PETROLEUM GEOLOGY OF THE LEONARDIAN AGE, HARKEY MILLS SANDSTONE: A NEW HORIZONTAL TARGET IN THE PERMIAN BONE SPRING FORMATION, EDDY AND LEA COUNTIES, SOUTHEAST NEW MEXICO

by

MARSHALL DEWAYNE DAVIS

Presented to the Faculty of the Graduate School of

The University of Texas at Arlington in Partial Fulfillment

of the Requirements

for the Degree of

MASTER OF SCIENCE IN ENVIRONMENTAL AND EARTH SCIENCE

THE UNIVERSITY OF TEXAS AT ARLINGTON

December 2014

Acknowledgements

I gratefully acknowledge the contributions of all the individuals whose intellectual and motivational support has helped me to complete this project. It has been a privilege to work and learn from the experienced and knowledgeable people who have facilitated in the development of my career as a petroleum geologist.

First and foremost, I would like to thank my family, above all my wife, Cristina. Your unparalleled support throughout my college career has meant everything to me.

I would also like to gratefully acknowledge BOPCO, L.P. for supplying all of the data that was needed to carry out this research. In addition, I would like to sincerely say thank you to everyone at BOPCO, L. P. who provided me with the technical and motivational support that I needed to complete this project.

Finally, I would like to thank my committee members, Dr. John Wickham, Dr. Majie Fan, Dr. Merlynd Nestell, Ms. Simianne Johnson-Hayden and Mr. Matthew Kearney.

November 18, 2014

Abstract

PETROLEUM GEOLOGY OF THE LEONARDIAN AGE, HARKEY MILLS SANDSTONE: A NEW HORIZONTAL TARGET IN THE PERMIAN BONE SPRING FORMATION, EDDY AND LEA COUNTIES, SOUTHEAST NEW MEXICO

Marshall Dewayne Davis, M. S.

The University of Texas at Arlington, 2014

Supervising Professor: John Wickham

Lowstand, siliciclastic turbidite and submarine fan deposits within the Leonardian Bone Spring Formation have proved to be prolific targets for horizontal drilling across the northern portion of the Delaware Basin. Reservoir sandstones in this area are very fine grained, with porosities of 8 – 12%, permeabilities of 1 – 2 md and water saturations between 40% and 60%. In Big Eddy, James Ranch and Poker Lake New Mexico Federal Units, a new target for horizontal drilling, the Harkey Mills sandstone, is proposed, which may have production comparable to the Second Bone Spring Sandstone. There are currently four horizontal wells producing form the Harkey Mills sandstone near Willow Lake West field (T24-25S, R27E) in south-central Eddy County, New Mexico, approximately 13 miles to the west of Poker Lake Unit. Within a 3-year period, these four wells have a combined cumulative production of approximately 176 MBO and 708 MMCF of gas.

The Harkey Mills sandstone is a lowstand submarine fan deposit incased in the Second Bone Spring Carbonate, between the Second and Third Bone Spring Sandstones. Using a network of stratigraphic and structural cross sections, the Harkey Mills sandstone was correlated and then mapped throughout Big Eddy, James Ranch and Poker Lake Federal Units in Eddy and Lea Counties, southeast New Mexico, encompassing a total area of approximately 870 mi^2 (2250 km^2). Based on well log analysis from 625 wells, the Harkey Mills sandstone can be subdivided into a slope fan, a basin-floor fan, and a modified lowstand wedge deposit that was sourced from the Northwest Shelf and distributed across the Federal Units with a regional dip to the southeast. The best reservoir rock occurs within the apex of turbidite channel deposits proximal to the slope fan, with net thicknesses up to 80 ft. containing at least 8% porosity and Rt values between 5 and 12 ohms. Trapping mechanisms are primarily stratigraphic, produced by upslope pinchouts and lateral porosity variations. Total Organic Carbon measurements and Rock-Eval Pyrolysis, from sidewall core samples from two wells in the Big Eddy Unit, indicated that the Harkey Mills sandstone averages 2. 1% TOC, and is oil and gas prone with Type II and III kerogen.

This new target for oil and gas was identified in the Bone Spring Formation, in the Big Eddy Unit, using various exploration techniques. Similar strategies and concepts can be used to extend the Bone Spring play to other regions in the Delaware Basin and may be used as a model to explore for similar lowstand submarine fan deposits.

Table of Contents

List of Figures

List of Tables

Chapter 1

Introduction

The Bone Spring Formation is a stratigraphically complex sequence of intercalated carbonate and siliciclastic rock deposited during a period of declining tectonic activity, as well as, a global change in climate and eustasy. Transgressive sea level successions during the Leonardian Series were frequently interrupted by regressive cycles, transporting allochthonous debris sediments basinward along the northern slope of the Delaware Basin through a series of turbidity channel and deep-submarine fan complexes. In the southeast New Mexico portion of the Delaware Basin, the Bone Spring Formation has been formally subdivided into three siliciclastic and three carbonate members which are, in order of deposition, the Third Bone Spring Sandstone, the Third Bone Spring Carbonate, the Second Bone Spring Sandstone, the Second Bone Spring Carbonate, the First Bone Spring Sandstone and the First Bone Spring Carbonate. Montgomery (Part I-1997) has informally recognized a fourth sandstone member, the Avalon sandstone, which is restricted to certain portions of the slope and northern basin. To date, the Harkey Mills sandstone has not been formally introduced as a member of the Bone Spring Formation.

The petroleum geology of the Bone Spring detrital sediments in the northern Delaware Basin has been substantially explored since the 1980's however; there are no publications identifying the Harkey Mills sandstone. Wiggins and Harris (1985) conducted a detailed study on the diagenetic processes affecting the deep-water allochthonous detrital carbonates of the Bone Spring Formation; Gawloski (1987) described the nature, distribution and petroleum potential of the First, Second and Third Bone Spring Sandstones, as well as, the First and Second Bone Spring Carbonates; Mazzullo and Reid (1987) and Mazzullo (1991) described in detail, the stratigraphy and facies distributions of the Bone Spring Formation in Lea County, New Mexico; Messa et al., (1996) conducted a case study specifically on the Second Bone Spring Sandstone; Montgomery (Parts I and II, 1997) described the First, Second, Third, and Avalon sandstone plays in the southeast New Mexico Portion of the Delaware Basin; and Pearson (1999) used an integrated analysis of well logs, cores and 3-D seismic data to investigate the sequence stratigraphy and log properties of the Second Bone Spring Sandstone.

The North American Commission on Stratigraphic Nomenclature (NACSN) refers to the term *formation* as a fundamental unit of lithostratigraphy. Furthermore, the NACSN defines a formation as a sufficiently distinctive and continuous body of rock that can be mapped on Earth's surface or traceable within the Earth's subsurface. The term *member* is a formal stratigraphic unit next in rank below a formation. The purpose of this research is to determine the petroleum geology of the Harkey Mills sandstone in Big Eddy, James Ranch and Poker Lake Federal Units, in Eddy and Lea Counties, southeast New Mexico and to: 1) establish the Harkey Mills sandstone as a informal member of the Leonardian Bone Spring Formation, and 2) evaluate the hydrocarbon potential of the Harkey Mills sandstone in Big Eddy, James Ranch and Poker Lake Federal Units using horizontal drilling.

Geographical Setting

Study Area

Three southeast New Mexico Federal Unit Leases are the primary study areas for this research: Big Eddy Unit, James Ranch Unit and Poker Lake Unit. These federal units are located along the northern slope of the Delaware Basin in Eddy and Lea counties, New Mexico (Figure 1.1). The northern most federal unit is Big Eddy Unit which covers approximately 117,500 acres (~180 mi^2) and is adjacent to the slope of the Capitan Reef Trend. Less than half of a township to the south and east is James Ranch Unit which encompasses approximately 13,500 acres (~20 mi^2). Directly to the south of James Ranch Unit is Poker Lake Unit which covers another 62,000 acres (~95 mi^2) of southeastern Eddy County. All three units are active leases in the exploration and production of oil and gas in the Delaware Basin. In order to avoid any gaps when interpreting the subsurface geology of these units, a one township halo around the Federal Units was incorporated into the study area. This brought the total size of the study area to approximately 870 mi^2 (2250 km^2).

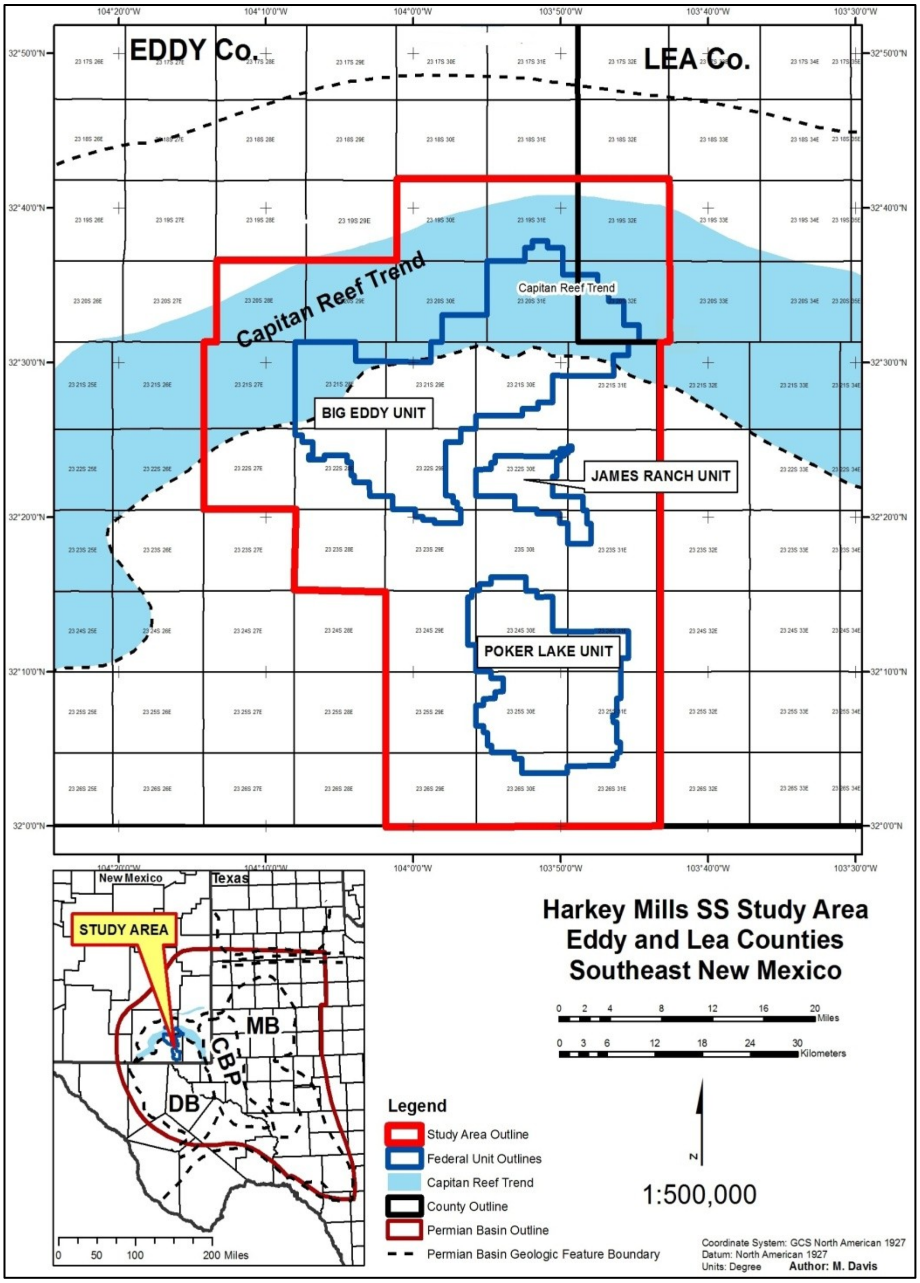


Figure 1.1. Geographic map depicting the study area for the Harkey Mills sandstone. The primary study area, the New Mexico Federal Units including Big Eddy Unit, James Ranch Unit and Poker Lake Unit, are outlined in dark blue. A one township halo around the study area is outlined in red. Geologic features modified from Frenzel et al., (1988).

Geologic Setting

Tectonic History

The Permian Basin in southeast New Mexico and west Texas is subdivided into three sub-basins: the Delaware (westernmost), Midland (easternmost) and Val Verde (southernmost) basins (Figure 1.2). The Delaware Basin is a virtually undisturbed shelf-basin transect that formed near the terminus of the Ouachita-Marathon orogenic belt, thus along the edge of western equatorial Pangea (Soreghan & Soreghan, 2013). It lies juxtaposed between the Marathon orogenic belt (south) and the basins and uplifts broadly associated with the waning Ancestral Rocky Mountains (north), and records flexural subsidence associated with the final assembly of Pangea (Ewing, 1993; Hills, 1984; Yang & Dorobek, 1992). Covering an area of more than 13,000 mi^2 (Hills, 1984), the Delaware Basin is bounded by the submerged Diablo (west) and Central Basin Platforms (east), the Northwest Shelf (north) and the Marathon foreland (south) which contains the Val Verde Basin.

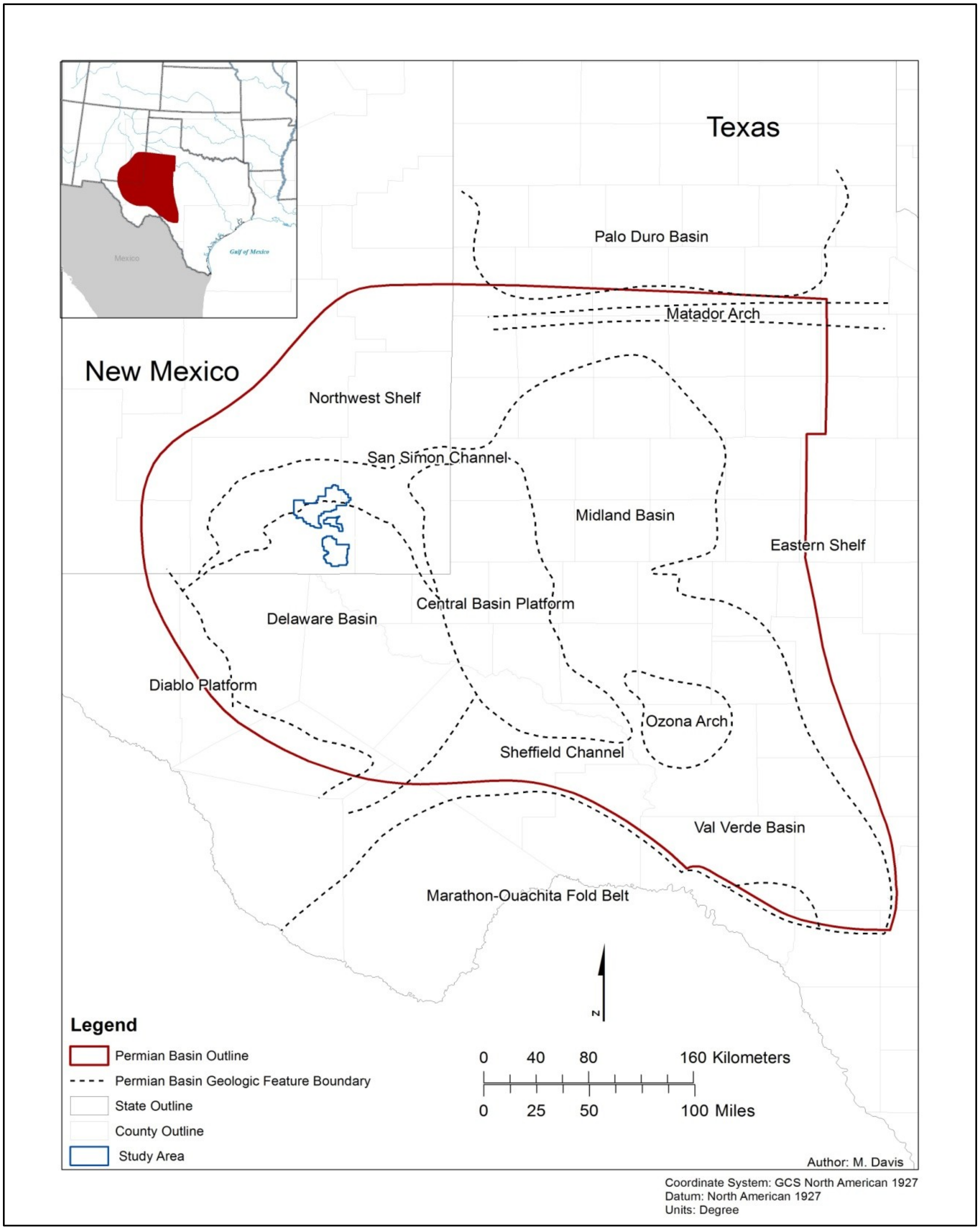


Figure 1.2. Geologic features of the Permian Basin in southeast New Mexico and west Texas. The major subdivisions and boundaries are outlined in black dashed lines. Modified from Frenzel et al., (1988).

Delaware Basin development can be traced back to the Late Precambrian with the formation of the Tobosa Basin (Galley, 1958) which existed until the Middle Paleozoic (Adams, 1965). The Tobosa Basin began as a north-south trending aulacogen, or failed rift arm (Walper, 1977), in the Late Proterozoic (Hills, 1963). By the beginning of the Phanerozoic, the Tobosa Basin region was welded to the southwest portion of the North American Craton (Galley, 1958), thus gradually deepening the basin and possibly connecting it with the ancestral Tethys Sea (Hills, 1984). Tectonic activity along a Proterozoic fault zone (Figure 1.3) that extends from Hobbs, New Mexico to Fort Stockton, Texas had ceased at this time and, combined with increased overburden, the Tobosa Basin continuously deepened until the end of the Mississippian. The main lithologic units deposited from the Late Cambrian to the Late Mississippian are represented by a series of platform carbonates and deep marine shales. The sequence in which these sediments were deposited is directly related to eustatic sea level fluctuations during the Paleozoic.

Vertical movement along the Proterozoic fault zone during the onset of the Late Paleozoic Ouachita-Marathon Orogeny deepened the incipient Delaware Basin giving it an eastern tilt (Hills, 1984; Soreghan & Soreghan, 2013). Also at this time, compression from the northeast moving Marathon fold belt caused the Central Basin ridge to rise along steeply dipping reverse faults (Cys & Gibson, 1988; Hoak et al., 1998) which eventually led to the separation of the Tobosa Basin in to the Delaware and Midland Basins. Meanwhile, the developing Delaware basin filled with deltaic sediments derived from the uplift of the Northwest Shelf in central New Mexico (Hills, 1984).

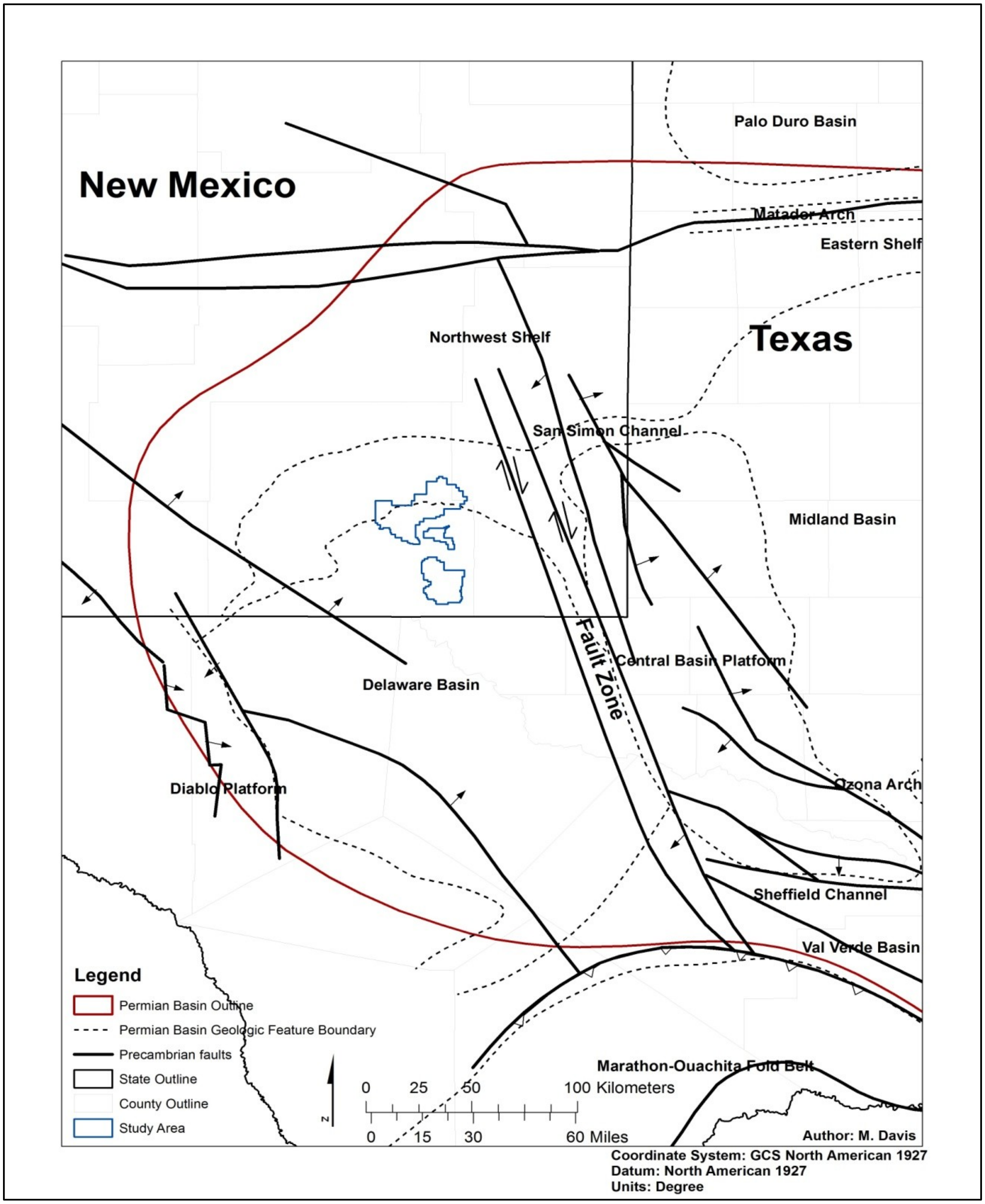


Figure 1.3. Tectonic map depicting the present configuration of the Precambrian basement and Proterozoic fault zones. Modified from Frenzel et al., (1988).

Tectonic activity increased during the Middle Pennsylvanian while carbonate shelves began to develop along the Delaware Basin margin and lasted through the end of the Pennsylvanian (Mazzulo, 1981). Adams et al., (1951) classified the Delaware Basin during Atokan time (Middle Pennsylvanian) as a starved basin due to carbonate banks trapping clastic material derived from the highlands to the north. This material would eventually be deposited into the central and southern portions of the Delaware Basin during the final convulsion of the Ouachita-Marathon Orogeny that thrusted geosynclinal rocks further northward in the Early Permian (Hills, 1984; Kinley, 2006). The Ouachita-Marathon Orogeny ended by the Middle Permian in what is now Mexico along an inferred transform boundary that extends northward toward the Cordilleran margin of western North America (Dickinson & Lawton, 2001; Stewart, 1988). From the Middle Permian on, the Delaware Basin remained tectonically stable (Hills, 1984) with the exception of minor overprinting of Cenozoic basin and range style extensional faulting on older structural features. Movement along these faults followed the pre-existing structural grain of the Delaware Basin region in a northwest to southeast direction (Shepard & Walper, 1982).

Permian Paleogeography and Paleoclimate

The Delaware Basin formed one of the southwestern most sedimentary basins of Permian Equatorial Pangea (Soreghan & Soreghan, 2013). At the beginning of Permian time, the Permian Basin region lay about 5-10˚ north of the equator (Soreghan & Soreghan, 2013; Ziegler et al., 1997), within an arid climate zone inferred from the abundance of evaporite and aeolian siliciclastic strata preserved across the greater region

(Fisher & Sarnthein, 1988; King, 1948; Oriel et al., 1967). Permian siliciclastic strata of the Delaware Basin accumulated predominantly within deep (basinal) to shallow (shelf) marine environments however, these sediments may have reached the shoreline not solely by fluvial systems, but via aeolian transport (Figure 1.4) (Fischer & Sarnthein, 1988; Soreghan & Soreghan, 2013). After the assembly of Pangea, the supercontinent extended as far north as latitude 85N and as far south as latitude 90S (Davies, 1997). Paleoclimitac models suggest that with a substantial exposed landmass such as Pangea, the atmospheric circulation patterns would be disrupted on a global scale creating a unique climate that transcended latitudinal boundaries (Davies, 1997). A mega-monsoonal (Dubiel, 1994) climatic condition existed during the Permian and Triassic which caused the Northwest Shelf to become increasingly arid, with winds coming from the northeast, and ephemeral fluvial systems on the shelf (Kocurek & Kirkland, 1988). A long period of oceanic retreat occurred during the close of the Permian (Hills, 1984) which supports the exposed landmass model from Davies (1997), and is probably the cause for the absence of Jurassic and Lower Cretaceous sediment in the Permian Basin.

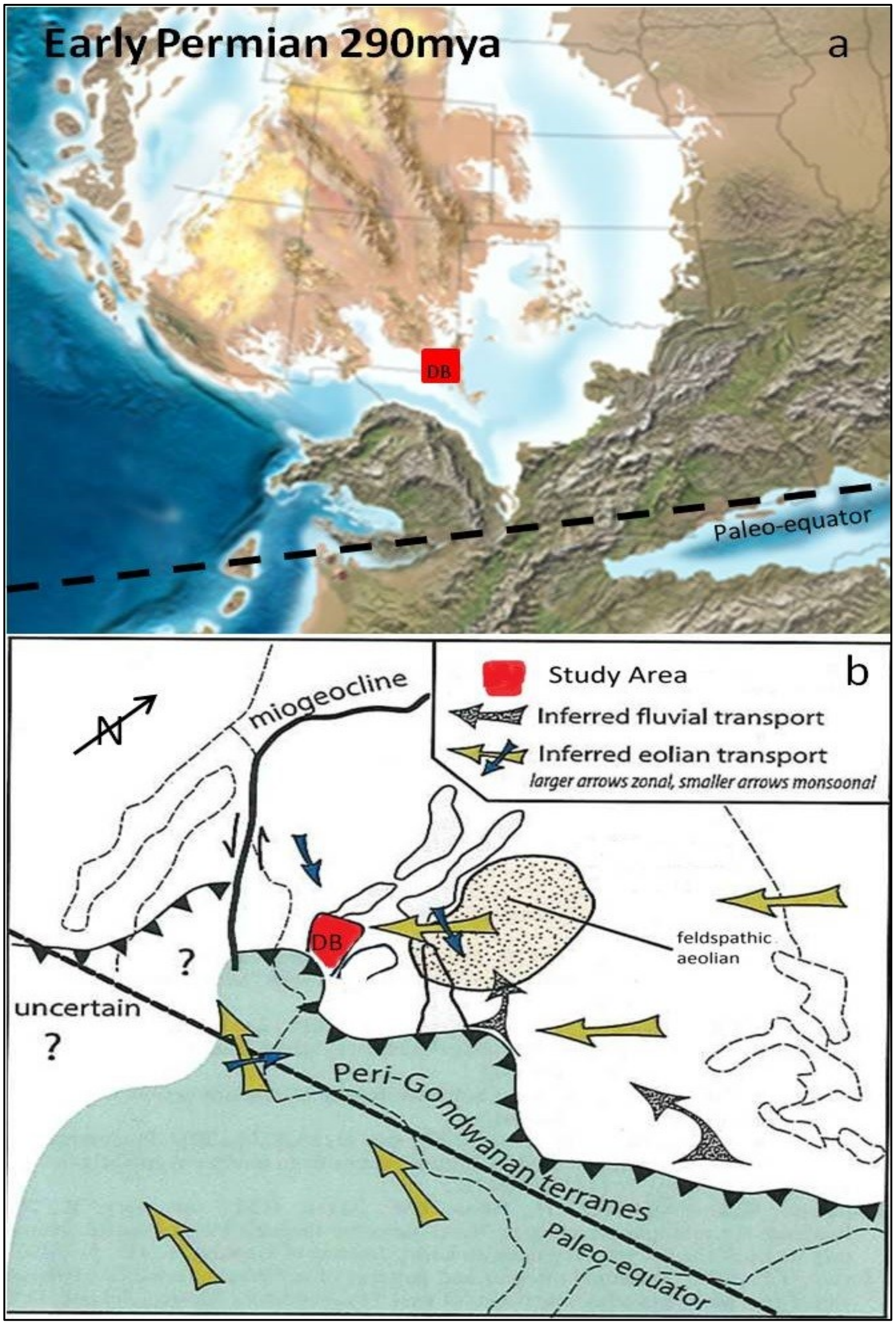


Figure 1.4. Paleogeographic map of Permian Equatorial Pangea approximately 290 Ma (a); and a map of paleo-fluvial and aeolian sediment transport pathways (b). The Delaware Basin study area is highlighted in both parts (a) and (b). Modified from Blakey (1980) and Soreghan & Soreghan (2013).

Chapter 2

Background on the Permian Bone Spring Formation

Stratigraphy

The Bone Spring Formation (Leonardian) in the southeast New Mexico portion of the Delaware Basin consists of up to 3,500 ft (1,067 m) of alternating carbonate and siliciclastic rocks that are the shelf-to-basin equivalent of the Abo-Yeso shelf sediments of the Northwest Shelf (Figure 2.1) (Gawloski, 1987; Mazzullo, 1991; Mazzullo & Reid, 1987; Saller et al., 1989). This heterolithic sequence of low- and highstand sedimentation overlies the Wolfcamp Formation (Wolfcampian) and underlies the Delaware Mountain Group (Guadalupian). In order of deposition, the Bone Spring Formation consists of the Third Bone Spring Sandstone, Third Bone Spring Carbonate, Second Bone Spring Sandstone, Second Bone Spring Carbonate, First Bone Spring Sandstone and the First Bone Spring Carbonate (Gawloski, 1987; Montgomery Part I, 1997; Pearson, 1999; Silver & Todd, 1969; Walsh, 2006). Montgomery (Part II-1997) has informally recognized a fourth sandstone member of the Bone Spring Formation that is incased in the First Bone Spring Carbonate. This relatively thin sandstone unit is the Avalon sandstone.

The stratigraphic unit that defines the upper boundary of the Bone Spring Formation in the Delaware Basin is a slope-to-basin sequence of dark limestones, siltstones, and allochthonous carbonate debris known as the Cutoff Formation (Figure 2.2) (Gawloski, 1987).

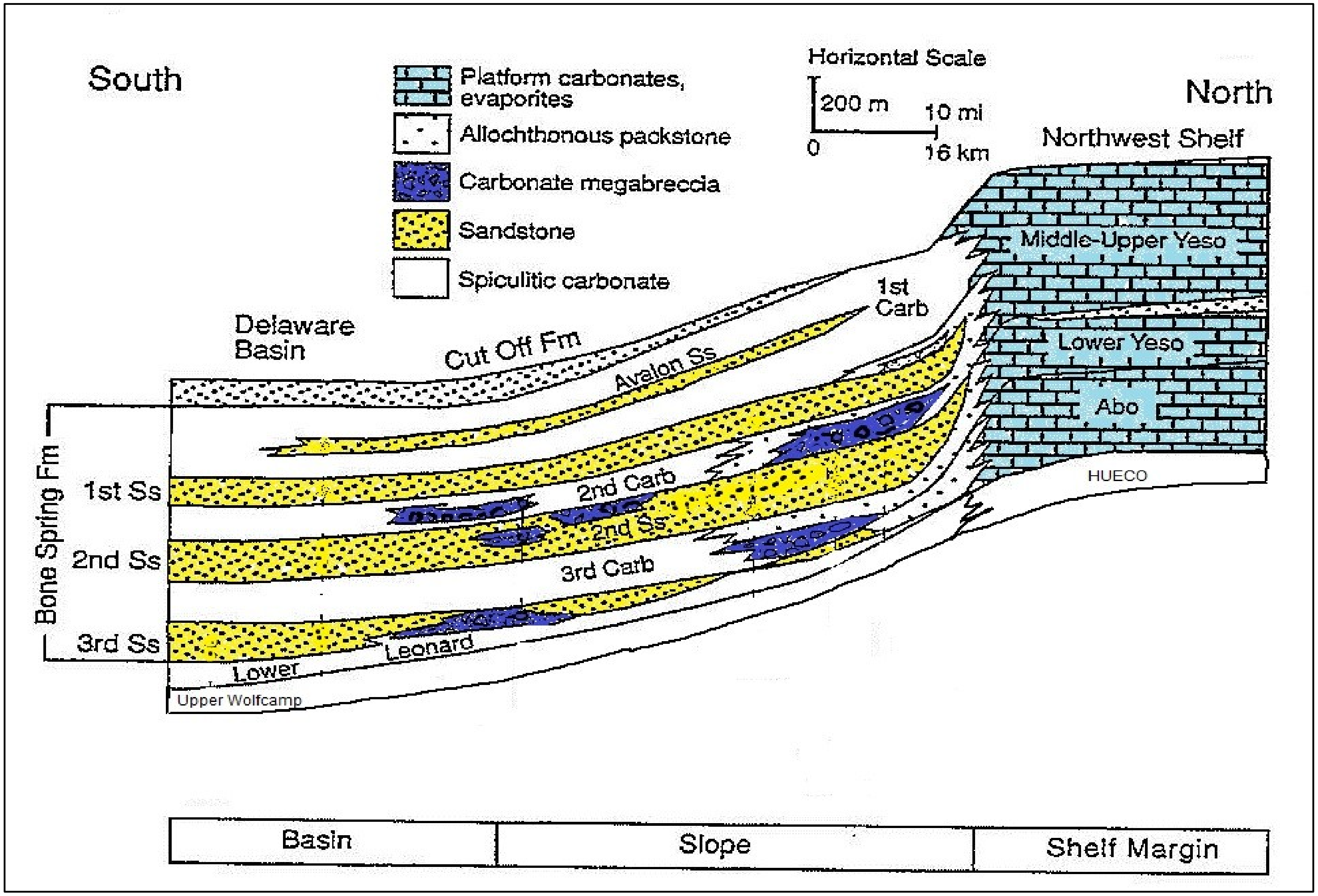


Figure 2.1. Schematic north-south regional cross section of the northern Delaware Basin, illustrating general shelf-to-basin relationships between the Bone Spring Formation and the Abo-Yeso shelf equivalent. Modified from Gawloski (1987), Mazzullo (1991) and Saller et al., (1989).

