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Applying modern interpretation techniques to old hydrocarbon fields to find new reserves: A case study in the onshore Gulf of Mexico, U.S.A.

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Applying modern interpretation techniques to old hydrocarbon fields to find new reserves: A case study in the onshore Gulf of Mexico, U.S.A.

A Thesis

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University of New Orleans

in partial fulfillment of the

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In
Earth and Environmental Sciences

By

Josiah Hulsey

B.A Wheaton College, 2013

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Acknowledgement

I would like to take this opportunity to thank several organizations/individuals whom greatly aided in the completion of this research. This work was partially supported by Haland Energy Company. J.P. Oil Holdings, LLC provided access to Shell Oil's internal documentation. SEI Seismic Exchange provided access to the seismic data used in this study. The Louisiana Department of Natural Resources was an invaluable tool in attaining a large part of my data. SMT Kingdom donated some of the seismic interpretation software used in this study. Discussions with Mike Ledet and Stephen Moshier greatly benefited this work. Courtney Hulsey aided in the creation of some of the illustrations. Genie Hulsey provided support in the editing process.

Table of contents

List of Figures

List of Tables

Nomenclature and Abbreviations

Three Dimensional	3D
Million Barrels of Oil	MMBO
Billion Cubic Feet of Gas	BCFG
Million Barrels of Oil Equivalent	MMBOE
Highstand Systems Tract	HST
Falling Stage Systems Tract	FSST
Lowstand Systems Tract	LST
Transgressive Systems Tract	TST
Maximum Flooding Surface	MxFS
Transgressive Surface	TS
Sequence Boundary	SB
Cib Haz	CH
Meter	m
Kilometer	km
Million Years	Myr
Million Years Ago	Ma
Spontaneous Potential	SP

Abstract

This study shows how the use of modern geological investigative techniques can reopen old, “drained” hydrocarbon fields. Specifically, it looks at the White Castle Field in South Louisiana. This field has pay sections ranging from late Oligocene to late Miocene. The late Oligocene package is underexplored and understudied and contains 3 primary reservoirs (Cib Haz (CH), MW, and MR). This study established the depositional history of these reservoirs. During most of the late Oligocene, the White Castle Salt Dome was located in a minibasin on the continental slope. The CH and MW deposited in this minibasin. The CH is an amalgamation of slumped shelfal limestones, sandstones, and shales deposited during a lowstand systems tract (LST). The MW comprises a shelf-edge delta that is part of a LST. The MR is an incised valley fill located in the continental shelf that was deposited during LST after the minibasin was filled.

Keywords: Salt Dome, Sequence Stratigraphy, Seismic, Well Log, Seismic Attribute

Introduction

The application of modern geological exploration techniques can bring new life to old hydrocarbon fields. While major oil companies likely need large fields and large discoveries to balance budgets, smaller to midsize independent companies can afford to look back at the historically “easy” hydrocarbon fields. Many of these “easy” hydrocarbon fields were drilled before the science of petroleum geology was firmly established. Since the drilling of these fields, the discipline of petroleum geology has greatly advanced, and, with new techniques and technologies emerging, these old “easy” fields still have plenty of “easier” hydrocarbons to offer compared to other alternatives. The White Castle Oil Field is a good example of this

Within the onshore Gulf of Mexico, the White Castle Salt Dome is located in South Louisiana near the city of White Castle (Figures 1 and 2). It was discovered in the 1920s using seismic refraction (Spiller et al. 1960) by Shell Oil Company and has produced in excess of 104 million barrels of oil equivalent (MMBOE) (93.5 million barrels of oil (MMBO) and 66.5 billion cubic feet of gas (BCFG)) (Brown, 2000). The majority of the production is from the Miocene sands found between 1,067 and 2,896 m. The late Oligocene (2,926-3,353 m +) is productive, but the sand packages are fewer in number and less developed than the Miocene sand packages. Deeper production (3,353 m) has been sparsely established around the dome, but has been largely unexploited thus far.

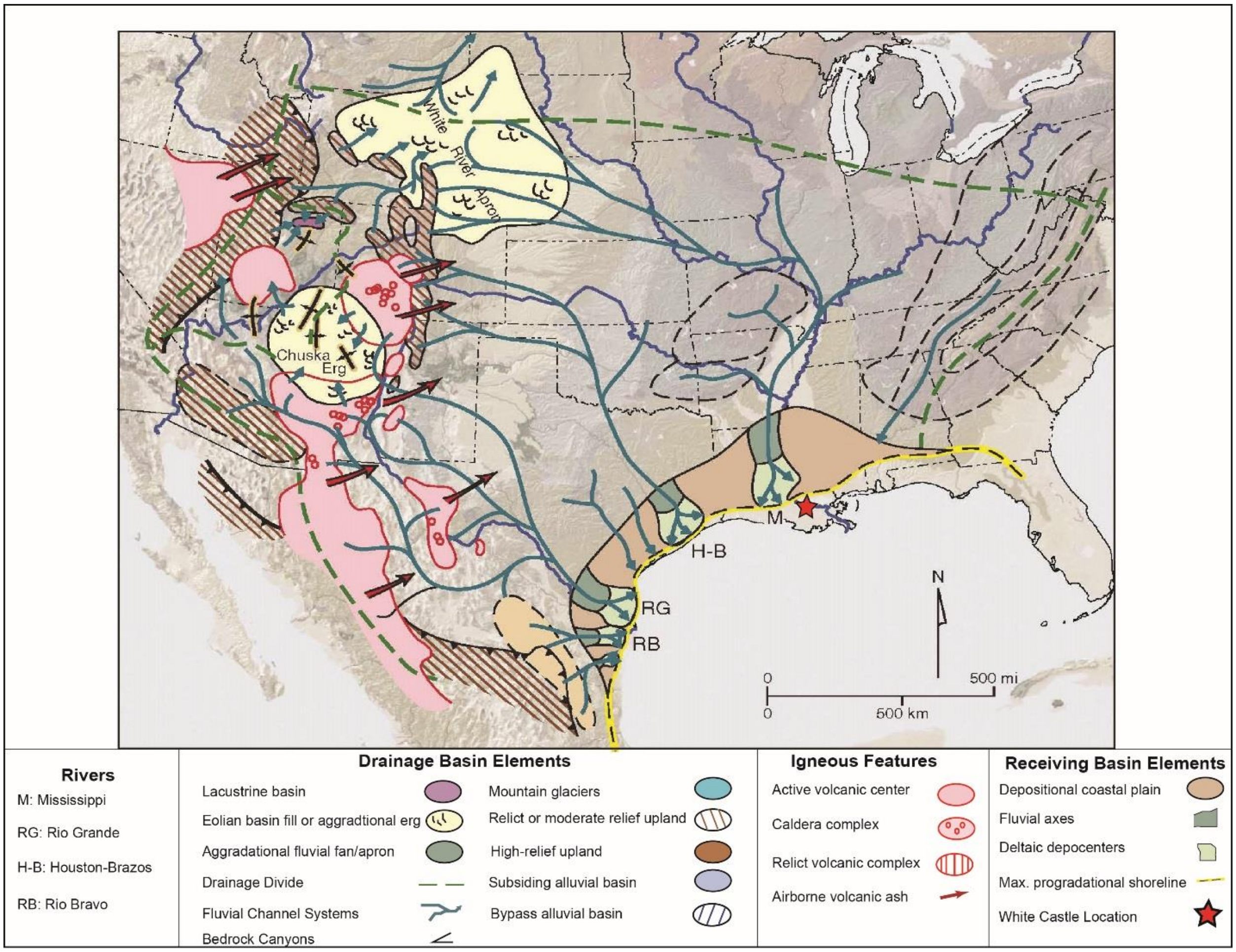


Figure 1. Map displaying the approximate position of the coastline of the Gulf of Mexico during the Oligocene and the location of paleoriver drainage systems. Note the study location of White Castle (red star) in Louisiana, U.S.A. (modified from Galloway et al., 2011).

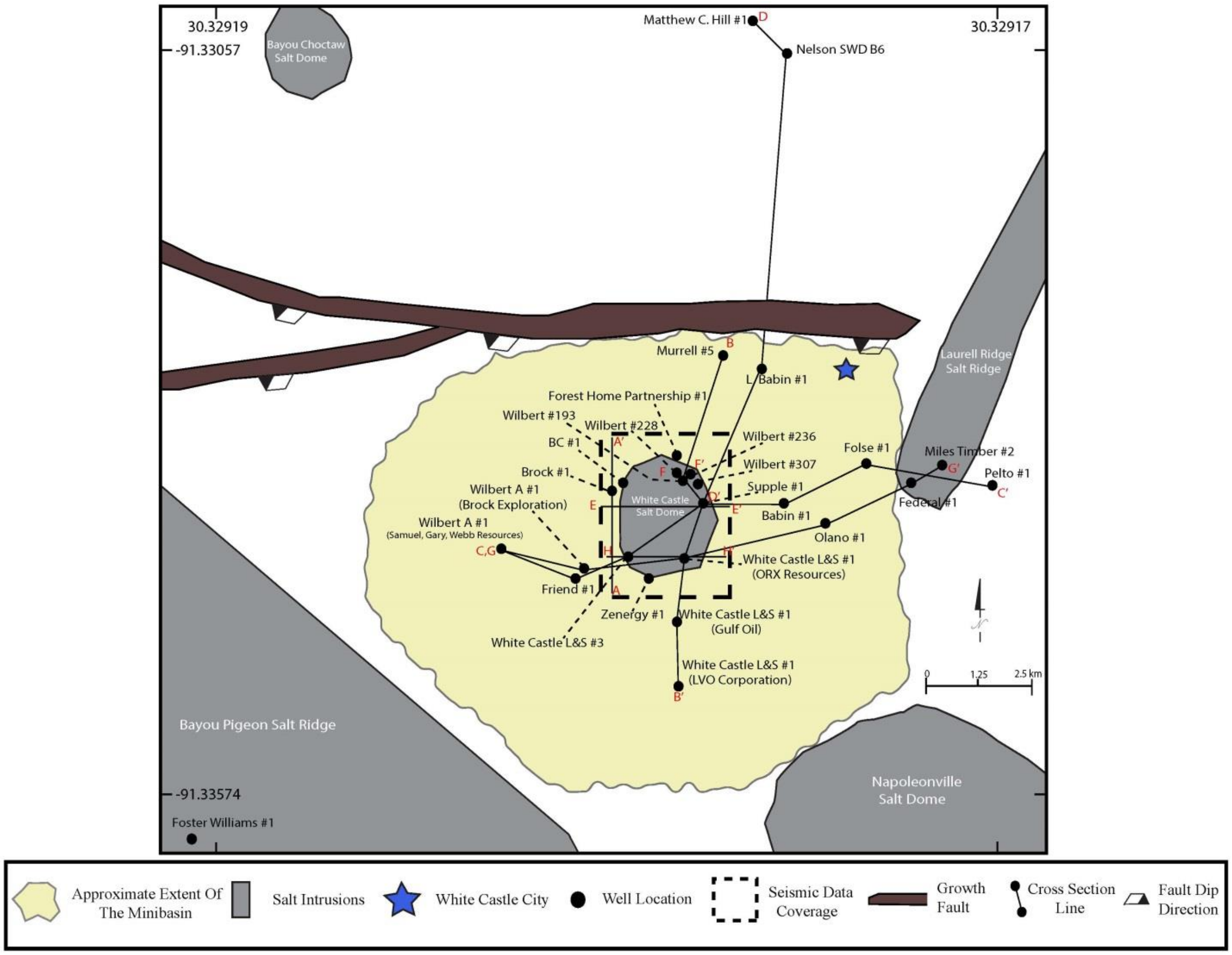


Figure 2. Study area map displaying the location of all cross sections (Figures 4,5, 6, and 10), seismic data coverage, wells, and the approximate outline of the White Castle minibasin.

Shell Oil Company conducted 13 field review studies of the White Castle Field between 1930 and 1984. These reviews were internally published and comprise the primary geological studies of the White Castle Field. Only 4 of these field reviews were able to be located for this study (Pike 1951, Rafidi 1961, Hjerpe 1966, and Conner 1973). There have been no published works solely on the White Castle Field since 1984. Cursory studies were performed by various universities and organizations that have included White Castle in broader scoped research and publications (Teas 1935, Smith et. al. 1970, Johnson et al. 1971, Bornhauser 1971, Smith et. al 1971, Schultz-Ela et. al. 1993, Fails 1995, Welch 2009).

This study seeks to demonstrate how the application of current geological topics like sequence stratigraphy, and new seismic interpretation techniques can reopen what were previously considered drained hydrocarbon fields. This is accomplished by interpreting the depositional settings and sedimentation history of the late Oligocene strata around the White Castle salt dome.

Geologic Setting

The White Castle Salt Dome is located in the middle of a region that has undergone extensive salt movement and tectonics (Figures 1 and 2). Within a 24 km radius of White Castle there are six salt domes and two prominent salt ridges (Figure 3). The large Napoleonville Salt Dome lies to the south (Figure 2) and the large Bayou Bleu Salt Dome lies to the northwest. Smaller piercement domes such as St. Gabriel, Darrow, and Bayou Choctaw are scattered through the study area. Moreover, the Laurel Ridge Salt Ridge lies to the east of White Castle, while an unnamed salt ridge (referred to here as the Bayou Pigeon Salt Ridge) lies to the south and west (Figure 2).

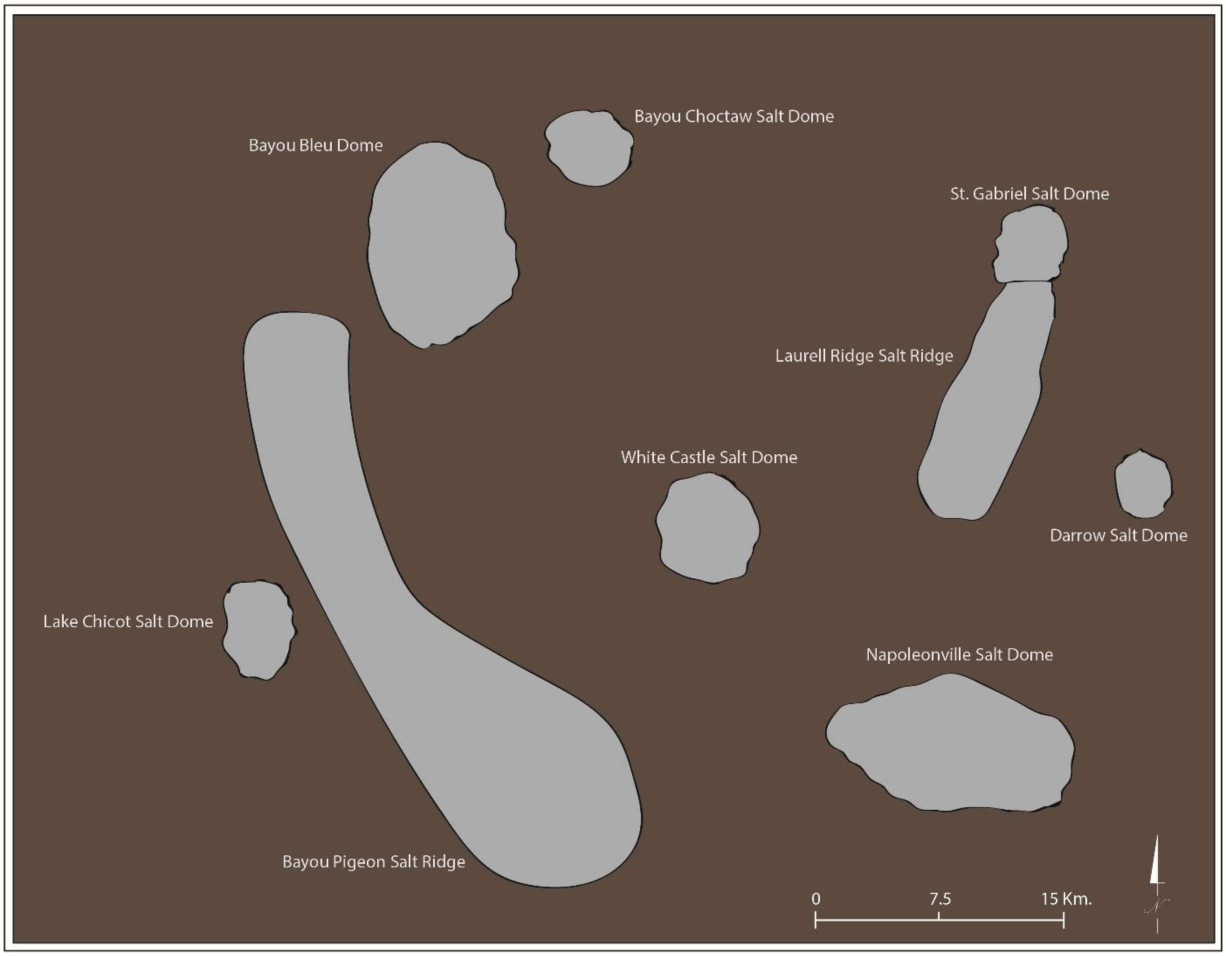


Figure 3. Map displaying the prominant salt features in the area around White Castle.

The White Castle Salt Dome is likely a secondary salt dome in a genetically related salt group created off of the initial instability caused by the growth a mother salt dome in the White Castle area. This mother salt dome's growth was likely caused by sediment overbudern deposited during the late Oligocene and resulted in the destabilization of the Lou Ann salt bed in the White Castle area (Halbouty, 1979). This destabilization led to the formation of the smaller piercement salt domes of Bayou Choctaw, St. Gabriel, White Castle, and Darrow.

The Ancestral Mississippi River Axis (Galloway et al. 2011) was likely the source of sediments in the study area (Figure 1). Tectonics in the Rocky Mountain area caused the source of sediment to shift away from the Northwestern United States to the Central and Eastern regions during the late Oligocene (Galloway et al., 2011). The climate at this time varied between arid and semi-arid (Cather et al., 2008).

During the late Oligocene, frequent volcanic activity in the western/northwest part of the North American continent produced large amounts of volcanic sediments that were deposited in the Gulf Basin (Figure 1; Chapin et al. 2004). The Rio Grande Axis (the paleo-delta to the west of the Mississippi) contains direct evidence of this volcanism by way of the sediment containing a high percentage of volcanic materials and feldspars (Loucks et al. 1986). The Mississippi Axis does not contain direct evidence of this volcanism, but it contains large amounts of diagenetically altered volcanic material (Galloway et al. 2000). The Oligocene was a time of extensive mud deposition along the Mississippi Axis, and the diagenetically altered volcanic materials comprised a large part of this mud. By the end of the Oligocene, an increase in clastic sedimentation took place, and the coastline began prograding once again. This progradation likely caused the sediment instability responsible for creating the White Castle Salt Dome (Peel, 1995).

The late Oligocene coastline was approximately 24-40 km landward of the White Castle Salt Dome (Figure 1; Galloway et al. 2011). With the onset of the Mississippi River Systems becoming a major source of sediment, sedimentation rates began to increase around the transition between the Oligocene and the Early Miocene (Galloway et al., 2000). This increase in sedimentation led to an overall progradational succession in the area of the White Castle Salt Dome.

Data and Methods

Internal Shell documentation was made available to this study by the current operators of the White Castle Oil Field (J.P. Oil Holdings, LLC.). These files were invaluable to this study, and contain field reviews, well logs, paleontological data, and core data.

