOC: 0.13 wt.%

☑ RockEval (Check mark indicates published RockEval data.)

Reference

Publication date 1987 Reference number 1

Author 1 last name Hatch Author 1 initials J.R.

Author 2 last name Jacobson Author 2 initials S.R.

Other authors B.J. Witzke, J.B. Risatti, D.E. Anders, W.L. Watney, K.D. Newell, and A.K. Vuletich

Citation Possible late Middle Ordovician Organic Carbon Isotope Excursion: Evidence from Ordovician oils and hydrocarbon source rocks, Mid-Continent and east-central United States, AAPG Bulletin, v. 71, p. 1342-1354

General summary report Source rock catalog number 10

Locality Data

Locality number 1

State Iowa

County Washington

Section 20 Township 76N Range 9W

Operator Natural Gas Pipeline

Well name and number E.M. Green #1

Depth 965.8 Feet core

Stratigraphic Data

System Ordovician

Formation Decorah

Member Spechts Ferry

TOC and RockEval Data

TOC: 0.48 wt.%

☑ RockEval (Check mark indicates published RockEval data.)

Reference

Publication date 1987 Reference number 1

Author 1 last name Hatch Author 1 initials J.R.

Author 2 last name Jacobson Author 2 initials S.R.

Other authors B.J. Witzke, J.B. Risatti, D.E. Anders, W.L. Watney, K.D. Newell, and A.K. Vuletich

Citation Possible late Middle Ordovician Organic Carbon Isotope Excursion: Evidence from Ordovician oils and hydrocarbon source rocks, Mid-Continent and east-central United States, AAPG Bulletin, v. 71, p. 1342-1354

General summary report Source rock catalog number 11

Locality Data

Locality number 1

State Iowa

County Washington

Section 20 Township 76N Range 9W

Operator Natural Gas Pipeline

Well name and number E.M. Green #1

Depth 966.9 Feet core

Stratigraphic Data

System Ordovician

Formation Platteville

Member McGregor

TOC and RockEval Data

TOC: 0.4 wt.%

☑ RockEval (Check mark indicates published RockEval data.)

Reference

Publication date 1987

Reference number 1

Author 1 last name Hatch

Author 1 initials J.R.

Author 2 last name Jacobson

Author 2 initials S.R.

Other authors B.J. Witzke, J.B. Risatti, D.E. Anders, W.L. Watney, K.D. Newell, and A.K. Vuletich

Citation Possible late Middle Ordovician Organic Carbon Isotope Excursion: Evidence from Ordovician oils and hydrocarbon source rocks, Mid-Continent and east-central United States, AAPG Bulletin, v. 71, p. 1342-1354

General summary report Source rock catalog number 12

Locality Data

Locality number 1

State Iowa

County Washington

Section 20 Township 76N Range 9W

Operator Natural Gas Pipeline

Well name and number E.M. Green #1

Depth 969.6 Feet core

Stratigraphic Data

System Ordovician

Formation Platteville

Member McGregor

TOC and RockEval Data

TOC: 5.5 wt.%

☑ RockEval (Check mark indicates published RockEval data.)

Reference

Publication date 1987

Reference number 1

Author 1 last name Hatch

Author 1 initials J.R.

Author 2 last name Jacobson

Author 2 initials S.R.

Other authors B.J. Witzke, J.B. Risatti, D.E. Anders, W.L. Watney, K.D. Newell, and A.K. Vuletich

Citation Possible late Middle Ordovician Organic Carbon Isotope Excursion: Evidence from Ordovician oils and hydrocarbon source rocks, Mid-Continent and east-central United States, AAPG Bulletin, v. 71, p. 1342-1354

General summary report Source rock catalog number 14

Locality Data

Locality number 1

State Iowa

County Washington

Section 20 Township 76N Range 9W

Operator Natural Gas Pipeline

Well name and number E.M. Green #1

Depth 998.7 Feet core

Stratigraphic Data

System Ordovician

Formation Platteville

Member McGregor

TOC and RockEval Data

TOC: 0.84 wt.%

☑ RockEval (Check mark indicates published RockEval data.)

Reference

Publication date 1987

Reference number 1

Author 1 last name Hatch

Author 1 initials J.R.

Author 2 last name Jacobson

Author 2 initials S.R.

Other authors B.J. Witzke, J.B. Risatti, D.E. Anders, W.L. Watney, K.D. Newell, and A.K. Vuletich

Citation Possible late Middle Ordovician Organic Carbon Isotope Excursion: Evidence from Ordovician oils and hydrocarbon source rocks, Mid-Continent and east-central United States, AAPG Bulletin, v. 71, p. 1342-1354

General summary report Source rock catalog number 15

Locality Data

Locality number 1

State Iowa

County Washington

Section 20 Township 76N Range 9W

Operator Natural Gas Pipeline

Well name and number E.M. Green #1

Depth 1008 Feet core

Stratigraphic Data

System Ordovician

Formation Platteville

Member brown shale

TOC and RockEval Data

TOC: 7.9 wt.%

☑ RockEval (Check mark indicates published RockEval data.)

Reference

Publication date 1987 Reference number 1

Author 1 last name Hatch Author 1 initials J.R.

Author 2 last name Jacobson Author 2 initials S.R.

Other authors B.J. Witzke, J.B. Risatti, D.E. Anders, W.L. Watney, K.D. Newell, and A.K. Vuletich

Citation Possible late Middle Ordovician Organic Carbon Isotope Excursion: Evidence from Ordovician oils and hydrocarbon source rocks, Mid-Continent and east-central United States, AAPG Bulletin, v. 71, p. 1342-1354

General summary report Source rock catalog number 16

Locality Data

Locality number 1

State Iowa

County Washington

Section 20 Township 76N Range 9W

Operator Natural Gas Pipeline

Well name and number E.M. Green #1

Depth 1011 Feet core

Stratigraphic Data

System Ordovician

Formation Glenwood

Member

TOC and RockEval Data

TOC: 21 wt.%

☑ RockEval (Check mark indicates published RockEval data.)

Reference

Publication date 1987

Reference number 1

Author 1 last name Hatch

Author 1 initials J.R.

Author 2 last name Jacobson

Author 2 initials S.R.

Other authors B.J. Witzke, J.B. Risatti, D.E. Anders, W.L. Watney, K.D. Newell, and A.K. Vuletich

Citation Possible late Middle Ordovician Organic Carbon Isotope Excursion: Evidence from Ordovician oils and hydrocarbon source rocks, Mid-Continent and east-central United States, AAPG Bulletin, v. 71, p. 1342-1354

General summary report Source rock catalog number 17

Locality Data

Locality number 1

State Iowa

County Washington

Section 20 Township 76N Range 9W

Operator Natural Gas Pipeline

Well name and number E.M. Green #1

Depth 1012 Feet core

Stratigraphic Data

System Ordovician

Formation Glenwood

Member

TOC and RockEval Data

TOC: 25.1 wt.%

☑ RockEval (Check mark indicates published RockEval data.)

Reference

Publication date 1987 Reference number 1

Author 1 last name Hatch Author 1 initials J.R.

Author 2 last name Jacobson Author 2 initials S.R.

Other authors B.J. Witzke, J.B. Risatti, D.E. Anders, W.L. Watney, K.D. Newell, and A.K. Vuletich

Citation Possible late Middle Ordovician Organic Carbon Isotope Excursion: Evidence from Ordovician oils and hydrocarbon source rocks, Mid-Continent and east-central United States, AAPG Bulletin, v. 71, p. 1342-1354

General summary report Source rock catalog number 18

Locality Data

Locality number 1

State Iowa

County Washington

Section 20 Township 76N Range 9W

Operator Natural Gas Pipeline

Well name and number E.M. Green #1

Depth 1012 Feet core

Stratigraphic Data

System Ordovician

Formation Glenwood

Member

TOC and RockEval Data

TOC: 4.6 wt.%

☑ RockEval (Check mark indicates published RockEval data.)

Reference

Publication date 1987 Reference number 1

Author 1 last name Hatch Author 1 initials J.R.

Author 2 last name Jacobson Author 2 initials S.R.

Other authors B.J. Witzke, J.B. Risatti, D.E. Anders, W.L. Watney, K.D. Newell, and A.K. Vuletich

Citation Possible late Middle Ordovician Organic Carbon Isotope Excursion: Evidence from Ordovician oils and hydrocarbon source rocks, Mid-Continent and east-central United States, AAPG Bulletin, v. 71, p. 1342-1354

General summary report Source rock catalog number 19

Locality Data

Locality number 1

State Iowa

County Washington

Section 20 Township 76N Range 9W

Operator Natural Gas Pipeline

Well name and number E.M. Green #1

Depth 1021 Feet core

Stratigraphic Data

System Ordovician

Formation Glenwood

Member

TOC and RockEval Data

TOC: 2.9 wt.%

☑ RockEval (Check mark indicates published RockEval data.)

Reference

Publication date 1987 Reference number 1

Author 1 last name Hatch Author 1 initials J.R.

Author 2 last name Jacobson Author 2 initials S.R.

Other authors B.J. Witzke, J.B. Risatti, D.E. Anders, W.L. Watney, K.D. Newell, and A.K. Vuletich

Citation Possible late Middle Ordovician Organic Carbon Isotope Excursion: Evidence from Ordovician oils and hydrocarbon source rocks, Mid-Continent and east-central United States, AAPG Bulletin, v. 71, p. 1342-1354

General summary report Source rock catalog number 20

Locality Data

Locality number 2

State Iowa

County Jackson

Section 29 Township 84N Range 9W

Operator Cominco

Well name and number SS-9 (Millbrook Farms #1)

Depth 662.5 Feet core

Stratigraphic Data

System Ordovician

Formation Decorah

Member Ion

TOC and RockEval Data

TOC: 0.64 wt.%

☑ RockEval (Check mark indicates published RockEval data.)

Reference

Publication date 1987

Reference number 1

Author 1 last name Hatch

Author 1 initials J.R.

Author 2 last name Jacobson

Author 2 initials S.R.

Other authors B.J. Witzke, J.B. Risatti, D.E. Anders, W.L. Watney, K.D. Newell, and A.K. Vuletich

Citation Possible late Middle Ordovician Organic Carbon Isotope Excursion: Evidence from Ordovician oils and hydrocarbon source rocks, Mid-Continent and east-central United States, AAPG Bulletin, v. 71, p. 1342-1354

General summary report Source rock catalog number 21

Locality Data

Locality number 2

State Iowa

County Jackson

Section 29 Township 84N Range 9W

Operator Cominco

Well name and number SS-9 (Millbrook Farms #1)

Depth 673 Feet core

Stratigraphic Data

System Ordovician

Formation Decorah

Member Guttenberg

TOC and RockEval Data

TOC: 40.1 wt.%

☑ RockEval (Check mark indicates published RockEval data.)

Reference

Publication date 1987

Reference number 1

Author 1 last name Hatch

Author 1 initials J.R.

Author 2 last name Jacobson

Author 2 initials S.R.

Other authors B.J. Witzke, J.B. Risatti, D.E. Anders, W.L. Watney, K.D. Newell, and A.K. Vuletich

Citation Possible late Middle Ordovician Organic Carbon Isotope Excursion: Evidence from Ordovician oils and hydrocarbon source rocks, Mid-Continent and east-central United States, AAPG Bulletin, v. 71, p. 1342-1354

General summary report Source rock catalog number 22

Locality Data

Locality number 2

State Iowa County Jackson

Section 29 Township 84N Range 9W

Operator Cominco

Well name and number SS-9 (Millbrook Farms #1)

Depth 675.6 Feet core

Stratigraphic Data

System Ordovician

Formation Decorah

Member Guttenberg

TOC and RockEval Data

TOC: 43.3 wt.%

☑ RockEval (Check mark indicates published RockEval data.)

Reference

Publication date 1987 Reference number 1

Author 1 last name Hatch Author 1 initials J.R.

Author 2 last name Jacobson Author 2 initials S.R.

Other authors B.J. Witzke, J.B. Risatti, D.E. Anders, W.L. Watney, K.D. Newell, and A.K. Vuletich

Citation Possible late Middle Ordovician Organic Carbon Isotope Excursion: Evidence from Ordovician oils and hydrocarbon source rocks, Mid-Continent and east-central United States, AAPG Bulletin, v. 71, p. 1342-1354

General summary report Source rock catalog number 23

Locality Data

Locality number 2

State Iowa

County Jackson

Section 29 Township 84N Range 9W

Operator Cominco

Well name and number SS-9 (Millbrook Farms #1)

Depth 678.5 Feet core

Stratigraphic Data

System Ordovician

Formation Decorah

Member Guttenberg

TOC and RockEval Data

TOC: 21.5 wt.%

☑ RockEval (Check mark indicates published RockEval data.)

Reference

Publication date 1987

Reference number 1

Author 1 last name Hatch

Author 1 initials J.R.

Author 2 last name Jacobson

Author 2 initials S.R.

