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REVISITING TIRED OLD FIELDS WITH NEW TECHNOLOGIES: THREE-
DIMENSIONAL MODELING AND STRUCTURAL ANALYSIS
OF THE DUDLEY POOL OIL RESERVOIR,
EDGAR COUNTY, IL

Jordan M. Martin

67 Pages

August 2015

The purpose of this thesis is to better understand the Dudley Pool oil reservoir, a small, mature oil field, using geologic and geophysical data. The research focused on three-dimensional subsurface modeling of stratigraphy, structure, and porosity, to establish a more thorough understanding of oil occurrence at the Dudley Pool. An emphasis was placed on calculations of potential recoverable oil in order to determine implications on future production possibilities. This thesis also discusses the efficacy of three-dimensional modeling as an effective tool for evaluating, and potentially modifying, production efforts in mature petroleum fields with limited and/or poor-quality data. The modeling and calculations were completed using Schlumberger's *Petrel*. Well information from all wells drilled within a one mile collar of the field was collected. The model generated contour maps, thickness maps, a facies model, cross sections, a porosity model, and updated volume calculations for the reservoir. The project established that the Dudley Pool is part of a major channel system heading toward the interior of the Illinois Basin, and thus may present additional resources for exploitation beyond the

current production limit of the field. Results from the volume calculations indicate that there is still substantial recoverable oil at the Dudley Pool.

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DIMENSIONAL MODELING AND STRUCTURAL ANALYSIS
OF THE DUDLEY POOL OIL RESERVOIR,
EDGAR COUNTY, IL

JORDAN M. MARTIN

A Thesis Submitted in Partial
Fulfillment of the Requirements
for the Degree of

MASTER OF SCIENCE

Department of Geography-Geology

ILLINOIS STATE UNIVERSITY

2015

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OF THE DUDLEY POOL OIL RESERVOIR,
EDGAR COUNTY, IL

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CHAPTER I

INTRODUCTION AND BACKGROUND

The purpose of this thesis is to better understand the Dudley Pool oil reservoir, a small, mature oil field, using geologic and geophysical data. The research focused on three-dimensional subsurface modeling of stratigraphy, structure, and porosity, to establish a more thorough understanding of oil occurrence at the Dudley Pool. An emphasis was placed on calculations of potential recoverable oil in order to determine implications on future production possibilities. The results of this process will be given to Henigman Oil Company, a small operator in the field. This thesis also discusses the efficacy of three-dimensional modeling as an effective tool for evaluating, and potentially modifying, production efforts in mature petroleum fields with limited and/or poor-quality data.

Petroleum is an integral part of the daily lives of billions of people across the globe. Approximately 75% of crude oil is refined into gasoline and other types of fuels while the remaining 25% is used in the production of products such as plastics, cosmetics, building materials, synthetic fabrics, and more (www.eia.gov, 2013). While there are huge reserves of oil around the world, efforts must be made to maximize production from any given source to ensure that worldwide supply will continue to

outpace demand. Peak oil, or the point when production has reached its maximum and demand becomes greater than supply, is extremely hard to predict because production will change with technological advances. Current work estimates that peak oil may still be 50 years away or more but it is something the industry must remain wary of as demand continues to increase (Mohr et al., 2014).

Global demand for petroleum products is expected to rise around 1% annually for the next 5 years, with world supply only barely keeping up with demand (OPEC, 2014). For example, in December of 2012, the United States produced an average of just over 7 million barrels of oil per day (www.eia.gov, 2013); while in 2013, Americans were using an average of nearly 19 million barrels per day (www.eia.gov, 2014). The U.S. must import petroleum to keep up to its citizen's growing demands. Implementing newer technologies to assess mature fields may yield additions to reserves in fields that have become less profitable due to increasing costs and declining production. Reserve additions include the discovery of new fields, uncertain assets becoming certain, or extensions within existing fields (Okullo and Reynes, 2011).

Commercial production of petroleum began in the mid-1800's, particularly after Edwin Drake first drilled an oil well in Titusville, Pennsylvania. For years, wells had been dug by hand which limited the depth of the well. Drake introduced the process of mechanically drilling wells using a steam engine and also solved the problem of a collapsing hole by using a drill pipe to maintain the integrity of the hole. These two ideas launched the oil boom of the 1800's and the subsequent technological advances as new ways of finding and producing oil became necessary.

The process of exploring for oil has changed drastically, from digging based on oil seeps to dowsing, which was less successful, to the more successful discovery of structural traps like salt domes and the development and use of electric logs in the early 1900's. Today, exploration is extremely complicated and typically involves seismic surveys and down-hole gamma ray, resistivity, spontaneous potential, sonic and/or neutron logs. This data is all gathered, compiled and analyzed, typically with software that can build a three-dimensional model that allows the user to interact with the environment and explore the subsurface like never before.

There are two distinct types of 3D models; the stratigraphic forward model and the three-dimensional geologic model. The stratigraphic forward model takes a 2D model and applies time as the third dimension to see how a reservoir or rock may change over time. The 3D geologic model is static and aims to generate a model displaying the structure and stratigraphy of a geologic situation as well as possible (Blendinger et al., 2004). The benefit of a computer generated model is that it allows for the integration of different types of data that can subsequently be updated, manipulated and changed quickly (Cancelliere et al., 2014). These models also allow the user to view the subsurface structures from any angle, permitting more expansive analysis of the reservoir.

Geology of the Region

The Illinois Basin is a cratonic basin that formed as result of a failed rift in the early to mid-Cambrian and multiple subsidence and uplift events though the Paleozoic (Leighton et al., 1990). The basin extends across much of Illinois, Indiana, Kentucky, and parts of Tennessee and Missouri. Basin boundaries include several large anticline and syncline systems on the east and west and large fault systems in the south (Figure 1.1) which are primarily a product of the ancestral Rocky Mountain Orogeny (McBride and Nelson, 1999). The LaSalle Anticlinal Belt across the eastern portion of the state is a complex system composed of multiple anticlines, synclines, monoclines and domes that formed from the early Mississippian through the early Pennsylvanian (Clegg, 1965a; Nelson, 2010). Many of anticlines in the region are fault-propagation folds related to faults in the Precambrian basement (Nelson, 2010).