The primary data used for this study were wireline logs, which were retrieved from the Louisiana Department of Natural Resource's website (Sonris.com), a commercial well log library (Cambe), and from Shell's internal records. All nomenclature for the mapped formations follow Shell's internal nomenclature. The White Castle minibasin has approximately 650 wells, many of which were drilled prior to efficient records keeping, and thus their locations can sometimes prove difficult to determine. A total of 3 different sources were used to compile well locations for this study. These sources are: Shell's internal documentation, Sonris.com, and P2 Energy Solutions. The majority of the wireline logs only contain SP and resistivity curves. Over 500 raster log files were depth-calibrated, uploaded into a seismic workstation, and correlated. The correlation of these wireline logs was aided by paleontological data taken from Shell's internal documentation and from a commercially produced paleontological data volume made available by Gulf Onshore Exploration Company. Sequence stratigraphic interpretations were made on the correlated logs by tying the paleontological data to a eustatic sealevel curve produced by Paleo Data, Inc.

Physical cores could not be located for this study. A geological analysis of a 5.8 m thick conventional core taken from the Cib Haz interval was located. The analysis of this core was done by Reservoirs, Inc. and contains thin section pictures and descriptions as well as core pictures and descriptions. Side wall core analyses from various Shell wells around the dome were also available, which include porosity, rock type, permeability, and grain size.

Basic information and the locations of the hydrocarbon fields surrounding White Castle were taken from Oil and Gas fields of South Louisiana (Volumes 1,2, and 3) and Typical Oil and Gas Fields of Southwestern Louisiana (Volumes 1 and 2). Salt maps were scanned from Salt Domes of South Louisiana (Volumes 1 and 3) and uploaded into a GIS program for georeferencing. After georeferencing, these maps were uploaded into a seismic workstation and the outlines of these salt maps were traced. This tracing was used to define the location and aerial extent of the salt intrusions in the studied area.

A 26 km^2 reprocessed, pre-stack and time-migrated seismic survey was available for this study, which was shot in 1998 and is centered on the White Castle Salt Dome (Figures 2, 2A, and 2B; Tables A1 and A2). The quality of the seismic data is moderate (55 m vertical resolution/37 m lateral resolution) and the salt-sediment interface is not imaged properly, which makes picking horizons and faults close to the flanks of the salt dome quite difficult. A time-depth chart was provided by Gulf Onshore Exploration Company that was used to tie the wells to the seismic data. While using only one time-depth chart for an entire field is less than ideal, most of the wells drilled around the dome did not contain sonic logs, as the wells were drilled before it was a common practice to take such readings.

As is common with piercement type salt domes, there is a complex degree of faulting surrounding the dome that makes autotracking particularly difficult (Figure 4). Several steps were taken to minimize the effect of this faulting on the autotracking algorithm. First, a spectral decomposition was run to isolate the dominant frequency (Brown, 2011). A cohesion volume was then produced from the decomposed data to aid in the interpretations of the faulting network around the dome. The cosine of the instantaneous phase was then calculated to make autotracking easier (Chopra and Marfurt, 2007). Once the seed points were established on the cosine of the instantaneous phase volume, horizons were autotracked along zero crossings to further reduce noise contamination (Chopra and Marfurt, 2014).

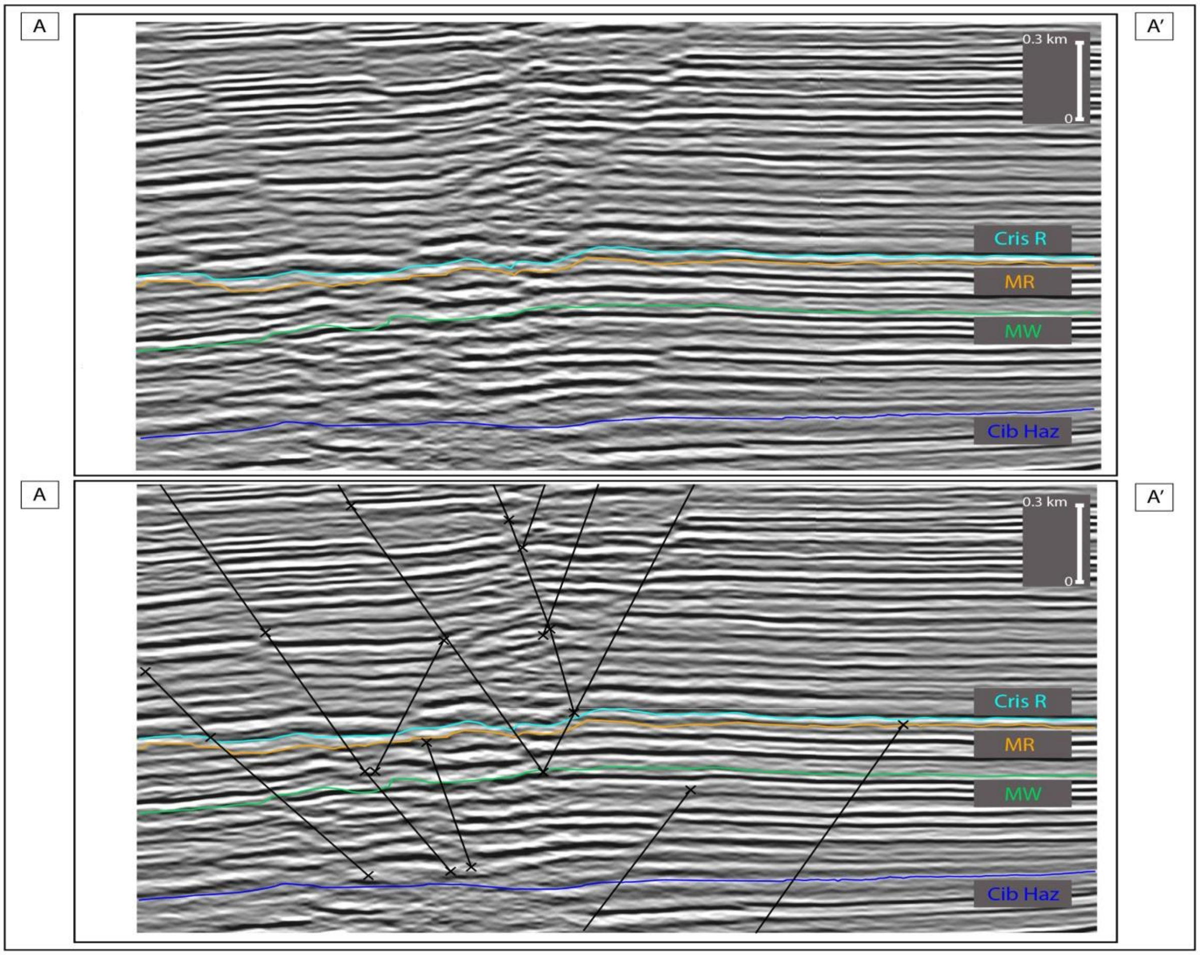


Figure 4. Seismic line displaying the severity of faulting on the White Castle Salt Dome. Both images are of the same line. The bottom image dispays the interpreted faulting. Seismic data owned by Seismic Exchange, Inc.

A statistical analysis study was conducted to quantify how many fields throughout the onshore sector of Louisiana exhibit the possibility for studies like the one conducted in this research. All of the production and activity statistics presented in this statistical study were calculated as a part of the research. The well data for each field in Louisiana was downloaded from Sonris.com. From this dataset, statistics for field activity and field production were generated. In total 177,586 wells were analyzed from 1,855 fields. Wild cat wells and wild cat fields were not included in this analysis.

The number of well permits were calculated for each field to determine the peak year of activity for the field. The year with the most permits was considered the year of peak activity for the field. The number of permits per field was also documents as part of this process. While not all permits resulted in a drilled well, it gives a good approximation to the number of wells drilled in a certain field. After all of the field peak activity values were generated, these values were averaged to find the peak activity year for Louisiana.

Two methods were used to get this value. First, the mode year of permit dates were taken from each field. From this distribution a histogram was created and analyzed to determine the year in which the most fields had the most number of permit requests. This method worked well in the majority of instances; however, small fields that had no wells drilled in the same year failed to yield a mode. Therefore, a second method was used.

The second method took the average permit date year from all fields. From this distribution a histogram was produced and analyzed to determine the year in which most fields had the most number of permit requests. This method worked well but the data had the possibility of being slightly skewed. A field of 10 wells with 5 drilled in 1930 and 5 drilled in 2000 would yield a peak activity date of 1965 when it was never operated during that time. This kind of time distribution of wells is unlikely, but the possibility exists. While both methods had their limitations, both yielded the same value as the peak production year in Louisiana. The mode data is presented throughout the paper since it had no skew and the only fields missing from it were small and relatively unsubstantial fields.

The primary operator was established by taking the mode of the operator codes listed for each well in each field. The main goal was to identify fields that had been operated primarily by major oil companies through their lives. Due to the limits of excel, operator codes with alpha numerical values were not able to be processed. However, every major oil company had a numerical code and was, therefore, successfully processed.

Success rates were established for each field. The success rates were determined by summing the number of successful wells with the number of unsuccessful wells and then dividing the number of successful wells by the sum to get the percent success of the field.

Results

A composite log was created for the studied section and can be seen in Figure 5. Three wells that contain the best preserved sections of the studied formations were selected and spliced together to make the composite log. Paleontological data from each of the three logs was used to determine biostratigraphic ages of the studied formations (Figure 5). Two cross sections of the study area were also created (N-S and E-W; Figures 6 and 7).

In response to the destabilization of the Lou Ann Salt layer, the dome began to form and salt withdrawal started to take place around the future domal area. As the salt was being pulled into the diapiric structure, the sediments surrounding the dome began to subside rapidly. This subsidence eventually led to the formation of the minibasin around the salt dome (Figure 8) (Hudec et al., 2011). A large E-W trending growth fault exists ~ 6.5 km north of the White Castle Salt Dome (Geomap, 2010) (Figures 2, 9, and 10). This growth fault likely marks the shelf break during the late Oligocene (c.f. Olariu et al., 2013). The minibasin is bound to the north by this growth fault and to the east and west by salt ridges. The southern boundary can not be firmly established, but it is likely related to either the Napoleonville Salt Dome or the Bayou Pigeon Salt Ridge that lay to the south of the field.

The formation of this minibasin took place sometime during the late Oligocene. This is evidenced by an asymmetrical growth history of the salt dome during this time caused by the influence of the minibasin squeezing the growing salt (Figure 11). Further, a sheath composed of late Oligocene shale exists on the southwestern part of the dome, also suggesting that the initial salt movement took place during this time.

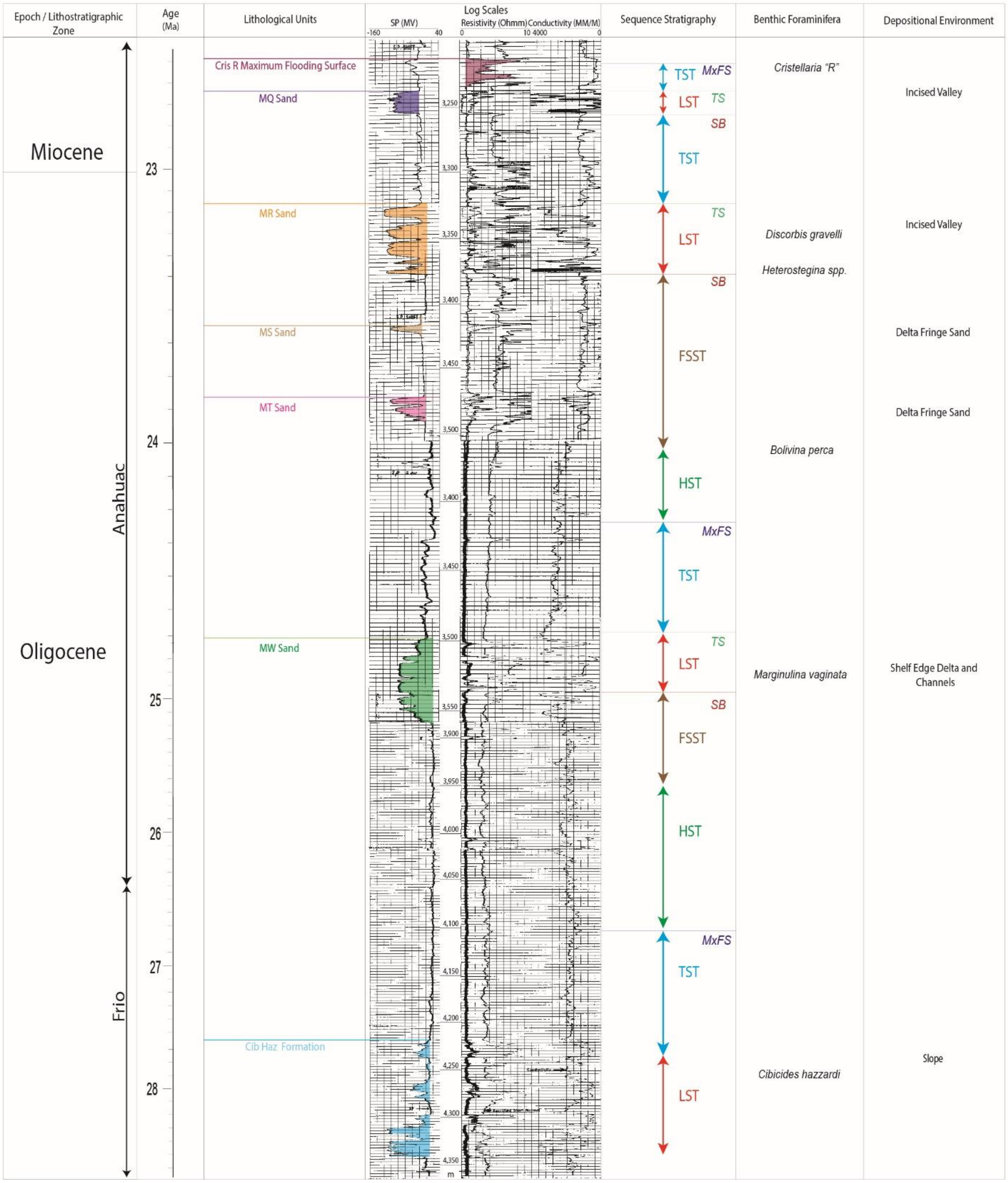


Figure 5.Stratigraphic column of the study area with composite type log. Depth values are in meters. SB: sequence boundary, MxFS: maximum flooding surface, TS: transgressive surface, HST: highstand systems tract, FSST: falling stage systems tract, TST: transgressive systems tract, LST: lowstand systems tract. Benthic foraminifera data taken from Shell internal reports and compared with sea level curves/biostratigraphic charts from Waterman et al., (2011 and 2012).

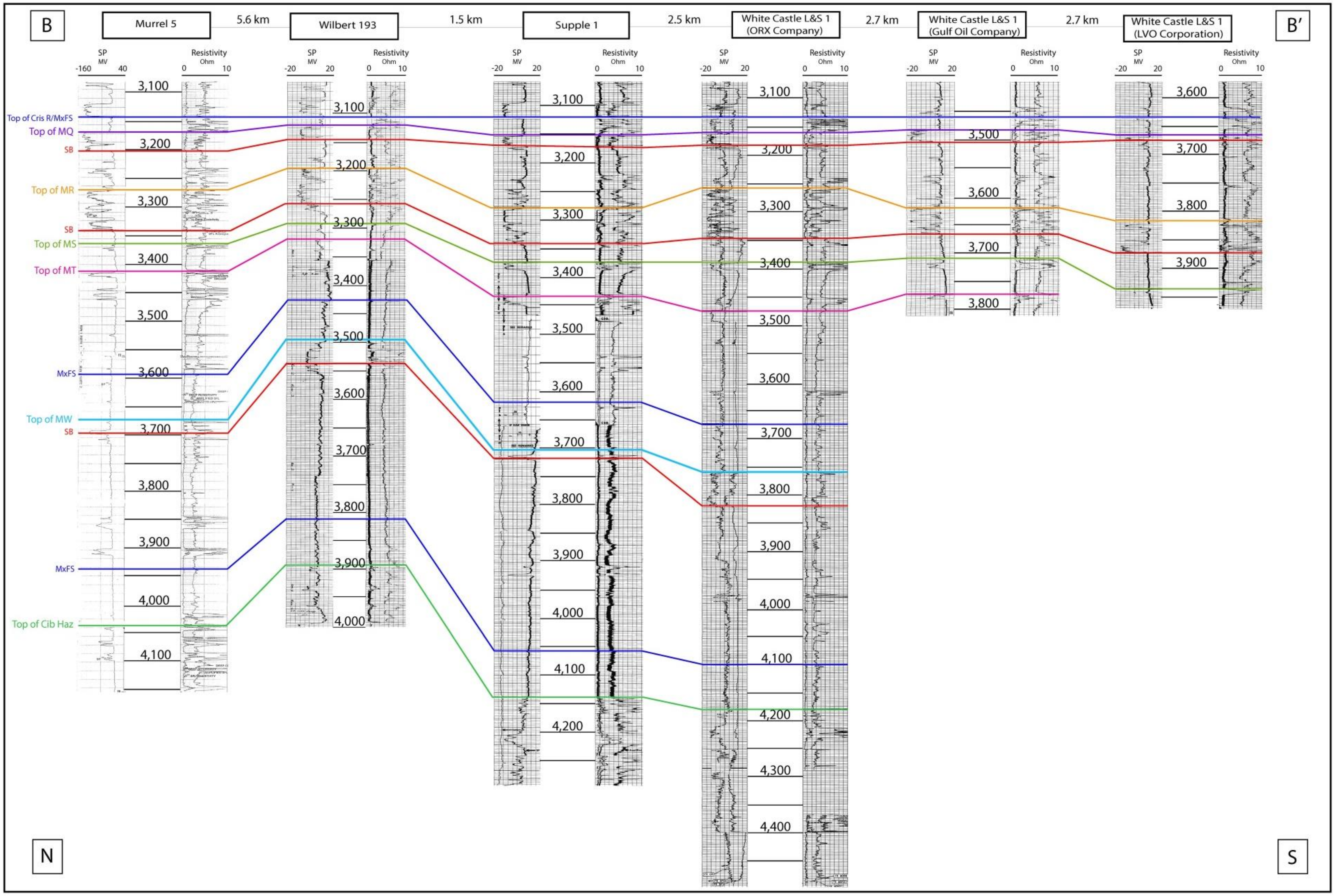


Figure 6. Stratigraphic cross section of the study area along depositional dip. Cris R maximum flooding surface is used as datum. SB: sequence boundary, MxFS: maximum flooding surface. See figure 2 for location of this cross section. Depth values are in meters.