Other authors B.J. Witzke, J.B. Risatti, D.E. Anders, W.L. Watney, K.D. Newell, and A.K. Vuletich

Citation Possible late Middle Ordovician Organic Carbon Isotope Excursion: Evidence from Ordovician oils and hydrocarbon source rocks, Mid-Continent and east-central United States, AAPG Bulletin, v. 71, p. 1342-1354

General summary report Source rock catalog number 24

Locality Data

Locality number 2

State Iowa

County Jackson

Section 29 Township 84N Range 9W

Operator Cominco

Well name and number SS-9 (Millbrook Farms #1)

Depth 679.5 Feet core

Stratigraphic Data

System Ordovician

Formation Decorah

Member Guttenberg

TOC and RockEval Data

TOC: 15.2 wt.%

☑ RockEval (Check mark indicates published RockEval data.)

Reference

Publication date 1987

Reference number 1

Author 1 last name Hatch

Author 1 initials J.R.

Author 2 last name Jacobson

Author 2 initials S.R.

Other authors B.J. Witzke, J.B. Risatti, D.E. Anders, W.L. Watney, K.D. Newell, and A.K. Vuletich

Citation Possible late Middle Ordovician Organic Carbon Isotope Excursion: Evidence from Ordovician oils and hydrocarbon source rocks, Mid-Continent and east-central United States, AAPG Bulletin, v. 71, p. 1342-1354

General summary report Source rock catalog number 25

Locality Data

Locality number 2

State Iowa

County Jackson

Section 29 Township 84N Range 9W

Operator Cominco

Well name and number SS-9 (Millbrook Farms #1)

Depth 683.3 Feet core

Stratigraphic Data

System Ordovician

Formation Decorah

Member Guttenberg

TOC and RockEval Data

TOC: 8.2 wt.%

☑ RockEval (Check mark indicates published RockEval data.)

Reference

Publication date 1987 Reference number 1

Author 1 last name Hatch Author 1 initials J.R.

Author 2 last name Jacobson Author 2 initials S.R.

Other authors B.J. Witzke, J.B. Risatti, D.E. Anders, W.L. Watney, K.D. Newell, and A.K. Vuletich

Citation Possible late Middle Ordovician Organic Carbon Isotope Excursion: Evidence from Ordovician oils and hydrocarbon source rocks, Mid-Continent and east-central United States, AAPG Bulletin, v. 71, p. 1342-1354

General summary report Source rock catalog number 26

Locality Data

Locality number 2

State Iowa

County Jackson

Section 29 Township 84N Range 9W

Operator Cominco

Well name and number SS-9 (Millbrook Farms #1)

Depth 684.3 Feet core

Stratigraphic Data

System Ordovician

Formation Decorah

Member Guttenberg

TOC and RockEval Data

TOC: 4.9 wt.%

☑ RockEval (Check mark indicates published RockEval data.)

Reference

Publication date 1987

Reference number 1

Author 1 last name Hatch

Author 1 initials J.R.

Author 2 last name Jacobson

Author 2 initials S.R.

Other authors B.J. Witzke, J.B. Risatti, D.E. Anders, W.L. Watney, K.D. Newell, and A.K. Vuletich

Citation Possible late Middle Ordovician Organic Carbon Isotope Excursion: Evidence from Ordovician oils and hydrocarbon source rocks, Mid-Continent and east-central United States, AAPG Bulletin, v. 71, p. 1342-1354

General summary report Source rock catalog number 27

Locality Data

Locality number 2

State Iowa County Jackson

Section 29 Township 84N Range 9W

Operator Cominco

Well name and number SS-9 (Millbrook Farms #1)

Depth 687.2 Feet core

Stratigraphic Data

System Ordovician

Formation Decorah

Member Guttenberg

TOC and RockEval Data

TOC: 2.1 wt.%

☑ RockEval (Check mark indicates published RockEval data.)

Reference

Publication date 1987 Reference number 1

Author 1 last name Hatch Author 1 initials J.R.

Author 2 last name Jacobson Author 2 initials S.R.

Other authors B.J. Witzke, J.B. Risatti, D.E. Anders, W.L. Watney, K.D. Newell, and A.K. Vuletich

Citation Possible late Middle Ordovician Organic Carbon Isotope Excursion: Evidence from Ordovician oils and hydrocarbon source rocks, Mid-Continent and east-central United States, AAPG Bulletin, v. 71, p. 1342-1354

General summary report Source rock catalog number 28

Locality Data

Locality number 2

State Iowa

County Jackson

Section 29 Township 84N Range 9W

Operator Cominco

Well name and number SS-9 (Millbrook Farms #1)

Depth 693.7 Feet core

Stratigraphic Data

System Ordovician

Formation Decorah

Member Spechts Ferry

TOC and RockEval Data

TOC: 0.47 wt.%

☑ RockEval (Check mark indicates published RockEval data.)

Reference

Publication date 1987

Reference number 1

Author 1 last name Hatch

Author 1 initials J.R.

Author 2 last name Jacobson

Author 2 initials S.R.

Other authors B.J. Witzke, J.B. Risatti, D.E. Anders, W.L. Watney, K.D. Newell, and A.K. Vuletich

Citation Possible late Middle Ordovician Organic Carbon Isotope Excursion: Evidence from Ordovician oils and hydrocarbon source rocks, Mid-Continent and east-central United States, AAPG Bulletin, v. 71, p. 1342-1354

General summary report Source rock catalog number 29

Locality Data

Locality number 2

State Iowa

County Jackson

Section 29 Township 84N Range 9W

Operator Cominco

Well name and number SS-9 (Millbrook Farms #1)

Depth 695.4 Feet core

Stratigraphic Data

System Ordovician

Formation Decorah

Member Spechts Ferry

TOC and RockEval Data

TOC: 1.1 wt.%

☑ RockEval (Check mark indicates published RockEval data.)

Reference

Publication date 1987 Reference number 1

Author 1 last name Hatch Author 1 initials J.R.

Author 2 last name Jacobson Author 2 initials S.R.

Other authors B.J. Witzke, J.B. Risatti, D.E. Anders, W.L. Watney, K.D. Newell, and A.K. Vuletich

Citation Possible late Middle Ordovician Organic Carbon Isotope Excursion: Evidence from Ordovician oils and hydrocarbon source rocks, Mid-Continent and east-central United States, AAPG Bulletin, v. 71, p. 1342-1354

General summary report Source rock catalog number 30

Locality Data

Locality number 2

State Iowa

County Jackson

Section 29 Township 84N Range 9W

Operator Cominco

Well name and number SS-9 (Millbrook Farms #1)

Depth 702.4 Feet core

Stratigraphic Data

System Ordovician

Formation Platteville

Member McGregor

TOC and RockEval Data

TOC: 0.48 wt.%

☑ RockEval (Check mark indicates published RockEval data.)

Reference

Publication date 1987 Reference number 1

Author 1 last name Hatch

Author 1 initials J.R.

Author 2 last name Jacobson

Author 2 initials S.R.

Other authors B.J. Witzke, J.B. Risatti, D.E. Anders, W.L. Watney, K.D. Newell, and A.K. Vuletich

Citation Possible late Middle Ordovician Organic Carbon Isotope Excursion: Evidence from Ordovician oils and hydrocarbon source rocks, Mid-Continent and east-central United States, AAPG Bulletin, v. 71, p. 1342-1354

General summary report Source rock catalog number 31

Locality Data

Locality number 2

State Iowa County Jackson

Section 29 Township 84N Range 9W

Operator Cominco

Well name and number SS-9 (Millbrook Farms #1)

Depth 718.5 Feet core

Stratigraphic Data

System Ordovician

Formation Platteville

Member McGregor

TOC and RockEval Data

TOC: 0.93 wt.%

☑ RockEval (Check mark indicates published RockEval data.)

Reference

Publication date 1987 Reference number 1

Author 1 last name Hatch Author 1 initials J.R.

Author 2 last name Jacobson Author 2 initials S.R.

Other authors B.J. Witzke, J.B. Risatti, D.E. Anders, W.L. Watney, K.D. Newell, and A.K. Vuletich

Citation Possible late Middle Ordovician Organic Carbon Isotope Excursion: Evidence from Ordovician oils and hydrocarbon source rocks, Mid-Continent and east-central United States, AAPG Bulletin, v. 71, p. 1342-1354

General summary report Source rock catalog number 32

Locality Data

Locality number 2

State Iowa

County Jackson

Section 29 Township 84N Range 9W

Operator Cominco

Well name and number SS-9 (Millbrook Farms #1)

Depth 727.2 Feet core

Stratigraphic Data

System Ordovician

Formation Platteville

Member McGregor

TOC and RockEval Data

TOC: 1.5 wt.%

☑ RockEval (Check mark indicates published RockEval data.)

Reference

Publication date 1987

Reference number 1

Author 1 last name Hatch

Author 1 initials J.R.

Author 2 last name Jacobson

Author 2 initials S.R.

Other authors B.J. Witzke, J.B. Risatti, D.E. Anders, W.L. Watney, K.D. Newell, and A.K. Vuletich

Citation Possible late Middle Ordovician Organic Carbon Isotope Excursion: Evidence from Ordovician oils and hydrocarbon source rocks, Mid-Continent and east-central United States, AAPG Bulletin, v. 71, p. 1342-1354

General summary report Source rock catalog number 33

Locality Data

Locality number 2

State Iowa

County Jackson

Section 29 Township 84N Range 9W

Operator Cominco

Well name and number SS-9 (Millbrook Farms #1)

Depth 750.8 Feet core

Stratigraphic Data

System Ordovician

Formation Glenwood

Member

TOC and RockEval Data

TOC: 6.1 wt.%

☑ RockEval (Check mark indicates published RockEval data.)

Reference

Publication date 1987

Reference number 1

Author 1 last name Hatch

Author 1 initials J.R.

Author 2 last name Jacobson

Author 2 initials S.R.

Other authors B.J. Witzke, J.B. Risatti, D.E. Anders, W.L. Watney, K.D. Newell, and A.K. Vuletich

Citation Possible late Middle Ordovician Organic Carbon Isotope Excursion: Evidence from Ordovician oils and hydrocarbon source rocks, Mid-Continent and east-central United States, AAPG Bulletin, v. 71, p. 1342-1354

General summary report Source rock catalog number 34

Locality Data

Locality number 2

State Iowa

County Jackson

Section 29 Township 84N Range 9W

Operator Cominco

Well name and number SS-9 (Millbrook Farms #1)

Depth 756.3 Feet core

Stratigraphic Data

System Ordovician

Formation St. Peter

Member

TOC and RockEval Data

TOC: 0.25 wt.%

☑ RockEval (Check mark indicates published RockEval data.)

Reference

Publication date 1987

Reference number 1

Author 1 last name Hatch

Author 1 initials J.R.

Author 2 last name Jacobson

Author 2 initials S.R.

Other authors B.J. Witzke, J.B. Risatti, D.E. Anders, W.L. Watney, K.D. Newell, and A.K. Vuletich

Citation Possible late Middle Ordovician Organic Carbon Isotope Excursion: Evidence from Ordovician oils and hydrocarbon source rocks, Mid-Continent and east-central United States, AAPG Bulletin, v. 71, p. 1342-1354

General summary report Source rock catalog number 35

Locality Data

Locality number 3

State Iowa

County Jackson

Section 35 Township 84N Range 2E

Operator Cominco

Well name and number SS-4A (Saunders #1)

Depth 326.9 Feet core

Stratigraphic Data

System Ordovician

Formation Maquoketa

Member Scales

TOC and RockEval Data

TOC: 0.13 wt.%

☐ RockEval (Check mark indicates published RockEval data.)

Reference

Publication date 1994

Reference number 2

Author 1 last name Guthrie

Author 1 initials J.M.

Author 2 last name

Author 2 initials

Other authors

Citation Organic geochemistry and cargon isotopic compositions of strata in the Upper Ordovician Maquoketa Group and oils in Ordovician reservoirs from the Illinois Basin, unpublished Ph.D. dissertation, Indiana University, Bloomington, Indiana, ____ p.

General summary report Source rock catalog number 36

Locality Data

Locality number 3

State Iowa County Jackson

Section 35 Township 84N Range 2E

Operator Cominco

Well name and number SS-4A (Saunders #1)

Depth 336.2 Feet core

Stratigraphic Data

System Ordovician

Formation Maquoketa

Member Scales

TOC and RockEval Data

TOC: 0.24 wt.%

☐ RockEval (Check mark indicates published RockEval data.)

Reference

Publication date 1994 Reference number 2

Author 1 last name Guthrie Author 1 initials J.M.

Author 2 last name Author 2 initials

Other authors

Citation Organic geochemistry and cargon isotopic compositions of strata in the Upper Ordovician Maquoketa Group and oils in Ordovician reservoirs from the Illinois Basin, unpublished Ph.D. dissertation, Indiana University, Bloomington, Indiana, ____ p.

