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Stratigraphy and Porosity Modeling of South-Central Illinois (USA) Chester (Upper Mississippian) Series Sandstones Using Petrel

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Abstract Maximizing resource extraction from mature oilfields requires enhanced and secondary recovery techniques. The success of these methods relies on knowledge and understanding of the reservoir geology and hydraulics. At the Loudon Oilfield (Illinois, USA), enhanced oil recovery is being used to extend the production life of the reservoir. The suitability and placement of additional wells for oil recovery processes required three-dimensional (3D) facies and porosity modeling of the oilfield. The purpose of this work was to assess the ability of a porosity model to predict sandstone facies. The facies model for the Loudon field was generated using data obtained from digitized-wireline logs. The facies model provided sand thickness and insight in the geometries and interconnections of the producing formations. The porosity model identified zones of high porosity, and illustrated the discontinuous nature of the porosity zones within the oilfield. Comparison of facies and porosity models revealed strong correlation and similarity between the models.

Keywords: *Illinois Basin, oilfields, facies modeling, porosity modeling*

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1. Introduction

More than four billion barrels of oil have been produced from Paleozoic strata in the Illinois Basin [1], with an estimated 400 million barrels recovered from the Loudon Oilfield [2]. The Loudon Oilfield (Figure 1), located in Fayette County, Illinois, occupies ~50 mi^2 and contains nearly 2000 (active production and injection) of the approximately 90,000 wells that penetrate the New Albany (source rock) petroleum system throughout the Illinois Basin [3]. The field is a northeast trending anticline with 165 feet of structural closure and 1° to 2° flank dips [4]. There are four main oil and gas-bearing sandstone units within the field. All units are Chesterian (Upper Mississippian) in age. From youngest to oldest, the sandstones are the Weiler, Paint Creek, Bethel, and Aux Vases (Figure 2). These sandstones were deposited in a fluvial deltaic setting [5]. In the Loudon Oilfield the Aux Vases sandstone has as a blanket geometry, and the Weiler, Paint Creek, and Bethel sandstones are discontinuous (pinch out). The Weiler sandstone ranges from 0-60 ft in thickness [6]. Both the Paint Creek and the Bethel have thicknesses that range from 0-40 ft. The Aux Vases is the thickest sandstone with a range between 60-80 ft. While the horizontal permeability value for all four sandstones is ~100 milli-darcies (mD), the mean porosity of the Weiler sandstone is ~20% compared to the mean of ~18% for the other three sandstones [7]. The Aux Vases is the most productive sandstone in all of Illinois, accounting for more than one third of all the petroleum recovered in the state [8,9].

Waterflooding has been used to enhance oil recovery efforts from the Loudon Oilfield for several decades. Waterflooding to sweep the sandstone reservoirs of additional oil involves the use of high pressure, high volume pumps to reinject formation water produced during oil recovery into a well to sweep the sandstone reservoirs of additional oil [10,11]. The water then travels through the rock body until being drawn into a nearby production well, which subsequently pumps the fluid (water and oil) to the surface. Properly executed, waterflooding can recover up to 60% of *in situ* petroleum in a sandstone carbonate reservoir system [12,13]. The primary consideration to the success of waterflooding concerns are oilfield geology, specifically facies changes, and dynamics of fluid, variations in porosity and permeability of the formation [14]. Approximately 150 new injection wells have been drilled in the past few years at Loudon with an estimated 100 to 200 more planned to be drilled in the upcoming years. New production wells are being drilled in response to the influx in reservoir fluid caused by the recent waterflooding efforts and to explore untapped areas of the field. The array of stratigraphic complexities at the Loudon Oilfield makes correlation and fluid dynamics complex and challenging. For example, sandstones 30-40 ft in thickness, as observed from well-logs, taper and eventually pinch out in a few hundred feet.

Open-hole well logs have been utilized in countless exploration and production projects to successfully analyze lithofacies [15] and to predict reservoir quality with respect to porosity [16]. In another related analysis, Xu*et al.* [17] used borehole images (12 wells) and open-hole logs from over 500 wells located at the Red Oak Gasfield of southeastern Oklahoma to investigate the structural and sedimentary characteristics of the lower Pennsylvanian Red Oak Sandstone of the Arkoma basin in an effort to better understand the behavior of this unit as a hydrocarbon reservoir. The images along with the logs, which included neutron, density, gamma-ray, array induction resistivity, and sonic, were used to correlate formations and to map the geology of the field.

