GEOLOGICAL CHARACTERIZATION AND CO_2 STORAGE POTENTIAL OF CRETACEOUS SANDSTONE IN THE DESOTO CANYON SALT BASIN OF THE MAFLA SHELF

By

AVINASH CHANDRA

Bachelor of Technology in Mining Engineering

Indian School of Mines

Dhanbad, India

2008

Submitted to the Faculty of the
Graduate College of the
Oklahoma State University
in partial fulfillment of
the requirements for
the Degree of
MASTER OF SCIENCE
May, 2018

GEOLOGICAL CHARACTERIZATION AND CO_2 STORAGE POTENTIAL OF CRETACEOUS SANDSTONE IN THE DESOTO CANYON SALT BASIN OF THE MAFLA SHELF

Thesis Approved:

Dr. Jack C. Pashin

Thesis Adviser

Dr. Jim Puckette

Dr. Ahmed Ismail

ACKNOWLEDGEMENTS

I am pleased to have this opportunity to thank everyone who have helped me with this research project. I am most indebted to my advisor, Dr. Jack Pashin, the chairman of this thesis, for sharing his research expertise, technical insights and moral support. I would also like to thank all of committee members, Dr. Jim Puckette and Dr. Ahmed Ismail for their invaluable input, inspiring questions, and support for both, the thesis and my academic progress.

I am thankful to the U.S. Department of Energy National Energy Laboratory for providing funding for this project through the Southern States Energy Board (Subgrant SSEB-SOSRA-981-OSU-2015-001rev).

This journey would not have even started in the first place if not for my exceptional mentors and friends I met during my initial professional life. Thanks for pushing me through and inspiring for greater accomplishments. A huge thanks to my friends and fellow graduate students at Boone Pickens School of Geology too, who made these couple of years enriching and rewarding. Naming just a few would not do justice to my immense gratitude for them all.

Finally, Ram, there are no steps taken without you. All my successes are mere reflections of your blessings!

Name: AVINASH CHANDRA

Date of Degree: MAY, 2018

Title of Study: GEOLOGICAL CHARACTERIZATION AND CO_2 STORAGE POTENTIAL OF CRETACEOUS SANDSTONE IN THE DESOTO CANYON SALT BASIN OF THE MAFLA SHELF

Major Field: GEOLOGY

Abstract: The southeastern U.S. constitutes more than 40% of anthropogenic CO_2 emissions in the U.S., and most of this is emitted within 50 miles of the coast. Uniform government ownership, high capacity, and favorable source location indicate that the offshore continental shelf could be an attractive location for anthropogenic CO_2 storage. This study focuses on understanding the depositional framework of the Cretaceous sandstone units in the Desoto Canyon Salt Basin in the Destin Dome, Mobile, Pensacola and Viosca Knoll Areas offshore of Mississippi, Alabama, and the Florida Panhandle and understand their potential for CO_2 storage. Detailed analysis of geophysical well logs indicate that sandstone of the Paluxy Formation (Lower Cretaceous) and the lower Tuscaloosa Group (Upper Cretaceous) are the principal Cretaceous targets for CO_2 storage in the study area. Target reservoir units in the Paluxy Formation are sealed by shale and limestone of the Washita-Fredericksburg interval, and those in the lower Tuscaloosa Group are sealed by a thick succession of Upper Cretaceous shale and chalk, as well as the overlying Paleogene mudrock successions.

The Paluxy Formation is a thick (>1,100 ft) progradational package of interbedded sandstone and mudstone that was deposited primarily by aggradation, apparently in coastal plain and shore-zone environments. The basal Washita-Fredericksburg interval (>1,000 ft) is predominantly limestone which passes upward into interbedded sandstone and mudstone resembling that in the Paluxy Formation. The lower Tuscaloosa Group contains the Massive sand (100-350 ft), which was deposited primarily as coastal deposits. Geophysical well log analysis reveals that while the lower Tuscaloosa and Paluxy sandstone are quartzose, thick (>120 feet), and generally possess high porosity (~18-21%), the reservoirs in the Washita-Fredericksburg interval have modest thickness (<60 ft).

Volumetric estimation of the storage resource in the reservoir units confirms Gt-class capacity in the nearshore part of the study area, where well control provides adequate volumetric constraint. The combined storage potential of the Cretaceous sandstone units is 28 Gt. Due to minimal seal and reservoir integrity risks, close well control, and thickest net sandstone (2.9 Mt/km^2), the stable shelf of Mobile and Viosca Knoll Areas has been identified as the optimal injection location. Each offshore block in this area is capable of sequestering annual emissions from 13 major power plants (~5 Mt/yr). Detailed understanding of reservoir architecture and depositional environment will help select field-scale commercialization strategies such as multi-zone, single-zone and directional injection of anthropogenic CO_2 to maximize the available potential.

TABLE OF CONTENTS

Chapter Page

LIST OF TABLES

Table Page

LIST OF FIGURES

Figure Page

LIST OF PLATES

PLATES Page

CHAPTER I

INTRODUCTION

Statement of Purpose

Anthropogenic CO_2 emissions in the U.S. were almost 6 gigatonnes (Gt) in 2012 according to the U.S. Environmental Protection Agency (EPA). About half of the U.S. population now resides within 50 miles of the coast (Markham, 2009) and is at risk from rising sea level and associated processes related to climate change. Concentration of coal-fired power plants in or near coastal regions makes offshore CO_2 storage an attractive option for greenhouse gas mitigation. Indeed, the Southeastern U.S. constitutes about 40% of the nation's anthropogenic CO_2 emissions (SSEB, 2013).

Numerous studies have assessed the potential for onshore CO_2 storage in the Southeastern U.S. (e.g., Koperna et al., 2009, 2012; Pashin et al., 2009; Esposito et al., 2010). Hills and Pashin (2010) have suggested that about 170 Gt of CO_2 can be stored in Miocene sandstone and at least another 30 Gt in deeper Cretaceous formations offshore of Alabama and Mississippi. However, a static geological assessment of the eastern Gulf of Mexico that is consistent with the methodology proscribed by the National Energy Technology Laboratory (NETL) (Goodman et al., 2011; NETL, 2012) is required to identify and quantify the potential for offshore CO_2 storage.

Uniform governmental ownership, favorable source-sink relationships, and apparently high capacity indicate that the offshore continental shelf could be an attractive location for anthropogenic CO_2 storage. The Southeast Offshore Storage Resource Assessment (SOSRA), funded by NETL through the Southern States Energy Board (SSEB), is designed to determine the CO_2 storage capacity in the eastern Gulf of Mexico. This study focuses on Desoto Canyon Salt Basin, which includes the Destin Dome, Mobile, Pensacola and Viosca Knoll Areas of the Mississippi-Alabama-Florida (MAFLA) shelf.

Geothermal data in the region suggests that the formations are geopressured at depths greater than 12,000 feet (Nagihara and Jones, 2005; Nagihara and Smith, 2005; Pashin et al., 2016), which would add significantly to development costs for offshore CO_2 storage. Cretaceous-age sandstone units above geopressure, however, are abundant and appear to constitute attractive storage objectives. Accordingly, this research focuses on characterizing the Cretaceous sandstone formations above geopressure in the study area, documenting their stratigraphy, sedimentology, and reservoir characteristics, and quantifying their static CO_2 storage potential.

The overarching goal of this research is to understand the geologic framework and determine the CO_2 storage capacity of the Cretaceous System in the DeSoto Canyon Salt Basin by developing a fundamental understanding of reservoir-seal distribution and reservoir quality. The working hypothesis behind this study is that the saline Cretaceous formations in each offshore block of the study area can store annual anthropogenic CO_2 emissions from multiple coal-fired power plants. To test this hypothesis, this thesis focuses on defining a prospective geological CO_2 storage complex in the study area and evaluate its storage potential using basic reservoir and fluid properties such as net thickness, porosity, and gas density. This study addresses the following fundamental questions:

- What are the potential Cretaceous reservoir units in the study area?
- What is the reservoir architecture and reservoir properties of these units?
- Does a suitable sink-seal relationship exist?
- What is the CO_2 storage potential of each identified reservoir?
- What are the most optimal CO_2 storage locations within the study area based on the above findings?

The key project objectives which are designed to test the hypothesis and answer these questions, are as follows: (1) Basic geological data were compiled. (2) Detailed reservoir characterization and volumetric assessment was performed. (3) Well log analysis was performed to identify and characterize potential CO_2 storage sinks and associated seals in the DeSoto Canyon Salt Basin. (4) Regional cross-sections and subsurface maps were constructed to characterize the regional stratigraphic framework and sink-seal geometry. (5) Porosity and net thickness were then used to assess the storage resource for each targeted unit. (6) Suitable injection sites were selected based on their storage potential, sink and seal integrity, and available well control. (5) A conceptual storage complex was then developed, and storage strategies were identified that may apply to the study area.

Regional Setting

The DeSoto Canyon Salt Basin contains a series of structural features and provinces, which were defined by Pashin et al. (2016) (Figure 1). The basin fill rests upon a Jurassic post-rift unconformity that is overlain by the Middle Jurassic Louann Salt. The major Mesozoic-Cenozoic structures in the basin have a salt-tectonic origin, and the regional structural style resembles that of the East Texas Salt Basin (Pashin et al., 2016). The Destin fault system is near the updip limit of Jurassic salt and is part of the regional peripheral fault system in the Gulf of Mexico Basin. Destin Dome is a major salt pillow-cored anticline that is downdip of the Destin fault system; smaller pillow-cored structures are south of Destin Dome. A salt diapir province is in the structurally deepest part of the basin, which is in the southern part of the study area. A major salt roller province characterized by arcuate extensional faults is developed in the western part of the study area; these faults extend into the diapir province.

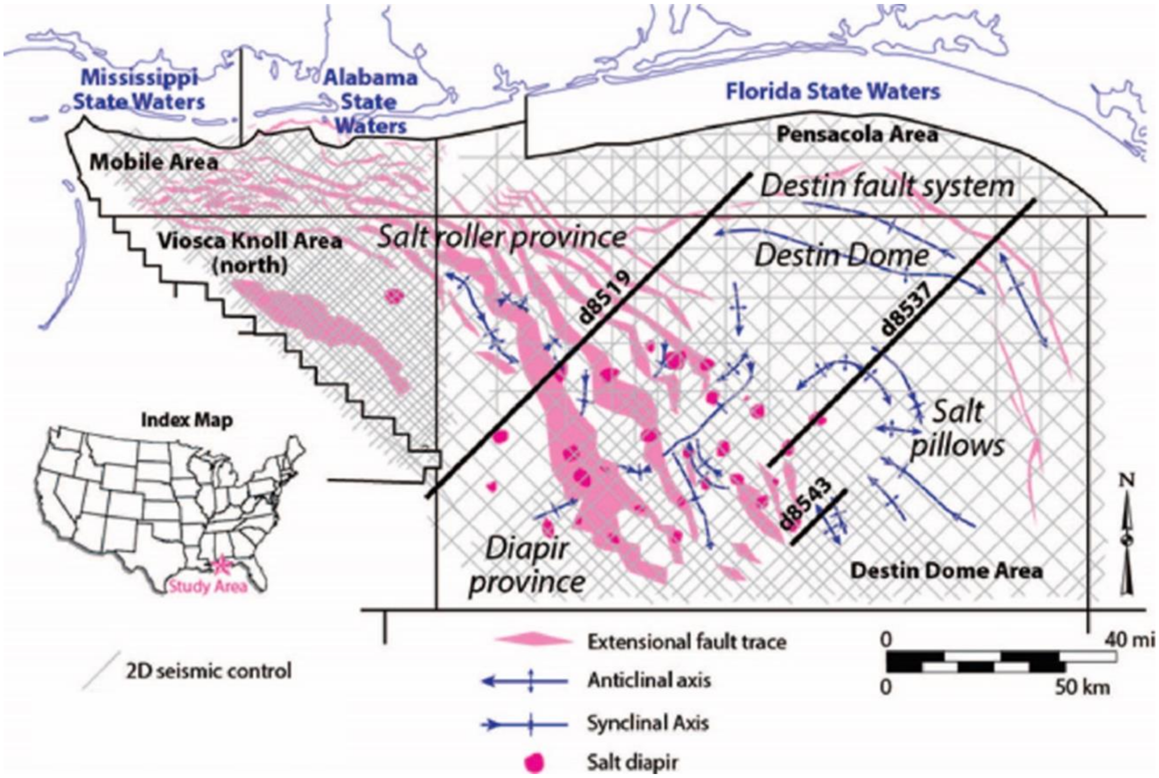


Figure 1. Map of study area with key structural elements and seismic coverage (modified from Pashin et al., 2016).

Petroleum exploration activities in DeSoto Canyon Salt Basin area have focused primarily on ultra-deep natural gas reservoirs in the Norphlet Formation (> 20,000 ft) and shallow Miocene gas reservoirs in (~3,500 ft) (Handford and Baria, 2003; Mancini et al., 1985; Story, 1998). Though deeper formations could be economically and technically challenging for CO_2 sequestration activities, some of the shallow Miocene and Cretaceous units could have significant storage potential (Hills and Pashin, 2010). The SECARB Phase III Anthropogenic test in the Mississippi Interior Salt Basin of southwest Alabama tested the storage capacity and injectivity of Paluxy sandstone and the overlying mudstone seal at the base of the Washita-Fredericksburg interval (Koperna et al., 2012; Folaranmi, 2015). Underneath these sandstone units, there are more sandstone units like the Hosston and Sligo Formations. These formations are separated from the Paluxy by a carbonate-evaporite section that includes the Ferry Lake Anhydrite, which has proven to be a reservoir seal onshore (Esposito et al., 2008). Also, the onshore SECARB test at Plant Daniel in southeast Mississippi evaluated the lower Tuscaloosa Group as a highly porous and permeable storage target sealed by the Marine shale of the Tuscaloosa Group (Koperna et al., 2009; Petrusak et al., 2009). However, little work has been performed to analyze the extent and geometry of these sandstone units and to quantify their CO_2 storage capacity offshore.

Figure 2 shows a generalized lithologic column identifying saline formations in the DeSoto Canyon Salt Basin based on 3 wells (Pashin et al., 2016). The Louann Salt is an evaporite succession that is absent at horizontal salt welds and is locally thicker than 20,000 feet in salt diapirs (Macrae and Watkins, 1993; Pashin et al., 2016). The Louann Salt is overlain by sandstone of the Norphlet Formation, which in turn is overlain by carbonate rocks of the Smackover Limestone and the Haynesville Formation. The Cotton Valley Group is dominated by siliciclastic strata and contains the Jurassic-Cretaceous boundary. The Knowles Limestone forms a distinctive high-amplitude seismic marker at the top of the Cotton Valley Group.

Lower Cretaceous strata consist primarily of sandstone in the northern part of the salt basin and pass basinward into platform carbonate (Pashin et al., 2016). The Lower Cretaceous section is subdivided by a high-amplitude Ferry Lake Anhydrite seismic marker that is of regional extent (Petty, 1995). The Paluxy Formation is composed of interbedded sandstone and mudstone. The Washita-Fredericksburg interval overlies the Paluxy Formation and contains interbedded limestone and shale near the base; sandstone is concentrated in the upper part of the formation. The limestone-dominated interval is regionally continuous and could serve as the topseal for the Paluxy Formation.

The Upper Cretaceous section disconformably overlies the Washita-Fredericksburg interval and includes the Tuscaloosa Group, the Eutaw Formation, and the Selma Group. The Tuscaloosa Group is subdivided into the lower Tuscaloosa Group, which includes a prominent sandstone unit called the Massive sand; the Marine Tuscaloosa shale, which contains a thick shale section; and the upper Tuscaloosa Group, which contains interbedded sandstone and mudstone (e.g., Mancini et al., 1987; Petty, 1995). The Marine Tuscaloosa shale is regionally extensive and is the topseal for lower Tuscaloosa reservoirs in onshore areas. The Eutaw Formation contains interbedded glauconitic sandstone and shale and disconformably overlies the Tuscaloosa Group (Mancini and Puckett, 2005). The Eutaw, in turn, is overlain by chalk of the Selma Group, and along with the overlying Paleogene mudrock of the Porters Creek Clay, acts as a topseal for Eutaw oil accumulations (Pashin et al., 2000). Above the Selma Group is a variety of Paleogene-Neogene siliciclastic and carbonate units, including the Midway Group, the Wilcox Group, the Tampa Limestone, and the Pensacola Clay (Pashin et al., 2016).

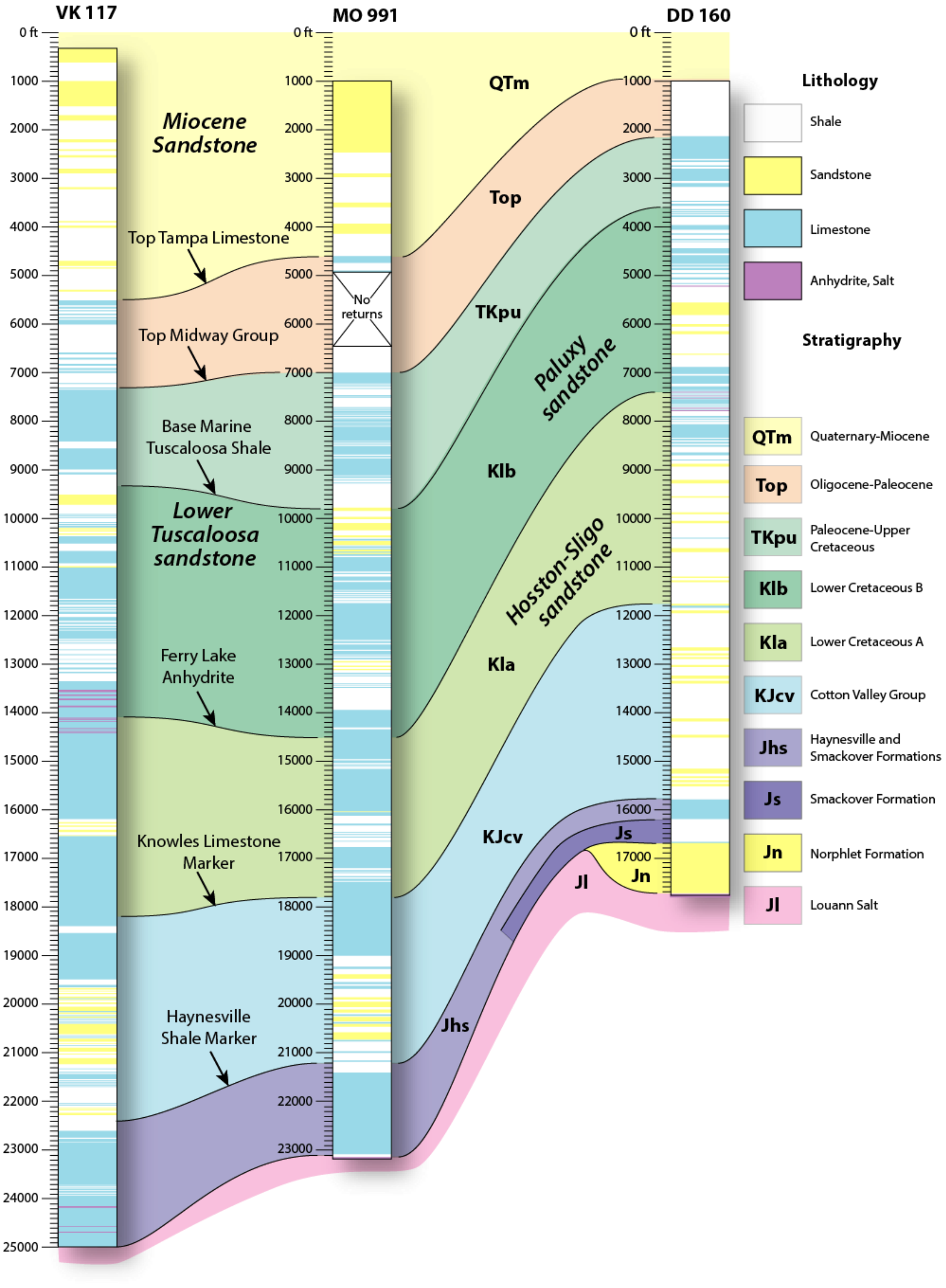


Figure 2. Generalized lithologic columns showing major stratigraphic units in the DeSoto Canyon Salt Basin (modified from Pashin et al. 2016).

CHAPTER II

ANALYTICAL METHODS

The analytical workflow for this research is broadly divided into two main components: (1) reservoir characterization and (2) volumetric assessment. This methodology was designed to characterize the stratigraphic framework of the Cretaceous formations in the DeSoto Canyon Salt Basin, determine reservoir properties, including thickness and porosity, and perform volumetric calculations to determine CO_2 storage capacity. The results of this analysis were then used to formulate a predictive framework that will help evaluate the geological CO_2 storage potential of the Cretaceous sandstone units, help identify candidate storage sites, and help formulate a commercial storage strategy.

Reservoir Characterization

A large volume of data have been released into the public domain by the Bureau of Ocean Energy Management (BOEM) through the Bureau of Safety and Environmental Enforcement (BSEE), including rasterized well logs (gamma ray, density, neutron, sonic and SP), wellbore velocity (checkshot) surveys, well deviation surveys, and 2D seismic reflection surveys. Wellbore data range from the sea surface to the top of the Louann Salt, and seismic data provide imaging into the subsalt basement. A database was generated with all well header, deviation surveys, and checkshot surveys, raster log images, and the 2D seismic reflection surveys in Kingdom 2D/3DPAK software. The major steps in the reservoir characterization process were (1) interpreting rock types and reservoir properties using wireline logs and mud logs, (2) characterizing the regional stratigraphic framework, (3) characterizing the thickness and geometry of sandstone units, as well as the presence and continuity of potential reservoir seals, and (4) identifying potential carbon storage sinks.

In order to understand the distribution of rock types and their reservoir and sealing properties, geophysical logs from 103 wells were analyzed. No core data are available from Cretaceous strata in the DeSoto Canyon Salt Basin, and so geophysical logs provided the sole source of data to determine reservoir and seal properties. The log suites used consist primarily of gamma ray (GR), spontaneous potential (SP), resistivity, density porosity, and neutron porosity logs. Rock types were identified using these logs following basic well log interpretation techniques (e.g., Asquith et al., 2004). Mud logs also were used where available to verify that rock types were interpreted correctly from the geophysical logs.

After defining the rock types, density porosity logs were used to determine the porosity of sandstone utilizing the methods described by Asquith et al. (2004). More than 75 wells in the basin have been logged using neutron and density tools. Effective porosity of the sandstone formation was determined using the following equation from Asquith et al. (2004):

$$\phi_{ND} = \sqrt{\frac{{\phi_N}^2 + {\phi_D}^2}{2}}$$

Where ϕ_N and ϕ_D are neutron porosity and density porosity, respectively. While most wells were logged using a limestone matrix, the Cretaceous sandstone units rarely showed gas effect. Porosity values were converted to sandstone matrix for determining porosity utilizing the following equation:

$$\phi_D = \frac{\rho_{matrix} - \rho_{bulk}}{\rho_{matrix} - \rho_{fluid}}$$

Where ϕ_D(fraction) is the density porosity, ρ_{matrix} (g/cm^3) is the density of the grain matrix, ρ_{fluid} (g/cm^3) is the density of the formation fluid and ρ_{bulk} (g/cm^3) is the bulk density of the formation (Asquith et al., 2004). A minimum thickness of 20 ft and a minimum porosity cutoff of 15% as calculated for sandstone matrix were used as qualifying criteria for identifying candidate reservoir zones.

