NIPER/BDM-0323

Status Report

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

Work Performed under the

Management and Operating Contract for the Department of Energy's National Oil and Related Programs

by

T. K. Reeves, Michael Spakiewicz, Genliang Guo, Bijon Sharma, Len Volk,
Sanjay Banerjee, Eugene Safley, John Jordan, William Johnson, Jill Fite, and Steve George
BDM Petroleum Technologies under contract to BDM-Oklahoma, Inc.

Colin Barker and Richard Erickson
University of Tulsa

and

Rhonda Lindsey
National Petroleum Technology Office, Department of Energy

September 1997

Work Performed Under Contract No.
DE-AC22-94PC91008

Prepared for
U.S. Department of Energy
National Petroleum Technology Office

NIPER/BDM-0323
September 1997

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

Work Performed under the

Management and Operating Contract for the Department of Energy's National Oil and Related Programs

Work Performed Under Contract No.
DE-AC22-94PC91008

Prepared for
U.S. Department of Energy
National Petroleum Technology Office

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, expressed or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

BDM-Oklahoma, Inc.
P.O. Box 2565
Bartlesville, Oklahoma 74005

Table of Contents

1.0 INTRODUCTION 1

2.0 GEOLOGIC SETTING 2

2.1 RIFT SEDIMENT DEVELOPMENT 2

2.2 TOTAL ORGANIC CARBON TESTING 5

2.3 SHIFT IN FOCUS TO PALEOZOIC SECTION 6

2.4 OZARK PLATEAU REGION FIELD TRIP 9

2.5 STRATIGRAPHY AND STRATIGRAPHIC/STRUCTURAL TRAPS IN THE SOUTH-CENTRAL MID-CONTINENT REGION 10

2.5.1 Truncation and Onlap Traps 10

2.5.2 Secondary Porosity Traps 12

2.5.3 Stratigraphic Traps 12

2.5.4 Fracture Traps 13

2.5.5 Future Targets 13

3.0 GEOLOGIC RESEARCH 13

3.1 GEOCHEMICAL AND HYDRODYNAMIC TECHNIQUES 13

3.1.1 Introduction 13

3.1.2 Project Description 14

3.1.3 Project Status 14

3.1.4 Planned Activities 14

3.1.5 Summary 14

3.2 MODELING OF BASIN HISTORY, FLUID DYNAMICS, AND HYDROCARBON GENERATION 15

3.2.1 Introduction 15

3.2.2 Project Description 15

3.2.3 Project Status 15

3.2.4 Planned Activities 16

3.2.5 Summary 17

3.3 POSSIBLE PETROLEUM GENERATION AND OCCURRENCE IN THE PRE-MESOZOIC PARTS OF THE FOREST CITY BASIN 17

3.3.1 Introduction 17

3.3.2 Project Description 18

3.3.3 Project Status 18
3.3.4 Planned Activities 20
3.3.5 Summary 20
3.4 REMOTE SENSING DATA AND SURFACE FRACTURE ANALYSIS 20
3.4.1 Introduction 20
3.4.2 Project Description 20
3.4.3 Project Status 21
3.4.3.1 FRAC-EXPLORE 21
3.4.3.2 Completion of an Extensive Statistical Analysis of Surface Lineaments and Fractures for Exploration 21
3.4.3.3 Presentations at Professional Meetings 22
3.4.4 Planned Activities 23
3.4.5 Summary 23
3.5. EVALUATION OF OIL AND GAS POTENTIAL 23
3.5.1 Introduction 23
3.5.2 Project Description 23
3.5.3 Project Status 24
3.5.3.1 Study of Lineaments and Fractures 24
3.5.3.2 Presentations at Professional Meetings 25
3.5.4 Planned Activities 25
3.5.5 Summary 26
3.6 INTEGRATION AND PROCESSING OF EXISTING WELL DATA 26
3.6.1 Introduction 26
3.6.2 Project Description 26
3.6.3 Project Status 26
3.6.4 Planned Activities 27
3.6.5 Summary 27
3.7 3D SEISMIC DATA INTERPRETATION 27
3.7.1 Introduction 27
3.7.2 Project Description 28
3.7.3 Project Status 28
3.7.3.1 Mapping of Stratigraphic Features 30
3.7.3.2 Detection and Mapping of Small Faults 30
3.7.3.3 Tracking a Thin Gas Sand in Osage County 31
3.7.4 Planned Activities 31
3.7.5 Summary 32
3.8 SURFACE GEOCHEMISTRY 32

3.8.1 Introduction 32
3.8.2 Project Description 33
3.8.3 Project Status 33
3.8.4 Planned Activities 34
3.8.5 Summary 34
3.9 REFERENCES 34

List of Figures

2—1 Cambrian-Ordovician Isopach Map of the Mid-Continent Region 6
2—2 Ordovician-Silurian Isopach Map of the Mid-Continent Region 8
2—3 Devonian Isopach Map of the Mid-Continent Region 8
2—4 Field Sample Locations in the Ozark Plateau Region 9

Abstract

There has been a substantial decline in both exploratory drilling and in seismic field crew activity in the United States over the last decade, since the major decline in the price of oil in the 1980s. To reverse this trend, the U.S. DOE is attempting to encourage hydrocarbon exploration activities in some of the unexplored and underexplored regions of the United States. This goal is being accomplished by conducting broad regional reviews of potentially prospective areas within the lower 48 states.

Early studies of the Mid-Continent Rift (MCR) system suggested that deep sediments in the South-Central Mid-Continent region could contain substantial quantities of oil that had migrated from the rift to concentrate in reservoirs in Paleozoic sediments. Subsequent work revealed that information on the organic content of the Precambrain sediments within the southern portion of the rift system is sparse, and that what information is available is disappointing. The few samples that have been studied show steadily decreasing amounts of organic material in the rift progressing from north to south.

It was also found that the tectonic history of the MCR did not favor the release of hydrocarbons. If hydrocarbons were generated in the rift sediments, they are likely to be widely dispersed in many small uncommercial traps in the Precambrian.

During the early phases of the study, a string of Ordovician reservoirs was observed along the east side of the Nemaha Uplift, running through the study area. Attention was turned to this resource. The focus of the study shifted from a concentration on Precambrian sources to possible local-sourcing for the Ordovician oil, or to origins further afield to the southeast in the Ozark region.

This document reports on the status of this research and the techniques being used.

1.0 INTRODUCTION

Following the decline of oil prices in the mid-1980s, both exploratory drilling and field crews for seismic work dropped off in the United States. The U.S. Department of Energy (DOE) 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 with a review of the hydrocarbon potential of the Black Mesa Basin in northeastern Arizona. Results of this analysis were presented in Reeves et al (1996) and Sharma et al (1996). This assessment was followed by work in the South-Central Mid-Continent, in deeper portions of the Forest City Basin, which is productive in the shallow section but underexplored in the deep formations, and in the Salina Basin, 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 then-current 1993 U.S. Geological Survey (USGS) estimates for undiscovered recoverable resources in the lower 48 states showed reasonably high values in this region. Also, the area was not currently under study by other federal and state agencies, an important factor, since the Exploration and Drilling (E&D) Research Program was designed to avoid overlap with any federal or state research programs.

It was recognized that the study area lay at the southern end of the Mid-Continent Rift (MCR) system 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. It was felt that this rift could have been the source of oil that was produced during the 1930s–1950s from Precambrian sediments which were drilled into a series of Precambrian monadnocks that project into the Paleozoic sequence in eastern Kansas.

Early analysis of the Precambrian potential of the MCR area was promising. Susan Landon, a Mid-Continent specialist working for Thomasson Partner Associates, Denver, Colorado, and editor of AAPG Memoir 59, "Interior Rift Basins," cited (personal communication 1994) estimates of 20 to 30 billion bbl in play in the rift system as a whole, with individual field sizes ranging from 500 million to 3 billion bbl, based on the type of deposits involved. This type of information encouraged further study.

As work on the project progressed, it became obvious that data from drilling done along the MCR system in the 1970s and 1980s, plus some earlier wells that took samples of the shallowest portion of the rift sequence, fell into a pattern of steadily decreasing organic contents within the rift sediments from high values in Minnesota to lower values in Iowa and still lower values in Kansas. The decrease was steady, progressing from north to south. Some of the samples from

Kansas had 0% organics in the apparent equivalent of the best potential source-bed shales from 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 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. Volcanic activity along the rift margins tends to produce a complex, interlocking series of seals.

Individual lake 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 rift lake sequences are ruptured, with the hydrocarbon accumulations migrating to a single, large reservoir in younger, porous reservoirs.

The Mid-Continent region lacks the widespread 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 (Rauzi 1990; Reeves 1996; Uphoff 1997). The combination of low organics and a lack of a large-scale penetrative or rupturing orogenic event in the South-Central Mid-Continent seemed to greatly reduce the chances of finding deeper hydrocarbons in the study area.

Despite these problems, it was recognized during the study that Ordovician-age oil has been found widely distributed east of the Nemaha Uplift in Kansas and southeastern Nebraska. Alternative sources were sought for this oil, with an eastern or southeastern source in the Ozark trough area considered a likely possibility.

This Status Report describes the change of focus in the project, and describes the diversity of approaches that are being used in the multidisciplinary study. Section 2 focuses on the geology of the region and the search for source beds and migration paths in the South-Central Mid-Continent, whereas Section 3 describes some of the innovative and interactive techniques being used for the study.

2.0 GEOLOGIC SETTING

2.1 RIFT SEDIMENT DEVELOPMENT

Organic-rich sediments tend to accumulate in a large number of small, very well sealed pockets within the rift sediment package. They generally mark the location of lake or inlet/estuary deposits, with volcanic sequences surrounding the best source beds. If significant quantities of

hydrocarbons were generated in localized deposits of organic-rich sediments in the Mid-Continent Rift, a means is still necessary to free this oil from the typically well-sealed pockets or pods.