General summary report Source rock catalog number 37

Locality Data

Locality number 3

State Iowa

County Jackson

Section 35 Township 84N Range 2E

Operator Cominco

Well name and number SS-4A (Saunders #1)

Depth 350.9 Feet core

Stratigraphic Data

System Ordovician

Formation Maquoketa

Member Scales

TOC and RockEval Data

TOC: 0.18 wt.%

☐ RockEval (Check mark indicates published RockEval data.)

Reference

Publication date 1994

Reference number 2

Author 1 last name Guthrie

Author 1 initials J.M.

Author 2 last name

Author 2 initials

Other authors

Citation Organic geochemistry and cargon isotopic compositions of strata in the Upper Ordovician Maquoketa Group and oils in Ordovician reservoirs from the Illinois Basin, unpublished Ph.D. dissertation, Indiana University, Bloomington, Indiana, ____ p.

General summary report Source rock catalog number 38

Locality Data Locality number 3

State Iowa County Jackson

Section 35 Township 84N Range 2E

Operator Cominco

Well name and number SS-4A (Saunders #1)

Depth 363.6 Feet core

Stratigraphic Data

System Ordovician

Formation Maquoketa

Member Scales

TOC and RockEval Data

TOC: 0.11 wt.%

☐ RockEval (Check mark indicates published RockEval data.)

Reference Publication date 1994 Reference number 2

Author 1 last name Guthrie Author 1 initials J.M.

Author 2 last name Author 2 initials

Other authors

Citation Organic geochemistry and cargon isotopic compositions of strata in the Upper Ordovician Maquoketa Group and oils in Ordovician reservoirs from the Illinois Basin, unpublished Ph.D. dissertation, Indiana University, Bloomington, Indiana, ____ p.

General summary report Source rock catalog number 39

Locality Data

Locality number 3

State Iowa

County Jackson

Section 35 Township 84N Range 2E

Operator Cominco

Well name and number SS-4A (Saunders #1)

Depth 374.9 Feet core

Stratigraphic Data

System Ordovician

Formation Maquoketa

Member Scales

TOC and RockEval Data

TOC: 0.21 wt.%

☐ RockEval (Check mark indicates published RockEval data.)

Reference

Publication date 1994

Reference number 2

Author 1 last name Guthrie

Author 1 initials J.M.

Author 2 last name

Author 2 initials

Other authors

Citation Organic geochemistry and cargon isotopic compositions of strata in the Upper Ordovician Maquoketa Group and oils in Ordovician reservoirs from the Illinois Basin, unpublished Ph.D. dissertation, Indiana University, Bloomington, Indiana, ____ p.

General summary report Source rock catalog number 40

Locality Data

Locality number 3

State Iowa County Jackson

Section 35 Township 84N Range 2E

Operator Cominco

Well name and number SS-4A (Saunders #1)

Depth 383.5 Feet core

Stratigraphic Data

System Ordovician

Formation Maquoketa

Member Scales

TOC and RockEval Data

TOC: 0.28 wt.%

☑ RockEval (Check mark indicates published RockEval data.)

Reference

Publication date 1994 Reference number 2

Author 1 last name Guthrie Author 1 initials J.M.

Author 2 last name Author 2 initials

Other authors

Citation Organic geochemistry and cargon isotopic compositions of strata in the Upper Ordovician Maquoketa Group and oils in Ordovician reservoirs from the Illinois Basin, unpublished Ph.D. dissertation, Indiana University, Bloomington, Indiana, ____ p.

General summary report Source rock catalog number 41

Locality Data

Locality number 3

State Iowa

County Jackson

Section 35 Township 84N Range 2E

Operator Cominco

Well name and number SS-4A (Saunders #1)

Depth 390.5 Feet core

Stratigraphic Data

System Ordovician

Formation Maquoketa

Member Scales

TOC and RockEval Data

TOC: 0.24 wt.%

☐ RockEval (Check mark indicates published RockEval data.)

Reference

Publication date 1994

Reference number 2

Author 1 last name Guthrie

Author 1 initials J.M.

Author 2 last name

Author 2 initials

Other authors

Citation Organic geochemistry and cargon isotopic compositions of strata in the Upper Ordovician Maquoketa Group and oils in Ordovician reservoirs from the Illinois Basin, unpublished Ph.D. dissertation, Indiana University, Bloomington, Indiana, ____ p.

General summary report Source rock catalog number 42

Locality Data

Locality number 3

State Iowa

County Jackson

Section 35 Township 84N Range 2E

Operator Cominco

Well name and number SS-4A (Saunders #1)

Depth 404.9 Feet core

Stratigraphic Data

System Ordovician

Formation Maquoketa

Member Scales

TOC and RockEval Data

TOC: 0.26 wt.%

☑ RockEval (Check mark indicates published RockEval data.)

Reference

Publication date 1994

Reference number 2

Author 1 last name Gúthrie

Author 1 initials J.M.

Author 2 last name

Author 2 initials

Other authors

Citation Organic geochemistry and cargon isotopic compositions of strata in the Upper Ordovician Maquoketa Group and oils in Ordovician reservoirs from the Illinois Basin, unpublished Ph.D. dissertation, Indiana University, Bloomington, Indiana, ____ p.

General summary report Source rock catalog number 43

Locality Data

Locality number 3

State Iowa

County Jackson

Section 35 Township 84N Range 2E

Operator Cominco

Well name and number SS-4A (Saunders #1)

Depth 408.4 Feet core

Stratigraphic Data

System Ordovician

Formation Maquoketa

Member Scales

TOC and RockEval Data

TOC: 0.22 wt.%

☐ RockEval (Check mark indicates published RockEval data.)

Reference

Publication date 1994

Reference number 2

Author 1 last name Guthrie

Author 1 initials J.M.

Author 2 last name

Author 2 initials

Other authors

Citation Organic geochemistry and cargon isotopic compositions of strata in the Upper Ordovician Maquoketa Group and oils in Ordovician reservoirs from the Illinois Basin, unpublished Ph.D. dissertation, Indiana University, Bloomington, Indiana, ____ p.

General summary report Source rock catalog number 44

Locality Data

Locality number 3

State Iowa

County Jackson

Section 35 Township 84N Range 2E

Operator Cominco

Well name and number SS-4A (Saunders #1)

Depth 422.6 Feet core

Stratigraphic Data

System Ordovician

Formation Maquoketa

Member Scales

TOC and RockEval Data

TOC: 0.22 wt.%

☐ RockEval (Check mark indicates published RockEval data.)

Reference

Publication date 1994 Reference number 2

Author 1 last name Guthrie

Author 1 initials J.M.

Author 2 last name

Author 2 initials

Other authors

Citation Organic geochemistry and cargon isotopic compositions of strata in the Upper Ordovician Maquoketa Group and oils in Ordovician reservoirs from the Illinois Basin, unpublished Ph.D. dissertation, Indiana University, Bloomington, Indiana, ____ p.

General summary report Source rock catalog number 45

Locality Data

Locality number 3

State Iowa

County Jackson

Section 35 Township 84N Range 2E

Operator Cominco

Well name and number SS-4A (Saunders #1)

Depth 428.9 Feet core

Stratigraphic Data

System Ordovician

Formation Maquoketa

Member Scales

TOC and RockEval Data

TOC: 0.41 wt.%

☑ RockEval (Check mark indicates published RockEval data.)

Reference

Publication date 1994

Reference number 2

Author 1 last name Guthrie

Author 1 initials J.M.

Author 2 last name

Author 2 initials

Other authors

Citation Organic geochemistry and cargon isotopic compositions of strata in the Upper Ordovician Maquoketa Group and oils in Ordovician reservoirs from the Illinois Basin, unpublished Ph.D. dissertation, Indiana University, Bloomington, Indiana, ____ p.

General summary report Source rock catalog number 46

Locality Data

Locality number 3

State Iowa County Jackson

Section 35 Township 84N Range 2E

Operator Cominco

Well name and number SS-4A (Saunders #1)

Depth 433.9 Feet core

Stratigraphic Data

System Ordovician

Formation Maquoketa

Member Scales

TOC and RockEval Data

TOC: 1.26 wt.%

☑ RockEval (Check mark indicates published RockEval data.)

Reference

Publication date 1994 Reference number 2

Author 1 last name Guthrie Author 1 initials J.M.

Author 2 last name Author 2 initials

Other authors

Citation Organic geochemistry and cargon isotopic compositions of strata in the Upper Ordovician Maquoketa Group and oils in Ordovician reservoirs from the Illinois Basin, unpublished Ph.D. dissertation, Indiana University, Bloomington, Indiana, ____ p.

General summary report Source rock catalog number 47

Locality Data

Locality number 3

State Iowa

County Jackson

Section 35 Township 84N Range 2E

Operator Cominco

Well name and number SS-4A (Saunders #1)

Depth 442.9 Feet core

Stratigraphic Data

System Ordovician

Formation Maquoketa

Member Scales

TOC and RockEval Data

TOC: 0.4 wt.%

☑ RockEval (Check mark indicates published RockEval data.)

Reference

Publication date 1994

Reference number 2

Author 1 last name Guthrie

Author 1 initials J.M.

Author 2 last name

Author 2 initials

Other authors

Citation Organic geochemistry and cargon isotopic compositions of strata in the Upper Ordovician Maquoketa Group and oils in Ordovician reservoirs from the Illinois Basin, unpublished Ph.D. dissertation, Indiana University, Bloomington, Indiana, ____ p.

General summary report Source rock catalog number 48

Locality Data Locality number 3

State Iowa County Jackson

Section 35 Township 84N Range 2E

Operator Cominco

Well name and number SS-4A (Saunders #1)

Depth 446.5 Feet core

Stratigraphic Data

System Ordovician

Formation Maquoketa

Member Scales

TOC and RockEval Data

TOC: 0.8 wt.%

☑ RockEval (Check mark indicates published RockEval data.)

Reference Publication date 1994 Reference number 2

Author 1 last name Guthrie Author 1 initials J.M.

Author 2 last name Author 2 initials

Other authors

Citation Organic geochemistry and cargon isotopic compositions of strata in the Upper Ordovician Maquoketa Group and oils in Ordovician reservoirs from the Illinois Basin, unpublished Ph.D. dissertation, Indiana University, Bloomington, Indiana, ____ p.

General summary report Source rock catalog number 49

Locality Data

Locality number 3

State Iowa

County Jackson

Section 35 Township 84N Range 2E

Operator Cominco

Well name and number SS-4A (Saunders #1)

Depth 448.2 Feet core

Stratigraphic Data

System Ordovician

Formation Maquoketa

Member Scales

TOC and RockEval Data

TOC: 1.86 wt.%

☑ RockEval (Check mark indicates published RockEval data.)

Reference

Publication date 1994

Reference number 2

Author 1 last name Guthrie

Author 1 initials J.M.

Author 2 last name

Author 2 initials

Other authors

Citation Organic geochemistry and cargon isotopic compositions of strata in the Upper Ordovician Maquoketa Group and oils in Ordovician reservoirs from the Illinois Basin, unpublished Ph.D. dissertation, Indiana University, Bloomington, Indiana, ____ p.

General summary report Source rock catalog number 50

Locality Data

Locality number 3

State Iowa

County Jackson

Section 35 Township 84N Range 2E

Operator Cominco

Well name and number SS-4A (Saunders #1)

Depth 450.9 Feet core

Stratigraphic Data

System Ordovician

Formation Maquoketa

Member Scales

TOC and RockEval Data

TOC: 2.42 wt.%

☑ RockEval (Check mark indicates published RockEval data.)

Reference

Publication date 1994

Reference number 2

Author 1 last name Guthrie

Author 1 initials J.M.

Author 2 last name

Author 2 initials

Other authors

Citation Organic geochemistry and cargon isotopic compositions of strata in the Upper Ordovician Maquoketa Group and oils in Ordovician reservoirs from the Illinois Basin, unpublished Ph.D. dissertation, Indiana University, Bloomington, Indiana, ____ p.

General summary report Source rock catalog number 51

Locality Data

Locality number 3

State Iowa· County Jackson

Section 35 Township 84N Range 2E

Operator Cominco

Well name and number SS-4A (Saunders #1)

Depth 454.4 Feet core

Stratigraphic Data

System Ordovician

Formation Maquoketa

Member Scales

TOC and RockEval Data

TOC: 0.67 wt.%

☑ RockEval (Check mark indicates published RockEval data.)

Reference

Publication date 1994 Reference number 2

Author 1 last name Guthrie Author 1 initials J.M.

Author 2 last name Author 2 initials

Other authors

Citation Organic geochemistry and cargon isotopic compositions of strata in the Upper Ordovician Maquoketa Group and oils in Ordovician reservoirs from the Illinois Basin, unpublished Ph.D. dissertation, Indiana University, Bloomington, Indiana, ____ p.

General summary report Source rock catalog number 52

Locality Data

Locality number 3

State Iowa County Jackson

Section 35 Township 84N Range 2E

Operator Cominco

Well name and number SS-4A (Saunders #1)

Depth 457.4 Feet core

Stratigraphic Data

System Ordovician

Formation Maquoketa

Member Scales

TOC and RockEval Data

TOC: 0.68 wt.%

☑ RockEval (Check mark indicates published RockEval data.)

