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Petroleum Play Study of the Keathley Canyon, Gulf of Mexico

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Keathley Canyon, Gulf of Mexico

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Master of Science
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By

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DEDICATION

This paper is dedicated to my wife Melissa and our four children, Madeline, Matthew, Katherine and Jackson, thank you for believing in me and helping me believe in myself. To my parents Donald and Eva, thank you for giving me life and never letting me give up.

ACKNOWLEDGMENT

We would like to thank PGS for their donation of seismic data. We would also like to thank Schlumberger and Ocean for their donations of Petrel Seismic Software;

Geodata Investigator and Blueback Toolbox.

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NOMENCLATURE AND ABBREVIATIONS

Gulf of Mexico……………………………………..GOM

Keathley Canyon……………………………………KC

Garden Banks……………………………………GB

Top of Salt……………………………………..ToS

Bottom of Salt……………………………………...BOS

Pre-Stacked Depth Migration……………………………………PSDM

Miocene/Oligocene ……………………………………...Mio/Olig

Oil Water Contact……………………………………OWC

Abstract

Beneath Keathley Canyon (KC) off the Southern Coast of Louisiana and Texas, allochthonous salt bodies have attained thicknesses of over 7620 m (25000 feet), providing excellent seals and migration pathways for hydrocarbons produced by post-rift sedimentary deposition. This study analyzes a small portion of the KC area, utilizing Petrel Seismic software and well information from the KC102 (Tiber) well.

An intra-Miocene wedge, expressed beneath salt, may provide information about movement of allochthonous salt over Wilcox sands, sediment compaction, and hydrocarbon pathways. Progradational sedimentation is the driving force which leads to faulting in the early Miocene, allowing Jurassic salt to rise, spreading laterally and upwards towards the surface, scarring the sediments beneath it in glacier-like form. This intrusion helped to create the proper conditions for formation of a petroleum play system, maintain reservoir quality sands and temperatures, and create a four way closure in the Eocene for prospective well location.

Keywords: Gulf of Mexico; Keathley Canyon; salt tectonics; Lower Tertiary; Tiber

Introduction

Inside the Keathley Canyon protraction area, off the Southern Coast of Louisiana and Texas, enormous allochthonous salt bodies have accumulated between sedimentary layers and attained thicknesses varying from 2100m, to greater than 6100m (7000 to > 20,000ft.) (Rains, *et al.*, 2007). These salt bodies provide excellent seals and migration pathways for hydrocarbons produced by post-rift sedimentary deposition. The Wilcox sands of the lower Tertiary have been an extensive source for hydrocarbon exploration both onshore and in the shallow waters of the Gulf of Mexico for well over 100 years. Well within the current trend of deep water gulf exploration, the Wilcox is located some 28,000 feet below sea level and includes discoveries to date exceeding 12 MBBL of oil in place. Spanning over 35,000 square miles, with recovery estimations per discovery in the 3 to 15 MBBL range (Meyer, 2005), and with the easiest finds already discovered and produced, the deep-water Wilcox Formation has become an important target in the Gulf of Mexico deep-water exploration effort (Figure 1).

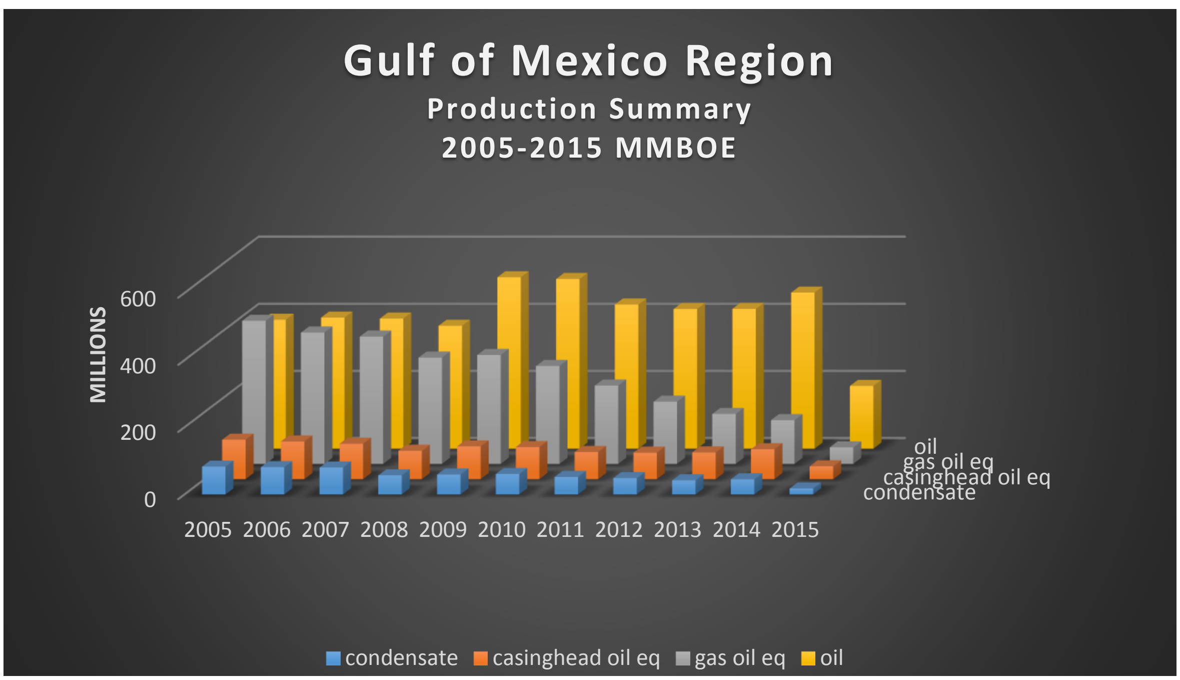


FIGURE 1- TEN YEAR PRODUCTION SUMMARY FOR GULF OF MEXICO. GRAPH REPRESENTS ALL PRODUCTION SINCE 2005 ALL IN MMBOE

The prevalent concept for the creation of allochthonous salt structures and salt movement is differential sedimentation loading caused by basin-ward progradation, (Humphris, 1978, Ge, *et al.,* 1997, Hudec, Jackson 2007). C.C. Humphris Jr., documents the forced initiation of salt domes relative to the slope on the outside of the shelf, stating that the arrangement, "demonstrates a close relationship between salt movement and sediment deposition" (Humphris, 1973). Scaled physical modeling further supports the concept of progradation triggering halokinetics; by duplicating structural salt, then differentially loading sediment layers. Resultant models mimic known salt structures throughout the modeling exercise (Ge, *et al*., 1997). While there have been several studies on salt tectonics of the Gulf of Mexico basin, very few have been about the glacial-like movement of salt intrusions and its effects on the surrounding sediments. Daniel D. Wenkert from the California Institute of Technology, while studying salt glacier formations in Iran observed through laboratory experiment that pure salt will deform under high stress by a process known as dislocation climb, which can be directly related to the salt structure that we are addressing in this study.

The Tiber prospect discussed in this paper will cover two wells, Tiber 1 and Tiber 2. The Tiber 1 well discovery is divided into two main pay sands in the lower Wilcox; the Upper Paleocene 2 and the Lower Paleocene 2. Both were thick and full-to-base in Tiber 1, while the Tiber 2 well was found to be completely dry. Tiber2 drilled too far down-dip and indicated stratigraphic complexities in the UP2 reservoir sands where vast deposits of non-reservoir siltstone were encountered. The Tiber 2ST (side track) was drilled in search of an oil-water contact (OWC). Pressure and fluids indicated two separate compartments in the shallow Eocene reservoir which divided the Eocene into the Eocene 1 and Eocene 2. Tiber 2ST encountered highest known water for the Eocene 1 and a solid OWC for the Eocene 2. The original predicted reserve range for this sand was between 125 and 450 MMBOE, with a mean recoverable of 270 MMBOE. However reserve estimates at Tiber have since decreased dramatically overall.

Objectives

This study has two main objectives, both of which focus on one small formation within the Keathley Canyon blocks of the Gulf of Mexico basin. The formation is an angled structure located at 7600 m (~25000ft) below the seabed. Dipping northward at 30° and overlain with 5200m (~17,000 ft.) of salt, the Tiber well (KC-102) drilled into this structure at a true vertical depth (TVD) of 10,685 m (35,056 ft.). The discovery was projected to be a 4 to 6 billion-barrel field.

The first objective of this paper is to define the complex geologic structure and determine where it fits into the progradation /differential loading paradigm. Utilizing Petrel Seismic software and 3D modeling, we identified horizons and sand intervals, then analyzed and documented all relevant aspects related to the origin of this structure.

The second objective of this study is to analyze the same small section of the Keathley Canyons Wilcox aged play in its entirety for hydrocarbon potential. By performing a complete petroleum play analysis, utilizing 3D seismic data and well log activity from KC 102 in the Tiber field, we investigate the causes behind the Tiber 2st well failure. We explain the reasons for its classification as a dry hole, and locate other potential drilling locations.

Regional

Keathley Canyon is one of the southern protraction areas in the U.S. Exclusive Economic zone of the GOM. Approximately 240 mi (386 km) off the coast of Texas and Louisiana, the protraction area covers an area of 5.7 million acres and is home to several major discoveries including, Kaskada, Moccasin, Hadrian and Tiber (Figure 5). Recent reserve predictions for these areas reach into the billions of barrels and discoveries are still being made.

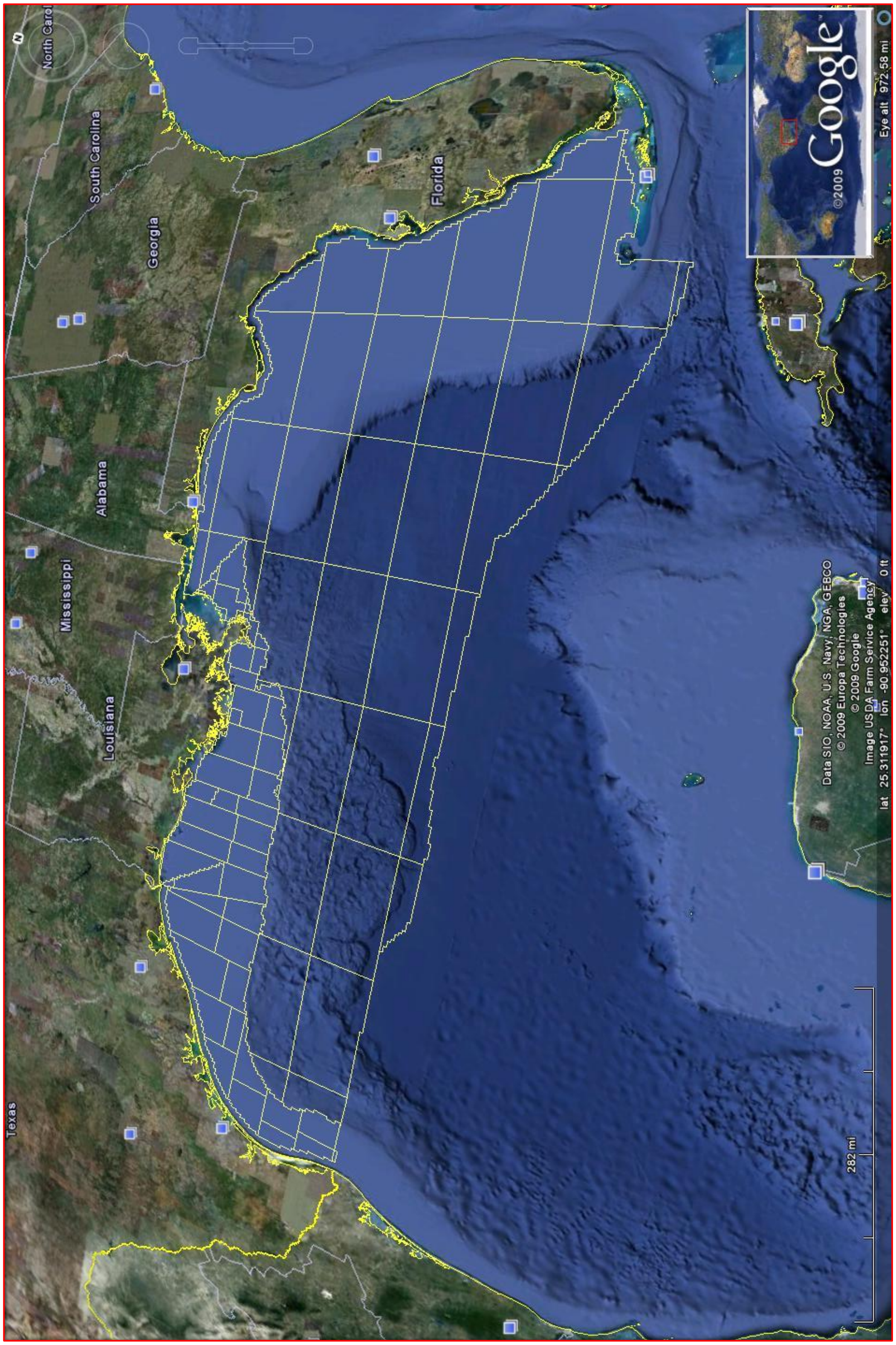
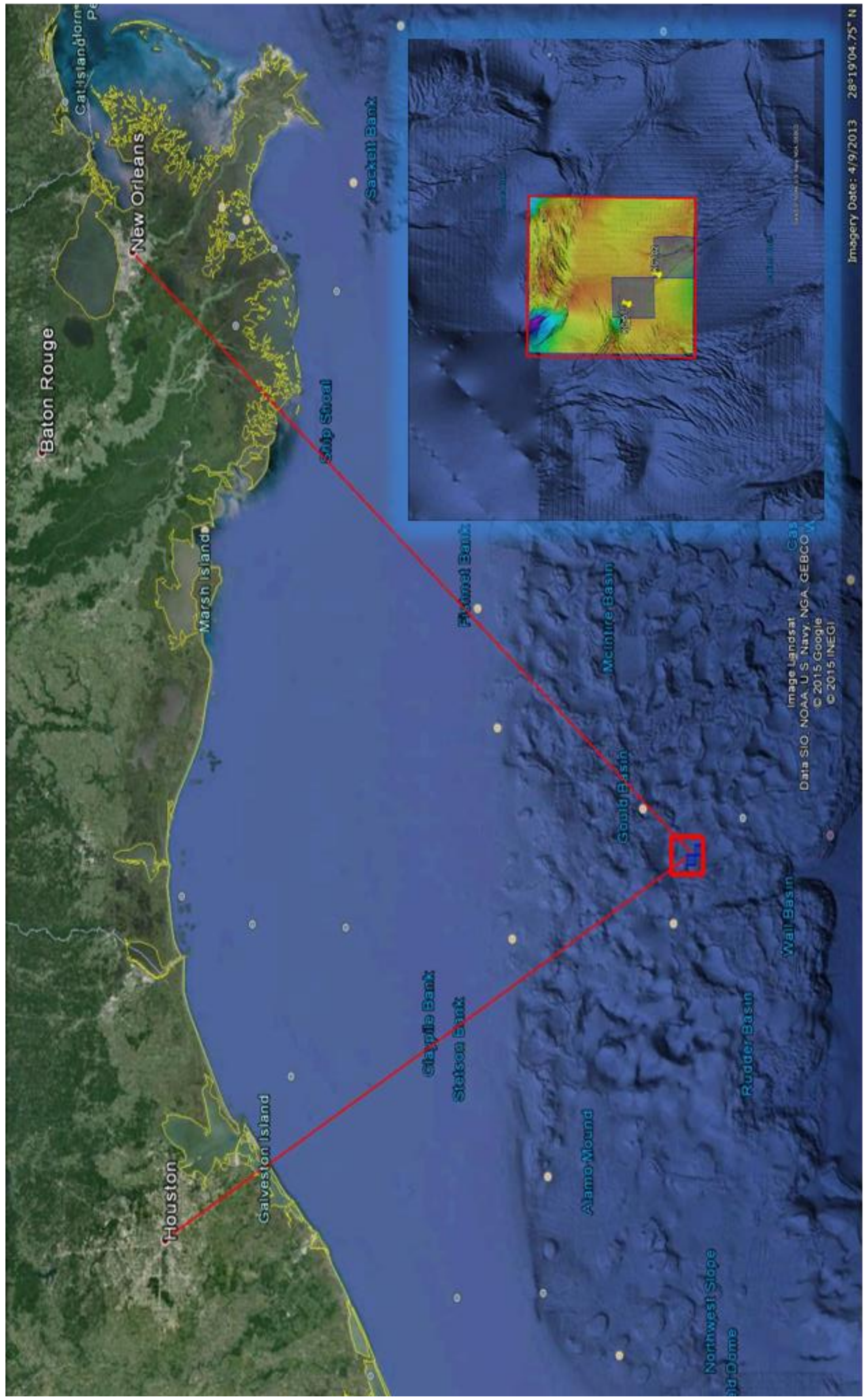


FIGURE 2 - GULF OF MEXICO EXTENT FROM GOOGLE EARTH, OUTLINED EXCLUSIVE ECONOMIC ZONES DIVIDED INTO PROTRACTION AREAS SPAN THE COASTLINES OF TEXAS, LOUISIANA, MISSISSIPPI, ALABAMA AND FLORIDA

FIGURE 3 - UTILIZING BLOCK DATA DOWNLOADED FROM THE BUREAU OF OCEANIC ENERGY MANAGEMENT (BOEM) AND GOOGLE EARTH, LOCATION MAPS WERE CREATED FOR THE SPECIFIC AREA OF STUDY WITHIN THE NORTHWESTERN REGION OF KEATHLEY CANYON, COVERING BLOCKS KC12 THROUGH KC15, KC56 THROUGH KC59 AND KC100 THROUGH KC103, AS WELL AS THE SOUTHERN BLOCKS OF GARDEN BANKS GB980 THROUGH GB983.



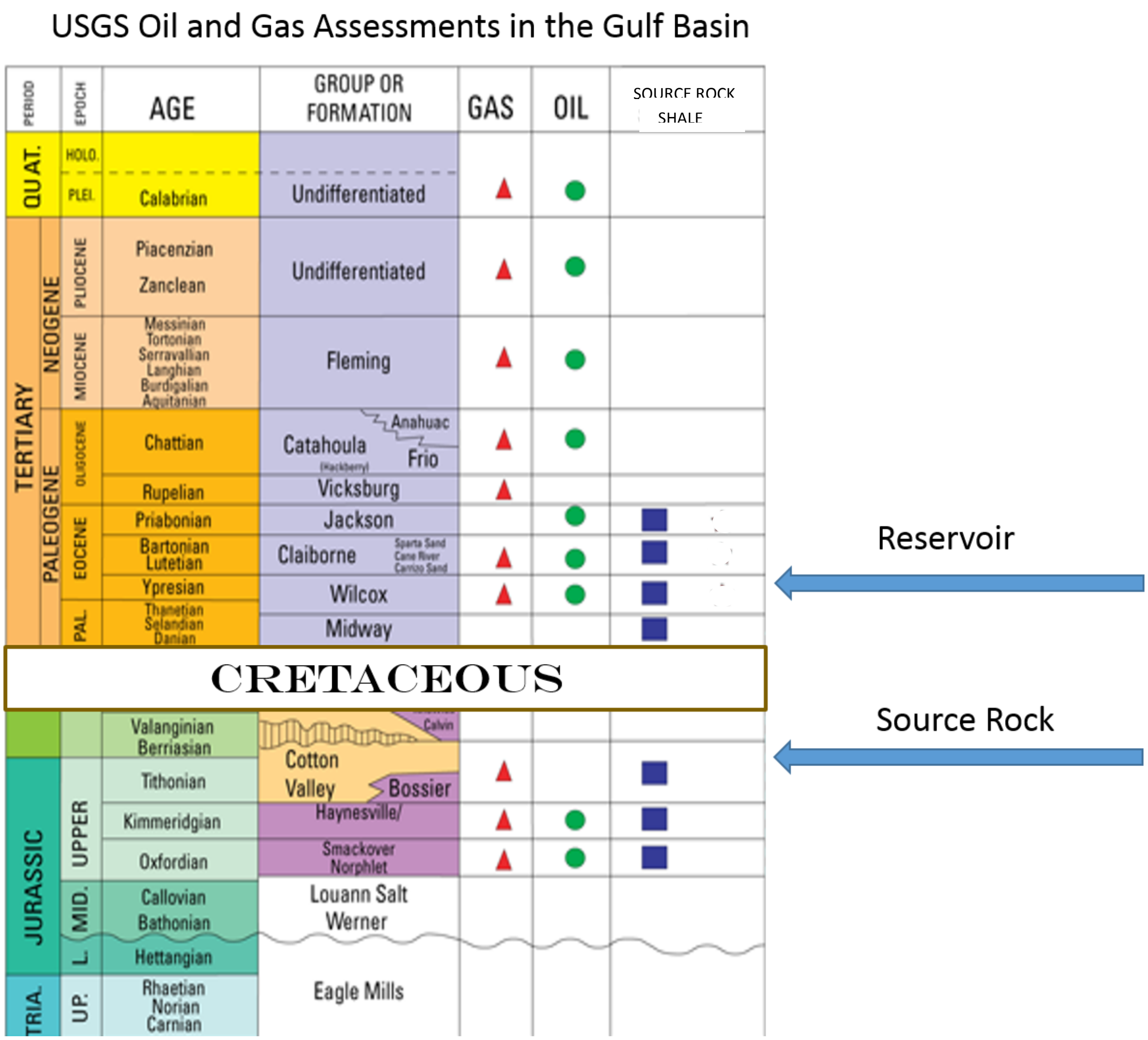


FIGURE 4 - A STRATIGRAPHIC COLUMN MODIFIED FROM USGS, LISTS THE GROUP FORMATIONS, SOURCE ROCKS AND TYPE OF OIL ASSOCIATED WITH EACH FORMATION. OUR RESERVOIR IS LOCATED IN THE LOWER TERTIARY AND SOURCE IS LOCATED IN UPPER JURASSIC TITHONIAN.

Dataset

The Pre-Stacked Depth Migration data from PGS Marine Geophysical was shot in the E/W direction with 4 sources and 10 streamers in July of 1999 at an interval of 25 meters at 9 sec below sea bottom. Seafloor horizon was interpreted in Petrel and compared against seafloor images from Google Earth for location confirmation. Processing parameters are listed in Table 1.

Keathley Canyon Discoveries		
Year	**Prospect**	**Area**
2004	Sardinia	KC681
2004	Hadrian	KC919
2006	Kaskida	KC292
2007	Cortez Bank	KC244
2009	Bass	KC596
2009	Tiber	KC102
2011	Moccasin	KC736
2012	Bioko	KC698

FIGURE 5 - LIST OF IMPORTANT KEATHLEY CANYON DISCOVERIES BY YEAR.

While very little well data is publicly available for the blocks inside the study area, the following well logs were obtained from the Bureau of Ocean Energy Management/Bureau of

Safety and Environmental Enforcement for well KC102 (Table 3). KC57 (Tiber 2) well logs and physical data are as of yet unreleased to the public.

TABLE 1 - PROCESSING PARAMETERS AND OTHER AVAILABLE DATASETS CONTRIBUTED BY PGS (PETROLEUM GEO-SERVICES, 2014).

PROCESSING PARAMETERS:	
Noise attenuation, Regularization, Acquisition footprint removal	
Surface-Related Multiple Attenuation (SRME)	
Tomographic sedimentary overburden velocity model building	
Salt geometry definition using both turning ray Kirchhoff and wave equation	
Prestack Depth Migration, Beam Migration	
Wave equation scanning for sub-salt velocity modeling	
DATA DELIVERABLES:	OTHER AVAILABLE DATASETS:
3D Kirchhoff depth migration	Wave Equation D.M., Depth Velocity
Beam migration	Kirchhoff depth gathers

TABLE 2 - WELL LOG INFORMATION ACQUIRED FOR PROJECT THOUGH BUREAU OF OCEAN ENERGY MANAGEMENT AND BUREAU OF SAFETY AND ENVIRONMENTAL ENFORCEMENT.

Well Logs Obtained from BOEM/BSEE
Borehole Profile (Schlumberger Well Surveying Corp) 1 IN 100’
Gamma Ray Log (Schlumberger Well Surveying Corp) 5IN_100FT
Combinable Magnetic Resonance (Schlumberger Well Surveying Corp) 5IN_100FT
AGREWR-M5-PWD-DIR (Halliburton- SPS LWD) 1IN 100FT (MWD) (TVD)
AGREWR-M5-PWD-DIR (Halliburton- SPS LWD) 5IN 100FT (MWD) (TVD)

Methodology

Utilizing Petrel seismic software, the 3D seismic dataset was loaded into a workstation and carefully analyzed along with well log data, well tops and a final velocity model. Seismic slices with well tops were compared with analog data to check for accuracy of interpreted labeled horizons. Since study only comprises of layers beneath salt structure, only seafloor and Top of Salt were picked above salt mass. Picked horizons, include from top (youngest) to bottom (oldest) include: Bottom of Salt/Miocene, Oligocene, Eocene A, B and C, Paleocene, and Cretaceous (Figure 6). Once each horizon was picked, each was converted to a surface and assigned the appropriate color bar for depth. RMS extractions for each horizon were created and analyzed for hydrocarbon potential, as well as time-slice images, to help better ascertain potential well locations within our dataset.