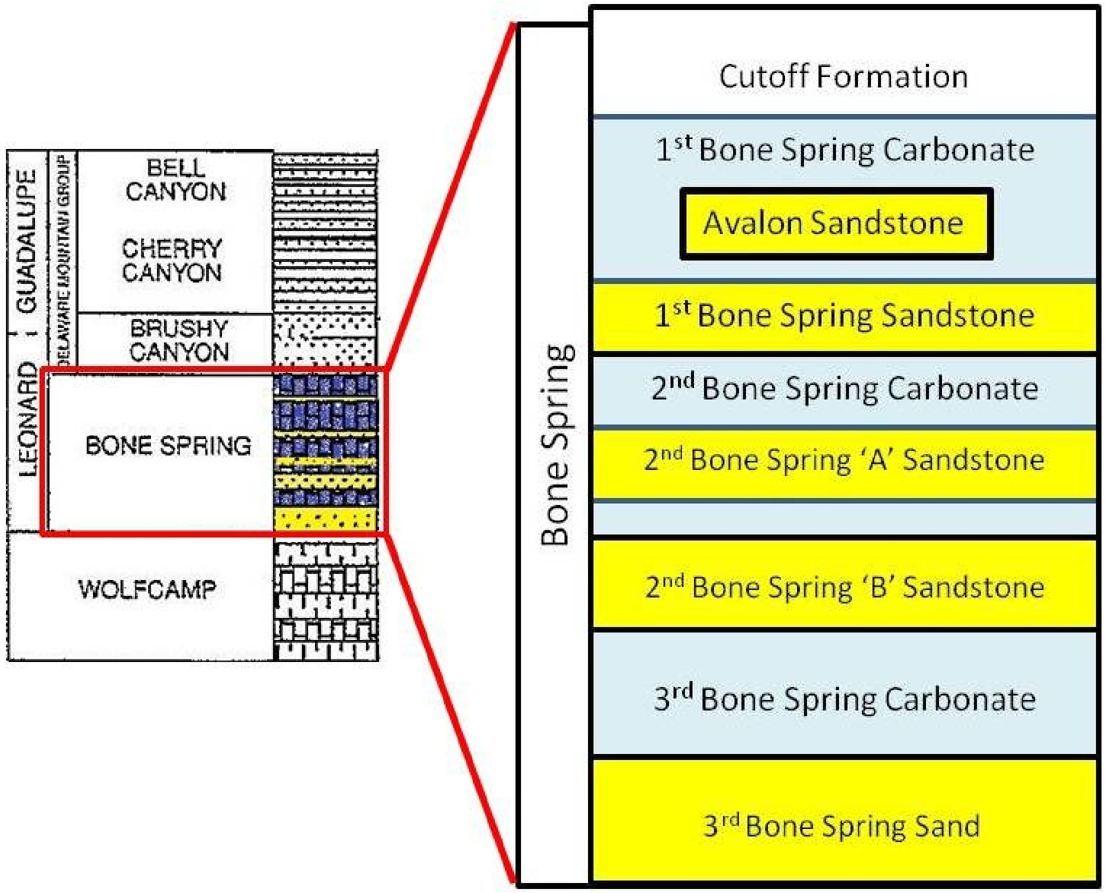


Figure 2.2. Regional stratigraphic column for the Permian Bone Spring Formation in the southeast New Mexico portion of the Delaware Basin. Depicted are the alternating siliciclastic and carbonate intervals of the Bone Spring Formation (Leonardian). Also shown are the Avalon Sandstone and Cutoff Formation. Modified from Montgomery (1997).

Stratigraphic Nomenclature

The United States Geological Survey (USGS) recognizes the Bone Spring Limestone as the correct stratigraphic unit that makes up the upper most portion of the Bone Spring Formation (Basset, 2012). Previously, this unit has been referred to as the First Bone Spring Carbonate (Figures 2.1 & 2.2). The Bone Spring Limestone is widely used in the Petroleum Industry as to mark the top of the Bone Spring Formation. There is often some confusion when discussing the nomenclature for the members of the Bone Spring Formation. Typically, when the top of the Bone Spring Formation is referred to as the Bone Spring Limestone and not the First Bone Spring Carbonate, the underlying units are numbered according to the order at which they appear when drilling. For example in Big Eddy, James Ranch and Poker Lake Federal Units, once the Bone Spring Limestone has been drilled, the underlying sandstones and carbonates are numbered starting with the First Bone Spring Sandstone, First Bone Spring Carbonate, Second Bone Spring Sandstone, Second Bone Spring Carbonate/Harkey Mills sandstone and then the Third Bone Spring Sandstone (Figure 2.3). The naming convention presented in Figure 2.3 will be used for the remainder of this research.

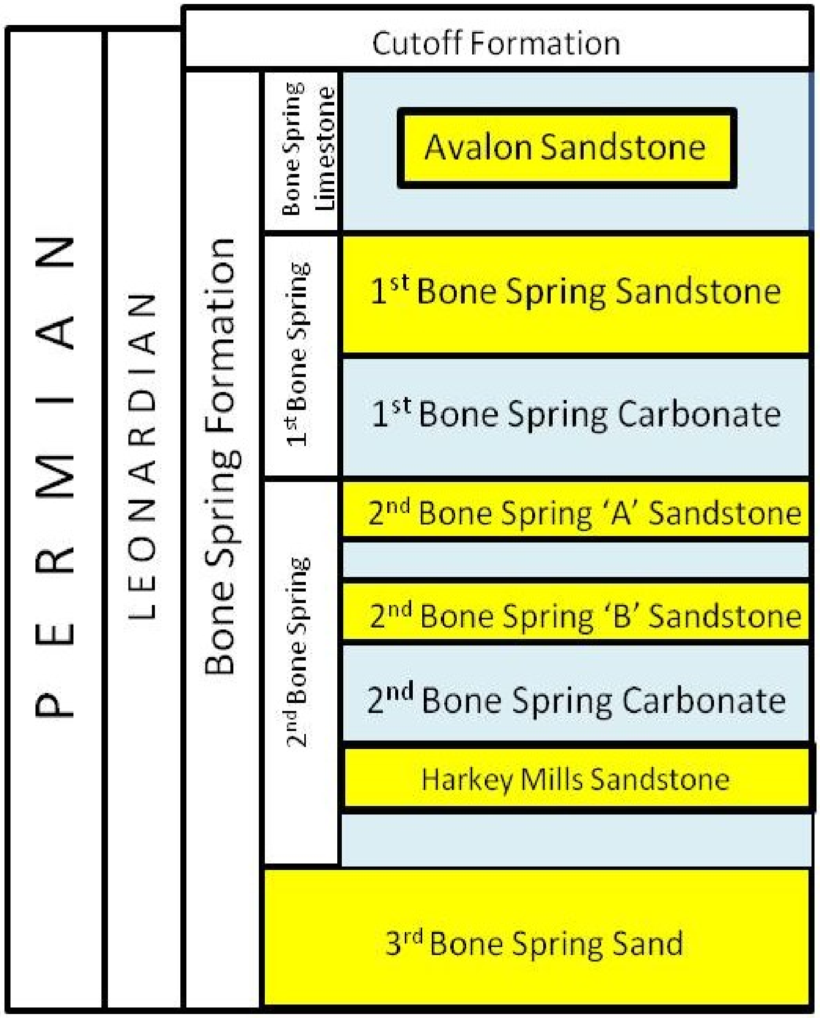


Figure 2.3. Stratigraphic column of the Bone Spring Formation in Big Eddy, James Ranch and Poker Lake Units, Eddy and Lea Counties, southeast New Mexico.

Previous Work

Geology of the Bone Spring Formation

The Bone Spring Formation is the slope-to-basin equivalent of the thick Abo-Yeso carbonate sequences that rimmed the Delaware Basin during the Leonardian Series (Montgomery, 1997; Saller et al., 1989). There was approximately 1,200 ft. – 1,500 ft. (365 m – 455 m) of depositional relief between the Northwest Shelf margin and the basinal slope (Gawloski, 1987; Saller et al., 1989; Wiggins & Harris, 1987). Sedimentation was controlled by a combination of cyclic sea level fluctuations (Saller et al., 1989; Silver & Todd, 1969), and basinal subsidence, which appears to have been fairly rapid. The cyclic sea level fluctuations are reflected by the alternating intervals of carbonate and siliciclastic strata represented in the Bone Spring Formation. Terrigenous siliciclastic material was transported to the Northwest Shelf margin and into deeper waters by turbidity currents during sea level lowstand (Figure 2.4) (Gawloski, 1987). During periods of sea level rise, carbonate production and deposition along the bounding shelves was presumably at a maximum (Montgomery, 1997). At maximum highstand, the Northwest Shelf margin was built to near sea level and produced significant amounts of carbonate detritus that periodically collapsed into turbidite debris flows that reached the slope (Montgomery Part I, 1997; Pearson, 1999).

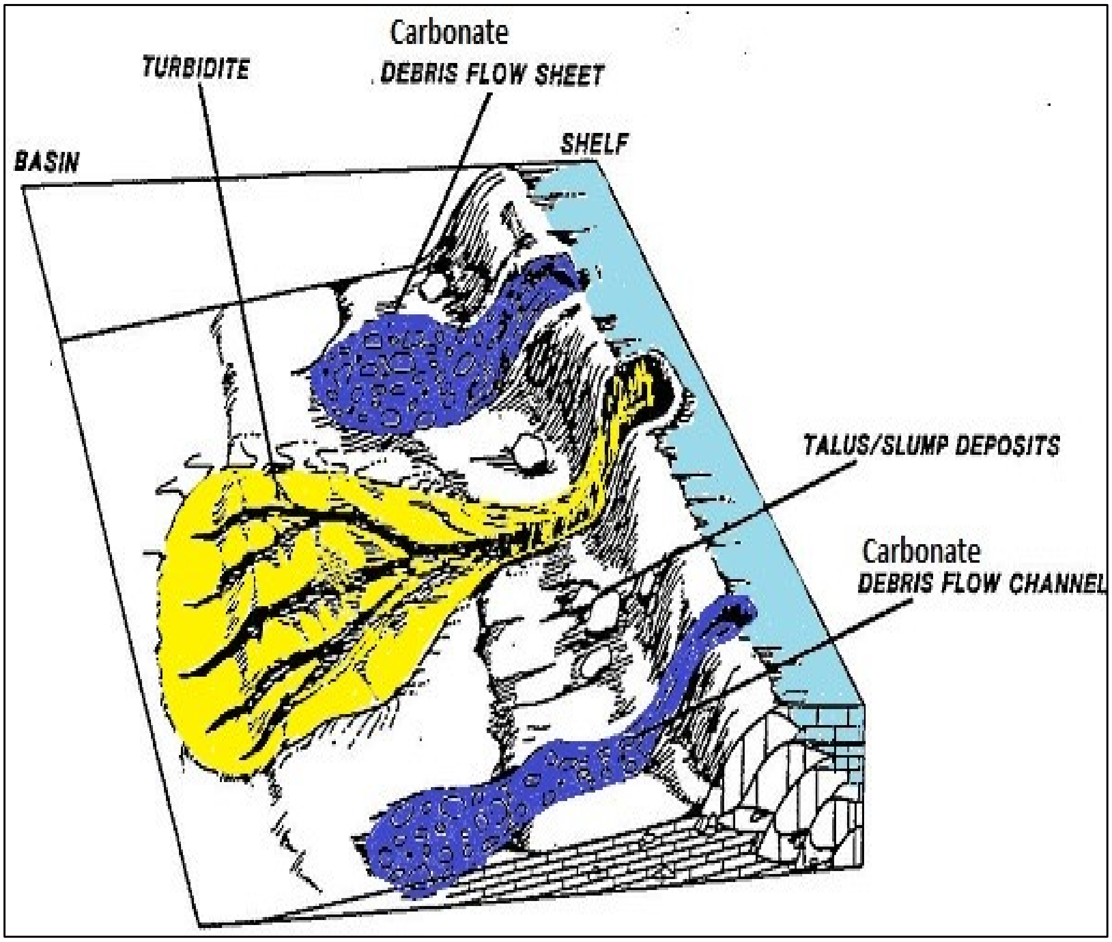


Figure 2.4. Schematic diagram showing the various depositional systems for the Bone Spring Formation. Modified form Cook et al. (1972), Gawloski (1987) and Wiggins & Harris (1985).

Initiation mechanisms for turbidity flow deposits into the Delaware Basin include both biological and physical features such as sediment failure, river outflow, floods, wave oscillations, storms and submarine landslides (Meiburg & Kneller, 2010; Middleton & Hampton, 1996). Interestingly however, the Bone Spring carbonate megabreccias extend for tens of miles into the basin and across Big Eddy, James Ranch and Poker Lake Federal Units. This might suggest that the carbonate debris flow deposits were initiated by a more catastrophic event. Such non-meteorological events could include earthquake-triggered subsea landslides (Dadson et al., 2005).

The Bone Spring Formation entered the oil window in the Early Permian (Leonardian) and has remained in the oil window some 200 million years later (Gawloski, 1987; Wiggins & Harris, 1985). Hydrocarbons generated during this time were preserved by fairly rapid burial and by the deposition of Late Permian (Ochoan) evaporite facies (Hills, 1984). The best petroleum reservoirs in the Bone Spring Formation occur in stratigraphic traps (upslope pinch outs and lateral facies variations) or diagenetic traps (varying degrees of dolomitization). Certain members of the Bone Spring Formation including the Second Bone Spring Sandstone and Third Bone Spring Sandstone are currently targets for horizontal drilling in and around the southeast New Mexico Federal Units.

Third Bone Spring Sandstone

The Third Bone Spring Sandstone member makes up the lowermost portion of the Bone Spring Formation. There is some controversy over the stratigraphic marker that separates the base of the Third Bone Spring Sandstone and the top of the Permian Wolfcamp (Wolfcampian) Formation. Currently, the Wolfbone oil play is a major target in the southern Delaware Basin, in west Texas. Horizontal wells completed in the Wolfbone are either in the lowermost Third Bone Spring Sandstone reservoir or the uppermost Wolfcamp Sandstone reservoir. Mazzullo and Reid (1987) argue that the Third Bone Spring Sandstone overlies a limestone bed that has been dated by fusulinids as Lower Leonardian and is the stratigraphic marker that separates the Bone Spring Formation from the Wolfcamp Formation.

Previous work by Gawloski (1987), Montgomery (Part II–1997) and Silver and Todd (1969) suggest that the Third Bone Spring Sandstone was deposited during a period of sea level lowstand along a sandstone depocenter that corresponds to the basinal axis of the Delaware Basin perpendicular to the shelf edge (Figure 2.5). The major reservoirs of the Third Bone Spring Sandstone are represented by density-current channel sandstones and related levee/overbank facies that were deposited in a turbidite submarine fan (Montgomery Part II, 1997). Submarine fan facies are often interbedded with organic shales and siltstones representing pelagic deposition (Figure 2.6). Turbidites are often episodic by nature – triggered by earthquakes or submarine slides.

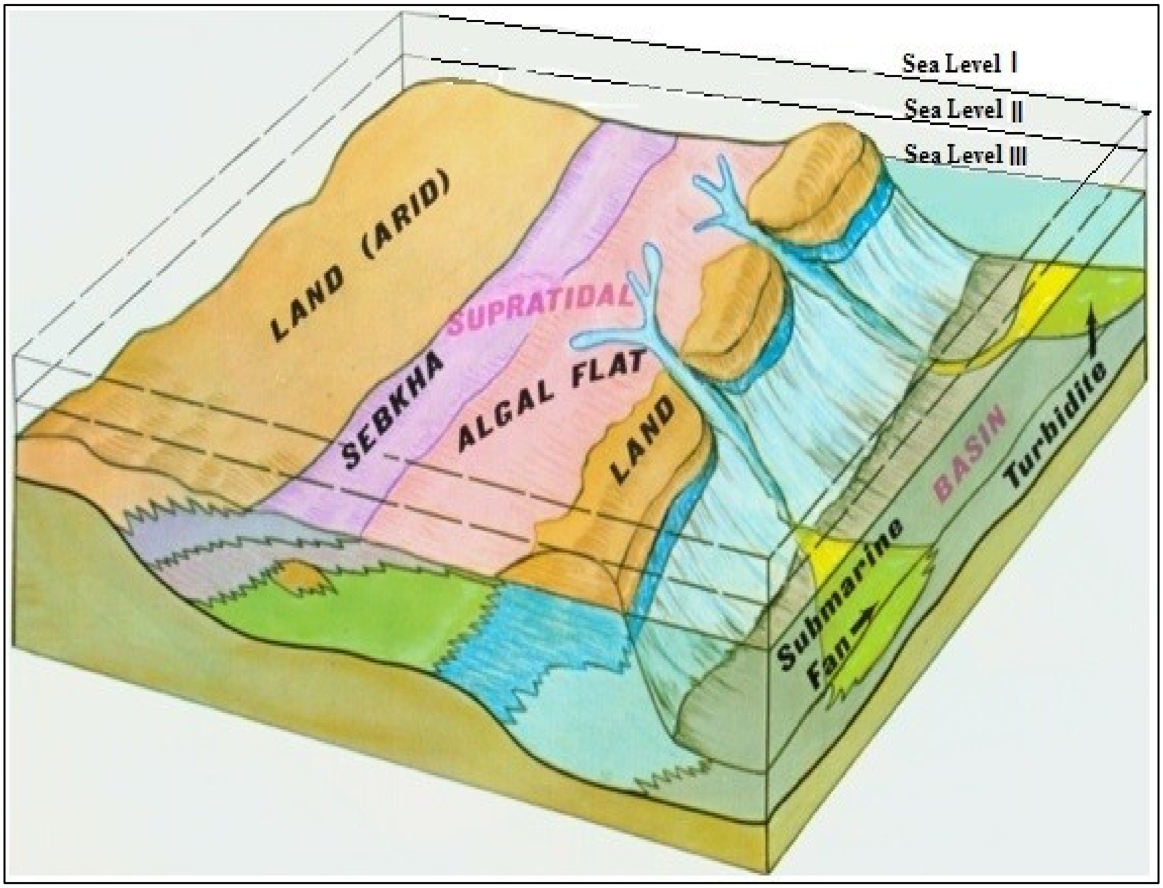


Figure 2.5. Schematic diagram illustrating deposition of submarine fan and turbidite sequences during a period of sea level lowstand (Silver and Todd 1969). Similar depositional environments existed for the Third Bone Spring Sandstone.

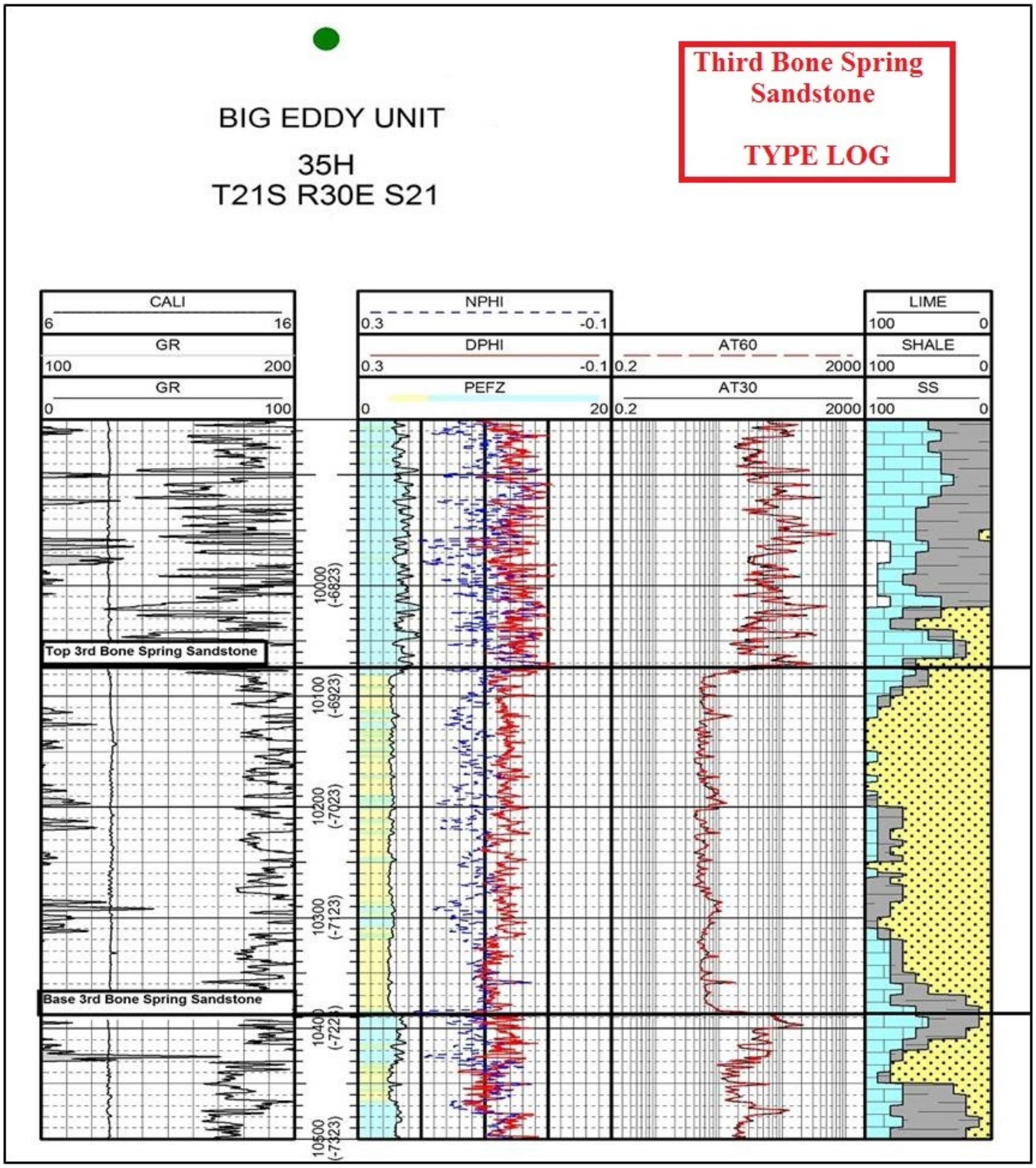


Figure 2.6. Type log from the Big Eddy Unit #35H pilot well in Eddy County, New Mexico showing the well log signature for the Third Bone Spring Sandstone. The average thickness for the Third Bone Spring Sandstone is roughly 390 ft (~118 m) and ranges from 250 ft. (~76 m) to 550 ft. (~167 m) across the study area. (Log scale abbreviations: CALI = caliper; GR = gamma ray (high readings indicate organic rich rock (Schmoker, 1981)); NPHI = neutron porosity; DPHI = density porosity; PEFZ = photo electric; AT60 = deep resistivity; AT30 = medium resistivity; LIME = limestone; SHALE = shale and SS = sandstone). Location of the Big Eddy Unit #35H is shown in Figures 2.7 and 2.8.

Dipmeter data, as well as structure and isopach patterns (Figures 2.7 & 2.8), indicate that the source area for the Third Bone Spring Sandstone is both from the northwest (Northwest Shelf) and from the northeast/east (Central Basin Platform). The lateral extent of the sandstone is widely distributed across the study area away from the shelf margins. The thickest portions of the Third Bone Spring Sandstone occur north of Big Eddy Unit, and east/southeast of James Ranch and Poker Lake Units (Figure 2.8). Productive Third Bone Spring Sandstone zones in these areas are very fine grained channel and levee/overbank facies with porosities of 7-18%.

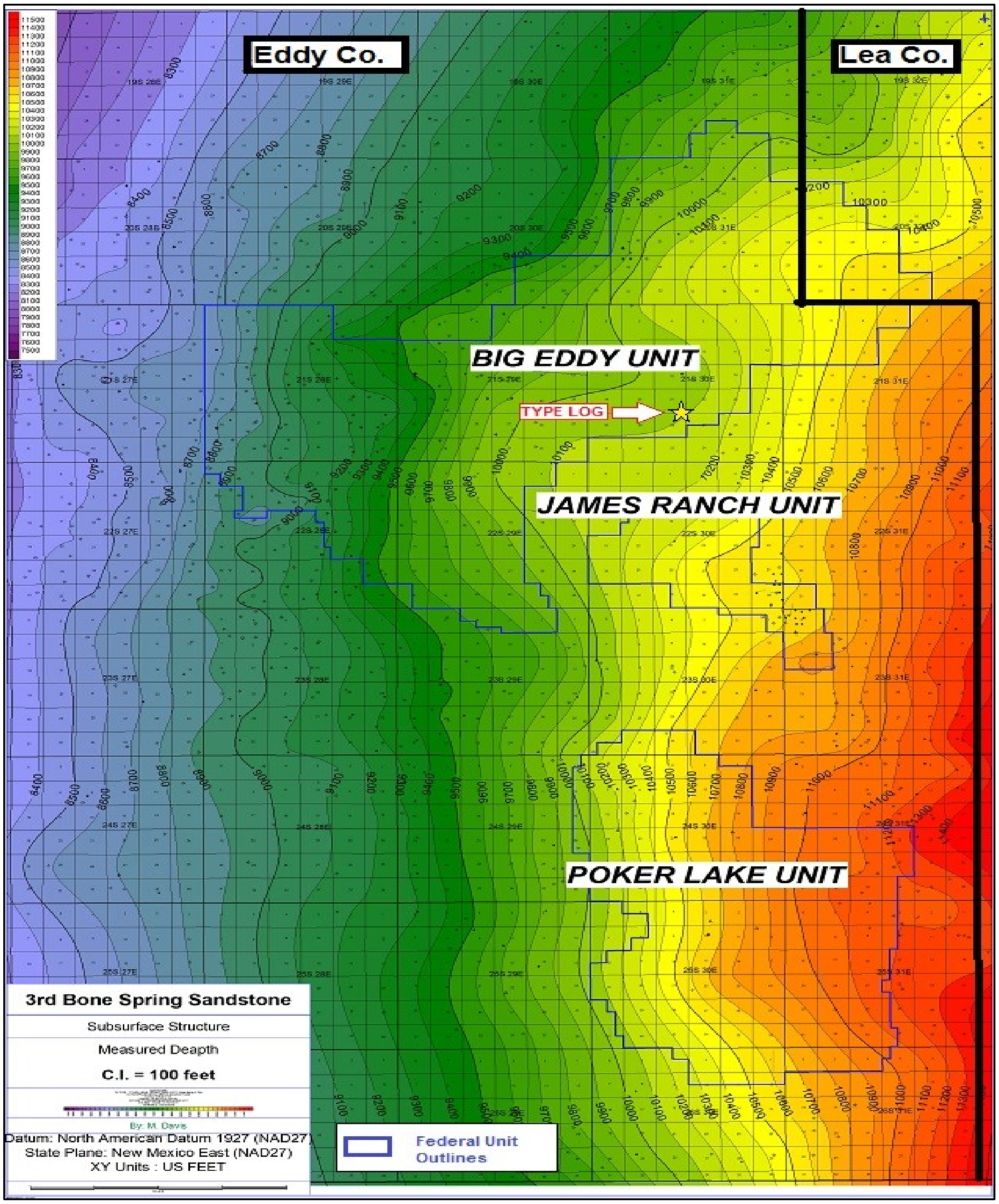


Figure 2.7. Subsurface structure map of the top of the Third Bone Spring Sandstone across Big Eddy, James Ranch and Poker Lake New Mexico Federal Units. The Third Bone Spring Sandstone is deepening to the east/southeast towards the Central Basin Platform. All wells from data set are plotted.

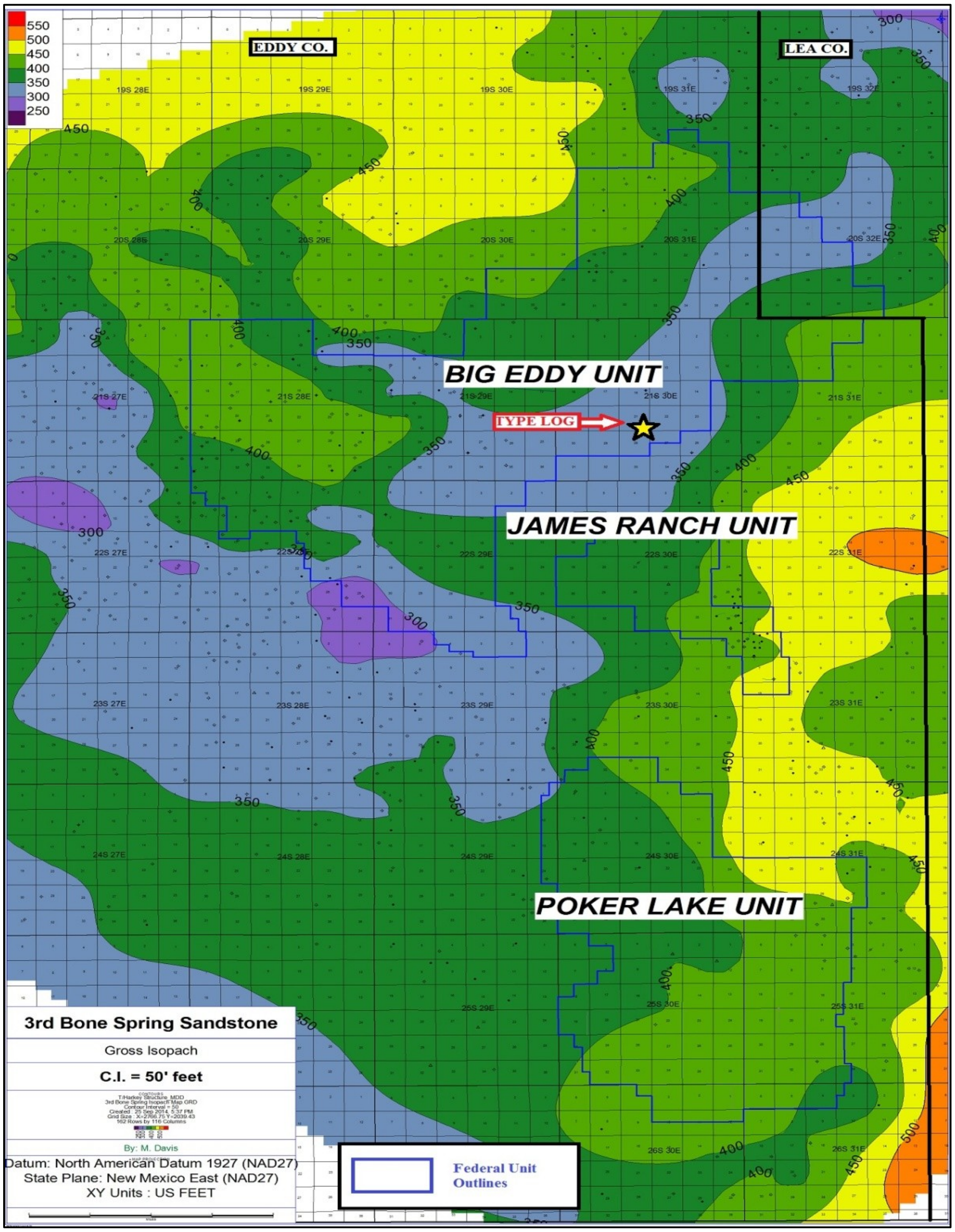


Figure 2.8. Isopach map of the Third Bone Spring Sandstone. The Third Bone Spring Sandstone is thickest in the areas north and east/southeast of the study area and thins towards the center of the study area. These isopach patterns indicate that the Third Bone Spring Sandstone was sourced from the north (Northwest Shelf) and from the east/southeast (Central Basin Platform).

Second Bone Spring Carbonate

Allochthonous Bone Spring carbonates were deposited in the Delaware Basin during sea level highstands when carbonate production on the Northwest Shelf was at a maximum (James & Mountjoy, 1983; Pearson, 1999; Ruppel & Ward, 2013). These carbonates consist largely of spiculitic, carbonaceous wackestones and lime mudstones (basinal), laminated dolomitic mudstone (slope), and dolomitized megabreccias (slope) (Gawloski, 1987). The Second Bone Spring Carbonate is composed of up to 900 ft. (275 m) of shelf derived carbonate material that was transported into the Delaware Basin via debris and turbidity flows that extend for tens of miles (Figure 2.9). Turbidite debris flows are the dominant mechanisms involved in the downslope transport of carbonate material in both modern and ancient shelf and basin slopes (Gawloski, 1987). The composition and texture of the Second Bone Spring Carbonate is directly related to the lithology and diagenetic history of the Abo-Yeso shelf counterparts (Figure 2.10) (Gawloski, 1987). The shelf derived clasts that comprise the Second Bone Spring Carbonate underwent early dolomitization prior to deposition (Wiggins & Harris, 1985).

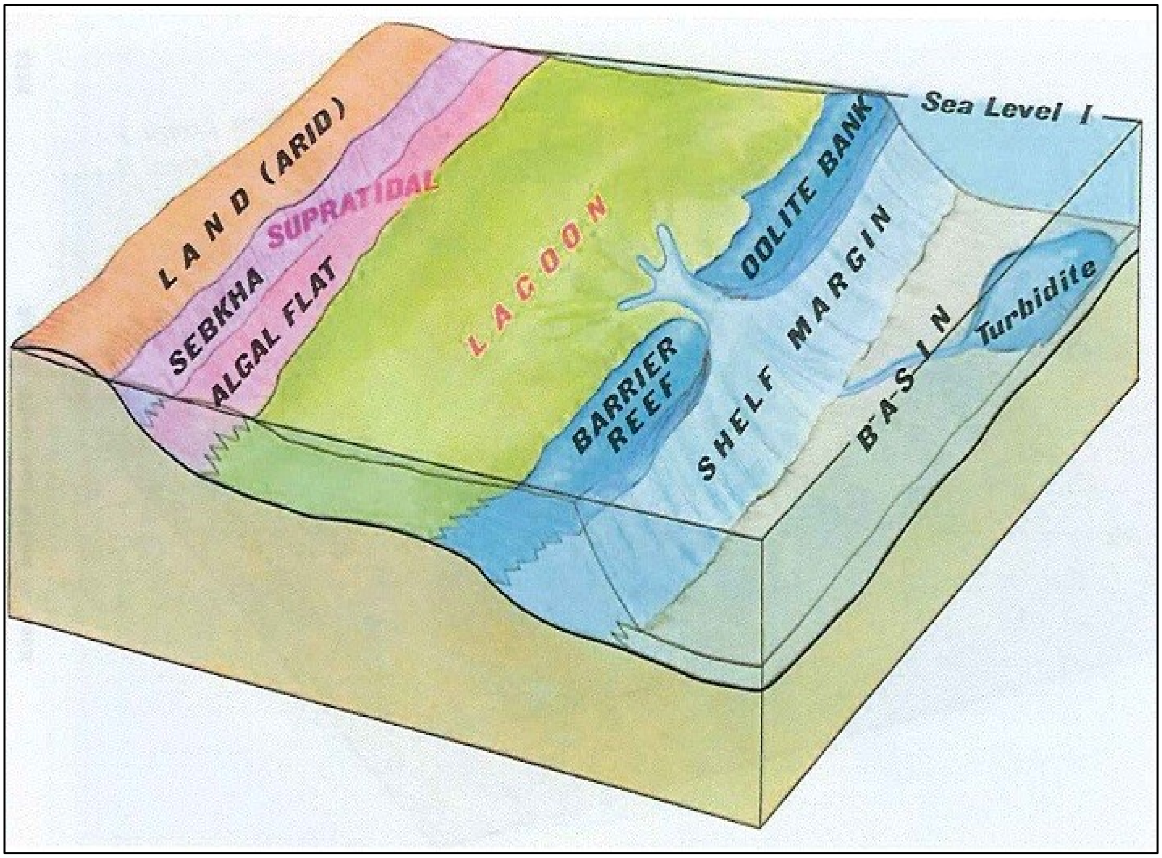


Figure 2.9. Schematic diagram illustrating the deposition of carbonate of debris flow and turbidite sequences during a period of sea level highstand (Silver and Todd 1969). Similar to the depositional environments for the Second Bone Spring Carbonate.

