

ANALYSIS OF PARASEQUENCES WITH PALEO-GEOGRAPHICAL RECONSTRUCTION
OF THE MIOCENE RESERVOIRS OF THE MAIN PASS REGION IN THE GULF OF
MEXICO

by
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THESIS

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Abstract

ANALYSIS OF PARASEQUENCES WITH PALEO-GEOGRAPHICAL RECONSTRUCTION OF THE MIOCENE RESERVOIRS OF THE MAIN PASS REGION IN THE GULF OF MEXICO

Reservoir sands in the Main Pass region of the Gulf of Mexico have proved to be highly productive, accounting for 56 million barrels of oil and 47 billion cubic feet of gas in just the 4 lease blocks covered in this study. Having a thorough understanding of the depositional trends that created these reservoirs and their relation to the reservoir's performance is paramount to the success of field development. Post depositional structure is removed through the process of correlation among chrono-stratigraphically equivalent surfaces. Characteristic log signatures from the wells in the trend are then interpreted, resulting in a model of the depositional environment. These depositional environments are the consequence of rising and falling sea levels, coupled with tectonics and climate fluctuations. Times of falling sea level result in deposition of fluvio-deltaic sand bodes deposited by the Paleo-Mississippi river, while times of rising sea level correspond to the deposition of low energy shales. The results of the study can be used to predict prospective adjacent reservoirs, as well as to provide insights into exploitation techniques and mechanisms. Previous performance is tied to the interpreted lithology and therefore depositional environment.

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I want to thank my supervising committee for being so patient and flexible with me in my final semester at the University of Texas Arlington. I want to thank Dr. John Wickham not only for being my supervising professor, but for guidance in countless other situations throughout graduate school.

Dedication

I dedicate my work in this study to my mother and father, which without this work would not have been a possibility. And to the continuous support of my fiancée Emily, thank you for your patience and support.

TABLE OF CONTENTS

COVER PAGE.....	1
ABSTRACT.....	2
ACKNOWLEDGEMENTS.....	4
DEDICATION.....	5
INTRODUCTION.....	7
GEOLOGICAL SETTING.....	14
CONTROLS ON SEDIMENTATION IN THE MIOCENE.....	16
DEFINING THE DELTA COMPLEX.....	18
PREVIOUS RESEARCH.....	20
OBJECTIVES.....	21
PROCEDURES.....	27
RESULTS.....	30
P-Sand.....	30
O-Sand.....	42
N-Sand.....	53
SUMMARY AND CONCLUSIONS.....	68
REFERENCES.....	70

Introduction

In the never-ending search for new oil and gas accumulations, the accurate prediction of the location and productive characteristics of petroleum reservoirs is becoming increasingly desirable. This information is key not only to stratigraphic plays, but also to structurally complex ones. To obtain this knowledge, the creation and evolution of these sediment bodies must be thoroughly understood.

The depositional environment and the subsequent alteration of said environment control the ultimate productivity of a petroleum reservoir. These sedimentary environments are defined by the mechanical, chemical, and biochemical processes that differentiate them from one another. Once an area of deposition has been established, sedimentary facies may be interpreted. Sedimentary facies as defined by Catuneanu in *Principles of Sequence Stratigraphy* are “bodies of sediment that are recognizably distinct from adjacent sediments that resulted from different depositional environments”.

Understanding how petroleum reservoirs are deposited and their coinciding characteristics leads to more efficient exploitation of subsurface accumulations. Be it a new exploration horizon, or a field that has been under development for 30 years, one must understand where the desired reservoirs were deposited, and why. This allows for optimal wellbore placement and hydrocarbon recovery, which in turn leads to lower expenses and higher revenues. Creating and executing projects with the highest possible net present value must be the goal for every petroleum geoscientist. Without this knowledge, every well may as well be a wildcat.

Geological Setting

The Gulf of Mexico is a relatively small ocean basin that lies between the Yucatan block, and the North American Plate (Figure 1). Over 65,000 feet of sediment lie within the basin, dating back to the Jurassic. The Gulf of Mexico is the product of the separation of the South American and African lithospheric plates from the North American plate (Miall 2008). These landmasses comprised Pangea, one of the largest supercontinents. The process of sea floor spreading is the cause of this massive break-up (Miall 2008). The divergent event began in the Triassic, but it initiated the formation of the Gulf of Mexico in the Jurassic.

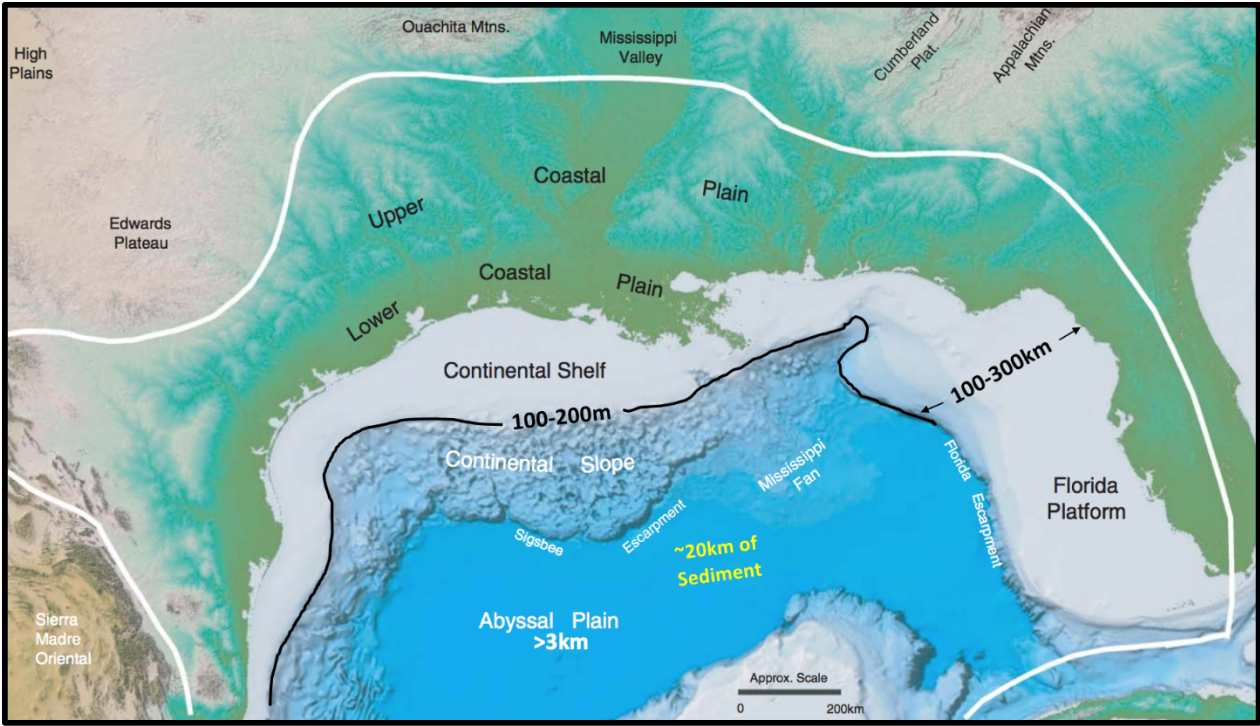


Figure 1. Present Day Gulf of Mexico with minor annotation, modified from Miall 2008.

The beginning of post-rift sedimentation, considered to be the base of sedimentary fill, is marked by the deposition of the Louann salt in the Middle Jurassic (Miall 2008). The

reactivation of sea-floor spreading brought an end to the salt deposition, which divided the gulf and the Louann salt into northern and southern portions. Subsequent deposition may be divided into three broad periods, Middle Jurassic, Cretaceous, and Cenozoic (Miall 2008).

The Middle Jurassic saw the deposition of the Louann, Norphlet, Smackover, and Cotton Valley formations, respectively (Winker 1988). The sequences are topped by the Valanginian (134-139 mya) unconformity, marking the end of sea-floor spreading (Marton 1999).

The formations of the Lower Cretaceous are dominantly carbonaceous and include the Upper Cotton Valley, Sligo, James, Glen Rose, Paluxy, and Stuart City (Kauffman 1997). The Upper Cretaceous is marked by some siliciclastic deposition including the Woodbine, Eutaw, San Miguel, and Nacatosh formations. A generalized stratigraphic column of the Mesozoic can be seen in Figure 2.

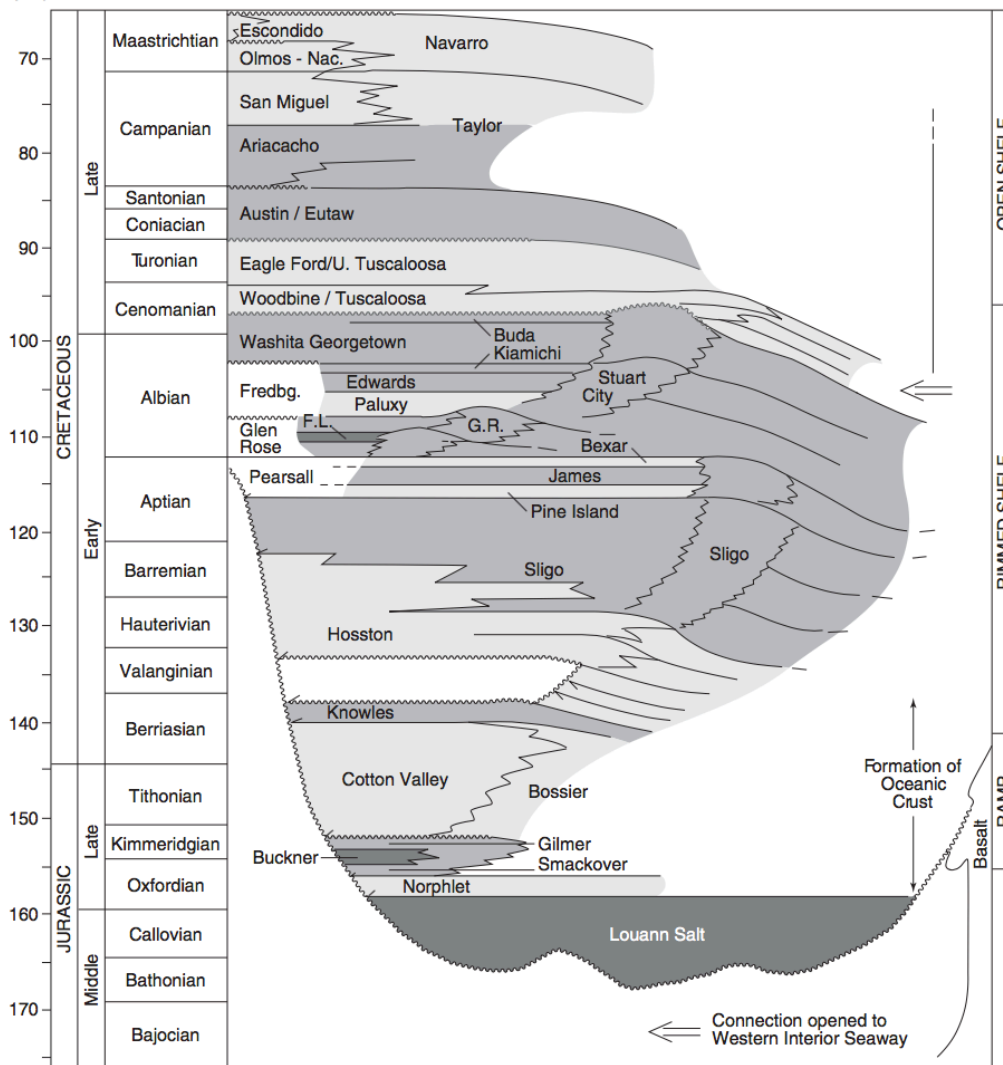


Figure 2: Generalized stratigraphic column for the Mesozoic (Gradstein 1995).

The depositional history of the Cenozoic is complex, comprising more than 20 unique depositional episodes, thus it will not be covered in detail for this study. Instead, the focus of this work, the Miocene, will be examined. The Miocene may be divided into just three major depositional episodes which equate closely to the early, middle, and late Miocene (Miall 2008). The lower Miocene sequence saw a significant influx of siliciclastic sediment over roughly 8 million years, and is capped by the widespread Amphistegina shale. During middle Miocene the

Paleo-Mississippi became the prominent drainage system and supplier of sediment to the Main Pass Region seen in Figure 1. The depositional load was so large that the continental margin prograded ~72km (Miall 2008). Successions of thick turbidites rapidly spilled down the continental slope into the basin (Galloway 2000). The late Miocene saw even more progradation (~120km), and a stabilization of the paleogeography. The continental slope assumed its present-day position. Sediment loading in the present day Main Pass Region during the Miocene led to an estimated 16,000 feet of additional subsidence (Miall 2008). The upper Miocene event ended with a regional flood marked by the last appearance of the benthic foraminifer *Robulus E* or “ROB E” (Galloway 2000). A generalized stratigraphic column of the Cenozoic can be seen in Figure 3.

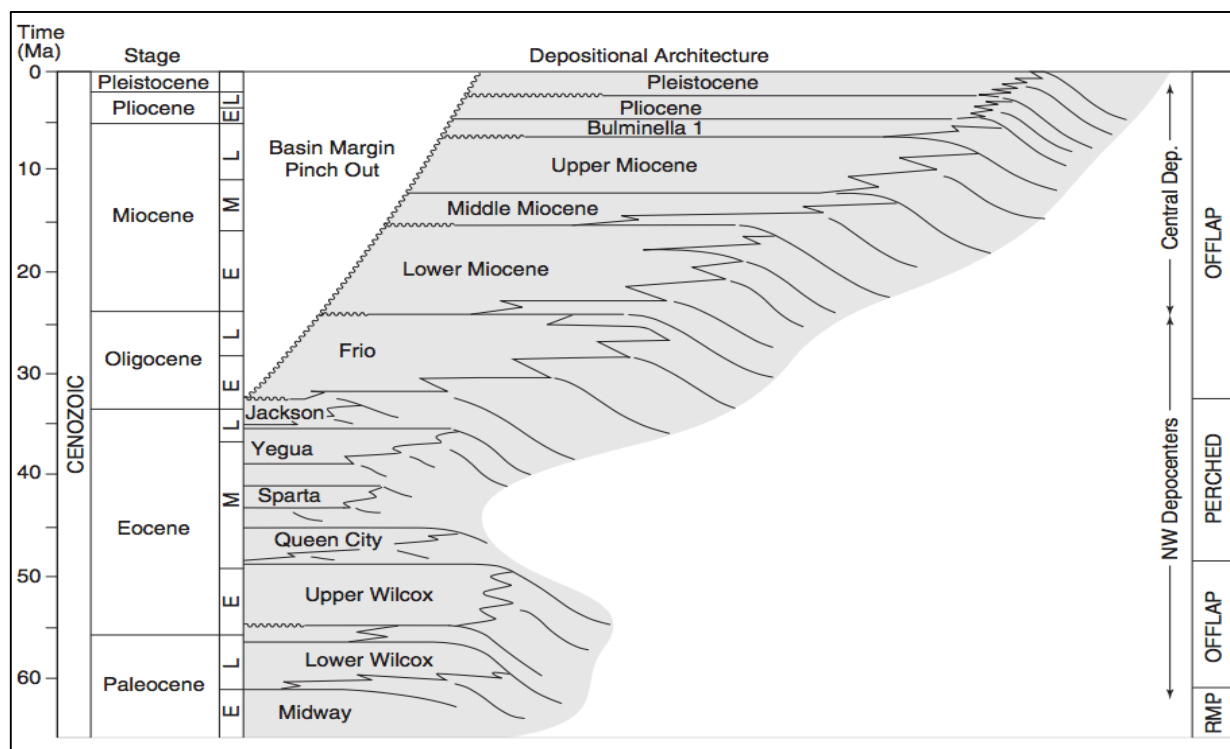


Figure 3: Generalized stratigraphic column for the Cenozoic (Gradstein 1995).

The area covered in this study are lease blocks MP 311, 312, 301, and 302 (Figure 4 and 5). These lease blocks span 9 square miles each, totaling 36 square miles (Figure 4 and 5). The region is located on the shelf immediately adjacent to the Mississippi delta. As explained, most of the sediment in this select area was transported and deposited by the Paleo-Mississippi drainage system. Figure 6 is a depth structure of an underlying formation, illustrating regional salt domes.



Figure 4. Map of the Main Pass region in the Gulf of Mexico (Amarsys 2012). Figure 5 is a zoomed in version of the Main Pass area showing lease blocks and the detailed study area.

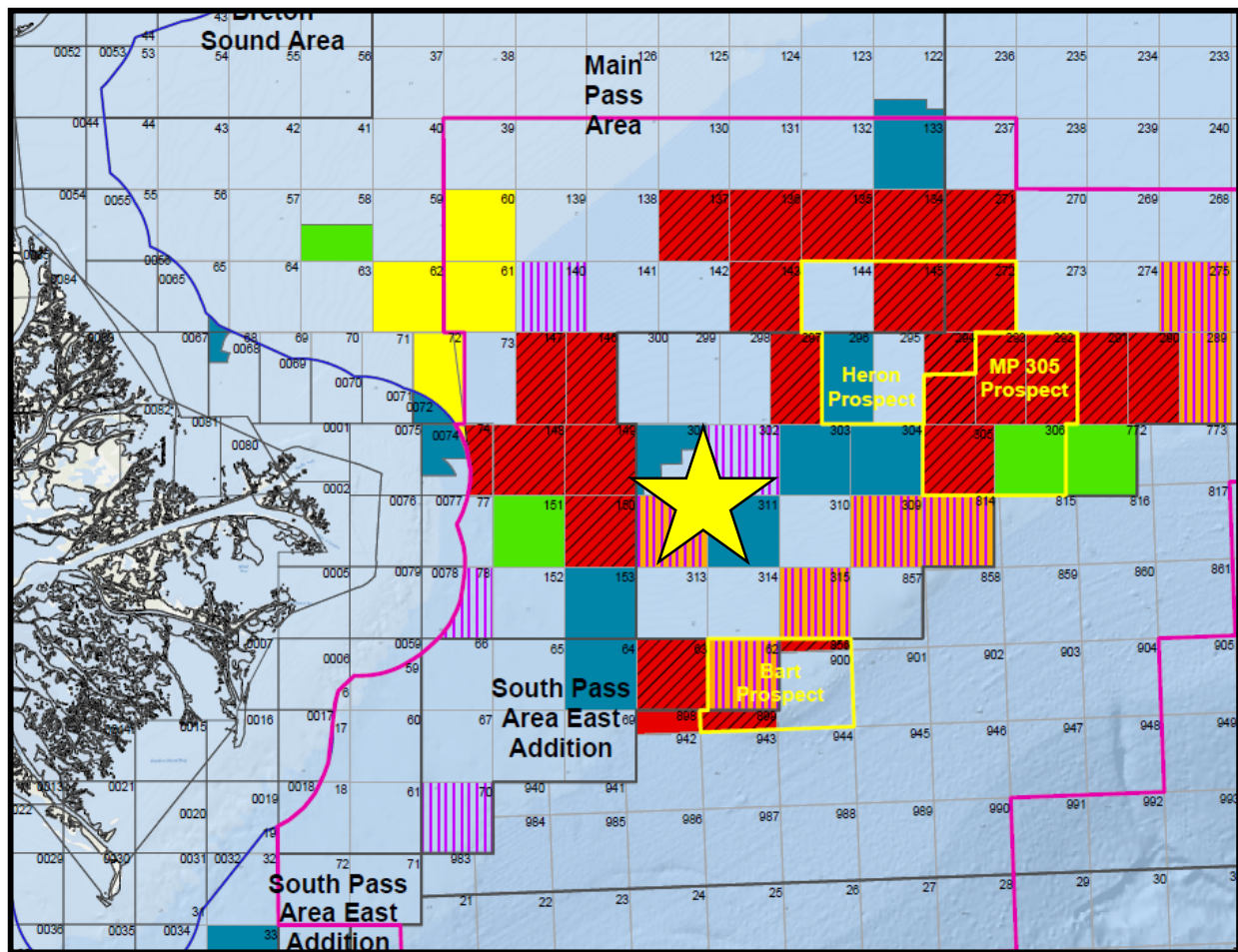


Figure 5. Map showing the lease blocks of the Main Pass Area. Yellow Star shows the study area consisting of Blocks 311, 312, 301 and 302. (Images courtesy of Energy XXI).

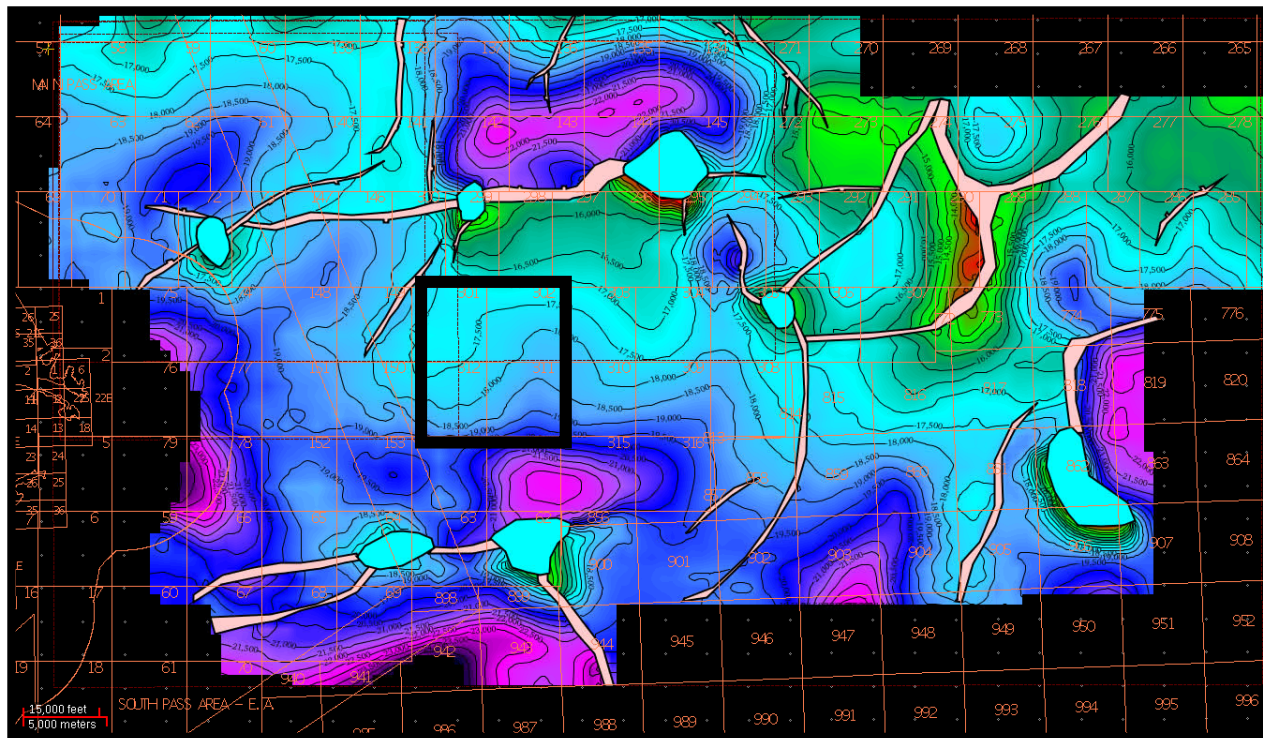


Figure 6. Structure map showing the region surrounding the study area, including salt domes and faults. The black box indicated the boundaries of the study area. (Image courtesy of Energy XXI).

