RESERVOIR CHARACTERIZATION AND MODELING OF THE GLORIETA AND THE CLEARFORK FORMATIONS, MONAHANS FIELD, PERMIAN BASIN, TEXAS

A Thesis

by

RYAN DAVID YEATMAN

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

August 2011

Major Subject: Geology

RESERVOIR CHARACTERIZATION AND MODELING OF THE GLORIETA AND THE CLEARFORK FORMATIONS, MONAHANS FIELD, PERMIAN BASIN, TEXAS

A Thesis

by

RYAN DAVID YEATMAN

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Approved by:

Chair of Committee,	Michael C. Pope
Committee Members,	Wayne M. Ahr
	Walter B. Ayers
Head of Department,	Andreas Kronenberg

August 2011

Major Subject: Geology

ABSTRACT

Reservoir Characterization and Modeling of the Glorieta and the Clearfork Formations, Monahans Field, Permian Basin, Texas. (August 2011)

Ryan David Yeatman, B.S., Texas A&M University

Chair of Advisory Committee: Dr. Michael C. Pope

Monahans Field of the Permian Basin in West Texas is a complex carbonate reservoir due to the lateral heterogeneity caused by facies changes throughout the Lower Guadalupian Glorieta Formation and the Upper Leonardian Upper Clearfork Formation. A facies model, porosity model, and a siltstone model were generated in Petrel® to better characterize the Monahans Field reservoir. Interbedded impermeable siltstone beds in Monahans Field partition the reservoir making oil production and water injection difficult. The facies model indicates that during deposition, a tectonically uplifted area (island) influenced sedimentation and also shows that the Upper Clearfork Formation is mainly subtidal facies and the Glorieta Formation consists mainly of tidal flat facies. The porosity model shows the greatest porosity to be in the diagenetically altered supratidal deposits. The siltstone model identified siltstone barriers that prograded across the platform when sea level was low. 4^{th}-order sequences occur within the larger 3^{rd}-order sequence. The models identified multiple flow units in Monahans Field. Preferential injection of water within the reservoir compartments, horizontal drilling, and hydraulic fracture stimulation may all provide mechanisms to more efficiently sweep the remaining reserves from the reservoir.

DEDICATION

I would like to dedicate this thesis to my family and friends who helped me get through school. Without them I would not be where I am at today.

ACKNOWLEDGEMENTS

I would like to thank my committee chair, Dr. Pope, and my committee members, Dr. Ahr, and Dr. Ayers, for their guidance and support throughout the course of this research. I would also like to give a special thanks to Occidental Petroleum for giving me the data set and to all at Occidental Petroleum who helped guide me through this thesis project.

NOMENCLATURE

API	Weight of Oil Compared to Water
Bbbl	Billion Barrels
Bbl	Barrels
BOPD	Barrels of Oil per Day
CBP	Central Basin Platform
K	Permeability
md	Millidarcy
MFS	Maximum Flooding Surface
MMBO	Million Barrels of Oil
MMBW	Million Barrels of Water
m.y.	Million Years
NPHI	Neutron Porosity
PHI_CORE	Core Porosity
QC	Quality Check
SGR	Spectral Gamma Ray Log
TD	Total Depth
TVDSS	True Vertical Depth Sub-Sea
UCF	Upper Clearfork
XPHITX	Cross Plotted Neutron-Density Porosity
Φ	Porosity

TABLE OF CONTENTS

Page

LIST OF FIGURES

Page

LIST OF TABLES

INTRODUCTION

The Permian Basin of West Texas is a dynamic petroleum province that has had many completion and drilling techniques used during its exploitation history. The basin was discovered in 1923 when the Santa Rita #1 well spudded in Big Lake Field. Hydrocarbon production in the Permian Basin has continued to decline since the peak production (715 MMBO) was reached in 1974 (IHS Energy Group, 2010). As of 2000, the Permian Basin had produced approximately 30 Bbbl of oil (Dutton et al., 2005). Permian carbonates deposited on a ramp and platform environment account for more than 32 Bbbl of the oil in place in the Permian Basin (Atchley et al., 1999). Primary, secondary, and tertiary hydrocarbon recovery methods including water injection, CO_2 injection, horizontal drilling, and fracturing the reservoir to promote fluid flow are currently used in the Permian Basin.

Previous Studies in Monahans Field

Monahans Field has been studied many times since its discovery in 1945 (Ruppel, 1994). A field study described the facies changes in great detail for the Clearfork Formation reservoir and includes evaluating the field for secondary recovery methods associated with reservoir quality throughout the field (Dowling, 1970). The Clearfork Formation reservoir in Monahans Field was subdivided into five separate zones labeled G, G-1, G-2, G-3, G-4, from top to bottom, respectively. G-4 was further subdivided into eleven sub-zones labeled “A” through “K” based upon different facies and depositional environments that range from supratidal to marine. Zone G is restricted marine

This thesis follows the style of AAPG Bulletin.

dolomites. G-1 is mixed marine and supratidal dolomites. The mixed marine sediments have nearly field-wide porosity, whereas the supratidal dolomite contains only localized porous zones. G-2 consists of field-wide restricted marine dolomite. G-3 consists of supratidal dolomites and is permeable in some areas due to secondary diagenesis associated with the dissolution of evaporites (Dowling, 1970). Dowling's study aimed to better understand reservoir quality and continuity in Monahans Field as well to identify undrilled pay zones. The depositional environments and diagenetic history of the Leonardian Series in Monahans Field were described by Ruppel (1992). These units contain numerous levels of cyclicity, porosity, permeability, and diagenesis in the reservoir resulting from sea level changes and the paleotopography during the time of, and after deposition. The Archie cementation exponent (m) and the Archie saturation exponent (n) were determined using a new statistical method of least error summation and also using dielectric water saturations (Saha, 1992). Three well logs, their coincident cores, and petrographic study of thin sections of these cores of the Glorieta-Clearfork formations were used to determine the stratigraphy, depositional environments, and reservoir facies in Monahans Field (Saha, 1992). A field study describes the field history, field geology, depositional cyclicity of reservoir rocks, porosity development, permeability development, and water flooding of Monahans Field (Ruppel, 1994). A structure map of the field along with a type log provides additional insight to the subsurface geology. Six cores from the field provide a cross-sectional view of the lateral facies variations within the Clearfork Formation in Monahans Field (Ruppel, 1994).

Statement of Problems

The Glorieta and the Upper Clearfork formations in Monahans Field are currently undergoing water flood to effectively sweep the remaining hydrocarbons. The lateral heterogeneity due to facies changes, and secondary diagenetic alteration associated with evaporites filling pore spaces creates problems when determining reservoir flow units versus barrier units. The amount of injected water does not correlate to the amount of produced water; also the amount of hydrocarbons produced is low compared to what is expected to be produced from the reservoirs. The water loss problem and low hydrocarbon production rates may be associated with thief zones and multiple unswept flow units within the reservoir.

Objectives

The objective of this study was to better characterize and understand the Glorieta and Upper Clearfork formation reservoirs of Monahans Field, Permian Basin, West Texas (Figure 1). This characterization was done by creating 3D property models using Schlumberger's Petrel® software; which is a geological modeling software. A facies model generated from facies logs that were created from core descriptions was used to map depositional environments spatially in Monahans Field. A porosity model was created to analyze the lateral changes throughout the reservoir. A siltstone model was used to identify siltstone barriers that subdivide flow units within the reservoir.

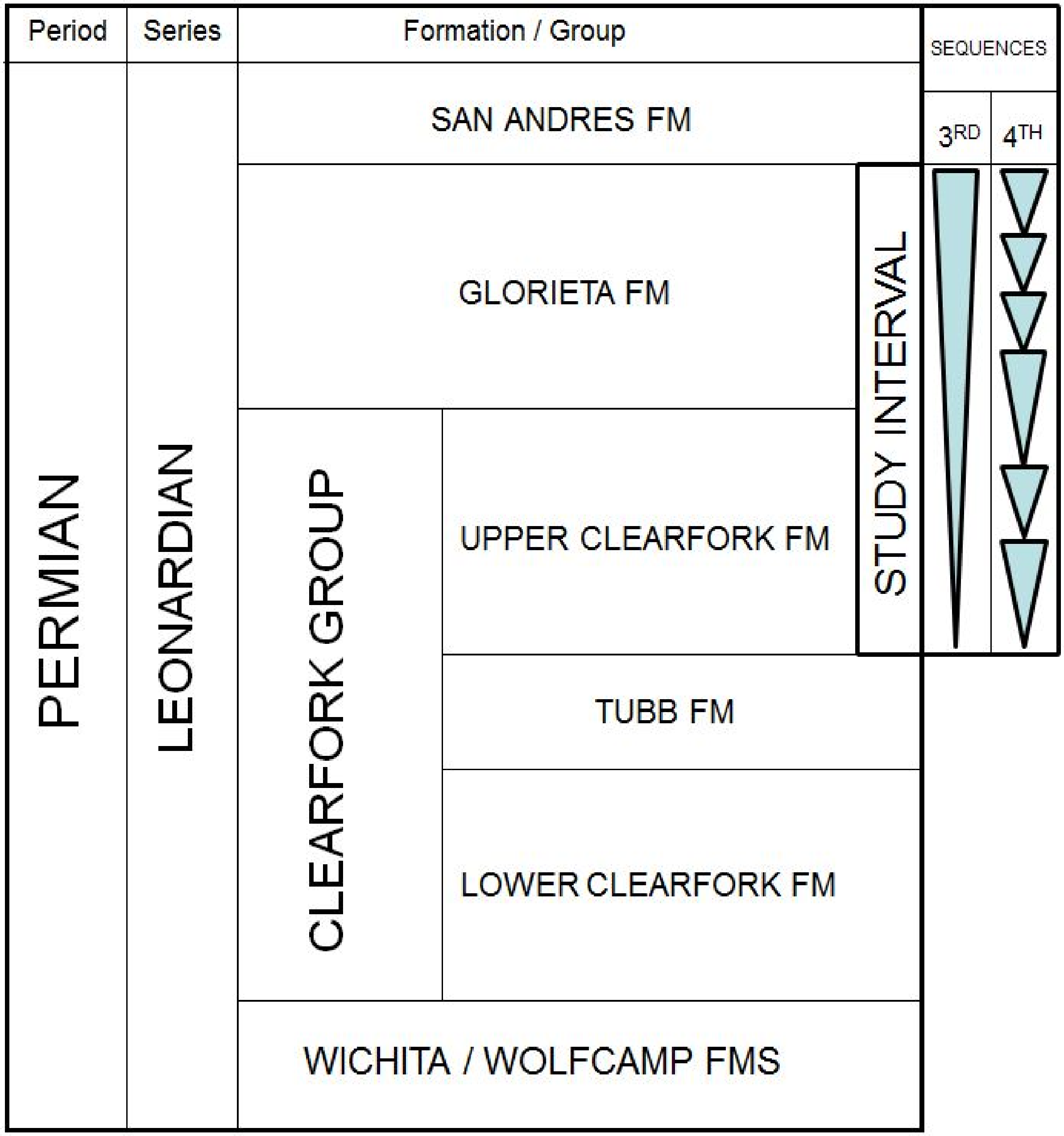

Figure 1. Stratigraphic column. Stratigraphic column of the units in Monahans Field. This study focuses on the Glorieta and the Upper Clearfork formations.

Methods

The methods (Figure 2) for reservoir characterization of the Glorieta and the Upper Clearfork Formations in Monahans Field are:

I. Facies logs were created from core descriptions (Ruppel, 1993,1994).

II. Facies logs were used to populate a model that spatially distributed depositional environments for the Upper Clearfork and the Glorieta formations across the field.

III. Sequences and parasequences were identified

IV. Siltstone intervals were identified from the spectral gamma ray logs and used to model the distribution of siltstone to determine reservoir compartments.

V. Corrected porosity logs which include Core Φ, Neutron-Density Φ, and Neutron Φ logs were upscaled to model the porosity in Petrel® to determine the distribution of reservoir versus non-reservoir rock.