Porosity is a controlling factor in the ability of a rock body to store fluid. Greater porosity equates to greater space for fluids, i.e. water, gas, and oil, to accumulate. Coupled with permeability, the porosity of a rock body is important to the petroleum industry. Oil companies want to locate the rocks with high porosity and permeability. Well logs displaying the porosity values for the rock units of a newly drilled well are generated by a logging tool recording within the wellbore. Subsequently, a porosity log can be correlated to porosity logs from other wells via modeling software with the goal of constructing an interpretive model. The resulting model illustrates the porosity of the geologic formations found in a particular area. Gamma-ray logs are used to identify rocks high in clay content, i.e. a higher gamma-ray count equates to higher clay content. Situations exist where a rock body may have high porosity on a log and have increased clay present. For example, a rock unit may have high porosity, but the presence of high amounts of shale can equate to low permeability.

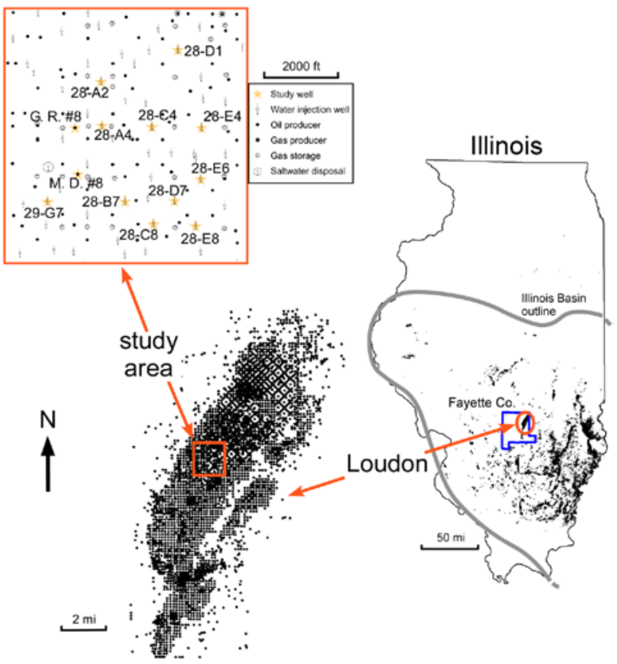

Figure 1. Oil and gas production and water injection wells in Illinois and study site including locations of 11 injection wells and two production wells with LAS files

To investigate the suitable placement and feasibility of additional wells for oil recovery processes (production or injection wells) within the Loudon Oilfield, 3D models depicting the facies and formation porosity were generated. The purpose of this work was to assess the ability of a porosity model to predict sandstone facies. The facies model for the Loudon field was generated using data obtained from digitized-wireline logs. All rock units (sandstones, shales, and carbonates) were delineated, particularly four sandstones (youngest to oldest): Weiler sandstone within the Cypress Sandstone; Paint Creek sandstone within the Paint Creek Group; the Bethel sandstone within the Yankeetown Formation; and the Aux Vases Sandstone. The porosity model was constructed using similar methods employed in building the facies model. Comparison between the facies model and the porosity model was conducted through the construction of a composite model, which provided the degree of precision that the porosity model indicated sandstone facies.

2. Stratigraphy of Loudon Oilfield

The Loudon Oilfield focuses on alternating sandstone and shaley-sand units with layers of carbonate above and below [5]. The materials were deposited in a tidal dominated deltaic environment during the Mississippian [5]. During the lower Chesterian, the Illinois Basin lay in the tropics between 5° and 15° south of the equator and was a shallow marine platform or ramp and at times an embayment open to the south [18]. Sand deposits formed elongate tidal bars and channel sands, explaining the pinching out nature of the present day rock units. The New Albany Shale (Devonian) serves as the source rock of the petroleum [19]. The primary producing formations are the Weiler sandstone, the Paint Creek sandstone, the Bethel sandstone, and the Aux Vases sandstone (Figure 2). As previously mentioned, sandstones at Loudon have a porosity values greater than >10%. Lateral and vertical porosity differences have been noted and can be noteworthy [14]. The shales and carbonates, with porosity values less than 10%, act as a cap unit [2]. Structurally, the region is a suite of small anticlines termed an anticlinorium [8,20].