The interpreted well logs were correlated and used to construct 2 regional stratigraphic cross-sections based on their GR, density, SP and resistivity pattern. Adobe Illustrator was used to display the logs and construct the cross-sections. Major stratigraphic boundaries were identified using the available geological literature and the existing subsurface literature (Pashin et al., 2016; Meng et al., 2017). The cross sections were constructed using the base of the Marine Tuscaloosa shale as datum, which is a key downlap surface that can be correlated regionally with high confidence in well logs and seismic profiles (Pashin et al., 2016). The cross sections were used to establish reservoir continuity, the presence of associated sealing strata, and to provide a detailed understanding of reservoir architecture.

Velocity survey data from 75 wells in the Mobile, Viosca Knoll, Pensacola, and Destin Dome Areas were used to help tie the wells to seismic profiles by analyzing time-depth relationships. While the major regional reflections were easy to trace, sandstone intervals tend to be too thin and discontinuous to image seismically. Moreover, well control is sparse in most of the DeSoto Canyon

Salt Basin, with wells generally located between seismic lines, in some instances about 1.5 miles away. Accordingly, the regional maps of sandstone thickness and porosity were constructed using the available well data.

Subsurface maps were constructed for prospective geological carbon sinks using depth and thickness information from the analyzed wells. The maps were gridded and contoured using a minimum curvature in Petrel software. Net sand isolith maps were also generated using the aforementioned sand thickness and porosity qualifying criteria. Average porosity for the qualified sandstone intervals was calculated in each well, and average porosity maps were constructed for the qualified sandstone column to understand porosity distribution.

Volumetric Analysis

Since Cretaceous formations are saline in the Gulf Coast region (Pashin et al., 2008; Koperna et al., 2009), the CO_2 storage resource was estimated using the procedures defined by Goodman et al. (2011) and National Energy Technology Laboratory (NETL, 2012) as:

$$G_{CO2} = A_t h_g \phi_{tot} \rho E_{saline}$$

Where,

$\mathbf{G}_{co2}$ is the reservoir CO_2 storage resource

$\mathbf{A}_t$ is the reservoir area

$\mathbf{h}_g$ is the gross formation thickness

ϕ_{tot} is the total porosity

$\boldsymbol{\rho}$ is the CO_2 density

$\mathbf{E}_{saline}$ is the CO_2 storage efficiency factor

The storage efficiency factor, $\mathbf{E}_{\text{saline}}$ is the fraction of total pore space occupied by injected CO_2 and is determined using Monte Carlo analysis driven by geological and displacement terms. Geological parameters include reservoir area, gross reservoir thickness, and mean porosity. Displacement parameters are dependent on the immediate volume surrounding an injection well that can be contacted by CO_2 and the fraction of pore space unavailable due to in situ fluids. The efficiency factor reflects the fraction of pore volume that is available for CO_2 storage as well as fluid displacement components that inhibit CO_2 from contacting the full pore volume (Goodman et al., 2011). Field data from oil and gas reservoirs coupled with laboratory and numerical simulations of relative permeability in CO_2-brine systems help derive working efficiency factors for saline formations. Based on the results of Monte Carlo analysis, $\mathbf{E}_{\text{saline}}$ ranges from 0.51 to 5.50% over a 10-90% probability range; i.e., P_{10} is 0.51%, P_{50} is 2.00%, and P_{90} is 5.50% (IEA GHG, 2009; Kopp et al., 2009).

Net sand isolith maps of the qualified reservoir zones were used to constrain reservoir area (A_t). Since net qualified reservoir thickness was determined, the saline formation efficiency factors utilizing the displacement terms in clastic reservoirs alone provide a more accurate representation of storage efficiency. For the qualified sandstone units, efficiency values range between 7.4 and 24% over a 10-90% probability range (i.e., P_{10} is 7.4%, P_{50} is 14%, and P_{90} is 24%) (Goodman et al., 2011). Average porosity at each grid node was determined from the well logs for each qualified sandstone unit and then recalculated for each assessment unit. The mean values for net thickness and total porosity (ϕ_{tot}) of the selected reservoir zones was determined from a tabulation of net thicknesses at grid nodes.

CHAPTER III

RESULTS

Geologic Framework

The main rock types identified in the geophysical well logs are sandstone, shale, limestone, anhydrite, chalk and clay. Cross sections are intended to establish reservoir geometry, seal location and geometry, and stratigraphic architecture. Two cross-sections from the DeSoto Canyon Salt Basin that were made where well spacing is closest are discussed presented herein (Plates 1, 2). Plate 1 is a strike cross-section traversing the Mobile Area, whereas Plate 2 is a dip cross section traversing Mobile and Viosca Knoll Areas. The cross-sections include Cretaceous strata shallower than 12,000 feet and include strata from the Lower Cretaceous Ferry Lake Anhydrite through the Paleogene mudstone section.

Owing to its low density porosity and high resistivity, the Ferry Lake Anhydrite was the most readily recognized stratigraphic marker in the section and was commonly used as an initial datum for correlating well logs. The Ferry Lake Anhydrite is about 400-600 ft thick in the study area is composed of interbedded anhydrite (20-60 ft), limestone (20-100 ft), and shale (10-20 ft). The anhydrite beds are discontinuous in cross-section A-A'. The Ferry Lake Anhydrite is overlain by the Mooringsport Formation, which is about 800-1,400 ft thick and is composed primarily of limestone (>90%) with some thin (<10%) intervals of shale; mudlog descriptions and porosity logs suggest that some tight sandstone units are present in the Viosca Knoll Area.

The Paluxy Formation overlies the Mooringsport Formation and is composed of interbedded sandstone, limestone and shale in the Mobile Area (Plates 1, 2). The Paluxy is 400 to 1,800 ft thick (Figure 3). Thickness is generally greater than 1100 ft in the Mobile and Viosca Knoll Areas and decreases to 400 ft in the northwestern Destin Dome Area. Thickness variation in the Paluxy Formation owes mainly to intertonguing with Mooringsport carbonate (Plate 2). Thickness of the Paluxy increases to about 1,800 ft in the salt withdrawal synclines around Destin Dome and thins to about 400 ft in the crestal region of the dome. The Paluxy becomes richer in limestone southwestward into the Viosca Knoll Area (Plate 2). Within the Paluxy there are more than 12 regional sandstone units; they range in thickness from about 20 to 140 ft.

The lower part of the Paluxy Formation is rich in mud and contains multiple single-storey sandstone lenses. The thickness of these sandstone lenses ranges from about 10 to 70 ft. The SP, GR, density and resistivity log curves are variable and include blocky and Christmas tree signatures. Blocky SP, GR and high resistivity signatures indicate little variation in grain size and porosity, whereas Christmas tree signatures typically reflect fining-upward trends with porosity also decreasing upward. These variations result in significant stratigraphic heterogeneity.

The upper Paluxy is dominated by sandstone bodies that tend to thicken upward in section. These sandstone units are thicker than 50 ft and more widespread laterally than the lower sandstone units and possess variable log signatures. These sandstone units are interbedded with fewer shale as compared to the lower Paluxy. This complex multi-storey stacking is observed in all drilled wells and is indicative of the depositional heterogeneity.

Porosity in the Paluxy Formation commonly exceeds 20%. Geophysical logs from well G02486 from the Destin Dome Area shows a typical Paluxy sandstone unit (Figure 4). The sandstone is about 80 ft thick and has porosity ranging between 12 and 26%; average average porosity is about 21.5%.

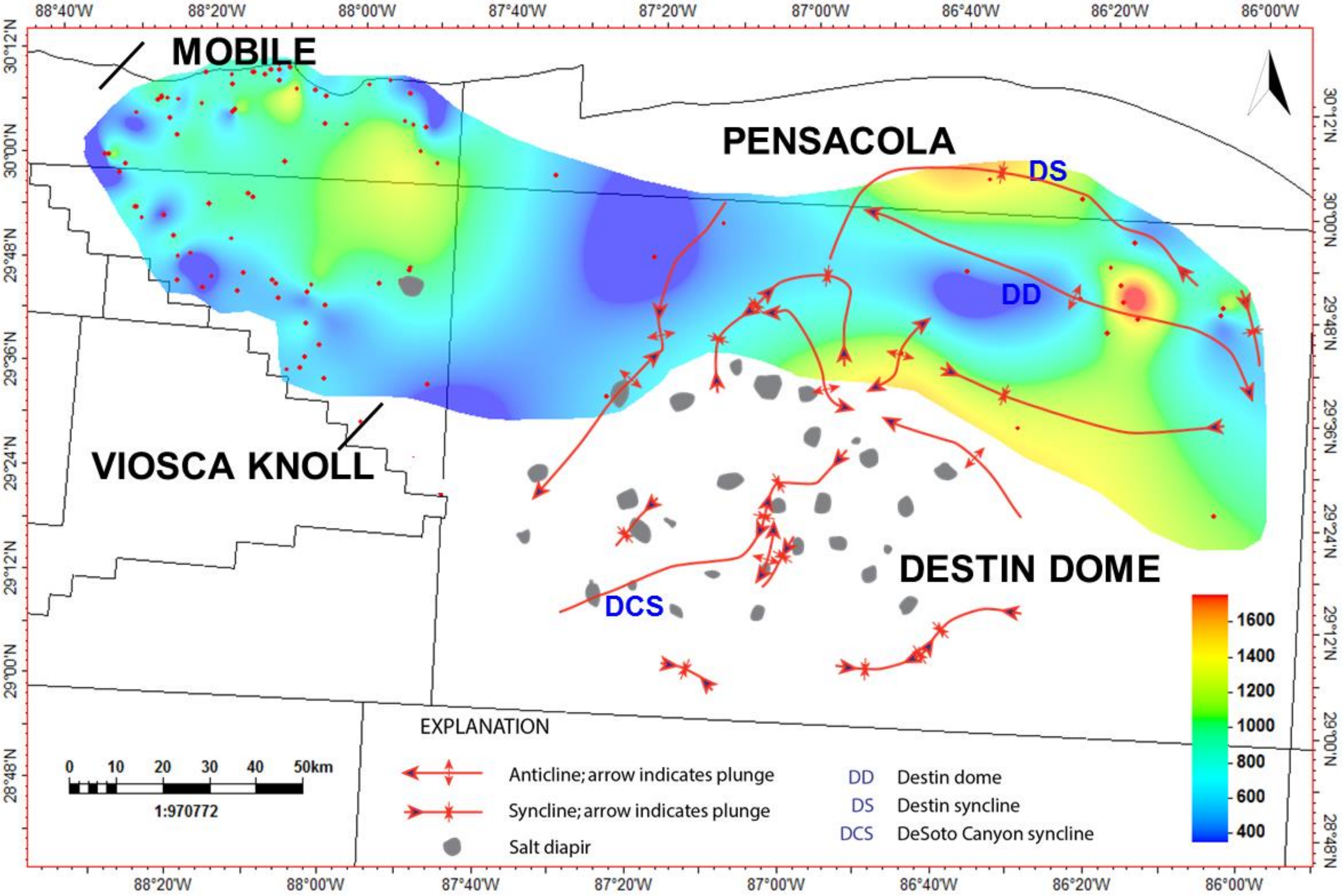


Figure 3. Isochore map of the Paluxy Formation. Contour interval = 200 ft.

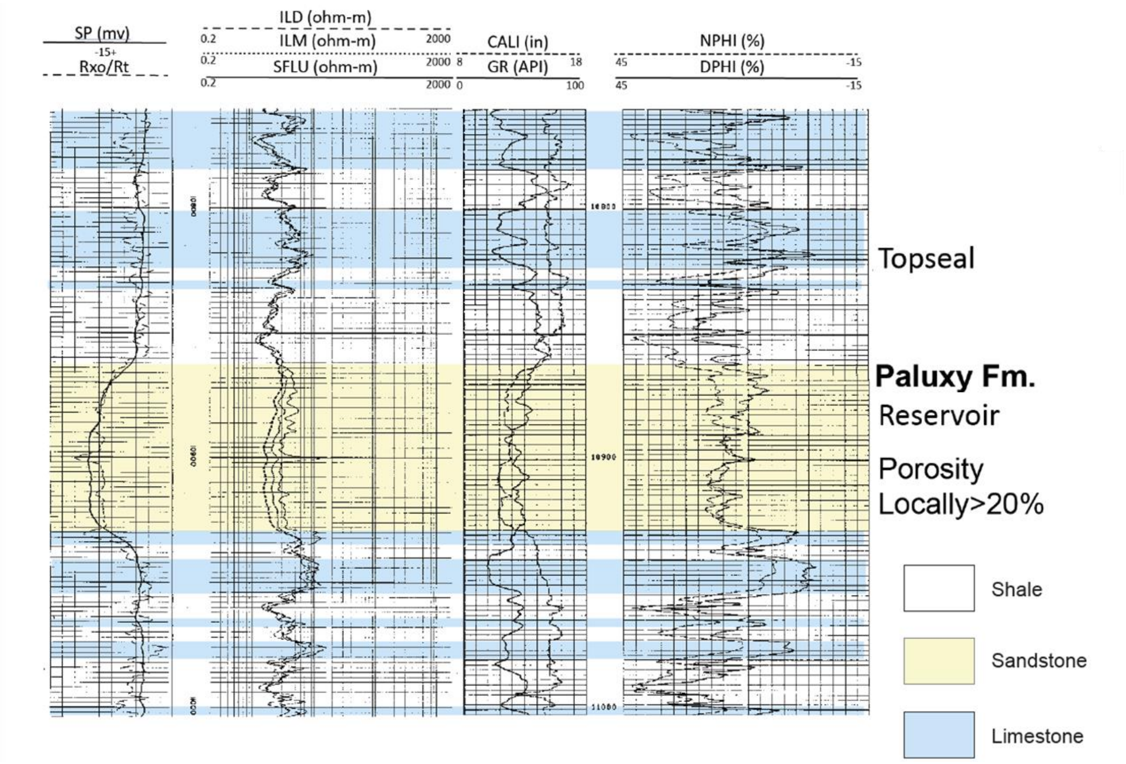


Figure 4. Interpretation of geophysical well logs of the Paluxy Formation in the Destin Dome Area.

The Paluxy Formation is overlain by the Washita-Fredericksburg interval, which has a total thickness of about 1,200 to 3,200 ft. An isochore map indicates that the thickest Washita-Fredericksburg sections are in the Mobile and Viosca Knoll areas (Figure 5). The lower part of the Washita-Fredericksburg interval is composed principally of limestone with numerous interbeds of shale and sandstone and gradationally becomes shale rich in the upper section (Plates 1, 2). This limestone-dominated section ranges in thickness from 1,000 to 2,000 ft (Figure 6). The percentage of limestone in the Washita-Fredericksburg section increases southward (Plate 2), and porosity of the limestone generally ranges between 0 and 4%. Sandstone bodies in the southern part of the Viosca Knoll Area are thin and discontinuous and typically have porosity less than 8%. The upper Washita-Fredericksburg section is rich in mudstone and contains numerous discontinuous sandstone bodies (Plates 1, 2). Few of these sandstone units have porosity greater than 15%, and

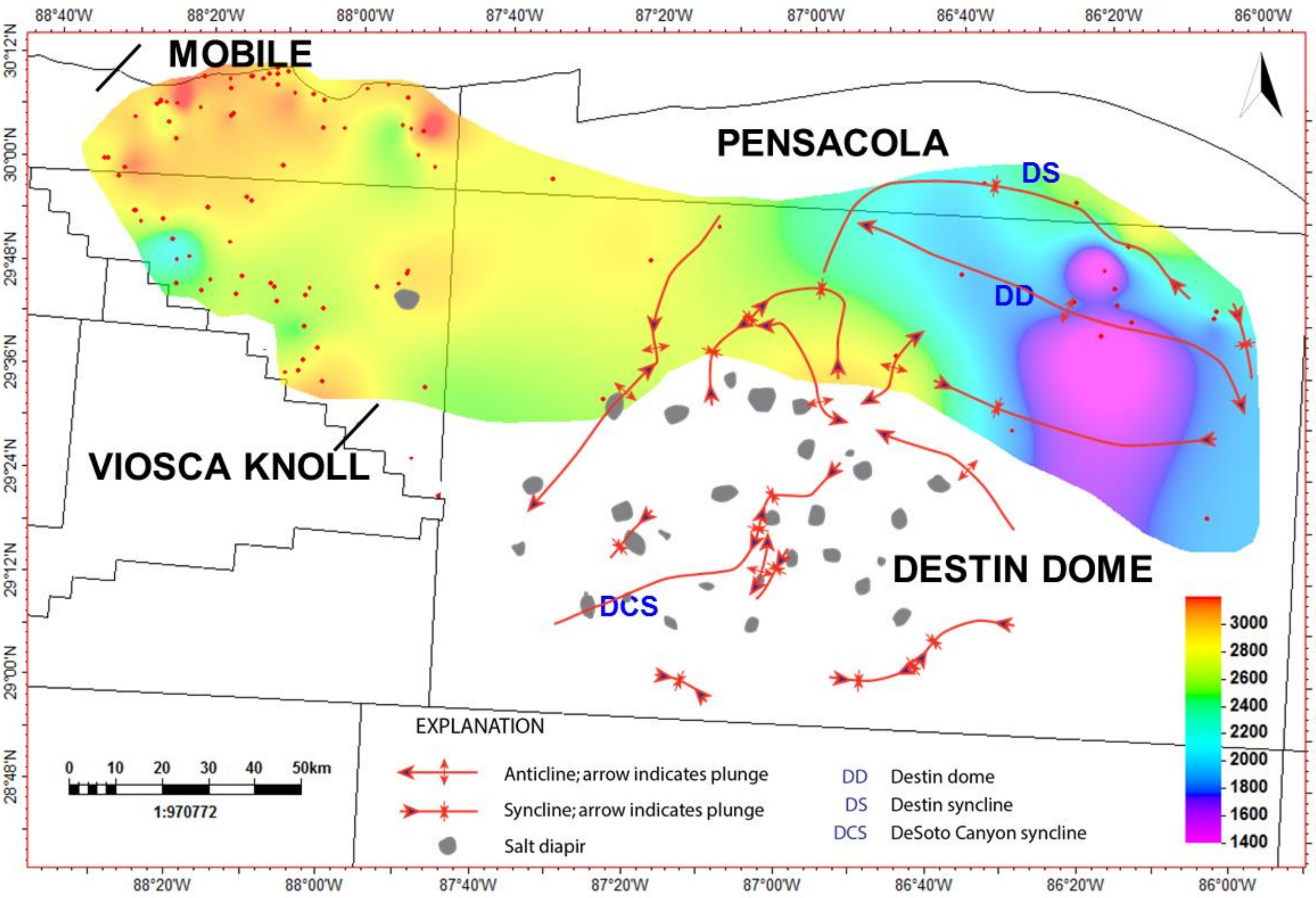


Figure 5. Isochore map of the Washita-Fredericksburg interval. Contour interval = 200 ft.

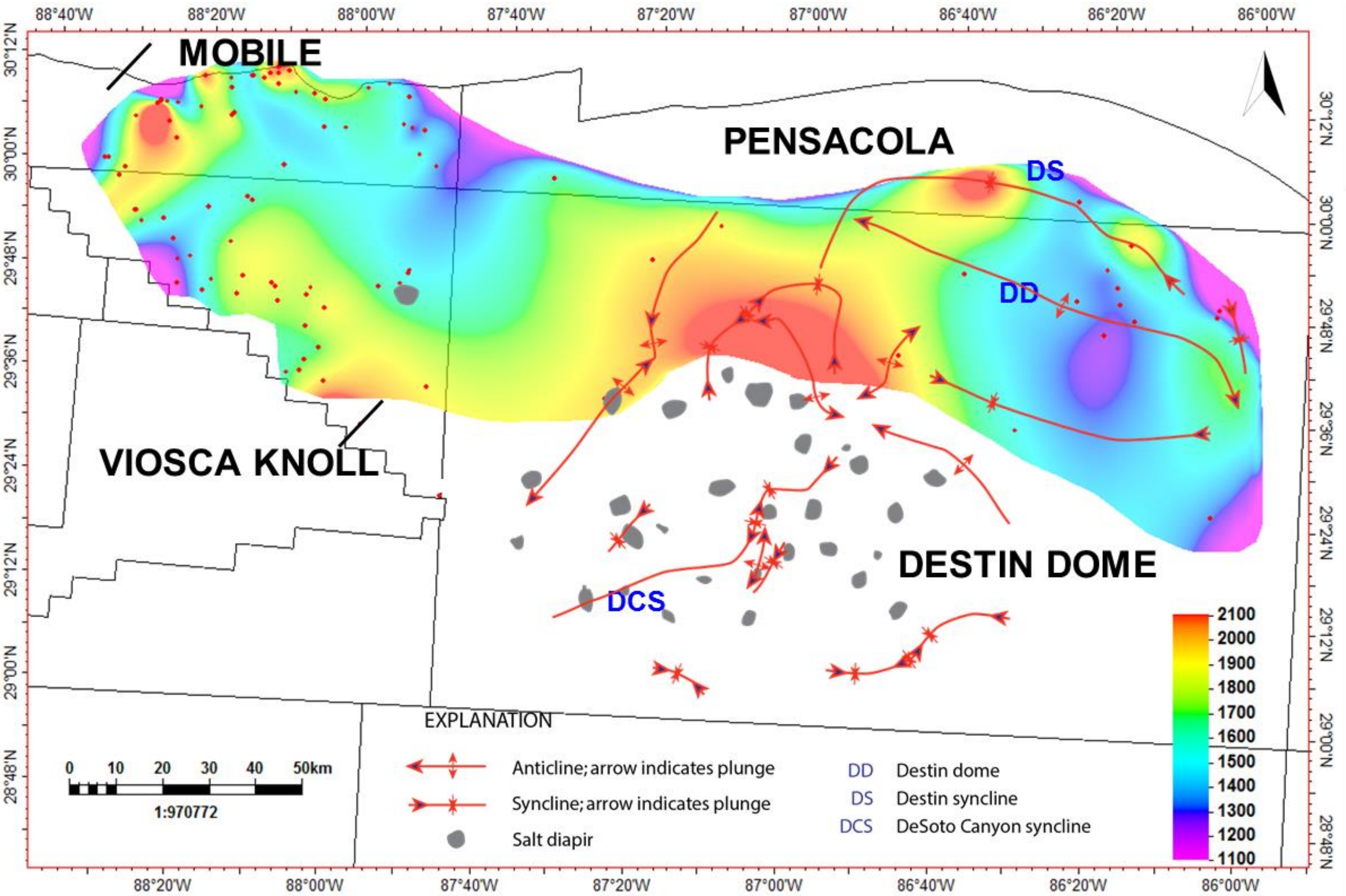


Figure 6. Isochore map of the basal limestone of the Washita-Fredericksburg interval. Contour interval = 100 ft.

