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DEPOSITIONAL SEQUENCE ANALYSIS AND SEDIMENTOLOGIC MODELING FOR IMPROVED PREDICTION OF PENNSYLVANIAN RESERVOIRS

(ANNEX I)

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Kansas Geological Survey
1930 Constant Avenue, Campus West
Lawrence, Kansas 66047

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Contracting Officer's
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ANNUAL REPORT

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ATTACHMENTS:

Attachment A: French, J.A., 1991, Stratigraphy and depositional setting of the oolitic reservoir analogs in the Lower Missourian (Pennsylvanian) Bethany Falls and Mound Valley limestones, southeastern Kansas, U.S.A.: in Midcontinent Core Workshop: Integrated Studies of Petroleum Reservoirs in the Midcontinent, Midcontinent AAPG Section Meeting, Wichita, pp. 83-97.

Attachment B: Feldman, H.R., and Franseen, E.K., 1991, Stratigraphy and depositional history of the Drum Limestone and associated strata (Pennsylvanian) in the Independence, Kansas, area -- A field guidebook and road log: Kansas Geological Survey Open-File Report 91-45, 24 p.

Attachment C: Miller, R.D., Feldman, H., Franseen, E., Knapp, R., and Black, R.A., 1991, Practical vertical resolution limits of CDP seismic-reflection data targeting reflectors less than 125 m deep near Independence, Kansas: Kansas Geological Survey Open-File Report 91-36, 11 p.

Attachment D: Miller, R.D., submitted, Normal moveout stretch mute on shallow-reflection data: Geophysics.

Attachment E: Baars, D.L., submitted for publication, Conjugate basement rift zones in Kansas, Midcontinent, USA.

Attachment F: Baars, D.L., and Watney, W.L., Paleotectonic control of reservoir facies, in, Franseen, E.K., Watney, W.L., Kendall, C.G.St.C., and Ross, W., Sedimentary Modeling: Computer simulations and methods for improved parameter definition, Kansas Geological Survey Bulletin 233, p. 254-262.

Attachment G: Watney, W.L., Wong, J.C., French, J.A., Jr., 1991, Computer simulation of Upper Pennsylvanian (Missourian) carbonate-dominated cycles in western Kansas: in, Franseen, E.K., Watney, W.L., Kendall, C.G.St.C., and Ross, W., Sedimentary Modeling: Computer simulations and methods for improved parameter definition, Kansas Geological Survey Bulletin 233, p. 415-428.

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FORWARD

The results reported on below for the second year of this grant reflect a team effort including individuals from the Kansas Geological Survey, The University of Kansas, and The University of Iowa. These researchers include Don Baars, Ross Black, John Doveton, Howard Feldman, Evan Franseen, John French, Willard Guy, Philip Heckel, Rick Miller, Lynn Watney, and Jan-Chung Wong. Student assistants who have contributed to various tasks during the last year include Rob Fillmore, Tracy Gerhard, Richard Harris, Dean Keiswetter, Lance Lambert, Mike Lambert, Larry Mason, and Ajit Verma.

ABSTRACT

Interdisciplinary studies of the Upper Pennsylvanian Lansing and Kansas City groups have been undertaken in order to improve the geologic characterization of petroleum reservoirs and to develop a quantitative understanding of the processes responsible for formation of associated depositional sequences. To this end, concepts and methods of sequence stratigraphy are being used to define and interpret the three-dimensional depositional framework of the Kansas City Group.

The investigation includes characterization of reservoir rocks in oil fields in western Kansas, description of analog equivalents in near-surface and surface sites in southeastern Kansas, and construction of regional structural and stratigraphic framework to link the site specific studies. Geologic inverse and simulation models are being developed to integrate quantitative estimates of controls on sedimentation to produce reconstructions of reservoir-bearing strata in an attempt to enhance our ability to predict reservoir characteristics.

Findings include:

1) Minor stratigraphic cycles (small-scale sequences and parasequences) and the associated subtle bounding surfaces that occur within major depositional sequences strongly influence porosity and permeability distribution in petroleum reservoirs.
2) The local structural setting significantly influenced the development of reservoir facies and provided the locus for oil migration and charging. Understanding the migration and charging patterns alone may be a critical factor in successfully characterizing reservoirs of marginal quality and those that reside in zones of transitional oil saturation.
3) The reservoir characteristics of carbonate grainstones, particularly oolites, commonly vary markedly due to complex associations among large-scale stratal sequences and minor cycles, sedimentary parameters (e.g. grain type, size, and sorting), early and late diagenesis, and contemporaneous relief within the field.
4) Time-series analysis of natural gamma ray logs of twenty Middle and Upper Pennsylvanian depositional sequences (upper Cherokee, Marmaton, and Lansing-

Kansas City groups) reveals both long- (2nd- and 3rd-order) and short-term (4th-order and higher) periodicity. The stratal signatures correlate closely with progradational and retrogradational carbonate and siliciclastic events that are well preserved along the shelf margin in southern Kansas and northern Oklahoma. Accordingly, this stratigraphic signal is interpreted to reflect relative sea-level history, which is a critical variable for successful stratigraphic simulation modeling.

5) Inverse methods show promise with regard to deriving sediment accumulation rates for depth-based, log-derived facies (electrofacies) and actual depositional facies.

6) Presentation format of the 2-D forward stratigraphic model, operational on the personal computer, has been refined. The model is being extended to the workstation.

EXECUTIVE SUMMARY

The difficulty in accurately predicting reservoir heterogeneity at interwell scales is a significant hinderance in improving oil recovery from existing fields. The problem of reservoir prediction is in many cases related to not integrating the geology of a reservoir into the large-scale geologic framework that the field fits into. The premise of this investigation is that an improved ability to predict reservoir properties can be accomplished when more precise and accurate knowledge of the reservoir framework is realized.

Many advances have been made in sedimentary geology that have not been or are only beginning to be incorporated and tested in oil-field-scale applications. These include: 1) the use of depositional-sequence analysis in the context of interdisciplinary studies to develop the high-resolution time stratigraphy needed for more precise correlations and quantitative modeling; 2) the application of methods such as time-series analysis and inversion techniques along with simulation modeling to develop an improved understanding of the larger-scale stratal packages that include the hydrocarbon reservoirs; 3) utilization of very high resolution seismic methods for characterization of analog stratigraphy.

Studies of oil fields and near-surface analogs are being linked with regional structural and stratigraphic framework. The latter is providing information on the regional controls that have affected sedimentation. An update and reinterpretation of the basement structure is underway to improve our understanding of the structural and subsidence history to better define the impact of structure on reservoir development. Sequence-stratigraphic mapping at specific sites as well as across the entire area is providing a frame-by-frame view of the geologic setting during deposition of temporally distinct stratigraphic units that both encompass and subdivide the petroleum reservoirs.

Near-surface and surface analog studies of oolitic grainstone and phylloid-algal carbonate units in the Upper Pennsylvanian Kansas City Group in southeastern Kansas include outcrop description, coring and wireline logging, high-resolution seismic surveys, and core analysis including porosity-permeability and stable isotopes. The objective of the analog studies is to evaluate the 3-D heterogeneity at the field and intrafield scales. The results include characterizing the geometries of stratal units and establishing their relationships to sea-level change and shelf configuration, orientation, and slope.

Studies of producing fields have included detailed correlation and stratigraphic mapping, derivation of reservoir properties from wireline logs, cores, core analysis, drill stem tests, and production information. Mapping the spatial distribution of reservoir properties has also been initiated with the goal of correlating these properties to information on sedimentology, stratigraphy, diagenesis, and structure revealed in these investigations.

Computer-assisted inverse modeling is being done to quantitatively resolve geologic processes behind the observed stratigraphic framework defined in this study. A goal is to establish the limits of deterministic process-based stratigraphic modeling. Techniques such as time-series analysis are showing promise in helping to identify and understand the causal mechanisms responsible for the observed stratigraphy and reservoir framework.

OBJECTIVES

The objectives of this research are to: 1) assist producers in locating and producing petroleum not currently being produced because of technological problems or the inability to identify details of reservoir compartmentalization, 2) to decrease risk in field development, and 3) accelerate the retrieval and analysis of baseline geoscience information for initial reservoir description. The interdisciplinary data sought in this research will be used to resolve specific problems in correlation of strata and to establish the mechanisms responsible for the Upper Pennsylvanian stratigraphic architecture in the Midcontinent. The data will better constrain ancillary problems related to the validation of depositional sequence and subsequence correlation, subsidence patterns, sedimentation rates, sea-level changes, and the relationship of sedimentary sequences to basement terranes. The geoscientific information, including data from field studies, surface and near-surface reservoir analogues, and regional database development, will also be used for development of geologic process-based computer simulation models tailored to specific depositional sequences for use in improving prediction of reservoir characteristics.

INTRODUCTION

Statement of Problem

The difficulty in accurately predicting reservoir heterogeneity at interwell scales is a significant hinderance in improving oil recovery from existing fields. In part, the problem stems from limited sampling and spacing of wells in a field. Engineering data such as pressure testing and performance analysis can be used to constrain the heterogeneity of a reservoir, and seismic data (where available) are useful in defining barriers such as faults and bedding. However, the prediction problem is in many cases related to our lack of integrating the geology of a reservoir into the larger-scale geologic framework. Aspects of this framework that we believe are especially important in the detailed evaluation of individual hydrocarbon accumulations are the stratigraphic, sedimentologic, diagenetic, and structural setting that pertain to each reservoir.

Summary of Research Approach

The premise of this investigation is that an improved ability to extrapolate and interpolate reservoir properties can be accomplished when a more precise and accurate knowledge of the geologic framework of the reservoir is available. In particular, a quantitative estimate of the controls on reservoir development can be used to generate a geologic model to test these estimates and evaluate reliability.

Many advances have been made in sedimentary geology that have not been or only are beginning to be incorporated and tested in oil-field-scale applications. These include: 1) the use of depositional sequence analysis in the context of multi-scale, interdisciplinary studies to develop the high-resolution time stratigraphy needed for more precise correlations and quantitative modeling; 2) the application of inversion techniques including time-series analysis and stratigraphic simulation modeling to develop an improved understanding of the larger-scale stratal packages that include the hydrocarbon reservoirs; 3) utilization of very high resolution seismic methods for characterization of analog stratigraphy.

Interdisciplinary studies of the Upper Pennsylvanian Lansing and Kansas City groups have been undertaken in order to improve the geologic characterization of petroleum reservoirs and to develop a quantitative understanding of the processes responsible for development of the depositional sequences that include important oil and gas reservoirs. The concepts and methods of sequence stratigraphy are used to define and interpret the three-dimensional depositional framework of the Kansas City Group; an important part of this study is the linking oil fields in central and western Kansas with easily studied near-surface and surface analogs in southeastern Kansas. Geologic simulation modeling is used to integrate quantitative estimates of controls on sedimentation to produce reconstructions of reservoir-bearing strata.

Analog studies of oolitic grainstone and phylloid algal carbonate units in the Kansas City Group in southeastern Kansas include outcrop descriptions, coring and wireline logging, high-resolution seismic reflection surveys, and porosity-permeability and stable carbon and oxygen isotopic analyses of core. The analog studies have permitted the construction of field- and interfield-scale, three-dimensional descriptions of complex stratal geometries in units that contain reservoir-quality rock. In order to accomplish this, seismic surveys and existing field-scale well distribution have been used to position core holes in strategic parts of the reservoir analog unit. We have been able to attain seismic resolutions of 1 meter vertically and 5 meters horizontally.

Regional mapping is used to link producing fields with the sites of analog studies and to evaluate with a high degree of resolution the controls on sedimentation, early diagenesis, and structural development of reservoir strata. The result is essentially a frame-by-frame view of the geologic evolution of these hydrocarbon reservoirs. This helps to establish correlations among the four-field study and two analog study locations.

Computer modeling continues to be an important part of the research effort. It includes 3-D visualization using the graphic workstation coupled with our stratigraphic model that simulates 11 carbonate facies; this facilitates comparisons of interpretations with the actual geology. The forward modeling is being refined during this study through the development and application of inversion methods that allow for the extraction of information on geologic processes, improving our ability to predict stratal characteristics.

Field investigation has consisted of detailed stratigraphic correlation and mapping, and derivation of reservoir properties such as effective porosity, pore type, water saturation, permeability using wireline logs, core analysis, drill stem tests, and production information. Also included to date is initiation of mapping of reservoir properties to better understand spatial distribution. Goal is to correlate distribution of reservoir properties to information on sedimentation, stratigraphy, diagenesis, and structure.

Summary of Results

Findings to date that are deemed useful in improving our understanding of reservoir heterogeneity are described in more detail below. The findings include:

1) Multi-scale reservoir heterogeneity is related to sedimentation and early diagenesis associated with separate, time-distinct carbonate depositional sequences in the Kansas City Group;
2) Minor cycles (small-scale sequences and parasequences) and the associated subtle bounding surfaces that occur within major depositional sequences strongly influence porosity and permeability distribution.
3) The local structural setting significantly influenced the development of reservoir facies, and provided the locus for oil migration and charging. Understanding this alone may be a critical factor in characterizing reservoirs of marginal quality and those that reside in zones of transitional oil saturation.
4) The reservoir characteristics of carbonate grainstones, particularly oolites, commonly vary markedly due to complex associations among large-scale stratal sequences and minor cycles, sedimentary parameters (e.g. grain type, size, and sorting), early and late diagenesis, and contemporaneous relief within the field.
5) Time-series analysis of natural gamma ray logs of Middle and Upper Pennsylvanian depositional sequences (upper Cherokee, Marmaton, and Lansing-Kansas City groups) reveals both long- (2nd and 3rd order) and short-term (4th order and higher) periodicity. The stratal signatures correlate closely with progradational and retrogradational carbonate and siliciclastic events that are well-preserved along the shelf margin in southern Kansas and northern Oklahoma. Accordingly, this stratigraphic signal is interpreted to reflect relative sea-level history, which is a critical variable for successful stratigraphic simulation modeling. Its cause(s) (subsidence or eustacy or some combination of both) are being evaluated. Forward models can explain observed stratigraphic patterns as a result of the dynamic interaction of shelf elevation and subsidence, eustasy, and sediment accumulation rate.
6) Inverse methods show promise with regard to deriving sediment accumulation rates for depth-based, log-derived facies (electrofacies) and actual depositional facies. The accumulation rate will be used to convert the stratigraphic-depth section to time. The

goal is to develop tailored sea-level curves for specific reservoir-bearing stratigraphic intervals for use in forward modeling. Periodicity observed from results in (5) above will allow for independent estimates of sequence character and timing.

7) The presentation format of 2-D forward stratigraphic model, operational on the personal computer, has been refined. The model is being extended to the workstation to permit rapid calculation. A major objective of modeling is to be able to test and experiment with data to develop an improved geologic interpretation to be used in predicting details of the spatial distribution of reservoir characteristics.
8) Building and testing quantitative sedimentary and stratigraphic models requires new types of stratigraphic databases characterized by increased precision and accuracy. Correlation of regionally and locally correlable, time significant depositional sequences is demonstrated here to be feasible from a practical standpoint serving as the foundation for modeling.