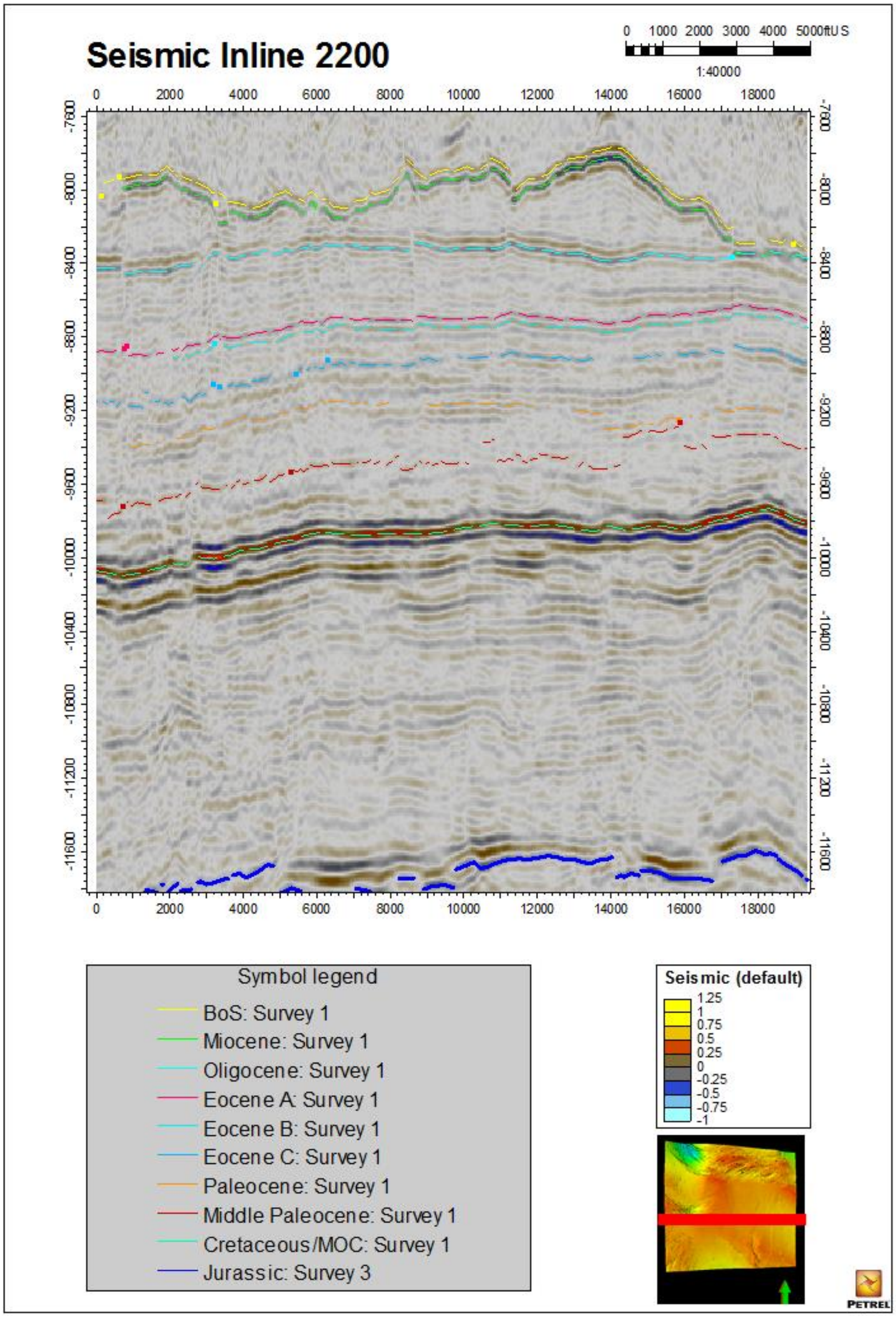


FIGURE 6 - SEISMIC INLINE #2200 LABELED WITH PICKED HORIZONS

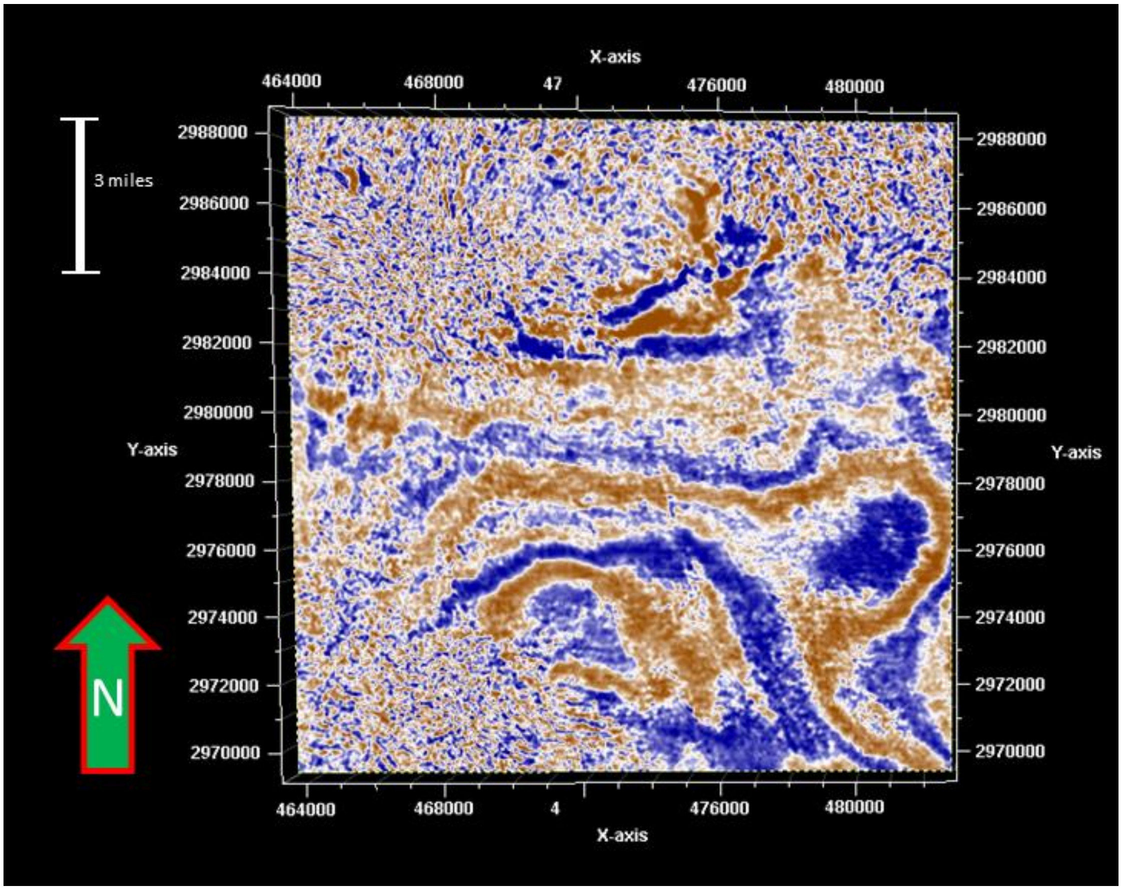


FIGURE 7 - PETREL CREATED DEPTH SLICE OF TOP OF EOCENE A HORIZON 28,000FT. (8650M)

The Wilcox group is represented between Eocene A and the middle of the Paleocene (Figure 6). Using these converted surfaces, a simple grid was made to explore the extent of the Wilcox volume inside our data area (Figure 8). A general smoothing of surfaces was applied with a low pass filter and spikes (data outliers), were removed.

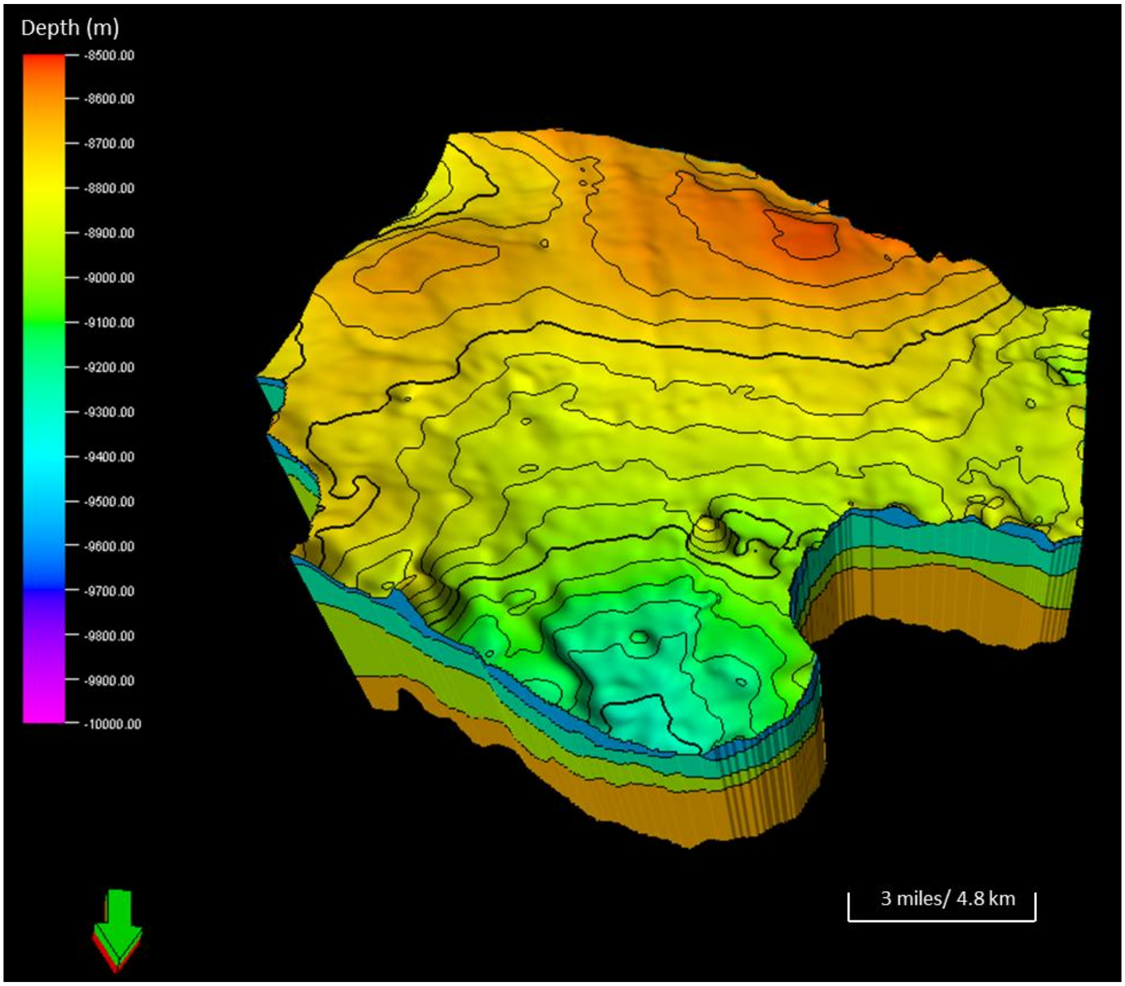


FIGURE 8 - WILCOX SIMPLE GRID. EOCENE A, B, C, PALEOCENE AND MID-PALEOCENE COMPILED INTO AN EXTRACTABLE VOLUME.

Gulf of Mexico

In order to better interpret the Keathley Canyon data in question, a thorough knowledge of the history of the GOM is required. Approximately 240 million years ago during the early-mid Triassic, an initial low angle detachment between what is now the Yucatan Peninsula and North America formed (Figure 8) (Pindell, 2007). This was the initial stage of the GOMs rifting event which took place during the breakup of the supercontinent Pangea. By the middle of the Jurassic, the Yucatan hanging wall separated from the North American Plate and a volcanic upper mantle extension forced its way upward creating oceanic crust. Subduction related tectonics along the eastern edge of North America allowed waters of the early Atlantic Ocean to spill into the newly formed basin, while huge Jurassic storms pushed ocean waters across what is now Mexico to collect in the shallow depressions created by continually subsiding grabens (Pindell, 2007).

Over countless cycles of replenishment and evaporation, the salinity of this body of water increased dramatically. These actions left behind isolated bodies of salt water which inhibited the oversaturation of the Gulf of Mexico's already hyper-saline waters and triggered halite precipitation (Dribus, et al, 2010). Evaporates collected due to a combination of heat from seafloor volcanics and the arid climate of the then equatorially located North American Plate (Pindell, 2007). Jurassic salt deposition, now knows as the Louann salt, continued throughout the formation of this basin and accumulated in amounts as high as 5km in some areas. These shallow water deposits consist of mainly halite, evaporated out of water channeled into the basin from one or more marine connections. These conditions remained until a major change in paleogeography took place. Higher than normal evaporation rates kept the accommodation space filled, ensuring that the depositional surfaces remained effectively flat and near sea level (Pindell, 2007). This shallow basin's depositional sequence would eventually give birth to one of the most fruitful oil and gas reservoirs in the world.

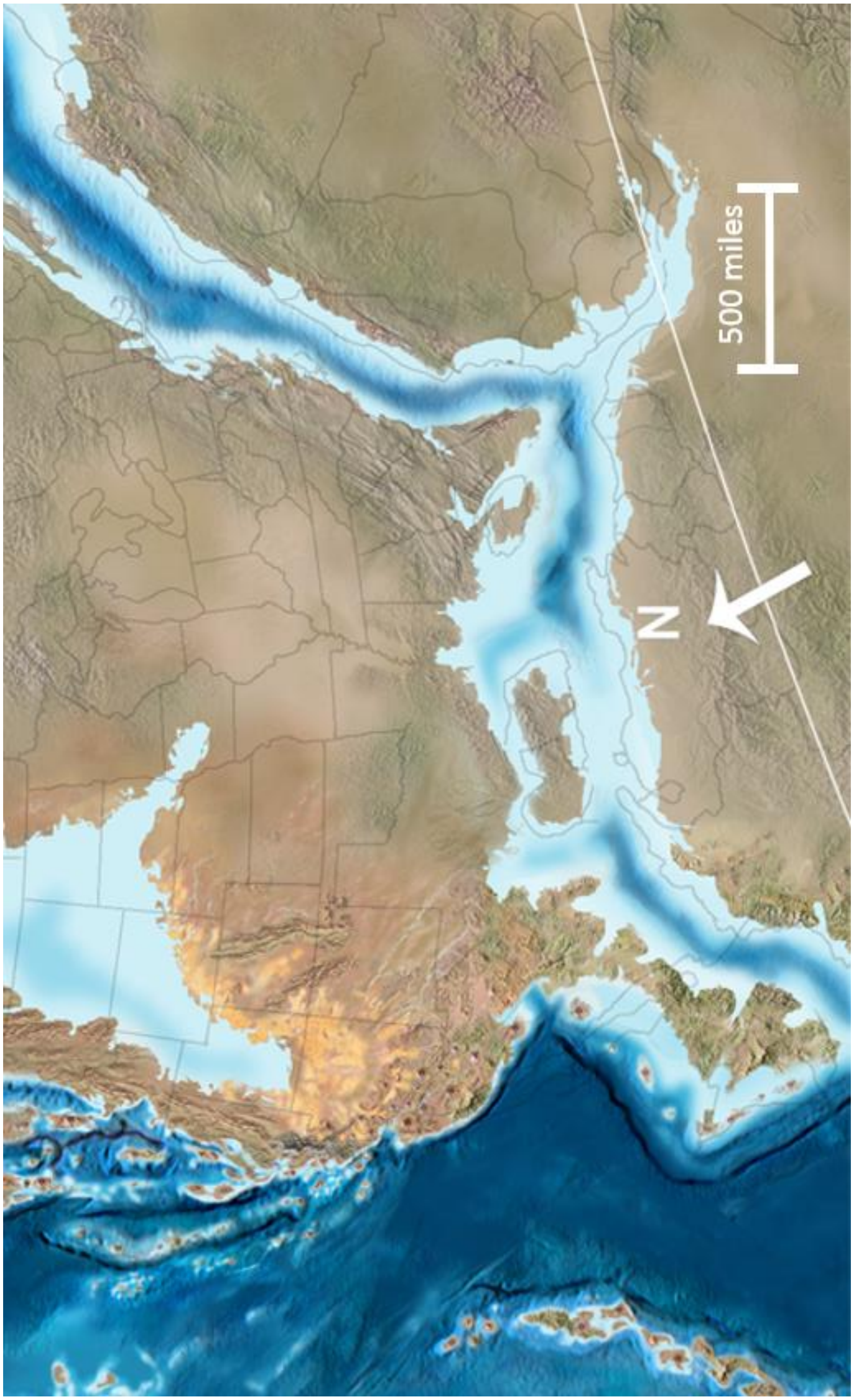


Figure 9 - Mid-Jurassic North America during GOM rifting event, Current U.S. map outlined on surface. (Blakey, 2011, www.cpgeosystems.com/paleomaps)

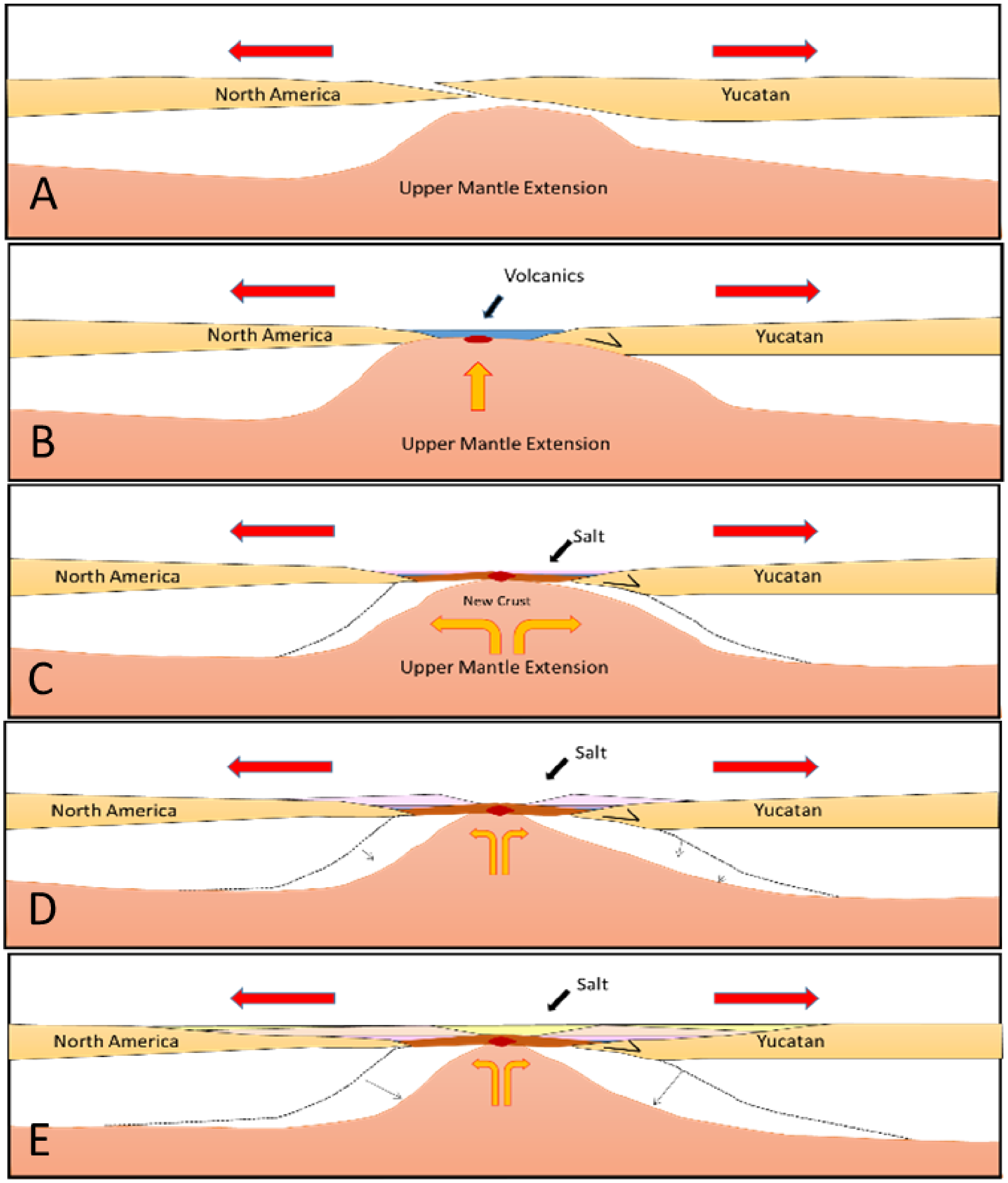


FIGURE 10 - A. NORTH AMERICAN PLATE AND YUCATAN PLATE BEGIN ASYMMETRICAL RIFT AND UPPER MANTLE EXTENSION RISES TOWARDS SURFACE. B. CONTINUED EXTENSION FURTHER OPENS NEWLY FORMED SHALLOW SEAWAY AND SMALL SCALE VOLCANIC ACTIVITY BEGINS. C. OCEANIC CRUST BEGINS TO FORM AS UPLIFT CONTINUES. D. HYPERSALINE WATERS BEGIN EVAPORATIONAL DEPOSITION AND MANTLE BEGINS TO RETRACT AS JURASSIC MARINE SEDIMENTS BEGIN TO ONLAP TOWARDS SHORE. E. DEPOSITION SWITCHES FROM CARBONATE TO CLASTIC AS BASIN OPENS AND NORTH AMERICAN SEDIMENTARY CYCLE BEGINS. (MODIFIED FROM PINDELL AND KENNAN, 2007)

Sedimentation

Above the Louann base of salt, erosional deposition began to take place. Triggered by the Laramide uplift, Lower Tertiary sands from North American continent began large-scale progradation, coating the gulf floor with a thick sedimentary layer (Mackey, et al., 2012). This progradation marked the transition from carbonate to clastic deposition and weighed down on the underlying salts to causing compaction of materials. This compaction and further sedimentation of the GOM basin, eventually moved the Louann salt above the sediment, creating the present day traps that keep hydrocarbons in place for discovery.

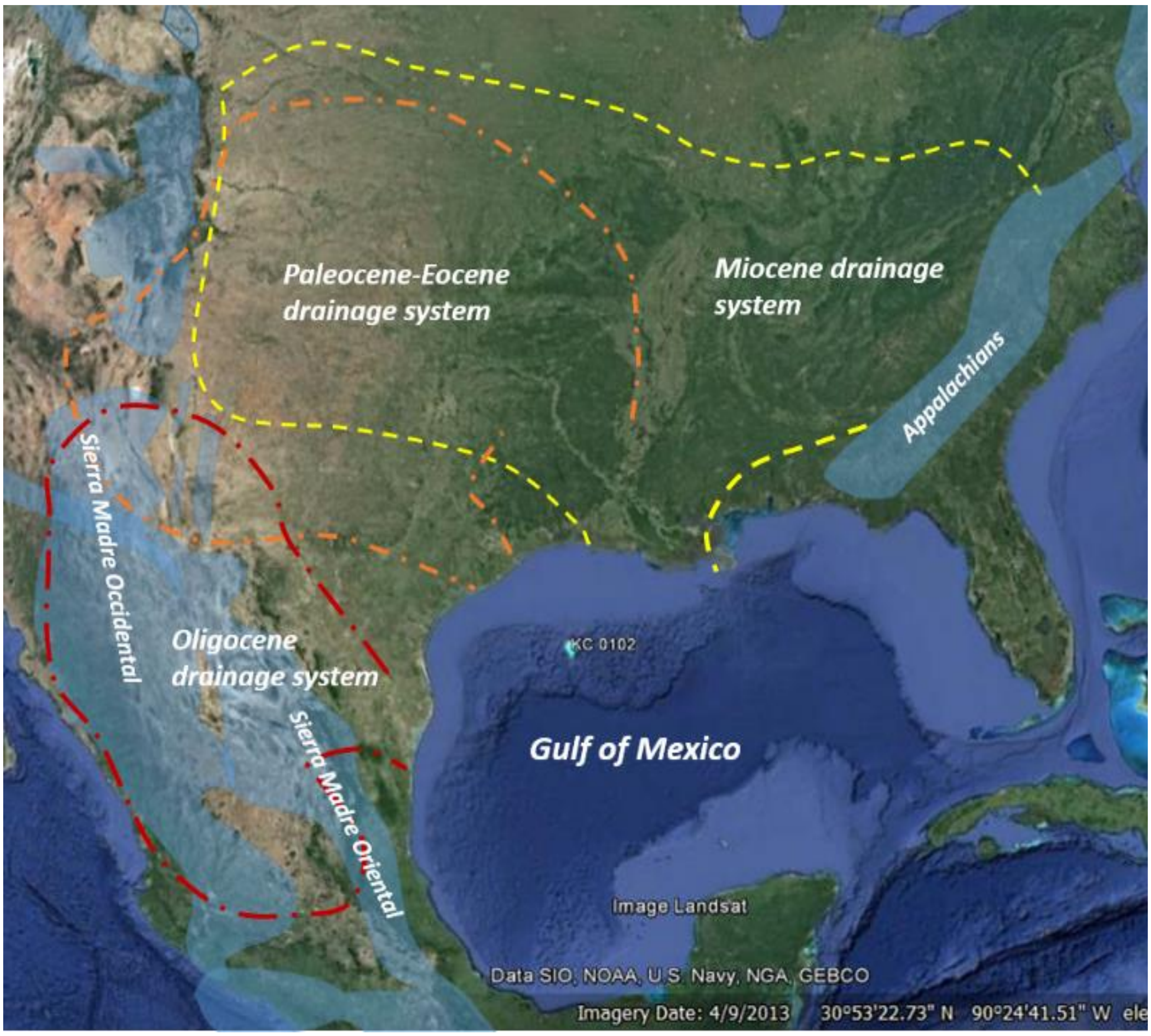


FIGURE 11 - NORTH AMERICAN PALEODRAINAGE SYSTEMS. A VAST AND STEADY SUPPLY OF GULF OF MEXICO SEDIMENTATION CONTRIBUTED MAINLY FROM THE LARAMIDE UPLIFT PASSES THROUGH THESE DRAINAGE SYSTEMS OVER THE COURSE OF MILLIONS OF YEARS. (MODIFIED FROM MACKEY, *ET AL*, 2012)

The onshore Wilcox formation is currently one of the leading Natural gas producing formations in the world. Located some 6,500 feet below sea level in Texas, Mississippi and Louisiana, inland from the GOM, it is just one of many strata the Earth buried with millions of years of deposition caused by erosion and land movement due to wind, water and tectonic motion. Estimated recoverable reserves of the onshore Wilcox trend are upwards of 30 Trillion Cubic feet (TCF) of natural gas (Lewis, et al 2009). Much of this onshore reserve has already been produced and the focus is now on the offshore Wilcox trend.

The Cretaceous/Paleogene shoreline was much different than it is today. Large wide-mouthed canyon systems cut through Cenozoic shelf margins, as rivers carried Wilcox aged sediments out into the deep-water basin (Beims, 2010). Distally, fine silty sediments reach the outermost depths and blanket the ocean floor forming Paleogene shales encompassing over 22,000 sq. miles.