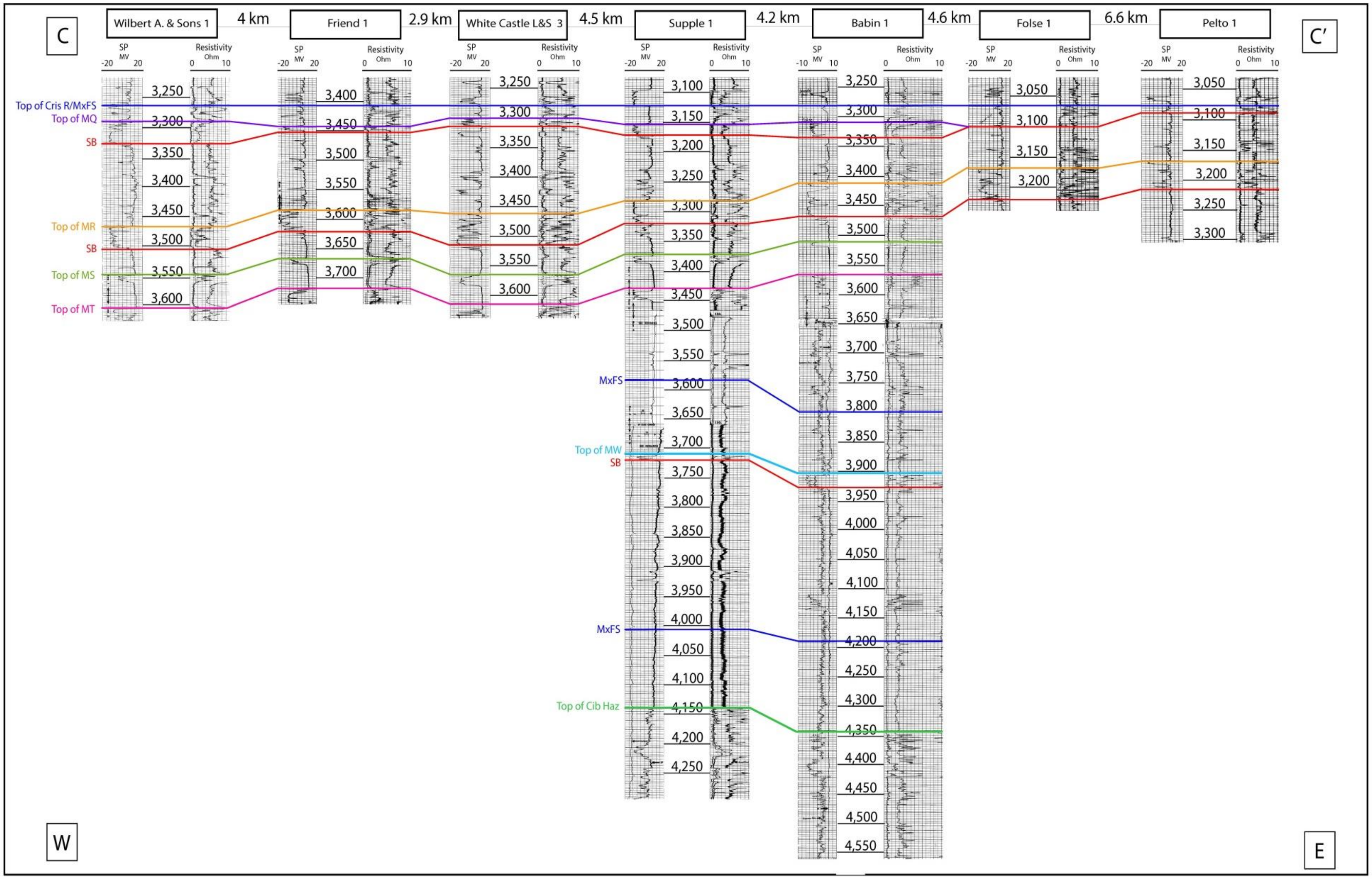


Figure 7. Stratigraphic cross section of the study area along depositional strike. Cris R maximum flooding surface is used as datum. SB: sequence boundary, MxFS: maximum flooding surface. For location of this cross section see figure 2. Depth values are in meters.

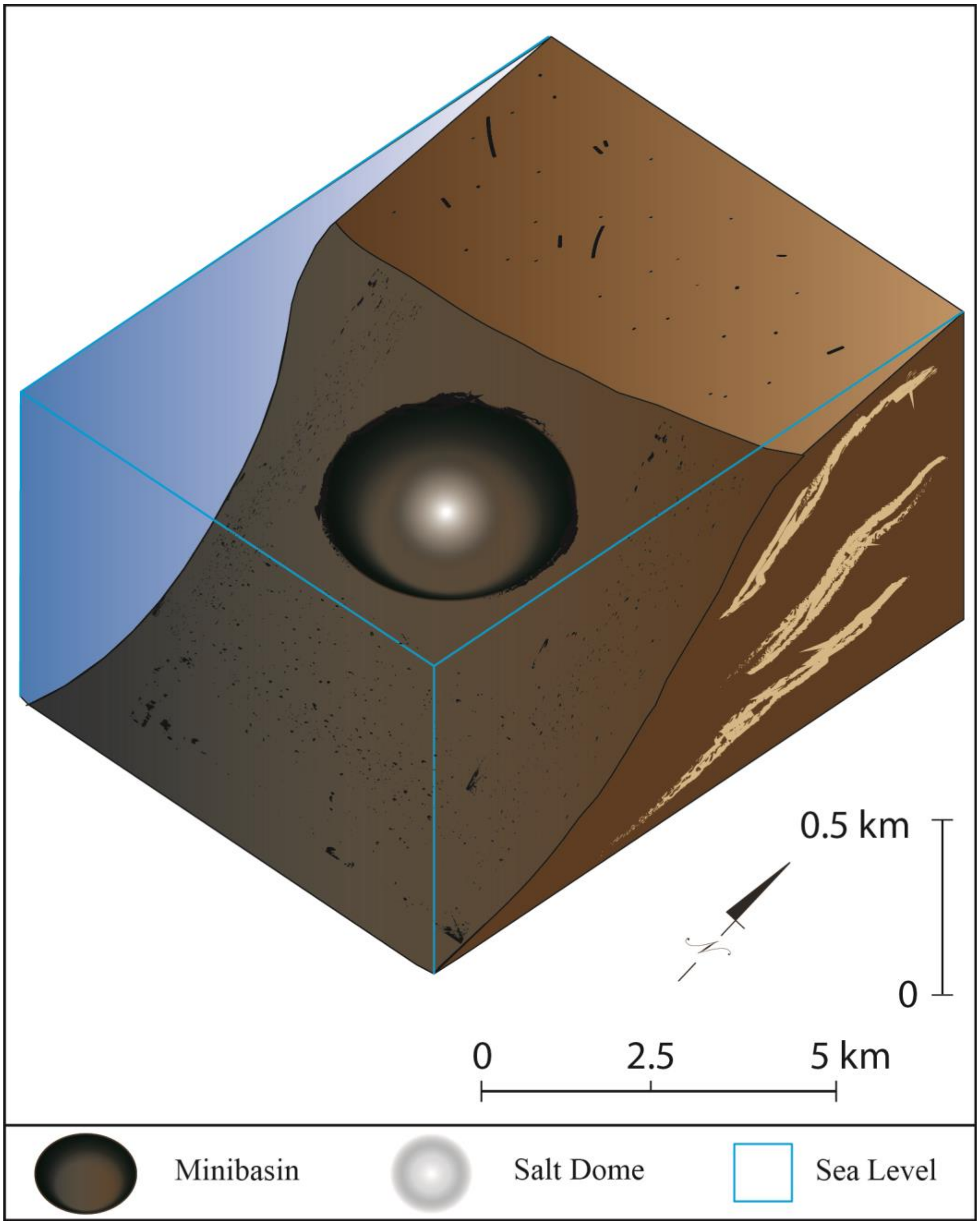


Figure 8. Schematic diagrams of the formation of the minibasin.

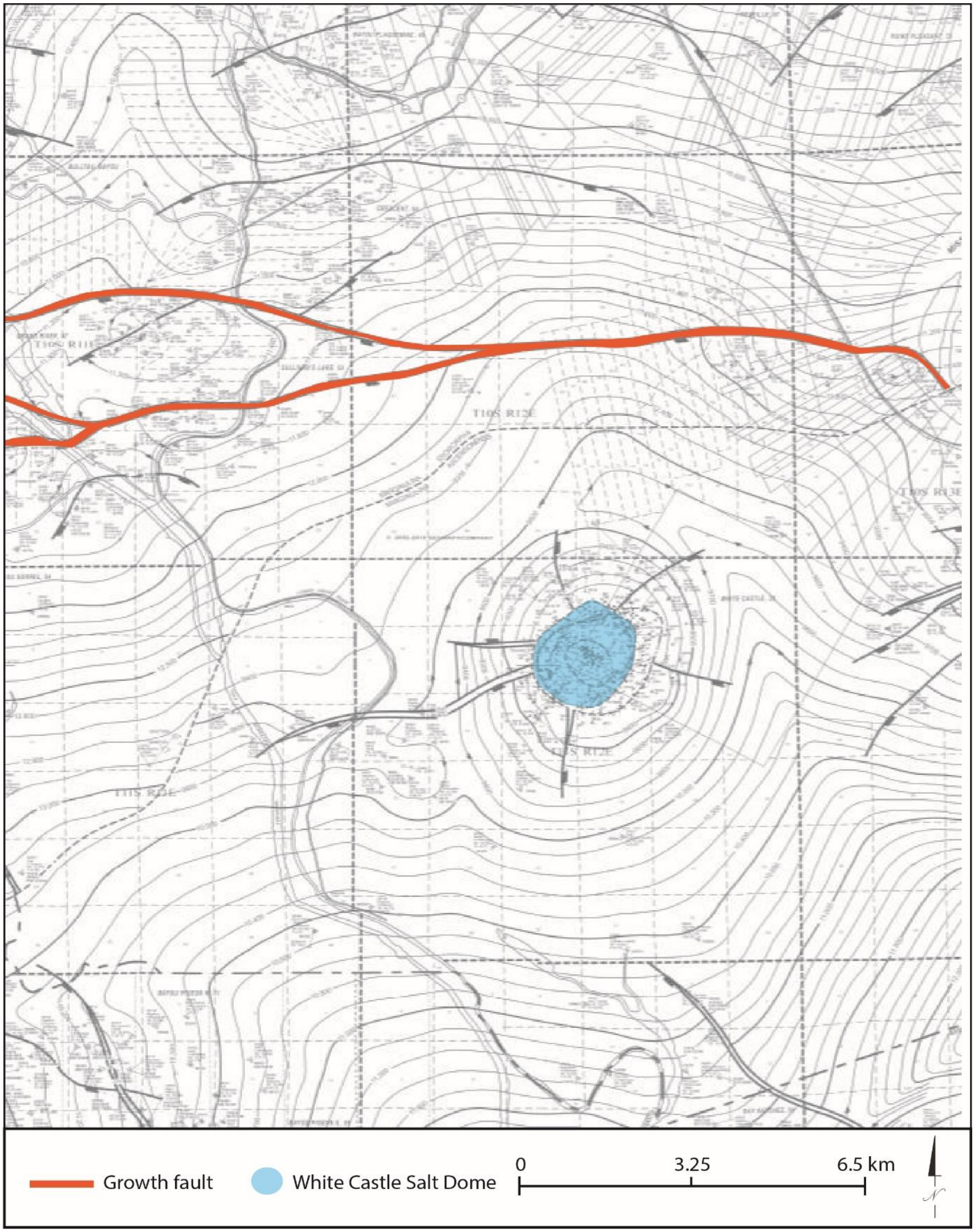


Figure 9. Figure modified from Geomap.com to show the growth fault bounding the White Castle Minibasin to the North.

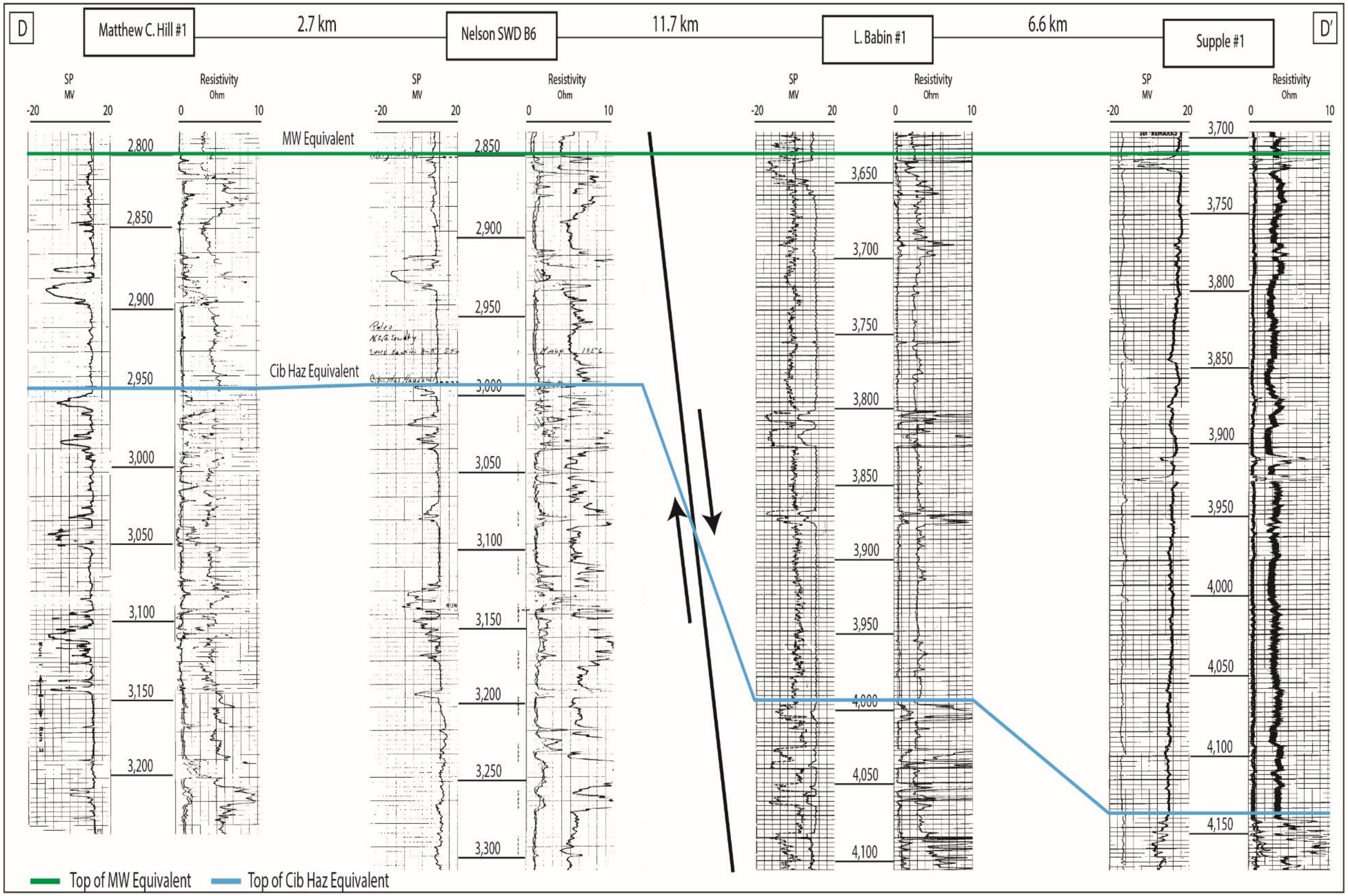


Figure 10. Dip cross section accross the growth fault displaying stratal thickening on the downthrown side of the fault. Cross section flattened on the top of the MW equivalent.

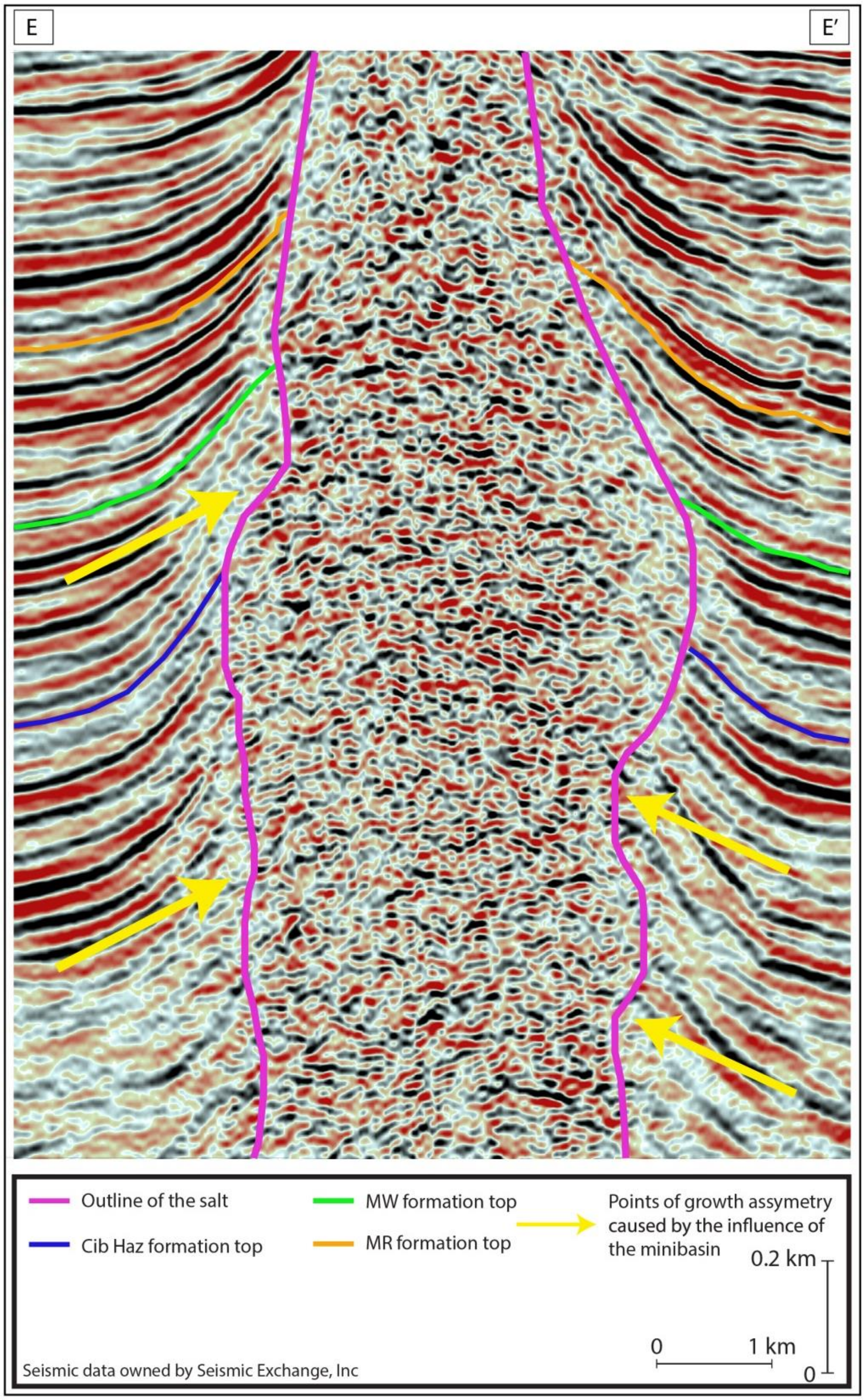


Figure 11. Seismic line displaying the asymmetrical growth of the salt dome caused by the influence of the minibasin during the Late Oligocene. For location of the seismic line (E-E′) see figure 2.

