INTEGRATED GEOSTATISTICAL MODELING AND SIMULATION

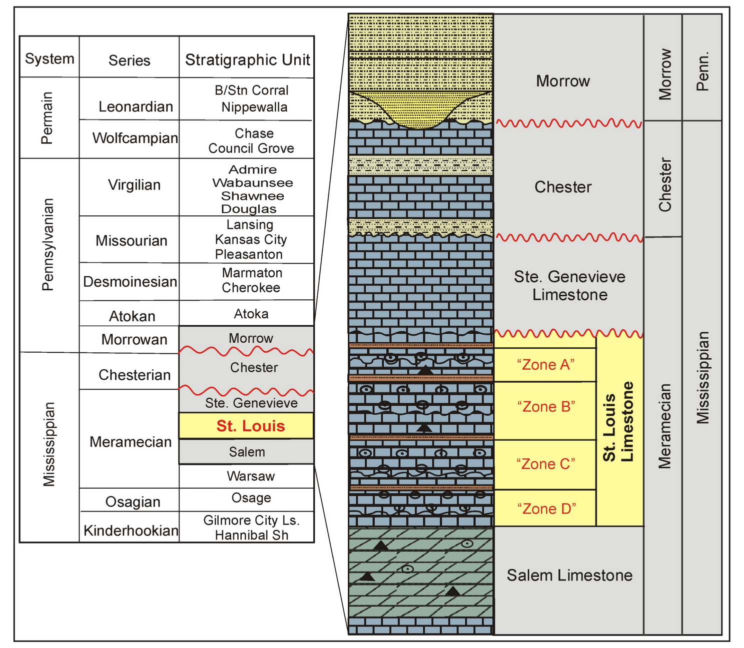
ABSTRACT

In the Hugoton Embayment of Kansas, reservoir units in the St. Louis Limestone consist of relatively thin (<4m), spatially scattered, highly heterogeneous oolitic grainstone deposits. Quantifying the distribution of such oolitic deposits is challenging, but essential for improving understanding of sedimentologic processes and developing efficient reservoir management strategies.

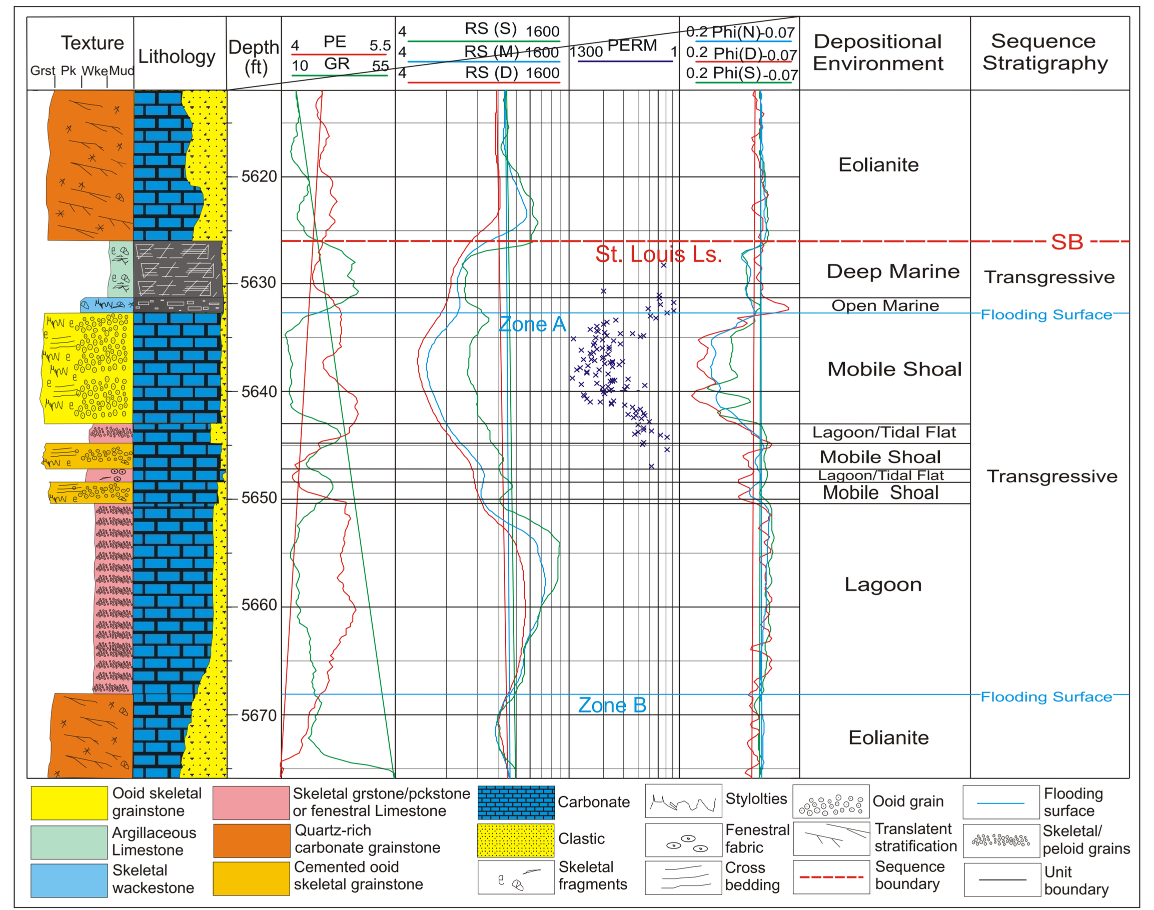
A single hidden-layer neural network was used to train and establish a non-linear relationship between lithofacies assignments from detailed core descriptions and selected log curves. Neural network models were optimized and used to predict lithofacies on the entire dataset of the 2,023 half-foot intervals from 10 cored wells. Predicted lithofacies compared to actual lithofacies displays absolute accuracies of 70.37 to 90.82%. Established quantitative relationships between digital well logs and core description data were applied in a probabilistic sense to predict lithofacies in 90 uncored wells across the Big Bow and Sand Arroyo Creek fields.