RESULTS OF RESEARCH

Subtask 1. Field Screening and Reservoir Analogue Identification

1.A. Field Selection

Selection of fields producing from the Lansing-Kansas City groups was completed during the first year. The four fields selected (Cahoj, Victory, Pen, and Collier Flats) represent the upper and lower shelf areas in central and western Kansas and include major producing trends. The field studies focus on determining the sequence-stratigraphic framework, and defining the structural setting, reservoir facies, and associated diagenesis. The studies are a compilation of existing data and development of sequence stratigraphic and reservoir information. The goals are : 1) describing reservoir heterogeneity for use in explaining field performance; 2) serving as control points for modeling geologic details (and reservoir development) within the depositional sequences at the various shelf positions; and 3) relating this data in defining trends with similar reservoir attributes so that analog relationships can be established among fields.

1.B. Near-Surface and Surface Reservoir Analogue Selection

Near-surface and surface locations of strata in the Kansas City and Pleasanton groups in eastern Kansas were selected to serve as analogs to the reservoirs in age-equivalent strata in oil fields of western Kansas (Figure 1.1). Specifically, the Drum Limestone (Westervale Limestone-Cherryvale Shale) and the Dennis-Swope-Hertha sequence set were chosen for detailed examination at selected sites (Figure 1.2). These units contain oolitic grainstones that are similar to the actual reservoir facies in coeval strata to the west. An extensive set of cores, seismic data, and porosity-permeability data from the cores have been acquired to improve understanding of the stratigraphic architecture, spatial distribution, and selected internal characteristics of these grainstone reservoirs for use in developing more precise and accurate quantitative process and analog models for reservoirs in western Kansas.

Subtask 2. Depositional Sequence Characterization

2.A. Near-Surface and Surface Reservoir Analogues

2.A.1. Hertha, Swope, and Dennis Limestone Project

Methodology. Depositional sequences were previously correlated in the Kansas City and Pleasanton groups in eastern Kansas and mapped regionally from the Kansas City area to the Oklahoma border. This sequence mapping from near 800 wells runs from the outcrop to some 50 miles westward and covers over 18,000 mi^2. This stratigraphic framework and associated outcrops along with cores provided the means to establish the paleogeographic setting and identify possible near-surface and surface reservoir analog sites.

The focus for this project in the last year was on the Swope (Bethany Falls and Mound Valley) oolitic grainstones developed along a clearly dipping depositional surface constrained by good outcrop and excellent subsurface control. An additional 1580 feet of core and associated wireline logs were taken, including a set of 6 cores at 20- to 40-acre offsets, to obtain a more detailed picture of the oolites and to further define and interpret the three-dimensional stratal architecture in the Lower Missourian depositional sequences. Total core cut for this particular project is over 5000 feet.

Cores have been slabbed, polished, and described. One-inch plugs were taken from the oolitic grainstones for porosity and permeability analysis carried out by a commercial laboratory. Arrangements were also made for carbon-oxygen isotopic analysis after the cores were described. The purpose of the isotopic analysis is to characterize the bounding and internal surfaces in and surrounding the oolitic units so that more precise geologic interpretations of these surfaces and associated diagenesis could be made. Two by 3-inch thin sections of representative genetic units, depositional facies, diagenetic textures, and porosity types, primarily within the oolites, have been made, and analysis of this data is ongoing.

Nine short (ave. 150 feet), continuous cores were taken along two transects crossing one of a series of northwest-southeast trending oolite bars in the Bethany Falls Limestone in Bourbon County. Mapping of these oolites has been based on existing log control from wells drilled to underlying Cherokee Group oil reservoirs coupled with outcrop control. This strike-oriented belt of oolitic grainstone overlies a depositional slope that resulted from thinning of the underlying Pleasanton Shale. There may be as many as three separate belts of oolite that developed at different paleoelevations along the Pleasanton slope. The selected coring site is located in a relatively downslope position within an area of excellent subsurface control, which allowed for precise locating of cores. The dimensions of the bar selected to be cored are approximately 4 miles long by 1.5 miles wide (Figures 2.1 and 2.2).

More detailed map of the Pleasanton Shale thickness in an eight township area in western Bourbon and eastern Allen County. The previous mapping and interpretation determined that this thickness essentially defines the topography on which the oolite was deposited. Additional maps of the oolitic units were done to resolve more details of the spatial distribution of the oolites.

At least two stacked oolitic grainstones are present in this particular bar, with the upper one apparently not extending as far shelfward (eastward) on the bar crest. The detailed stratigraphic relationships between the upper and lower oolites were revealed in a half-mile-long north-south transect of six cores that began near the center of the bar and extended northward to within a few hundred feet of its pinchout. Index maps (Figures 2.3 and 2.4) locate the six cores that were taken at 20 acre (or less) offsets. This locality was identified from closely spaced well logs related to an oil field in an underlying north-south-oriented shoestring sandstone within the Cherokee Group.

Figure 2.4 is a cross section comprised of graphic core descriptions of the six wells. A paleosol and inferred sequence boundary separate the two oolites on the southernmost core, defining what are probably the Mound Valley Limestone above and the Bethany Falls Limestone below. The Mound Valley is a minor marine cycle that laps out updip along the shelf in southeastern Kansas and thickens into a nonporous algal wackestone in a downdip direction. The Mound Valley and Bethany Falls limestones were deposited during different sea-level events. It is possible that the upper porous oolite is within the Bethany Falls, with the Mound Valley missing over the high created by the stacking of the two oolites; work aimed at determining the exact relationships among these units is ongoing.

The cores northward on the transect (keeping in mind that separation is less than 20-acre spacing) indicate a more subtle division of the two oolites due to loss of the paleosol and thinning of the upper oolite. Petrographic examination reveals that there are significant differences in grain composition and diagenesis, with variable development of effective porosity, in these two oolites. Even though they are in close vertical proximity their diagenetic histories are considerably different.

Oxygen and carbon stable isotope profiles are available for two of the cores (Woodward #2 and Woodward #3) in the Woodward transect (Figures 2.5 and 2.6). Two oolites separated by a thin, nonporous, finer-grained interval occur in both cores, but in the Woodward #3 there is no paleosol separating the oolites as there is less than 1000 ft to the south in the Woodward #2. An important question concerns whether there is any indication that a period of subaerial exposure preceeded deposition of the upper oolite in the Woodward #3; evidence of such exposure would suggest that the two oolites were deposited during different sea-level events, rather than as a stacked couplet of oolite that merely represented the migration of individual bars within one related complex. The isotopic data reveal unmistakable negative shifts in the carbon isotope profiles immediately below the paleosol in Woodward #2 and below the muddy, finer-grained zone in Woodward #3. If fact, the shift in Woodward #3 is one of the better examples. In addition, the oxygen isotope profile shows a slight positive shift beneath the finer-grained zone.

The significance of these relationships is that the muddy zone immediately overlies a subaerial surface which is very likely a sequence boundary that reflects a sea-level fall, subaerial exposure, and subsequent sea-level rise. The lower oolite was subjected to different early and late diagenetic conditions than was the overlying oolite. Moreover, this bounding surface appears to be associated with an impermeable zone that is relatively widespread. Because the two oolites appear to have experienced very different diagenetic histories, the zone probably has been a barrier to fluid flow throughout the history of these units at this location. It would be an effective lateral seal in other areas unless fractured.

These isotopic profiles are accompanied by detailed comparisons of depositional and diagenetic facies in thin section and polished slabs, and with porosity and permeability analyses. Very tentative observations and hypotheses regarding the distribution of porosity and permeability in the Bethany Falls/Mound Valley limestones in the KGS Woodward #3 core are as follows (Figure 2.7):

1) Porosity is dominantly oomoldic. There is little primary porosity left in these rocks, and it is common for the oomoldic porosity to have been reduced or occluded by calcspar. More on porosity follows.
2) Permeability is positively correlated with porosity. There appears to be a jump in permeability from sub-1-md values to higher values at about 20% porosity. This is seen in other cores as well, including the Woodward #4.
3) Porosity and permeability are positively correlated with average grain size and sorting. Intervals characterized by relatively coarse, well-sorted grains (dominantly ooids but with some skeletal grains as well) tend to have porosities >20%, with correspondingly high permeabilities.
4) Near the base of the lower oolite there are zones of relatively coarse, well-sorted grainstone (see figure), but many of the oomoldic pores have been occluded by baroque dolomite and silica cements. These cements are much less common in other zones.
5) The proportion of neomorphosed ooids seems to be relatively high in the finer-grained grainstones, indicating the possibility that fluid flow was much less dynamic in those lithofacies as compared to the coarser, better-sorted sediments. Higher rates of flow of fresh water may have resulted in more wholesale dissolution of ooids in the coarser lithofacies.

6) The most porous units are cross-stratified grainstones that are in general less than a meter thick. Significant differences in porosity and permeability can occur over very short distances at boundaries between coarse- and fine-grained bedsets (e.g. at about 77 ft in the core).

A preliminary conclusion to be further detailed in subsequent study is that the internal reservoir stratigraphy in this near-surface analog site exerts obvious control on the field-scale reservoir character. A clear understanding of these variations in terms of genesis and distribution will only be realized after integrating these local scale results with the regional-scale sequence stratigraphic analysis.

Cross sections, maps, and other displays were prepared for presentation at the Mid-Continent AAPG meeting held in Wichita. Presentations on intermediate results of this research were made at the Mid-Continent AAPG convention in a core workshop (French, 1991), poster and oral sessions (French and Watney, 1991). A copy of the paper by French (1991) is Attachment A.

A short paper describing the "Woodward transect" was also submitted for publication in the proceedings of The Third International Reservoir Characterization Technical Conference to be held on Nov. 3-5 in Tulsa (French et al., 1991).

Thirty-seven well logs were digitized through the Kansas City and Pleasanton groups in a six township area encompassing the "Woodward transect" described above. Objective is to further examine spatial variation and gamma ray and porosity distribution along this shelf-to-basin transition using 3-D software (Stratamodel™) on the graphics workstation. Digital data have been input into the workstation and preliminary analysis of this data completed. Sequence boundaries were correlated and entered as gridded surfaces into the program. The program interpolates the depth-based and sequence-constrained well attributes to a regular grid. The program is then used to view surfaces, cross sections, and 3-D panels from the area. The image can be manipulated freely to better understand spatial relationships. The preliminary results are discussed in Subtask 5 (Figures 5.9, 5.10).

A grid of new regional and local scale cross sections was prepared to aid in maintaining correlations of small-scale stratigraphic units (Figure 2.8). Multiple intersections are being used to verify correlations. Wells used in sections are tied to core- and outcrop-based correlations.

Plans include preparing several major manuscripts that will capture the latest results and help direct the remaining efforts to compare the analog sites with the actual reservoirs in western Kansas. The tentative titles of these papers are "Porosity distribution within an oolite reservoir analog, lower

Kansas City Group, southeastern Kansas" and " Characterization of depositional sequence development, lower Kansas City Group, southeastern Kansas."

Additional mapping, petrographic work, isotopic and porosity and permeability analyses continue. Further testing and development of computer stratigraphic simulation models is continuing based on this analog site, including the analysis of stratal stacking patterns beneath the oolitic grainstone and the development of the oolitic grainstone itself. In addition to understanding reservoir heterogeneity, other objectives of the combined geologic analysis and modeling effort at this analog site are:

1) to improve parameter definition based on a high resolution 3-D database;
2) to develop and test inverse modeling procedures to be able to more objectively refine parameters that are input into simulations and thereby expedite characterization of the sequence.

Coring and logging will continue during the third year to refine interpretations of the sequence stratigraphy at the other analog site of the Hertha-Swope-Dennis interval in Wilson County and to examine the western, updip portion of the oolite bar described above in Bourbon County.

The emphases of the final coring phase are on:

1) characterizing the shelf-slope-basin transition in the Sniabar Limestone, which ranges in thickness from less than 1 foot to over 90 feet across the study area. The abrupt thinning of this bank complex has affected the overlying Swope sequence, which thickens and changes facies basinward;
2) investigating apparent minor cycles within the Sniabar Limestone that have been recognized on well logs. These cycles occur in a relatively back-bank position, and include a porous unit that may be oolitic (in contrast to most of the Sniabar, which is dominantly algal);
3) understanding more fully the facies and distribution of oolitic low-order sequences and parasequences in the Bethany Falls and overlying Mound Valley limestones. There may be as many as three minor cycles within this succession, including stacked, possibly tidally influenced buildups that in places mimic actual reservoir development in fields in the western Kansas subsurface;
4) delimiting the relationships between the development of multiple grainstone units in the Winterset Limestone and the occurrence of shallowing-upward stratal units (probably parasequences) and deepening-upward units (probably retrogradational parasequences that comprise a previously unrecognized backstepping transgressive deposit) that characterize this unit.

The new coresite at the Swope oolite analog site will serve to test our ability to predict at this stage where and how oolite is developed. A corehole will be taken midway between a set of existing coreholes, along what is believed to be the axis of a single elongate, dip-oriented oolite bar in the Swope Limestone (Figure 2.9). Alternatively, the oolites east and west of the proposed core location may be portions of separate bars, with oolite thin or absent at the core site. The core would: 1) confirm the orientation, composition, and state of diagenesis of the oolite (if present), e.g., the updip vs. downdip diagenetic variability, and 2) if upper Mound Valley oolite is present at the core location, the site would provide constraints on the nature of the Mound Valley oolite at its westerly updip limit, including its contacts with the underlying Bethany Falls oolite and the overlying Galesburg Shale (see cross section in Figure 2.10).

The significant vertical stratigraphic separation of these oolites and their lateral discontinuities, which occur at an oil-field scale, are providing a very important perspective and working model that is being applied to improve understanding of heterogeneity in oil fields for equivalent reservoirs, namely in Victory and Collier Flats fields (both with Swope oolite reservoirs) that are presently being studied in western Kansas.

The other two coresites are located at a lower shelf to mid-slope location during early Kansas City deposition (Figure 2.11). A wireline log from a well adjacent to the proposed core site exhibits a distinctive and high-fidelity record of sedimentation in the lower Kansas City Group (including the Sniabar, Swope, and Dennis cycles) (Figure 2.12).

The proposed core site is situated on the northern (landward) portion of a thick (80+ ft) carbonate bank developed in the Sniabar Limestone (Figure 2.11). The carbonate bank sits just basinward of the Pleasanton "shelf margin" in southeastern Kansas. The log from an oil well adjacent to the proposed core site indicates cyclicity and porosity development in the Sniabar Limestone. The porosity development is potentially significant because the log character of the porous zone at this locality strongly resembles the oolitic porosity so common in the Swope and Dennis limestones, but which has not yet observed in the Sniabar Limestone in southeastern Kansas. In addition, we desire to know more about the depositional environment of the back-bank area to see if it is consistent with the surface exposures and cores to the east and south. The nature of the internal cyclicity in the Sniabar is very clearly developed in the well log; this is important because unequivocal examples of such "minor cyclicity" have not been observed in the Sniabar to date. The core would help to firm up our interpretation of the succession of stratigraphic events for incorporation in the simulation model. As mentioned, the stratigraphic and depositional characteristics of the porosity development at this shelf location are also important to our overall understanding. Similar porosity development produces at greater depths to the west, but has not been observed as yet in surface exposures or cores.

The Swope and Dennis limestone also exhibit high-fidelity interval cyclicity and porosity development at this mid-slope position. The site is situated along a thick, bank-margin carbonate buildup of the Dennis Limestone. The site represents a lower shelf position during the Swope Limestone deposition, but landward of the shelf margin. While it is unusual for the Swope to have evidence of internal cyclicity as suggested by the well log, the Dennis is commonly characterized by multiple stratigraphic packages across the shelf. However, what is unusual here is the greater thickness and stacking of porous intervals in the Dennis Limestone.