The down-dropped portions of rifts are generally typified by long, narrow water bodies, such as a gulf in a marine environment, like the Gulf of Suez, or a string of lakes, if on a continent. On the scale of a major rift, each individual lake is a small, very localized feature and relatively 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 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, such as major crust-penetrative faults shift and the rift realigns and adjusts to new stress states. Most major lakes are ultimately inundated by massive lava flows as the blocks move and sedimentation ends. When a new section along the trend drops, the former lake valleys frequently become an area where volcanic activity overwhelms clastic sedimentation. 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 the others. Extensive associated volcanism produces a complex series of seals around the lake deposits. Numerous dikes generally flank the former lake beds 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 above it.

The rift system surrounding the western and southern margins of the Arabian peninsula and continuing into Africa is a good example of an area where many reservoirs have remained tightly sealed during a highly-active tectonic history. A pattern of organic-rich source-bed shales closely associated with coarse-grained reservoirs surrounded by dikes and multiple layers of lava tend to lead to numerous isolated tightly encapsulated reservoirs. Faulting has had relatively little effect on the encapsulated 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.

Contemporaneous volcanism produces the original seals and can play a role in the maturation of the sediments. It is a second, later period of volcanism that, if sufficiently widespread, can cut through all the complex seals. This widespread volcanism punches 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 and continued into the historic period. Intrusives are widespread across the entire area, having swept the region in repeated waves.

This pattern would explain the migration history found at the 1994 BHP (Broken Hill Petroleum) well in southern Utah (Uphoff 1997). BHP reported that oil had migrated from the Precambrian Chuar formation into the Cambrian Tapeats sandstone during the Cretaceous, not earlier. The late Mesozoic plugs and dikes forced their way up through the Chuar section punching holes in seal after seal and finally rupturing the capsules that had contained the Chuar oil since late Proterozoic time. Volcanic activity continued in the region through the Tertiary period and into the Recent period, potentially allowing additional oil to migrate from numerous smaller Chuar traps into larger traps along monoclines or other deep porous structures. This pattern would 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 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 Humbolt system could allow quantities of oil to leak locally from a few reservoirs that were cut directly and breached, while many other compartments near to and away from the fault would still be intact.

Both the Chuar and the Mid-Continent Rift sediments could have generated significant quantities of oil which may 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 over-cooked, 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. Faulting or minor volcanic activity will not breach many of the seals. Widespread volcanism can 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 flanking volcanoes. When buried beneath several thousand feet of sediments, a slight misdirection of the drill bit could completely miss the lake (or oil pocket). In a single compartment (single ancient lake), reserves may be too limited to be of commercial interest depending on depth, cost of exploration, etc. For this reason, it makes sense to prospect for areas where individual reservoirs in the Proterozoic Rift sequence have been breached and the reserves from several pockets have combined in larger accumulations. The Mid-Continent region has been cut by occasional volcanic activity, but it is questionable if there has been sufficient activity to breach many of the Proterozoic compartments along the rift zone.

2.2 TOTAL ORGANIC CARBON TESTING

Detailed study and recent drilling results have shown that the southern end of the MCR appears to have much less potential than the northern section. While the Precambrian Nonesuch shale in the Mid-Continent, with its 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, while the Nonesuch formation at White Pine, Michigan, contained 2.8% or less. In Rice County, Minnesota, of 25 samples tested from the deep Lonsdale exploratory test, the richest sample contained 1.77% TOC, with all of the other samples ranking much lower. Testing in Iowa at the Eischeid deep well revealed a maximum of 1.4% TOC, from a single sample, and three deep basement wells in Kansas tested at 0.5% TOC or less. Some Kansas samples were totally oxidized. These figures represent an unvarying trend, with decreasing values in TOC toward the southern end of the MCR. However, a word of caution is in order. The number of sample points in the MCR is very small, so the data can be misleading. Geologic conditions and depositional environments vary rapidly in rift settings. One or two additional wells, just one location away from the existing tests, or a slight deviation of the bit in the existing holes might have reached zones with much higher organic contents. In the case of the Chuar exposures in Arizona, sample collectors have been able to pick and choose their locations, selecting only the blackest and best-looking exposures to test. In the case of a well and core, the bit could be just to the side of better material, or the core may have been taken 50 ft too soon. There may still be some hope for good source material in the MCR, but the limited testing to date has not been encouraging.

2.3 SHIFT IN FOCUS TO PALEOZOIC SECTION

As the apparent prospects for Precambrian-sourced oil from the MCR decreased in the study area, a more careful look was taken at the structural setting of the Paleozoic section across the region. Original attention had focused on the Upper Ordovician–Silurian-age North Kansas Basin and the Devonian-age Iowa Basin. Little attention had been paid to the earliest Paleozoic structural setting that had prevailed during the Cambrian and Lower Ordovician. In broad terms, it had been assumed that the region was essentially flat, with occasional monadnocks projecting above an essentially featureless plain.

Figure 2–1 is a greatly simplified regional isopach of the Cambrian–Lower Ordovician section, showing that the South-Central Mid-Continent region generally sloped gradually and relatively uniformly from the Trans-Continental Arch (running from the Black Mesa region through Colorado toward Lake Superior), through Kansas and Oklahoma, to southeastern Missouri. As the Ozark trough (following the general trend of the Reelfoot Rift, along the modern Mississippi valley) was approached, water depths and sediment accumulation increased abruptly. Most Cambrian and Lower Ordovician sedimentary sequences thicken from feather edges in Kansas or Oklahoma to the southeast, then begin to thicken dramatically near the Missouri-Arkansas-Tennessee border.

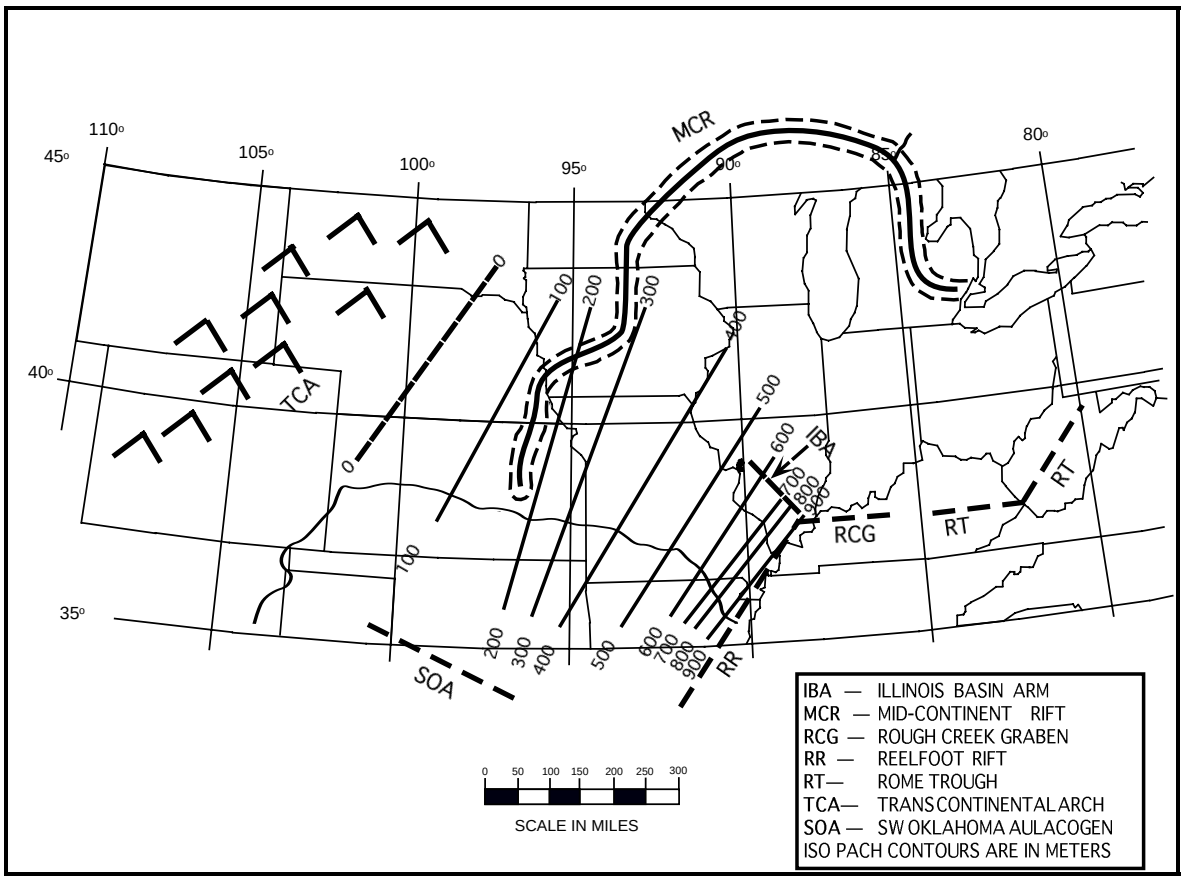

Figure 2–1 Cambrian-Ordovician Isopach Map of the Mid-Continent Region

Ozark trough sediments accumulated above an already thick rift sequence. The Reelfoot feature is generally believed to have opened at some time between 600 and 500 Ma, and was most active in 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. If hydrocarbons did form in this region, the logical place for them to migrate would be updip, to the northwest, toward the study area in the Forest City-Salina Basin region. Continuity of sedimentation did exist between the study area and the Ozark region during these early millennia of the Paleozoic. In recognition of this, the target of the program has shifted from looking at the MCR Proterozoic sediments to attempting to document depositional environments, lithologies, paleogeochemistry, hydrodynamics, and possibilities for long-range migration across Missouri, into Kansas, Oklahoma, Nebraska, and Iowa.

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. Detailed migration patterns would have been highly complicated, but the overall trend would have been to the northwest.