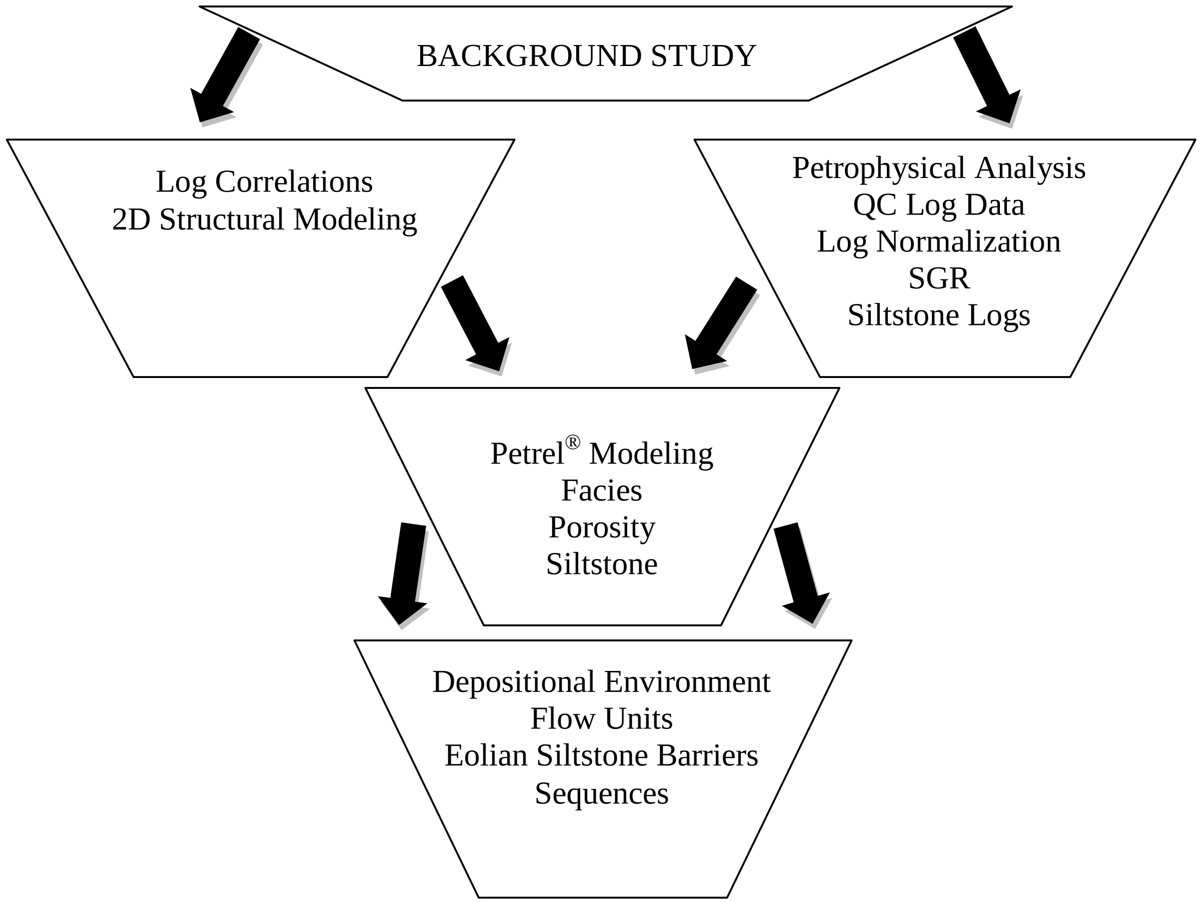

Figure 2. Workflow outline. Outline of the workflow used on the data set.

Data Set

The data used for this thesis research was provided by Occidental Petroleum Corporation and includes 270 well logs that were loaded into a Petrel® project prior to receiving the data. Core data from 17 wells in Monahans Field were also included in the data set. The core data includes the following: (1) capillary pressure data for wells 270 and 164; (2) plug-derived porosity and permeability values for wells 270, 40, 43, 44, 45, 47, 48, 49, 57, 59, 61, 64, 114, 125, 163, 164, 314; and (3) facies description for the 17 cored wells (Ruppel, 1993, 1994).

Field Location

Monahans Field of the Permian Basin is located two and a half miles north of Monahans, Texas on the Ward-Winkler county line (Figure 3). The field encompasses 2720 acres on the western side of the Central Basin Platform. During deposition, the field was located about twelve miles east of the western margin of the Central Basin Platform.

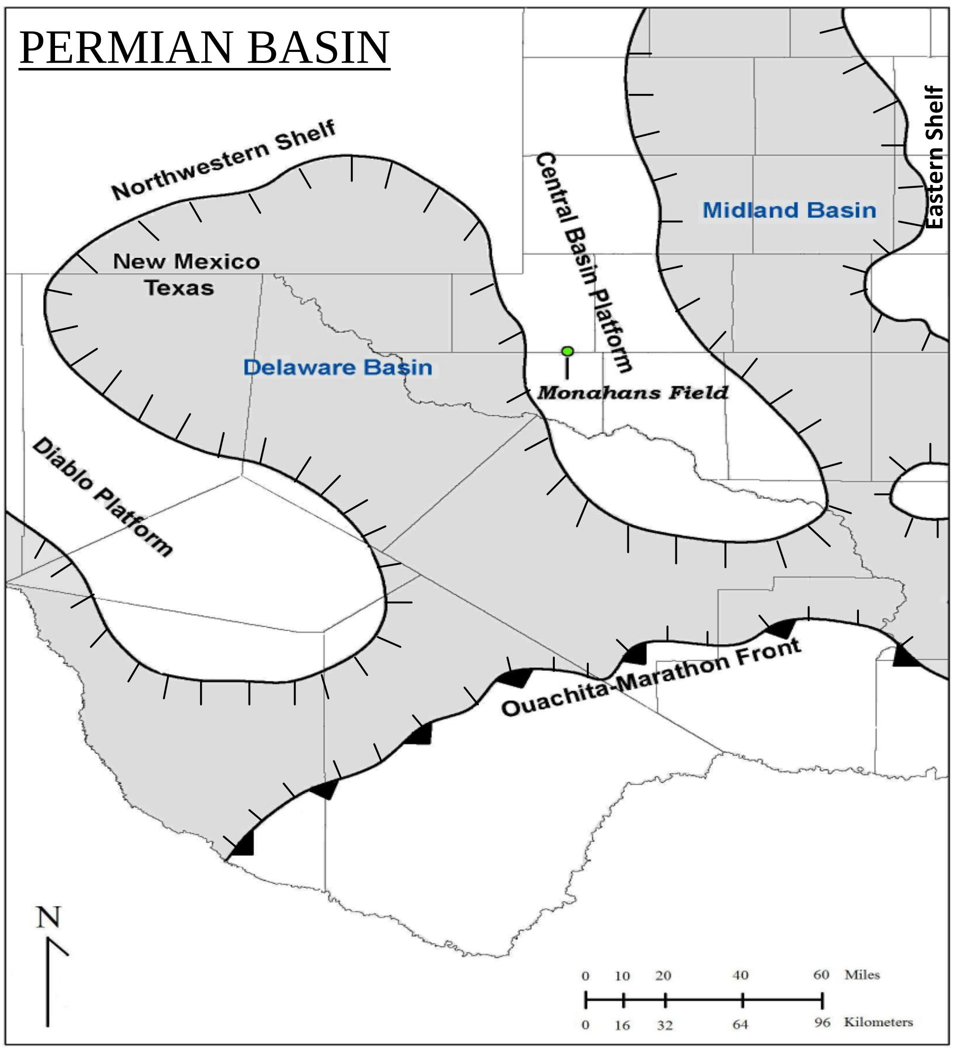

Figure 3. Location map. Location map of Monahans Field on the west side of the Central Basin Platform of the Permian Basin, west Texas.

Field History

Monahans Field was discovered by Shell on August 11, 1945 when the first well was drilled to a total depth of 8058 feet (Ruppel, 1994). The discovery well came on with initial production of 481 BOPD producing from the Guadalupian-Leonardian Lower San Andres, Glorieta, and the Upper Clearfork formations. Other productive reservoirs in the field include the Lower Ordovician Ellenburger Group, Silurian Fusselman Formation, Devonian Thirtyone Formation, multiple Mississipian reservoirs, the Leonardian Tubb Formation, and the overlying Guadalupian Queen Formation (Ruppel, 1994). The field was drilled on 40-acre spacing until 1962, when water injection began (Figure 4). Water was injected low on structure to create an artificial water front to sweep the reservoir under the assumption the Glorieta and the Clearfork formations were laterally homogeneous. From September 1962 to July 1969, 23.7 MMBW were injected into Monahans Field producing 1.1 MMBO and 1.2 MMBW (Dowling, 1970). The production data showed that the amount of oil produced was much lower than expected, and approximately 20 MMBW remained in the ground (Dowling, 1970).

Reservoir Description

Monahans Field (Figure 4) produces from an elongate northwest to southeast dome (anticline). The reservoir is primarily anhydritic dolostone with a range of porosities and permeabilities. Reservoir porosity ranges from 0.04% to 23.8% and the permeability ranges from 0.001 md to 146 md. The average porosity for Monahans Field is 5.9% and the average permeability is 0.6 md (Ruppel, 1994). Within the reservoir, tidal flat and grain-dominated subtidal rocks have the highest porosity values, and grain-dominated subtidal rocks have the highest permeability values (Ruppel, 1992). Porosity in Monahans Field is directly related to diagenetic alteration of reservoir rocks at, or near, parasequence or sequence boundaries. The drive mechanism for the field initially was solution gas, but the field was converted to water injection in 1962. The original oil-water contact was approximately -2600 TVDSS, and the top of the oil column was located at -1805 feet, TVDSS, thus, there was an initial oil column of 795 feet. The weight of the oil in Monahans Field is 36° API Gravity (Ruppel, 1994).

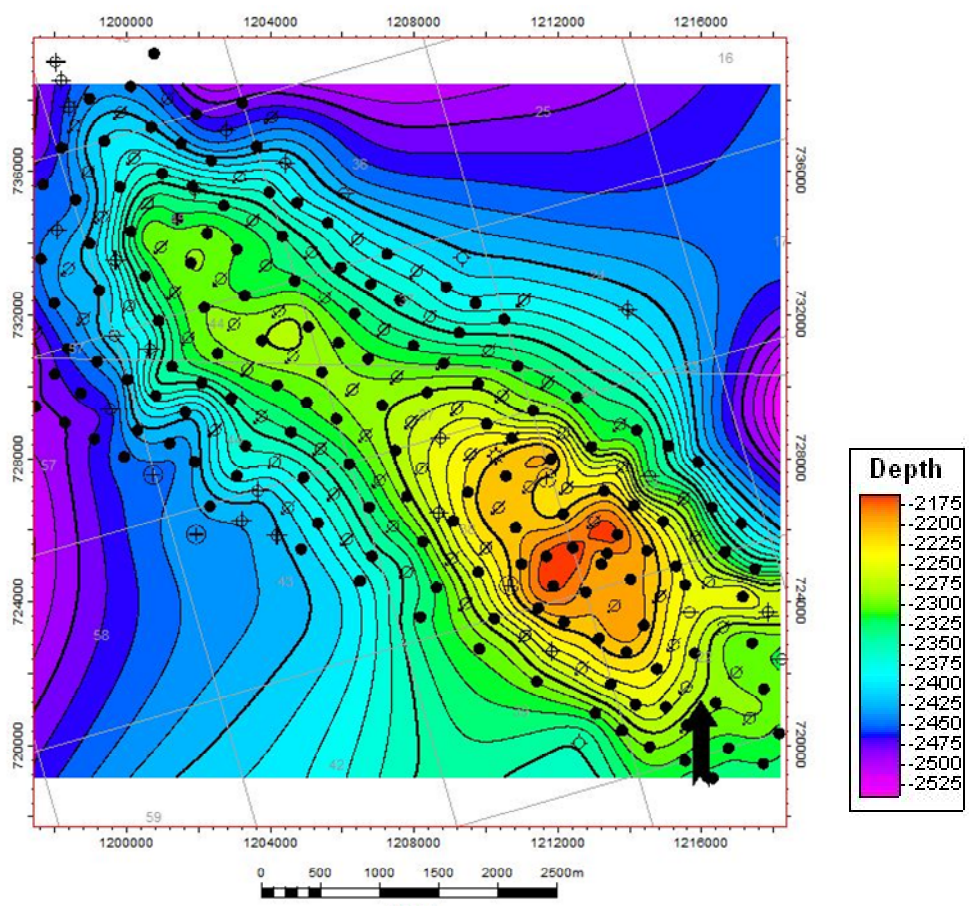

Figure 4. Drilling base map. Base map of Monahans Field showing well spacing and a structure map on the top of the Upper Clearfork Formation.