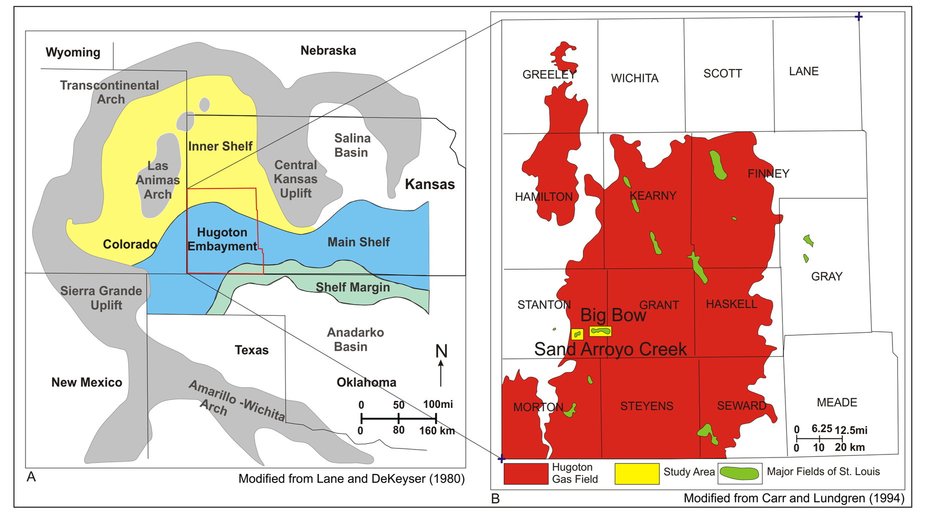
Predicted lithofacies were integrated with well data to build 3D geostatistical models and stochastic simulations of oolitic reservoirs. The models provide insight into the distribution of facies, the external and internal geometry, and the sedimentologic processes that generated the reservoir units. The depositional pattern and connectivity of modeled oolitic complexes suggest an accumulation of oolitic deposits during pulses of relative sea level rise followed by deepening near the top of the St. Louis. Neural networks and geostatistical 3D modeling can be applicable to other complex carbonate or siliclastic reservoirs in which facies geometry and distribution are the key factors controlling heterogeneity and distribution of rock properties.