This type of early sourcing, maturation, and migration could be the source of 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 for the South-Central Mid-Continent region changed significantly during the Upper Ordovician–Silurian (Figure 2–2) with the crust at the southern end of the ancient MCR subsiding, forming the North Kansas Basin. Most of the Missouri and Arkansas terrain was positive at this time, and the quick, direct migration pathway from the Ozark trough to Kansas would have been mostly eliminated.

During the Devonian (Figure 2–3), the center of deposition shifted to the northeast, as another crustal section along the MCR trend subsided, this time in Iowa. The Missouri-Arkansas area remained relatively positive at this time, again with no direct migration route from the trough to Kansas.

During Mississippian time, active tectonism fundamentally changed the picture, with uplifts beginning in the Ozark area and along the Nemaha trend.

The work on the Lowermost Paleozoic section began with a field trip to sample some of the exposures along the potential migration path through Missouri.

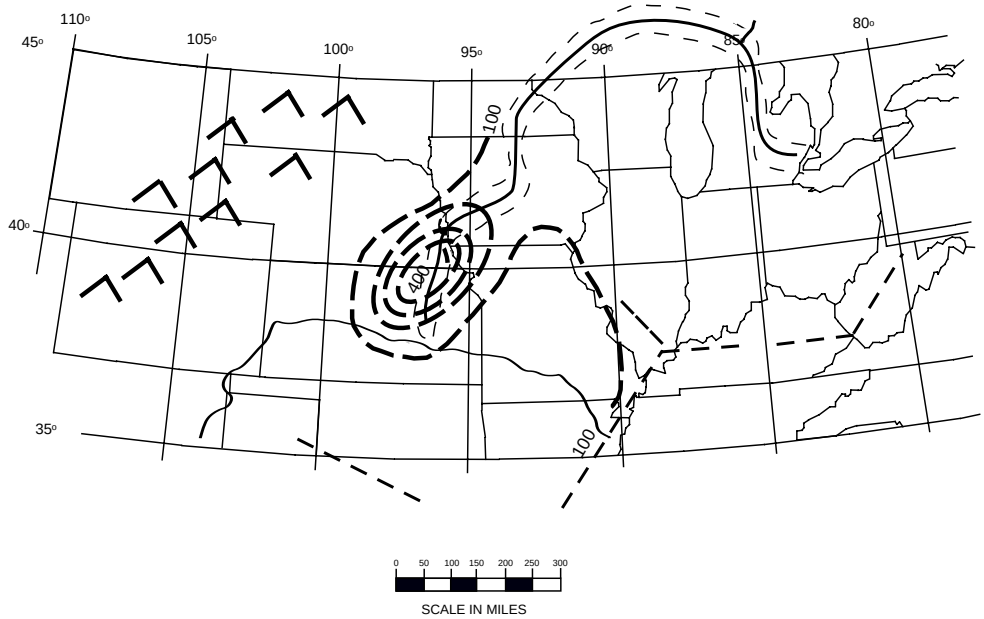

Figure 2–2 Ordovician-Silurian Isopach Map of the Mid-Continent Region

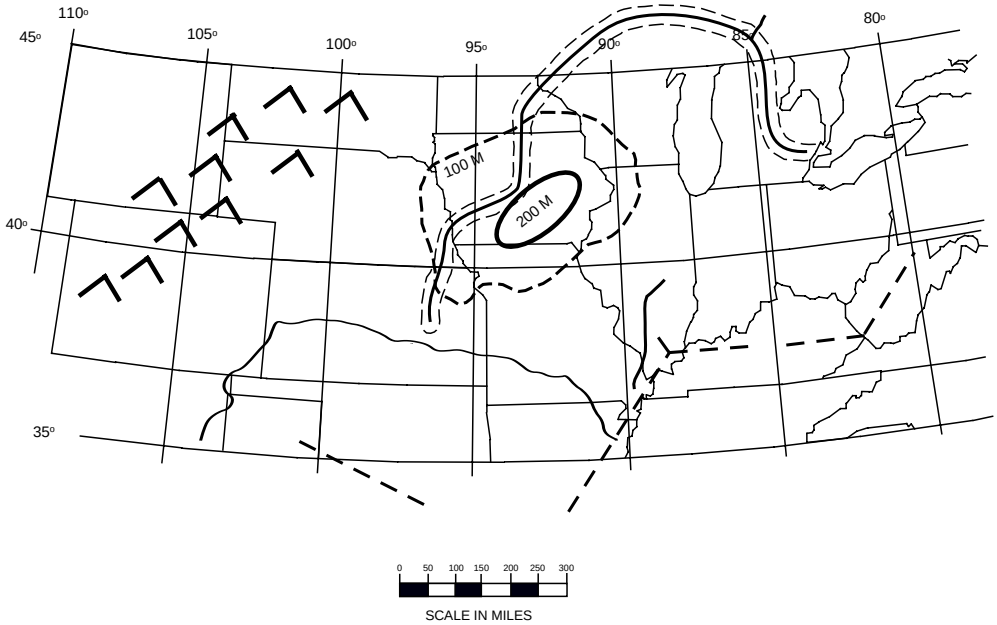

Figure 2–3 Devonian Isopach Map of the Mid-Continent Region Showing Influence of MCR in Iowa and Reelfoot Rift

2.4 OZARK PLATEAU REGION FIELD TRIP

A scouting trip to the Ozark Plateau region of Missouri was completed in June 1997. The Lower Paleozoic stratigraphic section was investigated to determine the possibility of collecting detailed, highly specific data for computerized basin modeling. Plans were made with the University of Minnesota for basin modeling studies of the South-Central Mid-Continent region.

The first trip objective was a field evaluation and lithofacies investigation for possible source and reservoir rocks flanking the Ozark Uplift. Samples were collected for petrographic and geochemical analysis in conjunction with the stratigraphic field assessment of the possible regional migration routes.

Scouting trip locations are illustrated in Figure 2–4. The predominantly carbonate stratigraphic intervals investigated included the Upper Cambrian, the Lower and Upper Ordovician, and the Lower Mississippian. At each outcrop, the depositional facies were determined, and organic-rich or potentially organic-rich rocks were sampled. The objective of the sampling was to look for fossiliferous and algal carbonates, and 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 studies. Some of these samples will be used for further geochemical analysis.

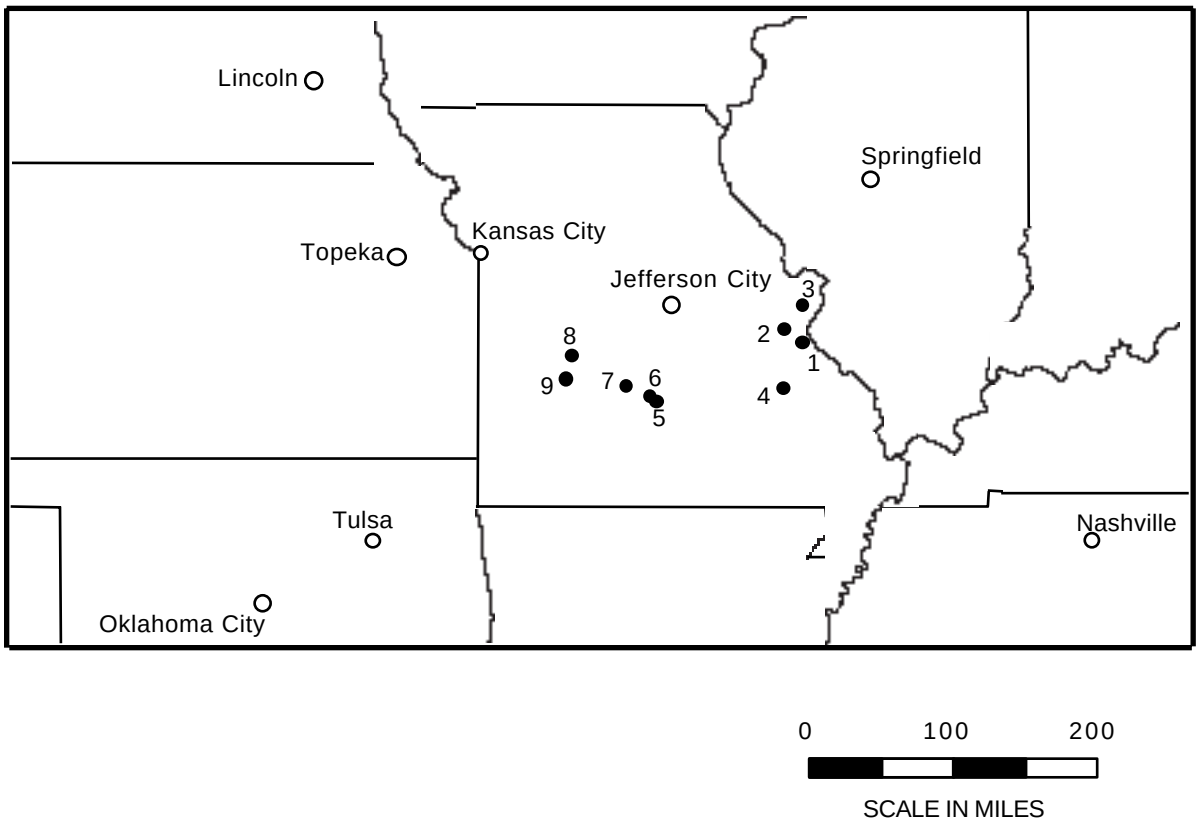

Figure 2–4 Field Sample Locations in the Ozark Plateau Region

A data collection trip to the Missouri Geological Survey in Rolla, Missouri, followed the scouting trip. Stratigraphic, well log, and geochemical data were collected for northwestern Missouri. This information is being compiled for use in the basin modeling program at the University of Minnesota.

A future trip is planned to the Kansas Geological Survey for a similar collection of stratigraphic, well log, and geochemical data in that state, as well as core samples for petrographic and geochemical analysis. A second trip to the Missouri Geological Survey will be made to collect additional core data. The core sampling objective is to correlate geochemical signatures identified in the subsurface to specific outcrop areas around the Ozark Uplift.