This stratigraphic resolution coupled with porosity makes this an ideal site for several reasons. The core hole would 1) reveal a detailed record of processes suited for simulation modeling, 2) document depositional facies and nature of porosity in the Dennis bank and mid-shelf development of the Swope Limestone, and 3) provide a clearer understanding of the interaction of topography, elevation, and sea-level change when integrated with other sampled sites of the upper (Kansas City area) and lower shelf (Wilson to Bourbon County).

This last potential core site is at a feature that has intrigued us since is was mapped and nearby cores taken, one on the crest of a 80+ foot-thick carbonate bank and the other off the toe of the bank. The proposed corehole resides between the bank-crest core and the basin core (Figure 2.13). We desire to identify the depositional facies associated with basinward face of the carbonate bank and the nature of the stratigraphic packaging of the bank and overlying units.

The slope break along the Sniabar bank at this proposed core site presently exhibits dips of over 40-feet per mile to the south over a lateral distance of two miles, with local dips of > 100 ft/mi (> 1 degree). This degree of depositional topography which occurred at the end of Sniabar time is great by Kansas standards, forming the precipitous "Sniabar bank margin".

The Sniabar carbonate bank was accredited to the shelf margin where relief was accentuated by thinning of the underlying Pleasanton Group shales. The Sniabar bank complex extended the shelf margin basinward about 15-20 mi (over roughly 300,000 years) and has been the object of both conceptual and simulation models. The core site is at the leading edge of the bank's break in slope, and therefore predominately high-energy carbonate deposits consisting of well-washed packstones and grainstones and that contain biota such as coral colonies may be present. This additional core hole will help us understand the nature of this steep carbonate margin along a major bank buildup which is not developed along the outcrop.

This last core site is also important from the standpoint of documenting the abrupt stratigraphic change in the overlying Swope and Dennis cycles that resulted from the topographic relief created by the Sniabar bank (Figure 2.13). Problems addressed by this core include: 1) additional documentation of the stratal changes in the Hushpuckney Shale, normally a very continuous and uniform black shale; 2) sampling the marked change of the Bethany Falls Limestone between a thin, porous crestal unit at bank crest to non-porous algal limestone in a more basinal core, e.g. the Gaddy well in Figure 2.13; 3) sampling the Ladore and Galesburg shales in position of change from relatively thick basin-filling facies to attenuated deposits over the bank crest; 4) sampling a position of maximum change in thickness (between 4.5 and 25 feet thick) of the Canville Limestone, a normally thin (1-3 ft. thick) marine flooding unit.

2.A.2. Drum Limestone Project

The Drum Limestone overlies the Dennis Limestone and underlies the Dewey Limestones of the Upper Pennsylvanian Kansas City Group in southeastern Kansas. The analog site is located in an area down slope from what is currently interpreted as the shelf margin of the underlying Dennis Limestone (Figure 2.14). The Drum Limestone is developed in the superjacent depositional sequence that began another episode of southward progradation of the carbonate-dominated shelf margin toward the basin.

Activities during the second year of the Drum project included acquisition of additional surface and subsurface data. Cores and seismic profiles were taken in the vicinity of Independence, Kansas, and a subsurface stratigraphic database for Montgomery County continued to be developed utilizing available wireline logs. Thin sections of major facies associated with the grainstone of the Drum Limestone have been made. Preliminary maps of the Drum Limestone and associated strata are in preparation.

The thin sections and other lithologic data collected will be the object of further study during the third year. Processing and modeling of the seismic data will also take place during the third year. Additional coreholes are also planned. Subsurface data in Montgomery County will be integrated into the larger sequence-stratigraphic database of lower Missourian (Pennsylvanian) strata being developed for the near-surface analog area in southeastern Kansas.

As more information is gathered, the three-dimensional distribution of oolitic grainstones within the Drum Limestone has been found to be quite complex. This necessitates more detailed study in order to adequately characterize the Drum such that predictions can be made. The nature and distribution of bounding surfaces within the Drum, as well as the unit's depositional history, are the objectives of the continuing seismic, surface, and subsurface geologic investigation.

Only three of seven planned cores were acquired late in the first quarter due to wet weather and poor field conditions. The three cores that were obtained range from 250 to 300 feet in length and contain the entire Drum Limestone interval. The cores are located along a north-south transition where the Drum Limestone thickens from just several feet of nonporous skeletal wackestone in the north to over 60 feet of porous oolitic skeletal grainstone to the south (Figure 2.15). Depth to the top of the Drum ranges from 150 feet to 300 feet below the surface, making it ideal for very high resolution seismic data acquisition. Previous mapping from nearby well-log control and seismic data indicates a thick lens of Drum Limestone encased in a rather uniform shale package (the Cherryvale Shale). The core transect is perpendicular to the east-west elongate trend of the Drum Limestone buildup.

An earlier core, the #2 Clarkson, located 1/2 mile south-southeast of the south end of cross section A-A' (Figure 2.15) recovered no Drum Limestone. Thus the cross sectional geometry of the Drum Limestone appears to be sigmoidal, as it thins both northward onto thick underlying shale and southward of the core transect as the underlying shale continues to thin (Figures 2.16 and 2.17).

Pertinent aspects of reservoir development that will be addressed include 1) more fully defining the geometry and nature of the stratigraphic surfaces; 2)understanding the conditions under which the grainstone formed; 3) finding whether the geometry had been modified by subsequent erosion; 4) determining the degree of predictability of reservoir quality rock development at the field and inter-field scale.

Five additional cores were taken during the third quarter at the main locality near Independence, Kansas. These cores were slabbed, described and analyzed. Data from Numerous well logs were analyzed and isopach maps were generated in order to plug these cores into our current understanding of the three-dimensional distribution of the Drum. Preliminary petrographic studies have been conducted which have concentrated on lithologic and diagenetic features.

Field work was done and data were analyzed in preparation for the field trip led for the Mid-Continent Section of AAPG on September 21. A field trip guidebook entitled "Stratigraphy and depositional history of the Drum Limestone and associated strata (Pennsylvanian) in the Independence, Kansas, area -- A field trip guidebook and roadlog" was written; it is available as Kansas Geological Survey Open-File Report 91-45 (Feldman and Franseen, 1991) (See Attachment B, open file report 91-45). Other results from this reservoir analog study were also presented as a display at the core workshop held at this same meeting on September 22.

A high resolution seismic line was shot along a 300-meter transect near Independence, Kansas during the third quarter. Shallow seismic-reflection experiments were also conducted near Independence to determine the necessity and potential of collecting data in a split-spread 48 channel format as opposed to the end-on 24 channel recording previously tested at the site. The data were collected during August of 1991 and consisted of approximately 150 shot points that were recorded on two 24 channel

EG&G Geometrics seismographs operated in tandem to simulate a single 48 channel system. The data record length was 250 msec with a sampling interval of 0.5 msec. The source was an experimental version of an auger gun (developed at the Survey) that fires 8 gauge black powder blank loads at a depth of 0.6 m. The receivers were strings of 3-40 Hz L28E Mark products geophones spread across a 1-m array with station spacings of 2.5 m. The source-to-nearest receiver was approximately 10 m. The data was recorded with 35-Hz analog low-cut filters and 500-Hz high-cut filters. The split-spread geometry was designed to improve dip control and velocity variability within the upper 100 m.

The reflections present on filtered field files possess dominant frequencies in excess of 180 Hz and therefore bed resolution of less than 1 m at this site (Figure 2.17). At least four strong reflection events can be interpreted above 100 msec. The apparent variation in arrival patterns on opposite sides of the source in this split-spread geometry are indicative of dipping beds and/or velocity variability. The exact cause of the non-uniformity in arrival patterns observed between the forward and reverse going energy can be determined and compensated for during CDP processing. A split-spread geometry is essential in order to accurately determine bed geometries and subtle stratigraphic features from seismic data at this site. The depth of interest and necessity of reflection coherency dictates the use of at least 24 channels per side with a spacing of between 2 and 3 m. This experiment will greatly assist in the acquisition of two 1-mile production high resolution lines to be collected in late October and November. Kansas Geological Survey Open-File Report 91-36 on resolution of the seismic data was written and submitted (Miller et al., 1991) (Figure 2.18). A copy of this paper is included as Attachment C. Another paper addressing the normal moveout stretch mute on shallow-reflection data was submitted to Geophysics (Miller, submitted) and is attached here as Attachment D.

Two additional very-high-resolution seismic lines were taken along a north-south line at the Drum analog site during the fourth quarter. These 3/4-mile-long lines were acquired through the thickest development of the oolitic facies using a 50-caliber and black powder source. A 48 channel field file was collected with a digital 15 bit Geometrics 2401x signal enhancing seismograph, giving 4800-fold information. Accordingly, data quality was improved.

The representative field file possesses several reflecting events with dominant frequencies in excess of 150 Hz (Figure 2.19). The potential resolution along this line is approximately 15 ft vertical and 15 to 20 ft horizontal. The reflection at approximately 25 msec is from a depth of about 70 ft. The reflection from 65 msec is from around 200 ft. A total of just over 1000 shot points was acquired along two lines separated by less than a mile. The receiver spacing was 8 ft, resulting in a nominal 24 fold stacked section with 4 ft between CDP traces. The primary target of this survey was any acoustic contrast between 30 and 250 ft. From the example field file the potential for resolution of several reflecting horizons between 30 and 350 is excellent.

The surface work is nearly complete and much of the results to date were presented during an AAPG sponsored field trip and core workshop (see guidebook as Attachment B). The trip was attended primarily by petroleum geologists, and several commented that the oolite was similar to reservoirs they were or had been developing.

Surface work will continue in the third year. Subsurface data has been collected from all of Montgomery County. Additional data is now being collected from adjoining counties. The goal of this database is to provide information to interpret larger-scale geometries and facies in the Drum. The complications that were noted above make it imperative that this broader perspective be obtained. In addition, underlying units, particularly the Galesburg Shale, will be examined for evidence of depositional and tectonic controls on Drum distribution. This information will be synthesized with data from basement maps in order to determine if basement structures affected Drum deposition. Computer-generated isopach maps have been produced, but the results to date are not satisfactory because the algorithm cannot adequately handle the abrupt thickness variations that typify the Drum in this area, or the ranges in density of the data.

The seismic lines acquired in this project will be compared with synthetic seismic lines in order to test models of Drum geometry. The KGS Open File Report 91-36 will be combined with the synthetic seismic data and submitted to the journal Geophysics. Results of all seismic work will be presented at a the annual meeting of AAPG in Calgary (Feldman et al., in press, included here as Attachment E). A paper based on the abstract is scheduled for the AAPG Bulletin.

A diagenetic study of the Drum Limestone will soon be undertaken. This study will be done primarily by graduate students under the direction of Paul Enos. Thin sections from all facies present in both outcrops and core will be analyzed. This study will be combined with an investigation of the bedding and potential compartmentalization of the oolite as exposed in the main quarry wall at Independence (Figure 2.20).

Four additional cores will be obtained during the summer of 1992. Two will be along the seismic lines, with the exact position of the cores depending on the results of seismic analysis. The two other cores will be taken along the outcrop belt and will be used to obtain complete stratigraphic sections of the Drum interval where they are not available.

Structural deformation concurrent with deposition of the Drum Limestone continues to be evaluated in its role in localizing the oolitic grainstone buildup in the Drum Limestone. Mapping of basement (top of Arbuckle Group) done to date indicates several large northwest and northeast trending faults in the vicinity of the oolite buildup (Figure 2.21). Up to 900 feet of displacement are mapped across a fault that is nearly coincident with the location of the isopach thick of the Drum. Additional analysis of the possible relationships will continue.

2.B. Regional Mapping of Depositional Sequences

Files of gamma ray neutron-density logs have been prepared and most have been correlated in the "new mapped area" located along the southern portion of Kansas (Figure 2.21). Files of these modern neutron-density wireline logs has also been developed for western Kansas to supplement the existing database. The estimated number of well files added over the last year is around 1000.

The objective of the database is to establish a regional sequence-stratigraphic framework extending from the reservoir analog areas of southeastern Kansas to the region of significant Lansing-Kansas City oil fields in central and western Kansas. A goal of mapping and cross section construction using this database is to establish the regional sedimentary response to controls such as inferred slope and configuration of the shelf, subsidence, and sea level history. Another goal is to establish correlations of these aspects with basement structure and heterogeneity, and particularly with evidence of recurrent movement that may have affected sedimentation. Inverse procedures are being applied to this database to establish high resolution subsidence and relative sea level histories.

Cross sections have been prepared in addition to the previously prepared regional stratigraphic/structural cross sections indexed in Figure 2.21. The purpose of the new stratigraphic cross sections is to characterize individual sequences in the interval between the base of the Pennsylvanian strata and the Virgilian age (Upper Pennsylvanian) Heebner Shale (Figure 2.22) along the shelf-to-basin (north to south) transition. The interval of detailed correlation brackets the Lansing-Kansas City groups.

Maps will eventually be made of the characteristics of individual depositional sequences (e.g the Drum, Dennis, Swope, and Hertha) in the lower Kansas City Group that include reservoirs in the oil fields selected for study and which have been chosen for analog studies. Additional maps will be prepared of the thicknesses between major radioactive marine shale markers in the interval from the Oakley Shale in the Middle Pennsylvanian Cherokee Group to the Virgilian Heebner Shale. These larger-scale maps and the cross sections of relatively thick stratigraphic intervals are aiding in the assessment of the areally extensive and longer-term trends in sedimentation. Understanding such trends is important in order to characterize the mechanisms responsible for deposition of these sequences.

Several new pieces of information assembled in this study provide a new insight into how the stratigraphic architecture was developed, particularly in the shelf-to-basin transition. First, biostratigraphic work reported on last year in this study has confirmed many of the physical correlations established through the area in the previous cross-section preparation. The physical correlations are based primarily on tracing the marine black shales (condensed sections) between closely spaced wells. Secondly, results of detailed outcrop and shallow corehole descriptions and log correlations expressed through construction of maps and cross sections in the near surface analog studies have provided the key to detailing how the shelf-to-basin transition occurs. Third, the distinction of depositional sequences and condensed sections places the sedimentation events in a temporal framework which is helping to reconstruct events that led to the observed stratal geometries.

The shelf-to-basin framework that existed during Pennsylvanian time in the Midcontinent runs from north-to-south across Kansas. The major basins lie south of Kansas. To the southwest are both the Anadarko basin, with a structural axis centered in western Oklahoma and the Texas Panhandle, and the Arkoma basin, which is centered in eastern Oklahoma and central Arkansas. Thus within this structural framework an east-to-west traverse between the analog sites in eastern Kansas and oil fields to the west is essentially on strike . The structural framework is described more in a section on basement structure. A detailed understanding of the shelf-to-basin transition is critical with regard to understanding the interaction of regional processes such as eustatic sea-level change, basin subsidence, and sedimentation. This is due primarily to the large area over which stratal geometries are developed on the shelf margin, and to the fidelity of the stratigraphic record at these locations. These same variables also affected the detailed accommodation history on the shelf, in effect controlling reservoir development at the field sites examined. The sedimentary response at that scale is more subtle and difficult to define,however, and the relationship to process variables is more difficult to decipher. However, techniques are under development to resolve this problem, such as the use of Th/U ratios from natural gamma ray logs (discussed in a later section). Understanding these variables is crucial to our effort to develop process-oriented simulation models.

