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Data Integration and Reservoir Characterization of the Pennsylvanian Bartlesville Sandstone

Caroline Vance O'Keefe
University of Arkansas, Fayetteville

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A thesis submitted in partial fulfillment
of the requirements for the degree of
Master of Science in Geology

By

Caroline Vance O'Keefe
Washington and Lee University
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ABSTRACT

The Glenn Pool Oil Field of Northeastern Oklahoma was established as the first major oil discovery of the fledgling state of Oklahoma. Fully developed by 1912, the field is now nearing depletion even under secondary and tertiary recovery efforts after production for approximately 100 years. Large amounts of residual oil estimated to still be in place have motivated exploration into other recovery methods, including polymer flooding and horizontal drilling. Success of these programs is dependent upon accurate characterization of the reservoir. Because most of the drilling occurred many decades ago, much of the data associated with this field predates electric well logging and has not been integrated with contemporary databases.

To establish a more accurate characterization of the reservoir, these data have been digitized and integrated with current data available to further delineate the Glenn Pool Reservoir. Using information from original drilling records, surveyed well locations, water flood studies, and historical maps, a more sharply defined characterization has been generated for the productive Bartlesville, or Glenn Pool, Sandstone.

This thesis is approved for recommendation
to the Graduate Council.

Thesis Director:

____
Dr. Doy Zachry

Thesis Committee:

____
Dr. Xiangyang Xie

____
Dr. Jackson Cothren

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I. INTRODUCTION

A. PURPOSE

The purpose of this study of the Pennsylvanian Bartlesville Sandstone in the Crow Unit of the Glenn Pool Field is to establish a more accurate understanding of the productive reservoir within the unit. Modern data readily available digitally represents only a small portion of the total data available over the area. Integration of historical data into the existing modern data set enhances the accuracy of the reservoir characterization.

B. GEOLOGIC SETTING

The Glenn Pool Oil Field of northeastern Oklahoma is located within the geologic province known as the Cherokee, or Northeastern Oklahoma, Platform. The Platform extends from southeastern Kansas down the eastern half of Oklahoma. It is bound to the west by the Nemaha Ridge and the Anadarko Basin beyond the ridge, to the Ozark Uplift to the east, and to the south by the Arkoma Basin and the Ouachita Mountains south of the Basin as shown in Figure 1 (Ye, Kerr, and Yang 1999).

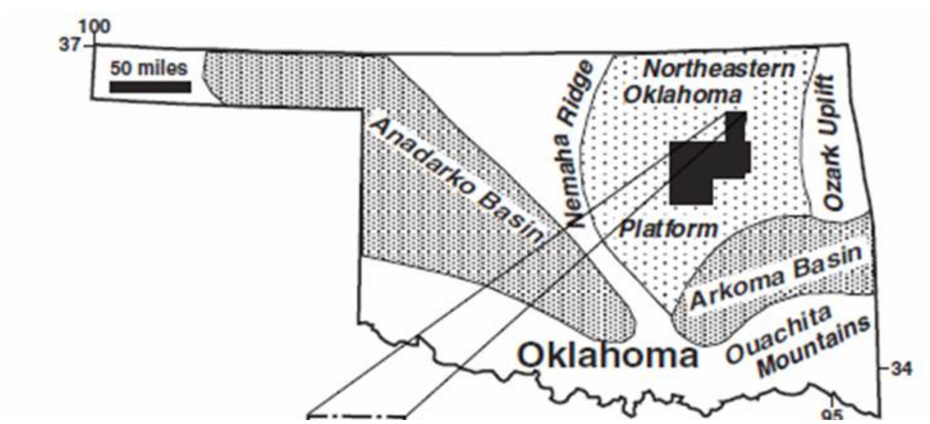

Figure 1. Location of Glenn Pool Field with surrounding geologic features. (Modified from Ye, Kerr, and Yang 1999)

Wells drilled in the Glenn Pool Field produce from Middle Pennsylvanian section of rocks. The Pennsylvanian age in northeastern Oklahoma represents a period of geologic change with the final stages of overthrusting of the Ouachita Mountains and the subsidence of the Arkoma Basin (Johnson 2008). Figure 2 below illustrates the rock types developed in the region during this time period.

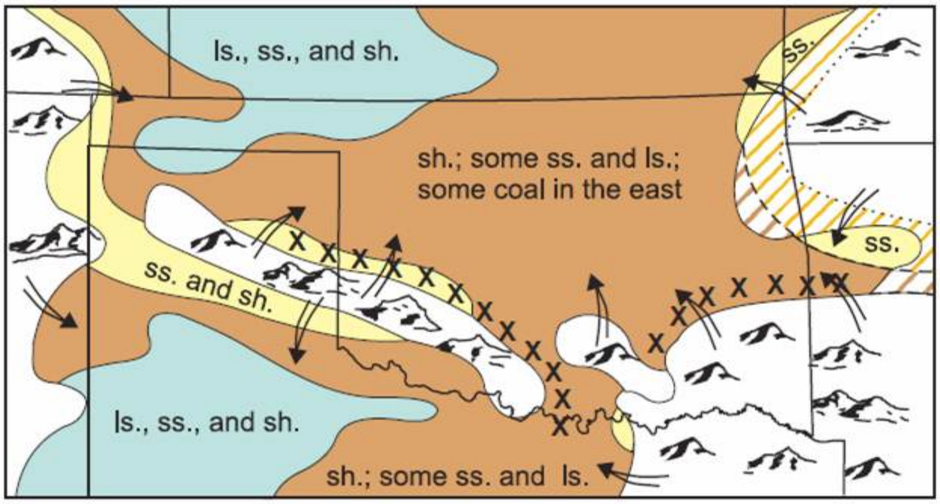

Figure 2. Principal rock types of Middle Pennsylvanian (Desmoinesian) age in Oklahoma (Modified from Johnson 2008).

C. PREVIOUS STUDIES

The Glenn Pool field has been studied over extensive period of time by various groups. Through these studies, the depositional model for the field has been altered and refined. The first studies addressing the depositional origin of the Bartlesville Sandstone attributed them to offshore marine deposits resulting in “shoe-string”, parallel sand bodies with rounded tops and flat bases (Bass 1936). Further drilling development in the field disproved this theory.

In the late 1960's and early 1970's, investigations were conducted by Glenn Visher and associates from the University of Tulsa. Their body of work examined both the subsurface and various outcrops to investigate a framework of a fluvial deltaic depositional system extending from southeastern Kansas down into the Arkoma Basin. They believed that a drop in sea level led to incision into underlying formations and the development of a large valley. The Bartlesville Sandstone represented the subsequent filling of the valley by the delta developed in the region. The study suggested a single regressive sequence during which the delta transitioned from north to the south-southeast from alluvial valley, to upper deltaic plain, to lower deltaic plain, to channel mouth bars (Visher 1968). Figure 3 illustrates Visher's interpretation.

