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The trouble with the curve: Reevaluating the Gulf of Mexico sea-level curve

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1. Introduction

Over the last 20,000 years, approximately 15–20 million km^2 of coastal landscape has been submerged worldwide, roughly the area of South America (Faure et al., 2002). Sea-level rise explains the relative rarity of coastal archaeological sites dating to the last glacial period, creating gaps in the history of human activity around the world. Accurately reconstructing sea-level rise since the Last Glacial Maximum (LGM) has challenged researchers for decades (Curray, 1960; Fairbanks, 1989; Lambeck et al., 2014; Pirazzoli, 1996). Identifying the location of shorelines throughout the terminal Pleistocene/Holocene transgression is vital for archaeologists studying the occupation and use of coastal regions now-drowned on the continental shelf of North America (Anderson and Bissett, 2015; Erlandson et al., 2011; Faught, 2002; Bradley and Stanford, 2004). The Gulf of Mexico's gently sloping continental shelf causes extreme coastline changes on the order of 10s of km with minor vertical shifts in sea-level, which has preserved portions of the landscape from the destruction caused by sea-level transgression (Anuskiewicz, 1988; Duggins et al., 2018; Faught, 2002, 2004; Faught and Donoghue, 1997). The increase in interest in the distribution of submerged archaeological sites on the continental shelf requires an accurate estimate of the elevation of the shoreline through time.

The Balsillie and Donoghue (2004) sea-level curve (hereafter B&D curve) has been the standard model for sea-level transgression in the Gulf of Mexico for over a decade. Their sea-level curve is utilized by researchers from a wide range of disciplines (Anderson and Bissett, 2015; Osterman et al., 2009; Paine et al., 2012; Shennan et al., 2015), despite differing from other Gulf of Mexico and global curves by 10s of meters (Bard et al., 1990; Fairbanks, 1989; Lambeck et al., 2014; Toscano and Macintyre, 2003).

Balsillie and Donoghue (2004) set out to comprehensively engage the compilation of irregular sea-level datasets to produce an accurate, local sea-level curve for the Gulf of Mexico. Local sea-level curves are necessary to reconstruct submerged landscapes due to regional isostatic rebound and changes in elevation due to tectonic and sediment loading processes since the LGM. These changes can dramatically alter land elevations by 10s of meters, impacting local sea-level as the land subsides or uplifts. Surficial paleo-hydrology systems can also change water table levels, affecting the availability of surface water inland. Balsillie and Donoghue (2004) used Pirazzoli (1996) as a guide to construct their curve and the Siddall et al. (2003) eustatic sea-level curve, which was developed from Red Sea proxy data, as a benchmark to compare their results. Yet when compared to the Siddall et al. (2003) model, ocean levels differ significantly, and seldom do the two curves correspond despite the tectonic stability of the Red Sea region (0.044 ± 0.022 m per 1000 years). The B&D curve differs from other local Gulf of Mexico and eustatic datasets by up to 25 m (see Fig. 1).

The accuracy of the B&D (2004) curve is limited by the nature of the sampling protocol, editing techniques, and the curve construction methods. Their curve relied on radiocarbon dating of proxy data collected from both secure and problematic samples from unsecured stratigraphic contexts. Compounding the issues with the dataset are the changes in standards for radiocarbon dating and sampling methodologies in the four decades that the proxy data were collected. Many of the samples were dated before AMS ^{14}C dating was available, and batch sampling was frequently required to obtain enough carbon to conduct the dating.

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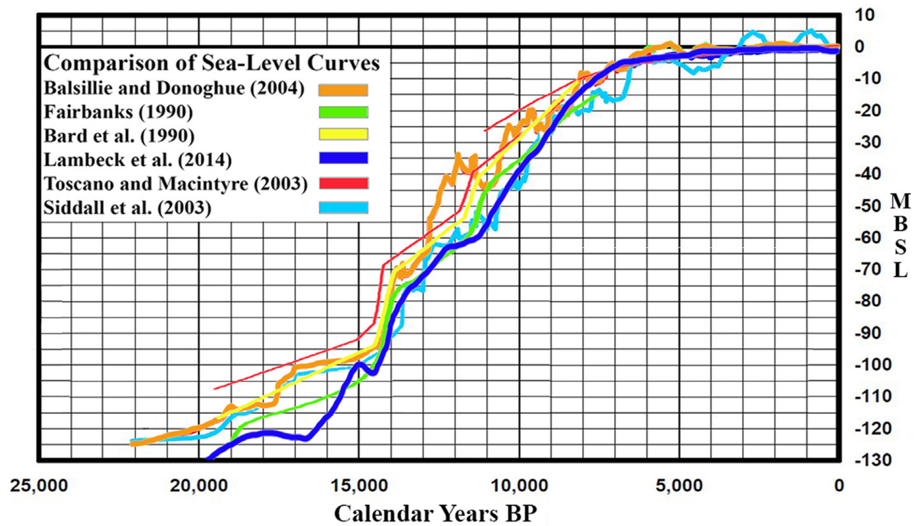

Fig. 1. A comparison of both eustatic and local sea-level curves to Balsillie and Donoghue (2004).