Reference

Publication date 1994 Reference number 2

Author 1 last name Guthrie Author 1 initials J.M.

Author 2 last name Author 2 initials

Other authors

Citation Organic geochemistry and cargon isotopic compositions of strata in the Upper Ordovician Maquoketa Group and oils in Ordovician reservoirs from the Illinois Basin, unpublished Ph.D. dissertation, Indiana University, Bloomington, Indiana, ____ p.

General summary report Source rock catalog number 53

Locality Data

Locality number 3

State Iowa

County Jackson

Section 35 Township 84N Range 2E

Operator Cominco,

Well name and number SS-4A (Saunders #1)

Depth 461.9. Feet core

Stratigraphic Data

System Ordovician

Formation Maquoketa

Member Scales

TOC and RockEval Data

TOC: 0.36 wt.%

☐ RockEval (Check mark indicates published RockEval data.)

Reference

Publication date 1994

Reference number 2

Author 1 last name Guthrie

Author 1 initials J.M.

Author 2 last name

Author 2 initials

Other authors

Citation Organic geochemistry and cargon isotopic compositions of strata in the Upper Ordovician Maquoketa Group and oils in Ordovician reservoirs from the Illinois Basin, unpublished Ph.D. dissertation, Indiana University, Bloomington, Indiana, ____ p.

General summary report Source rock catalog number 54

Locality Data Locality number 3

State Iowa County Jackson

Section 35 Township 84N Range 2E

Operator Cominco

Well name and number SS-4A (Saunders #1)

Depth 462.5 Feet core

Stratigraphic Data

System Ordovician

Formation Maquoketa

Member Scales

TOC and RockEval Data

TOC: 8.72 wt.%

☑ RockEval (Check mark indicates published RockEval data.)

Reference Publication date 1994 Reference number 2

Author 1 last name Guthrie Author 1 initials J.M.

Author 2 last name Author 2 initials

Other authors

Citation Organic geochemistry and cargon isotopic compositions of strata in the Upper Ordovician Maquoketa Group and oils in Ordovician reservoirs from the Illinois Basin, unpublished Ph.D. dissertation, Indiana University, Bloomington, Indiana, ____ p.

General summary report Source rock catalog number 55

Locality Data

Locality number 3

State Iowa County Jackson

Section 35 Township 84N Range 2E

Operator Cominco

Well name and number SS-4A (Saunders #1)

Depth 464.3 Feet core

Stratigraphic Data

System Ordovician

Formation Maquoketa

Member Scales

TOC and RockEval Data

TOC: 7.69 wt.%

☑ RockEval (Check mark indicates published RockEval data.)

Reference

Publication date 1994 Reference number 2

Author 1 last name Guthrie Author 1 initials J.M.

Author 2 last name Author 2 initials

Other authors

Citation Organic geochemistry and cargon isotopic compositions of strata in the Upper Ordovician Maquoketa Group and oils in Ordovician reservoirs from the Illinois Basin, unpublished Ph.D. dissertation, Indiana University, Bloomington, Indiana, ____ p.

General summary report Source rock catalog number 56

Locality Data

Locality number 3

State Iowa County Jackson

Section 35 Township 84N Range 2E

Operator Cominco

Well name and number SS-4A (Saunders #1)

Depth 465.3 Feet core

Stratigraphic Data

System Ordovician

Formation Maquoketa

Member Scales

TOC and RockEval Data

TOC: 8.68 wt.%

☑ RockEval (Check mark indicates published RockEval data.)

Reference

Publication date 1994 Reference number 2

Author 1 last name Guthrie Author 1 initials J.M.

Author 2 last name Author 2 initials

Other authors

Citation Organic geochemistry and cargon isotopic compositions of strata in the Upper Ordovician Maquoketa Group and oils in Ordovician reservoirs from the Illinois Basin, unpublished Ph.D. dissertation, Indiana University, Bloomington, Indiana, ____ p.

General summary report Source rock catalog number 57

Locality Data

Locality number 3

State Iowa County Jackson

Section 35 Township 84N Range 2E

Operator Cominco

Well name and number SS-4A (Saunders #1)

Depth 467.3 Feet core

Stratigraphic Data

System Ordovician

Formation Maquoketa

Member Scales

TOC and RockEval Data

TOC: 9.68 wt.%

☑ RockEval (Check mark indicates published RockEval data.)

Reference

Publication date 1994 Reference number 2

Author 1 last name Guthrie Author 1 initials J.M.

Author 2 last name Author 2 initials

Other authors

Citation Organic geochemistry and cargon isotopic compositions of strata in the Upper Ordovician Maquoketa Group and oils in Ordovician reservoirs from the Illinois Basin, unpublished Ph.D. dissertation, Indiana University, Bloomington, Indiana, ____ p.

General summary report Source rock catalog number 58

Locality Data

Locality number 3

State Iowa County Jackson

Section 35 Township 84N Range 2E

Operator Cominco

Well name and number SS-4A (Saunders #1)

Depth 468.3 Feet core

Stratigraphic Data

System Ordovician

Formation Maquoketa

Member Scales

TOC and RockEval Data

TOC: 1.2 wt.%

☑ RockEval (Check mark indicates published RockEval data.)

Reference

Publication date 1994 Reference number 2

Author 1 last name Guthrie Author 1 initials J.M.

Author 2 last name Author 2 initials

Other authors

Citation Organic geochemistry and cargon isotopic compositions of strata in the Upper Ordovician Maquoketa Group and oils in Ordovician reservoirs from the Illinois Basin, unpublished Ph.D. dissertation, Indiana University, Bloomington, Indiana, ____ p.

General summary report Source rock catalog number 59

Locality Data

Locality number 3

State Iowa

County Jackson

Section 35 Township 84N Range 2E

Operator Cominco

Well name and number SS-4A (Saunders #1)

Depth 469.3 Feet core

Stratigraphic Data

System Ordovician

Formation Maquoketa

Member Scales

TOC and RockEval Data

TOC: 0.66 wt.%

☑ RockEval (Check mark indicates published RockEval data.)

Reference

Publication date 1994

Reference number 2

Author 1 last name Guthrie

Author 1 initials J.M.

Author 2 last name

Author 2 initials

Other authors

Citation Organic geochemistry and cargon isotopic compositions of strata in the Upper Ordovician Maquoketa Group and oils in Ordovician reservoirs from the Illinois Basin, unpublished Ph.D. dissertation, Indiana University, Bloomington, Indiana, ____ p.

General summary report Source rock catalog number 60

Locality Data

Locality number 4

State Iowa

County Des Moines

Section 15 Township 71N Range 2W

Operator New Jersey Zinc

Well name and number H-33 (Anderson #1)

Depth 374.9 Feet core

Stratigraphic Data

System Ordovician

Formation Maquoketa

Member Clermont

TOC and RockEval Data

TOC: 0.22 wt.%

☐ RockEval (Check mark indicates published RockEval data.)

Reference

Publication date 1994

Reference number 2

Author 1 last name Guthrie

Author 1 initials J.M.

Author 2 last name

Author 2 initials

Other authors

Citation Organic geochemistry and cargon isotopic compositions of strata in the Upper Ordovician Maquoketa Group and oils in Ordovician reservoirs from the Illinois Basin, unpublished Ph.D. dissertation, Indiana University, Bloomington, Indiana, ____ p.

General summary report Source rock catalog number 61

Locality Data

Locality number 4

State Iowa

County Des Moines

Section 15 Township 71N Range 2W

Operator New Jersey Zinc

Well name and number H-33 (Anderson #1)

Depth 399.9 Feet core

Stratigraphic Data

System Ordovician

Formation Maquoketa

Member Clermont

TOC and RockEval Data

TOC: 0.17 wt.%

☐ RockEval (Check mark indicates published RockEval data.)

Reference

Publication date 1994 Reference number 2

Author 1 last name Guthrie Author 1 initials J.M.

Author 2 last name Author 2 initials

Other authors

Citation Organic geochemistry and cargon isotopic compositions of strata in the Upper Ordovician Maquoketa Group and oils in Ordovician reservoirs from the Illinois Basin, unpublished Ph.D. dissertation, Indiana University, Bloomington, Indiana, ____ p.

General summary report Source rock catalog number 62

Locality Data

Locality number 4

State Iowa

County Des Moines

Section 15 Township 71N Range 2W

Operator New Jersey Zinc

Well name and number H-33 (Anderson #1)

Depth 418.3 Feet core

Stratigraphic Data

System Ordovician

Formation Maquoketa

Member Clermont

TOC and RockEval Data

TOC: 0.12 wt.%

☐ RockEval (Check mark indicates published RockEval data.)

Reference

Publication date 1994

Reference number 2

Author 1 last name Guthrie

Author 1 initials J.M.

Author 2 last name

Author 2 initials

Other authors

Citation Organic geochemistry and cargon isotopic compositions of strata in the Upper Ordovician Maquoketa Group and oils in Ordovician reservoirs from the Illinois Basin, unpublished Ph.D. dissertation, Indiana University, Bloomington, Indiana, ____ p.

General summary report Source rock catalog number 63

Locality Data

Locality number 4

State Iowa County Des Moines

Section 15 Township 71N Range 2W

Operator New Jersey Zinc

Well name and number H-33 (Anderson #1)

Depth 427.4 Feet core

Stratigraphic Data

System Ordovician

Formation Maquoketa

Member Clermont

TOC and RockEval Data

TOC: 0.44 wt.%

☐ RockEval (Check mark indicates published RockEval data.)

Reference

Publication date 1994 Reference number 2

Author 1 last name Guthrie Author 1 initials J.M.

Author 2 last name Author 2 initials

Other authors

Citation Organic geochemistry and cargon isotopic compositions of strata in the Upper Ordovician Maquoketa Group and oils in Ordovician reservoirs from the Illinois Basin, unpublished Ph.D. dissertation, Indiana University, Bloomington, Indiana, ____ p.

General summary report Source rock catalog number 64

Locality Data Locality number 4

State Iowa County Des Moines

Section 15 Township 71N Range 2W

Operator New Jersey Zinc

Well name and number H-33 (Anderson #1)

Depth 429.7 Feet core

Stratigraphic Data

System Ordovician

Formation Maquoketa

Member Clermont

TOC and RockEval Data

TOC: 0.24 wt.%

☐ RockEval (Check mark indicates published RockEval data.)

Reference Publication date 1994 Reference number 2

Author 1 last name Guthrie Author 1 initials J.M.

Author 2 last name Author 2 initials

Other authors

Citation Organic geochemistry and cargon isotopic compositions of strata in the Upper Ordovician Maquoketa Group and oils in Ordovician reservoirs from the Illinois Basin, unpublished Ph.D. dissertation, Indiana University, Bloomington, Indiana, ____ p.

General summary report Source rock catalog number 65

Locality Data

Locality number 4

State Iowa County Des Moines

Section 15 Township 71N Range 2W

Operator New Jersey Zinc

Well name and number H-33 (Anderson #1)

Depth 431.7 Feet core

Stratigraphic Data

System Ordovician

Formation Maquoketa

Member Clermont

TOC and RockEval Data

TOC: 1.49 wt.%

☐ RockEval (Check mark indicates published RockEval data.)

Reference

Publication date 1994 Reference number 2

Author 1 last name Guthrie Author 1 initials J.M.

Author 2 last name Author 2 initials

Other authors

Citation Organic geochemistry and cargon isotopic compositions of strata in the Upper Ordovician Maquoketa Group and oils in Ordovician reservoirs from the Illinois Basin, unpublished Ph.D. dissertation, Indiana University, Bloomington, Indiana, _____ p.

General summary report　　Source rock catalog number 66

Locality Data　　Locality number 4

State Iowa　　County Des Moines

Section 15　Township 71N　Range 2W

Operator New Jersey Zinc

Well name and number H-33 (Anderson #1)

Depth 434.9 Feet　core

Stratigraphic Data

System Ordovician

Formation Maquoketa

Member Clermont

TOC and RockEval Data

TOC: 0.97 wt.%

☐ RockEval (Check mark indicates published RockEval data.)

Reference　Publication date 1994　Reference number 2

Author 1 last name Guthrie　Author 1 initials J.M.

Author 2 last name　Author 2 initials

Other authors

Citation　Organic geochemistry and cargon isotopic compositions of strata in the Upper Ordovician Maquoketa Group and oils in Ordovician reservoirs from the Illinois Basin, unpublished Ph.D. dissertation, Indiana University, Bloomington, Indiana, ____ p.

General summary report Source rock catalog number 67

Locality Data

Locality number 4

State Iowa County Des Moines

Section 15 Township 71N Range 2W

Operator New Jersey Zinc

Well name and number H-33 (Anderson #1)

Depth 442.9 Feet core

Stratigraphic Data

System Ordovician

Formation Maquoketa

Member Elgin

TOC and RockEval Data

TOC: 3.51 wt.%

☐ RockEval (Check mark indicates published RockEval data.)

Reference

Publication date 1994 Reference number 2

Author 1 last name Guthrie Author 1 initials J.M.