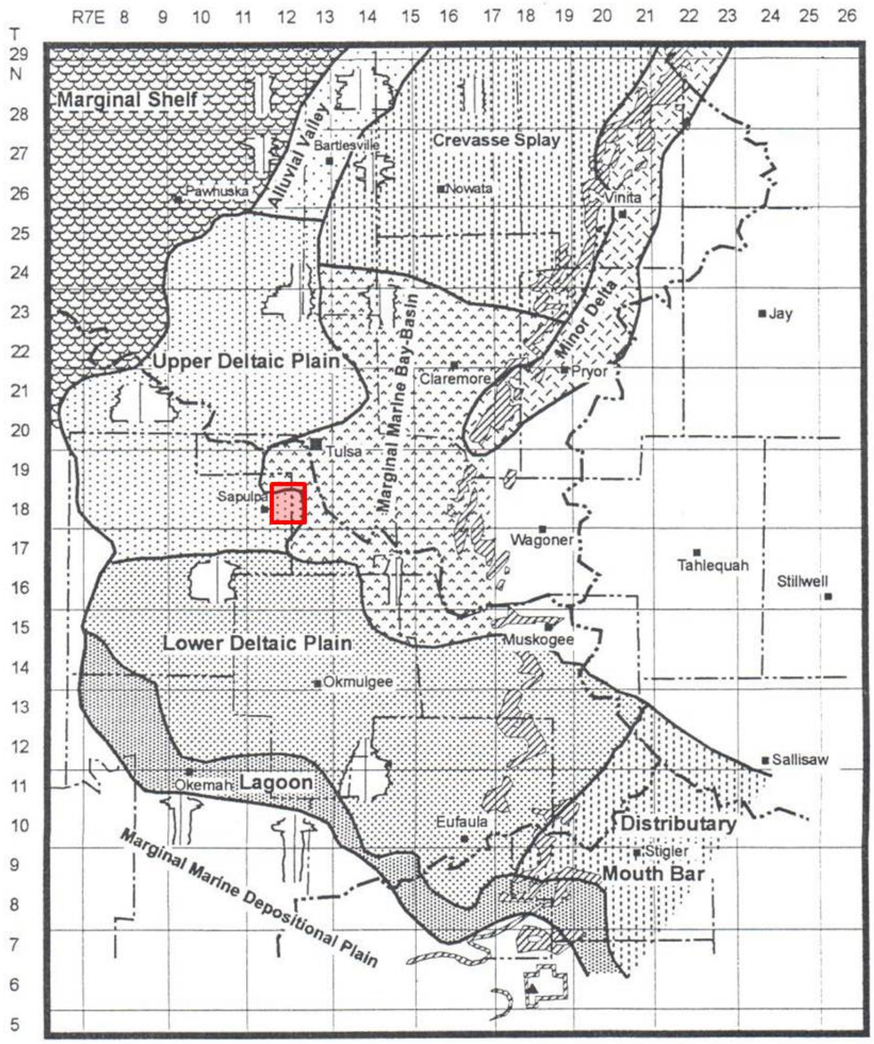

Figure 3. Middle Pennsylvanian environmental reconstruction with Glenn Pool Field highlighted (Modified from Visher, G., 1968)

The need for a more accurate reservoir characterization of the Bartlesville Sandstone within the Glenn Pool field led to investigation of the highly variable sand. Kuykendall and Matson divided the Bartlesville sand into 3 separate units: Upper, Middle, and Lower. Each of these units is separated by a nonporous break (Kuykendall and Matson 1992). These sands are highly variable laterally and represented a complicated, channelized depositional system.

More detailed reservoir characterization began in the early 1990's with the idea of discrete genetic intervals (DGIs) applied to the Bartlesville Sandstone. Liangmiao Ye and Dennis Kerr of the University of Tulsa integrated core data, well logs, outcrop observations, and borehole imagery to construct a depositional model with seven DGIs (Ye 1997 thesis). These DGIs are thought to effect to the stratigraphic hydrocarbon movement and concentration.

D. STRATIGRAPHY

The productive Bartlesville Sandstone is a member of the Boggy Formation of the Krebs Group. The Krebs Group is included within the Cherokee Group of the Desmoinesian Series of the middle Pennsylvanian. The Bartlesville Sandstone, indicated in Figure 4 below, is known formally as the Bluejacket Sandstone in outcrop, informally as the Bartlesville Sandstone in the subsurface, and within the Glenn Pool Field as the Glenn Sand (Kuykendall and Matson 1992).

The Bartlesville Sandstone is typically overlain by the Inola Limestone and underlain by the Brown Limestone. Overall thickness of the unit occurs at the expense of the underlying Savanna Shale unit suggesting incision into and, in some cases, subaerial exposure of the shale. This relationship supports the designation of the Bartlesville Sandstone as an incised valley fill depositional system (Ye and Kerr 2000).

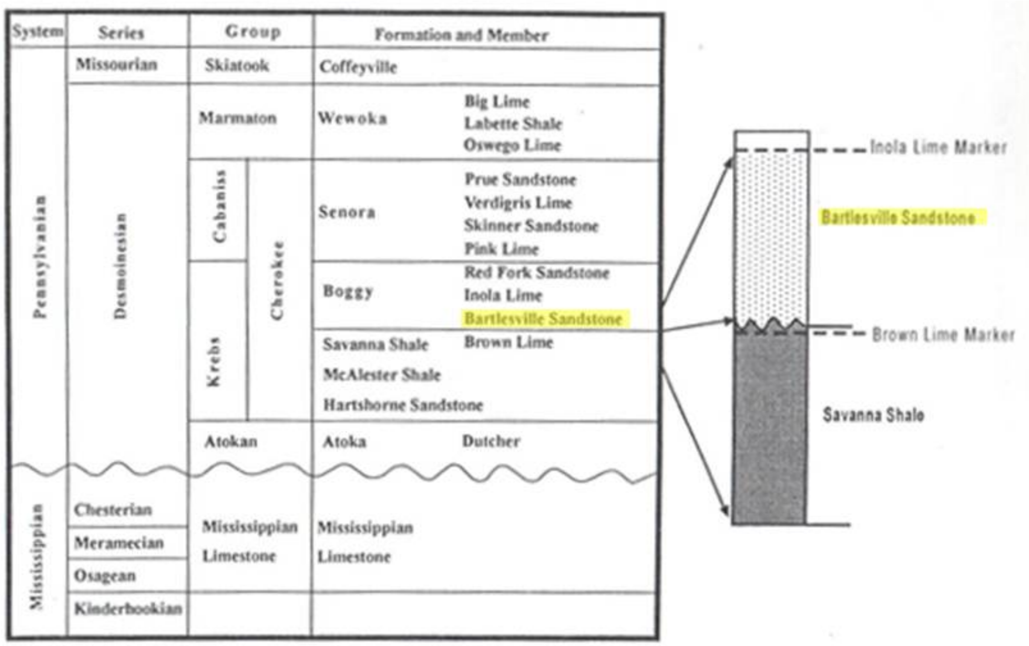

Figure 4. Stratigraphic Column of the Cherokee Platform of northeastern Oklahoma. (Modified from Ye 1997)

Within the study area, the Glenn Pool sandstone was originally considered to be 2 distinct systems and is therefore sometimes identified as separate Glenn I and Glenn II units in historical records (Finley 1967). The Glenn I sand refers to the upper portion of the Bartlesville Sand package and the Glenn II sand refers to the lower portion. These two separate groupings were tied to the model of seven DGIs (Ye 1997) by associating the lower sand package with the lowstand system track (LST) DGIs from sea level regression and the upper sand package with the transgressive system track (TST) DGIs from sea level rise (Ye, Kerr, and Yang 1999).

The upper Glenn I sandstone represents a meandering fluvial system (Ye and Kerr 2000) associated lower reaches of a fluvial deltaic system where a lower gradient leads to sinuous channels (Prothero and Schwab 2004). The sand is well-sorted, medium grained, and maintains good porosity and permeability across the unit. According to the original mapping done in the development of the Union Oil Company of California (UNOCAL) water flood study, the Glenn I pinches out to the northeast along a line from the center of the north line of section 5 to the southeast quarter of section 4, as seen in Figure 5 (Finley 1967).

The lower Glenn II sandstone represents a braided fluvial deposition (Ye and Kerr 2000) usually associated with upper reaches of a deltaic system where the sediment load exceeds the carrying capacity of the discharge (Prothero and Schwab 2004). The Glenn II is a fine-grained, dirtier sand with multiple shale laminations and lacking the favorable porosity and permeability of the Glenn I Sand (Finley 1967).

For the purposes of this study, the Glenn I and II Sands are treated as one cohesive sandstone package.