The literature that describes the development of these basins and surrounding shelf areas is significant and has been integrated with the present investigation. Pertinent results are summarized here to provide a perspective of the geologic history. The paleogeographic reconstruction by stratigraphic groups indicates that the carbonate shelf margin during the Middle Pennsylvanian (Late Desmoinesian) resided in northern Oklahoma (Figure 2.23). South of this margin was a basin in which siliciclastics were deposited. Rascoe describes this margin as a hinge line. By Middle Upper Pennsylvanian (Late Missourian), during the deposition of the Lansing Group, the carbonate shelf margin advanced shelfward, backstepping up to 100 miles northward into southern Kansas (Figure 2.24). The shelf margin during the Late Virgilian moved slightly more basinward (prograded) as compared to the Late Missourian (Figure 2.25). The recognition of shifts in shelf margin position at the stratigraphic group level is significant and suggests changes in the relative effects of processes such as subsidence, eustasy, and sedimentation.

Further comparison of the shelf margin history at a more detailed level in western Kansas by Rascoe (1962) shows that the Missourian shelf margin moved northward 50 miles (backstepped) during accumulation of the Kansas City and Lansing groups (Figures 2.26 and 2.27). Comparison of the shelf margin during deposition of the succeeding Virgilian Shawnee Group indicates that the shelf margin bordering the northern end of the Anadarko basin remained static while the eastern shelf prograded southward some 70 miles (Figure 2.28). By Wabaunsee time the shelf edge around the Anadarko basin had prograded to such a degree that only small restricted, enclosed area remained, defining the structural axis of the Anadarko basin in western Oklahoma (Figure 2.29).

The present study helps to sort out the timing of stratigraphic events and to resolve details of shelf and basin sedimentation. A south-to-north stratigraphic cross section comprised of gamma ray logs (Figure 2.30) was constructed from wells from the new database in eastern Kansas plus additional wells from northeastern Oklahoma to illustrate the carbonate shelf-to-siliciclastic basin transition. The index map for the cross section is found in Figure 2.24. The neutron-density curves accompanying the gamma ray were used to distinguish sandstones from limestones. However, these logs are not shown in this overview cross section overlying the Lansing-Kansas City. The datum is the Virgilian-age Heebner Shale found at the top of the section.

The Pennsylvanian stratigraphic succession is comprised of many depositional sequences, all of which are not resolved on this small-scale cross section. Typical depositional sequences have been documented in the outcrop and near surface from shelf-to-basin locations and are summarized in Figure 2.31. The shelf sequence consists of a thin basal flooding unit, which is overlain in succession by a marine shale (condensed section) and a highstand unit that is capped by a subaerial exposure surface. Thin, radioactive marine shales labeled along the side of the section with an asterisk (*) are correlatable across most or all of the shelf, including this section. These shales are thin, commonly black and radioactive, and are interpreted as sediment-starved intervals that were deposited during times of rapid flooding and marine submergence to a depth that precluded carbonate accumulation. The depth presumably was below the photic zone. The process of marine flooding itself may have encouraged the shallowing of the photic zone due to increased nutrient supply and organic matter production, leading to reduced clarity of the water column (Watney, et al., 1989). Accordingly, the thin marine shales are equated to the condensed sections that occur within a typical depositional sequence. The condensed section coincides with the maximum flooding surface, which represents the furthest landward extent of the sea.

A flooding unit often underlies the condensed interval, and typically consists of a thin marine limestone, a marine shale, or a coal or coal-limestone couplet. The flooding unit, although not resolvable on a cross section of this scale, can be identified on wireline logs when its thickness exceeds one or two feet. The basal contact is usually sharp and typically represents an abrupt facies shift, especially when the flooding unit is an offshore marine limestone. The flooding unit often lies on a regionally developed unconformity (erosion surface) that is commonly associated with one or more paleosols in various states of preservation. The capping unconformity is the boundary between depositional sequences.

A highstand marine carbonate unit was deposited on the shelf for the most part while the photic zone was deep enough that adequate sunlight hit the sea floor, as evidenced by the abundant algae in most of these deposits. Carbonate accumulation is restricted to this euphotic zone, which occurs between about 15 to over 150 meters in water depth (Hallock and Schlager, 1986). The slope and configuration of the shelf coupled with rates of sea-level change and subsidence determine the nature and thickness of these highstand carbonate units. Regional maps of the highstand carbonates indicate a predictable pattern of buildup along the shelf margins before they thin into a sediment-starved basinal setting (Watney, et al., 1989). The carbonate units essentially downlap onto the sediment-starved basin facies as they prograde. It is our premise that there is a predictable pattern to the deposits that is controlled by mechanisms that can be understood from detailed analyses of them.

Highstand siliciclastic deposition is common in some sequences, either supplanting the carbonate units or succeeding carbonate deposition during falling sea level. The thick Pleasanton Group shale in eastern Kansas is an example of a siliciclastic-dominated succession. It is comprised of several depositional sequences (Figures 2.32 and 2.33).

Sea-level falls at the end of each marine inundation resulted in emergence of the shelf. During these episodes of exposure, siliciclastic sediment appears to have bypassed the shelf via valleys incised into the underlying sediment. Paleosols are likely developed on the upland surface while valley formation proceeds (Watney, et al., 1989). The exposure surfaces or unconformities serve as the sequence boundaries and delineate time-distinct sedimentary events. The recognition of these bounding surfaces is straightforward in core and outcrop, but is difficult to decipher from most suites of wireline logs without sufficient lithologic control.

Mud and sand apparently were funneled thorough the valleys and subsequently were deposited in the basin. The basinal areas then become sites of active deposition. Rapid sedimentation occurs in the basin during this low stand of sea level. Several periods of lowstand sediment fill can be identified on the cross section, including sandstones that comprise the commonly gas-bearing "Layton" and "Stalnaker" sandstones (Figure 2.34). These sandstones are analogous to the lowstand Galesburg sandstones described in the outcrop (Watney, et al., 1989). The Ouachita mountain front also contributed significant volumes of clastic detritus to the Arkoma basin.

The more massive, fine-grained basinal-fill clastics beneath the lowstand sandstones may represent deposition during somewhat higher stands of sea level. These predominantly fine-grained intervals are the gray-toned units on the cross section (Figure 2.34). The Ouachita mountain system may have been an important source of these deposits in addition to the northern shelf.

The topography was maintained along the basin margin for several million years due in part to dynamic interaction of subsidence, eustatic sea level and sedimentation. The section on modeling will discuss the interaction of these variables that appears to be needed to generate this margin.

Individual carbonate highstand units prograde basinward, in places building an abrupt (for Kansas) basin-facing shelf margin analogous to the Sniabar bank described previously (Watney, et al., 1989). The buildups include both grain-rich lithofacies such as the Bethany Falls oolite and predominately muddy phylloid-algal accumulations as exemplified by the Sniabar bank (Figure 2.35). Marked progradation on the order of 10's of miles occurred during the deposition of individual sequences (Watney, et al., 1989). Apparently, this progradation reflected optimum conditions for carbonate deposition resulting from proper elevation of the depositional surface relative to sea level, depositional slopes that focussed currents and tides, and other environmental variables such as nutrient levels. An important extension of these observations, based on regional isopach mapping to date including Figure 2.36 and the preliminary simulation modeling, is that the interaction of these variables is also very important in affecting reservoir development on the shelf.

Later, siliciclastics (if they were available) episodically filled portions of the basin in front of the bank (Figure 2.34). The position of the shelf margin during the Middle and Upper Pennsylvanian changes through time, advancing (prograding) during certain periods and retreating or backstepping during other times (Figure 2.34). The overall pattern is flooding of the shelf, due to an apparent long-term rise in relative sea level up through the Virgilian Stage. The regional cross section confirms what was noted earlier from surface and near-surface studies of the Missourian deposits. The framework is consistent with the results of Rascoe (1962), as illustrated in previous figures.

Examples of wireline logs from a mid-shelf and basin location illustrate major stratigraphic changes that occur between these locations, including:

1) generally a significant thickening of depositional sequences in the basin in cases where the carbonates thin and pinch out, unless no siliciclastics were available in the basin such as in the Nuyaka Creek to Hushpuckney interval (Figure 2.37);

2) a change in lithology from predominantly carbonates on the shelf to mainly siliciclastics in the basin, with little or no highstand sedimentation in the basin but with siliciclastic deposition during lowstand time in the basin;
3) predominately shallow-water facies on the shelf and mixed deep- and shallow-water facies in the basin as water shallows;
4) both sites appear to have a predominant shallowing-upward succession, although evidence in outcrop and core demonstrate that siliciclastic sedimentation during the initial phases of sea-level rise in a particular depositional sequence (e.g. the Galesburg Shale in the Swope sequence) can be significant (Watney, et al., 1989);
5) abrupt termination of the carbonate-dominated Marmaton sedimentation in the basinal well suggests either major influx of siliciclastics occurred at that time or that there was an abrupt rise in sea level. Rascoe (1962) indicated that the Kansas City shelf margin is shifted significantly landward relative to the shelf margin of the Marmaton Group (Figure 2.23). This regional backstepping is noted from the analysis of the Th/U ratio work on the shelf described in a subsequent section.

Farther west in the Anadarko basin, where large volumes of siliciclastic sediments were not available, the relief across the shelf margin was in excess of 1200 ft. during the Upper Pennsylvanian (Kumar and Slatt, 1984). With no carbonate accumulation because of deep water and no clastics due to lack of a significant source, sediment-starved conditions were continuous through multiple episodes of fluctuating sea level. The probable explanation will be discussed in the modeling section.

In summary, strata in the cross section thicken significantly southward toward the Arkoma basin through eastern Kansas and northeastern Oklahoma. However, the thinning is not uniform as the limestones thin abruptly at their southern limits. The basinal siliciclastics are not time equivalent to the spatially adjacent limestones, but rather postdate them, having been deposited reciprocally during sea-level lowstands. The stratal architecture is very similar to that proposed by Rascoe (1978) for the Virgilian in the same area (Figure 2.38). The architecture is also compatible with the major sequence stratigraphic components described by Vail (1987) (Figure 2.39).

Results thus far are very encouraging. Plans are to continue toward completing this regional sequence database for: 1) develop stacking geometries for the Middle and Upper Pennsylvanian and lithofacies characterization between the field and analog studies and 2) utilize information for developing a quantitative understanding of processes responsible for sequence development.

Subtask 3. Correlation Methods

3.A. Biostratigraphic Analysis

Conodont processing of additional core samples of scattered condensed sections (black shales) from wells in western and eastern Kansas continues. Shales that have broken down to allow earlier processing have confirmed the log correlations in all cases.

3.B. Analysis of Natural Gamma Ray Log

Introduction

Wireline logs are the most common form of subsurface data and provide a continuous, quantitative record of the stratigraphy. Conventional wireline log interpretation provides information about the lithologies, pore space, and fluid types and saturation. Also, correlation of log signatures provides information on stratal geometries that is useful in both characterizing genetic units once they are calibrated with cores and in construction of a 3-D stratigraphic framework.

Because of the continuous record over potentially large stratigraphic intervals, wireline logs permit examination of subtle changes (patterns) in the rock record that have little chance in otherwise being resolved. These changes can be chemical in nature and go unseen via in any other means of detection. For these reasons, wireline logs are very important in stratigraphic modeling (Doveton, 1991).

The objectives here in examining the wireline logs are: 1) to evaluate the use of logs in automatically recognizing depositional sequences and component genetic units; 2) to resolve the nature of all short- and long-term periodicity exhibited on wireline logs and decipher the responsible processes; 3) perhaps to utilize inverse modeling procedures (rocks translated to process) on a routine basis to extract relative sea level curves and sediment accumulation rates for use in geologic simulation (forward) modeling via direct processing of wireline logs.

Recognition of Depositional Sequences and Genetic Units

The natural gamma ray log was initially examined in an effort to determine if the Th/U ratio, indicative of the oxidation state of the rock, could be used to recognize depositional sequences and the genetic components comprising the sequences. This was reported on last year. Comparing core descriptions with log responses indicated that the Th/U (thorium/uranium) ratio does respond to oxidation state, but was shown to correlate to both original depositional conditions and modifications attributed to diagenesis, a result consistent with other work (Doveton, 1991). Furthermore, the Th/U response was not unique to genetic units, but rather varied independently from the lithology, a relationship established through discriminant function analysis (Watney, et al., 1991).

Highest Th/U ratios occurred in oxidizing conditions associated with the development of paleosols. Thorium oxide (ThO_2) is very stable under oxidizing conditions, tending to become concentrated in such settings. As minerals are decomposed and leached in humid, tropical soils (laterites), thorium will concentrate as the oxide alongside with alumina (Al_2O_3). Thorium occurs in elevated concentrations in bauxite, an aluminum ore associated with extremely leached soils formed under tropical conditions. In contrast, uranium concentrations were very low in these oxidized soils, leading to high values for Th/U ratios.

In contrast, the Th/U ratio was lowest or most indicative of reducing conditions in the darker subtidal carbonate facies interpreted to represent deeper-water, dysaerobic conditions. Thorium and uranium are both high in thin, black radioactive marine shale (condensed sections). Thorium concentrations have been used to estimate the sedimentation rate of Recent and Quaternary deep sea sediments (Hillaire-Marcel et al., 1990).

The lowermost subtidal carbonate unit superjacent to he marine shale generally has a low ratio due to higher U with limited Th. This darker carbonate facies contains distinct flecks of organic macerals usually occurring in laminations. Pyrite replacement is common and silt-sized phosphate nodules have been seen in thin section. Scattered fine dolomite rhombs and silt-size quartz are common. These facies are thickest and most abundant on the lower shelf areas in southwestern Kansas based on available cores.

Figure 3.1 shows new wells that are now part of the continued Th/U analysis made this past year. Figures 3.2 through 3.4 are cross plots of the gamma ray versus the log Th/U ratio showing that the high gamma ray marine shale has a log Th/U ratio of approximately -0.3 or Th/U of 0.5. Furthermore, the cross plots show that unusually high Th/U strata are paleosols found in the upper portions of several 3rd-order cycles.

Time-series Analysis of Wireline Logs

Fourier analysis of the Th/U ratio was done to examine for any periodicity that might be present. A clear periodicity was described previously in the 1100 foot Middle and Upper Pennsylvanian interval in the Cox #A-4 well in Victory field, Haskell County, Kansas. With this encouraging result, the technique was extended to equivalent stratigraphic intervals at three other sites in western and central Kansas (Figure 3.1). Spectral gamma logs were digitized and a Fourier analysis was performed using Terrasciences Terrastation™ log analysis package. The analysis follows the procedures outlined by Davis (1986).

The intervals digitized extend from the Desmoinesian Oakley Shale in the Cherokee Group to the Virgilian Heebner Shale. Several common cycles are observed forming consistent patterns among the wells. The most obvious cycle is nearly 300-ft thick. In a shallowing direction the log Th/U ratio abruptly decreases followed by a longer-term trend of increasing Th/U ratio. Each cycle is comprised of four or five depositional sequences (Figures 3.5 through 3.7). The cycle begins and ends at the same stratigraphic depths, which coincide closely with the formal lithostratigraphic group boundaries, i.e., changes in sedimentary and lithologic assemblages. These boundaries are picked at the position of maximum shift. In all cases this coincides with prominent radioactive marine shale markers (condensed sections) including the Oakley Shale, Excello Shale, Nuyaka Creek Shale, Munice Creek Shale, and the Heebner Shale.

