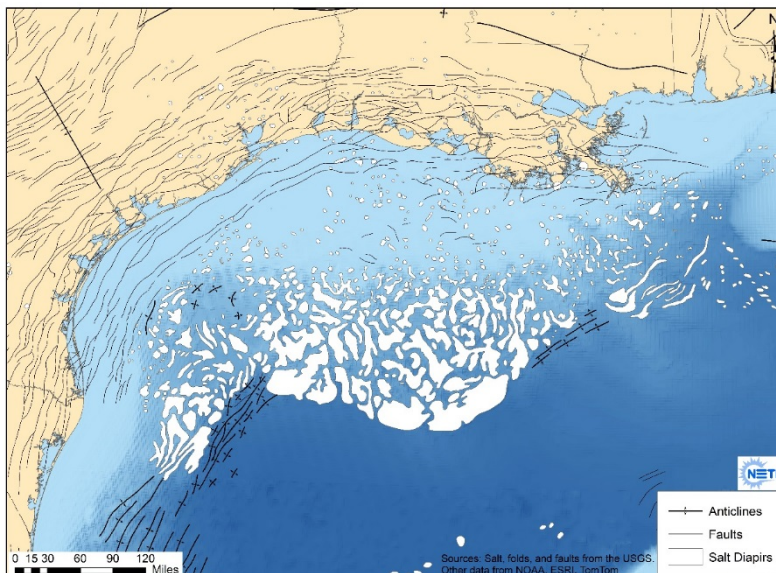




Gulf of Mexico Geology and Petroleum System: Overview and Literature Review in Support of Risk and Resource Assessments

16 July 2015



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Cover Illustration: Faults, folds, and salt in the northern Gulf of Mexico Basin. Structural geology plays an important role in the formation and location of petroleum systems. Data from (USGS, 2014).

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Gulf of Mexico Geology and Petroleum System: Overview and Literature Review in Support of Risk and Resource Assessments

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Acronyms, Abbreviations, and Symbols

Term	Description
Bbbl	Billion barrels
BOEM	Bureau of Ocean Energy Management
BSEE	Bureau of Safety and Environmental Enforcement
DOE	Department of Energy
GBDS	Gulf Basin Depositional Synthesis
GOM	Gulf of Mexico
NETL	National Energy Technology Laboratory
Tcf	Trillion cubic feet

Acknowledgments

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ABSTRACT

The Gulf of Mexico (GOM) basin has complex geology encompassing a well-established petroleum system of global economic importance. To date, an estimated 21.91 billion barrels (Bbbl) of oil and 192.4 trillion cubic feet (Tcf) of gas reserves have been produced and established reserves have been confirmed (Kazanis et al., 2014). These reserves coincide with a range of offshore energy and environmental systems pertinent to ensuring safe and reliable access to domestic energy supply for the future. In addition, the offshore system is increasingly becoming the focus of assessments for unconventional resources such as hydrates and shale, offshore enhanced oil recovery, carbon storage, and alternative energy. Finally, recent detrimental events such as natural hazards like hurricanes Katrina and Rita, as well as anthropogenic episodes like the Deepwater Horizon blowout have highlighted the unique challenges and needs for risk assessment in offshore settings. These varied but cross-cutting themes demonstrate the need within the U.S. Department of Energy (DOE) to develop a better understanding of the subsurface system that underpins all of these areas of interest. Research within academic institutions, governmental agencies, and industrial organizations has resulted in many publications focusing on in situ geology, geography, and hydrocarbon systems in the Gulf of Mexico. Information ranges from detailed, site-specific studies to broad, regional overviews, public and proprietary databases, geological and geophysical information, production records, and paleogeologic reconstructions. This report reviews the formation, sediment deposition, structure, and hydrocarbon systems of the Gulf of Mexico in support of the DOE's cross-cutting offshore interests. It also aims to provide an organized reference of relevant publications and resources on this area.

1. INTRODUCTION

The Gulf of Mexico (GOM) is an ocean basin adjacent to the Caribbean Sea. It is surrounded by eastern Mexico, Texas, the southeastern Gulf states of the United States, and Cuba (see Figure 1). The GOM has an array of resources that are important locally to the United States as well as globally in the form of oil exports (approx. 49 million barrels in 2013), commercial fishing, charter fishing, shipping, real estate, and tourism (EIA, 2015). The geographical location and geological history of the GOM have enabled accumulation of organic-rich sediments contributing to hydrocarbon accumulations in the basin.

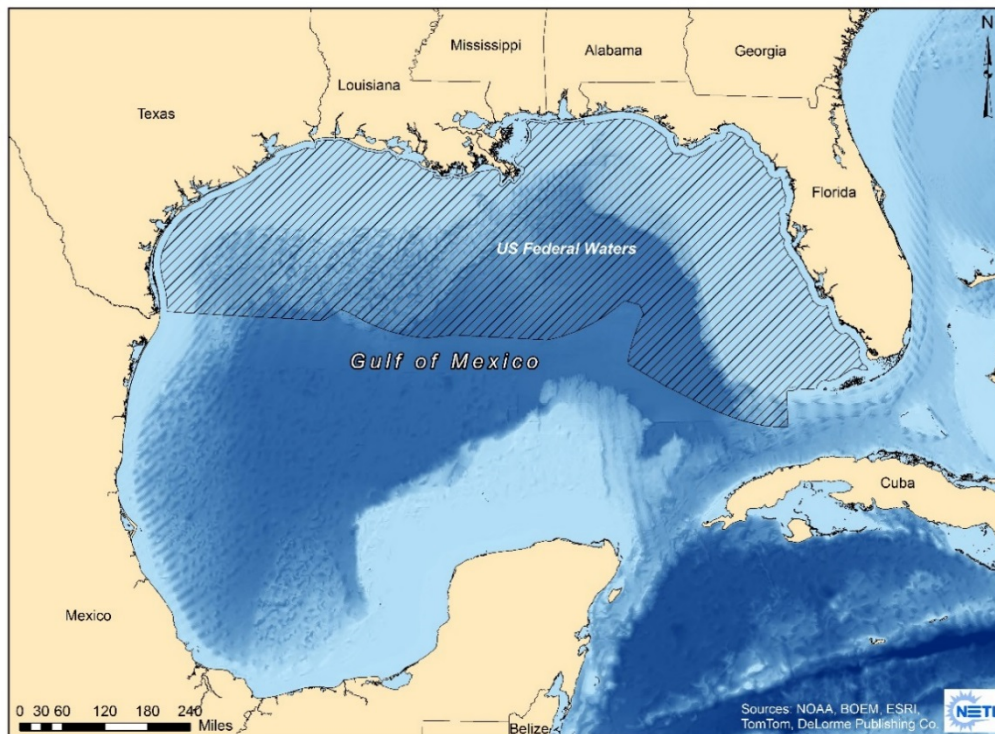


Figure 1: The Gulf of Mexico, showing the area in the GOM under U.S. federal jurisdiction.