The Cib Haz formation is comprised of slumped sandstones, limestones, and shales and was deposited during a lowstand systems tract (LST) (Figure 12). The top of the Cib Haz reservoir aligns up with a strong trough in the seismic data (Figure 11). The benthic foraminifera that dates this formation is the *Cibicdes hazzardi*, which dates to ~27.55 Ma (Waterman et. al, 2011). A 5.8 m conventional core was taken from one of the limestone sections of this formation in the Wilbert #307 well at a depth of 4,069-4,075 m (Figure 13 and Figure 14). The limestone exhibits poor reservoir quality with very low permeability and has a prevalent micritic matrix (Bruno and Kryza, 1994). This limestone was likely deposited in a series of shelf-edge reefs that formed during part of the LST. As this reef system grew, the talus from the reef front likely regularly slumped off of the shelf-break and into the minibasin (Hopley, 2006). The lithological composition of these slumps varied between sandstone, limestone, and shale which resulted in a reservoir that is highly irregular in composition. A depth map for this formation can be seen in Figure B1.

The salt dome likely blocked the sliding sediments from going further down the minibasin resulting in an increase in thickness of the Cib Haz interval around the northern flank of the salt dome, which can be seen in the isopach map of the Cib Haz formation (Figure 15).

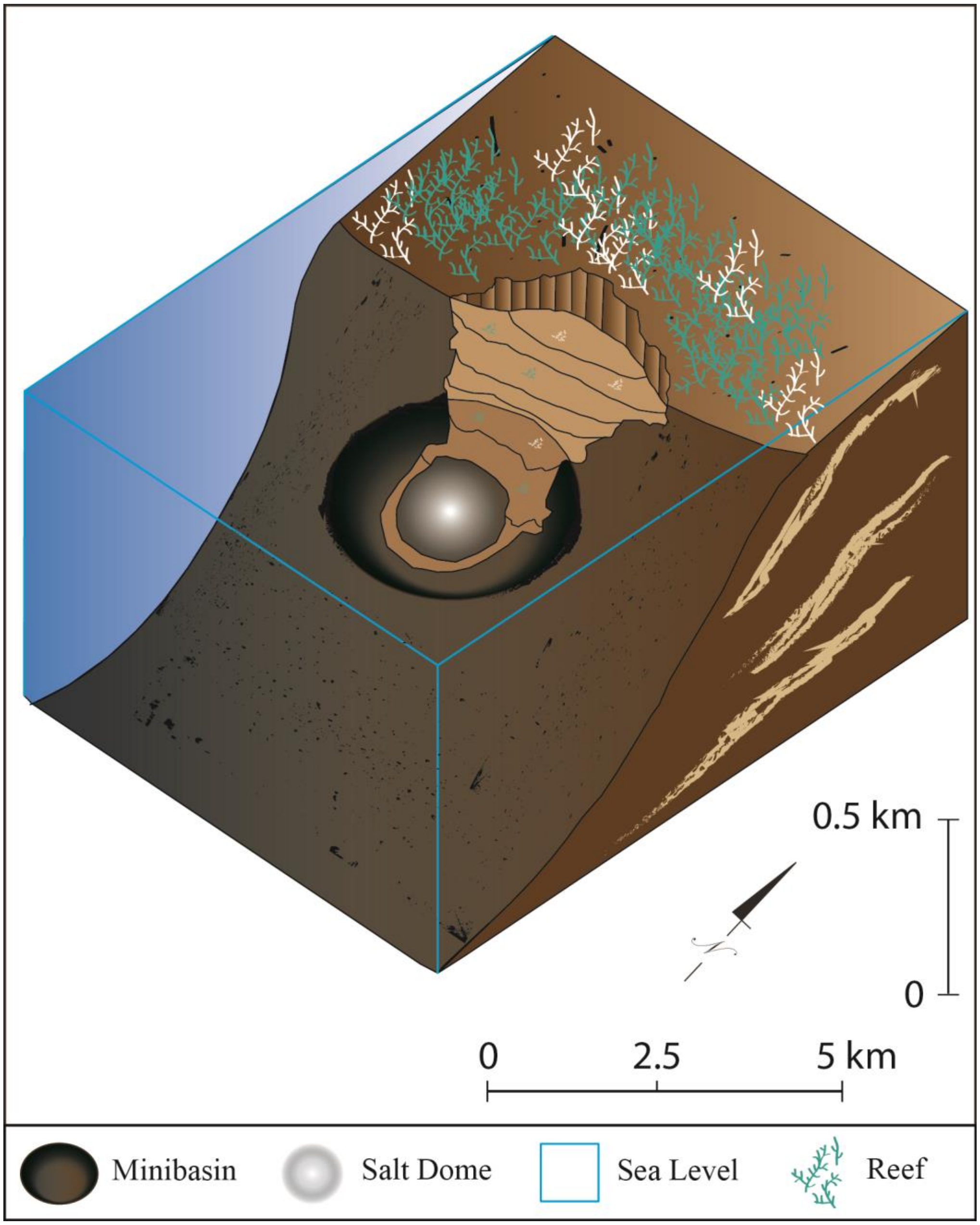


Figure 12. Schematic diagrams of the formation of the Cib Haz reservoir.

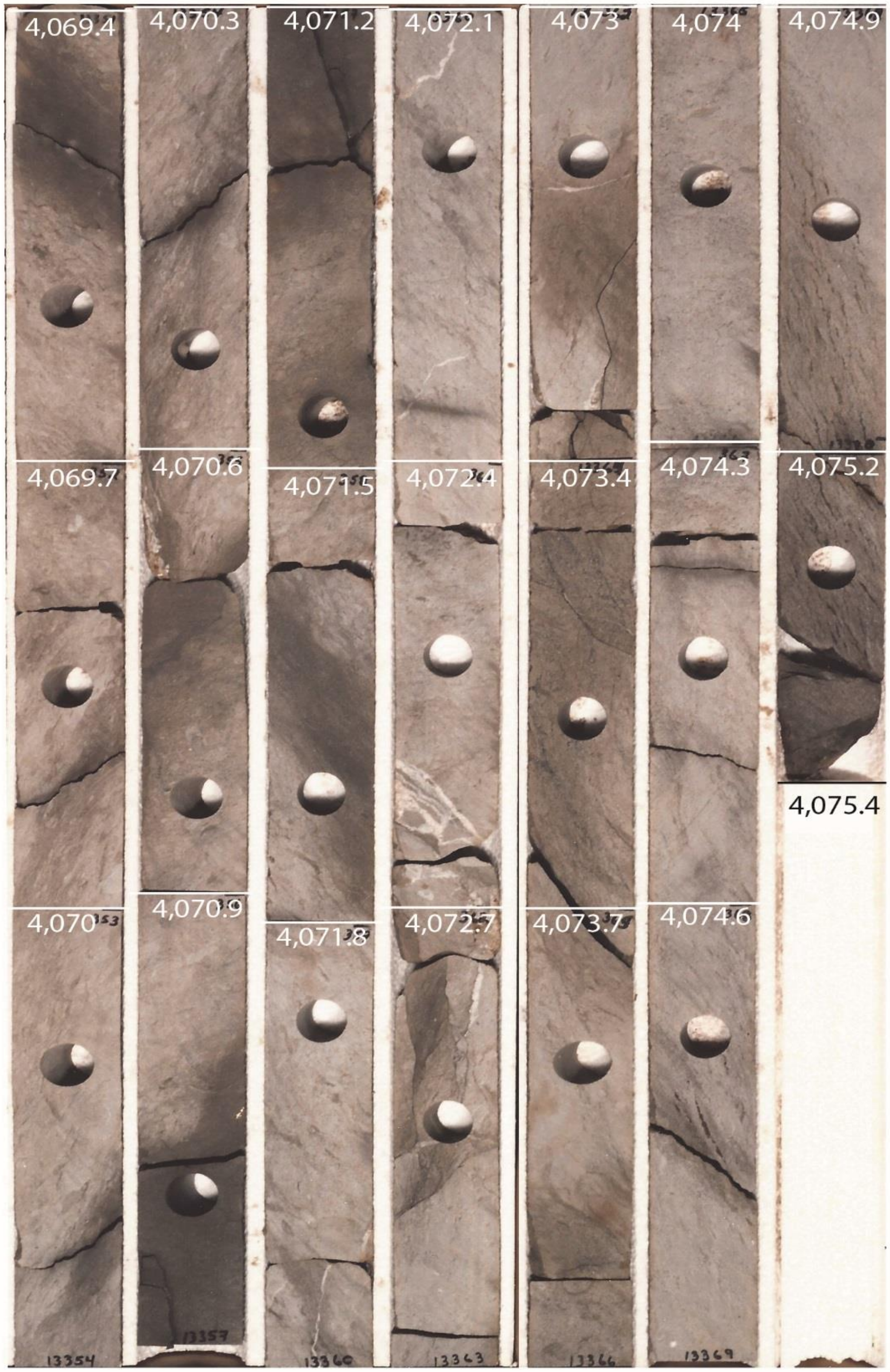


Figure 13. Core taken from the Cib Haz interval in the Wilbert #307 well (For well location see figure 2). Depth values are in meters.

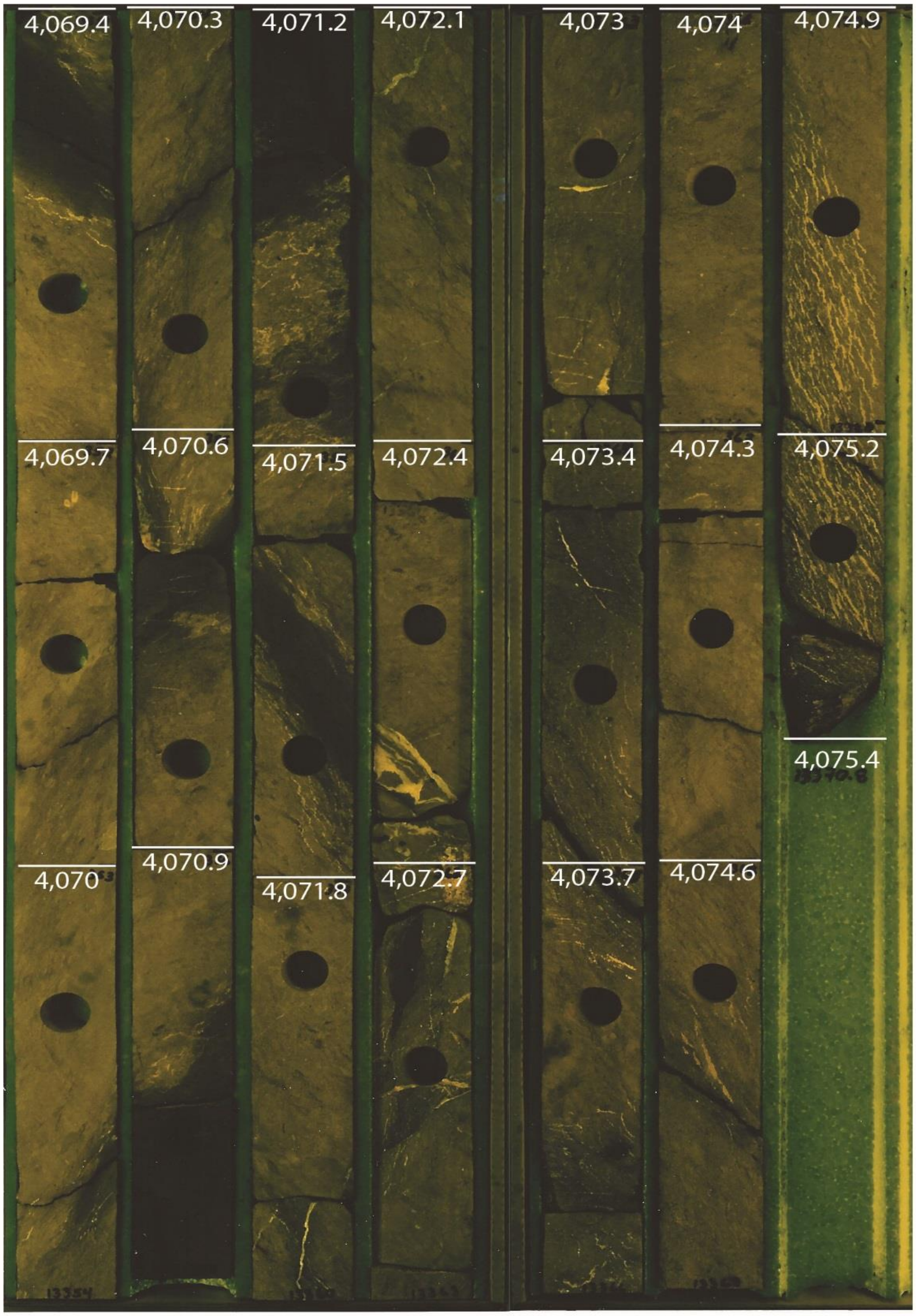


Figure 14. Core taken from the Cib Haz interval in the Wilbert #307 under ultra violet light. Depth values are in meters.

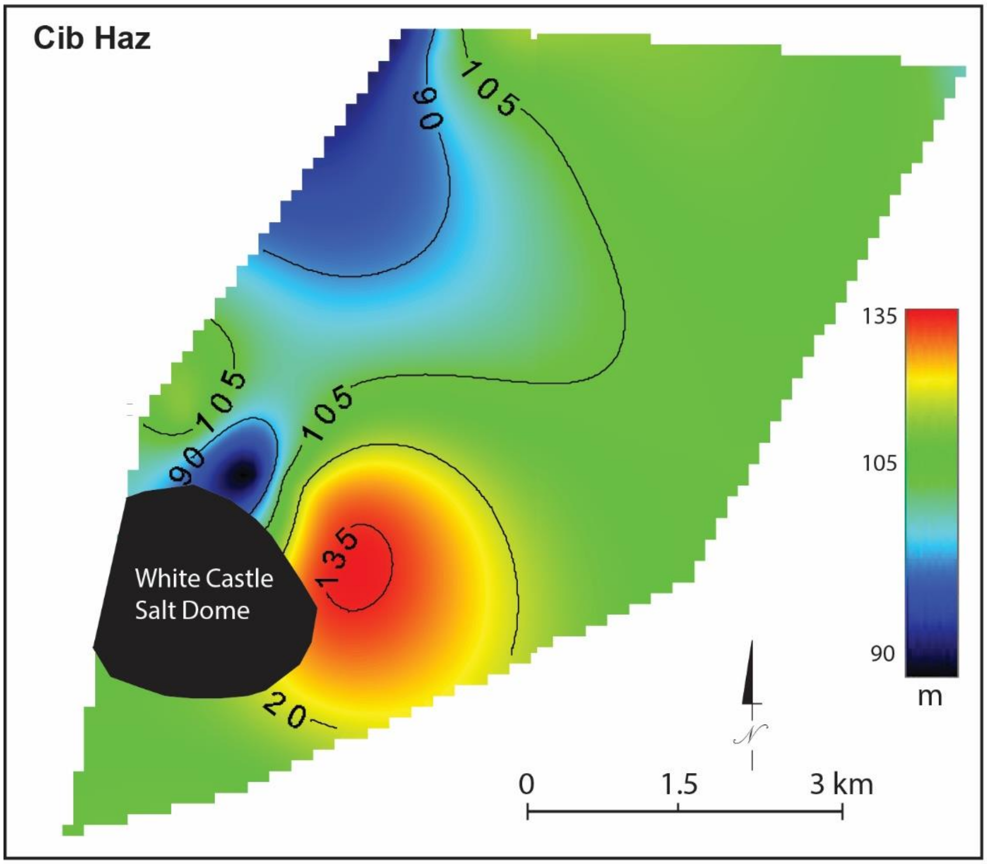


Figure 15. Isopach map of the Cib Haz.

Approximately 3 Myr separate the Cib Haz from the next major sand event. This intermittent time was marked by shale deposition in the White Castle minibasin as 305-457 m thick shale was deposited during this time with only minor (<30 m thick) sand intervals. The "MW" sand (24.63 Ma) is the first major sand deposition that occurred after the Cib Haz formation. The top of this formation aligns with a strong trough in the seismic data (Figure 11). The benthic foraminifera that dates the MW is the *Marginalina vaginita* (*Marg vag*), suggesting a depositional age of 24.6 Ma (Waterman et al, 2011). The MW sand was likely deposited during a LST. This formation likely represents a shelf-edge delta and associated distributary channel deposit that formed while the sea level was low (cf. Porebski and Steel, 2003). Wells that encountered axial channels of this delta system can show sand deposits to be ~60 m thick and thus provide good producing wells (Figure 16). Wells encountering the flanks of these channel systems found sands as thin as 15 m and thus provide poorer performing wells (Figure 16). The grain size of the MW sand ranges from very fine to fine with an average porosity of 25-30% (Slagle et al., 1994).

This delta system flowed off the shelf edge and into the White Castle minibasin. Well control is sparse for this basin except in the immediate vicinity of the dome. The well control around the dome suggests that the distributary channels of this delta flowed toward the salt dome and split into two different channel systems around the dome (Figure 17). The eastern channel system is more clearly defined by well control and appears to be a high quality sandstone reservoir. The western channel system, although only encountered by two wells, appears to be less developed and more shale prone based on the log response. A depth map for this formation can be seen in Figure B2.

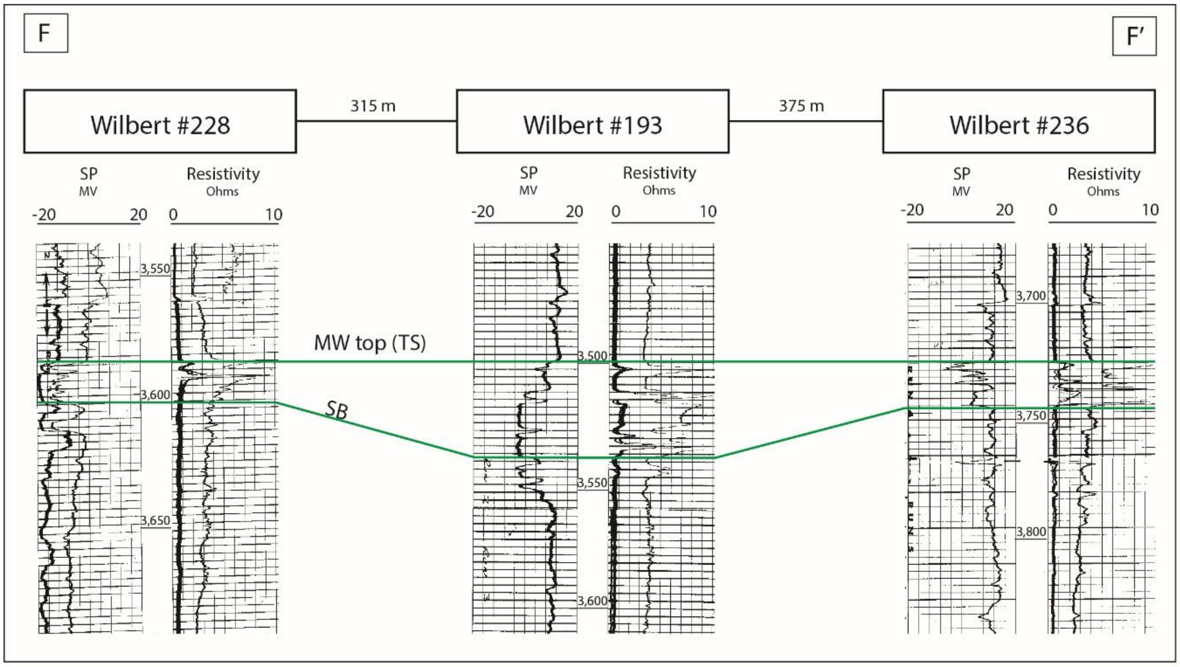


Figure 16. Cross section showing the MW shelf edge delta system. For location of the cross section, see figure 2. Depth values are in meters. TS: transgressive surface, SB: sequence boundary.