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

2.5 STRATIGRAPHY AND STRATIGRAPHIC/STRUCTURAL TRAPS IN THE SOUTH-CENTRAL MID-CONTINENT REGION

The recent focus for stratigraphic studies has been recognizing stratigraphic and structural traps in the South-Central Mid-Continent region. Multiple long-term carbonate cycles with minor shale and sandstone interruptions characterize the Lower Paleozoic stratigraphy in the South-Central Mid-Continent.

These carbonate cycles are directly related to Sloss (1963) cratonic sequences. In general, the sequences have widespread basal sands followed by thick carbonate successions with minor shale and sandstone intervals. Potential stratigraphic and structural traps have been considered based on the known stratigraphic relationships 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. Trap types include:

- Truncation and onlap traps
- Secondary porosity (erosional) traps
- Stratigraphic (depositional) traps
- Fracture traps

2.5.1 Truncation and Onlap Traps

Onlap traps are associated with paleotopographic relief features. The Trans-Continental Arch, extending from Minnesota, through Colorado, to the Four Corners region, was emergent, a positive structural feature throughout the Lower Paleozoic, acting as a western boundary for

deposition within the Mid-Continent region. Paleozoic formations successively onlapped the Trans-Continental Arch at various levels as sea level fluctuated during the Lower Paleozoic, only breaching low points along this structural high for short periods of time.

The Precambrian hills projected as much as 2,000 ft above the gently rolling regional surface (Bunker et al. 1988). Some of the taller topographic highs were not completely buried until Silurian time, and in a few cases, even later. Small-scale onlap occurred around each of these basement irregularities.

Many of these monadnock features in Kansas are associated with magnetic anomalies, possibly reflecting topographic highs related to ancient igneous or metamorphic activity. Magnetic anomalies can be seen in the present day Forest City Basin, along the Nemaha Uplift, following the disturbed rift trend of the Mid-Continent Rift system, and in the central Salina Basin.

Many activities, including slight folding or fault block movements, small-scale eustatic sea level retreats (and associated erosion), or other minor tectonic movements can generate widespread truncation traps on surfaces of very low relief. In general, during the early Paleozoic, the South-Central Mid-Continent region was precisely this type of depo-surface, where slight uplift pulses or local undulations would cause widespread erosion or alterations in depositional patterns.

A series of positive features, some local, others widespread, began to develop on the southern margin of the North American continent as early as late Ordovician time, producing numerous truncation-type traps around their flanks. Three of the most significant of these positive features include the:

- Central Kansas Uplift–Cambridge arch complex (an ancient positive trend that apparently influenced thinning of sediments as early as Cambrian through Upper Ordovician time, then rose significantly, becoming emergent during the Mississippian)
- Ozark Dome (a minor uplift in the late Ordovician, with slight reactivation during the Devonian, and significant reactivation as the Ozark Uplift during the Mississippian)
- Nemaha Uplift (a Mississippian structure)

These three major structural elements dramatically altered the depositional patterns in the Mid-Continent region as they rose, eroded, and were reactivated.

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 Humbolt Fault system. Stratigraphic relationships along the subcrop beneath the erosional surfaces generated during uplifts and erosion has to be inspected for possible truncation traps.

2.5.2 Secondary Porosity Traps

Frequently found along areas of truncation are bands of secondary porosity development, which form as a result of diagenetic activity. It is especially common, due to dissolution, in carbonate environments which have been subaerially exposed. The various episodes of Lower Paleozoic erosion may have created numerous significant secondary porosity reservoirs in the deep section around the various structures on the southern margin of the Paleozoic continent.

Several widespread unconformities/disconformities have been recorded in the Lower Paleozoic section in the South-Central Mid-Continent region. The primary regional erosion surfaces (Precambrian through Mississippian) occur:

- At the top of the Precambrian (major)
- Between Lower and Middle Ordovician (large)
- Between the Middle and Upper Ordovician (local, in Missouri)
- Between the Ordovician and Silurian (minor)
- At the end of the Silurian (major)
- At the end of the Devonian (variable)
- At the end of the Mississippian (variable, generally small)

Widespread zones of secondary porosity could have formed during any of these erosive periods across the existing carbonate shelf deposits. The Silurian-age Hunton Group in Oklahoma is one example of a prolific secondary porosity reservoir (Fritz and Medlock 1995). Secondary-porosity reservoirs can be isolated, local features or quite widespread on regional karst surfaces. Therefore, erosional surfaces and stratal relationships above and below require individual consideration when mapping and prospecting for secondary porosity zones.

2.5.3 Stratigraphic Traps

Stratigraphic (depositional) traps have considerable reservoir potential in the South-Central Mid-Continent. Throughout the Lower Paleozoic, organic and inorganic carbonate buildups were common on the gently dipping carbonate shelf. Inorganic buildups include oolitic, coquinoidal, and calcareous fragmentary sands. Reefs, most commonly recognized in the Silurian, and bryozoan-mud mounds, characteristic of the Mississippian, are examples of types of organic buildup in the lower Paleozoic. Reefing is present in the westernmost portions of the Illinois Basin, along the fringe of the Ozark Uplift. Similar inorganic buildups and reef growths could flank many of the other paleotopographic highs in the South-Central Mid-Continent region.

2.5.4 Fracture Traps

Extensive fracture systems have developed in the South-Central Mid-Continent region along and around the various structures and uplifts. The best developed of these are found in association with the Nemaha Uplift/Humbolt Fault system, the Mississippian to Pennsylvanian tectonic feature that separate the present day Forest City and Salina Basins. Fracture systems can affect oil production in two main ways. They can produce ready migration pathways, often allowing migration through otherwise effective seals. In addition, they can produce zones for in-situ oil accumulation within otherwise tight reservoirs, such as shales. Many producing fields at a variety of depths closely border the Nemaha Uplift/Humbolt Fault system. Fractures may have allowed vertical migration of hydrocarbons from many small reservoirs into larger, more economical accumulations in this region. Fracture zones are prime targets for fracture migration studies and should also be analyzed for reservoir potential.

2.5.5 Future Targets

Additional areas with reservoir potential should become evident as more stratigraphic information becomes available for the South-Central Mid-Continent. Because the paleotopography in this region was typified by relatively low relief during much of the Lower Paleozoic, each slight uplift or sag dramatically altered the local lithologies and depositional style. Regional migration pathways also varied dramatically through time. One of the major foci of the continuing project work will be to determine the small-scale alterations in the southern Mid-Continent basin morphology and the stratigraphic consequences during the Lower Paleozoic.

3.0 GEOLOGIC RESEARCH

3.1 GEOCHEMICAL AND HYDRODYNAMIC TECHNIQUES

3.1.1 Introduction

Geochemical studies form an important part of the research in the DOE basin studies and exploration methodologies program. This portion of the work focuses on the use of geochemical exploration techniques to trace concentrations of certain hydrocarbons dissolved in formation brines. A significant improvement in the reliability of these methodologies should be achievable by integrating geochemical methods with the hydrogeologic identification of the stratigraphic fluid-flow units and the hydrodynamics of the flow paths where the geochemical processes take place.

The geochemical brine-analysis exploration methodology is based on tracking the distribution and concentration of highly soluble hydrocarbons, typically found in oil-field brines, which can be sampled from unsuccessful (dry) holes in the explored area. The direction and distance from nearby hydrocarbon accumulations can be determined by an analysis of the benzene,

ethylbenzene, toluene, and xylene (BETX) aromatics, which are typically washed from oil in place by migrating brines.

3.1.2 Project Description

The theoretical basis for the improvement in existing geochemical exploration techniques is based on the fact that the hydrocarbon components of a hydrodynamic brine plume, which has interacted with a hydrocarbon accumulation, will usually migrate down the flow gradient in a manner similar to contaminant plumes, whose behavior is well known from environmental studies. The geochemical brine-analysis method will be reliable only within a rigorously identified flow unit that is hydraulically separate from other flow units in a multiaquifer (and potentially multireservoir) system. For this reason, individual flow systems have to be identified and characterized before the interpretation of the geochemical results can be undertaken.

3.1.3 Project Status

Characterization studies continue for the hydrodynamic and hydrogeochemical factors which can affect the accuracy of geochemical exploration methodologies.

3.1.4 Planned Activities

Plans are to modify and improve an existing three-step approach, using a tightly integrated fluid-flow and geochemical analysis, to provide breakthroughs in the development of novel exploration procedures.

3.1.5 Summary

A tightly integrated fluid-flow and geochemical analysis program using a three-step approach should provide significant breakthroughs in the development of novel exploration procedures. The opportunities for significant improvement in existing techniques are based on the fact that key, identifiable components of the geochemical, hydrodynamic system usually migrate down the flow gradient in a manner similar to contaminant plumes.

It is recognized that the geochemical brine-analysis methodology will be reliable only within a specifically identified flow unit, and that flow systems will have to be identified and characterized before the interpretation of the geochemical results is feasible. The current geochemical literature and U.S. patents do not provide guidance for such an integration of different techniques. Innovative procedures are being developed.

3.2 MODELING OF BASIN HISTORY, FLUID DYNAMICS, AND HYDROCARBON GENERATION

3.2.1 Introduction

A license has been renegotiated to test and use the updated version of the FHAMod/RIFT computer program. This software was developed by the Department of Geology and Geophysics at the University of Minnesota for the modeling of basin history and fluid dynamics in rift related sedimentary basins.

The original FHAMod program code was developed in 1994, then significantly upgraded and improved in 1995, in cooperation with the USGS. The latest version of the program, known as RIFT, will be tested in this program.

3.2.2 Project Description

During negotiations with the University of Minnesota in 1994 and 1995, it was anticipated that BDM-Oklahoma would play a significant role in the development of the RIFT program. Plans were for BDM personnel to be granted training for the program operation and subtleties, as well as being given unlimited access to the code.