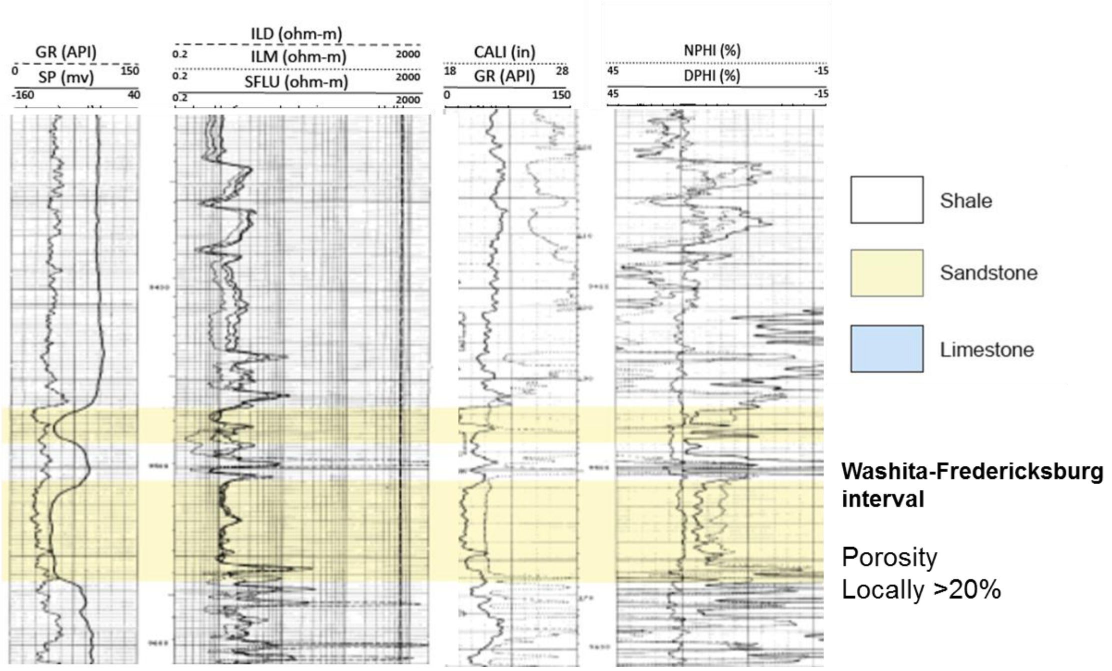


Figure 7. Interpretation of geophysical well logs of the Washita-Fredericksburg interval in the Mobile Area.

those that do are in the upper part of the Washita-Fredericksburg interval at the approximate level of the Dantzler sand (Chasteen, 1983). A major sandstone unit is developed in the strike cross-section (Plate 1). The SP logs typically have a blocky signature for this Washita-Fredericksburg sandstone unit. Geophysical logs from the Mobile Area show a typical reservoir sandstone unit from the upper Washita-Fredericksburg interval (Figure 7). The sandstone is about 90 ft in thickness and has porosity ranging between 21 and 26% with an average porosity of about 23%.

The lower Tuscaloosa Group sharply overlies the Washita-Fredericksburg interval. The thickness of the lower Tuscaloosa is generally between 200 and 400 ft (Figure 8). It thins rapidly out to 80-150 ft in the area of the Destin Dome anticline. The Massive sand, which forms the base of the Lower Tuscaloosa, ranges from 220 to 300 ft in thickness throughout the study area except in the crestal region of Destin Dome where it is only about 40 ft thick (Petty, 1997). The SP and GR curves tend to be blocky and thus reflect generally uniform grain size and porosity.

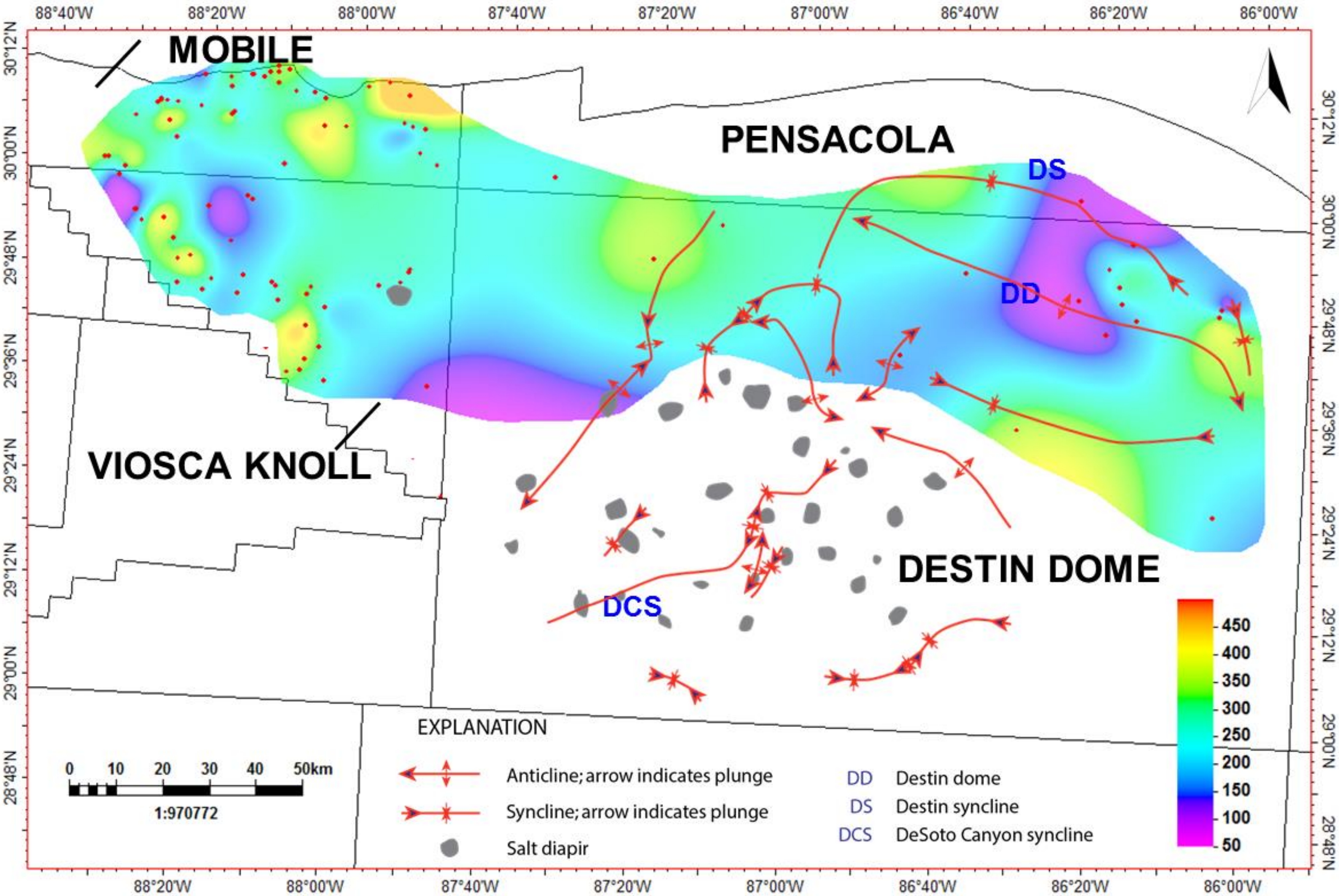


Figure 8. Isochore map of the lower Tuscaloosa Group. Contour interval = 50 ft.

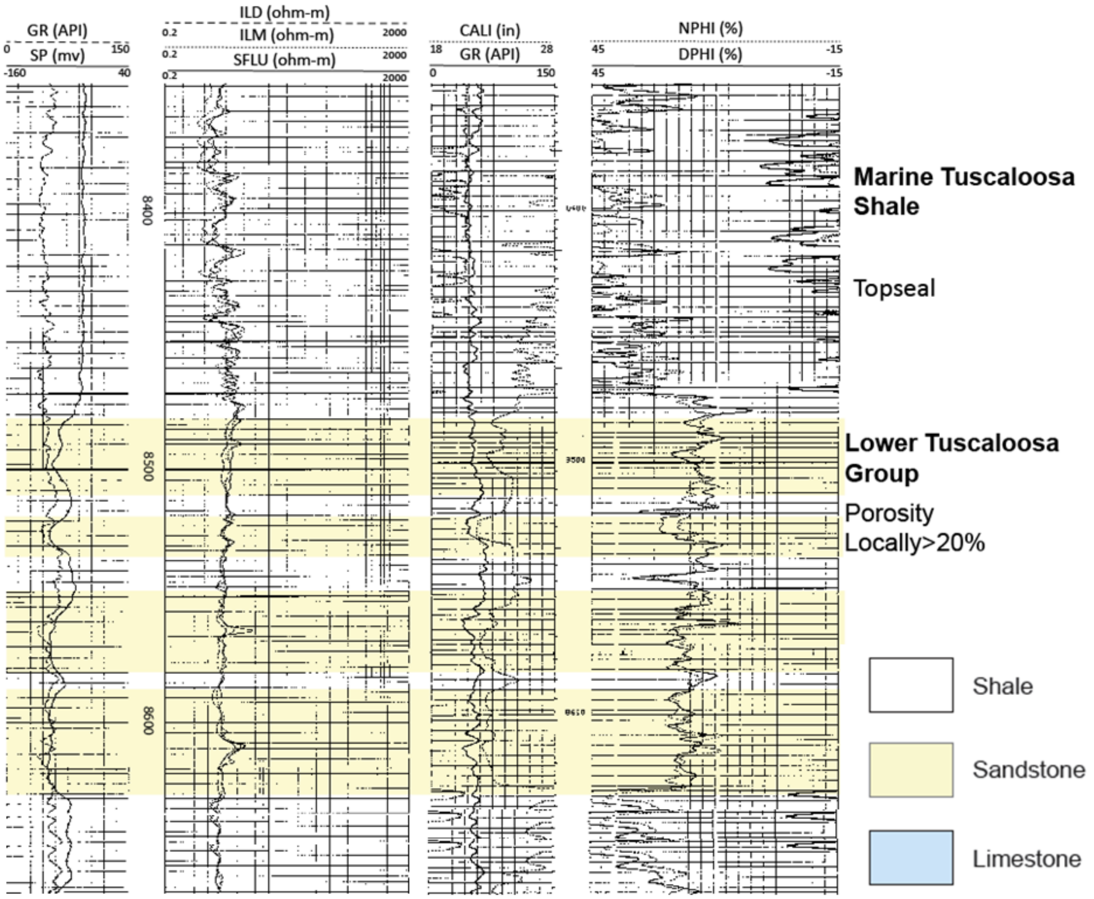


Figure 9. Interpretation of geophysical well logs of the lower Tuscaloosa Group in the Mobile Area.

Porosity of lower Tuscaloosa sandstone is typically between 18 and 22%. A well log from the Pensacola Area shows a sandstone section with a gross thickness of 150 ft (Figure 9). This sandstone has porosity ranging between 18 and 28% with an average porosity of about 22%.

A distinct positive SP deflection marks the base of the Marine Tuscaloosa shale, which is about 200-300 ft thick throughout the study area and is a regional seal for petroleum reservoirs the lower Tuscaloosa Group (Mancini et al., 1987; Petty, 1997) (Figure 5; Plates 1 and 2). The upper Tuscaloosa Group and Eutaw Formation contain little sandstone and are thus difficult to identify in the DeSoto Canyon Salt Basin. Accordingly, upper Tuscaloosa and Eutaw strata have been mapped with the Marine Tuscaloosa shale as a matter of practicality.

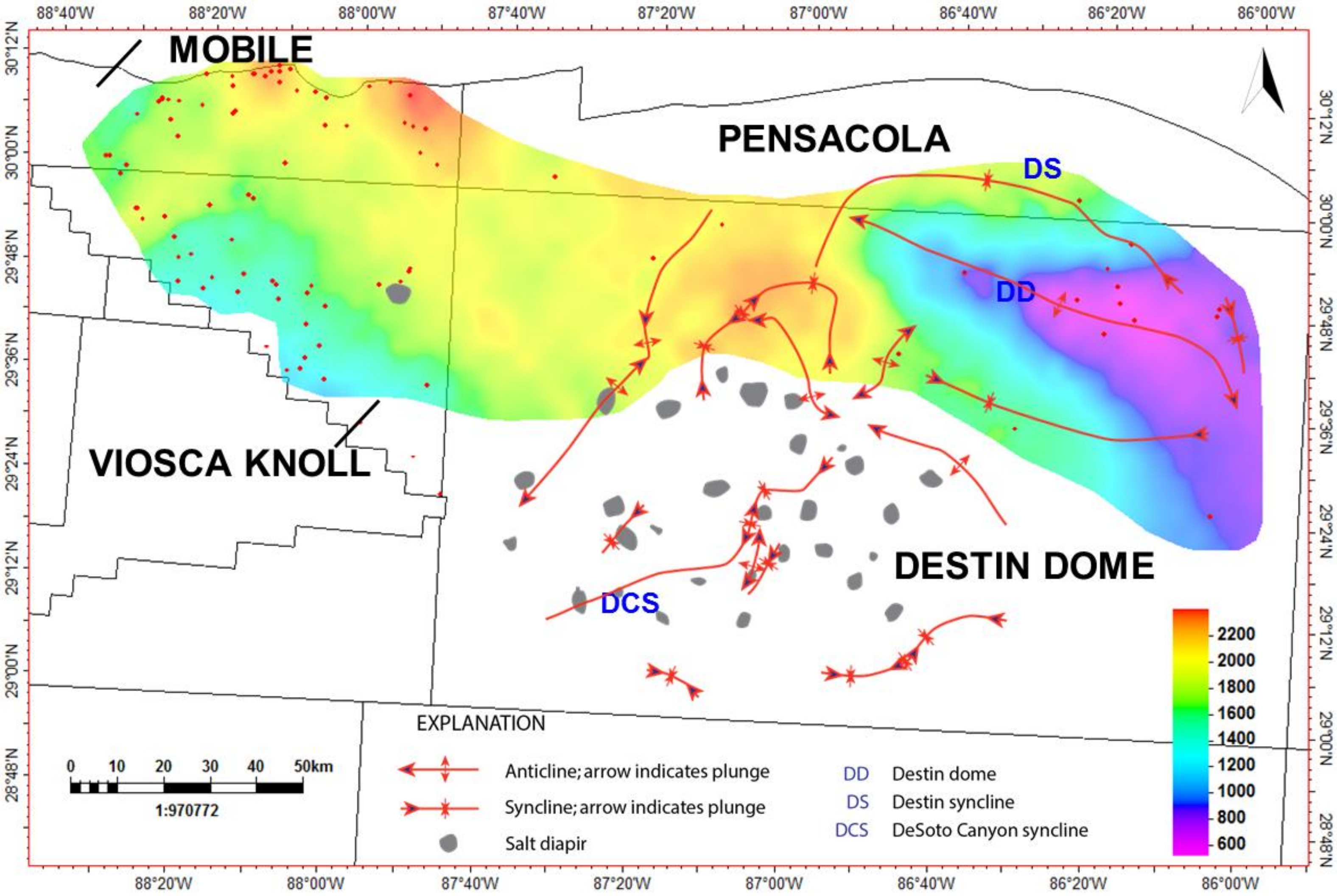


Figure 10. Isochore map of the Marine-Upper Tuscaloosa and Selma Group combined. Contour interval = 200 ft.

The Eutaw Formation is overlain by the thick chalk of the Selma Group. The Selma Group is about 1,100-1,450 ft thick (Plate 1) in the Mobile and Viosca Knoll Areas and can be easily correlated throughout the basin due to its consistent resistivity signature. An isochore map of the Marine-Upper Tuscaloosa and Selma group combined shows that the thickness varies between 600 and 2,300 ft (Figure 10). Thickness is generally greater than 1,500 ft in the Mobile and Viosca Knoll Areas and decreases to about 600 ft in the eastern Destin Dome Area.

The Selma Group is overlain by 1,500 to 2,300 ft of strata that are assigned to the Paleogene-age Midway, Wilcox, and Claiborne Groups (Pashin et al., 2016). This interval is dominated by mudstone, and several sandstone units are included that are beyond the scope of this study. Shallower strata include the Oligocene-Miocene-age Tampa Limestone and the Miocene Pensacola Clay, the latter of which contains significant natural gas reservoirs and additional potential CO_2 sinks that are outside the scope of this thesis research (Hills and Pashin, 2010).

The net sandstone isolith map of Paluxy Formation demonstrates the variability in sand distribution in the study area (Figure 11). Net sand thickness generally ranges from 100 to 350 ft across most of the study area but is as thin as 50 ft in the central part of the basin and in the western part of the crestal region of Destin Dome. The thickness increases to 370 ft in the salt withdrawal synclines on the flanks of Destin Dome.

The net sandstone isolith map of the Washita-Fredericksburg interval shows that the distribution of qualified sandstone is limited (Figure 12). Some sandstone is present in the Mobile and Viosca Knoll Areas with thickness varying between 0-120 ft with thickest accumulations along two northwest-southeast and north-south trending axes. Some reservoir quality sandstone is present in the salt withdrawal synclines on the flanks of Destin Dome with thickness generally ranging from 20 to 80 ft.

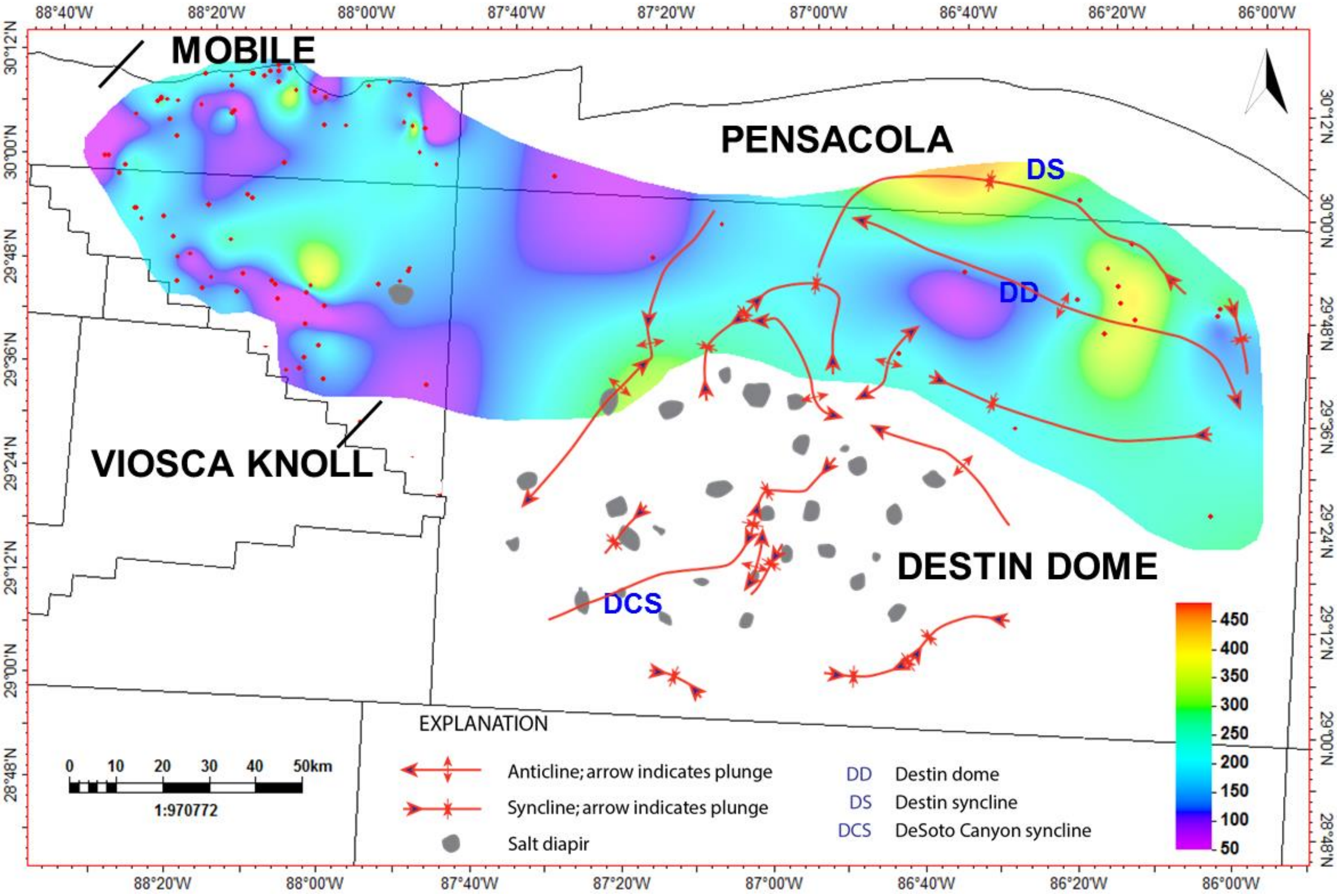


Figure 11. Net sandstone isolith map of the Paluxy Formation; Contour interval = 50 ft.