The spectral peak intensities derived from the Fourier analysis are found in Figures 3.8 through 3.10. These plots indicate a hierarchy of cycle thicknesses between wells. A plot of the thicknesses of the spectral peaks for the three new well locations shows a very close correspondence in thickness and arbitrary cycle number (Figures 3.11 and 3.12). The logs of the original Th and U concentrations do not reveal these trends (Figures 3.13 through 3.15).

The search for the significance of the stratigraphic periodicity is taking two paths: 1) establishing the processes responsible for the cycles, particularly the cycle of abruptly reducing to gradually more oxidizing, and 2) examining the relationship of the stratigraphic bundling to the depositional sequences, groups, markers and actual time that they represent. The consistency of reducing and oxidizing cycles on the shelf may be related to: 1) episodes of tectonic subsidence associated with foreland basin development; or 2) eustatic (global sea level) cycles related to glacio-eustacy (climate) or possibly changes in volume of the ocean basin.

As a means of comparison of this work to other studies and for clarity, the cycles observed here are placed in the context of a time hierarchy. The Pennsylvanian depositional sequences are considered to be 4th-order cycles with durations between 100 ky (1000 years) and 500 ky. The cycle bundles of four or five depositional sequences have a duration between 500 ky and 2 Ma and are considered to be 3rd-order (Goldhammer et al., 1991). The lower values of the log Th/U ratios appear to be controlled by the values associated with the subtidal carbonates. In these intervals, concentrations of thorium are generally depleted while uranium is relatively high as indicated earlier.

As the ratio increases as it does in the upper portion of the 3rd-order cycle, i.e., becomes more oxidizing, the ratio in this subtidal carbonate facies also increases. In addition, at the higher values of the ratio, the paleosols and uppermost highstand carbonate units also have higher ratios. Those sequences with highest ratios occur immediately beneath the Nuyaka Creek (end of Desmoinesian), at the top of the Dewey Limestone beneath the Muncie Creek Shale, and in the Douglas Group beneath the Heebner Shale (around the end of the Missourian). Thus, the changes are not due to simple facies or genetic units, but rather depend on covariant changes in facies acting in concert.

Correlation of the Th/U ratio to changes in the depositional sequences indicate that the abruptly reducing (low ratio) condition is probably related to deeper water during maximum inundation associated with a depositional sequence. The land mass and shoreline from which detritus would be supplied is probably more distant and thus less able to provide Th, resulting in lower concentrations and lower Th/U ratio. In contrast, uranium is relatively more abundant in these reducing conditions due to greater tendency for dysoxic and anoxic bottom conditions when deepening occurs. Marine flooding is thought to encourage elevated nutrient levels and encourage higher organic productivity. Moreover, this can lower oxygen levels and favor increased preservation of organic matter. Secondly, the more oxidized portion of the 3rd-order Th/U cycle is related to less uranium in both the subtidal carbonate and the paleosol. The carbonate units probably contain less uranium due to the shallower depositional conditions and more oxidizing and leaching conditions associated with more prolonged subaerial exposure affecting both the carbonate unit and the paleosol. Emergence of the entire shelf at the ends of most 4th-order cycles is well documented (Heckel, 1986).

It appears that the intensity of exposure is heightened at the end of the 3rd-order cycle. The shallowing may be due to sediment aggradation during reduced subsidence or may represent a eustatic drop in sea level. Independent observations on this part of the western Kansas shelf suggest that progradation occurs during these 4th-order cycles, e.g., during the K to H zones with subsequent backstepping by the next set of 4th-order cycles (previous annual report).

One or more carbonate units located at the beginning of the 3rd-order cycles are generally thicker than succeeding cycles. In part this depends on the shelf location. The often thicker marine sections located at the base of these third-order cycles include:

1) the Ardmore Limestone above the Oakley Shale;
2) the Ft. Scott Limestone above the Excello Shale;
3) the predominately marine Pleasanton clastic wedge and impressive bank development of the overlying Sniabar Limestone, both overlying the Nuyaka Creek Shale;
4) the very thick Iola Limestone over the western Kansas shelf superjacent to the Muncie Creek Shale;
5) and the regionally thick Oread Limestone lying above the regionally extensive and thick radioactive marine shale, the Heebner Shale.

Another independent observation that correlates with the 3rd-order cycle is the position of the shelf-to-basin hinge line. Rascoe's (1962) shifts in the shelf-margin hinge line (Figures 2.26 through 2.29) correspond with packages within separate 3rd-order cycles. The shifts identified by Rascoe are consistently northward indicating backstepping through the period of the Desmoinesian and Missourian. This suggests an overall rise in relative sea level. The regional sequence correlation and, in particular, the shelf-to-basin cross section from southeast Kansas and northeastern Oklahoma

(Figures 2.30 and 2.34) described in a previous section ties down the boundaries of the backstepping episodes to the <u>same</u> boundaries of the 3rd-order cycles defined from the time-series analysis. Thus the pattern is found in both eastern and western shelf areas in Kansas and in both the Arkoma basin margin and along the edge of the Anadarko basin.

Is this 3rd-order cycle one derived from eustatic rise or from tectonic subsidence? What is the magnitude of these changes? Subsidence will be analyzed in a subsequent section. Eustatic rise in sea level characterizes the early to mid Pennsylvanian worldwide. Vail et al. (1977) defined a global coastal onlap curve for the Phanerozoic that shows a 2nd-order sea level rise during the early to mid Pennsylvanian. This corresponds to a major North American transgression associated with the Absaroka cratonic sequence of Sloss (1963). Ross and Ross (1987) and Heckel (1986) define more detailed relative sea-level curves for the Pennsylvanian (Figures 3.16 and 3.17). Both agree with the general rise. 4th-order cycles have been correlated interbasinally and are attributed to the waxing and wanning of continental glaciers. 3rd-order cycles have not been fully recognized and documented until this present work.

Plans

Additional wells will be included in the Th/U ratio analysis incorporating new well data from eastern Kansas. Attempts will continue to find a spectrologger that is available to scan some of the existing cores from southeastern Kansas.

Subtask 4. Subsidence Patterns/Rates

The objectives of this subtask are to:

1) refine subsidence patterns that are responsible, in part, for the shelf configuration and sediment surface elevation;
2) establish the relationship of subsidence to basement heterogeneity and tectonism that occurred during the Pennsylvanian.

The reservoirs and near-surface analogues reside on platforms, ramps, and in shelf-margin settings that were developed due to the interaction of basin subsidence, eustatic sea-level change, and sediment accumulation. The section on regional sequence stratigraphy (2.B.) indicates that relative sea-level changes exert a major control on development of Pennsylvanian reservoirs, influencing stratal thicknesses and geometries, occurrence of favorable reservoir facies, and extent of weathering associated with subaerial exposure.

Subsidence and sediment compaction coupled with eustatic sea level change create space for sediment accumulation (accommodation) and must be evaluated in terms of rates, magnitudes, and durations. To understand the spatial and temporal variations of subsidence the tectonic forces that to a great extent control subsidence and the heterogeneity and structure of the basement, which provides a framework for subsidence, need to be evaluated.

Subsidence during the Pennsylvanian in Kansas was controlled, in part, by tectonically driven subsidence in what were then the Anadarko and Arkoma foreland basins (Figures 4.1, 4.2, and 4.3). Episodic subsidence apparently was associated with thrust loading in the Arbuckle/Wichita and Ouachita mountains (Brewer et al., 1983).

4.A. Basement Mapping

A Precambrian basement database continues to be updated in preparation of a revised geologic and surface configuration map of the Precambrian. An extensive set of basement penetrations together with potential field geophysics are being used to prepare this data set. The state configuration map is being hand contoured from postings made on 1:125,000 scale bases. Larger-scale, more detailed maps are being prepared at both the analog sites and the field studies. Figure 4.4 shows the portion of the basement configuration map for Kansas that has been mapped and digitized. Base maps in eastern Kansas are ready for digitizing. Data for western Kansas is presently being acquired. Figure 4.5 is a posting of tops on the Arbuckle in western Kansas. Automated contour version of this map is shown in Figure 4.6. Available control on the top of the Arbuckle Group, being mapped in western Kansas as basement is sparse. Accordingly, shallow datums are being used to help constrain the contouring (Figures 4.7 and 4.8). In addition, composition and basement fabric are incorporated in the interpretation (Figures 4.9 and 4.10).

Figure 4.11, d-d' indexed in figure 1.1 is a stick section version of a structural cross section D-D', prepared during the previous year. Significant thickening in the Pennsylvanian interval (including the Kansas City Group - Pkc) is noted along the section from Pen field on the upper shelf in northern Kansas to Victory field located on the lower southern shelf. The thickening is the result of increased accommodation space provided by subsidence. Subsidence must be understood at the scale and time period associated with the accumulation of individual cycles in order to conduct accurate simulation modeling.

A previous study of thickness patterns of the Pennsylvanian using the spatial analysis procedure called regionalization (Harff and Davis, 1990; Watney, et al., in press) indicates that western Kansas deformed along discrete blocks with clearly defined boundaries. The thickness (subsidence) patterns correlate with basement heterogeneity and the rates of thickening (subsidence) correlate with the proximity to the Anadarko basin. It was proposed that these boundaries of the regions undergo greater tendency for fracturing and faulting and may affect reservoir quality or act as conduits to charge the reservoirs with hydrocarbons (Watney, et al., in press). The patterns and potential influence that they may have continue to be evaluated.

A reprint is included by D.L. Baars as Attachment E, titled, "Conjugate basement rift zones in Kansas, Midcontinent, USA." The paper stems partly from this basement investigation and describes some of the broader implications on the origin of the basement heterogeneity. Another reprint by Baars and Watney is included as Attachment F describing influence of paleotectonics on reservoir facies.

4.B. Subsidence Modeling and Regional Cross Sections, and Pre-Permian Structural/Stratigraphic Database

The conodont biostratigraphic study of the Amoco Rebecca Bounds #1 core from Greeley County, Kansas, was initiated in 1990 and preliminary results were presented with various emphases orally and in poster form during 1991 (Watney, et al., 1991). The biostratigraphic work continues on selected wells in western Kansas in order to confirm physical correlations established with the wireline logs and cores. The level of correlation extends from verifying marker black shale units to confirming depositional sequences. Studies are focused on the Missourian and Desmoinesian intervals.

<u>Subsidence Modeling</u>

Subsidence modeling (one-dimensional backstripping with decompaction) was performed on six wells using an algorithm incorporating average lithologies within the time steps (stratigraphic interval). The rates, the time-series trend, the magnitude, and the spatial variation of subsidence appear to be linked to foreland basin development in the Anadarko and Arkoma basins. Subsidence rates during the Pennsylvanian and early Permian were very rapid compared to the rest of the Phanerozoic. Accordingly, the Permo-Pennsylvanian dominates the stratigraphic column in Kansas (Figures 4.2 and 4.11).

General subsidence pattern for the Midcontinent during the Upper Pennsylvanian (Missourian) shows greatest rates focused around the Anadarko basin with rates diminishing northward across Kansas (Figure 4.12). The resultant map from the regionalization analysis of Pennsylvanian thickness data established six broad areas of more coherent thickening or subsidence (Figure 4.13). Subsidence curves for the interval from early Pennsylvanian to lowermost Permian for these six areas using no compaction indicate different rates of subsidence for these six regions. However, all of the curves are convex upward, typical of foreland basin settings (Figure 4.14).

Figure 4.15 identifies names and locations of six wells that were used to determine subsidence using a decompaction algorithm (backstripping). Three of the westernmost wells are also located on <u>Figure 4.13, regions</u>. The wells are from contrasting structural sites including various class areas established from regionalization analysis, and locations from the Central Kansas uplift and the Anadarko, Sedgwick, and Cherokee basins.

Figure 4.16 is a depth-age representation of subsidence with compaction. The concave-up shapes of the curves are essentially the same as those in Figure 4.14. Figures 4.17 and 4.18 depict subsidence rate versus time. The first data point in the subsidence rate plot is not valid. The remaining data indicates that subsidence rates during the depositional interval containing the Lansing-Kansas City Group reservoirs under study (Missourian) between 305 (date given for Nuyaka Creek horizon) and 300 Ma (date given for Haskell horizon) range over a narrow set of values. The patterns and ranges of subsidence by geologic area include:

Cherokee basin (Batton well) -- a stable -0.037 m/ky through the duration of the interval

Sedgwick basin (Hiebert well) -- rate increasing from -0.025 to -0.035 m/ky

lower Hugoton shelf nearest the Anadarko basin in edge of Class #5 (Mai well) -- a very stable -0.03 m/ky

mid Hugoton shelf adjacent to Victory field in Class #6 (Orth well) --initial increase then slowing of rate from -0.025 to -0.035 to -0.027 m/ky

higher Hugoton shelf position in Class #2 (Bounds well) -- steady to slowing rate from -0.021 to -0.017 m/ky

on Central Kansas uplift near Pen field in Class 3 (Marshall well) -- relatively slow rate of -0.016 m/ka

The Bounds and Marshall wells are the same ones that the time-series analysis of the Th/U ratios was run on. The stratigraphic boundaries of the 3rd-order cycles recognized from spectral analysis of the log Th/U data coincide with the boundaries of the time increments used in this subsidence analysis. The reliability of the age dates precludes reducing the time any further.

The 3rd-order cycles are generally characterized by more rapid deepening and gradual shallowing. Cross sections across the shelf-to-basin hinge in southeastern Kansas indicate that the succession of 3rd-order cycles during the early to mid upper Pennsylvanian define backstepping stratigraphic successions indicating increasing inundation of the shelf through time. This could occur by an increasing subsidence rate. Such is the case for the Hiebert well in the Sedgwick basin where subsidence rate increases from -0.025 for the late Desmoinesian to -0.035 m/ky by the end of the

Missourian. However, the subsidence rate in the Batton well in the Cherokee basin remains steady. Rascoe (1962) demonstrated a backstepping of the Pennsylvanian shelf margin as described earlier (Figures 2.26 through 2.29). However, the subsidence rates in the Orth and Mai wells are rather steady through this interval of time. Any apparent close relationship between subsidence and the 3rd-order cycles remains equivocal.

Additional subsidence modeling will be done to compare with the structural mapping and time-series analysis of log data.

Inverse stratigraphic modeling as defined here includes the derivation of accumulation rates, stratal ages, and subsidence rates from the rock record for use in forward simulation modeling. The rates of subsidence and average sediment accumulation rates become very similar as long intervals of time (millions of years) are considered. As shorter times are considered, such as the duration of 3rd- and 4th-order cycles, 1.5 - 3 Ma and 100 - 500 ky, respectively, accounting for hiatuses or breaks in sedimentation become increasingly important. There is a distinct limit below which the durations of cycles can not yet be estimated accurately, making subsidence rates difficult to calculate. The lower acceptable limit for calculating subsidence rates is probably that which is used here.