Controls on Sedimentation in the Miocene

The early Miocene is marked by the shifting of the paleo-Mississippi eastward, integrating sediment sourced from Appalachians and the north-central Rocky Mountains. As previously mentioned, the Mississippi system was the dominant source of sediment for the Gulf, and has been so ever since. Through the middle Miocene, erosion in the Appalachians and the western U.S. led to a ~200% increase in sediment delivery through the Mississippi fluvial system (Galloway et al., 2011). The increase in sediment erosion in the Appalachian Mountains has been attributed to climate, as tectonic activity had been dormant for more than 200 years. In a study

completed by Poag and Sevon in 1989, the driver of increased sediment yield was determined to be increased Miocene precipitation. Their findings correlated closely to the known records of fossil mammal and plant communities. Significant lateral variation in formation isopachs and structures (Wu and Galloway, 2002) suggest that salt migration in eastern deep water zones influenced sediment accumulation. The figure below illustrates the evolution of sediment supply rate over the Miocene and Pleistocene. The progradation and retrogradation of the delta complex is primarily a function of sediment supply rate and water depth, as there was no relevant tectonic activity during this time.

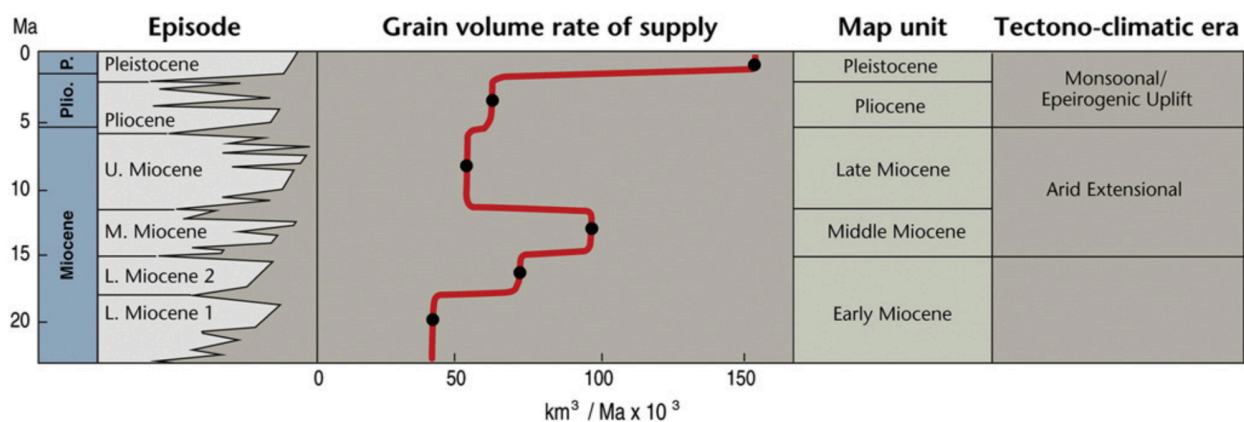


Figure 7: Controls on fluvial sediment supply to the Main Pass Region, Miocene to Pleistocene (Galloway et al., 2011).

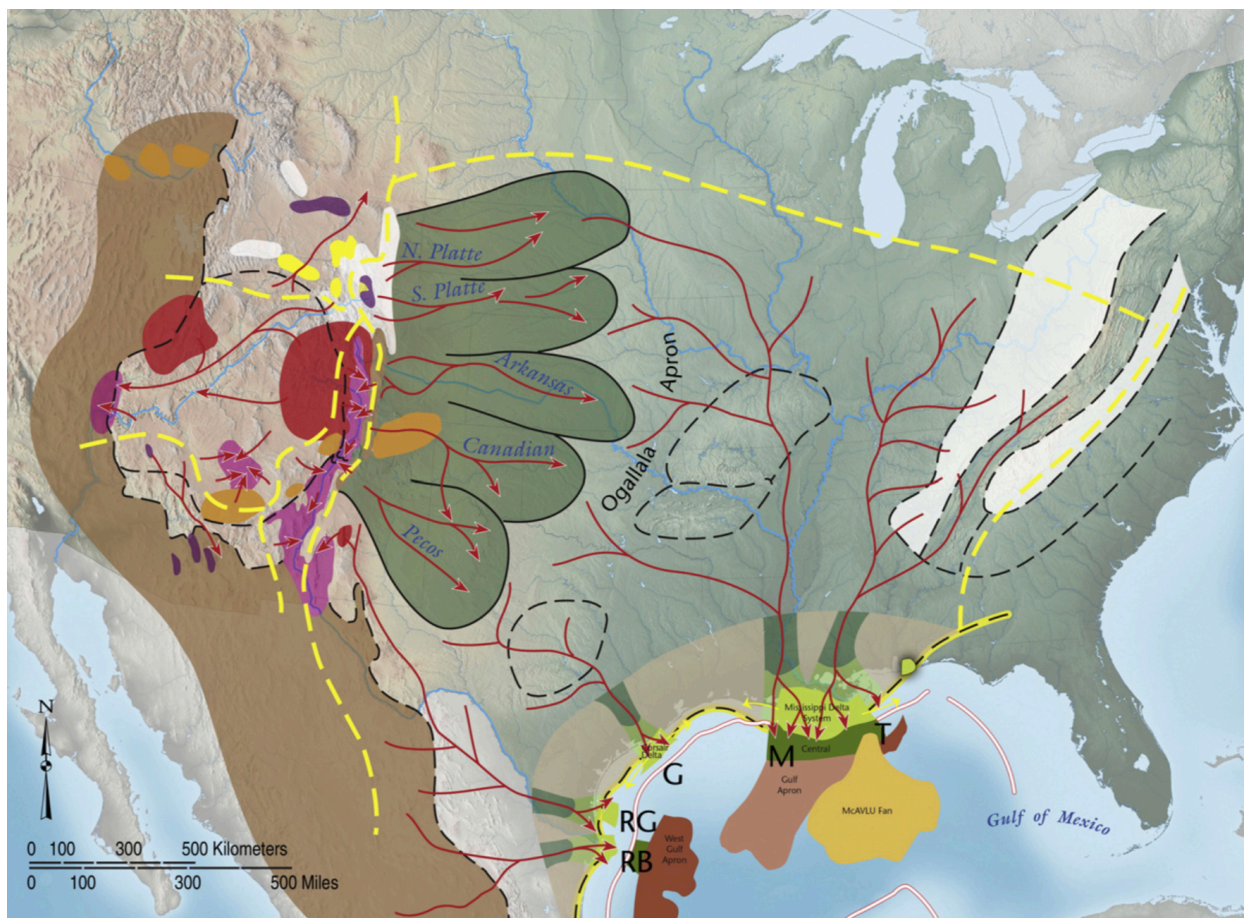


Figure 8: Depiction of the late Miocene depositional episode showing major continental fluvial axes, topographic and structural elements of the North American interior, and major depositional elements (Galloway et al., 2011).

Defining the Delta Complex

Deltas have been studied by geologists for countless years, and many choose to define parts of them differently. The terminology used in this paper will mirror that used in the study on distributary channels and transitional zones completed by Cornel Olariu and Janok Bhattacharya in 2006. As seen in figure 9, a typical delta can be divided into several different parts reflecting different sedimentary facies. The three main divisions of the delta detailed in this study will

include the “clean” sand zone, the lower transition zone, and the prodelta zone. The “clean” sand zone is comprised of poorly sorted, medium to coarse grained sandstone which is deposited in a high energy proximal environment. The transitional zone is comprised of interbedded sands and silts representative of a more distal environment where energy level is tapered off. The final zone is the prodelta zone which contains the silty clays and muds which are deposited in the most distal environment, meaning the lowest energy levels.

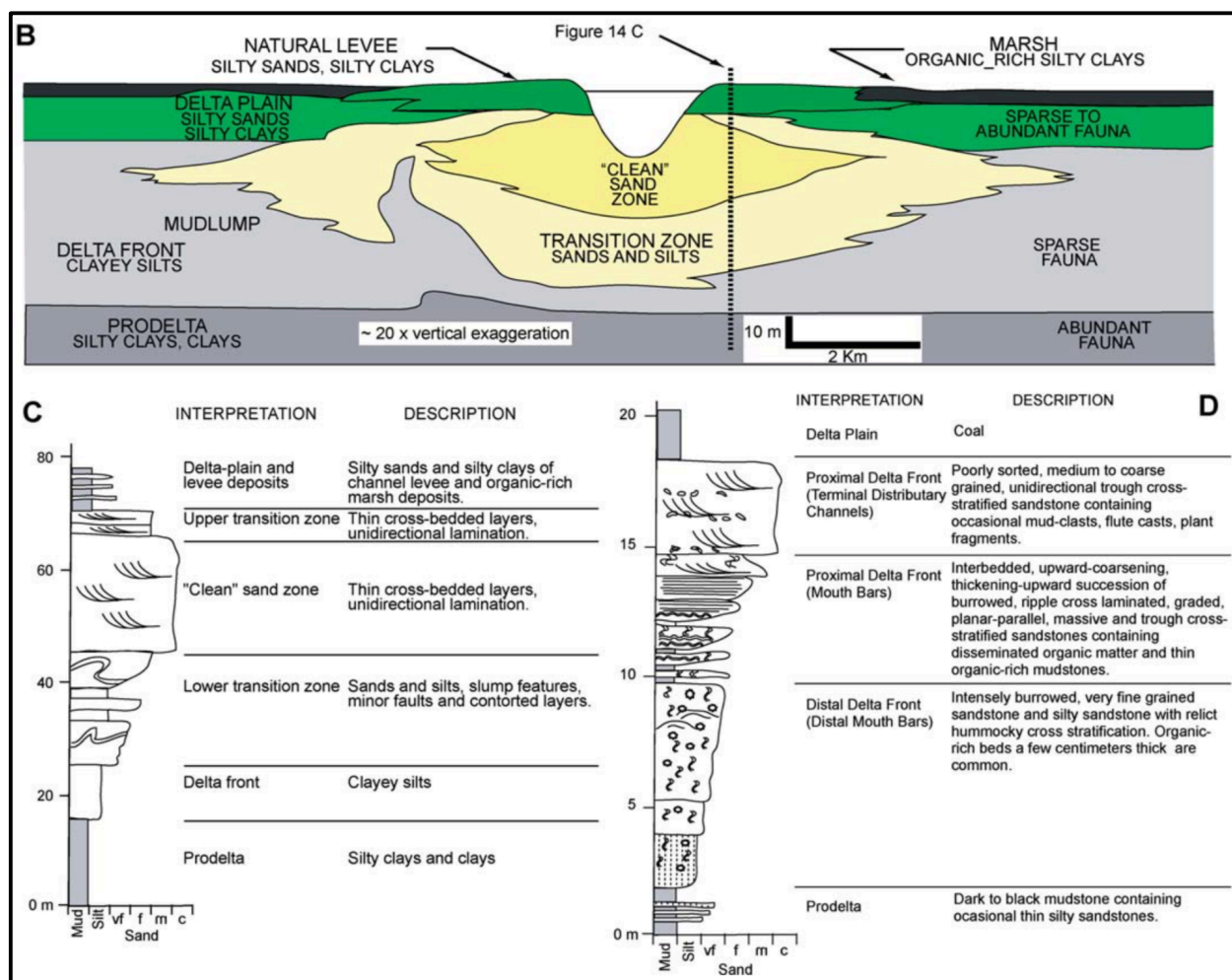


Figure 9: B) A cross section of a delta displaying the different sedimentary facies. C) Vertical column through the digitate delta. D) Vertical section of a river dominated delta (Olariu 2006).

Previous Research by Doris Curtis

The Gulf of Mexico at a basin scale has been studied countless times by many brilliant scientists all over the earth (Miall 2010, Stern 2010, Wood 2007). However, the Main Pass region has few published articles, particularly discussing the clastic depositional environments of the Miocene. The most relevant research was completed by Doris Malkin Curtis at Shell Oil Company in 1970. In her article “Miocene Deltaic Sedimentation, Louisiana Gulf Coast”, Curtis studies the evolution and structures associated with different types of delta systems that formed on the Louisiana gulf coast in the Miocene. The different types of deltas and their resultant reservoirs can be seen in the work done in this study. Curtis used thousands of electric well logs to interpret the morphology and stratigraphy of these delta systems. Her model uses two main variables, rate of deposition and rate of subsidence. The premise of the model is that the ratio of these two factors controls whether the delta progrades, retrogrades, aggrades, or spreads laterally. When deposition outpaces subsidence, Progradational deltas form and are associated with a regression of the shoreline. They display a typical vertical sequence beginning with marine clays/muds and coarsen upwards through successively landward facies. Her paper predated Sequence Stratigraphy, and these units are now referred to as parasequences, which is to be discussed further. As these deltas and sub-deltas continue to regress, younger deltas build seaward. The “bird-foot” delta seen in Figure 10 is typical of deltas where deposition outpaces subsidence. When the rate of deposition and subsidence are roughly equal, deltas will aggrade or spread laterally. The vertical sequence of Aggradational deltas are more homogenous, and can have thick sections representing a single delta facies. The morphology of these deltas depends on the energy of the system, and are known to have shoreline parallel marine features (Figure 11). When subsidence outpaces deposition, the deltas will retreat. Retrogradational deltas are

associated with a transgression of the shoreline. The vertical sequence will be the opposite of that seen in the progradational scheme, in other words it will fine upwards. The deltas in a regressive complex will become younger landward. The morphology created by this environment may be seen in Figure 12. These basic concepts will be applied in this study, as the model tracks the relative motion of the shoreline.

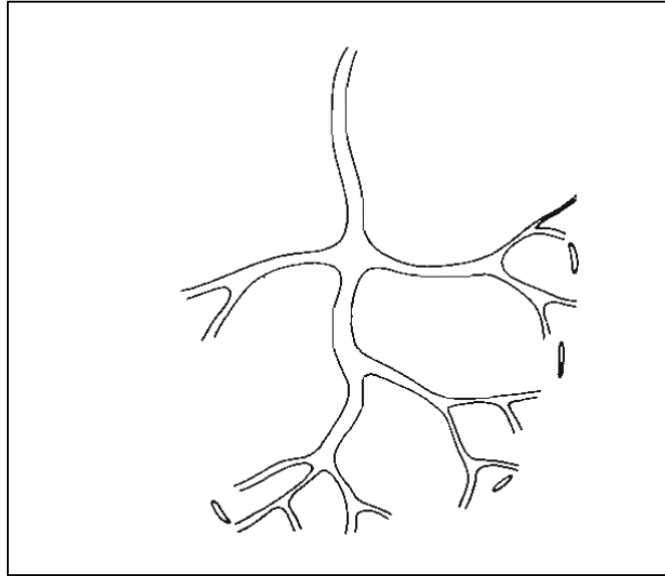


Figure 10. "Birds Foot Delta" showing branching channels typical of deltas where deposition outpaces subsidence. (Curtis 1970).

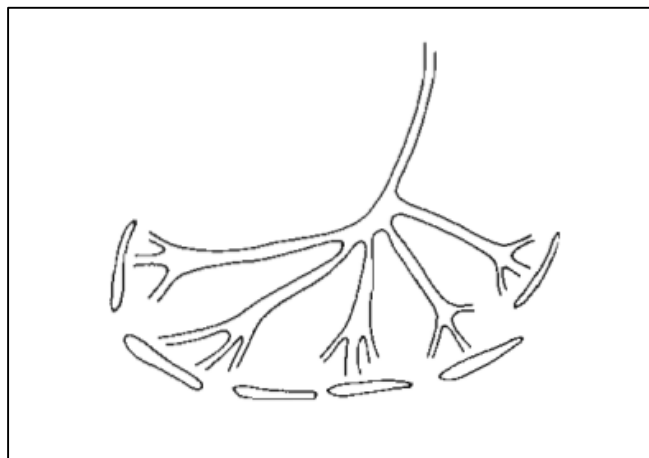


Figure 11. Morphology of an Aggradational delta showing branching channels with bars typical of equal deposition and subsidence. (Curtis 1970).

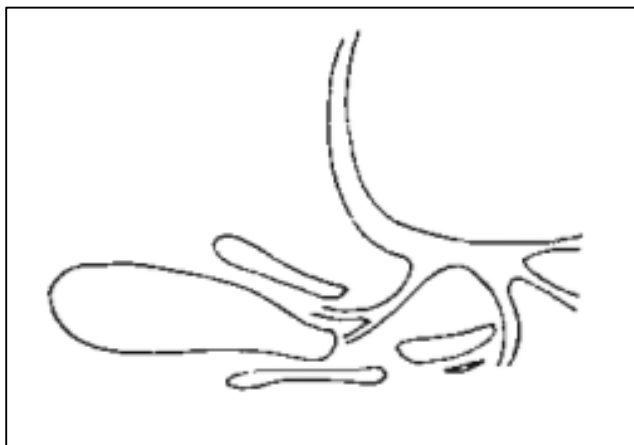


Figure 12. Morphology of an Retrogradational delta Showing channels and sand bodies as shoreline transgresses landward. (Curtis 1970).

Objectives

The objective of this work is to produce a depositional model throughout the Miocene, beginning with the deposition of the “P” reservoir sand, and continuing through the “N” sand. The model is to be a succession of layered isopach maps, with each layer representing deposition of a different facies. The maps not only show the deposition, but the interpreted movement of shoreline and sea level that brought about these changes. These reservoirs were chosen because they are the three most productive in the study area. Having this model allows the geologist to visually interpret the depositional environment. It can be seen where and what form deposition took place and then the area is assessed for productivity via porosity and permeability trends. The model is a visual representation explaining the effect of the depositional environment on the

variation in performance among the producing wells. Using the model, a prediction of adjacent unexploited reservoirs is made, possibly leading to new discoveries.

Procedures

A type log defining each reservoir and its cumulative production was constructed (Figure 13). The type log consist of sections from vertical wellbores for the sake of absolute thickness preservation. The type log is an amalgamation of several logs in the block; the logs with the most representative character for the reservoir were chosen. Sections from several logs were captured and matched to create a log with signatures that properly represent each reservoir. The reservoir depths for the type log are averages for the area.

All the electric well logs were transformed into true vertical depth logs by using directional surveys from the operating records. A full log suite is available for most of the wells in this study. Evaluation of each reservoir sand in each log then took place. The primary log used for interpretation of depositional environment is the Gamma Ray log, alongside Spontaneous Potential.

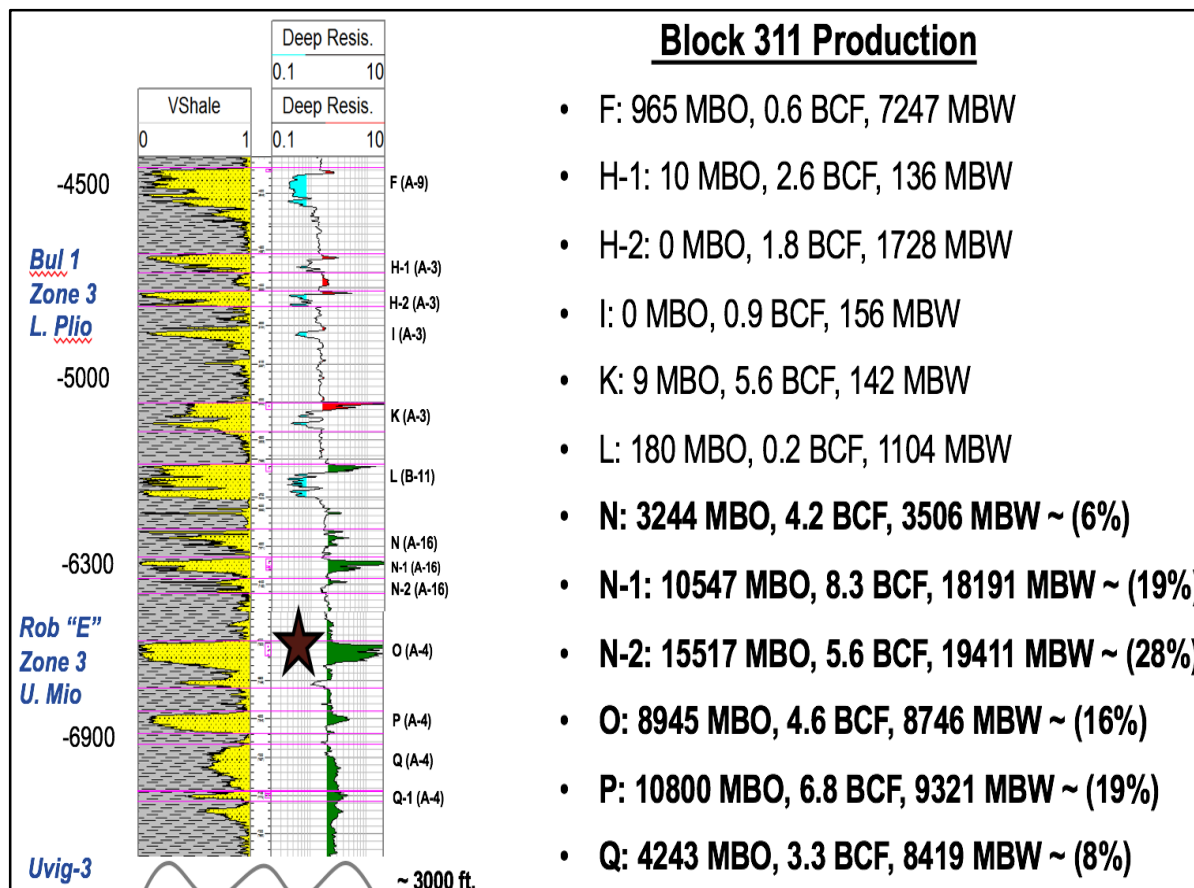


Figure 13. A type log created from various vertical wellbores for the Main Pass 311 lease block.