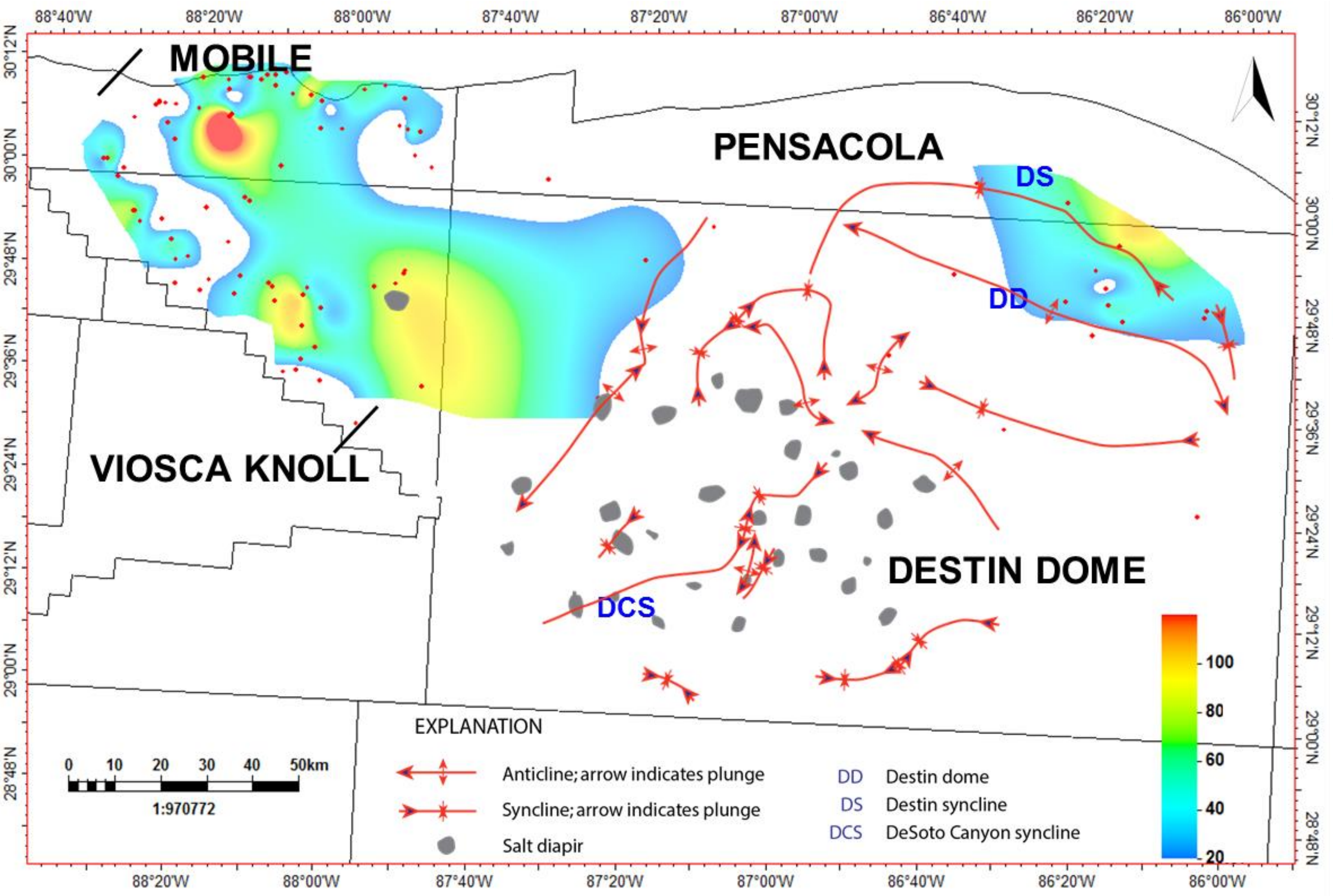


Figure 12. Net sandstone isolith map of the Washita-Fredericksburg interval; Contour interval = 20 ft.

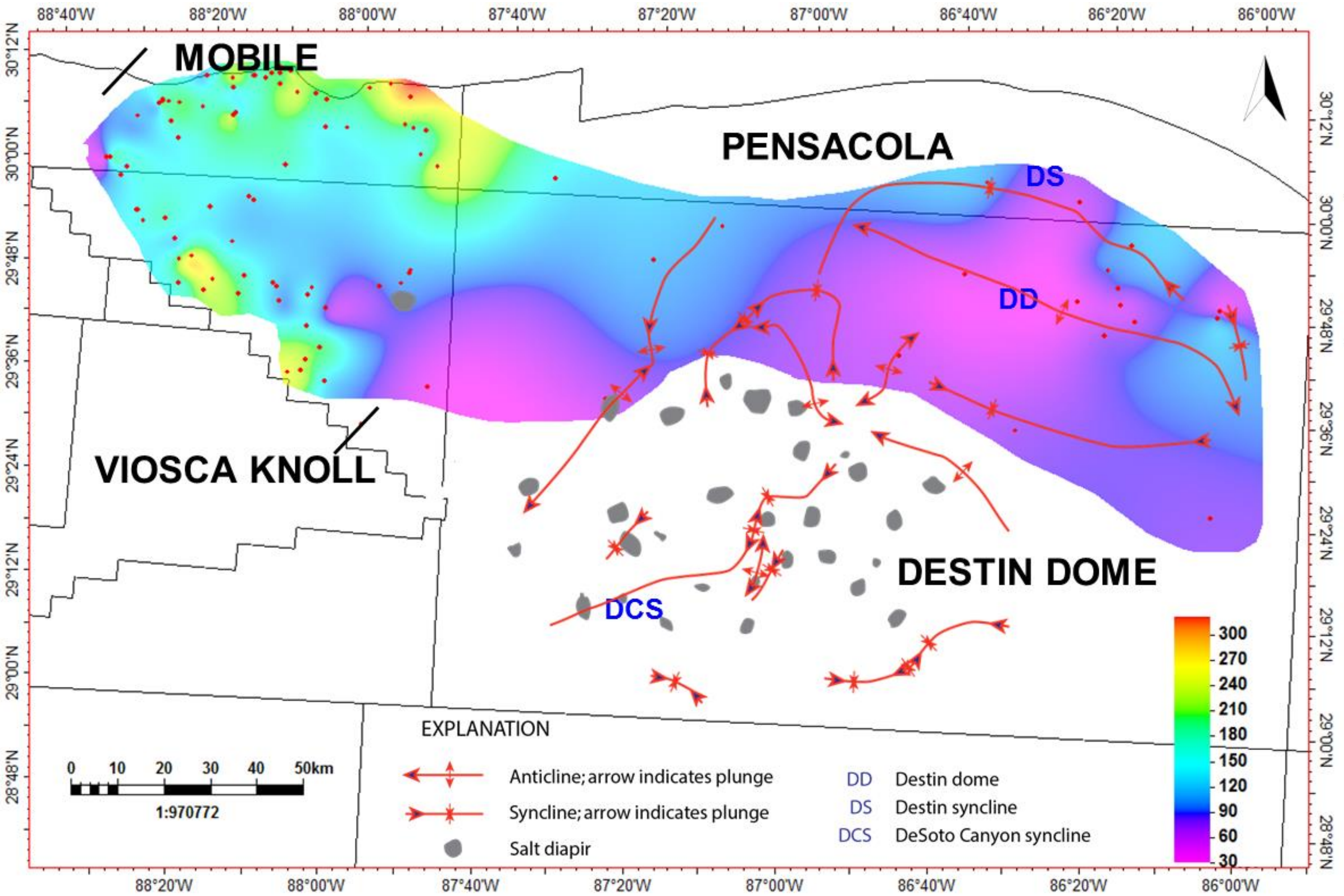


Figure 13. Net sandstone isolith map of the lower Tuscaloosa Group; Contour interval = 30 ft.

The lower Tuscaloosa net sandstone isolith map (Figure 13) shows that the sandstone unit is thickest in the Mobile, western Pensacol,a and Viosca Knoll Areas, with thickness ranging from 100 to 300 ft. It is however very thin (< 100 ft) in the southern and eastern part of the basin in the Destin Dome Area and is thinner than 30 ft in the crestal region of the Destin Dome anticline.

Reservoir Properties

Figure 14 is the average porosity map for qualified sandstone in the Paluxy Formation. The map shows that sandstone in the eastern part of the basin (Destin Dome and Pensacola Areas) in places has elevated porosity ranging from 20 to 24%. These high porosity values for the thin sandstone units in this area may be an artifact of sparse well control (Figure 11). On the other hand, sandstone in the western part of the basin (Mobile and Viosca Knoll Areas) generally has lower porosity (15-18%).

Since reservoir quality sandstone units in the Washita-Fredericksburg interval are limited to a very small area of the basin, including the Mobile and Viosca Knoll Areas and the northwestern part of the Destin Syncline, the porosity map highlights only this region. The average porosity values vary between 15 and 23% (Figure 13).

The Massive sand of the lower Tuscaloosa Group, on the other hand, has higher average porosity than the Paluxy Formation and the Washita-Fredericksburg interval (Figures 14-16). Average porosity of the lower Tuscaloosa generally varies from 20 to 25% in the Mobile and Viosca Knoll Areas (Figure 16). Porosity averages about 24% in the eastern part of the basin and is locally lower than 15%.

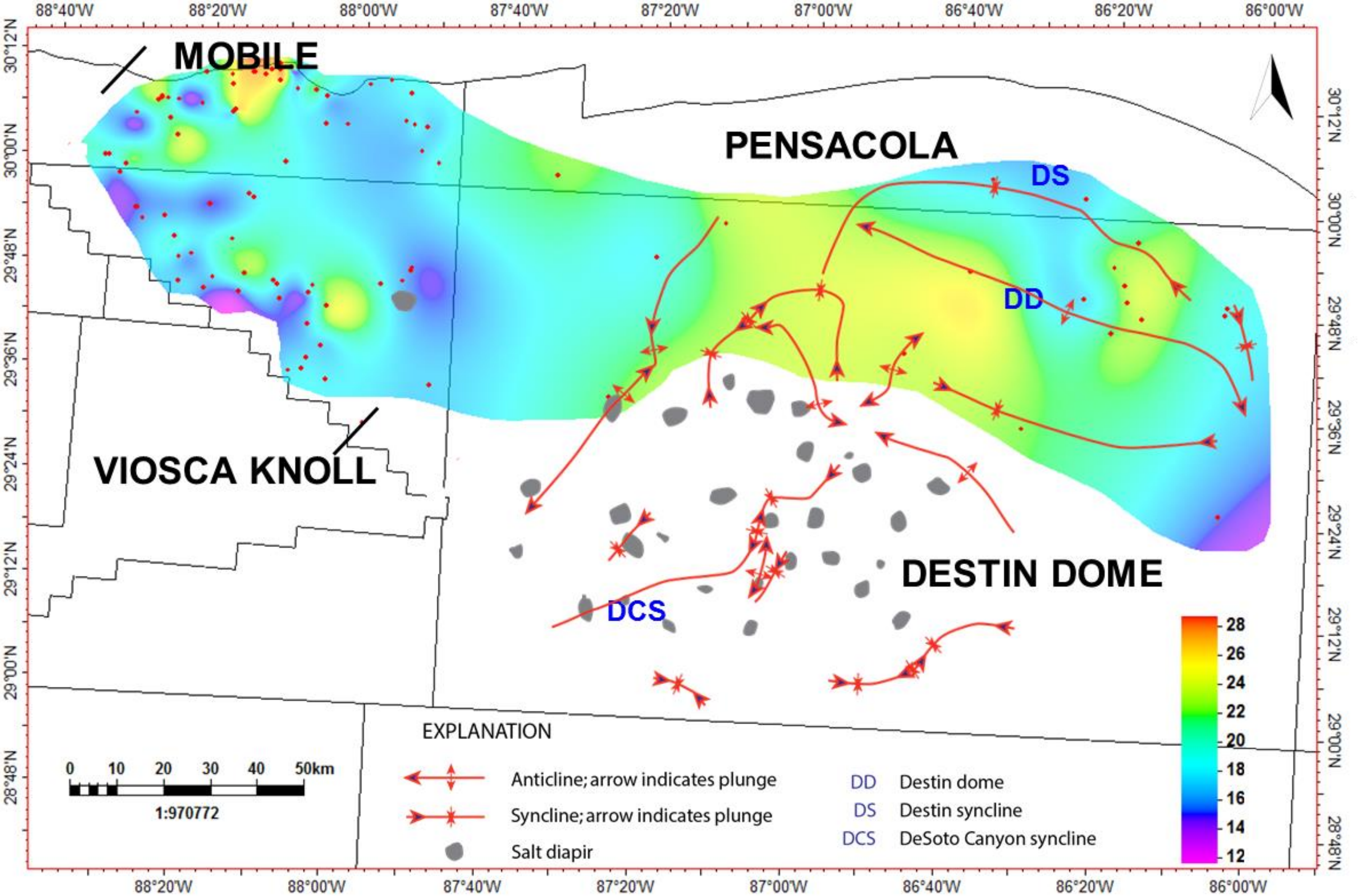


Figure 14. Average porosity of qualified sandstone in the Paluxy Formation. Contour interval = 2%.

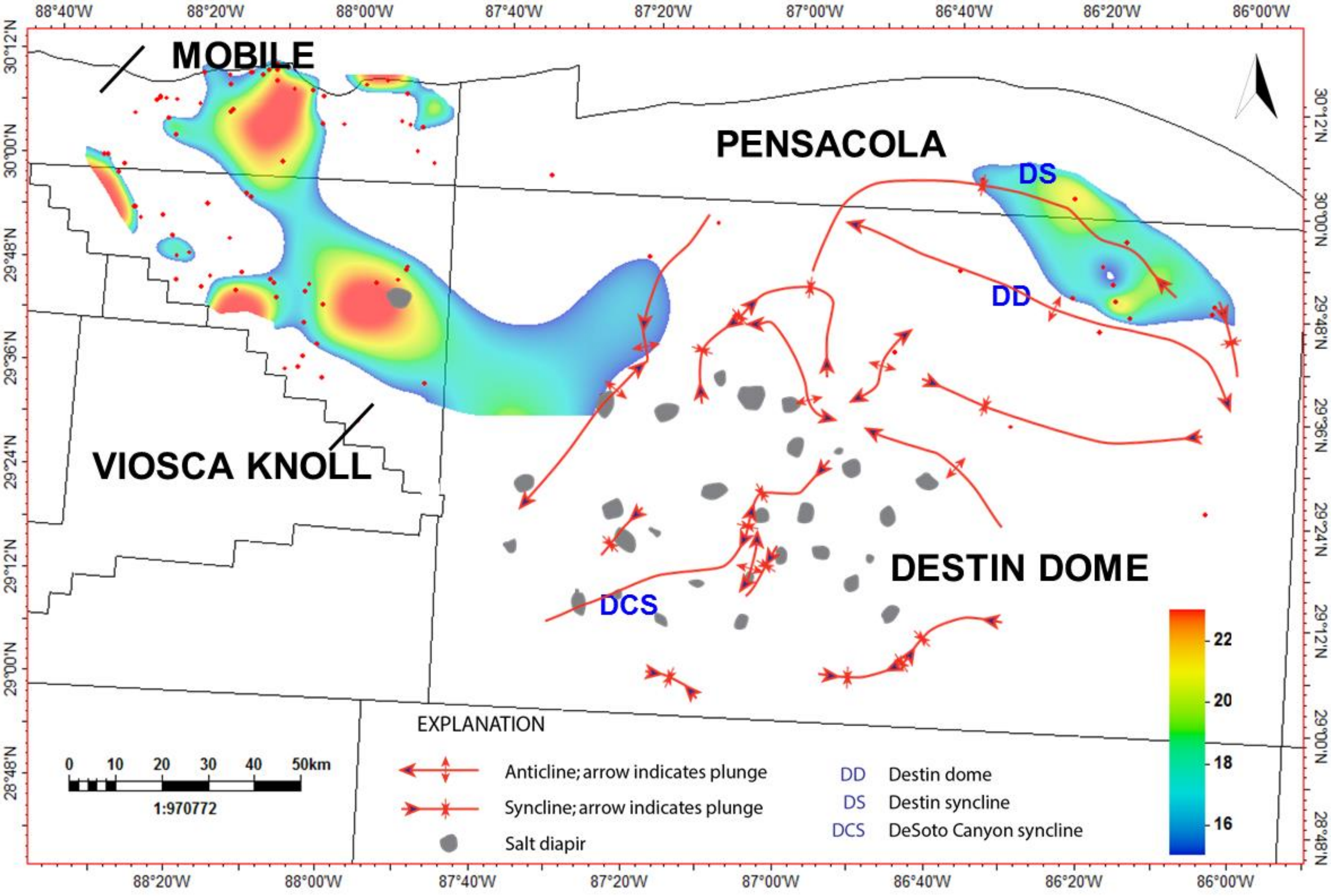


Figure 15. Average porosity of qualified sandstone in the Washita-Fredericksburg interval. Contour interval = 2%

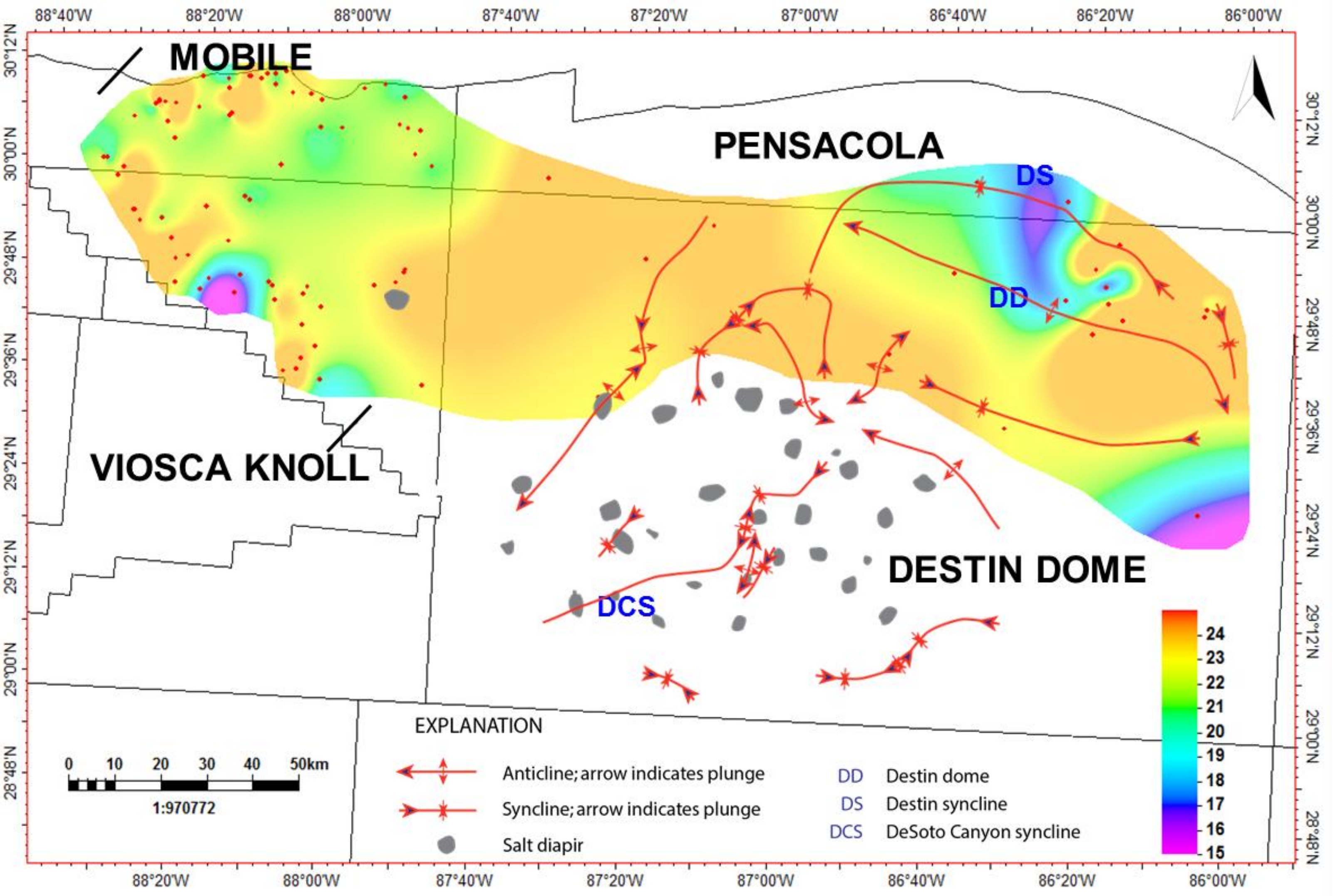


Figure 16. Average porosity of qualified sandstone in the lower Tuscaloosa Group. Contour interval = 1%.

Table 1 shows the variation of porosity values in all qualified Cretaceous reservoirs based on geophysical log analysis. Note that these values only represent sandstone meeting the qualification criteria, which are minimum porosity of 15% and sandstone thickness exceeding 20 ft. Since the range of the data and standard deviation are low, mean and median porosity values are close and reflect a normal population distribution. Of the three reservoirs evaluated, the lower Tuscaloosa Group has the highest mean porosity, which is estimated to be 22.5%.

Table 1. Porosity statistics for Cretaceous reservoirs in DeSoto canyon Salt Basin.

Stratigraphic Unit	Minimum	Maximum	Mean	Median	Standard Deviation
Lower Tuscaloosa Group	16.0	26.0	22.5	22.7	1.9
Washita-Fredericksburg interval	15.0	23.0	18.2	18.5	2.3
Paluxy formation	15.0	28.0	19.9	20.1	2.4

A lack of routine core analysis data means that the permeability of Cretaceous sandstone in the study area is unknown. However, onshore core data from these formations reveal basic porosity-permeability relationships in the formations being considered as storage targets (Pashin et al., 2008; Folarnmi, 2015). Figure 17 shows a regression plot of porosity vs. permeability in Cretaceous sandstone units (Pashin et al., 2008). The permeability values range from 125 to more than 5,000 mD and follow a log normal distribution. The geometric mean values are 236, 184, and 269 mD in the Paluxy Formation, Washita-Fredericksburg interval, and the lower Tuscaloosa Group, respectively.

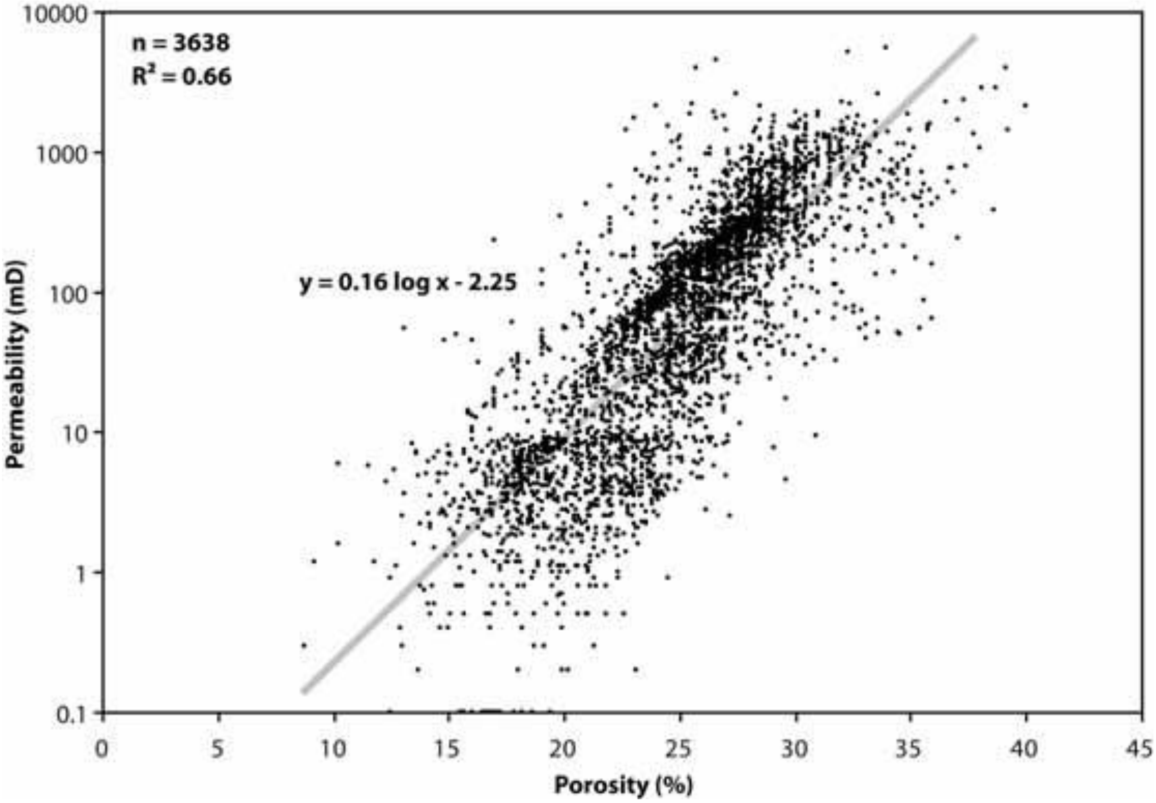


Figure 17. Cross-plot of porosity and permeability data from core analyses of Cretaceous sandstone in southwestern Alabama (modified from Pashin et al., 2008).