Coordination of offshore energy and environmental systems is critical to providing domestic energy security. Conventional hydrocarbon exploration and production are becoming increasingly focused in the deepwater and ultra-deepwater GOM, while all offshore depths are being evaluated for pertinence to future unconventional resource production, enhanced oil recovery, carbon storage, and alternative energy potential. Recent natural and anthropogenic hazards, including hurricanes Katrina and Rita and the Deepwater Horizon oil spill, emphasize the need for tools and data to support informed risk assessments in the offshore GOM. This review evaluates and collates what is known about GOM geology, geography, and petroleum systems to support future research in these areas of interest from the U.S. Department of Energy

(DOE) and other parties. The resulting compendium on GOM datasets, publications, and summary of previous research provides a basis from which the petroleum system may be comprehended, and supports a range of cross-cutting needs and purposes related to analyses and reduction of uncertainty in the subsurface GOM.

2. PALEOGEOGRAPHY

The GOM is located between the North and South American continents. The present geography of the ocean basin is a product of the breakup of Pangaea and associated tectonic movements during the Mesozoic Era (Galloway, 2008; Hudec et al., 2013b). The paleogeographic framework is important as it lays the foundation for events that have shaped today's modern petroleum system within the GOM basin. Numerous sources discuss the paleogeography of the region; those discussed here provide a general overview of information pertinent to the GOM basin and the formation of its hydrocarbon reservoirs.

The Geological Society of America publication *The Gulf of Mexico Basin* (Salvador, 1991b) is a seminal publication on GOM geology and is frequently cited in subsequent research efforts. It includes a section on the origin and development of the basin, with a comprehensive paleogeographic evaluation from the Paleozoic forward, including the proto-Atlantic as well as the assembly and break-up of Pangaea (see Salvador, 1991b, Figures 2–4, 6). The GOM region experienced two tectonic episodes involving the opening and closing of ocean basins that controls its paleogeography, with the process of the second cycle ongoing (Huerta, 2012). The first cycle of divergence and convergence was completed during the Precambrian and Paleozoic, followed by rifting in the Triassic and Jurassic as Pangaea broke apart (Huerta, 2012; Stern and Dickinson, 2010; Buffler and Thomas, 1994, Figure 7; Sawyer and Buffler, 1991, Figures 4–7). The modern GOM is characterized by a dormant rift zone that divided the pre-existing stratigraphy and formed oceanic crust, allowing thermal and depositional subsidence and subsequent accumulation of millions of years of sediment that have contributed to its hydrocarbon systems (Galloway, 2008).

Pindell and Kennan (2009) evaluate historical perspectives on Gulf paleogeography, building from Müller et al.'s (1993) reference framework. Integrating concepts and implications from more recent research to evaluate Gulf tectonic evolution, Pindell and Kennan emphasize updating models for the origin of the Caribbean region and the movement of the Yucatán tectonic block during the second cycle. The paleogeographic and geologic evolution in the Jurassic is especially uncertain (Hudec et al., 2013b). The Yucatán block's movement is of interest as its migration is postulated to have been driven by a spreading center (Hudec et al., 2013b; Buffler and Thomas, 1994; Marton and Buffler, 1999). This spreading center deposited the oceanic crust that composes the GOM basin floor and is believed to have split the originally continuous Callovian Salt into the Louann and Isthmian basins (Hudec et al., 2013b). The Louann Salt is a prevalent salt body in the north-central and north-western GOM, and is particularly relevant to the modern petroleum system in the GOM due to its deformation since the Mesozoic era (Figure 2). It influences the modern geography and bathymetry of the GOM basin as well as the underlying hydrocarbon system in the region (Hudec et al., 2013a).

The crustal structure of the resulting GOM basin comprises transitional, or stretched, continental crust along the exterior margins and oceanic crust in the center (Buffler and Thomas, 1994; Galloway, 2008; Sawyer et al., 1991; Buffler and Thomas, 1994, Figure 1). Rifting, the movement of the Yucatán Block, the formation of oceanic crust, and its later subsidence greatly influenced Mesozoic deposition and the GOM morphology (Galloway, 2008). Discussion on GOM depositional evolution, paleographic concepts from the Mesozoic forward, and a summary of previous research efforts can be found in Galloway's (2008) publication. His research indicates that the basin reached its present structural configuration in the Early Cretaceous. After

the cessation of the spreading center, over 65 million years of sediments have deposited in and loaded the GOM basin, largely dictating its present-day geographic and bathymetric features.

3. GOM DEPOSITION

Overview

The depositional history of the GOM provided critical components required to generate a robust petroleum system. Continental orogenies and climate change encouraged erosion over millennia: the Laramide uplift supported Early Cenozoic depositional episodes; uplift and erosion of central Mexico and the southwestern United States supplied Oligocene through Early Miocene deposition; and erosion of the Cumberland Plateau, the Appalachian orogeny, and the concurrent Rocky Mountain regional exhumation supplied sediment to the east-central Gulf basin in the Early to Middle Miocene (Galloway, 2008). These orogenic and erosional events supplied sediments and organic material to the GOM ocean basin via fluvial systems. Rapid burial, anoxia, and abundant organic matter supported the formation of GOM hydrocarbons, while impermeable layers of salt and shale provide the seals needed to contain the hydrocarbons and form petroleum reservoirs. The complex interaction of the GOM's depositional history with its structure and salt tectonics has resulted in a heterogeneous system that requires further research and use of varied techniques to evaluate the risk of hydrocarbon extraction.

The depositional history of the basin from the Middle Jurassic onward has received great attention due to its role in petroleum plays, though several studies have been done to understand earlier deposition. It is believed that prior to the Middle Jurassic, the region of the modern-day GOM basin was primarily composed of non-marine sediments (Galloway, 2008; Woods et al., 1991). However, due to disruptive rifting in the Triassic and a lack of wells penetrating deeper than Triassic sediments in the basin this is poorly understood. Much of the pre-Triassic history of the basin is derived from samples and observation of the basin's periphery on shore, which is not sufficient to complete a geologic reconstruction of the basin (see Woods et al., 1991, Figures 1–3; Sawyer et al., 1991, Figure 3).

