GCAGS JOURNAL
A Publication of the
Gulf Coast Association of
Geological Societies
www.gcags.org

VOLUME FRACTIONS OF LITHOLOGIC UNITS DEPOSITED PER GEOLOGIC EPOCH IN THE CENOZOIC, KEATHLEY CANYON AND WALKER RIDGE, DEEPWATER GULF OF MEXICO: PART 2—LIMESTONE AND MARL

Sharon Cornelius[1] **and Peter A. Emmet**[2]

[1]*Department of Earth and Atmospheric Sciences, University of Houston,*
Science and Research Bldg. 1, 3507 Cullen Blvd. #312, Houston, Texas 77204, U.S.A.

[2]*President, Brazos Valley GeoServices, Inc., 19831 Cypress Church Rd., Cypress, Texas 77433, U.S.A.*

ABSTRACT

There is virtually no literature describing the distribution of Cenozoic limestone in the deepwater Gulf of Mexico for two reasons: (1) most people assume any limestone found in the deepwater area is of Cretaceous age; and (2) because the limestone found in boreholes in the deepwater region is usually micritic in nature, and thus non-hydrocarbon bearing, there is little interest in it, even as a geologic curiosity. Within the study area that primarily covers Keathley Canyon and Walker Ridge Cenozoic limestone has been catalogued in 58 wells (and observed in another seven new wells). Additionally, there are two wells with rafted Cretaceous limestone and six wells with normally placed Cretaceous limestone at the bottom of the borehole. There also are six wells in southeastern Keathley Canyon with what may be rafted Eocene limestone on top of salt. A map view of the Cenozoic limestone well locations shows an interesting depositional pattern with an equally interesting void in the middle as does a map of Cenozoic marl occurrence. Contour maps of marl depositional thickness compared to those of limestone in the same geologic epoch show an inverse relationship, meaning in locations where there is a large volume fraction of limestone, there is a small volume fraction of marl, and vice versa. In the deepwater environment, there is a mineralogical relationship between the $CaCO_3$, silt, and clay components deposited on the seafloor, which we believe determines whether limestone or marl is deposited over time. These observations and interpretations are based primarily on wellbore data described and catalogued by onsite mudloggers during the drilling process.

INTRODUCTION

This study is a continuation of Part 1 (Cornelius and Emmet, 2018, this volume) that examined the distribution of sand, shale and siltstone per Cenozoic geologic epoch in the deepwater Gulf of Mexico study area shown in Figure 1. The objective of the study was to contour the volume fraction (percentage) of specific lithological units (such as sand, shale, siltstone, limestone, and marl) in the study area by geological epoch to observe changes over time. Part 2 (this paper) describes the distribution of limestone and marl by Cenozoic geologic epochs in the same study area, along with an isochore map of the allochthonous salt derived from 93 of these area wells. The well log database used in this study was created in 2014–2017 and continuously updated as new well data was posted on the Bureau of Safety and Environmental Enforcement (BSSE) government website (BSSE, 2018).

Study Area

The study area is in the deepwater Gulf of Mexico (Fig. 1) and comprises all of the Keathley Canyon and Walker Ridge protraction areas, plus the southeastern corner of Green Canyon, the Garden Banks Wilcox discovery in Block 959 by Cobalt, and the Anadarko discovery well in Sigsbee Escarpment Block 39. This region was chosen because industry drilling over the past ten years has resulted in a large number of drilled wells with sufficient borehole information to allow various studies with statistical sustainability (Fig. 1).

Database

There are 80 wells within the study area which have complete mudlog descriptions of the lithology in each borehole. Of the 42 paleontological reports available, 35 were considered usable for our purposes. A few of these paleontological reports

Manuscript received February 5, 2018; revised manuscript received March 15, 2018; manuscript accepted June 1, 2018.

GCAGS Journal, v. 7 (2018), p. 151–166.

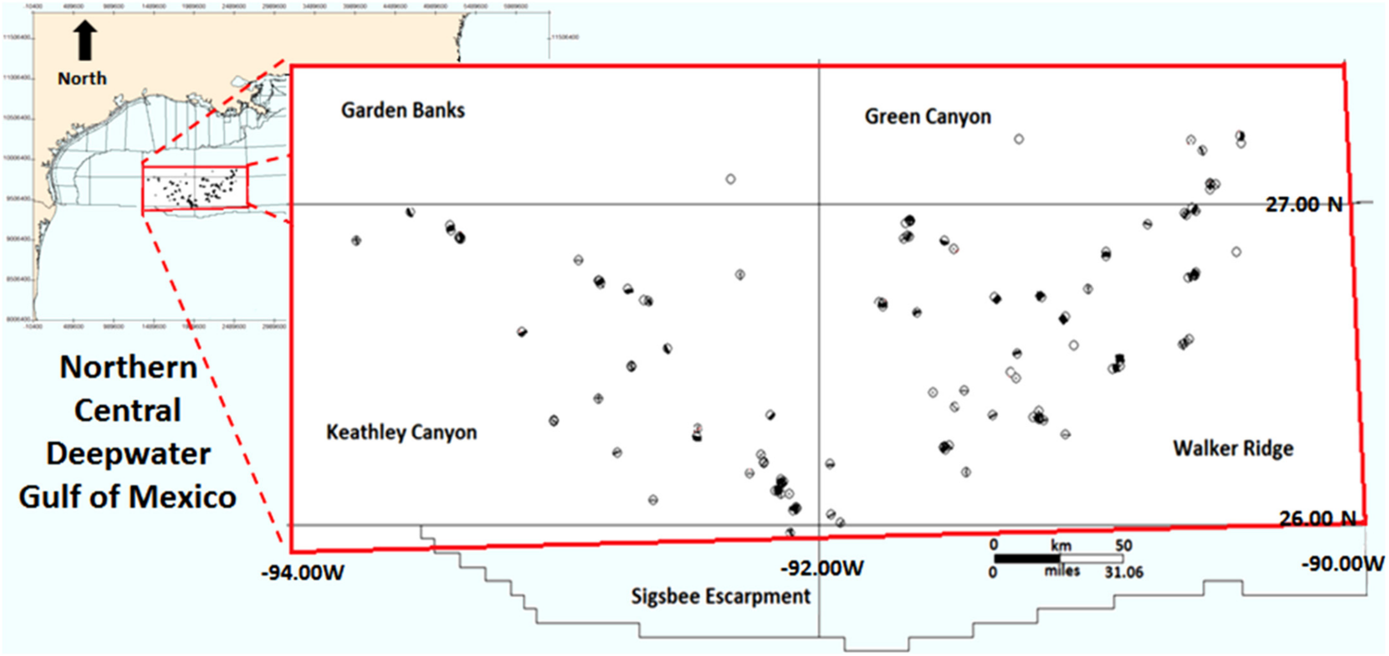


Figure 1. Deepwater Gulf of Mexico study area basemap showing all well locations incorporated as of November 2017. Clear circles indicate vertical boreholes while other boreholes show the plan view of deviated drilling. The study area includes Keathley Canyon, Walker Ridge, the southeastern corner of Green Canyon, one well in Garden Banks, and one well in Sigsbee Escarpment protraction areas.

cover only a portion of a given well; and a few contain data from debris flows or overturned zones, in which fossils are noticeably out of place in the stratigraphic column. The database contains a total of 108 mudlogs. Some of these are redundant due to well sidetracks and well-bypass drilling, although it is common for the lower part of these sidetracked or bypassed well zones to have different lithologies from that of the main borehole, because lithology can change noticeably over short lateral distances in this deepwater region.

DETERMINATION OF GEOLOGICAL EPOCHS

Geological epochs were determined in two ways: (1) direct correlation of a well log motif with a relevant paleontological report; and/or (2) correlation of sequence boundaries and maximum flooding surfaces using a combination of gamma ray (GR) and resistivity (RES) electric logs. In some instances, where the paleontological reports were not definitive, applying sequence stratigraphic methodology correlated with electric logs was more reliable.

Use of Paleontological Reports

In 31 of the 35 paleontological reports used in this study, the fossils present were sequential in age, so the epoch determination was fairly straightforward. The implication is that the limestone observed in 58 wells in the study area, mostly occurs below salt with other contemporaneous Cenozoic strata and is truly Cenozoic in age. The other four paleontological reports give evidence of rafted sections: two wells with rafted Cretaceous limestone and two with rafted Cenozoic sediments. If the limestone occurs above salt, the question becomes whether it was deposited in situ or rafted on top allochthonous salt. Seven wells located in the southern extreme of the study area (close to the Sigsbee Escarpment) show evidence of rafted sections above salt. These wells are listed in Table 1. Six of these wells are in the Lucius and Hadrian South fields in the southeastern corner of Keathley Canyon while the seventh well is near the southwestern corner of Walker Ridge. Only the Walker Ridge well has a paleontological report, which indicates that the rafted section is Cretaceous limestone with Paleocene and Eocene strata above it. A schematic diagram of the borehole is shown in Figure 2. Convincing seismic evidence that this well contained a rafted section was presented by Fiduk et al. (2016). No seismic data were used in the present study.

There are no paleontological reports for the six Keathley Canyon wells with rafted limestone above salt. The authors conclude that this limestone is not Cretaceous in age despite the lack of paleontological control for the following reasons:

(1) Mudlogs for two of these wells show presence of a volcanic tuff in a short interval above the limestone. As discussed in Part 1 (Cornelius and Emmet, 2018, this volume), this volcanic tuff is believed to be Miocene, Oligocene, or Eocene in age. There is a similar example of Eocene limestone with volcanic tuff found in the KC–102–001 well that is not in a rafted section.

(2) Within the study area, Cenozoic limestone may be found in the presence of sand and/or siltstone, while the top of Cretaceous limestone (of Maastrichtian age) found in regular stratigraphic order at the bottom of some wells in this deepwater area is found only with shale, marl, or calcareous claystone. Four of these six wells in southeastern Keathley Canyon have siltstone present with limestone, and three have sandstone.

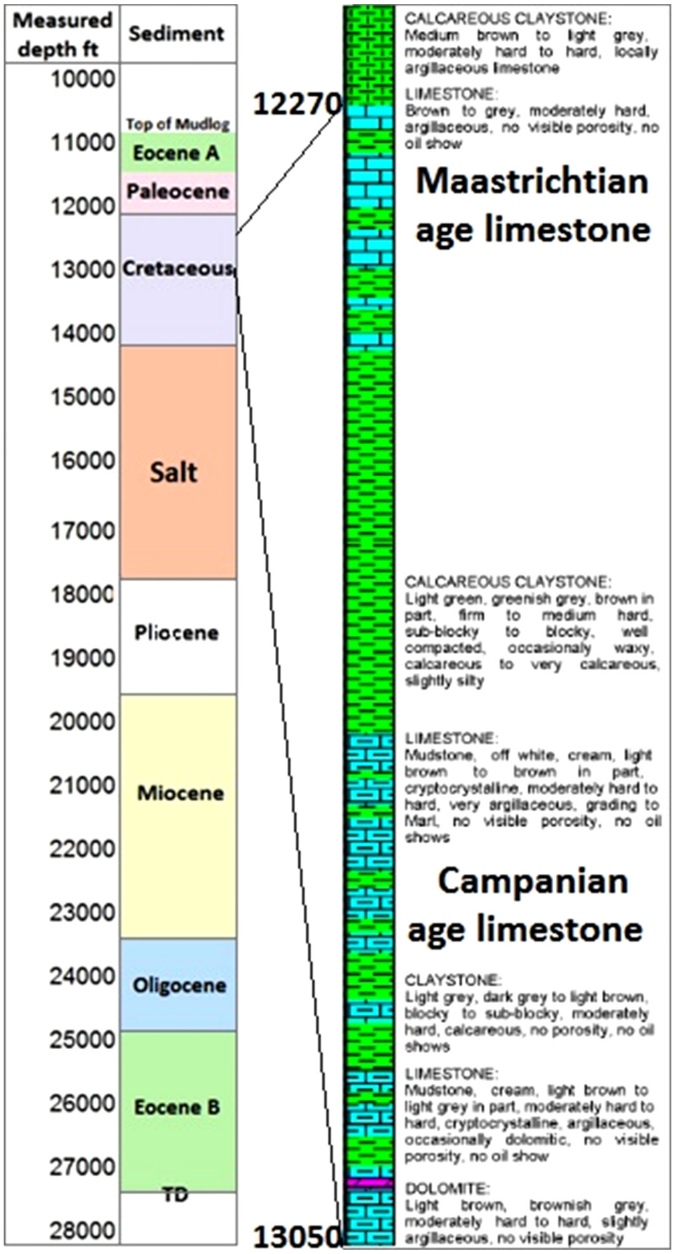
(3) There is a difference in the description of the limestone found in the mudlogs for Cenozoic and Cretaceous limestone. Cenozoic limestone is described as either micritic or microcrystalline, while Maastrichtian age limestone is not. The top of Cretaceous limestone is usually described as “very hard and blocky” and is usually brown or dark grey in color. Cenozoic limestone can be many colors.