Volumetric Analysis

Reservoirs under a normal hydrostatic gradient and normal geothermal gradient reach the critical point at a depth of about 2,480 feet, and therefore all zones being considered in the current study of offshore are expected to store CO_2 in a supercritical state (Figure 18). Pressure and temperature at average reservoir depth for the eastern part of the Gulf of Mexico Basin were determined using the pressure-depth and temperature-depth plots by Pashin et al. (2008) and have been listed in Table 2. A PVT chart for CO_2 under hydrostatic and lithostatic pressure conditions (Bachu, 2003) shows the range of CO_2 density for the selected reservoirs (Figure 19). The CO_2

density has been estimated at 790, 760 and 720 kg/m3 for the Paluxy Formation, Washita-Frederiskcburg interval and the lower Tuscaloosa Group, respectively.

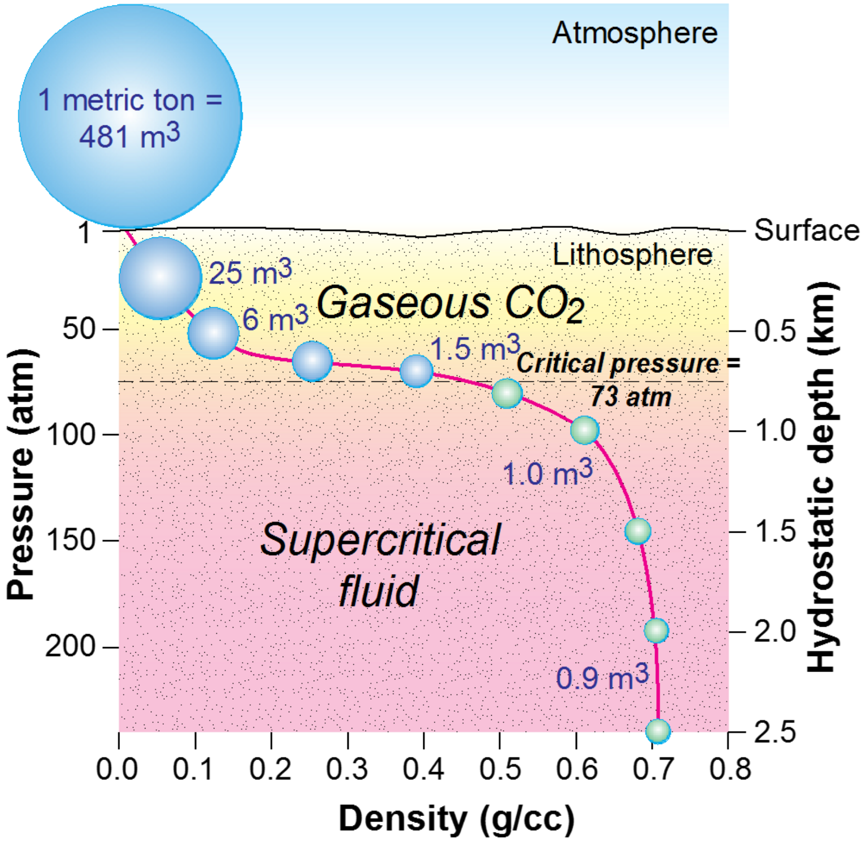


Figure 18. Effect of burial depth on CO_2 density (modified from Pashin, 2016).

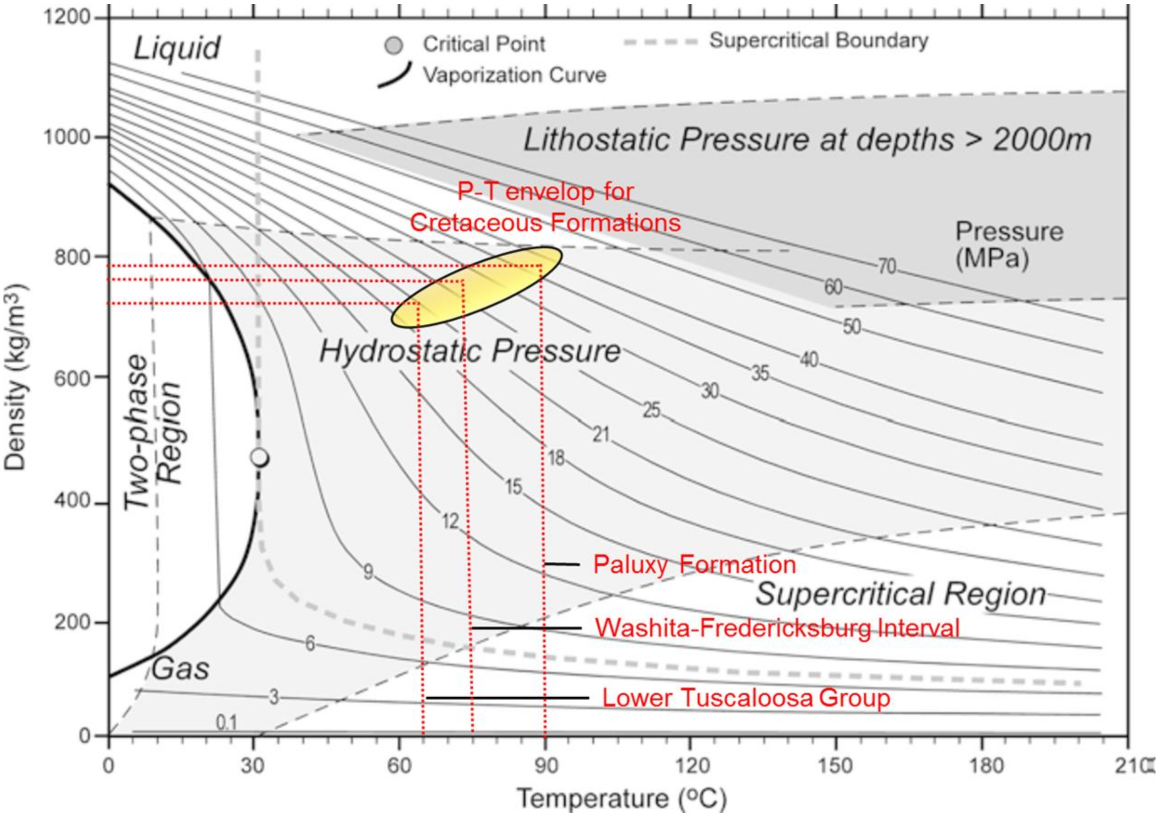


Figure 19. Variation of CO_2 density as a function of temperature and pressure (modified from Bachu, 2003).

Table 2 summarizes the reservoir properties used to calculate the CO_2 storage resource of the Paluxy Formation, Washita-Fredericksburg interval, and the Lower Tuscaloosa Group. Net sandstone thickness in the lower Tuscaloosa Group averages about half of that in the Paluxy Formation.

Table 2. Reservoir properties for the Paluxy Formation, Washita-Fredericksburg interval and the lower Tuscaloosa Group.

Reservoir Parameters	Paluxy	Washita-Fredericksburg	Lower Tuscaloosa
Reservoir Area (km^2)	13,467	13,467	13,467
Average Sandstone Thickness (ft)	190.0	25.5	104.6
Average Reservoir Porosity (%)	19.9	9.5	22.5
Average Reservoir Depth (ft)	10,000	8,500	7,000
Average Reservoir Temperature (^oC)	90	80	65
Average Reservoir Pressure (MPa)	37	28	21
CO_2 Density at Reservoir Depth (kg/m^3)	790	760	720
Reservoir Capacity at 100% CO_2 Saturation (Gt)	122.4	7.5	69.7

CO_2 storage resource of the Paluxy Formation, the Washita-Fredericksburg interval, and the lower Tuscaloosa Group estimated using the NETL methodology is shown in Table 3. The P_{50} storage resource estimated for these three stratigraphic units is about 2.45, 0.15 and 1.39 Gt, respectively. It is however important to note that the NETL formula (NETL 2012) employs very low values for the storage efficiency factor (E) because of uncertainty related to reservoir geology and fluid displacement factors. This value is further calculated for gross sandstone thickness rather than the net thickness values used in this study.

Table 3. CO_2 storage resource of the Paluxy Formation, Washita-Fredericksburg interval and lower Tuscaloosa Group based on basic NETL efficiency factors.

Categories	Paluxy	Washita-Fredericksburg	Lower Tuscaloosa
Reservoir Capacity at 100% CO_2 Saturation (Gt)	122.4	7.5	69.7
Efficiency Factor (P_{10}) %	0.51	0.51	0.51
Efficiency Factor (P_{50}) %	2.00	2.00	2.00
Efficiency Factor (P_{90}) %	5.50	5.50	5.50
Reservoir CO_2 Storage Resource (P_{10}) (Gt)	0.62	0.04	0.36
Reservoir CO_2 Storage Resource (P_{50}) (Gt)	2.45	0.15	1.39
Reservoir CO_2 Storage Resource (P_{90}) (Gt)	6.73	0.41	3.83

A more realistic estimate using efficiency factors where volumetric variables are well constrained follows the more detailed approaches of Goodman et al. (2011), and the results are shown in Table 4. The P_{50} CO_2 storage resource estimated using this method for Paluxy, Washita-Fredericksburg, and lower Tuscaloosa sandstone are 17.13, 1.06 and 16.73 Gt, respectively. Table 5 shows average storage capacity in million tonnes (Mt) per unit area (km^2, mi^2 and 9-mi^2 offshore blocks).

Table 4. CO_2 storage resource for the Paluxy Formation, Washita-Fredericksburg interval and lower Tuscaloosa Group using efficiency factors for displacement terms.

Categories	Paluxy	Washita-Fredericksburg	Lower Tuscaloosa
Reservoir Capacity at 100% CO_2 Saturation (Gt)	122.4	7.5	69.7
Efficiency Factor (P_{10}) %	7.40	7.40	7.40
Efficiency Factor (P_{50}) %	14.00	14.00	14.00
Efficiency Factor (P_{90}) %	24.00	24.00	24.00
Reservoir CO_2 Storage Resource (P_{10}) (Gt)	9.06	0.56	5.16
Reservoir CO_2 Storage Resource (P_{50}) (Gt)	17.13	1.06	9.76
Reservoir CO_2 Storage Resource (P_{90}) (Gt)	29.37	1.81	16.73

Table 5. P_{50} storage resource per unit area for the Paluxy Formation, Washita-Fredericksburg interval and lower Tuscaloosa Group.

Categories	Paluxy	Washita-Fredericksburg	Lower Tuscaloosa
G (P_{50}/km^2) (Mt)	1.27	0.08	0.72
G (P_{50}/mi^2) (Mt)	3.30	0.20	1.88
G (P_{50}/9 mi^2 offshore block) (Mt)	29.66	1.83	16.89

Maps showing the storage resource per unit area (tonnes/km^2) for the Paluxy Formation, the Washita-Fredericksburg interval and the lower Tuscaloosa Group, and the total resource of the three target units were drawn and are shown in Figures 20 through 23. Figure 20 shows that the Paluxy Formation has storage resource exceeding 2 Mt/km^2 in the withdrawal synclines around the Destin Dome. Capacity is highly variable in the Mobile and Viosca Knoll Areas, where resource ranges from 0 to 1.8 Mt/km^2. Storage resource in the Washita-Fredericksburg interval is concentrated largely in the Mobile and Viosca Knoll Areas. The highest capacity is observed along a northwest-southeast trending axis. These values ranges from 0.1 to 0.8 Mt/km^2 (Figure 21).

Storage resource in the lower Tuscaloosa Group also is concentrated along the shore in the Mobile Area and near the shelf margin of the Viosca Knoll Areas with about 85% of the storage resource being in this area (Figure 22). Figure 23 is a total storage resource map combining all three intervals. Average storage resource is 2.1 Mt/km^2. This map indicates that sandstone is concentrated near the shoreline in the Mobile Area in the withdrawal synclines flanking Destin Dome. While the sandstone concentration appears to be significantly less in the central part of the basin northeast to the Desoto Canyon Diapir Province in the Destin Dome and Pensacola Areas, a lack of well control limits their detailed assessment.

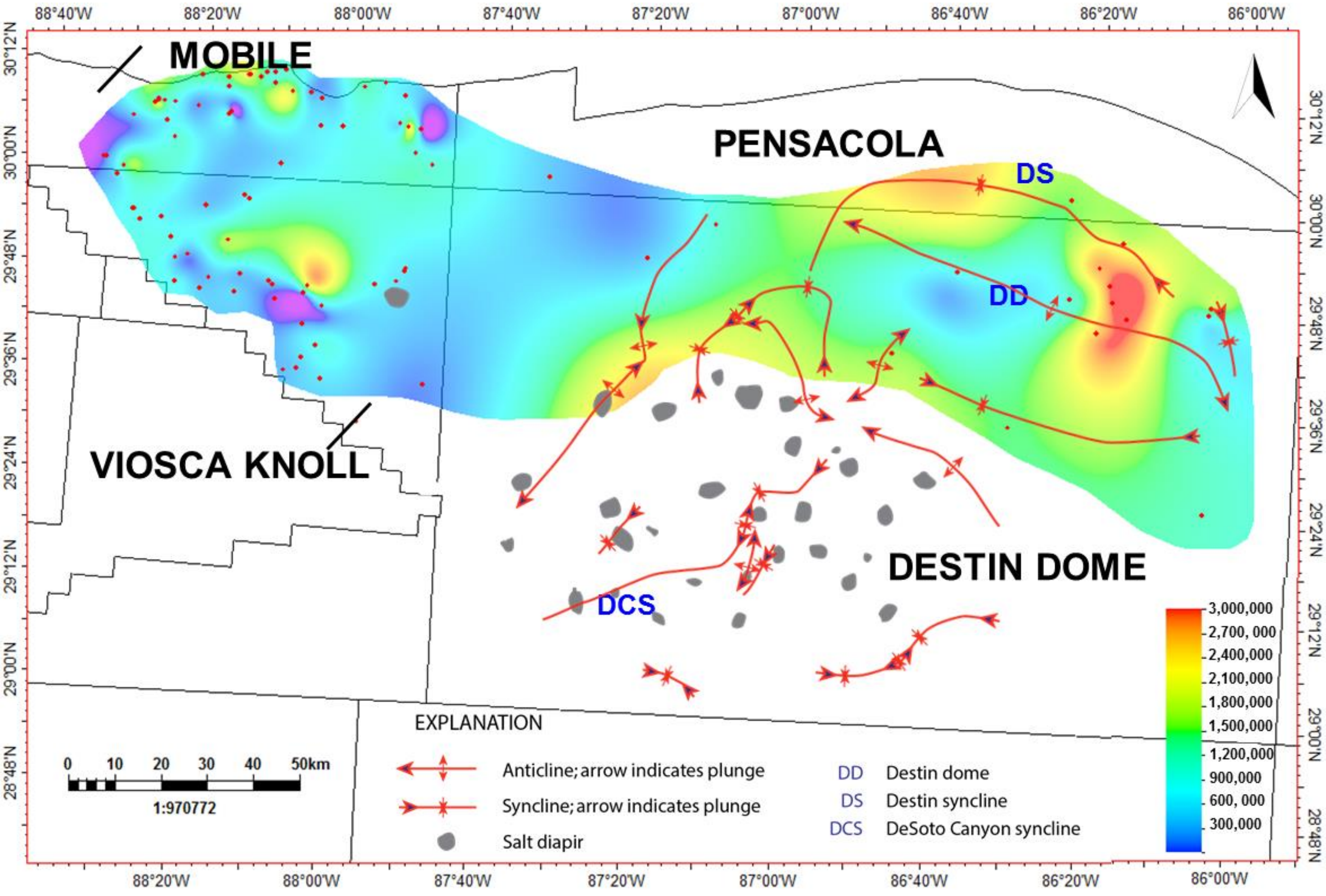


Figure 20. Storage resource map of the Paluxy Formation. Contour interval = 300,000 tonnes/km^2.

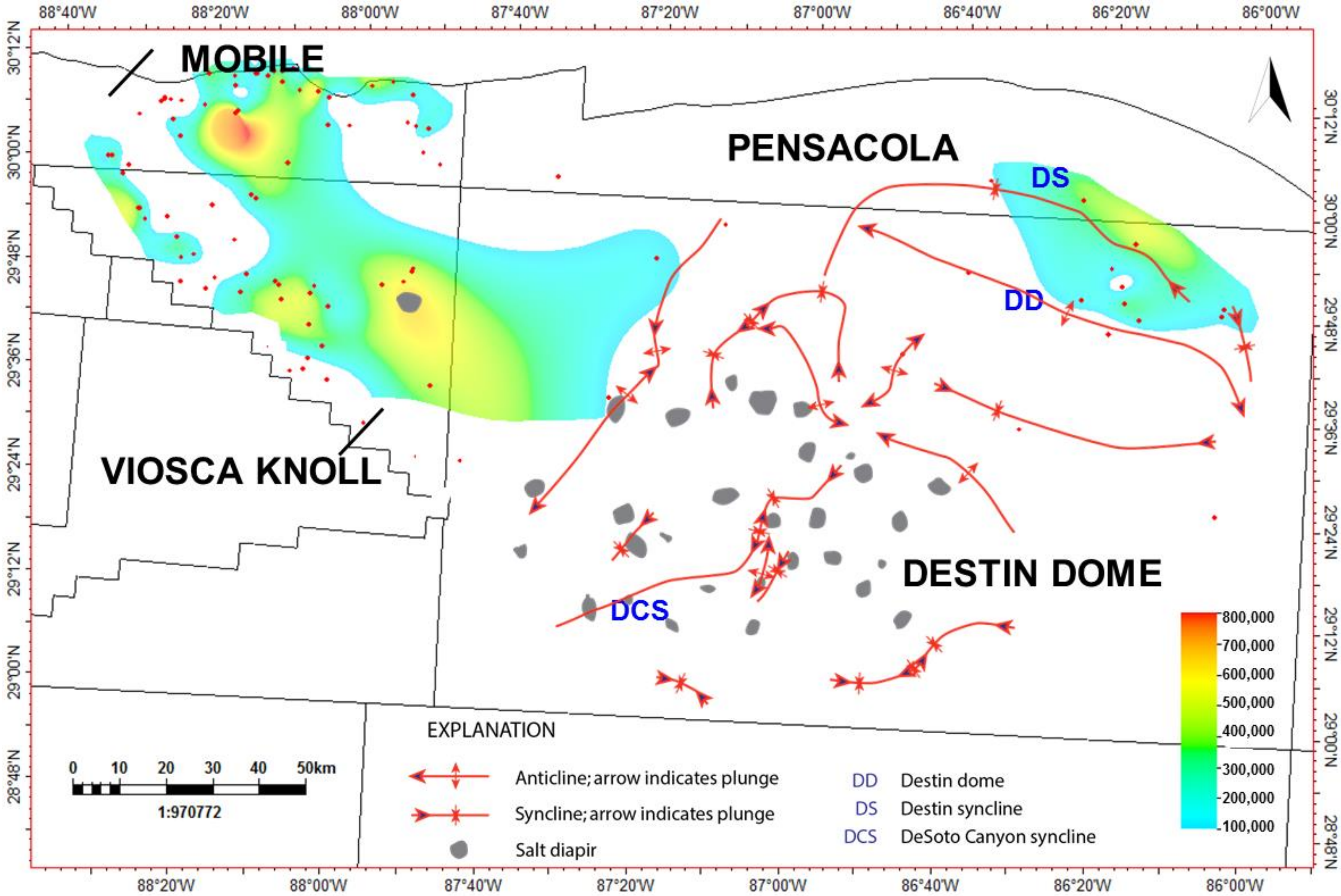


Figure 21. Storage resource map of the Washita-Fredericksburg interval; Contour interval = 100,000 tonnes/km^2.

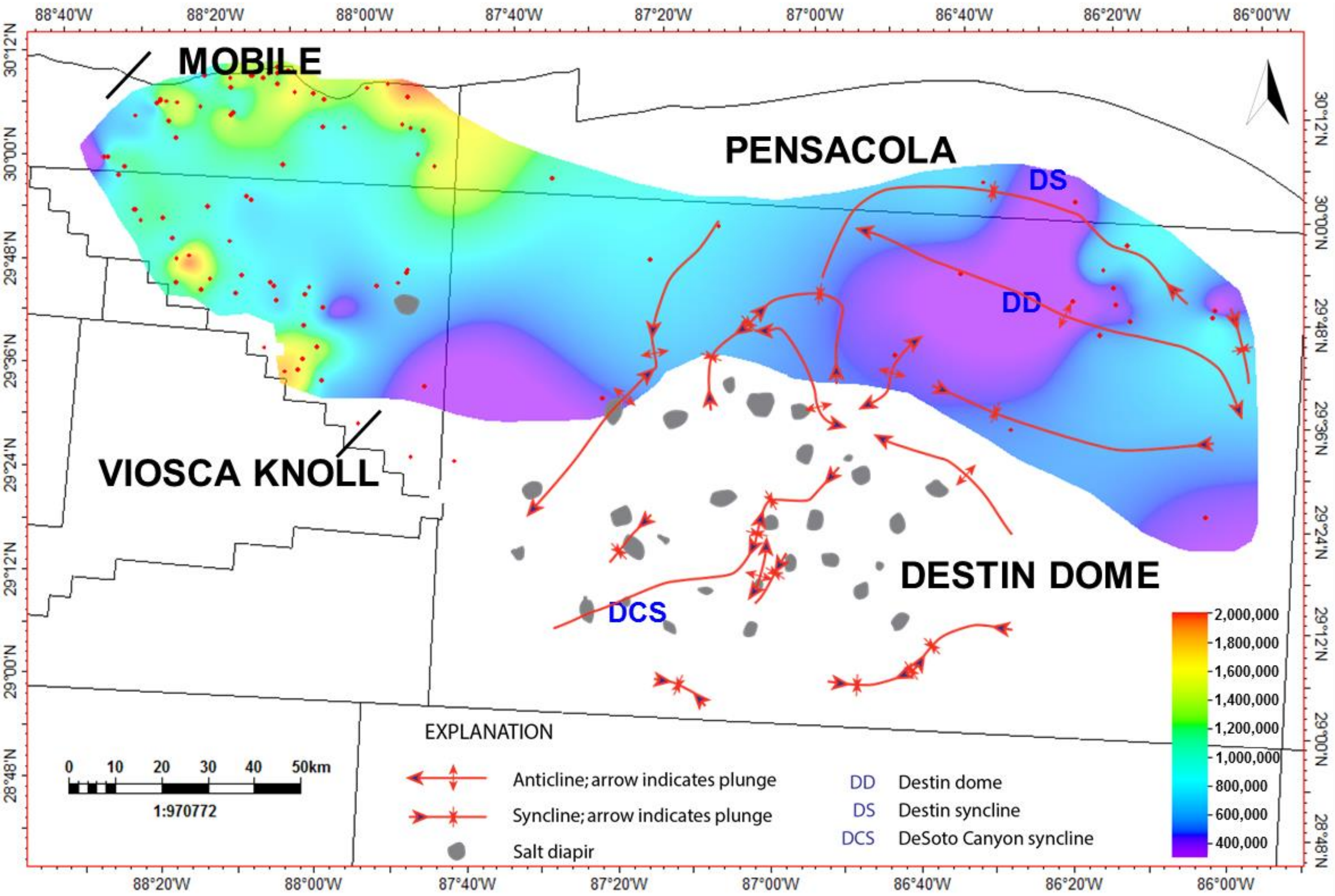


Figure 22. Storage resource map of the lower Tuscaloosa Group. Contour interval = 200,000 tonnes/km^2.