The letters next to the log in the right hand side are the names of the reservoirs.

The gamma ray tool is commonly used in sequence stratigraphy and the interpretation of depositional environments. This instrument is a passive measurement tool that records the natural radioactivity emitted by potassium, thorium, and/or uranium within the formation (Asquith 2004). Shales or other clay minerals tend to have very high concentrations of these elements and will give high counts, while sandier bodies lack these elements and will display a low reading. Shales comprised of these radioactive elements have a very small grain size, and sands which lack them have a larger grain size. For this reason, gamma ray is a useful proxy for grain size and thus depositional mechanisms. Reservoirs will always display a gamma ray

pattern, somewhere within the following five end members: count increasing upwards, decreasing upwards, boxy, serrated, or bowing (Figure 14). These Gamma Ray trends can be interpreted in terms of depositional environments. A summation of the patterns themselves and their various interpretations are seen in Figure 14. A “blocky” response has a sharp top and base, and commonly occur in Eolian, Braided River, and Deep-water turbidite systems. The “coarsening upwards” trend has a sharp top and is produced by prograding shoreline systems (beaches, deltas, tidal bars) as well as splays. A “fining upward” character has a sharp base, and commonly occurs in point bars, turbidites, and tidal channels. The “serrated” log response is introduced by environments characterized by thin sandy beds separated by shales. These types of environments include plains (flood, delta, coastal), flats, bays/lagoons, prodelta/offshore, and some deep-water turbidites (Mitchum 1990).

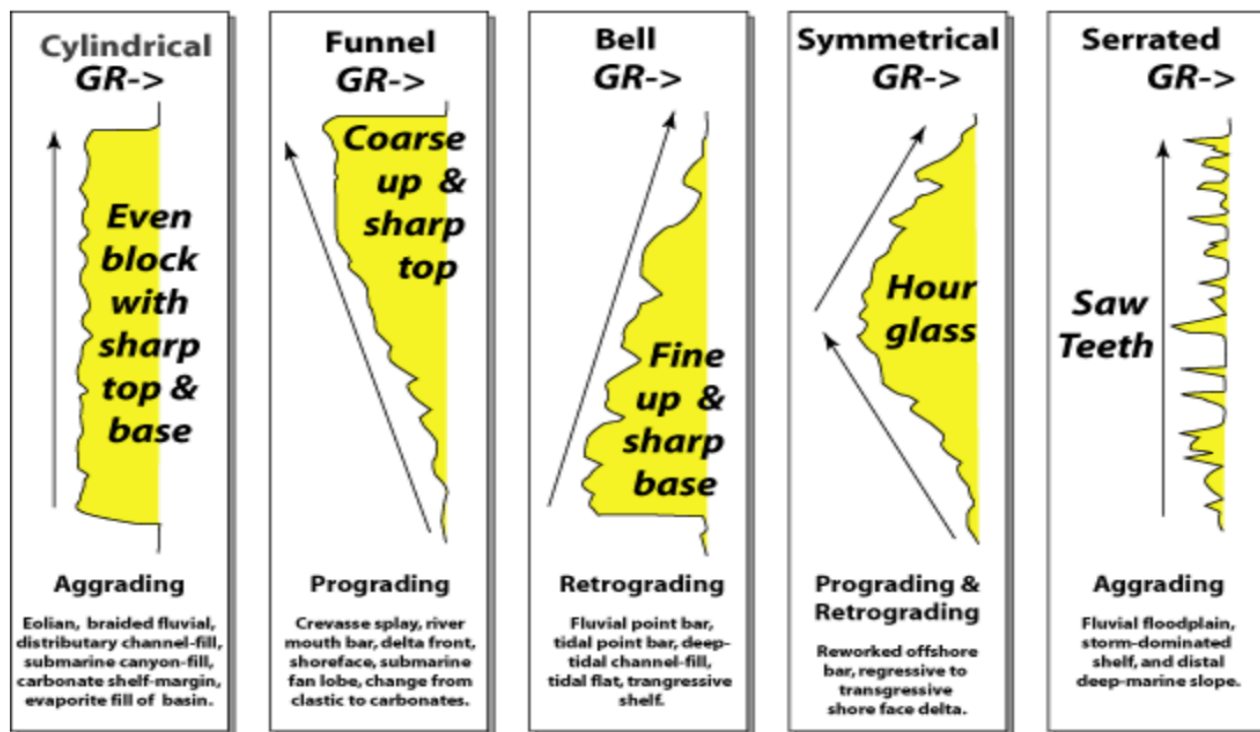


Figure 14. Common interpretations for the vertical trends in gamma ray readings (Emery 2009).

The Spontaneous Potential log is also useful in the interpretation of depositional environment. This instrument records the natural electrical current that is generated by the differences in salinity between the drilling mud and the formation water (Asquith 2004). A strong deflection in the SP log indicates that the ions move freely, and is an indicator of permeability. A minor SP deflection suggests that the ions have a tortuous path and take longer to travel, equating to little or no permeability. Spontaneous potential readings display trends very similar to those of the gamma ray, unless the pores are filled with cement or hydrocarbons. When the pore spaces are filled with hydrocarbon, the response from the SP log is suppressed, making it a useful hydrocarbon indicator. This indication is qualitative only, no numerical value can be extracted from the readings.

Sequence Stratigraphy

Parasequences are essential tools for core to well log correlation, and are among fundamental building blocks of sequence stratigraphy. A parasequence is a “relatively conformable, upward shallowing succession of genetically related beds or bed sets bounded by marine flooding surfaces or their correlative surfaces” (Van Wagoner, et al., 1988). These surfaces that bound the parasequences are approximate time lines with wide aerial extent, and allow for the creation of a chrono-stratigraphically correct framework. These parasequences are marked by cycles of sediment that either fine or coarsen upwards. The flooding surfaces create the sharp tops and bases seen in the gamma ray patterns. This abrupt change in energy reflected by the change in grain size is tied to the interaction of the transgressing/regressing sea atop the formation.

The parasequences expected to be seen in this study, judging by the geographical location and history of deposition, will be that of a delta complex and adjacent environments. The facies comprising these parasequences will begin with prodelta or offshore clays/muds displaying distal storm beds. Next are the transitional zone deposits comprised of silty sandstones and silty mudstones with graded bedding. Atop are the “clean” sand deposits, which are fine to very fine sandstones. The two possible facies that overlie the “clean” sand deposits are a distributary channel-fill, or an inter-distributary bay fill. The channel-fill is characterized by a sharp basal contact and fine grained sandstones. The inter-distributary bay fill will display s toothy patterns and be comprised of clay and silt. This all assumes a full parasequence cycle, which is rare. These facies and their lithologies can be seen in Figures 15 and 16.

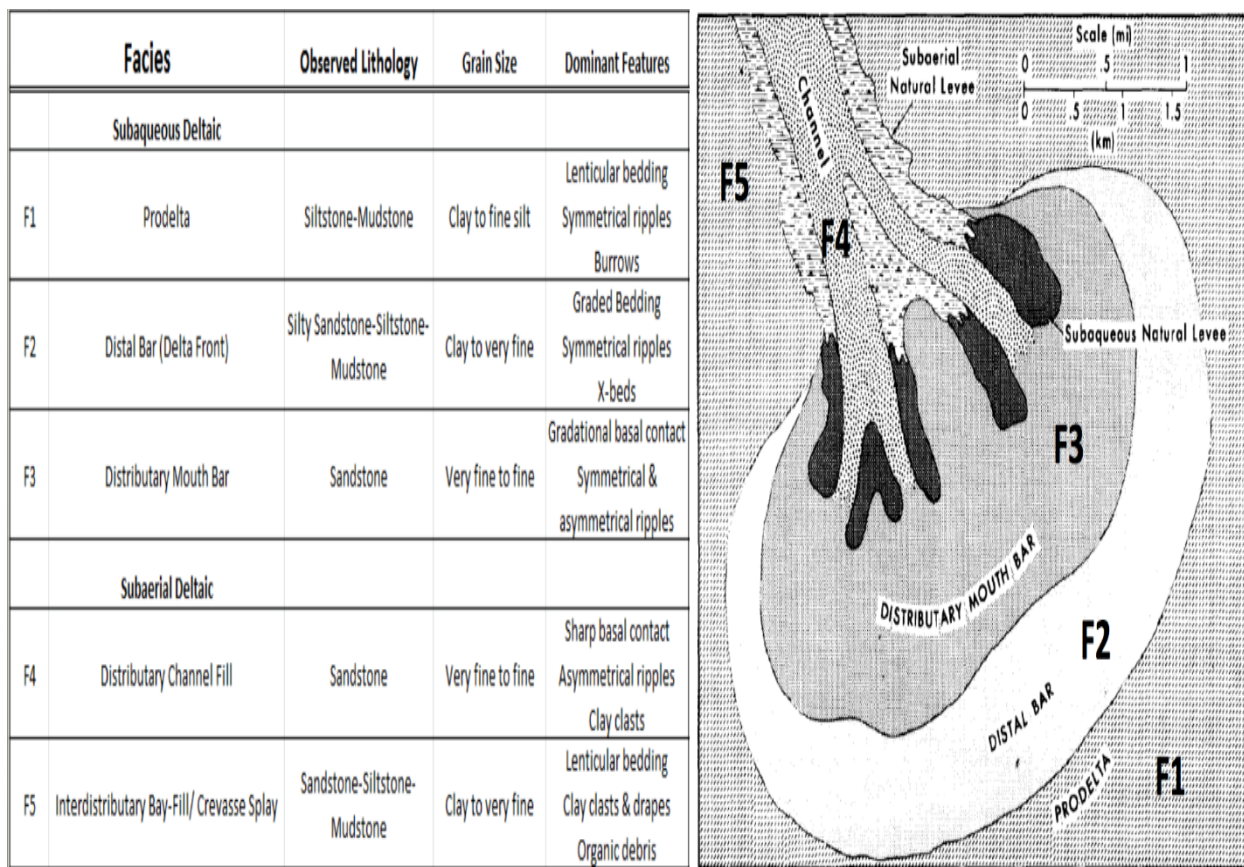


Figure 15. Facies and their related lithology, grain size, and features (Coleman and Prior 1980)

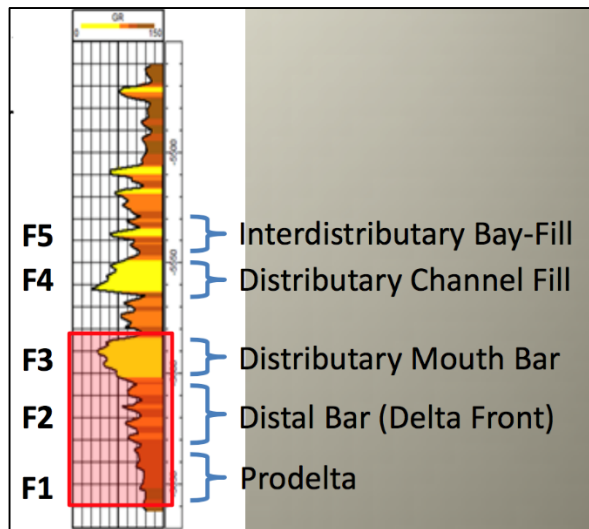


Figure 16. Vertical Gamma ray log through a prograding delta complex (Coleman and Prior 1980).

Once each log response for each reservoir was evaluated, the isopach maps were created. With all relevant data considered, the depositional environment is interpreted. Once a sand body is mapped for the entire region, the relation to sea level is determined. Between the reservoir sands lie low energy shale deposits which are to be described in the context of sea level transgression/regression. Once reservoirs “P” through “N” are modelled, the initial production rates from each reservoir are correlated to the location within the depositional environment. The placement of these wells within the environment is a major factor contributing to the success of a well. Finally, the entire area is surveyed and taken into a larger context of deposition.

The application of sequence stratigraphic principles allows the geologist to relate lithology and time within a section of sedimentary rock. While traditional principles such as lithological interpretation are applied, the chronostratigraphic framework reveals the evolution of

sedimentary succession. Traditional lithologic interpretation can be seen in Figure 17, and chronostratigraphic correlation using time equivalent surfaces can be seen in Figure 18.

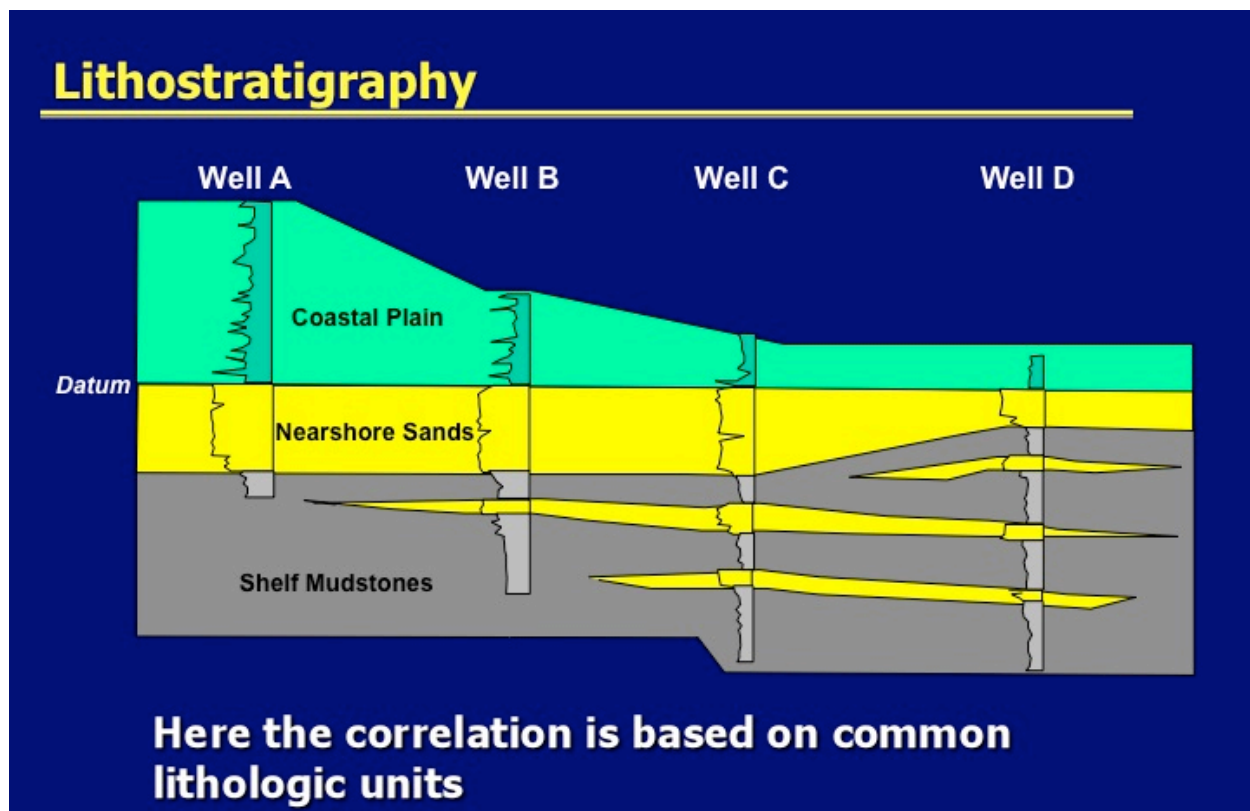


Figure 17. Correlation of well logs using traditional lithologic relationships (Van Wagoner et al., 1990).

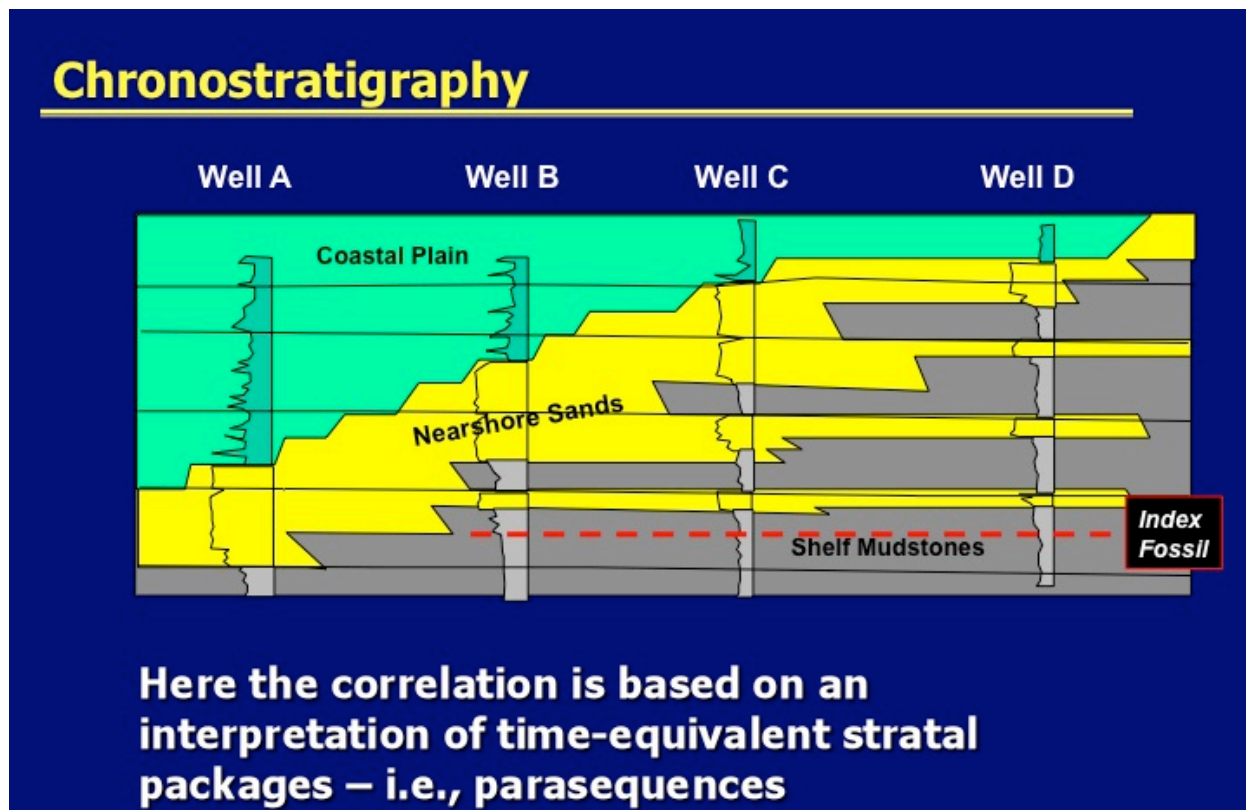


Figure 18. Correlation of well logs applying sequence stratigraphic principles (Van Wagoner et al., 1990).

The contrast between the two figures highlights how two different methods produce two different interpretations. The fundamental unit of sequence stratigraphy is the sequence, which is comprised of previously defined parasequence sets. These sequences are bound by widespread time equivalent conformable surfaces. These surfaces represent the same instant of time across an area. The tops of these sequences are bound by flooding surfaces. These flooding surfaces were created by a landward shift in facies and a dislocation of the sedimentary environment. These are identified by a gamma ray reading interpreted as deep water strata directly on top of a shallow water strata. This idea requires application of Walther's Law, which states that facies vertically adjacent to one another in a continuous sequence were accumulated in a laterally

adjacent setting. These flooding surfaces are fundamental because they are chrono-stratigraphically significant, and allow for temporal correlation. The “P”, “O”, and “N” sands in this study are all defined as separate parasequences, which are comprised of bed sets in a retrogradational, progradational, or aggradational manner. The “P” sand is a purely aggradational series, with a succession of offshore muds, followed by interbedded sands, silts and muds, topped by “clean” sands. The “O” sand and the “P” sand are more complex and represent a time of higher variability in sedimentation.

Limitations

The projected area for this study was approximately 36 miles², but when constrained by well location, the study area is closer to 20 miles². The study was intended to track the evolution of the delta complex evolving from distributary channel, to the “clean” sands, to the transitional zone, to prodelta along a time equivalent surface. After the sequence stratigraphic concepts were applied to the study area, it became apparent that the delta complex is too large to properly image fully. However, the concepts are properly applied, and there are insights and conclusions pertaining to depositional environment and log analysis that certainly have value. Also, in the context of production history, initial production data is normalized on a per foot perforation basis to display historical performance. Unfortunately, the N, O, and P reservoir production has been reported comingled, which leads to unreliable interpretations; this data was excluded.

Results

The “P-Sand” Parasequence:

Bed Set P-1:

The first bed set in the P parasequence is denoted in the GR log by a highly radioactive, flat spikey character (Figure 19). This pattern is interpreted to be the result of a homogenous mudstone absent of any sands or silts. Thin, repetitive, interbedded layers of radioactive silt and mud lead to this spikey gamma ray character. This sediment is indicative of the prodelta environment within the delta complex. The prodelta environment is notably low energy, and is located in relatively deep water (Xie and Heller, 2006). An isopach map of Bed Set 1 can be seen in Figure 20. This environment is the result of a transgressing water body and rising relative sea level that has outpaced sediment delivery (Figure 21).

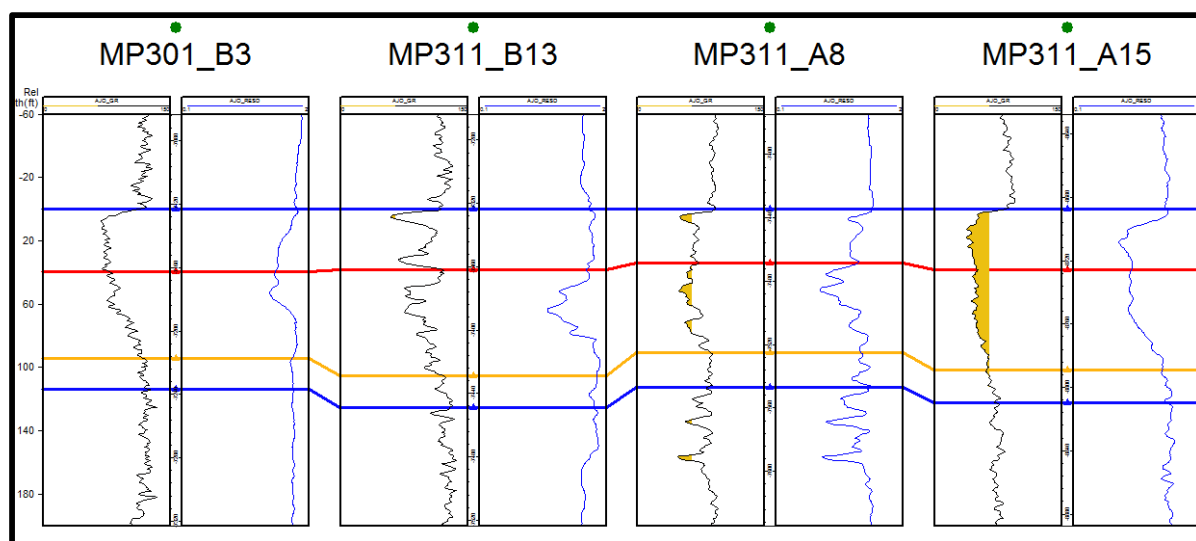


Figure 19. Type Log section of the “P-Sand” divided into bed sets by time equivalent surfaces. Black curve in track 1 is Gamma Ray, blue curve in track 2 is Resistivity. Bed set 1 is at the base, bed set 2 is in the middle, and bed set 3 is at the top.