(4) The lithology of the sedimentary units on top of the rafted limestone is primarily shale, in these six wells suggesting that the age is more likely Oligocene in age, not Paleocene.

An alternative explanation was offered by Fiduk et al. (2016) and by Pilcher et al. (2011) based on seismic data. Both of these independent studies clearly show both the Walker Ridge

Table 1. List of seven wells with rafted limestone sections on top of salt.

Well name	API–UWI	Date drilling completed	Presumed geologic age of rafted limestone above	Presumed geologic age of sediments above limestone	What is present with the limestone?
KC–874–ss001	608084003300	Dec. 2012	Eocene	Oligocene	shale, marl
KC–875–001–ST1	608084002001	Feb. 2010	Eocene	Oligocene	shale, sltst, chalk
KC–875–002	608084002400	June 2010	Eocene	Oligocene	shale, sltst, sand
KC–918–001–ST1	608084003201	Sept. 2012	Eocene	Oligocene	marl, claystone, sand
KC–919–002	608084001800	Nov. 2009	Eocene	Oligocene	marl, claystone, sltst
KC–919–003–BP1	608084002501	July 2011	Eocene	Oligocene	sand, shale, sltst
WR–969–001	608124004800	Oct. 2011	Middle to Upper Cretaceous	Paleocene	calcareous claystone



CALCAREOUS CLAYSTONE: Medium brown to light grey, moderately hard to hard, localy argillaceous limestone

LIMESTONE: Brown to grey, moderately hard, argillaceous, no visible porosity, no oil show

CALCAREOUS CLAYSTONE: Light green, greenish grey, brown in part, firm to medium hard, sub-blocky to blocky, well compacted, occasionaly waxy, calcareous to very calcareous, slightly silty

LIMESTONE: Mudstone, off white, cream, light brown to brown in part, cryptocrystalline, moderately hard to hard, very argillaceous, grading to Marl, no visible porosity, no oil shows

CLAYSTONE: Light grey, dark grey to light brown, blocky to sub-blocky, moderately hard, calcareous, no porosity, no oil shows

LIMESTONE: Mudstone, cream, light brown to light grey in part, moderately hard to hard, cryptocrystalline, argillaceous, occasionally dolomitic, no visible porosity, no oil show

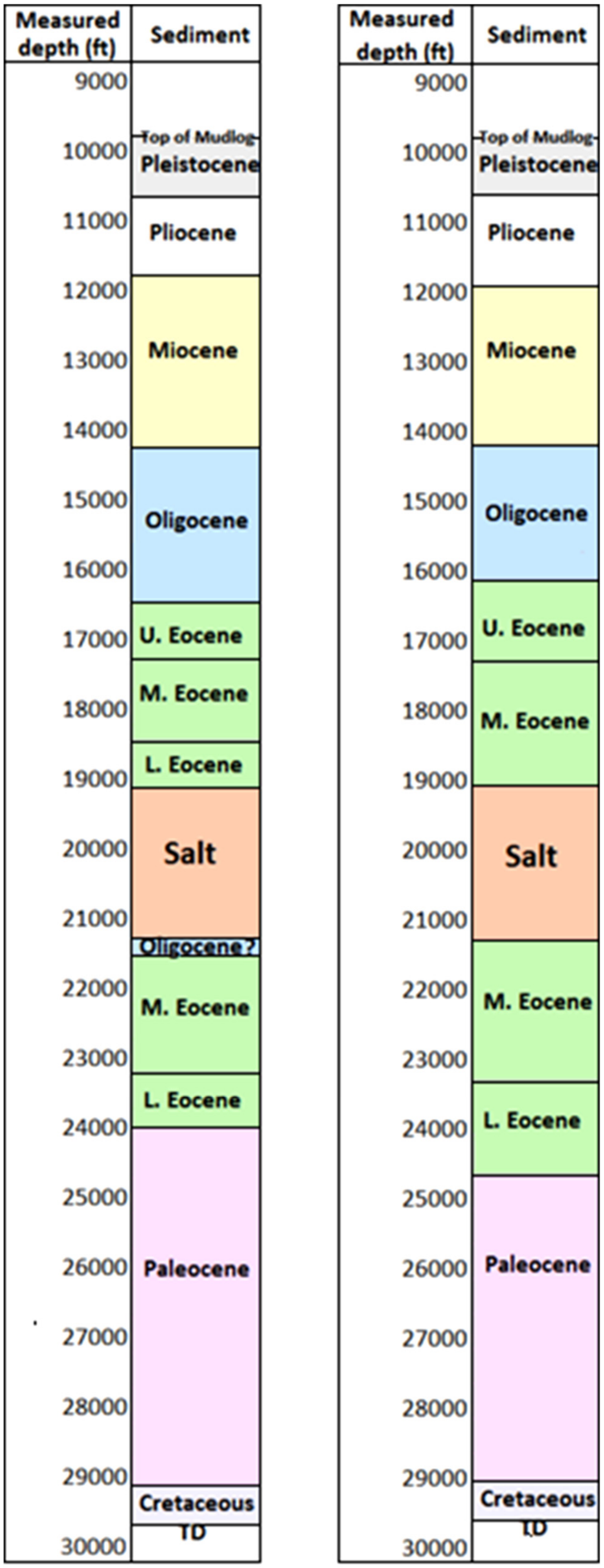
DOLOMITE: Light brown, brownish grey, moderately hard to hard, slightly argillaceous, no visible porosity

Figure 2. Stratigraphy of the WR–969–001 well as determined by paleontological data on the left side. To the right is a segment of the mudlog description of the limestone in the Cretaceous section. 1000 ft = ~305 m.

and the Keathley Canyon raft zones; and both studies suggest the base of these rafts contains Cretaceous age sediments. At the time of the Pilcher et al. (2011) publication, only data from one of these six wells was available (Table 1). Regardless, the lithologic units above salt in these six wells and in the WR–969–001 well **were not included** in the borehole volume fractions because these units did not originate within the respective borehole stratigraphic columns; i.e., these rafted sections originated elsewhere.

In a few locations, microfossils were stratigraphically out of place as noted by the presence of reworked fossils. However, these reworked fossils are a minority of all microfossils present, so they were ignored as anomalies in the normal stratigraphic sequence, possibly introduced by faulting or salt movement. In a few wells where salt was relatively thin, and a specific geologic epoch appeared both above and below the salt, interrupted only by salt extension rather than rafting, the sediment volumes were combined before calculating the component volume fractions. Generally speaking, where salt has displaced sediments from one or more geological epochs, the microfossils were reasonably sequential in time both above and below the salt. This is also true for the limestone and marls in these wells; which are Cenozoic in age and contemporaneous with other clastic sediments. The biostratigraphic chart used to determine the geologic epochs of the individual microfossils found in the deepwater Gulf of Mexico is from Witrock (2017). In the case of the KC–596–001 well, the paleontological evidence supporting a raft is not definitive, although it is convincing (Fig. 3). The microfossils used for analysis are not confined to a specific epoch, which adds uncertainty. More importantly, the overall borehole lithology for this well is lacking sandstone and has a high percentage of shale both above and below salt. This equivalent of the Wilcox strata in this well is a combination of sandy siltstone and silty sandstone. There are very small amounts of limestone below salt in both the Eocene and the Paleocene with massive Cretaceous limestone at the bottom of the borehole. In order to avoid confusion when calculating the volume fractions of the lithological components, the Eocene section above the salt was not included, even though the well log interpretation of epoch boundaries was used. Without further evidence, possibly seismic data, we cannot say conclusively that a rafted section appears in this well.

The KC–774–001 well is unusual in that it contains no salt, yet it has a rafted section according to the paleontological report for the well (see schematic in Figure 4). It is also the second well that has rafted Cretaceous limestone, but this limestone is not on top of salt, rather it sits on top of Miocene clastic sediment. A difficult question to answer is "How much of the Miocene is rafted and how much of the Miocene belongs to the borehole stratigraphic column?" This well also has more siltstone scattered throughout the borehole than any other well in the study area.



KC-596-001 Schematic from Paleo report

KC-596-001 Schematic from well log

Figure 3. Stratigraphy of the KC–596–001 well. The paleontological version is on the left and the well log version is on the right. The Oligocene section on the left is possibly an out-of-place rubble zone. If so, the Lower Eocene section on top of salt is a rafted section. 1000 ft = ~305 m.

Use of Well Log Sequence Stratigraphy

For the wells without a paleontological report and not near a well that does, the alternative approach was to apply sequence stratigraphic principles to correlate epoch boundaries. Two different sea-level charts were used as references: the 1987 version for global sea-level changes in the Cenozoic by Haq et al. (1987) (Fig. 5) and the 2000 version by Galloway et al. (2000) for sea-level changes in the Gulf of Mexico during the Cenozoic. Geological epoch transitions occur either at maximum flooding during sea-level rise or at sequence boundaries at the base of major sea-level falls (regressions). These defining stratigraphic surfaces are sometimes more recognizable on well logs than the transition zone of microfossils, which may occur over several hundred feet in the borehole.

Adjustment for Allochthonous Salt Presence

The presence of salt in the borehole was ignored when the stratigraphic column was sequential above and below the salt. In the instance where salt occurred twice in the same borehole, the interim sediment had to be classified as to whether it belonged to the subsalt stratigraphic column, or if it had been attached to the salt during continuous salt movement. The best analysis of the true stratigraphic column was found in the wells without salt. These few wells demonstrated the stratigraphic sequences uninterrupted by salt. Of course, the present stratigraphy is a function of locale, topographic lows or highs, contemporaneous or subsequent faulting, and sedimentation rates from sediment sources that migrated from west to east.

CALCULATION OF VOLUME FRACTIONS

Once every well had been subdivided into the geological epochs for that particular borehole, mudlogs (for each well) defined the amount of each depositional component present within each epoch, with percentages calculated for each component. There is a variety of depositional units, depending on well location and the contractor providing the mudlogs.

Three things to consider when viewing the resulting contour maps are that not all wells were drilled to the same depth, the water depths vary from 3958 ft (1206 m) to 9576 ft (2919 m), and mobile salt may have displaced one or more epochs in most locations. We feel that it is important to look at these maps as a reflection of what is actually in the well, which presents a more detailed representation than what a seismically-derived map would show. Admittedly, seismically-derived maps give better continuity than those based on scattered well control; but then how can one verify what lithology is present in the seismic data? One important lesson learned from analyzing these mudlogs is how quickly the lithology changes across short distances along both strike and dip, and we sustain that these rapid lithological changes are not visible on seismic data, especially beneath salt.