The basin is primarily carbonate rocks from the Ordovician through the mid-Devonian before transitioning to the New Albany Shale group from the mid-Devonian through the early Mississippian. Early to middle Mississippian rocks are made up of numerous limestone and shale groups with a single large sandstone, the Aux Vases, in the upper middle Mississippian. Late Mississippian rocks are dominated by interbedded sandstones and mudstones. The early Pennsylvanian is marked by a major sandstone group, the Raccoon Creek Group, which is made up of the Caseyville and Tradewater Formations. The middle Pennsylvanian is dominated by the Carbondale Formation which contains more than 90% of the coal reserves in the state and is some of the most heavily mined in the world (Greb et al., 2003). Upper Pennsylvanian rocks are mudstone,

shale, and sandstone with thick discontinuous carbonate units (Nelson and Jacobson, 2010). The deepest part of the basin is in the southern reaches of Illinois and is identified as the Fairfield Basin. North of this area, the Pennsylvanian rocks thin significantly as most of the Lower Pennsylvanian is missing and the upper has been extensively eroded (Nelson, 2010)

This study focused on the Dudley Pool in Edgar County along the eastern border of Illinois. The Dudley Pool is situated across several sections in T13N R13W, of the Grandview Quadrangle in Edgar County, approximately 13 kilometers west of Paris, Illinois. It is on the eastern shelf of the Illinois Basin along the edges of the La Salle Anticlinal Belt and Marshall Syncline (Clegg, 1965b). It is believed that the underlying Devonian New Albany Shale is the source rock for this reservoir (Macke, 1995). The Dudley Pool straddles the Carbondale and Tradewater formations in the Desmoinesian stage of the middle Pennsylvanian (Figure 1.2).

Figure 1.1

Illustration Showing Major Structures of the Illinois Basin in Illinois. The approximate location of Edgar County is outlined in red. Modified from Buschbach and Kolata (1991) and Nelson (2010).

Figure 1.2

Middle Pennsylvanian Stratigraphic Column. The approximate stratigraphic location of the Dudley Pool is boxed in red. Modified from Jacobson (2002).

The reservoir produces from depths between 90 and 135 meters below the surface from two discrete units, the Upper Dudley and the Lower Dudley which are separated by a 20-30 meter thick shale unit. Previous work on this field is extremely limited due to its size and extent but is included for reference. Both sands have been labeled as lenses on a monocline by the state survey (Illinois State Geological Survey, 2009). The lower sand is more heavily produced than the Upper Dudley and has been reported to have a thickness ranging from 18-19 meters in the center of the pool to as little as a meter or two on the edges of the deposit (Wilson Engineering, 1954). This lower sand is sub-divided by a thin shale bed, resulting in two zones, but is still regarded as a single production unit. Figure 1.3 shows an original structure map for the Lower Dudley Sand from Henigman Oil. The engineering report also determined that the top section of the Lower Dudley pinches out in all directions due to the dividing shale bed and the lower section dips into water sands on the outer edges of the pool. The Upper Dudley Sand is thinner than the lower sand with an average thickness of only three to four meters across the sand. Very little work has been done on Upper Dudley Sand previously.

Figure 1.3

Scan of the Original Structure Map for the Lower Dudley Sand. Additional original maps from Henigman Oil can be found in Appendix A.

Field History

Petroleum was discovered in the Illinois Basin in the late 1800's in southern Illinois. The majority of petroleum is found and produced from Mississippian age sandstones across most of the southeastern portion of the state with the Late Devonian New Albany Shale acting as the primary source rock. Macke (1995) does suggest that small amounts of petroleum may have been sourced from Mississippian or Pennsylvanian rocks as well. Figure 1.4a shows oil fields across Illinois which can be related to the "hydrocarbon kitchen," the area where temperatures and pressures were adequate to generate hydrocarbons (Figure 1.4b). These data show that the Dudley Pool is a stratigraphic outlier when considered against the majority of petroleum production in the Illinois Basin.

The Dudley Pool was discovered in 1948 and has produced a lifetime total of nearly 4.5 million barrels through 2009 according to the Illinois Oil Field Statistics. During 2009, the 135 active wells in the field produced 59,000 barrels of oil (ISGS, 2009), an average of just over one barrel per day per well. Overall, there have been approximately 300 wells drilled in the Dudley Pool and in the immediate vicinity (Figure 1.5). Many of these wells were dry or not economic, but some produced gas or were drilled as injection/disposal wells.

Figure 1.4

a) Map of Central and Southern Illinois Oil Fields. Oil fields are in green and Edgar County is highlighted in red. Modified from Illinois Oil & Gas Resources (<http://maps.isgs.illinois.edu/iloil>). ©2015 University of Illinois Board of Trustees. All rights reserved. Figure courtesy of the Illinois State Geological Survey. b) Map of Hydrocarbon Kitchen and Producing Counties in Illinois. Hydrocarbon kitchen is in dark brown and counties that have produced oil are in light brown. Modified from ISGS (2004).

Figure 1.5

Current Map of the Dudley Pool with Wells. The Dudley Pool in green with wells marked. Modified from Illinois Oil & Gas Resources (<http://maps.isgs.illinois.edu/iloil>). ©2015 University of Illinois Board of Trustees. All rights reserved. Figure courtesy of the Illinois State Geological Survey.

The Henigman Oil Company currently operates 32 wells on several leases in the Dudley Pool and reports that production has steadily declined over recent years. Data from the ISGS shows that production in this field peaked in 1995 at just over 100,000 barrels and production is currently below 60,000 barrels per year. Production data for the individual leases that Henigman Oil operates is unavailable. Of the 32 active wells, five have been converted to water injection wells. All producing wells are aided by waterflooding. The state survey was able to provide 61 well logs from the field, which included a combination of spontaneous potential, resistivity, gamma ray, neutron logs. An engineering report produced in 1954 stated that the Dudley Pool primary recovery would likely only produce a total of about 1.5 million barrels of oil; 500,000 of which had already been produced (Wilson Engineering, 1954), and also recommended against waterflooding as a means of secondary recovery.