Further discussion of Middle and Early Mesozoic deposition can be found in Woods, Salvador, and Miles' *Pre-Triassic* and Salvador's *Triassic-Jurassic* sections in *The Gulf of Mexico Basin* (Salvador, 1991b). Buffler and Thomas (1994) also discuss the basin's basement, crustal formation, and depositional history. Rifting and subsidence in the Mesozoic led to Middle Jurassic deposition of evaporites, primarily salt, recording the influx of seawater into the basin and forming the bottom of the sedimentary fill. This evaporite layer, which forms the Louann Salt in the northern GOM, has had great influence on the subsequent development of the GOM (Peel et al., 1995; Salvador, 1991c). Later Mesozoic sediments included clastics laid down by multiple active river systems as well as successions of carbonates that created thick carbonate platforms around the basin margins (Coleman et al., 1991; Galloway, 2008; McFarlan and Menes, 1991; Sohl et al., 1991).

Specific chapters in *The Gulf of Mexico Basin* address basin evolution and sedimentation in the Early and Late Cretaceous, Cenozoic, and Late Quaternary (Salvador, 1991b). Early Cretaceous deposition was primarily carbonates and evaporites on the shelves and bathyal areas, with continental and shallow-marine terrigenous clastics occurring around the northern and northwestern basin rims (McFarlan and Menes, 1991). Deposition in the Late Cretaceous was heavily influenced by sea level change, and most deposits of this age in the GOM are marine (Sohl et al., 1991). Large volumes of clastic sediments were deposited in the Cenozoic, which prograded the continental shelves and added more than 10,000 meters of sediment to some areas of the northern GOM (Galloway et al., 1991; Salvador, 1991a). Deposition in the Quaternary is

also characterized by thick, terrigenous sediments, which can be more than 3,600 meters thick under the present Texas-Louisiana continental shelf and 3,000 meters deep in the GOM basin (Coleman et al., 1991).

More recent interpretations of the depositional systems can be found in a number of articles. Galloway et al. (2000) discuss 20 previously identified Cenozoic stratigraphic sequences in detail, describing spatial extent, paleogeography, sediment sources, and specific environments of deposition, based on extensive information from published and unpublished sources, well data, and seismic interpretations. Galloway (2008) further incorporates new ideas and information, providing many sources of scholarly articles on the subject and discussing the evolution of the GOM throughout its history. He presents the depositional history as 29 depositional episodes, starting with the Middle Jurassic deposition of the Louann Salt, reviewing the depositional environments and the related tectonic and sea level changes that drove each episode. The examination by episodes can be compared to the breakdown by geologic time periods seen in *The Gulf of Mexico Basin* (Salvador, 1991b), both of which may have advantages depending on research objectives. Mancini and Puckett (2005) approach the evaluation of depositional history via cyclicity, creating a stratigraphic framework that utilizes intrabasin, interbasin, and global correlation. Their article includes a useful basin geologic history that gives subsidence rates, associated events, and general stratigraphic history.

Localized Studies

Researchers have isolated areas of interest and evaluated their depositional framework individually. For example, Weimer et al. (1998c), describe in detail the Pliocene and Pliostocene turbidite systems that form reservoirs in the northern Green Canyon/Ewing Bank region as part of Hurley and Weimer's *GOM Petroleum Systems*, AAPG Bulletin thematic issue. This issue also includes detailed examinations of biostratigraphy, seismic stratigraphy, salt systems, and the petroleum system in the same region (Hurley and Weimer, 1998). McDonnell et al. (2008) evaluate Paleocene to Eocene deep-water slope canyons in the western GOM as a method of understanding the provenance of the potentially productive deepwater plays of the Wilcox Formation. They mention the complication of salt deposits (see Section 4) in addition to exploring the stratigraphic characteristics of the area. In another example, Mancini et al. (2008), using the sequence stratigraphic approach outlined by Mancini and Puckett (2005), categorize petroleum reservoirs specific to the central and eastern Gulf coastal plain that are constrained by Jurassic and Cretaceous strata.

The stratigraphy of the GOM has been constrained using a range of subsurface datasets including well data and seismic imaging. Wu et al.'s (1990) evaluation of northeastern GOM structure and stratigraphy includes seismic data analysis in addition to well log data and biostratigraphic information. *The Gulf of Mexico Basin* includes a section on the basin's seismic stratigraphy, providing age approximations, typical reflection characteristics, and suggested depositional environment, depocenter, and/or source (Buffler, 1991). These endeavors form the basis for later works, such as the comprehensive AAPG memoir *Western GOM Basin: Tectonics, Sedimentary Basins, and Petroleum Systems*, which includes sequence-stratigraphic frameworks for the basin throughout the compilation of research (Bartolini et al., 2001).

4. SALT AND STRUCTURE

The dynamic of the Gulf of Mexico's salt and structure is integral to the architecture of its hydrocarbon systems. Evaporites deposited in the Jurassic, including the widespread Louann Salt, are considered to be the foundation of the basin's sedimentary fill, with portions of both the northern and southern Gulf underlain by significant salt accumulations (Galloway, 2008; Salvador, 1991a). Subsequent sedimentation and tectonic activity resulted in migration of these salt deposits and deformation of associated sediment layers, resulting in much of the structure now seen in the northwestern and north-central GOM, where salt diapirs and salt-related folds, faults, and other structures commonly act as traps for hydrocarbons. Figure 2 shows the distribution of salt and major fault and fold zones in the northern GOM.