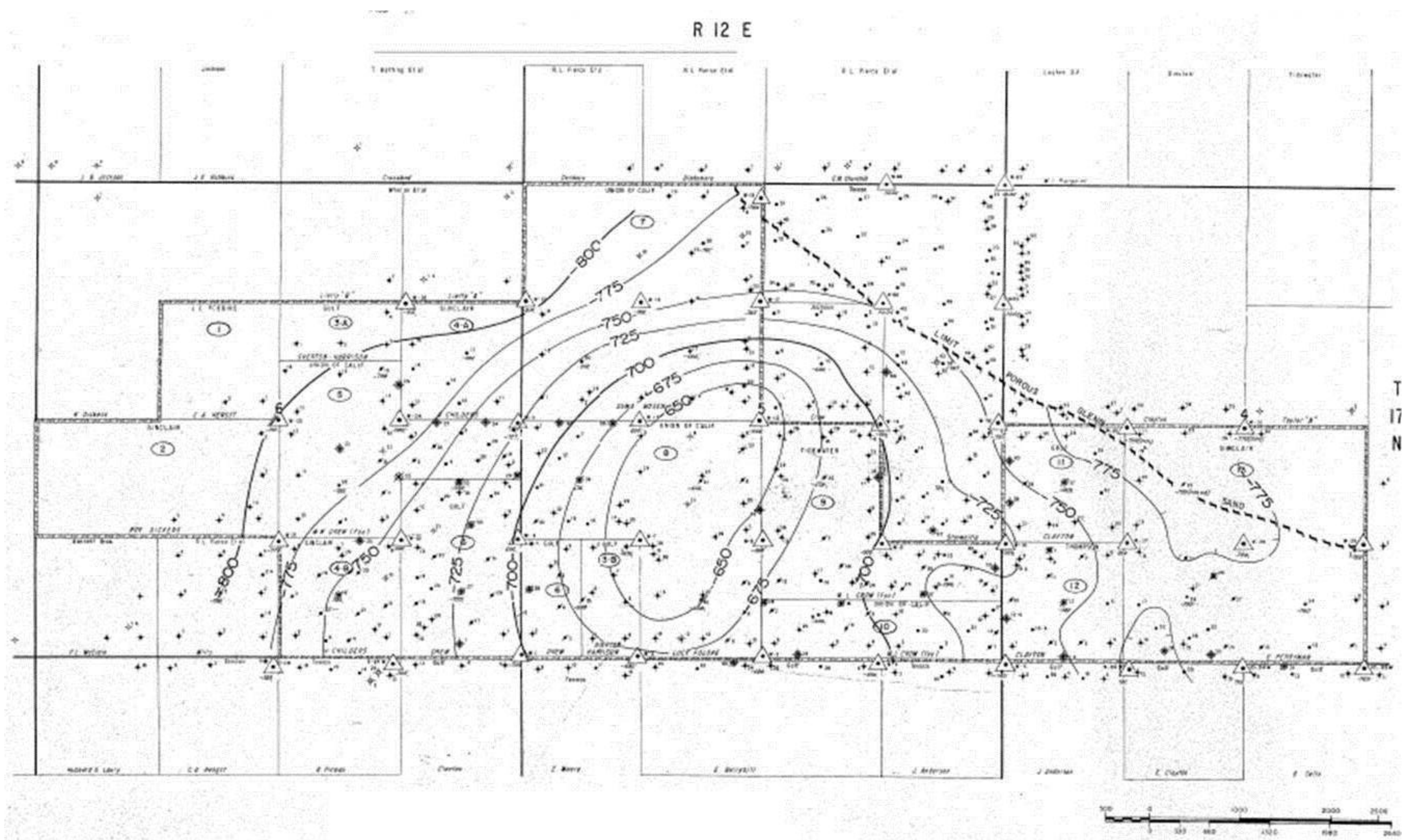

Figure 5. Structural Map of Glenn Pool I Sand from UNOCAL water flood showing pinchout in northeastern portion of study area.

The Glenn Pool sand package is typically correlated using two limestones from higher in the stratigraphic column which are both laterally pervasive. The most easily recognizable in electric well logs is the Big Lime of the upper Marmaton Group which is a thicker limestone interval and the Oswego Lime of the lower Marmaton Group which is a thinner limestone interval (Finley 1967). Figure 6 below is the type log for the Crow Unit of the Glenn Pool with the Big Lime, Oswego Lime, and Glenn Sand Package annotated.

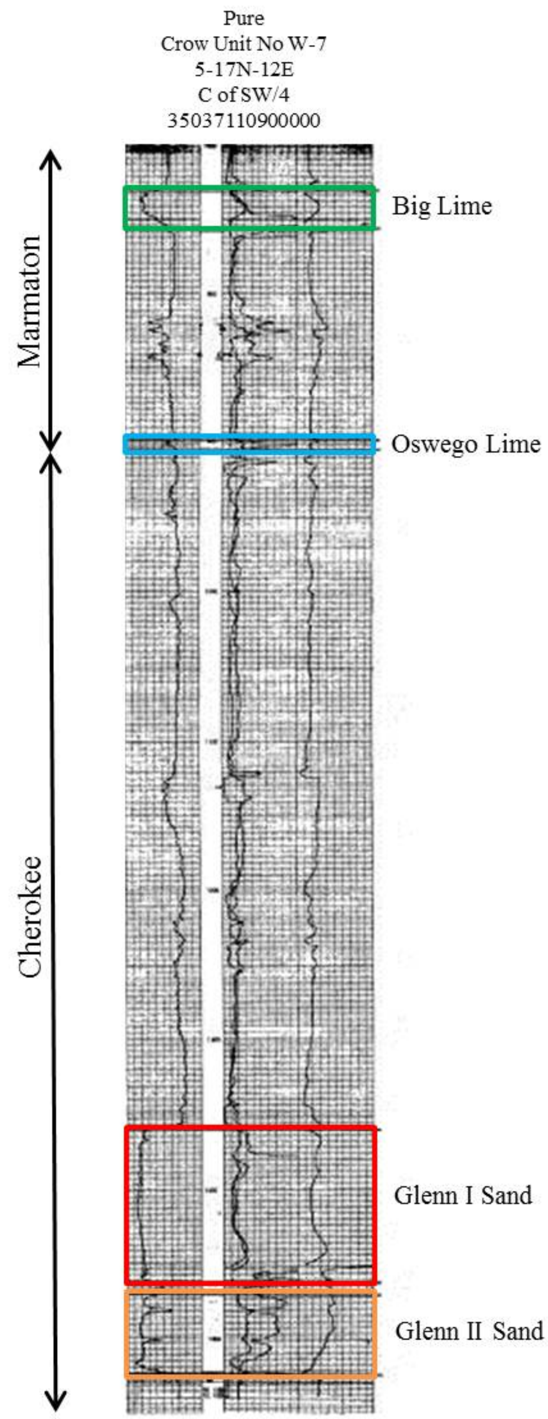

Figure 6. Type log for Crow Unit of the Glenn Pool Field. Well API #35037110900000 located in center of SW1/4 Section 5 (Modified from Finley 1967).

E. STRUCTURE

During the depositional time period of the Bartlesville sand, the Cherokee Platform had a structural dip to the east-southeast in the direction of the subsiding Arkoma basin. The Arbuckle Orogeny in the late Pennsylvanian reversed this dip to the west. The present-day monoclonal dip to the west is due to uplifting during the Jurassic and Cretaceous. The overall regional dip occurs at a rate of 35 to 50 feet per mile. The directional change of dip led to the development of small domal structures (Kuykendall and Matson 1992). Structural maps of the top of both the Glenn I and Glenn II sands exhibit the localized domal structure centered in section 5 (Finley 1967).

F. FIELD HISTORY

The Glenn Pool Oil Field is a well-known historic oil field located in Northeastern Oklahoma approximately 10 miles south of Tulsa. The field straddles the county line between Creek and Tulsa Counties and encompasses approximately 43 square miles. Figure 7 indicates the location of the Glenn Pool Oil Field of Oklahoma.

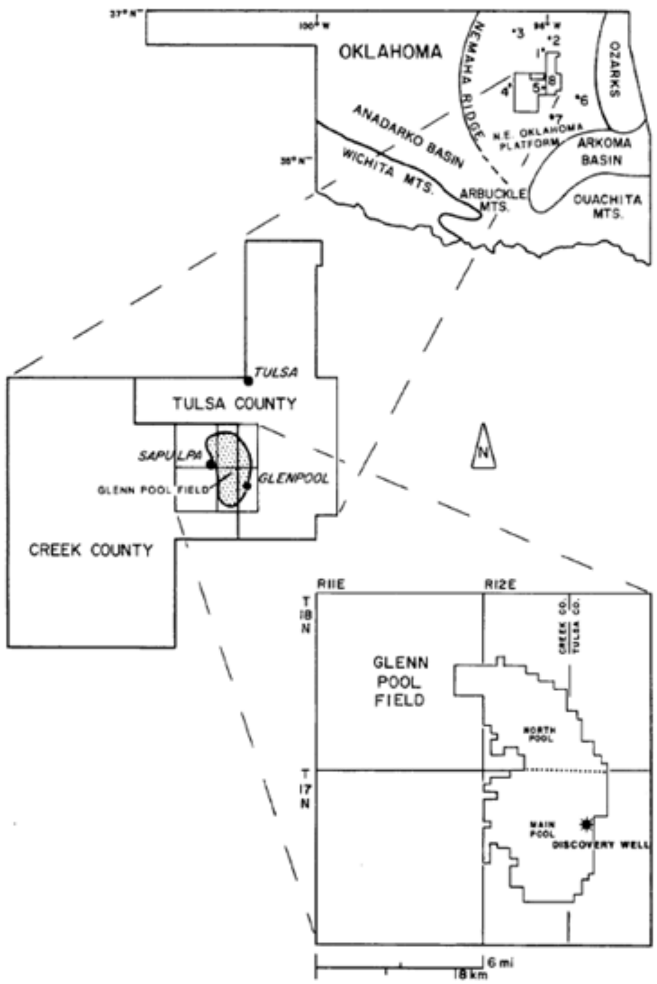

Figure 7. Location map for the Glenn Pool Oil Field in relation to the state of Oklahoma (modified from Kuykendall and Matson 1992).