GEOLOGIC BACKGROUND

Structural Evolution of the Permian Basin and CBP

The Permian Basin developed in the foreland basin of the Late Mississippian-Permian (Late Paleozoic) Marathon-Ouachita Orogeny. This orogenic belt was created from the collision of Gondwana with the North American continent (Dorobek, 1995). The larger Permian Basin is subdivided into two smaller basins (Delaware and Midland) separated by the fault-bounded Central Basin Platform. The Diablo Platform and the Eastern Shelf form the western and eastern boundaries of the basin respectively. The Central Basin Platform separated the antecedent Tabosa Basin, which was created by regional extension in the Precambrian-Early Cambrian, into the Midland and Delaware Basins (Yang and Dorobek, 1995). Structural styles across the Permian Basin are heterogeneous, and the mechanisms by which the Central Basin Platform was created are controversial. The Central Basin Platform was divided into two large structural blocks, Andector Block to the north and the Fort Stockton Block to the south, or it was divided into six blocks by fault bounded tectonics of the Ouachita Orogeny (Yang and Dorobek, 1995). Regardless of the number of blocks composing the Central Basin Platform, the platform blocks are bounded to the east and west by approximately N-S trending, right-lateral strike slip faults. Right-lateral slip produced clockwise rotation of the blocks within the interior shear zone that created left-lateral strike slip motion at the boundary between the blocks (Shumaker, 1992). Rotation created a space issue producing differential uplift on the individual blocks. The largest amount of vertical displacement occurred along high angle reverse faults located on the southwest and northeast corners of the blocks. The amount of vertical displacement decreases to the north along the western fault zone and to the south along the eastern fault zone (Yang and Dorobek, 1995).

Depositional Environment

Pennsylvanian faulting created localized structural highs and lows on the Central Basin Platform which controlled sediment thickness and facies patterns of the Glorieta and Clearfork formations (Ruppel, 1992). A network of small islands developed on the Central Basin Platform where tidal flat deposition occurred on the structural highs and subtidal deposition occurred on the flanks of the structure (DiMichele et al., 2000). During deposition of the Glorieta and Clearfork formations, the shelf margin was located 12 miles west of Monahans Field. Sediments deposited in deeper depositional environments, west to northwest of the field, have higher percentages of marine sediments than the sediments deposited in shallower water, east to southeast of Monahans Field (Saha, 1992). During tectonic quiescence, the Central Basin Platform was the site of shallow water platform carbonate production in supratidal to subtidal depositional environments. Cyclic alternations of subtidal to intertidal rocks are part of a larger shallowing upward 3^{rd}-order sequence within the Monahans Field reservoir.

Third-Order Sequences

The Glorieta and Clearfork Formations in Monahans Field were deposited during a 3^{rd}-order sequence that is about 250 meters (700 feet) thick and records about 5-6 m.y. of deposition. The 3^{rd} -order sequence has a shoaling upward deep subtidal base, a middle aggradational shallow subtidal portion, and an upper part composed of aggradational, high-frequency tidal flat cycles. 4^{th}-order sequences and 5^{th}-order parasequences occur in the reservoir at Monahans Field. 10-20 meter thick packages are 4^{th}-order sequences that contain smaller meter-scale cycles. The meter-scale cycles commonly have subtidal bases that shallow upwards into supratidal tops (parasequences) (Hendrick et al., 1993). The base of the Upper Clearfork Formation, or top of the Tubb Formation, is a maximum flooding surface overlain by a shallowing upward 3^{rd} -order sequence that continues through deposition of the Glorieta Formation (Atchley et. al., 1999).

Fourth-Order Sequences

Vertical stacking of fifth-order cycles group into fourth-order sequences, 10-20 meters (30-80 feet) that are readily identifiable on gamma ray logs. Fourth-order cyclicity is the result of stacking fifth-order cycles and produces vertical reservoir heterogeneity. Fourth-order sequences have well defined bases with high gamma-ray values corresponding to the subtidal carbonates. High value gamma-ray cycle tops are derived from their cycle capping siltstone composition (Ruppel, 1992).

PETROPHYSICAL ANALYSIS

A detailed petrophysical analysis is important when creating a reservoir model. The log data were analyzed to determine the following:

I. Check data quality

II. Porosity log normalizations

III. Siltstone logs/spectral gamma ray analysis

Quality Checking (QC) Log Data

The log data in Monahans Field were analyzed for erroneous data. Certain logs throughout the field were excluded from the model so that the level of accuracy was higher. Bad log data were a result of logging errors and false readings at TD locations. These values were deleted from the log data. Some of the logs in Monahans Field had negative porosity values through the study interval; these logs were removed from the model. Other logs had porosity values ranging from 50% to 90%; these logs were also removed after analyzing core Φ value to see what the maximum porosity should be.

Porosity Cutoffs

A maximum porosity was set at 25% to account for some of the erroneous porosity log data. This number was obtained by using the core derived porosity values and picking the highest porosity value as a maximum value. Petrel® cannot create a property model with negative log values, so negative porosity values were set at 0.001% porosity.

Log Normalization

Porosity logs were used to model reservoir porosity heterogeneity. Ultimately, core Φ should be honored when selecting a porosity curve to use for modeling. However, core

Φ data are not available in the majority of the wells in Monahans Field. Porosity logs used in modeling the reservoir porosity were neutron porosity, neutron-density cross plotted porosity, and core porosity. The neutron-density curve correlates closest to the core porosity. The neutron curve reads high in the reservoir, because the log was run on a limestone matrix and it was not corrected for the reservoir's dolomite matrix, or it reads high due to the shale effect. The shale effect will be further discussed in the NPHI log section. For the purpose of the porosity model, a hierarchy was created so that if the well had a core porosity curve it was upscaled directly into the model. If the well did not have a core porosity curve then a neutron-density curve was used. If the well did not have a core porosity curve or a neutron-density curve then a normalized or corrected neutron curve was used for upscaling. 112 neutron logs (of 137) were normalized for the modeling process.

PHI_CORE Logs

In Monahans Field five wells have core Φ logs generated from plugs from cores in the field. Only two core porosity curves were used in the modeling process; three were excluded due to incomplete log curves (Figure 5). In these three wells, a neutron density curve was used in the model.

XPHITX Logs

XPHITX logs are neutron-density cross plotted logs derived from the neutron porosity curve and the bulk density curve. 31 wells in Monahans field have XPHITX logs that were used to construct the porosity model. Cross plotting neutron logs and bulk density logs has the closest correlation to the core porosity logs when they are plotted together (Figure 6).

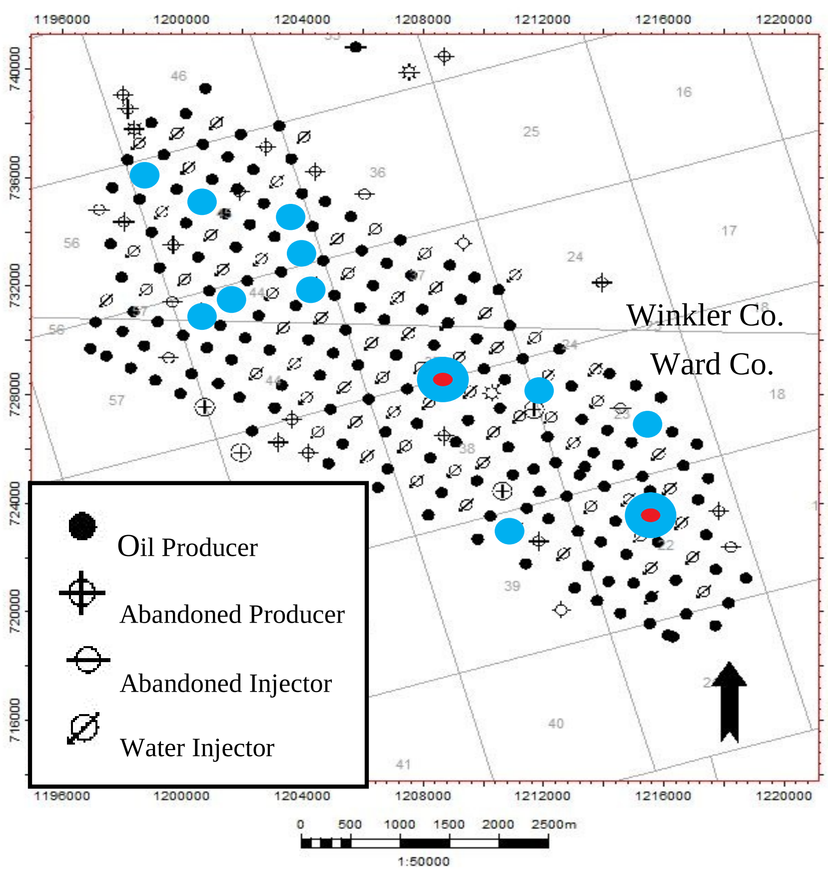

Figure 5. Well log base map. Base map showing well log coverage for Monahans Field. Wells highlighted in red have core porosity logs. These 2 wells were used to shift the neutron porosity curves. There are 3 others that have core porosity logs but they were excluded due to incomplete data. The wells highlighted in blue contain the facies logs used to create the facies model.

NPHI Logs

The neutron porosity log measures the hydrogen content of the formation to determine porosity values by creating neutrons in the logging tool and emitting them into the formation. Neutron logs can read anomalously high because of the shale effect as well as using an incorrect matrix (Asquith and Krygowski, 2004). In Monahans Field, the neutron log was run using an apparent limestone porosity (matrix) but the reservoir is primarily dolostone. The neutron logs can also read high when the logging tool encounters a clay-rich zone and reads the hydrogen atoms that are trapped within the clay-bound water as porosity. The neutron logging tool expects that all hydrogen atoms reside in pore spaces within the reservoir so it reads zones that are not porous as having porosity due to the hydrogen in the clay (Asquith and Krygowski, 2004). A correction is required to derive a more accurate porosity value. Core Φ logs were plotted against NPHI logs to see if the log derived porosity (NPHI) was continuously high, low, or if it correlated to the core Φ. The neutron porosity log values were consistantly high when plotted against the core Φ. Core Φ data were used to shift the neutron porosity curve in all of the wells by plotting core porosity versus neutron-density and also plotting core porosity versus neutron porosity. A line of best fit was applied to the data points. After the shift was applied, the neutron porosity values shifted closer to resemble the core to neutron density line of best fit (Figure 6).

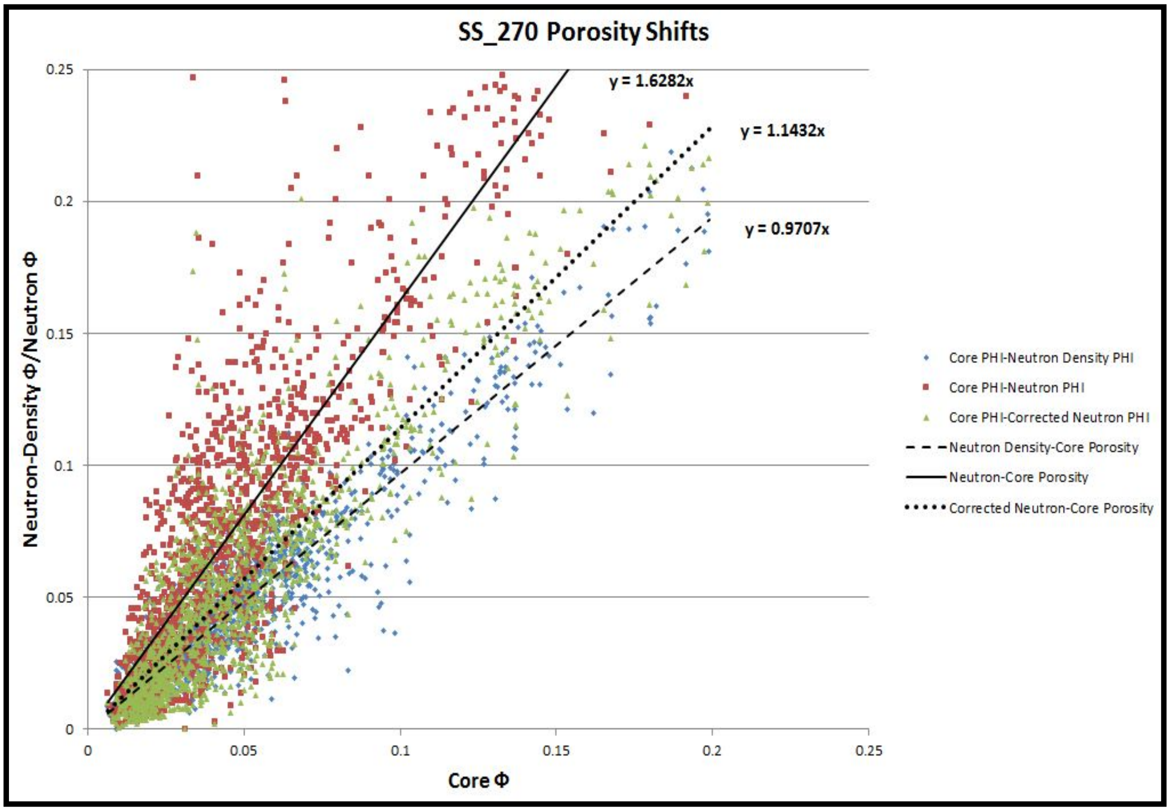

Figure 6. SS_270 porosity data. Shift has been applied to the neutron log data. The data moved closer to a one to one relationship after the averaged algorithm from the two cored wells (0.7021) was applied to the neutron porosity data. Equations for the line of best fit are displayed to show the relationships. Solid line is the data before shift, dashed line is the core Φ-neutron density data, and the dotted line is the shifted neutron porosity data.