CHAPTER II

METHODS

The three-dimensional modeling and calculations were completed using Schlumberger's *Petrel* 2012.3, industry standard software for reservoir characterization, and has been used for similar exploration style projects (Aadil and Sohail, 2014). The models developed in this process give an idea of the internal architecture of the reservoir, facies distribution and subsequently porosity and volume estimates. The Upper and Lower Dudley Sands were modeled in this project with the goal of aiding production efforts by providing Henigman Oil Co. with an interactive interpretation of the geometries of the storage field as well as volumetric calculations of recoverable oil. The model will be generated using primarily well logs collected from the Illinois State Geological Survey (ISGS). A core from a related oil field south of the Dudley was described as well.

Data Collection

The Illinois State Geological Survey has extensive petroleum well information available on ILOIL, a comprehensive online repository. As required by law, this site contains all available files for every well drilled in the state. These files can include well

logs, driller's logs, scout tickets, permits, core analysis and more. The information available can vary for each well, so not every well had the same data.

Data, retrieved from the ISGS, included well headers and formation (well) tops from 302 wells, and downhole logs from geotechnical borings of 61 wells. Well header elements include the well's API number (a permanent, 12-digit unique identifier), latitude and longitude, farm name, total depth of the well in feet, elevation, company name and more. Data from all wells drilled in a one mile collar of the Dudley Pool extent was collected regardless of the production status of the well. The addition of data from non-producing wells was included in an effort to make the stratigraphic and structural elements of the model as accurate and thorough as possible.

Data Preparation

The abundance of well header information was parsed through to remove the extraneous data that was not useful for the project. Location, API number, and total depth were kept while things like the farm name where the well was located and associated dates were not used. Once the data had been sorted, it was reformatted into a new excel spreadsheet with each well assigned a simple numeric or alphanumeric name for ease of viewing in *Petrel*. The version of *Petrel* used did not allow for latitude and longitude data to be directly loaded, so the location data was converted to X, Y pairs in meters from an origin southwest of the field. Subsequently, all depth information was converted to meters as well.

The ISGS also provided a well top file, but much of the information was too generic to be useful. Many of the wells had depth information only labeled as

Pennsylvanian rather than the Upper or Lower Dudley Sand. As such, I downloaded driller's logs (Figure 2.1) for each well in the field and picked out the sand units. The top and the bottom of each unit were used as a well top so the sand was fully defined.

The well logs from ILOIL were simply original paper logs scanned and available for download as image files. Image data is not compatible with *Petrel* and therefore must be converted to a usable format. The logs were converted to binary digital files in Log ASCII Standard, .las, format. This was completed using the software package *Neuralog*.

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ILLINOIS GEOLOGICAL SURVEY, URBANA

Page 1

Strata	Thickness	Top	Bottom
<u>Twin Well</u>			
Top soil		0	8
Gravel and sand		8	48
Heavy sand		48	64
Mud		64	85
Yellow sand, muddy		85	90
Sand fine heavy		90	105
Red rock		105	108
Gray sandy lime		108	147
Gray shale		147	159
Dark shale		159	198
Coal broken		198	204
Light shale		204	254
Gray shale		254	296
Dark shale		296	290
Light shale		290	301
Sand and oil		301	347
Light shale		347	353
Dark shale		353	381
Light shale		381	392
Gray shale		392	401
Sand, gray		401	411
Gray shale, soft		411	417
Sandy sack shale		417	414
Oil, sand, Free Oil.		414	464
Gray shale		464	466
Gray sandy lime, mottled trace of oil.		466	471
			TD
Casing: 8" set at 126' 7" set at 440'			

COMPANY	Walter W. Henigman	NO.	
FARM	Bussart, Lola	NO.	3A
DATE DRILLED	August, 1952	COUNTY NO.	425
AUTHORITY	Company		
ELEVATION			
LOCATION	690' N line, 600' W line of NE NE		
COUNTY	Edgar		9-13N-13W

Figure 2.1

Sample Driller's Log from the Dudley Pool. The orange box highlights the Upper Dudley and the red box indicates the Lower Dudley unit.

Neuralog

Upon opening *Neuralog* and loading the .tiff well log image, the first step is to set the depth axis. The depths shown on the log were in feet, but were digitized in meters to be consistent. Not all logs had both the upper and lower sand units recorded, so the depths varied between 80 and 180 meters below the surface. The scale axis is identified next with the left and right end points identified. For older logs such as those available for the Dudley Pool, a scale is not identified on the log, but rather an interval for the grid. A shale base line was chosen for each spontaneous potential (SP) log, with the measurements being negative to the left and positive to the right of this line. Once both axes have labels, the curve is traced and these steps are repeated for the second track on the log. Figure 2.2 shows a spontaneous potential/resistivity log with the axes and curve marked for the SP curve. The majority of logs were SP/resistivity with a few gamma ray/neutron logs. The process is the same regardless of the type of log. The log is then exported to a digital file. *Neuralog* reads the value of the curve at a set sampling interval for the entire depth track, and it is saved as a .las file.

Figure 2.2

A Spontaneous Potential/Resistivity Well Log from the Dudley Pool. The depth axis is marked in blue with top and bottom depths in meters. The scale axis is in red and is in millivolts. The SP curve is highlighted in yellow.

Petrel

All data that has been acquired was imported into *Petrel* starting with the well header files. When a file with location information is imported, a coordinate reference system (CRS) must be selected; this ensures that well placement and distances project correctly. For this project, NAD83-UTM 16N was used. The well header information was uploaded first to set up the basic files for the wells with locations and depths. A basic distance measurement at this point verified that wells were in the right location. By adding a well top folder, the tops were input by a simple copy/paste function into the “Well top spreadsheet” at this point. The well tops define the stratigraphic horizons of interest; in this project the tops used were the top and bottom of each of the Upper Dudley and Lower Dudley sands. Next the well logs were brought into the program. Figure 2.3 shows all uploaded wells on a grid with well tops and logs. The “Import on selection” command imported all .las format logs from the *Neuralog* folder on the computer. Using the scanned images of the well logs, lithology logs were manually “painted” onto the well logs for use in the facies modeling process later.