Discovered in 1905 by wildcatters Robert Galbreath and Frank Chesley, the Glenn Pool Field soon became the first major oil field in the region that would be ratified as the state of Oklahoma in 1907 (Kuykendall and Matson 1992). The first successfully completed well in the field was named the Ida Glenn #1 after the Creek Indian woman from whom Galbreath and Chesley had leased the land. The well was completed in the Pennsylvanian Bartlesville Sandstone which was named the Glenn Sand within the area of the Glenn Pool Field. The Glenn Sand sits stratigraphically below the Red Forks sand, which was the normal target interval for the area. Late night drilling and lack of sleep led to a deepening of the well beyond the Red Forks sand and resulted in the discovery of the productively superior Bartlesville or Glenn Sand (History of the Oil Boom 2012).

Upon completion, the well flowed at a rate of 75 barrels of oil per day (BOPD). A second and third well were drilled to the South and North, respectively, of the Ida Glenn #1 and came on at a rate of 800 BOPD and 1600 BOPD. A forth well was drilled to the East of the #1 and was determined to be a dry hole, establishing the eastern edge of the field. Many more wells were subsequently drilled and the lateral extents of the field were quickly established. By 1907 the field was well established and reached a peak production of 117,000 BOPD derived from the Glenn Sand at an average depth of approximately 1500 ft (Kuykendall and Matson 1992).

To date, the Glenn Pool Oil Field has produced an estimated 330 million barrels of oil from approximately 750 active wells producing a yearly cumulative production of more than 1 million barrels of oil (MMBO). It is believed the field will ultimately yield more than 400 MMBO (Kuykendall and Matson 1992). The Glenn Sand interval is also productive in several other nearby fields, including the Avant, Bartlesville, Burbank, Cushing, Muskogee, Okmulgee, and Red Fork. Figure 8 shows the regional distribution of these other fields.

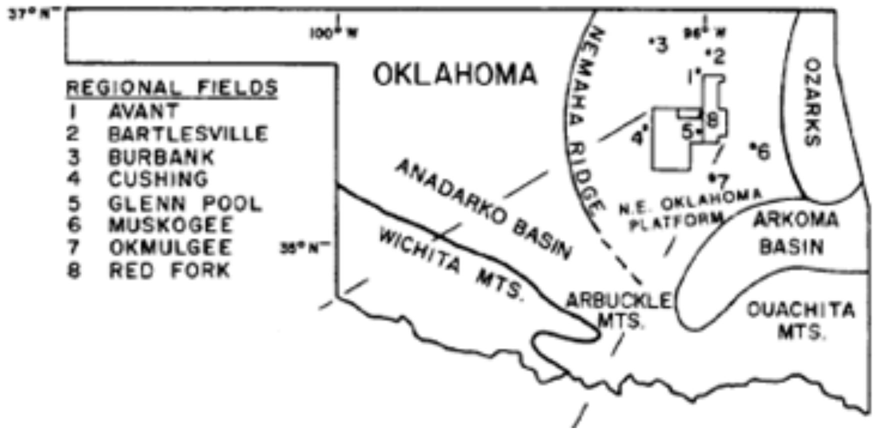

Figure 8. Location map of oil fields producing from the Bartlesville Sandstone. Modified from Kuykendall and Matson 1992).

The success of the Glenn Pool Field compared to surrounding areas is attributed in part to the 240 ft. of productive oil column, unique to the Glenn Pool. Secondary recovery efforts using gas injection began in the 1940's, followed by the development of water-flooding programs in the early 1960's. All were only sporadically successful (Finley 1967). Currently the field is undergoing stimulation through polymer flooding programs (Bae 1995).

G. UNIT HISTORY

The focus of this study is the Crow Unit, located in the west-central portion of the Glenn Pool Field as indicated in Figure 9.

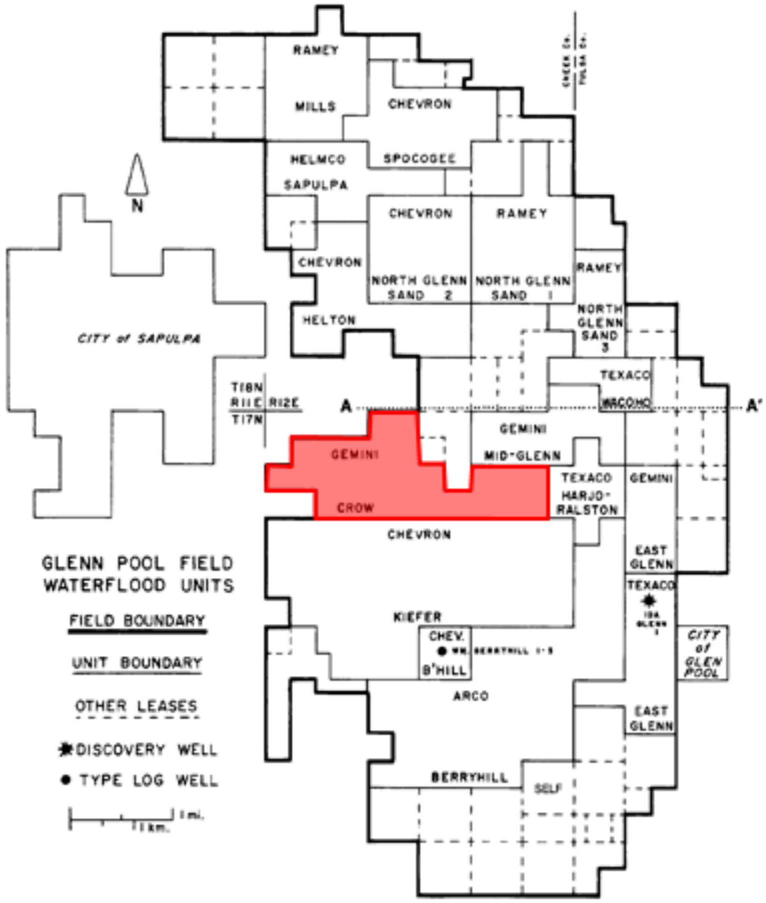

Figure 9. Water flood units in the Glenn Pool Oil Field. Crow Unit highlighted in red. (Modified from Kuykendall and Matson 1992).

The Crow Unit is located in sections 4, 5, and 6 of T17N, R12E and covers 3.25 square miles. The unit is comprised of 15 individual tracts which were later unitized in preparation for water flooding by Unocal. Wells within the Crow Unit have been productive since 1906 producing primarily out of the Glenn Sand.

Recovery efforts beyond initial completion have included steam flooding, gas injection, and water flooding which was the most effective to date (Finley 1967). The Crow Unit is of interest as a candidate for Micelar Polymer Flooding used in the William Berryhill Unit directly to the south (Crawford and Crawford 1985) and also as a candidate for horizontal drilling used in the

Self Unit to the south east of the Crow Unit (Kelkar, Kerr, and Liner 1998). The geographical relationships of these three units is indicated in Figure 10.