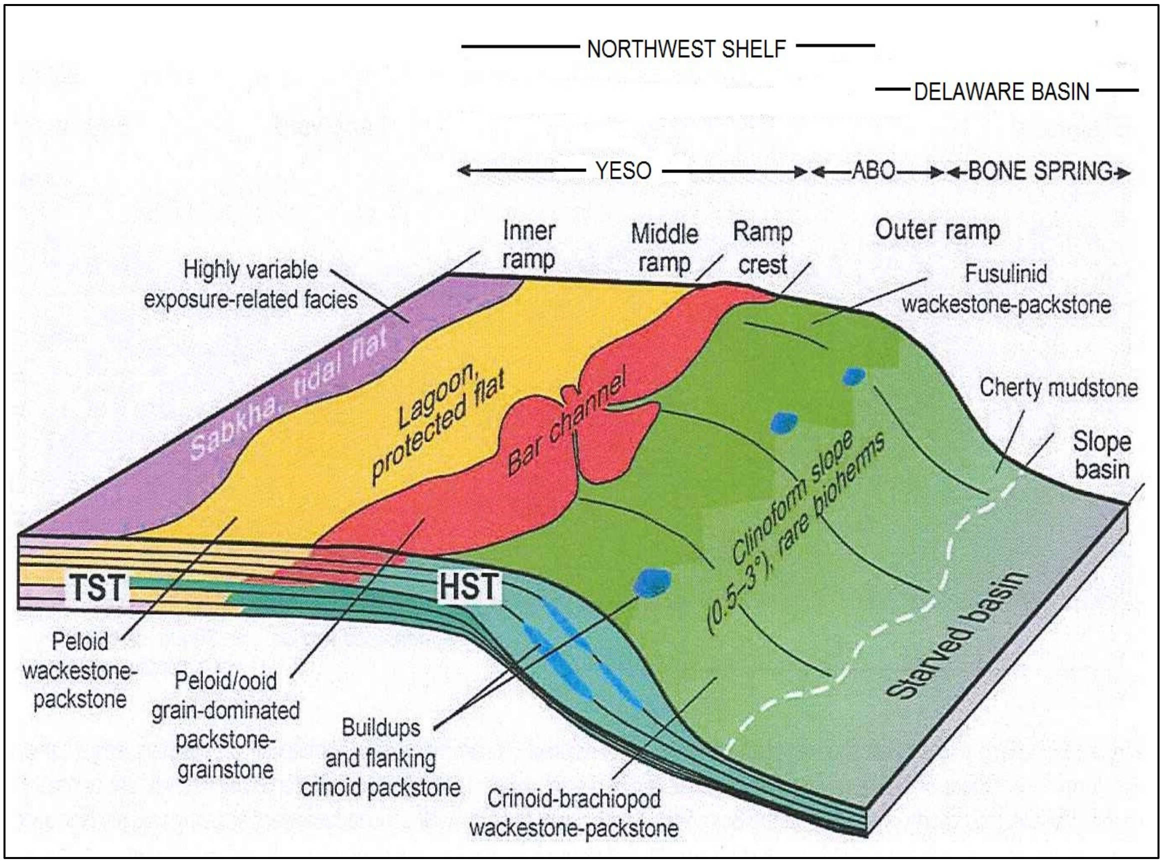


Figure 2.10. Depositional model for the Leonardian shallow-water carbonate platform in the Delaware Basin showing the general depositional setting of the study area. The depositional environment for the Leonardian carbonate platform is highly cyclic and comprised of aggradational upward-shallowing facies successions that vary according to accommodation and setting (Ruppel & Ward, 2013). HST = highstand systems tract; TST = transgressive systems tract.

In Big Eddy, James Ranch and Poker Lake Federal Units, the Harkey Mills sandstone is incased within the Second Bone Spring Carbonate. The siliciclastic members of the Bone Spring Formation are thought to have been deposited during periods of lea level regression and relative sea level lowstands (see Figure 2.5) (Pearson, 1999; Silver &Todd, 1969). Vertical facies variation and cyclic stacking patterns in the Second Bone Spring Carbonate indicates two depositional sequence systems, Type 1 and Type 2; based on sequence stratigraphic classifications from Van Wagoner et al., (1988). The first sequence (Type 1) involved a transition from a carbonate regressive systems tract to a siliciclastic lowstand systems tract. After the deposition of the Third Bone Spring Sandstone, the sea flooded the shelf margin, trapping sediment and starving the basin. In situ carbonate buildup on the Northwest Shelf would then collapse, resulting in 300-450 ft. of carbonate detritus deposited into the Delaware Basin. The sequence was then interrupted by a period of sea level lowstand that caused the subaerially exposed shelf to erode and allow sediment to bypass the shelf and to be deposited into the basin. This resulted in the deposition of the Harkey Mills sandstone. The second sequence (Type 2) consisted of a transition from a siliciclastic lowstand systems tract to a carbonate highstand systems tract. After the deposition of the Harkey Mills sandstone, sea level slowly rose toward the Abo-Yeso carbonate platform thus, once again starving the basin. Progradational stacking of in situ carbonate shelf deposits occurred in certain portions of the study area, particularly in Big Eddy Unit. Carbonate shelf deposits can be inferred on well logs by very low gamma ray and high density values (Figure 2.11).The thickness of the carbonate shelf deposits between the top of the Harkey Mills sandstone and the top of the Second Bone Spring Carbonate ranges from 160 to 400 ft. across the study area. Overall, the average thickness of the Second Bone Spring Carbonate is 700-800 ft.

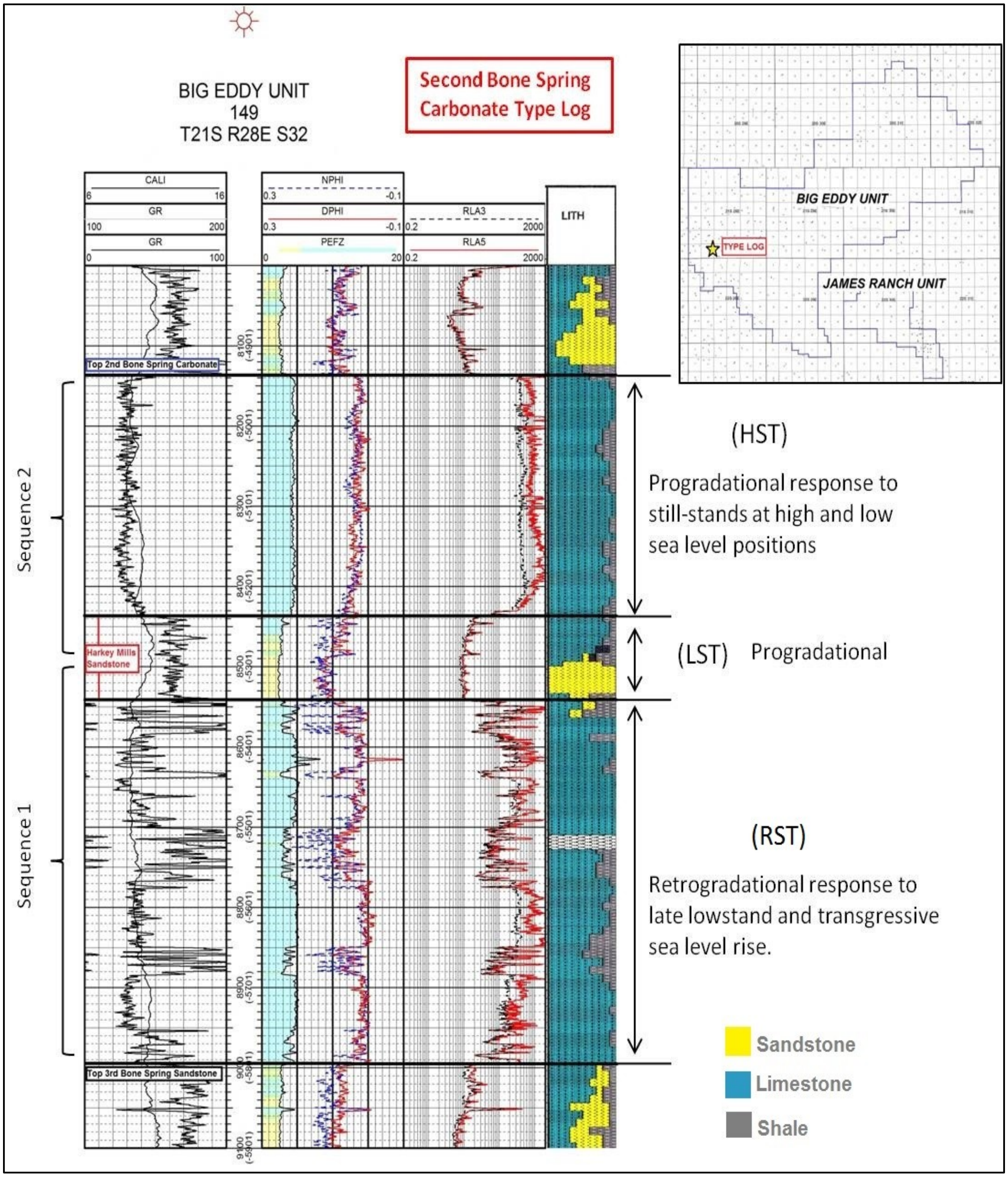


Figure 2.11. Type log from the Big Eddy Unit #149 well in Eddy County showing the well log signature and cyclic sequence patterns for the Second Bone Spring Carbonate. (Log scale abbreviations: CALI = caliper; GR = gamma ray; NPHI = neutron porosity; DPHI = density porosity; PEFZ = photo electric; RLA5 = deep resistivity; RLA3 = medium resistivity).

Second Bone Spring Sandstone

The Second Bone Spring Sandstone is a laterally extensive, heterogeneous assemblage of overlapping turbidity channels and submarine fan deposits representing a slope and basinal deep-marine sedimentary environment (Figure 2.12). Provenance studies by Hart (1997), Messa et al. (1996), Montgomery (Part I-1997) and Silver & Todd (1969), suggests that sediment for the Second Bone Spring Sandstone derived from both fluvial and aeolian process from the Northwest Shelf and was deposited into the Delaware Basin with a regional dip to the southeast. An aeolian component is indicated by the frosted texture of the quartz grains, the well sorted nature of the sediments, the noticeable lack of mud and the climatic conditions that existed during the Permian. Further to the east in Lea County, the Second Bone Spring Sandstone was probably sourced from the Central Basin Platform by submarine gravity flows (Figure 2.13) (Gawloski, 1987).

Carbonate debris flow deposits, similar to the Second Bone Spring Carbonate, occur as levee/overbank, slump and pelagic facies separate the Second Bone Spring Sandstone into an upper “A” sandstone and lower “B” sandstone (Figure 2.14). Facies distribution in this carbonate lens includes cross-bedded peloidal packstones and grainstones, bryozoans/algal boundstones and coral bearing skeletal debris (Gawloski, 1987; Saller et al., 1989). The thickness of this impermeable layer ranges from less than 10 ft. around the northern portion of Big Eddy Unit up to 100 ft. to the south in James Ranch and Poker Lake Units.

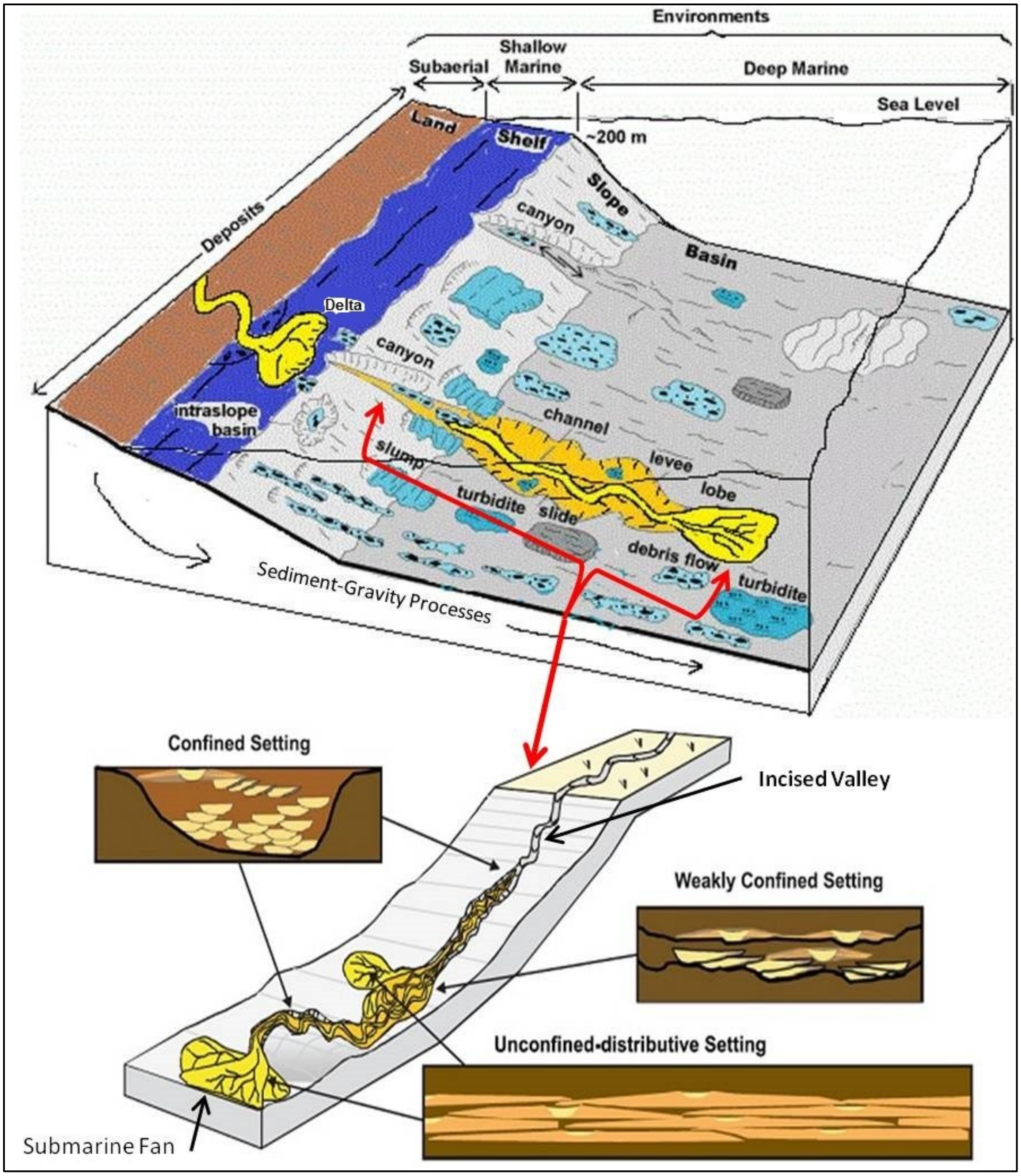


Figure 2.12. Schematic diagram showing the stratigraphic architecture of a fluvial depositional sequence influenced by deep marine (~650 ft.) turbidity channel and submarine fan deposits. Similar environments and depositional geometries may have existed for the Second Bone Spring Sandstone within the study area in the Delaware Basin. Modified from Funk, et al., (2012) and Shanmugam (2003).

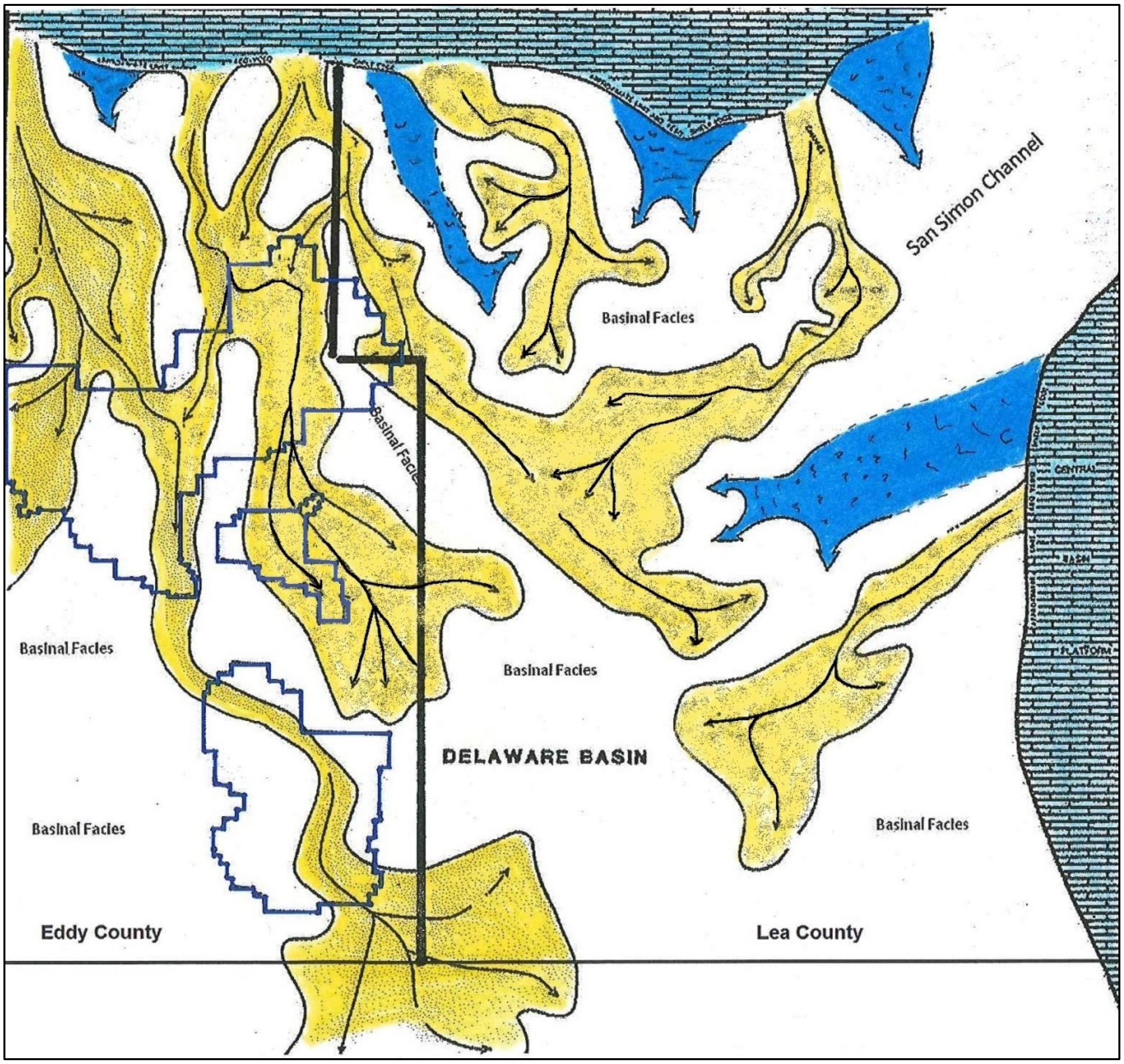


Figure 2.13. Distributions of turbidite channels and fans within the First Bone Spring Sandstone section in an approximate relation to Big Eddy, James Ranch and Poker Lake Federal Units. This distribution can also be used to model the geometries of the Second Bone Spring Sandstone. Modified from Gawloski (1987).

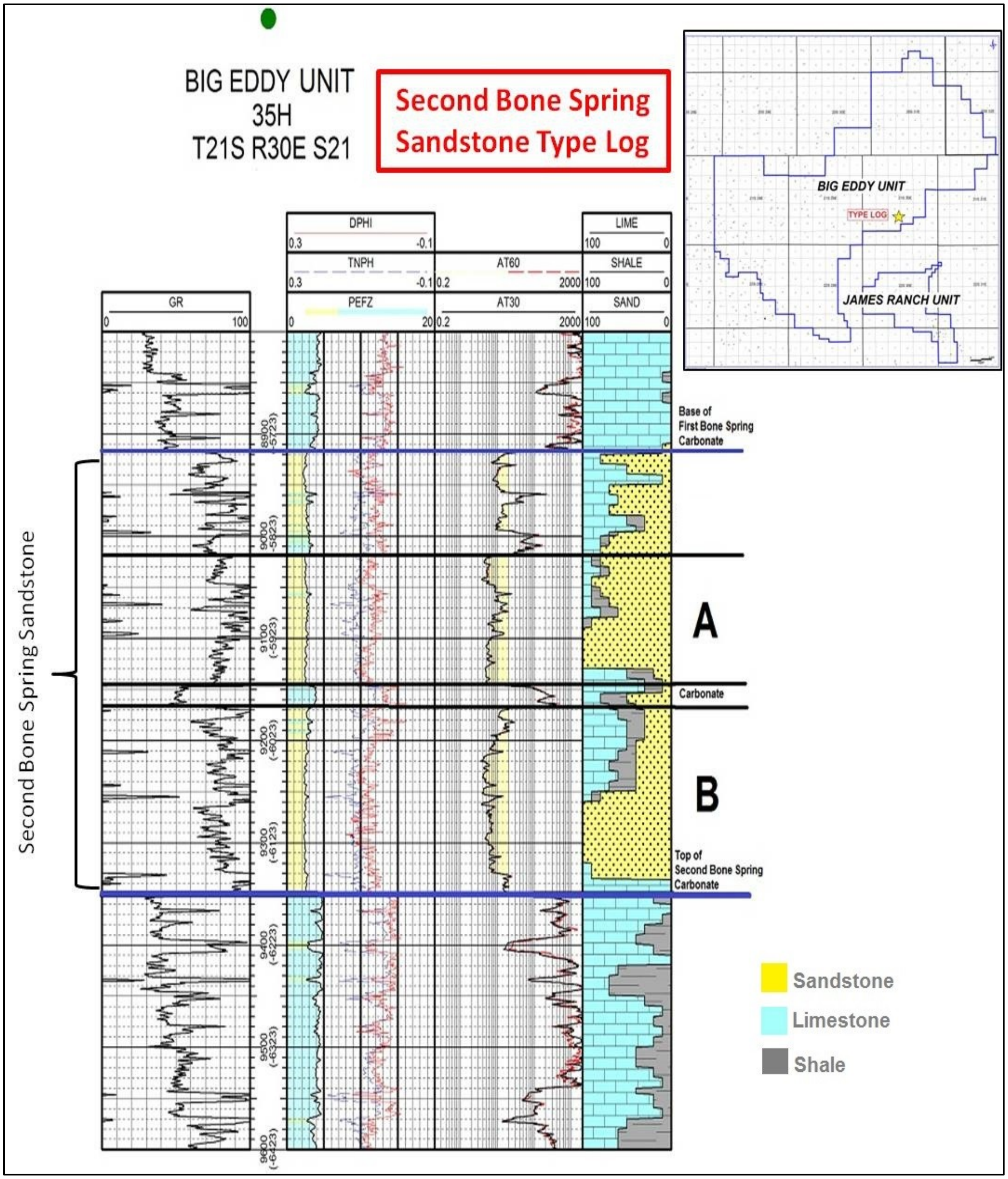


Figure 2.14. Type log from the Big Eddy Unit #35H pilot well in Eddy County showing the well log signature of the Upper 'A' and Lower 'B' Sandstones of the Second Bone Spring Sandstone. (Log scale abbreviations: GR = gamma ray; TNPH = neutron porosity; DPHI = density porosity; PEFZ = photo electric; AT60 = deep resistivity; AT30 = medium resistivity).

The Second Bone Spring Sandstone is one of the most active, horizontal drilling oil plays in the southeast New Mexico portion of the Delaware Basin including Big Eddy, James Ranch and Poker Lake Units (Figure 2.15). In the northernmost portion of the study area, proximal to the slope of the Northwest Shelf, stratigraphic straps in the turbidite sandstone deposits contain an estimated ultimate reserve between 300 and 400 MBO/well with an average initial production rate exceeding 1,300 BOE/day. Channel like deposits in the fairway of the turbidite tend to have the best reservoir quality rock with porosities (ϕ) between 8% to 20% and an average net pay thickness of 25 ft. using a porosity cutoff of 10% (Gawloski, 1987; Montgomery Part I, 1997). Distally, the Second Bone Spring Sandstone forms a submarine fan complex featuring stacked channel like sequences containing reservoir quality rock. The dominant reservoir traps are related to lateral pinch outs with thin impermeable siltstones acting as top seals.

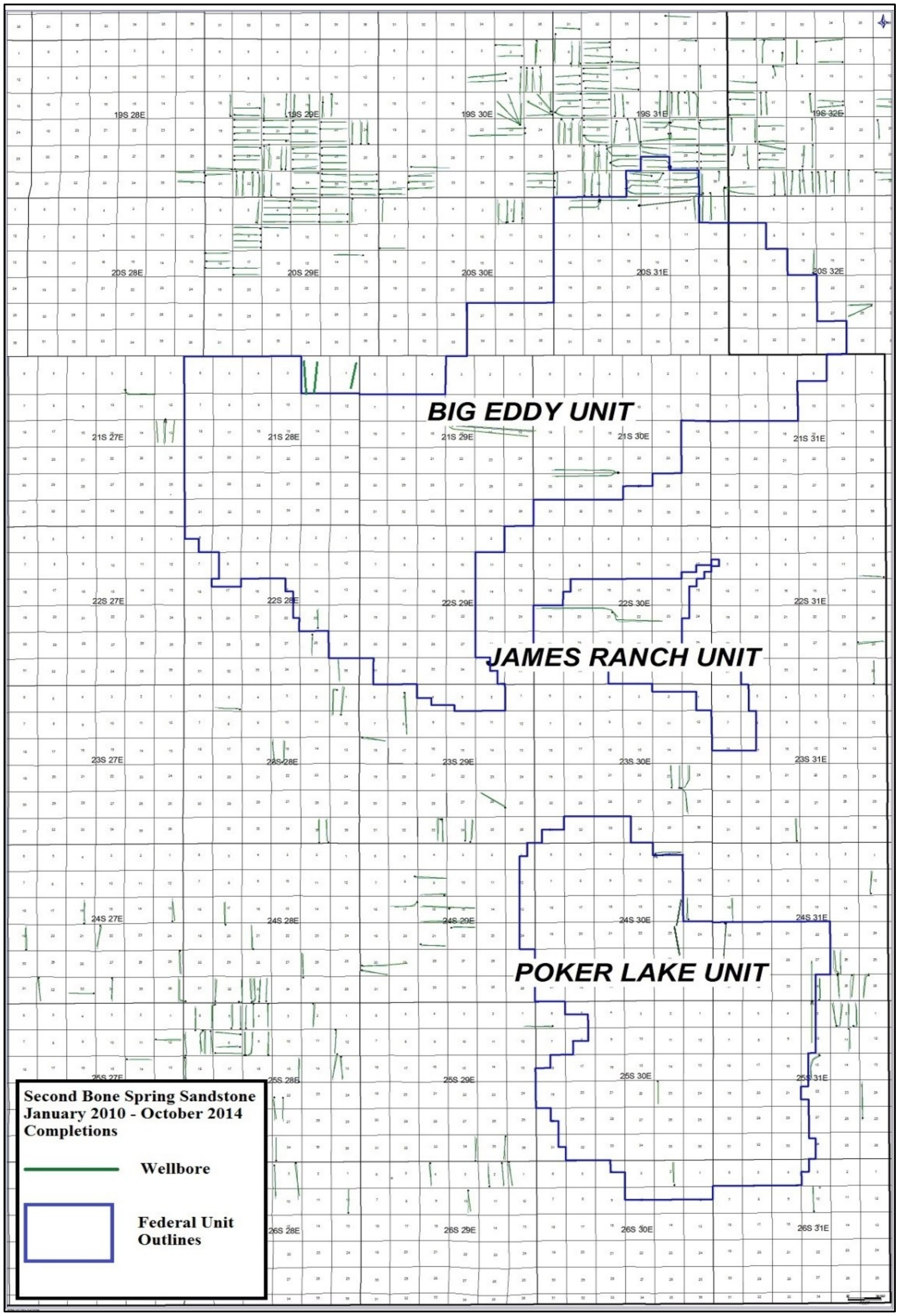


Figure 2.15. All Second Bone Spring Sandstone horizontal completions in the southeast New Mexico study area from January 2010 through October 2014.

Harkey Mills sandstone

The Harkey Mills sandstone is a siliciclastic sandstone interval interbedded with the Second Bone Spring Carbonate (Figure 2.16), that has not been formally defined as a member of the Bone Spring Formation. Historically, this sandstone was not a primary exploration target. Today, there are eight known vertical wells that produce from the Harkey Mills sandstone in Eddy County however; all of these wells were originally completed in a deeper zone. Among these wells is the Harkey 35 State #1(located in section 35 of T24S, R27E) which was recompleted to the Harkey Mills sandstone in 1995 (Figure 2.17). At the time this well was recompleted, no formal name had been given to this oil bearing sandstone interval within the Second Bone Spring Carbonate. Since then, this new vertical target has been referred to by some as the Harkey sandstone.

During this research it was found that the term Harkey is also used to informally refer a sandstone formation in the Midland Basin. Tindell (1954) published data on the Hiawatha et al., #1 Jeff Harkey well that was completed in a sub-member of the Canyon Formation locally known as the Harkey sandstone in Butler Canyon Field, Schleicher County, Texas. Also, Hoffacker (1990) published a type log featuring the Harkey sandstone form the Eastern Shelf in Schleicher County illustrating the thin, discontinuous sandstones present between the Strawn Carbonates and the overlying Palo Pinto and Adams Branch Limestones (Figure 2.18).

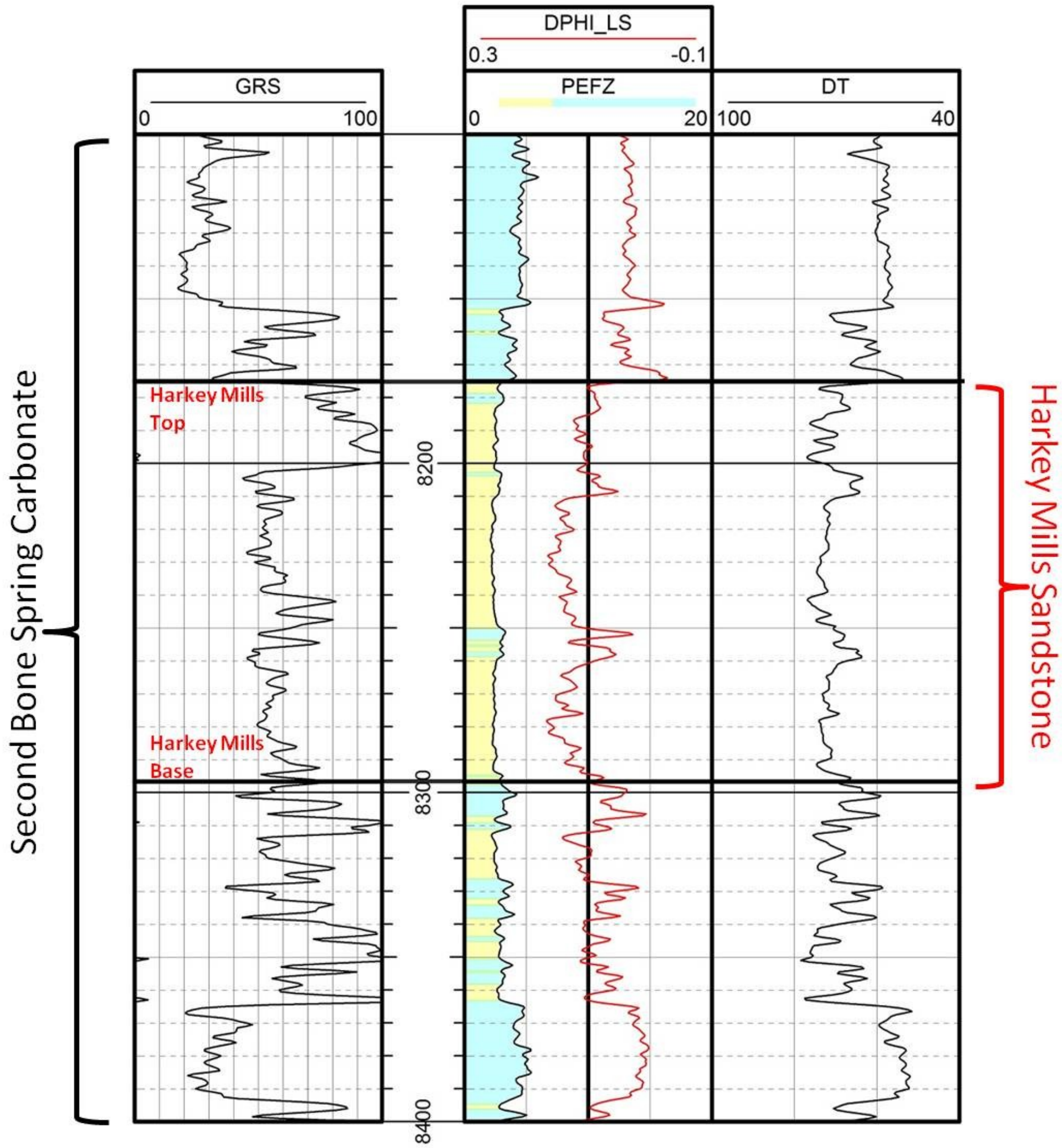


Figure 2.16. Well log signature of the Harkey Mills sandstone. The Harkey Mills sandstone is incased in the Second Bone Spring Carbonate. (Log scale abbreviations: GRS = gamma ray; DPHI_LS = density porosity on a limestone scale; PEFZ = photo electric; DT = sonic).