Author 2 last name Author 2 initials

Other authors

Citation Organic geochemistry and cargon isotopic compositions of strata in the Upper Ordovician Maquoketa Group and oils in Ordovician reservoirs from the Illinois Basin, unpublished Ph.D. dissertation, Indiana University, Bloomington, Indiana, ____ p.

General summary report Source rock catalog number 68

Locality Data

Locality number 4

State Iowa County Des Moines

Section 15 Township 71N Range 2W

Operator New Jersey Zinc

Well name and number H-33 (Anderson #1)

Depth 451.3 Feet core

Stratigraphic Data

System Ordovician

Formation Maquoketa

Member Elgin

TOC and RockEval Data

TOC: 3.82 wt.%

☐ RockEval (Check mark indicates published RockEval data.)

Reference

Publication date 1994 Reference number 2

Author 1 last name Guthrie Author 1 initials J.M.

Author 2 last name Author 2 initials

Other authors

Citation Organic geochemistry and cargon isotopic compositions of strata in the Upper Ordovician Maquoketa Group and oils in Ordovician reservoirs from the Illinois Basin, unpublished Ph.D. dissertation, Indiana University, Bloomington, Indiana, ____ p.

General summary report Source rock catalog number 69

Locality Data

Locality number 4

State Iowa

County Des Moines

Section 15 Township 71N Range 2W

Operator New Jersey Zinc

Well name and number H-33 (Anderson #1)

Depth 461.9 Feet core

Stratigraphic Data

System Ordovician

Formation Maquoketa

Member Elgin

TOC and RockEval Data

TOC: 4.3 wt.%

☐ RockEval (Check mark indicates published RockEval data.)

Reference

Publication date 1994

Reference number 2

Author 1 last name Guthrie

Author 1 initials J.M.

Author 2 last name

Author 2 initials

Other authors

Citation Organic geochemistry and cargon isotopic compositions of strata in the Upper Ordovician Maquoketa Group and oils in Ordovician reservoirs from the Illinois Basin, unpublished Ph.D. dissertation, Indiana University, Bloomington, Indiana, ____ p.

General summary report Source rock catalog number 70

Locality Data

Locality number 4

State Iowa

County Des Moines

Section 15 Township 71N Range 2W

Operator New Jersey Zinc

Well name and number H-33 (Anderson #1)

Depth 472.5 Feet core

Stratigraphic Data

System Ordovician

Formation Maquoketa

Member Elgin

TOC and RockEval Data

TOC: 4.23 wt.%

☐ RockEval (Check mark indicates published RockEval data.)

Reference

Publication date 1994

Reference number 2

Author 1 last name Guthrie

Author 1 initials J.M.

Author 2 last name

Author 2 initials

Other authors

Citation Organic geochemistry and cargon isotopic compositions of strata in the Upper Ordovician Maquoketa Group and oils in Ordovician reservoirs from the Illinois Basin, unpublished Ph.D. dissertation, Indiana University, Bloomington, Indiana, ____ p.

General summary report Source rock catalog number 71

Locality Data
Locality number 5

State Iowa County Johnson

Section 27 Township 79N Range 5W

Operator Fenix and Scisson

Well name and number Mid-America Pipeline #4

Depth 569.5 Feet core

Stratigraphic Data

System Ordovician

Formation Maquoketa

Member Brainard

TOC and RockEval Data

TOC: 0.05 wt.%

☐ RockEval (Check mark indicates published RockEval data.)

Reference
Publication date 1994 Reference number 2

Author 1 last name Guthrie Author 1 initials J.M.

Author 2 last name Author 2 initials

Other authors

Citation Organic geochemistry and cargon isotopic compositions of strata in the Upper Ordovician Maquoketa Group and oils in Ordovician reservoirs from the Illinois Basin, unpublished Ph.D. dissertation, Indiana University, Bloomington, Indiana, ____ p.

General summary report Source rock catalog number 72

Locality Data

Locality number 5

State Iowa

County Johnson

Section 27 Township 79N Range 5W

Operator Fenix and Scisson

Well name and number Mid-America Pipeline #4

Depth 575.6 Feet core

Stratigraphic Data

System Ordovician

Formation Maquoketa

Member Brainard

TOC and RockEval Data

TOC: 0.16 wt.%

☐ RockEval (Check mark indicates published RockEval data.)

Reference

Publication date 1994

Reference number 2

Author 1 last name Guthrie

Author 1 initials J.M.

Author 2 last name

Author 2 initials

Other authors

Citation Organic geochemistry and cargon isotopic compositions of strata in the Upper Ordovician Maquoketa Group and oils in Ordovician reservoirs from the Illinois Basin, unpublished Ph.D. dissertation, Indiana University, Bloomington, Indiana, ____ p.

General summary report Source rock catalog number 73

Locality Data

Locality number 5

State Iowa

County Johnson

Section 27 Township 79N Range 5W

Operator Fenix and Scisson

Well name and number Mid-America Pipeline #4

Depth 577.2 Feet core

Stratigraphic Data

System Ordovician

Formation Maquoketa

Member Brainard

TOC and RockEval Data

TOC: 0.15 wt.%

☐ RockEval (Check mark indicates published RockEval data.)

Reference

Publication date 1994

Reference number 2

Author 1 last name Guthrie

Author 1 initials J.M.

Author 2 last name

Author 2 initials

Other authors

Citation Organic geochemistry and cargon isotopic compositions of strata in the Upper Ordovician Maquoketa Group and oils in Ordovician reservoirs from the Illinois Basin, unpublished Ph.D. dissertation, Indiana University, Bloomington, Indiana, ____ p.

General summary report　　Source rock catalog number 74

Locality Data

Locality number 5

State Iowa　　County Johnson

Section 27　Township 79N　Range 5W

Operator Fenix and Scisson

Well name and number Mid-America Pipeline #4

Depth 587.6 Feet　core

Stratigraphic Data

System Ordovician

Formation Maquoketa

Member Brainard

TOC and RockEval Data

TOC: 0.25 wt.%

☐ RockEval　(Check mark indicates published RockEval data.)

Reference

Publication date 1994　Reference number 2

Author 1 last name Guthrie　Author 1 initials J.M.

Author 2 last name　Author 2 initials

Other authors

Citation　Organic geochemistry and cargon isotopic compositions of strata in the Upper Ordovician Maquoketa Group and oils in Ordovician reservoirs from the Illinois Basin, unpublished Ph.D. dissertation, Indiana University, Bloomington, Indiana, ____ p.

General summary report Source rock catalog number 75

Locality Data

Locality number 5

State Iowa

County Johnson

Section 27 Township 79N Range 5W

Operator Fenix and Scisson

Well name and number Mid-America Pipeline #4

Depth 599.7 Feet core

Stratigraphic Data

System Ordovician

Formation Maquoketa

Member Brainard

TOC and RockEval Data

TOC: 0.45 wt.%

☐ RockEval (Check mark indicates published RockEval data.)

Reference

Publication date 1994

Reference number 2

Author 1 last name Guthrie

Author 1 initials J.M.

Author 2 last name

Author 2 initials

Other authors

Citation Organic geochemistry and cargon isotopic compositions of strata in the Upper Ordovician Maquoketa Group and oils in Ordovician reservoirs from the Illinois Basin, unpublished Ph.D. dissertation, Indiana University, Bloomington, Indiana, ____ p.

General summary report Source rock catalog number 76

Locality Data

Locality number 5

State Iowa

County Johnson

Section 27 Township 79N Range 5W

Operator Fenix and Scisson

Well name and number Mid-America Pipeline #4

Depth 615.8 Feet core

Stratigraphic Data

System Ordovician

Formation Maquoketa

Member Brainard

TOC and RockEval Data

TOC: 0.15 wt.%

☐ RockEval (Check mark indicates published RockEval data.)

Reference

Publication date 1994 Reference number 2

Author 1 last name Guthrie

Author 1 initials J.M.

Author 2 last name

Author 2 initials

Other authors

Citation Organic geochemistry and cargon isotopic compositions of strata in the Upper Ordovician Maquoketa Group and oils in Ordovician reservoirs from the Illinois Basin, unpublished Ph.D. dissertation, Indiana University, Bloomington, Indiana, ____ p.

General summary report

Source rock catalog number 77

Locality Data

Locality number 5

State Iowa

County Johnson

Section 27 Township 79N Range 5W

Operator Fenix and Scisson

Well name and number Mid-America Pipeline #4

Depth 626.6 Feet core

Stratigraphic Data

System Ordovician

Formation Maquoketa

Member Brainard

TOC and RockEval Data

TOC: 0.26 wt.%

☐ RockEval (Check mark indicates published RockEval data.)

Reference

Publication date 1994

Reference number 2

Author 1 last name Guthrie

Author 1 initials J.M.

Author 2 last name

Author 2 initials

Other authors

Citation Organic geochemistry and cargon isotopic compositions of strata in the Upper Ordovician Maquoketa Group and oils in Ordovician reservoirs from the Illinois Basin, unpublished Ph.D. dissertation, Indiana University, Bloomington, Indiana, ____ p.

General summary report Source rock catalog number 78

Locality Data

Locality number 5

State Iowa

County Johnson

Section 27 Township 79N Range 5W

Operator Fenix and Scisson

Well name and number Mid-America Pipeline #4

Depth 666 Feet core

Stratigraphic Data

System Ordovician

Formation Maquoketa

Member Brainard

TOC and RockEval Data

TOC: 0.27 wt.%

☐ RockEval (Check mark indicates published RockEval data.)

Reference

Publication date 1994 Reference number 2

Author 1 last name Guthrie Author 1 initials J.M.

Author 2 last name Author 2 initials

Other authors

Citation Organic geochemistry and cargon isotopic compositions of strata in the Upper Ordovician Maquoketa Group and oils in Ordovician reservoirs from the Illinois Basin, unpublished Ph.D. dissertation, Indiana University, Bloomington, Indiana, ____ p.

General summary report Source rock catalog number 79

Locality Data

Locality number 5

State Iowa · County Johnson

Section 27 Township 79N Range 5W

Operator Fenix and Scisson

Well name and number Mid-America Pipeline #4

Depth 692.4 Feet core

Stratigraphic Data

System Ordovician

Formation Maquoketa

Member Brainard

TOC and RockEval Data

TOC: 0.29 wt.%

☐ RockEval (Check mark indicates published RockEval data.)

Reference

Publication date 1994 Reference number 2

Author 1 last name Guthrie Author 1 initials J.M.

Author 2 last name Author 2 initials

Other authors

Citation Organic geochemistry and cargon isotopic compositions of strata in the Upper Ordovician Maquoketa Group and oils in Ordovician reservoirs from the Illinois Basin, unpublished Ph.D. dissertation, Indiana University, Bloomington, Indiana, ____ p.

General summary report Source rock catalog number 80

Locality Data

Locality number 5

State Iowa

County Johnson

Section 27 Township 79N Range 5W

Operator Fenix and Scisson

Well name and number Mid-America Pipeline #4

Depth 715.3 Feet core

Stratigraphic Data

System Ordovician

Formation Maquoketa

Member Brainard

TOC and RockEval Data

TOC: 0.33 wt.%

☐ RockEval (Check mark indicates published RockEval data.)

Reference

Publication date 1994

Reference number 2

Author 1 last name Guthrie

Author 1 initials J.M.

Author 2 last name

Author 2 initials

Other authors

Citation Organic geochemistry and cargon isotopic compositions of strata in the Upper Ordovician Maquoketa Group and oils in Ordovician reservoirs from the Illinois Basin, unpublished Ph.D. dissertation, Indiana University, Bloomington, Indiana, ____ p.

General summary report Source rock catalog number 81

Locality Data

Locality number 5

State Iowa

County Johnson

Section 27 Township 79N Range 5W

Operator Fenix and Scisson

Well name and number Mid-America Pipeline #4

Depth 801.8 Feet core

Stratigraphic Data

System Ordovician

Formation Maquoketa

Member Brainard

TOC and RockEval Data

TOC: 0.75 wt.%

☐ RockEval (Check mark indicates published RockEval data.)

Reference

Publication date 1994

Reference number 2

Author 1 last name Guthrie

Author 1 initials J.M.

Author 2 last name

Author 2 initials

Other authors

Citation Organic geochemistry and cargon isotopic compositions of strata in the Upper Ordovician Maquoketa Group and oils in Ordovician reservoirs from the Illinois Basin, unpublished Ph.D. dissertation, Indiana University, Bloomington, Indiana, ____ p.

General summary report Source rock catalog number 82

Locality Data

Locality number 5

State Iowa County Johnson

Section 27 Township 79N Range 5W

Operator Fenix and Scisson

Well name and number Mid-America Pipeline #4

Depth 762.8 Feet core

Stratigraphic Data

System Ordovician

Formation Maquoketa

Member Elgin

TOC and RockEval Data

TOC: 1.05 wt.%

☐ RockEval (Check mark indicates published RockEval data.)

Reference

Publication date 1994 Reference number 2

Author 1 last name Guthrie Author 1 initials J.M.