GEOLOGICAL EPOCH ISOCHORE MAPS

This study utilized the IHS Markit Kingdom 2017 software application. We loaded the geological eras of each borehole into Kingdom as "zones", defined by the top and base of each epoch in each well. This allowed us to generate an isochore (vertical thickness) map for each epoch on a regional basis. These isochore maps for the Cenozoic era are displayed in Part 1 (Cornelius and Emmet, 2018, this volume). The next phase of the study was to enter all of the calculated volume fractions of the lithological components as "zone attributes" into each previously defined "zone." We defined our attributes as % sand, % shale, % siltstone, % limestone, and % marl, which are the most common components for each epoch, only in different proportions. The sand, shale, and siltstone volume fraction contour

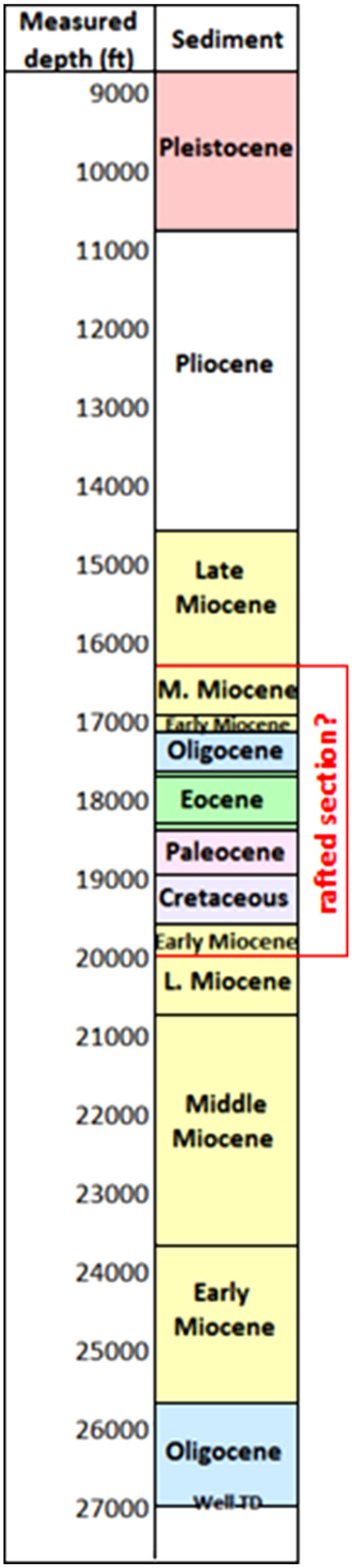


Figure 4. Stratigraphy of the KC–774–001 well as determined by paleontology showing the possible rafted section of Cretaceous to lower Miocene sediment overlying Miocene sediments. It is not clear how much of the Miocene was a part of the raft. Miocene sections above the top Oligocene are in normal biostratigraphic order. 1000 ft = ~305 m.

maps are illustrated and discussed in Part 1 (Cornelius and Emmet, 2018, this volume).

VOLUME FRACTION CONTOUR MAPS

The contour maps we will investigate in Part 2 (this paper) are those for limestone and marl distributions. It is informative to compare the distribution of individual lithological constituents in the study area throughout the Cenozoic. It should be realized that the volume fractions represent the relative amounts of lithologies deposited per geological epoch. These lithological percentages are probably more accurately represented for the Eocene and the Paleocene epochs, because they did not experience as much stratigraphic interference, caused by salt movement, as younger sediments. Whole or partial sections of Pleistocene, Pliocene, Miocene, and/or Oligocene are replaced in many boreholes by the salt canopy, or repeated by rafting in a few instances. Some wells do not penetrate beyond the Pliocene or Miocene, and there is no data for older epochs such as the Oligocene, the Eocene, or the Paleocene. Only 51 wells penetrate the Eocene, while 32 wells penetrate the Paleocene. The Oligocene has the highest number of well penetrations with 57 data points. Note that for all contour maps presented in this study cool colors represent high values of volume fractions and warm colors represent low values.

Cenozoic Limestone Distribution in the Study Area

The authors noticed the presence of limestone in some of the study area mudlogs and wondered how this came to be. How is limestone deposited on the ultra-deepwater portion of the slope? Without full paleontological analyses, a poster presented at the 2016 Gulf Coast Association of Geological Societies annual meeting in Corpus Christi, Texas (Lankford-Bravo et al., 2016) suggested that limestone could have been deposited in shallower water on the shelf, and later settled in the deepwater by way of debris flows. As more mudlogs were added to the database and the number of wells containing Cenozoic limestone increased to 58, it became apparent that there must be another explanation. The final piece of evidence that debris flows are not the answer is that in most all of the paleontological reports, the fossil assemblages are sequential. A literature search for Cenozoic limestone in the deepwater Gulf of Mexico yielded only one reference relevant to the study area: a brief mention of Eocene shale and limestone sequences above Wilcox sands in the Cascade, Chinook and St. Malo wells (Anonymous, 2007).

Almost all mudlog descriptions for the Cenozoic deepwater limestones indicate that they are “micritic” or “microcrystalline”. Micrite is a fine-grained carbonate sediment (or mud) that can be precipitated chemically or biochemically from seawater. It can be derived from the abrasion of pre-existing calcium carbonate grains, or formed during disintegration of calcareous green algae, which settle to the sea floor (Mutti, 2000). Micrite is a lithology composed of lime mud with fewer than 10% grains (ooids, peloids, bioclasts, or intraclasts); it is a carbonate rock with carbonate (calcite) cementing its very fine $CaCO_3$ grains (Mutti, 2000). We can only speculate as to the depth of the carbonate compensation depth (CCD) for the Gulf of Mexico during the Cenozoic. The CCD is the depth below which $CaCO_3$ will dissolve due to decreasing water temperature, increasing pressure, and increasing acidity of sea water. As long as the seafloor lies above the CCD, carbonate ($CaCO_3$) particles will accumulate in bottom sediments. It is a kinetic horizon: rigorously defined as the depth where the dissolution rate equals the rate of supply. There are two versions of the CCD, one for calcite (the more commonly used version, also known as the calcite compensation depth) and one for aragonite (the ACD). The ACD is always shallower than the CCD because aragonite solubility is a function of decreasing temperature and increasing pressure (Thurman and

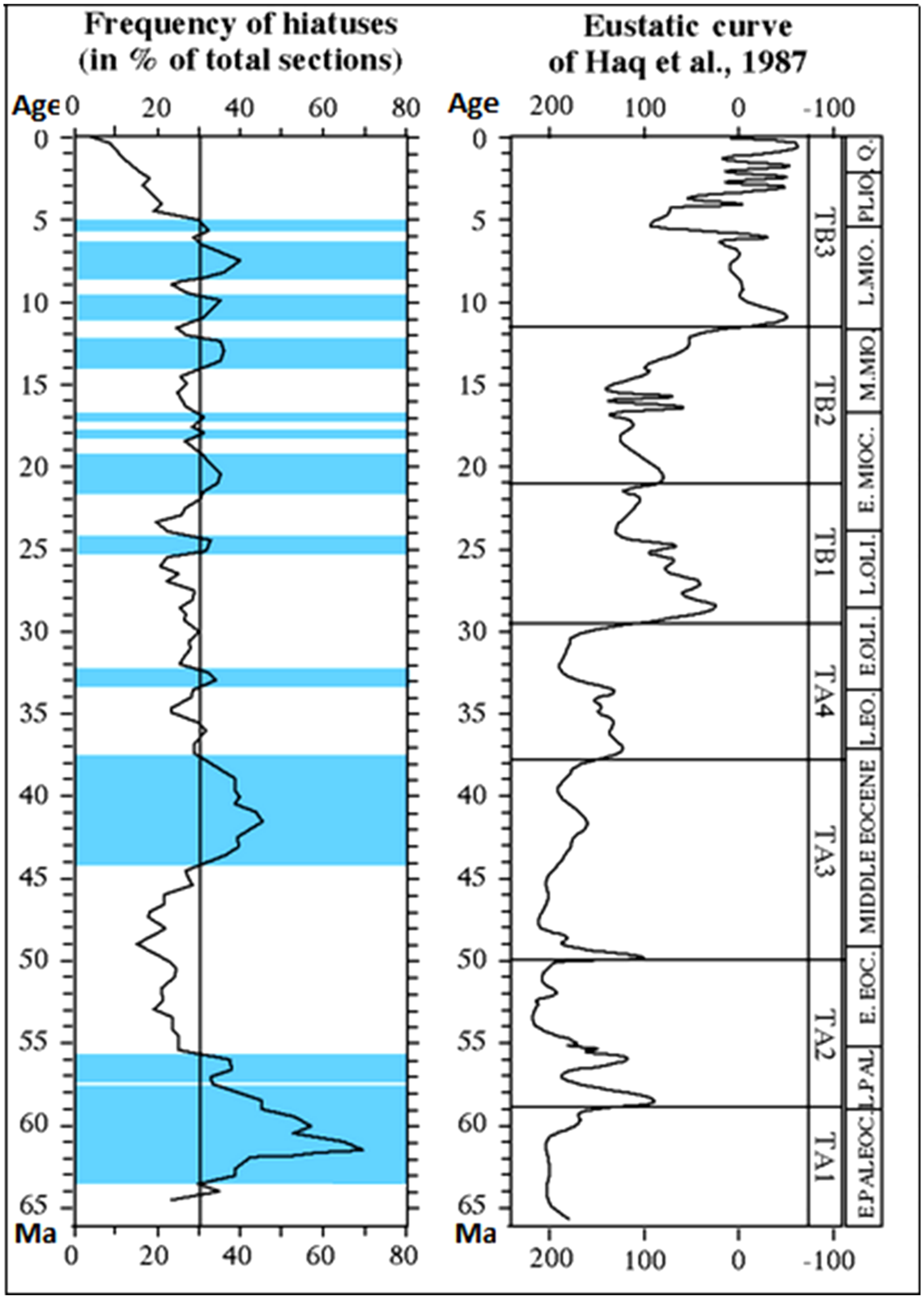


Figure 5. Global eustatic curve for the Cenozoic (modified after Haq et al., 1987). The vertical graph on the left shows the occurrence of transgressions (in white) and related hiatuses (in blue) that control the formation of condensed sections in the sedimentary column. These condensed sections are prone to the formation of marls in the deepwater environment. Horizontal scale of the right portion is in feet of sea level change.

Trujillo, 2004). CCD in the Atlantic Ocean is about 5000 m (or >16,400 ft) and we presume by extension that this is a reasonable estimate for the Gulf of Mexico. In the geological past, the depth of the CCD has shown significant variation. In the Cretaceous through the Eocene, the CCD was much shallower globally than it is today due to intense volcanic activity throughout that time period, which added to the atmospheric CO_2 and in turn to oceanic CO_2. During the late Eocene, the oceans transitioned from quite warm to very cold, coinciding with a deepened CCD (Bice, 2006). Because we have limestones in the study area dated for all epochs in the Cenozoic, the implication is that water depths did not exceed the CCD, at least in these localized areas.

There are only four wells that report Pleistocene limestone, and all four wells contain less than 1% limestone. Similarly, only four wells with Pliocene limestone were identified in the study area, and volume fractions range from 0.29 to 7.12%. Consequently, the younger ages are not presented and the isochore maps begin with the Miocene (Fig. 6) followed by the Oligocene (Fig. 7), the Eocene (Fig. 8), and the Paleocene (Fig. 9).