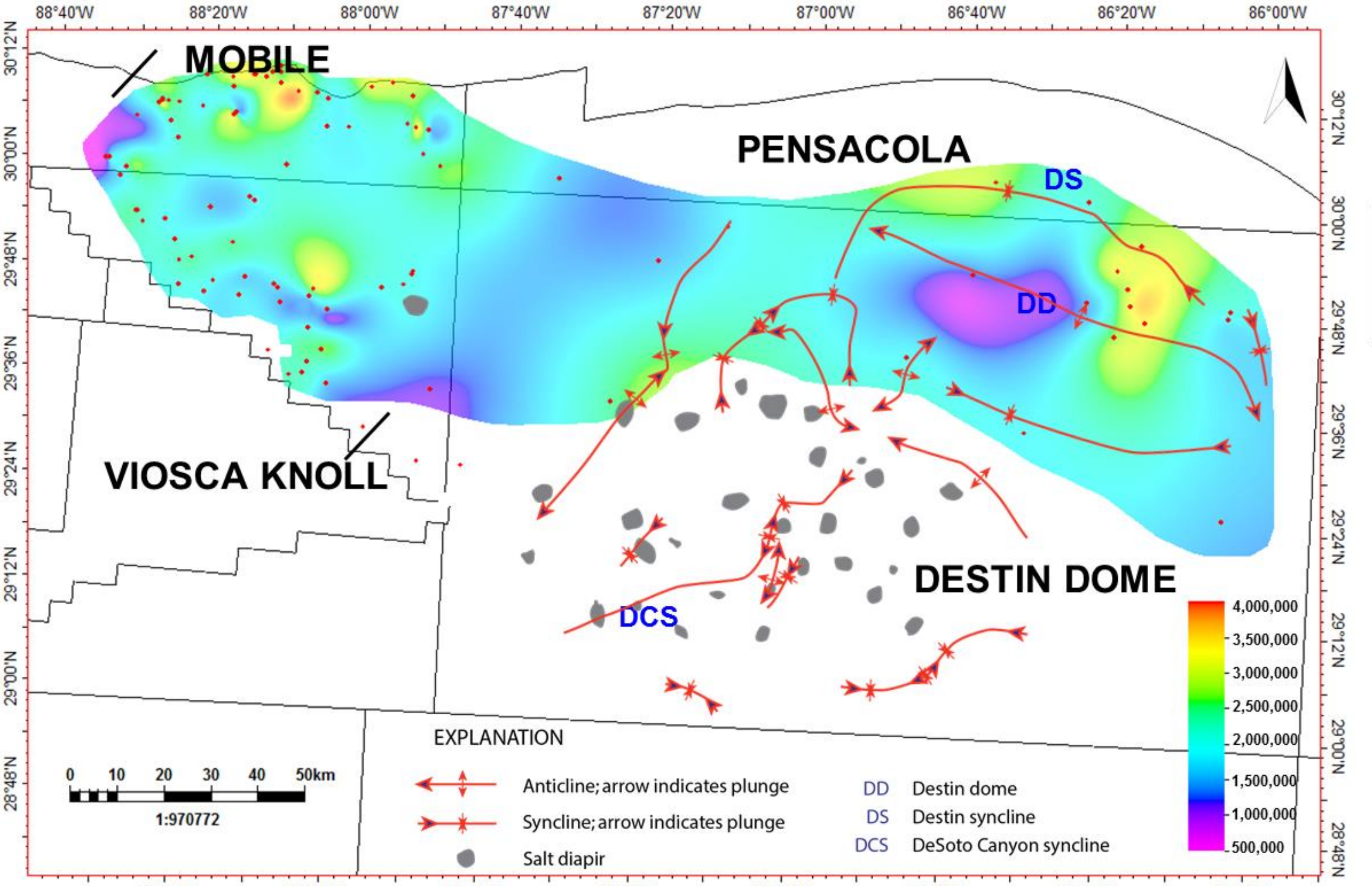


Figure 23. Cumulative storage resource map of the northern DeSoto Canyon Salt Basin (Paluxy Formation, Washita-Fredericksburg interval and lower Tuscaloosa Group). Contour interval = 500,000 tonnes/km^2.

CHAPTER IV

DISSCUSSION

Prior to this study, little was known about Cretaceous sandstone in the DeSoto Canyon Salt Basin. The Cretaceous strata include multiple saline formations that are thought to be under normal hydrostatic pressure. Although Lower Cretaceous sandstone intervals below the Ferry Lake Anhydrite, including the Hosston Formation, Sligo Formation, and the Donovan sand were penetrated locally at a depth shallower than 12,000 ft in the eastern Pensacola and northeastern Destin Dome Areas none, of the sandstone units are thicker than 20 ft and so did not satisfy the qualification criteria used in this study. Geophysical well log analysis reveals that only the Paluxy-lower Tuscaloosa section contains sandstone units satisfying the qualification criteria used in this study. Regional cross-sections (Plates 1, 2) and net sandstone isolith maps (Figures 11-13) reveal the regional distribution and heterogeneity of each target formation.

Potential Reservoirs

Stratigraphic analysis indicates that the Paluxy Formation is a net thickening- and coarsening-upward succession composed of interbedded sandstone, limestone and shale. The Paluxy Formation is considered a net progradational package of fluvial, coastal and shallow marine sandstone beds interbedded with shale (Mancini and Puckett, 2002). The variability observed in the SP log signatures from blocky to Christmas-tree is consistent with a range of possible depositional environments ranging from a bedload-dominated fluvial systems to coastal deposits. The Paluxy Formation becomes richer in limestone towards the Viosca Knoll Area as seen in the dip cross-section (Plate 2) where it is in facies relationship with the carbonate platform deposits landward of the Lower Cretaceous reef trend (Pashin et al., 2008).

Reservoir quality sandstone in the Paluxy Formation generally has net thickness greater than 200 ft on the stable shelf in the Mobile and Pensacola Areas and in the withdrawal synclines flanking Destin Dome (Figure 11). The concentration of sand in the withdrawal synclines around Destin Dome indicates that deposition of the Paluxy Formation was contemporaneous with salt movement and diversion of sand around the early uplift, which Pashin et al. (2016) referred to Ancestral Destin Dome. While sandstone units in the Paluxy Formation generally exhibit reservoir quality porosity, sandstone thickess and internal heterogeneity that are extremely variable, reflecting the complexity of the depositional systems (Plates 1, 2; Figures 11, 14). Petrologic analysis of Paluxy fluvial and interfluvial deposits onshore in southwest Alabama indicates depositional and diagenetic processes associated with reservoir architecture and paleosol development to be major causes of reservoir heterogeneity in the Paluxy Formation (Folaranmi, 2015); however, it remains unclear precisely how depositional and diagenetic processes in offshore areas, which may include coastal deposits, relate to those onshore.

The net sandstone isolith map in Figure 12 indicates that reservoir-quality sandstone units in the Washita-Fredericksburg interval are localized and tend to be restricted to the stratigraphic level of the Dantzler sand (Plates 1, 2; Figures 5, 12). The geophysical log signatures for individual units are predominantly blocky (Figure 6) and, the map patterns suggest that deposition occurred in a bedload-dominated fluvial systems (Figure 5). The most significant accumulation of Washita-Fredericksburg sandstone occurs in a southeast-tending belt suggestive of a fluvial axis along which sediment was transported toward the diapir province of the DeSoto Canyon Syncline. While Washita-Fredericksburg sandstone lacks regional continuity, it provides significant storage objectives locally and may be particularly attractive where it occurs in tandem with Paluxy and lower Tuscaloosa objectives. This lack of highly porous in the Washita-Fredericksburg interval contrasts with the observations made onshore (Pashin et al., 2008), where Washita-Fredericksburg is a sand rich interval and appears to be part of a braidplain. The linear trends offshore suggest formation of major transitive fluvial axes on a coastal plain. The braidplain was likely tributary to these axes. This transition, along with the presence of a thick basal limestone, indicates diminishing sediment supply and transition from continental to coastal and marine environments (Mancini and Puckett, 2002).

The Massive sand of the lower Tuscaloosa Group has been interpreted as stacked beach-barrier and inlet deposits in southwestern Alabama and southeastern Mississippi (Mancini et al., 1987; Petrusak et al., 2009). The dominant blocky geophysical log signature of the Massive sand has been interpreted as the product of aggradational sedimentation, whereas fining upward in the upper part of the sandstone is thought to indicate backstepping associated with marine transgression (Mancini and Puckett, 2005). Onshore cores in southeastern Mississippi contain marine fossils, and the basal disconformity at the base of the Massive sand is interpreted as the product of extensive marine reworking and ravinement formation (Pashin et al., 2008).

The isochore map of the lower Tuscaloosa Group in Figure 13 shows that the reservoir quality sandstone is over 200 ft thick on the stable shelf in the Mobile, western Pensacola and Viosca Knoll Areas. It thins out towards the south of the basin (<100 ft) and in the Destin Dome Area. This thinning of the Massive sand of the lower Tuscaloosa Group has been attributed to the growth of the Destin Dome anticline and distance from the sediment source (Petty, 1995). Structural restorations indicate that the main Destin Dome structure grew mainly during and after Tuscaloosa-Midway deposition (Pashin et al., 2016). The net sandstone isolith map of the lower Tuscaloosa Group indicates that large parts of the Mobile and Viosca Knoll Areas contain qualified sandstone with net thickness >150 ft that provide attractive locations for offshore CO_2 storage. The lower Tuscaloosa Group also has the highest average porosity of the sandstone units evaluated and is the shallowest of all the three potential CO_2 storage target, which make it a primary storage objective particularly close to shore in the Mobile Area.

Confining Seals

The main geological risk for CO_2 storage is arguably seal integrity (Damen et al., 2006). By definition, a prospective geological sink must not only have adequate porosity and permeability to store large volumes of carbon dioxide but should also be overlain by at least one regionally extensive sealing stratum. All proposed reservoirs are below several sealing stratigraphic units, including the nonporous basal carbonate of the Washita-Fredericksburg interval, the Marine Tuscaloosa shale, chalk of the Selma Group, and the Porters Creek Clay of the Midway Group. Careful examination of the well logs showed that while the upper part of the Washita-Fredericksburg interval contains some reservoir quality sandstone beds, there is very little sandstone in the basal Washita-Fredericksburg limestone unit, which is 1,000 to 2,000 ft thick across the basin. Density porosity logs indicate that porosity is effectively zero, and so the limestone section serves as the primary topseal above the Paluxy sandstone units. The Marine Tuscaloosa shale, which is interpreted as a condensed section (Mancini et al., 1996), immediately overlies the lower Tuscaloosa Group and is uniformly thick (200-300 ft) throughout the study area. The Marine shale is regionally extensive and is considered the primary seal for onshore petroleum accumulations in the lower Tuscaloosa Group (Mancini et al., 1987), which is the largest oil producer in Mississippi. The presence of multiple sealing layers in the Tuscaloosa-Midway section, including the Marine shale, the chalk of the Selma Group, and the Paleocene mudstone units, also helps minimize the risk of leakage.

Commercial Strategy: Reservoir Potential and Storage Risks

The DeSoto Canyon Salt Basin exhibits significant structural complexity in the Cretaceous section. The basin contains multiple anticlines cored by salt pillows, crestal faults atop the pillow-cored antliclines, and the peripheral faults of the Destin fault system, and the DeSoto Canyon diapir field (Pashin et al., 2016). Growth of the peripheral faults was mainly during Early Cretaceous time. While the faults are not mappable by seismic data in the Upper Cretaceous Formations, several seismic lines demonstrate that the tip regions of the faults extend into the Upper Cretaceous section (Pashin et al., 2016). Accordingly, caution is required when considering CO_2 sinks in proximity to the Destin fault system. In addition, crestal faults above salt pillows also pose risk, and so the crestal regions of the salt pillows may not be viable storage targets and may pose risk for plume migration along the anticlinal flanks near these structures.

The evaluated area is about 13,466 km^2 (~5200 mi^2) and the estimated P_{50} storage capacity for this area is about 17, 1 and 10 Gt for Paluxy, Washita-Fredericksburg and lower Tuscaloosa formations respectively. The combined storage capacity of the Cretaceous targets therefore is about 28 Gt in the DeSoto Canyon Salt Basin. The numbers obtained from this evaluation support the preliminary estimates made by Hills & Pashin (2010) that offshore Cretaceous formations in the study area can store more than 30 Gt of CO_2.

Volumetric analysis indicates that the Paluxy Formation and lower Tuscaloosa Group are the main reservoir units that have Gt-class CO_2 storage capacity and potentially high injectivity. Together, these two units account for almost 96% of the assessed storage capacity in the basin (Figure 24). The Washita-Fredericksburg interval has a relatively low storage potential ($P_{50} = 1$ Gt), but where qualified sandstone is present, it can be a viable storage objective and is also would be an attractive component of a stacked storage strategy.

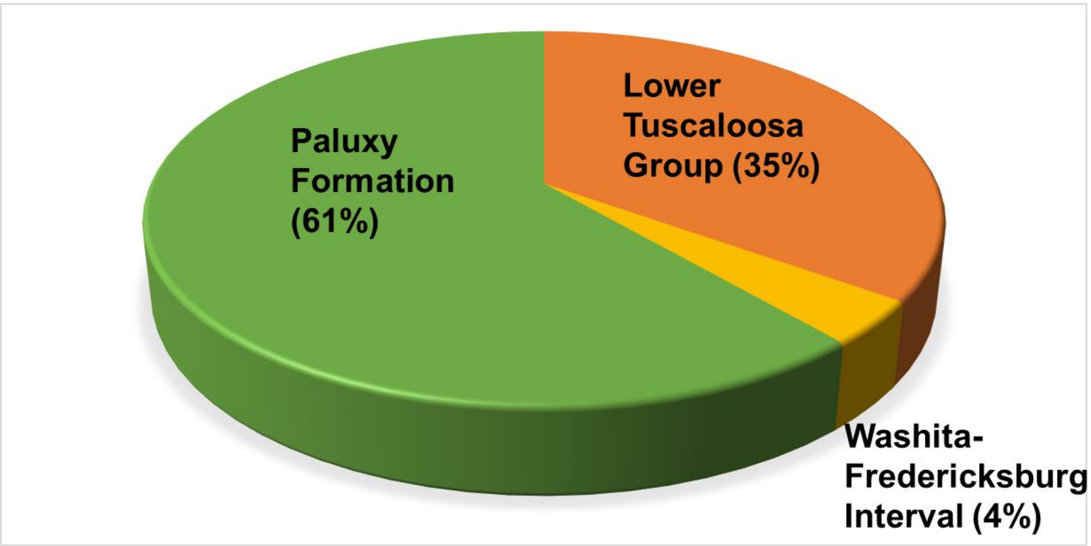


Figure 24. Relative CO_2 storage capacity of potential CO_2 storage objectives in the DeSoto Canyon Salt Basin.

While the Paluxy Formation has a greater net storage capacity than the lower Tuscaloosa Group, care must be taken to recognize the lateral heterogeneity and discontinuity of individual sandstone units. However, this proved not to be an obstacle for injection into the Paluxy Formation during the SECARB Anthropogenic Test (Koperna et al., 2012). Stratigraphic cross-sections reveal complex vertical stacking of lensoid sandstone units in the Paluxy Formation and the Washita-Fredericksburg interval (Plates 1, 2). The Massive sand of the lower Tuscaloosa Group, on the other hand, appears to be continuous across large parts of the salt basin and is especially thick in the Mobile Area closest to the modern coast. Figure 25 shows the well-based net sandstone isolith map of the Paluxy Formation mapped on the seismically defined structural surface of the Ferry lake Anhydrite. Similarly, Figures 26 and 27 show the well-based net sandstone isolith maps of the Washita-Fredericksburg interval and lower Tuscaloosa Group mapped on the seismically defined surface of the Marine Tuscaloosa shale. Figure 28 is a 3D visualization showing the net sandstone isolith of the full target zone, including the Paluxy Formation, the Washita-Fredericksburg interval, and the lower Tuscaloosa Group in the study area and their relative positioning with respect to the major structural provinces.

Net sandstone thickness and porosity maps (Figures 11 through 16) highlight the variability of reservoir quality and can help with selection of the most suitable injection locations in the study area. The Paluxy Formation has an extremely variable reservoir distribution with most of the capacity concentrated in the northeastern Destin Dome and eastern Pensacola Areas (Figure 20). Some of this storage capacity is in the Destin syncline. This area includes the peripheral faults of the Destin fault system and therefore may pose a risk to reservoir and seal integrity. The reservoirs in the Washita-Fredericksburg interval and the lower Tuscaloosa Group are concentrated in the stable shelf in the Mobile and Viosca Knoll Areas. The structure in this area is very simple, save for one major salt diapir (Figures 21, 22).

Figure 29 is a 3D visualization of the combined storage resource of the full Paluxy-lower Tuscaloosa target zone that shows how capacity relates to the major structural provinces. Based on the location of the reservoir units, the vertical stacking of the individual sandstone bodies, the structural framework of the region, and available well control, the Mobile and Viosca Knoll Areas appear to provide the most suitable locations for CO_2 injection in the DeSoto Canyon Salt Basin. The combined storage resource in this region ranges from 2 to 4 Mt/km^2 and averages about 2.9 Mt/Km^2 that is significantly higher than the basin average storage capacity of 2.1 Mt/km^2. The combined storage resource for an offshore block in this area is between 47 and 93 Mt with an average of about 69 Mt.

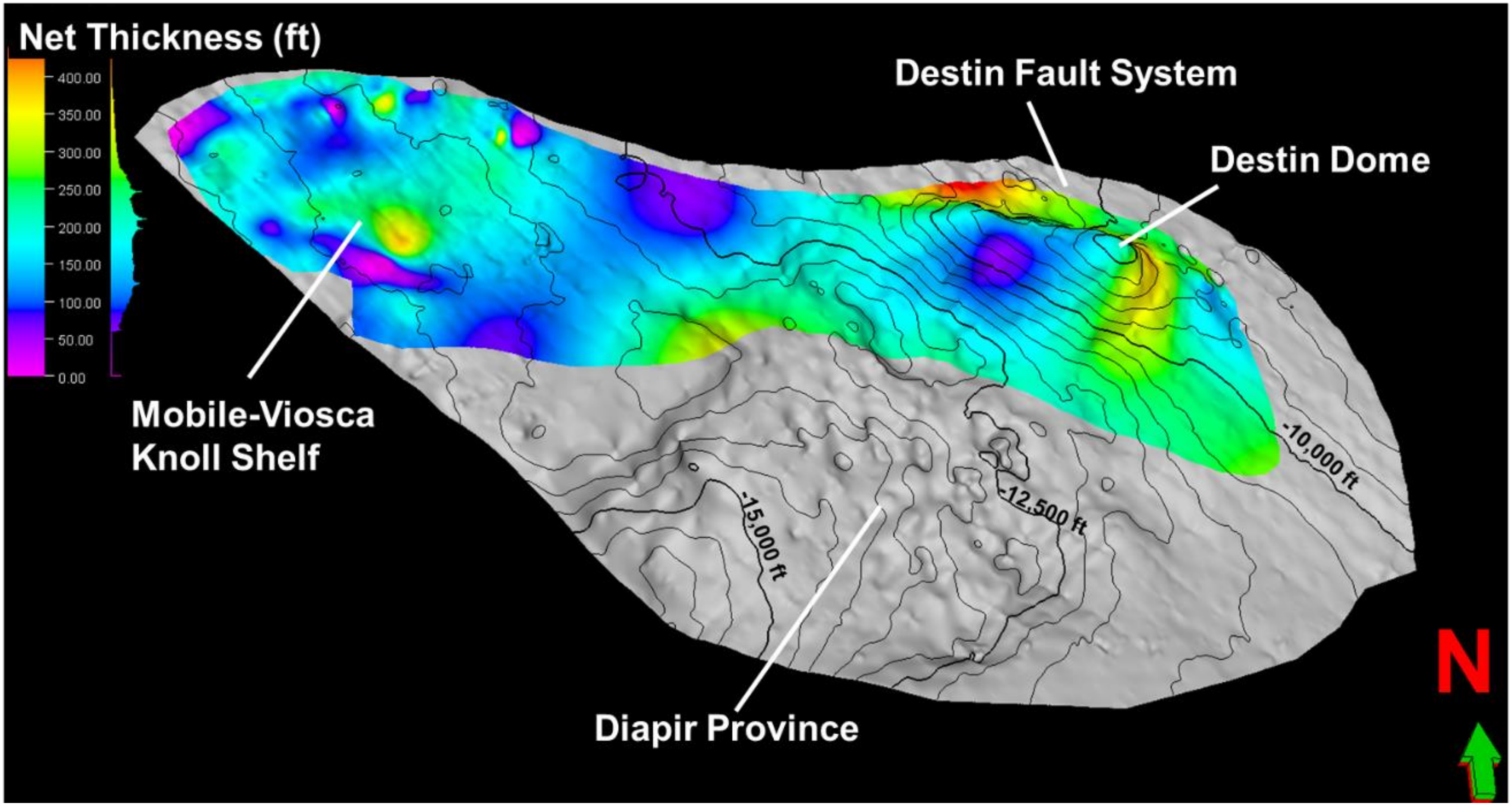


Figure 25. 3D visualization of the net sandstone isolith map of the Paluxy Formation draped on the structural surface of the top of the Ferry Lake Anhydrite.