Siltstone Logs

28 siltstone logs were used and upscaled for the purpose of modeling the position of the siltstone in the reservoir at Monahans Field. The siltstone logs were created from the spectral gamma ray log where it had spectral gamma-ray API value greater than 65. The siltstone logs do not have a numerical value associated to them; they indicate zones that are identified to be composed of siltstone from the SGR log. The siltstone logs were plotted against the SGR curve to see if the 65 API units was the value that was used to identify siltstone in the reservoir (Figure 7).

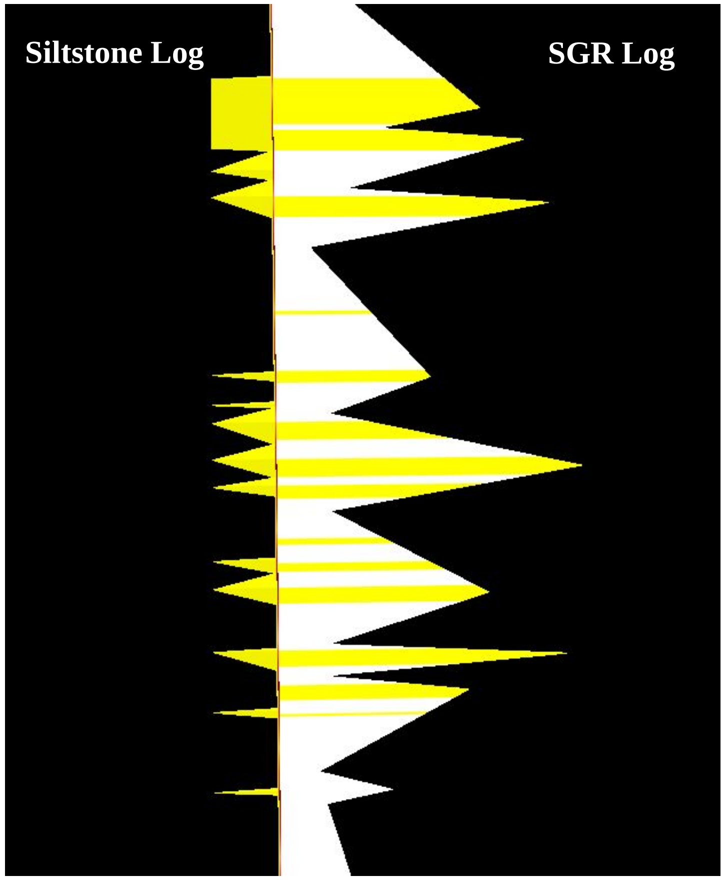

Figure 7. Siltstone and SGR log. Siltstone and SGR log are displayed on well SS_270 to show the SGR API value used to identify siltstone intervals within the reservoir. The SGR log (right side) is displayed to show values of 65 API units or higher to be yellow. The silt flag log (left side) was created to identify silts from the SGR log. The siltstone log and the filtered SGR log correlate. A 65 API unit was used to locate siltstone.

PETREL MODELING

Petrel Methodology

A three dimensional reservoir model using multiple parameters (e.g. porosity, facies, and siltstone) was created using Petrel® Geological Modeling software. This was done to characterize and model the spatial distribution of facies, siltstone barriers, and porosity of the Glorieta and the Upper Clearfork formations. The properties created can be compared and used together to better understand the reservoir properties.

Grid Construction

A 3D grid created a lattice network that was used as the base of the 3D cell generation in the model. Horizons were inserted into the model using well tops, and surfaces that were created from the well log data (Figure 8). The Glorieta Formation well tops through the U-A well tops were used when generating surfaces and horizons. The deeper zones in the reservoir did not have as much well control as the stratigraphically shallower zones and they were manually flexed to be stratigraphically correct. The flexed surfaces were then used to create horizons within the model.

Log Correlations

Log correlations were made using the type log SS_270 (Figure 9). The stratigraphically deeper Tubb and Lower Clearfork Formations are excluded from this analysis because; (1) the main water flood/productive intervals in Monahans Field are the Glorieta Formation and the Upper Clearfork Formation, and (2) a large portion of the wells do not penetrate the Tubb and Lower Clearfork formations. The Glorieta Formation and the Upper Clearfork Formation were further subdivided into smaller packages based on porosity units derived from the NPHI log (Figure 9). The Glorieta Formation is divided into four units (Glorieta, G-A, G-B, G-C) and the Upper Clearfork is divided into five units (UCF, U-A, U-B, U-C, U-D).

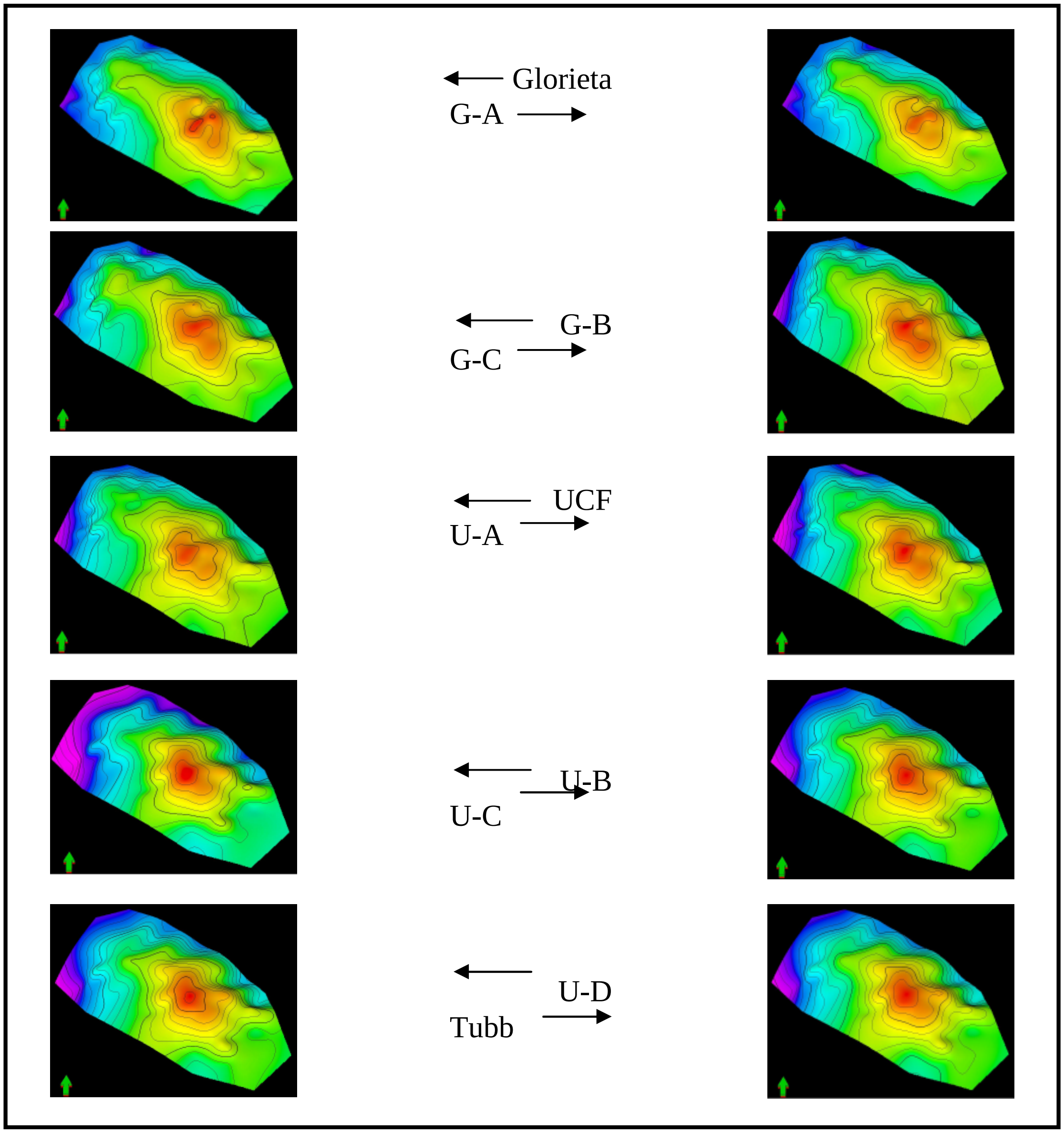

Figure 8. Horizons. Glorieta horizon through the Tubb horizon used for modeling surfaces.

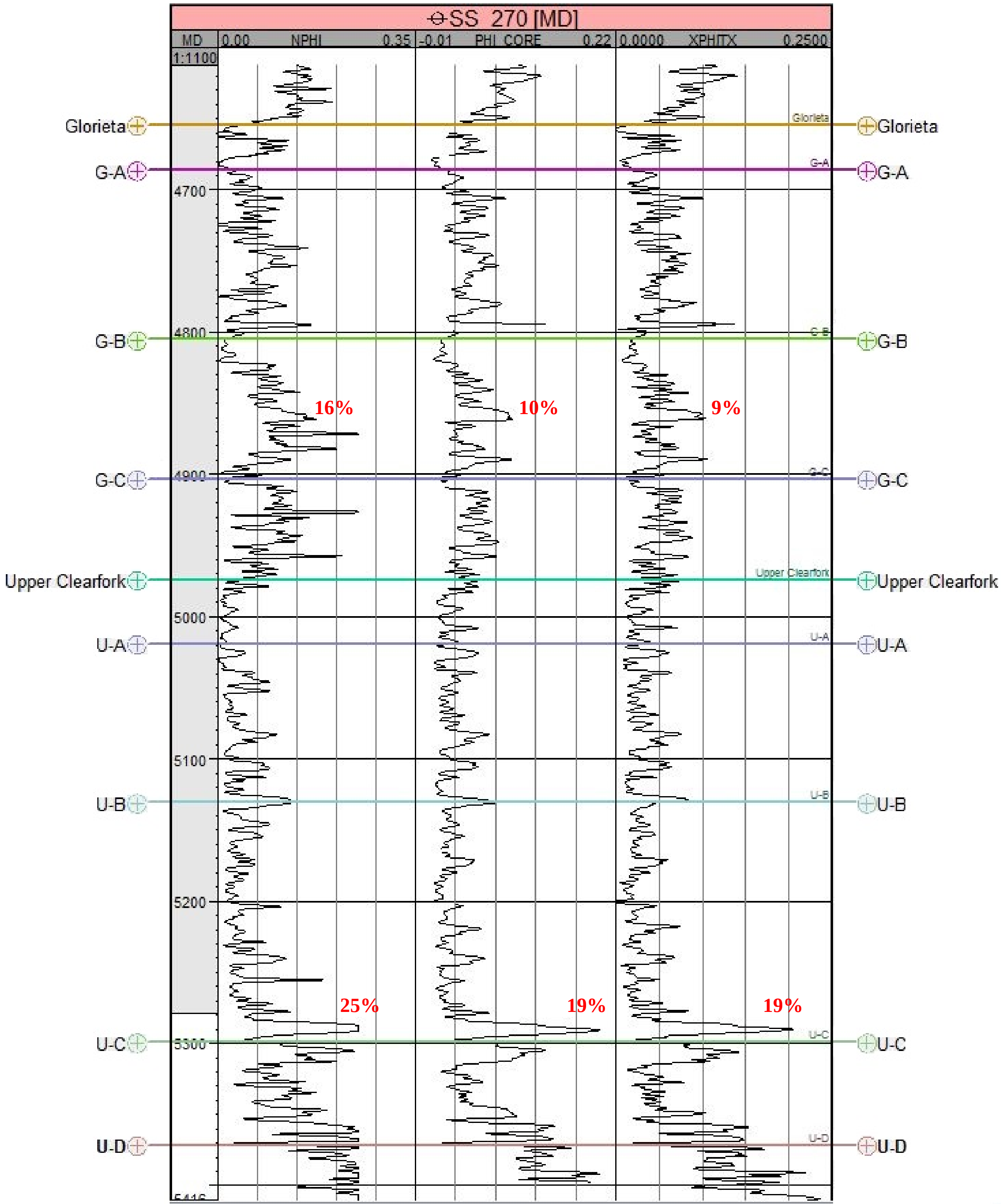

Figure 9. Type log. SS_270 Log with the Glorieta, Upper Clearfork and the Tubb formation well tops and the subdivisions of porosity. Type log displays a neutron porosity log, a core porosity log, and a Neutron-Density cross-plot log to show the correlation or non-correlation between log porosities.