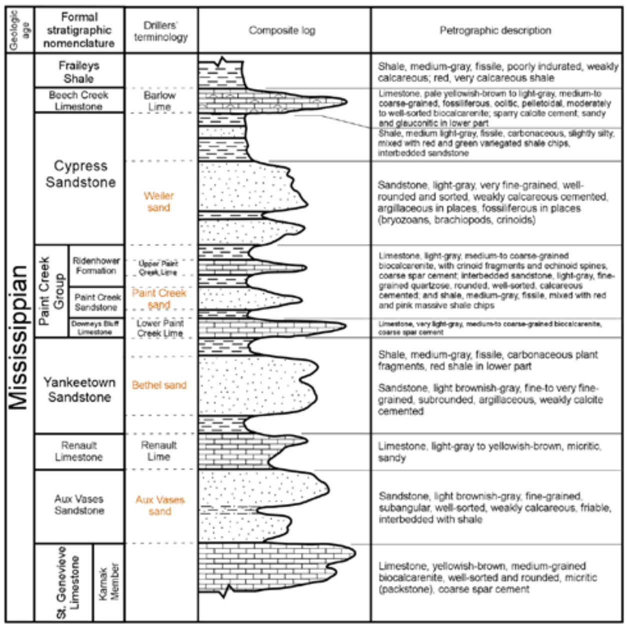

Figure 2. Stratigraphic column including petrographic description of Upper Mississippian rocks in southern central Illinois (modified from [6], drillers' terminology describes subunits within larger formations

3. Methodology

A three-dimensional (3D) facies model and a porosity model, representing a section of the Loudon Oilfield, were built in Petrel [21], the difference between the models was the type of log data used to populate the grid cells. Within the Loudon Oilfield, the sandstone reservoir rocks are notorious for abrupt facies and porosity changes, correlating to erratic thickness variations due to their channel sand deposition [22]. Due to a limited number of available well logs with gamma-ray, porosity, and spontaneous potential data, an area measuring ~1 mi^2 was chosen for the model (Figure 1). The area encompasses 13 wells: 11 injection wells and two production wells. Depths of the wells vary between 1600 feet to 1710 feet below ground surface.

Petrel requires a framework to build the model, either pillar gridding based on faults or a simple three-dimensional nodal grid. Since the region has no major faults, the simple grid method was used [2,23]. The facies model and porosity model are made up of 20 ft x 20 ft x 1 ft cells enclosed in a 3D grid of 300 rows by 300 columns and 200 layers consisting of vertical boundaries (horizons representing tops and bases of rock units) and a horizontal boundary that signifies the xy limit of the surface boundaries. A vertical grid spacing of 1 ft was used, the finest resolution the available processor could handle. Although it is very common to choose a more coarse resolution due to processor limitations, in this instance a fine scale model is preferable. Sand lenses as small as 0.5 ft with permeability as high as 300 mD can exist within the column that can dramatically affect the model [2]. Since this project seeks to identify the ability of porosity to indicate a sandstone facies, it is important to use the finest resolution possible in order to account for the influence of small lenses upon the model as a whole. The top and base of each of the four sandstones and the Barlow limestone (reservoir caprock) were manually picked from the 13 digitized spontaneous potential logs and combined with the tops and bases picked from paper spontaneous potential logs (no available porosity and gamma-ray logs) of the 70+ surrounding wells to create a database to be used in making surfaces and model boundaries. The grid cells were assigned facies designations and porosity values based upon data from the digitized gamma-ray logs and porosity logs for each well, respectively. Nodes between the unit boundaries are assigned values via upscaling, After the importation of the digitized well logs, Petrel automatically averages the continuous well log value and assigns a value to each node. The Random Gaussian Function simulation was selected as the algorithm for the petrophysical modeling process.