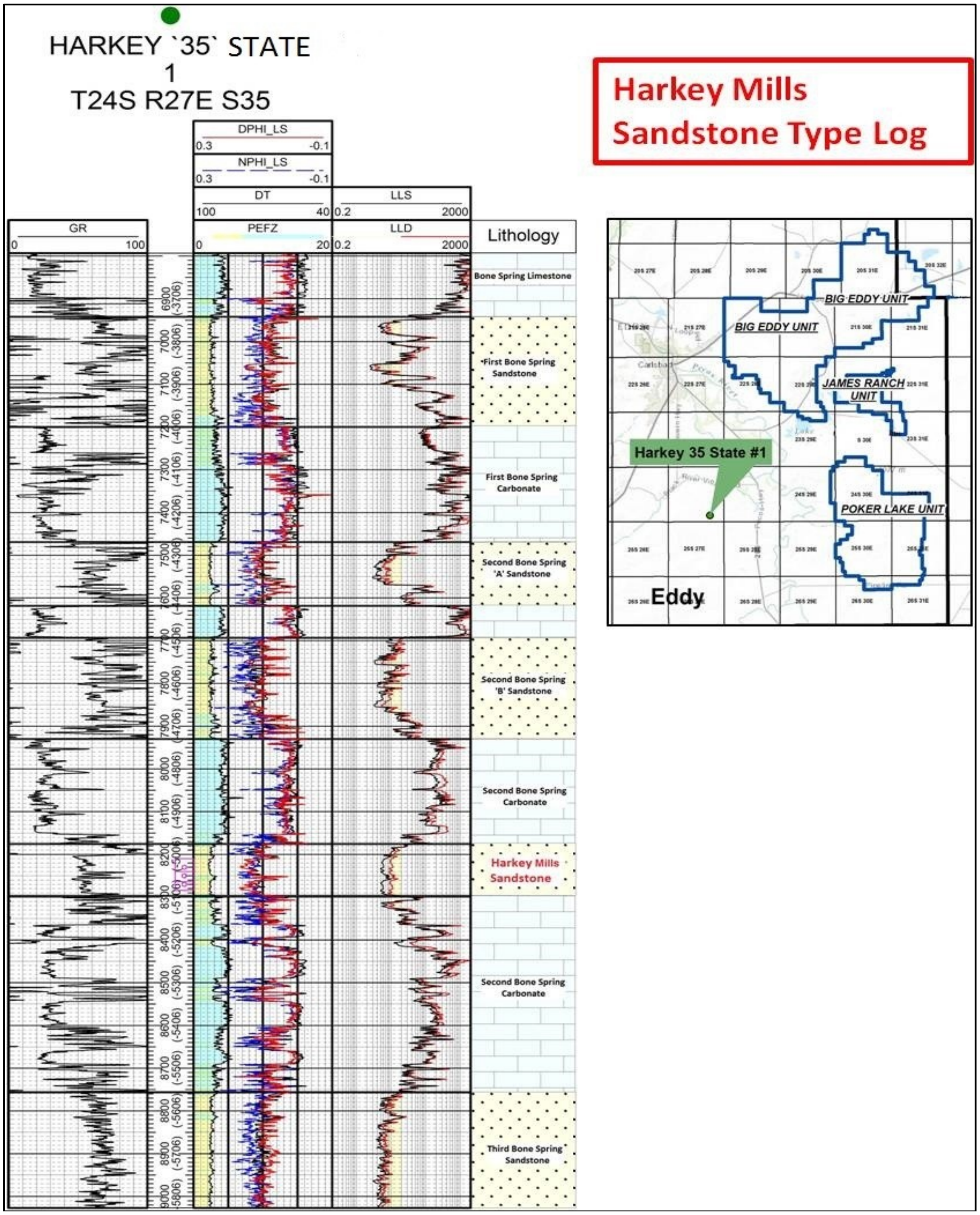


Figure 2.17. Type log from the Harkey 35 State #1 and reference location to Big Eddy, James Ranch and Poker Lake Federal Units. (Log scale abbreviations: GR = gamma ray; NPHI_LS = neutron porosity on a limestone scale; DPHI_LS = density porosity on a limestone scale; PEFZ = photo electric; DT = sonic; LLD = deep resistivity; LLS = shallow resistivity).

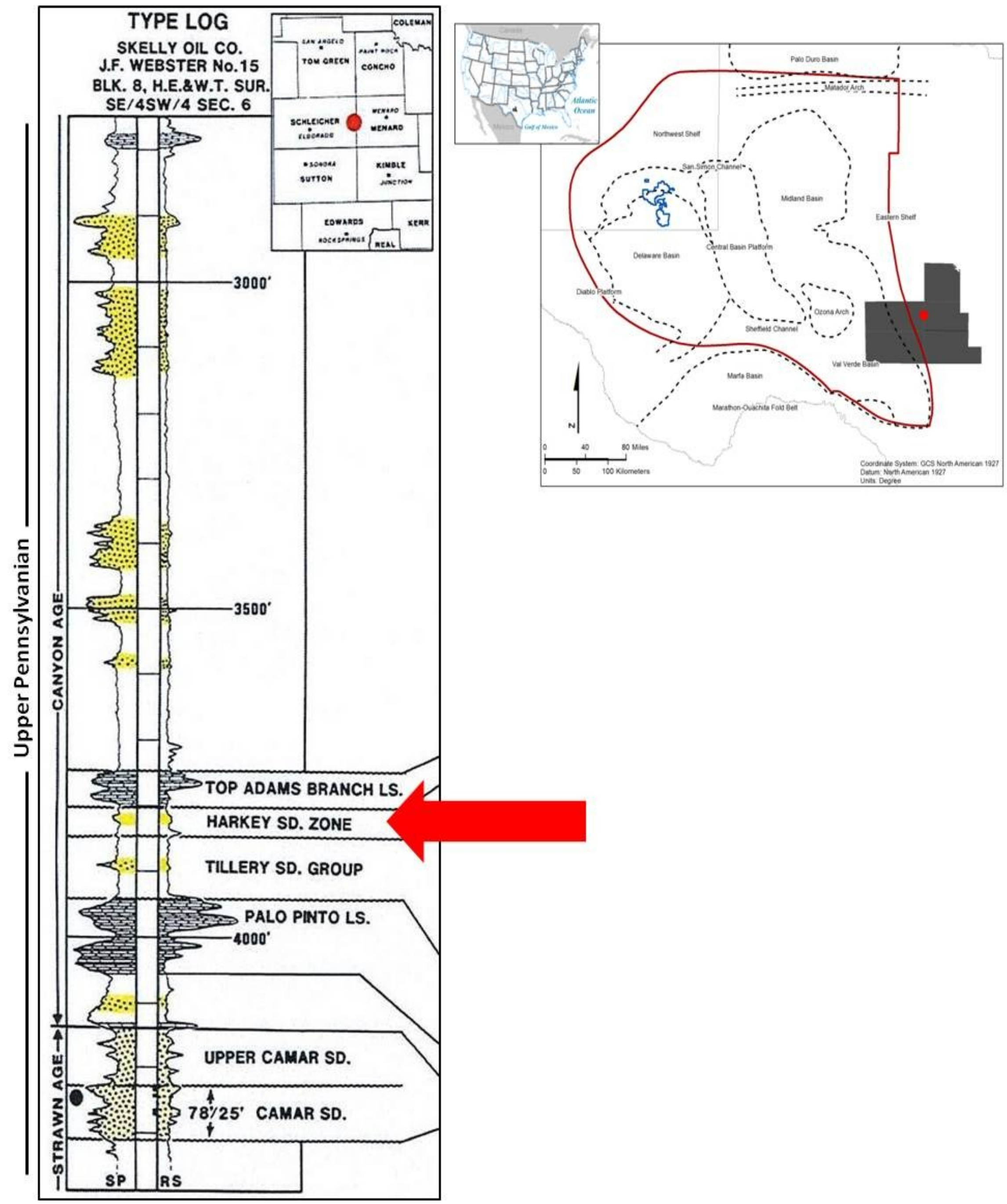


Figure 2.18. Type log from the Midland Basin depicting Pennsylvanian (Missourian) age strata in Schleicher County, Texas. Note: the Harkey sandstone depicted here is not equivalent to the Permian (Leonardian) Harkey sandstone in Eddy and Lea Counties, New Mexico. Modified form Hoffacker (1990).

All references to the Harkey sandstone in the Midland Basin refer to sandstone that is Upper Pennsylvanian (Missourian) in age and is a sub-member of the Canyon Formation. It is suggested that Harkey Mills sandstone be the correct stratigraphic nomenclature in the Delaware Basin in order to avoid any confusion with the older Harkey sandstone in the Midland Basin. The name Harkey Mills sandstone was derived from a geographic locale due south of the Harkey 35 State #1 well called the Harkey Double Mills.

Of the eight known vertical recompletions in the Harkey Mills sandstone, only one well is located within Big Eddy, James Ranch or Poker Lake Federal Units. The Eddy /C/ State #1 located in Big Eddy Unit (section 2 of T22S R28E) was completed in the Harkey Mills sandstone zone in 1980 and produced until 1984. The remaining vertical wells are located in the southwestern most portion of the study area (Figure 2.19). Since 2008, there are four known horizontal completions in the Harkey Mills sandstone in Willow Lake West field, Eddy County, New Mexico (Figure 2.20). These completions are located 13-20 mi to the south and west of Big Eddy, James Ranch and Poker Lake Federal Units. Production information for the completed Harkey Mills sandstone wells is located in Tables 2.1 and 2.2.

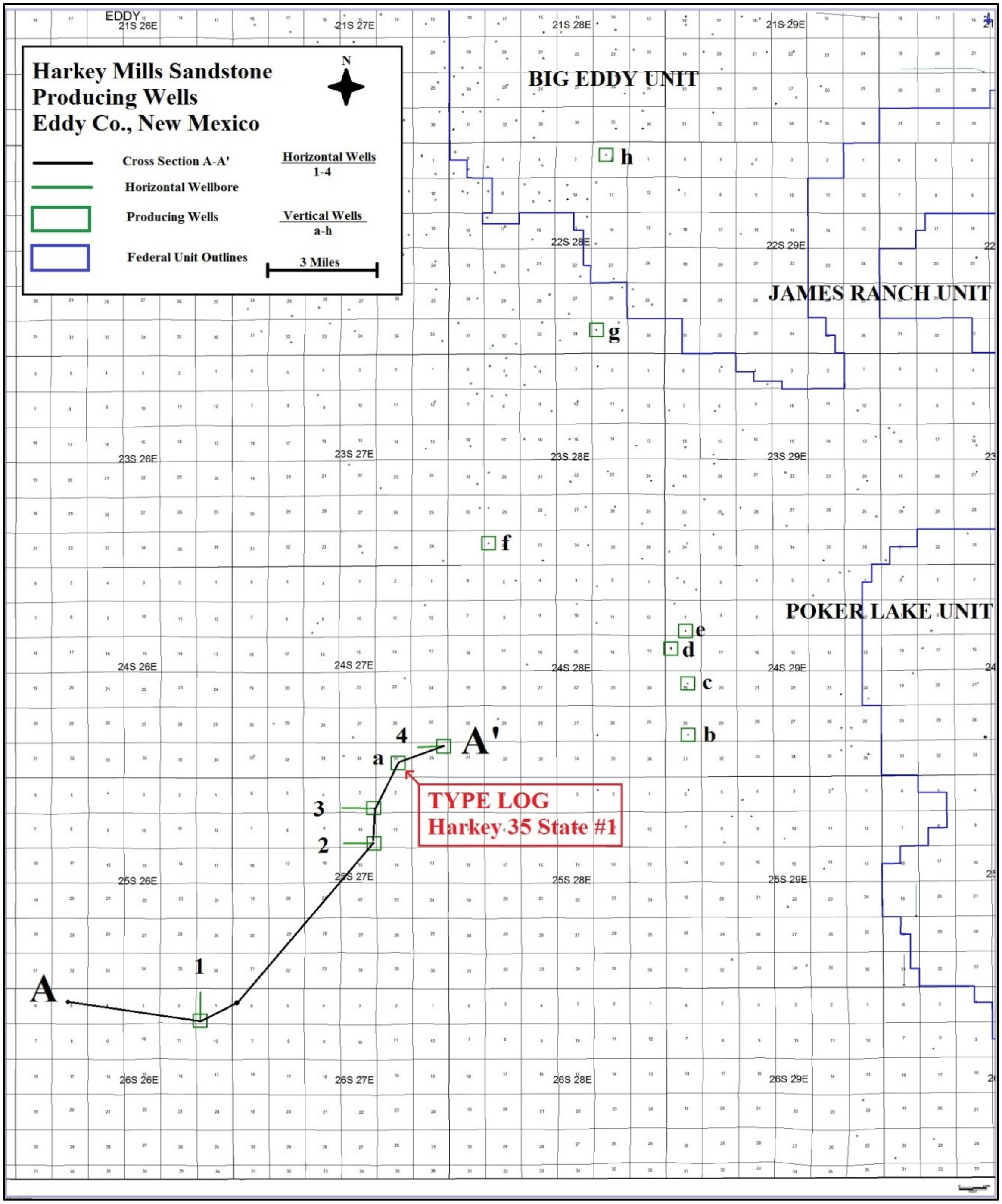


Figure 2.19. Map showing the location of all known Harkey Mills sandstone production in Eddy County, southeast New Mexico. Vertical producing wells are labeled a-h and horizontal producing wells are labeled 1-4. Also depicted is cross section line A-A' illustrating horizontal Harkey Mills sandstone completions.

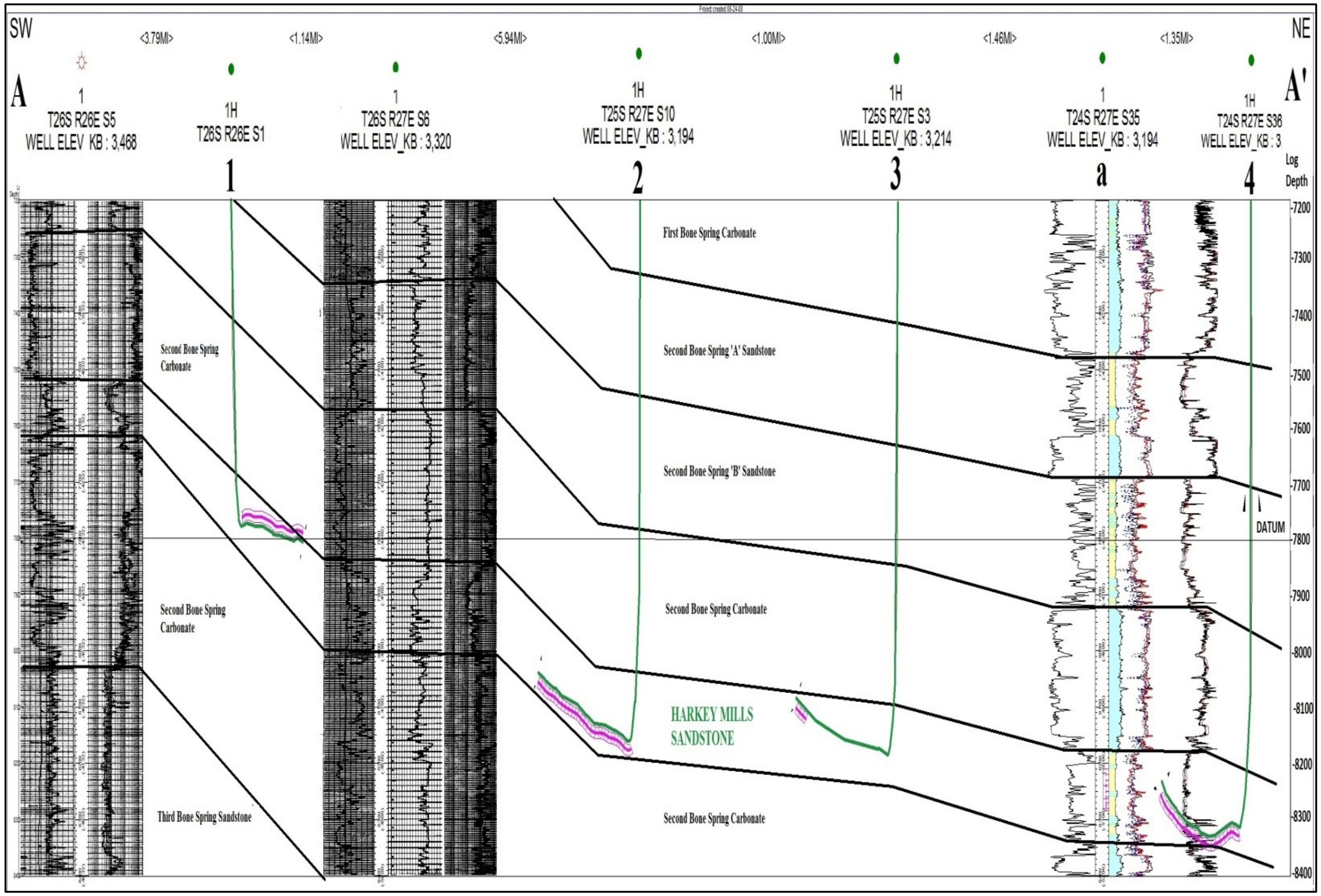


Figure 2.20. Structural cross section A-A’ illustrating all known Harkey Mills sandstone horizontal production in Eddy County, southeast New Mexico. Structural Datum = 7,800 feet below sea level. (Cross section location is shown in Figure 2.19).

Table 2.1. Harkey Mills sandstone horizontal production history in Eddy Co., New Mexico.

Horizontal Well	Completion Date	Initial Production/Day	Production Method	Cumulative Production	EUR	Current Status
1	8/2013	206BO + 250MCF + 619BW	Pumping	64MBO + 314MMCF + 53MBW	720 MBOE	Active
2	3/2011	148BO + 1,235BW	Flowing *	28.6MBO + 160MMCF + 56.5MBW	443 MBOE	Active
3	8/2011	154BO + 314MCF + 1,170BW	Pumping	40.5MBO + 160MMCF + 77.8MBW	613 MBOE	Active
4	11/2008	121BO + 190MCF + 113BW	Pumping	34MBO + 72MMCF + 32MBW	347 MBOE	Active

Table 2.2. Harkey Mills sandstone vertical production history in Eddy Co., New Mexico.

Vertical Well	Completion Date	Initial Production/Day	Production Method	Cumulative Production	EUR	Current Status
a	2/1995	35BO + 125MCF + 14BW	Pumping	33MBO + 688MCF + 21MBW	323 MBOE	Active
b	2/1997	14BO + 6BW	Pumping	11.8MBO + 1MBW	103 MBOE	Recompleted to a shallower zone
c	12/1990	77BO + 100MCF + 23BW	Pumping	10.6MBO + 14.5MMCF + 1.7MBW	152 MBOE	Recompleted to a shallower zone
d	6/1998	102BO + 260MCF + 20BW	Flowing	16.3MBO + 55.8MMCF + 7.6MBW	110 MBOE	Recompleted to a shallower zone
e	6/2014	80BO + 239MCF + 53BW	Pumping	773BO + 1.3MMCF + 53BW (*)	159 MBOE	Active
f	8/2007	24BO + 85MCF + 17BW	Pumping	6.7MBO + 36MMCF + 27MBW	49 MBOE	Active
g	8/1991	22BO + 72MCF + 9BW	Pumping	4.1MBO + 17.6MMCF + 1.5MBW	119 MBOE	Recompleted to a shallower zone
h	7/1980	64BO	Swab/Pumping	5.1MBO + 8.5MMCF + 4.2MBW	166 MBOE	Plugged and Abandoned

Table 2.1. Estimated Ultimate Reserve (EUR) was calculated based off of a 160 acre drainage area and 6:1 oil to natural gas ratio. (Note: (*) indicates that well #2 initially flowed for the first eleven days of production and then was put on artificial lift. This information was courteously provided by Yates Petroleum Corporation). Table 2.2. Estimated Ultimate Reserve (EUR) was calculated based off of a 25 acre drainage area and 6:1 oil to natural gas ratio. (Note: (*) indicates only the first month production information was available for well e). Production information was publically obtained through the New Mexico Oil Conservation Division (NMOCD) and/or Information Handling Service (IHS).

Chapter 3

Methods

Approximately 625 wells and three rotary sidewall core studies in Eddy and Lea Counties, southeast New Mexico were used to determine the petroleum geology of the Harkey Mills sandstone in Big Eddy, James Ranch and Poker Lake Federal Units. Deep vertical production, predating production from the Bone Spring Formation, from zones such as the Wolfcamp, Strawn, Atoka and Morrow Formations provided significant well log coverage through the Bone Spring Formation in the Federal Units. Total well control however, was somewhat limited in areas including eastern Big Eddy Unit, western James Ranch Unit and north of Poker Lake Unit due to active potash mining.

A network of stratigraphic and structural cross sections depicting the Bone Spring Formation was constructed in order to evaluate the subsurface geology of the Harkey Mills sandstone (Figure 3.1). Well-to-well log correlation of the Bone Spring Formation was used to identify the Harkey Mills sandstone across the study area and permitted a direct comparison between the geology of the Third and Second Bone Spring Sandstones. Subsurface structure and gross thickness (isopach) maps were also constructed to help illustrate the depositional geometries and patterns for the Harkey Mills sandstone. Well logs along with specific well data in New Mexico were downloaded from the New Mexico Oil Conservation Division.

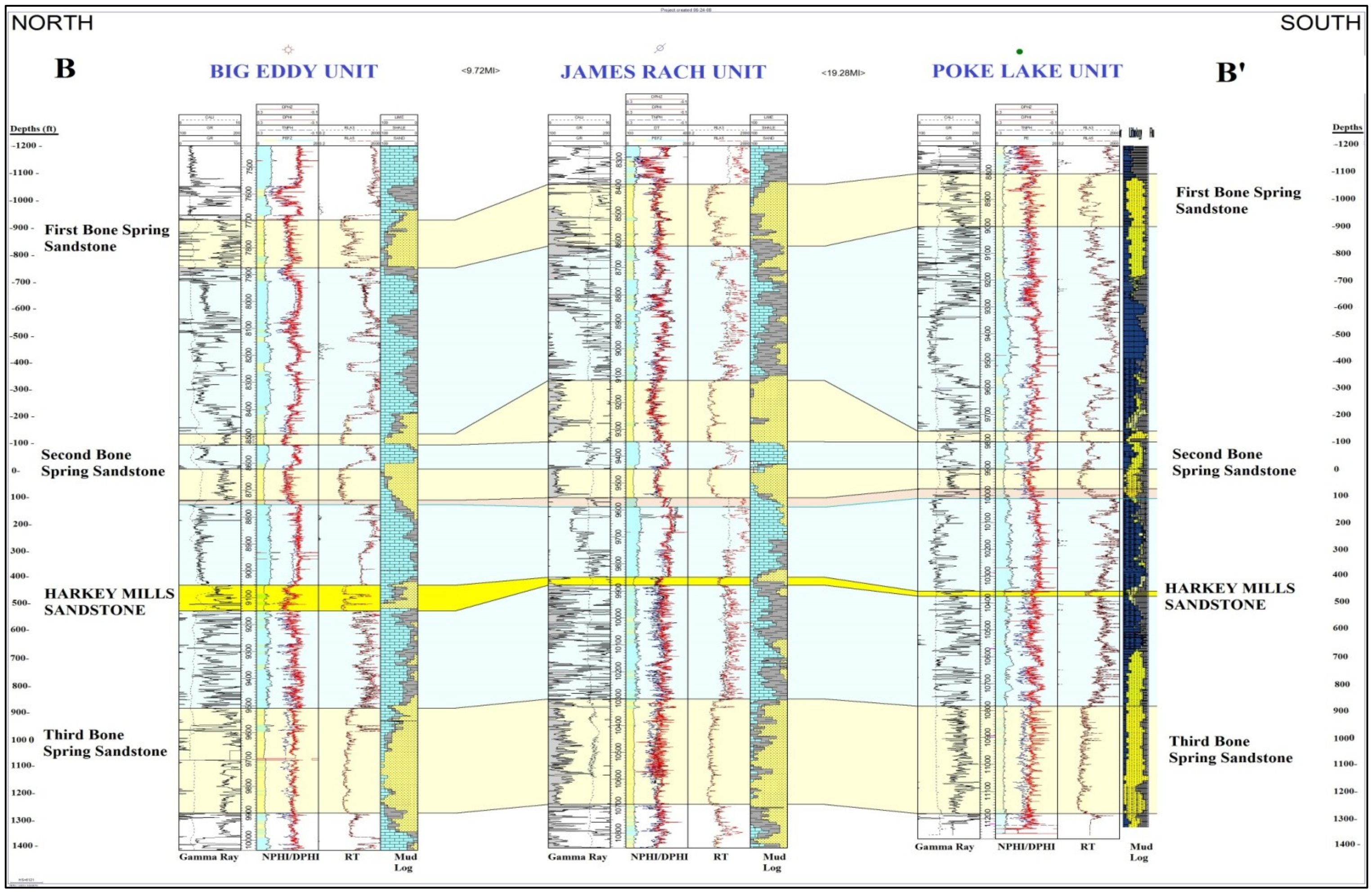


Figure 3.1. Stratigraphic cross section B-B' depicting the Bone Spring Formation across the study area. The datum is the top of the Second Bone Spring 'B' Sandstone

Reservoir parameters of the Harkey Mills sandstone were investigated by determining net thickness, water saturation (Sw) and apparent porosity-thickness (ϕH) values in Big Eddy, James Ranch and Poker Lake Federal Units from well logs (see wells in Appendix A). Net isopach maps were calculated using an 8% ϕ cutoff based on a sandstone matrix with Rt values of 5 – 12 ohms. Typically in the Delaware Basin, density/porosity logs are calibrated to a limestone matrix density (2.71 gm/cc) therefore, the curve is indexed as 'limestone equivalent porosity'. Since the Harkey Mills sandstone is predominately quartz (2.65 gm/cc) the density/porosity log must be corrected to index 'sandstone equivalent porosity'. This correction is made by subtracting 2 porosity units from the limestone porosity units to get apparent sandstone porosity.

The Archie equation (Table 3.1) was used to determine water saturations for the Harkey Mills sandstone in the Federal Units. Sandstone reservoirs within the Bone Spring Formation with water saturations up to 60% have proved to be economic in the Delaware Basin (Gawloski, 1987). Apparent porosity-thickness (ϕH) maps are used to help identify "sweet spots" and were created by taking a weighted average of the porosity per unit of thickness without correcting for TOC (Total Organic Carbon).

The petroleum geology of the Second Bone Spring Sandstone was investigated in order to properly quantify the horizontal production potential of the Harkey Mills sandstone in the New Mexico Federal Units. The Second Bone Spring Sandstone is currently one of the most active horizontal targets in the Federal Units and appears to have depositional geometries similar to the Harkey Mills sandstone. Geochemical data from rotary sidewall core data from three wells in Big Eddy (Big Eddy Unit #254H and

#35H pilot wells) and James Ranch (James Ranch Unit 21 #1 SWD) Units permitted a direct comparison between the reservoir parameters of the Second Bone Spring Sandstone and the Harkey Mills sandstone.

Table 3.1. Archie equation for estimating water saturation (Sw) (Archie, 1952). This modified equation will be used to estimate water saturations for the Harkey Mills sandstone in Big Eddy, James Ranch and Poker Lake Federal Units. (* values obtained from L. Ludwick, Petrophysical Specialist, BOPCO, L.P.).

$Sw = (F*Rw/Rt)^{1/n}$		
Variable	**Description**	**Value**
F	Formation Resistivity Factor	$F = (a/\phi^m)$
a m n	tortuosity factor (a) cementation exponent (m) saturation exponent (n)	a = 1* m = 1.8* n = 2*
Rw	resistivity of fluids in the rock	Rw = 0.03*
Rt	resistivity of the combined rock and fluid	measured by the deep induction resistivity tool

Chapter 4

Results

Using the well-to-well log correlation method, the Harkey Mills sandstone was identified and mapped across Big Eddy, James Ranch and Poker Lake Federal Units. The goal of this research was to determine the petroleum geology of the Harkey Mills sandstone and in doing so, define the Harkey Mills sandstone as a mappable unit in the Bone Spring Formation and determine the depositional geometries, reservoir properties and potential as a horizontal drilling target in the New Mexico Federal Units. To achieve this goal, it was crucial that all interpretations were: a) consistent throughout the study area, b) based off of the maximum amount of well control and c) geologically plausible.

The Harkey Mills sandstone is light gray to light brown, fine to very fine grain, well sorted and moderately cemented with calcite. Isopach patterns and lithofacies distributions indicate that the Harkey Mills sandstone was sourced from the Northwest Shelf to the north and northwest of the New Mexico Federal Units (Figure 4.1). The frosted texture of the sub-round to sub-angular grains suggests an aeolian transport system to the shelf prior to deposition into the basin. This would be consistent with the other sandstone members of the Bone Spring Formation that are thought to have once originated as a terrestrial dune field that migrated to the edge of the Northwest Shelf during the Early Permian.

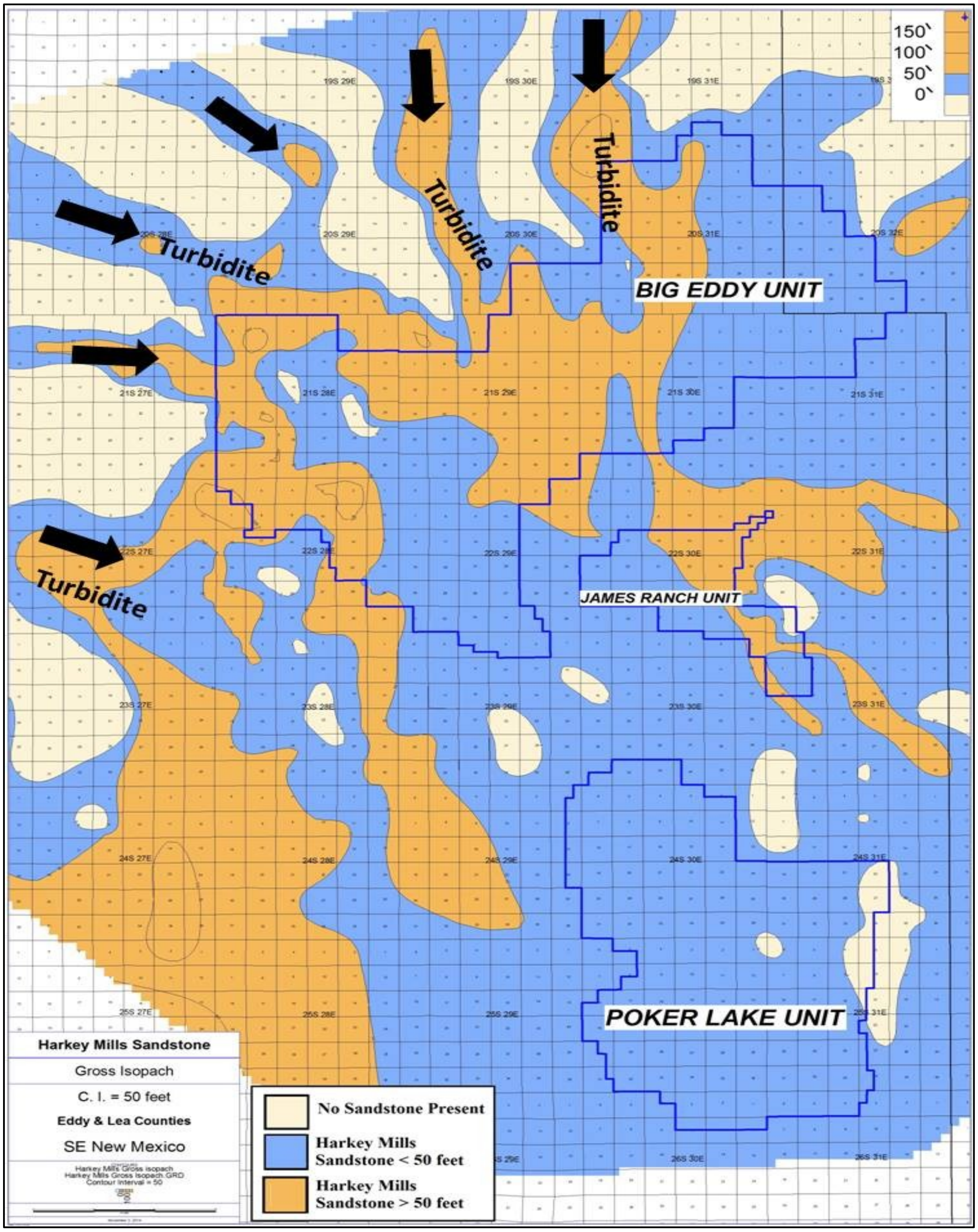


Figure 4.1. Gross isopach map (C.I. = 50 feet) showing the distribution and flow direction of sandstone turbidite pathways during the deposition of the Harkey Mills sandstone across Big Eddy, James Ranch and Poker Lake Federal Units.

During a lowstand sequence environment, the Harkey Mills sandstone was distributed into the basin through a series of thick (> 50 feet) channel like turbidite pathways. As the turbidity flow propagated deeper into the basin, the frontal lobe of the turbidite wedge transitioned into a distal fan deposit that formed a thin sheet of sediment over the study area (Figure 4.2). Sea level during this time was in a state of regression, so water depths were probably relatively shallow.

The Harkey Mills sandstone is laterally continuous across the study area with a regional dip to the southeast (Figure 4.3). The Harkey Mills sandstone was probably deposited as a turbidite “pulse” that spread sediment throughout the study area however, local paleo-highs in the Second Bone Spring Carbonate, before the deposition of the Harkey Mills sandstone, occur sporadically in the basinal areas where the sandstone is relatively thin. After deposition of the Harkey Mills sandstone, sea level slowly began to transgress back toward the shelf margin depositing 160 ft. to 400 ft. of in situ carbonate sediment between the top of the Harkey Mills sandstone and the base of the Second Bone Spring Sandstone.