Miocene Limestone

Miocene limestone (Fig. 6) is concentrated along the edge of the Sigsbee Escarpment in Walker Ridge, but the limestone percentage level is low in Keathley Canyon. The highest volume

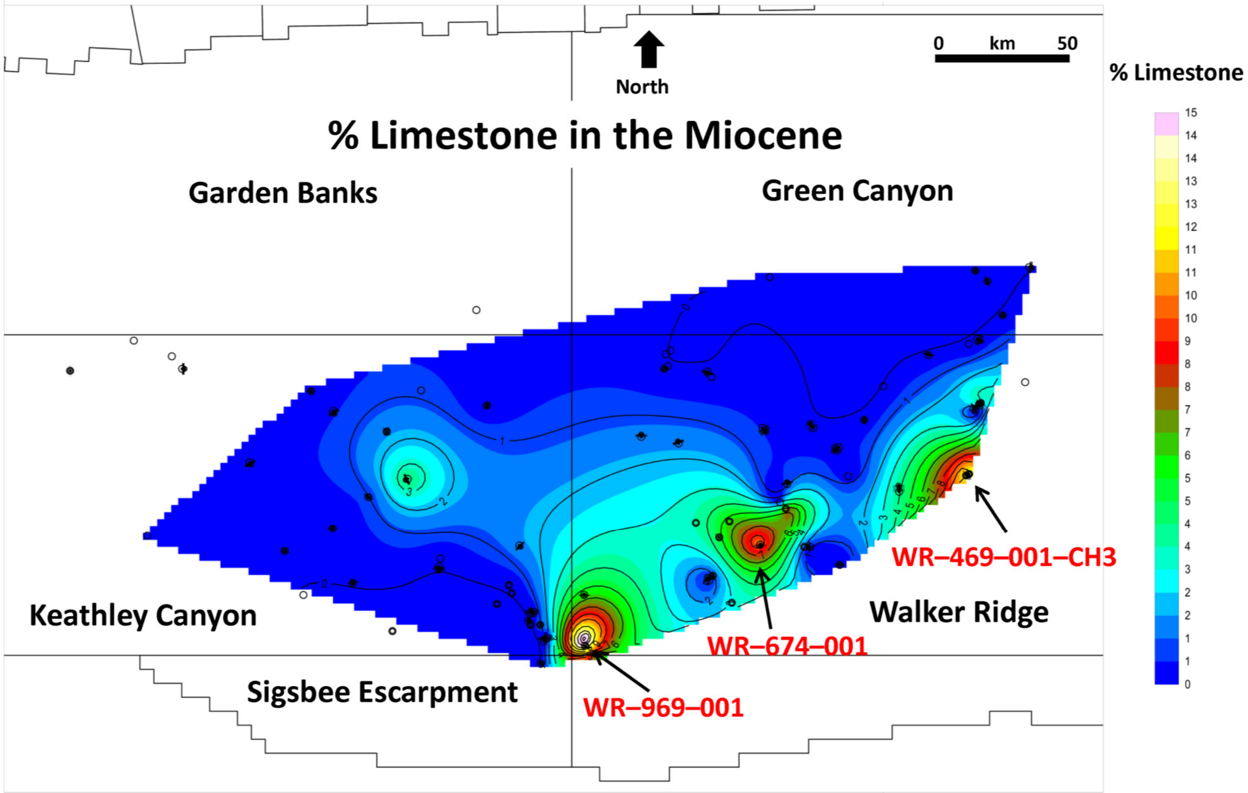


Figure 6. Volume fraction of limestone present in the Miocene. Wells WR–969–001, WR–674–001, and the WR–469–001–CH3 have the highest percentage of limestone. 50 km = ~31 mi.

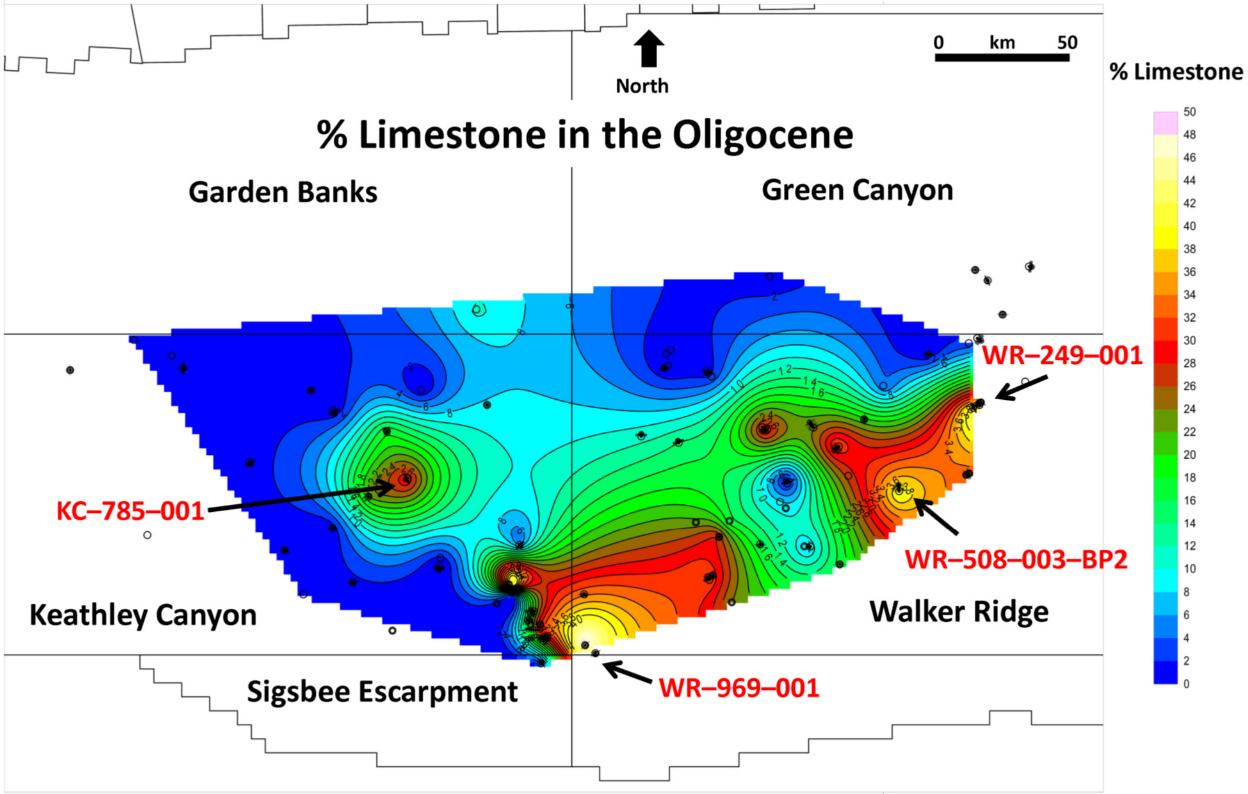


Figure 7. Volume fraction of limestone present in the Oligocene. Note that similar to the Miocene in Figure 6, the highest percentage of Oligocene limestone is found in the WR–969–001 well and is about three times the amount deposited during the Miocene. 50 km = ~31 mi.

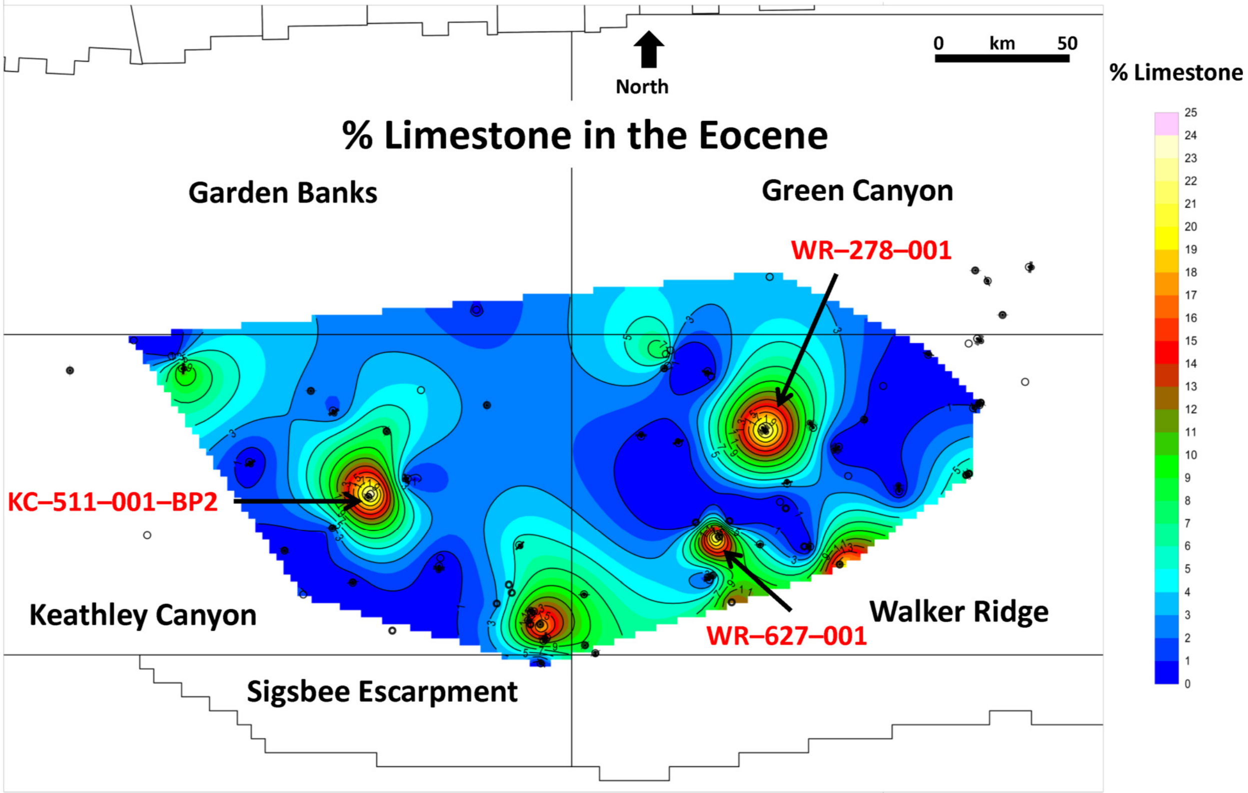


Figure 8. Volume fraction of limestone present in the Eocene. The two main depocenters for limestone during the Eocene are near the KC–511–001–BP2 and WR–627–001 wells. 50 km = ~31 mi.

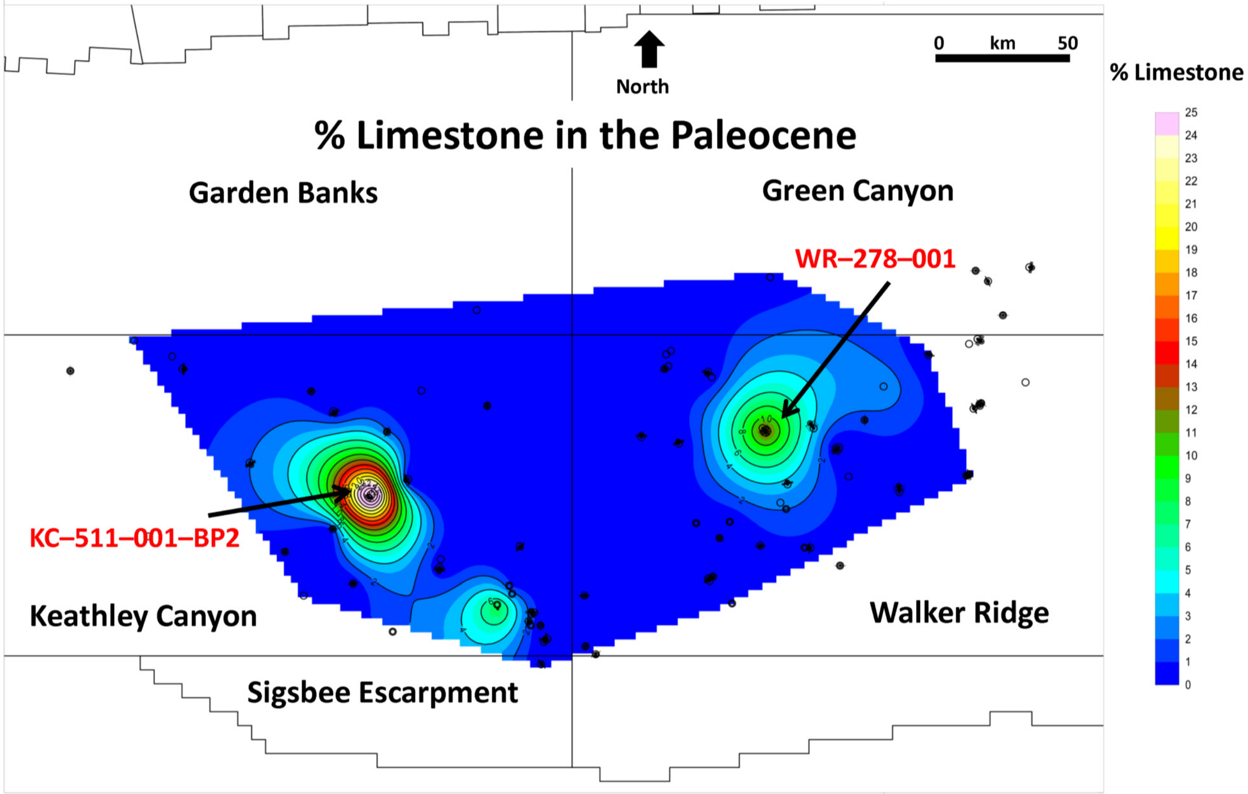


Figure 9. Volume fraction of limestone present in the Paleocene. The main depocenters for Paleocene limestone are similar to those for the Eocene (Fig. 8). 50 km = ~31 mi.

fraction of Miocene limestone is found in WR–969–001 below the salt. Shale dominates the Miocene stratigraphic section (Cornelius and Emmet, 2018, their figure 30, this volume) throughout the study area minimizing the percent of limestone.