This research addresses issues with sampling, dating, and analyzing sea-level proxy data and introduces new data and methodologies to improve the accuracy of the Gulf of Mexico sea-level curve with a focus on the peninsula of Florida. This research presents improved editing methods that reduce the number of outliers in the dataset and considers the environment (marine, brackish, terrestrial) and the indicative range of the dated sea-level indicators on separate trendlines. The 2019 Gulf of Mexico sea-level curve presented here is based on 654 samples collated from 32 publications spanning five decades of marine biological and sea-level research. The 2019 curve uses both linear regression and an age/depth Bayesian modeling program called Bchron (Parnell and Roland Gehrels, 2015) on 290 core samples of elkhorn coral (*Acropora palmata*). The resulting curve delineates paleo-coastlines within ± 5 m of their elevation compared to the B&D curve's ± 37.5 m envelope. Utilizing the new editing methods decreases the chances of including problematic samples in the Balsillie and Donoghue (2004) dataset. By using a 10 m envelope of acceptance instead of a 75 m envelope, the 2019 Gulf of Mexico curve vastly improves estimates of the elevation of the transgressing post-glacial coastline through time.

2. The Balsillie and Donoghue curve

Before Balsillie and Donoghue (2004), a comprehensive Gulf of Mexico sea-level curve had not been created, due in part to the contradictory datasets produced by several researchers spanning four decades (Curray, 1960; Fairbridge, 1974, 1989; Stapor and Stone, 2004). Balsillie and Donoghue (2004) postulated that the relative tectonic stability of the northern Gulf would provide them with the ability to combine sea-level datasets collected throughout the region to reconstruct regional and global (eustatic) post-glacial sea-level rise. They collected datasets from 23 researchers spanning over four decades of research. The radiocarbon dates were corrected using CALIB (Rev 4.4.2) (Stuiver et al., 1998), correcting terrestrial and freshwater samples using IntCal98 and marine samples with Marine98 (Stuiver et al., 1998). The samples were then scatter-plotted on an X,Y graph, and a single trendline was applied to represent the transgression event (Pirazzoli, 1996). They devised three data editing procedures (one geological, the other two statistical) to combine the different contradictory datasets by reducing the number of equivocal sea-level proxy data samples. The geological editing method excluded samples from locations subject to rapid rates of tectonic and sediment loading subsidence (e.g., the Mississippi Delta) (Yuill et al., 2009). The statistical methods involved using a 75 m acceptance envelope in which any data points that fell outside were considered outliers. The second statistical method utilized a seven-point floating average that creates a series of averages from the earliest seven data points, then averages the series with every data point within the collection to reduce the "noise" within the curve. Balsillie and Donoghue (2004) started with 353 data points from the Gulf of Mexico region while comparing 134 data points from New Guinea, Tahiti, and the Red Sea curves as a benchmark for their dataset (Balsillie and Donoghue, 2004). Twelve data points were identified as outliers and removed from their curve, resulting in 341 sea-level indicators to construct the curve.

Balsillie and Donoghue (2004) had a primary research goal to develop editing methods designed to identify spurious samples and remove them from the dataset. Balsillie and Donoghue state that, "While there is error associated with the ^{14}C age dating methodology, the bulk of error is undoubtedly associated with the indicator material chosen to represent sea-level elevation" (Balsillie and Donoghue, 2004:ix). They understood the nature of the level of error associated with sea-level proxy data, yet they fell short of devising methods to deal with these issues. The editing methods that they did employ were successful in identifying only 12 spurious data points. Utilizing a statistical envelope of 75 m allowed spurious samples to remain in the data collection, vastly affecting the trendline within the 75 m envelope. A difference of 75 m in sea-level rise along Florida's low gradient (0.2–4.0 m per km) western continental shelf would render the curve ineffective for locating paleo-shorelines.

The floating average method has been used to reduce the level of noise in other sea-level curves (e.g., Pirazzoli, 1996). This method reduces the degree of variability likely associated with sampling and dating errors while permitting longer-term trends to remain. However, plotting all of the samples on a single trendline was the true source of the noise, because it disregards the environments the samples represent. For example, samples from terrestrial environments must predate the transgression event but have the same influence on the trendline as samples from post-transgression environments. Plotting the data without considering the sample's environment can affect the inferred shoreline location. In other words, terrestrial wood and marine coral samples with the same date, which grew in different environments and at potentially dramatically different elevations relative to sea-level, will influence the trendline in opposite directions for the same time. This may have been the cause of the "noise" reported by Balsillie and Donoghue (2004).