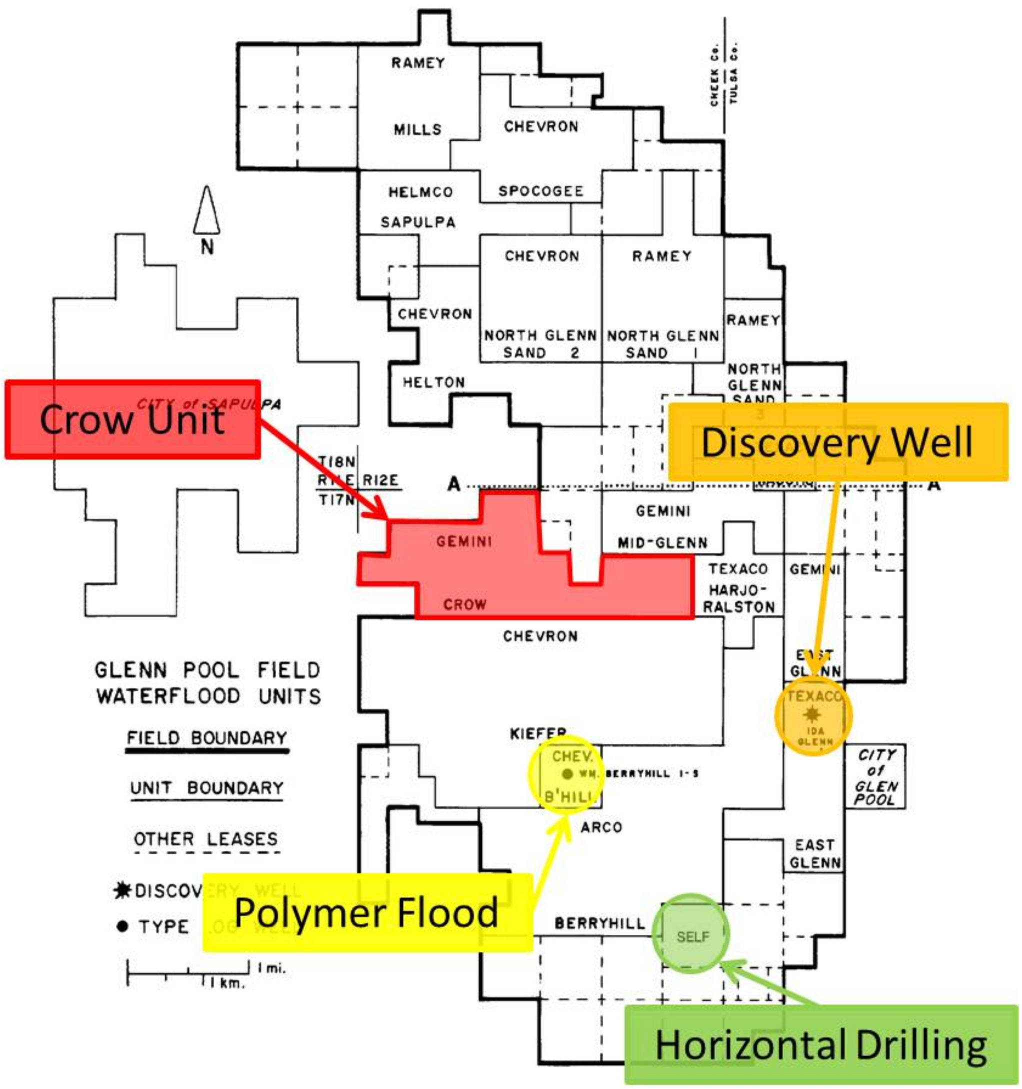

Figure 10. Location of quaternary recovery study units in the Glenn Pool Field. (Modified from Kuykendall and Matson 1992)

II. DATA SOURCES

Data for this study were provided through the generosity of Spyglass Energy of Tulsa, Oklahoma. These data included original drilling records, IHS data, surveyed well locations, raster logs, and water flood study information.

A. ORIGINAL DRILING RECORDS

The majority of the wells in the Glenn Pool Field were completed before the use of electric well logging, and as such, there exists only the original driller's logs for many of the wells within the Crow Unit of the Glenn Pool Field. These records were collected in the early 1960's during the unitization of the Crow Unit and are transcribed records from the logs of the original operating companies for each well.

Information contained in these drilling records is valuable, especially in the case that it is the only existing record of information for a particular well. The drilling records are sometimes exceptionally thorough, containing descriptions of lithology, hydrocarbon shows, and perforation or shot information. Many of the records, however, simply provide information on total drilling depth, datum elevation, and sometimes depths of formation tops. The location information provided on each of the records proved to be extremely valuable in correlating the historical record with an actual well location pinpointed on a map or stored in current era database through IHS, a global energy information company.

(Image included on accompanying disc)

Figure 11. Original drilling records data coverage.

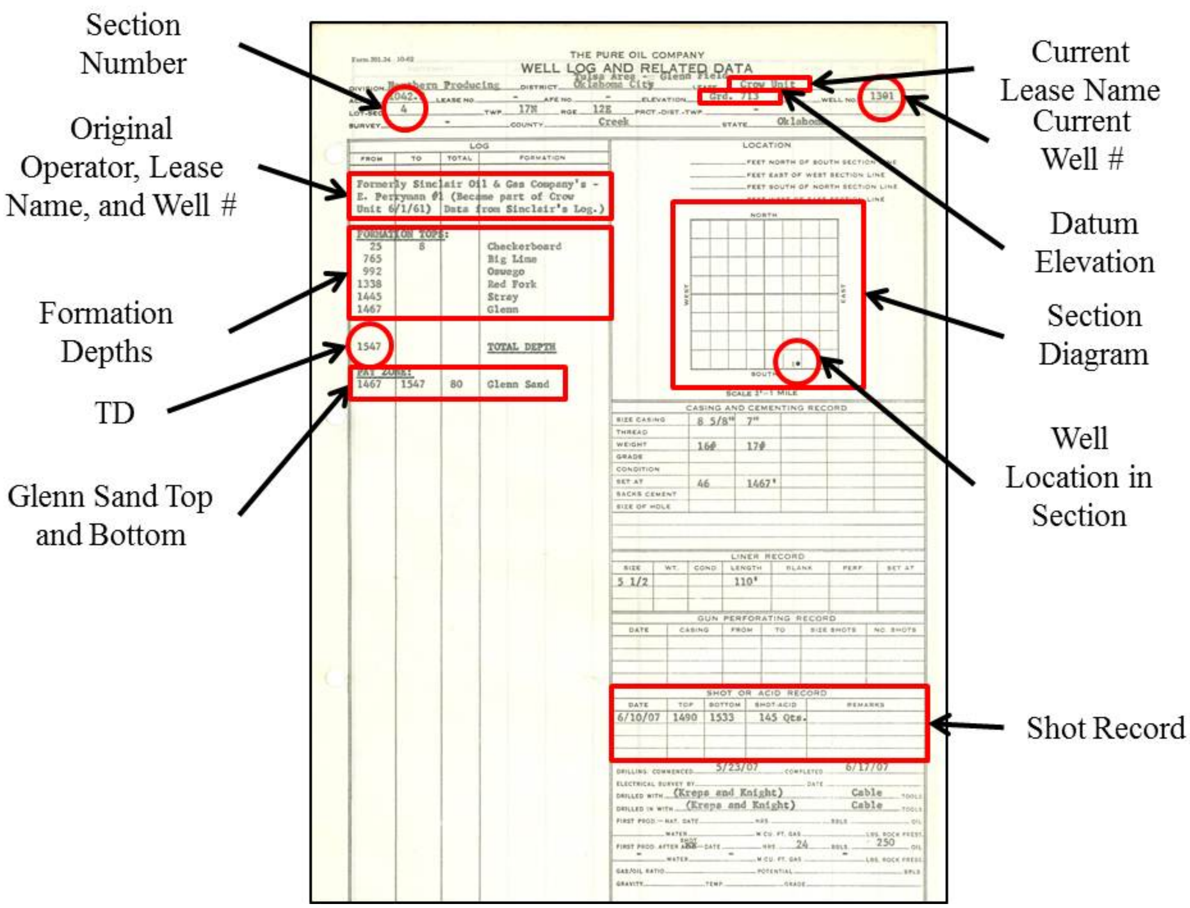

Figure 12. Example of original drilling record with available information highlighted.

B. IHS DATA

IHS is a global energy information company, which has compiled and can provide data associated with particular regions, fields, wells, and other relevant production information when available. The IHS data coverage over the Crow Unit area includes 327 data points (well spots) and provides information on specific American Petroleum Institute (API) numbers, operators, lease names, total depth, datum elevation, and location.

Although IHS provides information on more wells than any of the other well-data sources, the database was not always accurate or complete. It is based only on data provided by drillers and operators and has not been field-verified. It contains no information on formation tops, production, or lithology and can therefore serve only as a framework to pinpoint well locations and to relate original drilling records to API numbers. This was extremely valuable information, owing to the fact that most of the operator and lease names have changed over the years since each well was originally drilled.

(Image included on accompanying disc)

Figure 13. IHS data coverage.

C. SURVEYED WELL LOCATIONS

Spyglass Energy of Tulsa, OK surveyed ninety-two well locations within the Crow Unit. These surveys, completed in 2009, utilized real time kinematic (RTK) GPS technology which is accurate to within a centimeter. Ninety-two total well locations were surveyed. Locations were recorded as precise latitude and longitude coordinates; these were imported to a shapefile for integration with other relevant data over the area of the Crow Unit. These points provided information on exact well location and well number, which were correlated with both the original drilling records and IHS data to compile a more complete set of information for each well.

(Image included on accompanying disc)

Figure 14. Surveyed well locations.