Oligocene Limestone

The volume fraction of limestone increases significantly in the Oligocene (Fig. 7). Limestone sediments extend into Keathley Canyon, centered on the KC–785–001 well. Comparing the Oligocene and the Eocene, Oligocene limestone occurrences are similar to those in the Eocene, but in general, there is twice as much carbonate. This does not appear to be a local anomaly as it is evident on a regional basis.

Eocene Limestone

Limestone in the Eocene Epoch (Fig. 8) expands its distribution and now appears along the Sigsbee Escarpment area in Walker Ridge. In Keathley Canyon, limestone deposition is centered on the KC–511–001–BP2 well and in Walker Ridge the limestone deposition is centered on two wells, WR–278–001 and WR–627–001.

Paleocene Limestone

During the Paleocene (Fig. 9) limestone becomes more prominent in Keathley Canyon and centered on the KC–511–001–BP2 well. This same well acts as a depocenter for limestone in Keathley Canyon for the Eocene Epoch. The Paleocene section in the lower 700 ft (~210 m) of this well is very unusual in that limestone, sandstone and shale occur in roughly equal proportions. Compare this map with the sand contour map for the Paleocene (Cornelius and Emmet, 2018, their figure 13,this volume) and it will be seen that the area received significant sand, relatively speaking, overwhelming carbonate deposition.

Limestone Distribution in Study Area throughout the Cenozoic

Figure 10 is a map showing the 65 wells that contain Cenozoic limestone (of all epochs). There is a rather distinct distribution of limestone occurrence along with noticeable void areas. It is important to understand why limestone was deposited in some areas and not others. Is the distribution of limestone caused by faulting, salt movement, or the CCD, or is the apparent distribution of limestone an artifact caused by paucity of deep boreholes in these areas? Figure 10 includes seven newly added wells to the original database of 58 wells; all seven mudlogs indicate the presence of Cenozoic limestone below salt. These recent wells have not been analyzed for volume fractions. The most interesting well in this new group of wells is KC–129–001–BP1, located on the border between Keathley Canyon and Walker Ridge inside the “carbonate void.” This well is about 33,000 ft deep and contains neither marl nor limestone. Paleontological evidence suggests that sediments at the bottom of the well are no older than early Oligocene. Most all of these sediments below >20,000 ft (~6100 m) of salt are shale. This is a very unique well. The well is located within a basement low separating Garden Banks from Green Canyon, so it is possible that the KC–129–001–BP1 well area was below the CCD during the Paleocene, Eocene, and the Oligocene; but it offers no explanation for lack of carbonates in the other wells located within the “carbonate void.”

Cenozoic Marl Distribution in the Study Area

In areas where significant clay and silt are deposited together with $CaCO_3$, marl is the dominant lithology. The dominant carbonate mineral in most marls is calcite, but other carbonate minerals such as aragonite, dolomite, and siderite may also be present. The average carbonate content of limestone is 87.2 % but the average carbonate content of marl is 64.3%; and when limestone and marl occur in the same location, it usually is in the form of alternating layers (Munnecke and Westphal, 1996). However, this is not the case in this deepwater Gulf of Mexico study. There is no evidence of alternating layers in any single mudlog examined; but this could be a function of sampling frequency. When limestone and marl occur together, the distribution appears random, at least from the perspective of the borehole sample. The closest depiction of special layering is in the Eocene section of the KC–511–001–BP2 well; but instead of alternating layers of limestone and marl, there are layers of limestone and marl separated either by a layer of shale or siltstone.

The distribution of marl in the study area is presented in contour maps for the Pleistocene (Fig. 11), the Pliocene (Fig. 12), the Miocene (Fig. 13), the Oligocene (Fig. 14), the Eocene (Fig. 15) and the Paleocene (Fig. 16). In general, there is an inverse relationship between limestone and marl on the maps, so where marl is recognized in mudlogs, limestone is not. This is true for the Pleistocene, the Miocene, the Oligocene, the Eocene, and the Paleocene. The data points (only four) for limestone in the Pliocene were too scattered to draw any conclusion. However, in looking at the area mudlogs, it is not uncommon to see limestone and marl side by side in the borehole. It then becomes a matter of proportion; usually one will be more than the other.

Pleistocene Marl

The only Pleistocene marl (Fig. 11) concentrations are in Keathley Canyon with the highest volume fraction coming from Tiber Field in KC–102–001. Traces of marl are also found in northeastern Walker Ridge and in Sigsbee Escarpment (Fig. 11). Marl has shifted from Walker Ridge in the Pliocene (Fig. 12) to Keathley Canyon in the Pleistocene.

Pliocene Marl

Deposition of Pliocene marl apparently shifts from the northwest corner of Keathley Canyon in the Pleistocene to the southeast corner of Green Canyon in the Pliocene (Fig. 12). Keathley Canyon is almost devoid of Pliocene marl. No volume fractions were identified in 20 wells on the western side of the study area. Also, in the four northwestern wells (close to Garden Banks), the Pliocene has been displaced by salt. The highest concentration of marl is found in the GC–825–001–ST1 well in the northeast corner of the study area.

Miocene Marl

Miocene marl was concentrated in Keathley Canyon (Fig. 13), centered on the location of the KC–736–001 well. The Miocene marl distribution is an inverse of the Miocene limestone distribution as seen in Figure 6.

Oligocene Marl

As with Oligocene shale and Oligocene limestone, there is higher volume fraction of marl deposited in the Oligocene than any other epoch in the Cenozoic (Fig. 14). The highest volume fractions are found in five wells: KC–163–001, KC–736–001, WR–155–001, WR–372–001, and WR–543–001–BP1 as shown by the dark blue centers of deposition in Figure 14.

Eocene Marl

The Eocene marl distribution (Fig. 15) is significantly greater than that of the Paleocene below in Figure 16; but it is also much less than that of the Oligocene in Figure 14. The main concentration of marl is centered on the WR–96–001–BP1 well in the Shenandoah sub basin and the secondary is located around the KC–511–001–BP2 well.

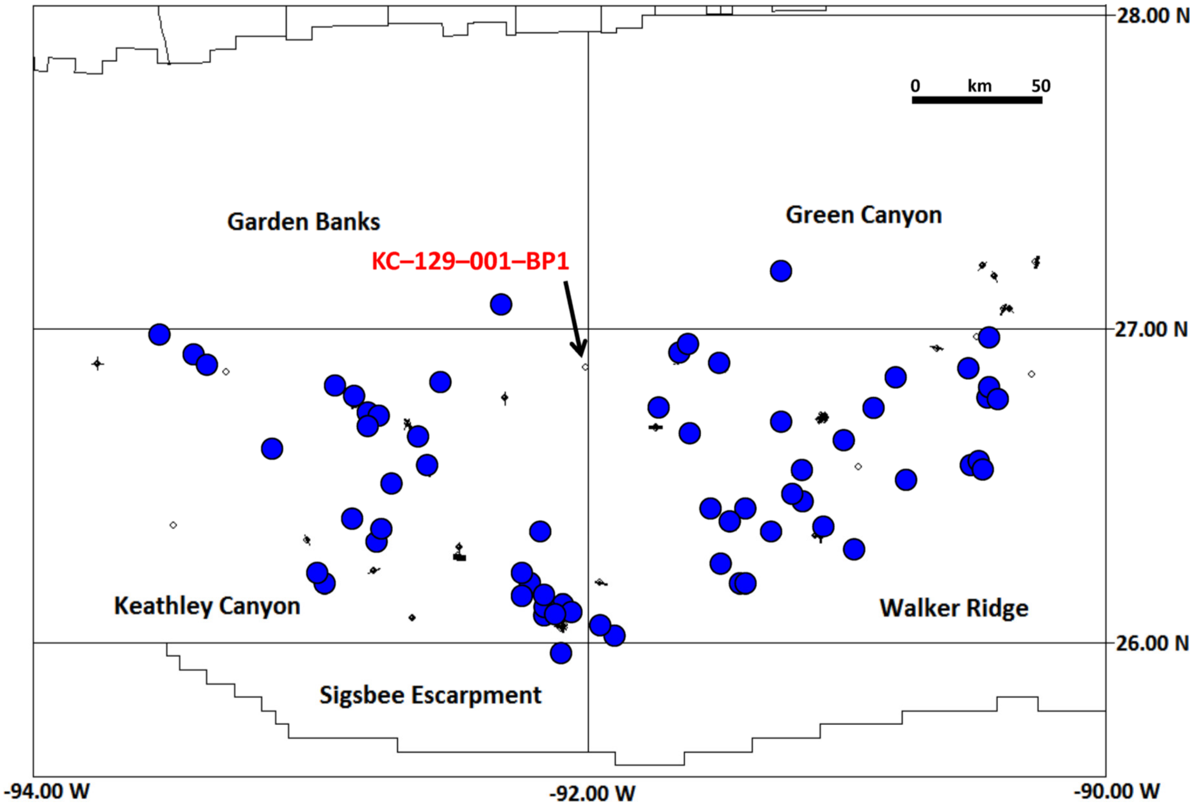


Figure 10. Location of all 65 wells in the study area having Cenozoic limestone. 50 km = ~31 mi.

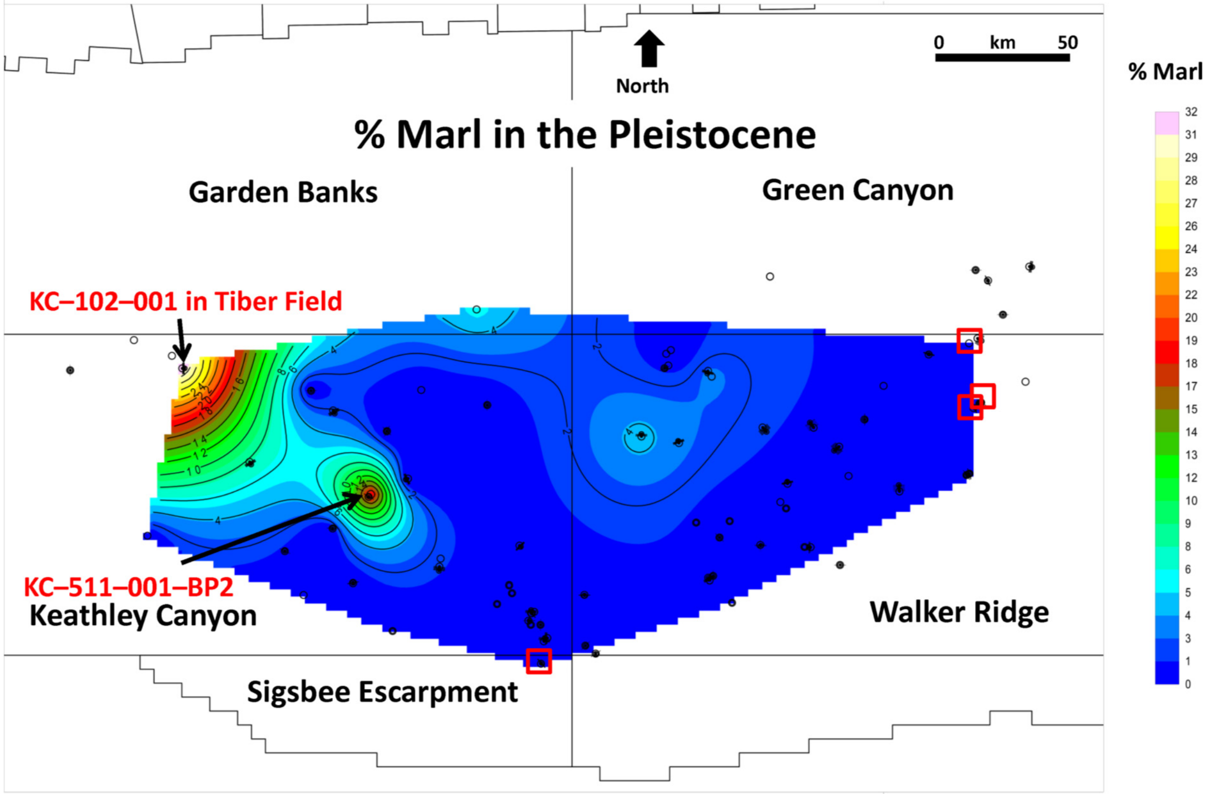


Figure 11. Volume fraction of marl deposited during the Pleistocene. The main Pleistocene marl depocenter is in the northwestern part of Keathley Canyon while three of the four wells containing traces of Pleistocene limestone (wells inside red rectangles) are in the northeastern corner of Walker Ridge; the fourth Pleistocene limestone occurrence is in Sigsbee Escarpment. 50 km = ~31 mi.