Eocene Upper Wilcox deposits become buried by layers of deep marine sands as well as interbedded deltaic sedimentary deposits (Figure 9). By the Middle Miocene GOM deposits were primarily sourced from the Mississippi River and deposits of sand rich turbidites formed across the basin floor (Scaife, 2012).

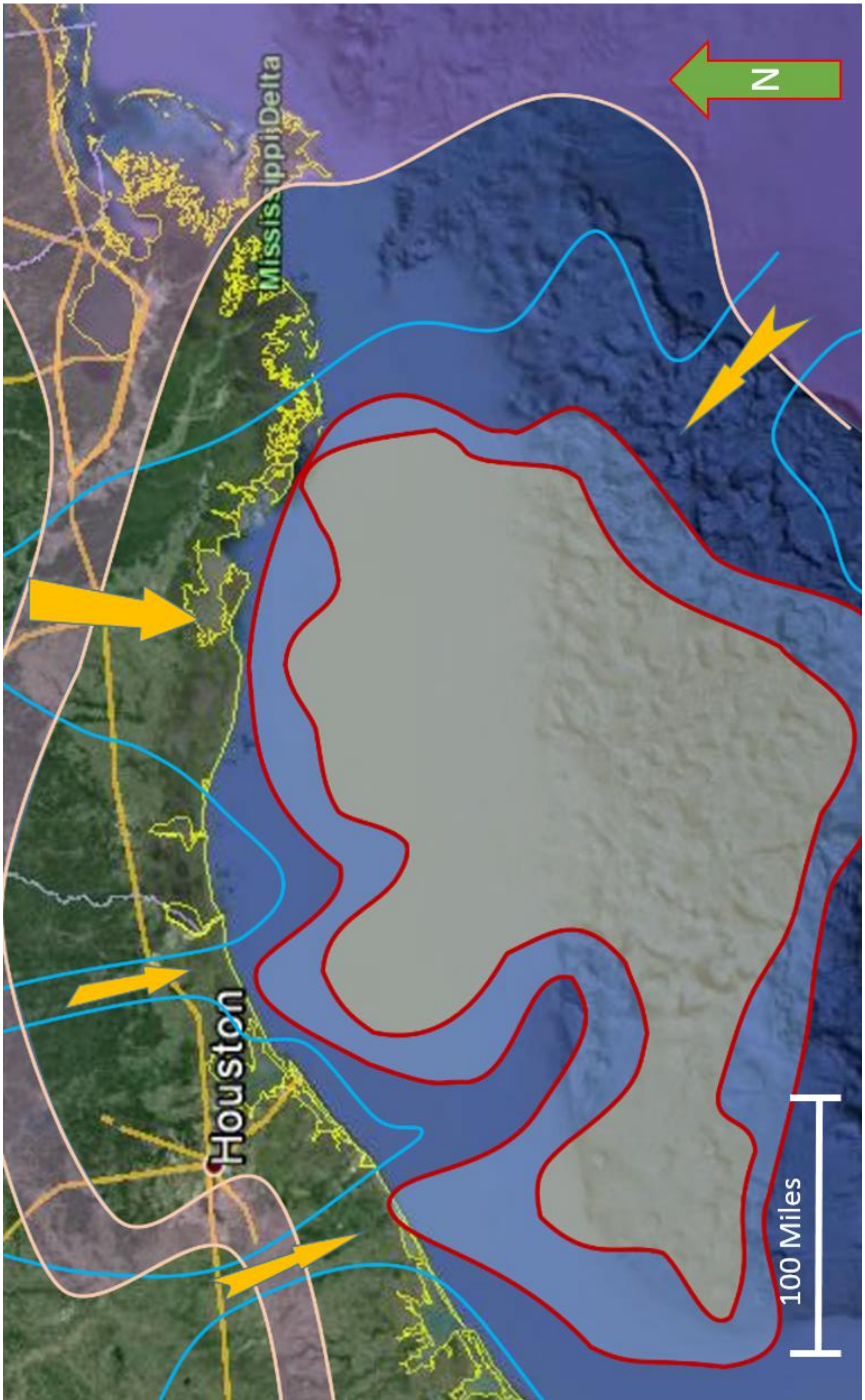


Figure 12 - Conceptual model of Paleocene/Eocene deltaic deposition for Wilcox depositional fairways, arrows show sources of sediment input. Pink shaded area represents Shelf/Slope location (Modified from Beams, 2010)

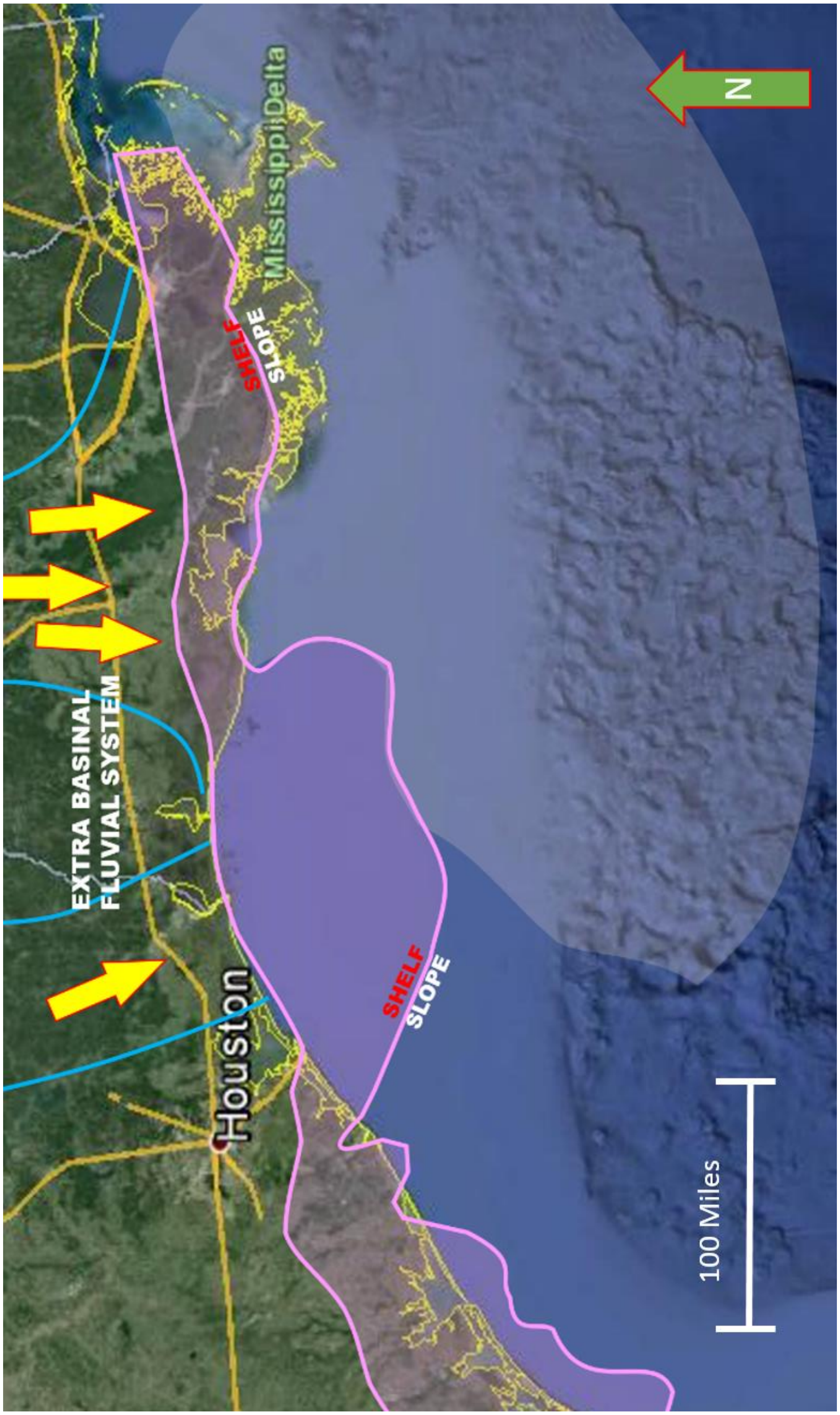


Figure 13 - Conceptual Model of Lower Miocene Gulf of Mexico Deposition, heavily influenced by Mississippi river system as represented with yellow arrows. Pink line again denotes shelf/slope location. fine sediments reach the most distal areas and compose deep water shales. (Modified from Beams, 2010)

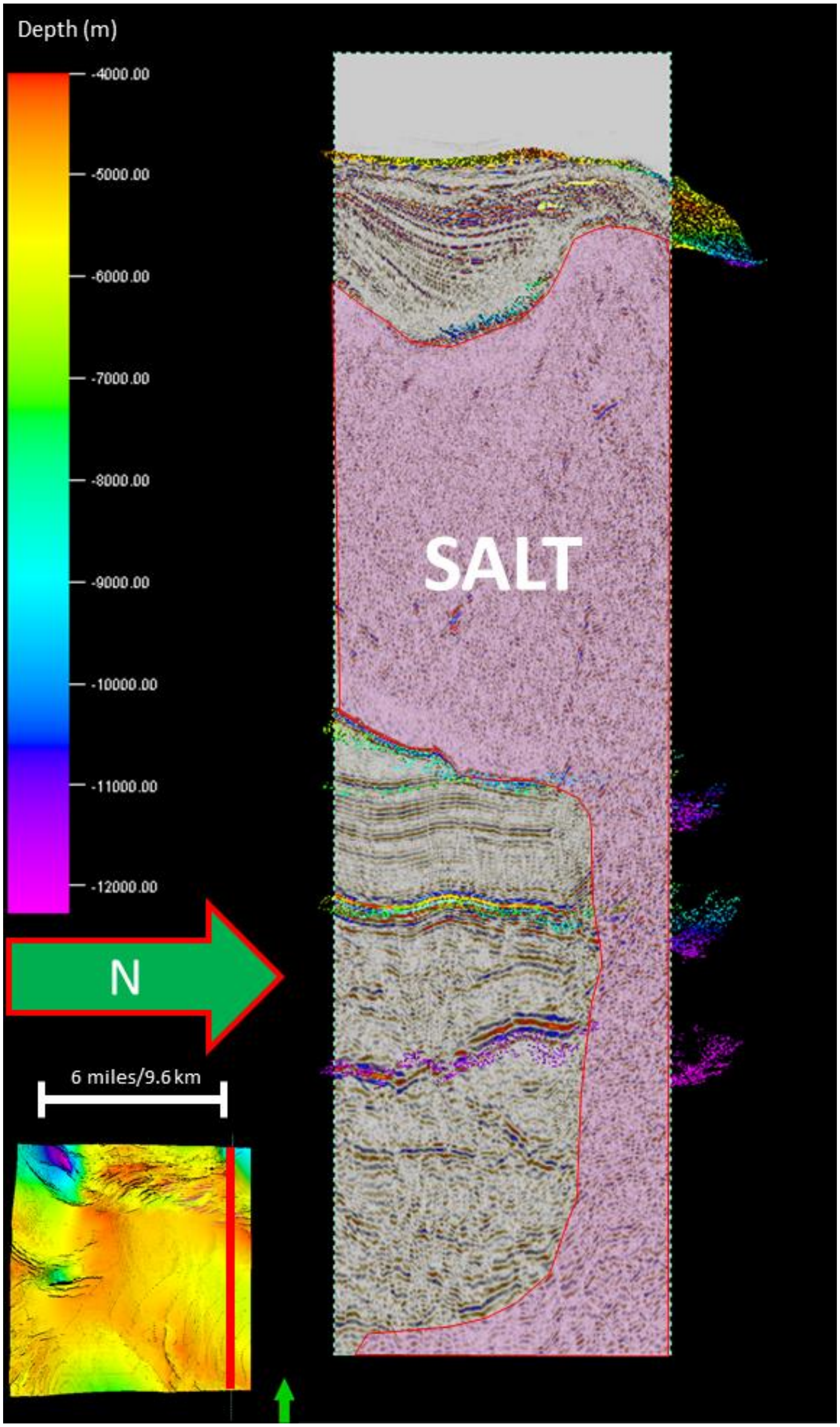


Figure 14 - Seismic inline in its entirety, showing the immensity of salt structure and path of salt stock. Top of salt, Bottom of salt, Miocene, Cretaceous and Jurassic horizons turned on.

CHAPTER 1 – Intra-Miocene Wedge

Salt tectonics

The GoM is home to several different types of salt structures; Diapers, nappes, salt sheets, and salt canopies are all common. Composed of mostly Halite (NaCl), salt is generally very weak and flows plastically like a fluid, especially at rapid strain rates (Hudec, 2007). Salt is far less dense than most carbonates and compacted siliciclastic rocks, is relatively incompressible, and is therefore inherently unstable. The primary driving force for salt tectonics is differential loading, (Hudec, 2007, Talbot, 1993), which is evident in the KC basin in which our study takes place.

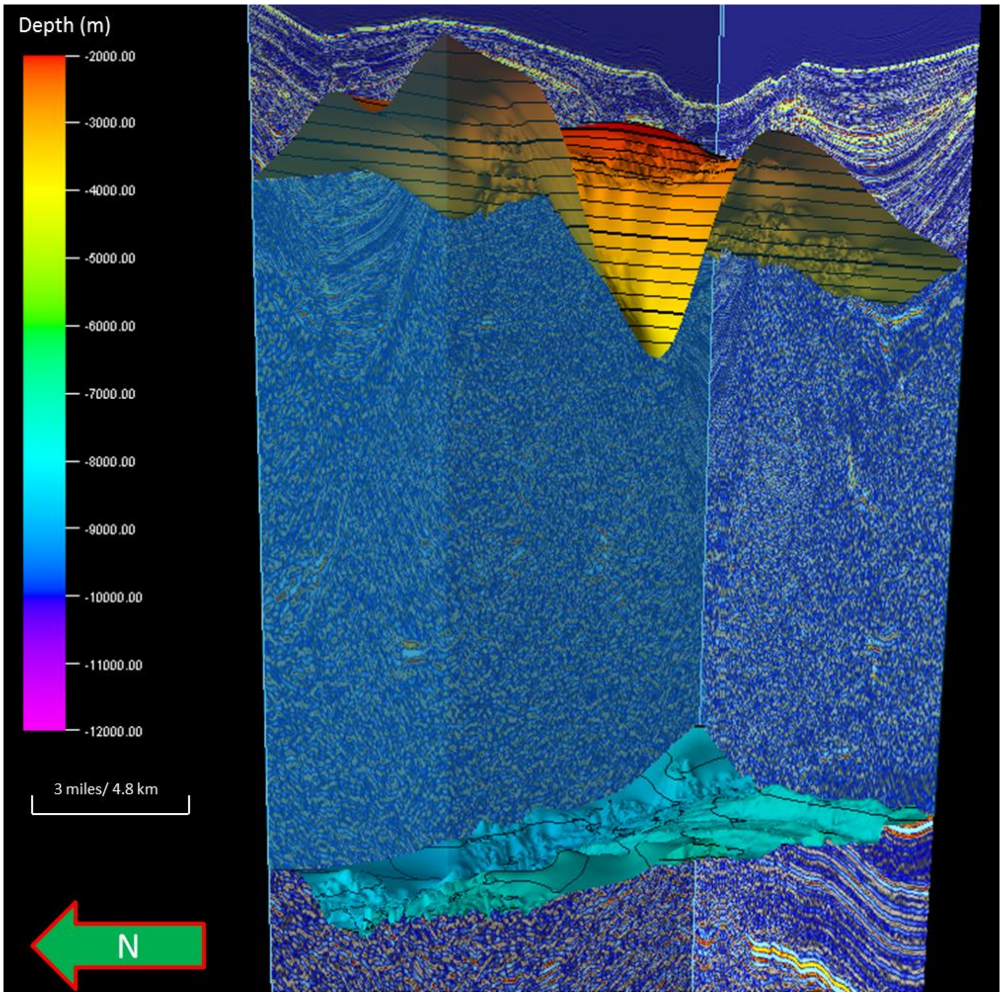


FIGURE 15 - SALT VOLUME BETWEEN TOP OF SALT AND BASE OF SALT SET AGAINST SEISMIC FOR SCALE

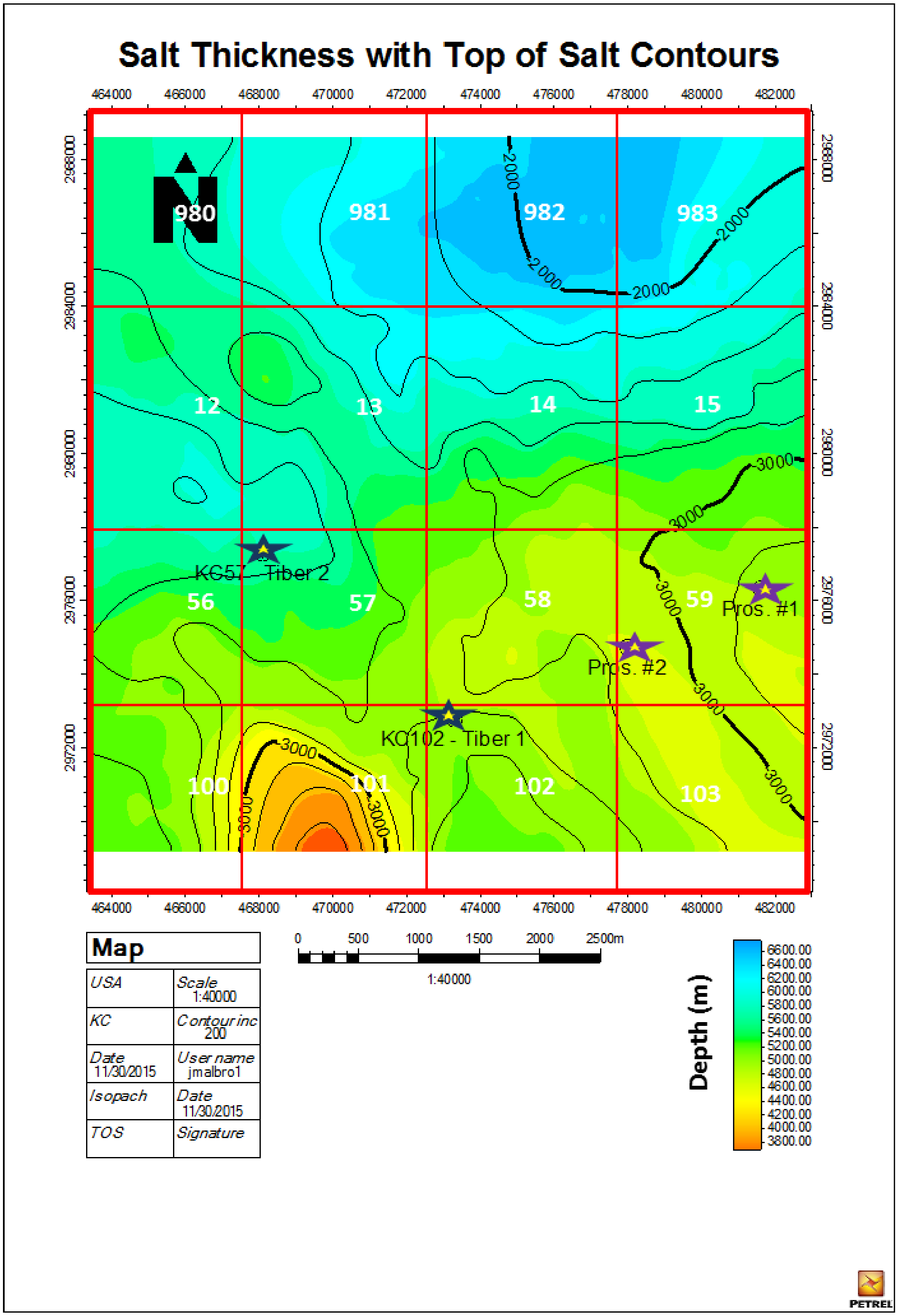


FIGURE 16 - ISOPACH OF KEATHLEY CANYON DATA AREA SALT THICKNESS WITH TOP OF SALT CONTOURS AND BLOCK NUMBERS. WELL LOCATIONS FOR KC57 AND KC102 ARE IN MUCH THICKER SALT THAN EAST IN KC59.

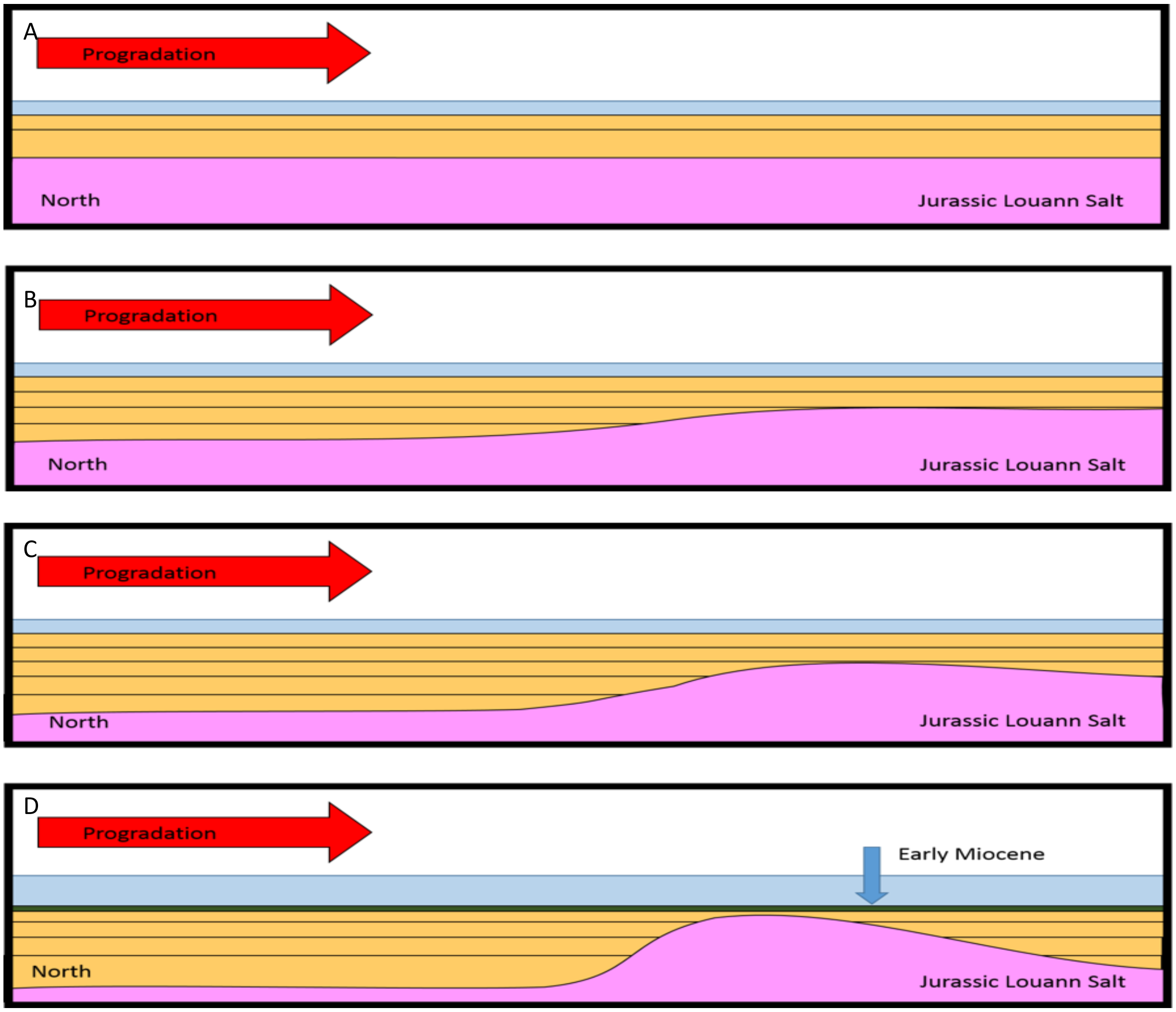


Figure 17 - A. Basin ward progradation of sediments over Jurassic salt. B. Continued loading causes compaction. C. Jurassic salt begins to flow basin ward. D. continued progradation forces salt flow farther basin ward and upward (modified from Hudec and Jackson, 2007)

Salt Movement

Basin-ward progradation from Paleocene through early Miocene created tremendous overburden above autochthonous Louann salt and begins to compress salt sheets horizontally (Figure 16). Overburden pressure causes salt bodies to compress and flow basin-ward, relieving compressional stresses. Deposition continues to take place in these areas where salt has evacuated, further compacting in situ sediments. Faulting in deep-water sediment-starved basins provide pathways for now flowing salts to rise through the rock and form salt tongues, nappes and other allochthonous salt formations (Figure 18).