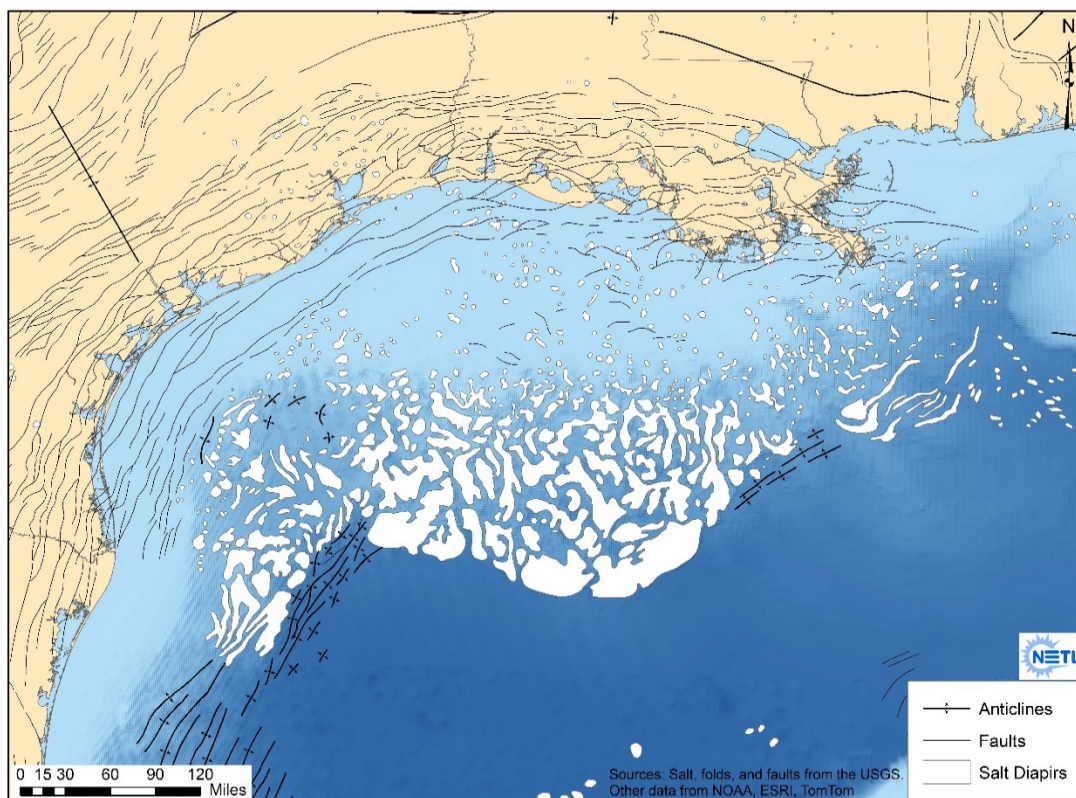


Figure 2: Faults, folds, and salt in the northern GOM Basin. Data from (USGS, 2014).

A foundation and overview of GOM salt and structure can be found in *The Gulf of Mexico Basin*, where Nelson (1991) reviews salt tectonics and the salt structures that are commonly found in the basin. This includes discussion of the growth faults responsible for much of the structural activity in the northern GOM, which are typically formed due to detachment on salt or shale layers. Significant research in the GOM is dedicated to understanding the role salt plays in the development of the Basin and its effect on petroleum systems.

The GOM's complex arrangement of detachments, growth faults, and extensive, variable salt bodies has prompted numerous efforts to classify the basin's structural provinces. One of the most highly referenced descriptions of the northern GOM's Cenozoic structural framework is provided by Diegel et al.'s chapter in *Salt Tectonics: A Global Perspective* (Diegel et al., 1995), where the authors divide the basin's northern margin into eight structural provinces based on structural and salt characteristics. These include foldbelt provinces at the toe of the continental slope, the Texas-Louisiana slope's "tabular salt-minibasin province," and several Early Cenozoic detachment and growth fault provinces currently on- and near-shore (see Diegel et al., 1995 Figure 2). In the same volume, Peel et al. (1995) delineate four major structural provinces in the Cenozoic GOM based on the ages of structural activity and salt tectonics and related similarities in structure. Many later studies build off of the interpretations and maps published by Diegel et al. and Peel et al., among others, including Hall (2002), Galloway (2008), Hudec et al. (2013a, 2013b), and Dooley et al. (2013), which are discussed below.

While Diegel et al. (1995) and Peel et al. (1995) discuss the Cenozoic structure of the GOM, several later works consider deeper structures, including the GOM basement and the deep Louann Salt. Hall (2002) discusses structure as it relates to the "mother" salt from which the shallow salt has migrated, defining a different set of structural provinces based on movement of the original salt layer. He also describes the presentation of modern salt bodies in each area, as well as the evidence for and timing of mother salt movement. Galloway (2008) separates his discussion of GOM structural features by structure type, separating basement structures and typically salt-related gravity tectonic structures, and classifies spatial structural provinces. He considers basement structure in how it affects overlying stratigraphy, and discusses six gravity tectonic structures: growth fault families and related structures, allochthonous salt bodies, salt welds, roho fault families, salt diapirs and their related withdrawal synclines and minibasins, and basin-floor compressional fold belts. Galloway (2008) also evaluates GOM's transitional crust and considers subsidence trends in relation to overall structure.

Several articles published in the AAPG Bulletin discuss more recent interpretations of salt provinces and the GOM basin formation. Using seismic data, Hudec et al. (2013a) and Hudec et al. (2013b) describe the structure of deep salt layers and the basin's basement and make inferences regarding salt movement and structural development during the Mesozoic and Cenozoic eras. The articles describe the influence that Mesozoic tectonics and associated deep salt structure have had on modern allochthonous salt and structural provinces, such as the fold belts at the toe of the continental slope, and Hudec et al. (2013a) include a discussion of the relationship between salt structure and hydrocarbon prospects. A third article describes salt structures found at depth on the northern GOM continental shelf, and proposes methods for their formation that have implications for past North American plate tectonics, GOM salt tectonics, and similar systems on other continental margins (Dooley et al., 2013).

Many studies of specific structural types, particular aspects of the structural or salt systems, or local or regional investigations are also available. For example, papers in the AAPG Bulletin themed volume *GOM Petroleum Systems* (Hurley and Weimer, 1998), which discuss the influence of allochthonous salt on a study region in northern Green Canyon and Ewing Bank (McBride, 1998; McBride et al., 1998a; McBride et al., 1998b; Rowan and Weimer, 1998). Rowan et al. (1999) classify faults in the GOM based on their geometry, relating fault types to deformation of underlying salt, while Fredrich et al. (2007) describe the composition of deepwater GOM salt bodies, the implications for salt deformation, and the consequences variable

salt behavior may have for the long-term integrity of wells drilled through salt. Hudec et al. (2009) discuss the mechanics of subsidence in salt-related minibasins.

5. GOM PETROLEUM SYSTEM

The Bureau of Ocean Energy Management (BOEM), a division of the United States Department of the Interior, aggregates and reports information on the hydrocarbon resources of the federal offshore GOM. From the 2014 report *Estimated Oil and Gas Reserves, GOM OCS Region, December 31, 2011*, they estimate that “Original Reserves,” which have been or are being produced, total 21.91 billion barrels (Bbbl) of oil and 192.4 trillion cubic feet (Tcf) of gas in the federal offshore GOM (Kazanis et al., 2014). “Contingent resources,” which are not yet under development, are estimated at 4.69 Bbbl of oil and 12.1 Tcf of gas. As of 2011, there were 1,292 fields identified in the GOM federal waters, and 782 were active (Kazanis et al., 2014).