Figure 2.3

Basic Grid Showing Wells Imported into *Petrel*. Logs and well tops (colored discs) are displayed. 7.5x vertical exaggeration.

The first step in the modeling process is to define the domain of interest. This can be done one of two ways. The most restrictive way to do this is to create boundary polygons. As many or as few boundaries can be created as are necessary. If no polygons are created, the system will define an X-Y grid that contains all data that is uploaded. The default domain is not ideal when the data is scattered or there are outliers because it forces the program to make more assumptions when interpolating between points. For this reason two boundary polygons were created; one polygon, named “All Sands,” contained all wells that showed Pennsylvanian sand in the driller’s log, and the second only enclosed wells that showed oil, regardless of if it was a producer, and was accordingly named “Oil Sands”. The production boundary polygon and wells used through the rest of the modeling process is shown in Figure 2.4, and is referenced with township, range, and section numbers.

Once the domain is defined, creating surfaces is the next step. Surfaces are a 2D grid with known or interpolated depth, or Z, data at each node on the grid; the Z data represents the surface. The surface alone is a contour map of the area. Surfaces are the primary step necessary for constructing a 3D grid. Using the “Make/edit surface” process (Figure 2.5), well tops are the Main input, with the boundary defined by the polygons created previously. An attribute from the well top data must be specified for mapping, depth, or Z, is used for surfaces so they are shown in the correct subsurface location. An algorithm for interpolation must be chosen with different results possible from each.

Figure 2.4

Illustration Showing Location with Relevant Boundary and Wells. Production boundary polygon, wells used during modeling process, and location referenced to the public land survey system are shown.

Figure 2.5

Screenshot of the “Make/edit surface” Command Window. This window was completed for the bottom surface of the Upper Dudley.

The next step is to calculate isochore data. An isochore is the vertical thickness between two surfaces (Figure 2.6); it is not corrected for any dip of the strata, such as an isopach. Isochore processing can give several different types of information; true vertical thickness, true vertical depth, and true stratigraphic thickness. Because all of the wells in this field were drilled vertically, the isochores gave true vertical thickness (TVT). Isochores were calculated for each zone between stratigraphic well tops from the “Convert to isochore points” command by right-clicking the lower stratigraphic well tops of the zone of interest. TVT was also calculated from the well top data in the “Well settings” window. This ensures that the zone spreadsheet updates appropriately with thickness values. Isochore data was used directly to generate thickness maps.

Thickness maps are highly useful when evaluating the reservoir for structural trends and are almost identical to surfaces in construction. Using the “Make/edit surface” process, isochore points were the main input rather than well tops. An attribute from the isochore data must be specified for mapping, in this case this was the TVT calculated at the end of the previous step. A boundary polygon must be selected, and finally an algorithm for the interpolation. As with the stratigraphic surfaces, Kriging was used to give a more realistic result. Many modifications can be made in this process that focus on corrections for well deviation, folding and/or faulting in the strata, but due to the simplicity of the data, these options were left at the default.

Figure 2.6

Drawing Demonstrating Difference between Isopach and Isochore. The isochore is giving TVT, as used in this project, and the isopach results in true stratigraphic thickness.

Figure 2.7

Screenshot of the “Make simple grid” Process Window. The boundary polygon and surfaces used as input data are shown.

At this point, the three-dimensional modeling process can begin. The first step in building the 3D model is using the “Make simple grid” command (Figure 2.7). This process uses a boundary polygon and surfaces as the basis for construction of a 3D skeleton. The skeleton is composed of three layers showing the top, bottom, and middle depths of the reservoir as measured from the surfaces. This step converts the surfaces to horizons, 3D versions of the surfaces, and also builds reservoir edges that visualize how the reservoir changes around the outside. Zones are defined as the areas between surfaces, and in this project these are the Upper Dudley, Lower Dudley, and the area between the two sands, the Upper-Lower Dudley. The Upper Dudley and Lower Dudley zones were subdivided using the “Layering” process. The Upper Dudley was divided into 5 layers and the Lower Dudley into 9 (Figure 2.8), following the *Petrel* guide. The layers do not have a uniform thickness, but rather run continuously across the units. This breaks the zones into significantly smaller cells that allow for heterogeneities to be realized. Each cell is 50 meters by 50 meters with varying thicknesses depending on its location within the layers.

Figure 2.8

Screenshot of the Skeleton of the Simple Grid. Showing are the top (blue), middle (green) and bottom (yellow) layers of the skeleton with edges and cells. The pink-edged section is the Upper Dudley zone, with 5 layers visible, and the yellow is the Lower Dudley with 9 layers. 10x vertical exaggeration.

The next step is to upscale the well logs to assign values to the cells that the well goes through. Each cell in the model can only have one value, and the process of upscaling averages all values in the cell to achieve one value. This was done for lithologies and porosity. When the “Scale up well logs” process is opened, a property can be edited or a new one created. I chose to create a new property since only logs existed rather than properties. For the input, “Well logs” was selected, and then the appropriate log from the drop-down menu. The settings were left at the default options (Figure 2.9). All wells that have a log for the property were included in the upscaling process automatically.

After upscaling is facies modeling. This will take the upscaled lithology data and distribute it across the area and between the wells using a selected algorithm. This step yields a three-dimensional model that gives an idea of what the distribution of rock types could actually be. The modeling process can be rerun as many times as necessary to get a model that is both viable, in that it does not break any geological rules, and admissible, meaning that it conforms to previously established fact about the reservoir. The Upper and Lower Dudley Sands were modeled while the zone between them was not as it is primarily shale and is not of interest to oil production. In the process window a zone is selected, then unlocked with the padlock button. This populates the rest of the window with modeling options. The first option is the choice of algorithm. Ultimately a Gaussian simulation algorithm was selected. Under the Facies tab, lithologies that are listed with a percentage are present in the zone according to the well logs. Each is selected and moved. Fractions and trends at the bottom can be adjusted if necessary. These were changed several times to see the differences how the model varied, but were

ultimately left at the system calculated values. The remaining tabs were left at the default state (Figure 2.10).