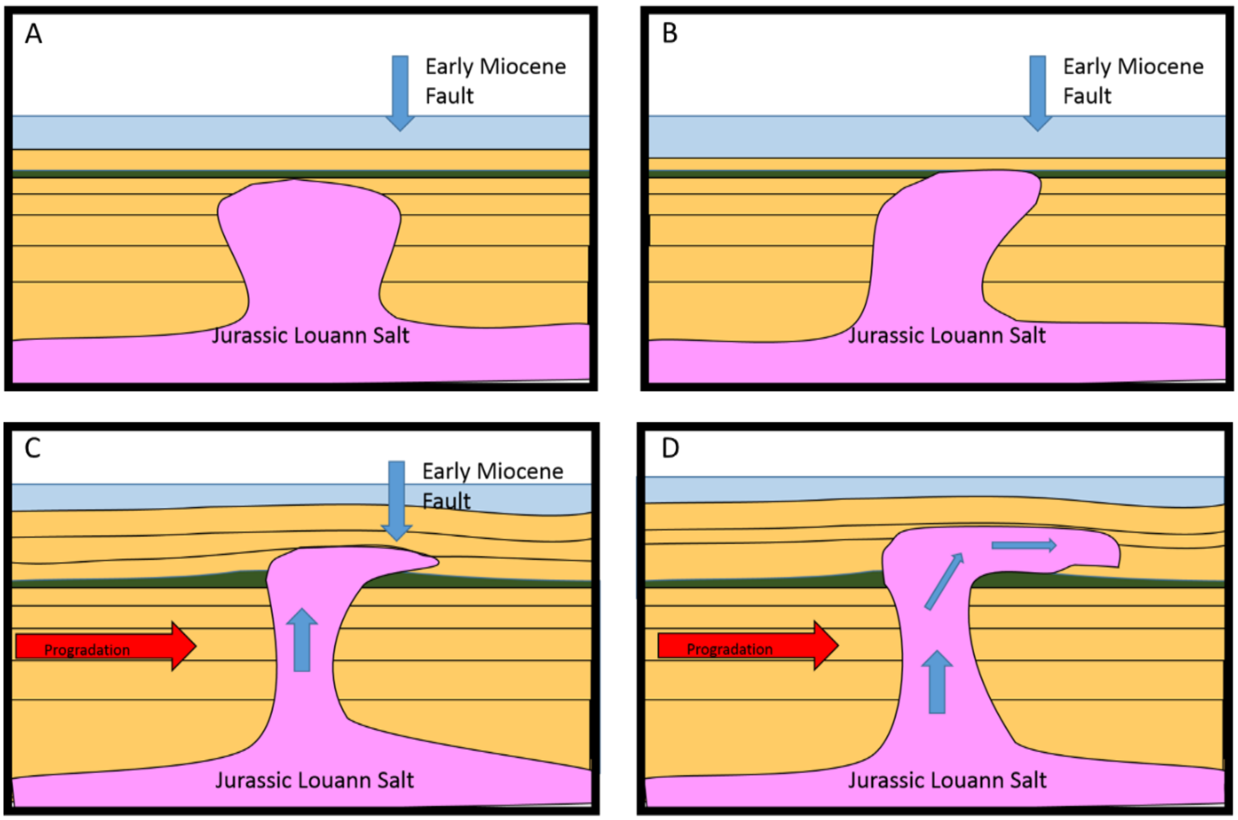


FIGURE 18 - A. SALT RISES BUOYANTLY FROM CONTINUED PROGRADATION. B. SALT PIERCES THROUGH THIN MIOCENE LAYER. C. CONTINUED SEDIMENTATION CAUSES LATERAL SPREADING. D. SALT NAPPE GROWS THROUGH CONTINUAL DIAPIRIC SUPPLY. (MODIFIED FROM HUDEC AND JACKSON, 2007)

Distally emplaced salt bodies move upwards from salt basement due to progradational loading, looking for the path of least resistance. In the case of our dataset, fine-particle Miocene deposits provide the perfect medium in which to move. Salt flows upwards towards the surface and breaks through at the soft, muddy Miocene horizon, most likely at a zone of weakness such as a fault (Figure 18). As salt rises it is met by more resistant sands above and spreads laterally in all directions. Salt beds that have been flattened by denser sediments above them, may still flow upwards as a diaper, through the overlying sediments (Wenkert, 1979) (Figure 19).

Once piercement has followed its way through faulting and into a softer, less compressible sediment layer, salt will flow plastically to fill accomodation space. When this space is filled, gravity will spread the salt laterally in all directions and as long as there is a feeder source, (such as a diaper or stalk), the salt mass will grow.

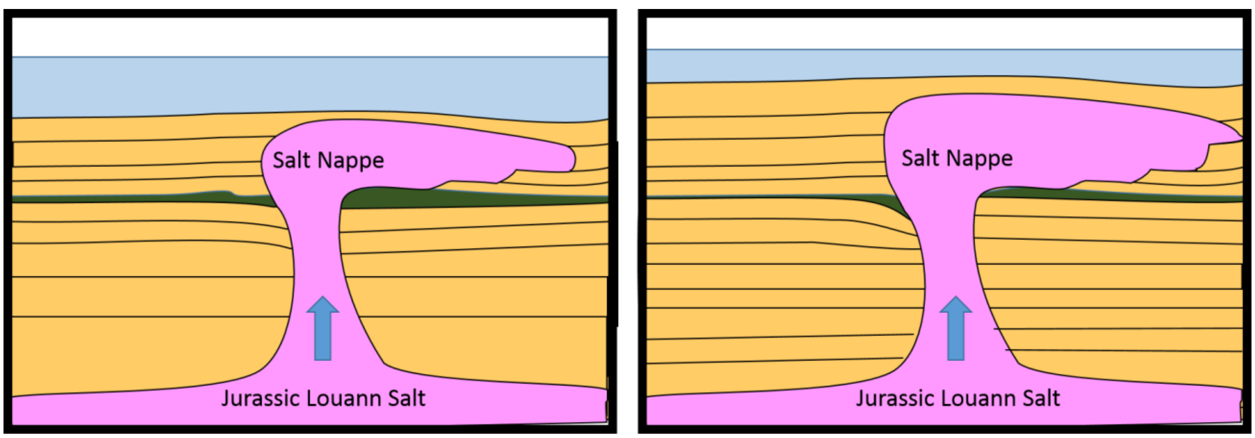


FIGURE 19 - SALT NAPPE GROWS BASIN WARD AWAY FROM DEPOSITION AND UPWARD DUE TO CONTINUALLY FED DIAPIRIC ACTION (MODIFIED FROM HUDEC AND JACKSON 2007).

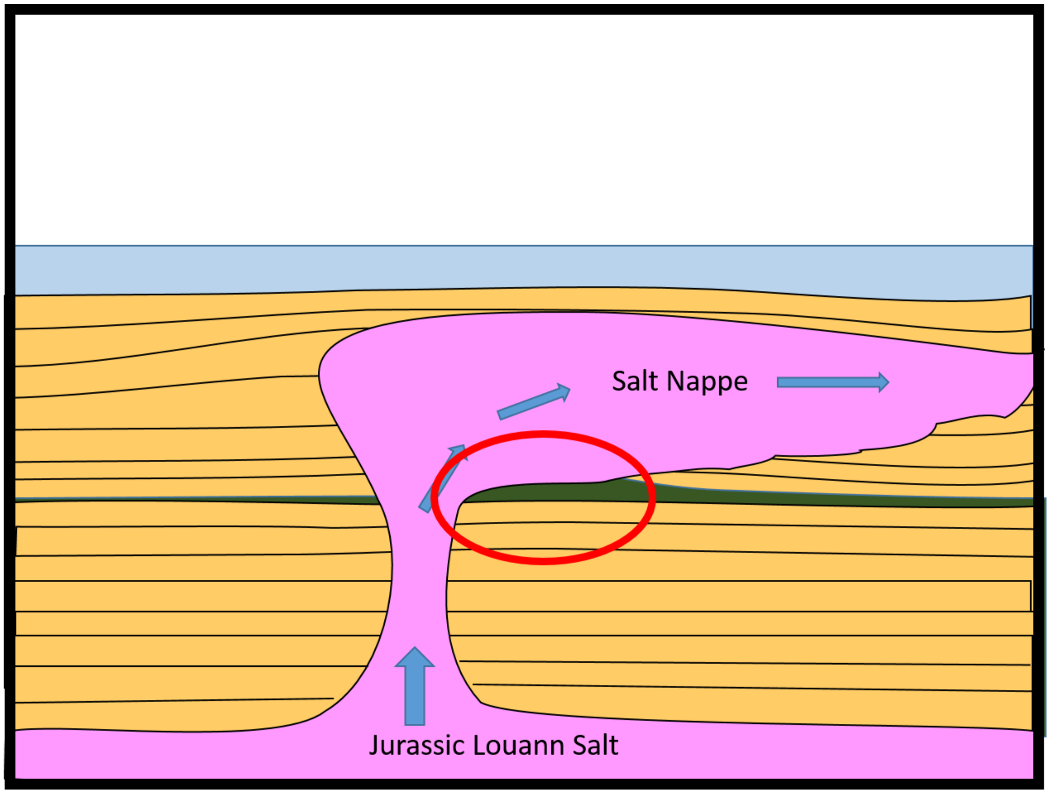


FIGURE 20 - SALT NAPPE WITH COMPACTED AREA UNDER MIOCENE CIRCLED IN RED, SIMILAR TO THE CHARACTERISTICS OF OUR STUDY AREA. (MODIFIED FROM HUDEC AND JACKSON, 2007)

A typical basin-ward salt intrusion follows a simple stepped pattern, which consists of a series of ramps and rises (Figures 20, Figure 21), away from the sediment loading (Pindell, 2007). Occasionally, this salt mass will flow or creep as does an ice glacier. This glacier can pick up chunks of sediment and rock as it moves slowly upwards, leaving behind sharp erosional features in a channel-like structural pattern, closely resembling the Arêtes and hanging valley of a glacier. Our complex structure is remnants of exactly that, a subsurface salt glacier.

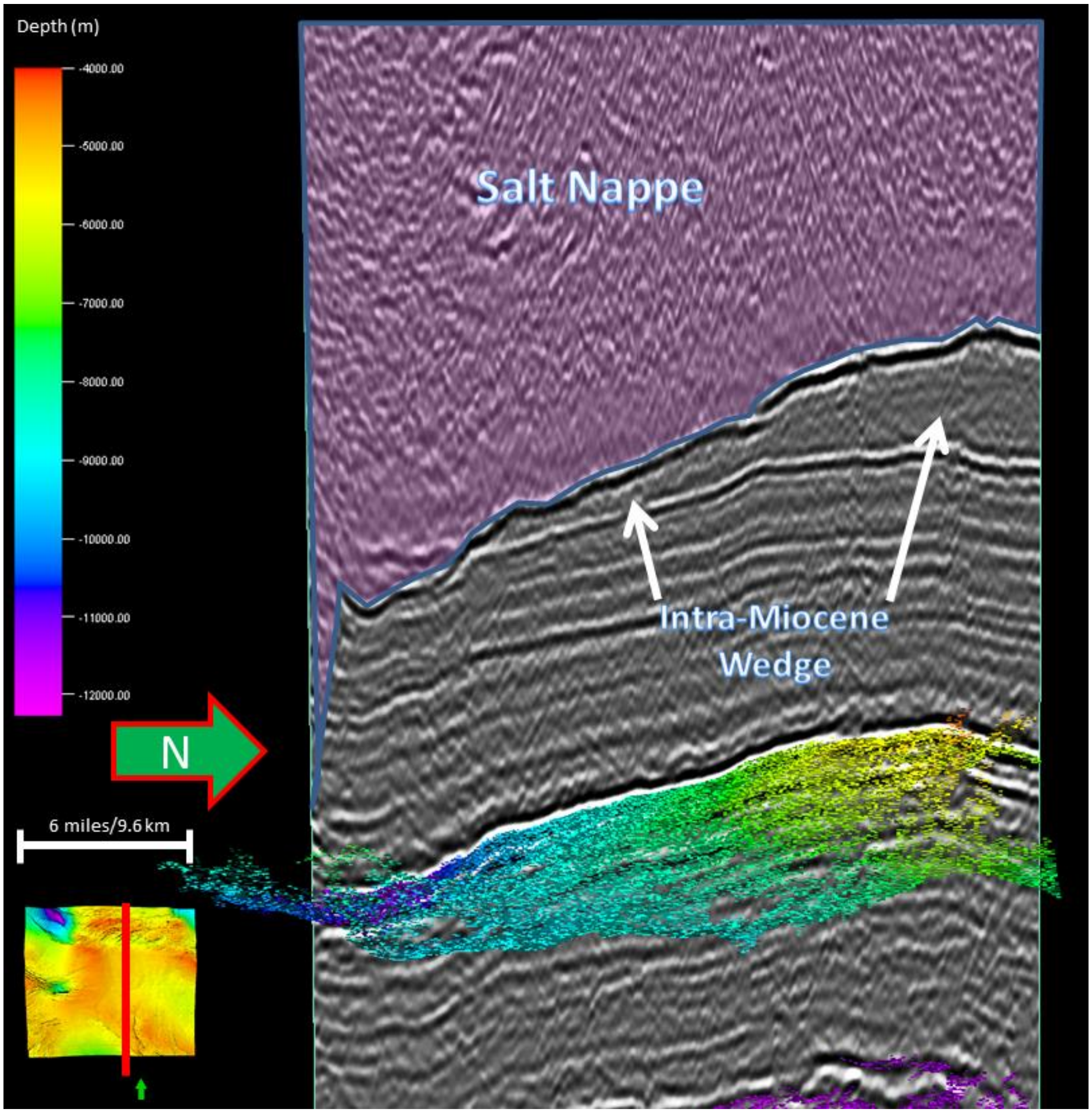


FIGURE 21 - SEISMIC INLINE FOR COMPARISON BETWEEN ABOVE SALT NAPPE DIAGRAM AND OUR INTRA-MIOCENE WEDGE FORMATION.

Salt Glaciers

Glacial movement of ice is controlled by gravity and internal deformation. Ice flows plastically at depths greater than 160 ft., (50m) (National Snow & Ice Data Center, 2015) just as salt flows plastically under compaction (Hudec, 2007). Salt glacier movement is controlled by bouyency and salt supply. When salt masses are more bouyent than their surrounding rock, they want to travel upwards and will migrate toward the path of least resistance, such as a fault.

In both ice and salt glaciers, there are certain comperable scars left behind in the sediment below. While Ice Glaciers are typically flowing downward and retreating, salt glaciers can move upward as long as there is a sufficient supply of salt through active diapirism (Hudec, 2007). This causes the similar structures to appear in opposite directions (Figure 22, Figure 23).

Not every characteristic from Ice glaciers is prevalent in salt glaciers, such as Cirques and Tarns. However features such as hanging valleys and Arêtes are clearly visible in both the diagram and interpreted horizon.

In the case studied here, piercement takes place in the early Miocene, through distally deposited marls and siltstones. The continuous supply of compacted rising salt forces its way through this layer, dragging with it pieces of sediment and rock.

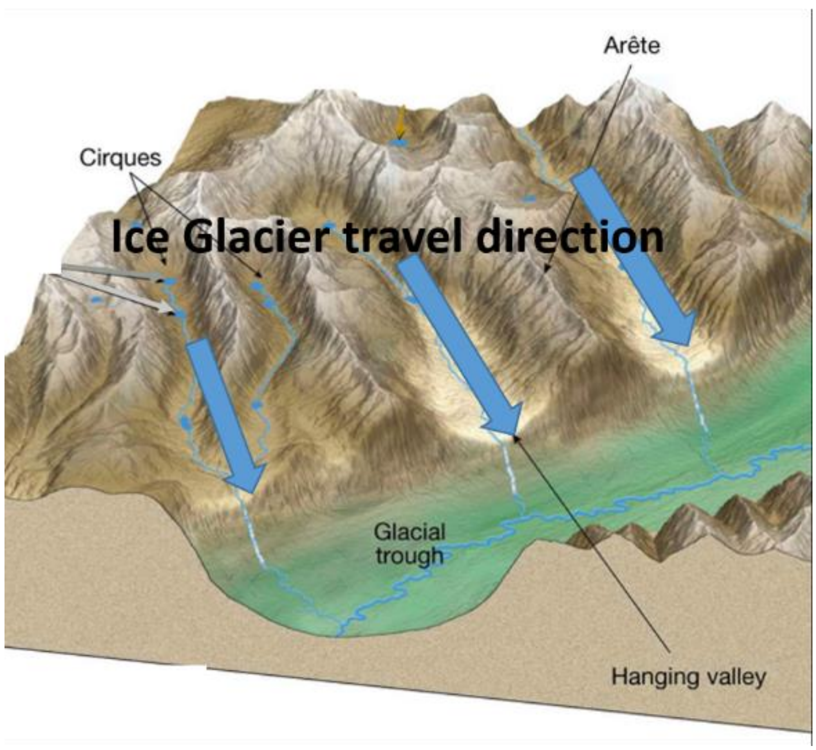


FIGURE 22 - DIAGRAM OF SCARRING LEFT BEHIND BY GLACIAL MOVEMENT. GLACIAL TROUGH, ARÊTES, AND HANGING VALLEY CAN BE COMPARED TO SALT GLACIER SCARRING BELOW. ARROWS DENOTE ICE FLOW (ONLINE IMAGE ARCADE (HTTP://IMGARCADE.COM/1/GLACIERS-DIAGRAM/ , 2015)

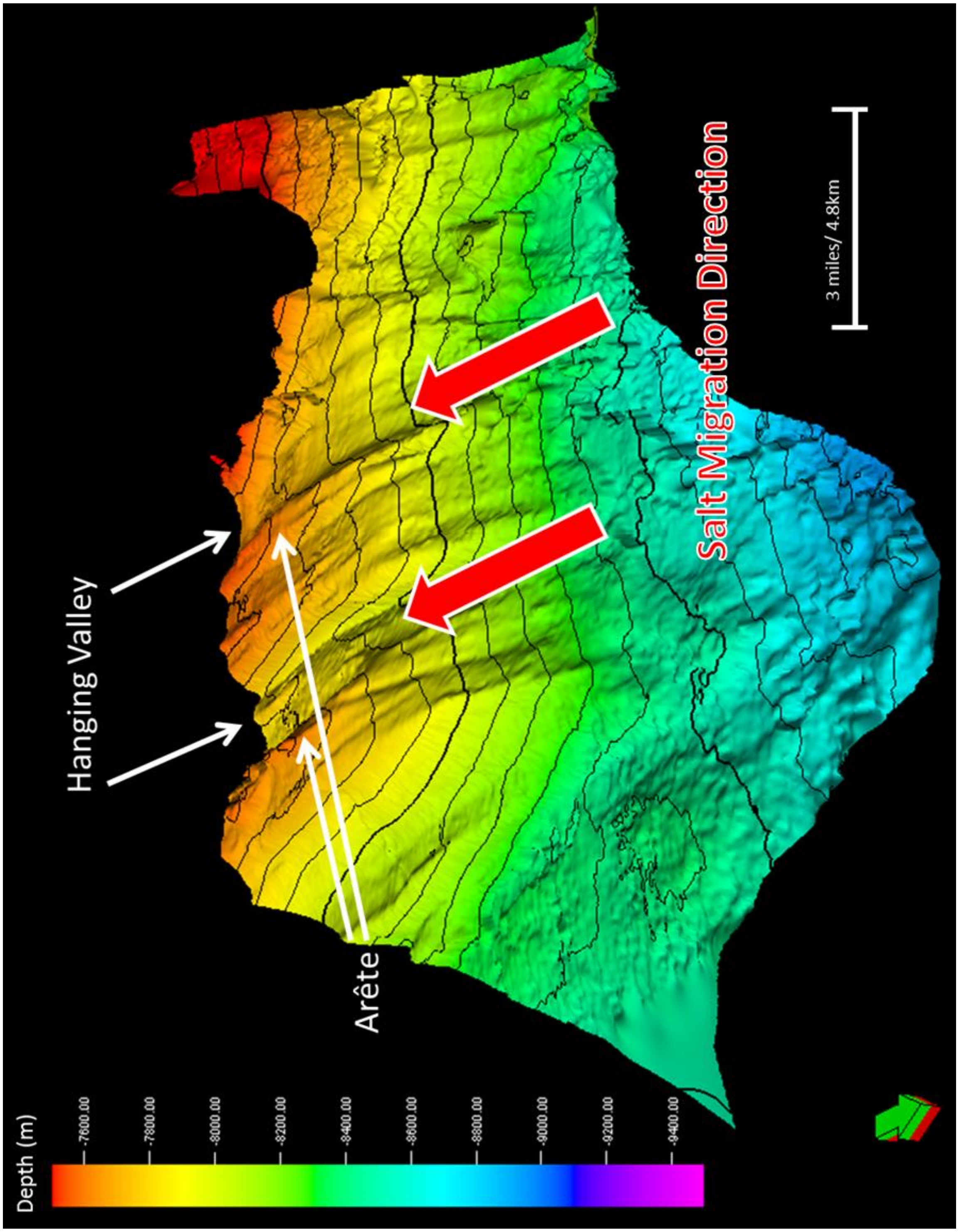


Figure 23 - Petrel image of Base of salt. Features shown in previous diagram of ice glacier are evident in this horizon, Hanging walls and Arêtes being most noticeable.

Results

Utilizing well log information from KC102, horizons were picked in the 3D seismic, to represent several different depositional phases and times. These surfaces were combined with well top information in ASC format. The uppermost interpreted layer represented in this study is the base of allochthonous salt and the lowest interpreted surface represents the Cretaceous. Depths of horizons have been determined for the Eocene A, Eocene B, Eocene C and Paleocene, all of which are Wilcox aged deposits. Salt breached the Miocene horizon (Figure 6).

The angled surface referred to here as the top of wedge, represents the interface between the bottoms of the allochthonous salt body that rests atop lower Miocene deposition. The base of wedge consists of Oligocene deposits. Allochthonous Louann Salt began migration in mid-Miocene. The Rising salt diaper pushed upward through the faulted Miocene layer leaving behind glacier like stratifications in the sediment atop this early Miocene deposition. Strike runs E to W and dip is Northward at 30°. The thinnest area of formation is to the north while the thickest is at the southern portion of the data set. This can be observed in well KC 102, where the thickness between BOS and Lower Oligocene ranges from 800 m to 200m.

After careful analysis of the channel like structures at the BOS for KC102, it was determined that the observed structure was in fact not channel like at all. First and foremost, the angle of dip was facing the wrong way. In addition, channel structures have a meandering path that dips in the direction of travel and gets wider at the bottom, which was not observed in the data.

The Intra-Miocene wedge has extremely straight channels, which are deep and widen at the top, indicating an upward travel direction. If incisions were made by a channel at any time in this structures life, the dip would be facing in the southern direction instead of due north.

The incisions are wide and smooth, almost flat in some areas, whereas fluvial incisions are v-shaped and would be much deeper at this 30° angle. There are also an undetermined number of sedimentary inclusions in the salt above. Salt glaciers, much like ice glaciers will pick up rocks and dirt, (glacial till) and instead of depositing it somewhere down the line it will stay folded in the salt column and continue to move with it (Figure 24).

The peaks atop of the glacial gouges are pointed in an almost knifelike ridge. This formation is called an Arête, which is French for edge or ridge. These points appear on the seam between two glaciers, on the rocks separating the two valleys. Rising from a depth of ~30,000 ft., this salt intrusion rode on top of the Late Miocene sedimentary deposits, weighing down the underlying sediments with the full force of 17,000 feet of salt.

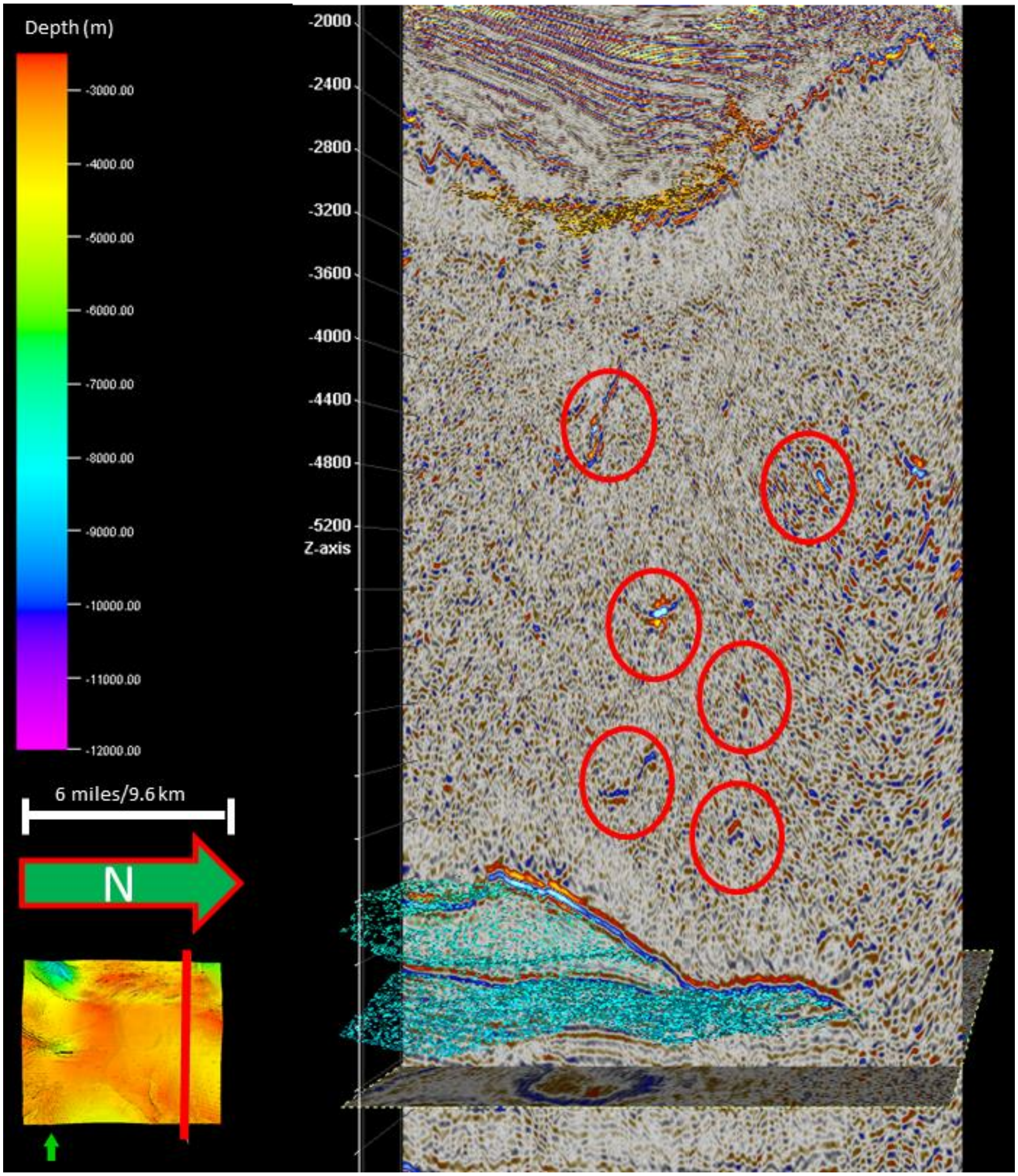


FIGURE 24 - HIGH REFLECTANCE SEDIMENTARY INCLUSIONS IN SALT ABOVE STRUCTURE. BELIEVED TO BE SEDIMENT AND ROCK PICKED UP BY SALT MOVEMENT AND INCORPORATED INTO SALT BODY MUCH LIKE GLACIAL TILL.

