DOE/BC/14434--8

Distribution DE92 017584

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

Quarterly Report for the Period
January-March 1992

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Work Performed Under Grant No. DE-FG22-90BC14434

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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 terrains. The geoscientific information, including data from field studies, surface and near-surface reservoir analogues, and regional data base development, will also be used for development of geologic computer process-based simulation models tailored to specific depositional sequences for use in improving prediction of reservoir characteristics.

SUMMARY OF TECHNICAL PROGRESS

Subtask 2. Depositional sequence characterization

Drum Limestone Study, Montgomery County, Kansas.

Two additional very-high-resolution seismic lines were taken along a north-south line at the Drum analog site in January 1992. 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 1). 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.

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). 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 of facies and structure will continue.

Plans include conducting a diagenetic study of the Drum oolite. Also four additional coring sites have been selected.

Hertha, Swope, and Dennis Limestones, southeastern Kansas.

Oxygen and carbon stable isotope profiles are available for two of the cores (Woodward #2 and Woodward #3) in the Woodward transect (Figure 3). A core description and carbon/oxygen isotopic profile from the Woodward #3 is illustrated in Figure 4. Two oolites are separated by a thin, nonporous, finer-grained interval that occur in both the Woodward #3 and Woodward #2, 1000 feet apart. A paleosol separates the oolites in Woodward #2, but not in #3. Isotopic evidence in Woodward #3 suggests that a subaerial exposure surface separates the two oolites and it is inferred that different sea-level events are associated with each oolite. 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. In 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.

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 5):

- 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.

New coring is planned to further improve the resolution of the relative sea-level curve based on application of sequence stratigraphy to area along shelf-to-basin transition. Coring is scheduled to begin in the next quarter. 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.
- 2) investigating apparent minor cycles within the back portion of the thick algal bank of the Sniabar Limestone that have been recognized on well logs in the Wilson County area.
- 3) understanding more fully the facies and distribution of oolitic low-order sequences and parasequences in the Bethany Falls and overlying Mound Valley limestones. As many as three minor cycles appear to be developed in this interval, including stacked oolites that in places closely resemble observed geometries in reservoirs in Victory field.
- 4) delimiting a stack of multiple grainstone units in the Winterset Limestone in the context of shallowing-upward stratal units (probably 5th-order parasequences). Also deepening-upward cycles (probably retrogradational parasequences that comprise a previously unrecognized backstepping transgressive deposit) will be examined.

Subtask 5. Computer modeling.

Computer simulation modeling

One-dimensional simulation (forward) modeling of 3rd- and 4th-order cycles was done to examine the affect of parameter change (sedimentation, eustasy, subsidence) on variations in shelf elevation and, in particular, drowning/backstepping of the carbonate shelf margin. A heirarchy of cycles was developed during accumulation of the Middle and Upper Pennsylvanian strata as established by shelf-to-basin cross sections and time-series analysis of profiles of Th/U ratio. Subsidence rates were derived from backstripping analysis done in Subtask 4. Third-order cycles (bundles of 5 or more 4th-order cycles) incorporated in the modeling were originally derived from time-series analysis of the Th/U ratio from shelf-bound wells (Figures 6 and 7). A simple abrupt 20 meter rise in sea level was followed by a gradual fall in sea level was used to generate the 3rd-order cycle (Figure 8) similar to that observed.

This modeling reveals distinct changes in sediment response among contrasting shelf positions (upper, middle, and lower shelves). Third- and 4th-order cycles on the upper shelf locations (higher elevation) are thin because marine sedimentation occurs only during limited intervals of marine inundation. Between sedimentation events, the upper shelf was subaerially exposed for relatively long periods of time compared to the lower shelf. On the lower shelf time during sedimentation is longer and thus 4th-order cycles are thicker. These cycles are also thicker at the beginning of a 3th-order cycle than at the end of one. Accordingly, the 4th-order cycles are more prone to exhibit small-scale, higher frequency sea-level events near the base of 3rd-order cycles or on lower shelf locations.