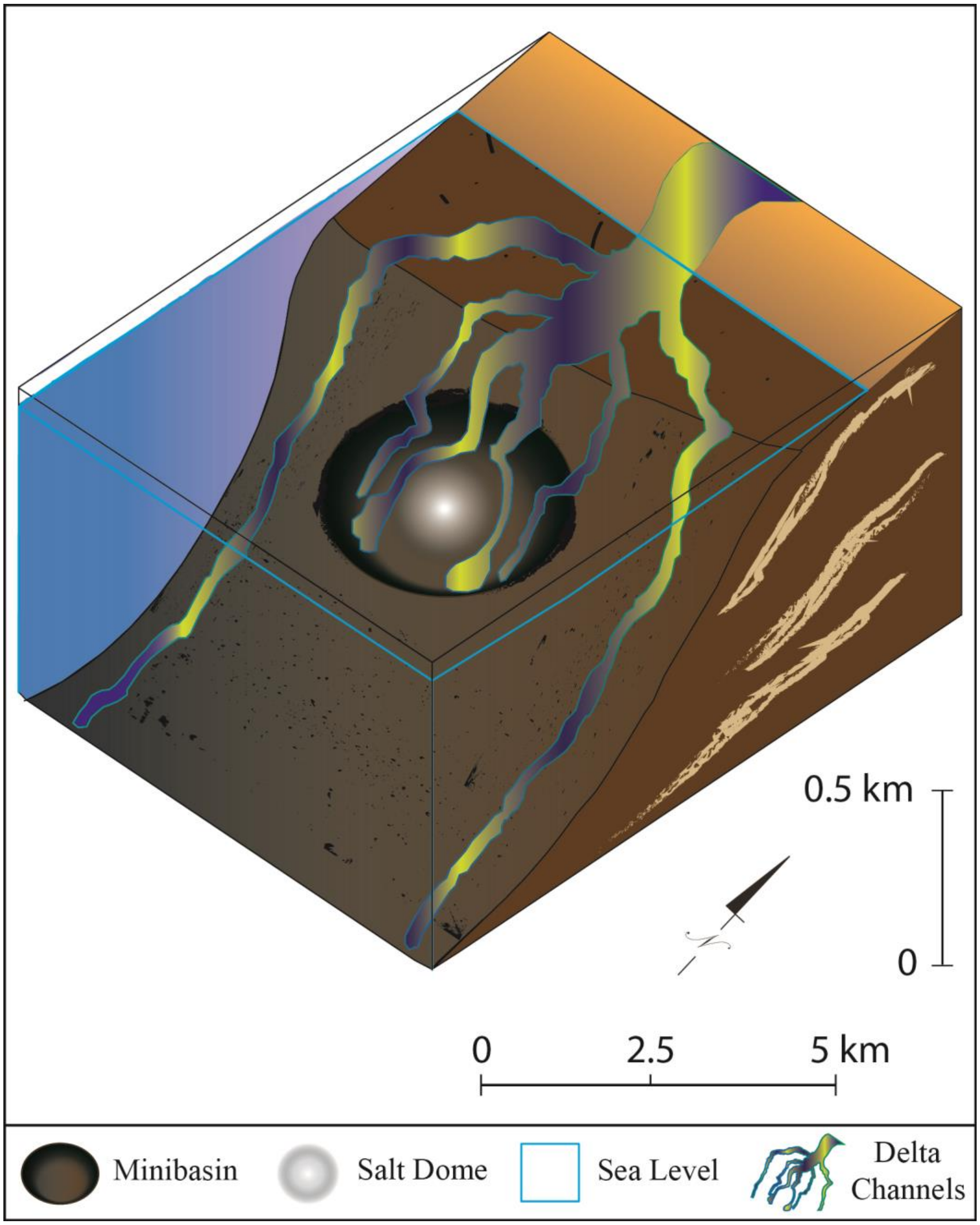


Figure 17. Schematic Diagram of the MW shelf edge delta

Another episode of thick mud (~152 m) deposition occurred following the MW sand. This mud deposition likely filled the White Castle minibasin. Consequently, the depositional environment shifted from slope to shelf during this time. At the top of this mud deposition, the *Bolvinia perca* benthic foraminifera marker signals the start of a falling stage systems tract (FSST) around 24 Ma (Figure 5). Two distinct sandbodies, called the MS and MT sands, were deposited during this

FSST (Figure 5). These sands likely represent delta-fringe sands deposited in an outer neritic environment (Pirson, 1977). The MS and the MT are not as laterally extensive as the overlying MR, but still can be correlated with an 8 km radius around the dome (Figures 6 and 7). Both MS and MT sands exhibit a thinning trend towards the dome (Figure 6), suggesting a synchronous deposition to salt uplift.

The FSST that deposited the MS and MT sands ended ~23 Ma when shelfal mud that surrounded White Castle was likely subaerially exposed. During this time, a river system likely incised into the exposed shelfal mud, creating a multi-storied incised valley-fill deposit (MR Sand) (Figures 18 and 19). The MR stratal package was difficult to pick in the seismic data due to poor signal quality. A reflector interpreted as a the Cris R Maximum Flooding Surface was mapped near the MR sand (figure 5). This reflector has the best signal quality and offered the most mapable surface. Snapped horizons were created off of this zero crossing down to the approximate top of the MR sand (Roden, 2015; Figure 11). A regional erosional unconformity formed during this valley incision, marking the base of the MR sand (Figure 5). The valley fill of this system can be dated by the presence of *Discorbis gravelli* benthic foraminifera to ~23 Ma (Waterman et. al, 2011). The valley fill, with a width to depth ratio of 393:1, is composed of unconsolidated to loosely consolidated sandstone ranging in grain size from very fine to fine sand with an average porosity of 30% (Shell Core Analysis Books). Similar to the MS and MT reservoirs, the MR sand thins towards the dome, suggesting a synchronous deposition to salt uplift. It appears that the axis of the incised valley system lay to the east of White Castle as indicated by the sands being the thickest there (Figure 20). The top of the MR signals a marine transgression as deposition of shelfal mudstone resumed. A depth map for this formation can be seen in Figure B3.

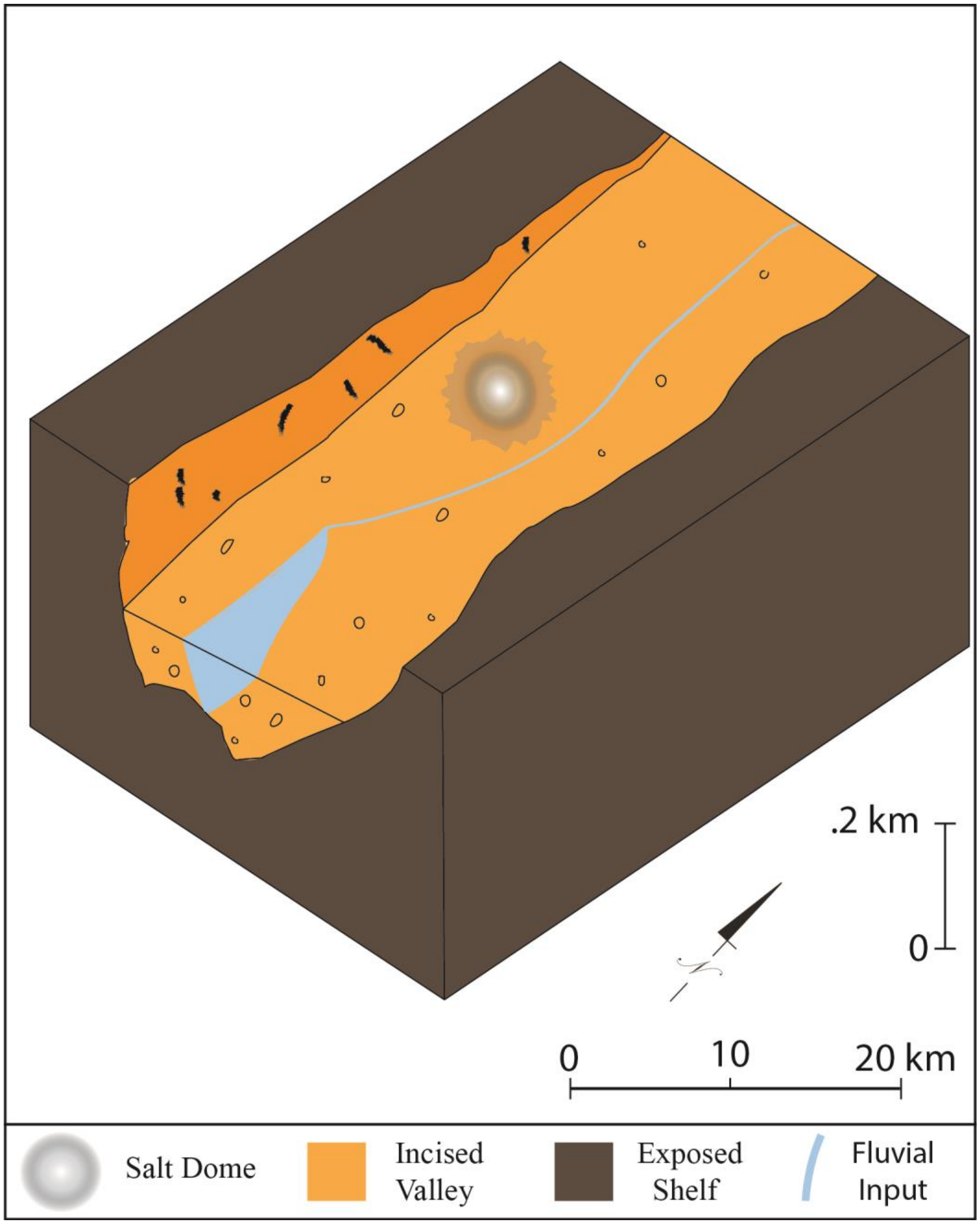


Figure 18. Schematic diagram of the MR incised valley.

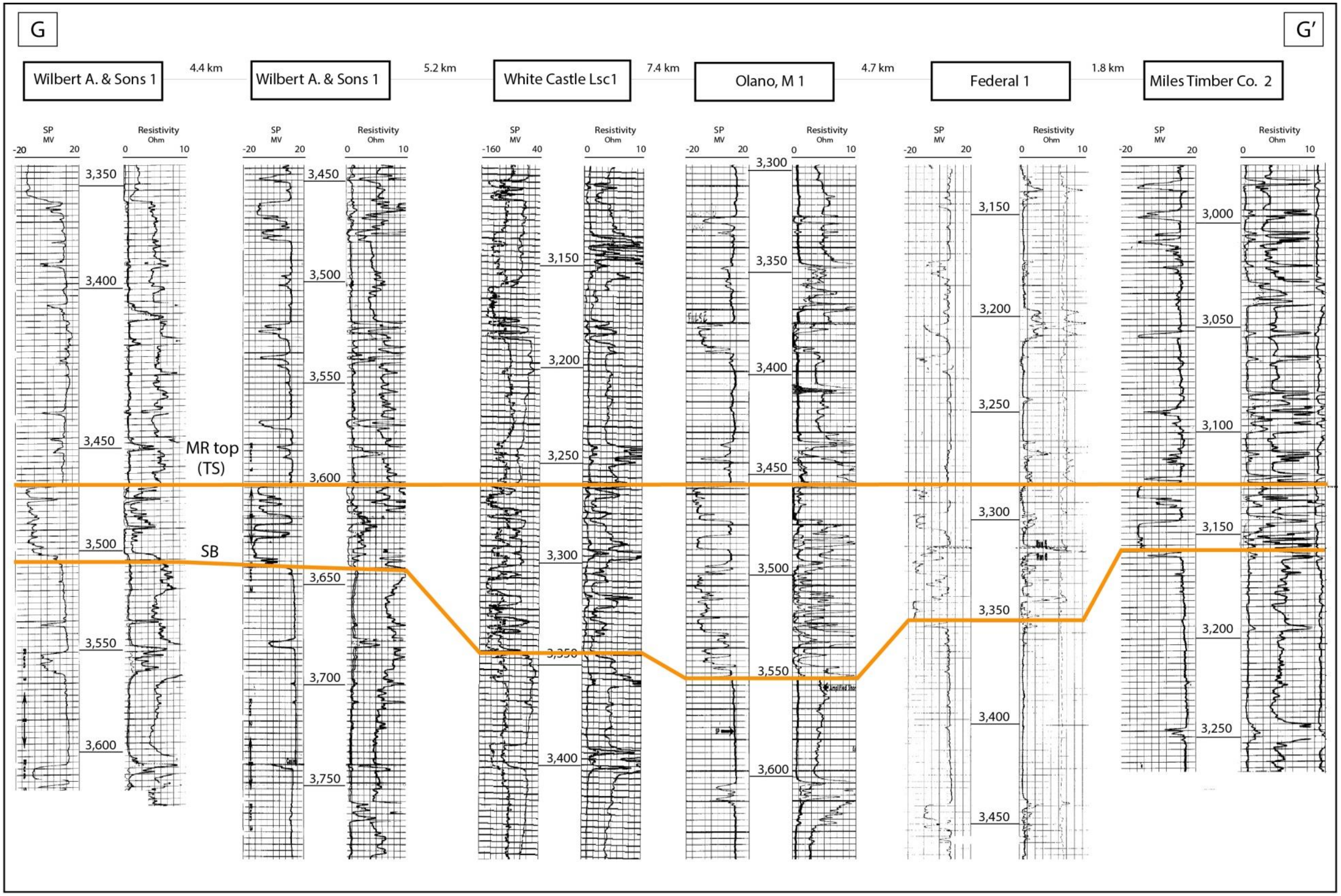


Figure 19. Cross section showing the MR incised valley system. Depth values are in meters. TS: transgressive surface, SB: sequence boundary.

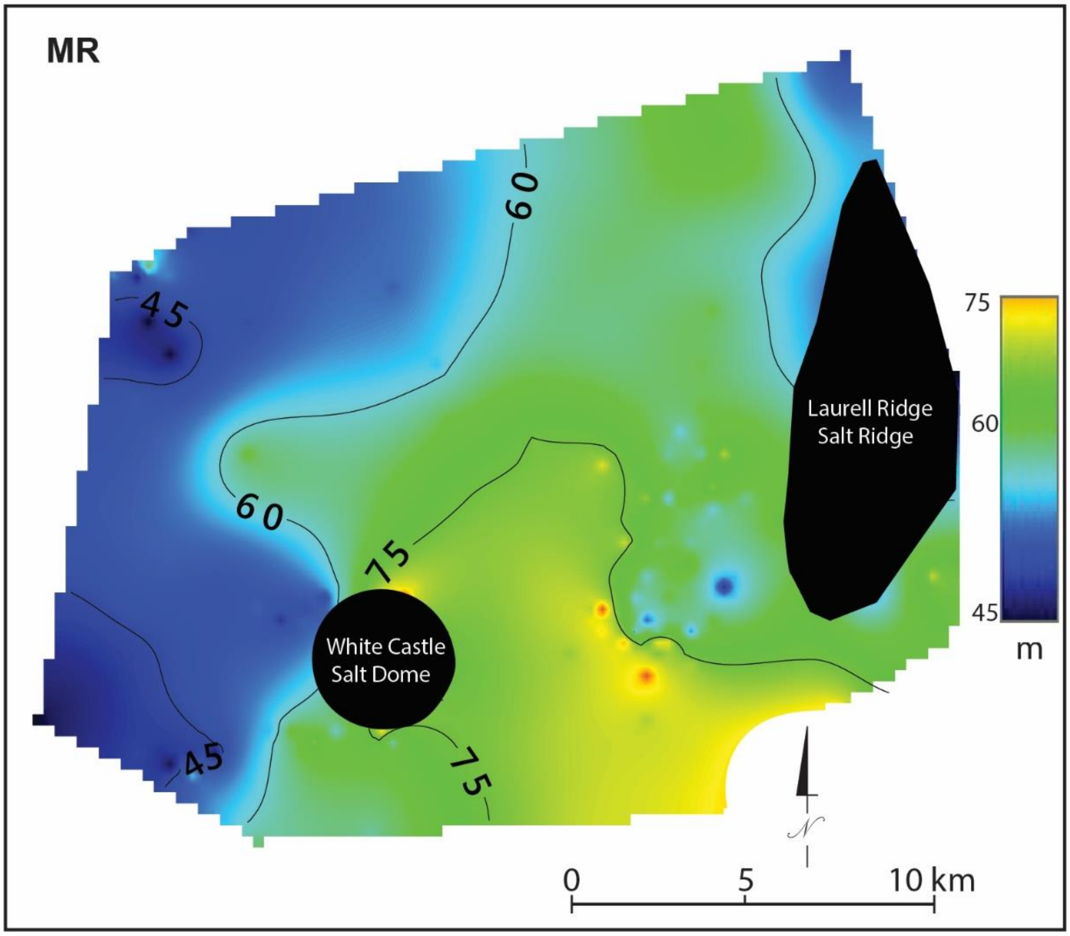


Figure 20. Isopach map of the MR

The transgression immediately following the MR sand was short-lived and is followed by the deposition of the MQ sand. The MQ sand likely represents another incised valley system caused by another sea-level drop in the study area, during which fluvial systems incised into the shelfal mud. This valley system is thinner and less wide than the MR system. The MQ sand is composed of unconsolidated to loosely consolidated sandstone ranging in grain size from very fine to fine sand with an average porosity of 31% (Shell Core Analysis Books). Like the MR sand, it thins as it approaches the White Castle salt dome, suggesting that the incised valley system was deposited contemporaneously with salt uplift. At the top of the MQ lies another transgressive surface that signals the beginning of a transgressive systems tract (TST).

The *Cristellaria "R"* benthic foraminifera tops the studied interval and was deposited during a TST. This Cris R interval, dated at 23 Ma (Waterman et. al, 2012), represents a calcareous shale that likely indicates development of a condensed section and associated maximum flooding surface Figure 5.

The statistical analysis conducted of the onshore sector of Louisiana revealed a total of 1,161 fields that were primarily operated before 1980. Out of the 1,161 fields, 37 fields almost identically match the production history of White Castle (i.e. they were operated by a major oil company, contain over 100 wells, and had a previous drilling success rate of <76%).

Discussion

The Cib Haz formation varies greatly in its reservoir quality throughout the White Castle minibasin (Figure 5). In some places, it offers a good quality reservoir (e.g.,Forest Home Partnership #1; porosity data was unavailable, but the well produced significant amounts of hydrocarbons). However, in other places (e.g.,Wilbert #307, 8.9% porosity) it offers a tight reservoir (Figure 2; Sonris, 2015; Bruno and Kryza , 1994). This ambiguity in reservoir quality detracts from this formation being an appealing exploration target. However, potential exists particularly on the northwestern, western, and southwestern flanks of the White Castle Dome.