Channel-like morphology on BOS displays characteristics of a salt glacier and amalgamated pieces of rock with high reflectance can be seen trapped in the salt above. Salt tectonics plays a large role in the formation of this structure. Basin-ward progradation of sediments during the late Tertiary created an overburden pressure above the autochthonous salt formations and salt moved upward through a small fault, necking into the above layers of younger sediment. These sediments alternate between fine-grained silts (shales) and larger grained sandy deposits.

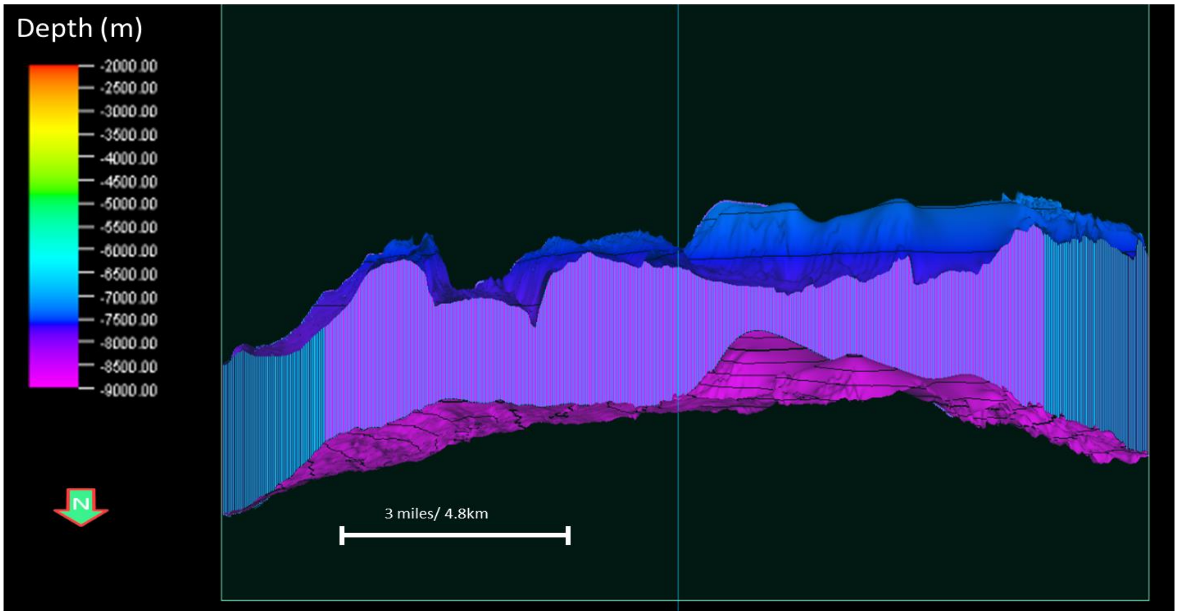


FIGURE 25 - CROSS SECTION OF INTRA-MIOCENE WEDGE FORMATION, FACING SOUTH. THE BLUE LINE IN THE CENTER OF DIAGRAM REPRESENTS THE KC102 WELL LOCATION. LOWER HORIZON IS THE TOP OF OLIGOCENE. THICKNESS AT WELL IS APPROXIMATELY 5000FT.

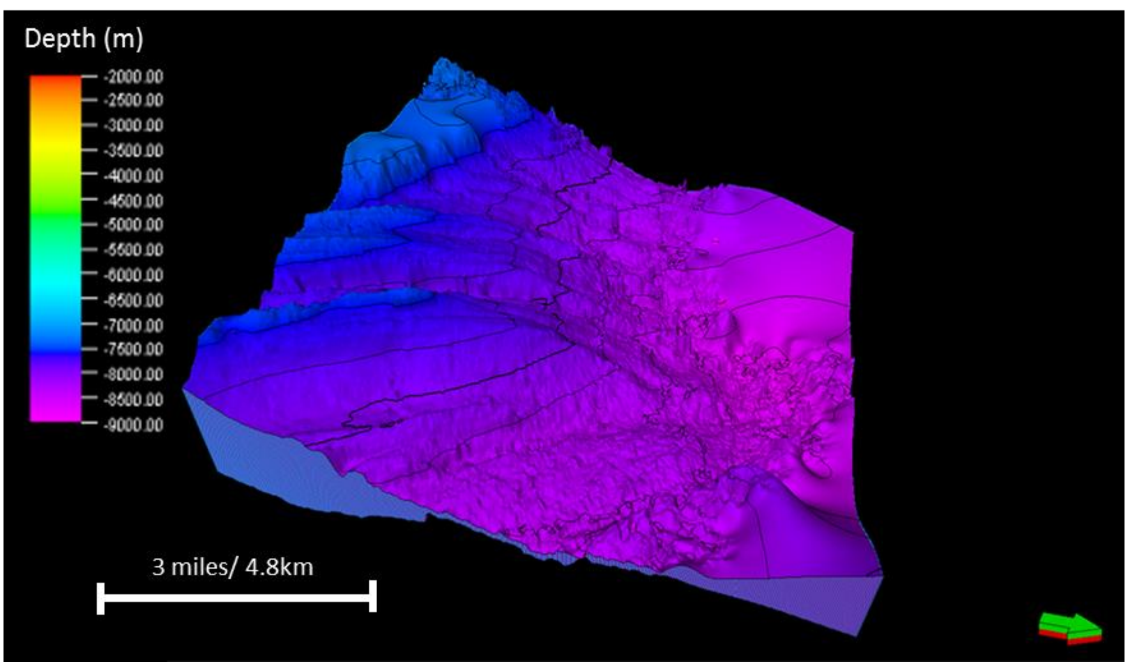


FIGURE 26 - SIDE VIEW OF INTRA MIOCENE WEDGE SHOWING CHANGE IN THICKNESS FROM SOUTH TO NORTH

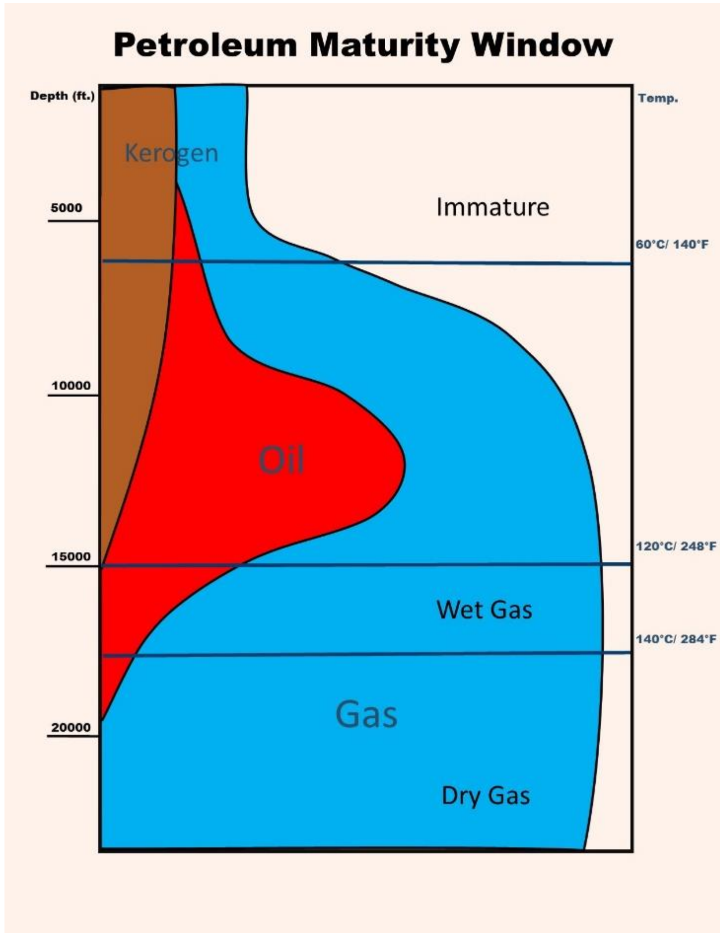


FIGURE 27 - STANDARD OIL AND GAS RESERVOIR MATURITY WINDOW. (MODIFIED FROM WEST, 2014)

CHAPTER 2 - WILCOX

The Texas coastal Wilcox group records the change from Cretaceous carbonate reef deposits to a thick clastic sedimentary base, driven by the Laramide uplift. Marked progradation of the shelf edge and the first fluvial systems in the GOM, including deltaic and coastal systems (Mackey, et al., 2012), are buried beneath several km of sediment and have been recorded within the Wilcox group. Comprised of mostly Upper Paleocene and Mid-late Eocene sands and muds, the deepwater trend covers~30,000+ sq. miles and wells target depths ranging from 12,000 to 35,000 ft. Extensive salt canopies cover roughly 90% of the trend and carry thicknesses from 7000 to upwards of 25,000 ft. Over 20 wildcat wells have been drilled inside the Wilcox extent uncovering 15 discoveries with the potential to recover between 40 and 500 MMBOE (Lewis, *et al*, 2009). Overlain by thick Reklaw shales, these same lower Tertiary turbidites have also been documented 200 – 300 miles east in new exploration wells, furthering the reach of this fruitful trend (Rains, 2007).

Source rocks for the Wilcox are Upper Jurassic (Tithonian) in origin and consist of tight shales (Swanson and Karlsen, 2009). The geothermal gradient for Wilcox wells, puts the reservoir within a safe range to deter degradation while Tithonian source rocks can be traced back to within the oil and gas maturity window for generation (Figure 27). Viscosity varies vertically and laterally within individual structures, suggesting complex filling histories and fluctuating sand quality. The average API is between 22-41° (Rains, 2007), which puts resources in the medium to light crude oil category.

With generally low permeability and porosities between 15% - 25%, Wilcox reservoir rocks are described as, fine-grained massive sandstones that are both lithic-rich and thinly interbedded (Lewis, *et al*., 2009). Divided into the Upper and Lower Wilcox, grain size in the Upper Wilcox is characteristically very fine, ranging from coarse silt to fine sand and generally poorly sorted.

TABLE 3 - CHARACTERISTICS FOR UPPER AND LOWER DEEPWATER WILCOX

Deepwater Wilcox Characteristics Upper Wilcox: Eocene A, B	
1	Unconfined inner, middle and outer distributary fan.
2	Tractional Facies with higher permeability
3	Compaction of ductile grains
Lower Wilcox: Eocene C and Paleocene	
1	Permeability is generally higher in channelized fan systems
2	Higher Quartzose content
3	Preservation of permeability and porosity by chlorite coating
4	Quartz grains display overgrowth from cementation

The Upper Wilcox sands are a product of unconfined deposition within the inner, middle and outer portions of the distributary fan system. Alternatively the deposition in the Lower Wilcox appears to be confined inside a channelized system, with higher permeability and relatively well sorted, coarser grained deposits (Table 3, Figure 28, Rains, 2007).

Of the challenges faced in exploration of the Wilcox trend, the logistics of drilling and maintaining a well in water depths of 4000 to 10,000 ft. can be quite intricate. There are very few rigs that can accomplish such complex drilling programs at such depths, and their availability can be very limited. Furthermore, until infrastructure can be established, production in any capacity will be very limited.

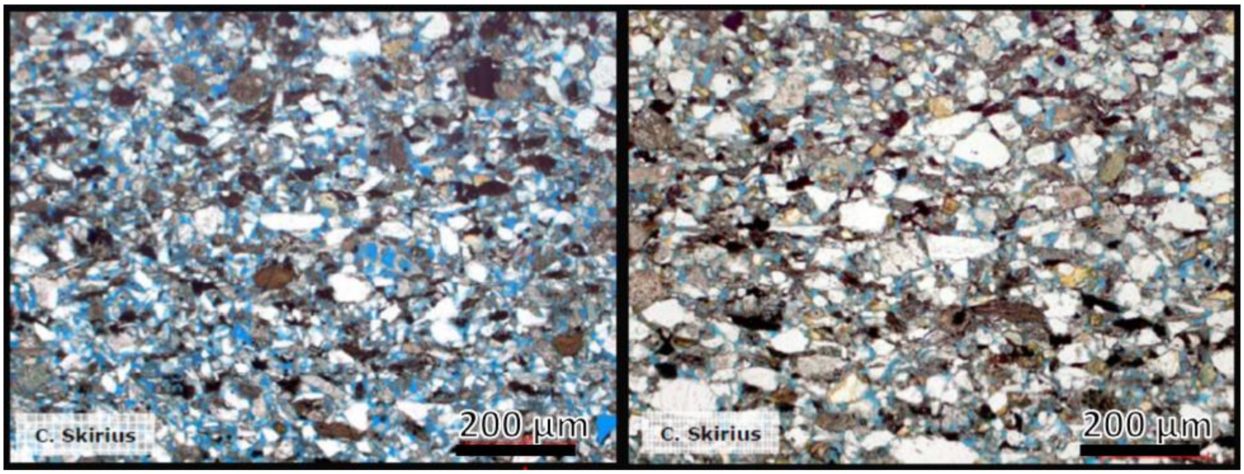


FIGURE 28 - UPPER WILCOX'S FINER GRAINED SANDS ON LEFT, COARSER GRAINED LOWER WILCOX SANDS ON RIGHT (MODIFIED FROM RAINS, 2007)

KC102 Well log analysis

Analysis of well log data from KC102 shows 17,000 ft. of salt over 4,000 ft. of layered sediment. Depths from 8300 to 9400m (27,300 to 30,800ft.) are Wilcox-aged sands of the Eocene and Paleocene. Strong Gamma and resistivity readings exhibit characteristics of intermixed sand and shale deposition with some carbonates, which are wet and indicate the presence of oil. This is a total of 3500 ft. of Wilcox sand present in KC102. In the Lower Wilcox, the upper and Lower Paleocene are full-to-base. The Paleocene 1 reservoir appears thin and found to have residual oil to base. Original Lower Paleocene reserves that were estimated between 125 and 450 MMBOE with a mean of about 280MMBOE, have now been reduced to a recoverable amount of between 100-250 MMBOE with a mean of 150MMBOE. Originally considered a Billion-barrel field, Tiber would do well to recover 400-500MMBOE.

Temperature Gradient

The Geothermal gradient for several KC wells has been calculated using borehole temperatures, from well log headers, and compared to a standard geothermal gradient of 1°F change per 100ft. depth change (below mudline). Temperature at the seafloor, (4100 ft. in KC102), was universal at 40°F. A temperature correction widget was utilized to find the true temperature from these log-derived readings (Max Tool Temp), which were logged while drilling. The formula for $T_{true\ is}$ as follows

$$T_{true} = T_{surf} + f * (T_{meas} – T_{surf}) – 0.00139(Z-4498)$$

Where;

T_{meas} = the measured log temperature (C°)

Z = the measured depth in meters

C° = surface temperature (here it was seafloor)

f = correction factor, a function of time since mud circulation (TSC)

Once temperature corrections were made in C°, temperatures was converted to F° and thermal gradient was calculated.

Geothermal Gradient = Corrected Temp. – Surface Temp. / Formation depth – water column

The temperature at the mudline (seafloor) was used for Surface Temp. In these calculations and the depth at mudline was used for water column. (Forrest, *et al*, 2007)

The data was plotted as depth vs. temperature. A trend line was calculated using this plotted data and the R^2 was compared to a standard line of 1.0 for each well. Typical thermal gradients for wells in this area range from 1.0 to 1.25. Wells for comparison were chosen according to thickness of salt mass and limited to the Keathley Canyon area.

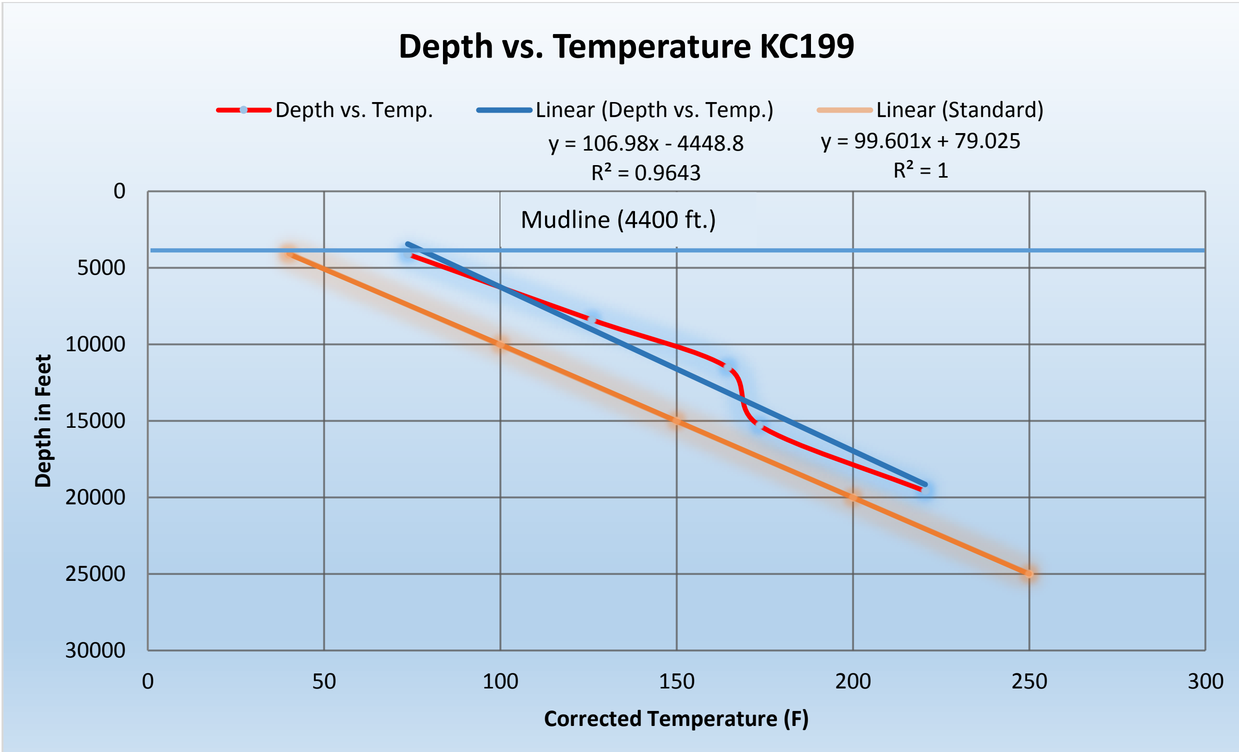


FIGURE 29 - DEPTH V. TEMPERATURE GRAPH FROM KC199 WELL LOG, LESS THAN 100 MILES FROM DATASET IN SIMILAR DEPTH WATER WITH 16,500 FEET OF SALT OVER WILCOX.

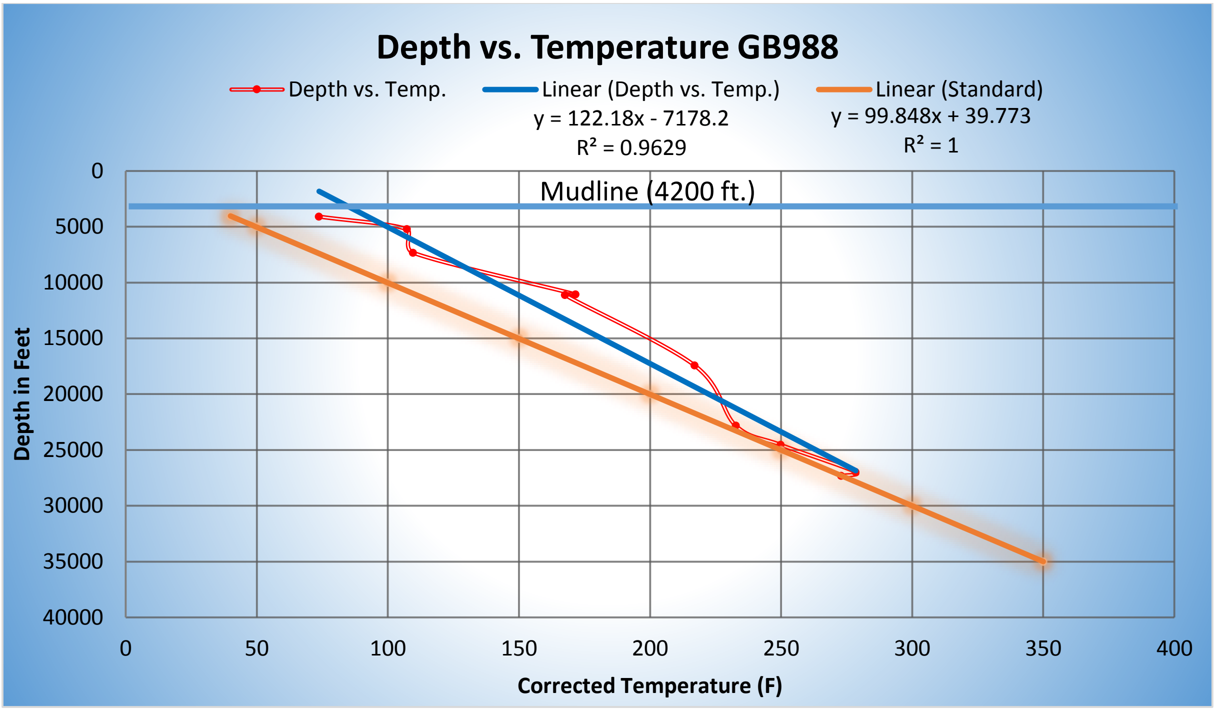


FIGURE 30 - DEPTH V. TEMPERATURE FROM WELL LOG OF GB988, LESS THAN 80 MILES FROM DATASET AND AGAIN SIMILAR WATER DEPTH AND SALT THICKNESS.

RMS

The Wilcox trend in KC 102 is divided into Eocene A, B and C and the upper Paleocene. RSM extractions of these layers provide an enhanced look at amplitudes for each specific layer by emphasizing the higher amplitudes and attenuating the lower amplitudes.

Using Petrel 2013, each RMS was calculated using the “horizon to horizon” method. By squaring the amplitude of the signals and calculating the square root of its mean, all of the negative signals will be filtered out. This method requires a base and top horizon (search window) and calculates the signal between the two. For the Eocene A RMS, Eocene A to Eocene B window was used. For the Eocene B RMS, Eocene B to Eocene C window was used, and so on concurrently through the Paleocene.

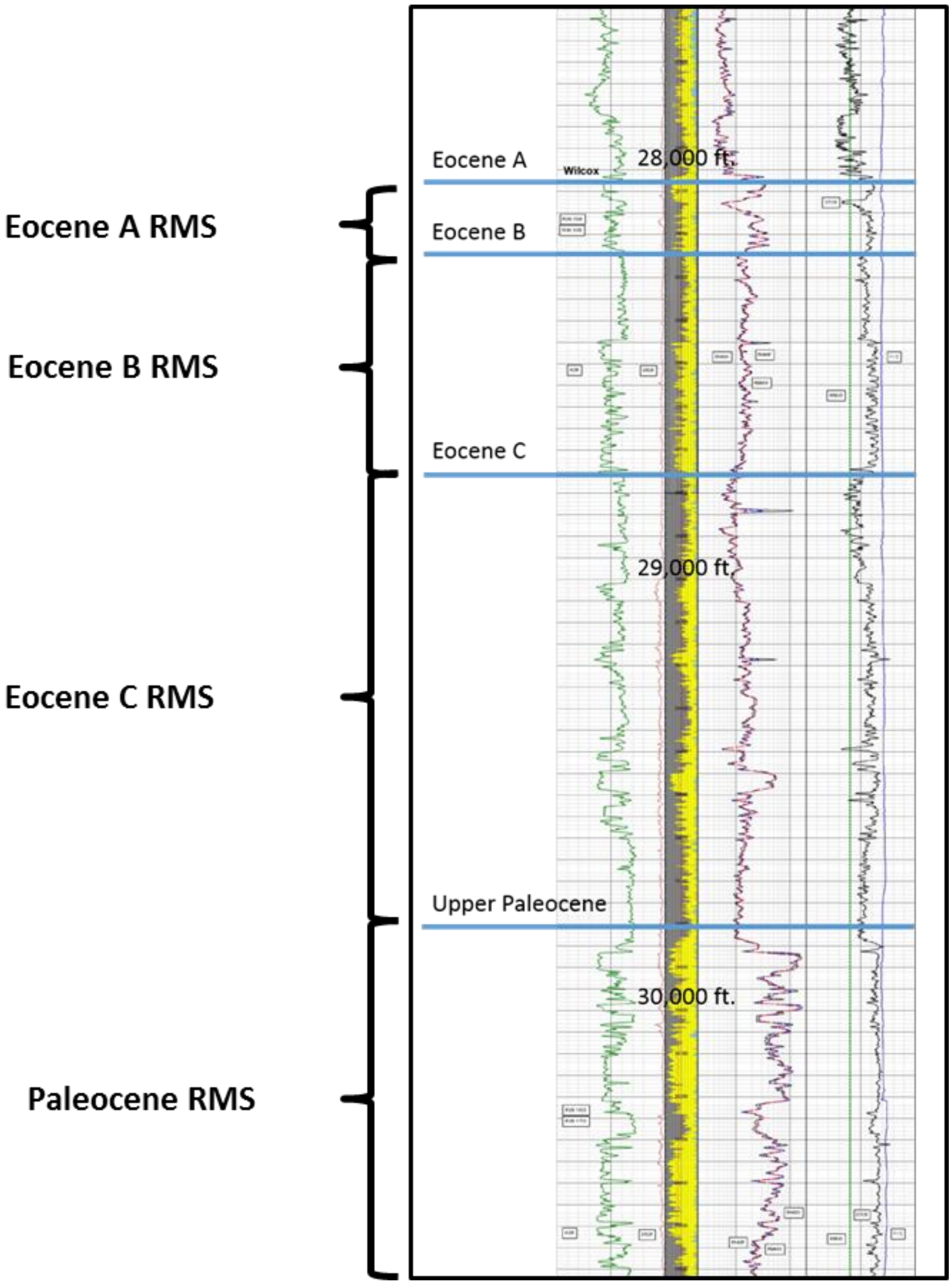


FIGURE 31 - COMBINATION OF HORIZONS USED TO INTERPRET EACH RMS EXTRACTION.

The surface input was entered for each and the program was instructed to calculate the signal from above the largest peak in the upper horizon, to below the largest peak in the lower horizon. This method isolates the signals between the two layers, filtering out negative signals and providing a positive amplitude base view of the area.