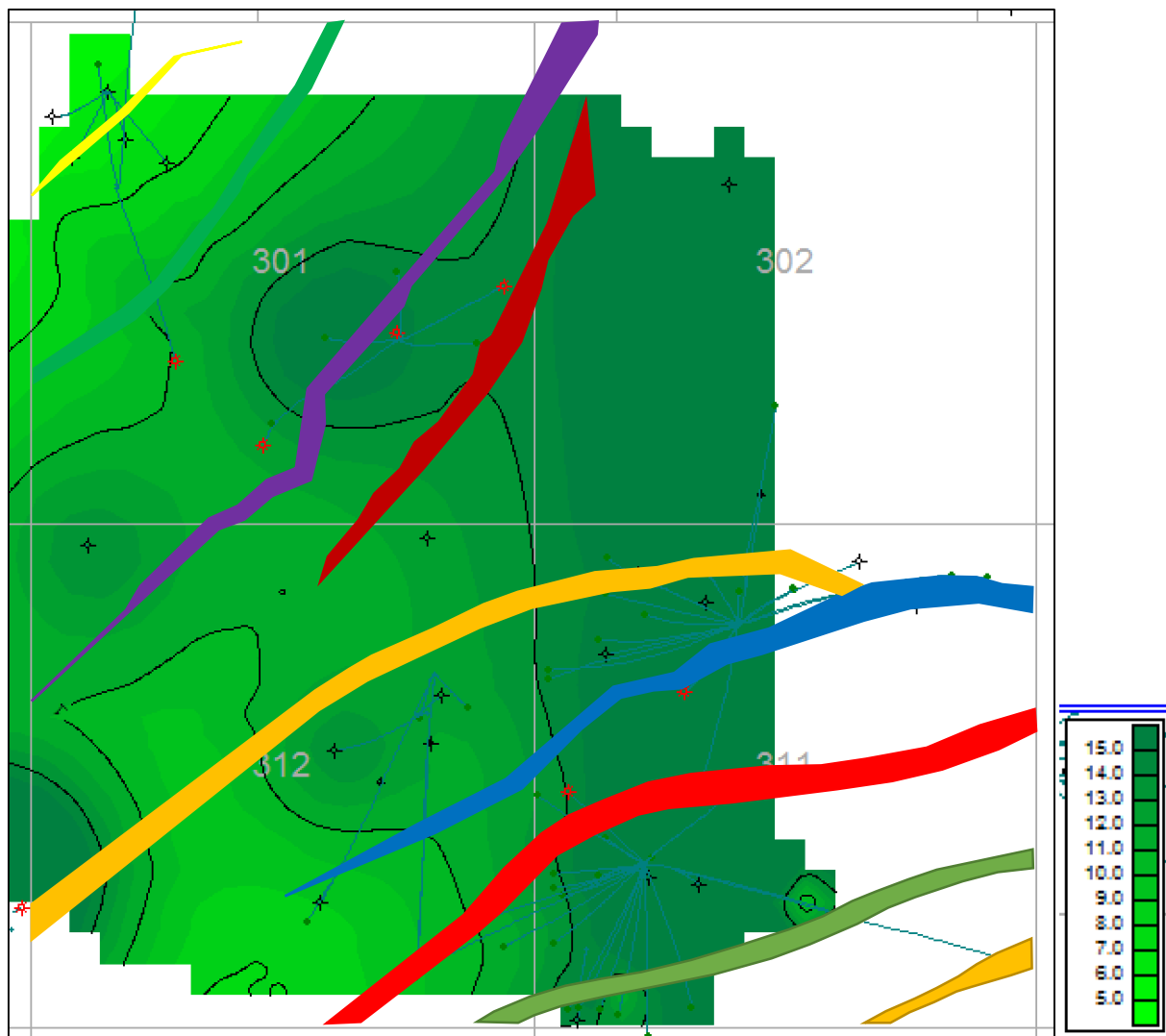


Figure 20. Isopach map of P-Sand bed set #1, the scale ranges from 5 feet (light green) to 15 feet (dark green). The colored bands are faults in the area.

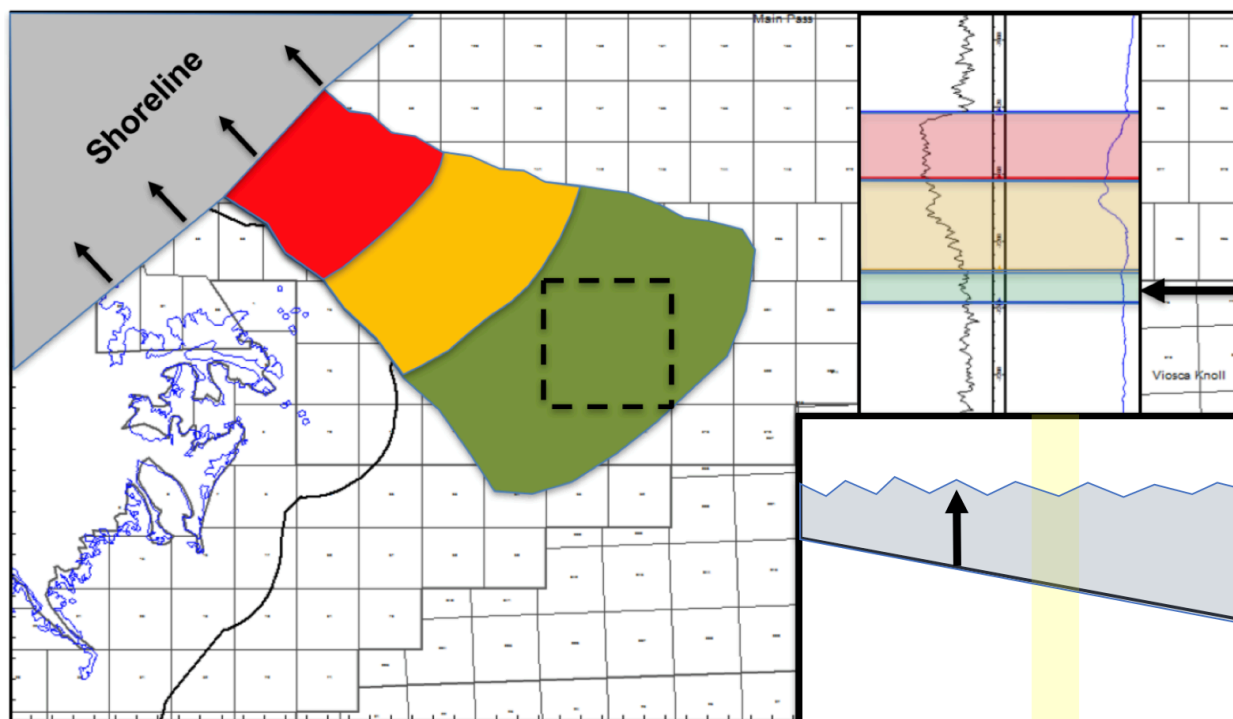


Figure 21. Interpreted environment, movement of shoreline, and water depth for “P-Sand” bed set #1. The colors in the delta figure represent the three different environments with red being the “clean” zone, yellow being the transitional zone, and green being the prodelta. The grey area represents the shoreline, and the arrows represent the interpreted movement that deposited the sediments within the bed set. The box in the right bottom corner represents interpreted sea level, with the highlighted zone being the study area and the arrow representing the interpreted change in water depth resulting in the deposition of the bed set.

Bed Set P-2:

The log character of bed set two is characterized by decreasing gamma radiation in a “coarsening upward” sequence that is funnel shaped (Figure 19). This type of gamma ray reading

is interpreted to be due to the increasing introduction of fine sands and silts to the radioactive muds. This sediment pattern is indicative of the transitional zone. The transitional zone is a medium energy environment and lies in a moderate level of water (Xie and Heller, 2006). An isopach map of Bed Set 2 can be seen in Figure 22. The deposition of these transitional zone sands and silts above the prodelta muds is interpreted to be due to a seaward shift in shoreline, a fall in relative sea level, and a progradation of the delta complex due to an increased influx of sediment. In this context, younger sediment will be increasingly deposited seaward (Figure 23).

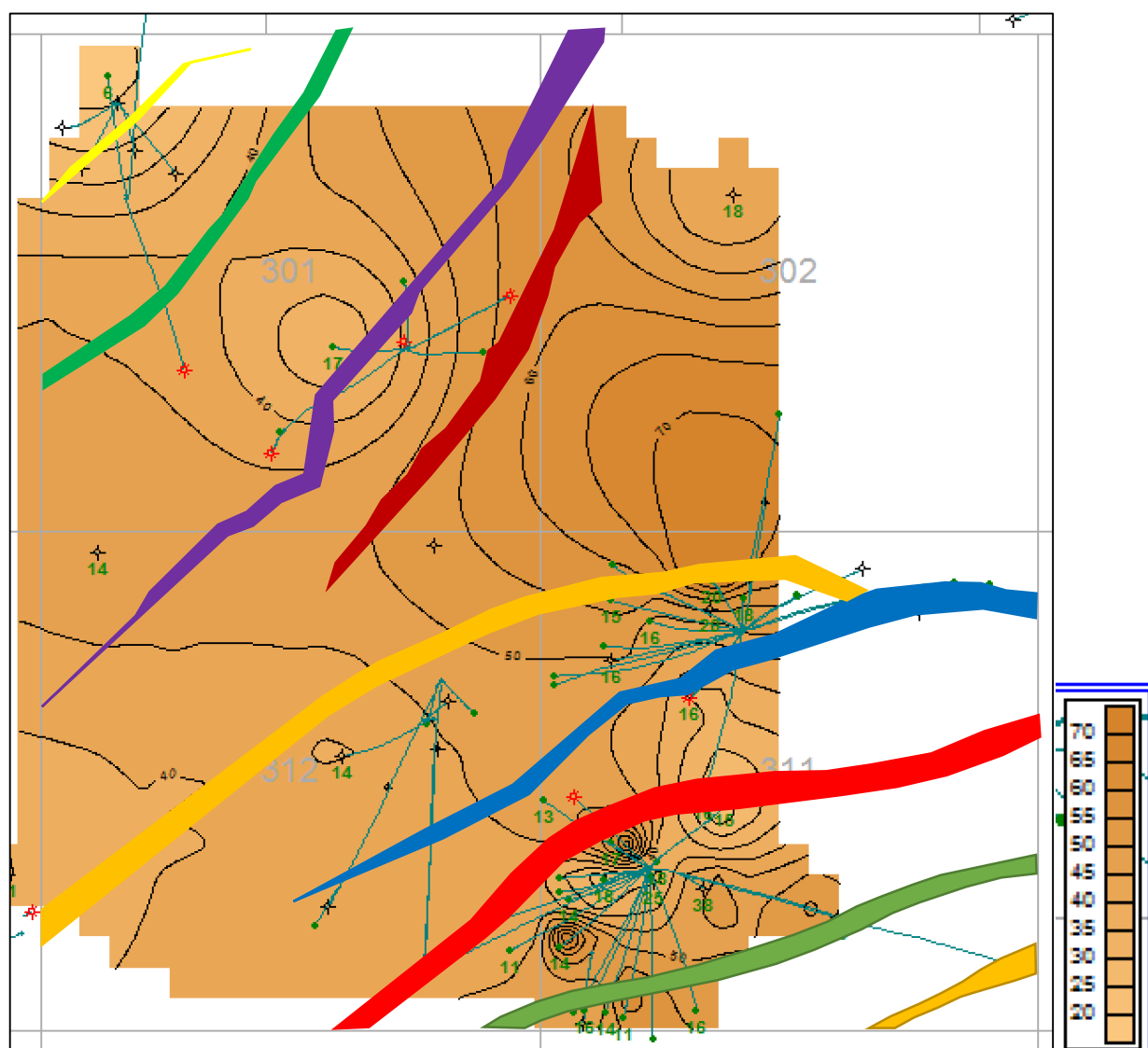


Figure 22. Isopach map of P-Sand bed set #2, the scale ranges from 20 feet (light orange) to 70 feet (dark orange). The colored bands are faults in the area.

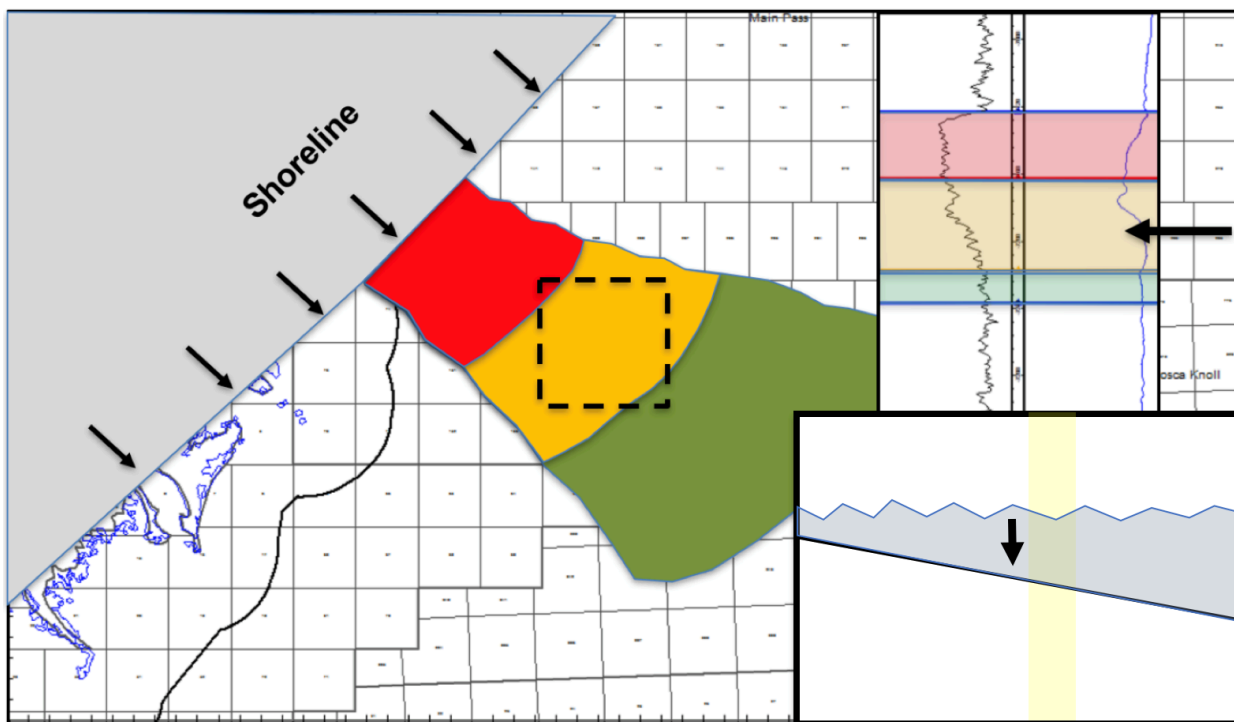


Figure 23. Interpreted environment, movement of shoreline, and water depth for “P-Sand” bed set #2. The colors in the delta figure represent the three different environments with red being the “clean” zone, yellow being the transitional zone, and green being the prodelta. The grey area represents the shoreline, and the arrows represent the interpreted movement that deposited the sediments within the bed set. The box in the right bottom corner represents interpreted sea level, with the highlighted zone being the study area and the arrow representing the interpreted change in water depth resulting in the deposition of the bed set

Bed Set P-3:

The log signature in bed set 3 is marked by a termination of the coursing upward trend and a stabilization of low gamma ray reading in a flat, boxy character (Figure 19). This is interpreted to be the result of the absence of radioactive silts and muds and dominance of clean sandstone. The environment that deposits this type of sediment is the “clean” zone of the delta. The “clean” zone is a high-energy environment and has relatively shallow water (Xie and Heller, 2006). An isopach map of Bed Set 3 can be seen in Figure 24. For “clean” sand deposits to overlie that of the transitional zone, the shoreline is interpreted to have shifted seaward and relative sea level fallen. This would lead to a progradational delta complex and the deposition of increasingly younger sediment in the seaward direction, as sediment delivery outpaces sea level rise (Figure 25).

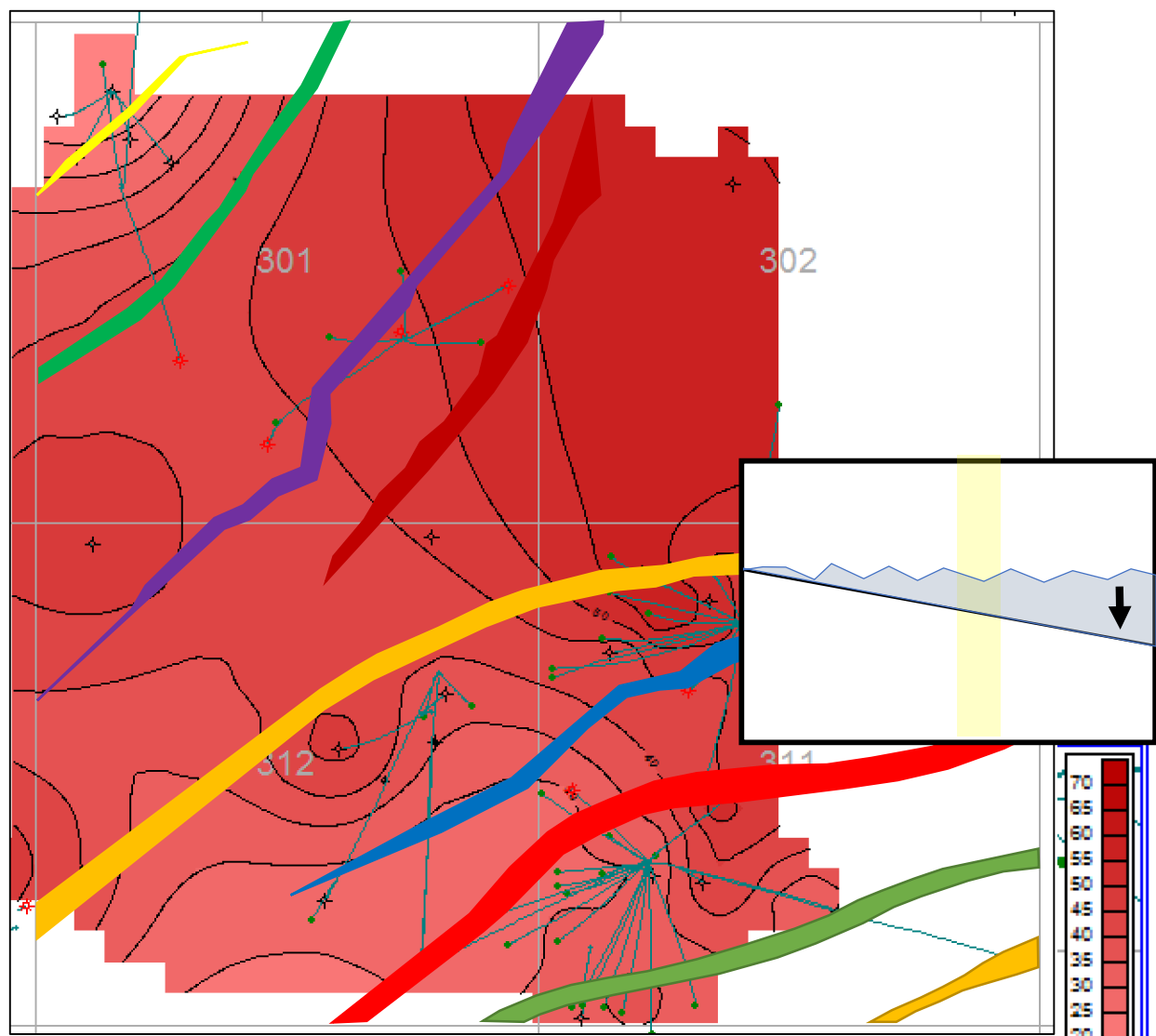


Figure 24. Isopach map of P-Sand bed set #2, the scale ranges from 20 feet (light red) to 70 feet (dark red). The colored bands are faults in the area.