Abrupt deepening during onset of a 3rd-order cycle on the lower shelf can lead to drowning of the shelf due to very small increases in subsidence on the order of 0.01 m/ka, if subsidence is relatively high. While one cycle is carbonate dominated the superjacent one become sediment starved (Figure 8).

These results provide evidence that even with large rates and magnitudes of eustatic sea-level change, subsidence is critical to sediment preservation and can lead to significant modifications, such as the transformation of a shelf to a basinal setting.

Fischer plots, patterned after Alfred Fischer's technique (Fischer, 1964), provides a means to recognize higher-order relative sea-level cycles (e.g. 2nd- and 3rd-order) by estimating changes in the sediment surface elevation associated with a succession of 4th-order cycles. Cycle thickness (vertical column) and subsidence (diagonal line) are graphically depicted for each cycle. The assumptions used in making these diagrams include the duration of each cycle is the same and that subsidence rate is constant (Figure 6, index map, and Figure 9, Fischer plot).

Fischer plots were prepared for a series of mid to upper Pennsylvanian 4th-order cycles in four wells from the western Kansas shelf: Marshall #E-22, Bounds #1, Tedord #1-10, and Cox #A-4. The stratigraphic locations where episodic drowning of the shelf margin is initiated and where the profile of the Th/U ratio suggest more reducing conditions and inferred increased flooding of the shelf occur at locations of notable changes of trend on the Fischer plots. However, a trend of simple increasing accommodation associated with each 3rd-order cycle is not clear on the Fischer plots (Figure 9). Third-order cycles are characterized on the Fischer plots by both apparent increases and decreases in accommodation. However, the magnitude of increasing accommodation is generally greater than the decreases, leading to an overall increase in accommodation through this stratigraphic interval. The longer trend toward increasing accommodation is interpreted here as a 2nd-order cycle of rising sea level. This agrees with what has previously been documented for the Pennsylvanian.

Significant increases in accommodation do not occur until reaching the Kansas City Group (between the Nuyaka Creek Shale and the Muncie Creek Shale). Younger cycles generally return to a level, constant accommodation up through the Haskell Limestone, immediately below the Heebner Shale. In contrast, the Marshall #E-22 well, located high on the shelf, shows essentially constant thickness and even decreasing accommodation space. Variations in accommodation are reflected in the internal character of the cycles and thus is important to understanding reservoir development. Knowledge about the accommodation trends is figures very significantly in discerning mechanisms responsible for cycle development.

Forward Modeling

Two-Dimensional Modeling. The output of the 2-D simulation model now includes large, high-resolution data files limited only by the RAM available. The file can be used for 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. This data file is used to construct 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 continuous profile (Figure 10 and 11). The stratigraphic columns are generated in a separate window from the 2-D profile 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.

Examples output from the 2-D simulation program shown in Figures 10 and 11 include two 4th-order marine carbonate-dominated cycles deposited along a sloping depositional surface modeled after the Sniabar and Swope cycle development in the analog area in 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. Each cycle is distinguished by a black stratum (the marine shale) deposited at the base of each cycle corresponding to the lower Mound City Shale and overlying Hushpuckney Shale. The high-energy facies (lightest, coarsest dotted pattern) occurs along the two breaks in slope on the shelf.

There is considerable lateral variation in the stratigraphic succession that occurs within both cycles resulting from the interaction of shelf elevation, slope, sea level, and sediment accumulation. The lower cycle is very thin across the upper shelf (positions 300, 450, and 600 in Figure 11), much like the actual 4th-order cycles, e.g., the Sniabar Limestone. The stack of facies in each 4th-order cycle on the upper shelf consists of simple, shallowing-upward sets. The sea-level curve for the first cycle (Figure 10) fell steadily with no stillstands during carbonate accumulation on the upper shelf resulting in a simple, attenuated shallowing-upward succession.

Limited thickness of high-energy carbonate sediments (lighter colored, dotted pattern) deposited on the lower shelf is the result of sediment starvation. The thick carbonate buildup in the lower 4th-order cycle consists of a set of smaller 5th-order cycles that punctuate the section.

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. Inverse modeling techniques are being pursued to acquire more precise and accurate parameter information.

Subtask 6. Reservoir development, prediction, and play potential.