Kansas Paleozoic Stratigraphy

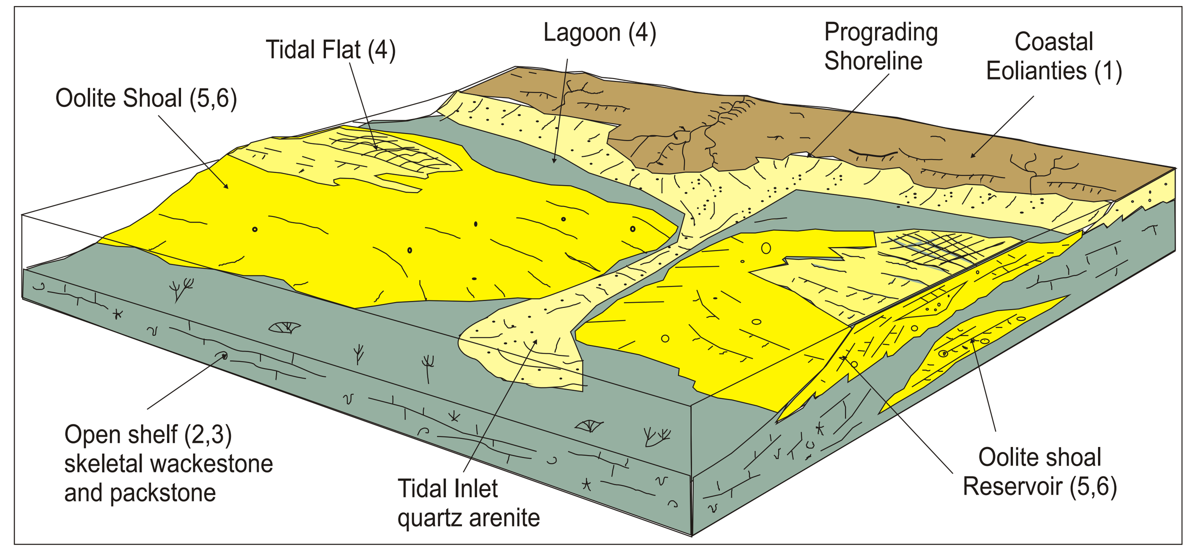


Upper Paleozoic stratigraphic column in southwest Kansas showing the carbonate-dominated St. Louis Limestone and the oolitic grainstone intervals classified into local informal subtidal reservoir zones. Predicting the location of individual St. Louis Limestone oolitic deposits, which are isolated and relatively thin intervals (< 4m) interbedded within a thicker (~ 20m) sequence of non-porous deeper-shelf, tidal flat and eolianite deposits, provides a challenge to successful exploration and efficient field development.





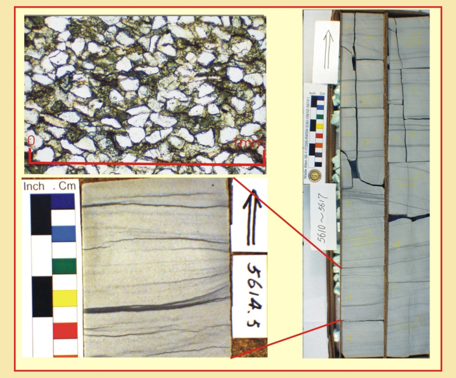
Mississippian paleogeography of study area in southwestern Kansas showing the location of Big Bow and Sand Arroyo Creek fields included in the study. The two fields are part of a complex of oolitic reservoirs showing alignment across the Hugoton Embayment. St. Louis Limestone oolitic deposits are distributed as a series of isolated linear belts of shoals trending approximately northwest-southeast across the Hugoton area or laterally confined platform shoals that show a spatial relationship to Mississippian sea-floor highs and barrier islands. During Mississippian time a coincidence of global paleoclimatic, eustatic, and geochemical factors, along with ideal regional paleogeographic and tectonic conditions, resulted in widespread deposition of carbonate oolitic deposits across the North American continent. Significant occurrences of hydrocarbons have been discovered in oolitic reservoirs in the Ste. Genevieve Limestone of the Illinois Basin and the St. Louis Limestone of the Hugoton embayment of southwest Kansas.



Based on core descriptions of cored wells, thin sections, and previous work on the St. Louis Limestone, six major lithofacies were recognized, classified, and interpreted at half-foot intervals. The six classified lithofacies are: 1) quartz-rich carbonate grainstone; 2) argillaceous limestone; 3) skeletal wackestone; 4) skeletal grainstone/packstone; 5) porous ooid grainstone; and 6) cemented ooid grainstone. Based on a variety of evidence including presence of sedimentary structures, general presence of fauna or fossil fragments and grain composition, all six lithofacies were interpreted and associated with depositional environments that follow earlier work.

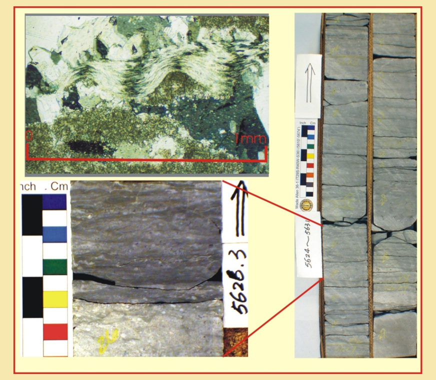
The six major lithofacies are: 1) quartz-rich carbonate grainstone some of which was deposited by eolian processes adjacent to a coastline; 2) argillaceous limestone deposited in the deepest marine environment; 3) skeletal wackestone deposited in open marine settings; 4) skeletal grainstone/packstone deposited in a restricted lagoonal environment or tidal flat; 5) porous ooid grainstone indicating deposition of shallow-marine shoals on an open shelf; and 6) cemented ooid grainstone deposited in a similar environment as ooid grainstone, but with reduced porosity and permeability due to late compaction and cementation.