One well (Brock #1) has penetrated the Cib Haz formation and found it to be dry on the northwest flank (Figure 2). This should not render the entire northwest flank of the dome to be hydrocarbon barren. The White Castle Salt Dome typically has a very thin halo of oil in the immediate vicinity of the salt-sediment interface (Hjerpe, 1967). This well likely was located too far down dip from the salt dome to encounter hydrocarbons. Moreover, no well along the western flank has penetrated deep enough to test the Cib Haz sands. Both the northwestern and the southwestern flank contain the Cib Haz formation. It is likely that the Cib Haz reservoir rock should exist between these two locations. Finally, only one well (Zenergy #1) was drilled on the southwestern flank to test the Cib Haz (Figure 2). This well suffered from mechanical trouble and was unable to take a sidewall core of the Cib Haz formation. This well also never perforated the sand interval, which leaves this location as an untested area (Sonris, 2015).

The MW reservoir offers the most promise for exploration targets (Figure 5). While not laterally extensive around the White Castle Dome, the MW has proven to be the best reservoir in the White Castle Field. In fact, the Wilbert #193 well (Figure 2) produced over 5.4 MMBO and 8.4 BCFG from the MW. The MW reservoir defies the convention of looking up dip for recoverable reserves on a salt dome. The MW channel systems were deflected away from the structural high created by the dome and deposited in the structurally low areas surrounding the domal relief (Figure 17; Fails, 1995). Although the western branch of the deltaic channel system displays a poorly developed reservoir, it has been tested by only two wells (BC #1 and Brock #1; Figure 2). This makes the entire western flank of White Castle prospective in the search for a better developed reservoir. Seismic geomorphology could be suitable for exploration of this sand. Unfortunately, the seismic data available for this study was not of sufficient quality to be able to image any channels.

Apart from the Dorceyville field that lies along the northern boundary of the minibasin, the MW sand has largely been untested in the eastern part of the minibasin. Acquisition of a high resolution 3D seismic survey in this area could illuminate if there are any other channel branches of this shelf edge delta system. If any such branches exist, they will likely offer excellent exploration targets.

The MS and MT sands have produced sporadically throughout the White Castle field with the only semi-reliable production coming from the northeastern flank (Brown, 2000). However, a well drilled in 2008 (Zenergy #1; Figure 2) on the south side of the White Castle field discovered an oil-bearing MS/MT section. This discovery was extremely important, as the southern flank of the White Castle Dome is largely hydrocarbon barren in the late Oligocene section compared with the other flanks of the dome (Brown, 2000). Earlier, it was believed that an off structure faulting system likely prevented hydrocarbon migration to the southern flank of the dome (Hjerpe, 1967). As a result of this recent discovery, several prospects in the MS/MT now exist on the south flank of the field.

The MR sand has been productive in both the Laurel Ridge field and the White Castle field (Figures 2 and 5; McCormick and Kline, 1983). Although both fields appear to have drained this sand extensively, this study suggests one exploration possibility associated with the MR sand in the study area. This exploration target coincides with the off structure faulting discovered in the Zenergy #1 well (Figures 2 and 21). The Zenergy well log is difficult to correlate as there is no paleontological data available for this well and it was a 4,572 m directional well that considerably distorted the SP log response. However, it appears that this well did not encounter the MR sand in the off structure fault closure in which the productive MS/MT was located. Instead, it encountered the MR sand in a down-dip fault block that abuts the salt. This leaves the off structure faulting network as a completely untested area of exploration for the MR sand.

The MR fluvial system presents an exploration target outside the study area. The delta system that the MR incising fluvial channel fed would also be a good exploration target. It is likely that this was a shelf edge delta system located basinwards (south) of the White Castle area. A likely location for this delta system would have been in the proximity of the Napoleonville Salt Dome

(Figure 2). This dome,(located 19 km southeast from White Castle, likely formed its own minibasin that would have acted as a sediment sink for this delta system.

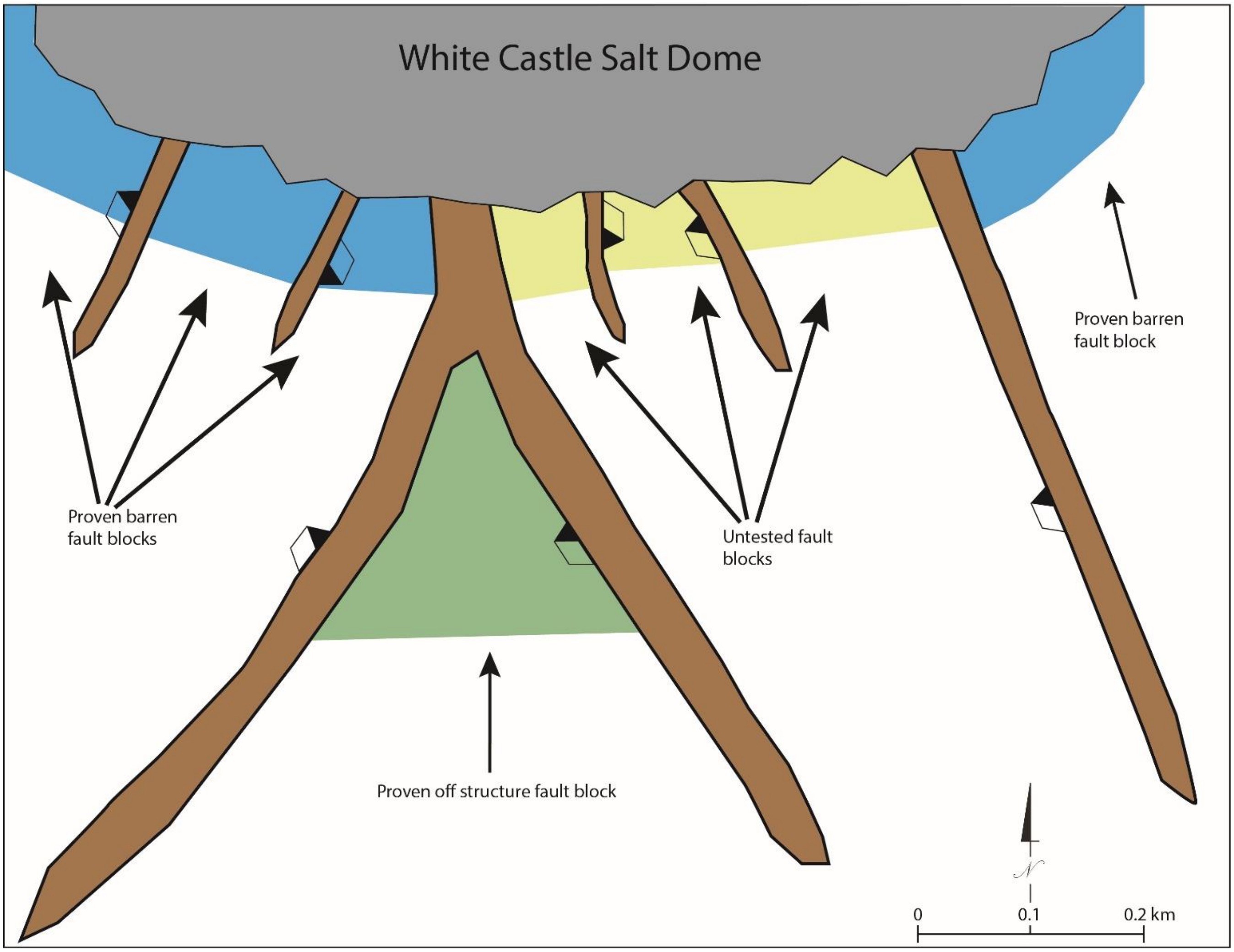


Figure 21. Generalized structure map of the off structure faulting on the southern flank of the dome. Depths not shown per request by Haland Energy.

There remains deeper potential at White Castle. The base of the salt was not imaged by the seismic data, and the deepest well penetrates to ~4,572 m. The sheath that is present in the southwestern part of the dome is composed of Frio (lithographic zone of late Oligocene) shales (Figures 5 and 22). This suggests that the salt dome’s initial movement was during the Frio time and that the minibasin could be as old as 30 Ma. The top of the Cib Haz formation dates to 27.55 Ma, which leaves up to 2.45 Myr of deposition unaccounted for. There could be reservoirs that were deposited in this unaccounted time. According to the sea level chart used for this study (Waterman et al., 2011), two sea level rise/fall cycles occurred during the Frio time prior to the Cib Haz deposition. The LST's of these cycles could allow for the deposition of reservoir quality rock in the White Castle Minibasin. The corresponding foraminifera for these LST's are the *Marginulina texana* (~28.5 Ma) and the *Bolvinia mexicana* (~29.6 Ma) (Figure 23).These possible reservoirs likely represents either abysal fan deposits or slumped continental shelf deposits similar to the Cib Haz. The Bayou Pigeon Salt Ridge that lies to the southwest of White Castle contains a sandy interval in the *Marginulina texana* time period (Foster Williams #1 well; Figure 2 and 24; Sonris). This salt ridge likely functions as the southwestern boundary of the White Castle Minibasin, and the existence of sand at the southwestern margin of the minibasin further reinforces the theory that sandy intervals during these times could exist.

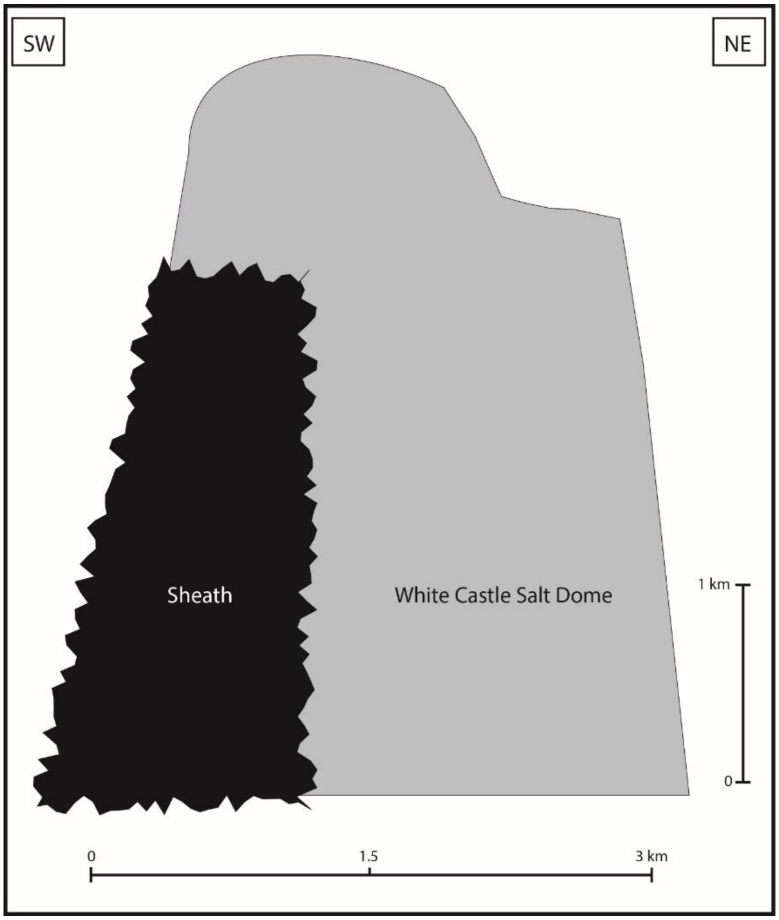
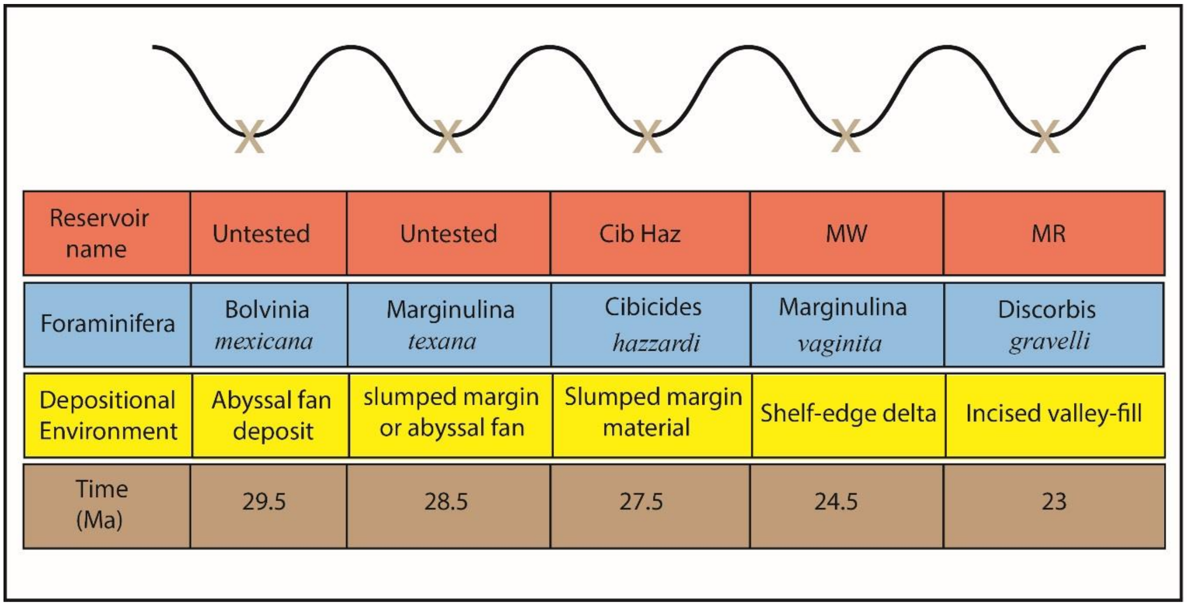


Figure 22. Schematic Diagram of the Frio aged sheath located on the southwest flank of the dome.



Reservoir name	Untested	Untested	Cib Haz	MW	MR
Foraminifera	Bolvinia *mexicana*	Marginulina *texana*	Cibicides *hazzardi*	Marginulina *vaginita*	Discorbis *gravelli*
Depositional Environment	Abyssal fan deposit	slumped margin or abyssal fan	Slumped margin material	Shelf-edge delta	Incised valley-fill
Time (Ma)	29.5	28.5	27.5	24.5	23

Figure 23. Sea level curve highlighting the lowstands responsible for reservoir deposition in the study area. The Bolvinia *mexicana* and Marginulina *texana* reservoirs have never been tested and are prospective.

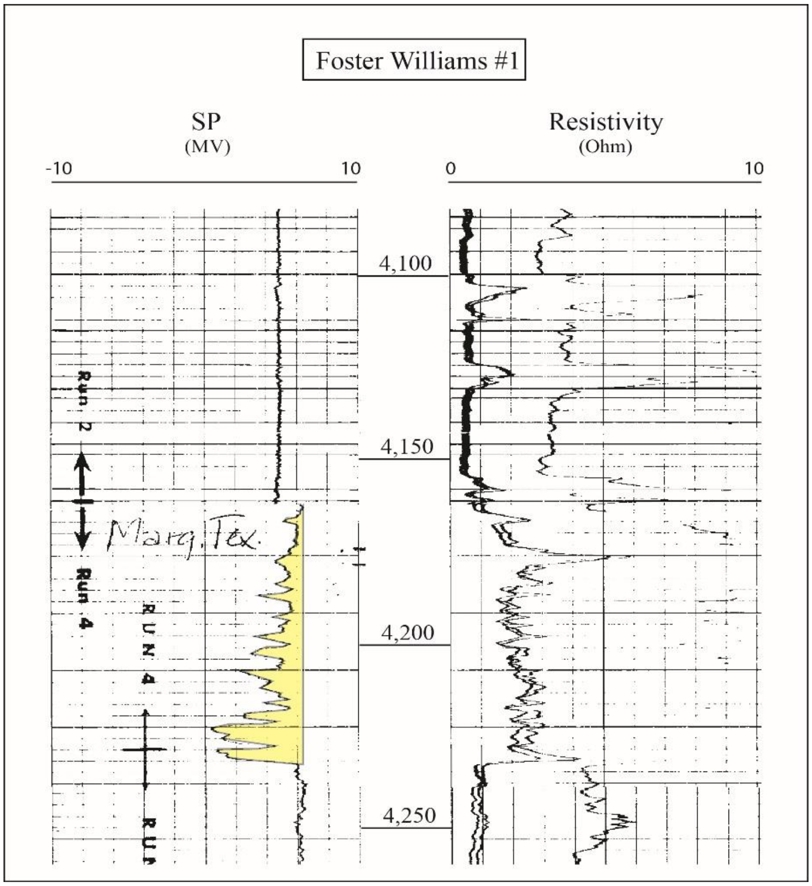


Figure 24. Log signature from the North Bayou Pigeon Field showing a sandy interval during the Marginulina *texana* time. Sandy interval highlighted in yellow. Depth values are in meters.

The cohesion volumes generated to study the faulting for this study discovered a large overhang on the southern part of the field in the late Oligocene section (Figure 25). If reservoir quality sandstone would be discovered below the Cib Haz, this overhang would become an appealing exploration target.

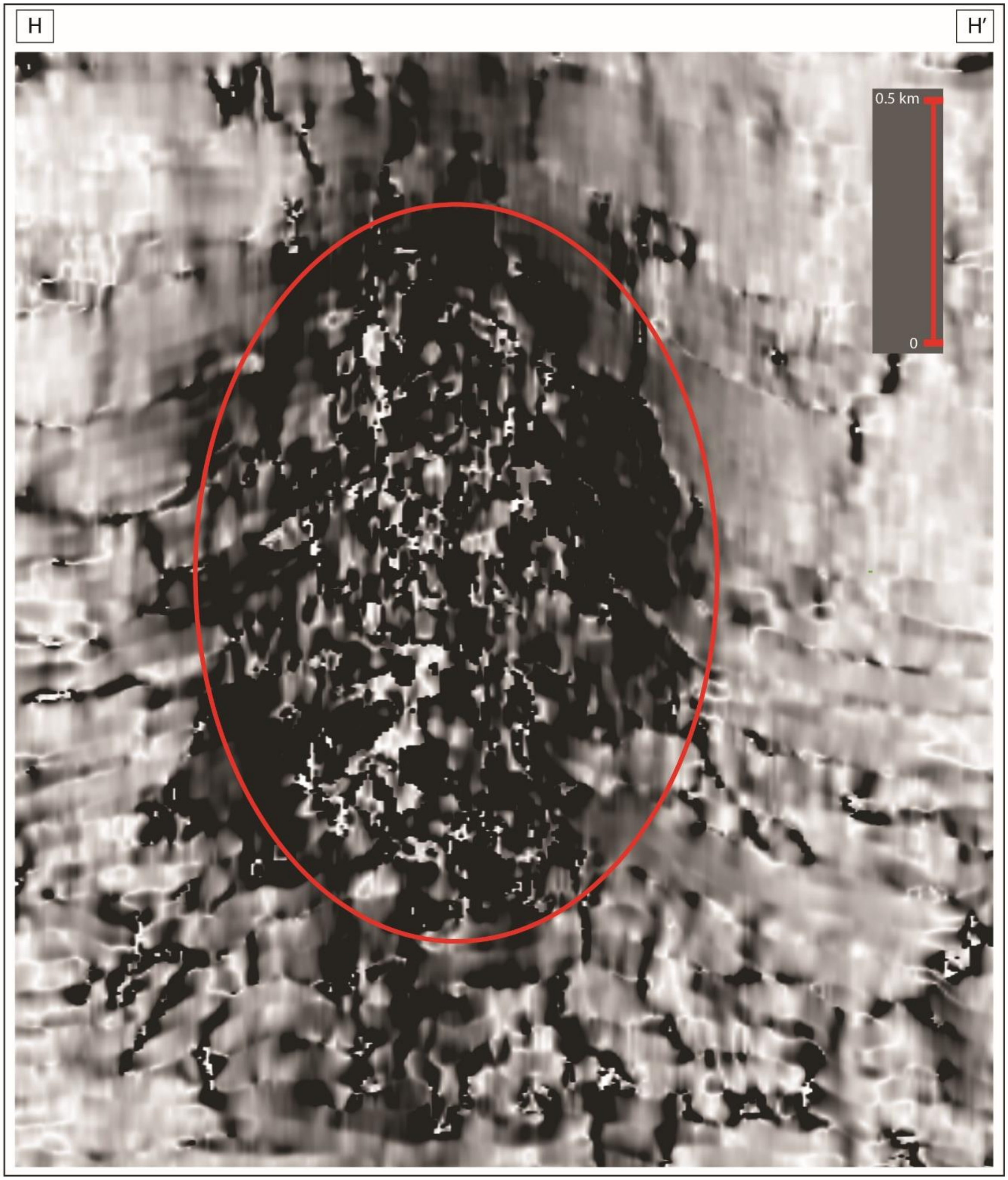


Figure 25. Cohesion vertical seismic line displaying the salt overhang on the southern flank of White Castle. The overhang is circled in red. Seismic data owned by Seismic Exchange, Inc.