D. RASTER LOGS

Modern raster images of electric logs are available for 38 wells in sections 4, 5, and 6 of T17N, R12E. Sixteen of the 38 wells are located within the Crow Unit. These wells were logged primarily during the development of the water flooding recovery efforts in the late 1950's to early 1960's. Most of these logs contain a spontaneous potential (SP) curve and a resistivity curve. A few also have micro logs and gamma-ray curves. Even with only the SP and resistivity curves, the Glenn Pool sand package can be delineated and provide information on the quality of the sand, lithology, thickness, etc.

(Image included on accompanying disc)

Figure 15. Raster logs data coverage.

E. UNOCAL PURE OIL WATER FLOOD STUDY

In 1961 UNOCAL conducted a water flood study of the Crow Unit. This study provided an enormous body of information, including structural maps, isopach maps, floodable sand maps, gas injection data, well status, injection and production data. That study generated 21 cross-sections utilizing 59 total wells.

The cross sections are valuable because they contain images of well logs that are not available from any other source. With this addition, the coverage of logged wells over the Crow Unit nearly tripled, from 38 to 92 wells. Figure 16 illustrates the original cross-section index map.

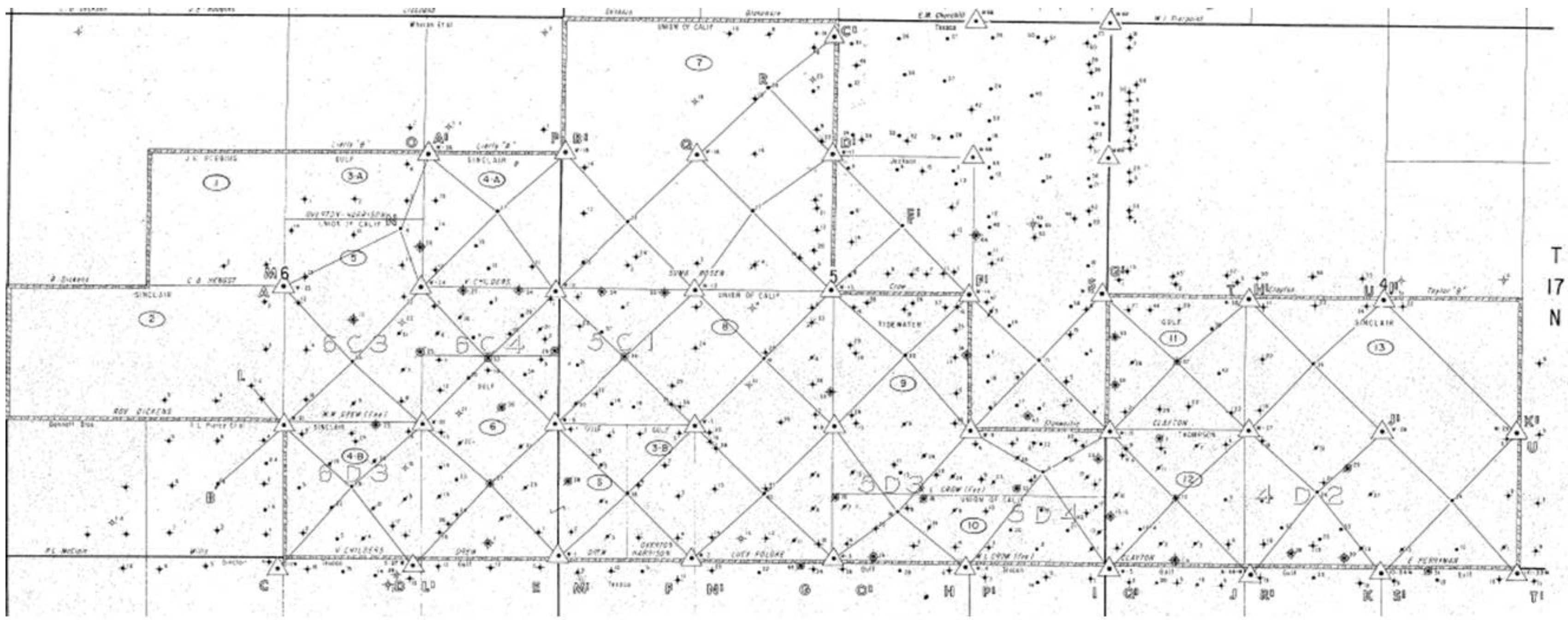

Figure 16. Cross section index map (Modified from UNOCAL Study)

III. METHODS

A. SOFTWARE USED

The integration of historical data was done primarily using 3 programs: ArcMap, Microsoft Excel, and Petra. A complete list of well locations was established using ArcMap, then exported to Excel for additional data integration from historical maps and logs, and finally imported into Petra for correlation and mapping.

B. WELL LOGS FROM WATER FLOOD STUDY

In compiling a complete study of the Crow Unit in preparation for water flooding, UNOCAL compiled 21 cross sections utilizing 59 electric well logs, as mentioned previously. Most of these well logs were not available in a digital format, and, as such, physical analog copies are of great value. The existing physical copies are contained in the final presentation book compiled by UNOCAL in Tulsa, Oklahoma. Each log had been previously correlated and annotated with formation tops and bottoms, as well as some limited production data. In order to integrate these logs with the existing digital database, the physical cross sections were photographed individually using a digital camera. The camera was positioned directly above the subject to minimize obliquity and therefore any warping of the generated digital image. The images were then pieced together digitally to create an image of a complete individual well log as seen in Figure 17. Once in a digital format, these logs were correlated to the preexisting raster log images and added to the complete database. With formation tops already established from the water flood study, these cross sections establish an expanded type log framework for correlation to other raster log images.

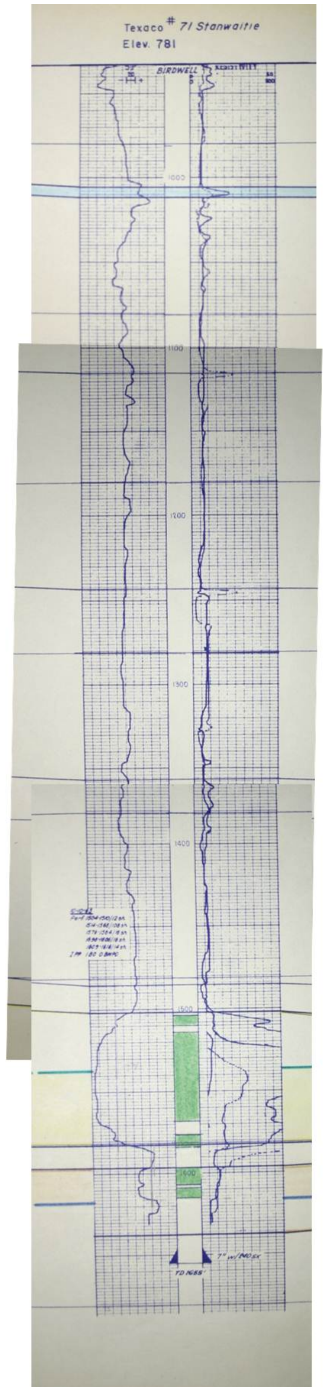

Figure 17. Reconstructed log photographed from UNOCAL cross sections.

C. CORRELATION OF ORIGINAL DRILLING RECORDS TO EXISTING WELL LOCATIONS

One of the initial hurdles in integrating the historical data with more recent data was assigning up-to-date standardized well identification numbers (API numbers) to historical records. In most cases, the operator had changed multiple times, the lease name had changed after unitization, and the drilling of the well predated the API numbering system. First, each original drilling record was carefully read for location information to gain a general idea of original well location within the section and, if possible, the individual tract. Using the well number, which rarely changed, and the general location information, the majority of the original well records were correlated with a well location listed in the IHS database. In the few cases that there was not an API number that could be accurately assigned to the drilling record, a unique, arbitrary API number was assigned and then added to the new database.

D. HISTORICAL MAPS

Included in the physical copy of the UNOCAL Water Flood Survey were blueprint images of the maps generated during the study. The maps were scanned using a commercial extra large scanner. While generating a very clear digital copy of the original, the scanning process did lead to some stretching of the resulting digital image. Each of these maps was imported into ArcMap and georeferenced using section corners as reference points for accuracy. A second order polynomial transformation was used to neutralize the stretching effect of the image. The importation of these maps was essential to the compiled database because the maps provided the best approximation of the original locations of those wells that preceded the water flood study. The maps were contoured on various data categories that were each noted on the maps according to individual well contribution. Once these maps were rectified, this data could be integrated into the database.