Layering

The number of layers in the model defines the resolution of the model. Layering is the internal layering reflecting the deposition of a particular zone. When creating layers in Petrel®, the average total thickness of the formation between horizons is divided by 2 to get the number of layers for the model. The smallest interval on the log scale is 2 feet so the average total thickness of the formation is divided by two to resemble the logging tool and to create a higher degree of accuracy in the model.

Property Modeling

The initial step to property modeling is to scale up the well logs used in the reservoir modeling process. Multiple types of well logs or log data can be upscaled for the modeling procedure in Petrel®. The purpose of upscaling well logs is to assign well log values to the cells in the 3D grid that are penetrated by the well bore. Each cell in the model can hold only one value, therefore the log data is averaged, or upscaled, to distribute the property data between the wells where data is not present. The logs that were upscaled for the purpose of modeling the Glorieta and the Upper Clearfork formations in Monahans Field were the porosity logs, siltstone logs, spectral gamma ray logs, and facies logs that were created from core facies descriptions.

Facies Logs

Facies logs were created from the 10 facies of the Upper Clearfork and Glorieta formations (Ruppel, 1993, 1994). For the facies modeling, the ten facies were grouped into four broader facies (Table 1). The 13 facies logs were upscaled to create a 3D facies model of the reservoir. The wells that have facies logs are wells 43, 44, 45, 47, 48, 49, 57, 61, 114, 125, 163, 164, and 270.

Table 1. Facies Descriptions

Bureau Facies Descriptions **(From Ruppel, 1993, 1994)**	**Grouped Facies Descriptions** **(This Study)**
1. Tidal Flat	1. Tidal Flat (Anhydrite-Gypsum) - 1. Tidal Flat - 6. Gypsum - 9. Silty Tidal Flat
2. Mudstone	
3. Pelletal Wackestone	
4. Pellet Packstone-Grainstone	2. Mudstone - 2. Mudstone - 7. Shale - 10. Vertical Burrowed Mudstone
5. Skeletal Packstone-Grainstone	
6. Gypsum	
7. Shale	3. Pelletal-Skeletal Wackestone - 3. Pelletal Wackestone - 11. Skeletal Wackestone
8. No Core	
9. Silty Tidal Flat	
10. Vertically Burrowed Mudstone	4. Pelletal-Skeletal Packstone-Grainstone - 4. Pellet Packstone-Grainstone - 5. Skeletal Packstone-Grainstone
11. Skeletal Wackestone	

Facies Modeling

The facies logs were upscaled into the model and data analysis was applied to the upscaled facies logs. Data analysis, or geostatistics, is the process of analyzing, quality checking the input data, and to gain a better understanding of the data along with its associated trends (Schlumberger, 2010). The data analysis in the horizontal direction was in the form of probability maps. The maps were derived to distribute the data on a given horizon. A total of 32 maps were created (8 zones and 4 facies). The data analysis in the vertical direction for the facies logs was in the form of vertical proportion curves (Figure 10). These curves allow for adjustments to be made on the percentages of each facies in each zone in the reservoir in the vertical direction for every well that has a facies log.

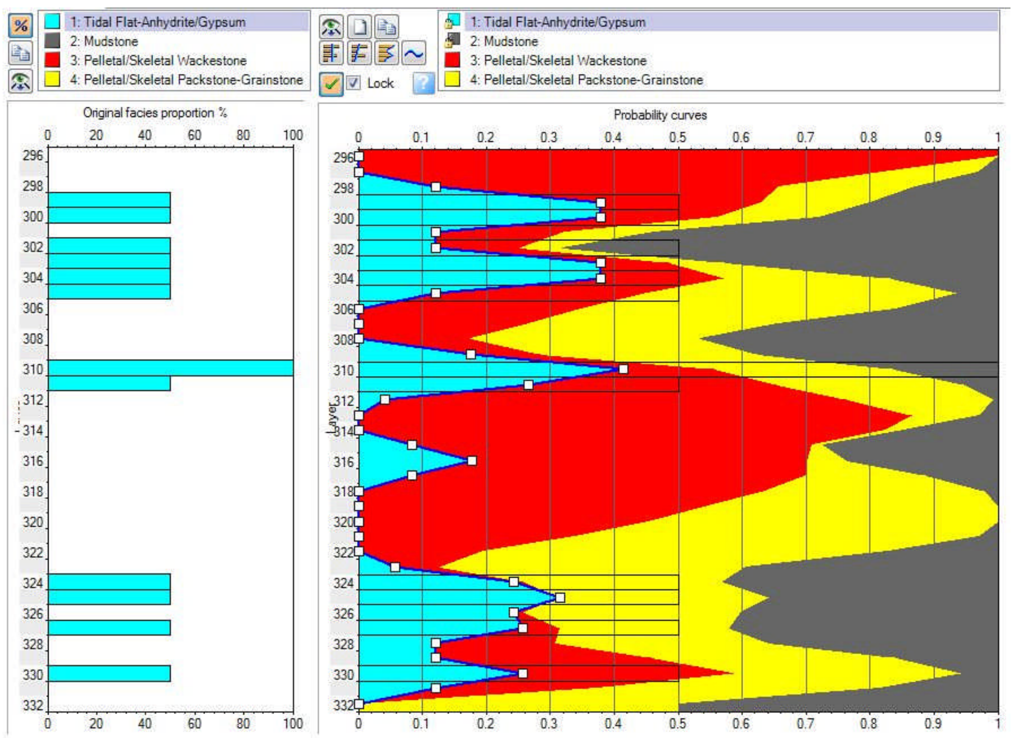

Figure 10. Vertical proportion curve. Vertical proportion curves allow for the percentage of each facies to be manually adjusted for individual zones within the reservoir. Adjustments were made by using facies descriptions.

Variogram Analysis

A variogram describes the amount of spatial variation in a reservoir based on the fact that closely located samples are more likely to have more of a correlation than samples that are far from one another (Schlumberger, 2010). Variograms were created for the porosity subdivisions throughout the Glorieta and the Upper Clearfork formations to calculate the orientation of the trend, or the orientation of reservoir porosity continuity, as well as to see if there were different azimuths of the trend in different packages of porosity in the Glorieta and the Clearfork formations. The variograms for the Glorieta Formation showed that there was a similar trend in the data at around 0° (Figure 11). The variograms for the Upper Clearfork Formation show a trend at approximately -60° (Figure 12). These different azimuths were applied to the data analysis to orient the data in the general direction of the azimuth from the variograms to create the porosity model.

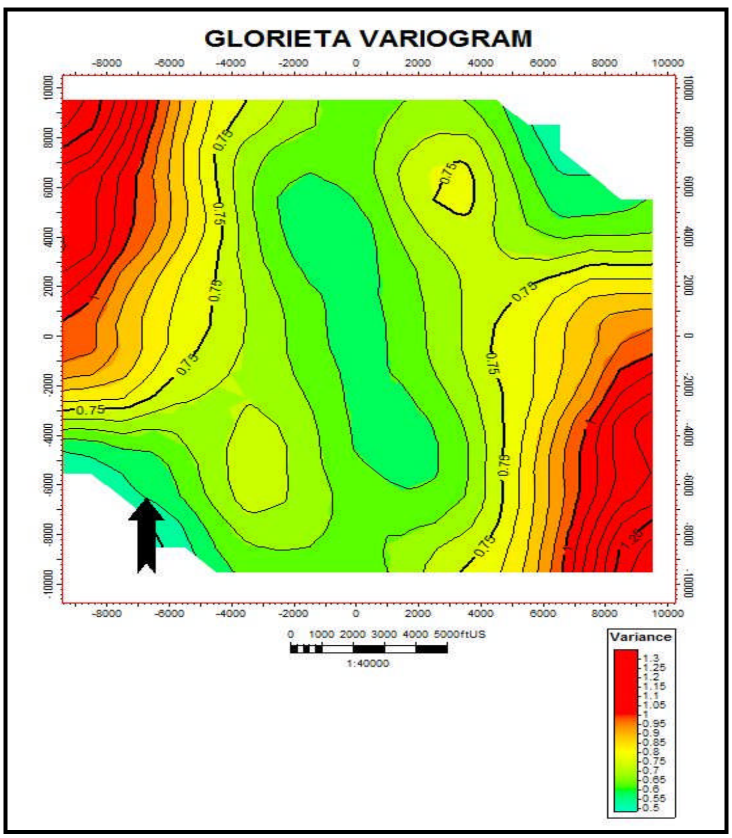

Figure 11. Glorieta variogram. Created from upscaled porosity logs indicate an apparent trend in the data of 0°. This variogram is representative of all the zones in the Glorieta Formation.

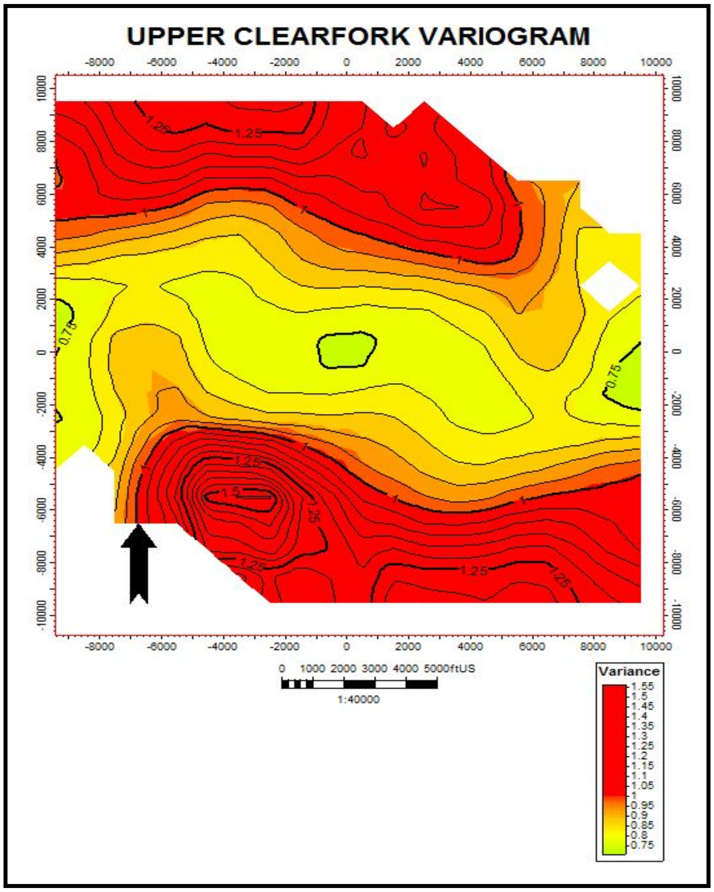

Figure 12. Upper Clearfork variogram. Created from upscaled well logs indicate an apparent trend in the data of approximately -60°. This variogram is representative of all the zones in the entire unit.

RESULTS

UCF Formation Facies Model

The facies within the Upper Clearfork Formation are mostly subtidal pelletal-skeletal wackestone, packstone, and grainstone; but there are also large volumes of mudstones in this unit that represents deeper subtidal depositional environments on the flanks of the structural highs. The facies on the structural highs in the field are preferentially grainstone. In the Upper Clearfork Formation, there are thin zones of tidal flat facies recording high frequency sea level falls. Tidal flat and grainstone facies in the Upper Clearfork Formation transition into deeper subtidal facies moving off the structural high; indicating that there was vertical relief of the island during deposition (Figure 13). The base of the Upper Clearfork Formation is the maximum flooding surface of the 3^{rd}-order sequence and is overlain by the shallowing upward deposition of the Glorieta Formation. The Tubb Formation which is directly below the Upper Clearfork Formation is a siltstone-rich interval recording a sea level lowstand.