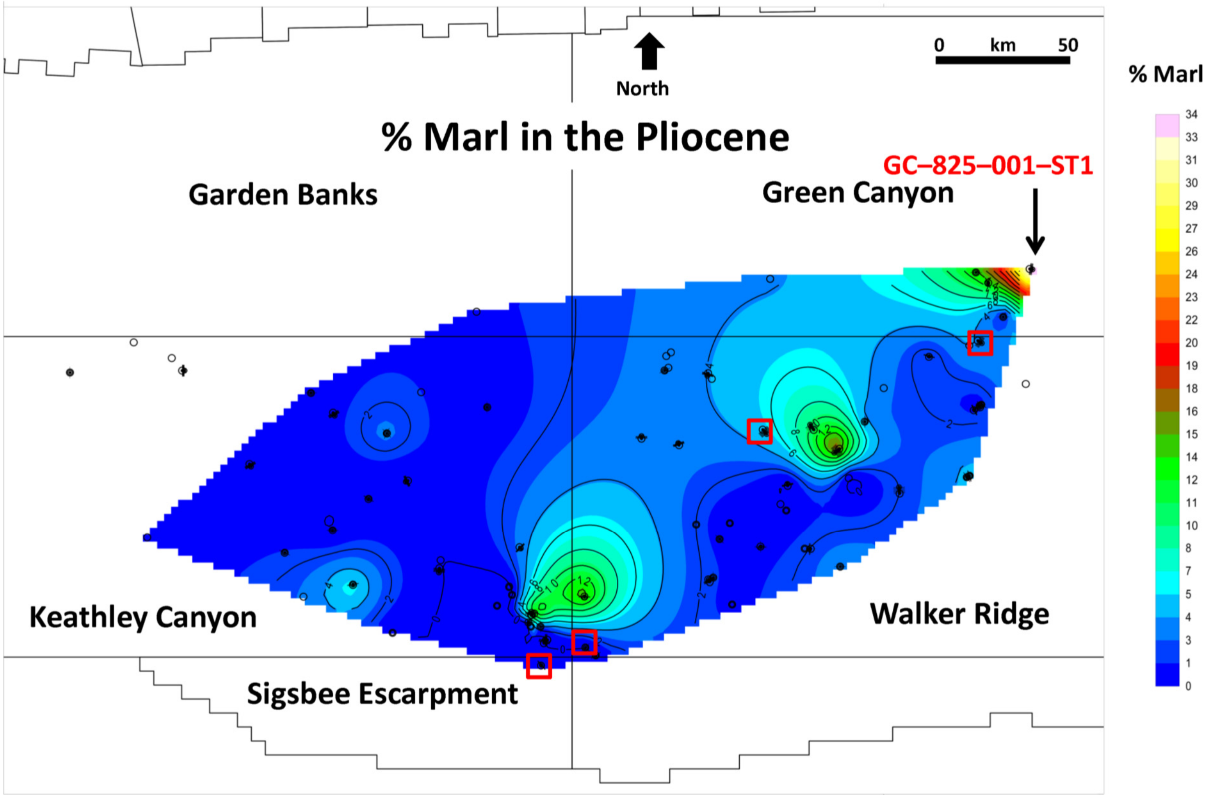


Figure 12. Volume fraction of marl deposited during the Pliocene. The main depocenter for Pliocene marl is in the northeast corner of the study area, near well GC–825–001–ST1. Four wells contain traces of Pliocene limestone are indicated by the red rectangles. 50 km = ~31 mi.

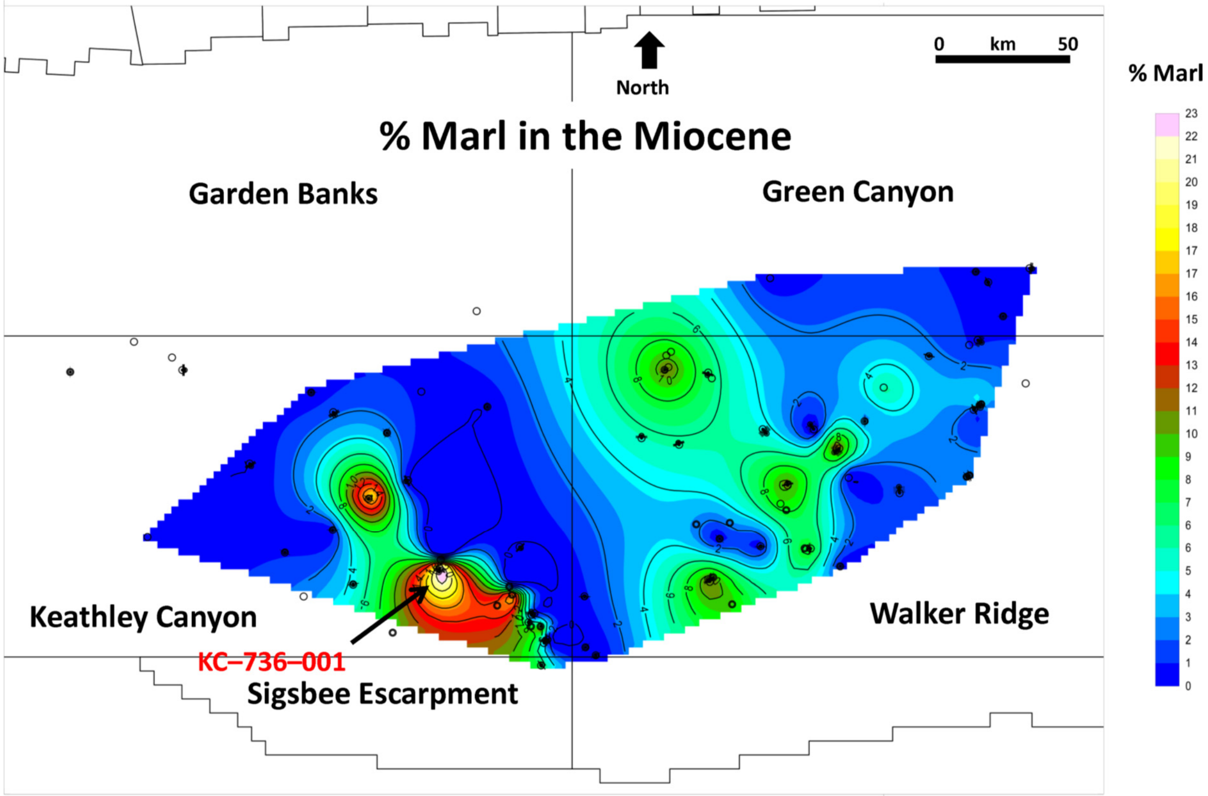


Figure 13. Volume fraction of marl deposited during the Miocene. The main depocenter is located around the KC–736–001 well in southeastern Keathley Canyon. 50 km = ~31 mi.

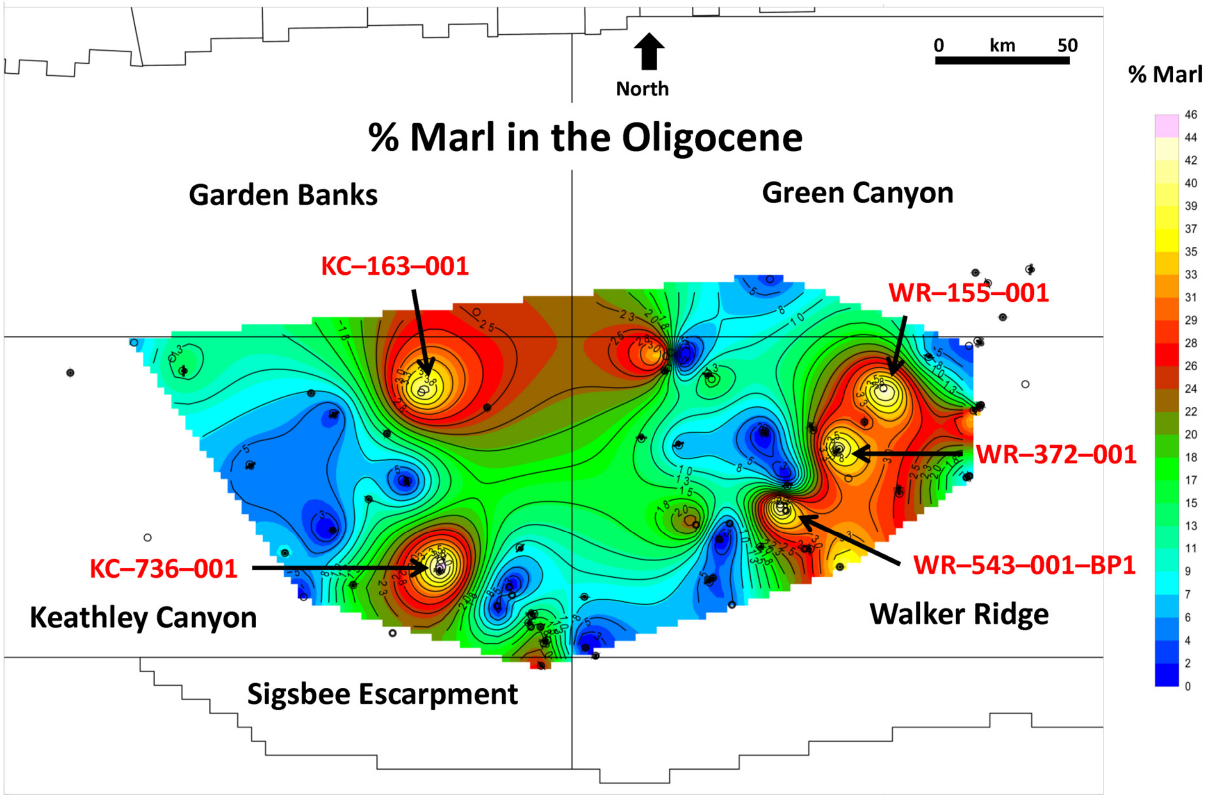


Figure 14. Volume fraction of marl deposited during the Oligocene. Depocenters are located in Walker Ridge and Keathley Canyon. There are five primary depocenters in the study area: two in Keathley Canyon and three in Walker Ridge. 50 km = ~31 mi.