Figure 2.9

Screenshot of the “Scale up well logs” Process Window. Settings for scaling up the lithology logs is shown.

Figure 2.10

Screenshot of the “Facies modeling” Process Window. Showing is the set up for the Lower Dudley model.

Cross-sections can be generated any time after the 3D grid has been constructed with horizons, but was done after the facies modeling was completed so that the lithologic distribution could be seen as well as the structure. By opening a new well section window (WSW), a new cross section is automatically created in the input pane. While on the active WSW, the well manager spreadsheet was opened and the wells of interest for a cross section selected (Figure 2.11). The order of the wells was corrected from numerical order to geographic order in the settings. In a 3D window, with the cross-section activated on the input pane, the option to visualize on a plane is selected, and then finally, the lithologies are turned on from the models pane. Five cross sections were made in this manner.

Figure 2.11

Screenshot of a Well Section Window. Three of the active wells have SP and lithology logs shown with stratigraphic surfaces correlated across the wells.

Petrophysical modeling is the process of distributing data, in this case porosity, across the model grid. The primary input for this step was the upscaled porosity log. Fortunately, this step allows for the model to be conditioned to the facies model. This means that porosity ranges with mean and standard deviation for each lithology. This allowed for adjustments to be made for the lack of data. Figure 2.12 shows the parameters set for sand. Typically the system will average the values and set mean and standard deviation automatically, but with only two logs to work with, this was not possible. There were several core analysis documents available on ILOIL and those were used to set the restrictions for each lithology. By conditioning the porosity model to the facies, it ensures that the lower porosity values were seen where shale was predicted and higher values were seen with sand.

Figure 2.12

Screenshot of the “Petrophysical modeling” Process Window. Porosity parameters for sand are displayed.

At this point, the *Petrel* model is complete and volume calculations are the final step. Several pieces of data are necessary to make more accurate estimations. First, the oil-water contact must be set. The lower unit dips into water sands and this must be accounted for or the volumes could be considerably off. The contact is set with the “Set contacts” function. A contact was only set for the Lower Dudley because the Upper Dudley is a self-contained unit. From driller log assessment, the contact was set at 150 meters below the surface. Oil and water saturation values were averaged from the core analysis reports used previously for porosity ranges (Table 1). Finally, a recovery factor is set since 100% recovery is not possible. This can be done manually as well because the report gives hydrocarbon pore volume and the recovery factor is a multiplier of this value. I chose to calculate at a conservative value of 30 percent, although fields under secondary recovery methods can see recovery as high as fifty percent (Sandrea and Sandrea, 2007). Calculations were conditioned to the facies model developed previously and run with the modeled porosity values and secondly with a set porosity of 0.181, an average from the core analysis reports. The calculation was run twice because extensive porosity information is not available and this allows for a comparison of both sets of parameters.

Table 1.

Property Values Used in Volume Calculations

Properties in Oil Interval	
Water Saturation	0.4857
Oil Saturation	0.3541
Gas Saturation	1-Sw-So

CHAPTER III

RESULTS

One of the primary goals of this project was to assist an operator in the Dudley Pool by increasing understanding of the reservoir. The modeling resulted in a surface contour map and thickness map of each the upper and lower sand units, five cross-sections, a 3D lithology model, a 3D porosity model, and volume calculations with recoverable oil modeled as well.

Contour Maps

Contour maps were created from the surfaces that were generated previously to see any overall structure that dominates the reservoir. Several modeling algorithms were tested for interpolation, including Isochore Interpolation and a Gaussian function, but most gave a non-geologically feasible result with unusual dips and bumps that jump as much as 20 meters that would be difficult to explain through geological processes (Figure 3.1). Kriging returned the most realistic surfaces apparent valleys and ridges (Figure 3.2). The images in Figure 3.2 show the contour map for the top of the sand of the Upper and Lower Dudley, respectively. The red indicates that the area is higher in the section, or closer to the land surface, and the purple is deeper for each map.

Figure 3.1

Contour Map of the Top of the Lower Dudley Sand Using Isochore Interpolation. Note the peaks and troughs cannot be easily described through geological processes.

Figure 3.2

Contour Maps of the Upper and Lower Dudley Sands. Upper (top) and Lower (bottom) contour maps resulting from the Kriging algorithm.

Thickness Maps

Next, thickness maps were built by calculating the depths between known well tops. The upper sand shows the thickest region being more than 12 meters thick in the southern extent of the reservoir, which may be associated with data error, and a zone that is 7-8 meters thick in the north-central area that coincides with the heaviest production (Figure 3.3). The lower unit pinches out in the south and is thickest, at 12+ meters, in the north-central zone, similar to the Upper Dudley (Figure 3.3).

Figure 3.3

Thickness Maps of the Upper and Lower Dudley Sands. The top image is shows the thickness of the Upper Dudley and the bottom image shows the Lower Dudley.

Facies Model

By distributing the known lithology logs across the production zone, the three dimensional model is a representation of what the reservoir sands are like and is a good visualization of potential problematic zones (Figure 3.4). A Gaussian simulation algorithm was selected for the interpolation because, unlike before, Kriging generated a model with bulls-eyes around the wells because of the small amount of upscaled logs. The distribution of each lithology is shown in Table 2; these values are generated by *Petrel* during the modeling process, not set by the user. Each unit is primarily sand with the Upper Dudley as about 76 percent sand and the rest being shale or a sand-shale mixture. The lower unit has comparable values at 81 percent sand and the remaining 19 percent being shale, sandy shale, or shaley sand. In the Lower Dudley, a blue and green layer can be seen from the east side that extends across the majority of the unit.

Table 2

Lithology Distributions from the Facies Model

	Upper Dudley	Lower Dudley
Sand	0.76	0.81
Sand and Shale	0.10	0.12
Shale	0.12	0.07

Figure 3.4

Three Dimensional Facies Model of the Upper and Lower Dudley. Yellow represent sand, green is shale, and blue is a sand and shale mixture, i.e. sandy shale or shaley sand.