According to BOEM’s *Assessment of Technically Recoverable Hydrocarbon Resources of the GOM Outer Continental Shelf as of January 1, 2009*, 99% of the proved and unproved reserves in the GOM are in Cenozoic-age sediments, and just over a quarter of these are located on the continental slope in the deep- and ultra-deep water. Though Mesozoic reservoirs have fewer reserves, the authors discuss evidence and analogs that indicate active petroleum systems exist in older sediments as well (Klazynski et al., 2012).

The *Atlas of Northern GOM Gas and Oil Reservoirs* Volume 1 (Seni et al., 1997) and Volume 2 (Hentz et al., 1997) and its update (Bascle et al., 2001) describe many of the plays and reserves of the GOM in detail, as does the AAPG Bulletin thematic issue *Gulf of Mexico Petroleum Systems*, which provides descriptions, logs, and seismic data for many discoveries and fields in their shelf-edge to deepwater study area (Hurley and Weimer, 1998; Weimer et al., 1998a; Weimer et al., 1998b; Weimer et al., 1998c). Nehring (1991) reviews the petroleum reserves and reservoir characteristics of each stratigraphic unit of the GOM basin. Disenhof et al. (2014) overview both the petroleum system as well as the resources available to obtain more information and data.

Nunn and Sassen (1986) show that the timing and amount of sediment influx to the GOM through the Mesozoic and Cenozoic have greatly influenced the modern petroleum system. Using seismic data to model stratigraphy, they modeled burial histories of the GOM continental slope and determined that deep Mesozoic rocks may act as hydrocarbon sources for the GOM continental slope (Nunn and Sassen, 1986). In their analysis of hydrocarbon migration pathways, Hood et al. (2002) published a map of GOM regions that share similar source intervals, using data from hydrocarbon seeps and correlations to better-known areas to identify deepwater sources more specifically (see Hood et al., 2002, Figure 2).

Hood et al. (2002), Shedd (2012), and Bernard et al. (1976) discuss hydrocarbon seeps and their use in determining information about hydrocarbon systems, including sources and migration pathways. BOEM has identified thousands of seismic anomalies commonly indicative of these seeps in the GOM and has confirmed seeps at more than 400 of these (Figure 3) (BOEM, 2013b).

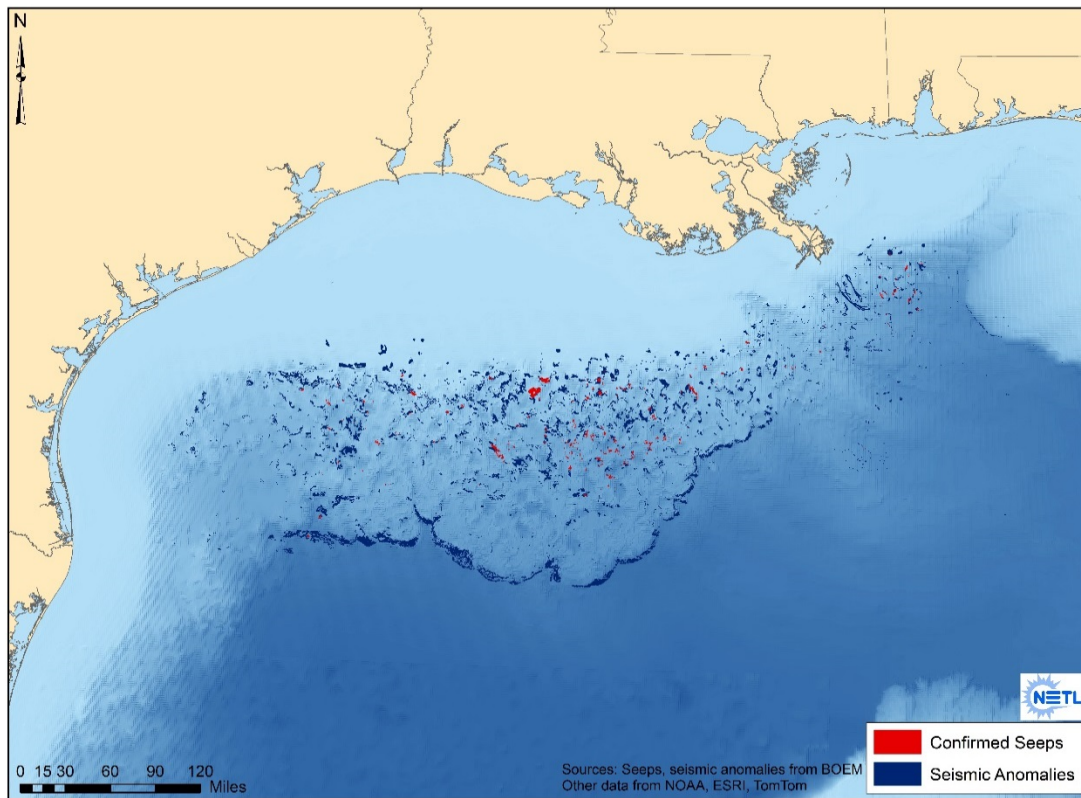


Figure 3: Map indicating seismic anomalies in the GOM, indicative of hydrocarbon seeps. The map illustrates the wide distribution of known seeps in red, and locations where seeps are suspected based on seafloor anomaly data. The relatively ubiquitous distribution of known and suspected seeps illustrates the breadth of the hydrocarbon system in the deep and ultra-deepwater GOM as a whole. The data are artificially limited to the west and east by availability of seismic datasets used for the seismic anomaly interpretations. Data is from BOEM (2013b).

6. RESEARCH RESOURCES AND DATA LOCATIONS

As petroleum exploration expands throughout the GOM, so does valuable geologic data and analyses to support characterization of the subsurface system, including pore-filling media such as hydrocarbon, natural gas hydrates, and brines. Hydrocarbon exploration and production companies drive a significant portion of data collection and analysis. However, as domestic energy supply diversifies, the information from commercial as well as other sources is increasingly relevant to a range of purposes beyond that of hydrocarbon exploration and production alone. Multiple projects in both academic labs and government agencies are dedicated to researching the GOM. The efforts of predominant organizations are cited in Table 1.