St. Louis Limestone Lithofacies



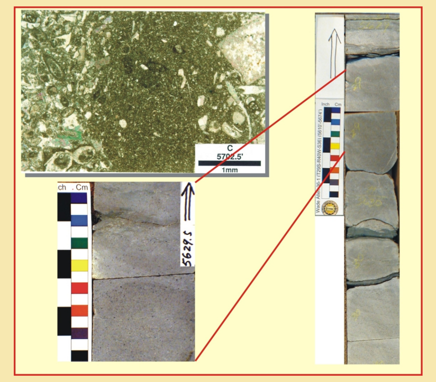
Lithofacies 1
Cross-bedded Quartz-rich Carbonate Grainstone

Mixed siliciclastic and carbonate grainstone Contains very fine quartz (up to 40 ~ 50%) and medium grained peloids, skeletal fragments, ooids. Inverse translatent stratification and stylolites are common. Angles of cross bedding most commonly are in the 10 to 20 degree range. Permeability is less than 1md, most <0.01md. Non-reservoir facies.



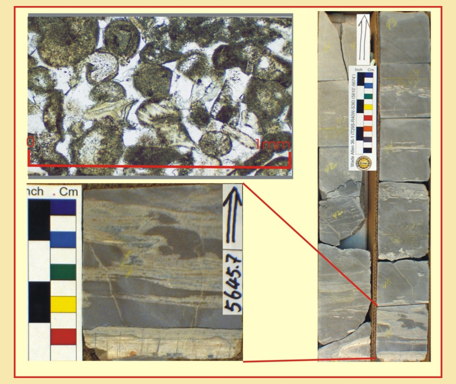
Lithofacies 2
Argillaceous Limestone

Thin, laterally extensive condensed section, characterized by thin bedded, often fissile olive green to gray argillaceous limestone. Primarily wackestone /packstone with abundant bryozoans and crinoids and minor brachiopods and ostracods. On electric logs, displays a distinctively higher gamma-ray response. Non-reservoir facies.



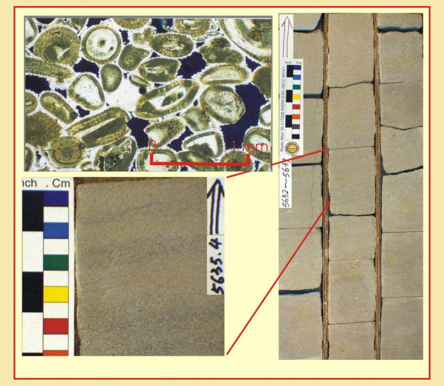
Lithofacies 3
Skeletal Wackestone

Very poorly sorted, greenish to dark yellowish-brown wackestone with large, relatively un-abraded skeletal fragments. Crinoids and fenestrate bryozoans are the most abundant skeletal fragments, with echinoderms, brachiopods, gastropods, and foraminifera also present. Porosity averages less than one percent, with permeability of 0.01 md. Non-reservoir facies.



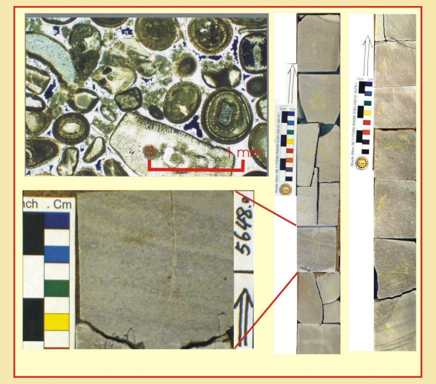
Lithofacies 4
Peloidal Grainstone/ Fenestral Limestone

Very fine peloidal grainstone with some very fine quartz and fine ooid grains. The fenestral limestone is characterized by "bird's-eye" or fenestral fabric (indicator of intertidal to supratidal deposition). Typically occurs adjacent to the ooid-skeletal grainstone facies. Non-reservoir facies.



Lithofaices 5
Ooid Skeletal Grainstone

Reservoir facies characterized by medium to very coarse moderately sorted ooids. The ooids have a radial concentric structure and are usually unbroken. Large skeletal grains and peloids present. Main porosity is interparticle with minor moldic porosity. Total porosity ranges from 3 percent to 20 %. Distinctive log response with higher porosity and lower resistivity. Accumulates in a high-energy, open-marine environment.