Cross Sections

To show how the Upper and Lower Dudley sands change across the region, five cross sections were constructed. Three sections run east to west across the reservoir and two run north-south (Figure 3.5). The northern area of the reservoir was emphasized in the cross sections as a quality control check because the majority of information is concentrated in that portion of the Dudley Pool.

Figure 3.5

Map Showing Locations of Cross Sections. The production area is shown with cross-sections labeled.

The following pages show each section with intersecting wells included. The zone between the Upper and Lower Dudley was not modeled. As before, yellow indicates sand, green is shale, and blue indicates a sand-shale mixture. The shale and sand-shale mixture decrease as you move towards the south in the Upper Dudley Sand (Figures 3.6, 3.7, 3.8). The upper unit becomes slightly thicker from Figure 3.6 to Figure 3.7 before thinning considerably in Figure 3.8 towards the south. The Lower Dudley shows similar lithology and thickness trends to that of the upper unit, with the proportion of sand increasing while thinning overall. These changes can be seen in the north-south cross sections (Figures 3.9, 3.10) as well but shows a thickening of the upper sand in the far south while the lower unit continues to thin. A fence diagram showing how the cross-sections intersect is shown in Figure 3.11.

Figure 3.6

45 Cross Section A-A'. East-west cross-section. Depth in meters below surface. 10x vertical exaggeration.

Figure 3.7

Cross Section B-B'. East-west cross-section. Depth in meters below surface. 10x vertical exaggeration.

Figure 3.8

Cross Section C-C'. East-west cross-section. Depth in meters below surface. 10x vertical exaggeration.

Figure 3.9

Cross Section D-D'. North-south cross section. Depth in meters below surface. 10x. vertical exaggeration.

47 *Figure 3.10*

Cross Section E-E'. North-south cross-section. Depth in meters below surface. 10x vertical exaggeration.

Figure 3.11

Fence Diagram Showing Intersection of Cross Sections. View from the northwest. 10x vertical exaggeration.

Porosity Model

The three-dimensional petrophysical model shows an approximation of porosity distributions as controlled by the facies model. Figures 3.12 and 3.13 show how the porosity changes vertically through the layers defined 3D model set-up of each the lower and upper units, respectively. The low porosity zones correspond with the shale rich areas of the facies model and the higher porosity with the areas that are primarily sand.

Figure 3.12

Porosity of Lower Dudley Layers. The nine layers of the Lower Dudley Sand from the top to the bottom, a) through i). Red indicates high porosity, around 20%, and purple is low porosity, ~2%.

Figure 3.13

Porosity of Upper Dudley Layers. The five layers of the Upper Dudley Sand from the top to the bottom, a) through e). Red indicates high porosity, around 20%, and purple is low porosity, ~2%.

Volume Calculations

Volume calculations were run for two reasons. First, this was done as a quality check to see if the model has realistic results as compared to known production of the reservoir. Secondly, the values produced will help fulfill both goals of this project in assisting Henigman Oil Co in determining future potential of the Dudley Pool but also to establish the soundness of reevaluating mature fields with *Petrel* or similar software.

The calculation process was run twice, each yielding moderately different results. Oil in place and recoverable oil, in millions of barrels, for both processes is summarized in Table 3. The results using the modeled porosity came back slightly lower than those from the set porosity. In the end, *Petrel* estimates 8-9 million barrels of recoverable oil in the current extent of the Dudley Pool, including what has already been extracted.

Table 3

Results from Volume Calculation Process (in millions of barrels)

	Modeled Porosity		Porosity = 0.181	
	Oil in Place	Recoverable	Oil in Place	Recoverable
Upper Dudley Sand	9.2	2.8	10.1	3.0
Lower Dudley Sand	17.2	5.2	18.9	5.7
Total Sand	26.4	7.9	29.1	8.7

Core Description

A core was selected from Clark County, just south of Edgar County, as there were no cores available from the Dudley Pool. The core described is from an oil well that produces from Pennsylvanian sands that are most likely related to the reservoir investigated here. An illustration and description of the core is seen in Figure 3.14.

The core shows two sand units. The upper sand begins 141 meters below the surface, about 50 meters deeper than in the Dudley, and is approximately 8.5 meters thick, with only the upper third showing oil staining. The lower sand starts at 152 meters, or 30 meters lower than in Edgar County, is fully saturated and just under 11 meters thick. Both sands are mica rich and show a general fining upward with the base of the each unit being more massive with coarser grains transitioning from medium to medium-fine sand. Several intervals of flaser bedded sandstone and siltstone were identified as well with a thin coal bed or paleosol at the top of the upper sand unit.

Figure 3.14

Illustration of the Description for Core C-14055 from Clark County, IL.

CHAPTER IV

INTERPRETATIONS AND CONCLUSIONS

There were two primary goals of this project. First and foremost was to improve the understanding of oil occurrence, structure, and stratigraphy of the Dudley Pool oil reservoir. This information will be offered to Henigman Oil Company to assist in production of the reservoir. The second objective was to determine if three-dimensional modeling is a worthwhile tool for evaluating mature oil fields with limited and/or poor-quality data. A 3D model of the pool was created using Schlumberger's *Petrel* 2012.3 that offers insight into the governing structures and lithologic distribution within the field, and to generate new volume calculations through porosity modeling. The usefulness of modeling in this type of scenario is discussed by a comparison of the resulting model with the original maps, the potential value to an operator, and a company's accessibility to the tool.

The Dudley Pool

The core that was described (Figure 3.14) showed very distinct patterns that can be combined with the *Petrel* model for a more expansive analysis of the structure in the region than the model alone can offer. Estuarine deposits with flaser-bedding are found on top of both of the sand units with a coal or paleosol above the upper sand. The

combination of the estuarine deposits between the fining-upward sands, the organic drapes, and the consistent cross-bedding is indicative of sea-level fluctuations affecting deltaic plain deposits (Adnan and Shukla, 2014; Kvale and Barnhill, 1994).