Figure 4.19 is a diagram from Schlager (1981) comparing the rates of longer-term subsidence (0.01 to 0.5 m/ky) with various processes, including rates of eustatic sea-level changes associated with glacio-eustacy (0.3 to 8 m/ky), and instantaneous sedimentation rates for modern sediments. Coral growth can be extremely rapid, and sedimentation rates for oolites are also quite high (0.6 to 2 m/ky). Long-term subsidence rates such as those that typified the Kansas shelf during the Pennsylvanian (-0.015 to -0.035 m/ky), although high relative to other times, are about an order of magnitude or two lower than sediment accumulation and up to some 200 to over 500 times lower than Pleistocene glacio-eustatic sea-level rise (8/.035 = 228 and 8/0.015 = 533).

The subsidence results are important to our efforts to develop a quantitative inverse model that will be used to extract process information from the rocks for simulation modeling. Our goal is to tailor parameters to specific cycles. Distinctive and consistent stratigraphic patterns apparently exist; these patterns are subtle and have been unrecognized until now. Further inverse procedures are described in the section on computer modeling.

Plans include digitizing the remaining portions of the lower Pennsylvanian section in wells that have already been analyzed in order to examine longer-term trends leading to the Upper Pennsylvanian. Other wells will also be incorporated into subsidence analysis in order to test for consistency of the observed patterns and further improve our understanding of the relationship between subsidence and basement characteristics.

Subtask 5. Computer Modeling

5.A. Database Development

A customized DBM program was completed to edit multiple databases, to extract various fields to prepare composite data bases, to perform plot file generation, to aid in implementing selected map cartographic options, to generate maps, and to print maps (Figure 5.1). Data from field, analog, basement, and regional sequence studies continue to be added to the data base system. Numerous maps were prepared for editing and analysis. The DBM program will be very useful when various combinations of maps are needed. The documentation being included will facilitate data retrieval in the future.

5.B. Geologic Modeling

This effort is an inductive simulation modeling approach. Several avenues of research are being pursued simultaneously to quantify the geologic processes responsible for reservoir development, including:

1) collection of regional- and local-scale data for integrated interpretation ; data types include stratigraphic, sedimentologic, conodont bioassemblages, structural, lithologic, sequence stratigraphic, reservoir characteristics, wireline log values, seismic records, and geochemical;
2) quantitative definition of parameters for stratigraphic modeling:
   a) identification, description, correlation, mapping and interpretation of geometries of temporally distinct genetic units (depositional sequences);
   b) compaction and subsidence analysis;
   c) time-series analysis of logs and lithologic data;
   d) inverse modeling to derive independent estimates of timing and rates of sediment accumulation;
3) integration of parameters through process of informed constrained synthesis of this geologic system;
4) simulation of observed geology and prediction of characteristics between control at regional and local scales.

<u>Forward Modeling of 3rd- and 4th-order Cycles</u>

Time-series analysis of Th/U ratios derived from natural gamma ray logs (described in an earlier section) reveals a hierarchy of stratigraphic cycles, including 4th-order cycles, which are the major depositional sequences. The 4th-order cycles can be readily correlated on well logs and identified in core and outcrop. 3rd-order cycles were noted from the same time-series analysis. These longer-period cycles are not easily identified by casual observation of stratigraphic data. The boundaries of the 3rd-order cycles identified here occur in the same stratigraphic position at four different shelf locations. This suggests some kind of unified forcing mechanism that is currently under further investigation.

One-dimensional simulation (forward) modeling of these 3rd- and 4th-order cycles was done using parameters that are currently the best available estimates. The goal of this modeling is to establish possible the most likely scenarios of cycle development. Upper-, mid-, and lower-shelf locations were incorporated in this modeling effort, consistent with interpretations of the configuration of the Upper Pennsylvanian paleotopography in western Kansas. Elevations of the shelf sites are estimates based on rates and thickness of the depositional sequences, development of black shale unit, and subaerial exposure index of individual 4th-order cycles (Watney et al., 1991). Subsidence rates are derived from the backstripping analysis described in an earlier section. Sediment accumulation rate varies at rates that are low in comparison with recent sedimentation rates. The depth of the photic zone, above which primary carbonate production takes place, is set at about 30 meters, which is a moderate depth compared to modern ranges (15 meters to 150 meters). Carbonate sediment accumulation is reduced during rapid deepening (> 1m/ky) by an arbitrary linear function. The current 2-D model suggests that this extra function is not necessary due to the rapid rates of sea-level rise that probably characterized the Pennsylvanian.

The remainder of the input parameters used in the modeling include:

sediment accumulation rate -- 0.1 and 0.2 m/ky

subsidence rate (upper, mid, lower shelf) -- -0.015, -0.03, -0.04 m/ky

initial sediment surface elevation -- -35, -60, -90 meters

The characteristics of the 4th-order curve closely resemble the Pleistocene sea-level signature, both having 4th-order cycles modulated by the buildup and melting of continental glaciers. The period of the 4th-order cycle was set at approximately 350 ka, 3.5 times longer than the Pleistocene (Fischer, 1986). The amplitude of sea-level change used to create the 4th-order cycle was set at 100 meters, a value similar to the Pleistocene range of glacio-eustacy.

The 3rd-order cycle was imposed on the shorter 4th-order cycle by adding an abrupt rise in sea level of between 20 to 25 meters at the end of five 4th-order cycles. This rise was followed by a slow linear decline in the 3rd-order sea level back to an original level. The results are shown in Figures 5.2 through 5.6.

The modeling reveals distinct changes in sediment response among the three shelf positions. Third-order cycles on the upper shelf are thin because marine sedimentation occurs only during limited intervals of marine inundation when the sea-level signature is a simple rise and fall. Between sedimentation events, the upper shelf was subaerially exposed for relatively long periods of time. Fourth-order cycles are thicker at the beginning of the 3th-order cycle than they are at the end of the 3rd-order cycle. The 4th-order cycles are more prone to exhibit small-scale sea-level events near the base of 3rd-order cycles.

The mid-shelf site is situated at a lower elevation than the upper shelf; at these locations marine sedimentation associated with the 4th-order cycles occurs over longer periods and the sea-level signature is more complex than at higher positions on the shelf. Again, 4th-order cycles are thicker near the base of the 3rd-order cycles.

At lower-shelf positions, cycles develop that tend to be thicker than at either of the other shelf positions due to longer periods of marine sedimentation. Note that the elevation of the sediment surface declined over the course of three separate 3rd-order cycles even though sedimentation was relatively more continuous on the lower shelf. This was due to differential subsidence with only partial compensation by sedimentation, leading to enhanced topographic relief.

Figure 5.5 illustrates what can happen on the lower shelf when subsidence is increased from -0.04 to -0.05 m/ky with other variables held constant. The sediment surface elevation begins to decrease more quickly during the first 3rd-order cycle. Sea level abruptly increases at the beginning of the second 3rd-order cycle and this lower shelf location is subsequently drowned. Even during a later fall in sea level after the next 4th-order cycle, the sediment surface has declined significantly. Subsidence continues, uncompensated for by sedimentation. The site continues to be sediment starved and the sediment surface subsides even further. The site that was once part of a shelf that was undergoing active shallow-water sedimentation has now become basinal.

Considerable space is now available for siliciclastics or carbonates to fill the basin through a process of progradation and aggradation of sediment from the shelf margin or beyond. Filling of the basin will occur if subsidence rate decreases so that the shelf margin can prograde, sedimentation rates increase, or sea level falls to again establish shallow-water conditions (effectively increasing sedimentation rates).

Each 4th-order cycle on the shelf actually goes through a stage of sediment starvation (marine shale or condensed section) when the water depth rapidly increases and water depth exceeds 30 meters. Sea level then falls to again establish shallow-water sedimentation.

This 1-D simulation model only roughly approximates these processes, but it presents a reasonable, quantitative scenario of the response of a carbonate shelf to two cycles of base-level fluctuation, and furthermore demonstrates how the interaction can lead to retrogradation of the carbonate shelf margin. Rapid subsidence coupled with fluctuating sea level and resulting episodic sediment production are the ingredients for drowning of the shelf. Although the large rates and magnitudes of eustatic sea-level change interpreted for the Pennsylvanian appear to have produced the dominant signature seen in the sedimentary record, subsidence is critical to sediment preservation and can lead to significant modifications, such as the transformation of a relatively shelf to a more basinal setting.

Another summary observation is that the fidelity of the sedimentary record is diminished on the upper shelf due to its elevation and the low rate of subsidence. In effect, the upper shelf "sees" a very simple sea-level curve, whereas the opposite tends to be true on the lower shelves. The recognition of the details of stratigraphic packaging, including such details regarding the completeness of the stratigraphic record at different shelf locations, is critical to our understanding of reservoir architecture.

The 3rd-order cycles have been linked with backstepping carbonate margins during the Upper Pennsylvanian (Figure 2.30). Accordingly, the modeling would more accurately reflect reality if the 3rd-order cycles were tied to a longer term, 2nd-order sea-level rise. Drowning of the shelf margin would occur more easily, leading to the observed backstepping or retrogradation. Independent evidence supports this 2nd-order longer-term cycle of sea level rise (Sloss, 1963; Vail et al., 1977; Ross and Ross, 1987; Haq et al., 1987). The object here is to estimate values in order to establish what variables are important and what the sensitivities are.

More accurate modeling, including the ability to prograde sediment, has been accomplished in this project with the 2-D carbonate simulation model (French and Watney, 1990). New features added to it will be illustrated below. Before reviewing this model, inverse methods that are being used to improve estimation of process parameters will be discussed.

Fischer Plots

Fischer plots, patterned after Alfred Fischer's technique (Fischer, 1964), provides a means to examine higher-order relative sea-level cycles (e.g. 3rd-order) by estimating the sediment surface elevation of successive 4th-order cycles by plotting cycle thickness (vertical column) and subsidence (diagonal line) for each cycle, assuming that each cycle has the same period. Subsidence rate is typically not varied in a single plot. One of the basic assumptions used in this method is that sea-level and subsidence changes (changes in accommodation space) are directly reflected in cycle thickness. This assumption does not seem to hold true, as shown in the results provided below.

Fischer plots were constructed for the mid to upper Pennsylvanian 4th-order cycles in four wells from the western Kansas shelf: the Cox #A-4, Marshall #E-22, Tedford #1-10, and Bounds #1. The

1-D model suggest that thicker 4th-order cycles will develop early in each 3rd-order cycle. The stratigraphic locations of the boundaries of the 3rd-order cycles identified in these plots were obtained earlier through analysis of Th/U ratio and observation of stratal geometries along the shelf margin (Figure 2.30).

The plots are very similar except for the Marshall #E-22 well situated on the high shelf and Central Kansas uplift (Figure 3.1). A series of 4th-order cycles does not show thickening until the Kansas City Group (between the Nuyaka Creek Shale and the Muncie Creek Shale). At that point is a series of 4th-order cycles that thicken through the Kansas City interval and up through the Iola Limestone (overlying the Muncie Creek Shale). Younger cycles show a return to constant thickness up through the Haskell Limestone, immediately below the Heebner Shale marker. In contrast, the Marshall #E-22 well shows essentially constant thickness and even decreasing accommodation space.

Overall, It appears that evidence for deepening in the beginning of the 3rd-order cycles is not often observed here. Because of the limited slope of the shelf and minimal input of clastics, the sediment accumulation rate may have been very limited. The duration of marine sedimentation during the 4th-order cycles may be very limited on the shelf as suggested by the 1-D modeling example described above. Consequently, the sediment fills only a portion of the accommodation space available. These hiatuses when no sedimentation and perhaps erosion occurs may represent a significant part of the 4th-order cycle. This would be even more the case higher on the shelf, e.g., at the Marshall #E-22 site. Therefore, the typical Fischer plot results are subject to rather equivocal estimates of accommodation history. This is one reason why it is difficult to detect the 3rd-order cycles on the shelf based strictly on thickness patterns.

Inverse Methods

Inverse modeling is done to assist in deriving some of the parameters that are responsible for sedimentation by employing certain mathematical procedures to rock data. These parameters include sea-level history, elevation changes in sediment surface as result of compaction and subsidence, timing and rates of sediment accumulation, and duration of hiatal surfaces.

Testing of the Gamma Method

Material included in this section is condensed from comments submitted by preliminary numerical analysis and testing of the "gamma" by Ross Black, Department of Geology, Kansas University. The gamma method of Bond, et al. (1991) was applied to the facies succession defined from 890 feet of core from the top of the Desmoinesian Marmaton Group to the top of the Lansing Group in the Amoco Cox #A-4 well in Haskell County, Kansas.

The following report documents an initial attempt to apply the 'gamma' method of Bond, et al. (1991) to cyclic sedimentary units of Pennsylvanian age in eastern Kansas. The gamma method provides a means of viewing a geological column as a time series that can be analyzed in terms of sedimentary cyclicity. Application of the method entails logging individual facies occurrence versus depth in a core or measured section, conversion of stratigraphic unit (facies) thicknesses to equivalent geologic time, and finally Fourier analysis of the resulting time series.

The conversion of stratigraphic thickness to geologic time is the heart of the gamma method. The gamma term calculated during the analysis is the conversion coefficient multiplied by the facies thickness to convert it to a time duration. This conversion is theoretically quite simple. In reality, however, the conversion can become a very difficult non-linear inverse problem, dependent on the data set available for the inversion. Because of the potential difficulties in calculating the conversion coefficients, an initial Fourier analysis is also performed on the facies data as a function of depth for comparison with the time series results.

A simple test of the method was attempted utilizing a small data set taken from a single core through 15 Pennsylvanian cyclothems in western Kansas. The facies data were tabulated from core samples of the Cox #4 well reposited at the Kansas Geological Survey. Each facies was assigned a identifying rank qualitatively linking the facies to relative water depth. Facies rank was plotted versus depth from the top of the cored interval. True depths of the units within the hole are approximately 1300 m greater than the depths indicated within this cored interval.

Spatial Fourier Analysis. In order to facilitate Fourier analysis, the facies rank sequence was resampled at a regular depth interval. The facies were resampled at an interval of 0.1 m to insure adequate sampling of the thinnest of facies units in the data set. Spectra calculated on these depth series are functions of spatial frequency (cycles/m). Conversion from depth to time is considered in a later section (after conversion to time the Fourier spectra are functions of true time frequency).

Amplitude spectra were calculated for the resampled facies using two independent 'canned' fast Fourier transform (FFT) subroutines. The spectra calculated with the two routines were identical, indicating that, although the program coding was completely different, both routines use the same theoretical development, the Cooley-Tukey algorithm (Claerbout, 1976). Neither plot showed any spectral peaks of obvious significance. Both plots displayed an exponential decline in amplitude with spatial frequency.

Inversion of facies thickness to time - the general problem. The total time required to deposit the j'th sedimentary cycle is:

$$t_j=\Sigma_i(T_{ij}\gamma_i) \qquad (1)$$

where T_{ij} is total thickness of an individual facies type 'i' within the cycle and γ_i is the thickness to time conversion coefficient for facies 'i'. The coefficient γ is expressed in units of depositional time/unit thickness (i.e. k.y./m). Equation 1 assumes that each facies type has a consistent depositional rate from cycle to cycle within the sedimentary package. This is probably a valid assumption since the individual facies are interpreted in terms of unique depositional environments and associated energy regimes.