Author 2 last name Author 2 initials

Other authors

Citation Organic geochemistry and cargon isotopic compositions of strata in the Upper Ordovician Maquoketa Group and oils in Ordovician reservoirs from the Illinois Basin, unpublished Ph.D. dissertation, Indiana University, Bloomington, Indiana, ____ p.

General summary report Source rock catalog number 83

Locality Data

Locality number 5

State Iowa

County Johnson

Section 27 Township 79N Range 5W

Operator Fenix and Scisson

Well name and number Mid-America Pipeline #4

Depth 780.8 Feet core

Stratigraphic Data

System Ordovician

Formation Maquoketa

Member Elgin

TOC and RockEval Data

TOC: 0.71 wt.%

☐ RockEval (Check mark indicates published RockEval data.)

Reference

Publication date 1994

Reference number 2

Author 1 last name Guthrie

Author 1 initials J.M.

Author 2 last name

Author 2 initials

Other authors

Citation Organic geochemistry and cargon isotopic compositions of strata in the Upper Ordovician Maquoketa Group and oils in Ordovician reservoirs from the Illinois Basin, unpublished Ph.D. dissertation, Indiana University, Bloomington, Indiana, ____ p.

General summary report Source rock catalog number 84

Locality Data

Locality number 5

State Iowa

County Johnson

Section 27 Township 79N Range 5W

Operator Fenix and Scisson

Well name and number Mid-America Pipeline #4

Depth 783.8 Feet core

Stratigraphic Data

System Ordovician

Formation Maquoketa

Member Elgin

TOC and RockEval Data

TOC: 0.72 wt.%

☐ RockEval (Check mark indicates published RockEval data.)

Reference

Publication date 1994

Reference number 2

Author 1 last name Guthrie

Author 1 initials J.M.

Author 2 last name

Author 2 initials

Other authors

Citation Organic geochemistry and cargon isotopic compositions of strata in the Upper Ordovician Maquoketa Group and oils in Ordovician reservoirs from the Illinois Basin, unpublished Ph.D. dissertation, Indiana University, Bloomington, Indiana, ____ p.

General summary report Source rock catalog number 85

Locality Data

Locality number 5

State Iowa County Johnson

Section 27 Township 79N Range 5W

Operator Fenix and Scisson

Well name and number Mid-America Pipeline #4

Depth 794.8 Feet core

Stratigraphic Data

System Ordovician

Formation Maquoketa

Member Elgin

TOC and RockEval Data

TOC: 0.61 wt.%

☐ RockEval (Check mark indicates published RockEval data.)

Reference

Publication date 1994 Reference number 2

Author 1 last name Guthrie Author 1 initials J.M.

Author 2 last name Author 2 initials

Other authors

Citation Organic geochemistry and cargon isotopic compositions of strata in the Upper Ordovician Maquoketa Group and oils in Ordovician reservoirs from the Illinois Basin, unpublished Ph.D. dissertation, Indiana University, Bloomington, Indiana, ____ p.

General summary report　　Source rock catalog number 90

Locality Data　　Locality number 3

State Iowa　　County Jackson

Section 35　Township 84N　Range 2E

Operator Cominco

Well name and number SS-4A (Saunders #1)

Depth　Feet　core

Stratigraphic Data

System　Ordovician

Formation　Galena

Member　Dubuque

TOC and RockEval Data

TOC: 22.9 wt.%

☑ RockEval　(Check mark indicates published RockEval data.)

Reference　Publication date 1996　Reference number 4

Author 1 last name Guthrie　　Author 1 initials J.M.

Author 2 last name　　Author 2 initials

Other authors

Citation　Molecular and carbon isotopic analysis of individual bilogical markers: evidence for sources of organic matter and paleoenvironmental conditions in the Upper Ordovician Maquoketa Group, Illinois Basin, U.S.A., Organic Geochemistry, v. 25, p. 439-460

General summary report Source rock catalog number 91

Locality Data

Locality number 3

State Iowa

County Jackson

Section 35 Township 84N Range 2E

Operator Cominco

Well name and number SS-4A (Saunders #1)

Depth Feet core

Stratigraphic Data

System Ordovician

Formation Decorah

Member Guttenberg

TOC and RockEval Data

TOC: 21.0 wt.%

☑ RockEval (Check mark indicates published RockEval data.)

Reference

Publication date 1996

Reference number 4

Author 1 last name Guthrie

Author 1 initials J.M.

Author 2 last name

Author 2 initials

Other authors

Citation Molecular and carbon isotopic analysis of individual bilogical markers: evidence for sources of organic matter and paleoenvironmental conditions in the Upper Ordovician Maquoketa Group, Illinois Basin, U.S.A., Organic Geochemistry, v. 25, p. 439-460

General summary report Source rock catalog number 92

Locality Data

Locality number 3

State Iowa County Jackson

Section 35 Township 84N Range 2E

Operator Cominco

Well name and number SS-4A (Saunders #1)

Depth Feet core

Stratigraphic Data

System Ordovician

Formation Decorah

Member Guttenberg

TOC and RockEval Data

TOC: 28.2 wt.%

☑ RockEval (Check mark indicates published RockEval data.)

Reference

Publication date 1996 Reference number 4

Author 1 last name Guthrie Author 1 initials J.M.

Author 2 last name Author 2 initials

Other authors

Citation Molecular and carbon isotopic analysis of individual bilogical markers: evidence for sources of organic matter and paleoenvironmental conditions in the Upper Ordovician Maquoketa Group, Illinois Basin, U.S.A., Organic Geochemistry, v. 25, p. 439-460

General summary report Source rock catalog number 93

Locality Data Locality number 12

State Minnesota County Hennepin

Section 22 Township 29N Range 24W

Operator Minnesota Geol. Surv.

Well name and number Core 91708-A

Depth 33.2 Feet core

Stratigraphic Data

System Ordovician

Formation Glenwood

Member

TOC and RockEval Data

TOC: 0.38 wt.%

☑ RockEval (Check mark indicates published RockEval data.)

Reference Publication date 1998 Reference number 5

Author 1 last name Barker Author 1 initials C.

Author 2 last name Erickson Author 2 initials R.J.

Other authors

Citation (This paper)

General summary report Source rock catalog number 94

Locality Data

Locality number 12

State Minnesota

County Hennepin

Section 22 Township 29N Range 24W

Operator Minnesota Geol. Surv.

Well name and number Core 91708-A

Depth 51.6 Feet core

Stratigraphic Data

System Ordovician

Formation Glenwood

Member

TOC and RockEval Data

TOC: 0.31 wt.%

☑ RockEval (Check mark indicates published RockEval data.)

Reference

Publication date 1998

Reference number 5

Author 1 last name Barker

Author 1 initials C.

Author 2 last name Erickson

Author 2 initials R.J.

Other authors

Citation (This paper)

General summary report Source rock catalog number 95

Locality Data Locality number 7

State Iowa County Washington

Section 19 Township 76N Range 9W

Operator Natural Gas Pipeline

Well name and number M.M. Flynn #2

Depth 1116 Feet core

Stratigraphic Data

System Ordovician

Formation Glenwood

Member

TOC and RockEval Data

TOC: 12.3 wt.%

☑ RockEval (Check mark indicates published RockEval data.)

Reference Publication date 1998 Reference number 5

Author 1 last name Barker Author 1 initials C.

Author 2 last name Erickson Author 2 initials R.J.

Other authors

Citation (This paper)

General summary report Source rock catalog number 96

Locality Data

Locality number 8

State Iowa

County Washington

Section 20 Township 76N Range 9W

Operator Natural Gas Pipeline

Well name and number W.F. Flynn #2

Depth 977 Feet core

Stratigraphic Data

System Ordovician

Formation Decorah

Member Guttenberg

TOC and RockEval Data

TOC: 14.1 wt.%

☑ RockEval (Check mark indicates published RockEval data.)

Reference

Publication date 1998

Reference number 5

Author 1 last name Barker

Author 1 initials C.

Author 2 last name Erickson

Author 2 initials R.J.

Other authors

Citation (This paper)

General summary report Source rock catalog number 97

Locality Data

Locality number 8

State Iowa

County Washington

Section 20 Township 76N Range 9W

Operator Natural Gas Pipeline

Well name and number W.F. Flynn #2

Depth 977 Feet core

Stratigraphic Data

System Ordovician

Formation Decorah

Member Guttenberg

TOC and RockEval Data

TOC: 1.45 wt.%

☑ RockEval (Check mark indicates published RockEval data.)

Reference

Publication date 1998

Reference number 5

Author 1 last name Barker

Author 1 initials C.

Author 2 last name Erickson

Author 2 initials R.J.

Other authors

Citation (This paper)

General summary report Source rock catalog number 98

Locality Data

Locality number 22

State Iowa County Jackson

Section 14 Township 84N Range 3E

Operator Cominco

Well name and number SS-3

Depth 675 Feet core

Stratigraphic Data

System Ordovician

Formation Decorah

Member Guttenberg

TOC and RockEval Data

TOC: 41.2 wt.%

☑ RockEval (Check mark indicates published RockEval data.)

Reference

Publication date 1998 Reference number 5

Author 1 last name Barker Author 1 initials C.

Author 2 last name Erickson Author 2 initials R.J.

Other authors

Citation (This paper)

General summary report Source rock catalog number 99

Locality Data

Locality number 9

State Iowa

County Clayton

Section 20 Township 95N Range 6W

Operator Iowa Geol. Survey Bur.

Well name and number BS-4

Depth 481 Feet core

Stratigraphic Data

System Ordovician

Formation Decorah

Member Guttenberg

TOC and RockEval Data

TOC: 5.9 wt.%

☑ RockEval (Check mark indicates published RockEval data.)

Reference

Publication date 1998

Reference number 5

Author 1 last name Barker

Author 1 initials C.

Author 2 last name Erickson

Author 2 initials R.J.

Other authors

Citation (This paper)

General summary report Source rock catalog number 100

Locality Data

Locality number 1

State Iowa

County Washington

Section 20 Township 76N Range 9W

Operator Natural Gas Pipeline

Well name and number E.M. Green #1

Depth 952.3 Feet core

Stratigraphic Data

System Ordovician

Formation Decorah

Member Guttenberg

TOC and RockEval Data

TOC: 23.3 wt.%

☑ RockEval (Check mark indicates published RockEval data.)

Reference

Publication date 1988

Reference number 3

Author 1 last name Jacobson

Author 1 initials S.R.

Author 2 last name Hatch

Author 2 initials J.R.

Other authors S.C. Teerman, and Rosemary Askin

Citation Middle Ordovician Organic Matter Assemblages and their effect on Ordovician-derived oils, AAPG Bulletin, v. 72, p. 1090-1100

General summary report Source rock catalog number 101

Locality Data

Locality number 1

State Iowa

County Washington

Section 20 Township 76N Range 9W

Operator Natural Gas Pipeline

Well name and number E.M. Green #1

Depth 953.3 Feet core

Stratigraphic Data

System Ordovician

Formation Decorah

Member Guttenberg

TOC and RockEval Data

TOC: 25.7 wt.%

☑ RockEval (Check mark indicates published RockEval data.)

Reference

Publication date 1988

Reference number 3

Author 1 last name Jacobson

Author 1 initials S.R.

Author 2 last name Hatch

Author 2 initials J.R.

Other authors S.C. Teerman, and Rosemary Askin

Citation Middle Ordovician Organic Matter Assemblages and their effect on Ordovician-derived oils, AAPG Bulletin, v. 72, p. 1090-1100

General summary report Source rock catalog number 102

Locality Data

Locality number 1

State Iowa County Washington

Section 20 Township 76N Range 9W

Operator Natural Gas Pipeline

Well name and number E.M. Green #1

Depth 976.7 Feet core

Stratigraphic Data

System Ordovician

Formation Platteville

Member McGregor

TOC and RockEval Data

TOC: 0.23 wt.%

☑ RockEval (Check mark indicates published RockEval data.)

Reference

Publication date 1988 Reference number 3

Author 1 last name Jacobson Author 1 initials S.R.

Author 2 last name Hatch Author 2 initials J.R.

Other authors S.C. Teerman, and Rosemary Askin

Citation Middle Ordovician Organic Matter Assemblages and their effect on Ordovician-derived oils, AAPG Bulletin, v. 72, p. 1090-1100

General summary report Source rock catalog number 103

Locality Data

Locality number 1

State Iowa

County Washington

Section 20 Township 76N Range 9W

Operator Natural Gas Pipeline

Well name and number E.M. Green #1

Depth 986.8 Feet core

Stratigraphic Data

System Ordovician

Formation Platteville

Member McGregor

TOC and RockEval Data

TOC: 0.51 wt.%

☑ RockEval (Check mark indicates published RockEval data.)

Reference

Publication date 1988 Reference number 3

Author 1 last name Jacobson Author 1 initials S.R.

Author 2 last name Hatch Author 2 initials J.R.