The industry-supported Gulf Basin Depositional Synthesis (GBDS) project at University of Texas at Austin focuses on synthesizing the Cenozoic and Mesozoic fill of the entire GOM basin and deepening the understanding of the basin's framework and depositional history. The Jackson School of Geosciences at UT Austin dedicates much research to energy geosciences, with researchers evaluating aspects of the GOM basin such as salt tectonics, reservoir characterization, and subsurface analysis. Texas A&M's Petroleum Geosciences Research Cluster investigates many facets of the basin's geology, including petrophysics, reservoir characterization, sequence stratigraphy, and sedimentary facies analysis. Given the economic value that the GOM represents, geologic research is conducted by many companies supporting the fossil fuel industry. One of these is Tectonic Analysis, a geological consulting company whose research on paleogeography and tectonics is available in several atlases as well as numerous papers and reports published by organizations such as Geological Society of America, American Association of Petroleum Geologists, and the Journal of Petroleum Geology. ION Geoventures is another company contributing valuable research to GOM. Their mega-regional seismic study GulfSPAN aids in the reconstruction of the geologic framework and depositional history of the basin, and is also affiliated with the GBDS.

Dedicated to the motivation to increase America's energy independence, several United States federal agencies have efforts to improve the safety, efficiency, and recovery of fossil resources. The Bureau of Ocean Energy Management (BOEM) and the Bureau of Safety and Environmental Enforcement (BSEE) both collect data on GOM petroleum geology and resources. BOEM's Resource Evaluation Program identifies outer continental shelf plays, maintains a reserves inventory, acquires and analyzes data related to hydrocarbon accumulation, and improves regulations and risk assessment for fossil energy recovery. Much of their data is made publically available, including information on geology, geophysics, reserves, production, and infrastructure (BOEM, 2014). BSEE's Oil Spill Response Research aims to "improve the methods and technologies used for oil spill detection, containment, treatment, recovery and cleanup" (BSEE, 2014). The U.S. DOE's National Energy Technology Laboratory (NETL) has also studied the offshore GOM through a series of research efforts over the past two decades related to natural gas hydrate systems, hurricane response support following Katrina and Rita in 2000, ensuring safe and reliable domestic energy supply under the Energy Policy Act of 2005, and most recently supporting risk assessment and risk reduction research and development in support of spill prevention.

Table 1: Organizations researching the Gulf of Mexico as of 2015*

Organization	Contact Website
Jackson School of Geosciences, University of Texas at Austin	http://www.jsg.utexas.edu/
Gulf of Mexico Basin Depositional Synthesis Project, Institute for Geophysics, University of Texas at Austin	https://ig.utexas.edu/energy/gulf-of-mexico-basin-depositional-synthesis/
Petroleum Geosciences Research Cluster, Texas A&M University	https://geoweb.tamu.edu/research/petroleum-geosciences-research/index.html
Tectonic Analysis, West Sussex, England	http://www.tectonicanalysis.com/
ION Geoventures	http://www.iongeo.com/About_Us/Corporate_Overview/GeoVentures/
National Energy Technology Laboratory, United States Department of Energy	https://edx.netl.doe.gov/offshore
Bureau of Ocean Energy Management, United States Department of the Interior	http://www.boem.gov/
Bureau of Safety and Environmental Enforcement, United States Department of the Interior	http://www.bsee.gov/

*All links were active as of 4/2015 when this report was finalized. If links are no longer active, please consider using the information in the "Organization" column to search for updated information online.

7. CONCLUSION

Extensive research of GOM geology has supported decades of hydrocarbon exploration and production in the region, providing jobs, economy, and energy security for the United States. The amount of information available on the GOM basin is immense. This literature review supports NETL's integrated assessment modeling for GOM hydrocarbon systems in addition to being useful as an organized review of research for GOM geology. With hydrocarbon exploration reaching into deeper and deeper water, the risks of drilling and production, already high, continue to increase (Elshahawi, 2014). Offshore energy from renewable resources such as geothermal, wind, tidal, and solar are gaining interest in addition to enhanced oil recovery and carbon storage in geologic media related to offshore GOM systems. As a result, the data, information and existing knowledge base about the subsurface GOM is increasingly important to reduce both the human and environmental impact of each of these energy resources. The data sources and references outlined in this report highlight the robust groundwork already available that can be used to support analyses, models, and continuing research for a range of end users and purposes.

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8. REFERENCES

- Bartolini, C., Buffler, R. T., Cantu-Chapa, A., Eds. *The Western Gulf of Mexico Basin: Tectonics, Sedimentary Basins, and Petroleum Systems* (AAPG Memoir 75); American Association of Petroleum Geologists: Tulsa, OK, 2001; p 480.
- Bascle, B. J.; Nixon, L. D.; Ross, K. M. *Atlas of Gulf of Mexico Gas and Oil Sands as of January 1, 1999*; OCS Report; U.S. Department of Interior: New Orleans, LA, 2001.
- Bernard, B. B.; Brooks, J. M.; Sackett, W. M. Natural gas seepage in the Gulf of Mexico. *Earth and Planetary Science Letters* **1976**, 31, 48–54.
- BOEM, 2013a, Deepwater Natural Gas and Oil Qualified Fields. http://www.data.boem.gov/homepg/data_center/other/tables/deeptbl2.asp
- BOEM, 2013b, Seismic Water Bottom Anomalies Map Gallery. <http://www.boem.gov/Seismic-Water-Bottom-Anomalies-Map-Gallery/>
- BOEM, 2014, Resource Evaluation Program, Bureau of Ocean Energy Management, U.S. Department of the Interior. <http://www.boem.gov/Resource-Evaluation-Program/>
- BSEE, 2014, Oil Spill Response Research, Bureau of Safety and Environmental Enforcement, U.S. Department of the Interior. <http://www.bsee.gov/Technology-and-Research/Oil-Spill-Response-Research/index/>
- Buffler, R. T. Seismic Stratigraphy of the Deep Gulf of Mexico Basin and Adjacent Margins. *The Gulf of Mexico Basin, The Geology of North America*; Salvador, A., Ed.; Geological Society of America: Boulder, CO, 1991.
- Buffler, R. T.; Thomas, W. A. Crustal structure and evolution of the southeastern margin of North America and the Gulf of Mexico basin. *Phanerozoic Evolution of North American Continent-Ocean Transitions, v. DNAG Continent-Ocean Transect Volume*; Speed, R. C., Ed., Geological Society of America: Boulder, CO, 1994.
- Coleman, J. M.; Roberts, H. H.; Bryant, W. R. Late Quaternary sedimentation. *The Gulf of Mexico Basin, The Geology of North America*; Salvador, A., Ed.; Geological Society of America: Boulder, CO, 1991.
- Diegel, F. A.; Karlo, J. F.; Schuster, D. C.; Shoup, R. C.; Tauvers, P. R. Cenozoic structural evolution and tectono-stratigraphic framework of the northern Gulf Coast continental margin. *Salt Tectonics: a Global Perspective* **1995**, 65, 109–151.
- Disenhof, C.; Mark-Moser, M.; Rose, K. The Gulf of Mexico Petroleum System- Foundation for Science-Based Decision Making. *Journal of Sustainable Energy Engineering* **2014**, 2, 225–236.
- Dooley, T. P.; Jackson, M. P. A.; Hudec, M. R. Coeval extension and shortening above and below salt canopies on an uplifted, continental margin: Application to the northern Gulf of Mexico. *AAPG Bulletin* **2013**, 97, 1737–1764.
- Elshahawi, H. Deepwater Exploration and Production in the Gulf of Mexico-Challenges and Opportunities. *Petrophysics* **2014**, 55, 81–87.
- EIA, 2015. U.S. Exports of Crude Oil. http://www.eia.gov/dnav/pet/pet_move_exp_dc_nus-z00_mbbldpd_a.htm