Equation 1 is valid for the j'th cycle within the sedimentary column. Assuming there are 'm' such cycles equation 1 can be rewritten as the multiplication of a matrix and a vector. The resulting equation:

$$\begin{array}{lll} T_{11}\ T_{12}\ldots TT_{1n} & \gamma_1 & & t_1 \\ T_{21}\ T_{22}\ldots T_{2n} & \gamma_2 & & t_2 \\ & & = & \\ . \quad . \quad . \quad . & . & & . \\ . \quad . \quad . \quad . & . & & . \\ . \quad . \quad . \quad . & . & & . \\ T_{m1}\ T_{m2}\ldots T_{mn} & \gamma_n & & t_m \end{array}$$

is the general form of the simple linear problem. Each row of the T matrix represents a set of cumulative facies thicknesses for a given sedimentary cycle. Each column of the matrix represents the set of thicknesses for a given facies across all the cycles sampled.

Since absolute age control is normally not available at each cycle boundary, a further assumption must be made to make use of equation 1. This assumption is that the time period represented by each t_j is approximately the same. Also, since even the mean duration time of the cyclothemic deposits is well known, the time entries for the cycles are usually simply normalized to one (i.e. the basic time unit is one cycle period, whatever that may be). The unit cycle period can then simply be scaled to comply with any assumptions made in later analyses. Using this assumption equation 1 can be rewritten in matrix and vector notation as:

$$T\gamma=t \qquad (2)$$

where **T** is an m by n dimensional matrix containing the facies thicknesses, and γ is an n dimensional vector of unknown coefficients. The m dimensional vector **t** consists of entries of one in each component location.

Equation 2 would appear to define a very simple linear problem that could be solved using standard linear inversion methods. Several techniques were used to solve this problem using the small data set from the Cox #4 well described above. Results of the analysis indicate that many pitfalls surround applications of inverse theory to geological data consisting of interpreted rank information.

Linear Inversion. The least-squares solution to the standard overdetermined linear inverse problem (equation 2) is given by (Menke, 1989):

$$\gamma = (\mathbf{T}^{T}\mathbf{T})^{-1}\mathbf{T}^{T}\mathbf{t} \qquad (3)$$

This type of solution is convenient because several ancillary calculations can be made from the results to check the resolution and variance of the solution.

The least-squares problem of equation 2 was solved for the Cox #4 data set using equation 3. The results indicate that there are some problems in directly applying a least-squares technique to this data set. The most obvious problem is that there are negative γ coefficients. This is, of course, physically impossible unless erosion is the dominant mechanism acting in this depositional system. Upon analysis of the resolution matrices (Menke, 1989) it was determined that, although the problem probably is slightly overdetermined, the data are inconsistent enough that the generalized inverse matrix is nearly singular, and also, the global minimum in the function they describe truly is in the negative half-space along certain parameter axes.

Three possible solutions to these problems were attempted. First, the data set was reparameterized. Three of the ten existing facies types were grouped together to reduce the number of unknown parameters to eight. Secondly, a damping factor was added to the generalized inverse matrix. Such a damping should be subjectively fine tuned to provide 'optimum' results in some sense. In this first cut attempt, however, only a single, very small, damping factor was added to the matrix. The results for both the original and reparameterized data sets were encouraging, although there was still one parameter with a negative coefficient. The third method used to improve the solution to the problem was the use of parametric constraints. This simply means that the output coefficients were forced to be positive by redefinition of the problem.

Simple linear least-squares techniques do not allow these types of constraints to be added to a problem, so the problem was redesigned as a non-linear, iterative procedure. A black-box approach was attempted first using a commercial statistical software package. This package provided both simplex and quasi-Newton general non-linear modeling algorithms. The quasi-Newton algorithm was chosen after testing indicated it was slower but more stable when run on this data set. The algorithm iteratively steps toward the area in parameter space where the error function is a minimum. The desired solution is at this minimum. The constraints are supplied as large steps or walls in the error function. When the algorithm steps into one of these walls at $\gamma_i = O$, the next step is forced away from the wall. The results of the black box non-linear analysis indicate that the main problem is that there is a range of five orders of magnitude in the parameters. This is probably not physically reasonable. One parameter indicates that there was a depositional rate of nearly 100,000 m/m.y.

The second constrained, non-linear algorithm involved use of a simple reparameterization of the problem to solve for the square root of g. In this way the final solution was forced to be positive since it was the square of the non-linear algorithm' output. Results of using this algorithm are by far the most encouraging. Further work needs to be done, but the parameters are now positive and more realistic in their range of values.

The basic findings of the work so far are that the more sophisticated inversion algorithms help the results and that the problem of inverting for depositional rate is poorly posed with ten parameters to be estimated and only fifteen equations on which to base the estimate.

Plans are to extend the gamma method to well log information, particularly gamma ray and porosity logs. This data are continuous and are only limited by the recording resolution of the logs. Success in this approach would be more widely applicable and could be automated for expeditious analysis. Moreover, the success to date with identification of periodicity in the logs is significant.

In addition, plans include combining a data set from the same stratigraphic interval in multiple wells located on depositional strike and in proximity to one another. This increase in the degrees of freedom and should help to make the results more reliable.

The possibility exists that there is a natural resonance in the basin that established the periodicity or oscillation that is specific to a basin or shelf or parts thereof. Therefore, it is best not to enter assumptions about the nature of periodicity based on current hot topics. The first goal is to establish and document occurrences of cyclicity.

Forward Modeling

Two-Dimensional Modeling. The 2-D model for the personal computer has had additional options added since the last annual report. The output can now include large, high-resolution data files limited only by the RAM available on a particular machine for use in additional analysis and display.

These files include information generated at each time step across the entire two-dimensional model "area", including facies and thickness information as well as temporal data, such that the duration of the hiatuses and the relative ages of unconformities can now be captured. This intermediate file is used to output a series of high-resolution stratigraphic columns showing the succession of facies and surfaces generated at shelf positions chosen by the user from the 2-D output. The stratigraphic columns are output in a separate window from the 2-D model run using Desqview™ multitasking software. The latest version of Microsoft Windows™ (version 3.1) should also allow for the viewing of multiple windows, greatly increasing the utility of the model. The windows can be easily and freely manipulated in this environment. A 486-33 or 50 Mhz CPU with at least a 128 kb cache memory is recommended because runs can be cut from over two hours on a 386-25 to less than 30 minutes. Each parameter saved (e.g. facies type or the age of each increment of strata) takes over 2 Megabytes of memory, so a great deal of memory is needed in order to create large RAM disks, which store the information during each run. The availability of new, fast, 486-based PCs will make it feasible to modify the existing model such that "real-time" subsidence and compaction can be incorporated into the model's algorithms.

The screen output can be captured as a bit-mapped image for printing on a black and white laser or dot matrix printer. A commercial screen capture program is used. The captured graphic can also be converted to pcx format for input into Corel Draw™ for additional labeling and color selection. The graphic can then be printed to a color postscript laser printer using Corel Draw.

An example output from the 2-D simulation program is shown in Figures 5.7 and 5.8. Included is the 2-D image of two 4th-order marine carbonate-dominated cycles deposited along a sloping depositional surface modeled after the Swope analog area eastern Kansas. A color screen image was converted to gray tones for reproduction in this report. However, this transformation eliminated the contrast between the component facies. Color copies are available upon request. The 2-D output (Figure 5.7) is very similar to that shown previously. The major development is the addition of detailed stratigraphic profiles showing high-resolution detail of the facies succession (Figure 5.8).

The parameters used to build the model run that is illustrated here include:

1) two cycles of rise and fall of sea level with a range of 100 meters characterized by rapid deepening and gradual shallowing, patterned after late Quaternary eustatic fluctuations;
2) depositional slope estimated from isopach data with a relief of 100 meters;
3) sediment accumulation rates determined by water depth and slope of depositional surface;
4) subsidence of -0.02 m/ky at right and -0.2 m/ky at left;
5) the depth of the photic zone in which carbonates accumulated was set at 35 meters.

The two cycles that are displayed are distinguished by the black stratum (the marine shale) deposited at the base of each cycle. The high-energy facies (lighter colors) occur along the two breaks in slope on the shelf. The subaerial surfaces (sequence boundaries) representing emergence of the shelf are denoted by thin white lines.

Figure 5.8 shows detailed stratigraphic columns developed along eight different positions of the shelf. The numbers on the base of the columns correspond to shelf position from Figure 5.7. The black facies is the marine shale developed at the base of each 4th-order cycle in this example. The lines were added to emphasize the correlation of the two cycles.

There is considerable lateral variation that occurs within both cycles resulting from the interaction of shelf elevation and slope. The lower cycle is very thin across the upper shelf (positions 300, 450, and 600 in Figure 5.8), much like the actual 4th-order cycles, e.g., the Sniabar Limestone. The stack of facies on the upper shelf is a simple shallowing upward set. The sea-level curve for the first cycle (Figure 5.7) fell steadily with no stillstands during carbonate accumulation on the upper shelf.

Limited thickness of high-energy carbonate sediments (lighter colored, dotted pattern) are deposited in the lower cycle on the basinward slope of the upper shelf (position 270 in Figure 5.8). Carbonate deposition on the middle shelf occurs later during subaerial exposure on the upper shelf. The duration of sedimentation on the middle shelf is extended in the lower cycle and consequently a thick bank of carbonates was deposited (positions 140 and 210 in Figure 5.8). The complex stratigraphic succession in the carbonate bank of the lower cycle is due to short-period sea-level oscillations. The thickness, shelf setting, and internal stratigraphy are very similar to that observed in the Sniabar bank in southeastern Kansas.

The lowermost shelf on the left side of Figures 5.7 and 5.8 experienced limited carbonate sedimentation during the first cycle. Low-shelf or basinal settings usually show no evidence of subaerial exposure. Rather, the basin and low shelf are the sites of sediment-starved conditions typified by accumulation of dark marine shale (black facies in stratigraphic column #30 in Figure 5.8). Reduced sedimentation rates over most of the cycle in this low shelf, due to greater water depths coupled with limited extent of bank progradation in this time frame, resulted in preservation of depositional topography in front of the carbonate bank. This relief would continue until either subsidence rate declines to permit more progradation of siliciclastics or carbonates or until eustatic sea level falls enough to bring the low shelf area into the photic zone, permitting relatively rapid carbonate production. Again, these facies and geometries are analogous to those observed for the Sniabar Limestone in southeastern Kansas.

The upper 4th-order cycle developed in response to an asymmetric sea level fluctuation, where the overall sea-level fall was characterized by several smaller-scale fluctuations (Figure 5.7, 2-D). These oscillations occurred when shallow-water conditions were developed on the upper shelf. The result is that this upper cycle is significantly thicker than the lower one and exhibits intervals of short-term deepening and shallowing (minor cycles) (columns #300, 450, and 600, Figure 5.8). The edge of the upper shelf is the site of high-energy grainstone deposition in the upper cycle. The section is similar to the underlying cycle at this position (column #270, Figure 5.8), but it is thicker, reflecting longer periods of sedimentation due to a slower fall in sea level.

In contrast to the lower cycle, the upper cycle is much thinner on the middle shelf (#140 and 210, Figure 5.8). This is due to a rapidly falling sea level during the upper cycle shelf elevation and time (Figure 5.7, 2-D). The condensed section is also very thick, indicating a longer period of sediment starvation on the middle shelf. Finally, on the lower shelf only limited carbonate sedimentation occurred due to the elevation and resultant deeper water. The low shelf had subsided more due to longer periods of low sedimentation rates, and consequently the location was sediment starved. The character of this upper cycle is very analogous to that observed in the Bethany Falls Limestone.

Plans. Plans for the PC-based simulation (forward) modeling include using detailed RAM files to construct Wheeler diagrams (time-space diagrams) to examine temporal changes in sedimentation. We will investigate the use of simulated geology as input to test inverse models. The objective of the inverse model would be to derive parameters used to construct the original simulation. One of our goals would be to test our ability to detect and characterize hiatuses (gaps in the record). Knowledge about hiatuses in the rock record is limited at this time, thereby making them difficult to constrain and test.

Modeling on Workstation

The Pascal code of the 1-D and 2-D modeling programs began to be translated into C on the graphics workstation during 1991. The objective is to convert existing code into standard C. This will eliminate the use of involved hardware-dependent library routines so as to optimize the program's performance. Program refinements are being made on the new IRIS 4.0 operating system.

The Personal IRIS workstation was reconfigured to connect it with the Ethernet backbone on the KU campus. Files can now be more easily uploaded from the mainframe, where present database development and SURFACE III mapping are done. Several system administration routines have been developed to enhance the input/output on the workstation environment.

A basic philosophy of design was established concerning the type of graphic drawing function, user interface, elements of model input, mechanics of the model run, and types of output.

Conversion of existing code and model implementation on the workstation is planned by the end of the 3rd year.

<u>3-D Visualization</u>

The new version of Stratamodel (SGM 2.0) has been installed on the Personal IRIS which has significant enhancements in the color display, attribute modeling, model operation, as well as in output options. A training session was held in April for optimizing use of this new software.

A pilot project was implemented to examine 3-D wireline log data from the Dennis-Swope-Hertha analog site located in southeastern Kansas. 3-D visualization was used to examine changes in geometries of depositional sequences along a prominent depositional slope. The pilot project has consisted of digitizing 37 gamma ray and porosity logs in the vicinity of the "Woodward transect" area of this analog site which is described in an earlier section. The objective is to examine the geometries of the depositional sequences and characterize variation in porosity along this break on the shelf where oolitic grainstones were deposited.

The preliminary results are shown in photos (Figures 5.9 and 5.10). Figure 5.9 includes only the surfaces of several prominent datums: the upper is the Winterset Limestone, the next is the Bethany Falls Limestone, followed by the datum on the top of the Sniabar Limestone. The lowermost horizons are at the base of the Pleasanton Group. The datum is the Nuyaka Creek Shale found at the base of this image. The overlying surfaces dip southeastward, with the Sniabar dipping more than the Winterset Limestone. The slope is interpreted to closely represent the actual depositional surface. The slope progressively diminishes higher in the section due to the aggrading and prograding of sediments along the shelf. Included in this framework are oolitic grainstone reservoir analogs developed on an increased depositional slope in the Bethany Falls Limestone (the second surface from the top).

Figure 5.10 is a panel diagram depicting the gamma radiation within the stratigraphic interval from the base of the Pleasanton Group to the top of the Bethany Falls Limestone. The side of the panel reveals the wedge-shaped nature of the Pleasanton Group shales (darker-colored facies). The carbonate units of the overlying Sniabar and Bethany Falls are shown mainly as the lighter colors as they vary from shelf positions to those along the slope. The small arrow in the center of the image indicates the location of the Woodward transect that crosses an oolite bar developed within the Bethany Falls Limestone.

Additional data at both the field, analog, and regional scale will be viewed using this tool as a means to improve our understanding of the stratigraphic framework.

<u>Other Developments</u>

A new process interpretation of black shale, an important stratal unit (the condensed section) comprising many Pennsylvanian depositional sequences, was the topic of a paper published in 1991 (Coveney et al., 1991). The interdisciplinary approach taken to refine interpretations of the rocks as brought out in this paper is an important step toward making geologic models (analog and simulation) more precise and capable of explaining or reconstructing the observed geology.

Three invited seminars on the topics of computer simulation development and results were presented during the year by Watney and French at universities in the region including Arkansas, Iowa, and Kansas. Additional papers utilizing modeling results were presented including an invited paper delivered at a conference on Predictive Stratigraphic Analysis organized by U.S. Geological Survey and at the Mid-Continent AAPG meeting.