Unresolvable computer problems, including hardware or software conflicts and incompatabilities with the preprocessor, prevented the system from being loaded and run on the available computer platforms at NIPER in 1995. With the program now updated and improved, the proposal and arrangement has been reconsidered and renewed in FY 1997 by BDM Petroleum Technologies. A new attempt will be made to see if the system can be installed and run on the current BDM Petroleum Technologies computers.

3.2.3 Project Status

According to the agreement with the University of Minnesota, the BDM Petroleum Technologies research team will be responsible for providing the extensive, multiple data sets required for cross-sectional basin modeling in the Mid-Continent region. Intensive data acquisition from multiple sources, such as published literature, archives of Geological Surveys, master's and doctoral theses, and the Internet is ongoing.

A set of petrographic and geochemical data is being generated from outcrop samples collected at a series of exposures of the Lower Paleozoic potential source rock sequences across the state of Missouri. Plans are for the data sets to be used in September to perform the code sensitivity analysis at the University of Minnesota.

Access to a second software modeling program, the 3D CIRF.B (Chemical Interaction of Rocks and Fluids for Basin Analysis) computer code has been sought with the encouragement of DOE

managers. This code is being developed by the Laboratory for Computational Geodynamics at Indiana University under the sponsorship of DOE, the Gas Research Institute, and Phillips Petroleum Company.

Dr. Peter Ortoleva, principal investigator and code author, was initially contacted in February 1997. Specific discussions regarding conditions of BDM Petroleum Technologies' participation in the consortium were initiated in April 1997. Use of this code will be contingent upon funding, and the negotiating of a satisfactory contract.

The CIRF.B 3D forward modeling system is designed to enable the prediction of resource location and characteristics using basin-specific geological data. The simulator incrementally replicates the geologic state of the basin development at selected time intervals. The BDM Petroleum Technologies research team has agreed to provide basin-specific geological data and information on sedimentary/tectonic/geochemical variables from the study area.

CIRF.B uses the types of data generally acquired in exploration and resource development, including surface, downhole subsurface, and remote-sensed geological data. Most of the physico-chemical data are available in the CIRF.B internal database.

In June 1997, the results and status of the DOE AO4 Drilling and Exploration Project, including the modeling related portion of Task 1, were reported at the DOE Contractor Review Meeting in Houston, Texas.

3.2.4 Planned Activities

BDM Petroleum Technologies will start a joint research project with the University of Minnesota, aimed at developing a cross-sectional model of the evolution of the South-Central Mid-Continent sedimentation history, compaction, structure, and erosional evolution. The work will include groundwater flow data, heat transfer, and hydrocarbon generation. A sedimentary evolution software package, RIFT, developed at the University of Minnesota in cooperation with USGS, will be used for the computer modeling.

Collection and organization of the data for the computer simulation will continue at BDM Petroleum Technologies. A cross-section is being constructed through the Salina Basin, across the Nemaha Uplift and the southern end of the Mid-Continent Rift, and then across the Forest City Basin. Sensitivity analysis of the model parameters for the RIFT code in the South-Central Mid-Continent setting will be initiated in September 1997 at the University of Minnesota. The most recent version of the RIFT code is scheduled to be transferred to BDM Petroleum Technologies this fall.

Geochemical analyses of the outcrop samples collected from the Lower Paleozoic rock sequences in Missouri will be completed and their source rock potential will be evaluated. Core

intervals from the Lower Paleozoic in selected wells in the Salina and Forest City Basins in Kansas and Missouri will also be geologically examined and sampled for geochemical analyses. Geochemical results from these core and outcrop samples should provide critical input to the computer modeling work concerning the potential for hydrocarbon generation and migration in the region.

A joint research program with Indiana University to refine the 3D CIRF.B computer code will start in FY 1998, if appropriate funds are found or designated by DOE.

3.2.5 Summary

A cooperative research agreement was renegotiated in the spring of 1997 with the Gibson Computational Hydrogeology Laboratory of the University of Minnesota. In June 1997, a proposal was submitted to DOE for applying the FHAMod-2D/RIFT computer code to modeling the history of fluid migration and hydrocarbon generation in the Mid-Continent region, currently being studied by BDM Petroleum Technologies. The contract was approved by DOE's National Petroleum Technology Office (NPTO) management in late July. Administrative procedures for the program are still being set up, but the BDM Petroleum Technologies team has already begun gathering required data for the modeling work.

A proposal was submitted to DOE in May 1997 for joint research between the Reservoir Management and Characterization Group at BDM Petroleum Technologies and the Laboratory for Computational Geodynamics Group at Indiana University. The objective would be to refine the Indiana University CIRF.B computer code, which simulates hydrocarbon generation in rifted environments, with specific application to the rift-related geologic settings in the Mid-Continent region.

In addition to the plans to initiate cooperation with the University of Minnesota and Indiana University, discussion has also been initiated with Argonne National Laboratory and interested industry partners for joint research in the area of integrated basin analysis and 3D modeling.

3.3 POSSIBLE PETROLEUM GENERATION AND OCCURRENCE IN THE PRE-MESOZOIC PARTS OF THE FOREST CITY BASIN

3.3.1 Introduction

The University of Tulsa (TU) has been a key participant in the investigation of the Forest City and Salina basins since the initiation of the project. Work has progressed under two contracts. The first contract began on May 8, 1996, and was concluded with the submission of a final report in February 1997. Work under the current contract began on April 29, 1997. Information contained in the February 1997 final report is not repeated in this status report.

3.3.2 Project Description

An outline of previous work has been given in the 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." The current contract between BDM and the TU Geoscience Department includes the identification of petroleum geochemical characteristics from various sources.

In addition to the previously discussed possible Precambrian source rocks, petroleum in the Forest City Basin could have originated in as many as three main Paleozoic source series:

- Pennsylvanian
- Upper Devonian to Lower Mississippian
- Ordovician

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

3.3.3 Project Status

The current contract between BDM and the TU Geoscience Department includes testing to identify and define petroleum geochemical characteristics from various sources in the South-Central Mid-Continent. Paleozoic-sourced petroleum in the Forest City Basin could have originated in as many as three main source rock series: Pennsylvanian, Upper Devonian to Lower Mississippian, or Ordovician. Gas chromatogram studies of oils derived from a Pennsylvanian source versus samples from Ordovician source rocks clearly indicate that there are major geochemical differences in the composition of the two types of oil. The results of this study were described in detail in the **Quarterly Technical Progress Report**, NIPER/BDM-0311, April 1, 1997–June 30, 1997, p. 144–146.

In July 1997, R. Erickson of TU visited the Minnesota Geological Survey core repository in Hibbing, Minnesota, and the Iowa Geological Survey Bureau core repository in Iowa City, Iowa. Cores were examined and the samples listed below were borrowed.

Sample 1 - Hollandale core, Sec. 7, T103N, R19W, Freeborn County, Minnesota; McGregor Member, Platteville formation; quarter slab of core from 447.5 ft to 448.0 ft

Sample 2 - Hollandale core, Sec. 7, T103N, R19W, Freeborn County, Minnesota; Decorah shale; core piece from 429 ft

Sample 3 - Hollandale core, Sec. 7, T103N, R19W, Freeborn County, Minnesota Decorah shale; core piece from 430 ft

Sample 4 - NGPCA M.M. Flynn No. 2 (W14380), Sec. 19, T76N, R9W, Washington County, Iowa; Glenwood shale; half slab of core from about 1115.4 ft to 1116.4 ft

Sample 5 - NGPCA W.F. Flynn No. 2, Sec. 20, T76N, R9W, Washington County, Iowa; Guttenberg Member, Decorah formation; core piece from 976 ft

Sample 6 - NGPCA W.F. Flynn No. 2, Sec. 20, T76N, R9W, Washington County, Iowa; Guttenberg Member, Decorah formation; core piece from 977 ft

Sample 7 - Cominco SS-3, Jackson County, Iowa; Guttenberg Member, Decorah formation; 1 5/8-inch-long half slab of core from 675 ft

Sample 8 - Cominco SS-3, Jackson County, Iowa; Guttenberg Member; Decorah formation

Sample 9 - Iowa Geological Survey Bureau BS-4, Sec. 20, T95N, 6W, Clayton County, Iowa; Guttenberg Member, Decorah formation; core piece from 481.0 ft to 481.7 ft

Sample 10 - Core 91708-A B3A, Sec. 22, T29N, R24W, Hennepin County, Minnesota; Glenwood shale; core chips from 33.2 ft

Sample 11 - Core 91708-A B7A, Sec. 22, T29N, R24W, Hennepin County, Minnesota; Glenwood shale; core chips from 51.6 ft

TU personnel are monitoring all new well drilling permits in Kansas to identify wildcat wells in the Forest City and Salina Basins. The operators of such wells have been contacted and arrangements have been made to receive samples from those wells. It is expected that TU will continue to receive samples until the end of this project. The primary focus will be to acquire rock samples from intervals that have been identified as potential source rocks, rock samples from intervals containing shows of oil or gas, and crude oil samples from any oil recovered during drillstem tests.

During the summer of 1997, the TU Geosciences Department purchased a large plotter. All the Kansas geographic data purchased from Weststar last year have been loaded, and base maps are being generated using Geographix. The availability of other no-cost or low-cost geographic data from the Iowa State Geological Survey Bureau and USGS is being researched. The range of the TU mapping capabilities should expand in the near future.

3.3.4 Planned Activities

The source-rock samples collected from the field are being prepared for TOC analysis and Rock-Eval pyrolysis. Samples containing oil will have the oil extracted and analyzed by gas chromatography. Thin sections will be made of some samples, based on condition and information to be gained.

A database of published geochemical data is being compiled to combine with the results of the TU analyses. R. Erickson has reviewed the categories of data to be included in the database with J. Jordan of BDM. All new well drilling permits in Kansas will continue to be monitored.

3.3.5 Summary

Core samples have been obtained from the northern extremity of the Forest City Basin and are being prepared for analysis. Base maps of the Kansas part of the Forest City Basin are being plotted, and all new exploration activity is being monitored.