E. COMPILING/ASSIGNING WELL LOCATIONS AND API NUMBERS

With data being drawn from original drilling logs, historical maps, water-flood study documentation, surveyed points, and the IHS database, it was vital to compile a single comprehensive database in which all data could be collected. The best way to link all data related to a particular well is through individual API numbers. A shapefile was created in ArcMap to initially accomplish this task. The various data sources were qualitatively arranged in order of potential accuracy of location information, from best to worst: (1) surveyed well locations, (2) locations from historical maps, (3) log header information from raster logs, (4) locations from the IHS database, and (5) locations indicated on original drilling record illustrations. These data sources and the information available through them are listed in Table 1.

Data Source	API #	Operator	Lease	Well #	TD	Datum	Location Information
Surveyed Locations				X			X
Historical Maps		X	X	X			X
Raster Logs	X	X	X	X	X	X	rarely
IHS Database	X	X	X	X	X	X	unreliable
Original Drill Records		X	X	X	X	X	X

Table 1. Information available through data sources for correlation.

Using this preference order, a point was manually picked within ArcMap for each well and assigned its correctly corresponding API number. In a few cases, there exists no up-to-date records in the IHS database for a well that is indicated on historical maps or original drilling records. In these cases, no official API number had been assigned and an arbitrary API value was created solely for the purposes of this study to link all data related to that particular well.

The correlation of well location, API number, and physical historical records was particularly important for the use of the photographed well logs used in the UNOCAL water flood study. The API numbers for these particular wells, which were used extensively throughout the study, were never noted but were instead labeled with the operator, well name, and well number. Using this information and the general locations indicated on the cross section index map included in the study, each of these logs was assigned its correct API number.

After assigning all well locations for which there was some form of record, the exact latitudinal and longitudinal coordinates were calculated through the field calculator function of ArcMap. These coordinates for each specific well are essential for importation to Petra and for accurate mapping of each data category.

F. CALCULATING NET SAND

In the interest of accurate mapping of the Glenn I sand, the Glenn II sand, and the total Glenn Pool sand package, it was necessary to calculate not only calculate the gross thickness but also the net feet of sand for each well log in the study area. In the interest of accuracy and consistency, each well log was printed and notated by hand. First, depths were determined for each formation top or bottom previously marked on the photographed logs. These included the top and bottom of the Oswego Limestone, the top and bottom of the Glenn I sand, and the top and bottom (if recorded on the log) of the Glenn II sand. For the printed raster images, the logs were correlated using the images of the photographed and previously marked water flood study well logs.

Once formation boundaries were established, calculation of net sands could begin. The Glenn Pool Sand package is not 100 percent sand in most cases. In order to determine the actual amount of sand within the package rather than the overall thickness of the package, a cutoff was established for the spontaneous potential (SP) curve of the well logs. Two different cutoffs were used in order to later determine which cutoff produced the best visible resolution of the net sands during the mapping that would follow. The SP curve records direct current voltage between two electrodes, one from depth within the well bore and the other at the surface (Asquith reference). The SP log is used as a measure of gross lithology and, as such, a cutoff value allows differentiation between shale and sandstone or limestone. The typical shale baseline for the majority of the well logs in the study area is measured to be between +4 and +8 millivolts, with sands registering a lower SP value and shales registering a higher SP value. For net sand calculations in this study, SP cutoffs were established at first a +4 millivolts cutoff and then at a 0 millivolts cutoff. The second cutoff would later provide a higher resolution lithology distinction.

Owing to the nature of the original depositional environment, the thickness of the Glenn Pool Sand package rapidly changes laterally across the Crow Unit. In order to normalize the net sand values for these thickness changes, the net sand value was divided by the gross thickness value for each well resulting in a percentage of sand within the total sand package and therefore a measure of the reservoir quality at the well location.

G. BUILDING A COMPREHENSIVE DATABASE

The shapefile of wells created in ArcMap was exported to a Microsoft Excel spreadsheet, along with information on API numbers and location coordinates. Columns for additional information were inserted into this basic spreadsheet and included: API number, latitude, longitude, section number, tract number, operator, lease name, well number, total depth, datum elevation, formation top of the Glenn Pool I sand, bottom of the Glenn Pool I sand, top of the Glenn Pool II sand, bottom of the Glenn Pool II sand, total gross feet of Glenn Pool sands, total gross feet of Glenn Pool I sand, total gross feet of Glenn Pool II sand, net feet of total Glenn Pool sands (both cutoffs), net feet of Glenn Pool I sand (both cutoffs), net feet of Glenn Pool II sand (both cutoffs), net/gross ratio for total Glenn Pool sands (both cutoffs), net/gross ratio for Glenn Pool I sand (both cutoffs), net/gross ratio for Glenn Pool II sand (both cutoffs), and data sources for each well.

With this framework in place, data from all sources was examined and catalogued with its corresponding API number in the spreadsheet.

H. WORK COMPLETED IN PETRA

With all data correctly affiliated with its correct API number, the comprehensive database was imported into the PETRA software. This program allows for analysis of spatial relationships within the data. To accommodate the data, however, several additional zones were generated within PETRA first. These zones were labeled as listed in Table 2.

Zone Name	Units	Description
GP_GROSS	feet	Total Gross Glenn Pool
GP1_GROSS	feet	Glenn Pool I Gross
GP2_GROSS	feet	Glenn Pool 2 Gross
GP_NET5	feet	Total Net for Glenn Pool at 0 millivolts cutoff
GP1_NET5	feet	Glenn Pool I Net at 0 millivolts cutoff
GP2_NET5	feet	Glenn Pool II Net at 0 millivolts cutoff
GP_NET4	feet	Total Net for Glenn Pool at +4 millivolts cutoff
GP1_NET4	feet	Glenn Pool I Net at +4 millivolts cutoff
GP2_NET4	feet	Glenn Pool II Net at +4 millivolts cutoff
RATIO_GP_5	percentage	Net/Gross for Total Glenn Pool at 0 millivolts cutoff
RATIO_GP_4	percentage	Net/Gross for Total Glenn Pool at +4 millivolts cutoff
RATIO_GP1_5	percentage	Net/Gross for Glenn Pool I at 0 millivolts cutoff
RATIO_GP1_4	percentage	Net/Gross for Glenn Pool I at +4 millivolts cutoff
RATIO_GP2_5	percentage	Net/Gross for Glenn Pool II at 0 millivolts cutoff
RATIO_GP2_4	percentage	Net/Gross for Glenn Pool II at +4 millivolts cutoff

Table 2. Names of zones used in Petra.

After this step, the comprehensive spreadsheet could be loaded into the software and correctly compartmentalized. With this data in place, a general map with all well locations could be generated. The raster logs were imported next and, using their API numbers, were tied to the appropriate well locations.

IV. RESULTS

The integration of all available data into one cohesive database has allowed for mapping of the Glenn Sand within the Crow Unit at a much higher resolution than would have been available using only easily accessible information. This information would be the 38 original raster well logs over the area. The sections A through D each compare the results of mapping with only these readily available logs to the results of mapping with all integrated data, historical and contemporary.

A. STRUCTURE

Figure 18 is a structural map of the top of the Glenn Sand package based off of the original raster logs. The map exhibits the structural high around the middle of the unit which was mentioned in previous literature. The high-point is centered in the northwest quarter of the southeast quarter of section 5 with the flanks of the domal structure dipping gently away to the west and south and more steeply away to the north and east. The high-point has a subsea depth of -637.

Figure 19 is the same structural map of the top of the Glenn Sand but with all available data points included. With this addition, well control over the Crow Unit increases from 38 wells to 215 wells. Additional well information increases the accuracy of the map and shifts the apex of the structural high-point approximately 1,400 feet to the west to the center of the northeast quarter of the southwest quarter of section 5 and decreases the high-point to a subsea depth of -615.

(Image included on accompanying disc)

Figure 18. Structure map of top of Glenn Pool Sand Package based only off of 38 original raster logs.

(Image included on accompanying disc)

Figure 19. Structure map of top of Glenn Pool Sand Package based on all available data.

B. GROSS THICKNESS

Figure 20 is a map of gross thickness of the Glenn Pool Sand Package using the 38 original raster logs. The maximum gross thickness is 165 feet which centers the thick portion of the sand package in the southeast corner of section 5. There is a second high of 154 feet approximately 3600 feet to the west with a lower value of 56 feet separating the two lobes. Within the Crow Unit boundaries, sands of at least 150 feet thick are limited to southern half of section 5.