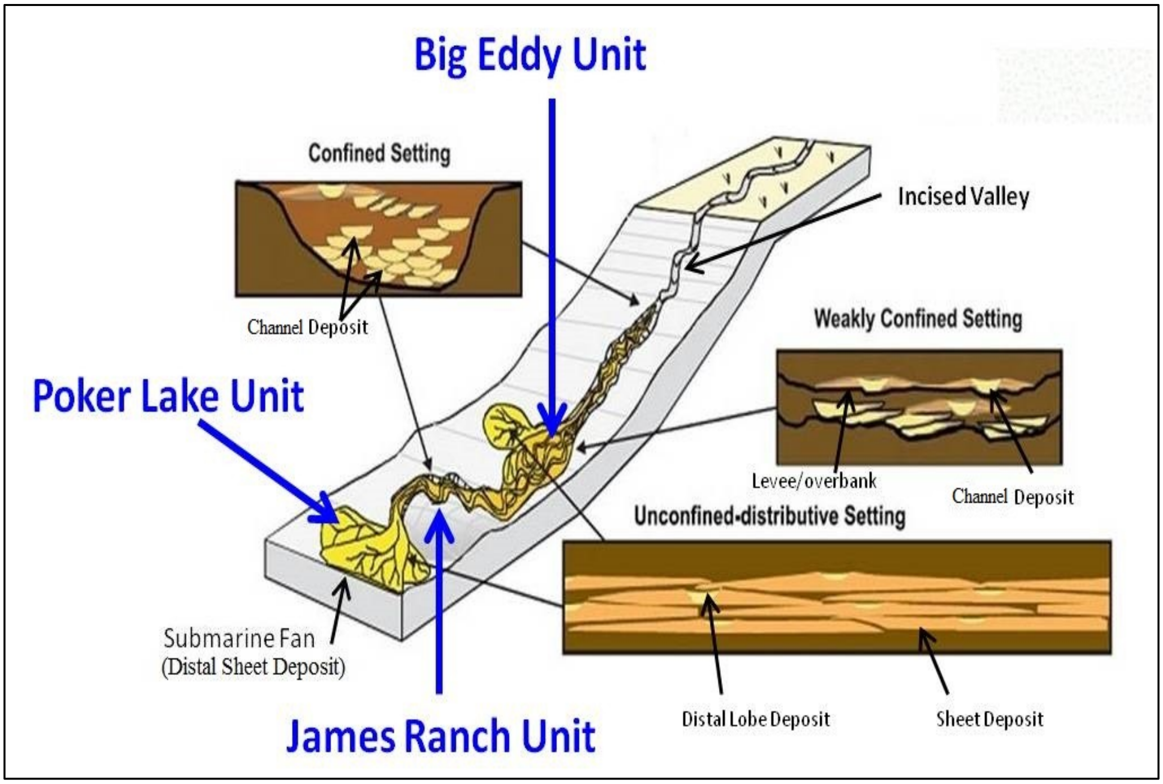


Figure 4.2. Depositional model for the Harkey Mills sandstone depicting turbidite pathway and submarine fan deposits and their associated depositional settings for Big Eddy, James Ranch and Poker Lake Federal Units. Similar depositional geometries may have existed for the Second Bone Spring Sandstone within the study area in the Delaware Basin. Modified from Funk et al., (2012) and Shanmugam (2003).

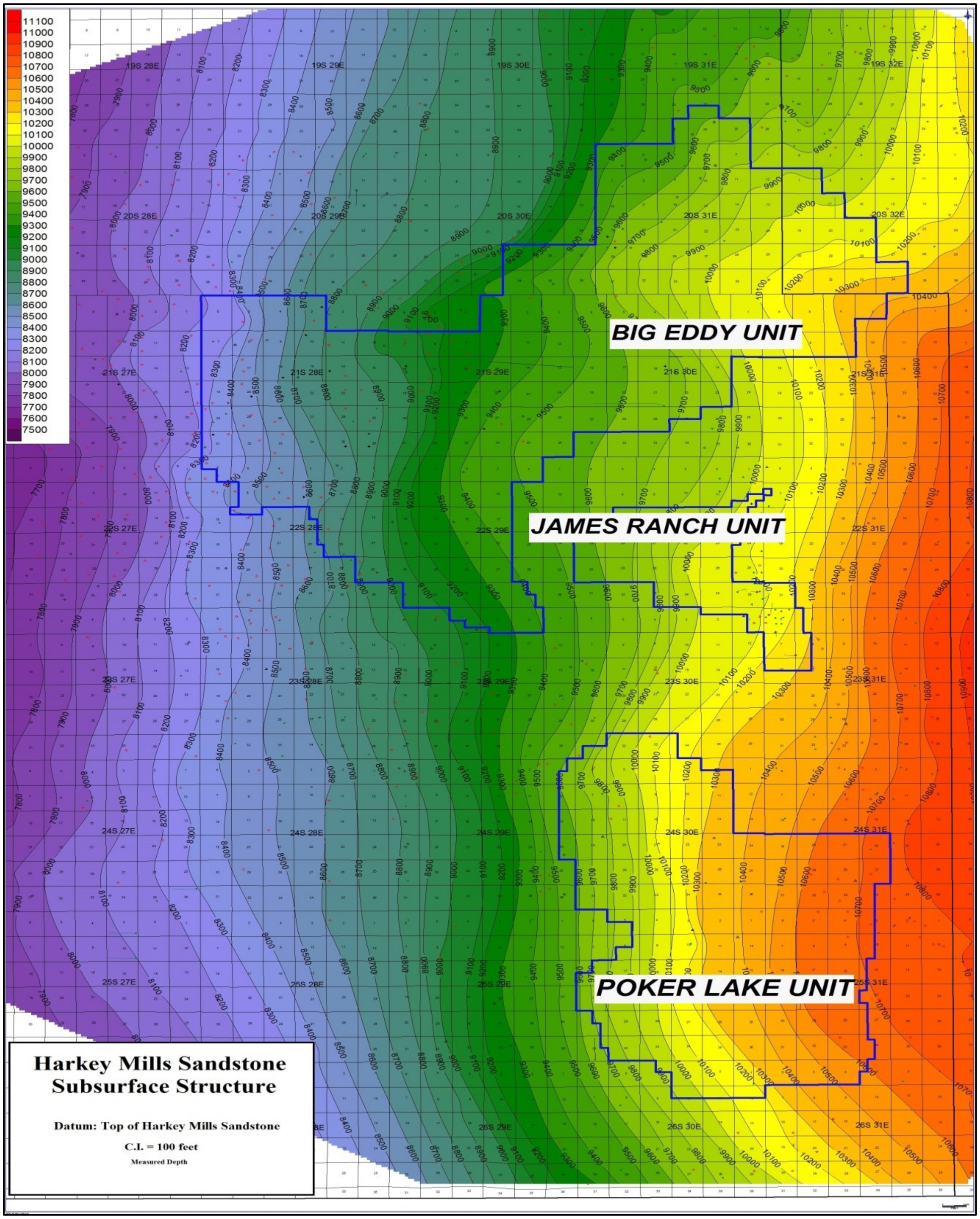


Figure 4.3. Subsurface structure below sea level (measured depth) of the top of the Harkey Mills sandstone. The structure shows a regional east/southeast dip across the study area.

Big Eddy Unit

The Harkey Mills sandstone in Big Eddy Unit consists of a weakly confined distributive turbidite channel and levee deposits (Figure 4.4). Big Eddy Unit is the most proximal unit to the slope of the Northwest Self and therefore is at the depocenter of the turbidite fans prograding from the north and northwest. The average gross thickness of the Harkey Mills sandstone in this area is 75 ft ±5 ft., with the thickest accumulations of sediment located on the western margin and directly in the center of Big Eddy Unit in areas where the turbidite channels appear to comingle. The net thickness of the Harkey Mills sandstone with $\phi > 8\%$ ranges between 30 ft and 80 ft in these areas (Figure 4.5). Overall, the average net thickness of the Harkey Mills sandstone in Big Eddy Unit is 22 ft. with porosity ranges from 8%-13%, water saturation of 45% and deep resistivity (Rt) values between 6 and 12 ohms.

In the center of the western portion of Big Eddy Unit, sediment pathways for the Harkey Mills sandstone divert around an apparent paleo-high in the Second Bone Spring Carbonate. For this reason, the Harkey Mills sandstone is thin or absent in this area (Figure 4.6). The distributive nature of the sandstone becomes more unconfined and fan like towards the south and southwest in the James Ranch and Poker Lake Units.

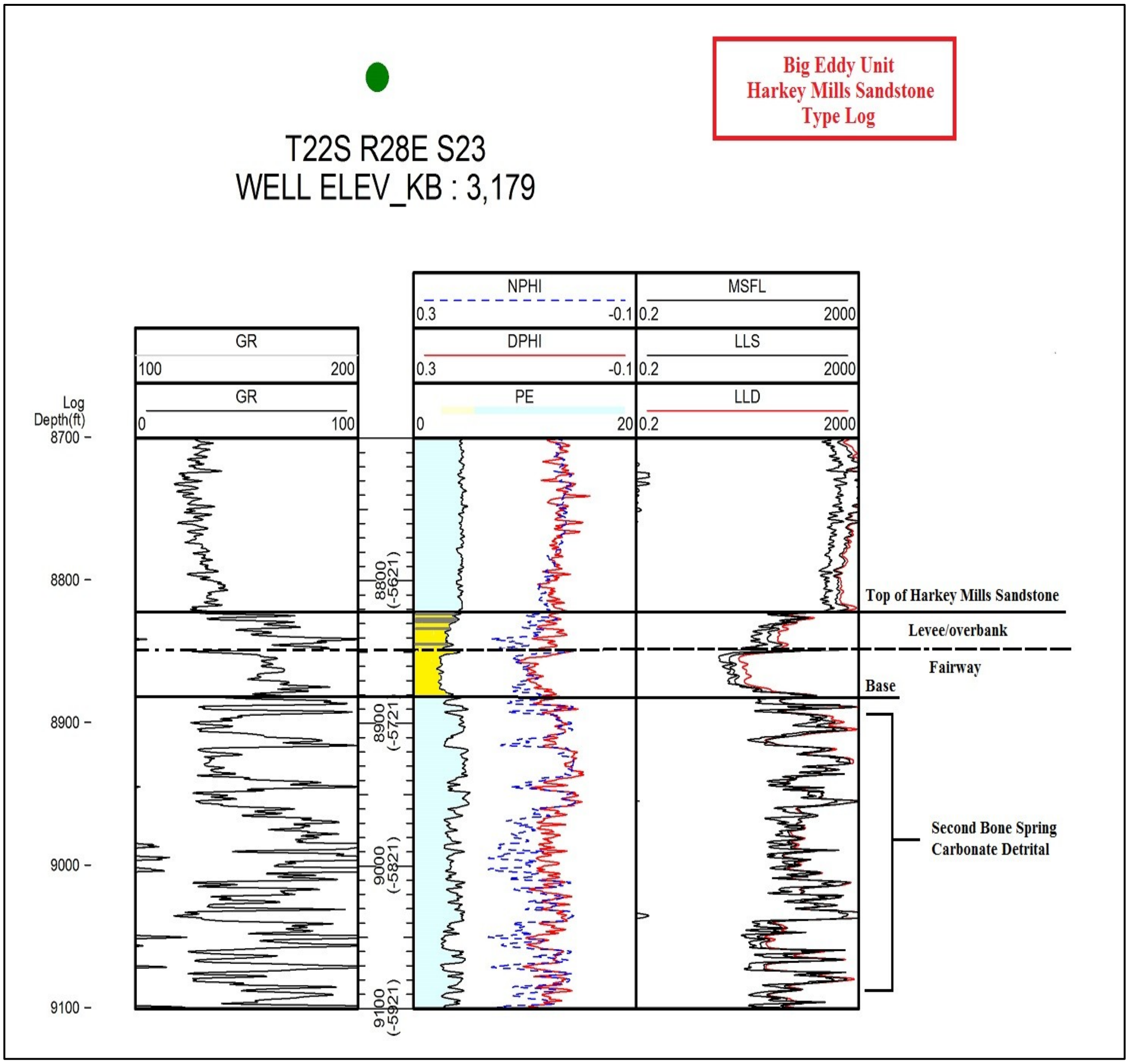


Figure 4.4. Type log of the Harkey Mills sandstone in Big Eddy Unit (see location in Figure 4.5) displaying channel like pathway and levee/overbank log signatures. (Log scale abbreviations: GR = gamma ray; NPHI = neutron porosity; DPHI = density porosity; PE = photo electric; LLD = deep resistivity; LLS & MSFL = shallow resistivity)

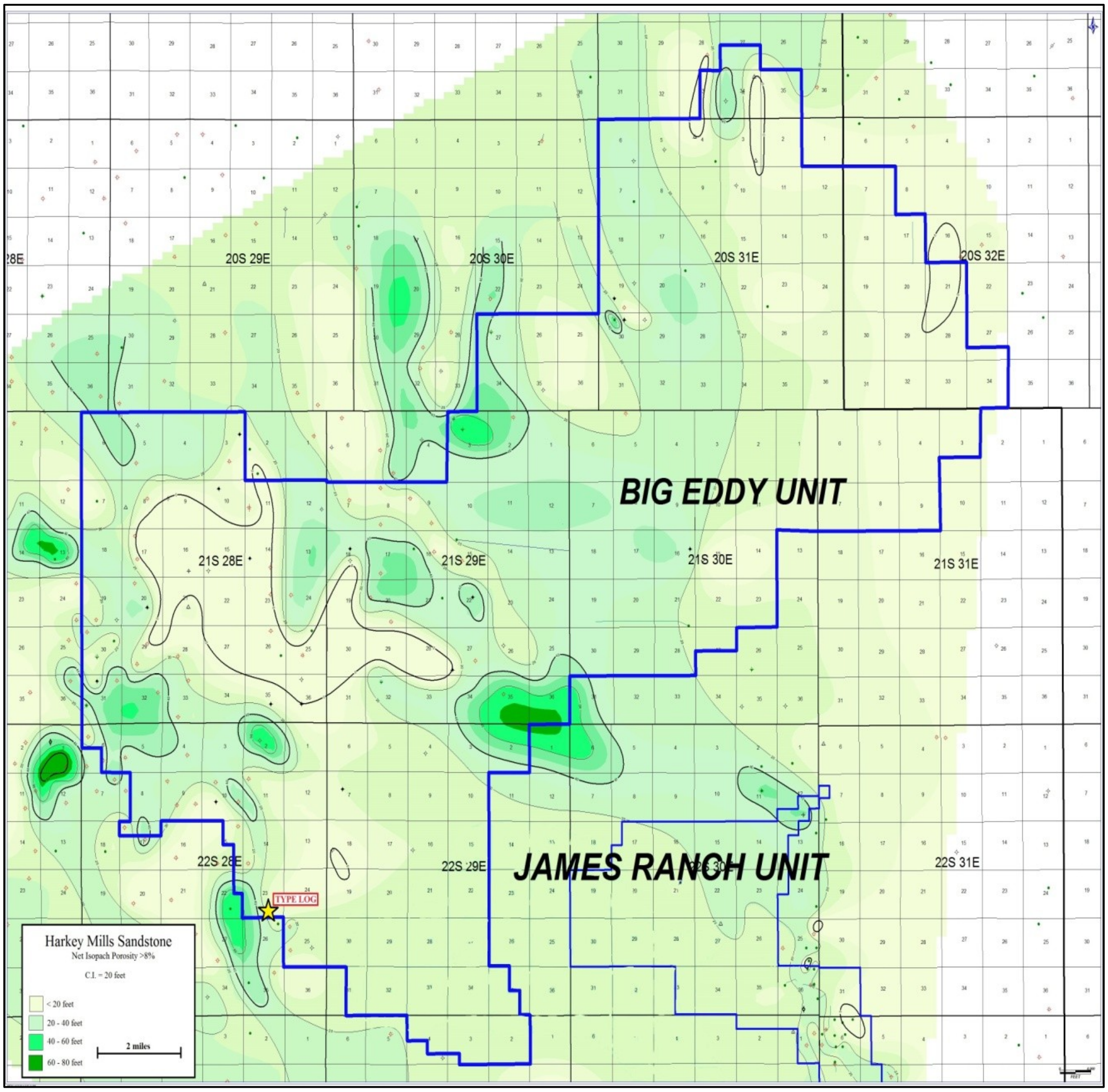
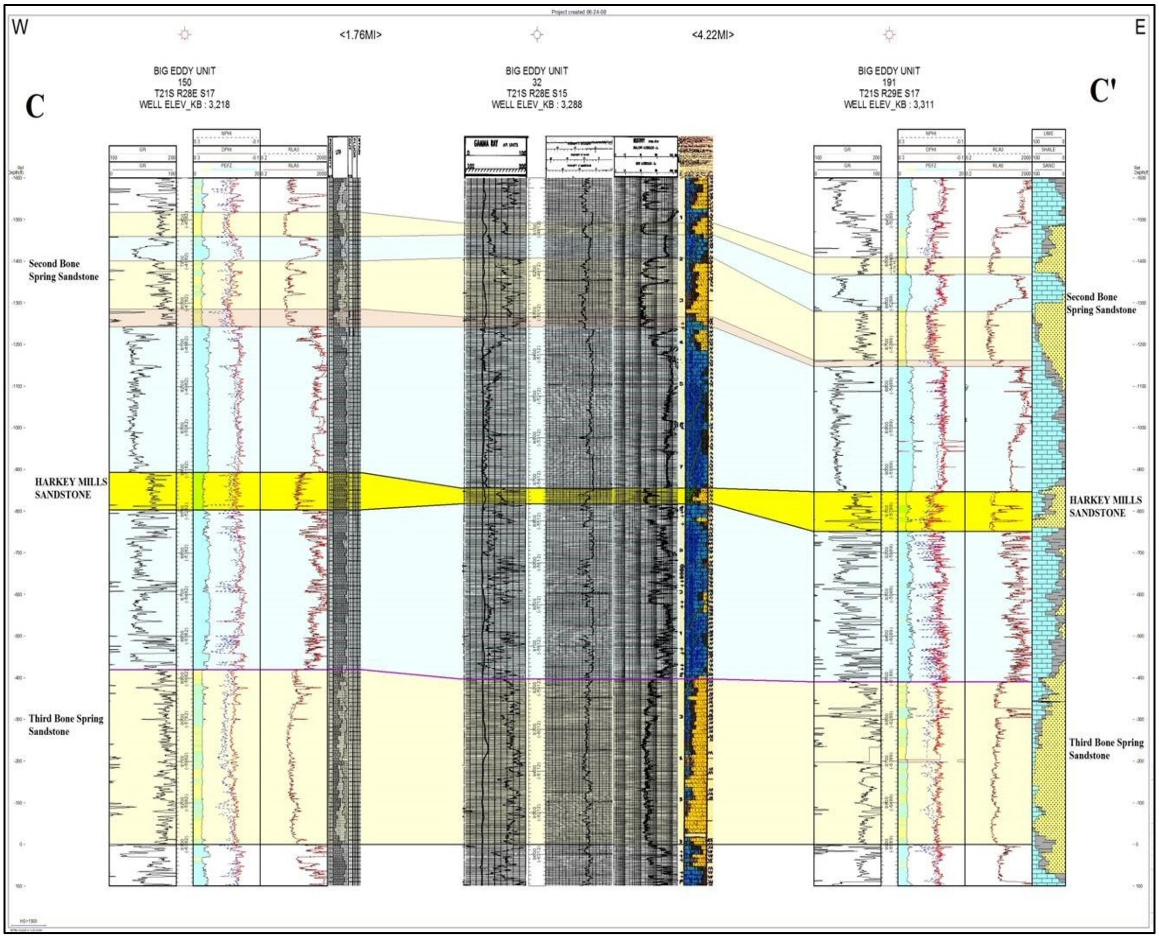


Figure 4.5. Net isopach map for the Harkey Mills sandstone in Big Eddy Unit using an 8% ϕ cutoff. Contour interval = 20 feet. Dark green areas represent a thickness of 60 ft. to 80 ft.



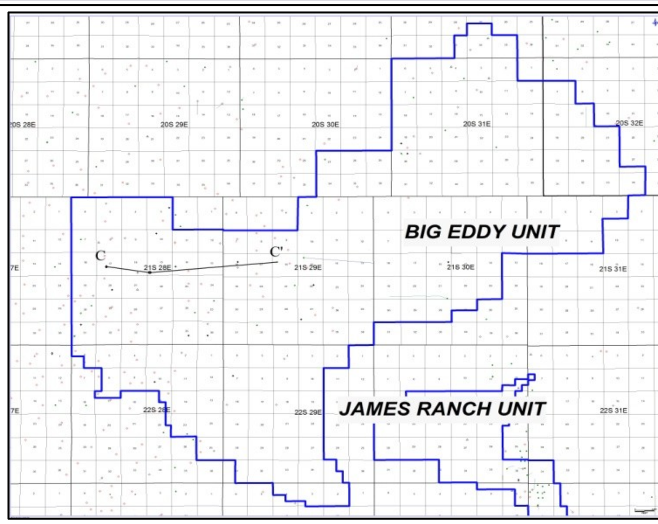


Figure 4.6. Cross section C-C’ illustrating lateral thickness variations within the Harkey Mills sandstone in western Big Eddy Unit.

Geochemical evaluation of rotary sidewall core samples from Big Eddy Unit #254H pilot well was conducted by Weatherford Laboratories to determine the source rock characterization of the Harkey Mills sandstone (Figure 4.7). Specifically, measurements of total organic carbon (TOC) and Rock-Eval pyrolysis are used to evaluate the petroleum generative potential and thermal maturity of the rock samples (Hunt, 1996).

The TOC and Rock-Eval pyrolysis results are illustrated in Figures 4.8 – 4.11. As seen in Table 4.1, the Harkey Mills sandstone from Big Eddy Unit #254H pilot well shows good to excellent values for TOC, S_1 and S_2 with an average TOC of 2.1%, S_1 of 1.56 mg HC/g and an S_2 of 3.6 mg HC/g. The Oxygen Index (OI) was calculated to be an average of 38 mg CO_2/g and the Hydrogen Index (HI) or "oil proneness" of the organic matter was calculated to have an average of 161 mg HC/g which indicates that the Harkey Mills sandstone is both oil and gas prone. Generally, HI values between 100 and 200 mg HC/g are treated as 50% Type II and 50% Type III kerogen types.

In the more distal portion of Big Eddy Unit, rotary sidewall core samples from Big Eddy Unit #35H pilot well displayed porosities from 8.4% to 10.3% and permeabilities between 0.013 md and 0.034 md (Table 4.2). Also from the core data, the Harkey Mills sandstone had a slight oil show with 60%-90% fluorescence (Figure 4.12).

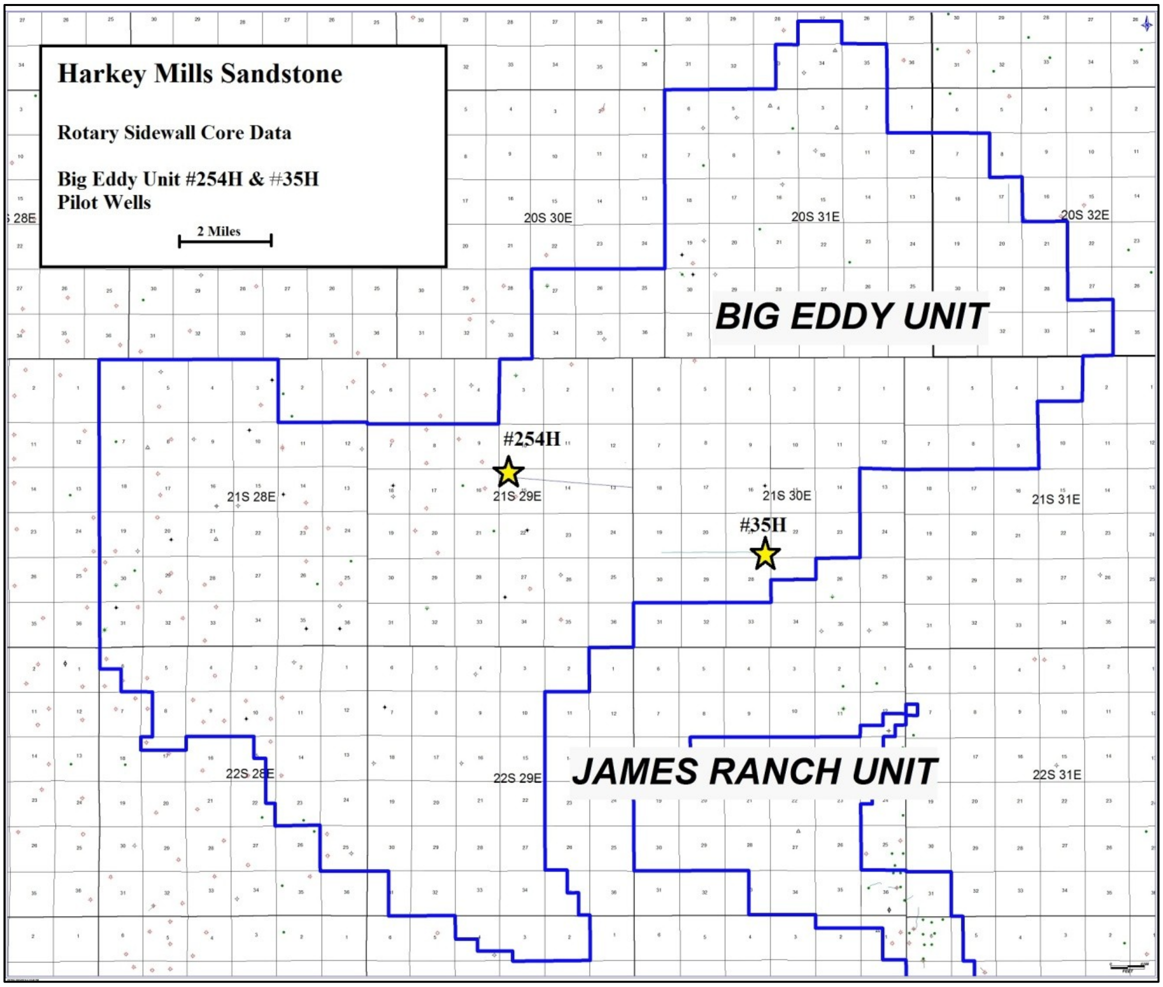


Figure 4.7. Base map of Big Eddy Unit showing the location of the Big Eddy Unit #254H and #35H pilot wells with sidewall core data in the Harkey Mills sandstone.

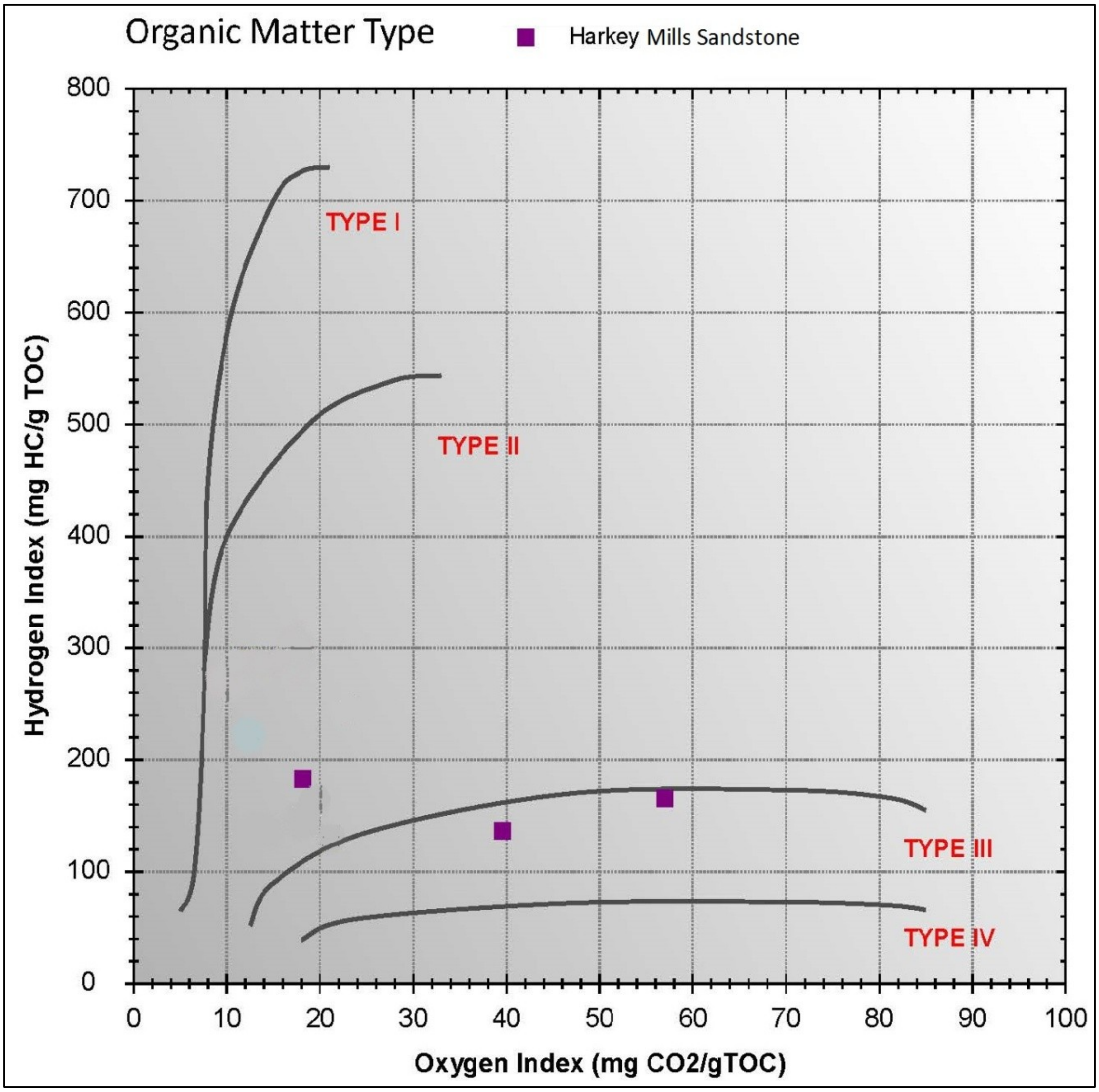


Figure 4.8. Hydrocarbon Type Index for the Harkey Mills sandstone (Weatherford Laboratories).

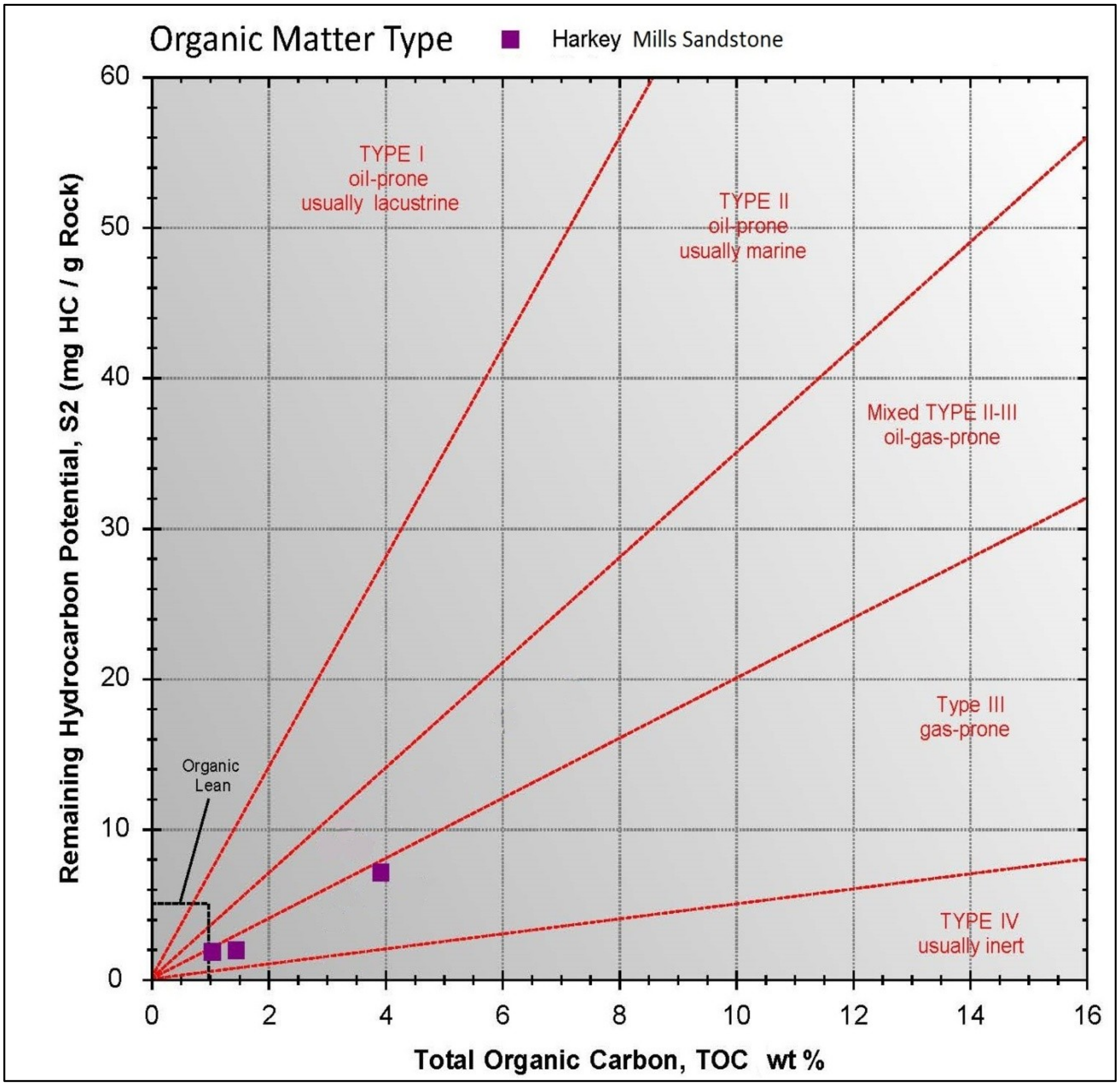


Figure 4.9. Remaining Hydrocarbon Potential verses Total Organic Carbon for the Harkey Mills sandstone (Weatherford Laboratories).