3.4 REMOTE SENSING DATA AND SURFACE FRACTURE ANALYSIS

3.4.1 Introduction

The objective of the Exploration Techniques task in the DOE Basin Analysis program is to review, recommend, and/or develop cost-effective methodologies, techniques, and tools for oil and gas exploration, focusing on the independent operator. FRAC-EXPLORE Version 2.0 has been developed and refined for the application of remote sensing data and surface lineament and fracture analysis in oil and gas exploration at a reasonable cost.

3.4.2 Project Description

Using remote sensing and surface fracture analysis for exploration, significant accomplishments have been made. These include the:

- Completion of FRAC-EXPLORE Version 2.0, a comprehensive user-friendly computer software package for the use of remote sensing data and surface lineament and fracture analysis in oil and gas exploration
- Completion of an extensive statistical analysis of surface lineaments and fractures. This work has been done to identify the probability functions of natural fracture characteristics for stochastic simulation of subsurface fault systems
- Presentation of papers and poster sessions on new techniques, methodologies, and software packages at various society and professional meetings

3.4.3 Project Status

3.4.3.1 FRAC-EXPLORE

FRAC-EXPLORE Version 2.0 is based on a quantitative methodology developed in 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 and to add new capabilities to the software, the second version of FRAC-EXPLORE was completed in August 1997. Version 2 contained significant improvements over the first version. The following improvements were made:

- The Graphical User Interface (GUI) was improved for consistency and clarity.
- All variables were explicitly defined to reduce computer memory requirements.
- The "Save Graphics" menu was modified to be more user-friendly.
- Color legends were added to most graphics outputs to assist in anomaly interpretations.
- A new form was added for anomaly displays using mixed types of structural indicators.
- The basic recompilation was done using Visual Basic 5.0, a significantly improved compilation program.

As a result of these improvements, FRAC-EXPLORE Version 2.0 runs at least 21 times faster than FRAC-EXPLORE 1.0.

3.4.3.2 Completion of an Extensive Statistical Analysis of Surface Lineaments and Fractures for Exploration

Thirty-six sets of surface lineaments and fractures mapped from satellite images and/or aerial photos from parts of the Mid-Continent and Colorado Plateau regions were digitized and statistically analyzed in order to obtain probability distribution functions of natural fractures in those areas. This information was then used to characterize subsurface fault systems.

The orientations and lengths of the surface linear features were calculated using the digitized coordinates of the two end points of each individual linear feature. The spacing data of the surface linear features within each individual set were obtained using an analytical sampling technique. Statistical analyses were performed to find the best-fit probability-distribution functions for the orientation, length, and spacing of each data set. 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 which produced the lowest chi-square goodness-of-fit value was considered the best-fit distribution.

The following procedures were used for the statistical analyses of surface lineament and fracture characteristics:

- Rose diagram analysis to identify the number of subsets in a surface lineament and/or fracture system
- Filtering analysis to partition a surface-fracture system into subsets
- Sampling analysis to collect surface-fracture spacing data using a new analytical technique
- Best-fit analysis to obtain distribution functions for surface lineament and fracture orientation, length, and spacing

This extensive statistical analyses led to the following conclusions:

- 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.
- The probability distribution functions identified for the characterization of natural fracture characteristics through surface lineaments and fractures can be used for stochastic simulations of subsurface fault systems. This means that basement-fault-controlled oil and gas traps can be delineated and occurrences quantified through these techniques.

3.4.3.3 Presentations at Professional Meetings

The following presentations were made at various professional meetings to transfer the new methodologies, techniques, and software to industry:

- Paper entitled "A New Methodology and a Computer Software for Delineating Oil and Gas Reservoirs Using Surface Lineament and Fracture Analysis," SPE 38125, by G. Guo presented at the 1997 SPE Petroleum Computer Conference, Dallas, Texas, June 8–11.
- Paper entitled "A New Methodology for Delineating Hydrocarbon Reservoirs Using Remote Sensing Data and Surface Fracture Analysis" by G. Guo, S. A. George, and R. P. Lindsey presented at the 1997 AAPG Annual Meeting, Dallas, Texas, April 6–9.
- Paper entitled "Statistical Analysis of Surface Lineaments and Fractures for Characterizing Naturally Fractured Reservoirs," 4RC-052, by G. Guo, S. A. George, and

R. P. Lindsey presented at the 4th International Reservoir Characterization Conference, Houston, Texas, March 2–4, 1997.

- Paper entitled "Applications of Surface Lineaments and Fractures for Optimal Horizontal Well Drilling and Production Potential Estimation," SPE 37150, by G. Guo, S. A. George, and R. P. Lindsey presented in the 1996 SPE International Conference on Horizontal Well Technology, Calgary, Alberta, Canada, November 18–20.

3.4.4 Planned Activities

The user's manual for FRAC-EXPLORE will be revised and updated to accommodate the new features, innovations, and improvements in the second version.

A study will be conducted to correlate the production data and surface fracture anomalies in Osage County, Oklahoma.

A poster entitled "FRAC-EXPLORE, a New Computer Software for Locating Oil and Gas Reservoirs Using Remote Sensing Data and Surface Fracture Analysis" will be presented at the Twelfth International Conference and Workshops on Applied Geologic Remote Sensing, Denver, Colorado, November 17–19, 1997.

3.4.5 Summary

The completion of FRAC-EXPLORE Version 2.0, and its user's manual will make a comprehensive user-friendly computer software package available to industry. This package will allow the small independent operator to apply remote-sensing data and surface-lineament and fracture analysis to oil and gas exploration.

3.5. EVALUATION OF OIL AND GAS POTENTIAL

3.5.1 Introduction

The objective of the Basin Analysis portion of the DOE program is to evaluate the oil and gas potential in selected domestic basins using state-of-the-art technologies developed in Task 1.

3.5.2 Project Description

Both regional and detailed local analyses have been conducted in the study area using remote sensing and surface fracture analysis. In eastern Kansas, 13 counties were selected for remote sensing data studies and surface fracture analysis for oil and gas exploration. The results of these case studies have been presented in professional meetings.

3.5.3 Project Status

3.5.3.1 Study of Lineaments and Fractures

A regional study was conducted to investigate the structural styles, typical oil and gas trapping mechanisms, and exploration strategies for the Mid-Continent region through an analysis of surface and subsurface lineaments and fractures. The main features of the studies are as follows:

- Regional study of surface and subsurface linear features including the collection and digitization of a large number of surface lineaments and fractures, gravity and magnetic lineaments, and basement fault systems in the Mid-Continent region
- Orientation and analysis of these linear features to identify the structural styles and trapping mechanisms in the region
- Correlation analysis of surface linear features and subsurface oil and gas traps (Guo et al. 1996c)

The Mid-Continent study produced the following conclusions:

- The surface and subsurface linear features follow two major sets of trends, one oriented northeast-southwest, the other northwest-southeast. The surface linear features and gravity and magnetic trends also include minor components trending east-west or north-south. It was concluded that 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 indicates that the systematic fault systems in the basement in the Mid-Continent region probably have acted as continuing zones of weakness that have been reactivated many times. These faults have been propagated upward to the surface. Therefore, the structural style and many surface features in the Mid-Continent region appear to be basement influenced or controlled.
- The basement fault systems in the region may have acted as loci for the development of other geological structures including oil and gas traps in the Mid-Continent area.

An 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. It is reasonable to hypothesize that this relationship also exists in other parts of the Mid-Continent. Therefore, it has been concluded that surface lineament and fracture analyses can be employed as a cost-effective tool for hydrocarbon exploration in the Mid-Continent region.

These conclusions are considered to be applicable in the 13-county study area in eastern Kansas, where a more detailed study was conducted. This study area, which lies in the southwest portion of the Forest City Basin, is bounded on the west by the Nemaha Uplift and on the south

by the Bourbon Arch. The area transects north-northeast trending strata that range in age from Cretaceous to Pennsylvanian, becoming progressively older to the east.

Four hundred high-altitude black and white aerial photographs have been studied. These photos were taken in 1981 from an altitude of 40,000 feet. Each photograph covers an area of 11 square miles (scale 1:80,000). Fracture lineament interpretation has been completed on more than 200 photos. Much of the data has been transferred to 1:100,000-scale topographic maps.

Recognition of fracturing on the aerial photos is based on visual identification of actual rock displacement, straight drainage segments, alignments of vegetation growing along fractures, tonal or color changes in surface soil and rocks, and cliff edges or faces.

3.5.3.2 Presentations at Professional Meetings

The following presentations were given at professional meetings to present the results of the case studies using surface lineament and fracture analysis for oil and gas exploration:

- "Using Remote Sensing Data and Surface Lineament and Fracture Analysis for Hydrocarbon Exploration in Northeastern Arizona," by G. Guo, T. K. Reeves, S. A. George, and R. P. Lindsey presented at the 1997 AAPG Annual Meeting, Dallas, Texas, April 6-9.
- "Using Surface Lineament and Fracture Analysis to Delineate Additional Reserves in a Mature Field: A Case Study in Osage County, Oklahoma," SPE 37414 by G. Guo, H. B. Carroll, W. I. Johnson, S. A. George, A. H. Falls, and R. P. Lindsey presented at the 1997 SPE Production Operations Symposium, Oklahoma City, Oklahoma, March 9-11.

3.5.4 Planned Activities

Plans for the first quarter of 1998 include fracture lineation interpretation on the remaining 200 photos. The transfer of the data to topographic maps will be completed. Relationships between surface fracture orientations and oil and gas production will be investigated. The lineations will be digitized and analyzed using the FRAC-EXPLORE program.

All aerial photos will be interpreted for the mapping of surface fractures. Of fourteen SPOT images inspected to cover the 13 counties in eastern Kansas, one was purchased. It will be used for the mapping of medium-scale surface linear features. The SPOT image will be interpreted using ER-Mapper, a comprehensive computer software package which was purchased for enhancing satellite images and mapping surface linear features.