Figure 21 is a map of gross thickness utilizing all available data. This map has a maximum value of 196 feet of gross thickness which centers the thickest areas of sand just south of the center of the southern section line of section 5 suggesting a possible continued thickening south of the Crow Unit. Sands of at least 150 feet thick extend across the southern half of section 5 into section 4 to the east and section 6 to the west. The lateral variability in sand thickness becomes clear in this map.

(Image included on accompanying disc)

Figure 20. Gross thickness map of Glenn Pool Sand Package based only on 38 original raster logs.

(Image included on accompanying disc)

Figure 21. Gross thickness map of Glenn Pool Sand Package based on all available data.

C. NET THICKNESS

As mentioned previously, net thickness is used as a measure of sand quality and therefor reservoir quality. The amount of net feet over the 0 millivolt SP curve cutoff is mapped in Figures 22 and 23 below. Figure 22 represents net feet of sand in the 38 original raster logs while Figure 23 represents net feet of sand calculated for 77 wells.

The mapping of the net sands without the additional wells indicates two small lobes of higher net feet, one in the southeast quarter of section 5 and the other along the southern section line between sections 5 and 6 with a very thin value separating the two. The maximum is 151 feet located in the first lobe.

Inclusion of all the available data provides enough data to confirm a more widespread distribution of the thicker net sand vales. The low spot mapped in the previous figure can be excluded as a bad data point based off of the addition of multiple surrounding points of similar net sand values. The contouring of the data also suggests extension of this thick area of net feet into the unit to the south of the Crow Unit.

(Image included on accompanying disc)

Figure 22. Net feet map of Glenn Pool Sand Package based only on 38 original raster logs.

(Image included on accompanying disc)

Figure 23. Net feet map of Glenn Pool Sand Package based on all available data.

D. NET VS. GROSS THICKNESS

With the amount of lateral variability in thickness of the Glenn Sand, net thickness is not as reflective of sand quality as one would like. The amount of net feet for each well was normalized for overall thickness to gain a better measure of the quality of the sand volume at each well location. The value for this ratio is expressed as a percentage in the following figures.

Figure 24 is based only on the original 38 raster logs and has a maximum value of 87 percent along the southern end of the eastern section line of section 6. The map indicates areas of more than 85 percent net to gross thickness ratios but these are extrapolations made by the contouring algorithm.

Figure 25 is based on all available data and has a maximum value of 100% at 2 wells. Additionally, 8 of the wells exhibit values of more than 90%. These additional data points confirm what had previously been extrapolated by the contouring program of Petra. There is a distribution of higher quality sands surrounding the structural high on the flanks to the east, south, and west.

(Image included on accompanying disc)

Figure 24. Net vs. Gross feet of Glenn Pool Sand Package based only on 38 original raster logs.

(Image included on accompanying disc)

Figure 25. Net vs. Gross feet of Glenn Pool Sand Package based on all available data.

E. GAS SATURATION

Within the literature associated with the UNOCAL Water Flood Study conducted in the 1967, Finley indicated that there were two sets of core data for the Crow Unit. One set was taken in from 1943 to 1948 in the development of the gas injection project and the other set was taken from 1961-1962 during the water flood development. Both sets of cores indicated that there were consistent depths for water to oil contacts at around -755 and gas to oil contacts at around -826. These depths did not change significantly over the length of time between the sampling periods (Finley 1967).

Operating under the assumption that these depths have not changed significantly since this time period, the feet of the Glenn Sand package located within the gas saturated zone could be calculated. If the depth of the Glenn Sand package formation top is shallower than -755 feet, the amount of feet between -755 and the formation top represents feet of gas saturation at the well location.

These calculated values are mapped out in Figure 26 below. As would be expected, the highest amount of feet of gas saturation coincides with the structural high of the Glenn Sand package in the northeast quarter of the southwest quarter of section 5.

(Image included on accompanying disc)

Figure 26. Feet of gas saturation of the Glenn Pool Sand Package.

F. OIL SATURATION

Operating under the same assumptions used in calculating the amount of gas saturation, the same concept was applied in calculating oil saturation. The upper boundary for the oil saturation zone is -755 at the oil to gas contact and the lower boundary for the oil saturation zone is -826 at the oil to water contact. For each well, the total feet of the Glenn Sand package residing between these two depths were calculated.

Figure 27 is a map of these vales and, as with the gas saturation zone, the distribution of the values seems to mimic the structure of the top of the Glenn Sand package. The highest vales occur on the flanks of the structure to the southeast, south, and west which also coincide with the distribution of the highest quality sand based off of the net to gross feet ratio.

(Image included on accompanying disc)

Figure 27. Feet of oil saturation of Glenn Pool Sand Package.

G. CUMULATIVE OIL PRODUCTION

Included in the water flood study compiled by UNOCAL was a map which indicated cumulative oil and cumulative water production values both measured in thousands of barrels (bbls) for 96 wells across the Crow Unit (Finley 1967). These values were manually imported into Petra and associated with the correct API number.

Figure 28 below illustrates the distribution of these values. The highest value in the area is 119 bbls in the southeast quarter of the northeast quarter of section 6. The higher values of oil production occur primarily on the western flanks of the structural high.

(Image included on accompanying disc)

Figure 28. Cumulative oil production.

H. CUMULATIVE WATER PRODUCTION

The same map used as the data source above also contained cumulative water production values for each of the wells for which cumulative oil production was measured (Finley 1967). Figure 29 indicates the distribution of these values. The highest cumulative water production occurs at two points in particular: in the southeast quarter of the northeast quarter of section 6 and in the southwest quarter of the southeast quarter of section 6. Both locations occur on the western flank of the structural high in section 5.

(Image included on accompanying disc)

Figure 29. Cumulative water production.

I. CUMULATIVE OIL VS. WATER PRODUCTION

Values for both the cumulative oil production and the cumulative water production had very broad ranges. In order to generate a more consistent comparative value from well to well, these values were normalized by dividing the cumulative oil production value by the cumulative water production value. The resulting number provides an indication of overall quality of oil production.

The extremely high values in the center of the southern half of section 4 represent wells that had a higher number of barrels of oil than barrels of water but had a much lower number of total produced barrels of oils. As such, these values can be disregarded. The distribution of the other data points mimics the distribution of the calculated oil saturated zone illustrated in Figure 30.

(Image included on accompanying disc)

Figure 30. Cumulative oil vs. water production.

V. CONCLUSIONS

Previous studies of the Glenn Pool Field concur that the distribution of hydrocarbons is controlled stratigraphically by an updip pinchout of the Glenn Sand to the northeast of the field. On a smaller scale, however, other smaller pooling areas may be due to smaller scale structural changes (Kuykendall and Matson 1992). Within the Crow Unit, hydrocarbon distribution may be driven by both structural and stratigraphic influences.

Structurally, the Crow Unit experiences a structural high in the northeast quarter of the southwest quarter of section 5 providing a typical pooling area. If this is the case, an original gas cap may still be in place. Using the structure of the top of the Glenn Sand, the assumption of a gas to oil contact at a depth of -755, and the calculated amount of gas saturation, it can be reasonably assumed that there is producible gas present and structurally collected in the Crow Unit. This assumption was not able to be definitively proven in this study, however, due to lack of availability of any gas production data.

Stratigraphically, distribution of the highest quality sands based off of mapping of the net to gross ratio of sand (Figure 25) occurs from the southeast quarter of section 6, across the southern half of section 5, and into the southern half of the southwest quarter of section 4. Pooling of oil within these stratigraphically favorable areas is supported by the distribution of the normalized cumulative oil production values (Figure 30). This distribution may not be solely based off of stratigraphy, however. Comparing the net to gross ratio map (Figure 25) to the map of calculated oil saturation (Figure 27), the highest values are distributed similarly. The net to gross ratio was based off of the quality of the rock while the calculated oil saturation was based off of the structural depth and thickness of the Glenn Sand.

This correlation suggests that either the original deposition of the sand may have been structurally effected or the hydrocarbon distribution is controlled by both the structure and stratigraphy of the Glenn Sand within the Crow Unit.

Further production of hydrocarbons from the Crow Unit would be most favorable within areas that meet the criteria of high net to gross sand ratios, high values of calculated oil or gas saturation, and location within a structurally positive area.

VI. FUTURE WORK

Further study within the Crow Unit will be essential for more detailed stratigraphic characterization of the Bartlesville Sandstone within the unit. Potential future studies include:

- Collection of new core data to confirm or update oil to water and gas to oil contacts as well as to collect data on porosity and permeability and determine distribution.
- Integration of more recent and more complete production data to support either structurally or stratigraphically driven hydrocarbon distribution.
- In-depth stratigraphic study applying the idea of DGIs which would boost quaternary recovery efforts.

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