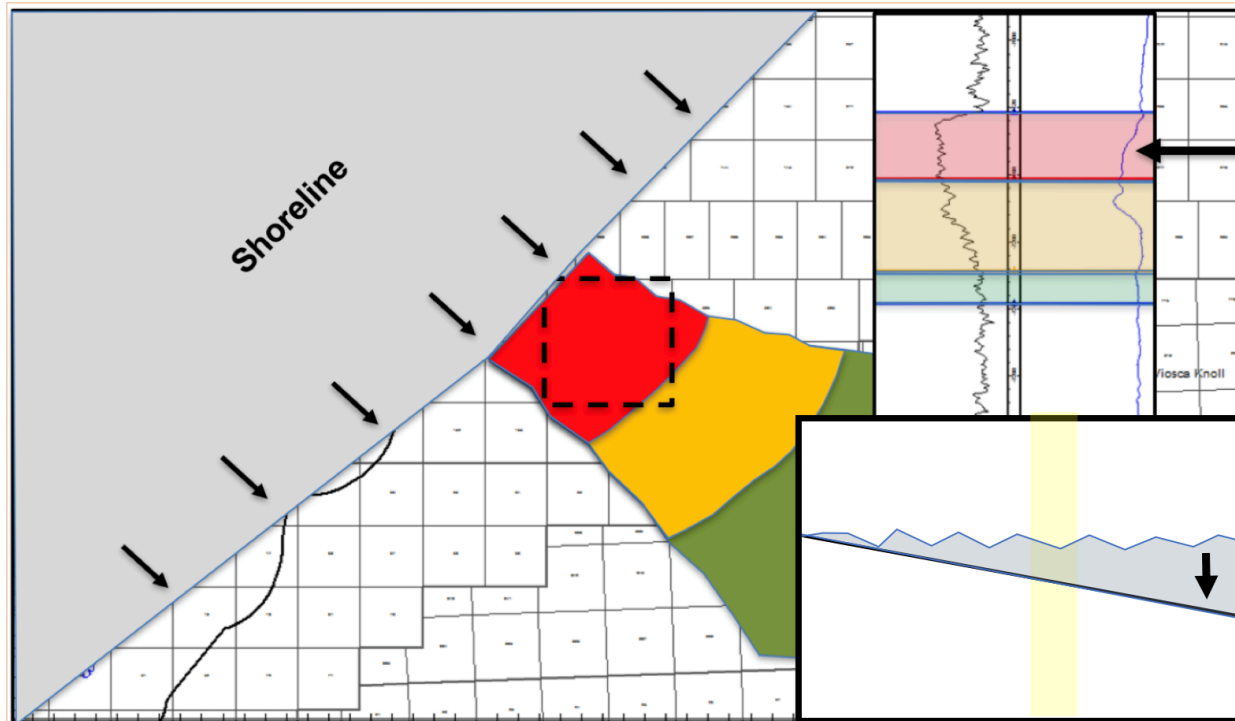


Figure 25. Interpreted environment, movement of shoreline, and water depth for “P-Sand” bed set #1. The colors in the delta figure represent the three different environments with red being the “clean” zone, yellow being the transitional zone, and green being the prodelta. The grey area represents the shoreline, and the arrows represent the interpreted movement that deposited the sediments within the bed set. The box in the right bottom corner represents interpreted sea level, with the highlighted zone being the study area and the arrow representing the interpreted change in water depth resulting in the deposition of the bed set.

Insights and Conclusions, P Sand:

The substantial insights do not come from the individual bed sets, but the relationships between them as they comprise a parasequence. The “P-Sand” reservoir is a textbook example of a progradational delta sequence. Deposition of offshore muds, below a series of increasingly sandy and silty mud, topped by a “clean” sandstone is a characteristic vertical profile of a

prograding delta. The shoreline was migrating increasingly closer to the study area, bringing the delta complex overtop and leaving behind a full record of the sedimentation pattern.

In the context of reservoir exploitation, understanding depositional environment leads to better understanding of reservoir performance and recovery methods. If the reservoir was deposited by a deltaic environment that was sourced from the northwest, the distribution of porosity and permeability within the setting can be inferred. For example, these directional factors play a large role in drainage patterns; and migration of hydrocarbons out of the reservoir will be greatest in the direction of favorable porosity/permeability (Figure 26). In the case of the “P-Sand” this will be in the north-west direction. This leads to a better understanding of the drainage area, and allows for better exploitation through well placement.

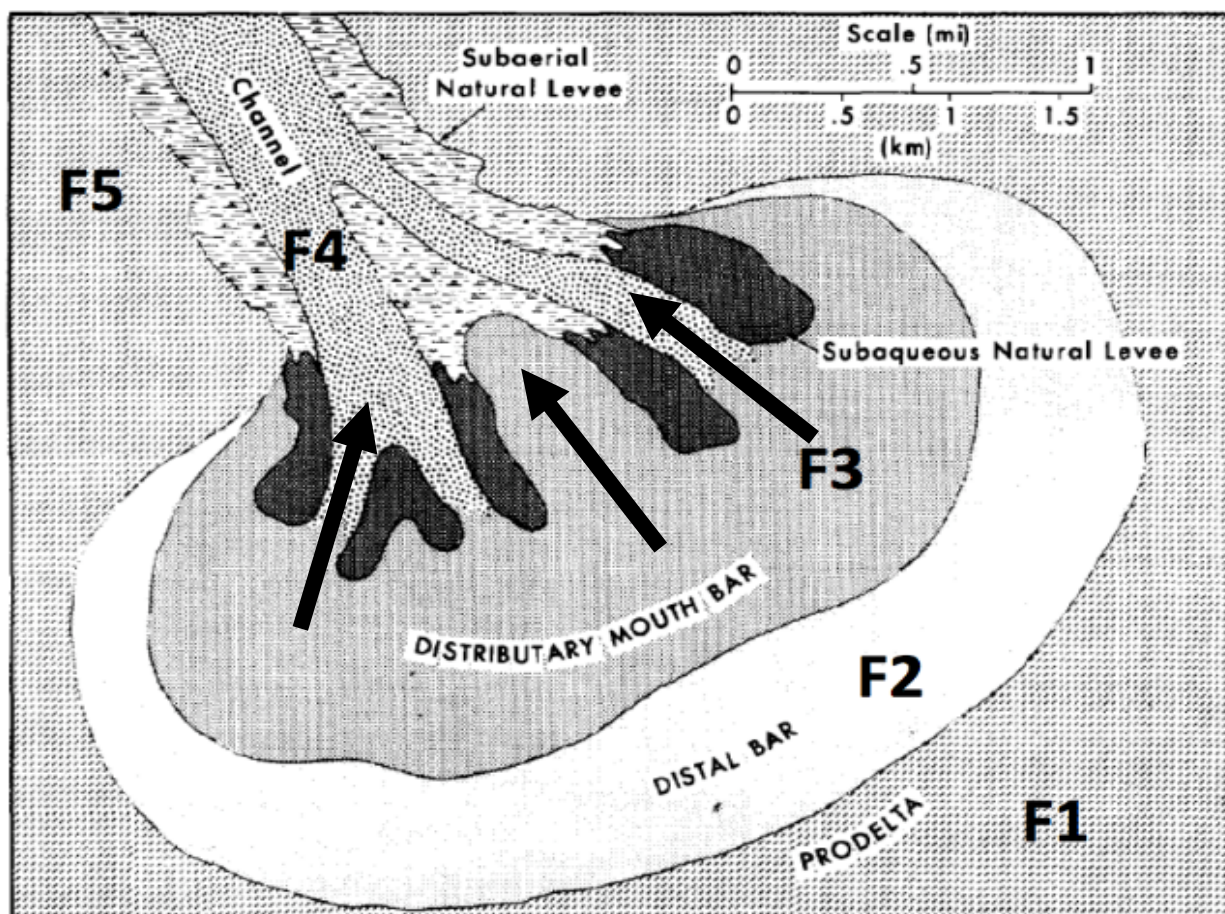


Figure 26. Example of a delta with arrows highlighting preferential drainage pathways along trends in favorable porosity and permeability (Coleman and Prior 1980).

The practice of log analysis allows for the interpretation of depositional environment, leading to an understanding reservoir porosity and permeability. Through log analysis it is determined that the P reservoir “coarsens” upwards, which is a key input when discussing secondary recovery methods. Reservoirs such as this one that are interpreted to be prograding delta complexes are great candidates for horizontal drilling into “bypassed pay”, due to the high reservoir quality parameters present in the upper portion. Traditional vertical wells often result in a “coning effect” (Figure 27) that leaves a significant amount hydrocarbons unexploited. The P reservoir has only been penetrated vertically; therefore I believe that the “P-Sand” reservoir would make a great candidate for secondary horizontal recovery.

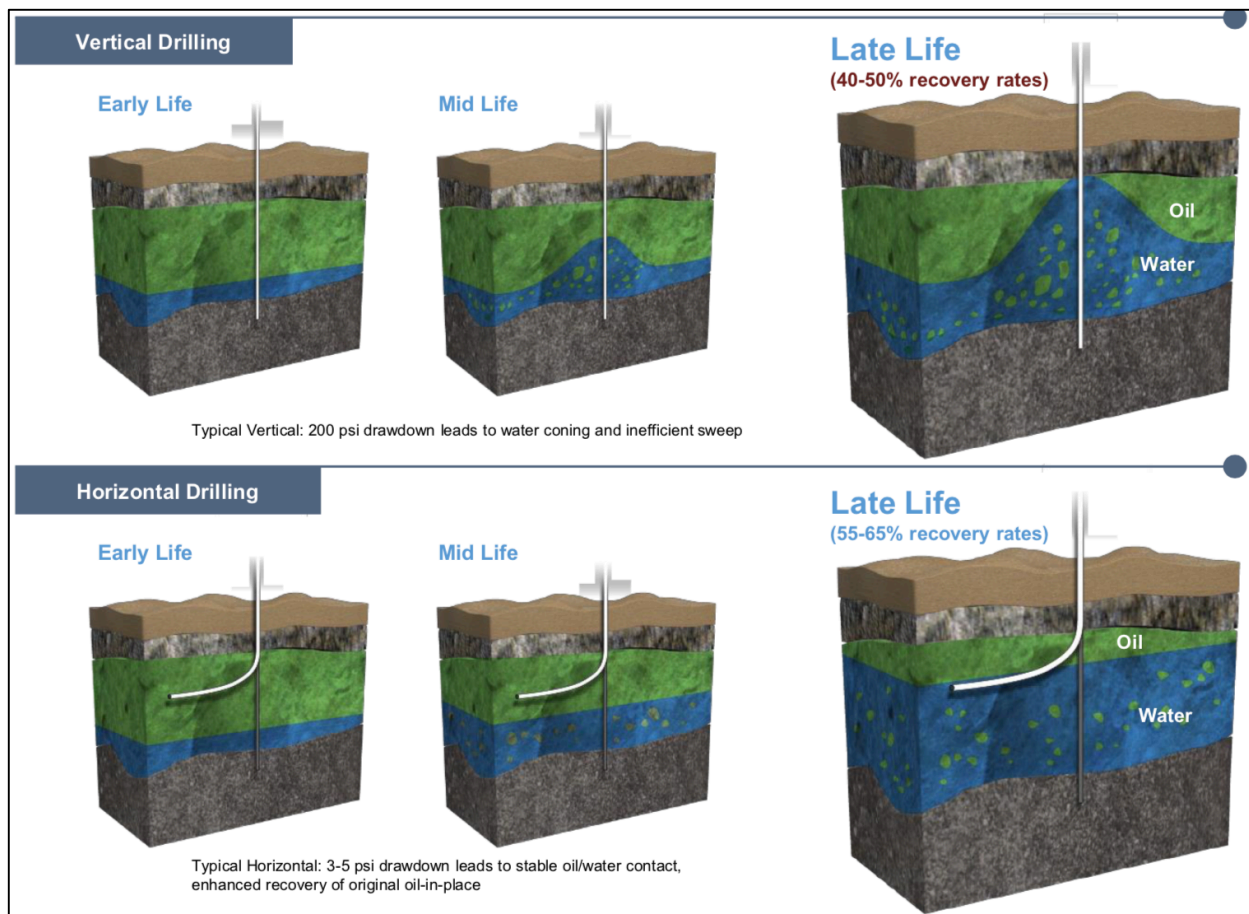


Figure 27. Example of “coning effect” of vertical exploitation, highlighting significant residual hydrocarbon left unexploited in coarsening up reservoirs. The horizontal secondary recovery eliminates this coning effect and results in greater exploitation volumes. (Image courtesy of Energy XXI).

The most prospective bed set within the P-Sand parasequence is bed set #3, which has been interpreted to be deposited in a “clean” zone environment. This is because the sediment deposited in this environment is known to have the highest porosity and permeability relative to the other bed sets. This is proven by the historical exploitation of these reservoirs - bed set #3 was the zone of choice for perforations by previous operators.

Initial production data from several wells were taken and plotted in the chart below (Figure 28). Initial production data was normalized by dividing the IP by the perforation length. More IP data was available, however the N, O, and P production has been reported comingled, which leads to unreliable interpretations.

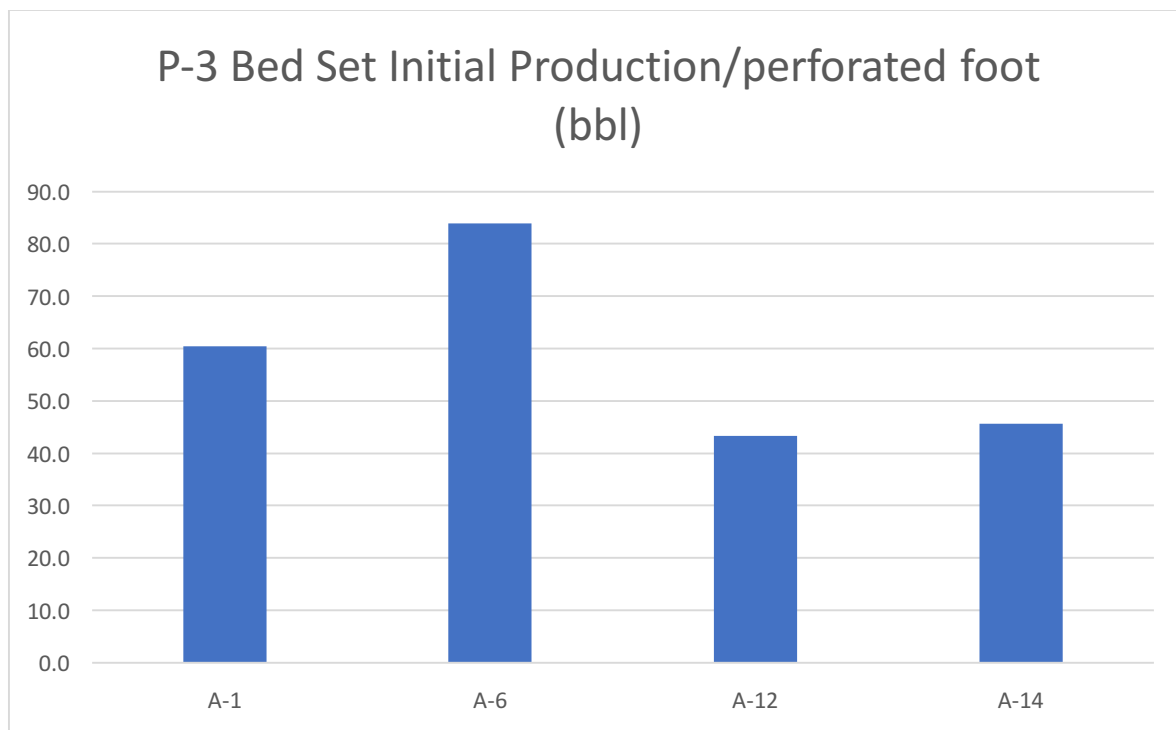


Figure 28. Chart showing initial production in 4 wells. Initial production was divided by perforation length to obtain a normalized measure.

In exploration, understanding the depositional environment and how the different facies relate spatially to one another can predict with reasonable certainty the location of adjacent facies. Within the study area, the “clean” sand deposits of the “P-Sand” do not transition into transitional zone nor prodelta deposits. Understanding that these sands were deposited from the north-west by a prograding delta complex, and that during this period sea level is falling, it is reasonable to predict the presence of this reservoir in the south-east direction. The complete

absence of distributary channel fill deposits is also a factor. Because these deposits are present in all delta systems, they must be present in the direction of the shoreline to the north-west.

The “O-Sand” Parasequence:

Bed Set O-1:

Bed set 1 in the “O” sequence is seen in the log as a trend of decreasing radioactive sediments that forms a funnel shaped pattern (Figure 29). This pattern is interpreted to be the result of an increasing amount of sand and silt into a muddy section. The deltaic environment that deposits these types of sediment is the transitional zone. The transitional zone is a moderate energy environment found in moderate levels of water. An isopach map of bed set 1 can be seen in Figure 30. The shoreline is interpreted to have moved in the seaward direction due to a fall in relative sea level and an increase in the rate of sediment supply. This would have caused the delta complex to prograde seaward and have increasingly younger sediment deposited seaward (Figure 31).

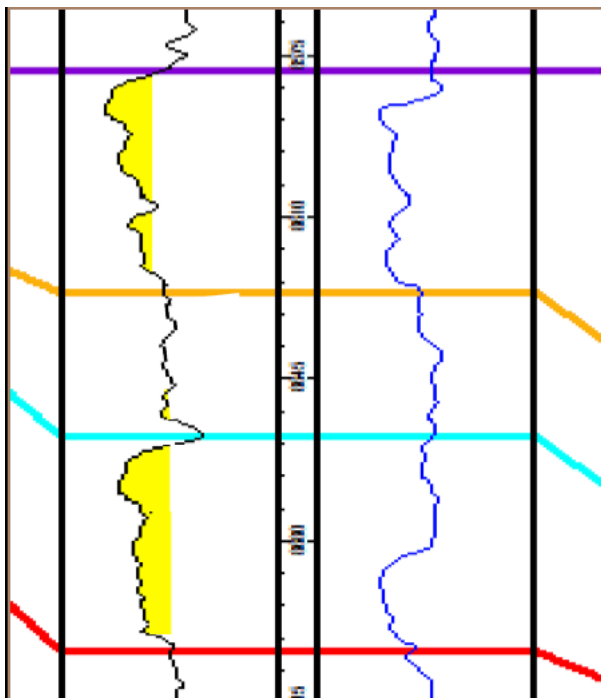


Figure 29. Type Log section of the “O-Sand” divided into bed sets by time equivalent surfaces. Black curve in track 1 is Gamma Ray, blue curve in track 2 is Resistivity. Bed set 1 is at the base, bed set 2 is in the middle, and bed set 3 is at the top.

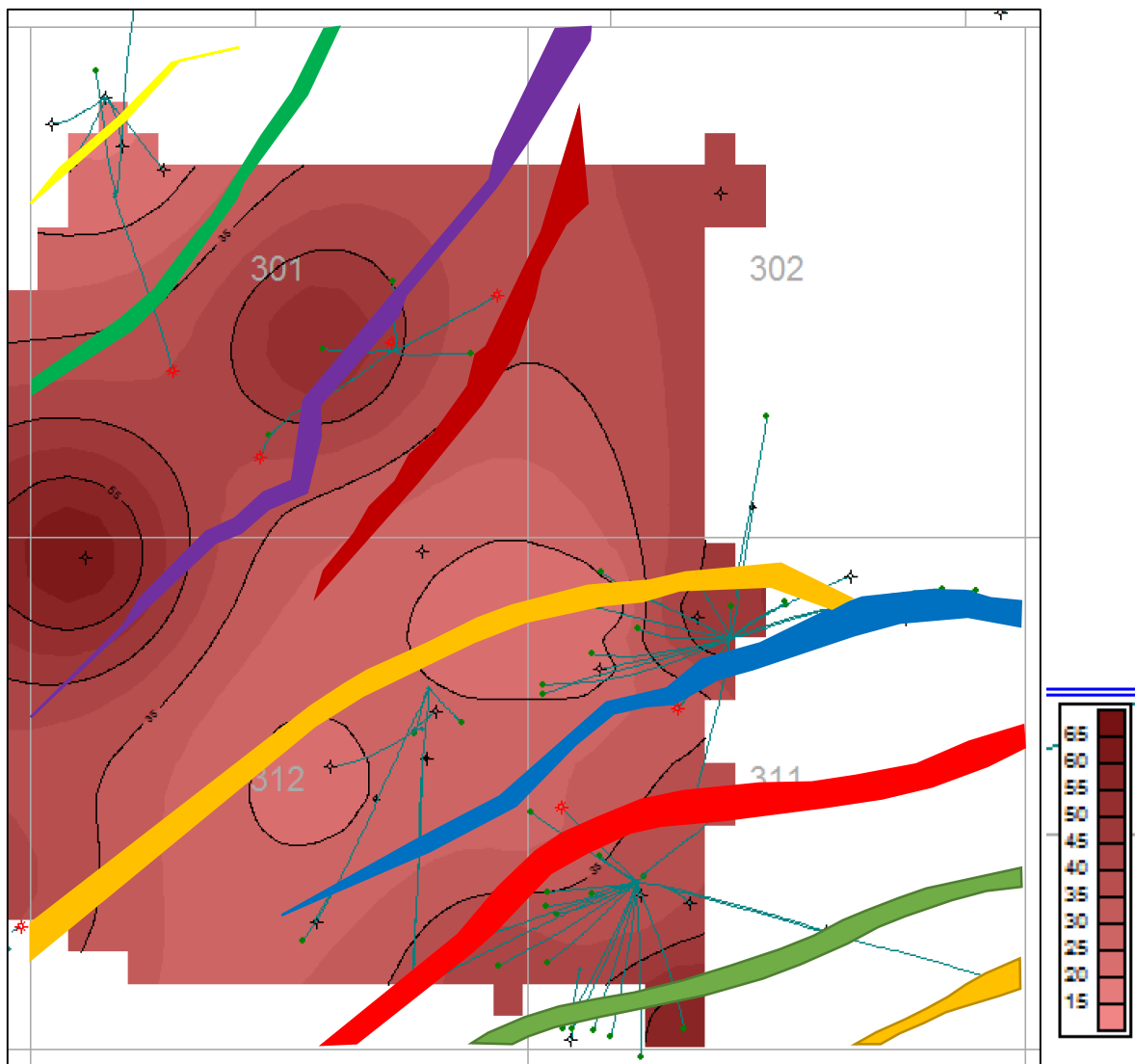


Figure 30. Isopach map of O-Sand bed set #1, the scale ranges from 15 feet (light red) to 65 feet (dark red). The colored bands are faults in the area.