Extractions from Eocene A, B and C were also used in determining suitable drilling prospects inside the Wilcox area.

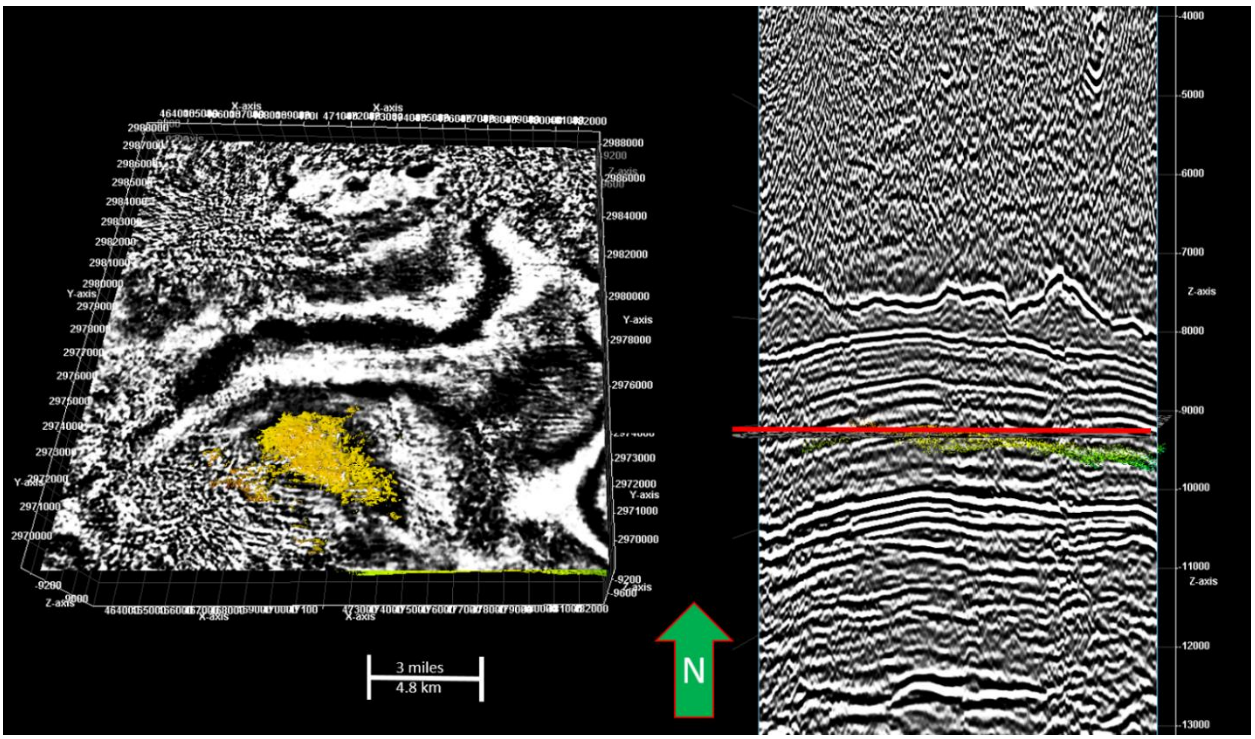


FIGURE 32 - DEPTH SLICE OF TOP OF PALEOCENE 29,855 FT. (9100M). DISPLAYS CLOSURE DRILLED BY KC102

Results

After a thorough analysis of data and analog information, the resultant interpretation of the Keathley Canyon blocks in question is as follows:

The Wilcox Tertiary sands indicated in the KC blocks provided within our dataset, possess all the necessary conditions to produce and trap hydrocarbon components within its structure. Preliminary findings from Offshore Drilling Scouts and Halliburton Drilling reports for KC102 consider the KC102 well as a production worthy well once infrastructure has been established. Still unconfirmed reports of less than satisfactory conditions at the KC57 site could be due to a number of different circumstances (KC57 well data has not been made available to the public as of publication date of this paper).

Seismic interpretation at KC102 shows a well-structured four way closure in the mid to lower Paleocene. Well completion reports note seven shows with substantial gas and oil levels between the 28,000 and 34,000 ft. zones. Mud logs recorded an oil/water ratio of 73/27 throughout.

While there has been no published biostratagraphic data for KC102, Regional Paleogeography acquired from BOEM/BSEE for wells GB988 (salt thickness of 16,350 ft.) and KC199, where similar salt and sedimentation conditions exist, confirm the existence of Danian Calcareous nanoplanktonic regional and local markers, *Globorototalia trinidadensis, Markalius inversus astroporus,* Thanetian *Fasciculithus tympaniformis* and *Subbotina pseudoboillides.* While not confirmed in the KC102 well it can be inferred, due to both the close proximity of wells and the depths in which the Paleocene markers are located, that they would be present in KC102 in the Paleocene Epoch, confirming geologic time of structure.

Well log and borehole temperature information for KC102 has been calculated and graphed (Figure 34, Table 4).

Table 4 - Well log data for KC102 Max Tool Temperature was corrected with Zeta ware tool and used to calculate Geothermal Gradient for well.

Generation	Temp.	Temp. C°	Depth	Corrected Temp. C°	Corrected Temp. F°
	40	4.444444	4100		65.6
	59	15	5322	22.54	98.172
	96	35.55556	5739	49.53	146.754
	96	35.55556	7430	28.99	109.782
Peak oil	120	48.88889	10999	64.92	174.456
	176	80	21091	101.76	240.768
	180	82.22222	22763	82.22	205.596
	194	90	26534	112.67	260.406
	204	95.55556	27340	119.67	273.006
End oil	183	83.88889	27473	104.19	245.142
	203	95	28177	118.58	271.044
	221	105	30241	130.92	293.256
Peak Gas	230	110	31111	137.16	304.488
	252	122.2222	31398	153.19	333.342
	257	125	33375	156.03	338.454
	271	132.7778	33815	166.12	356.616
	275	135	34473	168.78	361.404
	282	138.8889	34815	173.77	370.386
	296	146.6667	35050	183.95	388.71

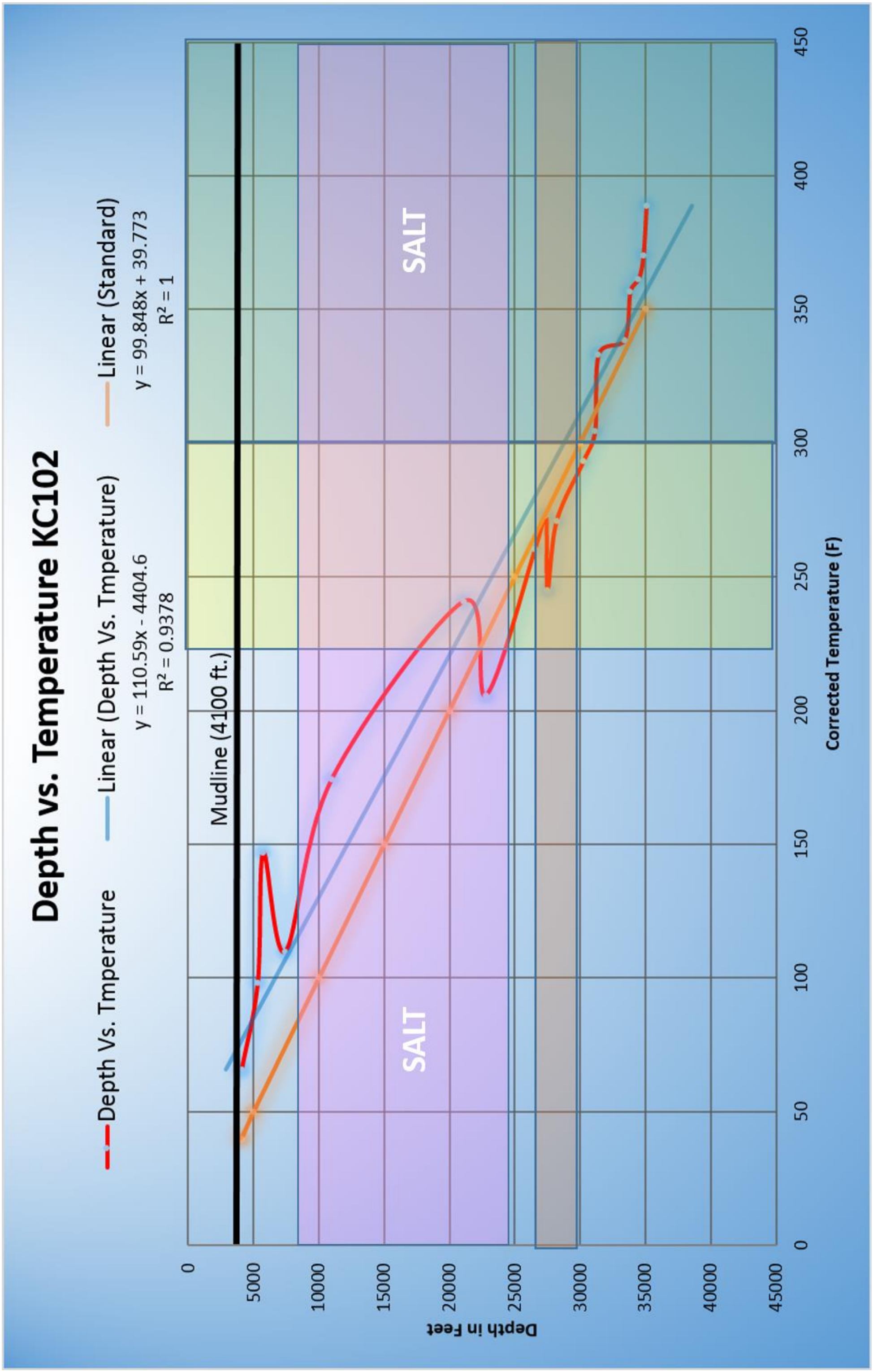


Figure 33 - KC102 Depth vs. Temperature. Well is within peak oil reservoir conditions. Red bar at 27,500 represents Wilcox aged sands. Green bog represents gas production. Pink from 8480 to 24980 represents salt mass above intra-Miocene wedge in KC102

Well temperature vs. depth shows a very close relationship to the normal geothermal gradient. Oil and gas maturity is shown in colored shaded areas on chart; transparent yellow from 157°F to 250° F represents peak oil production and the transparent red section at depth 27,500 represents the Wilcox thickness in the KC102 well. Reservoir temperatures in the Wilcox at KC102 are in the proper range for oil storage without degeneration or over-generation.

Source rocks for the Wilcox are Tithonian in age and located at approximately 39, 000 ft., 4,000 ft. out of the reach of our KC102 well. Primarily composed of Marls and carbonates, this rich rock source has TOCs between 10 and 15% (Stern, Dickenson, 2010). While the depth of Tithonian rocks are very difficult to attain, samples from seeps and a few wells east of the Mississippi river have been analyzed and found to be highly mature and organic rich (Hood, 2002)

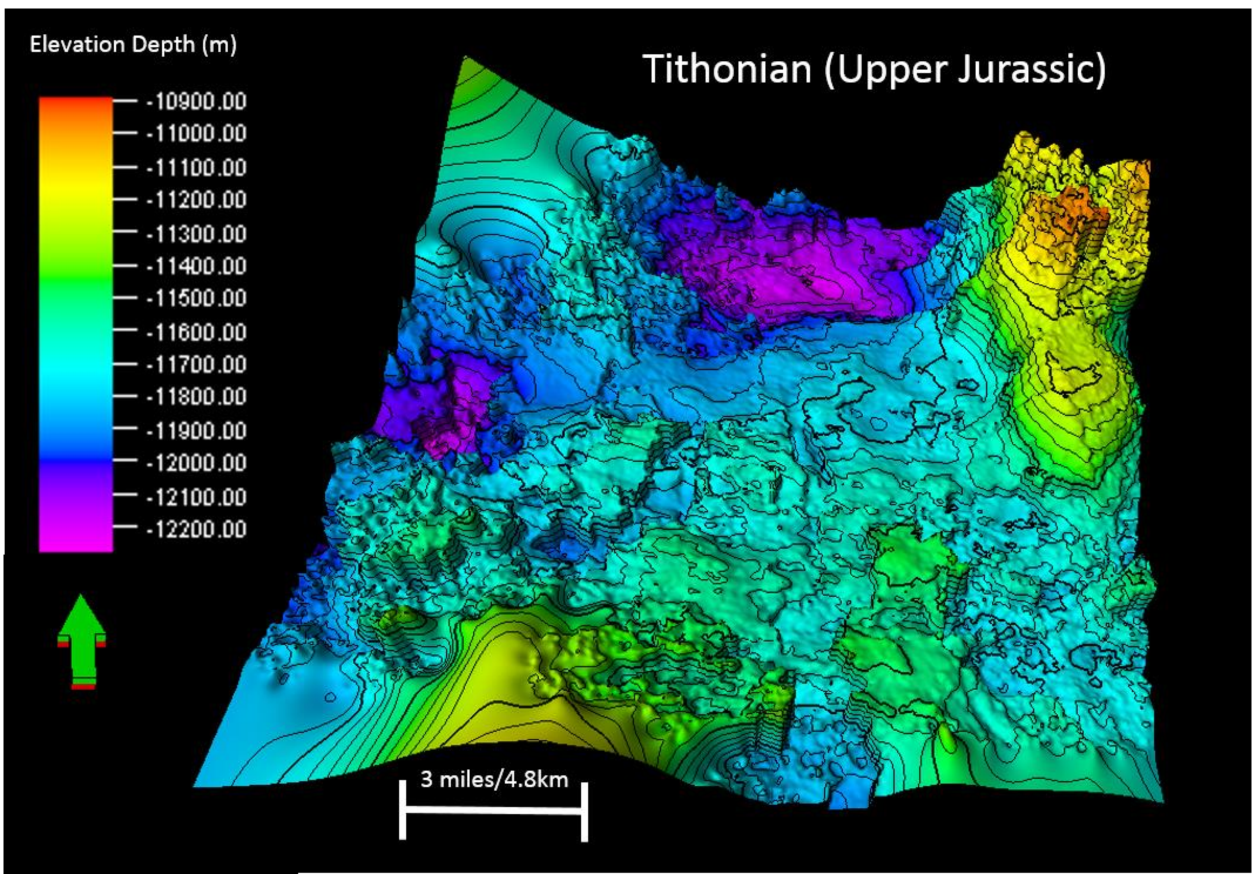


FIGURE 34 - MAP OF TITHONIAN (LOWER JURASSIC) HORIZON. CONSIDERED SOURCE ROCKS FOR DEEPWATER WILCOX FORMATION.

When calculating temperature gradients that extend into the Tithonian source rock, we can see temperatures in excess of 350°, which is considered too high for oil to retain its composition without degeneration. If we consider the placement of salt above, and understand that its migration took place during the Miocene, we can infer that without the overlain salt this late Jurassic horizon would have been at the appropriate depth for peak oil generation during that salt migration. The movement of this salt may have also been the migratory path that the oil followed to entrain itself in the Wilcox sands.

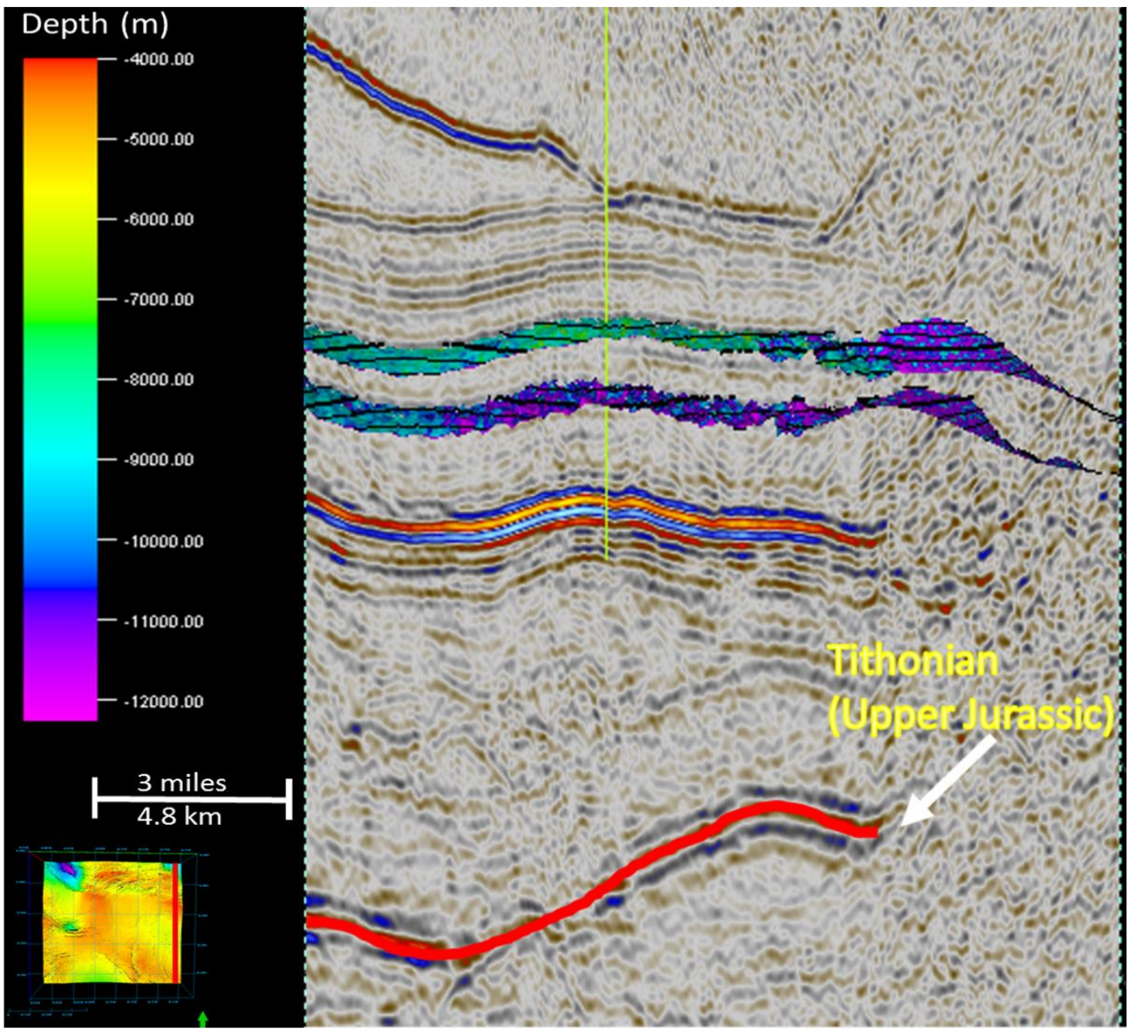
used 

FIGURE 35 - SEISMIC REPRESENTING KC59 WELL PROSPECT EXTENT INTO CRETACEOUS. TITHONIAN SOURCE ROCKS LOCATED BELOW.

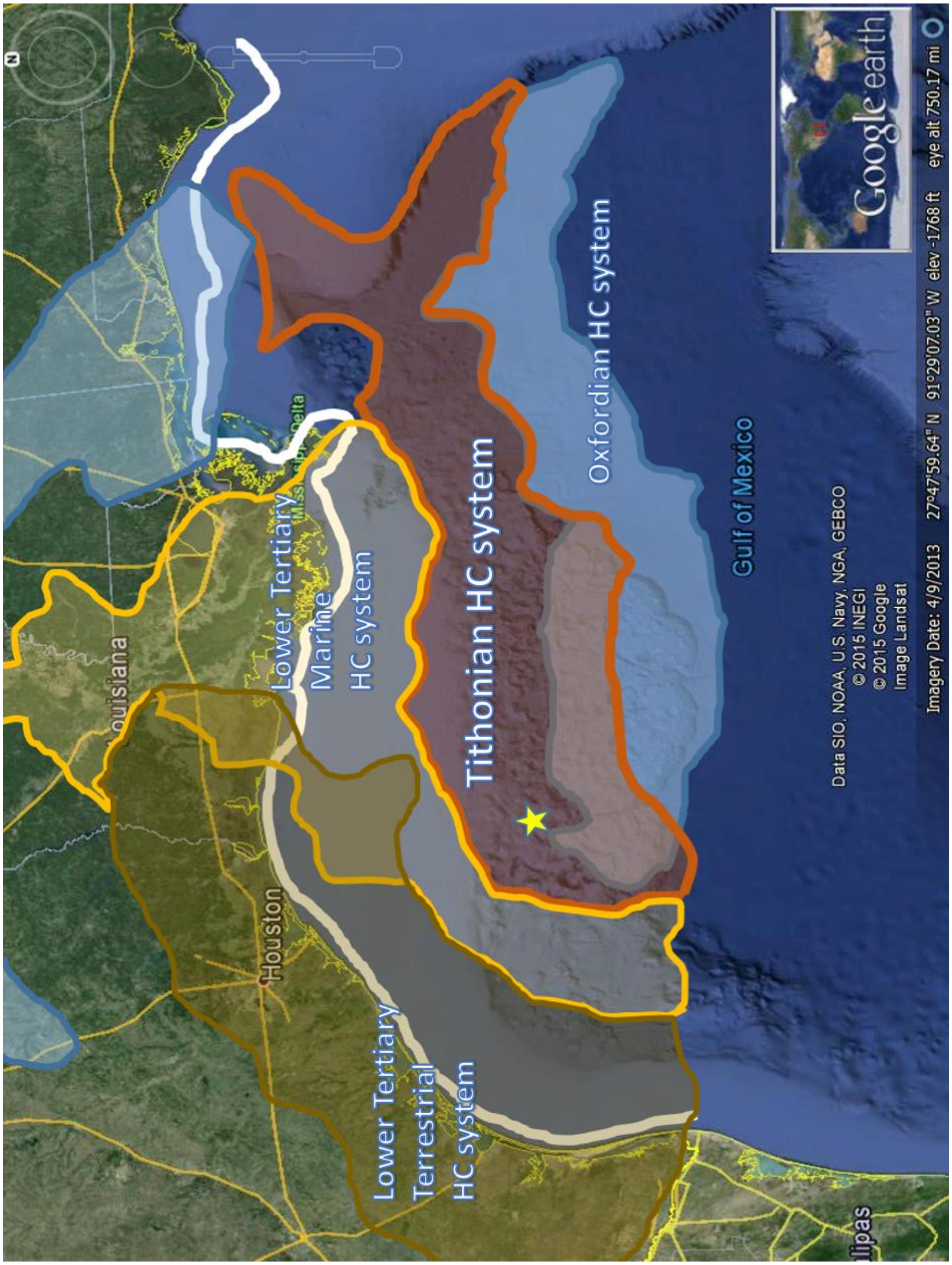


Figure 36 - Gulf of Mexico coastal regional map showing source rock locations for Tithonian, Oxfordian and Lower Tertiary. Star is KC102, inside Tithonian source region (Modified from Hood, 2002).

RMS Interpretations

RMS calculations for the Eocene Wilcox horizons A, B and C, reveal several high amplitude anomalies, which could be indicative of hydrocarbon activity. When observing the placement of wells 102 and 57, they appear to have been drilled in areas of higher amplitudes.

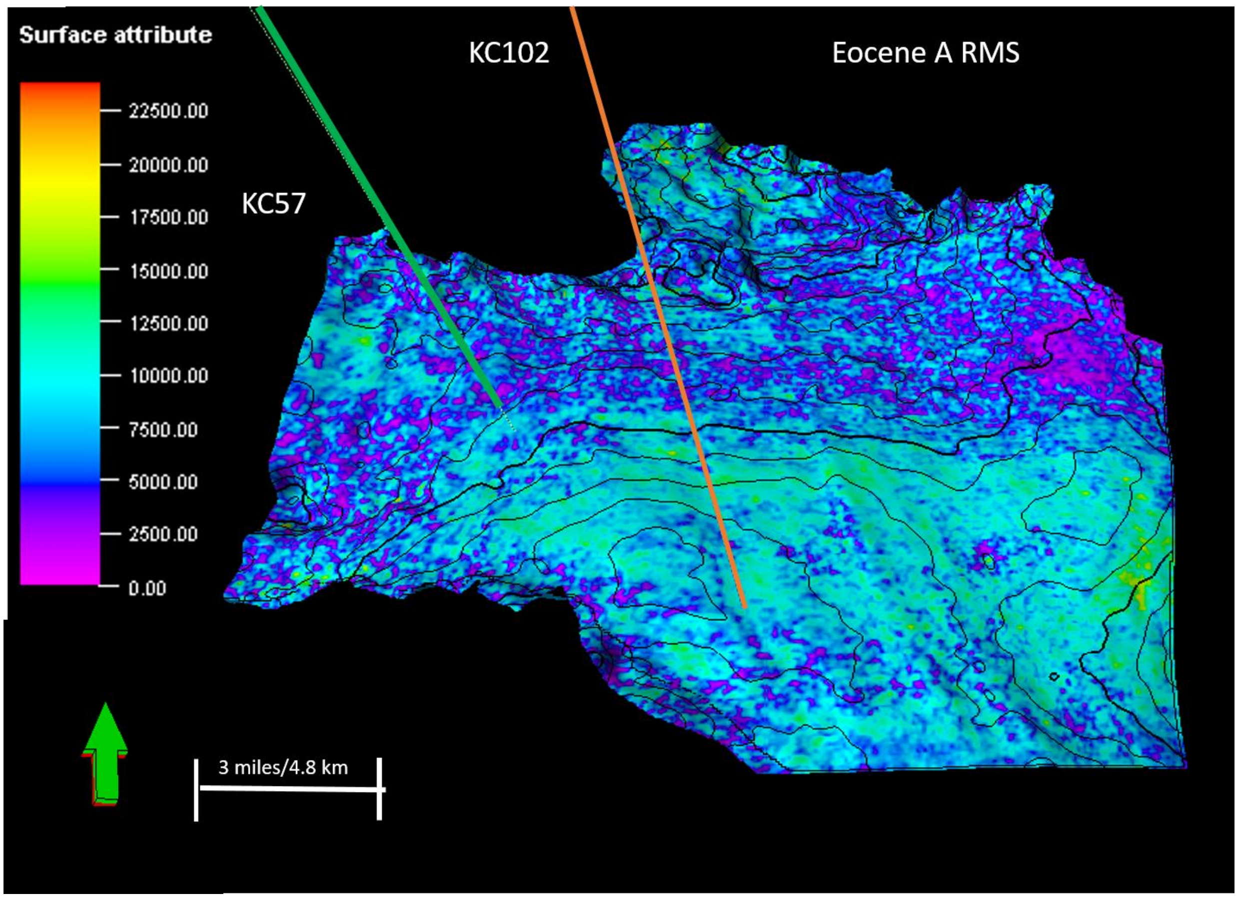


FIGURE 37 - RMS EXTRACTION FOR EOCENE A. SHOWS HIGH AMPLITUDE ANOMALIES SURROUNDING KC102.