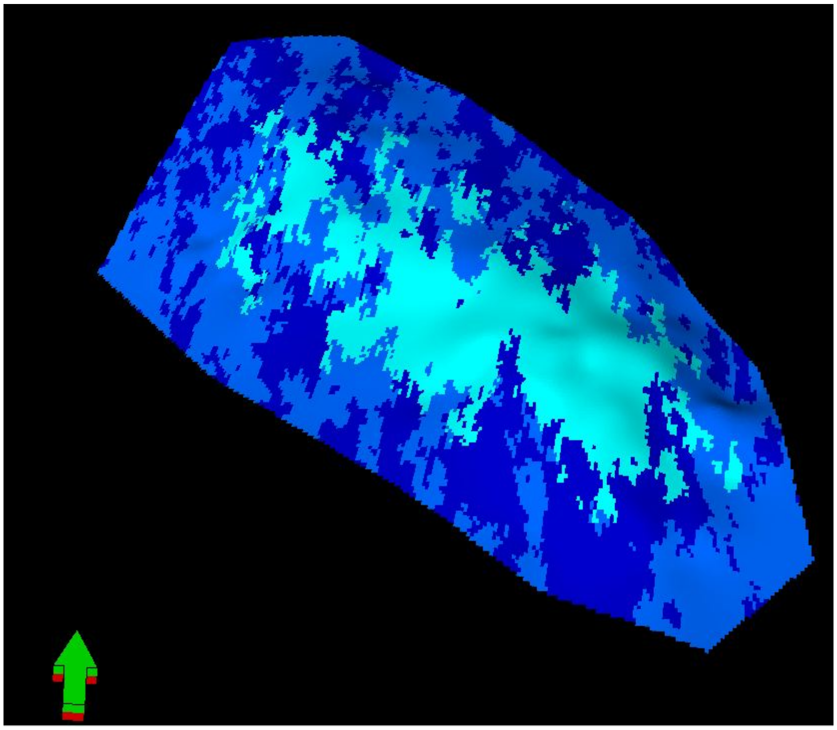

Figure 13. Upper Clearfork facies model. Lateral facies distribution of the facies in the Upper Clearfork Formation. This figure is representative of all of the sub-zones of the Upper Clearfork Formation. Grainstone facies are on the structural highs and transition to deeper subtidal facies on the flanks of the structure. Colors in the image correspond to table 2.

Glorieta Formation Facies Model

The Glorieta Formation is predominantly tidal flat facies with minor stringers of subtidal facies. The stringers are relatively continuous across the structural high indicating the localized high was occasionally submerged below sea level. When grainstone formed, they were prolific on the structural highs in the field and transition into deeper subtidal facies off the flanks of the structure. As a whole, the Glorieta Formation represents a highstand in sea level with minor sea level rises and falls, composed of smaller parasequences within the larger 3rd-order sequence. Tidal flat facies are on the structural highs in the field and transition into deeper subtidal facies off the flanks of the structure (Figure 14).

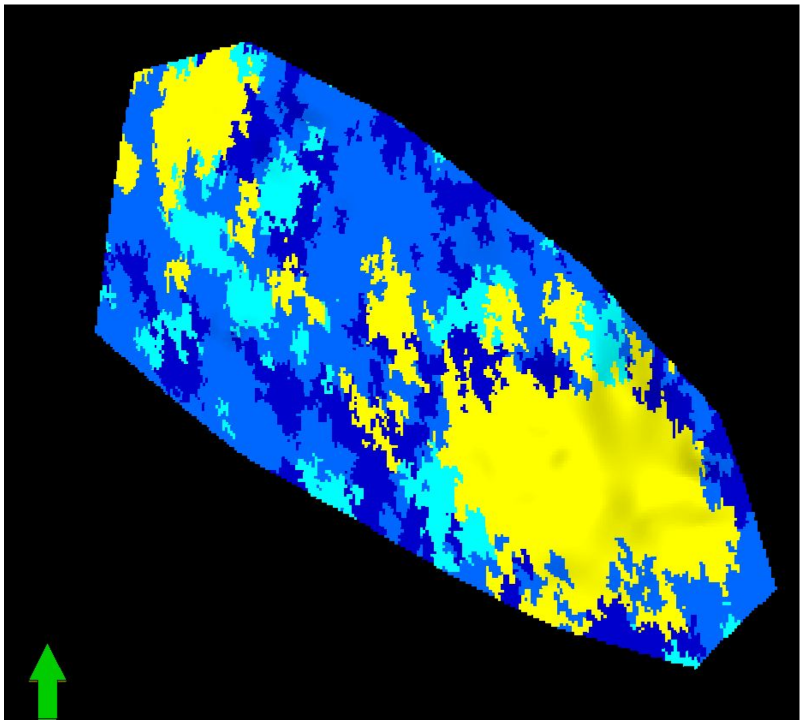

Figure 14. Glorieta facies model. Lateral facies distribution of the facies in the Glorieta Formation. This figure is representative of all of the sub-zones of the Glorieta Formation. Tidal flat facies are on the structural highs and transition to deeper subtidal facies on the flanks of the structure. Colors in the image correspond to table 2.

UCF Formation Siltstone Model

The siltstone model of the Upper Clearfork Formation shows that there is little to no siltstone within this unit indicating the Upper Clearfork Formation records predominantly subtidal deposition (Figure 15). The rare occurrences of siltstone in the Upper Clearfork Formation are located within the tidal flat facies; indicating there was subaerial exposure during high frequency sea level falls. Subzones UCF and U-D contain little to no siltstone in them. Subzones U-A, U-B, and U-C have minor siltstone in comparison to the Glorieta Formation.

Glorieta Formation Siltstone Model

The large volumes of siltstone in the Glorieta Formation record periods when sea level was at its lowest point allowing for eolian silt to prograde across the platform. The siltstone occurs at the tops of the high-frequency sequences or parasequences within the Glorieta Formation. The largest volumes of siltstone are associated with the tidal flat facies which indicates subaerial exposure of the tidal flats led to eolian siltstone deposition. The subzones within the Glorieta Formation that have the largest volume of siltstone are G-B and G-C. The volume of siltstone decreases above G-B in the Glorieta Formation section (Figure 15).

Table 2. Siltstone/Facies Chart

Facies Model/Silt Model	**Color**
Tidal Flat (Supratidal)	Yellow
Mudstone (Subtidal)	Dark Blue
Pelletal/Skeletal Wackestone (Subtidal)	Blue
Pelletal/Skeletal Packstone-Grainstone (Subtidal)	Light Blue
Siltstone	Black
Non-Siltstone	White

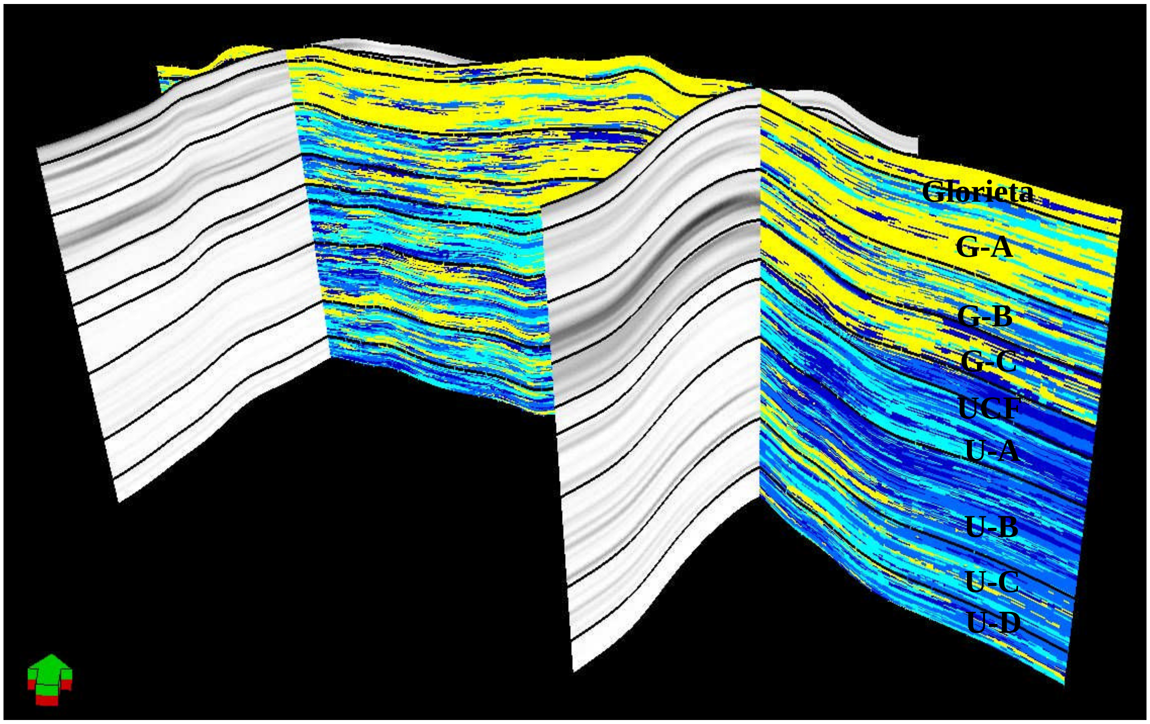

Figure 15. Facies/Siltstone model. Model shows the spatial distribution of the siltstones within the tidal flat facies. Tidal flats are shown in yellow and subtidal rocks are shown in blue. Siltstone is black and the non-siltstone is white on the transverse cut. Colors correspond to table 2.

Sequences

The Glorieta and the Upper Clearfork formations at Monahans Field are a part of a large 3^{rd}-order, shallowing upward sequence from a maximum flooding surface within predominately subtidal facies of the Upper Clearfork Formation through the predominately peritidal Glorieta Formation. Six 4^{th}-order sequences are identified in the Glorieta and the Upper Clearfork formations. Smaller 5^{th}-order parasequences that are not identified make up the 4^{th}-order sequences (Figure 16). 5^{th}-order parasequences are not identifiable in petrophysical logs; cores are best to be used to identify 5^{th}-order parasequences. The typical facies of a cycle/sequence is a subtidal base consisting of mudstone-wackstone shallowing up into a subtidal skeletal/pelletal packestonegrainstone and capped by a muddy high frequency tidal flat facies that typically is overlain by eolian siltstone.

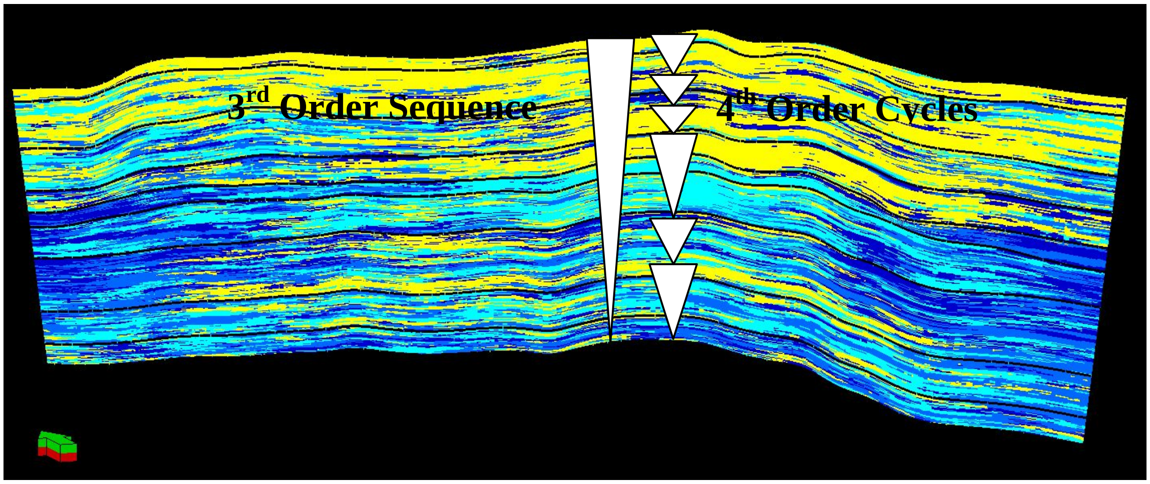

Figure 16. Sequences. Facies model cross section showing the larger 3rd-order sequence from the base of the Upper Clearfork to the top of the Glorieta Formation. A total of six 4th-order cycles were identified based on facies distribution. Tidal flat facies are shown in yellow and subtidal facies are shown in different shades of blue (Table 2).