All surface linear features will be digitized. A paper entitled "Analysis of Surface Lineaments and Fractures for Hydrocarbon Exploration and Production Optimization in the Mid-Continent

Region" will be presented at the 1997 SPE 72nd Annual Technical Conference & Exhibition, San Antonio, Texas, October 5–8 .

3.5.5 Summary

The close relationship between the orientation and position of surface linear features and subsurface oil and gas traps observed in this study has led to the conclusion that this relationship may also exist elsewhere in the Mid-Continent region. Surface lineament and fracture analyses can be employed as cost-effective tools for hydrocarbon exploration in the Mid-Continent region.

3.6 INTEGRATION AND PROCESSING OF EXISTING WELL DATA

3.6.1 Introduction

Identification and collection of available thermal data, formation pressures, and waterhead readings for Kansas have been initiated. Various sources such as geological survey and regulatory agency information, well operator data, and Masters and Ph.D. theses were collected to map pressure distribution by formation or depth. Ultimately, this data will be integrated with other information that have been collected for basin modeling in the Mid-Continent region.

3.6.2 Project Description

Subsurface temperature and geothermal-gradient data for Kansas were collected from a University of Illinois-Urbana Masters thesis published in 1980. Geothermal gradients were extrapolated from bottomhole temperatures recorded in more than 42,500 wells. The subsurface temperature distributions and geothermal gradients were related to basement topography, magnetic and gravity anomalies, and to thermal conductivity information for the sedimentary section.

Much of the formation pressure measurement and waterhead data available are included in the well-drilling and completion data records that are required to be filed with state regulatory agencies. Drillstem test results generally include the hydrostatic pressure, reservoir pressure, and flowing pressure for specific formations and intervals.

3.6.3 Project Status

Working with the Kansas Geological Survey, a query of the available pressure data is underway. The dataset includes the following information:

- Well name

- Well number
- Township and range
- Section and footage call (or latitude-longitude)
- Kelly bushing
- Total depth
- Depth of measurement
- Formation tested
- Hydrostatic pressure
- Final shut-in pressure
- Final flow pressure

3.6.4 Planned Activities

Future plans include importing the reservoir pressure data into the GeoGraphix software system to map pressure distribution by formation and/or by depth. The information will be integrated with geothermal-gradient data, geochemical source-rock data, stratigraphy, and tectonic history for basin modeling of the Mid-Continent region.

3.6.5 Summary

Data from a variety of sources have been collected for basin modeling of the Mid-Continent region. The use of GeoGraphix software will facilitate the mapping of pressure distribution by formation or depth.

3.7 3D SEISMIC DATA INTERPRETATION

3.7.1 Introduction

The Exploration Techniques portion of this project includes research on the cost-effective use of 3D seismic data in the South-Central Mid-Continent. A software program, 3dPAK from Seismic Micro-Technology, is being used because it permits the interpretation of 3D seismic data on desktop personal computers. The hardware and software requirements for loading and interpreting the data have been designed with the small independent operator in mind.

3.7.2 Project Description

As part of the DOE program, a 3D seismic program was conducted in Osage County, Oklahoma, during late 1996 to early 1997. In the study area, data were collected for 55-ft bin sizes, then processed both as 55-ft and 110-ft bin data. The research survey was contiguous with a larger shoot that was conducted using a 110-ft bin size.

The large, 110-ft bin configuration 3D survey in Osage County was shot over a 16.75 mi^2 area in T22N-23N, R9-10E. Within that survey area, 6 mi^2 were covered with a 55-ft bin configuration. The objective of collecting data with the 55-ft bin size was to see if the close scanning of the subsurface could cost-effectively improve imaging capabilities for very subtle structural and stratigraphic features that are important for oil and gas exploration. It was known that tighter bin sizes would improve the quality of the imaging, but the primary question was whether the improvement would be sufficient to justify the increased acquisition costs for small independent operators.

The seismic data acquisition was completed using state-of-the-art equipment and a vibroseis crew in February 1997 after vibrating a total of 5,778 points. The field tapes were sent to Geo Trace Technologies Inc. in Dallas 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 specific data-processing routines. The processed seismic data, ready for interpretation, were received in the last week of May and the first week of June l997.

The interpretation of the 3D survey was initiated by investigating certain important features of the data and then evaluating the imaging capabilities and contrasts for the data collected with the 55-ft bin size vs. the 110-ft bin size. A significant increase in resolution was noticed and then documented by tracking the Layton gas sand from an area where it is productive to an area where the Layton has been dry.

3.7.3 Project Status

The processed seismic data have been loaded onto IBM-compatible personal computers at BDM Petroleum Technologies. 3dPAK from Seismic Micro-Technology is being used for interpretation of the data.

The first step before interpretation of the 3D seismic data was loading the large volume of processed 3D data from the 55-ft bin and the 110-ft bin surveys. The data installation into the personal computers was fairly straightforward, but precautions were taken to ensure that the computer had adequate disc storage space. The field data set for the two surveys in Osage County alone required about 600 Mb of hard drive storage space. At least 16 Mb of RAM and a math coprocessor also were needed to run the software smoothly.

The data were loaded onto Pentium Pros with 6 Gb of hard disc space and smoothly running programs. Minor glitches in the procedures caused only temporary setbacks, as these problems invariably could be circumvented by following alternative processes. Such minor glitches inevitably seem to occur with almost all interpretation software involving complex mathematical manipulations with large volumes of data, and were not considered to be serious.

Seismic reflections in 2D surveys are always traditionally assumed to be from the midpoint between the shot and the receiver. In a 3D survey, all seismic reflections from within a certain volume (called a "bin") are 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. Therefore, the 110-ft bin data involved averaging information acquired over a larger area than the 55-ft bin data.

At each bin location, the seismic traces are sampled at discrete intervals, for example, 2 msec, extending from 0.0 seconds to the total length of the record, for example, 5.0 seconds. The length of the record is determined by the depth of investigation.

For each 3D survey, the data acquisition contractor prepares a paper base map which identifies the location of each seismic trace on the ground surface. Each 3D seismic survey has a regular grid of bins, so individual traces can be identified either by map coordinates or by the line/trace coordinates prepared by the seismic contractor. A seismic processor defines a regular grid of lines and traces (sometimes called X lines or crosslines). Traces or common depth point (CDP) bins in this reference system are located in pairs of line numbers and trace numbers.

The line/trace diagram for the Osage County 3D seismic survey can be displayed on a base map whenever a seismic section or a map is being interpreted. For the larger 110-ft bin survey, the line numbers run from 1 to 264 and trace numbers from 1 to 229. For the smaller, 55-ft bin survey, line numbers run from 160 to 528 and trace numbers from 1 to 200.

The vital first step in interpreting seismic data was identifying the various reflections on the seismic section. This correlation of seismic reflection with geology was best done with the help of synthetic seismograms generated from the sonic and density logs. The procedure for correlating the different reflectors with synthetics generated at different well locations began with the collection of various well logs (particularly sonic, density, gamma ray, neutron, and resistivity/induction). In Osage County, log libraries are maintained by the Bureau of Indian Affairs at Pawhuska, Osage County, and at the Oklahoma Well Log Library in Tulsa. Besides well logs, production data and well completion reports were also collected from these and other sources.

Several interesting horizons, representing either producing formations (such as the Bartlesville sandstones or the Arbuckle dolomites) or distinctive marker beds (like the Woodford shales) were identified on the seismic sections from available synthetic seismograms. These seismic reflectors were mapped along both inlines and crosslines, forming a closed loop to ensure that the starting and the ending reflectors matched.

Because the 110-ft bin size involved averaging over a larger area, it followed that the 110-ft bin data would appear smoother than the 55-ft bin data, and that it would lack certain details. Key questions were:

- How much variability was present in the 55-ft data?
- Could this variability be meaningfully interpreted to provide information on subtle geological features of relevance to oil and gas exploration?

The relative usefulness of the 55-ft and 110-ft data sets was compared using seismic sections from several different areas.

3.7.3.1 Mapping of Stratigraphic Features

The 55-ft bin data appear to contain higher frequencies; consequently, subtle stratigraphic features could be imaged better in the 55-ft bin data than with the 110-ft bins. This was illustrated by seismic data along different sections.

It may be noted that if the data are collected with a 55-ft bin size, then it is relatively easy to generate a simulated 110-ft bin data set, simply by averaging over a larger area, but the reverse, adding data that were not collected, i.e., to obtain simulated 55-ft bins from data acquired with 110-ft bin layouts, is not possible.

3.7.3.2 Detection and Mapping of Small Faults

While studying the 55-ft bin data for line 516, two small faults were noticed at the intersections of traces 128 and 132 and time 0.44 seconds. The 40 ft displacement of the topmost bed was clearly observed, and the faults were traceable through the lower portion of the section, down to the basement. A second fault was identifiable at trace 86 and time 0.50 seconds, dipping to the west (toward the lower trace numbers). The 110-ft bin data display for line 258 at the same location (trace 65) did not clearly indicate the presence of two separate faults. Because of the averaging effect, displacements were not indicated by sharp breaks as in the 55-ft bin data. In addition to the fact that the 55-ft bins eliminate many of the detrimental effects of averaging, the sharpness of the 55-ft data could result from a larger percentage of higher frequencies.

It was observed that boosting the relative amplitudes of the seismic data helped in mapping fault traces in both of the data sets. The versatility of the interpretation package allowed the viewing of seismic data while tweaking parameters and emphasizing different attributes, such as boosted amplitudes. From the processed data cube, vertical and horizontal sections were obtained for very detailed interpretation and integration with geology.

3.7.3.3 Tracking a Thin Gas Sand in Osage County

The high resolution quality of the Osage County seismic data was tested by tracking a thin gas-saturated sand in Osage County from productive to unproductive areas. The sand under investigation was the Pennsylvanian-age Layton sand, which was encountered at a depth of

about 1100 ft. This unit has widespread distribution in Osage County and produces oil and gas in many different parts of the county.