4. Results and Discussion

4.1. Facies Model

The facies model (Figure 3) illustrates the geometry of the rock bodies. The model depicts the Weiler sand as the most variable in terms of thickness and lithology. The Weiler is the thickest in the southern and eastern portion of the area, where it is designated as sand. In the northern and western areas, the Weiler is thinner and has been designated as shale. Overall, the Weiler has an average thickness of 39.5 feet with a standard deviation of 18.1 feet. The Paint Creek and the Bethel sands are the thinnest units, with mean thicknesses of 15.9 feet and 13.6 feet respectively. The Paint Creek is represented as containing lesser amounts of sand and more shale and carbonate. In the western area, the Bethel sand is thick and comprised of more sand. Transitioning east, the Bethel sand thins and grades into shale and carbonate. The Aux Vases is the thickest and most consistent sand unit, with a mean thickness of 52.6 feet and a standard deviation 1.5 ft. While some lenses of shale are apparent, the Aux Vases is primarily sand.

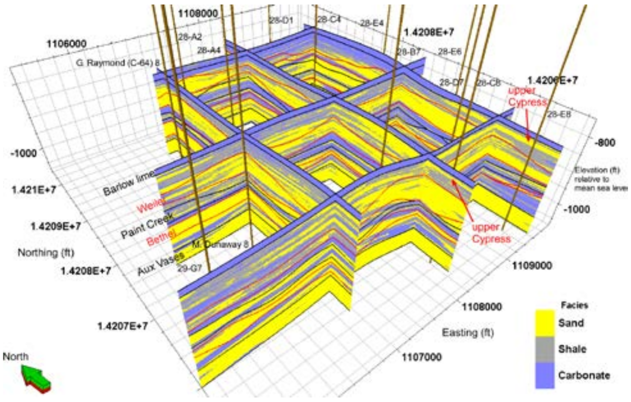

Figure 3. Fence diagram illustrating the results of the facies model. Facies included are sand (yellow), shale (grey), and carbonate (blue). The 13 study wells are included for perspective—see Figure 1 for well locations. The delineation of the sands, based upon spontaneous potential logs, are indicated by red lines for the Weiler and Bethel sands and by black lines for the Paint Creek and Aux Vases sands. The Barlow lime is also outlined by black lines.

4.2. Porosity Model

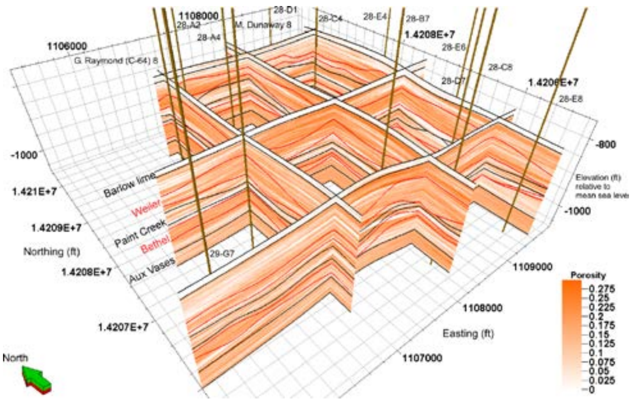

Figure 4. Fence diagram illustrating the results of the porosity model. Porosity values range from 0 (white) to 0.03 (30%) (orange). The 13 study wells are included for perspective—see Figure 1 for well locations. As with Figure 3, the locations of the sands are defined by red lines for the Weiler and Bethel sands and by black lines for the Paint Creek and Aux Vases sands. The Barlow lime is also outlined by black lines

The established sandstone zones (Weiler, Paint Creek, Bethel, Aux Vases) contain the vast majority of high porosity cells (Figure 4), though areas of high porosity exist outside of the sandstones. Similar to the facies model, decreased amounts of interior partitions resulted in increased amounts of high porosity (high enough to qualify as a sandstone facies) cells existing outside of the sandstone zones established by the well log data. High porosity cells are located north and southwest of 28-B7 in the zone between the top of the Weiler and the base of the Barlow. While the Weiler sand tends to have some of the highest porosity values, the areas are discontinuous and spatially variable. The Paint Creek sands tend to have lower porosity values, consistent with the lack of sand designation within the facies model. The simulation reveals that the Aux Vases has the most consistent porosity values.