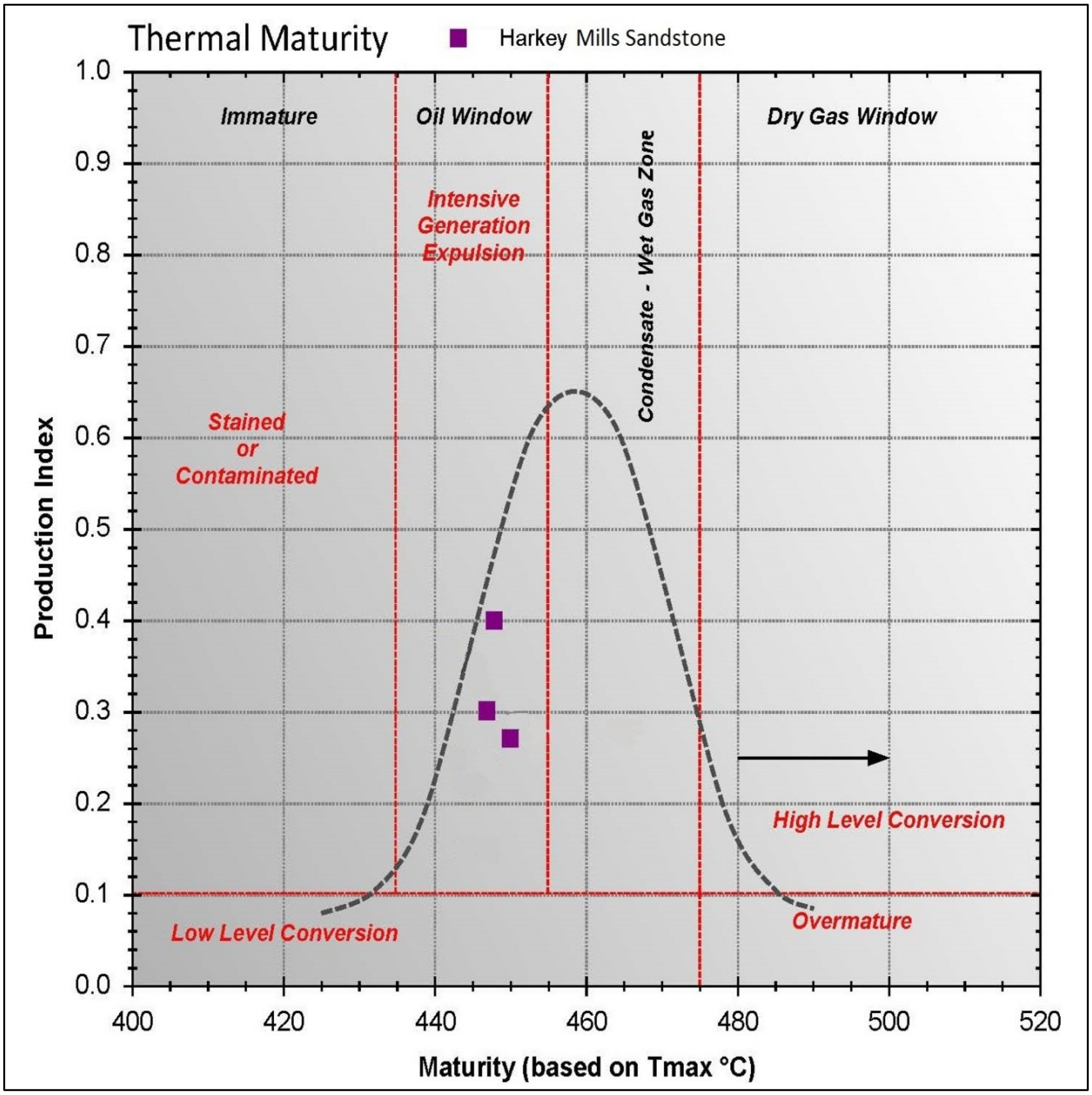


Figure 4.10. Thermal Maturity measurements for the Harkey Mills sandstone (Weatherford Laboratories).

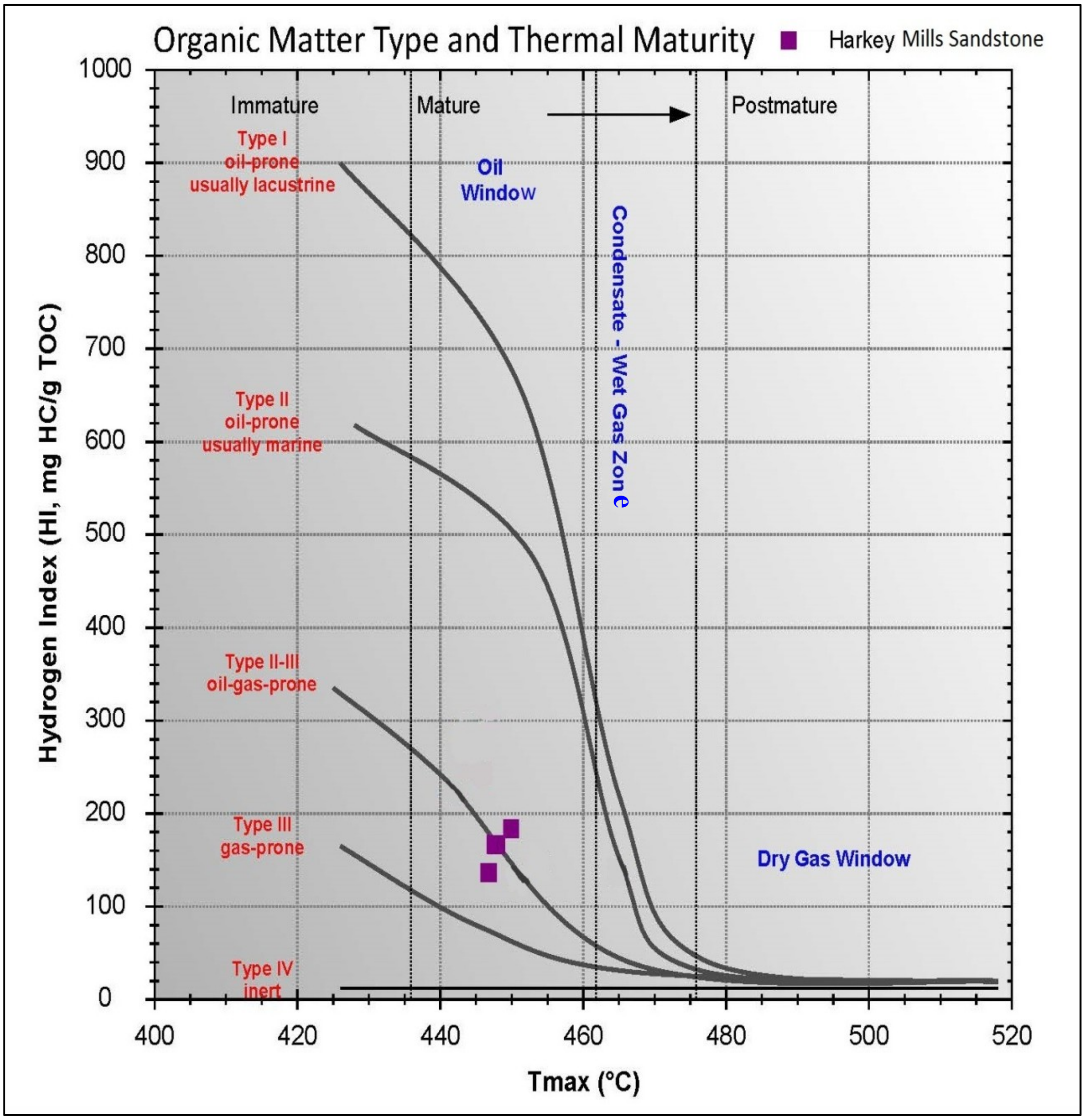


Figure 4.11. Organic Matter Type verses Thermal Maturity for the Harkey Mills sandstone (Weatherford Laboratories)

Table 4.1. TOC and Rock Eval results for the Harkey Mills sandstone in the Big Eddy Unit #254H pilot well (Weatherford Laboratories).

Depth Feet	**TOC**	**S1**	**S2**	**S3**	**TMax (˚C)**	**HI**	**OI**	**S2/S3**	**% S1/TOC**	**PI**
9,370	3.9	2.7	7.1	0.7	450	182	18	10.1	68	0.27
9,374	1.5	0.08	2.0	0.6	447	135	40	3.4	58	0.30
9,577	1.1	1.2	1.7	0.6	448	166	57	2.9	110	0.40

*Source Rock Evaluation Data Types and Values from Weatherford Laboratories can be found in Appendix B.

Table 4.2. Rotary Sidewall Core Analysis for the Harkey Mills sandstone in the Big Eddy Unit #35H pilot well (Weatherford Laboratories).

Sample No.	Depth Feet	Grain Density	ϕ %	Perm. (k) %	Sw	So	Gas Units	Flour. %	Lithology Description
1	9,688	2.70	8.4	0.013	22.3	17.3	675	90	Sandstone, gray/tan, very fine grain, sub-round/sub-angular, calcite cemented.
2	9,690	N/A	N/A	N/A	N/A	N/A	631	90	Sandstone, gray/tan, very fine grain, sub-round/sub-angular, calcite cemented.
3	9,704	2.68	10.3	0.034	19.2	17.4	770	60	Sandstone, gray/tan, very fine grain, sub-round/sub-angular, calcite cemented.

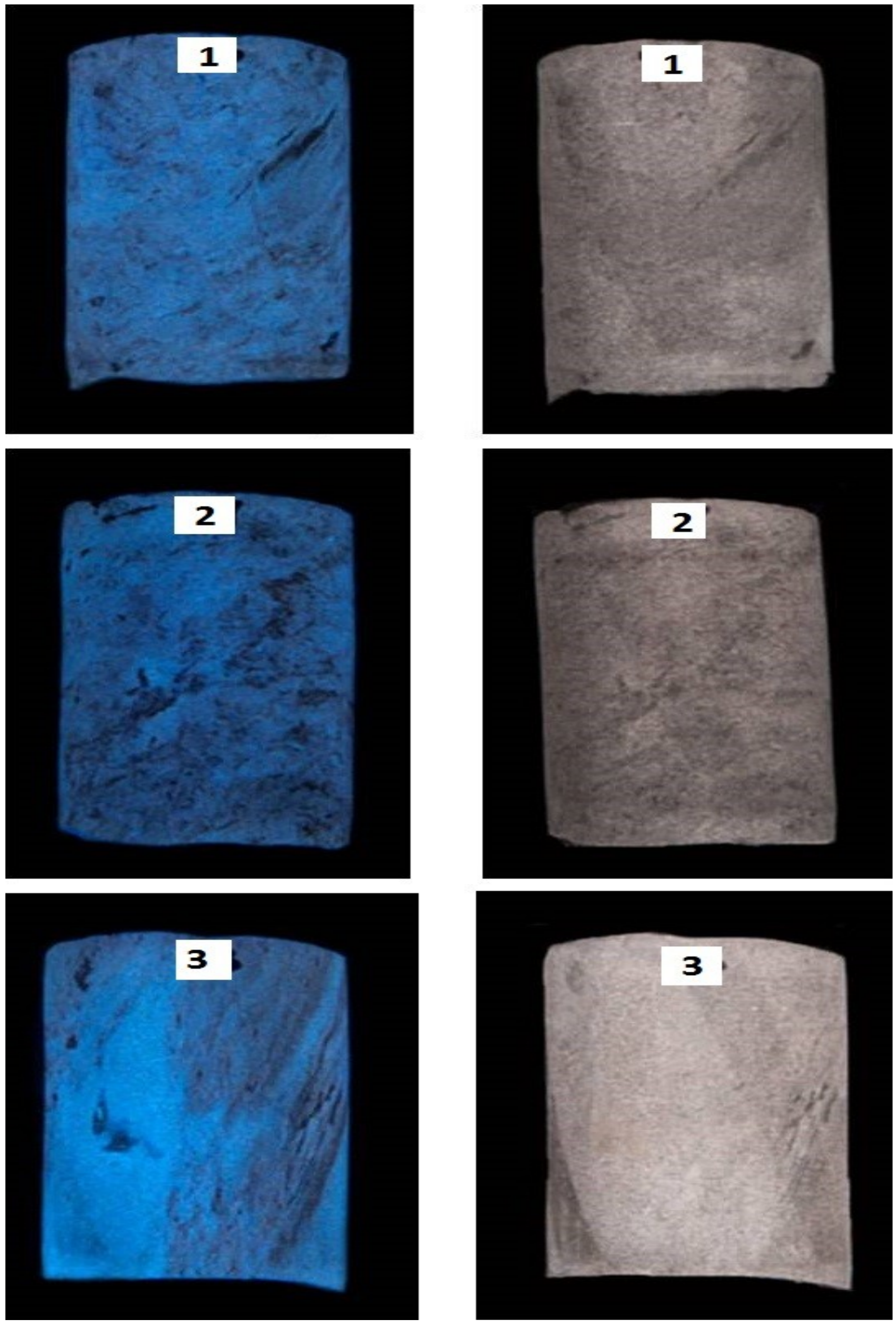


Figure 4.12. Rotary sidewall core images of the Harkey Mills sandstone in the Big Eddy Unit #35H pilot well. Each sample is shown under fluorescent (left column) and plain (right column) light.

James Ranch Unit

The Harkey Mills sandstone in James Ranch Unit consists of thin channel and levee/overbank deposits within a confined distributive setting (Figure 4.13). A northwest to southeast trending turbidite deposit, with a net thickness averaging 33 ft. of porosity greater than 8%, indicates that the Harkey Mills sandstone is at the medial submarine fan stage and is possibly transitioning from a channel dominated to a sheet dominated system. The best reservoir quality rock is contained within channels with porosities ranging from 6% to 13%, 46% average water saturation and Rt values between 10 and 20 ohms (Figure 4.14). Overall, the Harkey Mills sandstone in James Ranch Unit has an average gross thickness of 43 ft. with 17 ft. of net ϕ greater than 8%.

Two rotary sidewall core samples from the James Ranch Unit 21 #1 salt water disposal well were analyzed by Weatherford Laboratories for TOC and Rock-Eval Pyrolysis measurements (Figure 4.15). The average TOC is much lower in James Ranch Unit compared to Big Eddy Unit with a value of 0.43%. Although the Harkey Mills sandstone is not organic rich, the information in Table 4.3 suggests that the sandstone does contain traces of oil. Several mud log oil shows with 20% to 40% fluorescence are found in the Harkey Mills sandstone along the southeast trend of the dominate turbidite channels previously mentioned (Figure 4.16).

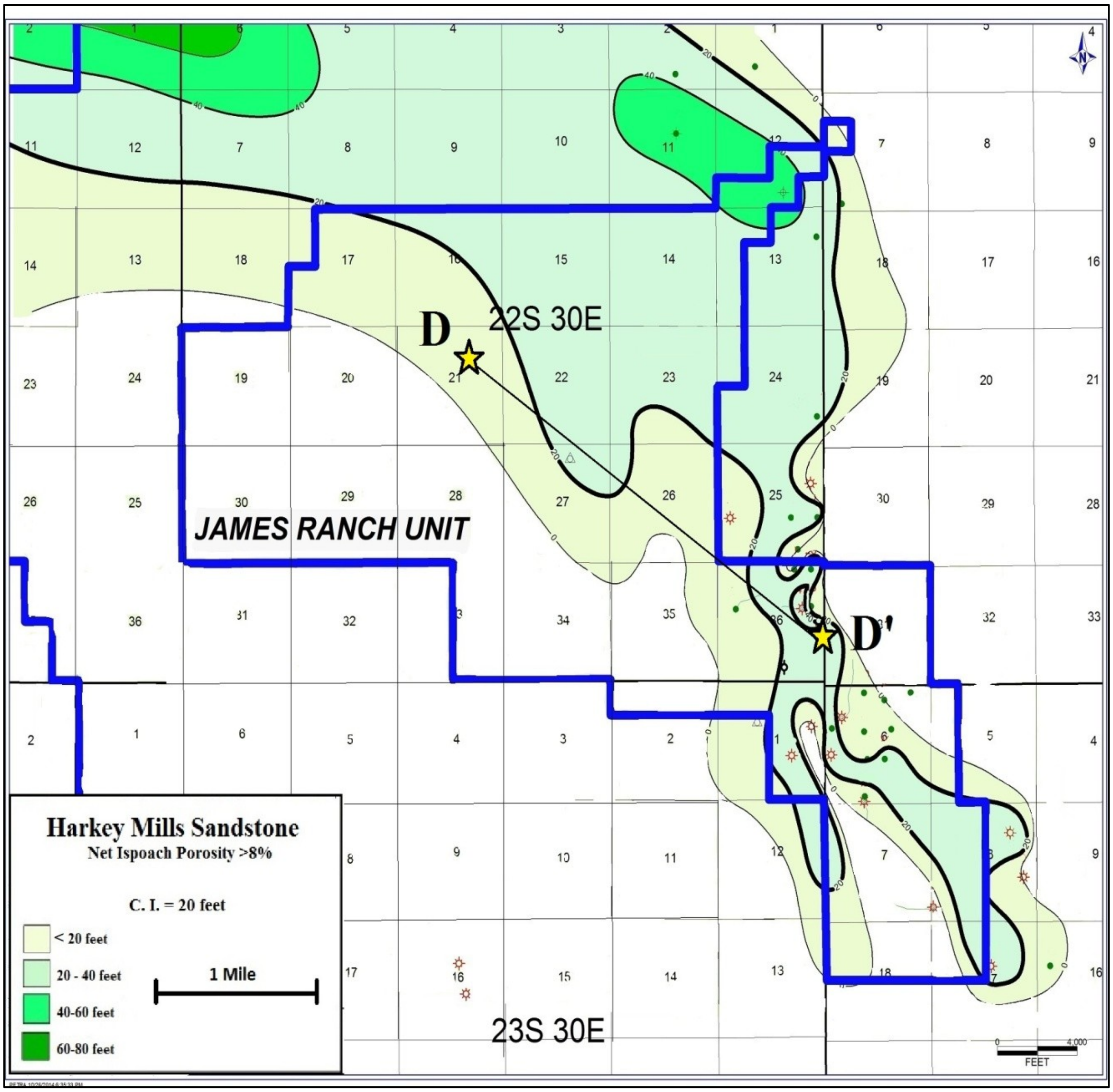


Figure 4.13. Net isopach map of the Harkey Mills sandstone in James Ranch Unit using an 8% ϕ cutoff. Contour interval = 20 feet.

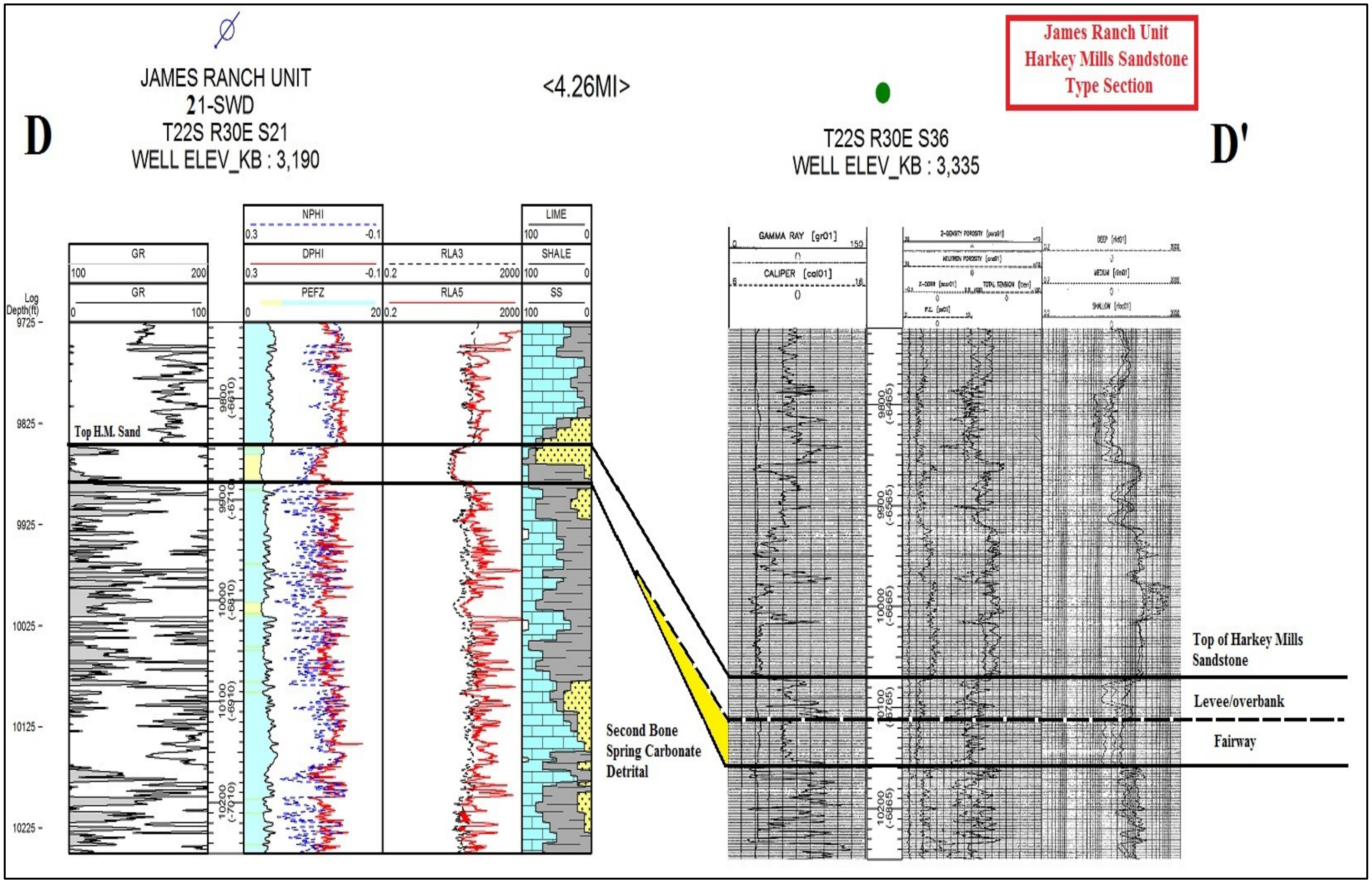


Figure 4.14. Structural cross section D-D' of the Harkey Mills sandstone in James Ranch Unit illustrating the confined channel like fairway and related levee/overbank deposits. (Cross section reference can be seen in Figure 4.13). (Log scale abbreviations: GR = gamma ray; NPHI = neutron porosity; DPHI = density porosity; PEFZ = photo electric; RLA5 = deep resistivity; RLA3 = medium resistivity).

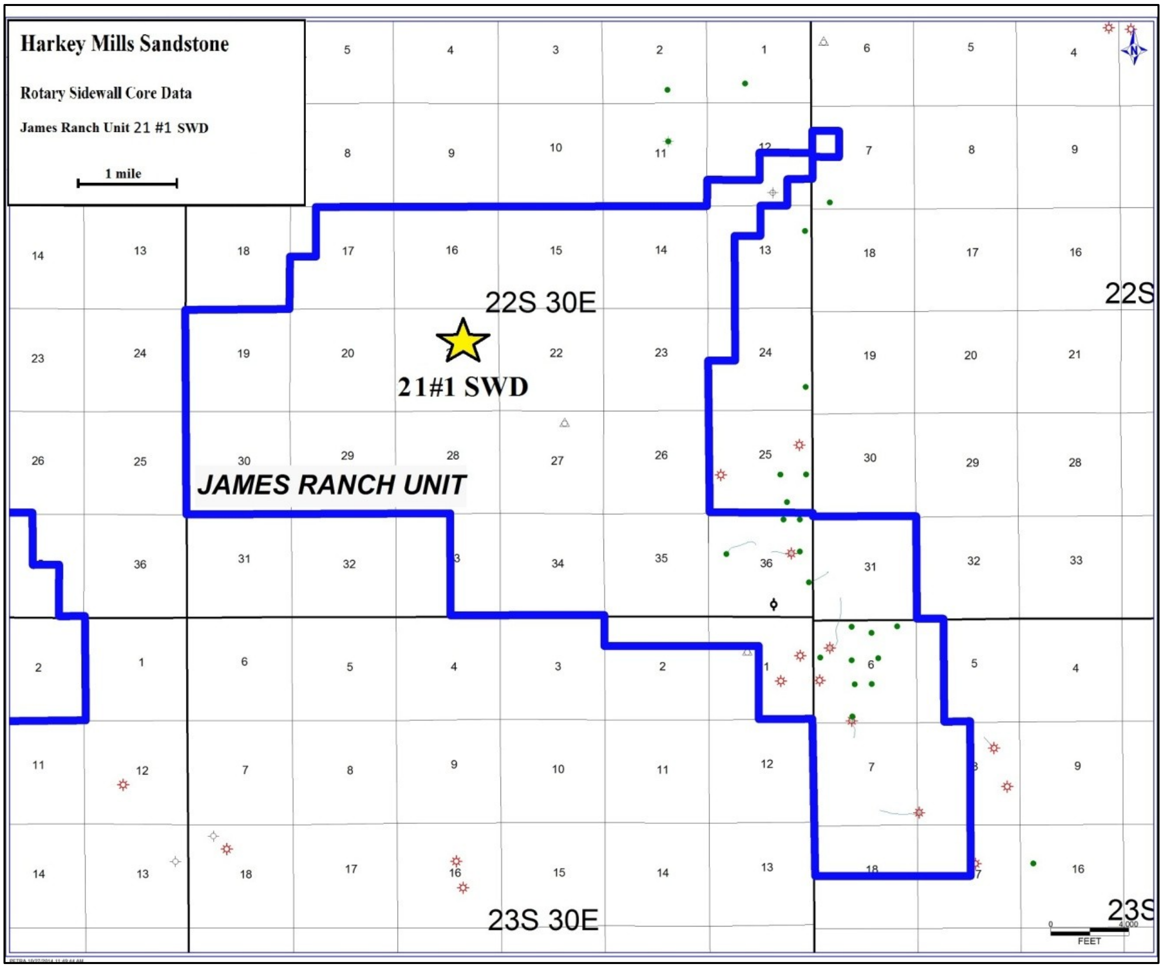


Figure 4.15. Base map of James Ranch Unit showing the location of the James Ranch Unit 21 #1 SWD.

Table 4.3. TOC and Rock Eval results for the Harkey Mills sandstone in the James Ranch Unit 21 #1 SWD well (Weatherford Laboratories).

Depth Feet	TOC	S1	S2	S3	Tmax (˚C)	HI	OI	S2/S3	% S1/TOC	PI
9,866	0.41	1.63	0.66	0.52	418	161	127	1.3	396	0.71
9,873	0.45	1.58	0.74	0.47	418	164	104	1.6	351	0.68

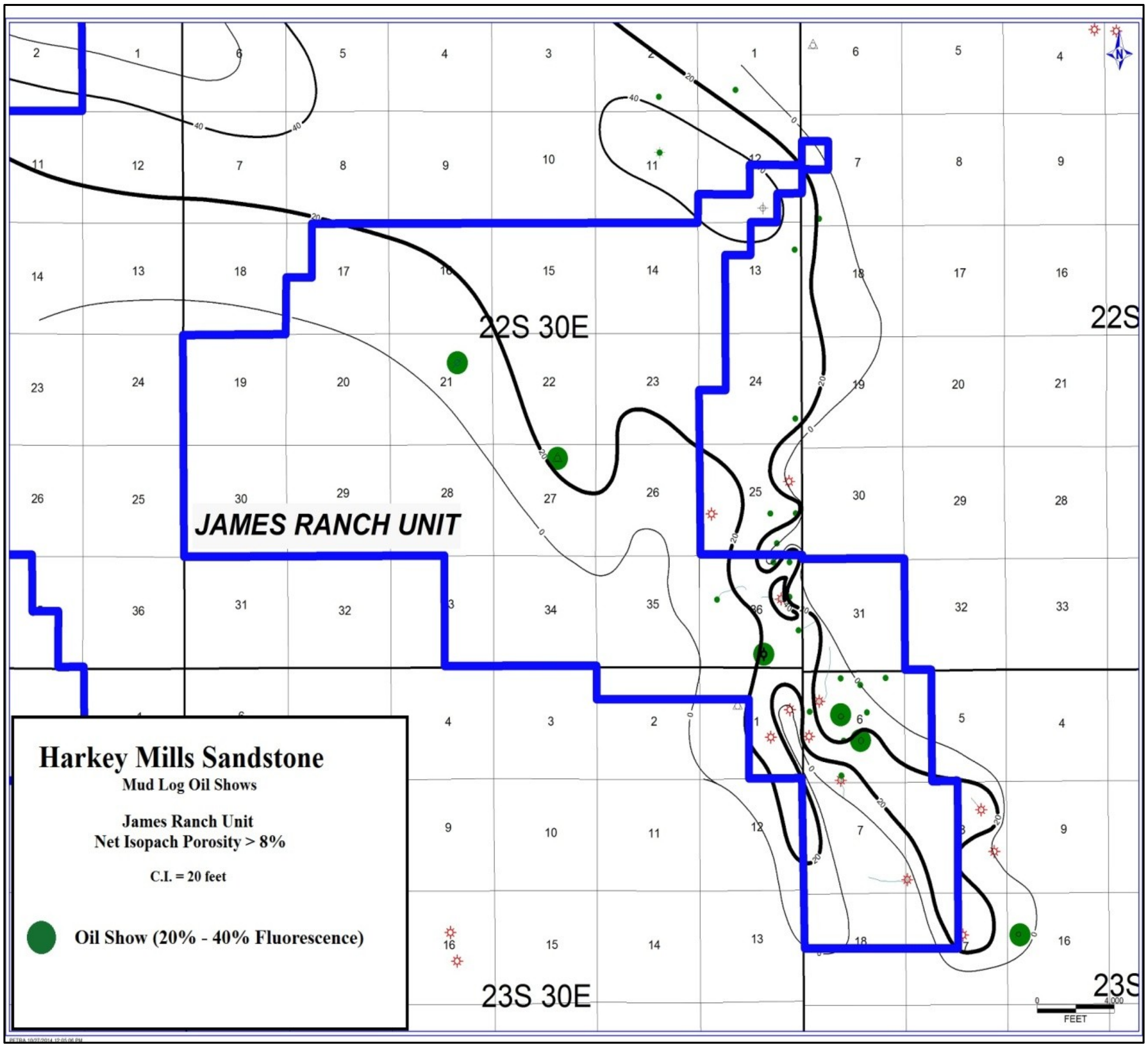


Figure 4.16. Net Isopach and mud log oil show map of the Harkey Mills sandstone in James Ranch Unit.

The Rock-Eval results from the James Ranch Unit 21 #1 SWD well indicate that Harkey Mills sandstone is slightly immature with a Tmax value equal to 418˚C. Also, the Sandstone appears to be more gas prone with a Hydrocarbon Type Index of 1.3 mg HC/g and 1.6 mg HC/g, indicating Type III kerogen. The complete results for the TOC and Rock-Eval pyrolysis are seen in Figures 4.17 – 4.20. High Production Index (PI) values and low TOC values as seen in Figure 4.19 suggest that there is either migrated oil or oil contamination, perhaps from oil based drilling mud, throughout the Harkey Mills sandstone section.

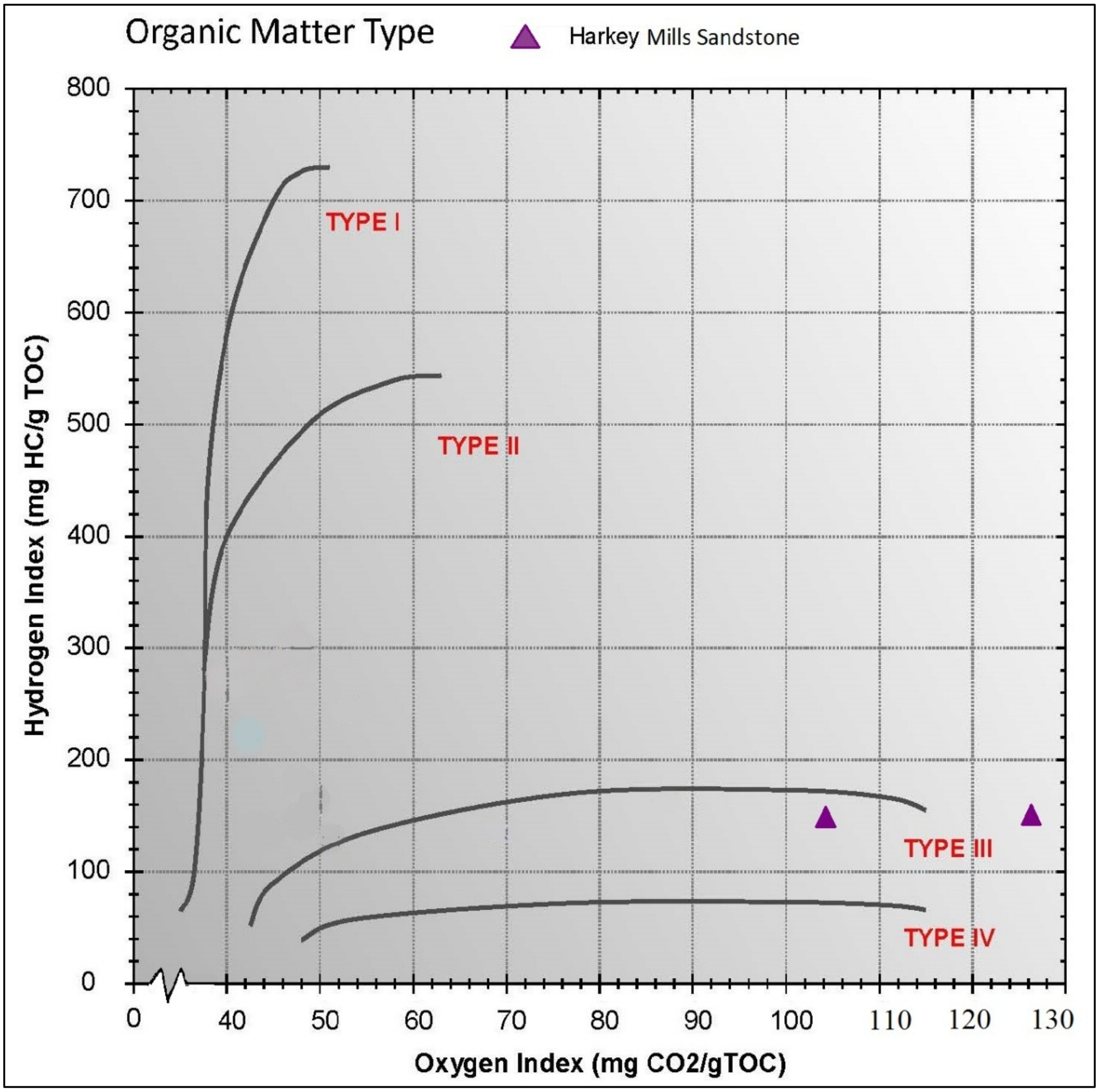


Figure 4.17. Hydrocarbon Type Index for the Harkey Mills sandstone in the James Ranch Unit 21 #1 SWD well (Weatherford Laboratories).