The several discrepancies with both the editing of the dataset and the methods of constructing their sea-level curve resulting in significant inconsistencies between the B&D curve and local and eustatic curves not associated with local geological factors. The Siddall et al. (2003)

curve differ by 20 m from the B&D curve and seldom do both curves correspond. When the B&D curve is compared to the more recent (Lambeck et al., 2014) eustatic curve, the depths differ between the two models by 23 m. When compared to more local datasets, Toscano and Macintyre (2003) differ by 15 m. Bard et al. (1990) and Fairbanks (1990) Uranium Thorium (U–Th) curve differs by 20–25 m, respectively (see Fig. 1).

3. Challenges in constructing sea-level curves

Accurately constructing sea-level curves relies on the quality of the proxy data which is collected and analyzed (Pirazzoli, 1996). Including problematic samples into the sea-level dataset, due to faulty sampling methodology or radiocarbon dating, can skew the sea-level curve. The downfall of the B&D curve was not the number of data points, but the quality of the data. The first line of thought while reevaluating the B&D curve was that the radiocarbon samples needed to be recalibrated using the latest radiocarbon calibration curve, IntCal13 and Marine13. Recalibrating the Balsillie and Donoghue (2004) dataset from IntCal98 and Marine98 to IntCal13 and Marine13 required a review of the material originally sampled, and then apply the appropriate radiocarbon calibration. During this process, all publications cited by Balsillie and Donoghue (2004) were scrutinized for sampling, dating, and reported methodologies to ensure that the data used would pass the modern radiocarbon sampling standards. In most cases, the dated sample material was in both Balsillie and Donoghue (2004) and the original research publication. In other cases, the sample material was neither reported in Balsillie and Donoghue (2004) nor the original publication (e.g., Fairbridge, 1961, 1974). During the review, it became apparent that the troubles with the curve were not simply due to inaccuracies associated with previous calibrations, but that of sampling and dating procedures and the insufficient editing of problematic data. Throughout the original publications Balsillie and Donoghue (2004) used to compile their dataset, it was clear that many of the authors had doubts about the validity of their data (Davies, 1980; Kuehn, 1980; Schnable and Goodell, 1968; Schroeder et al., 1995; Shier, 1969). For example, Schnable and Goodell (1968) had noted contamination with their peat samples by younger material, and the oyster samples could have been redeposited (Schnable and Goodell, 1968). Similarly, Davies (1980) was concerned that younger mangrove roots contaminated the peat samples. Kuehn (1980) excluded dates from her research due to an unconformity, as sections of the peat were eroded and then redeposited (Kuehn, 1980). Schroeder et al. (1995) collected weathered and encrusted oyster samples from surface contexts where they could have become redeposited. Shier's (1969) samples did not report the actual radiocarbon dates or errors. Shier assigned an arbitrary standard deviation of 150 years to the dates. The age and depth of samples were approximate from a figure. Additionally, many of the pre-1980 materials were sampled for radiocarbon dating using batch or bulk sampling methods (Behrens, 1966; Curray, 1960; Kuehn, 1980; McFarlan, 1961; Schnable and Goodell, 1968; Scholl and Stuiver, 1967; Shepard, 1960; Spackman et al., 1966). Batch or bulk sampling radiocarbon dates are known to be fraught with contamination leading to inaccurate dates (Mook and Van de Plassche, 1986; Terasmae, 1984).

Balsillie and Donoghue's methods fell short of identifying spurious data within the dataset. Balsillie and Donoghue (2004) included sample within their dataset despite the original authors stating that samples were contaminated or collected from a loose or disturbed context and not used in the original research (Curray, 1960; Davies, 1980; Kuehn, 1980; Schnable and Goodell, 1968; Schroeder et al., 1995).

4. Environmental and dating issues and methods for evaluating sea-level samples in the Gulf of Mexico

Collecting and editing sea-level datasets must take into consideration the inherent issues with the proxy data as they pertain to dating methods and their representative environments. Sea-level proxy data represent past environmental conditions relative to the transgression event. Terrestrial and freshwater samples represent a period before the transgression but do not indicate where the coastline was when the sample was deposited. They indicate the presence of non-marine environments. Brackish samples represent the closest period for the transgression event because those environments are close to the shoreline where saline and freshwater mix. Marine samples represent a time period where the transgression event has already taken place. However, many of these samples do not indicate when the transgression took place due to the habitat depth ranges in which they were deposited. Samples such as elkhorn coral can represent narrow depth ranges, whereas samples such as oysters can represent vast ranges in depth and salinity (Abdul et al., 2016; Barnes et al., 2007). Compounding these issues, marine and brackish sample habitation environments rely on the assumption that ocean and atmospheric conditions were similar in the past as they are to modern conditions. However, levels of temperature and salinity have fluctuated over time, especially in the Gulf of Mexico (Flower and Kennett, 1995).