The White Castle minibasin offers the possibility of a self-contained petroleum system (Lerche and Douglas, 1987). While the Eocene has been established as a possible source for the White Castle area (Pitman and Rowan, 2012), Galloway et al (1982) suggests that the Frio section could also serve as a source rock. The formation of the basin by salt withdrawal provided sufficient accommodation space for source and reservoir rocks to be deposited. The large sections of shale deposited in the basin offer good sealing potential as well as high organic content possibility. As evidenced by the uniform thinning of late Oligocene sediments towards the salt dome (Figure 6), the salt dome was at or near the surface throughout the life of the minibasin. This close proximity to the surface allows for the possibility of the salt dome being exposed to ocean water. If this was the case, the minibasin would have developed a hyper-saline environment which would have been ideal for preserving organic material (Lerche and Douglas, 1987). Since salt is a better conductor of heat than other types of sedimentary rocks, the salt would have magnified the geothermal gradient locally and increased the temperature of the source rocks resulting in the maturation of organic-rich shale and generation of hydrocarbons (Obrien and Lerche, 1984). There were ample pathways for upward migration of hydrocarbons, as there exists an extensive faulting network around the dome (cf. Sorkhabi et. al 2005). Finally, the salt dome itself provided an excellent trap due to salt's impermeability. If the White Castle minibasin is a self-contained petroleum system, a localized shale play may also exist. The sandstones in the basin are already proven as reservoirs for hydrocarbons, which could have generated from abundant shale located within the minibasin. Further, the shale immediately surrounding the dome likely developed favorable fracturing networks due to the stresses imposed on them by the growing salt dome.

Each of the 1,161 fields that were identified through the statistical study conducted during this research are candidates for a study like the one conducted here. The 37 fields that almost identically match the production history of White Castle provide the best targets. As can be seen by the large amount of onshore fields operated before 1980, there is ample opportunity throughout the onshore sector of Louisiana for studies like the one described in this research to take place.

Conclusions

This study shows how the application of modern geological concepts and technology can reopen hydrocarbon fields that were previously considered drained. As hydrocarbons become scarcer, companies have to look to more extreme environments and unconventional plays to locate reserves. Any type of additional reserves that are located in a field where hydrocarbons have already been found can prove invaluable, as it reduces risk and operating cost.

The White Castle Salt Dome is a good candidate for the application of new techniques to an old field. Here we provide the first sequence stratigraphic analysis of the study area, which led to a better understanding of the depositional processes that were responsible for depositing the reservoirs in the White castle Minibasin. The existence of deeper sands in the *Marginulina texana* and *Bolvinia mexicana* lowstands of sea level is possible and evidenced by a *Marginulina texana* sand located in the southwestern margin of the White Castle Minibasin near the Bayou Pigeon Salt Ridge.

A well drilled on the north east flank of the White Castle Salt dome targeting these sands has the best chance of encountering thick reservoirs as the principle direction of sedimentation was from the southwest during the late Oligocene. The western branch of the MW shelf edge delta system has only been tested by two wells. One of these wells proved to be productive, suggesting that there is more potential remaining on the western flank of the dome. The eastern branch of this system has produced over 12 MMBOE, proving that this formation is a good reservoir. This also bolsters the idea of unrecovered reserves in the western branch. Further, this play could be extended to the surrounding minibasin should other branches of this delta systems be discovered away from the dome. The southern flank of the dome is missing 1 MMBOE from the MR section. The off structure faulting that was located in this study is the likely cause of this missing production in the MR. Several wells targeting this off structure faulting should ensure the recovery of this missing oil. As is common with salt domes, the pay sands in the late Oligocene section are stacked and are able to be targeted by one well, which greatly decreases the overall risk of drilling these prospects.

Even though the quality of the 3D seismic data used in this study was moderate, it helped better illuminate the faulting networks around the dome and in identifying a new overhang of the dome. The aquisition of a high-resolution 3D seismic survey across the entire area of the White Castle minibasin can reveal more hydrocarbon prospects as outlined in this study. While these prospects are likely not large enough to attract the attention of a major oil company, smaller to midsize independent companies can likely operate these plays profitably.

Out of the 37 fields that closely matched White Castle in their production histories, the Darrow Field provides an exceptional opportunity for a study like the one conducted in this paper. The Darrow Field exists 24 km east of White Castle. Like White Castle, this field has a salt dome acting as its primary trap and is a member of the White Castle Salt family group. This dome likely formed a minibasin similar to the one at White Castle. There has been no 3-D seismic survey shot over this dome, and the primary exploration was done through log correlations. The field reached peak activity in 1966 and was operated by the then major oil company Humble Oil and Refining. The previous operators success rate is only 65% and the entire western flank appears to be underexplored.

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Appendix A: Seismic Data Set

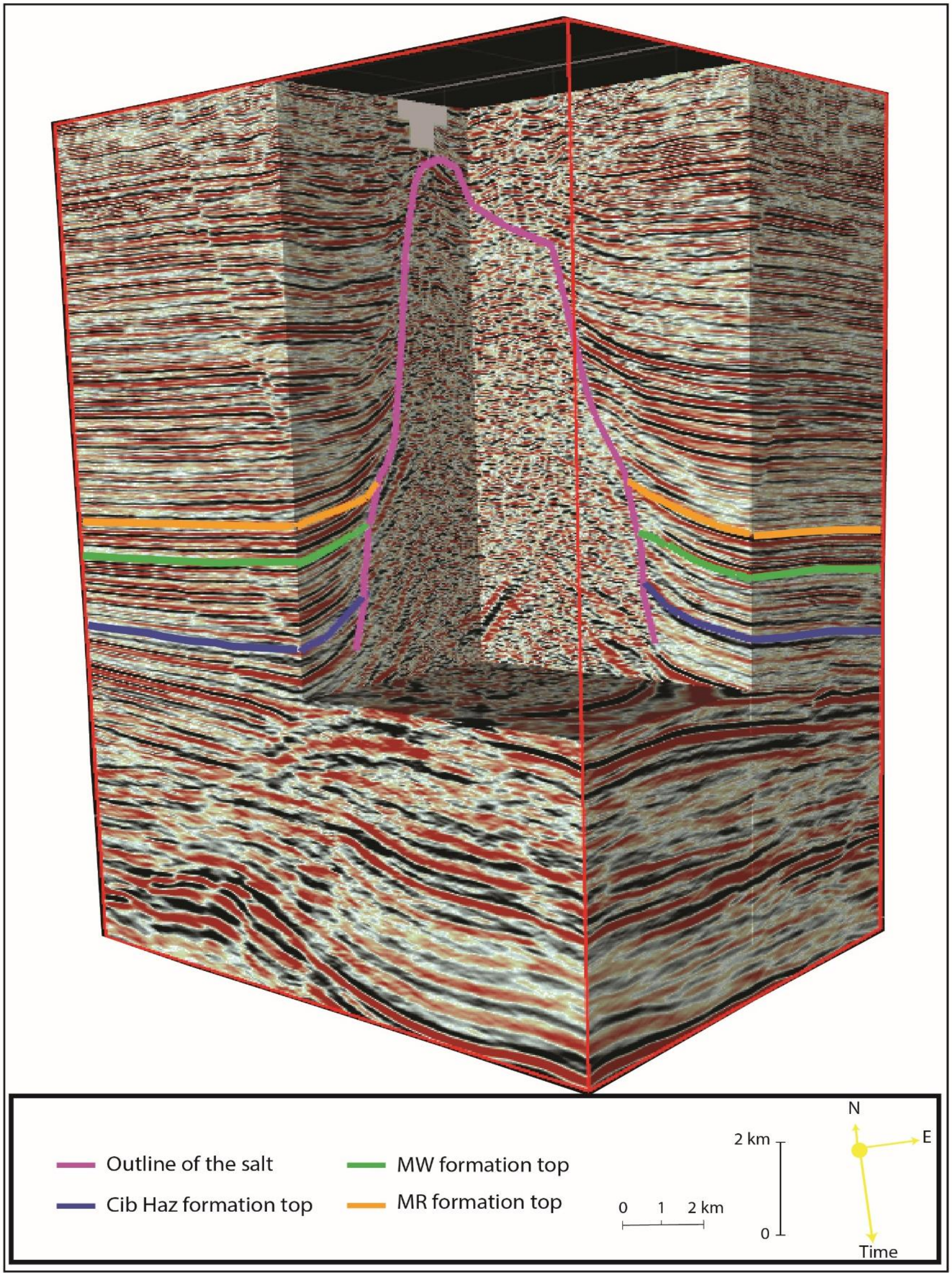
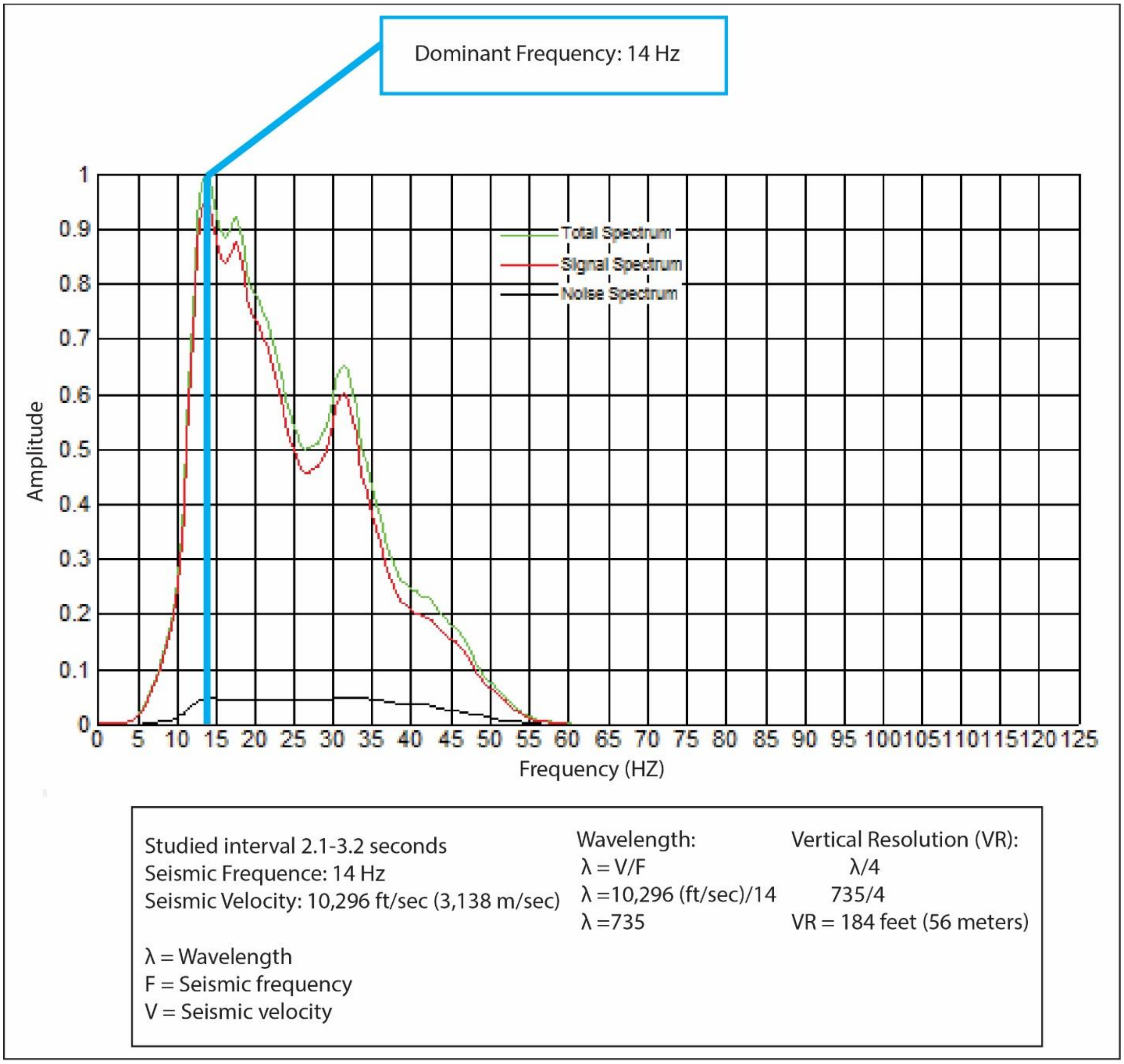


Figure A1. Example of 3D seismic data used in this study. Note the White Castle Salt Dome at the middle of the seismic volume. Seismic data owned by Seismic Exchange, Inc.



Studied interval 2.1-3.2 seconds
Seismic Frequence: 14 Hz
Seismic Velocity: 10,296 ft/sec (3,138 m/sec)

λ = Wavelength
F = Seismic frequency
V = Seismic velocity

Wavelength:
λ = V/F
λ =10,296 (ft/sec)/14
λ =735

Vertical Resolution (VR):
λ/4
735/4
VR = 184 feet (56 meters)

Figure A2. Vertical Resolution of the studied section

Shot Date: 08/1996
Shot By: United Seismic Acquisitions, Inc.
Bin Size: 75x75
Record Length: 10
Sample Interval: 10
Fold: 32
Energy Source: Dynamite

Table A1. Seismic acquisition parameters. Seismic data owned by Seismic Exchange, Inc.

PROCESSING FLOW: (3D PRESTACK TIME MIGRATION STACK FXY RHO AGC1000)
REFORMAT SEGY 4MS.
GEOMETRY Q.C.
AMPLITUDE RECOVERY
FK LINEAR NOISE ATTENUATION
WTF NOISE ATTENUATION
TFD NOISE ATTENUATION
HAND EDITING
SURFACE CONSISTANT SCALING C30 SURFACE CONSISTANT DECON(SPIKE)
DESPIKE
RESIDUAL STATICS
PRESTACK TIME MIGRATION
STACK ALL OFFSETS
FXY DECON
RHO FILTER
AGC 1000

Table A2. Seismic processing workflow. Seismic data owned by Seismic Exchange, Inc.

Appendix B: Depth Maps

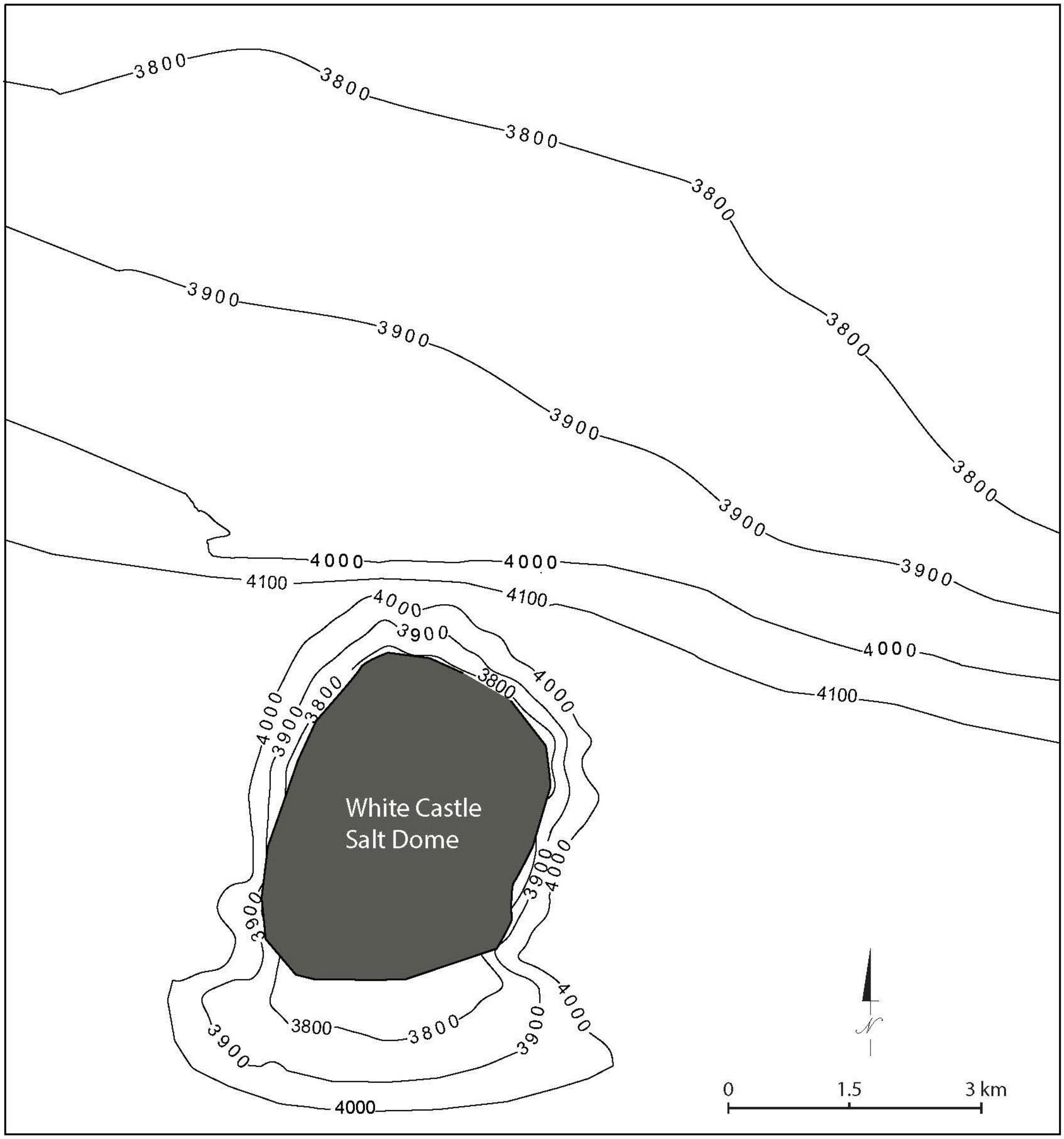


Figure B1. Depth map of the Cib Haz reservoir. Depth units are in meters. Map was created by merging seismic data (where available) with interpolated data from well log picks. Contour interval: 100 meters.