SUMMARY

The Glorieta and the Upper Clearfork formation reservoirs at Monahans Field are heterogeneous and contain facies that compartmentalize the reservoir into multiple flow units that make production difficult. Identifying flow units within these units can yield higher volumes of hydrocarbons with the aid of new drilling techniques, reservoir stimulation, and completion techniques.

Eolian Siltstone Compartments

The occurrence of tight siltstone units within the reservoir at Monahans Field creates production and injection problems due to non-communication between reservoir flow units. Siltstone creates different compartments within the reservoir and make it difficult to effectively sweep the hydrocarbons from the reservoir. Attempting to sweep the hydrocarbons from the reservoir is done by injecting water into the reservoir to create an artificial water front to push the oil to producing wells in the field. If these compartments are effectively located to determine their lateral extent, then horizontal drilling, preferential injection, or down spacing (infill wells) can yield a higher volume of hydrocarbons. The Glorieta Formation reservoir in Monahans Field is the zone that has the highest production yet it is also the zone that has the largest volumes of tidal flat siltstone; which in turn creates a large number of reservoir compartments (Figure 17). The porosity development in the Glorieta Formation is diagenetically induced from secondary processes (Montgomery, 1998). Anhydrite has filled pores and pore throats in the reservoir and also was dissolved to create vuggy, moldic, and intercrystalline porosity (Montgomery, 1998). These porosity types and the siltstone units compartmentalizing the reservoir do not allow for optimal oil migration. Horizontal drilling coupled with artificially fracturing the reservoir to create pathways for oil to migrate along and preferentially injecting water into the individual compartments will enhance production volumes.

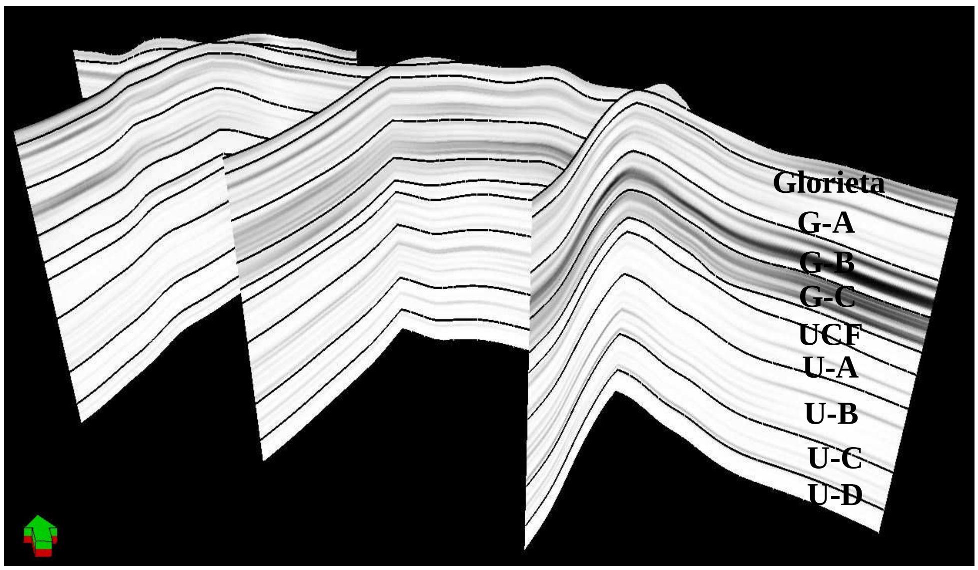

Figure 17. Siltstone model. Siltstones are displayed in black versus the non-siltstone rock in white. Reservoir is highly compartmentalized creating production problems.

Preferential Injection

The wells in Monahans Field are top set; meaning that the casing in the well stops at the top of the formation and the rest of the well bore is open to the reservoir. Water is injected downhole and moves laterally into the reservoir once it passes the base of the casing. The majority of the porosity is in the uppermost part of the Glorieta Formation. This could be the part of the reservoir that the majority of the water flows through. Injection profiles need to be analyzed in order to determine if the majority of the water is entering the uppermost part of the Glorieta Formation where the porosity exists. The highest porosity zones in the upper portion of the Glorieta Formation occur in the northwestern portion of the field (Figure 18). The water likely enters the Glorieta Formation and flows laterally through the reservoir.

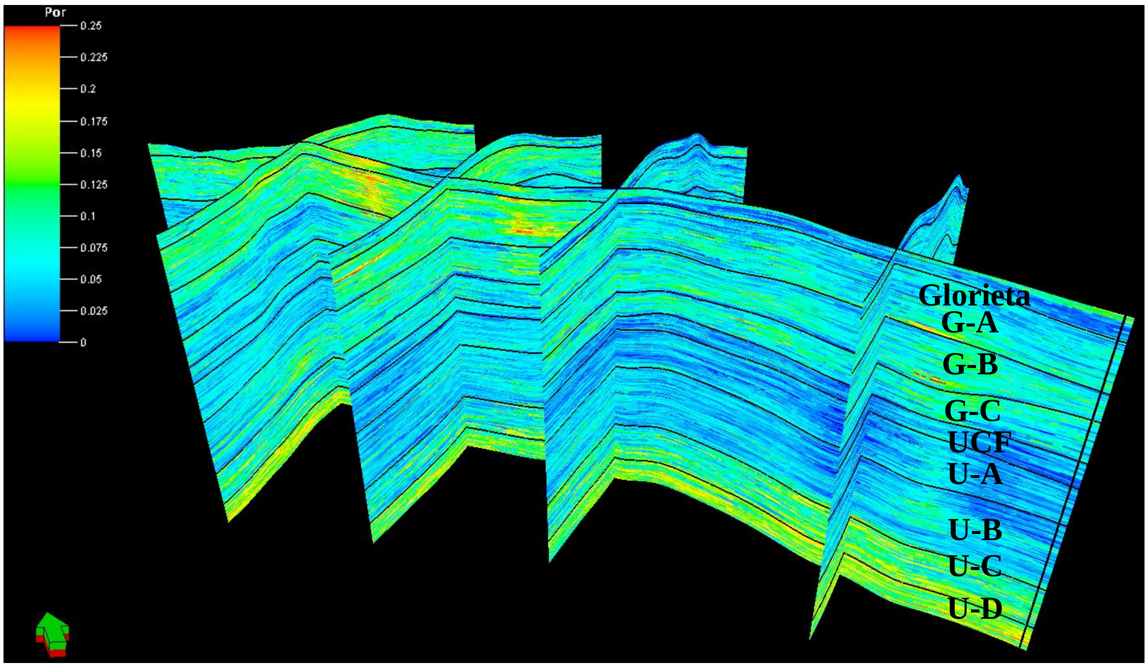

Figure 18. Porosity model. The majority of the porous zones are located in the upper part of the Glorieta Formation towards the northwestern part of the field. Could be the zone were majority of the injected water in entering the reservoir.

The zones that are isolated by the interbedded eolian siltstone do not allow water to migrate through them to sweep the oil from the pores. If water was preferentially injected into the individual compartments by using wellbore liners in the injection wells that penetrate the compartments then the remaining oil could possibly be produced. Liners are installed by hanging smaller diameter pipe on the bottom of the casing. This will act as if the entire well bore is cased to TD. Perforations can be made in the liners to allow water to enter the reservoir at a specified location determine by the spectral gamma ray log to identify siltstone barriers. The water enters the reservoir and flows laterally where the reservoir rock will allow it (Figure 19). Well bore liners can be installed at the base of the already existing casing allowing for preferential injection into the multiple reservoir compartments. Multiple sets of perforations can be made in the casing to inject water into compartments at different levels in the reservoir (Figure 20).

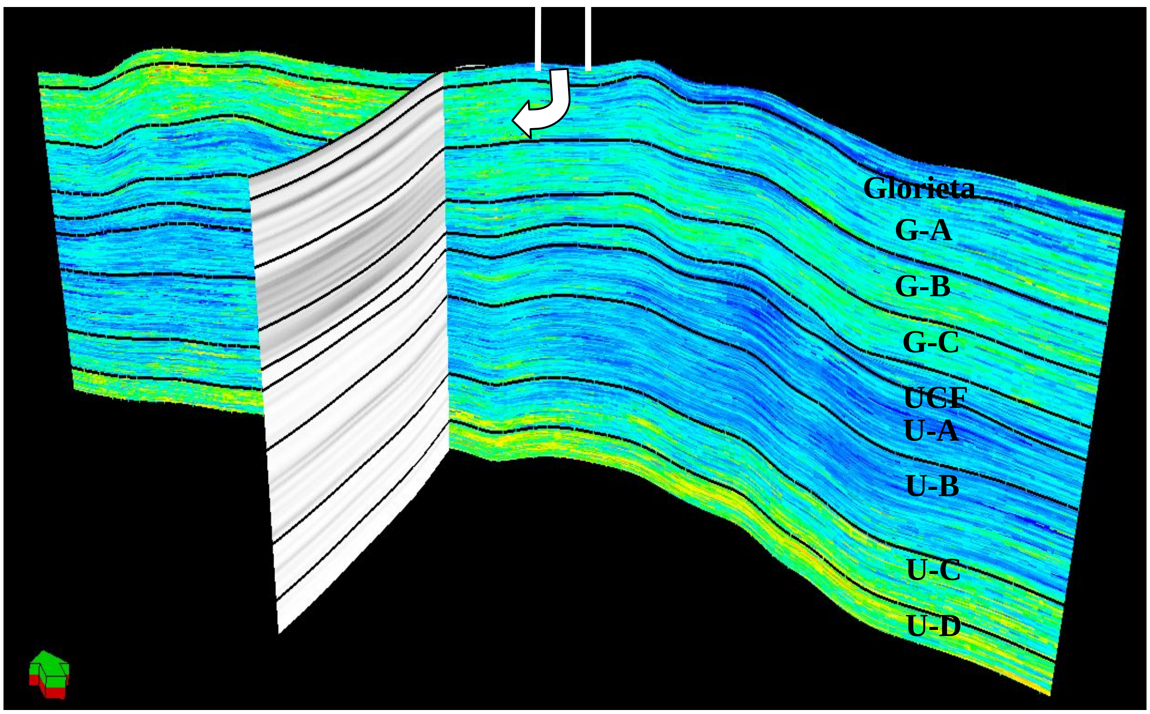

Figure 19. Top set casing. Figure shows how injected water enters the reservoir at the base of the casing and flows where porosity allows it to migrate. The Glorieta Formation is the zone where the majority of the porosity is located. This could mean majority of the water is entering this formation and not interacting with the rest of the reservoir.

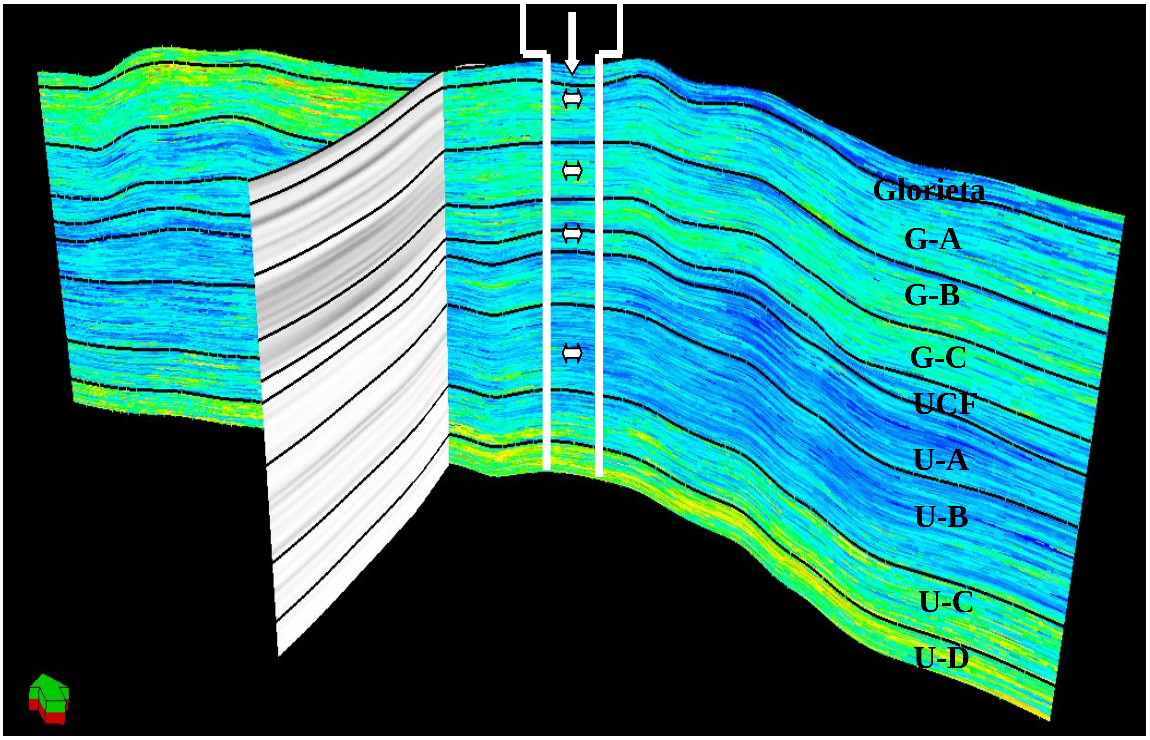

Figure 20. Well bore liners. Well bore liner installed allows for preferential injection. Perforations can be made in the liner within the individual flow units and remaining hydrocarbons can be swept.