The construction of sea-level curves relies on inherently vague, and at times problematic, proxy data. Understanding the strengths and weaknesses in the proxy data are imperative to edit sea-level datasets from containing an overwhelming number of spurious data points. These data do represent an environmental condition (terrestrial, brackish, and marine) yet, they do not represent the actual transgression event.

When editing the 2019 dataset, it became apparent that some samples were spurious based on the intrinsic complications in dating and sampling methods, and environmental ranges. In some cases, numerous samples would differ from other samples of the same type by 10s of meters during the same time period. To reduce the influence of inaccuracies associated with the age and habitat range of some sample materials on the sea-level curve, a rating system was developed to rank the quality of coastline indicators (Pirazzoli, 1996). The rating system was used to compare similar samples types with comparable dates, but with varying depths. The rating scale was used to highlight which samples may be problematic and which ones closely represented the transgression event. To determine which data points were outliers, samples that varied in depth by more than 10 m from the surrounding eight samples, four lower and four higher, were removed. The rating system assisted in determining which data points may have been an outlier due to sample methodologies, versus a local sea-level transgression phenomenon or geological processes (see Table 2). Using a tighter 10 m envelope of acceptance and the rating system, 29% of the dataset were considered outliers. Balsillie and Donoghue (2004) original research consisted of a statistical envelope of 75 m in which data were considered viable. Using this method, only 3.5% of the dataset were considered outliers. Balsillie and Donoghue (2004) 75 m envelope allowed spurious samples to remain in the data collection, vastly affecting the trendline. This research strived to tighten the outlier envelope to ± 5 m accuracy by effectively assessing the data for errors associated with sampling methods.

4.1. Elkhorn coral (*Acropora palmata*) and U-Series dating

Coral can be accurately and precisely dated using uranium-series (U-series) disequilibrium methods (Polyak et al., 2016; Rasbury and Cole, 2009; Scholz and Hoffmann, 2008). U-series dating is preferred over radiocarbon dating because it incorporates the calibrations required due to fluctuations in atmospheric and marine ^{14}C (Edwards and Peltier, 1995; Fairbanks, 1990; Pirazzoli, 1996).

Elkhorn coral (*Acropora palmata)* can be outstanding sea-level proxies (Bard et al., 1990; Fairbanks, 1989; Toscano and Macintyre, 2003). In particular, the range of elkhorn coral generally extends to 5 m below surface. Researchers working with sea-level curves have used U-series dating of coral to avoid the inaccuracies associated with radiocarbon dating (Abdul et al., 2016; Bard et al., 1990; Brock et al., 2008; Fairbanks, 1990; Toscano and Macintyre, 2003; Toscano, 2016).

However, using coral for sea-level proxy data has drawbacks. Eroded corals can be washed up or down slope and redeposited at different levels relative to their growth location. Here, coral samples recovered in secure stratigraphic context and had undergone U-series dating are considered more trustworthy than samples dated by radiocarbon.

Overall, elkhorn coral is an excellent sea-level proxy. Its habitat range of water depths no deeper than of 5 m, its capacity to be U-series dated, and the ability to determine the possibility of redeposition make it an outstanding proxy. Therefore, U-series dated corals received a rating of 5, and radiocarbon samples a rating of 4 due to the shortcoming of radiocarbon calibration curves.

4.2. Wood and charcoal samples

Dating of charcoal or large pieces of wood can potentially introduce significant error due to the “old wood paradox” (Blong and Gillespie, 1978; Törnqvist et al., 1992). The old wood paradox pertains to samples of charcoal or wood that have been alive for hundreds to thousands of years before the event being dated. Additionally, wood that may have been preserved underwater for hundreds of years may have been eroded and redeposited in a younger stratigraphic unit. Those samples will not accurately date the transgression.

4.3. Peat and mangrove samples

Contamination can occur in peat deposits, especially in mangrove peats. Roots from living mangroves can grow into older peats and contaminate the deposit with younger material (Davies, 1980). Peat deposits are also subject to compaction as the weight of overlying sediments increases with accumulation, thereby skewing the actual elevation of deposition (Otvos, 2004).

Samples of wood and peats were given a mid-range rating due to the “old wood problem” (Olsen et al., 2013; Talma and Vogel, 1993; Törnqvist et al., 1992), and contamination and compaction, respectively (Davies, 1980; Mook and Van de Plassche, 1986; Otvos, 2004). Contamination from younger materials and compaction can also occur during the formation of peat and mangroves (Mook and Van de Plassche, 1986; Turetsky et al., 2004). Freshwater peats and wood samples represent a time before the transgression, and mangroves represent a period just before the transgression. Peat and wood samples received a score of 3 and scrutinized for contamination and redeposition.