Lithofaices 6
Cemented Ooid Skeletal Grainstone

Composed of medium to very coarse size and moderately sorted ooids. The ooids have a radial concentric structure and are usually unbroken. Large skeletal grains, especialy crinoids, and peloids are present. Heavy syntaxial cementation occludes interparticle voids. Porosity and permeability are very poor. Non-reservoir facies.

- 1. Data Preparation & Conditioning
- 2. Facies prediction, data analysis & variables calibration
- 3. Construct a 3D stratigraphic framework
- 4. Geostatistical facies and petrophysical modeling:
  - 4.1. Create 3D modeling grids
  - 4.2. Facies distribution modeling by stochastic simulations
  - 4.3. Rock property modeling by stochastic simulations
- 5. 3D visualization, upscaling and streamline simulation:
  - 5.1. 3D Visualization of models
  - 5.2. Creating 3D flow simulation grids and upscaling for reservoir parameters
  - 5.3. Streamline simulation

Neural network modeling

Removing structural tilting

geometric data & facies proportion constraints

Schematic illustration of the major steps of integrated geostatistical modeling and simulation used in the study of St. Louis Limestone reservoirs. Major aspects in integrated reservoir characterization include data collection, stratigraphic modeling, facies modeling, rock property modeling, and static model ranking and upscaling. Details of the methods differ depending on the availability, quantity and quality of data set, and more importantly the geology of the target reservoirs. In this study, an integrated geostatistical approach was focused to address the modeling and simulation of the relatively thin oolitic reservoirs of the St. Louis Limestone. The procedure used in this study involves five major steps.

1) Available data were collected for the selected reservoir. As is typical of the smaller fields of the Mid-continent U.S., 3D seismic data were not available. Available data were primarily associated with wells and comprised of different types of data (core descriptions and petrophysical measurements, wire-line logs, stratigraphic tops, and fluid production), at different scales (vertical, horizontal, fine-scale core data, coarse-scale wire-line log data) and degrees of quantification (descriptive facies, interpreted depositional environments, digital logs, and reported fluid production). All collected data from Archer Field were assembled into a relational database.

2) With the selected neural network parameters, a single layer neural network model was trained from digital well logs based on 1,000 half-foot intervals of cored wells (network size of 35, and damping parameter of 0.01). Core data were used to calibrate the log depths in cored wells, and digital well logs were obtained in all wells. In the St. Louis Limestone A, the model was used to predict lithofacies in wells where core is absent. Rock properties from core analysis were calibrated and correlated with digital well log data. Available core-measured petrophysical data were studied to build porosity-permeability transforms within each lithofacies.

3) Wells from the field areas with stratigraphic horizons in the St. Louis Limestone were assembled through a database. Predicted lithofacies curves were used to verify the top picks for zones of the St. Louis Limestone along with the traditional log markers and patterns. Without seismic data, original structural maps of St. Louis Limestone zones were built from stratigraphic horizons along with available fault information. Removing the effect of tilting during the Laramide orogeny was a key to recovering the original stratigraphic framework during deposition of the St. Louis Limestone. Structural maps of St. Louis Limestone zones were used to build a stratigraphic framework.

4) Based on available data, appropriate dimensions were selected to construct 3D modeling grids from the stratigraphic framework. Raw well data (facies and petrophysical data) were entered, blocked, and centered at the geological framework grids. Facies-proportion information calculated from well data and available geometric data of depositional facies was used as constraints for facies modeling. Various geostatistical and stochastic methods (object-based and indicator simulations) were applied to construct 3D facies models. With the available lithofacies curves at well locations, and the collected geometric data for the main depositional facies, object-based stochastic methods were used to build three-dimensional models of facies in the St. Louis Limestone. Facies proportion maps calculated from well data were used as soft constraints. Geometry data and azimuth range were used to generate facies objects around the wells that honor the well data.

5) Visualization tools were used to visualize 3D facies and petrophysical models. A coarse simulation grid was built and the rock parameter simulations were upscaled to the corresponding cells. The porosity and water saturation were upscaled using arithmetic averages. The permeability was upscaled using arithmetic-harmonic average. Streamline simulations were used to evaluate the realizations of the property distributions that are reasonable from both geologic and fluid flow properties after upscaling the geologic models. Drainage functions were calculated from the results of streamline simulation. The streamlines display different fluid flow paths among wells for different facies models and were used to evaluate the geological models generated by geostatistical techniques.