Although the Layton sand can reach thicknesses of 30-40 ft, the gas-saturated zone in well 1-15 in Section 15 is only about 8 ft thick. The combined density/neutron log for the well clearly shows the well-known "gas effect" crossover for this gas sand where the density curve crosses the neutron curve and gives very low readings. The density curve shows low density values because the effective density of a gas-saturated sand is low, and the neutron curve shows slightly higher values because, compared with a water-saturated sand, there are comparatively fewer hydrogen atoms in a gas-saturated sand to slow down the bombarding neutron atoms. This results in the emission of gamma radiation away from the source, relatively close to the detector. This results in high neutron readings. In the case of a water-saturated sand, gamma emission occurs close to the source due to too many collisions with hydrogen atoms resulting in a lower neutron log reading.

About a mile to the east of well 1-15, the same Layton sand becomes shaley, it no longer shows the "gas effect" because the effective density of the sand is relatively high. The gamma ray logs from wells 1 and 2 in sections 14 and 15 clearly indicate that the clean sand in well 1-15 has become much shalier in these wells. The objective of the survey study was to determine if the saturation change in the thin gas sand could be detected from lateral variations in amplitude of the seismic reflector over this gas sand.

The seismic section of line 460 passing through well 1-15 and wells 1 and 2 in Sections 14 and 15 to the east clearly demonstrated a sharp increase in amplitude in areas where the gas saturations are high. The amplitude dropped markedly in areas where wells did not encounter any significant gas saturation. Exactly the same effect had been reported in the literature by Geoquest International from an Upper Tertiary gas sand which was about 40 ft thick and which was encased in shale that had high sonic velocities, compared to the gas sand. While top and bottom reflection events of the Upper Tertiary gas sand could not both be seen on the section because the frequencies were not high enough, there was a sharp increase in negative seismic amplitude from the top of the gas sand because of the low acoustic impedance of the gas-saturated sand. The same effect was also believed to be observed in the seismic section of line 460.

3.7.4 Planned Activities

The superior imaging capabilities of the high-resolution seismic data obtained with the 55-ft bin configuration has significantly improved our abilities to conduct detailed investigations in the subsurface, including the mapping of subtle structural and stratigraphic features for oil and gas exploration. Detailed correlation with wireline logs, core, and production data will be conducted to determine the seismic response to variations in lithology, facies changes, and fluid saturations.

Seismic attributes like amplitude, frequency, and phase-interval velocity will be extracted from the seismic data to determine how the distribution of seismic attributes is related to varying geological and fluid-saturation conditions. An attempt will be made to determine the environment of deposition from seismic sequence stratigraphy using this high-resolution data.

The cost of conducting such high-resolution seismic surveys, especially from the point of view of small independent operators, is being investigated and will be presented in a future report.

3.7.5 Summary

To image subtle geological features in depositional environments, such as the shallow-water platform deposits of Osage County where there are rapid changes in lithologies and facies, the high resolution 55-ft data will be extremely useful. For some other depositional environments that involve imaging of larger features, the 110-ft bin data may be adequate. The 110-ft data may even prove to be more useful in certain instances where the objective is to map the dominant structural trends without being distracted by interference effects from small geological features.

3.8 SURFACE GEOCHEMISTRY

3.8.1 Introduction

A surface geochemical study was conducted in the Bigheart area, the same region of Osage County, Oklahoma, where the 3D seismic survey just described was conducted. The sample sites for the geochemical survey matched the seismic stations to take advantage of the precision survey and flags that had been set for the geophysical work.

Many surface geochemical indicators, or markers, for hydrocarbon seeps depend on the presence of clays in the shallow soil because of the high surface area of those clays and their affinity for ions and organic compounds.

Examples of these markers are iodine-hydrocarbon complexes, the radiometric elements (potassium-40, uranium, and thorium daughter products), and possibly soil gas itself. If this is the case, then the amount of these indicators may be dependent on the amount of clay present. If so, then clay variations within a survey area could mask or cause false indications of a seep.

3.8.2 Project Description

Experts in the field acknowledge that the absolute amount of a geochemical indicator species depends upon the geographic location. At least three processes can be proposed:

(1) Clay adsorbs the indicator species and limits the ultimate amount of the species retained. Because 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 GM for the limited number of absorption sites on the clay.

(2) The geochemical marker is present in very small quantities, so that even in the presence of small amounts of surface-active material (silts, clays), there is always an abundance of absorption sites, and they compete very favorably with other soil components in the absorption process.

(3) Chemical (or biological, including microbial) processes not related to adsorption reduce the mobility of the geochemical marker, resulting in an elevated concentration in the hydrocarbon plume.

If (1) is the correct process, then there will be a strong correlation between the geochemical marker and the specific surface area of the soil.

3.8.3 Project Status

To evaluate the importance of process (1), one must have a relative measure of the surface area. Because clays contain the vast majority of the active surface area in a soil, and soil science considers the clay fraction in soil to be those particles smaller than 2 μm, then one needs a method of measuring the particles smaller than 2 μm. Material smaller than 50 μm but larger than 2 μm is classified as silt (primarily extremely fine-grained 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

$$t = x\sqrt{\frac{9\eta}{2g\,r^2(\rho-\rho_o)}}$$

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. Because researchers here are interested only in a relative value for correlation purposes, these restrictions are not important. One can, therefore, use the settling time of a soil suspension to select a maximum particle size remaining in suspension, and use

scattered light to measure the amount of material remaining in suspension. The scattered light will actually be proportional to the cumulative surface area of the particles left in suspension. For the geometry of this light scattering equipment, only particles smaller than 50 μm remain in suspension after 2-1/2 minutes, and after 27 hr, only particles smaller than 2 μm will be suspended.

To test the validity of process (1), 109 samples were randomly selected in the Bigheart Osage survey area for which we had iodine analyses. Based on the scattered light, the amount of clay (surface area) varied 27 fold over the survey area. The correlation between the clay surface area and the iodine 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 high (0.869), meaning that the correlation between the silt and iodine was also very low (0.068).

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 test performed here, we can not distinguish between the importance of processes (2) or (3), or some other unknown process. Indeed, if process (3) actually occurs, then there may be other geochemical markers that may depend on the soil surface area.

3.8.4 Planned Activities

There are no plans for more work on surface area studies at the present time.

3.8.5 Summary

The change in the surface area of particles in the soil samples was found to have no effect on the use of iodine as a geochemical marker. The same may be true for other markers as well.

3.9 REFERENCES

Bunker, B. J., B. J. Witzke, W. L. Watney, and G. A. Ludvigson. 1988. Phanerozoic history of the central Mid-Continent, United States. *In* L. L. Sloss, ed., *Sedimentary Cover–North American Craton*; U.S. Boulder, Colorado, Geological Society of America. The Geology of North America, Vol. D-2. p. 243–260.

Fritz, R. D. and P. L. Medlock. 1995. Recognition of Unconformities and Sequences in Mid-Continent Carbonates. *In* N. J. Hyne, ed., *Sequence Stratigraphy of the Mid-Continent*, Tulsa Geological Society Special Publication no. 4. p. 49–80.

Guo, G., and H. B. Carroll. 1995. A New Methodology for Oil and Gas Exploration Using Remote Sensing Data and Surface Fracture Analysis. DOE Report No. NIPER/BDM-0163, August.

Guo, G., I. Chang, and S. A. George. 1996a. *User's Manual for FRAC-EXPLORE, A Software Package for Oil and Gas Exploration Applying Surface Fracture Analysis.* DOE Report No. NIPER/BDM-0261, July.

Guo, G., S. A. George, and R. P. Lindsey. 1996b. "Applications of Surface Lineaments and Fractures for Optimal Horizontal Well Drilling and Production Potential Estimation," SPE 38150 accepted for presentation in 1996 SPE International Conference on Horizontal Well Technology, Calgary, Alberta, Canada, November 18–20.

Guo, G., and S. George. 1996c. An Analysis of Surface and Subsurface Lineaments and Fractures for Oil and Gas Exploration in the Midcontinent Region. DOE Report No. NIPER/BDM-0223, March.

Landon, S. M., ed. 1994. Interior Rift Basins. American Association of Petroleum Geologists Memoir 59.

Landon, S. M. 1994. Personal communication, October 20.

Quarterly Technical Progress Report. 1997. NIPER/BDM-0311, April 1, 1997–June 30, 1997, p. 144–146.

Rauzi, S. L. 1990. *Distribution of Proterozoic Hydrocarbon Source Rock in Northern Arizona and Southern Utah.* Arizona Geological Survey O&GCC Special Publication 6, 1990, 19 p.

Reeves, T. K. and H. B. Carroll. 1994. *Selection and Prioritization of Basins for Study in the Exploration and Drilling Program.* Status report NIPER/BDM-0061, September.

Reeves, T. K., M. Szpakiewicz, B. Sharma, G. Guo, L. Volk, C. Barker, R. Erickson, S. George, and H. Carroll. 1996. *Investigations on the Structure, Tectonics, Geophysics, Geochemistry, and Hydrocarbon Potential of the Black Mesa, Northeastern Arizona.* For Management and Operating Contract for the Department of Energy's National Oil and Related Programs, Final Report NIPER/BDM-0226, March.

Sharma, B., T. K. Reeves, M. Szpakiewicz, and S. George. 1996. *Applications of Geophysical and Geological Techniques to Identify Areas for Detailed Exploration in Black Mesa Basin, Arizona.* For Management and Operating Contract for the Department of Energy's National Oil and Related Programs, Report NIPER/BDM-0262.

Sloss, L. L. 1963. Sequences in the Cratonic Interior of North America. Geological Society of America Bulletin 74: p. 93–114.

Uphoff, T. L. 1997. Precambrian Chuar Source Rock Play: An Exploration Case history in Southern Utah. American Association of Petroleum Geologists Bulletin 81: p. 1–15.