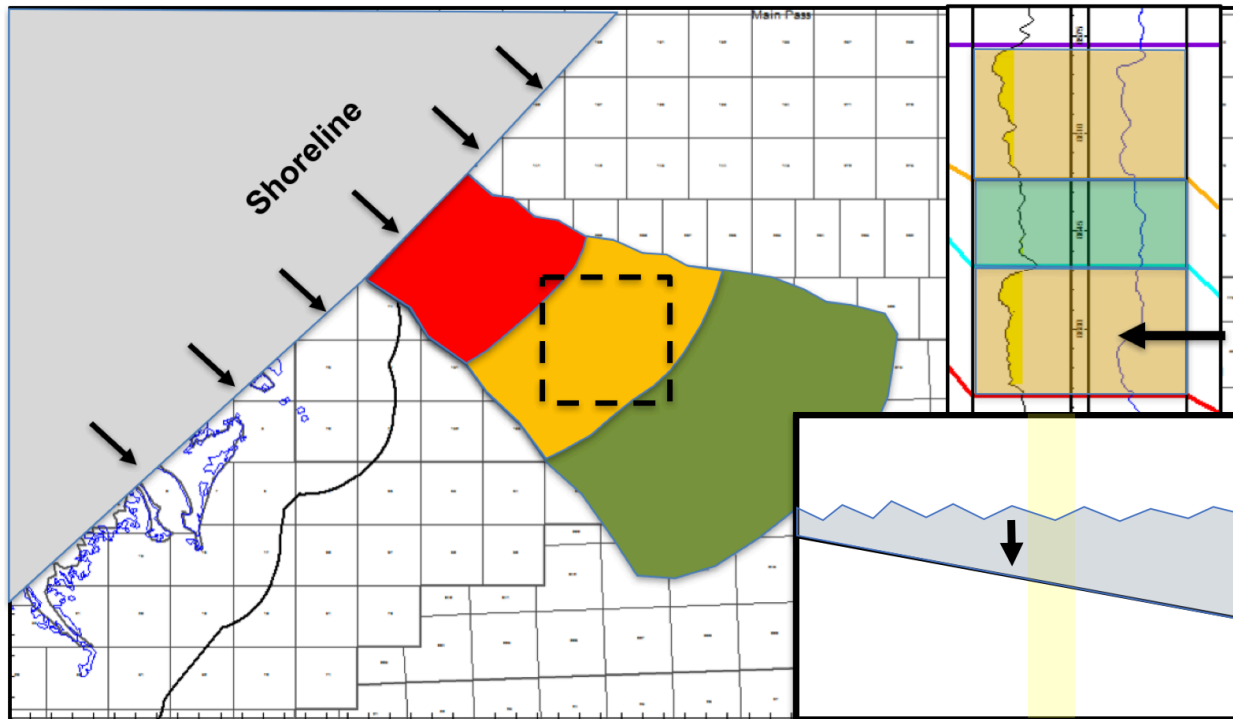


Figure 31. Interpreted environment, movement of shoreline, and water depth for “O-Sand” bed set #1. The colors in the delta figure represent the three different environments with red being the “clean” zone, yellow being the transitional zone, and green being the prodelta. The grey area represents the shoreline, and the arrows represent the interpreted movement that deposited the sediments within the bed set. The box in the right bottom corner represents interpreted sea level, with the highlighted zone being the study area and the arrow representing the interpreted change in water depth resulting in the deposition of the bed set.

Bed Set O-2:

The log character defining bed set two is a sharp increase and stabilization of gamma ray reading in a “toothy” pattern (Figure 29). This reading is interpreted to be due to an influx of mud with the absence of any sand or silt. The environment that deposits this type of log pattern is the prodelta. This environment is notably low in energy and lies in relatively deep levels of water. An isopach map of bed set 2 can be seen in Figure 32. This is interpreted to be the result of a shift in shoreline landward, sea level rise outpacing sediment input, and a retrogradational delta complex (Figure 33).

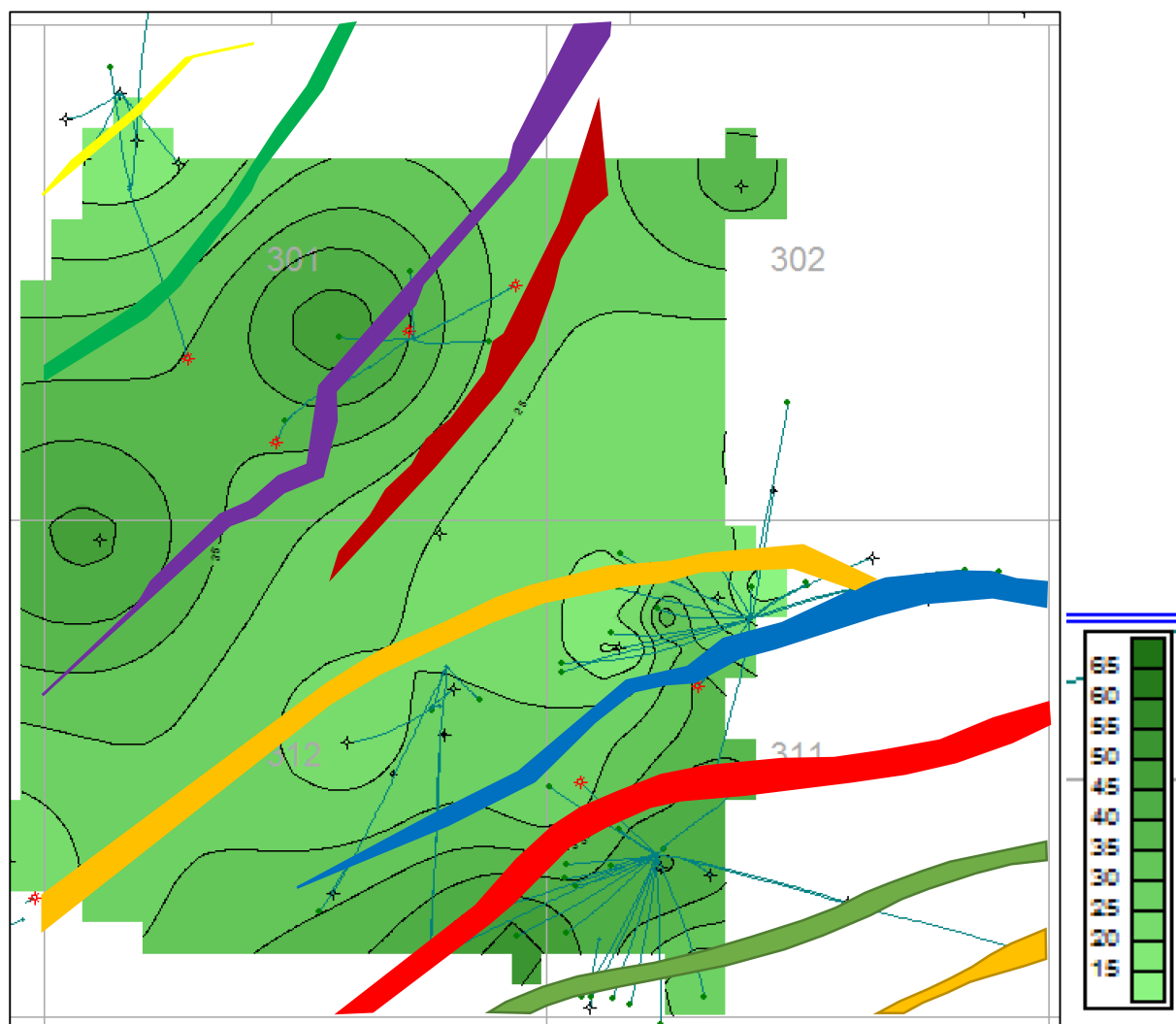


Figure 32. Isopach map of O-Sand bed set #2, the scale ranges from 15 feet (light green) to 65 feet (dark green). The colored bands are faults in the area.

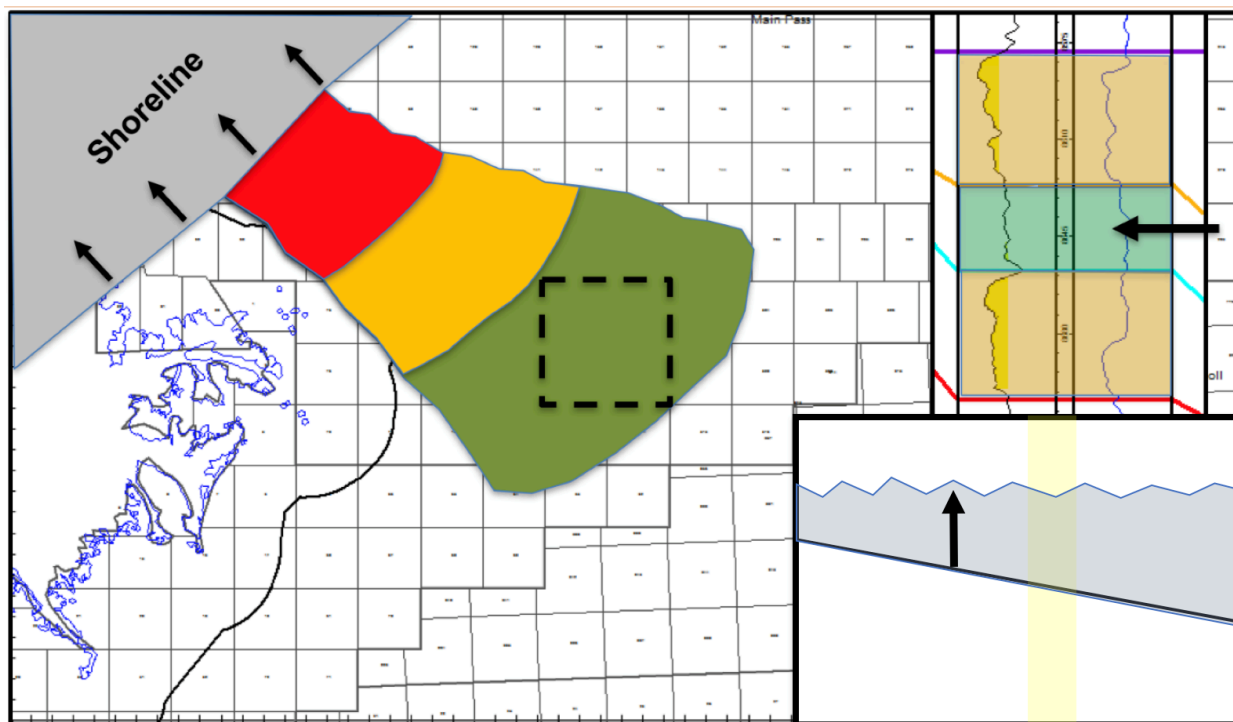


Figure 33. Interpreted environment, movement of shoreline, and water depth for “O-Sand” bed set #2. The colors in the delta figure represent the three different environments with red being the “clean” zone, yellow being the transitional zone, and green being the prodelta. The grey area represents the shoreline, and the arrows represent the interpreted movement that deposited the sediments within the bed set. The box in the right bottom corner represents interpreted sea level, with the highlighted zone being the study area and the arrow representing the interpreted change in water depth resulting in the deposition of the bed set.

Bed Set O-3:

Bed set number three is seen in the log is a funnel shaped pattern of vertically decreasing gamma ray reading (Figure 29). This pattern is interpreted to be the result of the continual introduction of sands and silts to the underlying mudstone. The transitional zone environment characteristically deposits these types of sediment. This is a medium level energy environment that is found in a moderate water depth. An isopach map of bed set O-3 can be seen in Figure 34. Shoreline movement is interpreted to be seaward accompanied by a fall in relative sea level, and an increase in the rate of sediment supply. This would have caused the delta complex to prograde seaward (Figure 35).

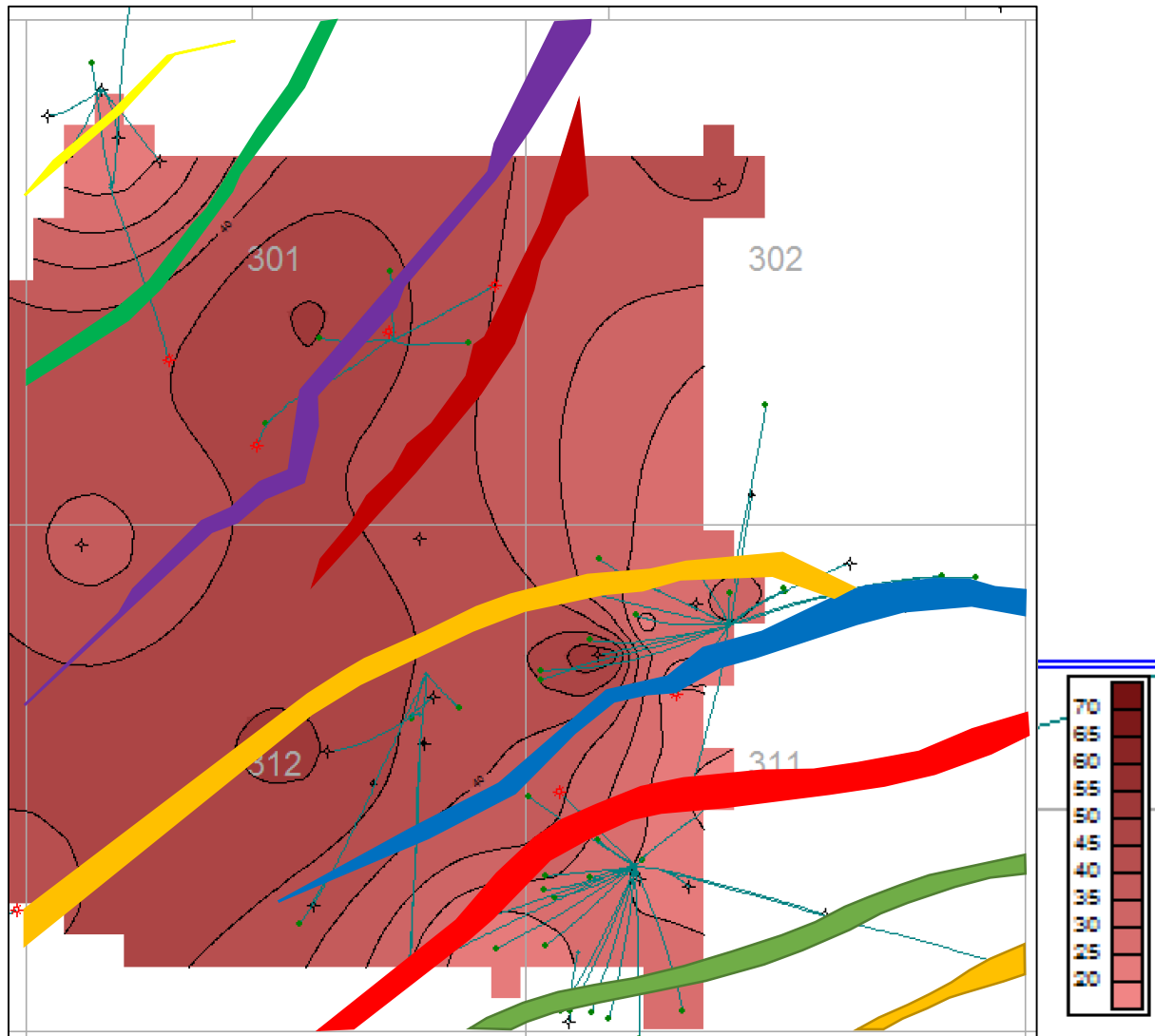


Figure 34. Isopach map of O-Sand bed set #3, the scale ranges from 15 feet (light red) to 65 feet (dark red). The colored bands are faults in the area.

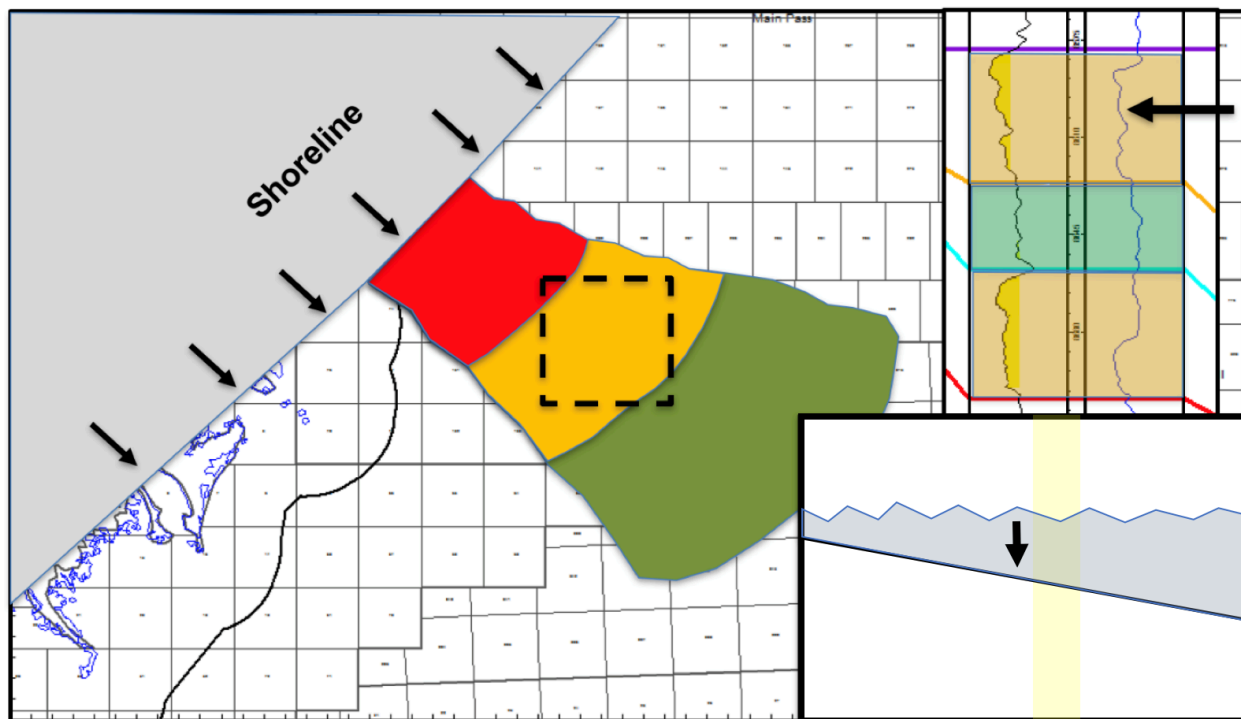


Figure 35. Interpreted environment, movement of shoreline, and water depth for “O-Sand” bed set #3. The colors in the delta figure represent the three different environments with red being the “clean” zone, yellow being the transitional zone, and green being the prodelta. The grey area represents the shoreline, and the arrows represent the interpreted movement that deposited the sediments within the bed set. The box in the right bottom corner represents interpreted sea level, with the highlighted zone being the study area and the arrow representing the interpreted change in water depth resulting in the deposition of the bed set.

Insights and Conclusions:

The “O-Sand” is a peculiar reservoir for a couple of reasons. The entire parasequence is comprised of a small retrogradation from bed set 3 to 2 and a progradation from bed set 2 to 1. Deposition of the series of the increasingly sandy and silty mud of bed set 1, topped by the prodelta muds of bed set 2 indicates a regression of the delta complex. Atop of these prodelta muds lies another deposit of transitional zone sands and silts comprising bed set 3, indicating a progradation of the delta that is then halted. While the middle/late Miocene is known to have a trend of falling sea level, this is evidence of short lived fluctuations.

With reservoir exploitation, an understanding of the depositional environment leads to better estimate of reservoir parameters. As explained before, the increasing trends in porosity and permeability will be in the north-east direction. This will help predict increasing drainage patterns for the “O-sand” reservoir. Knowing that the highest potential zone from the “O-Sand” is the transitional zone silty and sandy mixture (bed set 1 & 3) with subprime porosity and permeability, some form of reservoir stimulation may be necessary. The most prospective bed sets within the O-Sand parasequence are bed set #1 and bed set #3, both of which were interpreted to have been deposited in a transitional zone environment. This is because the sediment deposited in this environment is known to have the highest porosity and permeability relative to the other bed set. While the results of this study indicate that both bed sets #1 & #3 are prospective, only bed set #3 has been tested previously. Initial production data from several wells were taken and plotted in the chart below (Figure 36). Initial production data was normalized by dividing the IP by the perforation length. While the sample size is small, and the variation is significant, the IP numbers are lower than that of the previously discussed P-Sand. This is due to the higher silt and mud content of the environment of the O-3 bed set, which decreases porosity

and permeability. More IP data was available, however the N, O, and P production has been reported comingled, which leads to unreliable interpretations.

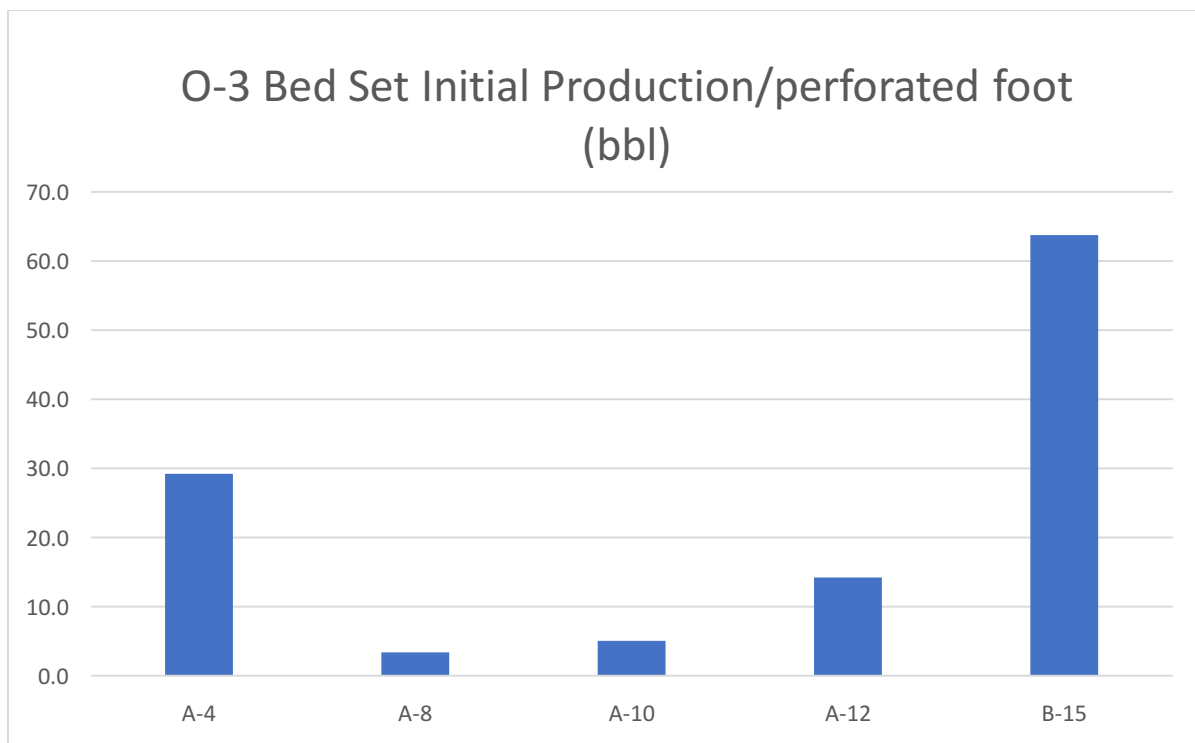


Figure 36. Chart showing initial production in 5 wells, Initial production was divided by perforation length to obtain a normalized measure.

Understanding the spatial relationships within the delta complex, adjacent facies can be predicted with reasonable certainty. This is a valuable tool in hydrocarbon exploration. Within the study area, the “clean” sand deposits of the delta complex are not present, only the transitional zone and prodelta deposits. Understanding that these sands were deposited from the north-west by an active delta complex, and that during this period sea level is (generally) falling, it is reasonable to predict that “clean” zone sediments would be present in the north-west direction, possibly as proximal as block 300.