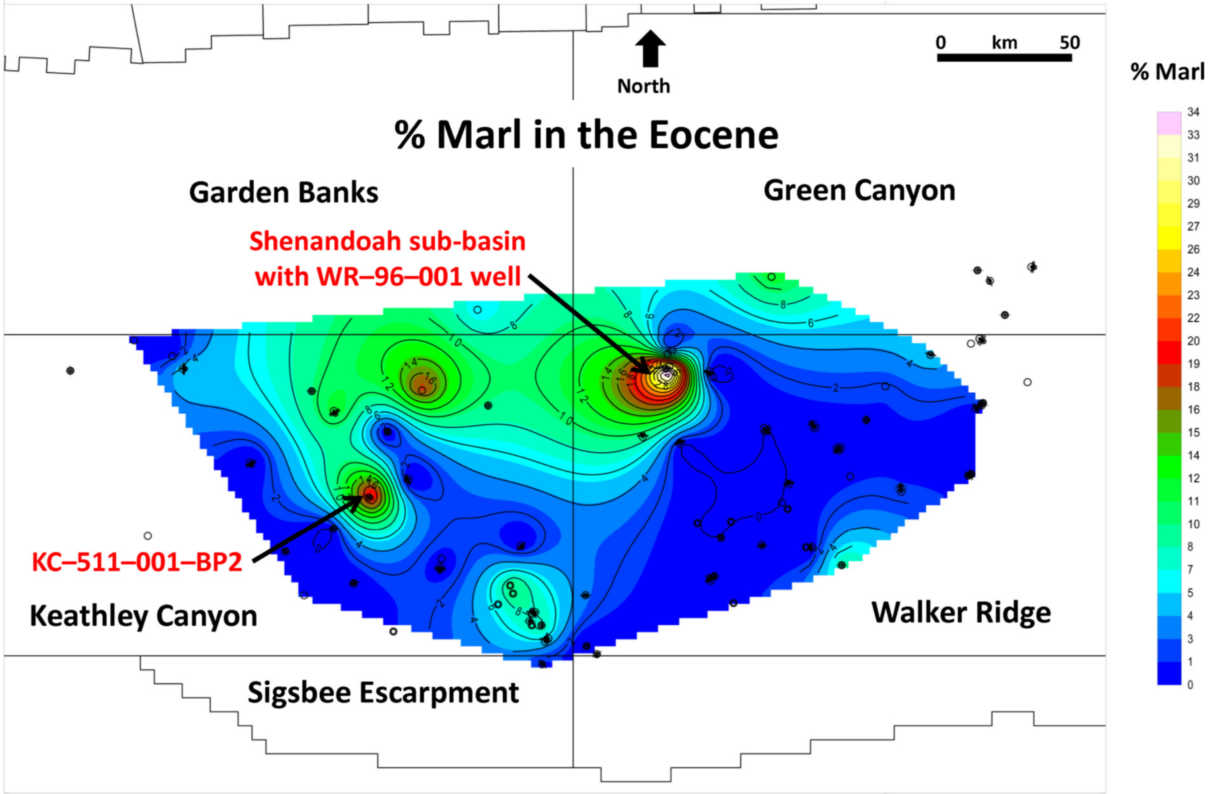


Figure 15. Volume fraction of marl deposited during the Eocene. The primary depocenter is located in Shenandoah sub-basin in Walker Ridge with a secondary depocenter is located in Keathley Canyon. 50 km = ~31 mi.

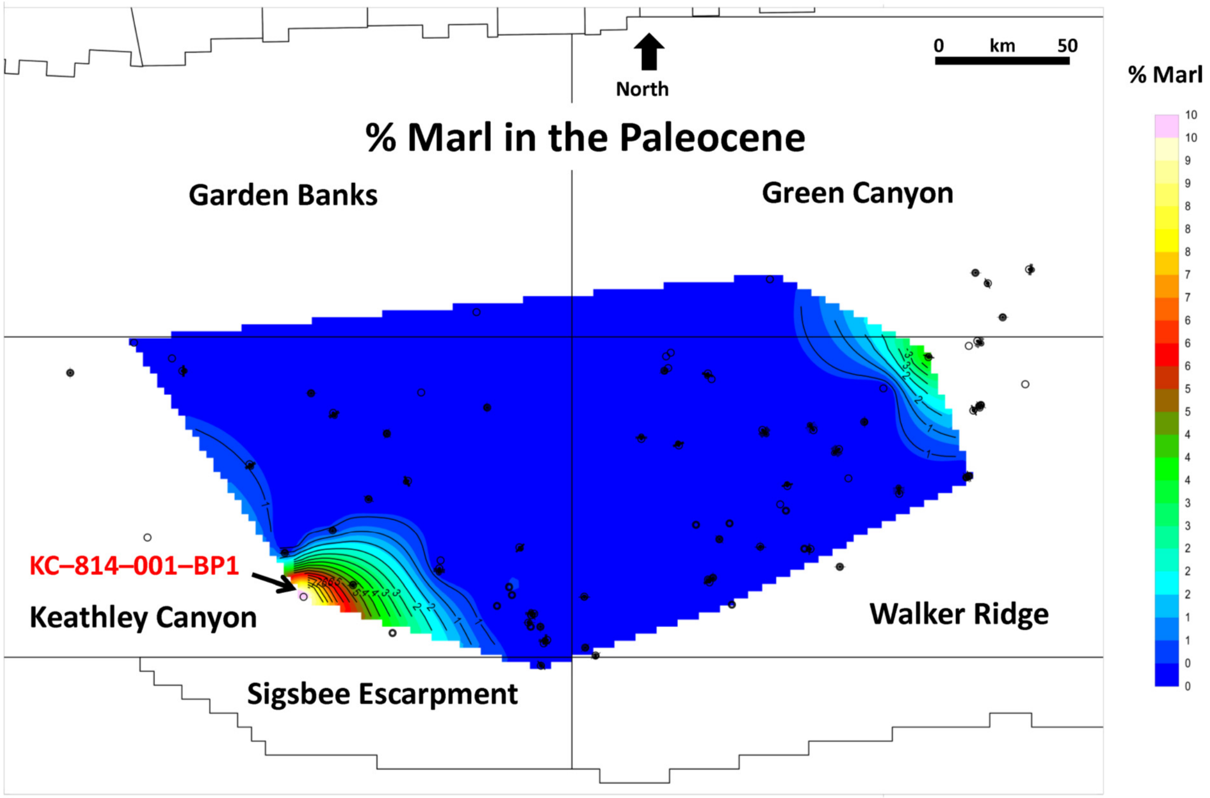


Figure 16. Volume fraction of marl deposited during the Paleocene. The KC–814–001–BP1 well located in the south-central part of Keathley Canyon is the only significant depocenter. 50 km = ~31 mi.

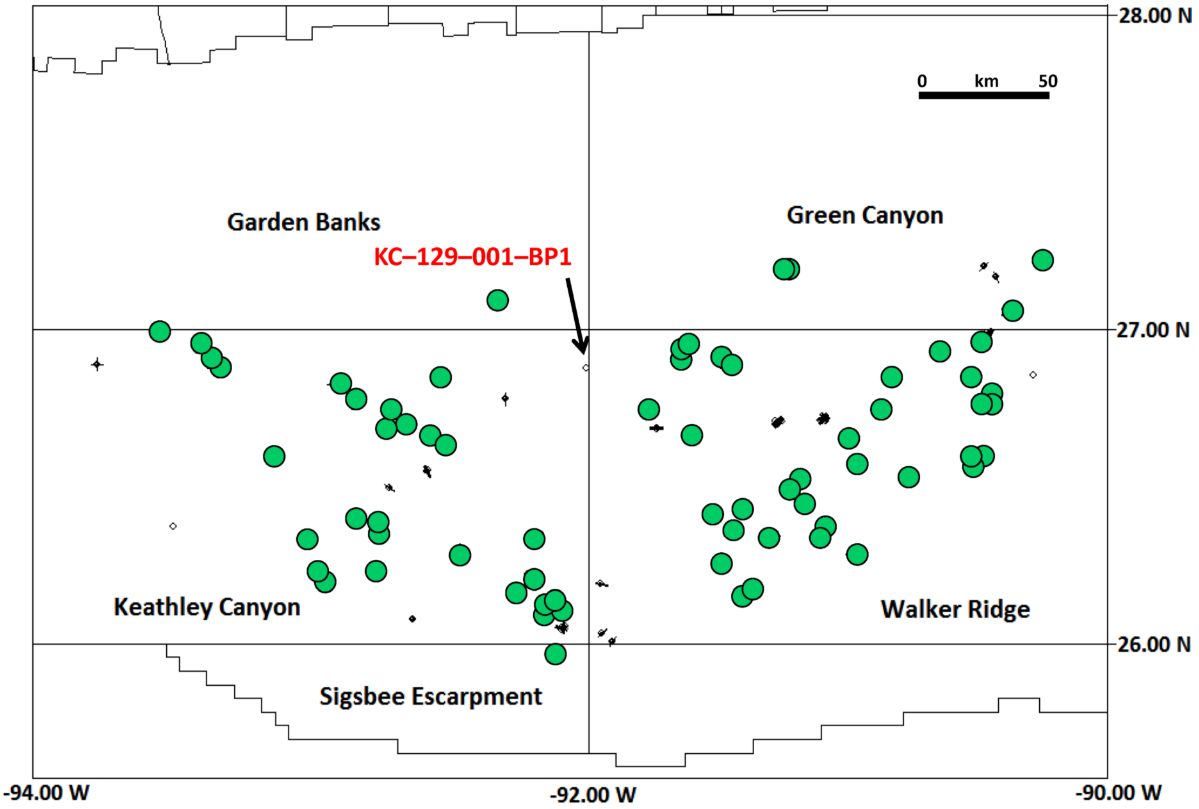


Figure 17. Location of the 66 wells in the study area with Cenozoic marl indicated in the mudlogs. 50 km = ~31 mi.

Paleocene Marl

There is almost no marl found in wells in the Paleocene Epoch (Fig. 16). The highest volume fraction of marl is found in the KC–814–001–BP1 well, close to southwestern corner of the study area, where it is only about 10%.

Marl Distribution in the Study Area throughout the Cenozoic

A map showing the 66 wells that contain Cenozoic marl (of all epochs) is displayed in Figure 17. Again, a pattern similar to the limestone distribution occurs (Fig. 10). Some of the wells without marl are the same as those without limestone. Four wells in Green Canyon contain marl while only one contains limestone, but since Green Canyon is closer to the source of clastic sedimentation, it is likely that silt or clay mixed with carbonate as the sediment was deposited, depositing marl rather than limestone. Six of the newly added wells to the database have Cenozoic marl indicated in their mudlogs; but these new wells have not yet been analyzed for volume fraction content.

SALT ISOCHORE OF STUDY AREA USING DATA FROM 93 WELLS

There are fourteen wells in the study area that do not contain salt. Most are on the eastern edge in front of the Sigsbee Escarpment; but others are scattered throughout the study area. The westernmost well with no salt is KC–627–001 and the easternmost well with no salt is WR–165–001. Figure 18 is an isochore map of salt thickness.

DISCUSSION

This study is a preliminary look at lithologic data in the deepwater Gulf of Mexico with conclusions drawn on readily obvious observations. The sheer volume of data and the paucity of wells mean that it will take time to understand the subtle lithology variations of the Cenozoic epochs. Determining biostratigraphic age boundaries is not always precise, because fossils usually have overlapping age ranges. Another possible source of error was caused by the large volume of shale in the deepwater study area, so picking a maximum flooding surface (MFS) on well logs was not always definitive, although it is not expected to vary more than a few hundred feet within the borehole.

There is variability in the interpretation by different mudlogging contractors such as differences in the details of the rock descriptions and differences in the frequency of the samples described. Some mudlogs have descriptions every 30 ft (~9.1 m) while some only have descriptions every 100 ft (~30 m). Mudlogs are generated on a round-the-clock basis while drilling, so there will be subtle differences in the descriptions as mudloggers change shifts. Overall, we found the quality of mudlog data to be quite good and reliable as we assembled regional maps of the lithology distribution. Regarding anomalous values, it is difficult to distinguish between geological outliers and errors in rock descriptions because deepwater lithology can change very quickly over short lateral distances, as observed with sidetrack and bypass wells.

The calculated volume fractions for the limestone and marl lithologies are summarized in Figure 19. More marl than limestone was deposited in all epochs except Oligocene and the Paleocene. The Oligocene Epoch was a period of transgression, or rising sea level generating a highstand in the study area, with limited sand and siltstone deposition. In the Paleocene sand deposition averaged twice that of siltstone, so there were fewer silt and clay particles in the water column to form marl with the available amount of $CaCO_3$ in the water.

Table 2 lists the specific boreholes used within a specified area block (mentioned in this paper) with their American Petroleum Institute–Unique Well Identifier (API–UWI) numbers.

CONCLUSIONS

The authors feel comfortable with the epochal boundaries selected in each well; and the literature that supports our interpretation for the volume fractions of sand, shale, and siltstone in Part 1 (Cornelius and Emmet, 2018, this volume) lend credence to the contour maps derived here in Part 2 (this paper) for limestone and marl. The contour maps show an inverse relationship between marl and limestone, although both are commonly found side-by-side at the same depth in many boreholes. This usually means the issue is a matter of ratio or proportion of the two carbonate constituents, e.g., 90% limestone with 10% marl, 90% marl and 10% limestone. There are only ten wells with roughly the same proportion of limestone and marl for any Cenozoic epoch, i.e. it is a rare event.