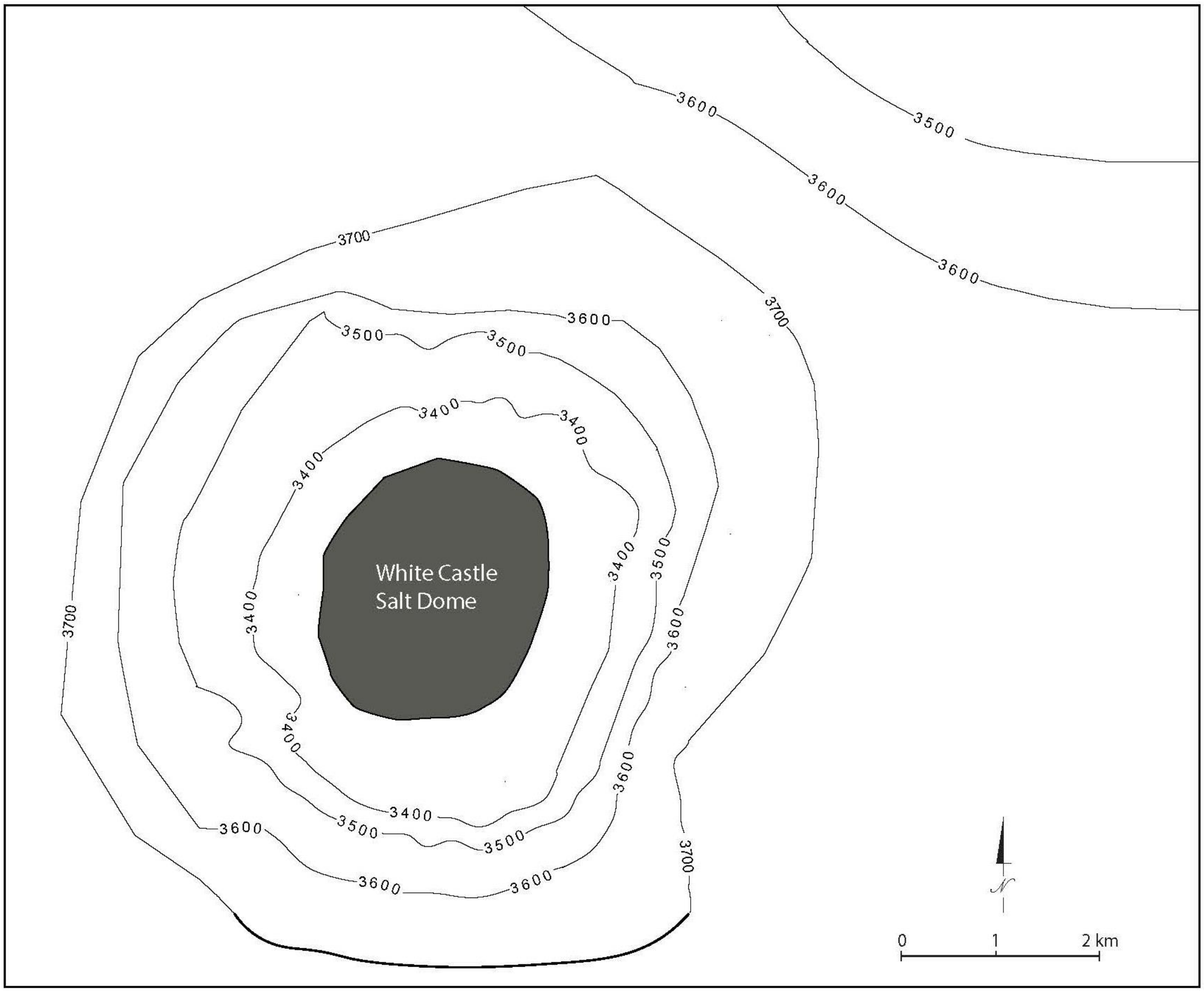


Figure B2. Depth map of the MW reservoir. Depth units are in meters. Map was created by merging seismic data (where available) with interpolated data from well log picks. Contour interval: 100 meters.

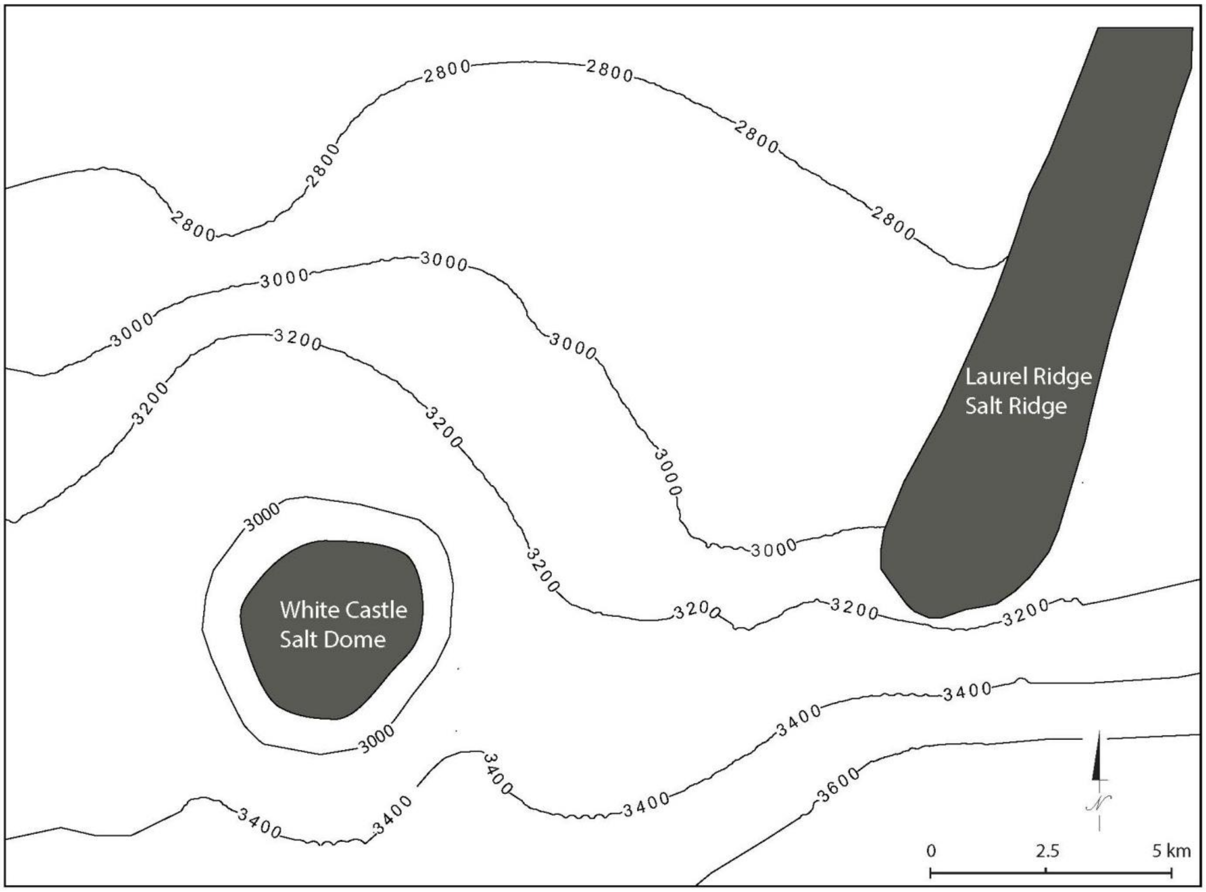


Figure B3. Depth map of the MR reservoir. Depth units are in meters. Map was created by merging seismic data (where available) with interpolated data from well log picks. Contour interval: 200 meters.

Permission to use seismic data from Seismic Exchange, Inc.

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Mr. Mark Margason
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1 North Wacker Drive
Suite 4000
Chicago, Illinois 60606

Re: Permission to Publish SEI Seismic Data

Dear Mr. Margason and Mr. Hulsey,

Haland Energy Partners, LLC ("Haland") has requested permission for Josiah Hulsey ("Josiah") to publish proprietary 3D seismic data owned or controlled by Seismic Exchange, Inc. ("SEI"), located in Iberville Parish, Louisiana and referred to as the White Castle Dome 3D Survey ("Data"). Josiah is a graduate student at The University of New Orleans and has utilized the Data for his thesis and an article to be published in *AAPG Interpretation*, both entitled "Applying modern interpretation techniques to old hydrocarbon fields to find new reserves: A case study in the onshore Gulf of Mexico, U.S.A.". The Data was licensed to Haland for use under Supplemental Agreement No. 13-0515-3D dated October 11, 2013, SEI hereby grants permission for Josiah to utilize the Data for the purposes stated above and subject to Josiah and Haland both executing and complying with the terms of this agreement.

Haland agrees that it shall be fully responsible for ensuring Josiah's compliance herewith including, but not limited to, ensuring that the Data is returned to Haland immediately following completion of Josiah's thesis and article.

Haland and Josiah acknowledge that SEI's proprietary seismic data is a valuable trade secret and asset of SEI and the following terms and conditions must be complied with in the use of the Data:

1. The Data as displayed on Exhibit "A" ("Data Image(s)") will not be disclosed to any outside parties except as described herein for inclusion in the thesis and article or in accordance with the License as defined below.
2. The Data Image(s), in paper form, shall be no larger than 8.5" x 11".
3. The Data Image(s) have been modified to comply with SEI's requirements and any further changes or modifications must be reviewed and approved by SEI in writing in advance of the disclosure. Any disclosure of Data that is not in compliance with the Master Geophysical Data Use License by and between SEI and Haland effective October 9, 2013 (the "License"), or this agreement, shall be deemed a material breach of the License.
4. SEI may request the return of the Data at an earlier date in the event that SEI determines that such disclosures of the Data are counter to the interests of SEI.
5. In no event shall any third party to whom Josiah discloses the Data or Data Image(s) be allowed to work, interpret, or utilize the Data in any manner.

6. In the event Josiah ceases to be enrolled as a graduate student at The University of New Orleans, then this permission for publication shall terminate and Josiah shall have no further right to use and/or publish the Data. Upon completion of his thesis, Josiah shall immediately return any and all copies of the Data to Haland, but may retain copies of the Data Image(s).

Please let me know if you have any questions regarding the above terms and conditions. If these terms and conditions are acceptable, please so indicate by signing below. Please let us know if we may be of further assistance.

Sincerely,
Seismic Exchange, Inc.

Julie Kay Hardie
Julie Kay Hardie
Vice President - Legal

Agreed to and accepted this 9th day of February, 2016

By:
Josiah Hulsey
The University of New Orleans

Agreed to and accepted this 9th day of FEBRUARY, 2016

By:
Mark Margason
Haland Energy Partners, LLC

Exhibit A

Figure 6

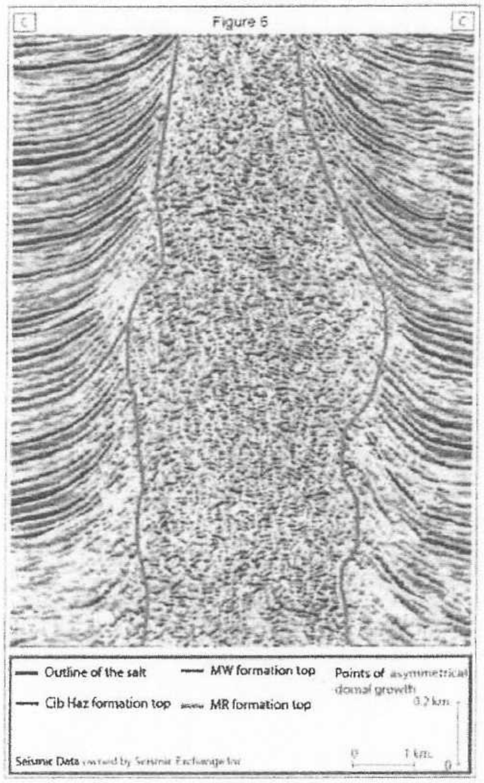
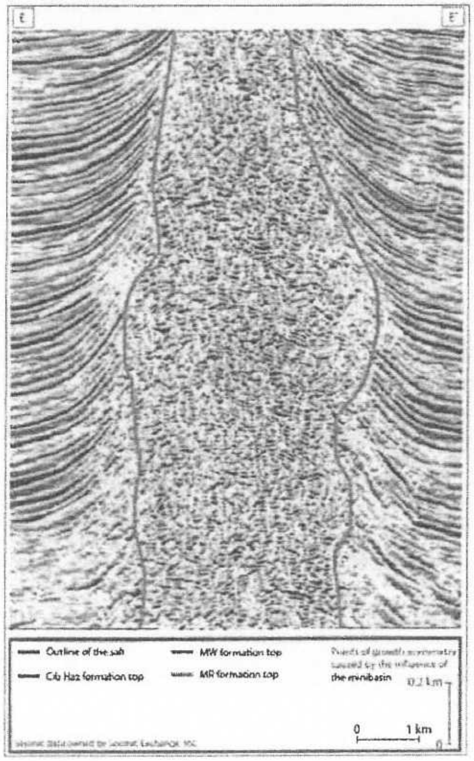
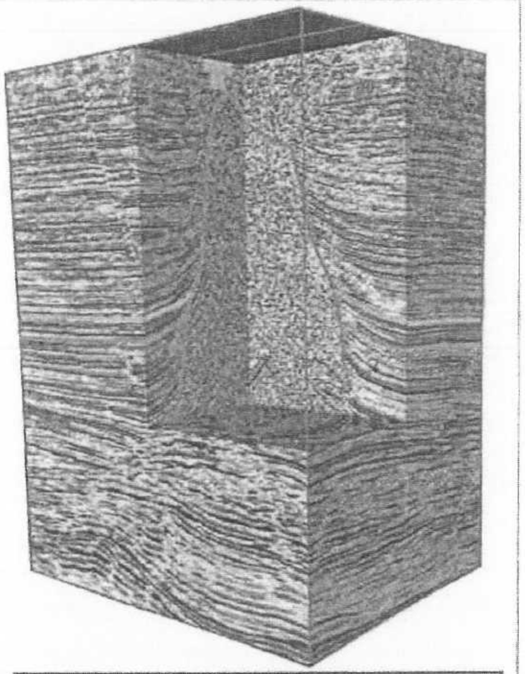


Figure 6



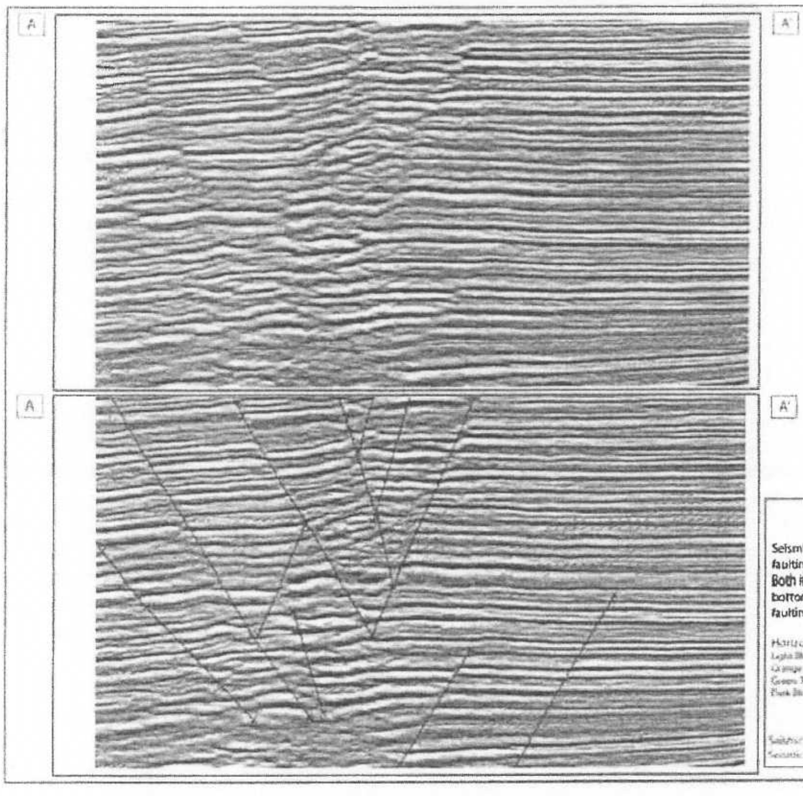


Appendix Figure 2

Example of 3D **seismic data** used in this study. **Note the White Castle** Salt Dome is at the middle of the seismic volume.

- Outline of the salt
- Cib Haz formation top
- MW formation top
- MR formation top

Seismic data owned by Seismic Exchange, Inc.

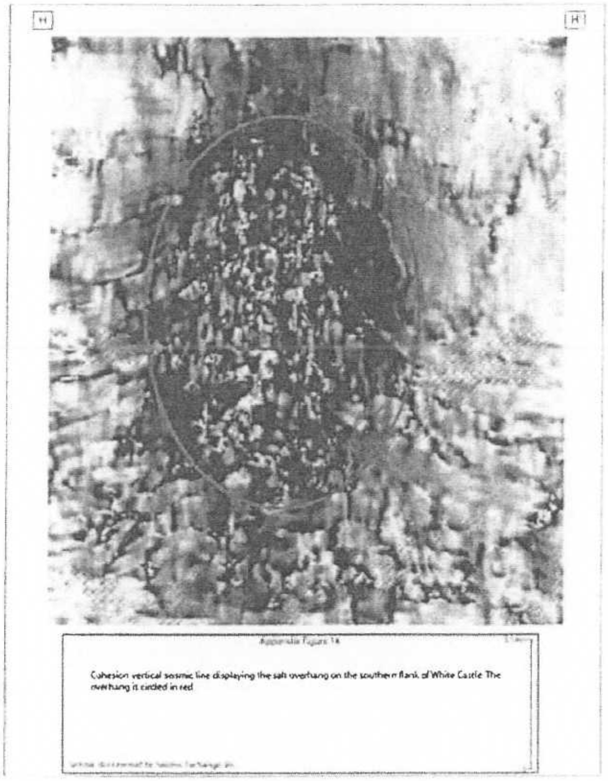


Appendix Figure 5

Seismic line displaying the severity of faulting on the White Castle Salt dome. Both images are of the same line. The bottom image displays the interpreted faulting.

Horizons:
Light Blue: Top of Cris R Maximum Flooding surface
Orange: Top of MR Sand
Green: Top of MW Sand
Dark Blue: Top of Cib Haz

Seismic data owned by
Seismic Exchange, Inc.



Appendix Figure 14

Cohesion vertical seismic line displaying the salt overhang on the southern flank of White Castle The overhang it circled in red

Vita

The author was born in Evansville, Indiana, in 1991. Josiah completed his high school work at Triad High School in Troy, Illinois, in 2009. From there he attended Southwestern Illinois Community College (SWIC) for a year to obtain core college credits. Following SWIC, he attended Wheaton College (Illinois) and obtained his Bachelor’s degree in geology in 2013. After graduating from Wheaton College, Josiah began work as a geologist for Haland Energy Company. Haland requested the author obtain his Master’s degree at the University of New Orleans, and in 2014 he joined the University of New Orleans Earth and Environmental Science Graduate Program to pursue a MS in Earth and Environmental Sciences.