4.4. Eastern oyster (Crassostrea virginica) and shellfish samples

The B&D data contained 36 oyster samples, with roughly half of those samples dating between 16,000 and 10,700 cal BP. Eastern oyster is a problematic proxy for paleo-brackish conditions and paleo-shorelines because of its tolerance for a wide range of salinity and water depth. Oyster can grow kilometers up rivers and at depths greater than 30 m (Barnes et al., 2007). The species' survival is limited only by salinity and the availability of suitable substrate. Adult oysters can tolerate salinities ranging from 0 to 42.5 parts per thousand (ppt), with normal distribution occurring between 5 and 40 ppt (Lorio and Petrone, 1994). The optimum salinity for growth and reproduction is between 10 and 28 ppt (Barnes et al., 2007). Larvae will not metamorphose into spat when salinity is less than 6 ppt (Wilson, 1975), and adult oyster can endure indefinitely in salinities up to 35 ppt (Buroker, 1983). Under modern conditions in Florida, oyster has been found up to 14 km inland and 7 km offshore (Florida Fish and Wildlife Conservation Commission 2017). Given the proper substrate to which they could attach, oysters could have populated regions hundreds of kilometers from the shoreline between 16,000 and 10,700 cal BP when salinity in the Gulf was much lower than modern levels (Flower and Kennett, 1995). This wide habitable zone makes using oyster an imprecise proxy for shoreline location in modern conditions, but it is a much less precise proxy for terminal Pleistocene shorelines when influxes of glacial meltwater into the Gulf significantly changed both temperature and salinity ranges (Flower and Kennett, 1995).

Flower and Kennett. (1995) study of the planktonic foraminifera *Globigerinoides ruber* from Orca Basin cores (EN32-PC4 and EN32-PC6) gives a detailed look into the temperature and salinity changes during the last deglaciation. Flower and Kennett. (1995) cores were taken 290 km south of the Mississippi delta near the edge of the continental shelf. *G. ruber* can survive in lower salinity sea-water more successfully than other planktonic species, and changes in the relative proportion of plankton indicate changes in the extent of salinity (Bijma et al., 1990). At 16,000 cal BP, warm-water foraminifera become more prevalent, which replaced cold-water plankton species in response to deglaciation (Flower and Kennett, 1995). *G. ruber* were ubiquitous in the Gulf of Mexico, reflecting the low-salinity conditions during the meltwater influx from 16,000 to 10,700 cal BP. Thus, oyster could have lived upwards of 100 km offshore and to depths of 30 m during this time.

The Schroeder et al. (1995) oyster samples may represent this phenomenon. Their data indicate that sea-levels increased only 9 m (−40 to −31 m) between 18,000 and 10,200 cal BP. During the same period, Lambeck et al. (2014) eustatic sea-level increased by 75 m, Siddall et al. (2003) by 72 m, and Balsillie and Donoghue (2004) by 87 m. Shepard (1960) data also includes samples of oyster that date to the same age, yet differ in depth by over 20 m **(see** Table 1).

Other problematic shellfish, including coquina (*Donax variabilis*), have been used as coastline proxies. Milliken et al. (2008) used 30 samples of coquina clams to construct their Holocene sea-level curve for the northern Gulf of Mexico. Coquina are a small species of clam, generally less than 2.5 cm in length, which inhabit sandy beaches. Within the Gulf, coquina range from Texas to Florida and are adapted to live within the wash zone as the tides ebb and flow across beaches (Ruppert and Fox, 1988). However, coquina can quickly burrow up to 11 m into the sand to avoid being swept away by waves (Rosenberg, 1993). The species is also a preferred prey for sea birds, which along with their small size increases the likelihood that coquina may become redeposited further inland or offshore.

Paleo-oyster samples should be considered a poor coastline indicator and sea-level proxy data due to fluctuating salinity in the Gulf of Mexico, as well as the vast ranges of habitats. In editing the 2019 dataset, 76% of the samples of oyster (n = 41) were outliers. These samples represent a period as the landscape was being transgressed to well after the transgression event had taken place. Samples of shellfish, including eastern oyster, received a rating of 2 due to their range in habitat, the likelihood of redeposition, and uncertainty involved in radiocarbon calibration.

4.5. Bulk samples and radiocarbon dating

Before the advent of AMS dating, some radiocarbon samples

Table 1
Habitat range of eastern oyster within the dataset.