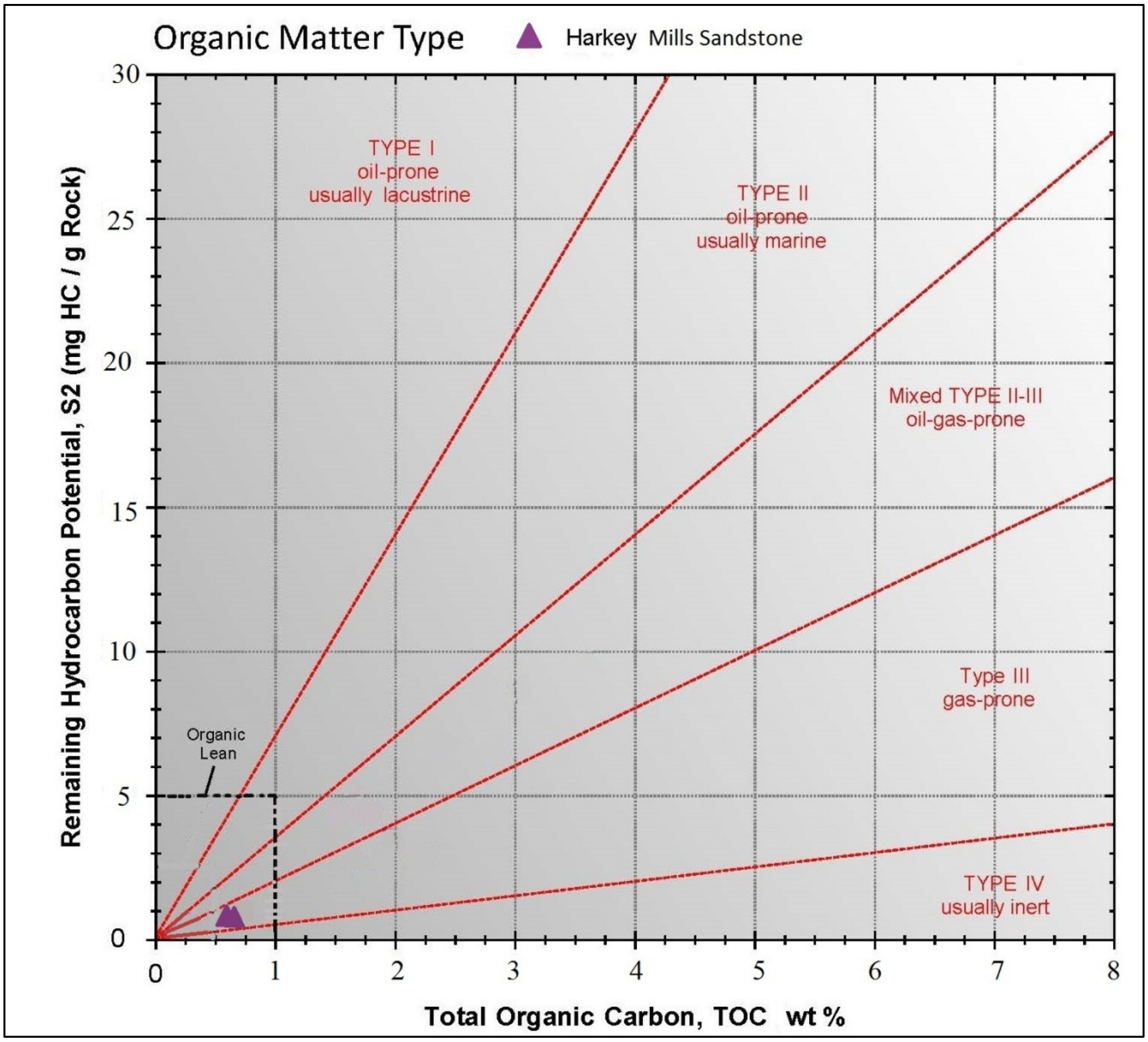


Figure 4.18. Remaining Hydrocarbon Potential verses Total Organic Carbon for the Harkey Mills sandstone in the James Ranch Unit 21 #1 SWD well (Weatherford Laboratories).

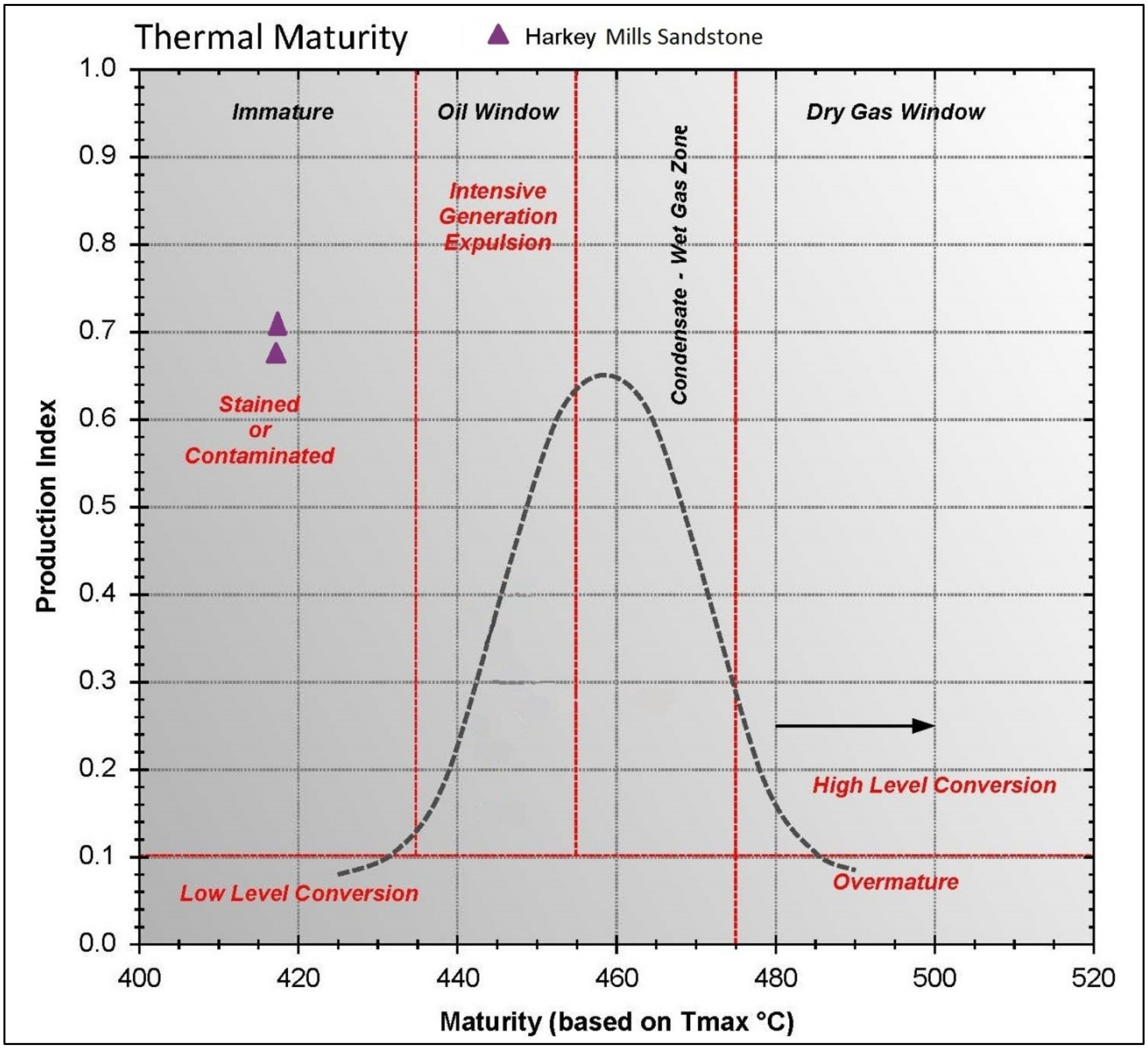


Figure 4.19. Thermal Maturity for the Harkey Mills sandstone in the James Ranch Unit 21 #1 SWD well (Weatherford Laboratories).

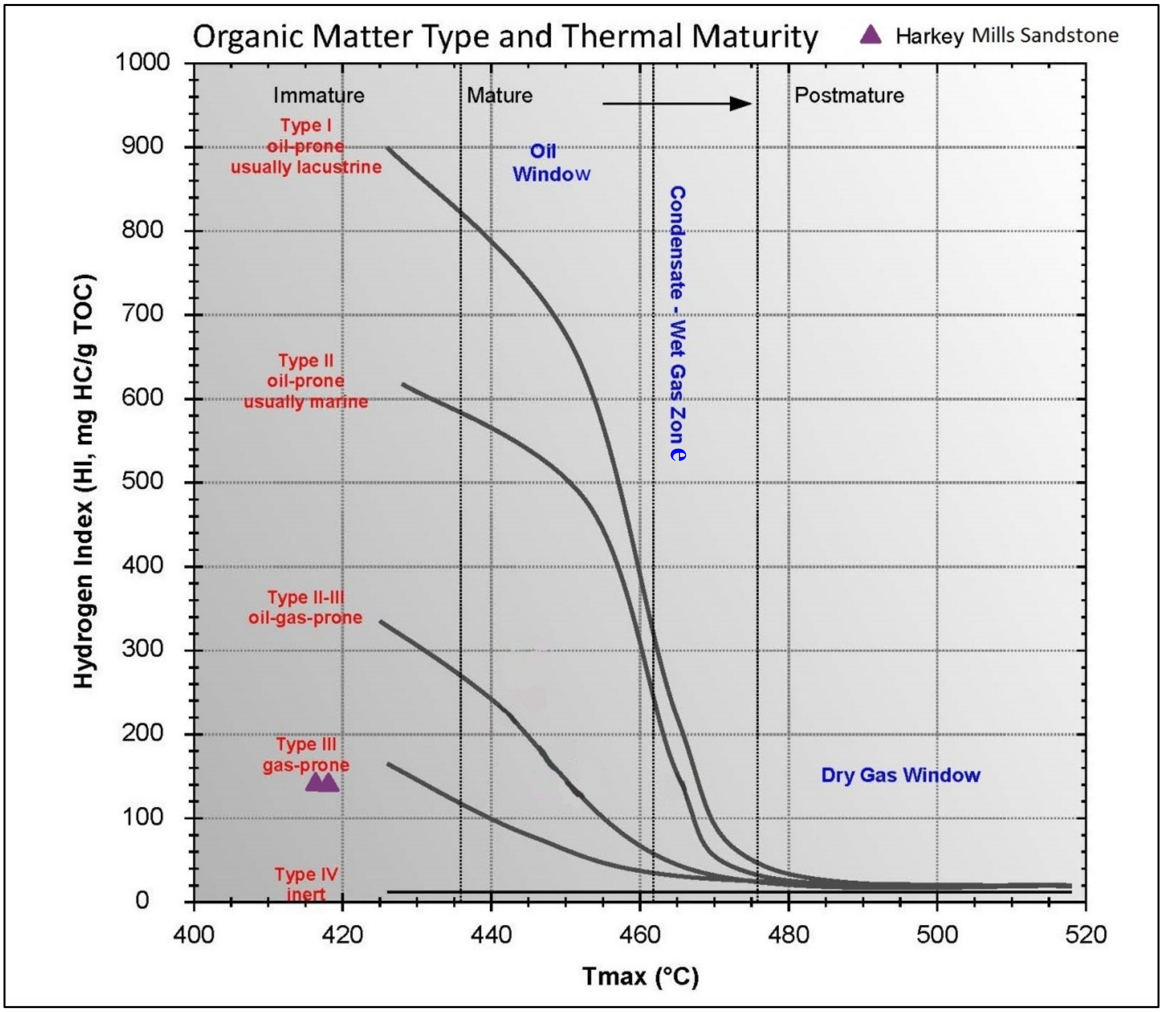


Figure 4.20 Kerogen Type verses Thermal Maturity for the Harkey Mills sandstone in the James Ranch Unit 21 #1 SWD well (Weatherford Laboratories)

Poker Lake Unit

The Harkey Mills sandstone in Poker Lake Unit is represented by a distal sheet deposit with unconfined and thinly bedded turbidite lobes distributed throughout the unit in a southeast direction (Figure 21). The average overall gross thickness of the Harkey Mills sandstone throughout the unit is 20 ft. and the average net thickness with porosity greater than 8% is 9 ft. (Figure 4.22). Mud log descriptions of the Harkey Mills sandstone describe the sediment texture as fine to very fine grained, well sorted, sub-round to round and moderately consolidated with an abundance of calcite cement.

Two oil shows were recorded from mud log data containing 10% to 15% of scattered fluorescence. These wells are located on the edge of a turbidite lobe located in the center of the unit (see Figure 4.22). The dominant trapping mechanisms for the Harkey Mills sandstone are related to lateral porosity pinchouts with no influence from structural variation. Water saturations for the sandstone are slightly higher in Poker Lake Unit with an average of Sw of 51% based off of Rt values between 6 and 12 ohms. Rotary sidewall core samples have yet to be taken from the Harkey Mills sandstone in Poker Lake Unit.

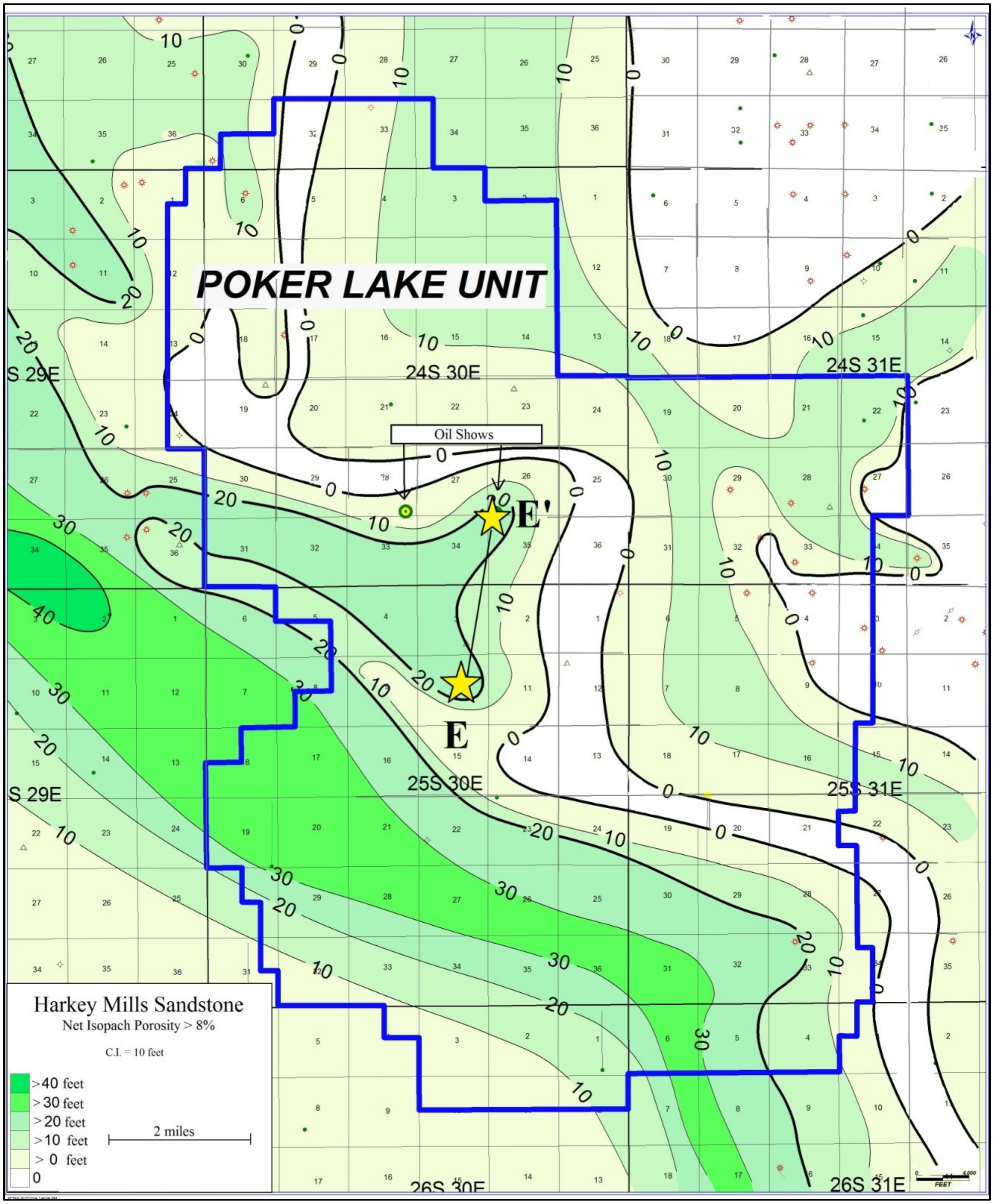


Figure 4.21. Net isopach map for the Harkey Mills sandstone in Poker Lake Unit using an 8% ϕ cutoff. Contour interval = 10 feet. Note the two oil shows on the edge of a distal turbidite lobe extending towards the center of the unit.

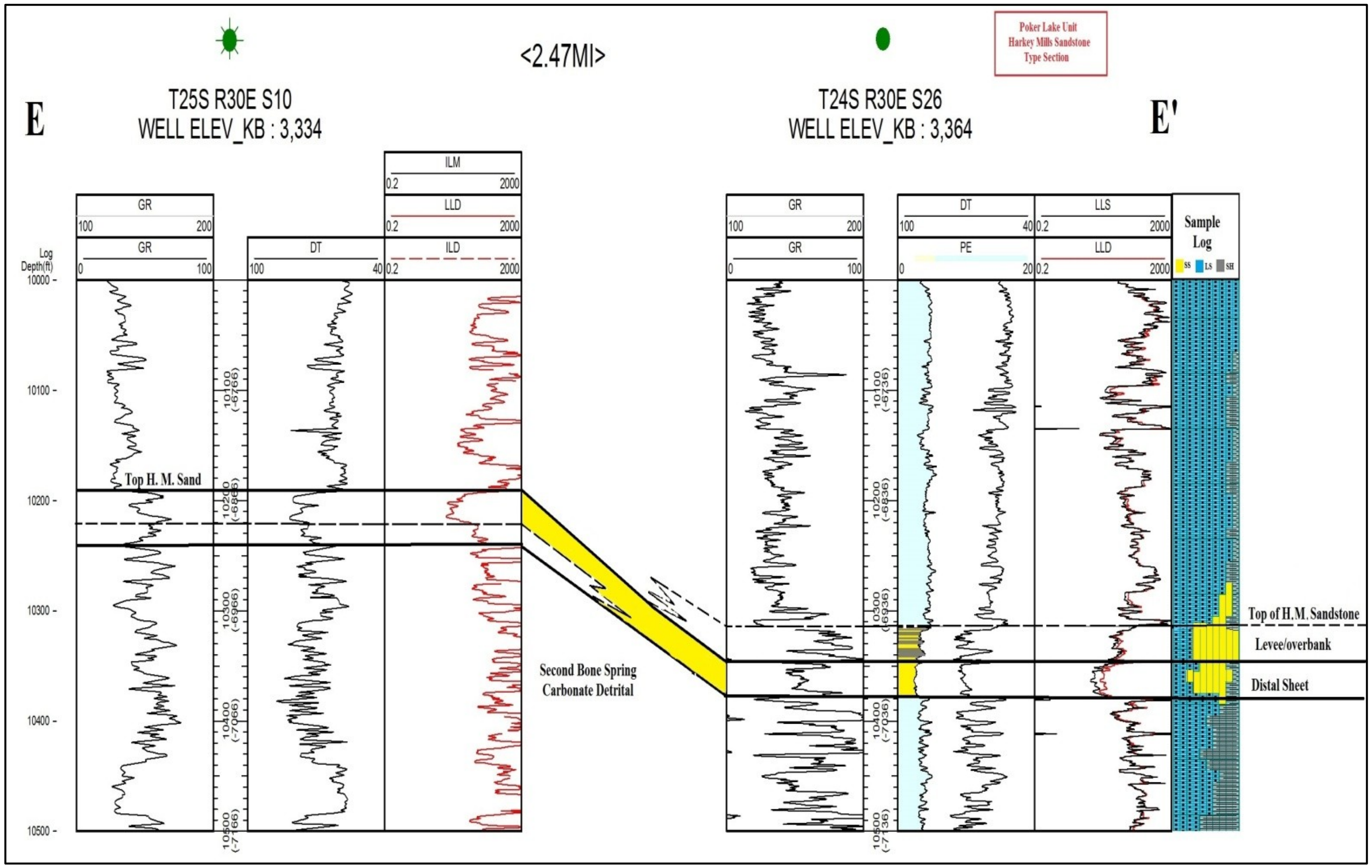


Figure 4.22. Structural cross section E-E’ of the Harkey Mills sandstone in Poker Lake Unit illustrating the unconfined, thinly bedded distal sheet and related levee/overbank deposits. (Cross section reference can be seen in Figure 4.21). (Log scale abbreviations: GR = gamma ray; DT = sonic; PE = photo electric; LLD/ILD = deep resistivity; ILM = medium resistivity; LLS = shallow resistivity).

Chapter 5

Harkey Mills sandstone vs. Second Bone Spring Sandstone

The Second Bone Spring Sandstone is a uniform, very fine to fine grained sandstone that consists of overlapping 75 ft. to 250 ft. turbidite deposits. Currently, successful horizontal wells are being completed in both the upper “A” and lower “B” sandstones that have a net reservoir thickness greater than 25 ft., average water saturations between 40% and 60%, porosities between 8% and 16% and Rt values typically between 3 to 8 ohms. Like the Harkey Mills sandstone, the best porosity development in the Second Bone Spring Sandstone is located in the center of the turbidite channels. The primary trapping mechanisms for the Second Bone Spring Sandstone are due to upslope and lateral porosity pinchouts with minimal influence from structure.

Source rock characterization based on TOC and Rock-Eval Pyrolysis was also analyzed from rotary sidewall core data from the Second Bone Spring Sandstone in the Big Eddy Unit #254H pilot and James Ranch Unit 21 #1 SWD wells. The results are found in Tables 5.1 and 5.2. In the Big Eddy Unit #254H pilot well, one core sample from the Second Bone Spring ‘B’ Sandstone showed a 3.3% TOC value as well as a Hydrogen Index of 166 mg HC/g, indicating that the lower “B” sandstone is oil and gas prone with Type II and III kerogen. Samples from both the upper “A” (four samples) and lower “B” (three samples) sandstones were analyzed from James Ranch Unit 21 #1 SWD well.

Table 5.1. TOC and Rock-Eval results for the Second Bone Spring "B" Sandstone in the Big Eddy Unit #254H pilot well (Weatherford Laboratories).

Depth Feet	**TOC**	**S1**	**S2**	**S3**	**TMax ˚C**	**HI**	**OI**	**S2/S3**	**% S1/TOC**	**PI**
8,930	3.3	1.9	5.5	0.6	447	166	19	8.6	57	0.25

Table 5.2. TOC and Rock Eval results for the Second Bone Spring “A” and “B” Sandstones in the James Ranch Unit 21 #1 SWD well (Weatherford Laboratories).

Depth Top	Formation	TOC	S1	S2	S3	TMax ˚C	HI	OI	S2/S3	S1/TOC *100	PI
9,152	A	0.016	0.07	0.05	0.29	444	31	179	0.2	44	0.59
9,192	A	0.49	0.91	0.68	0.43	428	139	88	1.6	186	0.57
9,232	A	0.51	1.29	0.86	0.47	427	168	92	1.8	251	0.6
9,296	A	0.31	0.77	0.4	0.4	404	127	127	1	246	0.66
9,480	B	0.25	0.13	0.07	0.19	402	28	76	0.4	52	0.65
9,499	B	0.27	0.34	0.17	0.37	407	62	136	0.5	124	0.67
9,514	B	0.24	0.74	0.37	0.36	385	152	148	1	303	0.67

The Hydrocarbon Type Index is the ratio between the amount of hydrocarbons (S_2) and the amount of carbon dioxide (S_3) in the rock and is also an indicator of kerogen type. The "A" sandstone contained an average TOC of 0.366% and an average Hydrocarbon Type Index of 1.15 mg HC/g indicating a Type III kerogen type. The lower "B" sandstone contained an average TOC of 0.25% and an average Hydrocarbon Type Index of 0.63 mg HC/g which also indicates Type III kerogen type.

Completion Methods and Recommendation

Based off an average lateral length of 4,000 ft., the Second Bone Spring Sandstone is typically completed using a fifteen stage plug and perf method with X-link gel, 1.3 million pounds of 20/40# resin coated sand and 1.4 million gallons of fluid. Horizontal Second Bone Spring Sandstone wells typically offset vertical production three to five times, producing an average cumulative production of 300 to 400 MBO.

Of the four known horizontal Harkey Mills sandstone wells, the most recent well was completed by acidizing with 85 thousand gallons of 7 ½% hydrochloric acid and then fracturing with 3.5 million pounds of 16/30# resin coated sand using the plug and perf method. Within a 3-year period, these four wells have produced combined cumulative of approximately 176 MBO and 708 MMCF and have an estimated ultimate reserve of 2.12 MMBOE.

Based on the subsurface geology, the net apparent porosity-thickness (ϕH) (Figure 5.1), and the reservoir parameters determined for the Harkey Mills sandstone, western Big Eddy Unit appears to have the best potential for a successful horizontal well. Estimated Ultimate Reserves (EUR) are 684 MBOE (6:1 oil to natural gas ratio) based on volumetric calculations using a 100 ft. gross reservoir thickness, 55 ft. net ϕ>8%, a water saturation of 50% and a horizontal well length of 5,700 ft. The drainage area used was 160 acres with a recovery efficiency of 4.5%.

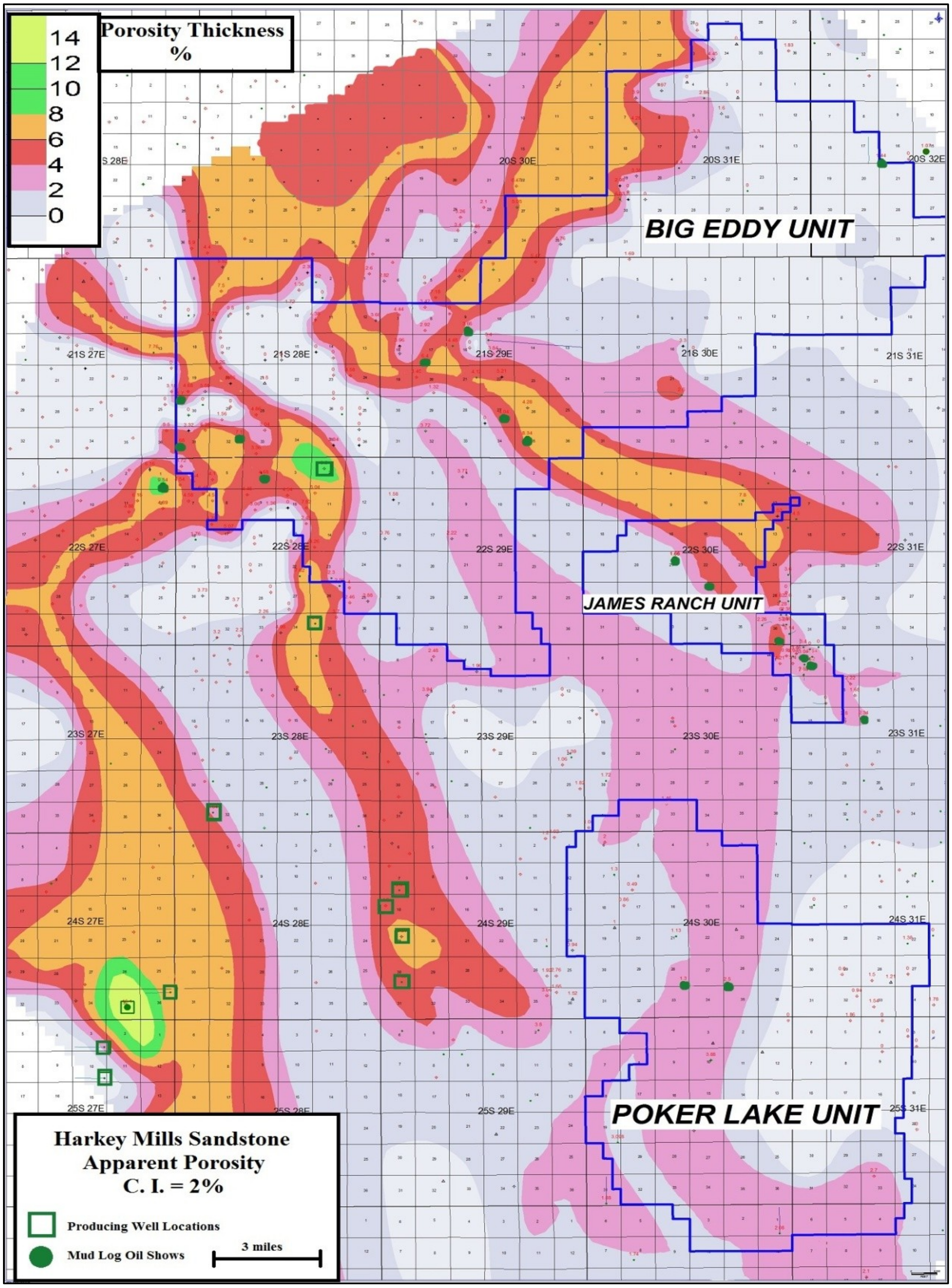


Figure 5.1. Porosity-thickness (ϕH) map for the Harkey Mills sandstone.

Chapter 6

Conclusions

Through a network of both stratigraphic and structural cross sections depicting the subsurface geology of the Leonardian Bone Spring Formation, the Harkey Mills sandstone was correlated and then mapped throughout Big Eddy, James Ranch and Poker Lake Federal Units in Eddy and Lea Counties, southeast New Mexico. Well-to-well log correlation not only helped determine the petroleum geology of the Harkey Mills sandstone but also permitted a direct comparison to the other sandstone members of the Bone Spring Formation.

Similar to the Second and Third Sandstone members of the Bone Spring Formation, the Harkey Mills sandstone was deposited in the Delaware Basin during a rapid sea level regression that interrupted a long term period of sea level transgression occurring in Leonardian time. Prior to deposition of the Harkey Mills sandstone, sea level rose (transgressive systems tract) towards the shelf margin, trapping sediment and thus starving the basin. Meanwhile, in situ carbonate buildup on the shelf margin would collapse into fluidized gravity flows and propagate into the basin. This sequence then transitioned to a lowstand systems tract, during which sediment bypassed the shelf margin forming incised valleys that fed sediment towards the basin floor. Deep submarine fan development at the toe of the shelf slope further distributed sediment across the basin via turbidity currents. Regional structure and gross isopach maps suggest that the Harkey Mills sandstone was sourced from the Northwest Shelf and was dispersed into the basin with a regional dip to the southeast. The same mechanisms occurred for the

Second Bone Spring Sandstone member which consists of a basin-floor fan, a slope fan, and a prograding turbidite wedge (Pearson, 1999).

The Harkey Mills sandstone is well developed near the slope fan, such as in western Big Eddy Unit. Here, the distributive setting for the Harkey Mills sandstone is weakly confined to thick (>50 ft.) channels and related levee/overbank facies deposits that extend through the unit to the south and southeast. The average gross thickness of the Harkey Mills sandstone in Big Eddy Unit is 75 ft., with a maximum thickness of 150 ft. In James Ranch Unit, the Harkey Mills sandstone is confined to a turbidite wedge that has an average gross thickness of 43 ft. and extends from the northwest down through the eastern portion of the unit. Based on gross and net isopach patterns, James Ranch Unit is at the medial fan stage of deposition, transitioning from a turbidite channel dominated to a distal fan dominated depositional system. To the south of James Ranch Unit, the Harkey Mills sandstone forms a submarine fan complex featuring thin (20 ft. average gross thickness) overlapping sheet deposits that are unconfined throughout Poker Lake Unit.

Source rock characterization based on TOC and Rock-Eval pyrolysis conducted by Weatherford Laboratories from the Big Eddy Unit #254H pilot and the James Ranch Unit 21 #1 SWD wells produced comparable results between the Harkey Mills sandstone and the Second Bone Spring Sandstone. In Big Eddy Unit, the Harkey Mills sandstone and the Second Bone Spring Sandstone are both organic rich with 2.16% to 3.9% TOC and are at the peak level of thermal maturity with Tmax values between 447˚C and 450˚C. Hydrogen Index values also suggested Type II and III kerogen types for both formations, indicating that the Harkey Mills sandstone is also oil and gas prone. In James Ranch Unit, both sandstone formations are classified as thermally immature with Type III kerogen types however, high Production Index values and low TOC percentages suggests that there is migrated oil in both the Harkey Mills and Second Bone Spring reservoirs.

The reservoir parameters of the Harkey Mills sandstone are also comparable to the Second Bone Spring “A” and “B” Sandstones in Big Eddy Unit. The Second Bone Spring Sandstone is a uniform, very fine to fine grained, sandstone with an overall gross thickness between 75 ft. and 250 ft. Porosities normally range between 8% and 12% and can increase up to 16% in the apex of the turbidite channel deposits. Successful horizontal wells completed in either the “A” or “B” sandstones have a net thickness greater than 25 ft., water saturations between 40% and 60% and low Rt values between 3 and 8 ohms. The Harkey Mills sandstone has not been horizontally explored in Big Eddy, James Ranch or Poker Lake Federal Units however, there are four known producing horizontal wells approximately 13 miles to the southwest of the study area. Based on offset vertical well data, these wells produce from reservoirs with an 8% average porosity, approximately 100 ft. gross thickness and greater than 22 ft. net, 44% water saturations and Rt values between 8 and 15 ohms. Similarly, in Big Eddy, James Ranch and Poker Lake Units, the Harkey Mills sandstone is a tight, uniform sandstone with Rt values between 6 and 12 ohms. The best reservoir development is in the center of the turbidite channels that are distributed along the western and central portions of Big Eddy Unit and confined through James Ranch Unit. The average net thickness with an 8% porosity cutoff is 22 ft., with a maximum thickness up to 80 ft. in western Big Eddy Unit.