- Fredrich, J. T.; Fossum, A. F.; Hickman, R. J. Mineralogy of deepwater Gulf of Mexico salt formations and implications for constitutive behavior. *Journal of Petroleum Science and Engineering* **2007**, 57, 354–374.
- Galloway, W. E. Depositional evolution of the Gulf of Mexico sedimentary basin. *The Sedimentary Basins of the United States and Canada: Sedimentary Basins of the World*; Miall, A. D., Ed.; Elsevier, 2008; p 505–549.
- Galloway, W. E.; Bebout, D. G.; Fisher, W. L.; Dunlap, J. B. J.; Cabrera-Castro, R.; Lugo-Rivera, J. E.; Scott, C. M. *The Gulf of Mexico Basin: The Geology of North America*; Salvador, A., Ed.; Geological Society of America: Boulder, CO, 1991.
- Galloway, W. E.; Ganey-Curry, P. E.; Li, X.; Buffler, R. T. Cenozoic depositional history of the Gulf of Mexico basin. *AAPG Bulletin* **2000**, 84, 1743–1774.
- Hall, S. H. The role of autochthonous salt inflation and deflation in the northern Gulf of Mexico. *Marine and Petroleum Geology* **2002**, 19, 649–682.
- Hentz, T. F.; Seni, S. J.; Wermund, E. G. J., Eds. *Pliocene and Pleistocene Reservoirs: Atlas of Northern Gulf of Mexico Gas and Oil Reservoirs Volume 2*; Bureau of Economic Geology, The University of Texas at Austin, 1997.
- Hood, K. C.; Wenger, L. M.; Gross, O. P.; Harrison, S. C. Hydrocarbon Systems Analysis of the Northern Gulf of Mexico: Delineation of Hydrocarbon Migration Pathways Using Seeps and Seismic Imaging. *Surface Exploration Case Histories: Applications of Geochemistry, Magnetism, and Remote Sensing*; Schumacher, D., LeSchack, L. A., Eds.; AAPG Studies in Geology No. 48 and SEG Geophysical References Series No. 11, 2002; p 25–40.
- Hudec, M. R.; Jackson, M. P. A.; Peel, F. J. Influence of deep Louann structure on the evolution of the northern Gulf of Mexico. *AAPG Bulletin* **2013a**, 97, 1711–1735.
- Hudec, M. R.; Jackson, M. P. A.; Schultz-Ela, D. D. The paradox of minibasin subsidence into salt: Clues to the evolution of crustal basins. *Geological Society of America Bulletin* **2009**, 121, 201–221.
- Hudec, M. R.; Norton, I. O.; Jackson, M. P. A.; Peel, F. J. Jurassic evolution of the Gulf of Mexico salt basin. *AAPG Bulletin* **2013b**, 97, 1683–1710.
- Huerta, A. D. Wilson cycles, tectonic inheritance, and rifting of the North American Gulf of Mexico continental margin. *Geosphere* **2012**, 8, 374–385.
- Hurley, N.; Weimer, P. Gulf of Mexico theme issue: Gulf of Mexico Petroleum Systems. *AAPG Bulletin-American Association of Petroleum Geologists* **1998**, 82, VII–VII.
- Jackson, P. A.; Roberts, D. G.; Snelson, S., Eds., Salt Tectonics: A Global Perspective. *AAPG Memoir 65*; American Association of Petroleum Geologists, 1995; p 454.
- Kazanis, E. G.; Maclay, D. M.; Shepard, N. K. *Estimated Oil and Gas Reserves, Gulf of Mexico OCS Region, December 31, 2011*; OCS Report; Office of Resource Evaluation, Reserves Section, 2014.
- Klazynski, R.; Klocek, E.; Nixon, L.; Petty, A.; Post, P. *Assessment of Technically Recoverable Hydrocarbon Resources of the Gulf of Mexico Outer Continental Shelf as of January 1,*