	Location	Material	Cal BP	Sigma	MBSL
Schroeder et al.	NE Gulf Coast	Oyster	10,200	110	−31
Schroeder et al.	NE Gulf Coast	Oyster	10,535	147	−30
Schroeder et al.	NE Gulf Coast	Oyster	11,083	164	−35
Schroeder et al.	NE Gulf Coast	Oyster	11,376	220	−33.5
Schroeder et al.	NE Gulf Coast	Oyster	12,261	235	−40
Schroeder et al.	NE Gulf Coast	Oyster	12,330	182	−40
Schroeder et al.	NE Gulf Coast	Oyster	18,048	122	−40
Shepard, 1960	Texas	Oyster	10,167	384	−22.8
Shepard, 1960	Texas	Oyster	10,232	330	−41

Table 2
Sample Rating System.
Samples that received a rating of 5 were considered excellent. Samples given a rating of 4 may suffer from inaccuracies from reservoir effects. Samples that were rated 3 may be stratigraphically secure but may experience contamination from younger or older carbon. A rating of 2 was assigned to samples that may have been eroded and redeposited or were poor environmental indicators. Samples that may have a combination of the conditions above, and/or were underreported by modern standards were assigned a rating of 1.

Rating	Sample Type	Dating Method	Number of Outliers
5	Elkhorn Coral	U/Th	10
4	Elkhorn Coral	Radiocarbon	12
3	Wood, Peats, Mangroves	Radiocarbon	30
2	Shellfish, Foraminifera	Radiocarbon	59
1	Various Material	Batch Radiocarbon	66

consisted of bulk soils or sediments, which increased the likelihood of contamination by younger or older carbon (Törnqvist et al., 1992). Bulk sampling utilized by 10 of the original researchers Balsillie and Donoghue (2004) had used, with a total of 131 bulk samples included in the dataset (Behrens, 1966; Curray, 1960; Fairbridge, 1989; Kuehn, 1980; McFarlan, 1961; Nelson and Bray, 1970; Schnable and Goodell, 1968; Scholl and Stuiver, 1967; Shepard, 1960; Spackman et al., 1966). A “rejuvenation effect” may take place in batch samples where root contamination occurs from above may introduce younger carbon into the sample.

Samples were given a lower score if they were bulk or batch radiocarbon dated rather than U-series and radiocarbon AMS dated. Batch testing increases the chances that samples have been contaminated with younger or older material, yielding an inaccurate date. For this reason, all batch samples from Balsillie and Donoghue (n = 42) were given a rating of 1 for consideration in the 2019 curve.

In sum, none of the types of samples are perfect proxy. However, identifying outliers becomes more apparent by understanding the inherent problems associated with sample types and dating. Additionally, by assigning each sample type to above the shoreline (terrestrial), shoreline (marine peat, shellfish), and below the shoreline (marine submerged), one can better constrain the shoreline location estimate.

5. The 2019 curve methods

The 2019 Gulf of Mexico sea-level curve considered 654 samples from 32 separate publications spanning five decades of marine biological and sea-level research (see Appendix B**)**. This research used samples from tectonically stable sections of the continental shelf, such as Texas (Nelson and Bray, 1970) and Florida (Willett, 2006), where the range of vertical tectonic movement was considered negligible and not factored into sample depth.

Glacial isostatic adjustment (GIA) has had an impact on landform elevations due to the compaction and forebuldge of the lithosphere due to the immense weight of glacial formation during the LGM (Peltier, 2006). The Gulf of Mexico is within a region of forebuldge collapse since the end of the LGM (Mitrovica and Milne, 2002). GIA and geological processes, such as limestone dissolution and sediment loading impact regions of the Gulf differently. Both GIA and limestone dissolution affect the Florida platform elevation. The dissolution of limestone produces an uplift, while the forebuldge collapse created subsidence. Willett (2006) has calculated the GIA and the dissolution of limestone rates since the mid-Quaternary (1.6 million years). Using the results of calculation C from Willett (2006), Florida is uplifting approximately 3.5 cm per 1000 years. Using these calculations, Florida has uplifted 63 cm since 18,000 cal BP (Willett, 2006).

The Louisiana coastal subsidence is a multifaceted process that includes GIA, sediment loading and compaction from the Mississippi Delta, tectonics, and fluid withdraw. The Louisiana coastal subsidence has been calculated to be upwards of 68 mm per year (Yuill et al., 2009) (**See** Table 3). This subsidence was not calculated into the 2019 Gulf of Mexico sea-level curve and must be subtracted from the relative depths.

Table 3
Coastal subsidence rates for coastal Louisiana.

Process	Range of Subsidence Rates	Affected Areas
Tectonic	.1–20.0 mm per year	Coastal Regions, Delta
Holocene Compaction	1–5 mm per year	Holocene Deltas
Sediment Loading	1–8 mm per year	Holocene Deltas
Fluid Withdrawal	Up to 23 mm per year	Coastal Regions
GIA	.6–2.0 mm a year	Gulf of Mexico
Water Management	.1–10.0 mm per year	Developed Wetlands
Totals	**3.8–68 mm per year**	**Coastal Louisiana**

Subsidence rates associated with GIA for the Texas Coast south of Galveston Bay average 0.05 mm per year or less for the last 120,000 years (Paine, 1993). However, the withdrawal of water and oil/gas has created historic period subsidence rates of upwards of 22 mm per year where fluid extraction is most intense. Areas where fluid extraction is moderate to low, regional subsidence rates average 3–7 mm per year (Paine, 1993).