Other authors S.C. Teerman, and Rosemary Askin

Citation Middle Ordovician Organic Matter Assemblages and their effect on Ordovician-derived oils, AAPG Bulletin, v. 72, p. 1090-1100

General summary report Source rock catalog number 104

Locality Data Locality number 2

State Iowa

County Jackson

Section 29 Township 84N Range 9W

Operator Cominco

Well name and number SS-9 (Millbrook Farms #1)

Depth 673.9 Feet core

Stratigraphic Data

System Ordovician

Formation Decorah

Member Guttenberg

TOC and RockEval Data

TOC: 22.8 wt.%

☑ RockEval (Check mark indicates published RockEval data.)

Reference

Publication date 1988 Reference number 3

Author 1 last name Jacobson Author 1 initials S.R.

Author 2 last name Hatch Author 2 initials J.R.

Other authors S.C. Teerman, and Rosemary Askin

Citation Middle Ordovician Organic Matter Assemblages and their effect on Ordovician-derived oils, AAPG Bulletin, v. 72, p. 1090-1100

General summary report Source rock catalog number 105

Locality Data

Locality number 2

State Iowa

County Jackson

Section 29 Township 84N Range 9W

Operator Cominco

Well name and number SS-9 (Millbrook Farms #1)

Depth 677.8 Feet core

Stratigraphic Data

System Ordovician

Formation Decorah

Member Guttenberg

TOC and RockEval Data

TOC: 10.2 wt.%

☑ RockEval (Check mark indicates published RockEval data.)

Reference

Publication date 1988

Reference number 3

Author 1 last name Jacobson

Author 1 initials S.R.

Author 2 last name Hatch

Author 2 initials J.R.

Other authors S.C. Teerman, and Rosemary Askin

Citation Middle Ordovician Organic Matter Assemblages and their effect on Ordovician-derived oils, AAPG Bulletin, v. 72, p. 1090-1100

General summary report Source rock catalog number 106

Locality Data

Locality number 2

State Iowa

County Jackson

Section 29 Township 84N Range 9W

Operator Cominco

Well name and number SS-9 (Millbrook Farms #1)

Depth 680 Feet core

Stratigraphic Data

System Ordovician

Formation Decorah

Member Guttenberg

TOC and RockEval Data

TOC: 13.5 wt.%

☑ RockEval (Check mark indicates published RockEval data.)

Reference

Publication date 1988 Reference number 3

Author 1 last name Jacobson Author 1 initials S.R.

Author 2 last name Hatch Author 2 initials J.R.

Other authors S.C. Teerman, and Rosemary Askin

Citation Middle Ordovician Organic Matter Assemblages and their effect on Ordovician-derived oils, AAPG Bulletin, v. 72, p. 1090-1100

General summary report Source rock catalog number 107

Locality Data

Locality number 2

State Iowa County Jackson

Section 29 Township 84N Range 9W

Operator Cominco

Well name and number SS-9 (Millbrook Farms #1)

Depth 751.3 Feet core

Stratigraphic Data

System Ordovician

Formation Glenwood

Member

TOC and RockEval Data

TOC: 9.5 wt.%

☑ RockEval (Check mark indicates published RockEval data.)

Reference

Publication date 1988 Reference number 3

Author 1 last name Jacobson Author 1 initials S.R.

Author 2 last name Hatch Author 2 initials J.R.

Other authors S.C. Teerman, and Rosemary Askin

Citation Middle Ordovician Organic Matter Assemblages and their effect on Ordovician-derived oils, AAPG Bulletin, v. 72, p. 1090-1100

General summary report Source rock catalog number 108

Locality Data

Locality number 23

State Kansas

County Rice

Section 2 Township 20S Range 8W

Operator Northern Natural Gas

Well name and number Caldwell #1

Depth 3280 Feet core

Stratigraphic Data

System Ordovician

Formation Viola

Member

TOC and RockEval Data

TOC: 1.1 wt.%

☑ RockEval (Check mark indicates published RockEval data.)

Reference

Publication date 1987 Reference number 1

Author 1 last name Hatch Author 1 initials J.R.

Author 2 last name Jacobson Author 2 initials S.R.

Other authors B.J. Witzke, J.B. Risatti, D.E. Anders, W.L. Watney, K.D. Newell, and A.K. Vuletich

Citation Possible late Middle Ordovician Organic Carbon Isotope Excursion: Evidence from Ordovician oils and hydrocarbon source rocks, Mid-Continent and east-central United States, AAPG Bulletin, v. 71, p. 1342-1354

General summary report Source rock catalog number 109

Locality Data

Locality number 23

State Kansas

County Rice

Section 2 Township 20S Range 8W

Operator Northern Natural Gas

Well name and number Caldwell #1

Depth 3300 Feet core

Stratigraphic Data

System Ordovician

Formation Simpson

Member shale

TOC and RockEval Data

TOC: 0.47 wt.%

☑ RockEval (Check mark indicates published RockEval data.)

Reference

Publication date 1987

Reference number 1

Author 1 last name Hatch

Author 1 initials J.R.

Author 2 last name Jacobson

Author 2 initials S.R.

Other authors B.J. Witzke, J.B. Risatti, D.E. Anders, W.L. Watney, K.D. Newell, and A.K. Vuletich

Citation Possible late Middle Ordovician Organic Carbon Isotope Excursion: Evidence from Ordovician oils and hydrocarbon source rocks, Mid-Continent and east-central United States, AAPG Bulletin, v. 71, p. 1342-1354

General summary report Source rock catalog number 110

Locality Data Locality number 23

State Kansas County Rice

Section 2 Township 20S Range 8W

Operator Northern Natural Gas

Well name and number Caldwell #1

Depth 3322 Feet core

Stratigraphic Data

System Ordovician

Formation Simpson

Member shale

TOC and RockEval Data

TOC: 0.29 wt.%

☑ RockEval (Check mark indicates published RockEval data.)

Reference Publication date 1987 Reference number 1

Author 1 last name Hatch Author 1 initials J.R.

Author 2 last name Jacobson Author 2 initials S.R.

Other authors B.J. Witzke, J.B. Risatti, D.E. Anders, W.L. Watney, K.D. Newell, and A.K. Vuletich

Citation Possible late Middle Ordovician Organic Carbon Isotope Excursion: Evidence from Ordovician oils and hydrocarbon source rocks, Mid-Continent and east-central United States, AAPG Bulletin, v. 71, p. 1342-1354

General summary report Source rock catalog number 111

Locality Data

Locality number 23

State Kansas County Rice

Section 2 Township 20S Range 8W

Operator Northern Natural Gas

Well name and number Caldwell #1

Depth 3329 Feet core

Stratigraphic Data

System Ordovician

Formation Simpson

Member shale

TOC and RockEval Data

TOC: 0.68 wt.%

☑ RockEval (Check mark indicates published RockEval data.)

Reference

Publication date 1987 Reference number 1

Author 1 last name Hatch Author 1 initials J.R.

Author 2 last name Jacobson Author 2 initials S.R.

Other authors B.J. Witzke, J.B. Risatti, D.E. Anders, W.L. Watney, K.D. Newell, and A.K. Vuletich

Citation Possible late Middle Ordovician Organic Carbon Isotope Excursion: Evidence from Ordovician oils and hydrocarbon source rocks, Mid-Continent and east-central United States, AAPG Bulletin, v. 71, p. 1342-1354

General summary report Source rock catalog number 112

Locality Data

Locality number 23

State Kansas

County Rice

Section 2 Township 20S Range 8W

Operator Northern Natural Gas

Well name and number Caldwell #1

Depth 3330 Feet core

Stratigraphic Data

System Ordovician

Formation Simpson

Member shale

TOC and RockEval Data

TOC: 1.2 wt.%

☑ RockEval (Check mark indicates published RockEval data.)

Reference

Publication date 1987

Reference number 1

Author 1 last name Hatch

Author 1 initials J.R.

Author 2 last name Jacobson

Author 2 initials S.R.

Other authors B.J. Witzke, J.B. Risatti, D.E. Anders, W.L. Watney, K.D. Newell, and A.K. Vuletich

Citation Possible late Middle Ordovician Organic Carbon Isotope Excursion: Evidence from Ordovician oils and hydrocarbon source rocks, Mid-Continent and east-central United States, AAPG Bulletin, v. 71, p. 1342-1354

General summary report Source rock catalog number 113

Locality Data

Locality number 23

State Kansas

County Rice

Section 2 Township 20S Range 8W

Operator Northern Natural Gas

Well name and number Caldwell #1

Depth 3332 Feet core

Stratigraphic Data

System Ordovician

Formation Simpson

Member shale

TOC and RockEval Data

TOC: 0.13 wt.%

☑ RockEval (Check mark indicates published RockEval data.)

Reference

Publication date 1987

Reference number 1

Author 1 last name Hatch

Author 1 initials J.R.

Author 2 last name Jacobson

Author 2 initials S.R.

Other authors B.J. Witzke, J.B. Risatti, D.E. Anders, W.L. Watney, K.D. Newell, and A.K. Vuletich

Citation Possible late Middle Ordovician Organic Carbon Isotope Excursion: Evidence from Ordovician oils and hydrocarbon source rocks, Mid-Continent and east-central United States, AAPG Bulletin, v. 71, p. 1342-1354

General summary report Source rock catalog number 114

Locality Data

Locality number 23

State Kansas

County Rice

Section 2 Township 20S Range 8W

Operator Northern Natural Gas

Well name and number Caldwell #1

Depth 3333 Feet core

Stratigraphic Data

System Ordovician

Formation Simpson

Member shale

TOC and RockEval Data

TOC: 0.15 wt.%

☑ RockEval (Check mark indicates published RockEval data.)

Reference

Publication date 1987 Reference number 1

Author 1 last name Hatch Author 1 initials J.R.

Author 2 last name Jacobson Author 2 initials S.R.

Other authors B.J. Witzke, J.B. Risatti, D.E. Anders, W.L. Watney, K.D. Newell, and A.K. Vuletich

Citation Possible late Middle Ordovician Organic Carbon Isotope Excursion: Evidence from Ordovician oils and hydrocarbon source rocks, Mid-Continent and east-central United States, AAPG Bulletin, v. 71, p. 1342-1354

General summary report Source rock catalog number 115

Locality Data

Locality number 23

State Kansas County Rice

Section 2 Township 20S Range 8W

Operator Northern Natural Gas

Well name and number Caldwell #1

Depth 3333 Feet core

Stratigraphic Data

System Ordovician

Formation Simpson

Member shale

TOC and RockEval Data

TOC: 0.33 wt.%

☑ RockEval (Check mark indicates published RockEval data.)

Reference

Publication date 1987 Reference number 1

Author 1 last name Hatch Author 1 initials J.R.

Author 2 last name Jacobson Author 2 initials S.R.

Other authors B.J. Witzke, J.B. Risatti, D.E. Anders, W.L. Watney, K.D. Newell, and A.K. Vuletich

Citation Possible late Middle Ordovician Organic Carbon Isotope Excursion: Evidence from Ordovician oils and hydrocarbon source rocks, Mid-Continent and east-central United States, AAPG Bulletin, v. 71, p. 1342-1354

General summary report Source rock catalog number 116

Locality Data
Locality number 23

State Kansas County Rice

Section 2 Township 20S Range 8W

Operator Northern Natural Gas

Well name and number Caldwell #1

Depth 3346 Feet core

Stratigraphic Data

System Ordovician

Formation Simpson

Member shale

TOC and RockEval Data

TOC: 0.77 wt.%

☑ RockEval (Check mark indicates published RockEval data.)

Reference
Publication date 1987 Reference number 1

Author 1 last name Hatch Author 1 initials J.R.

Author 2 last name Jacobson Author 2 initials S.R.

Other authors B.J. Witzke, J.B. Risatti, D.E. Anders, W.L. Watney, K.D. Newell, and A.K. Vuletich

Citation Possible late Middle Ordovician Organic Carbon Isotope Excursion: Evidence from Ordovician oils and hydrocarbon source rocks, Mid-Continent and east-central United States, AAPG Bulletin, v. 71, p. 1342-1354

General summary report Source rock catalog number 117

Locality Data

Locality number 23

State Kansas

County Rice

Section 2 Township 20S Range 8W

Operator Northern Natural Gas

Well name and number Caldwell #1

Depth 3335 Feet core

Stratigraphic Data

System Ordovician

Formation Simpson

Member shale

TOC and RockEval Data

TOC: 0.71 wt.%

☑ RockEval (Check mark indicates published RockEval data.)

Reference

Publication date 1987

Reference number 1

Author 1 last name Hatch

Author 1 initials J.R.

Author 2 last name Jacobson

Author 2 initials S.R.

Other authors B.J. Witzke, J.B. Risatti, D.E. Anders, W.L. Watney, K.D. Newell, and A.K. Vuletich

Citation Possible late Middle Ordovician Organic Carbon Isotope Excursion: Evidence from Ordovician oils and hydrocarbon source rocks, Mid-Continent and east-central United States, AAPG Bulletin, v. 71, p. 1342-1354

General summary report Source rock catalog number 118

Locality Data

Locality number 23

State Kansas

County Rice

Section 2 Township 20S Range 8W

Operator Northern Natural Gas

Well name and number Caldwell #1

Depth 3336 Feet core

Stratigraphic Data

System Ordovician

Formation Simpson

Member shale

TOC and RockEval Data

TOC: 1.1 wt.%

☑ RockEval (Check mark indicates published RockEval data.)