Victory Field.

Calculations of water saturation commonly vary as a gradient in depth in the "K"- zone oolitic reservoir in Victory field. This is true for almost every producing well and is clearly demonstrated in the R_p -porosity (Pickett) cross-plots. Furthermore, no single oil/water contact is noted in the field. These observations suggest that the reservoirs exist 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 additional understanding to the nature of the pore space in these oolitic grainstones.

Isopach maps of individual 4th-order depositional sequences are being prepared along with maps of 3rd-order cycles. These maps and maps of reservoir attributes will be used together to locate potentially bypassed oil and to ascertain controls on the heterogeneity. Preliminary observation of isopach maps of 3rd- and 4th-order cycles in the Lansing-Kansas City reveal changing depositional topography and episodic structural growth.

Engineering data are still being sought to detail the permeability and capillarity from any Lansing-Kansas City reservoirs. The capillary data will determine approximate thicknesses of oil columns necessary to migrate oil into the different types of reservoirs and could account for the common wet wells located on structure. 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 will 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.

Figure 1. Representative seismic field file for data collected January, 1992.

Basement structure (solid) and Isopach map of Drum Limestone (dashed)

Montgomery County, Kansas

Figure 2.

Basement data from Baars and Watney (pers. com.)

Figure 3. North-south stratigraphic section on Woodward lease showing graphic core descriptions that transects oolitic bar.

Stable Isotope Data KGS Woodward #3

Figure 4. Stable isotope profile in KGS Woodward #3 core from north-south core transect of Bethany Falls-Mound Valley oolite lobe.

Figure 5. Porosity and permeability values and estimated grain size ranges within Bethany Falls-Mound Valley limestones, KGS Woodward #3 core. Lithofacies are dominantly ooid-skeletal grainstones with skeletal-peloid packstones also present.

Th/U STUDY

Figure 6. Oil and gas map of Kansas showing locations of wells used in the Th/U ratio analysis.

MURFIN #1-10 TEDFORD

Sec. 10-30s-25w Clark Co KS

Figure 7. Murfin Tedford #1-10 well. Description same as Figure 3.5.

[illegible]

Figure 8. One-dimensional stratigraphic model for examination of interaction of 4th- and 3rd-order sea-level cycles. Sediment added during 4th-order cycle is vertical distance between diagonal lines whose slope is equal to rate of subsidence. Sea-level curve consists of higher frequency (4th-order), jagged asymmetric traces with 350 ka period and magnitude of 110 meters. The 3rd-order cycles span five 4th-order cycles, each characterized by abrupt 20 meter rises in sea level followed by gradual fall in sea level. The mid-shelf diagram in (a) shows thickening of the 4th-order cycles at the beginning of 3rd-order cycles. The lower shelf diagram (b) illustrates abrupt drowning of the shelf occurring at the beginning of the second 3rd-order cycle.

Figure 9. Fischer plots (time vs. sediment surface elevation) for the stratigraphic interval from the Middle Pennsylvanian Excello Shale to the Upper Pennsylvanian Heebner Shale for four wells on the western Kansas shelf. Vertical segments correspond to cycle thickness. The slope of the diagonal segment is subsidence rate. The horizontal length of each segment is a constant 350 Ka. Stratigraphic location of boundaries of 3rd-order cycles established independently based on shelf margin stacking geometries and analysis of Th/U ratio profiles are identified in each well as follows: EX = Excello, Nc = Nuyaka Creek, Mc = Muncie Creek, and between Ha = Haskell and He = Heebner.

Figure 10. Two-dimensional model result based on shelf to basin transition in southeastern Kansas. Original example is in color. Two cycles of sea level change result in two 4th-order cycles of sedimentation. High resolution stratigraphic output at particular positions of shelf are shown in next figure.

Figure 11. High-resolution output of two-dimensional model produced by saving pixel data on facies to file and replotting facies files for specific locations. Two 4th-order cycles are shown with the surface separating them indicated by black line. Dark facies is marine shale (condensed section). Light-colored, dotted facies is high-energy oolite. Columns closely resemble facies successions observed in Hertha and Swope sequences in the area modeled.

END

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