Review of the thickness maps (Figure 3.3) generated by *Petrel* shows that the thickest sands of the Upper Dudley follow a north to southeast trend. The southern portion of the Upper Dudley is unusually thick and contrary to what is known of the field, as such, potential for error in the model will be discussed later. The thickest sand of the Lower Dudley trends from northeast to west. These directional trends suggest that the Dudley sands could be channel deposits. Considering that the core shows a deltaic signature, combined with apparent channel forms, I believe that the Upper and Lower Dudley sands are part of a previously identified extensive channel system that is positioned in a northeast-southwest direction towards the interior of the basin (ISGS, 2000). If the Dudley sands are not simply lenses but channel deposits, they might be able to be exploited elsewhere.

The lithologic distribution from the 3D model shows that the units are primarily sand with around 20 percent shale or sand-shale mixture scattered throughout the reservoir. The Upper Dudley sands exhibit good continuity across the field without any significant disruption from the shale layers. The shale appears in several layers across the top and bottom of the unit primarily concentrated in the northern portion of the reservoir, which also happens to be the best producing. The Lower Dudley shows considerable shale accumulation in the northern section as well. As discussed in the introduction, the shale in the lower unit separates the sand into two sub-units. The shale

bedding appears to reach all but the southern extent of the reservoir, unlike previously thought. Towards the south the sand thins with considerably less shale, possibly pinching out beyond the field's production limit (Figure 3.9).

The porosity model was conditioned to the lithology distribution of the facies model, thus the predicted porosities follow the patterns seen in that model. The porosity was used to directly calculate volumes for the reservoir. As seen in Table 3, the volume calculations indicate that there may be two million or more barrels of recoverable oil in the Dudley Pool, even considering the uncharacteristic thickness in the southern Upper Dudley. As expected, the north-central region where *Petrel* distributed thicker sand and higher porosities resulted in more recoverable oil, and the areas with shale show significantly less oil present. Relative recoverable oil is shown in Figure 4.1 for both the Upper and Lower Dudley.

Figure 4.1

Map of Recoverable Oil in the Upper and Lower Dudley. Oil presence of the Upper Dudley (top) and Lower Dudley (bottom) is shown in relative scale, with red indicating a higher amount of oil recoverable and blue indicating less.

3D Modeling for Mature Fields

To determine if three-dimensional modeling is a reasonable method for reevaluating mature fields, especially those without extensive or high-quality data available, I took into consideration three things: the quantity and quality of the information generated, the potential value to the operator, and accessibility to the tool.

There is very little information with which to compare the *Petrel* models, which is largely the purpose behind the project. The Dudley Pool has two original sets of maps, a structure map and a thickness map for each unit, discussed in the introduction. A simple side-by-side comparison shows that the new contour and structure maps follow the same directional trends seen on the originals. This demonstrates that the process will generate viable and admissible interpretations of the reservoir. The new contour and thickness maps also show that the sand units continue beyond the production area and may indicate possible new areas that could be exploited, i.e. reserve additions. Much of the additional information achieved through this process, such as the cross sections and volume calculations, could be produced by hand, but the ease at which the 3D model can be manipulated and edited offers a different type of value, one of convenience. The biggest impediment is the accessibility to reservoir modeling software. If a company does not have the resources to purchase a modeling software package, they must rely on willing graduate students or hire a consultant.

Conclusions

This thesis is composed of a multi-step *Petrel* model that resulted in the generation of contour maps, thickness maps, a facies model, five cross sections (with unlimited more possible), a porosity model, and updated volume calculations of the Dudley Pool in Eastern Illinois. These components were designed to improve understanding of this mature oil field in an attempt to assist Mr. Gary Henigman of Henigman Oil Co. in his production and management of the reservoir. This project was also completed to evaluate three-dimensional modeling as an effective method for reexamining mature oil fields.

Previous discussion establishes that the Dudley Pool is part of major channel system heading from the north towards the interior of the Illinois Basin. The thicker Lower Dudley unit continues to the north-northeast and could be explored for additional petroleum resources. The porosity model and volume calculations indicate that there are upwards of two million or more barrels of recoverable oil in the reservoir. However, expectations should be that production will not increase in terms of barrels per day due to the asymptotic relationship between field age and production as shown by Abbaszadeh et al (2013).

As mentioned previously, there is inevitably error in the model, as seen with the unusual thickening of the Upper Dudley unit. By definition, models rely on many assumptions, and error is thus inherent. Since I hand-picked many of the well tops before the modeling process even began, if a unit was identified or entered into *Petrel* incorrectly, it would only propagate through the rest of the modeling process. The

software relies on the data entered, but each step requires additional assumptions which compound any error. All efforts are made to reduce error, but even the algorithms used during the actual modeling processes introduce some risk of error.

This thesis is meant to provide insight into a complicated issue. It also demonstrates that modern technology, such as *Petrel*, can be applied in situations where only limited or poor-quality data is available. The usefulness of this methodology is apparent, despite the hurdles discussed, as new directions of exploration could emerge or calculated reserves in the modeled reservoir may increase. Any additional reserves are significant, as they may assuage a decline in production.

Determining the future production potential of a mature oil field is a complex geologic and economic problem. The use of modern technologies and software facilitates the development of high quality results that lead to a better understanding of a reservoir. Ultimately, I would recommend this process for reevaluating a field, even with limited data.