Reference

Publication date 1987

Reference number 1

Author 1 last name Hatch

Author 1 initials J.R.

Author 2 last name Jacobson

Author 2 initials S.R.

Other authors B.J. Witzke, J.B. Risatti, D.E. Anders, W.L. Watney, K.D. Newell, and A.K. Vuletich

Citation Possible late Middle Ordovician Organic Carbon Isotope Excursion: Evidence from Ordovician oils and hydrocarbon source rocks, Mid-Continent and east-central United States, AAPG Bulletin, v. 71, p. 1342-1354

General summary report Source rock catalog number 119

Locality Data

Locality number 23

State Kansas

County Rice

Section 2 Township 20S Range 8W

Operator Northern Natural Gas

Well name and number Caldwell #1

Depth 3338 Feet core

Stratigraphic Data

System Ordovician

Formation Simpson

Member shale

TOC and RockEval Data

TOC: 0.92 wt.%

☑ RockEval (Check mark indicates published RockEval data.)

Reference

Publication date 1987

Reference number 1

Author 1 last name Hatch

Author 1 initials J.R.

Author 2 last name Jacobson

Author 2 initials S.R.

Other authors B.J. Witzke, J.B. Risatti, D.E. Anders, W.L. Watney, K.D. Newell, and A.K. Vuletich

Citation Possible late Middle Ordovician Organic Carbon Isotope Excursion: Evidence from Ordovician oils and hydrocarbon source rocks, Mid-Continent and east-central United States, AAPG Bulletin, v. 71, p. 1342-1354

General summary report Source rock catalog number 120

Locality Data

Locality number 23

State Kansas

County Rice

Section 2 Township 20S Range 8W

Operator Northern Natural Gas

Well name and number Caldwell #1

Depth 3339 Feet core

Stratigraphic Data

System Ordovician

Formation Simpson

Member shale

TOC and RockEval Data

TOC: 0.32 wt.%

☑ RockEval (Check mark indicates published RockEval data.)

Reference

Publication date 1987 Reference number 1

Author 1 last name Hatch

Author 1 initials J.R.

Author 2 last name Jacobson

Author 2 initials S.R.

Other authors B.J. Witzke, J.B. Risatti, D.E. Anders, W.L. Watney, K.D. Newell, and A.K. Vuletich

Citation Possible late Middle Ordovician Organic Carbon Isotope Excursion: Evidence from Ordovician oils and hydrocarbon source rocks, Mid-Continent and east-central United States, AAPG Bulletin, v. 71, p. 1342-1354

General summary report Source rock catalog number 121

Locality Data

Locality number 23

State Kansas County Rice

Section 2 Township 20S Range 8W

Operator Northern Natural Gas

Well name and number Caldwell #1

Depth 3343 Feet core

Stratigraphic Data

System Ordovician

Formation Simpson

Member shale

TOC and RockEval Data

TOC: 0.21 wt.%

☑ RockEval (Check mark indicates published RockEval data.)

Reference

Publication date 1987 Reference number 1

Author 1 last name Hatch Author 1 initials J.R.

Author 2 last name Jacobson Author 2 initials S.R.

Other authors B.J. Witzke, J.B. Risatti, D.E. Anders, W.L. Watney, K.D. Newell, and A.K. Vuletich

Citation Possible late Middle Ordovician Organic Carbon Isotope Excursion: Evidence from Ordovician oils and hydrocarbon source rocks, Mid-Continent and east-central United States, AAPG Bulletin, v. 71, p. 1342-1354

General summary report Source rock catalog number 122

Locality Data

Locality number 23

State Kansas

County Rice

Section 2 Township 20S Range 8W

Operator Northern Natural Gas

Well name and number Caldwell #1

Depth 3345 Feet core

Stratigraphic Data

System Ordovician

Formation Simpson

Member shale

TOC and RockEval Data

TOC: 0.65 wt.%

☑ RockEval (Check mark indicates published RockEval data.)

Reference

Publication date 1987

Reference number 1

Author 1 last name Hatch

Author 1 initials J.R.

Author 2 last name Jacobson

Author 2 initials S.R.

Other authors B.J. Witzke, J.B. Risatti, D.E. Anders, W.L. Watney, K.D. Newell, and A.K. Vuletich

Citation Possible late Middle Ordovician Organic Carbon Isotope Excursion: Evidence from Ordovician oils and hydrocarbon source rocks, Mid-Continent and east-central United States, AAPG Bulletin, v. 71, p. 1342-1354

General summary report Source rock catalog number 123

Locality Data

Locality number 23

State Kansas County Rice

Section 2 Township 20S Range 8W

Operator Northern Natural Gas

Well name and number Caldwell #1

Depth 3347 Feet core

Stratigraphic Data

System Ordovician

Formation Simpson

Member shale

TOC and RockEval Data

TOC: 0.18 wt.%

☑ RockEval (Check mark indicates published RockEval data.)

Reference

Publication date 1987 Reference number 1

Author 1 last name Hatch Author 1 initials J.R.

Author 2 last name Jacobson Author 2 initials S.R.

Other authors B.J. Witzke, J.B. Risatti, D.E. Anders, W.L. Watney, K.D. Newell, and A.K. Vuletich

Citation Possible late Middle Ordovician Organic Carbon Isotope Excursion: Evidence from Ordovician oils and hydrocarbon source rocks, Mid-Continent and east-central United States, AAPG Bulletin, v. 71, p. 1342-1354

General summary report Source rock catalog number 124

Locality Data Locality number 6

State Iowa County Plymouth

Section 2 Township 92N Range 45W

Operator Iowa Geol. Survey

Well name and number Camp Quest #1

Depth 606.3 Feet core

Stratigraphic Data

System Ordovician

Formation Decorah

Member

TOC and RockEval Data

TOC: 0.4 wt.%

☑ RockEval (Check mark indicates published RockEval data.)

Reference Publication date 1988 Reference number 3

Author 1 last name Jacobson Author 1 initials S.R.

Author 2 last name Hatch Author 2 initials J.R.

Other authors S.C. Teerman, and Rosemary Askin

Citation Middle Ordovician Organic Matter Assemblages and their effect on Ordovician-derived oils, AAPG Bulletin, v. 72, p. 1090-1100

General summary report Source rock catalog number 125

Locality Data

Locality number 6

State Iowa

County Plymouth

Section 2 Township 92N Range 45W

Operator Iowa Geol. Survey

Well name and number Camp Quest #1

Depth 706.3 Feet core

Stratigraphic Data

System Ordovician

Formation Platteville

Member shale

TOC and RockEval Data

TOC: 1 wt.%

☑ RockEval (Check mark indicates published RockEval data.)

Reference

Publication date 1988 Reference number 3

Author 1 last name Jacobson Author 1 initials S.R.

Author 2 last name Hatch Author 2 initials J.R.

Other authors S.C. Teerman, and Rosemary Askin

Citation Middle Ordovician Organic Matter Assemblages and their effect on Ordovician-derived oils, AAPG Bulletin, v. 72, p. 1090-1100

General summary report Source rock catalog number 126

Locality Data Locality number 6

State Iowa County Plymouth

Section 2 Township 92N Range 45W

Operator Iowa Geol. Survey

Well name and number Camp Quest #1

Depth 714.6 Feet core

Stratigraphic Data

System Ordovician

Formation Platteville

Member limestone

TOC and RockEval Data

TOC: 1.1 wt.%

☑ RockEval (Check mark indicates published RockEval data.)

Reference Publication date 1988 Reference number 3

Author 1 last name Jacobson Author 1 initials S.R.

Author 2 last name Hatch Author 2 initials J.R.

Other authors S.C. Teerman, and Rosemary Askin

Citation Middle Ordovician Organic Matter Assemblages and their effect on Ordovician-derived oils, AAPG Bulletin, v. 72, p. 1090-1100

General summary report Source rock catalog number 127

Locality Data

Locality number 6

State Iowa

County Plymouth

Section 2 Township 92N Range 45W

Operator Iowa Geol. Survey

Well name and number Camp Quest #1

Depth 717.5 Feet core

Stratigraphic Data

System Ordovician

Formation Glenwood

Member

TOC and RockEval Data

TOC: 5.6 wt.%

☑ RockEval (Check mark indicates published RockEval data.)

Reference

Publication date 1988 Reference number 3

Author 1 last name Jacobson Author 1 initials S.R.

Author 2 last name Hatch Author 2 initials J.R.

Other authors S.C. Teerman, and Rosemary Askin

Citation Middle Ordovician Organic Matter Assemblages and their effect on Ordovician-derived oils, AAPG Bulletin, v. 72, p. 1090-1100

General summary report Source rock catalog number 128

Locality Data

Locality number 6

State Iowa

County Plymouth

Section 2 Township 92N Range 45W

Operator Iowa Geol. Survey

Well name and number Camp Quest #1

Depth 720.5 Feet core

Stratigraphic Data

System Ordovician

Formation Glenwood

Member

TOC and RockEval Data

TOC: 0.7 wt.%

☑ RockEval (Check mark indicates published RockEval data.)

Reference

Publication date 1988

Reference number 3

Author 1 last name Jacobson

Author 1 initials S.R.

Author 2 last name Hatch

Author 2 initials J.R.

Other authors S.C. Teerman, and Rosemary Askin

Citation Middle Ordovician Organic Matter Assemblages and their effect on Ordovician-derived oils, AAPG Bulletin, v. 72, p. 1090-1100

General summary report Source rock catalog number 129

Locality Data

Locality number 6

State Iowa

County Plymouth

Section 2 Township 92N Range 45W

Operator Iowa Geol. Survey

Well name and number Camp Quest #1

Depth 746.9 Feet core

Stratigraphic Data

System Ordovician

Formation Glenwood

Member

TOC and RockEval Data

TOC: 0.4 wt.%

☑ RockEval (Check mark indicates published RockEval data.)

Reference

Publication date 1988

Reference number 3

Author 1 last name Jacobson

Author 1 initials S.R.

Author 2 last name Hatch

Author 2 initials J.R.

Other authors S.C. Teerman, and Rosemary Askin

Citation Middle Ordovician Organic Matter Assemblages and their effect on Ordovician-derived oils, AAPG Bulletin, v. 72, p. 1090-1100

General summary report

Source rock catalog number 130

Locality Data

Locality number 6

State Iowa

County Plymouth

Section 2 Township 92N Range 45W

Operator Iowa Geol. Survey

Well name and number Camp Quest #1

Depth 762.2 Feet core

Stratigraphic Data

System Ordovician

Formation St. Peter

Member brown shale

TOC and RockEval Data

TOC: 2.9 wt.%

☑ RockEval (Check mark indicates published RockEval data.)

Reference

Publication date 1988

Reference number 3

Author 1 last name Jacobson

Author 1 initials S.R.

Author 2 last name Hatch

Author 2 initials J.R.

Other authors S.C. Teerman, and Rosemary Askin

Citation Middle Ordovician Organic Matter Assemblages and their effect on Ordovician-derived oils, AAPG Bulletin, v. 72, p. 1090-1100

General summary report Source rock catalog number 131

Locality Data

Locality number 6

State Iowa

County Plymouth

Section 2 Township 92N Range 45W

Operator Iowa Geol. Survey

Well name and number Camp Quest #1

Depth 762.8 Feet core

Stratigraphic Data

System Ordovician

Formation St. Peter

Member brown shale

TOC and RockEval Data

TOC: 9.3 wt.%

☑ RockEval (Check mark indicates published RockEval data.)

Reference

Publication date 1988 Reference number 3

Author 1 last name Jacobson Author 1 initials S.R.

Author 2 last name Hatch Author 2 initials J.R.

Other authors S.C. Teerman, and Rosemary Askin

Citation Middle Ordovician Organic Matter Assemblages and their effect on Ordovician-derived oils, AAPG Bulletin, v. 72, p. 1090-1100

General summary report Source rock catalog number 132

Locality Data

Locality number 6

State Iowa

County Plymouth

Section 2 Township 92N Range 45W

Operator Iowa Geol. Survey

Well name and number Camp Quest #1

Depth 776.2 Feet core

Stratigraphic Data

System Ordovician

Formation St. Peter

Member brown shale

TOC and RockEval Data

TOC: 1.2 wt.%

☑ RockEval (Check mark indicates published RockEval data.)

Reference

Publication date 1988 Reference number 3

Author 1 last name Jacobson Author 1 initials S.R.

Author 2 last name Hatch Author 2 initials J.R.

Other authors S.C. Teerman, and Rosemary Askin

Citation Middle Ordovician Organic Matter Assemblages and their effect on Ordovician-derived oils, AAPG Bulletin, v. 72, p. 1090-1100