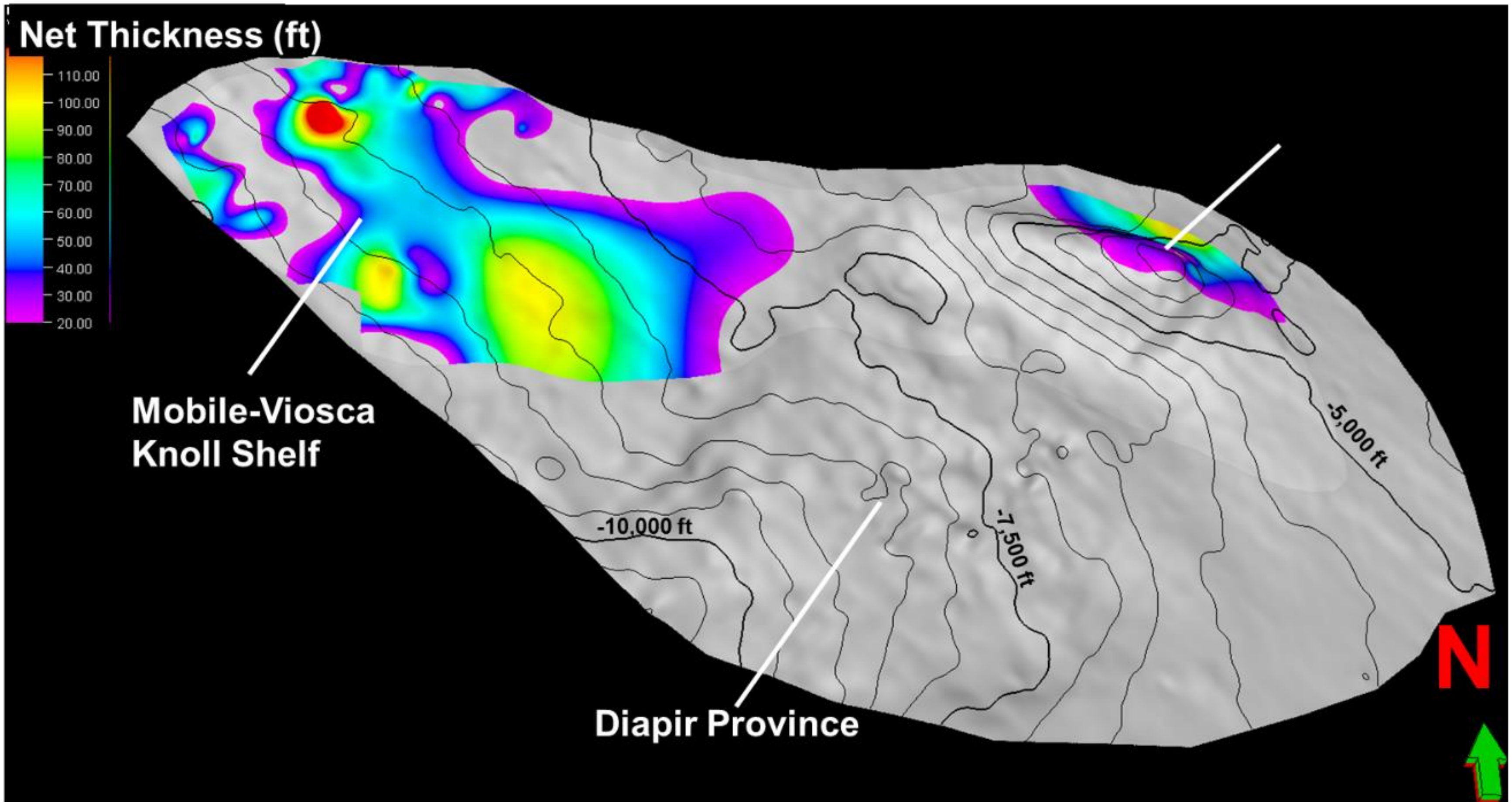


Figure 26. 3D visualization of the net sandstone isolith map of the Washita-Fredericksburg interval draped on the structural surface of the top of the Marine Tuscaloosa shale.

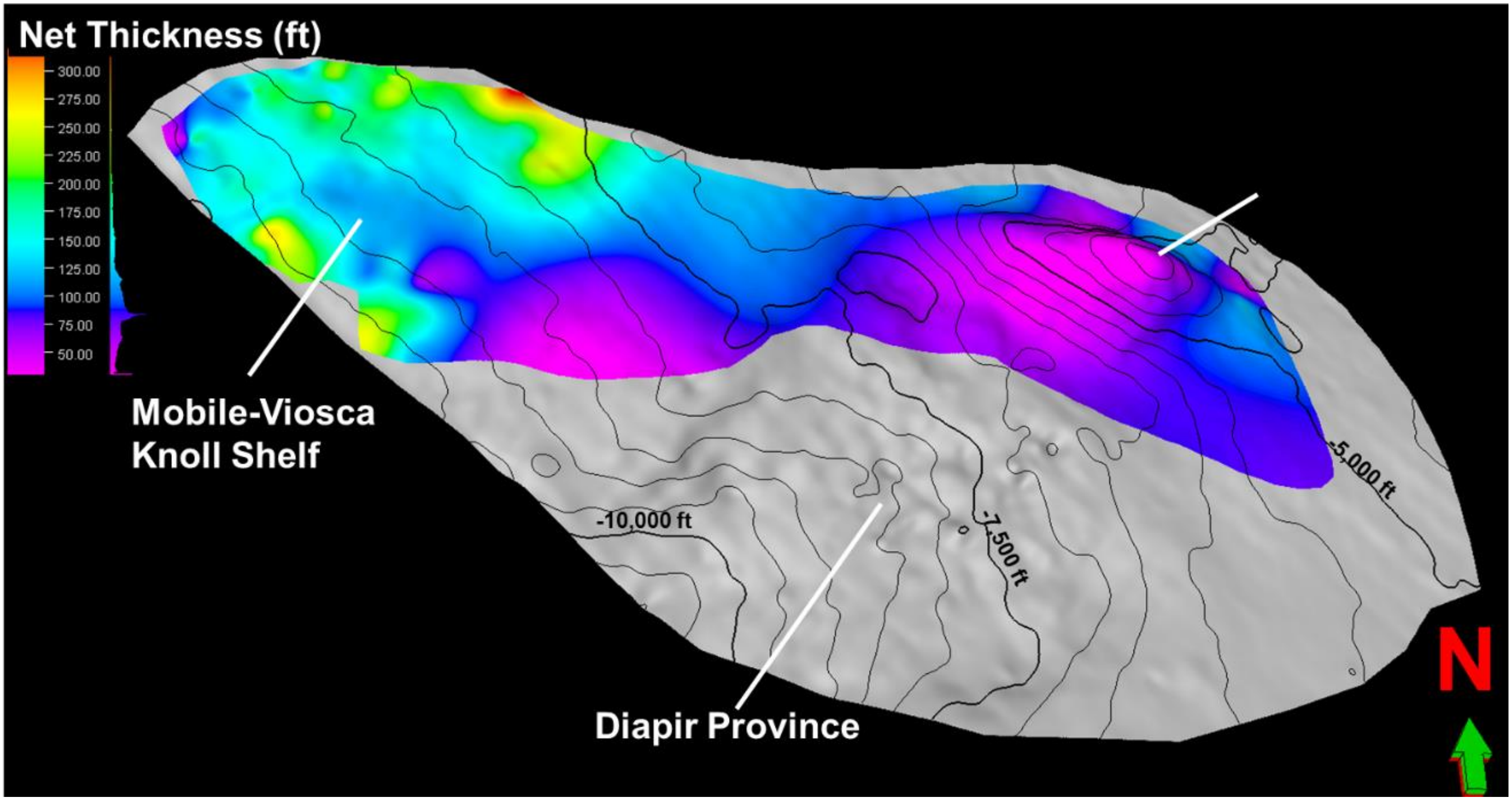


Figure 27. 3D visualization of the net sandstone isolith map of the lower Tuscaloosa Group draped on the structural surface of the top of the Marine Tuscaloosa shale.

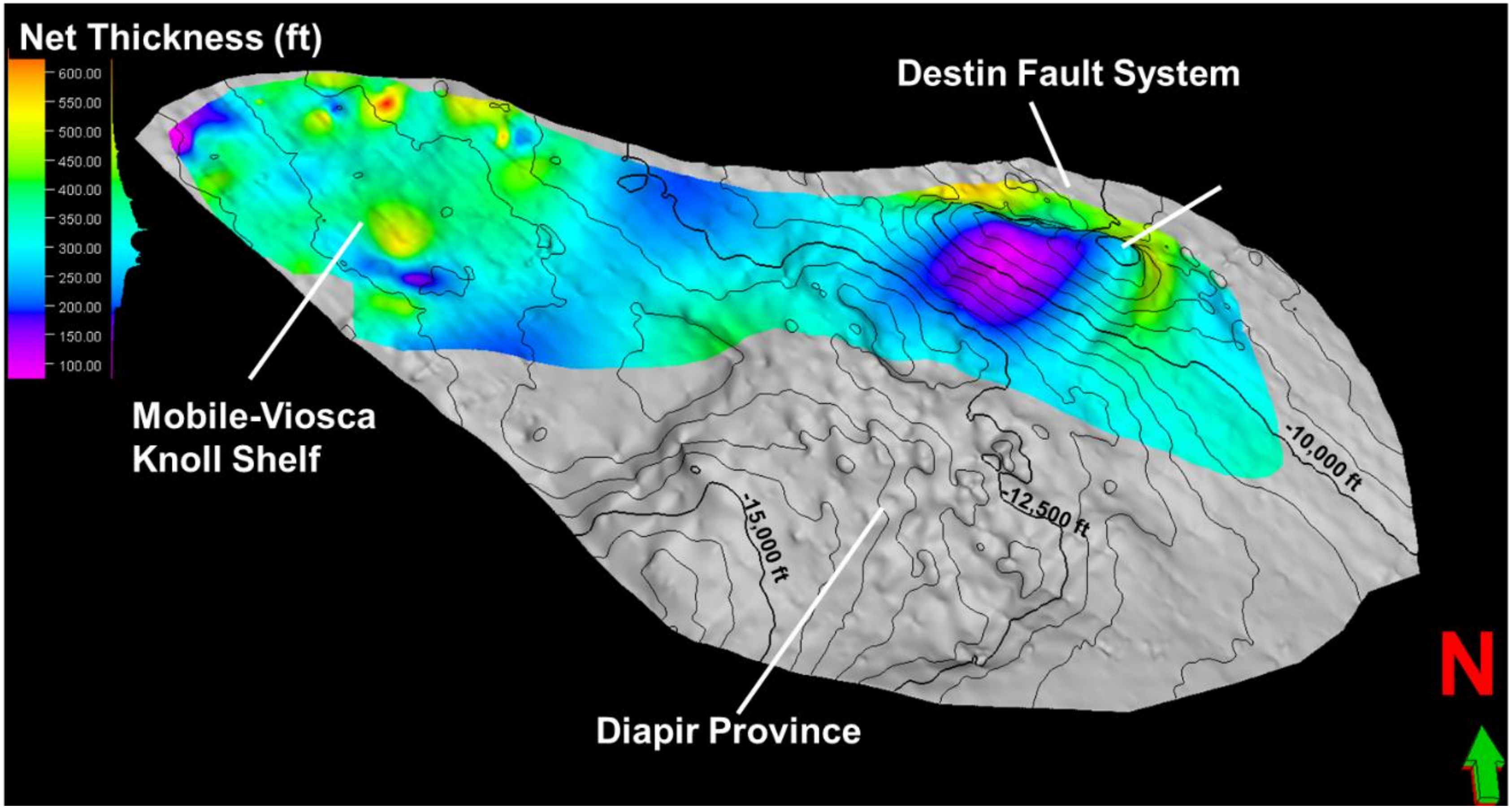


Figure 28. 3D visualization of the net sandstone isolith map of the full Cretaceous target zone draped on the structural surface of the top of the Ferry Lake Anhydrite.

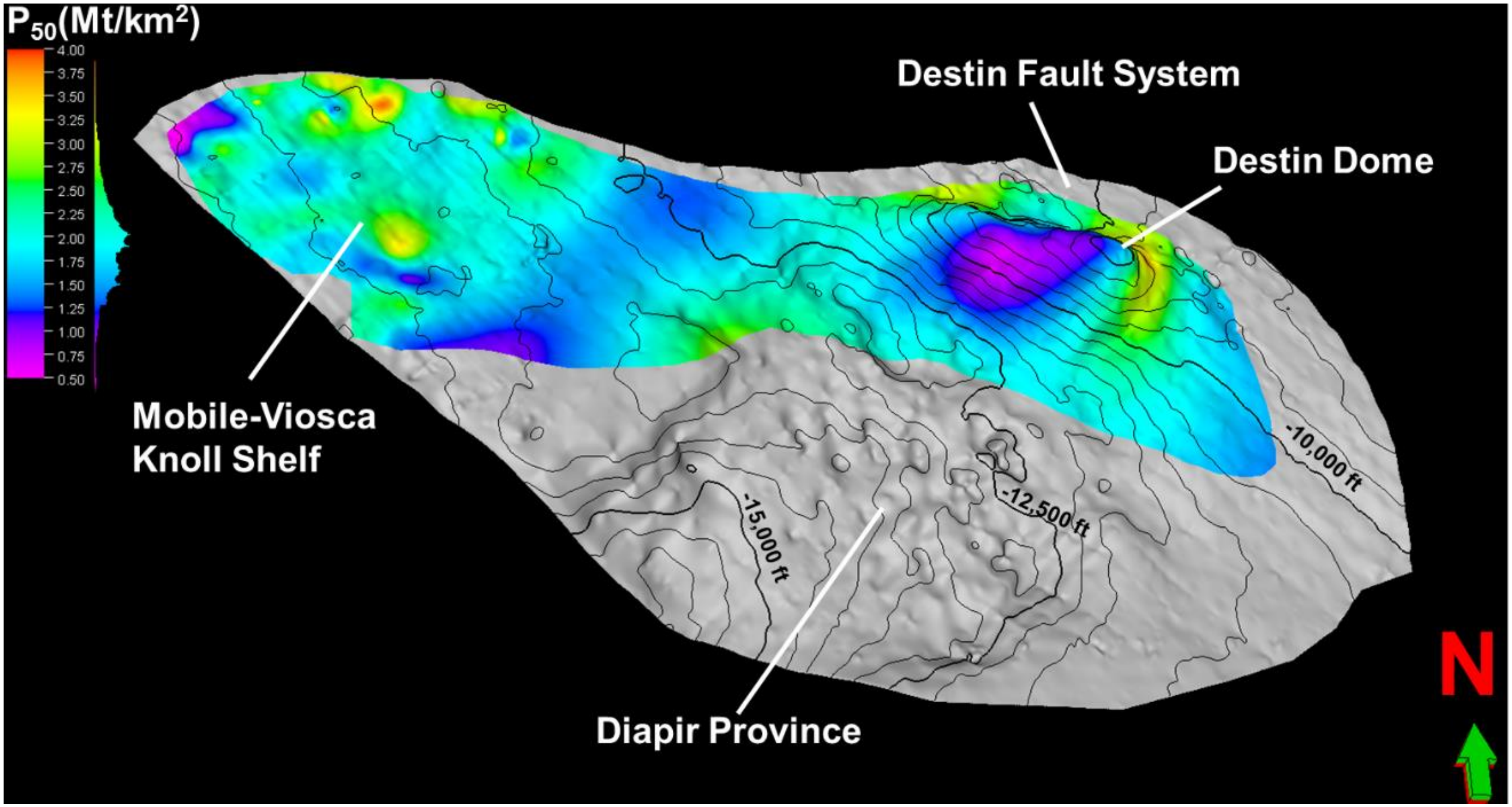


Figure 29. 3D visualization of the cumulative storage resource in the Paluxy-lower Tuscaloosa target zone draped on the structural surface of the top of the Ferry Lake Anhydrite.

These storage resource numbers are encouraging. According to the U.S. GHG inventory (https://ghgdata.epa.gov/ghgp/main.do), the 2016 greenhouse gas emissions from few key power plants close to shore, such as Plant Barry in Alabama, Plant Daniel in Mississippi, and Plant Crist in Florida were 7.5 Mt, 5.2 Mt and 3.1 Mt, respectively. Plants Barry and Daniel have been used in pilot CO_2 storage programs led by the Southeastern Regional Carbon Sequestration Partnership (SECARB) and have successfully demonstrated CO_2 sequestration in the offshore Cretaceous reservoirs (Koperna et al., 2009, 2012). The combined emissions from Plants Barry, Daniel, and Crist is about 15.8 Mt with an average of 5.3 Mt per year. Considering this as average annual emissions from a major coal-fired power plant, each offshore block (9.0 mi^2; 23.3 km^2) in the Mobile and Viosca Knoll Areas is capable of sequestering emissions from 13 such power plants.

Leakage risks from CO_2 storage can occur through manmade pathways (e.g., wells) or natural pathways (e.g., faults, fractures). Presence of multiple sealing beds of regional extent above the lower Tuscaloosa Group helps minimize risk, and the shale and tight limestone beds within the main sandstone-bearing intervals can serve as baffles and barriers to cross-formational flow. In addition, porous sandstone units above the target injection zone may act as buffers that can trap fugitive CO_2 before it reaches the major reservoir seals. Pressure data and regional geochemical data (Hills et al., 2016) indicate that the reservoirs in the study area are normally pressured. However, geomechanical studies will be helpful for identifying and mitigating any potential risks related to reservoir and seal integrity.

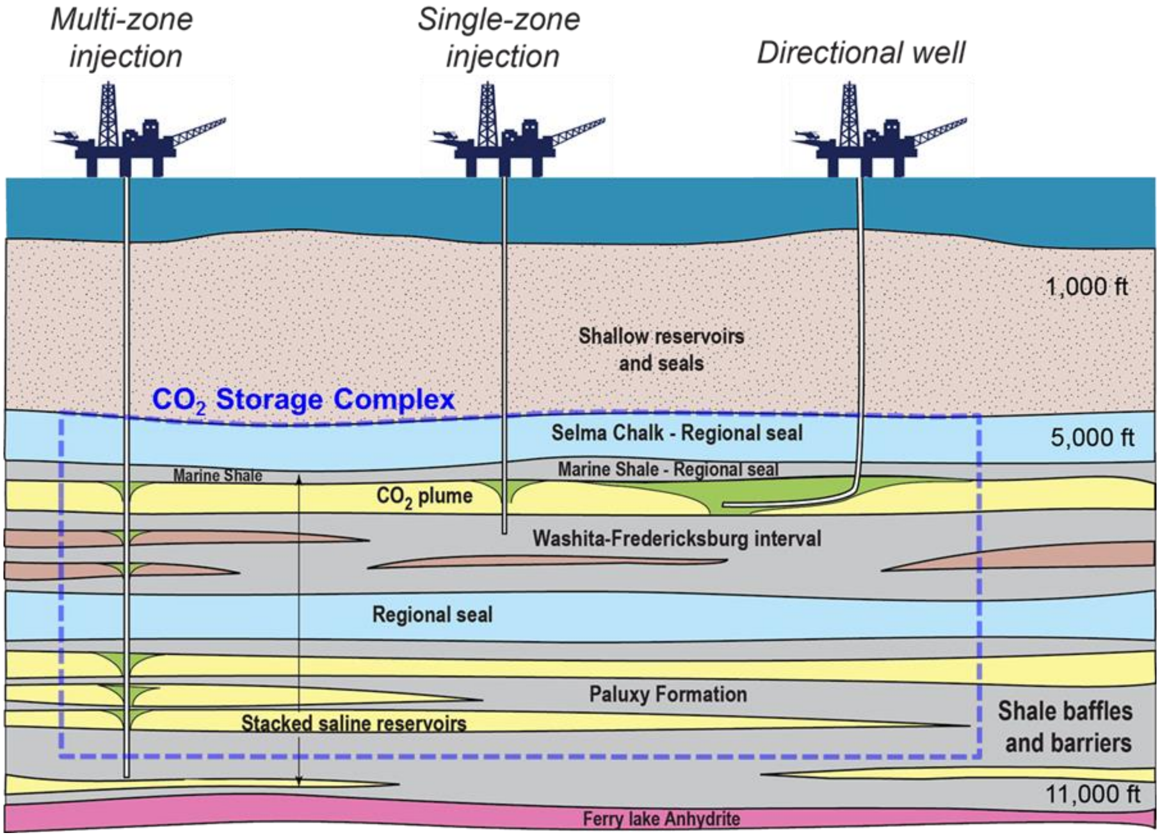


Figure 30. Conceptual model of a geological CO_2 storage complex in the targeted reservoirs over the stable shelf in the Mobile and Viosca Knoll Areas.

While thick sealing intervals help minimize the risk of CO_2 migrating out of the storage complex the biggest challenge for CO_2 storage, especially in the Paluxy Formation, will be managing stratigraphic heterogeneity, especially in areas with sparse well control. Offsetting existing wells will be an effective strategy to maximize the probability of contacting thick and porous sandstone bodies. The SECARB Phase III Anthropogenic test has established the feasibility of large scale CO_2 sequestration in the Paluxy Formation in Alabama (Koperna et al., 2012). A small-scale test conducted at Plant Daniel in southeast Mississippi evaluated the lower Tuscaloosa Group (Koperna et al., 2009; Petrusak et al., 2009), and a large-scale SECARB Phase III test was performed at the Cranfield Field in Mississippi (Hovorka et al., 2013). These tests have stressed the importance of high-resolution reservoir characterization and simulation for accurate long term

CO_2 plume prediction for commercial-scale storage. A variety of CO_2 monitoring, verification and accounting (MVA) strategies were used in these tests that provide vital information on plume extent, plume geometry, pressure footprint, and confinement of CO_2 in the reservoir zone. Numerous wells in the Mobile Area reach total depth in ultra-deep Jurassic gas reservoirs of the Norphlet Formation. Cretaceous strata are typically behind the long string of well casing. Dry holes, however, are typically not cased and thus pose the greatest risk of cross-formational flow. Understanding wellbore-related risks is important, because offshore CO_2 storage wells may make use of existing infrastructure and offset older exploratory and production wells.

Figure 30 illustrates a conceptual model of the storage complex including the reservoirs, baffles, barriers and seals that defines the container where CO_2 can be stored in the Cretaceous System. It also depicts injection through single-zone, multi-zone, and directional wells following the model of Pashin et al. (2008). Single-zone wells are well suited for areas where only one sandstone interval, such as the Massive sand of the lower Tuscaloosa Group, is prospective. A stacked storage strategy employing wells completed in multiple sandstone units helps limit the overall geographic and pressure footprint of the plume. Directional wells, by contrast, maximize reservoir contact, injection rate, and storage efficiency.

CHAPTER V

CONCLUSIONS

The DeSoto Canyon Salt Basin is a part of the Gulf of Mexico continental shelf that extends from offshore Mississippi to the western Florida Panhandle. A complex geological history has created a diverse suite of tectonic structures, including salt pillows, salt rollers, salt domes, salt diapirs and peripheral faults. The basin contains a thick succession of siliciclastic, carbonate, and evaporite deposits of Mesozoic and Cenozoic age.