REFERENCES

- Aadil, N., and Soahil, G.M., 2014, 3D geological modeling of Punjab Platform, Middle Indus Basin Pakistan through integration of wireline logs and seismic data: *Journal Geological Society of India*, v. 83, p. 211-217.
- Abbaszadeh, A., Bresch, D., Desjardins, B., and Grenier, E., 2014, Asymptotic production behavior in waterflooded oil reservoirs: Decline curves on a simplified model: *European Journal of Mechanics B-Fluids*, v. 43, p. 131-134.
- Adnan, A., and Shukla, U.K., 2014, A case of normal regression with sea level transgression: Example from the Ganurgarh Shale, Vindhyan Basin, Maihar Area, MP, India: *Journal of the Geological Society of India*, v. 84, no. 4, p. 406-416.
- Blendinger, W., Brack, P., Norborg, A.K., and Wulff-Pedersen, E., 2004, Three-dimensional modelling of an isolated carbonate buildup (Triassic, Dolomites, Italy): *Sedimentology*, v. 51, no. 2, p. 297-314.
- Buschbach, T.C., and Kolata, D.R., 1990, Regional Setting of Illinois Basin: Chapter 1: Part I. Illinois Basin: Regional Setting, *in* Leighton, M. W., Kolata, D. R., Oltz, D. T., and Eidel, J. J. eds., *M 51: Interior Cratonic Basins: American Association of Petroleum Geologists*, p. 29-55.
- Cancelliere, M., Viberti, D., and Verga, F., 2014, A step forward to closing the loop between static and dynamic reservoir modeling: *Oil & Gas Science and Technology*, v. 69, no. 7, p. 1201-1225.
- Clegg, K.E., 1965a, The La Salle Anticlinal Belt and adjacent structures in east-central Illinois: *Illinois Academy of Science Transactions*, v. 58, no. 2, p. 82-94.
- Clegg, K.E., 1965b, Subsurface geology and coal resources of the Pennsylvanian system in Clark and Edgar counties, Illinois: *Illinois State Geological Survey*, Cir 380.
- Greb, S.F., Andrews, W.M., Eble, C.F., DiMichele, W., Cecil, C.B., and Hower, J.C., 2003, Desmoinesian coal beds of the Eastern Interior and surrounding basins: The largest tropical peat mires in Earth history, *in* Chan, M.A., and Archer, A.W., eds, *Extreme depositional environments: Geological Society of America, Special Paper 370*, p. 127-150.

- Griffin, J., and Fantini, A., eds, 2014, World Oil Outlook: Organization of the Petroleum Exporting Countries, 367 p.
- Illinois Oil & Gas Resources (map service), 2015, Illinois State Geological Survey, <http://maps.isgs.illinois.edu/iloil/> (accessed April 2015).
- Illinois State Geological Survey, 2000, Depositional history of the Pennsylvanian rocks in Illinois: Geonotes 002.
- Illinois State Geological Survey, 2009, Illinois Oil Field Statistics: <http://isgs.illinois.edu> (accessed August 2014).
- Illinois State Geological Survey, 2014, Oil Fields in Illinois: <http://isgs.illinois.edu> (accessed October 2014).
- Jacobson, R., 1985, Coal resources of Grundy, La Salle, and Livingston Counties, Illinois: Illinois State Geological Survey, Cir 536.
- Jacobson, R., 2002, Pennsylvanian Stratigraphic Column: Illinois State Geological Survey.
- Kolata, D.R., compiler, 2005, Bedrock geology of Illinois: Illinois State Geological Survey, Illinois Map 14, 1:500,000.
- Kvale E.P., and Barnhill M.L., 1994, Evolution of lower Pennsylvanian estuarine facies within two adjacent paleovalleys, Illinois Basin, Indiana, *in* Dalrymple, R.W., Boyd, R., and Zaitlin, B., eds, Incised-Valley Systems: Origin and Sedimentary Sequences: SEPM Special Publication 51, p. 191-207.
- Larue, D.K., and Friedmann, F., 2005, The controversy concerning stratigraphic architecture of channelized reservoirs and recovery by waterflooding: Petroleum Geoscience, v. 11, no. 2, p. 131-146.
- Leighton, M.W., Kolata, D.R., Oltz, D.T., and Eidel, J.J., 1990, M 51: Interior Cratonic Basins, American Association of Petroleum Geologists, p. 25.
- Macke, D.L., 1995, Illinois Basin Province (064), *in* Gautier, D.L., Dolton, G.L., Takahashi, K.I., and Varnes, K.L., eds., 1995 National assessment of United States oil and gas resources--Results, methodology, and supporting data: U.S. Geological Survey Digital Data Series 30.
- McBride, J.H., and Nelson, W.J., 1999, Style and origin of mid-Carboniferous deformation in the Illinois Basin, USA—Ancestral Rockies deformation?: Tectonophysics, v. 305, no. 1-3, p. 249-273.

- Mohr, S.H., Wang, J., Ellem, G., Ward, J., and Giurco, D., 2015, Projection of world fossil fuels by country: *Fuel*, v. 141, p. 120-135.
- Nelson, W.J., 2010, Structural features, *in* Kolata, D.R., and Nimz, C.K., eds, *Geology of Illinois*: Illinois State Geological Survey, p. 90-104.
- Nelson, W.J., and Jacobson, R.J., 2010, Pennsylvanian Subsystem and Permian System (Absaroka Sequence), *in* Kolata, D.R., and Nimz, C.K., eds, *Geology of Illinois*: Illinois State Geological Survey, p. 187-205.
- Nickel, E., Jensen, G., and Rostron, B., 2011, Refinement of the Weyburn geological model: Overcoming challenges in data compilation and management: 10th International Conference on Greenhouse Gas Control Technologies, v. 4, p. 4785-4792.
- Okullo, S.J., and Reynes, F., 2011, Can reserve additions in mature crude oil provinces attenuate peak oil?: *Energy*, v. 36, no. 9, p. 5755-5764.
- Sandrea, I., and Sandrea, R., 2007, Recovery factors leave vast target for EOR technologies: *Oil & Gas Journal*, v. 105, no. 41, p. 44-47.
- U.S. Energy Information Administration, 2012, How much of the oil produced in the United States is consumed in the United States?: <http://www.eia.gov> (accessed August 2014).
- U.S. Energy Information Administration, 2013, How much oil is consumed in the United States?: <http://www.eia.gov> (accessed August 2014).
- U.S. Energy Information Administration, 2012, What are the products and uses of petroleum?: <http://www.eia.gov> (accessed August 2014).
- Wilson, B.L., 1954, Engineering Study: Secondary recovery possibilities Dudley Pool, Edgar County, Illinois, Wilson Engineering, Mt. Vernon, Illinois.

APPENDIX A

SCANS OF ORIGINAL THICKNESS AND STRUCTURE MAPS FROM

HENIGMAN OIL CO.

Original Lower Dudley structure map

Original Upper Dudley thickness map