Some workers in the Gulf of Mexico assume that all limestone found in boreholes was Cretaceous. This study demonstrates the existence of limestone in Cenozoic strata in the deep water areas of Keathley Canyon and Walker Ridge. Only two wells (WR–969–001 and KC–774–001) are indicated to have salt-rafted Cretaceous-age limestone that is out of chronological sequence in the borehole. Seven other instances of salt-rafting exist (the six wells in Lucius and Hadrian South Fields plus the KC–470–001 well from Part 1 [Cornelius and Emmet, 2018, this volume]); but the sediments involved are most likely Cenozoic in age, including the limestone. There is a possible eighth instance of rafted sediments in the KC–596–001 well. There are six wells that penetrate Cretaceous limestone (or marl) at the bottom of the borehole; but these instances do not affect the study results that demonstrate 65 wells contain Cenozoic limestone.

ACKNOWLEDGMENTS

We wish to thank Dr. Walter Wornardt of Micro-Strat, Inc. for checking some of the paleontological boundary decisions, Dr. Peter Vail of Rice University for teaching us sequence stratigraphy as grad students in the late 1980s, and to IHS Markit for suggestions on how best to utilize their software application (Kingdom 2017).

REFERENCES CITED

Anonymous, 2007, Deep-water Gulf of Mexico: GEO ExPro, v. 4, no. 1, <https://www.geoexpro.com/articles/2007/01/deep-water-gulf-of-mexico> Last accessed August 21, 2018.

Bice, K., 2006, Warmer than a hot tub: Atlantic Ocean temperatures much higher in the past, <https://phys.org/news/2006-02-warmer-hot-tub-atlantic-ocean.html> Last accessed August 27, 2018.

Bureau of Safety and Environmental Enforcement (BSSE), 2018, <https://www.bsee.gov/> Last accessed August 27, 2018.

Cornelius, S., and P. A. Emmet, 2018, Volume fractions of lithologic units deposited per geologic epoch in the Cenozoic, Keathley Canyon and Walker Ridge, deepwater Gulf of Mexico: Part 1—Sand, shale, and siltstone: Gulf Coast Association of Geological Societies Journal, v. 7, p. 121–150, <http://gcags.org/Journal/2018.GCAGS.Journal/2018.GCAGS.Journal.v7.08.p121-150.Cornelius.and.Emmet.Part1.pdf>.

Fiduk, J. C., V. Robertson, M. Clippard, G. A. Jamieson, and S. Power, 2016, Extensional salt keels detached on the Eocene-Oligocene sediments in the deepwater northern Gulf of Mexico: Insights into canopy advancement, salt-sediment interplay, and evidence for unrecognized mass sediment displacement: Gulf Coast Association of Geological Societies Journal, v. 5, p. 47-63, <http://gcags.org/Journal/2016.GCAGS.Journal/2016.GCAGS.Journal.v5.03.p47-63.Fiduk.et.al.pdf> Last accessed August 21, 2018.

Galloway, W. E., P. Ganey-Curry, X. Li, and R. T. Buffler, 2000, Cenozoic depositional history of the Gulf of Mexico Basin: American Association of Petroleum Geologists Bulletin, v. 84,

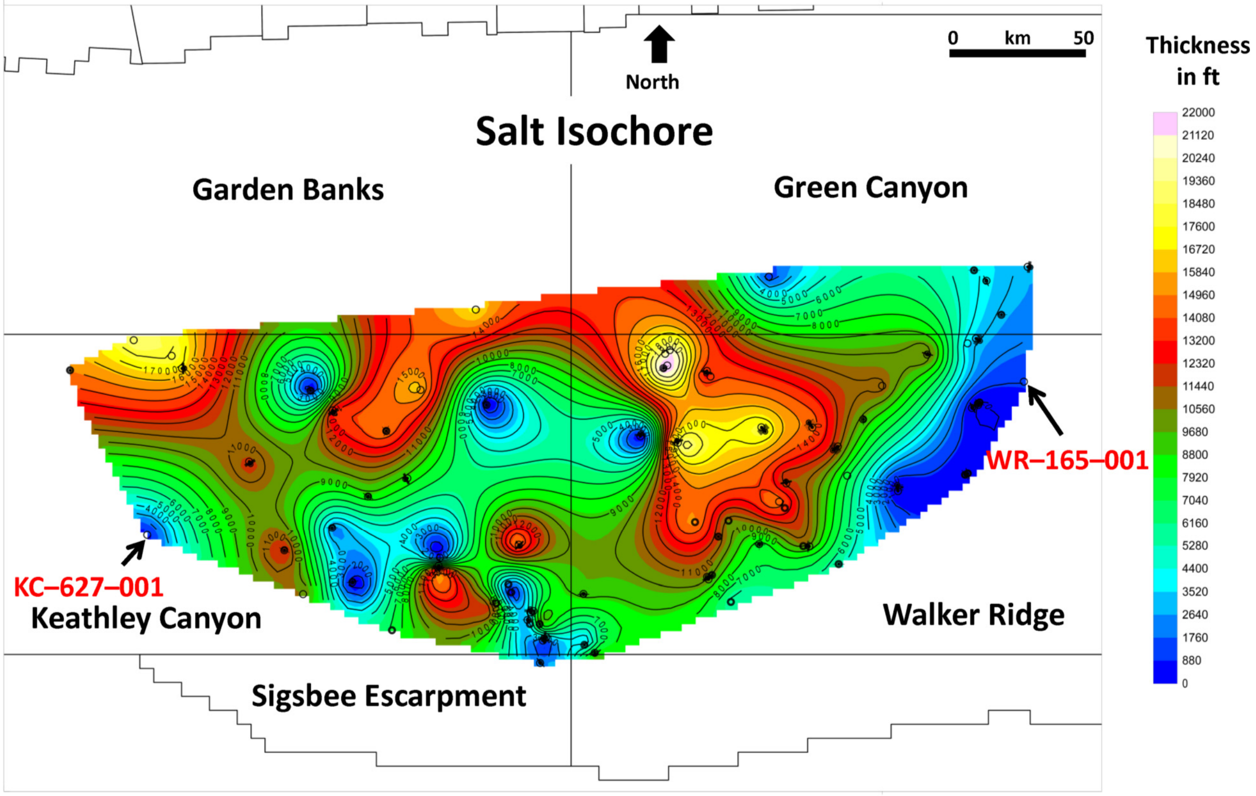


Figure 18. Salt isochore (vertical thickness) map within study area with data from 93 wells.

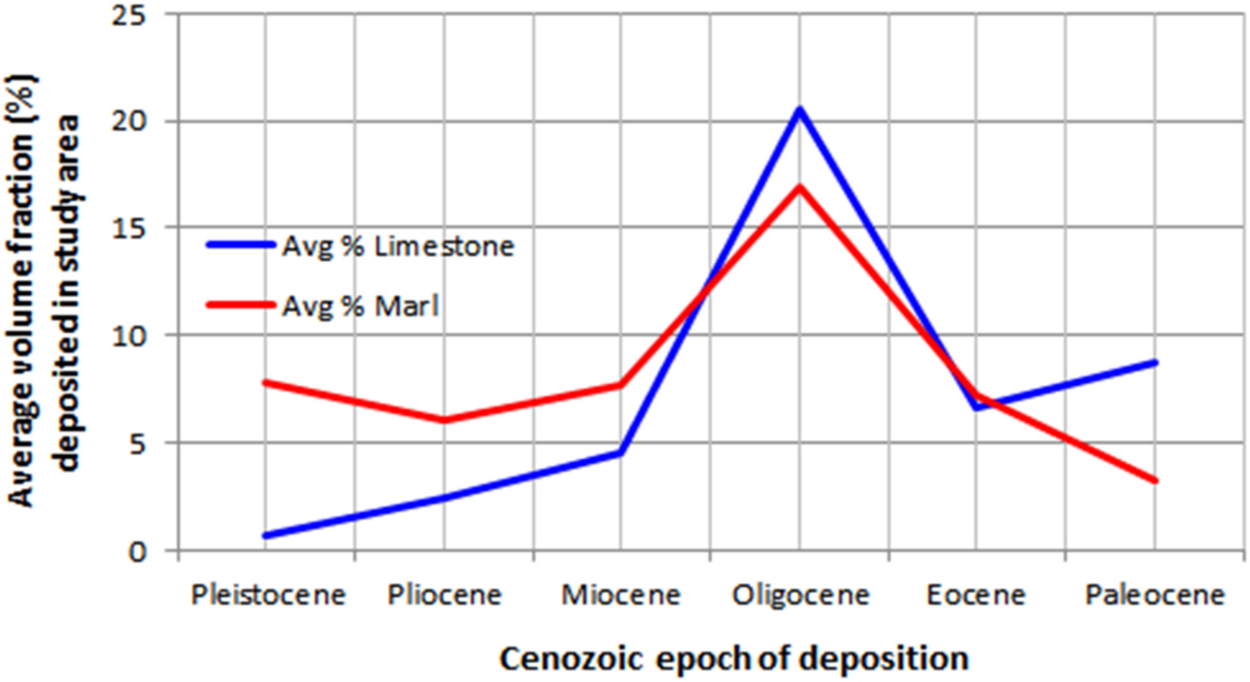


Figure 19. Graphic display of the average volume fractions (%) for limestone and marl deposited within the study area over the six Cenozoic epochs. The Paleocene and Oligocene epochs were times of high limestone deposition, suggesting a lower clastic input from North America.

p. 1743–1774, doi:10.1306/8626C37F-173B-11D7-8645000102C1865D.

Haq, B. U., J. Hardenbol, and P. R. Vail, 1987, Chronology of fluctuating sea levels since the Triassic: Science v. 235, p. 1156–1167, doi:10.1126/science.235.4793.1156.

Lankford-Bravo, D., M. Nawaz Bugti, S. L. Cornelius, and P. Mann, 2016, Documentation of isolated lenses of high-velocity, Eocene to Miocene limestone within clastic rocks above and below allochthonous salt bodies, north-central Gulf of Mexico: Gulf Coast Association of Geological Societies Transactions, v. 66, p. 995.

Munnecke, A., and H. Westphal, 1996, Precursor mineralogy of limestone-marl alternations, <www.pal.uni-erlangen.de/am/lma>, Accessed December 27, 2017.

Mutti, M., 2000, Chapter 14: Microbial origin of microcrystalline carbonate sediment and cements filling fractures in basalts recovered at site 1001, Caribbean Sea: Proceedings of the Ocean Drilling Program, Scientific Results, v. 165, p. 227–232, <http://www-odp.tamu.edu/publications/165_SR/VOLUME/CHAPTERS/SR165_14.PDF> Last accessed August 27, 2018.

Pilcher, R. S., B. Kilsdonk, and J. Trude, 2011, Primary basins and their boundaries in the deep-water northern Gulf of Mexico: Origin, trap styles, and petroleum system implications: American Association of Petroleum Geologists Bulletin, v. 95, p. 219–240, doi:10.1306/06301010004.

Thurman, H., and A. Trujillo, 2004, Introductory oceanography, 10th ed.: Prentice Hall, Upper Saddle River, New Jersey, 624 p.

Witrock, R. B., 2017, Biostratigraphic chart of the Gulf of Mexico offshore region, Jurassic to Quaternary: Bureau of Ocean Energy Management, New Orleans, Louisiana, 1 chart, <https://www.data.boem.gov/Paleo/Files/biochart.pdf> Last accessed August 27, 2018.

Table 2. Wells mentioned in the text with their API–UWI designations.

Well name	API–UWI
GC–825–001–ST1	608114043501
KC–102–001	608084001500
KC–129–001–BP1	608084005701
KC–163–001	608084003500
KC–511–001–BP2	608084000402
KC–736–001	608084002200
KC–785–001	608084002100
KC–814–001–BP1	608084004901
WR–155–001	608124002801
WR–165–001	608124000100
WR–249–001	608124003600
WR–278–001	608124002500
WR–372–001	608124003000
WR–469–001–CH3	608124001000
WR–508–003–BP2	608124003202
WR–543–001–BP1	608124004501
WR–627–001	608124002400
WR–627–001	608124002400
WR–674–001	608124008000
WR–96–001	608124009101
WR–969–001	608124004800