Although the regional geology of the eastern Gulf of Mexico has been studied (Buffler and Sawyer, 1985; MacRae and Watkins, 1993; Pindell, 1985; Pashin et al., 2016), only limited research has been performed on the Cretaceous formations in the region (Mancini and Puckett, 2002; Pashin et al., 2016; Petty, 1997). Previous studies have indicated huge potential for onshore CO_2 storage in the Southeastern U.S. (e.g., Koperna et al., 2009, 2012; Esposito et al., 2010), and it is probable that this potential includes offshore areas.

This study evaluated the sequestration potential of Cretaceous-age saline reservoirs in the DeSoto Canyon Salt Basin by identifying potentially viable saline reservoirs, analyzing the stratigraphic framework, quantifying storage capacity, and determining optimal areas for CO_2 injection. These goals were achieved by employing diverse analytical methods, including geophysical well log analysis, stratigraphic analysis, digital mapping, and volumetric assessment.

Stratigraphic analysis using well logs has helped identify several potential saline reservoir units in the Cretaceous System. These reservoirs are in the Paluxy Formation, the Washita-Fredericksburg interval, and the lower Tuscaloosa Group. The Paluxy Formation and lower Tuscaloosa Group are areally extensive, contain thick porous zones (>120 feet) with high porosity (18-21%), and are confined below multiple regionally extensive sealing layers, including the basal limestone of Washita-Fredericksburg interval, the Marine shale of Tuscaloosa Group, chalk of the Selma Group and the basal mudstone of the Midway Group.

The sandstone units are interpreted to have accumulated in diverse terrestrial through marginal-marine environments. The Paluxy Formation is a thick, heterogeneous succession containing sandstone with variable reservoir quality that is interbedded with mudstone units that form complex baffles and barriers to flow. The sandstone units are interpreted as aggradational deposits formed in fluvial to coastal settings. The Washita-Fredericksburg interval is interpreted to have been deposited in fluvial systems. The Washita-Fredericksburg has modest storage potential at the regional scale. However, capacity is significant on a local basis, specifically along the major fluvial axes. Sandstone units in the lower Tuscaloosa Group are more continuous and are interpreted to have accumulated in marginal-marine environments. The result of Cretaceous sedimentation is a thick and geometrically complex succession of interbedded limestone, sandstone and shale, which presents opportunities for single- and multi-zone carbon storage.

Subsurface mapping indicates that a large volume of reservoir-quality sandstone is present throughout most of the study. An exception is the crestal region of Destin Dome, where thinning of the sandstone indicates diversion of coarse-grained sediment around the uplifting dome. In contrast, subsidence in salt withdrawal synclines adjacent to the dome favored accumulation thick sandstone successions.

Volumetric assessment reveals that the P_{50} CO_2 storage capacity of Cretaceous-age sandstone units in the DeSoto Canyon Salt Basin is about 28 Gt. Although the Paluxy Formation has the highest P_{50} capacity of 17.1 Gt, it is also the deepest and most heterogeneous unit assessed. By contrast, the Washita-Fredericksburg interval has P_{50} capacity of only 1.1 Gt, but local capacity of 0.8 Mt/km^2 indicates utility along the main fluvial axes, particularly where storage can be stacked with other saline reservoirs. Key parameters for selecting CO_2 injection sites include storage capacity, drilling depth, position relative to major sealing strata, and reservoir heterogeneity. The storage capacity maps combined with regional structural traces also highlight that the stable shelf in the Mobile and Viosca Knoll Areas may provide optimal injection locations due to (1) minimal seal and reservoir integrity risks such as faults, (2) a thick accumulations of reservoir quality sandstone (up to 2.9 Mt/km^2), (3) well control that helps reduce uncertainty in reservoir location, and (4) low regional dip, which will help limit the migration of injected CO_2.

These numbers clearly indicate that significant storage capacity exists in Cretaceous formations in the Eastern Gulf of Mexico. On an average, each offshore block can potentially store CO_2 emissions from 9 major coal-fired power plants (~ 5 Mt/yr). The potential is higher on the stable shelf in the Mobile and Viosca Knoll Areas and can store emissions equivalent to those from 13 power plants per offshore block emitting 5 Mt/yr each. An informed examination the storage strategy, selection of the most suitable blocks based on the reservoir quality and stacking pattern, and application of advanced storage technologies along with the lessons learned from analogous storage sites can help improve and optimize storage efficiency.

REFERENCES

Asquith, G. B., Krygowski, D., and Gibson, C. R., 2004, Basic well log analysis: Tulsa, American Association of Petroleum Geologists, 216 p.

Bachu, S., 2003, Screening and ranking of sedimentary basins for sequestration of CO_2 in geological media in response to climate change: Environmental Geology, v. 44, p. 277-289.

Buffler, R. T., and Sawyer, D. S., 1985, Distribution of crust and early history, Gulf of Mexico Basin: Gulf Coast Association of Geological Societies Transactions, v. 35, p. 333-344.

Chasteen, H.R., 1983, Re-evaluation of Lower Tuscaloosa and Dantzler Formations (middle Cretaceous) with emphasis on depositional environments and time-stratigraphic relationships: Gulf Coast Association of Geological Societies Transactions, v. 33, p. 31–40.

Damen, K., van Troost, M., Faaij, A., and Turkenburg, W., 2006, A comparison of electricity and hydrogen production systems with CO_2 capture and storage. Part A: Review and selection of promising conversion and capture technologies: Progress in Energy and Combustion Science, v. 32, p. 215-246.

Esposito, R.A., Pashin, J.C., Hills, D.J., and Walsh, P.M., 2010, Geologic assessment and injection design for a pilot CO_2-enhanced oil recovery and sequestration demonstration in a heterogeneous oil reservoir: Citronelle Field, Alabama, USA: Environmental Earth Sciences, v. 60, p. 431-444.

Esposito, R.A., Pashin, J.C., and Walsh, P.M., 2008, Citronelle Dome: A giant opportunity for multizone carbon storage and enhanced oil recovery in the Mississippi Interior Salt Basin of Alabama: Environmental Geosciences, v. 15, p. 53-62.

Folaranmi, A. T., 2015, Geologic characterization of a saline reservoir for carbon sequestration: The Paluxy Formation, Citronelle Dome, Gulf of Mexico Basin, Alabama: Stillwater, Oklahoma State University, unpublished Master's thesis, 96 p.

Goodman, A., Hakala, A., Bromhal, G., Deel, D., Rodosta, T., Frailey, S., Small, M., Allen, D., Romanov, V., and Fazio, J., 2011, US DOE methodology for the development of geologic storage potential for carbon dioxide at the national and regional scale: International Journal of Greenhouse Gas Control, v. 5, p. 952-965.

Handford, C.R., and Baria, L.R., 2003, Exploration potential and high-resolution sequence stratigraphy of shelf-sand reservoirs, Miocene, south Mississippi: Gulf Coast Association of Geological Societies Transactions, v. 53, p. 304-312.

Hills, D. J., and Pashin, J. C., 2010, Preliminary assessment of offshore transport and storage of CO_2: Southeastern Regional Carbon Sequestration Partnership Final Report, prepared for Southern States Energy Board, 11 p.

Hills, D. J., Pashin, J. C., and Redden, M. R., 2016, Investigating the eastern Gulf of Mexico for potential geologic storage of CO_2: Geological Society of America Abstracts with Programs, v. 48, no. 7, doi: 10.1130/abs/2016AM-280642.

Hovorka, S. D., Meckel, T. A., and Trevino, R. H., 2013, Monitoring a large-volume injection at Cranfield, Mississippi—project design and recommendations: International Journal of Greenhouse Gas Control, v. 18, p. 345-360.

IEA Greenhouse Gas R&D Programme (IEA GHG), 2009, Development of storage coefficients for CO_2 storage in deep saline formations; v. 13, 118 p., http://www.ieaghg.org/docs/General_Docs/Reports/2009-13.pdf

Koperna, G., Riestenberg, D., Kuuskraa, V., Rhudy, R., Trautz, R., Hill, G.R., and Esposito, R., 2012, The SECARB anthropogenic test: a US integrated CO_2 capture, transportation and storage test, *in* International Journal of Clean Coal and Energy, v. 1, p. 13-26.

Koperna, G., Riestenberg, D., Petrusak, R., Esposito, R., and Rhudy, R., 2009, Lessons learned while conducting drilling and CO_2 injection operations at the Victor J. Daniel power plant in Mississippi: SPE 124003. 2009 SPE Annual Technical Conference and Exhibition Proceedings, New Orleans, p. 4-7.

Kopp, A., Class, H., and Helmig, R., 2009, Investigations on CO_2 storage capacity in saline aquifers: Part 1. Dimensional analysis of flow processes and reservoir characteristics: International Journal of Greenhouse Gas Control, v. 3, p. 263-276.

MacRae, G., and Watkins, J. S., 1993, Basin architecture, salt tectonics, and Upper Jurassic structural styles, DeSoto Canyon salt basin, northeastern Gulf of Mexico: American Association of Petroleum Geologists Bulletin, v. 77, p. 1809-1824.

Mancini, E.A., Mink, R.M., Bearden, B.L., and Wilkerson, R.P., 1985, Norphlet Formation (Upper Jurassic) of southwestern and offshore Alabama: Environments of deposition and petroleum geology: American Association of Petroleum Geologists Bulletin, v. 69, p. 881-898.

Mancini, E.A., Mink, R.M., Payton, J.W., and Bearden, B.L., 1987, Environments of deposition and petroleum geology of Tuscaloosa Group (Upper Cretaceous), South Carlton and Pollard fields, southwestern Alabama: American Association of Petroleum Geologists Bulletin, v. 71, p. 1128-1142.

Mancini, E. A., Puckett, T. M., and Tew, B. H., 1996, Integrated biostratigraphic and sequence stratigraphic framework for upper Cretaceous strata of the eastern Gulf Coastal Plain, USA: Cretaceous Research, v. 17, p. 645-669.

Mancini, E.A., and Puckett, T.M., 2002, Transgressive-regressive cycles in Lower Cretaceous strata, Mississippi Interior Salt Basin area of the northeastern Gulf of Mexico, USA: Cretaceous Research, v. 23, p. 409-438.

Mancini, E.A., and Puckett, T.M., 2005, Jurassic and Cretaceous transgressive-regressive (TR) cycles, northern Gulf of Mexico, USA: Stratigraphy, v. 2, p. 31-48.

Markham, V., 2009, U.S. Population, Energy and Climate Change, Center for Environment and Population, New Canaan, Connecticut, 30 p. www.cepnet.org/documents/USPopulationEnergyandClimateChangeReportCEP.pdf

Meng, J., Pashin, J., and Chandra, A., 2017, In-situ Stress in the DeSoto Canyon Salt Basin, Eastern Gulf of Mexico, Geological Society of America Abstracts with Programs, v. 49, no. 6, doi:10.1130/abs/2017AM-297935

Nagihara, S., and Jones, K.O., 2005, Geothermal heat flow in the northeastern Gulf of Mexico: AAPG Bulletin, v. 89, p. 821-831.

Nagihara, S., and Smith, M.A., 2005, Geothermal gradient and temperature of hydrogen sulfide-bearing reservoirs, Alabama continental shelf: AAPG Bulletin, v. 89, p. 1451-1458.

NETL, 2012, The United States 2012 Carbon Utilization and Storage Atlas (4th Edition): Pittsburgh, National Energy Technology Laboratory, 130 p.

Pashin, J. C., Guohai Jin, and Hills, D. J., 2016, Mesozoic petroleum systems and structure in the Mobile, Pensacola, Destin Dome, and Viosca Knoll Areas of the MAFLA Shelf, in Lowery, C., Snedden, J. W., and Blum, M. D., eds., Mesozoic of the Gulf Rim and Beyond: New Progress in Science and Exploration of the Gulf of Mexico Basin: GCSSEPM Perkins-Rosen Special Publication, p. 416-449.

Pashin, J. C., McIntyre, M. R., Grace, R. L. B., and Hills, D. J, 2008, Southeastern Regional Carbon Sequestration Partnership (SECARB) Phase III: Final Report prepared for

Advanced Resources International, 57 p.

Pashin, J. C., Raymond, D. E., Alabi, G. G., Groshong, R. H., Jr., and Guohai Jin, 2000, Revitalizing Gilbertown oil field: Characterization of fractured chalk and glauconitic sandstone reservoirs in an extensional fault system: Alabama Geological Survey Bulletin 168, 81 p.

Petrusak, R., Riestenberg, D., Goad, P., Schepers, K., Pashin, J. C., Esposito, R. A., and Trautz, R., 2009, World class CO_2 sequestration potential in saline formations, oil and gas fields, coal and shale: The U.S. Southeast Regional Carbon Sequestration Partnership has it all: San Diego, SPE International Conference on CO_2 Capture, Storage and Utilization, paper SPE 126619, 18 p.

Pindell, J. L., 1985, Alleghenian reconstruction and subsequent evolution of the Gulf of Mexico, Bahamas, and Proto-Caribbean: Tectonics, v. 4, p. 1-39.

Petty, A.J., 1997, Lower Tuscaloosa clastic facies distribution (Upper Cretaceous), federal and state waters, eastern Gulf of Mexico: Gulf Coast Association of Geological Societies Transactions, v. 47, p. 453-462.

Petty, A.J., 1995, Ferry Lake, Rodessa, and Punta Gorda Anhydrite bed correlation, Lower Cretaceous, offshore eastern Gulf of Mexico: Gulf Coast Association of Geological Societies Transactions v. 45, p. 487–493.

Story, C., 1998, Norphlet Geology and 3-D Geophysics of Fairway Field Mobile Bay, Alabama: The Leading Edge, v. 17, p. 243-248.

Tew, B. H., Armbrecht, C., Eugene, D. W., Hills, D., Duncan, I., Moody, J., Pashin, J. C., Sams, K., Hwang, L., Rogers, S. M., Esposito, R. A., Carpenter, S., and Meckel, T., 2013, Preliminary Evaluation of Offshore Transport and Geologic Storage of Carbon Dioxide: Atlanta, Southern States Energy Board, Interstate Oil and Gas Compact Commission, and U.S. Department of Energy National Energy Laboratory, 107 p.

Plate 1: West-East Stratigraphic Cross-Section of the Cretaceous-age Formations, Mobile Area.

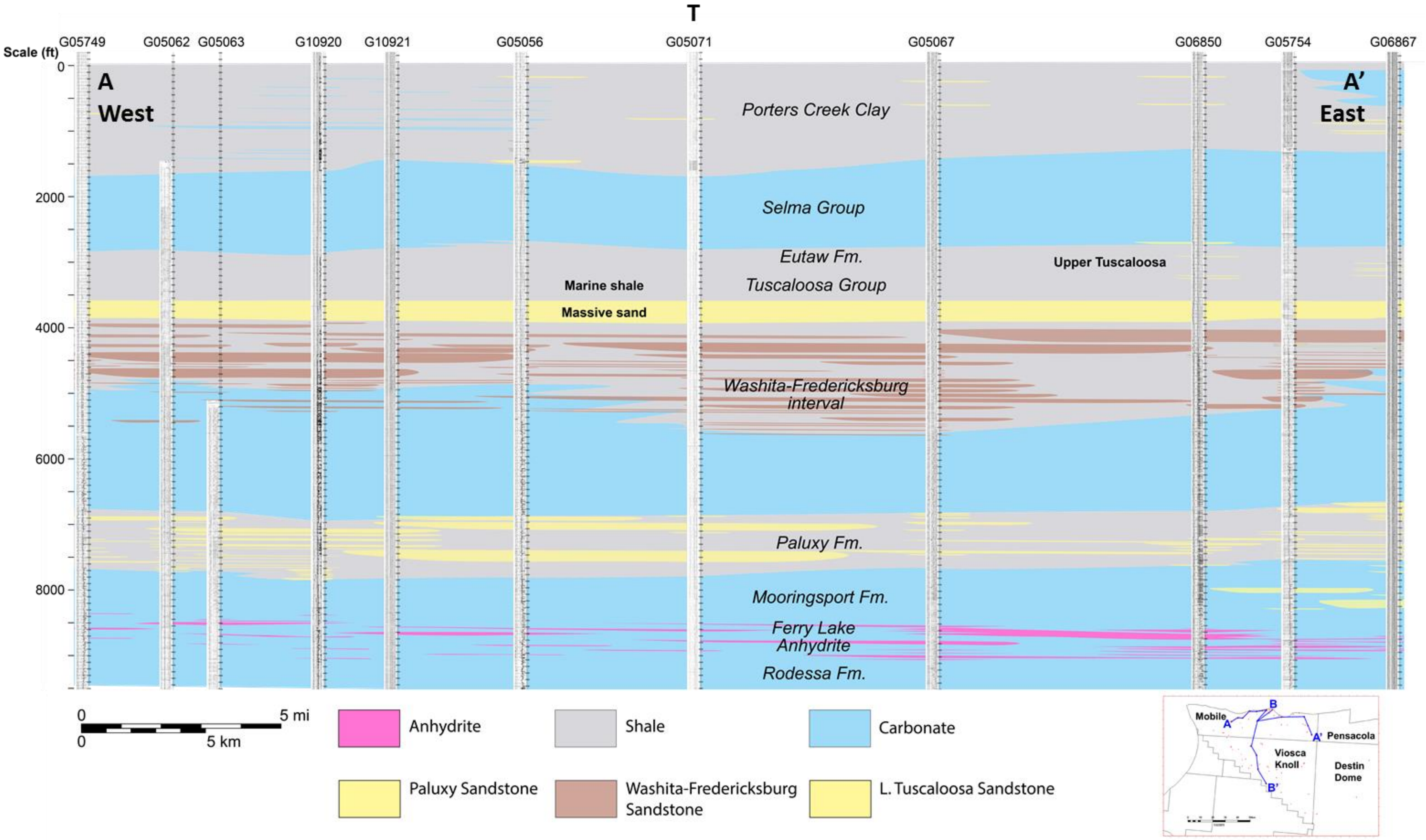
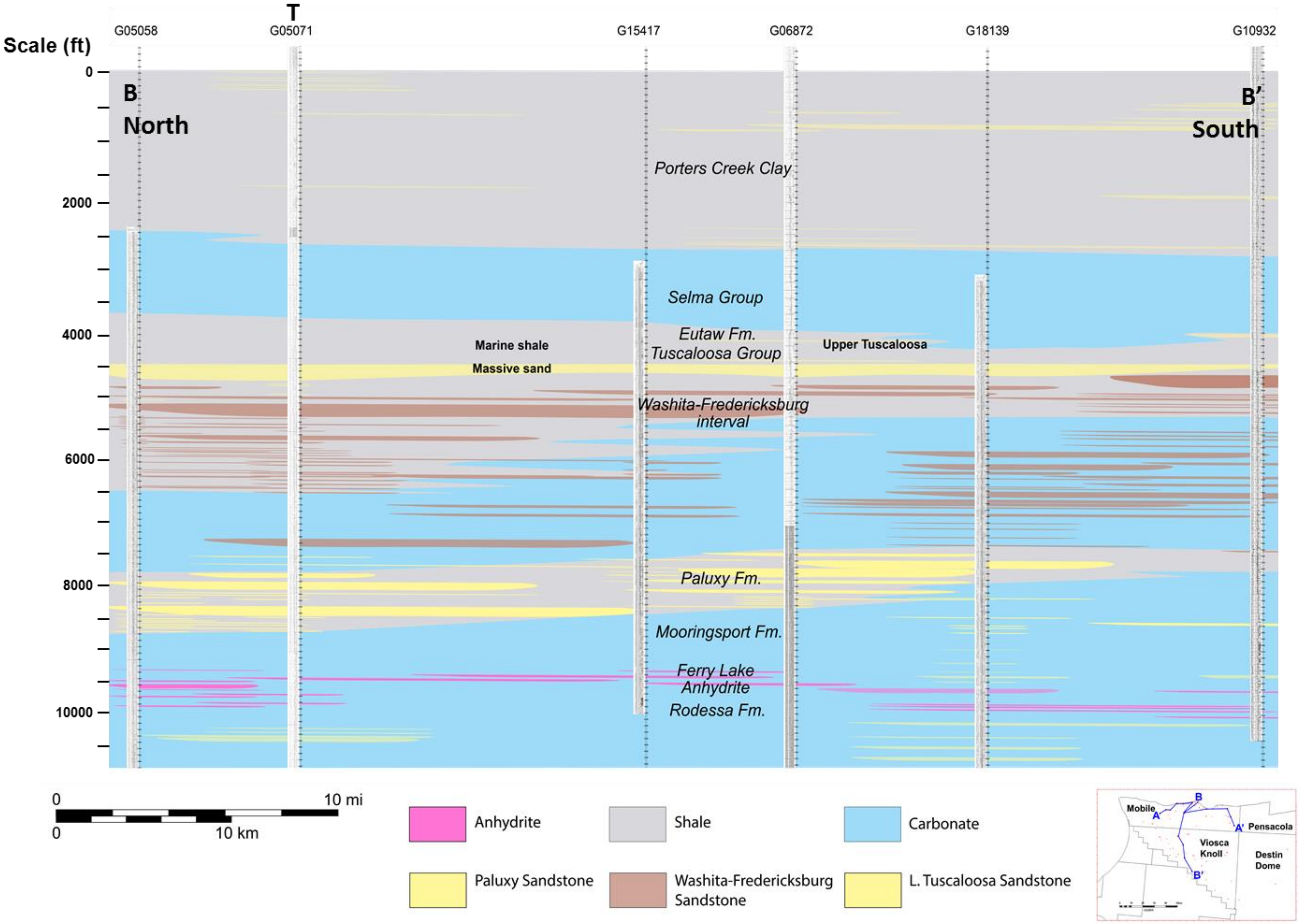


Plate 2: North-South Stratigraphic Cross-Section of the Cretaceous-age Formations, Mobile and Viosca Knoll Areas.



VITA

Avinash Chandra

Candidate for the Degree of

Master of Science

Thesis: GEOLOGICAL CHARACTERIZATION AND CO_2 STORAGE POTENTIAL OF CRETACEOUS SANDSTONE IN THE DESOTO CANYON SALT BASIN OF THE MAFLA SHELF

Major Field: Geology

Biographical:

Education:

Completed the requirements for the Master of Science in Geology at Oklahoma State University, Stillwater, Oklahoma in May, 2018.

Completed the requirements for the Bachelor of Technology in Mining Engineering at Indian School of Mines, Dhanbad, Jharkhand, India in 2008.

Experience:
Geosciences Summer Intern, BP, Gulf of Mexico (May 2017 – Aug 2017)
Technologist (Production & Geosciences), BP, India (Mar 2013 – Aug 2016)
Senior Subsurface Analyst, Talisman Energy, India (Oct 2012 – Feb 2013)
Senior Subsurface Analyst, Halliburton, India (June 2008 – Oct 2012)

Professional Memberships: AAPG, GSA, SPE