4.3. Facies Model - Porosity Model Comparison

To analyze the ability of the porosity model to indicate sandstone facies another model was constructed. The goal of the model was to compare porosity model values with facies model values to discern which porosity values did not represent a sandstone facies. Using the log calculator function a new comparison log was created that assigned qualitative values of “good”, “bad”, and “not applicable” to grid cells based on the values from the porosity and facies models. If a log interval was designated sandstone on the facies log, had a porosity greater than 0.1 on the porosity log, and had a value less than 60 American Petroleum Institute units (API) on the gamma-ray log (an indicator of sandstone), then the log interval on the comparison log was designated “good”. If a log interval was designated sandstone on the facies log, had a porosity greater than 0.1 on the porosity log, and had a value greater than 60 API on the gamma-ray log (an indicator of shale), then the log interval on the comparison log was designated “bad”. If a log interval was designated shale or carbonate on the facies log, then the log interval on the comparison log was designated “not applicable” and were ignored in subsequent analysis. The limit values of 0.1 porosity and 60 API units were based on density porosity and gamma-ray log values of known facies intervals (e.g. Barlow lime, Weiler sand). Among sediments, shales possess by far the highest level of radiation, making the gamma-ray log a suitable representation of a rock body’s shale content (and permeability). For the entire model domain, 82% of the cells were classified as “good” compared to the 18% that were “bad”. Cells within Aux Vases and Bethel sands were designated as “good” exhibiting better correlation between facies and porosity, while the Paint Creek sand had the highest portion of “bad” cells. The comparison model appears to provide a more accurate way of identifying the actual of sands than using only facies or porosity to find zones of production.

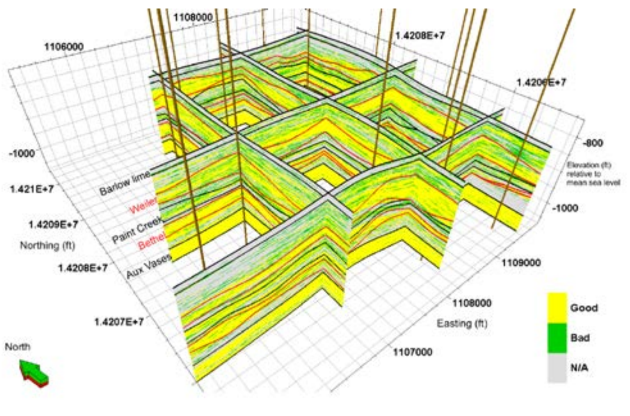

Figure 5. Zone-partitioned facies/porosity comparison model

The comparison model illustrates the combined analyses of the facies model and the porosity model. The coupling of sand facies and consistent higher porosity values of the Aux Vases illustrate why the formation is the highest producing formation in the Illinois Basin. An important feature to the Aux Vases that makes it more productive than the above units is the presence of several thick sand horizons, which can reach up to 5 meters in thickness [19]. These ancient sandbars, with higher porosity (21%) and permeability (125 mD) than the other units allow for a much higher primary recovery percentage (upwards of 40%). These sandbars can be quite large in their distribution, potentially kilometers in length and a kilometer in width [19]. The results of the models suggests installation of waterflooding within the Aux Vases has a greater potential for success than within the other sands of the Loudon Oilfield.

5. Conclusion

The goal of the project was to assess the ability of a Petrel porosity model to predict sandstone facies. Examination of the facies/porosity comparison logs showed that the percentage of the log that represented a good sand indicator by the porosity log (82%) was the same as the good sand indicator percentage of the zone-partitioned model. Data provided by both the facies and porosity models were largely a product of interpolation by the modeling algorithm, so error in cell assignments is assumed to exist in the models to a certain degree. The most reliable data in the models are the cell values at the locations of the wellbores because the data were generated by the logging tool. The validation exercise that involved the exclusion of certain well logs and rerunning of the facies models showed that the cell assignments produced by the algorithm in the two examples were at least ~80% accurate. Though modeling in Petrel provides a reasonable interpretation of reservoir rock characteristics, efforts incorporating Petrel-based modeling should involve consideration of the potential error in cell values a given distance from log-truthed well data.

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