A publication of the Kansas Geological Survey on sedimentary modeling published in 1991 provides current thinking in both approaches to simulation modeling and parameter definition for improving future modeling efforts. This volume has served as a forum to capture some of the converging ideas and approaches in modeling efforts today (Franseen et al., 1991). This publication includes a paper on the early one-dimensional simulation modeling effort to aid in interpreting cyclic sedimentation of the Lansing-Kansas City (Watney, et al., 1991). The paper is included here as Attachment G.

Subtask 6. Reservoir Development, Prediction, and Play Potential

Introduction

The major objectives of the field studies within the context of this study are 1) to geologically characterize Lansing-Kansas City reservoirs as they occur in the various settings that have been discussed; 2) to compare and contrast reservoir development; 3) to define processes which led to the development of reservoirs and the depositional sequences that contain them; 4) to build a quantitative stratigraphic model that incorporates the reservoir characteristics. The premise, based on observations made to date in the regional, analog, and field studies, is that stratigraphic architecture and related early diagenetic events play a major role in reservoir formation. Therefore, understanding processes that operated through the course of deposition of the Pennsylvanian, such as sea-level history and sediment response, will aid significantly in the prediction of reservoir properties at multiple scales. Such an understanding is important in both reservoir development within existing fields as well as in exploration plays associated with individual depositional sequences.

Studies of Collier Flats, Victory, and Pen fields are well underway. The studies of Collier Flats and Pen fields were undertaken through cooperation with thesis projects supported by TORP. The Pen field is located on the Central Kansas uplift in an area that is considered to be the upper shelf (Figure 1.1). Collier Flats and Victory fields occur on the lower shelf. Significant differences exist in the stratigraphy and character of reservoirs within the Lansing-Kansas City between these two sites.

The Collier Flats and Victory fields produce from oolitic and skeletal carbonate grainstones and packstones that occur within the Bethany Falls Limestone. The Bethany Falls Limestone is only a minor reservoir in the Pen field. Other producing zones in Victory field include the "B" zone (correlated here as the Iatan Limestone of the Douglas Group), the Dewey and Sniabar limestones of the Kansas City Group, and additional pays in the Marmaton, Cherokee, Morrow, and Mississippian. The lower-shelf setting of Collier Flats and Victory fields is similar to the shelf location of the analog site of the Bethany Falls and Sniabar (Hertha) limestones in Bourbon County, southeastern Kansas which was described in Subtask 2 (Figure 1.1).

The Drum Limestone ("I" zone) is the major reservoir in Pen field and is the focus of the analog study in Montgomery County, southeastern Kansas. The shelf positions of the Drum analog site and actual reservoir are significantly different, providing an opportunity to demonstrate contrasts as a function of shelf setting as well as to establish similarities. The Drum produces from a series of fields across the state and results will therefore be applicable to these areas also.

The Victory field is the focus of this annual report as all phases of the geological analysis are funded through this program. The methods used in the study of this field are summarized below.

The first task was to establish a data base of attributes of Lansing-Kansas City reservoirs in Victory field. Well logs were stratigraphically correlated based on analysis of a continuously cored well in field (the Cox #A-4) and use of the regional cross-section framework. Depositional sequences and component genetic units were identified. Working cross sections were prepared.

The second phase of this study of Victory field consisted of characterization of the reservoir units. This was initiated based on interpretation of wireline logs, drill stem tests, and core analysis. Gamma ray, neutron, density, and sonic logs are generally available, but some of the original wells drilled in the 1960's have only spontaneous potential and resistivity logs. R_o, S_{wirr}, minimum effective porosity, pore type and S_w, and m, the cementation exponent in the Archie S_w calculation, k*h, and moveable oil are some of the variables that are being sought though a series of analyses being conducted, including the preparation and interpretation of porosity-resistivity (Pickett) cross plots, Horner plots, porosity-permeability plot, $R_{xo}/R_t \cdot R_{mf}/R_w$ ratio estimation of S_w and moveable oil.

Capillary pressure data is being sought from companies to aid in assessing pore structure and distribution and its role in defining hydrocarbon saturation.

A third phase of this project is mapping the 3-D distribution of reservoir properties, depositional sequences and components, stratigraphic datums, and structure. The objectives are to ascertain trends, patterns, and anisotropy in reservoir development and related stratigraphic and structural variables in order to establish covariation and to determine how reservoir-quality rocks developed. The goal is to develop a predictive geologic model for reservoir development useful in evaluating potential for additional hydrocarbon recovery from this field. As stated earlier, the working hypothesis being tested is that the stratigraphic architecture and associated processes exert a dominant effect on reservoir distribution. Special mapping done to date includes K*h, 1st-derivative mapping of structural elevation, and mapping of the maximum gamma radiation of marine shale that are developed beneath the carbonate reservoirs.

The fourth and final phase of this project has yet to be done. The tasks include:

1) to correlate reservoir parameters obtained to date with lease and well production;
2) the integration of results from the various analog studies;
3) the comparison of parameters determined from the other field investigations;
4) drawing relationships about geological processes that can be used in the simulation modeling to reconstruct the stratigraphic framework of the reservoirs.

The objective is to refine both spatial and stratigraphic distribution of the critical reservoir parameters and relate these to reservoir volume and fluid flow. Companies are supplying details of production data and are very interested in the results. This and subsequent phases will be completed during the last year of this grant.

Summary of Progress

A computer data base on some 200 wells has been prepared for Victory field. Twelve thousand entries have been entered including 60 sets of data for each well. The data base includes structural datums, boundaries of sequence-stratigraphic units, reservoir thickness, thickness of effective porosity, porosity-feet, and maximum gamma ray of the marine shales underlying each carbonate reservoir. These variables are in the process of being mapped and selected ones are included in this report.

All available drill stem tests (DST's) have been compared and evaluated in Victory field to better understand permeability variation. Thirty DST's have detailed pressure data and are being used to establish a "model" for the remaining tests that do not have this level of information. Eighty DST's have two shut-in pressures, and 22 more have only one shut-in pressure. Mesa Petroleum has recently provided additional DST and well production data and will assist in our analysis.

Several production curves have been made for selected leases and the total field.

Resistivity-porosity cross plots of the B (Iatan), H (Dewey), K (Bethany Falls), and L (Sniabar) zones have been prepared from selected wells in Victory field. To date 56 wells have been cross plotted. A goal is to further characterize the carbonate reservoirs through examination of the spatial variation of the cementation exponent (slope of a log-log plot of R_t vs. porosity) within each sequence. The cementation exponent, m, is used to transform porosity into the formation factor, F, which is used to calculate water saturation ($S_w = (FR_w/R_t$, where R_w is water saturation and R_t is true formation resistivity). R_{xo}/R_t and R_{mf}/R_w ratios are also being used to independently determine water saturation and movable oil. This is also being compared with water saturation determined using the typical Archie equation.

Carbonate buildups and anomalous development of associated depositional sequences vary from subtle to very pronounced, and typically occur in proximity to or overlying present-day structure. Structure mapping includes first derivative maps to highlight areas of relatively great dip, which may be related to possible fractures or faulting and, in turn, to production or porosity trends or patterns. The derivative maps delimits areas in the field affected by greater amounts of structural flexure.

The natural gamma ray (spectrolog) of the #4 Cox well was used as a guide to identify and map the thickness of a low uranium "leached" zone in the Swope (K) sequence. This low-gamma-ray zone is correlated to other gamma ray logs in other wells by similar thin, slightly lower gamma-ray deflections located at the top of the carbonate unit. Thus far there does not appear to be any relationship of this deflection to effective reservoir porosity. Further evaluation is needed.

The entrapment of hydrocarbons and reservoir development within the Lansing-Kansas City succession at Victory field is complicated by a combination of many subtle depositional, structural, and diagenetic factors. For example, parasequence scale units, e.g., minor internal cycles in the Bethany Falls Limestone, appear to compartmentalize reservoirs vertically and possibly laterally as well. The results from the analog study of the Bethany Falls Limestone in eastern Kansas indicate that the bounding surfaces associated with the minor cycles are themselves usually very low-porosity, tightly cemented or muddy zones. In addition, diagenetic overprinting associated with some of the boundaries, e.g., subaerial exposure, strongly alter the original pore network and result in contrasting porosity preservation. Lateral and vertical interwell-scale variations of diagenesis and porosity are now a focus in the analog study.

The nature of hydrocarbon charging of these stacked discontinuous reservoirs appears to be a significant factor leading to varied hydrocarbon saturations (determined via wireline log calculation) throughout the field. Charging inefficiency is thought to be due to several factors, including very gentle structural dips and little or no structural closure, thin oil and gas columns coupled with capillarity, and varying effective porosity distribution. A result of this limited charging in the more heterogeneous reservoirs such as the Bethany Falls Limestone is that the reservoir commonly resides in the transition zone in terms of fluid saturation and capillarity.

Examples of Results

Oil production in Victory field occurs in the Iatan Limestone ("B" zone), Cement City ("H") of the Dewey sequence, Bethany Falls ("K") of the Swope sequence, and Sniabar ("L") of the Hertha depositional sequence. Figure 6.1 (a and b) shows a type log of the Middle and Upper Pennsylvanian interval in the Amoco #A-4 Cox well labeled with the stratigraphic zones. Cross sections of the interval between the "G" and "M" zones are shown in Figures 6.2 and 6.3. Preceding figures are indexed in base map of Victory field in Figure 6.4. Note variations in internal porosity distribution that are estimated within the "J", "K", and "L" zones. Pay thickness rarely exceeds 10 feet in any one zone, but two or more zones overlap in many producing wells.

A structural contour map of the "B" zone is shown in Figure 6.5. Although Victory field is located on a broad south-plunging anticline, structural closure is minimal. The minimal closure coupled with variable reservoir quality and permeability barriers has probably led to the fact that only the better reservoir-quality rocks are charged with hydrocarbon in scattered areas across the field. The widespread distribution of wells producing from the "B" zone is an exception. Seemingly good reservoir rock on the crestal areas of the structure were tested and calculated to be wet.

Porosity-permeability plots and representative core photomicrographs for the "B" and "K" zones in the Cox #A-4 well illustrate the contrast in their reservoir character (Figures 6.6 through 6.10). The "B" zone is the best reservoir in the field as suggested from these illustrations. The "B" zone reservoir rock is an abraded, well-sorted carbonate grainstone with good interconnected intergranular pore space as well as vugs and molds. Effective porosity for this interval is the standard 8%.

In contrast, the porosity in the oolitic grainstones in the "H", "K", and "L" zones is generally moldic and commonly lack interconnection unless further leaching or fracturing took place. Production associated with these oolitic reservoirs appears to be controlled primarily by the distribution of effective porosity (i.e. high-permeability lithologies) . Opportunities may be available to recompletion or infill drilling if the trends and controls of porosity distribution in these reservoirs can be determined. Analysis of wireline logs and DST data for the oolitic reservoirs indicate that effective porosity is 20 percent or more.

The permeability for a zone in a well is best estimated by the DST. K*h has been determined from available DST data using a Horner plot. Additional DST data will be made available by the operator. An example of the Horner plot from an oolitic grainstone reservoir in the Sniabar ("L") zone is shown in Figure 6.11. The well penetrated a lobe of exceptional development of oolitic grainstone within the Sniabar. The producing area was only recently discovered downdip from the crestal area of the anticline.

Calculations of water saturation commonly vary as a gradient in depth in the "K"- zone oolitic reservoir (Figures 6.12 and 6.13). This is true for almost every producing well and is clearly demonstrated by the Pickett cross-plots. Furthermore, no single oil/water contact is noted in the field. These observations suggest that the reservoir exists in a transition zone or gradient with no clear wet or fully saturated region. This phenomenon is being more completely investigated. Capillary pressure data should add to additional understanding to the nature of the pore space in these oolitic grainstones.

The cementation exponent, m, in determining the formation factor for S_w calculations in log analysis varies considerably. Thus the use of ratios of flushed zone to true resistivity is a better method to determine water saturation than using the Archie equation. Although further refinement is to be done, the critical water saturation appears to be approximately 40%.

A selection of maps, including reservoir structure, 1st-derivative of structure, carbonate isopach, thickness of porous carbonate, porosity-feet, k*h, DST BHP, and maximum gamma ray maps of the Bethany Falls Limestone, follows (Figures 6.14 through 6.24). The 40- to 60-ft-thick bank carbonate consisting of in excess of 20 feet of oolite is developed in the Bethany Falls Limestone ("K") on the southern crestal area of the present-day structure (Figure 6.16). Underlying isopach information suggests that the present structure exhibited paleotopographic relief prior to deposition of the Bethany Falls. In contrast, a map of the Sniabar thickness and productive area indicates an oolitic grainstone buildup several miles to the northeast on the flanks of the present crest of the anticline (Figure 6.17). A comparison of the Sniabar with overlying Bethany Falls limestone isopach indicates that the Bethany Falls is thin over the thick Sniabar, whereas the Sniabar shows only moderate thickening over the southern end of the present-day structure. The compensating nature of successive sequence deposition is suggested. Similar relationships have been recognized in the analog studies.

Spatial relationships of these reservoir-bearing strata indicate the divergent nature of the their stacking in the field. The changing sites of reservoir deposition were probably caused by variations in accommodation due to local relief and to complex sea-level histories that led to the development of shoal-water conditions at different paleoelevations within a sequence.

A series of isopach maps of these individual depositional sequences is shown in Figures 6.25 through 6.28. They reveal the effects of changing depositional topography or episodic structural growth during each sequence (each of which was approx. 300 ka in duration). More work will be done with this and supporting mapping and analysis of production during the 3rd year.

Isopach maps of three 3rd-order sequence sets within the Excello Shale to Nuyaka Creek, Nuyaka Creek to Muncie Creek, and Muncie Creek to Heebner intervals are included in Figures 6.29 to 6.31. Figure 6.32 is a structure map of the base of the Iola sequence to be used for comparison. The 3rd-order cycles were described in the section on computer modeling. These isopach maps primarily reflect the accommodation space that was available during deposition of these longer, time-distinct intervals. Thickness anomalies associated with episodic depositional or structural topography are not seen in the isopachs of the 3rd-order cycle, rather only those that are longer-lasting are noted (1.5 to 2 Ma in duration).

Although basic interpretations have yet to be made, it is clear that there is a shift in northwest-southeast-oriented thinning, from the present-day structural axis during the older Excello to Nuyaka Creek interval to a position southwest of the present structural axis during the overlying younger Nuyaka Creek to Munice Creek interval, to notable northeastward shift of the axis of thinning during the youngest interval from the Muncie Creek to Heebner. This may reflect the course of the longer contemporaneous deformation of the structure that set up the topography on which fluctuating sea level and sedimentation responded. Further analysis will continue during the 3rd year.

Plans

Engineering data are still being sought to detail the permeability and capillarity from any Lansing-Kansas City reservoirs. The capillary data would be used to determine guidelines for the thickness of oil columns necessary to migrate oil into the different types of reservoirs. Secondly, the information would be used to classify different types of reservoirs and determine the "original" residual water saturation and the entry pressure range. These results would provide an independent determination of effective porosity and help assess why wells have preformed the way that they have.

Key wells and data will be digitized for 3-D display on the graphics workstation to assist in interpreting varying spatial and stratigraphic relationships of the reservoirs.

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