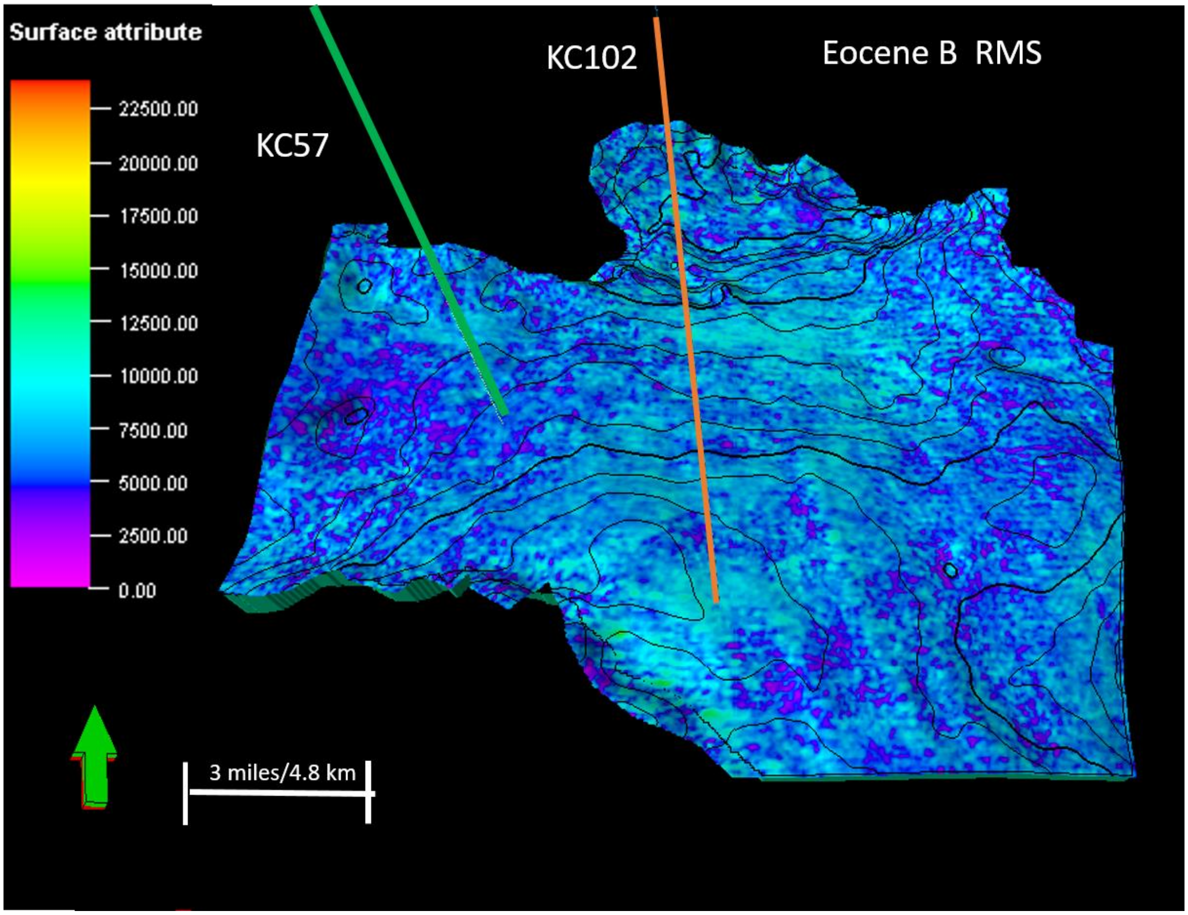


Figure 38 - RMS extraction for Eocene B, Noe high amplitude area at KC102 well penetration.

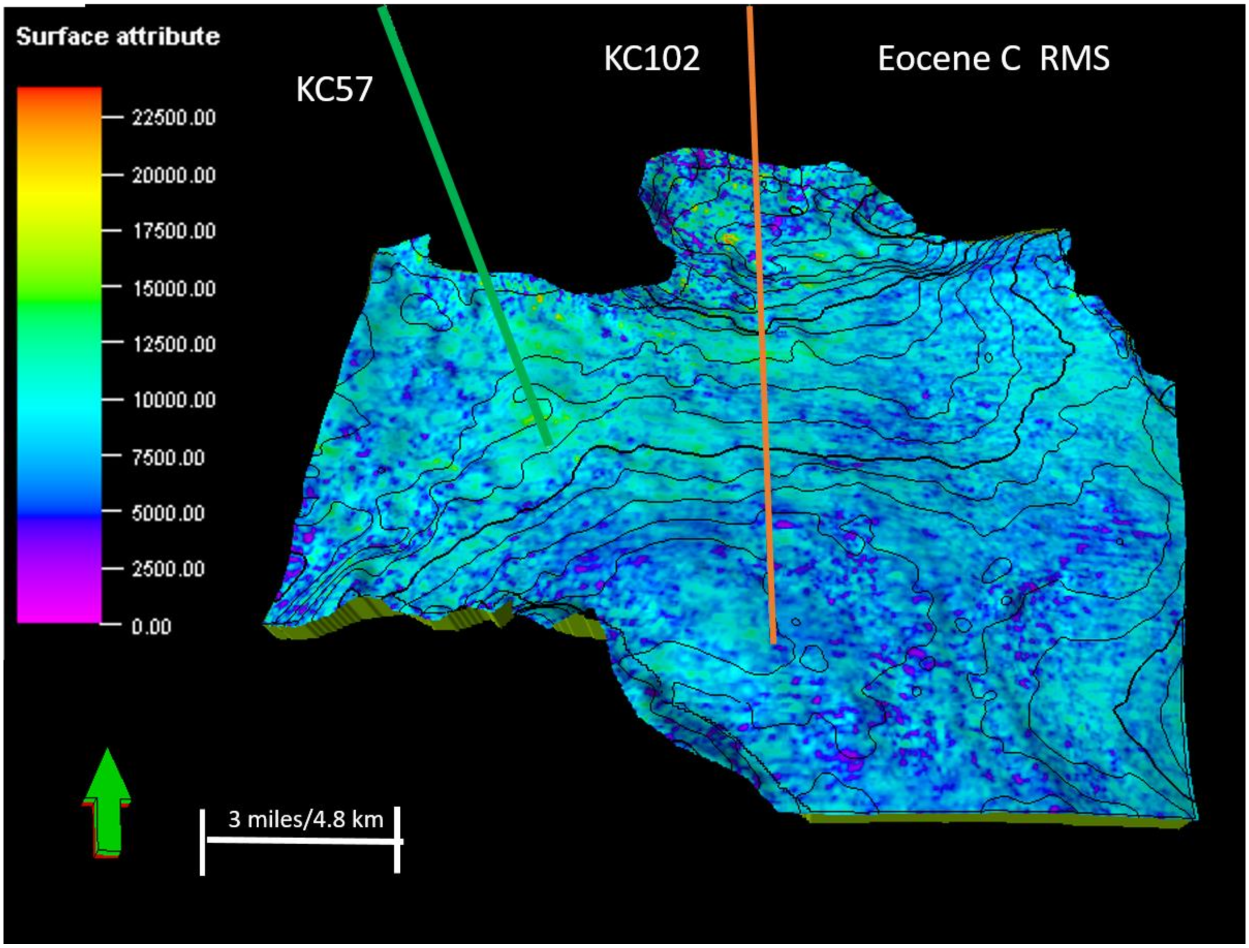


FIGURE 39 - RMS EXTRACTION FOR EOCENE C. MUCH HIGHER AMPLITUDE DOWN-DIP OF DRILL SITE.

The deeper Wilcox layers Eocene B and Eocene C (Figure 35 and 36), display higher amplitudes compared to Eocene A (Figure 34). Areas located farther up dip from the compacted northern edge, display the brightest amplitudes.

The Upper Paleocene RMS (Figure 37) displays lower amplitude than its upper Wilcox counterpart, which supports the interpretation of upwards hydrocarbon migration due to salt compaction on the northern edge.

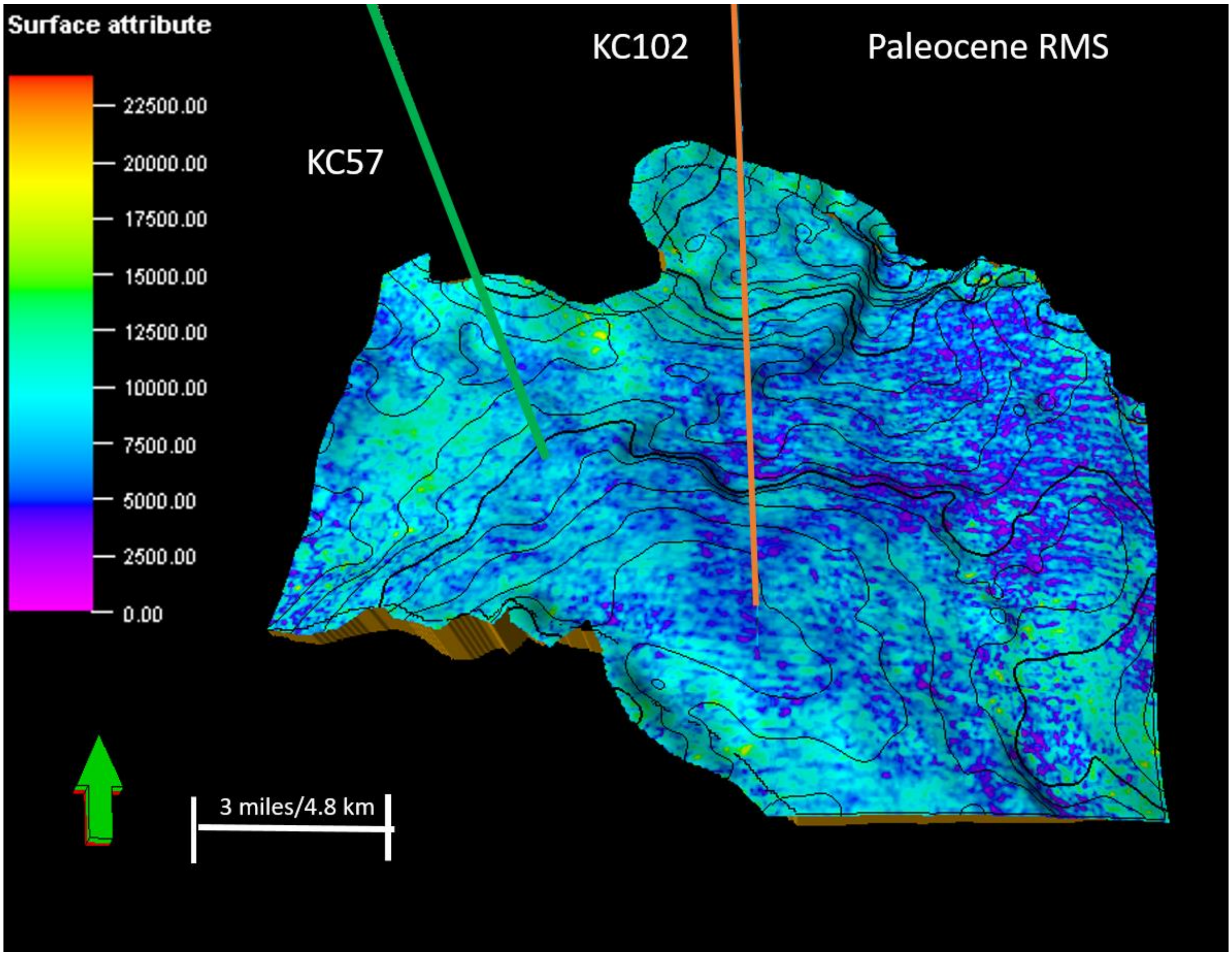


FIGURE 40 - RMS EXTRACTION FOR PALEOCENE. TROUGH OF HIGH AMPLITUDES RUNNING NORTHEAST FROM KC102 TO KC57, BUT UP-DIP FROM WELL LOCATIONS.

Dry Hole Analysis

While the Tiber well KC 102 has proven potential, other wells in this study area have had difficulties and therefore have reduced production potential estimates for the area. A complete dry hole analysis is virtually impossible to ascertain without the appropriate well log information, however we can make these qualifying judgements according to the scouting reports created by the Offshore Oil Scouts Association; KC 57s original hole was drilled too far down-dip and had been found completely dry due to an indicated stratigraphic complexity in the Upper Paleocene reservoir, where tight sands and non-reservoir siltstones were encountered. The area in question is located in an area where a tremendous amount of sedimentary compaction has occurred (Figure 41).

A second well, directionally drilled towards the up-dip, was drilled in search of some oil-water contacts. A solid OWC was found in the Eocene C and the highest known water was encountered in the Upper Eocene (combination of Eocene A and B).

While still under evaluation, this reservoir will not likely be considered an important part of projected reserves. As none of the Well or drilling data has been made available to the public, a better evaluation should be conducted in the future.

Discussion

Considering the dataset provided, covering blocks 12-15, 56-59 and 100-103 of the Keathley Canyon and 980-983 of the Garden Banks, several factors go into determining where future drilling should take place. For the purpose of this study, the results listed above were used to determine where suitable drilling conditions will exist, in order to maximize drilling potential.

Beneath the Miocene/Oligocene wedge discussed in Chapter 1, channel-like structures carved by salt should be considered a sound trap for hydrocarbon activity and migration. Features should be further explored on the up-dip side (southern border). Special attention should be paid to the blocks further south of studied structure, as the 30° angle of dips termination is unknown. Blocks KC 146 and 147 would be of primary interest in this venture as the Intra-Miocene wedge turns slightly in the Southwestern direction. Blocks 144 and 145 are located over an area of salt intrusion which appears to be a feeder for Jurassic salt, therefore less likely to possess Wilcox aged sands.

FIGURE 41 - KC BLOCKS OF INTEREST FOR FURTHER STUDY (COURTESY OFFSHORE OIL SCOUTS ASSOCIATION, 2015)

Scouting reports from the Offshore Oil Scouts Association do indicate well activity in KC 147, operated by BP. At a current depth of 30,790 ft., the salt structures thickness is similar to our study area at 18,300 ft. BP is not entirely excited about this discovery as it appears to hurt their reserve size. KC147 Wilcox sands are thicker and have oil in the C, the lower sands are thick and wet, and with some areas reaching up to 160 ft., overall summary of this report indicates that poor reservoir quality and sand thickness may be a problem for production out of KC147.

This narrows our well placement window to block 146, however without proper seismic data, an appropriate analysis for well location would not be precise. More information is needed to make that determination.

Within our dataset there are two points of interest for exploratory well locations. Points of interest are focused on Paleocene and lower Eocene reservoir locations.

Prospects

The previously drilled wells in the KC dataset have shown some degree of success and will most likely be viable for production in the near future. Two other locations have been determined as possible resources sand are still within our original dataset.

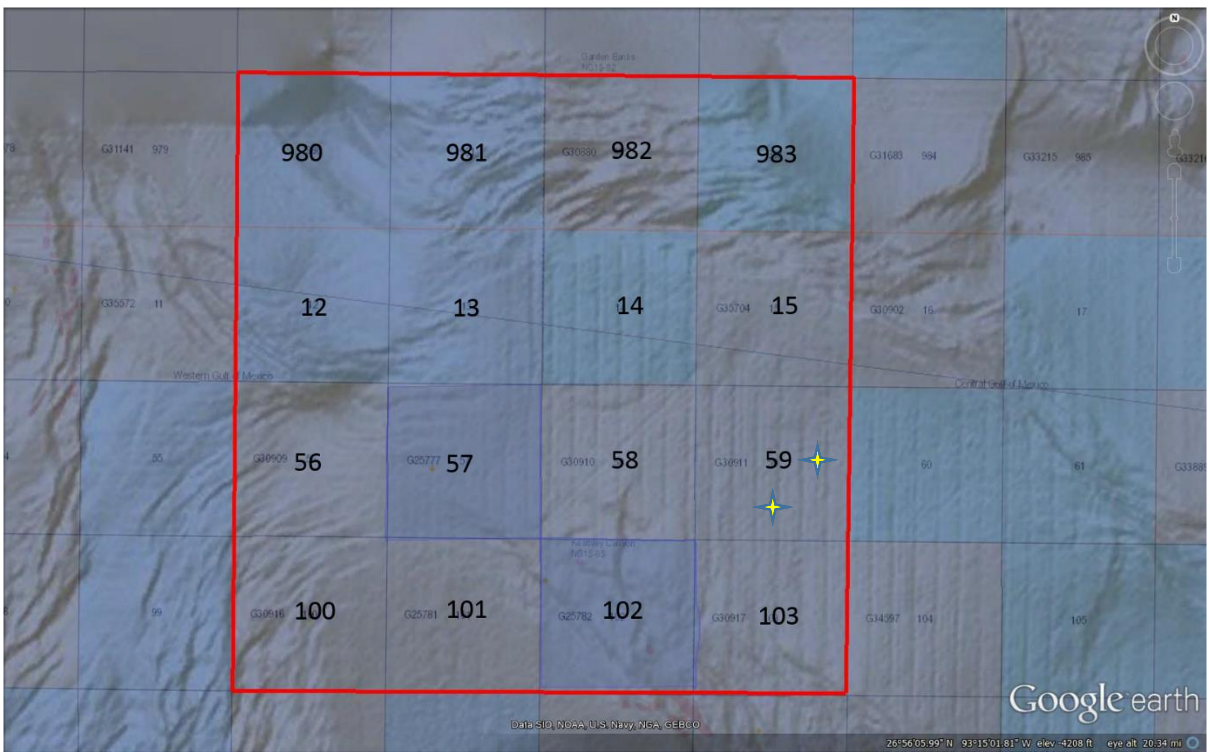


FIGURE 42 - KC BLOCKS WITH PROSPECTIVE DRILLING AREAS IN KC 59, FROM GOOGLE EARTH.

Both prospects are located inside KC 59 over the rising section of the intra-Miocene wedge, through 17-18,000 feet of salt and into the Wilcox sands, concentrating primarily on the Eocene C and Eocene A horizons. RMS extractions from these two horizons show high amplitude anomalies in the Eastern region of the area in Eocene C (Figure 44), as well as an attractive spike in the Eocene A (Figure 45). The Eocene B and Paleocene were not used in the Speculation of these prospects, however the B did show a rather high reading in the central area on the down dip side of the wedge. Sand quality and reservoir potential has been appraised as higher in the chosen horizons through scouting reports of wells KC57 and KC147. The same characteristics were considered in these prospective areas due to similar depositional patterns, burial history and preservation methods.

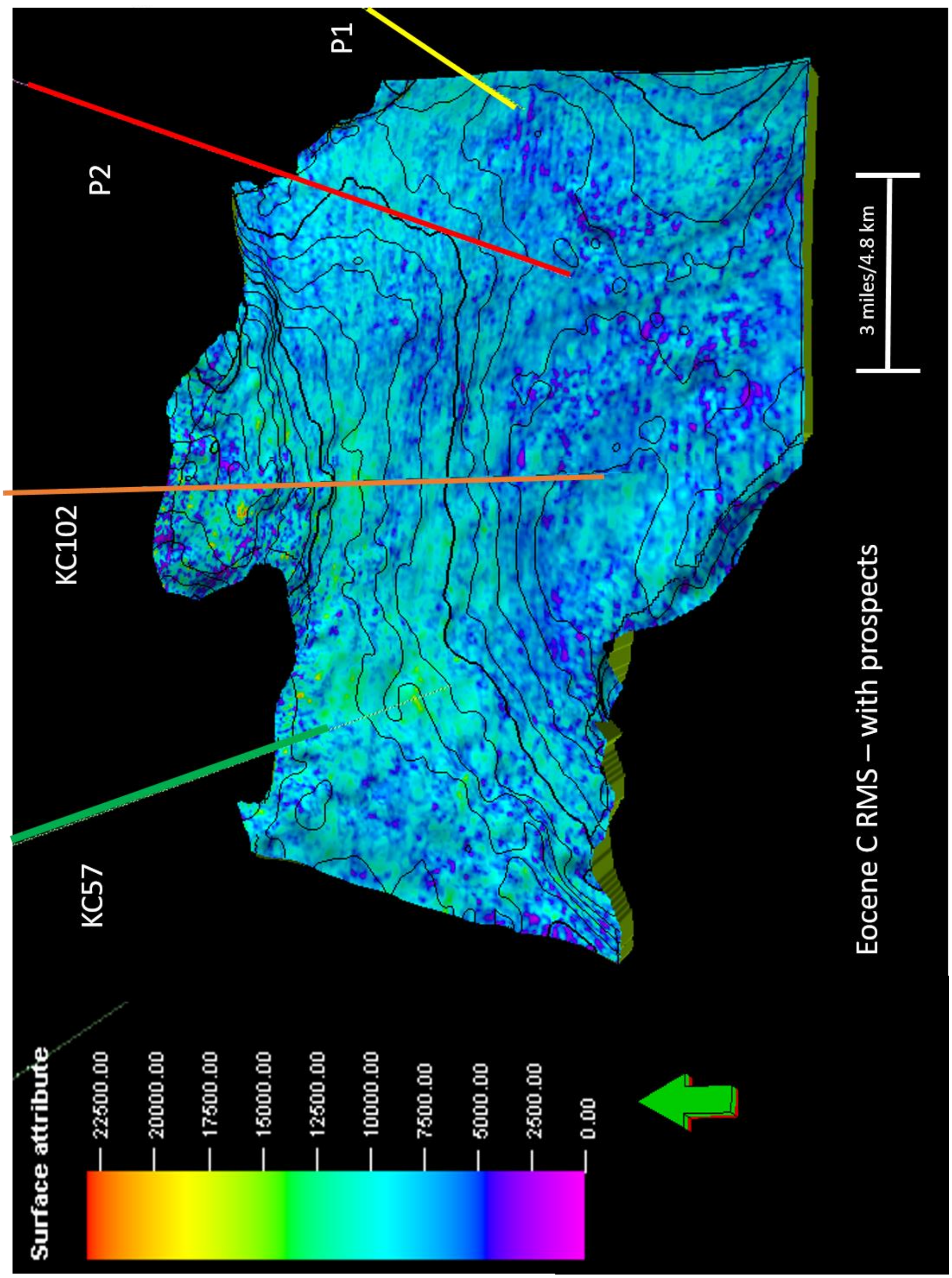


FIGURE 43 - EOCENE C WITH PROPOSED WELLS.

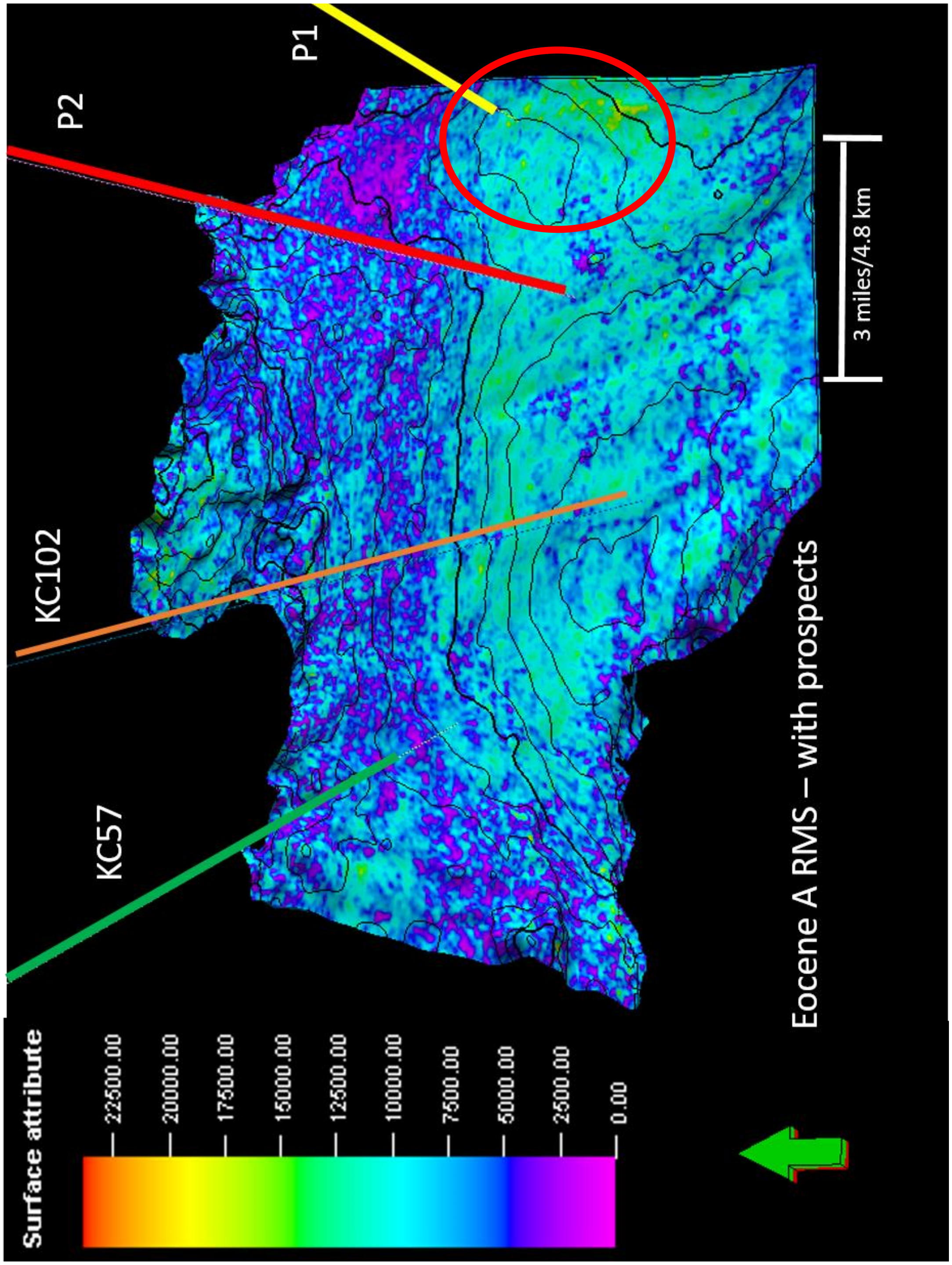


FIGURE 44 -EOCENE RMS WITH ALL WELLS INCLUDING PROSPECTS, RED CIRCLE DENOTED HIGH AMPLITUDE READING FOR EOCENE A.