A new horizontal drilling target was identified in western Big Eddy Unit by exploring the petroleum geology of the Harkey Mills sandstone. Estimated Ultimate Reserves are 684 MBOE for a 5,700 ft. horizontal well having a drainage area of 160 acres with a recovery efficiency of 4.5%. This study shows that the utilization of principal exploratory techniques, along with correlation between log characteristics, reservoir properties and geochemistry, can be used to further develop the Bone Spring play in analogous areas in the Delaware Basin. The results achieved here have applications beyond the Delaware Basin and may be used a model for the future exploration of turbidite reservoirs.

Appendix A

List of Wells Used to Determine the Reservoir Parameters

for the Harkey Mills sandstone

Big Eddy Unit

Unique Well UD	KB Elevation (Ft.)	Gross Thickness Ft.	Net Thickness φ >8%	Apparent Porosity φ-H	Water Saturation % Sw
30015024750000	3222	30	N/A	N/A	N/A
30015036860000	3433	42	N/A	N/A	N/A
30015058190000	3514	45	N/A	N/A	N/A
30015058290000	3515	47	N/A	N/A	N/A
30015100640000	3198	55	26	3.59	41
30015103530000	3463	54	39	3.9	40
30015106200000	3489	56	45	4.45	38
30015107650000	3549	0	0	0	N/A
30015107750000	3578	79	61	6.03	N/A
30015107790000	3533	52	25	3.38	41
30015107850000	3549	48	19	2.98	44
30015107870000	3541	0	0	0	N/A
30015108390000	3568	0	0	0	N/A
30015108670000	3309	37	N/A	N/A	N/A
30015108880000	3388	86	49	5.47	27
30015200250000	3471	57	40	4.62	29
30015200360000	3412	93	69	9	28
30015200920000	3505	55	37	4.28	38
30015201750000	3235	62	39	5.52	35
30015202250000	3523	69	38	4.4	N/A
30015203090000	3288	37	N/A	N/A	N/A
30015203690000	3495	53	16	2.86	49
30015205850000	3482	26	17	1.97	24
30015208190000	3351	70	38	5.05	49
30015208660000	3373	40	32	3.66	29
30015209010000	3490	36	8	1.6	38
30015209450000	3199	31	N/A	N/A	N/A
30015211170000	3458	53	50	5.21	N/A
30015213250000	3198	65	4	2.84	38
30015214550000	3331	42	34	3.72	39
30015214940000	3185	56	13	2.88	60
30015215290000	3324	44	31	3.3	34
30015220750000	3208	15	4	0.8	N/A
30015221330000	3195	36	3	1.56	67
30015221910000	3096	83	60	6.18	43
30015223980000	3222	114	36	6.86	42

30015225440000	3432	65	14	3.84	73
30015226700000	3149	71	4	3.32	57
30015226820000	3235	34	0	0	N/A
30015227490000	3130	36	0	0	N/A
30015228390000	3236	0	0	0	N/A
30015228590000	3285	37	1	1.36	N/A
30015229450000	3113	52	20	3.06	63
30015229660000	3301	0	0	0	N/A
30015229890000	3448	72	5	3.42	75
30015230040000	3313	23	10	1.58	56
30015231310000	3166	50	23	3.36	49
30015232360000	3303	58	6	2.39	55
30015233010000	3176	132	61	8.9	34
30015233560000	3440	90	13	4.28	71
30015233600000	3452	31	5	1.76	29
30015233850000	3239	30	6	1.8	53
30015234730000	3237	0	0	0	N/A
30015235770000	3154	115	53	7.82	51
30015235780000	3337	35	2	1.72	51
30015235900000	3479	63	13	3.3	47
30015236240000	3236	20	0	0	N/A
30015236290000	3382	44	22	2.92	38
30015237850000	3435	91	12	3.77	30
30015238460000	3429	63	13	2.6	47
30015239680000	3327	59	34	3.96	61
30015239690000	3201	88	20	4.86	56
30015239760000	3268	36	0	0.76	90
30015240600000	3214	28	0	0	N/A
30015240830000	3297	14	0	0	N/A
30015240840000	3320	59	42	4.48	53
30015240850000	3330	37	10	2.22	66
30015241380000	3427	76	64	8.34	41
30015242100000	3179	46	18	3.04	52
30015247070000	3173	21	0	0	N/A
30015248240000	3191	92	22	4.72	43
30015250090000	3566	23	15	1.69	24
30015259070000	3180	0	0	0	N/A
30015262630000	3413	54	32	4.12	44
30015274540000	3502	41	0	0	N/A
30015296130000	3381	53	0	0	N/A

30015300520000	3129	80	30	4.89	49
30015300580000	3365	64	41	4.48	55
30015326080000	3118	90	80	9.54	38
30015327050000	3133	65	39	4.68	41
30015329550000	3194	31	3	4.68	57
30015331030000	3197	80	43	5.7	44
30015331570000	3199	0	0	0	N/A
30015332310000	3218	89	0	0	N/A
30015336990000	3170	85	55	6.38	43
30015339720000	3199	105	55	7.1	50
30015340120000	3340	27	5	1.32	67
30015341790000	3133	75	33	4.54	35
30015342860000	3122	73	31	4.58	48
30015342910000	3491	113	53	7.18	52
30015343390000	3461	81	0	2.82	70
30015343440000	3087	89	15	4.88	63
30015343990000	3149	41	15	2.46	53
30015348610000	3213	66	25	4.26	36
30015348790000	3179	58	3	2.3	70
30015349210000	3176	57	28	4	49
30015351450000	3157	25	2	1.36	53
30015351460000	3140	89	37	5.64	55
30015351690000	3218	48	0	0	N/A
30015351710000	3522	42	0	0	N/A
30015352510000	3213	151	39	7.5	44
30015352690000	3180	95	14	5.04	44
30015353450000	3187	64	35	4.68	55
30015353480000	3430	0	0	0	N/A
30015354810000	3225	18	0	0	N/A
30015355710000	3316	0	0	0	N/A
30015355910000	3151	37	14	2.46	52
30015355920000	3478	62	24	4.04	62
30015357530000	3153	88	8	4.26	62
30015360180000	3109	54	3	1.82	50
30015360190000	3347	82	15	4.38	47
30015360200000	3395	91	9	4.44	57
30015360210000	3277	0	0	0	N/A
30015362890000	3148	67	30	4.54	53
30015362900000	3159	69	26	4.45	51
30015362910000	3311	96	45	6.4	48

30015362920000	3295	60	38	4.58	46
30015362930000	3156	91	32	5.52	60
30015362940000	3146	80	6	3.72	60
30015362970000	3102	118	15	4.78	53
30015363380000	3127	85	31	4.54	46
30015364550000	3396	64	13	3.66	52
30015365600000	3513	19	0	0	N/A
30015367360000	3128	87	47	6.48	40
30015402880000	3493	21	0	0	N/A
30015417980000	3469	53	22	3.4	67
30015420070000	3176	39	17	2.6	57
30025364370000	3539	0	0	0	N/A
30015339740000	3116	92	70	7.62	46
30015231000000	3335	43	1	1.52	81
30015297780000	3390	11	0	0	N/A
30025417710000	3538	44	0	1.44	44

James Ranch Unit

Unique Well ID	KB Elevation (Ft.)	Gross Thickness Ft.	Net Thickness ϕ >8%	Apparent Porosity ϕ-H	Water Saturation % Sw
30015047340000	3309	53	N/A	N/A	N/A
30015047350000	3327	62	N/A	N/A	N/A
30015202320000	3311	62	33	4.21	45
30015208030000	3319	42	34	3.4	38
30015209960000	3221	64	55	7.8	20
30015212470000	3338	60	4	2.84	49
30015221620000	3180	30	5	1.66	48
30015230750000	3317	30	0	0.94	100
30015233770000	3324	40	10	2.26	52
30015240620000	3331	68	5	3.46	49
30015244200000	3327	32	12	2.04	53
30015247800000	3339	0	0	0	N/A
30015260210000	3347	32	26	2.8	34
30015262960000	3360	36	0	1.68	61
30015263820000	3367	33	18	2.34	40
30015272080000	3344	63	47	5.24	58
30015274100000	3391	0	0	0	N/A
30015274780000	3362	32	17	2.28	43
30015277040000	3330	50	24	3.52	47
30015277840000	3327	58	15	3.04	40
30015279270000	3338	38	28	2.38	35
30015279950000	3331	0	0	0	N/A
30015280120000	3359	75	57	6.52	30
30015280930000	3378	72	19	4.3	47
30015289790000	3326	53	19	3.4	49
30015291730000	3311	33	30	2.94	26
30015310330000	3335	84	30	5.14	54
30015310560000	3345	0	0	0	N/A
30015327200000	3356	37	21	2.6	45
30015327970000	3360	74	26	4.62	53
30015328680000	3338	10	0	0	N/A
30015342770000	3321	32	12	2.04	53
30015343280000	3347	34	18	2.52	43
30015345940000	3356	29	21	2.22	28
30015410740000	3190	30	5	1.66	48
30015275870000	3425	48	27	3.6	40

30015286230000	3334	71	15	3.86	60
30015331140000	3327	55	13	2.94	53

Poker Lake Unit

Unique Well ID	KB Elevation (Ft.)	Gross Thickness Ft.	Net Thickness ϕ >8%	Apparent Porosity ϕ-H	Water Saturation % Sw
30015036910000	3045	17	14	1.39	41
30015047490000	3379	39	N/A	N/A	N/A
30015047620000	3311	31	N/A	N/A	N/A
30015047650000	3430	0	0	0	N/A
30015108590000	3496	17	12	1.21	45
30015202100000	3508	18	16	1.78	N/A
30015209330000	3391	21	3	1.13	61
30015210950000	3334	27	27	4.88	17
30015229280000	3122	21	12	1.52	47
30015232830000	3460	0	0	0	N/A
30015234300000	3270	24	0	0.86	66
30015237830000	3412	0	0	0	N/A
30015240410000	3117	23	19	1.92	42
30015241470000	3326	33	26	2.7	44
30015241550000	3374	0	0	0	N/A
30015241900000	3519	0	0	0	N/A
30015241960000	3218	21	0	0.49	100
30015252630000	3445	0	0	0	N/A
30015255930000	3102	24	24	2.76	32
30015260840000	3375	23	8	1.46	46
30015261520000	3106	24	0	0.94	62
30015266300000	3577	0	0	0	N/A
30015280320000	3109	25	13	1.72	34
30015285260000	3549	14	13	1.38	32
30015285760000	3081	40	40	3.8	45
30015293180000	3058	22	2	1	92
30015293450000	3455	0	0	0	N/A
30015296030000	3612	18	12	1.34	32
30015304850000	3236	28	20	2.1	56
30015310850000	3470	23	0	0.94	49
30015311770000	3463	35	7	1.86	50
30015313810000	3436	0	0	0	N/A
30015314120000	3285	27	16	2	40
30015314990000	3084	34	4	1.74	79
30015315110000	3052	20	1	1.06	53
30015317740000	3200	18	4	1.08	56

30015321260000	3231	23	3	1.3	57
30015324350000	3544	0	0	0	N/A
30015331640000	3480	9	3	0.6	33
30015334690000	3105	24	12	1.66	57
30015336880000	3085	31	29	3.06	38
30015347830000	3464	36	1	1.54	49
30015351210000	3082	24	17	1.82	43
30015365060000	3492	20	11	1.5	43
30015371840000	3252	17	5	1.02	40
30015382970000	3140	18	7	1.2	44
30015397130000	3213	17	3	1	44
30015404350000	3348	25	N/A	N/A	N/A
30015409350000	3460	21	6	1.38	60
30015416390000	3394	18	2	0.78	62
30015407640000	3406	17	0	0.66	62
30015367750000	3126	37	3	1.88	86
30015378000000	3204	40	36	3098	43
30015366750000	3277	25	13	1.74	43
30015368300000	3318	23	4	1.3	72
30015370310000	3364	28	21	2.5	30
30015370300000	3237	31	18	2.08	45

Appendix B

Source Rock Evaluation Data Types and Values

(Weatherford Laboratories)

Evaluation of Potential Source Rocks

Evaluation of source rock potential requires knowledge of the **quantity** of organic matter (OM), the **quality** of OM, and the **maturity** of the OM. For these reasons, the analytical methods of total organic carbon (TOC) and Rock-Eval pyrolysis are used routinely to evaluate the petroleum generative potential and thermal maturity of source rock samples (Hunt, 1996). The Rock-Eval pyrolysis technique involves passing of stream of helium through ~100 mg. of pulverized rock sample that is heated initially to 300°C. The temperature is then programmed to increase at approximately 25°C/minute, up to 600°C.The vapors are analyzed with a flame ionization detector (FID), resulting in peaks (S_1, S_2, S_3, and S_4) shown on Figure 1

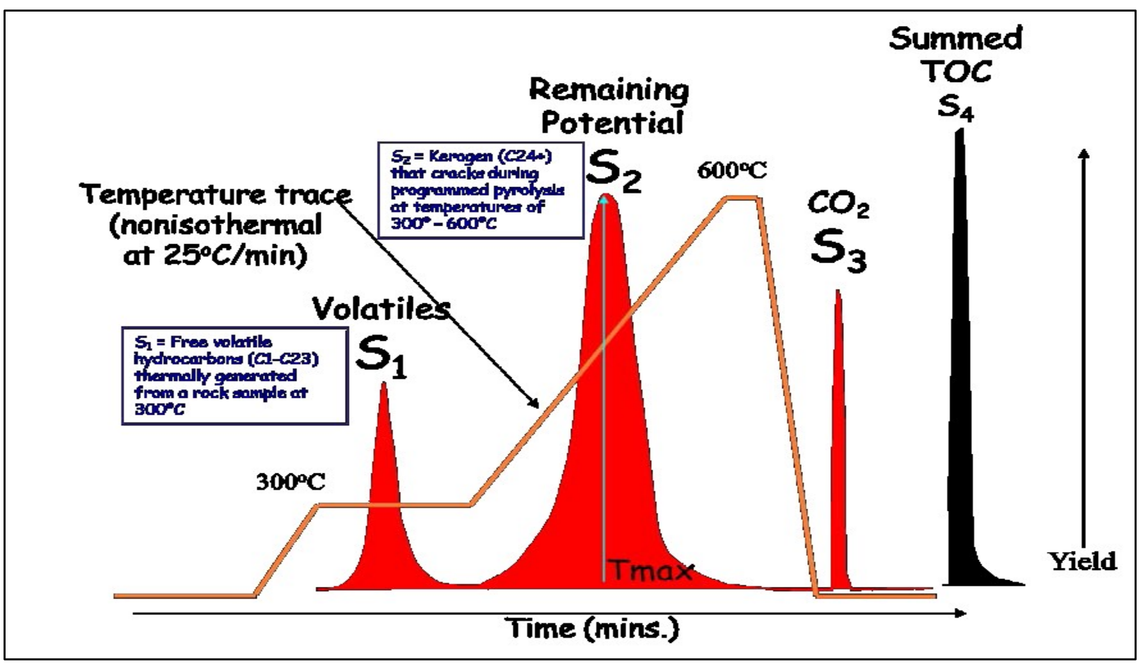


Figure 1. Schematic of a pyrogram showing the evolution of hydrocarbons and CO_2 from a rock during heating (increasing time and temperature from left to right).

For TOC determination, the sample is heated again to oxidize residual carbon (S4). Hydrogen and oxygen indices are calculated by dividing the S2 and S3 values by TOC (x 100), respectively. TOC also may be determined by separate analysis (LECO). A Rock-Eval pyrogram (Figure 1) provides several useful measurements and calculated parameters:

S1 measures the amount of free hydrocarbons (mg HC/g rock) that can be volatilized out of a rock without cracking the kerogen at about 300°C. This is the petroleum already in the sample. S1 increases at the expense of S2 with thermal maturity (i.e., depth of burial). S1 typically is high in active source rocks or petroleum reservoir rocks.

S2 measures the amount of hydrocarbons (mg HC/g rock) generated by pyrolysis from the cracking of kerogen and represents the potential of a rock to generate petroleum. S2 is high in both potential and active source rocks, but is lower in thermally mature source rocks that have already generated hydrocarbons, as well as in non-source rocks, and in reservoir rocks.

Tmax is an indicator of thermal maturity and corresponds to the Rock-Eval pyrolysis oven temperature (°C) at maximum S2 generation. (T_{max} should not be confused with geologic burial temperature.) T_{max} generally agrees with other independent measures of thermal maturity, such as vitrinite reflectance (%R_o).

S3 measures the amount of carbon dioxide (mg CO_2/g rock) generated from the organic matter in a rock during programmed pyrolysis.

Production Index (PI) is calculated [PI = S1/ (S1+S2)] and gradually increases with depth of burial as thermally labile components in the kerogen (S2) are converted to free hydrocarbons (S1).

Hydrogen Index (HI) is calculated [HI = S2/TOC x 100], as is **S2/S3**, and both are proportional to the amount of hydrogen in the kerogen and therefore indicate the potential of the rock to generation oil. High hydrogen indices indicate great or rich generative potential.

Oxygen Index (OI) is calculated (OI = S3/TOC x 100] and is related to the amount of oxygen in the kerogen.

S2/S3 is the *Hydrocarbon Type Index*. Similar to a modified van Krevelen diagram (crossplot of HI vs. OI), the Hydrocarbon Type Index is an indicator of kerogen type (i.e., gas-prone, gas- & oil-prone, or oil-prone).

Table 1 below provides Rock-Eval interpretation guidelines from Peters (1986); and Peters and Casa (1994).

Table 1: Source Rock Evaluation Data Types and Values

Quantity	**Poor**	**Fair**	**Good**	**Excellent**
Rock-Eval S2	0-2.5	2.5-5	5-10	10+
TOC	0-0.5	0.5-1.0	1.0-2.0	2+
Rock-Eval S1	0-0.5	0.5-1	1.0-2.0	2+

Quality	**Gas-prone**	**Gas & Oil-prone**	**Oil-prone**
Hydrogen Index	0-150	150-200	300+
Rock-Eval S2/S3	0-3	3.0-5.0	5+
Kerogen Type	Pred. vitrinite	Mix	Pred. amorphous

Maturity	**Immature**	**Early**	**Peak**
Rock-Eval Tmax	< 435˚C	435-440° C	440-470° C
Vitrinite Reflectance (Ro)	< 0.5	0.5-0.6	0.6-1.4
Thermal Alteration Index (TAI)	< 2.0	2.0-2.5	2.5-3.3
Production Index (PI)	< 0.1	~0.1	~0.4

References

Adams, J.E., H.N. Frenzel, M.L. Rhodes, and D.P. Johnson, 1951, Starved Pennsylvanian Midland Basin: American Association of Petroleum Geologists Bulletin, v. 35, p. 2600-2607.

Adams, J.E., 1965, Stratigraphic-tectonic development of Delaware Basin: American Association of Petroleum Geologists Bulletin, v. 24, p. 2140-2148.

Archie, G.E., 1952, Classification of carbonate reservoir rocks and petrophysical considerations: AAPG Bulletin, vol. 36, no. 2, p. 218–298.

Bassett, D.A., 2012, Evaluation of chemostratigraphy in interpreting stratigraphic architecture of the Bone Spring Formation in the Delaware Basin, Eddy County, New Mexico [MS Thesis]: Oklahoma State University, 192 p.

Blakey, R.C., 1980, Pennsylvanian and Early Permian paleogeography, southern Colorado Plateau and vicinity: in Paleozoic Paleogeography of west central United States, Rocky Mountain Section, Society of Economic Paleontologists and Mineralogists, p. 239-258.

Cook, H.E., P.N. McDaniel, E.W. Mountjoy, and L.C. Pray, 1972, Allochthonous carbonate debris flows at Devonian bank ("reef") margins, Alberta, Canada: American Association of Petroleum Geologists Bulletin, v. 20, no. 3, p, 439-497.

Cys, J.M., and W.R. Gibson, 1988, Pennsylvanian and Permian geology of the Permian Basin region, *in* H. N. Frenzel et al*.,* 1988, The Permian Basin region *in* L.L. Sloss, ed., Sedimentary cover – North America Craton: The Geology of North America: The Geological Society of America, v. D-2. P. 277-289.

Dadson, S., N. Hovius, S. Pegg, W.B. Dade, M.J. Horng, and H. Chen, 2005, Hypercanal river flows from an active mountain belt, Journal of Geophysics Res: 110LF04016, doi: 10.1029/2004Jf000244.

Dahl, J.E., 2014, Geochemical Evaluation of Core Samples from the Big Eddy Unit DI28 No. 254H Well, Weatherford Laboratories Confidential Report.

----2014, Source Rock Characterization Based on Total Organic Carbon and Rock-Eval Pyrolysis for the James Ranch Unit 21 Federal No. 1 SWD Well, Weatherford Laboratories Confidential Report.

----2014, Source Rock Characterization Based on Total Organic Carbon and Rock-Eval Pyrolysis for the Big Eddy Unit DI9 #35 Well. Weatherford Laboratories Confidential Report.

Davies, G.R., 1997, The Triassic of the western Canadian Sedimentary Basin: Tectonic stratigraphic framework, paleogeography, Paleoclimate, and biota: Bulletin of Canadian Petroleum Geology, v. 45, p. 434-460.

Dickinson, W.R., and T.F. Lawton, 2001, Carboniferous to Cretaceous assembly and fragmentation of Mexico: Geological Society of America Bulletin, v. 113, p. 1142-1160.

Dubiel, R.F., 1994, Triassic deposystems, paleogeography and Paleoclimate of the western interior, *in* Caputo et al., eds., Mesozoic Systems of the Rocky Mountain Region, U. S. A.: Denver, Rocky Mountain Section, Society for Sedimentary Geology, p. 133-168.

Ewing, T.E., 1993, Erosional margins and patterns of subsidence in the Late Paleozoic west Texas Basin and adjoining basin of west Texas and Southeast New Mexico, *in* Love, D.W., J.W. Hawley, B.S. Dues, J. W. Adams, G.S. Austin, and J.M Barker eds., Carlsbad Region, New Mexico and West Texas: New Mexico Geological Society, 44th Annual Field Conference, p. 155-166.

Fischer, C.R., and M. Sarnthein, 1988, Airborne silts and dune-derived sands in the Permian of the Delaware Basin: Journal of Sedimentary Petrology, v. 58, p. 637-643.

Flawn, P.T., 1956, Basement Rocks of Texas and southeast New Mexico: University of Texas Publication 5605, 261 p.

Frenzel, H.N., R.R. Bloomer, R.B. Cline, J.M. Cys, J.E. Galley, J.M. Hills, W.E. King, W.R. Seager, F.E Kottlowski, S. Tompson III, G.C. Luff, B.T. Pearson, and D.C. Van Siclen, 1988, The Permian Basin region, *in* L.L. Sloss, ed., Sedimentary cover – North American Craton: The Geology of North America: The Geological Society of America, v. D-2, p. 261-306.

Funk, J. E., R.M. Slatt, and. R. Pyles, 2012, Quantification of static connectivity between deep-water channels and stratigraphically adjacent architectural elements using outcrop analogs, AAPG Bulletin, v. 96, no. 2, p. 277–300.

Galley, J.E., 1958, Oil and geology in the Permian basin of Texas and New Mexico, *in* L. G. Weeks, ed., Habitat of oil: American Association of Petroleum Geologists Bulletin, p. 395-446.

Gawloski, T.F., 1987, Nature, distribution, and petroleum potential of Bone Spring detrital sediments, northern Delaware Basin: Mitchell Energy Corporation Publication, p. 44-69.

Hart, B.S., 1997, Slope to basin transition: Bone Spring Formation reservoirs, Delaware Basin [abs]: American Association of Petroleum Geologists Annual Meeting with Abstracts, p. A-48.

Hartman, J.K., and L.R. Woodard, 1971, Future petroleum resources in post-Mississippian strata of north, central, and west Texas and eastern New Mexico, *in* I.H. Cram, ed., Future Petroleum Provinces of the United State – Their Geology and Potential: American Association of Petroleum Geologists, Memoir 15, v. 1, p. 752-800.

Hills, J.M., 1963, Late Paleozoic tectonics and mountain ranges, western Texas to southern Colorado: American Association of Petroleum Geologists Bulletin, v. 47, p. 1709-1725.

----1984, Sedimentation, tectonism, and hydrocarbon generation in Delaware Basin, west Texas and southeastern New Mexico: American Association of Petroleum Geologists Bulletin, v. 68, no. 3, p. 250-267.

Hoak, T., P. Sundberg, , and P. Ortoleva, 1998, Overview of the structural geology and tectonics of the Central Basin Platform, Delaware Basin, and Midland Basin, west Texas and New Mexico: Science Applications International Corporation Publication 9915, 56 p.

Hoffacker, B.F. Jr., 1990, Camar, *in* A.L. Vanderhill, C.B. Godfrey, and F. Heard, eds., Oil and gas fields in west Texas, volume V: West Texas Geological Society Publication, v. 90-86, p. 45-51.

Hunt, J.M., 1996, Petroleum geochemistry and geology: San Francisco, W.H. Freeman Co., 743 p.

James, N.P., and E.W. Mountjoy, 1983, Shelf-slope breaks in fossil carbonate platforms – an overview; *in* D.J. Stanley, and G.T. Moore, eds., The Shelfbreak – Critical Interface on Continental Margins: Society of Economic Paleontologists and Mineralogists, Special Publication 33, p. 198-206.

King, P.B., 1948, Geology of the Southern Guadalupe Mountains, Texas: U.S. Geological Survey, Professional Paper 215, p. 148.

Kinley, T.J., 2006, Geology and hydrocarbon potential of the Barnett Shale (Mississippian) in the northern Delaware Basin, west Texas and southeastern New Mexico [MS Thesis]: Texas Christian University, 56 p.

Kocurek, G., and B.L. Kirkland, 1998, Getting to the source: aeolian influx to the Permian Delaware Basin region: Sedimentary Geology, v. 117, p. 143-149.

Mazzullo, S.J., 1981, Facies and burial diagenesis of a carbonate reservoir – Chapman deep (Atoka) field, Delaware County, Texas: American Association of Petroleum Geologists Bulletin, v. 65. p. 650-685.

----1991, Permian stratigraphy and facies, Permian Basin (Texas-New Mexico) and adjoining areas in the midcontinent United States, *in* P. A Scholle, T.M. Peryt, and D.S. Ulmer-Scholle, eds., The Permian of northern Pangea, v. 2: Berlin, Springer-Verlag, p. 41-60.

Mazzullo, L.J., A.M. Reid, Jr., 1987, Stratigraphy of the Bone Spring Formation (Leonardian) and depositional setting in the Scharb field, Lea County, New Mexico, *in* D. Cromwell and L. J. Mazzullo, eds., The Leonardian facies in west Texas and southeast New Mexico and Guidebook to the Glass Mountains, west Texas: Permian Basin Section Society of Economic Paleontologists and Mineralogists, Publication 87-27, p. 107-111.

Meiburg, E., and B.C. Kneller, 2010, Turbidity currents and their deposits, Annual Reservoir Fluid Mechanics, v. 42, p. 135-156.

Messa, J.F., L.L. Brooks, S.M. Yates, and J.D. Underwood, 1996, Second Bone Spring Sand Study: Internal report, Harvey E. Yates Company, 55 p.

Middleton, G.V., and M. A. Hampton, 1976, Subaqueous sediment transport and deposition by sediment gravity flows, *in* D.J. Stanley, and D.J.P. Swift, eds., Marine Sediment Transport and Environmental Management: New York (Wiley-Interscience), p. 1-38.

Montgomery, S.L., 1997, Permian Bone Spring Formation: Sandstone play in the Delaware Basin part 1 – slope: American Association of Petroleum Geologists Bulletin, v. 81, no. 8, p. 1239-1258.

----1997, Permian Bone Spring Formation: Sandstone play in the Delaware Basin part 2 – Basin: American Association of Petroleum Geologists Bulletin, v. 81, no. 9, p. 1423-1434.

North American Commission on Stratigraphic Nomenclature: American Association of Petroleum Geologists Bulletin, v. 89, no. 11 (2005), p. 1547-1591.

Oriel, S.S., D.A. Myers, and E.J. Crosby, 1967, West Texas Permian Basin region, Chapter C, *in* McKee, E.D., and S.S. Oriel, eds., Paleotectonic Investigations of the Permian System in the United States: U.S. Geological Survey, Professional Paper P 0515, p. 17-60.

Pearson, R.A., 1999, Sequence stratigraphy and seismic-guided estimation of log properties of the Second Sand Member of the Bone Spring Formation, Delaware Basin, New Mexico [MS Thesis]: New Mexico Institute of Mining and Technology, 124 p.

Peters, K.E. 1986, Guidelines for evaluating petroleum source rock using programmed pyrolysis, AAPG Bulletin v. 70, no. 3, p.318-329.

Peters, K.E., and Casa, M.R., 1994, Applied source rock geochemistry, *in* L.B. Magoon and W.G. Dow, eds., The Petroleum System, From Source Rock to Trap: AAPG Memoir, v. 60, AAPG, p. 93-120.

Ruppel, S.C., and W.B. Ward, 2013, Outcrop-based characterization of the Leonardian carbonate platform in west Texas: Implications for sequence-stratigraphic styles in the Lower Permian: American Association of Petroleum Geologists Bulletin, v. 97, no. 2, p. 223-250.

Saller, A.H., J.W. Barton, and R.E. Barton, 1989, Slope sedimentation associated with a vertically building shelf, Bone Spring Formation, Mescalero Escarpe Field, southeastern New Mexico, *in* D. Cromwell and L. J. Mazzullo, eds., the Leonardian facies in west Texas and southeast New Mexico and Guidebook to the

Glass Mountains, west Texas: Permian Basin Section Society of Economic Paleontologists and Mineralogists, Publication 87-27, p. 275-288.

Schmoker, J.W., 1981, Determination of organic-matter content of Appalachian Devonian shales from gamma-ray logs: American Association of Petroleum Geologists Bulletin, v. 65/7, p. 1285-1298.

Shanmugam, G., 2003, Deep-marine tidal bottom currents and their reworked sands in modern and ancient submarine canyons: Marine and Petroleum Geology, v. 20, p. 471–491.

Shepard, T.M., and J.L. Walper, 1982, Tectonic evolution of Trans-Pecos, Gulf Coast Association of Geological Societies Transactions, v. 32, p. 165-172.

Silver, B.A., and R.G. Todd, 1969, Permian cyclic strata, northern Midland and Delaware Basins, west Texas and southeastern New Mexico: American Association of Petroleum Geologists Bulletin, v. 53, no. 11, p. 2223-2251.

Soreghan, G.S., and M.J. Soreghan, 2013, Tracing clastic delivery to the Permian Delaware Basin, U. S. A.: Implications for paleogeography and circulation in westernmost equatorial Pangea: Journal of Sedimentary Research, v. 83, p. 786-802.

Stewart, J.H., 1988, Latest Precambrian and Paleozoic southern margin of North America and the accretion of Mexico: Geology, v. 16, p. 186-189.

Tindell, W.N., 1954, Butler and Toenail Fields, Schleicher County, Texas: American Association of Petroleum Geologists Data page Archives, p. 7-9, Abilene Geological Society, Geological Contributions (2008).

Van Wagoner, J.C., H.W., Posamentier, R.M. Mitchum Jr., P.R. Vail, J.F. Sarg, T.S. Loutit, and J. Gardenbol, 1988. An overview of the fundamentals of sequence stratigraphy and key definitions *in* Wilgus, C.K., B.S. Hastings, C.G.St.C. Kendall, H.W. Posamentier, C.A. Ross, and J.C. Von Wagoner, eds., Sea-level Changes: An Integrated Approach: Society of Economic Paleontologists and Mineralogists Special Publication no. 42, p. 39-45.

Walper, J.L., 1977, Paleozoic tectonics of the southern margin of North America: Transactions of the Gulf Coast Association of Geological Societies, V. 27, p. 230-241.

Walsh, P., 2006, Geologic Trends of oil and gas production in the Secretary of the Interior's Potash Area, southeastern New Mexico: New Mexico Bureau of Geology and Mineral Resources, a division on New Mexico Institute of Mining and Technology, open file report 498: final report to the Bureau of Land Management, 43 p.

Ward, R.F., C.G.St.C. Kendall, and P.M. Harris., 1986, Upper Permian (Guadalupian) facies and their association with hydrocarbons: Permian basin, west Texas and

New Mexico: American Association of Petroleum Geologists Bulletin, v. 70, p. 239-263.

Wiggins, W.D., and P.M. Harris, 1985, Burial diagenetic sequence in deep-water allochthonous dolomites, Permian Bone Spring Formation, southeast New Mexico, *in* P. D Cromwell and P. M. Harris, eds., Deep water carbonates: buildups, turbidites, debris flows and chalks: Society of Economic Paleontologists and Mineralogists Core Workshop 6, p. 140-173.

Yang, K.M., and S.L Dorobek, 1992, Mechanisms for Late Paleozoic synorogenic subsidence of the Midland and Delaware Basins, Permian Basin, Texas and New Mexico, *in* Murk, D.H, and B. C. Curran, eds., Permian Basin exploration and Production Strategies: Applications of Sequence Stratigraphic and Reservoir Characterization Concepts: West Texas Geological Society, Symposium, p. 45-60.

Ziegler, A.M., M.L. Hulver, and D.B. Rowley, 1997, Permian world topography and climate, *in* Martini, I. P., ed., Late Glacial and Postglacial environmental Changes: Quaternary, Carboniferous-Permian, and Proterozoic: Oxford, U.K., Oxford University Press, p. 111-146.

Biographical Information

Marshall Dewayne Davis is a Geologist for Bass Operating and Production Company L. P. in Fort Worth, Texas. He received his Master of Science degree in Petroleum Geoscience from the University of Texas at Arlington, Arlington, Texas in December, 2014. Prior to his graduate studies; Marshall received his Bachelor of Science in Geology, *Cum Laude*, from Sam Houston State University, Huntsville, Texas in August of 2013.

For the past year and a half, Marshall has worked in the Delaware Basin, southeast New Mexico, researching the subsurface geology of, specifically, the Wolfcamp (Wolfcampian) and Bone Spring (Leonardian) Formations. Prior to becoming a Geologist, Marshall worked as an Intern Geologist, assisting in the development of unconventional resource plays in the Delaware Basin. Marshall also worked as a Teaching Assistant at Sam Houston State University, teaching Historical Geology Lab classes.

Marshall is a member of the American Association of Petroleum Geologists, the West Texas Geological Society and the Fort Worth Geological Society.