- 2009; U.S. Department of the Interior Bureau of Ocean Energy Management Gulf of Mexico OCS Regional Office Office of Resource Evaluation: New Orleans, LA, 2012.
- Mancini, E. A.; Obid, J.; Badali, M.; Liu, K.; Parcell, W. C. Sequence-stratigraphic analysis of Jurassic and Cretaceous strata and petroleum exploration in the central and eastern Gulf coastal plain, United States. *AAPG Bulletin* **2008**, 92, 1655–1686.
- Mancini, E. A.; Puckett, T. M. Jurassic and Cretaceous Transgressive-Regressive (T-R) Cycles, Northern Gulf of Mexico, USA. *Stratigraphy* **2005**, 2, 31–48.
- Marton, G. L.; Buffler, R. T. Jurassic-Early Cretaceous Tectono-Paleogeographic Evolution of the Southeastern Gulf of Mexico Basin. *Caribbean Basins: Sedimentary Basins of the World*, v. 4; Mann, P., Ed.; Elsevier Science B. V.: Amsterdam, 1999; p 63–91.
- McBride, B. C. The evolution of allochthonous salt along a megaregional profile across the northern Gulf of Mexico Basin. *AAPG Bulletin-American Association of Petroleum Geologists* **1998**, 82, 1037–1054.
- McBride, B. C.; Rowan, M. G.; Weimer, P. The evolution of allochthonous salt systems, northern Green Canyon and Ewing Bank (offshore Louisiana), northern Gulf of Mexico. *AAPG Bulletin-American Association of Petroleum Geologists* **1998a**, 82, 1013–1036.
- McBride, B. C.; Weimer, P.; Rowan, M. G. The effect of allochthonous salt on the petroleum systems of northern Green Canyon and Ewing Bank (Offshore Louisiana), northern Gulf of Mexico. *AAPG Bulletin-American Association of Petroleum Geologists* **1998b**, 82, 1083–1112.
- McDonnell, A.; Loucks, R. G.; Galloway, W. E. Paleocene to Eocene deep-water slope canyons, western Gulf of Mexico: Further insights for the provenance of deep-water offshore Wilcox Group plays. *AAPG Bulletin* **2008**, 92, 1169–1189.
- McFarlan, E. J.; Menes, L. S. Lower Cretaceous. *The Gulf of Mexico Basin: The Geology of North America*; Salvador, A., Ed.; The Geological Society of America: Boulder, CO, 1991.
- Müller, R. D.; Royer, J. Y.; Lawver, L. A. Revised Plate Motions Relative to the Hotspots from Combined Atlantic and Indian-Ocean Hotspot Tracks. *Geology* **1993**, 21, 275–278.
- Nehring, R. Oil and Gas Resources. *The Gulf of Mexico Basin: The Geology of North America*; Salvador, A., Ed.; Geological Society of America: Boulder, CO, 1991.
- Nelson, T. H. Salt tectonics and listric-normal faulting. *The Gulf of Mexico Basin: The Geology of North America*; Salvador, A., Ed.; Geological Society of America: Boulder, CO, 1991.
- Nunn, J. A.; Sassen, R. Framework of Hydrocarbon Generation and Migration, Gulf of Mexico Continental Slope. *AAPG Bulletin-American Association of Petroleum Geologists* **1986**, 70, 1187–1187.
- Peel, F. J.; Travis, C. J.; Hossack, J. R. Genetic structural provinces and salt tectonics of the Cenozoic offshore US Gulf of Mexico: A preliminary analysis. *Salt Tectonics: a Global Perspective* **1995**, 65, 153–175.

- Pindell, J. L.; Kennan, L. Tectonic evolution of the Gulf of Mexico, Caribbean and northern South America in the mantle reference frame: an update. *Origin and Evolution of the Caribbean Plate* **2009**, 328, 1–55.
- Rowan, M. G.; Jackson, M. P. A.; Trudgill, B. D. Salt-related fault families and fault welds in the northern Gulf of Mexico. *AAPG Bulletin-American Association of Petroleum Geologists* **1999**, 83, 1454–1484.
- Rowan, M. G.; Weimer, P. Salt-sediment interaction, northern Green Canyon and Ewing Bank (offshore Louisiana), northern Gulf of Mexico. *AAPG Bulletin-American Association of Petroleum Geologists* **1998**, 82, 1055–1082.
- Salvador, A. Origin and development of the Gulf of Mexico basin. *The Gulf of Mexico Basin: The Geology of North America*; Salvador, A., Ed.; Geological Society of America: Boulder, CO, 1991.
- Salvador, A., Ed. *The Gulf of Mexico Basin: The Geology of North America*; Geological Society of America: Boulder, CO, 1991b.
- Salvador, A., Triassic-Jurassic. *The Gulf of Mexico Basin: The Geology of North America*; Salvador, A., Ed.; Geological Society of America: Boulder, CO, 1991c.
- Sawyer, D. S.; Buffler, R. T.; Pilger, R. H. The crust under the Gulf of Mexico basin. *The Gulf of Mexico Basin: The Geology of North America*; Salvador, A., Ed.; Geological Society of America: Boulder, CO, 1991.
- Seni, S. J., Hentz, T. F., Kaiser, W. R., Wermund, E. G. J., Eds. *Miocene and Older Reservoirs: Atlas of Northern Gulf of Mexico Gas and Oil Reservoirs Volume 1*; Bureau of Economic Geology, The University of Texas at Austin, 1997.
- Shedd, W.; Boswell, R.; Frye, M.; Godfriaux, P.; Kramer, K. Occurrence and nature of “bottom simulating reflectors” in the northern Gulf of Mexico. *Marine and Petroleum Geology* **2012**, 34, 31–40.
- Sohl, N. F.; Martínez, E. R.; Salmerón-Ureña, P.; Soto-Jaramillo, F. Upper Cretaceous. *The Gulf of Mexico Basin: The Geology of North America*; Salvador, A., Ed.; Geological Society of America: Boulder, CO, 1991.
- Stern, R. J.; Dickinson, W. R. The Gulf of Mexico is a Jurassic backarc basin. *Geosphere* **2010**, 6, 739–754.
- USGS. USGS Energy Data Finder, United States Geological Survey, 2014.
- Weimer, P.; Crews, J. R.; Crow, R. S.; Varnai, P. Atlas of Petroleum Fields and Discoveries, Northern Green Canyon, Ewing Bank, and Southern Ship Shoal and South Timbalier Areas (Offshore Louisiana), Northern Gulf of Mexico. *AAPG Bulletin: Gulf of Mexico Petroleum Systems* **1998a**, 82, 878–917.
- Weimer, P.; Rowan, M. G.; McBride, B. C.; Kligfield, R. Evaluating the petroleum systems of the northern deep Gulf of Mexico through integrated basin analysis: An overview. *AAPG Bulletin-American Association of Petroleum Geologists* **1998b**, 82, 865–877.

- Weimer, P.; Varnai, P.; Budhijanto, F. M.; Acosta, Z. M.; Martinez, R. E.; Navarro, A. F.; Rowan, M. G.; McBride, B. C.; Villamil, T.; Arango, C.; Crews, J. R.; Pulham, A. J. Sequence stratigraphy of Pliocene and Pleistocene turbidite systems, northern Green Canyon and Ewing Bank (offshore Louisiana), northern Gulf of Mexico. *AAPG Bulletin-American Association of Petroleum Geologists* **1998c**, 82, 918–960.
- Woods, R. D.; Salvador, A.; Miles, A. E. Pre-Triassic. *The Gulf of Mexico Basin: The Geology of North America*; Salvador, A., Ed.; Geological Society of America: Boulder, CO, 1991.
- Wu, S. G.; Vail, P. R.; Cramez, C. Allochthonous salt, structure and stratigraphy of the north-eastern Gulf of Mexico. Part 1. Stratigraphy. *Marine and Petroleum Geology* **1990**, 7, 318–332.

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