Horizontal Drilling and Fracturing

The multiple flow units within the reservoir can be produced more effectively if horizontal drilling is applied (Figure 21). Extending the wellbore laterally through the compartments will give the wellbore more surface area to produce the remaining reserves. Multi-stage fracturing of the reservoir also can improve fluid flow from the reservoir to the production casing. If a large enough fracture stimulation is applied, multiple vertical and lateral reservoir compartments could possibly be connected (Figure 21).

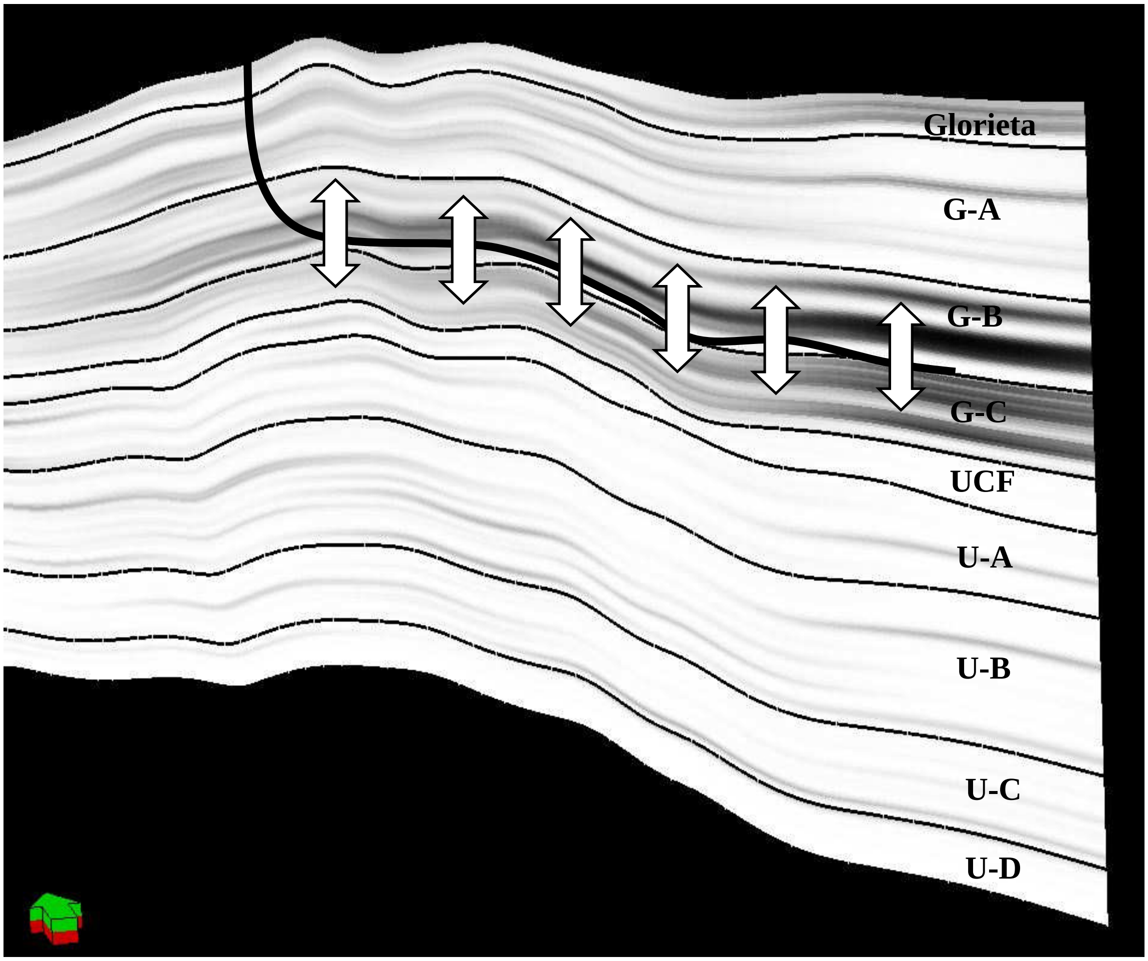

Figure 21. Horizontal well bore. Siltstone model displayed showing the siltstone in black and the non-siltstone in white. The figure shows the compartmentalization of the reservoir. Possible horizontal well bore and fracture pattern is displayed to ultimately connect multiple flow units.

Further Infill Drilling

North Robertson Unit is an analog field to Monahans that also produces from the Glorieta and Upper Clearfork formations (Montgomery, 1998). The field is located in southern Gaines County on the northeastern margin of the Central Basin Platform. The reservoir rocks were deposited in a similar depositional environment; a paleo-structural high or island that was created by prior faulting. The North Robertson Unit also contains interbedded siltstone, which in turn creates lateral discontinuities in reservoir facies (Montgomery, 1998). Two in depth studies determined individual flow units are associated with reservoir facies changes. The first study aimed to identify individual flow units to ultimately reduce the well spacing from 20-acre spacing down to 10-acre spacing (Montgomery, 1998). A total of 14 producing wells and 4 injector wells were drilled after the study was complete and production was increased exponentially. The second study was aimed to identify different pore types, flow units, rock types, flow capacity, and the remaining reserves within the reservoirs. The study concluded that a total of seven different pore types were identified based on pore size, connectivity, pore shape, coordination number, and the aspect ratio (Montgomery et al., 1998). The individual flow units within the Glorieta and the Upper Clearfork Formations in Monahans Field are similar to the characteristics of the reservoir rocks at North Robertson Unit. The model created for this project and the flow units depicted could allow for further infill drilling to be done on the field to maximize separate flow units to increase reserves and production.

Data Required

Three dimensional property models were created for the purpose of this research. In order to efficiently sweep the remaining hydrocarbons from the reservoir at Monahans Field, more data is required. Production data coupled with injection profiles could help determine where the injected water is entering and being produced from the reservoir. The injection profiles will tell which zone in the reservoir is taking the water and the production data would give the zones in the field where the injected water is being produced from. Analyzing the data would yield an answer for the injected water thief zones in the field. These models will be used to run simulations on the reservoir to determine the flow characteristics of the Upper Clearfork and Glorieta formations.

Conclusions

The Permian Glorieta and Upper Clearfork formation reservoirs of Monahans Field, Texas are laterally and vertically heterogeneous due to facies changes. The facies changes and the eolian silts that were deposited during sea level falls created multiple isolated flow units within the reservoir. Models of facies, porosity, and siltstone distribution in the Permian Glorieta and Upper Clearfork formations were generated in Petrel® to better characterize the Monahans Field reservoir. The facies model indicates that during deposition a tectonically uplifted area (island) influenced sedimentation allowing for the preferential deposition of tidal flat facies that cap 3rd through 5th order sequences and parasequences. Porosity occurs throughout the field but is greatest in the supratidal facies in the northwest margin of the field due to secondary diagenetic enhancement of porosity. Tight eolian siltstone, that prograded across the CBP when sea level was low compartmentalized the reservoir in many isolated fluid flow units. Infill drilling, horizontal drilling, and fracturing may all provide mechanisms to recover more petroleum from this field.

REFERENCES CITED

Asquith, G., D. Krygowski, 2004, Basic Well Log Analysis: Second edition. Tulsa, Oklahoma, AAPG, 244 p.

Atchley, S.C., M.G. Kozar, L.A. Yose, 1999, A predicitve model for reservoir distribution in the Permian (Leonardian) Clearfork and Glorieta Formations, Robertson field area, West Texas. AAPG Bulletin, v. 83, no. 7, p. 1031-1056.

DiMichele, W. A., D. S. Chaney, W. H. Dixon, W. J. Nelson, R. W. Hook, 2000, An early Permian coastal flora from the Central Basin Platform of Gaines County, West Texas, PALAIOS, v. 15, no. 6, p. 524-534.

Dorobek, S. L., 1995, Synorogenic carbonate platforms and reefs in foreland basins: controls on stratigraphic evolution and platform / reef morphology, *in* Dorobek, S. L., G. M. Ross, Stratigraphic evolution of foreland basins: SEPM Special Publication 52, p. 127-145.

Dowling, P. L., 1970, Application of carbonate environmental concepts to secondary recovery projects, Society of Petroleum Engineers, SPE Special Publication 2987, p. 1-4.

Dutton, S.P., Kim, E.M., Broadhead, R.F., Breton, C.L., Raatz, W.D., Ruppel, S.C., and Kerans, Charles, 2005, Play analysis and digital portfolio of major oil reservoirs in the Permian Basin: The University of Texas at Austin, Bureau of Economic Geology Report of Investigations no. 271, 287 p., CD-ROM.

Hendrick, C.L., S.L. Dorobek, S.C. Ruppel, 1993, Sequence stratigraphy, diagenesis, and porosity / permeability distribution in Permian carbonate reservoirs, Monahans Field, West Texas. AAPG Search and Discovery Article #90987.

IHS Energy Group., 2010, Petroleum Information/Dwights Plus Information Database, 15 Inverness Way East, Englewood, CO 80112-5710.

Landreth, R. A., 1977, Depositional environments and diagenesis of the Lower Clear Fork Group, Mitchell County, Texas. Thesis in geoscience, Texas Tech University, Lubbock, Texas, 79 p.

Montgomery, S. L., 1998, Permian Clear Fork group, North Robertson unit: Integrated reservoir management and characterization for infill drill, part I-geological analysis, AAPG Bulletin, v. 82, no. 10, p. 1797-1814.

Montgomery, S. L., D. K. Davies, R. K. Vessell, J. E. Kamis, W. H. Dixon, 1998, Permian Clear Fork group, North Robertson unit: Integrated reservoir management and characterization for infill drill, part II-petrophysical and engineering data, AAPG Bulletin, v. 82, no. 11, p. 1985-2002.

Ruppel, S. C., 1992, Styles of deposition and diagenesis in Leonardian carbonate reservoirs in West Texas: Implications for improved reservoir characterization, Society of Petroleum Engineers, SPE Special Publication 24691, p. 313-320.

Ruppel, S. C., 1994, Oil & gas fields in West Texas: West Texas Geological Society, v. 6, p. 195-202.

Saha, S. 1992, Petrophysical study of the Glorieta-Clearfork dolomite in the Monahans field, Ward County, Texas, Dissertation in geoscience, Texas Tech University, Lubbock, Texas, 98 p.

Schlumberger, 2010, Petrel 2010 introduction G & G manual, Schlumberger Technology Corporation Three Allen Center, Suite 1900, 333 Clay St, Houston, Texas 77002, USA.

Shumaker, R. C., 1992, Paleozoic structure of the central basin uplift and adjacent Delaware basin, West Texas: AAPG Bulletin, v. 76, n. 11, p. 1804-1824.

Yang, K-M. and S. L. Dorobek, 1995a, The Permian Basin of West Texas and New Mexico: Flexural modeling and evidence for lithospheric heterogeneity across the Marathon foreland, *in* Dorobek, S. L., G. M. Ross, Stratigraphic evolution of foreland basins: SEPM Special Publication 52, p. 37-50.

Yang, K-M. and S. L. Dorobek, 1995b, The Permian Basin of West Texas and New Mexico: Tectonic history of a “composite” foreland basin and its effects on stratigraphic development, *in* Dorobek, S. L., G. M. Ross, Stratigraphic evolution of foreland basins: SEPM Special Publication 52, p. 149-173.

VITA

Name:	Ryan David Yeatman
Address:	Department of Geology and Geophysics, MS 3115 Texas A&M University College Station, Texas 77843-3115
Email Address:	yeat8@neo.tamu.edu

Education:	B.S. Geology, Texas A&M University, 2008. M.S. Geology, Texas A&M University, 2011.