In areas that are considered relatively tectonically stable, such as Barbados' 0.34 mm per year uplift, the difference in vertical displacement was factored into the sample's reported depths by the original researchers (n = 206) (Abdul et al., 2016; Bard et al., 1990; Fairbanks, 1989). Samples recovered in areas that are tectonically variable and complex, such as Louisiana and Mississippi coasts, were avoided by both this research and Balsillie and Donoghue (2004).

All data were calibrated via OxCal (Rev 4.3), utilizing the Marine13 calibration for marine samples and IntCal13 for terrestrial samples (Reimer et al., 2013). Balsillie and Donoghue (2004) utilized (Fairbridge, 1974) who neglected to publish both the material sampled or the standard deviation associated with the radiocarbon dates (n = 51). Due to the inability to accurately calibrate the sample dates, Fairbridge, 1974) was excluded from this research.

Of the 654 samples collected, this research evaluated 603 samples and utilized 425, 71% of the collected data, (see Appendix B). Median dates were utilized as a single data point, and error bars were assigned to each sample representing 95% probability distribution and vertical bars for ranges in depth (Bachand, 2008; Lambeck et al., 2002; Pirazzoli, 1996). The error bars allow researchers using the 2019 Gulf of Mexico curve to fully evaluate the data being utilized throughout the possible ranges in time and depth in association with the linear curve (Pirazzoli, 1996). The calibrated and edited datasets were entered into an Excel spreadsheet according to environmental indicator and placed into descending order according to median dates. Coral samples were plotted separately and represent a period at which the ocean levels for the location were no deeper than 5 m. Brackish samples represent the closest actual time and depth at which sea-levels transgressed and relative location of the coastline for the period. Freshwater peat and terrestrial samples represent a time in which the sea-level had yet to transgress the area. Separating the different environments on independent trendlines creates a bracket in which samples of vastly different environments do not interfere with one another. The transgression event falls between the coral trendline and the freshwater trendline (see Fig. 2) (see Fig. 3).

6. Bchron: age-depth modeling

Bchron is a non-parametric chronology model designed to estimate unknown age/depths within sediment cores using a Compound Poisson-Gamma model (Haslett and Parnell, 2008). Bchron uses a modified Markov chain Monte Carlo algorithm that converges sample depths to make probability estimations for sections of cores without known dates. Bchron functions by converting the Law of Superposition into a