Prospect 1 is situated on top of an anticline that is being deformed by salt overburden. This shape can provide an excellent reservoir in which to trap hydrocarbons. The well should be deep enough to penetrate the Cretaceous, as there were significant oil shows in the Cretaceous of KC 102. Several directional deviation wells can be drilled from this location, but the primary focus will be on the Wilcox sands under the four way closure.

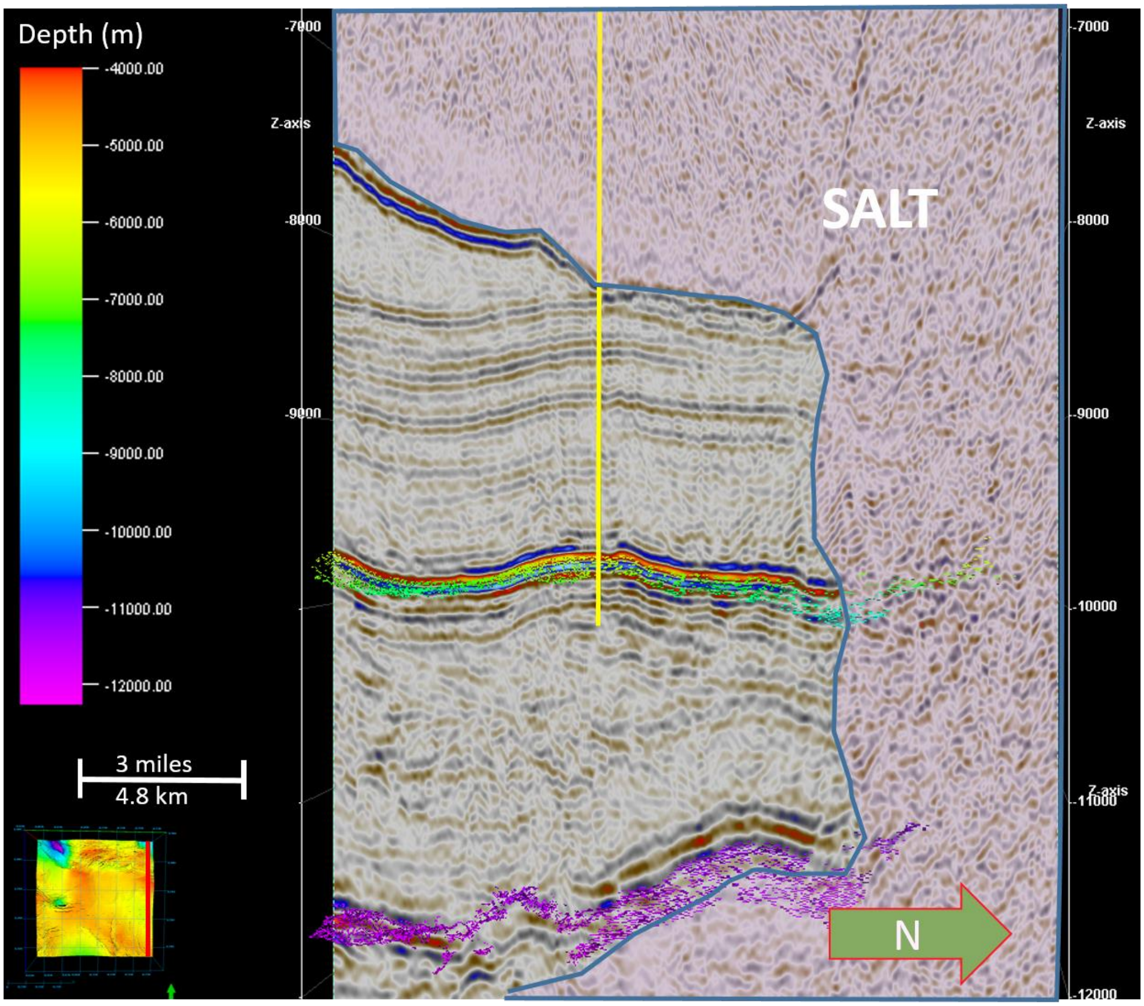


FIGURE 45 - PROPOSED WELL LOCATION IN KC59 IS OVER FOUR WAY CLOSURE. SHOULD ALSO REACH CRETACEOUS.

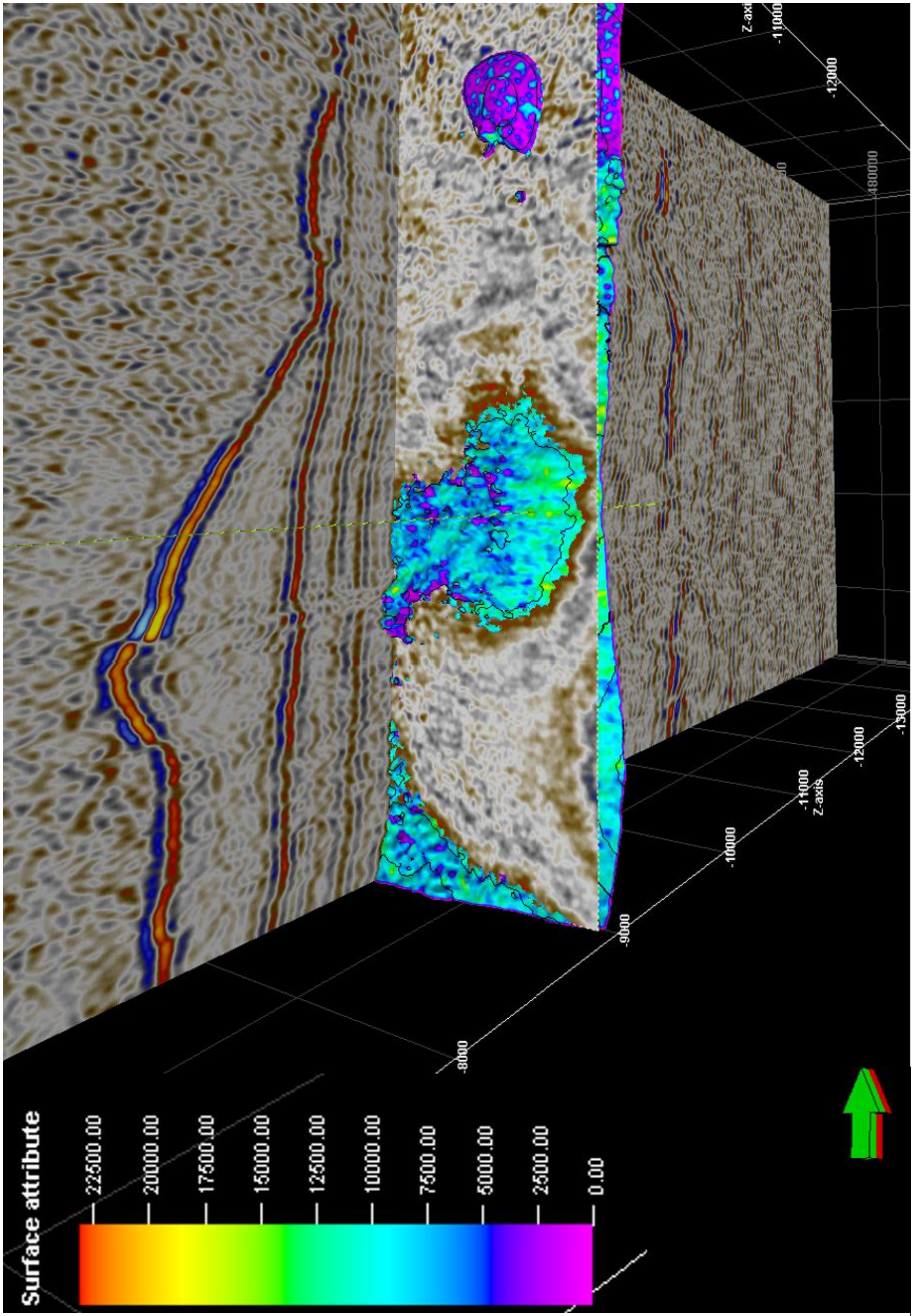


FIGURE 46 - CLOSURE AT KC59 PROPOSED WELL SHOWS RMS HIGH AMPLITUDE INSIDE STRUCTURE AT THE TOP OF THE EOCENE C, 29,035FT. (8850M).

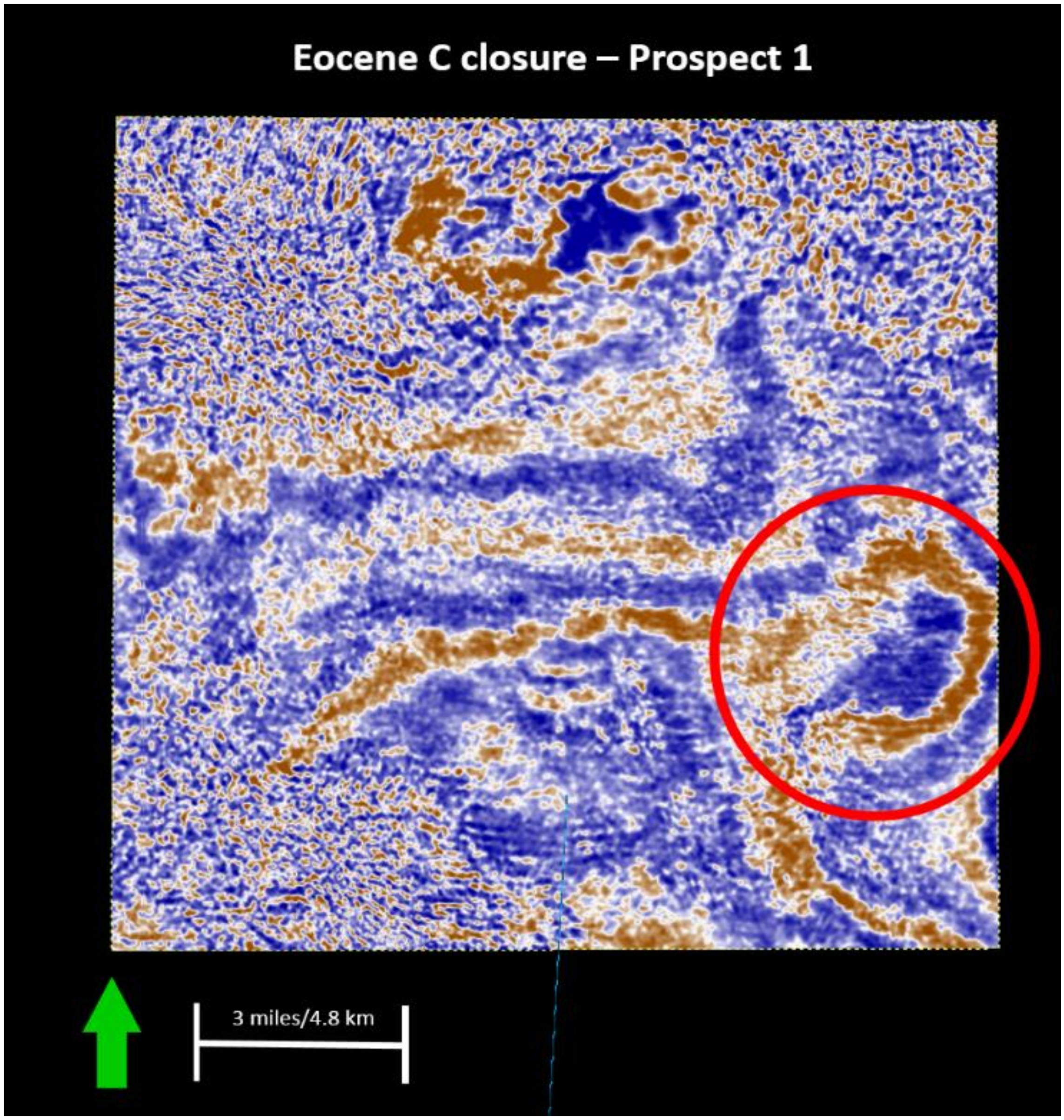


Figure 47 – Depth slice of Eocene C closure where Well has been proposed at 29,035ft. (8850m).

The second Prospect will concentrate on the Eocene A and may ideally be drilled as a side track instead of a stand-alone well. However for the purpose of this paper it will be considered as a straight well.

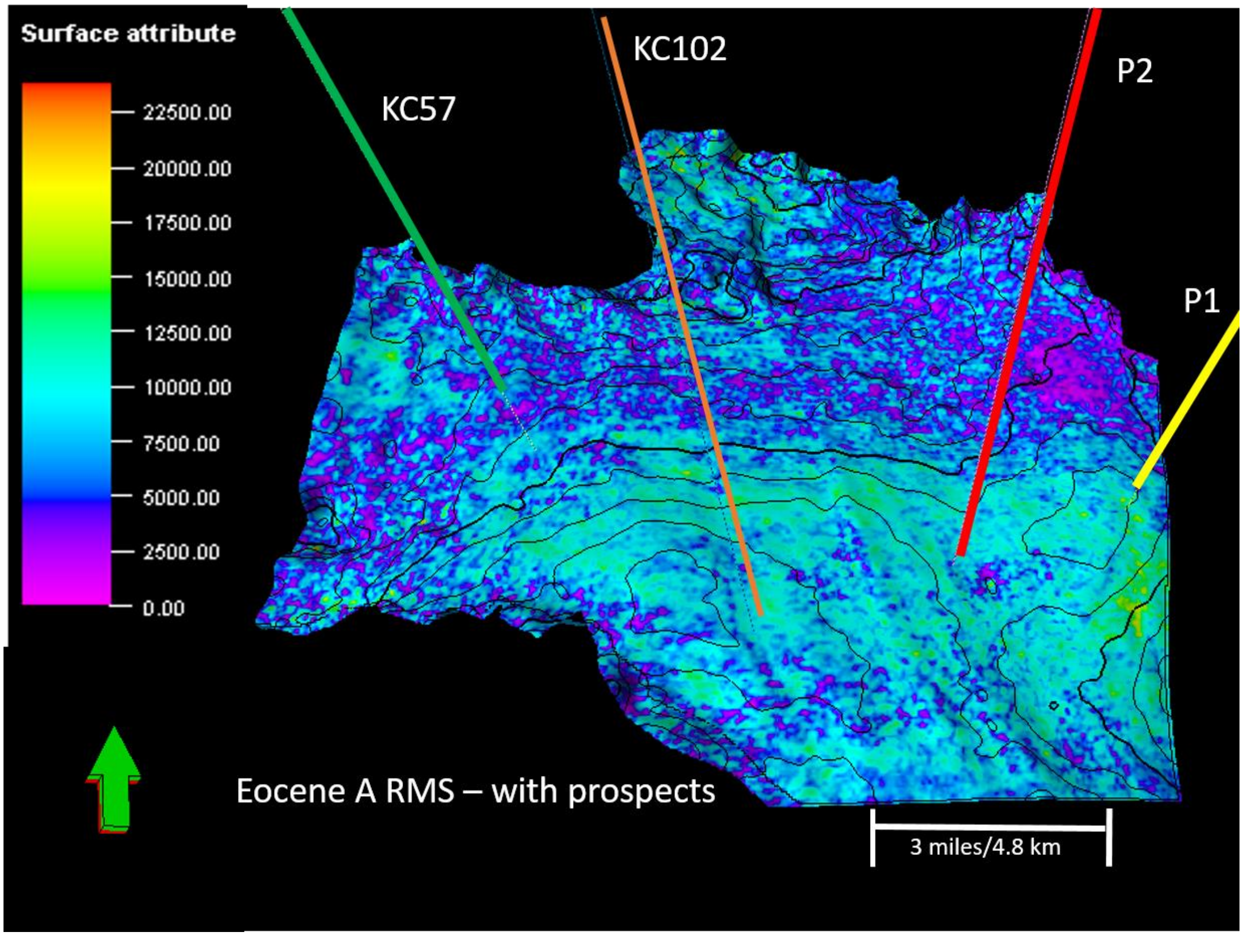


FIGURE 48 - PROSPECT 2 CONCENTRATION IS WITHIN EOCENE A.

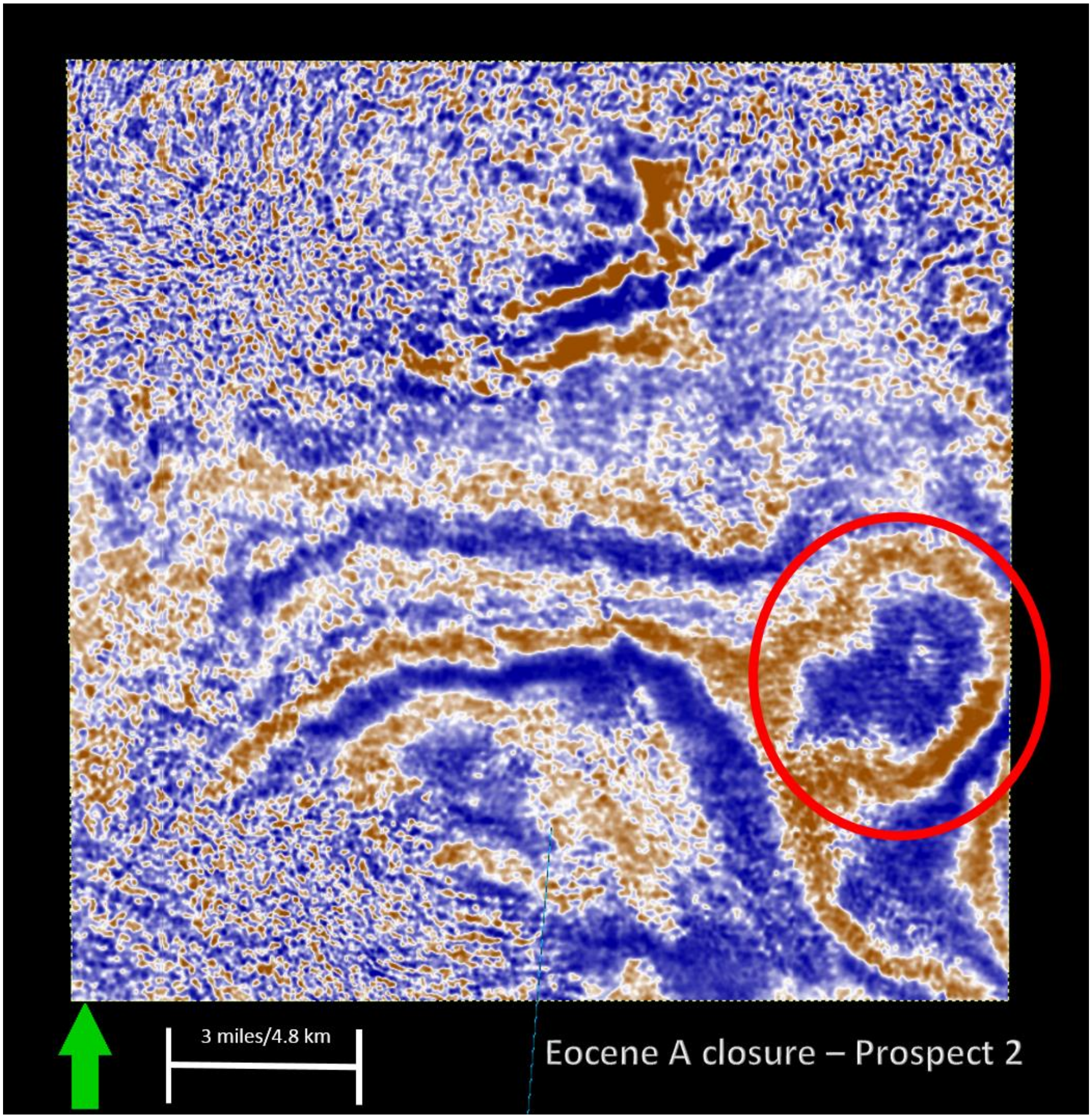


Figure 49 - Tight closure in depth slice, top of Eocene A at 28,000ft. (8650m)

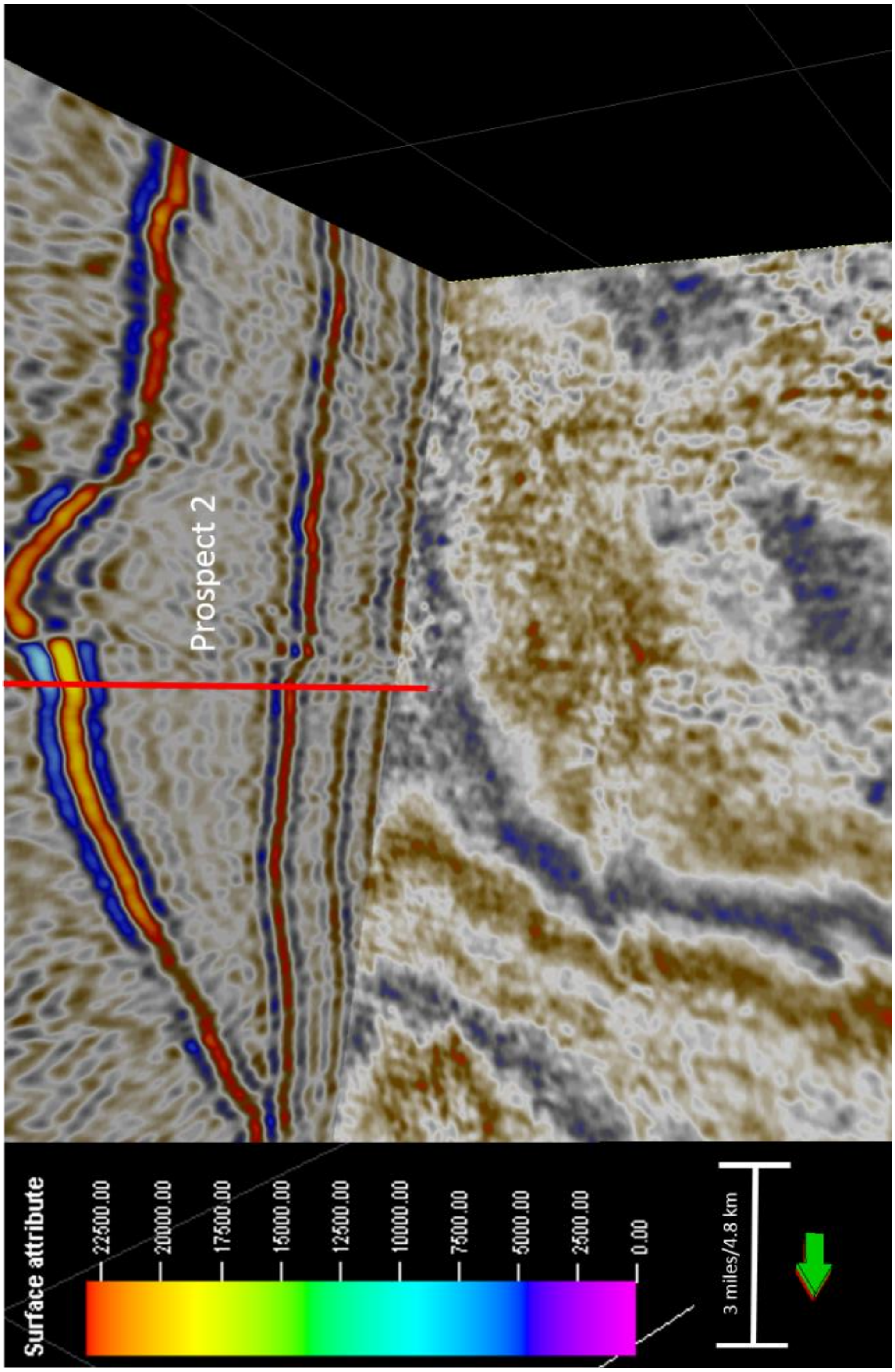


FIGURE 50 - PROSPECT 2 IS PROPOSED JUST OUTSIDE CLOSURE SEEN IN FIGURE 50, BUT MAY BE DRILLED AS A SIDETRACK FROM PROSPECT 1.

Conclusion

Allochthonous salt intrusions form several different types of structures, many of which have been modeled and replicated in a lab setting. However, on occasion something slightly atypical is formed and creates a question. How did this object form? What are the common characteristics? The salt glacier which formed above the Miocene/Oligocene wedge analyzed within this paper is no exception.

For over 20 Million years, the salt overburden of the Miocene/Oligocene wedge has eroded and compacted the sediments below, creating a series of channel-like structures on the horizon in between. This structure, capped with impermeable salt, may be considered a viable pathway for the migration of hydrocarbons,

The Louann salt formed during the Jurassic rifting and evaporation cycles in the GOM and migrated seaward through progradation sediment loading during the lower Tertiary until the late Pleistocene. While the structures created by this process are not uncommon, the characteristics left behind make this one rather unique.

The study shows that salt intrusion occurring while prograding basin ward, can create glacier-like scaring on the underlying rock, and sharply peaked Arête's at the top of peaks. Modeling from C.J. Talbot and Michael Hudec confirm of this type formation due to the glacial movement of subsea salt. Seismic detail also shows a tremendous amount of inclusions, comparable to glacial till, in the salt canopy above.

The recommendation for further study would require the acquisition of seismic and well data from the blocks south of this study area, specifically KC147. Due to the angle of the wedge and considering the effectiveness of salt at trapping hydrocarbons, we believe it would be a worthwhile venture to track the remaining up dip sections of this structure and determine its reservoir capabilities within the Wilcox sands.

Additional data is needed to confirm prospective well locations in the KC 59 block, as while RMS data was used to recommend target areas, there has been no confirmation of direct Hydrocarbon Indicators in this specific area.

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