The “N-Sand” Parasequence:

Bed Set N-1:

The first bed set to be deposited in the “N” parasequence is comprised of highly radioactive prodelta muds (Figure 37). These muds were deposited in a low energy environment that was far from the mouth of the delta complex. These sediments are the result of an environment with a relatively deep water depth. An isopach of bed set 1 can be seen in Figure 38. These sediments were deposited after a landward shift in facies, as sediment input is outpaced by sea level rise, shifting the shoreline north-west (Figure 39).

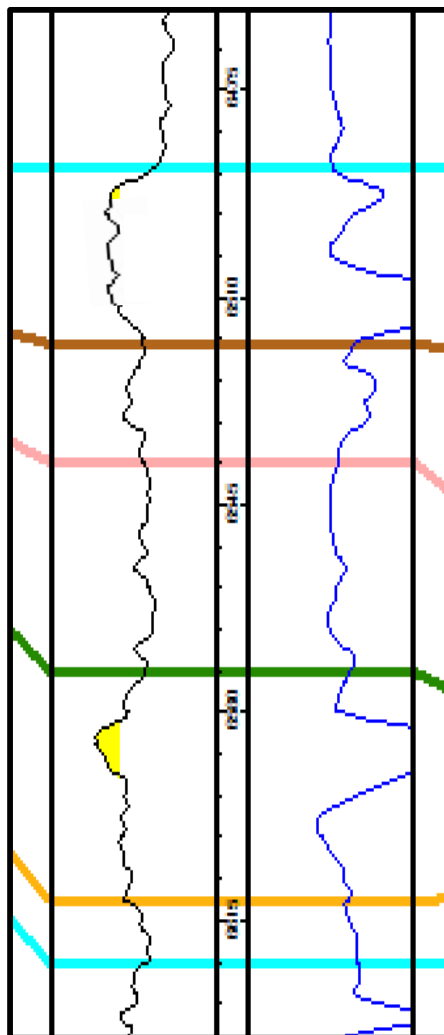


Figure 37. Type Log section of the “N-Sand” divided into bed sets by time equivalent surfaces. Black curve in track 1 is Gamma Ray, blue curve in track 2 is Resistivity. Bed set 1 is at the base, followed by bed set 2, bed set 3, bed set 4, and at the top is bed set 5.

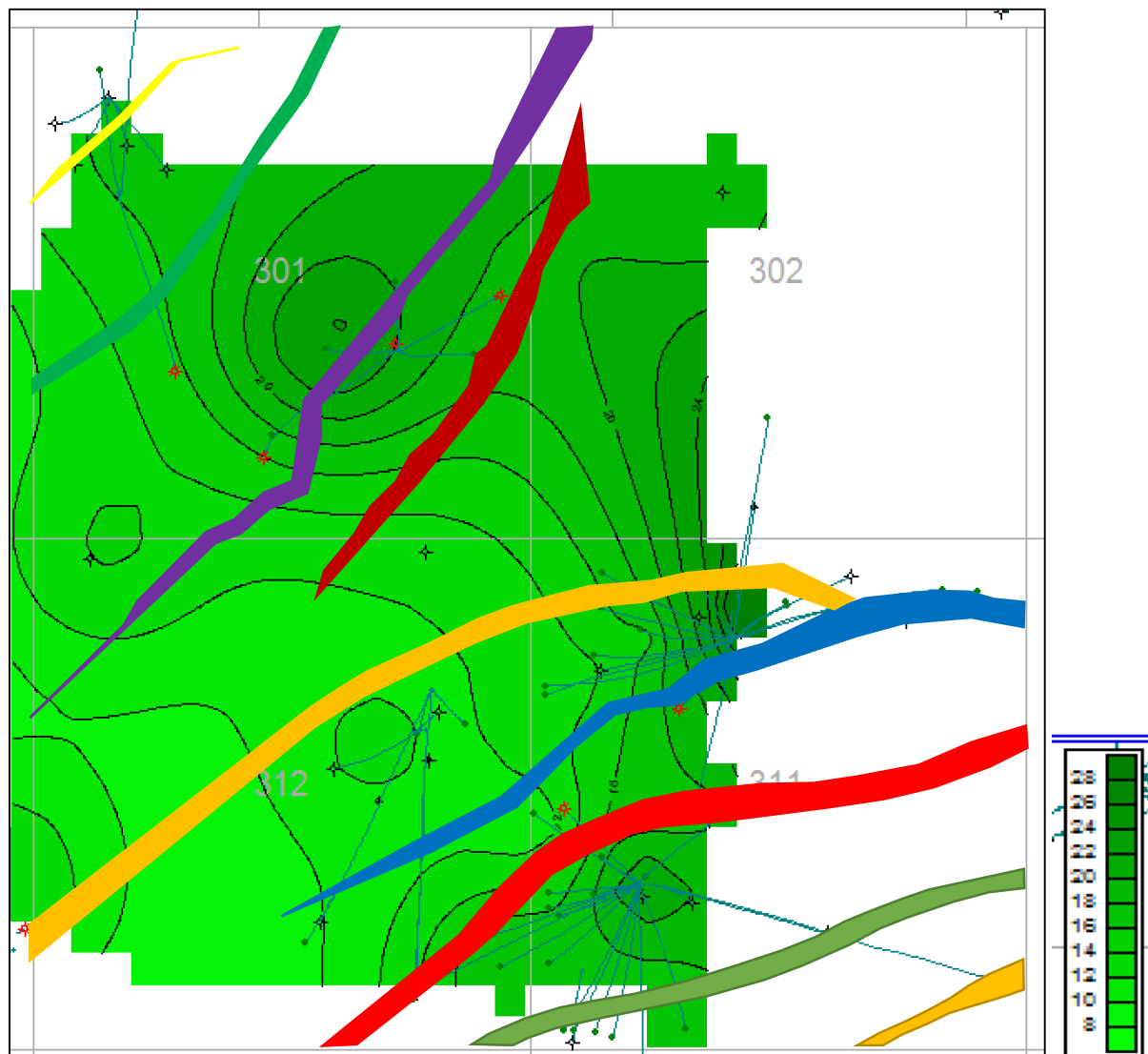


Figure 38. Isopach map of N-Sand bed set #1, the scale ranges from 8 feet (light green) to 28 feet (dark green). The colored bands are faults in the area.

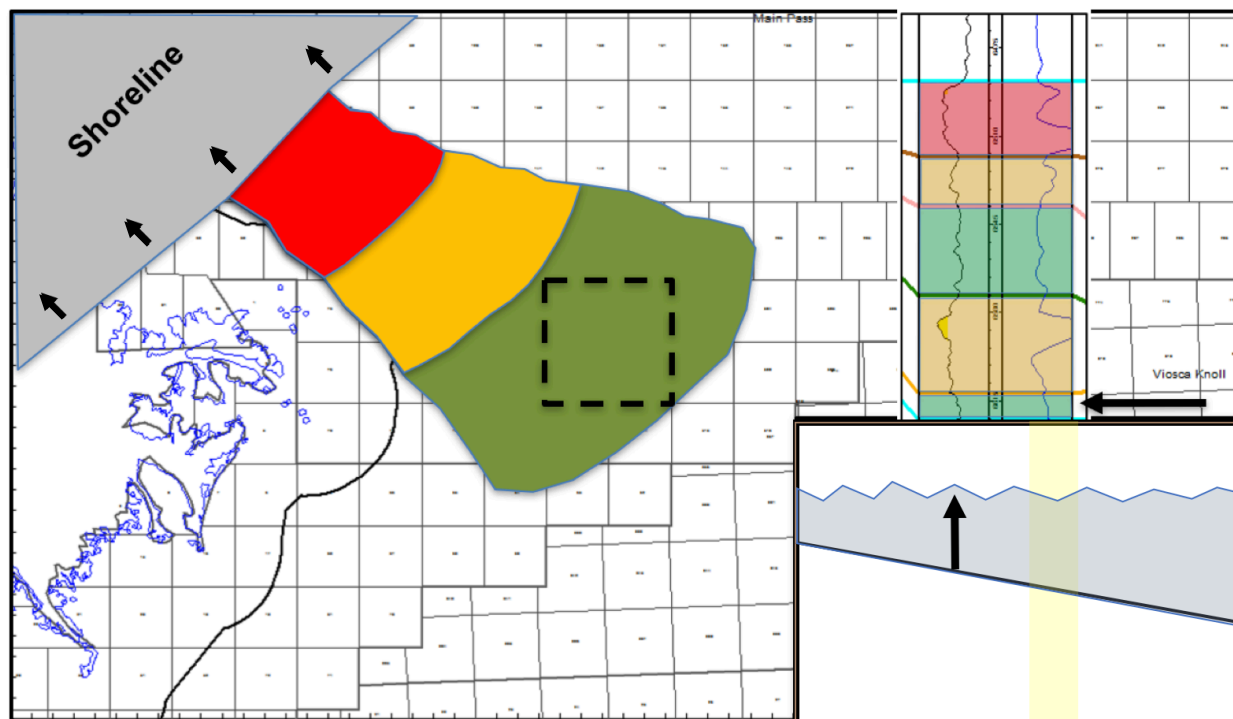


Figure 39. Interpreted environment, movement of shoreline, and water depth for “N-Sand” bed set #1. The colors in the delta figure represent the three different environments with red being the “clean” zone, yellow being the transitional zone, and green being the prodelta. The grey area represents the shoreline, and the shoreline arrows represent the interpreted movement that deposited the sediments within the bed set. The box in the right bottom corner represents interpreted sea level, with the highlighted zone being the study area and the arrow representing the interpreted change in water depth resulting in the deposition of the bed set.

Bed Set N- 2:

The log character that defines the second bed set is low in gamma radiation and has a boxy signature (Figure 37). This is interpreted to be a “clean” sand deposit, and be comprised of sandstone with little to no mud or silt. The deposition of these types of sediment indicates a

high-energy environment, and a relatively low water depth. An isopach of bed set 2 can be seen in Figure 40. This is a result of a rapid regression of the shoreline and a falling sea level (Figure 41). Sequentially, there should have been transitional zone deposits between the offshore muds and the “clean” sand deposits. But the sediment supply was so much greater than the rise in sea level that these sediments were not deposited/preserved.

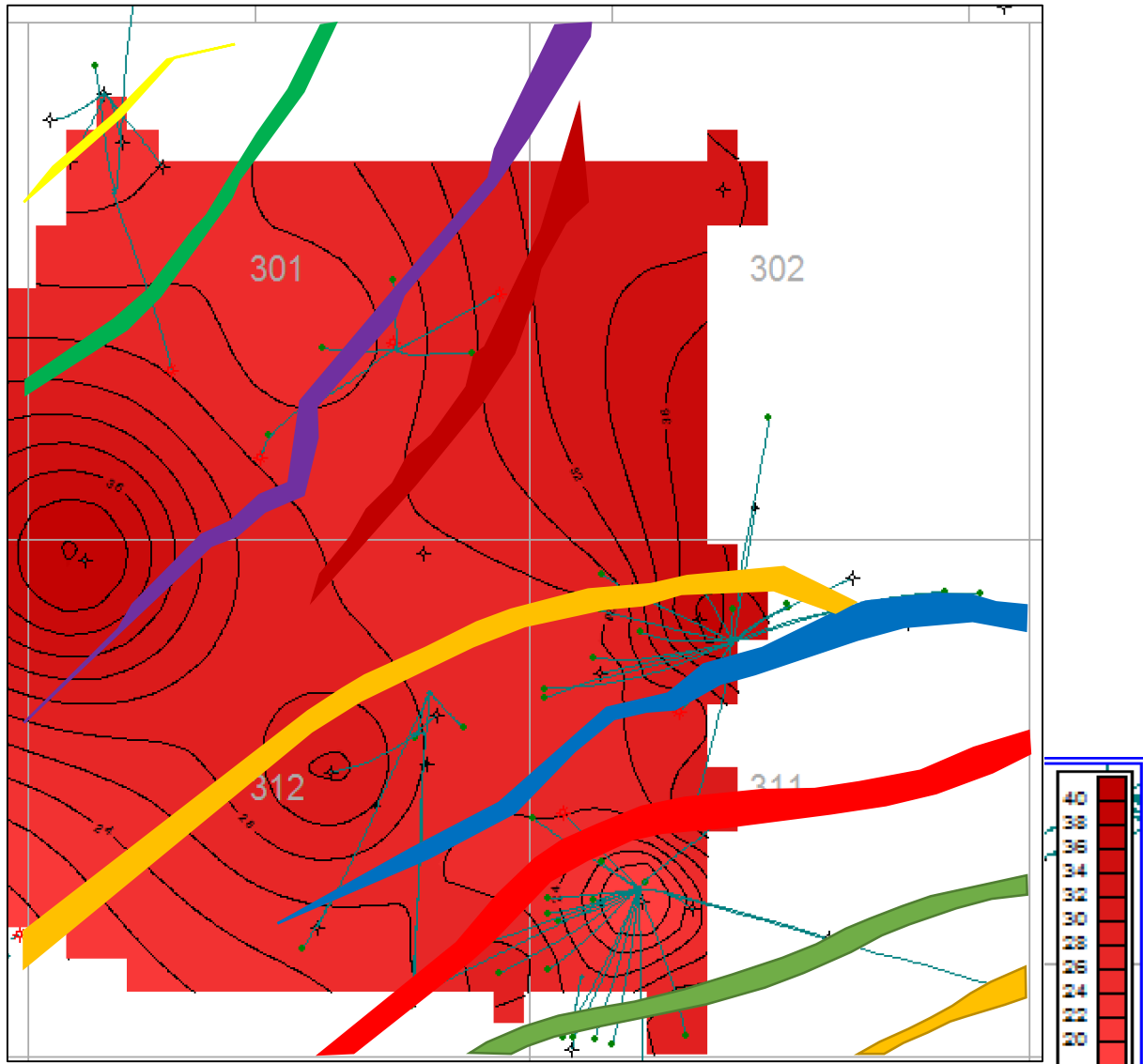


Figure 40. Isopach map of N-Sand bed set #2, the scale ranges from 20 feet (light red) to 40 feet (dark red). The colored bands are faults in the area.



Figure 41. Interpreted environment, movement of shoreline, and water depth for “N-Sand” bed set #2. The colors in the delta figure represent the three different environments with red being the “clean” zone, yellow being the transitional zone, and green being the prodelta. The grey area represents the shoreline, and the arrows represent the interpreted movement that deposited the sediments within the bed set. The box in the right bottom corner represents interpreted sea level, with the highlighted zone being the study area and the arrow representing the interpreted change in water depth resulting in the deposition of the bed set.

Bed Set N-3:

The base of bed set three is seen in the log by a sharp increase in gamma ray radiation (Figure 37). This is interpreted to be the result of the deposition of muds without significant sand or silt. In the context of the delta, this type of sediment is found in the prodelta environment. This environment is distal to the mouth of the fluvial complex, and is a very low energy environment, which will have a relatively deep water depth. An isopach of bed set 3 can be seen in Figure 42. A rapid transgression had to have taken place to deposit these prodelta muds on top of the “clean” sands, sea level rise was much greater than sediment supply rate; once again, the transitional zone sands and silts are absent (Figure 43).

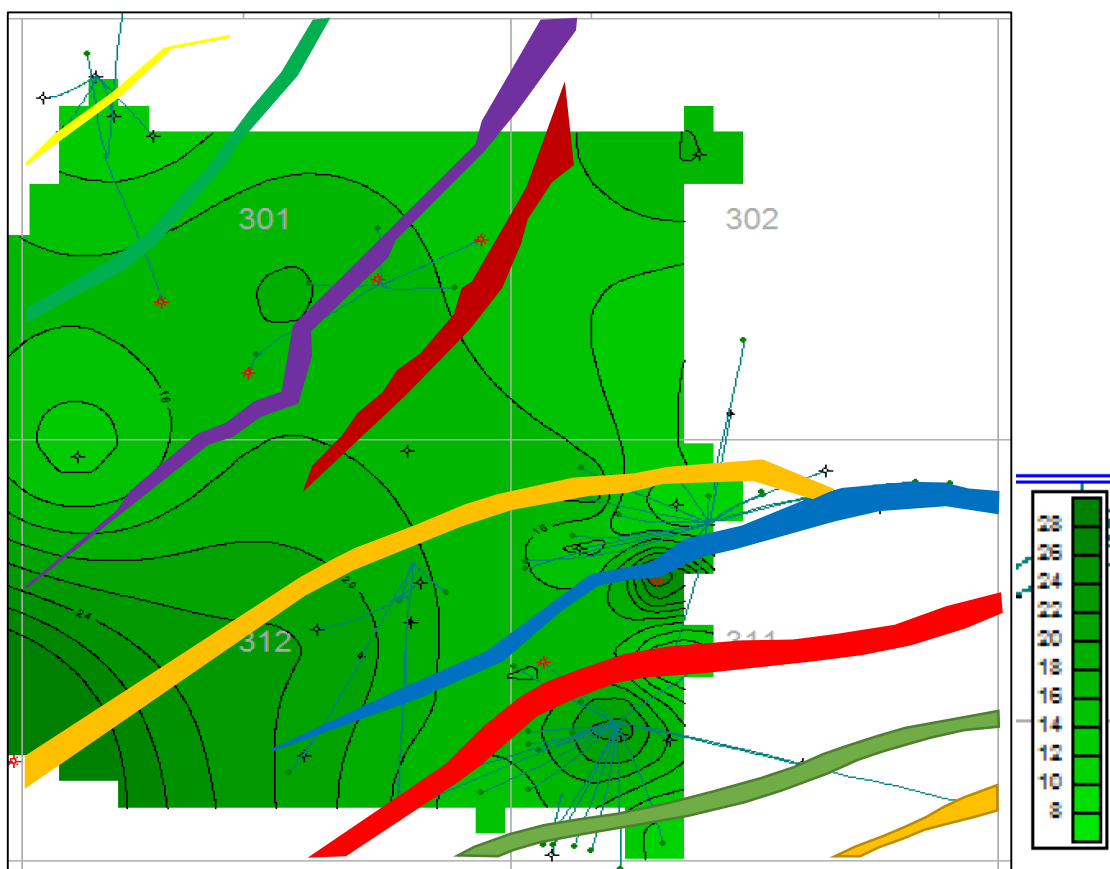


Figure 42. Isopach map of N-Sand bed set #3, the scale ranges from 8 feet (light green) to 28 feet (dark green). The colored bands are faults in the area.

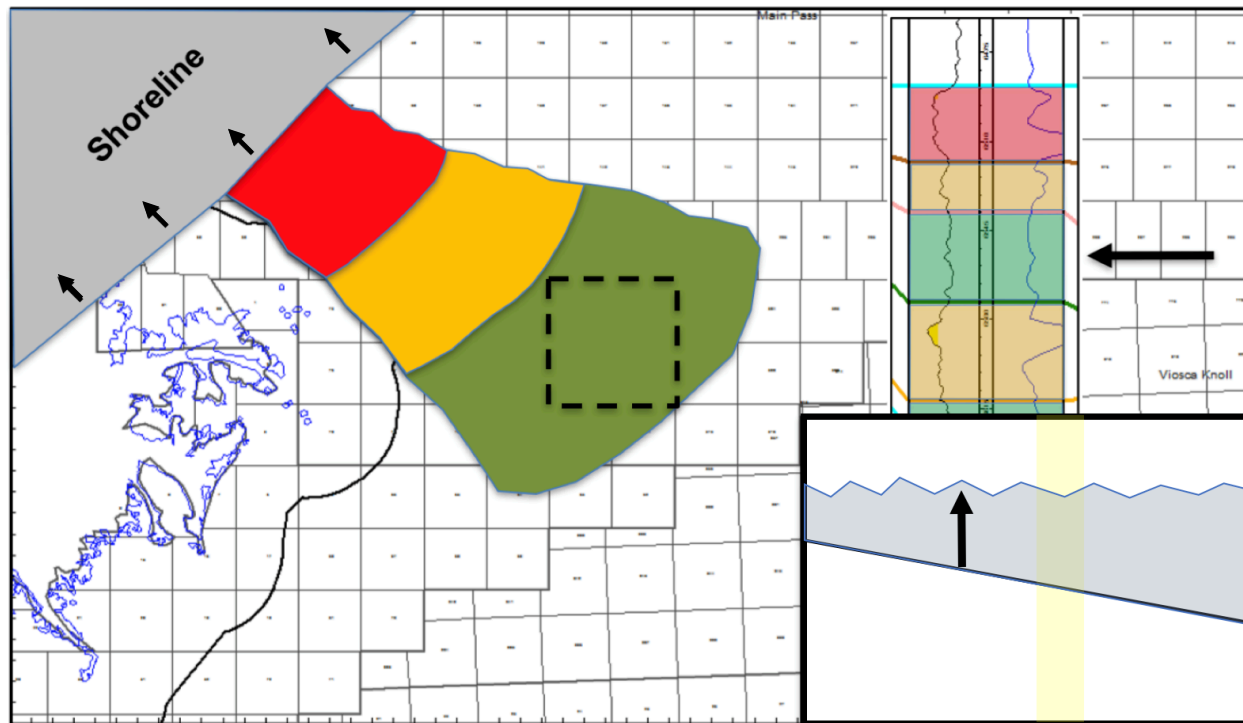


Figure 43. Interpreted environment, movement of shoreline, and water depth for “N-Sand” bed set #3. The colors in the delta figure represent the three different environments with red being the “clean” zone, yellow being the transitional zone, and green being the prodelta. The grey area represents the shoreline, and the arrows represent the interpreted movement that deposited the sediments within the bed set. The box in the right bottom corner represents interpreted sea level, with the highlighted zone being the study area and the arrow representing the interpreted change in water depth resulting in the deposition of the bed set.

Bed Set N-4:

In the log, bed set number four is represented by a “coarsening up” character, meaning that the gamma ray radiation from the section decreases vertically in a funnel pattern (Figure 37).

This is interpreted to be the result of the increasing proportion of fine sands and silts, which damped the radiation of the mudstones. The type of environment in which these sediments are found within a delta complex is the transitional zone. The transitional zone is a moderate energy environment, and lies in moderate level of water. An isopach of bed set 4 can be seen in Figure 44. The movement from prodelta to transitional zone environment is the result of a fall in relative sea level, an increase in sediment supply, and caused the delta to prograde towards the sea with progressively younger sediment being deposited seaward (Figure 45).

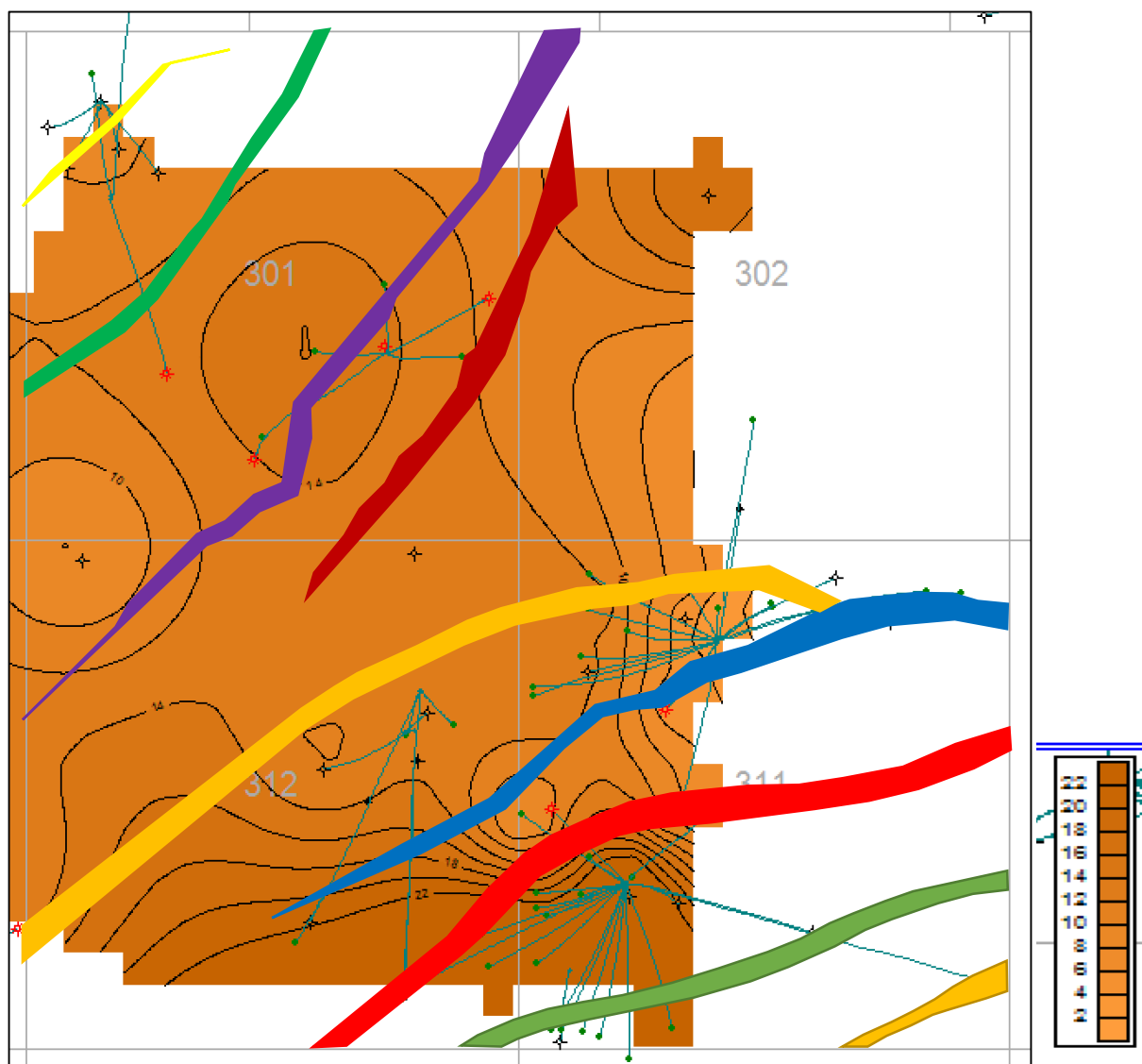


Figure 44. Isopach map of N-Sand bed set #4, the scale ranges from 2 feet (light orange) to 22 feet (dark orange). The colored bands are faults in the area.



Figure 45. Interpreted environment, movement of shoreline, and water depth for “N-Sand” bed set #4. The colors in the delta figure represent the three different environments with red being the “clean” zone, yellow being the transitional zone, and green being the prodelta. The grey area represents the shoreline, and the arrows represent the interpreted movement that deposited the sediments within the bed set. The box in the right bottom corner represents interpreted sea level, with the highlighted zone being the study area and the arrow representing the interpreted change in water depth resulting in the deposition of the bed set.

Bed Set N-5:

Bed set five has a log signature with very low gamma ray reading and a flat, boxy character (Figure 37). This is interpreted to be the product of an influx of low radiation sandstone with little to no silt/mud. These sediments are indicative of a high energy, “clean” sand environment with a relatively low water depth. An isopach of bed set 1 can be seen in Figure 46. The deposition of “clean” sands atop the transitional zone silts and sands indicates a fall in sea level, and increase in sediment supply, and a progradation of the delta complex seaward (Figure 47). In this context, younger sediment is being deposited increasingly seaward.

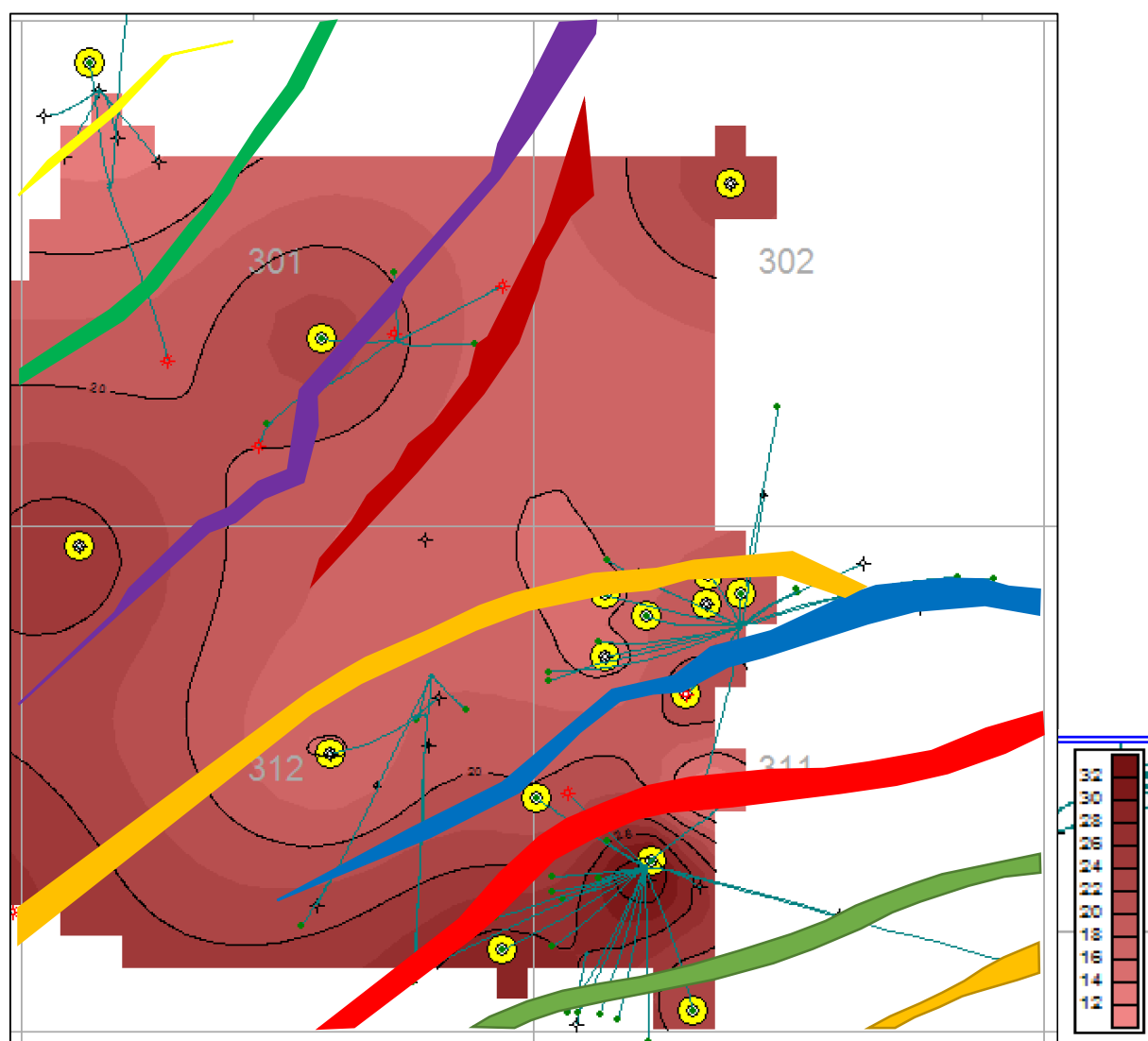


Figure 46. Isopach map of N-Sand bed set #4, the scale ranges from 12 feet (light red) to 32 feet (dark red). The colored bands are faults in the area.

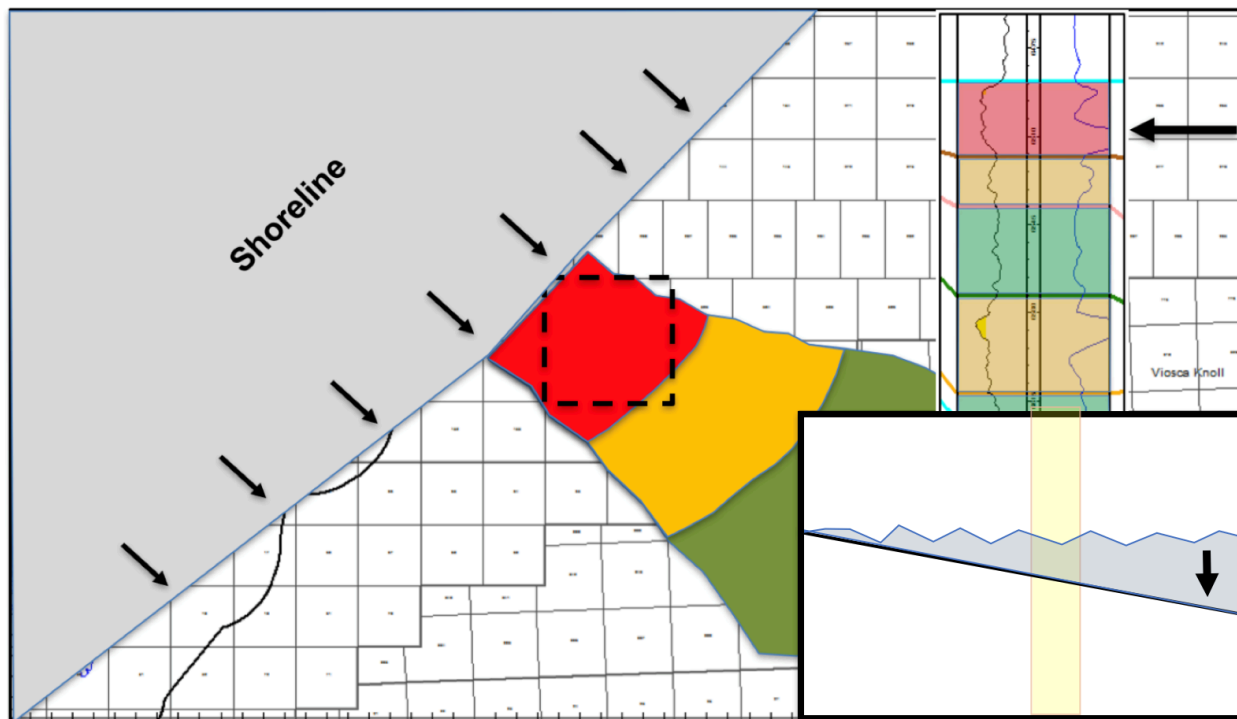


Figure 47. Interpreted environment, movement of shoreline, and water depth for “N-Sand” bed set #5. The colors in the delta figure represent the three different environments with red being the “clean” zone, yellow being the transitional zone, and green being the prodelta. The grey area represents the shoreline, and the arrows represent the interpreted movement that deposited the sediments within the bed set. The box in the right bottom corner represents interpreted sea level, with the highlighted zone being the study area and the arrow representing the interpreted change in water depth resulting in the deposition of the bed set.

Insights and Conclusions, N-Sand:

The “N-Sand” is a complex reservoir sequentially. The parasequences represent a full progradation of the delta, with a rapid retrogradation and subsequent progradation. This indicates that sea level was fluctuating to a greater degree than in the time of deposition of the “P-Sand”. Minor fluctuation in sea level rising and falling can create highly complex deposits but present an opportunity for locally stacked pays.

For the exploitation of a reservoir, knowledge of the depositional environment leads to greater understanding of reservoir parameters such as porosity and permeability. As explained before, the trends in greater porosity and permeability will be in the north-east direction. This will help predict drainage patterns for the “N-sand” reservoir as well as the others. The bed set that has the highest potential for conventional production is bed set number 3 due to the thickness as well as the interpreted porosity and permeability. This bed set was termed the “N-2 strand” by the geologists at Energy XXI, and the majority of the production from this parasequence is attributed to this layer.

The most prospective bed sets within the N-Sand parasequence are bed set #1 and bed set #4, both which were interpreted to have been deposited in a “clean” sand environment. This is because the sediment deposited in this environment is known to have the highest porosity and permeability relative to the other bed set. Both of these bed sets have been tested and proved productive by previous operators. Initial production data from several wells were taken and plotted in the chart below (Figure 48 and 49). Initial production data was normalized by dividing the IP by the perforation length. The bed sets of the N-Sand are much greater than that of the O-Sand, due to the prospectivity of the interpreted environment. This is due to the lower silt and mud content of the “clean” zone depositional environment of the N bed sets, which heightens

porosity and permeability. More IP data was available, however the N, O, and P production has been reported comingled, which leads to unreliable interpretations.

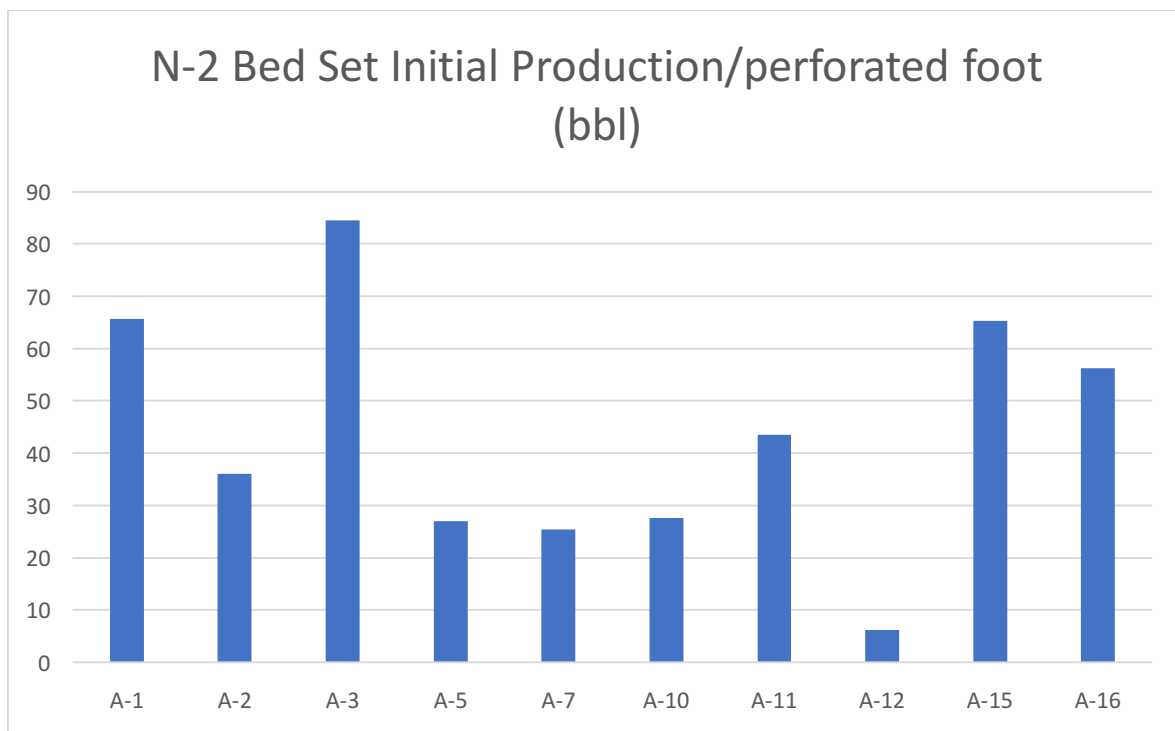


Figure 48. Chart showing initial production in 10 wells, Initial production was divided by perforation length to obtain a meaningful measure.

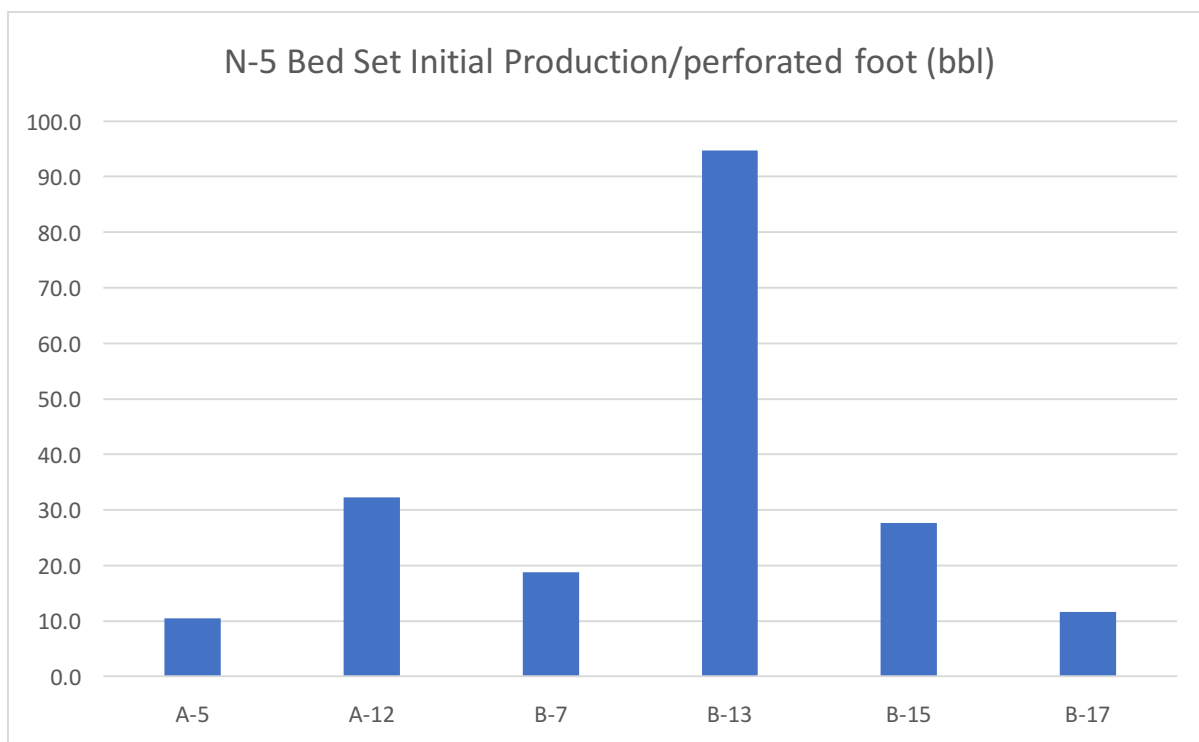


Figure 49. Chart showing initial production in 6 wells, Initial production was divided by perforation length to obtain a meaningful measure.

Using the adjacent facies relationships comprising a delta complex, logical predictions can be made. Being able to predict the location of reservoirs in a manner that is consistent with depositional evidence is a valuable tool. The proven “N-5 strand” is a small but quality reservoir that does not terminate into transitional zone deposits in the study area. Understanding the sequence, it is known that at some location this “clean” sand deposit does become a transitional zone sand/silt, and this does not occur in the study area. Judging by the direction of deposition it is reasonable to infer this reservoir would continue in the south-east direction. This could be confirmed by exploration in blocks 314, 315, 310.

Summary and Conclusions

Additional Work:

The most promising bed set for the “P-Sand” reservoirs is bed set #3. This is due to the interpreted depositional environment, the “clean” zone, which characteristically deposits sediment with high porosity and permeability. This bed set was deposited on top of bed set #2 due to the fall in relative sea level and progradation of the delta complex as the shoreline migrated seaward. Because the termination of bed set #3 is not seen in the study area along a time relevant surface, it is reasonable to suggest that it is present further along the trend of deposition. Main Pass lease block 314 and 315 will very likely host this same prolific bed set, and if the reservoir does not terminate along a time relevant surface it may extend further.

For the “O-Sand” the bed sets with highest prospectivity are the first and third bed sets. This is due to the interpreted depositional environment, the transitional zone, which is known to deposit sediments with significant proportions of sand. Both bed sets have moderate levels of porosity and permeability, but are substantially better than the second bed set which is comprised of prodelta mud. The first and third bed set was deposited due to the fall in relative sea level and progradation of the delta complex as the shoreline migrated seaward. Because the “clean” sand deposits for the O reservoir are not seen within the study area along a time equivalent surface, it is reasonable to assume that it is present more proximal to the source of sedimentation. The prolific transitional zone deposits within this study area must be tied to a prospective “clean” sand deposit in the north-west direction, most likely in Main Pass lease blocks 300 and 299.

Lastly, the “N-Sand” reservoir has two beds with potential for hydrocarbon productivity, bed set #2 and #5. These are the most promising due to the interpretation of their depositional

environment, the “clean” zone, which routinely deposits sediment with high porosity and permeability. These bed sets were deposited due to the fall in relative sea level and progradation of the delta complex as the shoreline migrated seaward. These proven reservoirs do not terminate along a time surface within the study area, therefore it is reasonable to assume they are present along the trend of deposition. Similar to the “P-Sand” reservoir, Main Pass lease block 314 and 315 will very likely contain these same proven bed sets, and if the reservoir does not terminate along a time relevant surface it may extend further.

As stated in the limitations, this study is limited by the size of the study area. The delta complex studied is too large to be fully imaged in the area, and for a true sequence stratigraphic framework to be complete the entire complex needs to be visible. A three-dimensional seismic shoot over the entire delta complex would yield the best interpretation. However, the concepts of time equivalent surfaces, and sequential deposition within the study area have led to a greater understanding of the depositional history, and provided some useful insights into reservoir exploitation and introduced some high-level ideas for reservoir exploration.

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