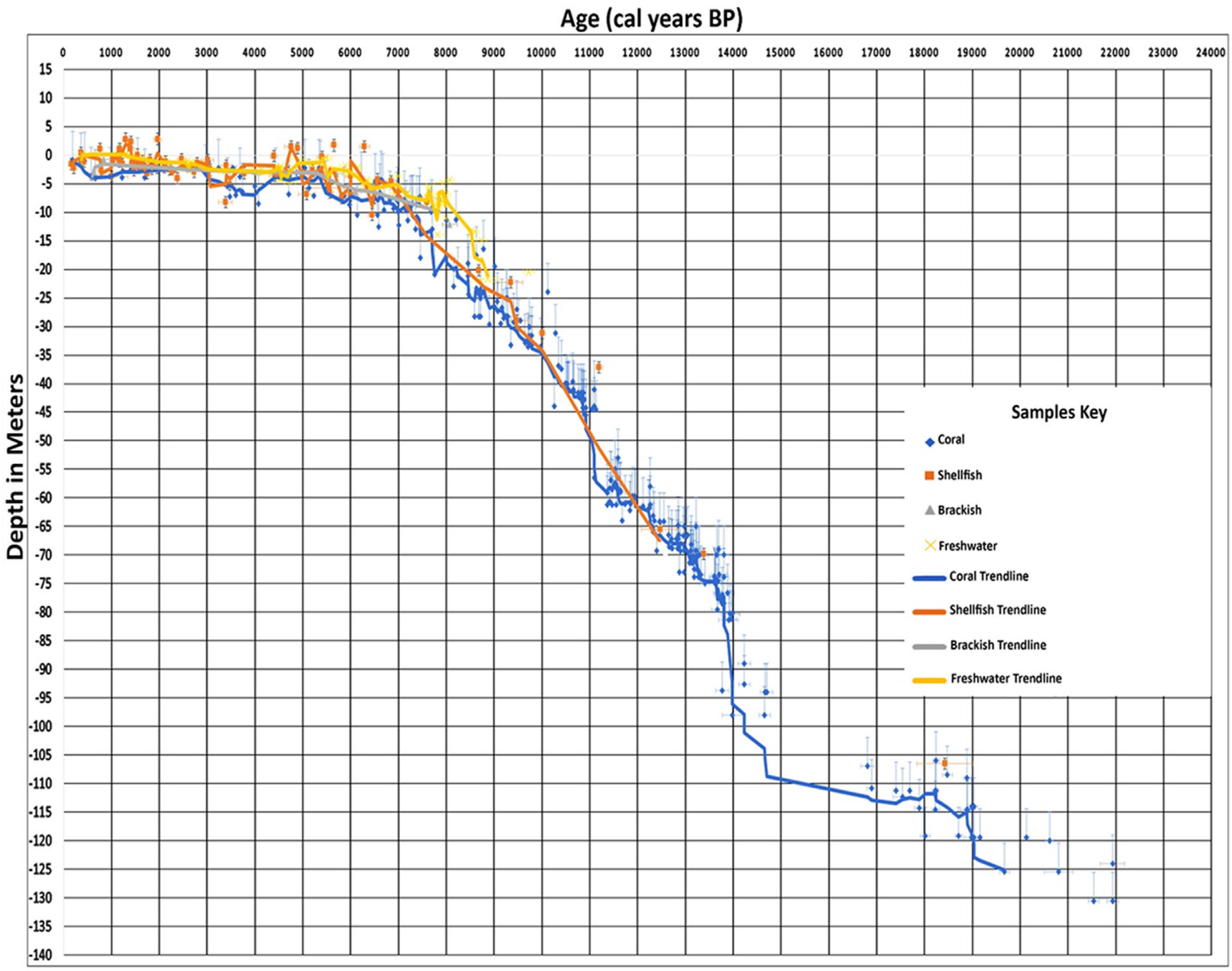

Fig. 2. 2019 Gulf of Mexico sea-level curve linear regression model separated into separate depositional environments.

mathematical principle known as monotonicity. Monotonicity is a function of order that only increases or decreases. Utilizing the Bchron program, dated stratum within the core can be used to determine the probability distribution of the estimated age of undated stratums (Parnell and Roland Gehrels, 2015). The monotonic restriction confines the probability distribution of date ranges by eliminating probability ranges that pre- or post-date samples lower or higher in the sediment core. Using this method also increases the ability to identify outlier dates within the series (Parnell and Roland Gehrels, 2015).

Use of the Bchron program allowed for accounting the uncertainties in depth and calibration; the linear transgression method cannot account for these. Utilizing the new edited dataset in the 2019 Gulf of Mexico sea-level curve has reduced the level of "noise" in the B&D curve, revealing a monotonic pattern for a majority of sea-level rise in the Gulf of Mexico. Bchron was developed to reconstruct sedimentation rates in lakes and salt marshes by using core data. The program does not discriminate between what type of medium is increasing or decreasing (i.e., sediment or water levels). Here, the entire Gulf of Mexico is treated as a single core, and sedimentation rates are replaced with increases in sea-level (see Figs. 4 and 5).

Coral samples were used to reduce the complication in uncertainties within the dataset. I used all coral samples collected during this research, averaging one sample every 40 cm, to test the viability of the model on a regional scale. The Bchron chronology model utilized the entire unedited coral dataset for several reasons. First, determining the increase in water levels using peats, wood, or shellfish would be problematic due to the inability to calculate the water depth at the time of deposition accurately. The constrained habitat range of elkhorn coral of 5 m is ideal for estimating shorelines because we know an in-place sample must be ≤ 5 m below sea level. Second, many of the elkhorn corals' calcium carbonate skeletons were U-series dated and do not require calibration. This simplifies the Bchron algorithm by eliminating the need for the program to calibrate the samples (Haslett and Parnell, 2008).

The entire elkhorn coral dataset (including outliers identified during the linear regression editing) were utilized for the chronology model (n = 290). The entire unedited coral dataset was used to include samples that may have been outliers in order for the program to fully assess the totality of the dataset and to avoid unintended "data dredging" by excluding samples that may not have been spurious (Wasserstein and Lazar, 2016). This allowed the program to determine which samples were outliers based on statistical probability. Uncalibrated radiocarbon and U-series dates and their associated errors were entered into an Excel spreadsheet. An arbitrary sample thickness of 4 cm was assigned each sample representing the size of the area in which the samples were taken from the cores. Bchron assigned coral samples that were radiocarbon dated a Marine13 reservoir calibration, and U-series dates were entered as "normal" and did not receive calibration. Then, the file was saved as a CSV file. The statistical program R (R Core Team , 2013) was used to run Bchron (see Appendix A and D).

7. The 2019 Gulf of Mexico sea-level curve

The 2019 Gulf of Mexico sea-level curve increases the accuracy of

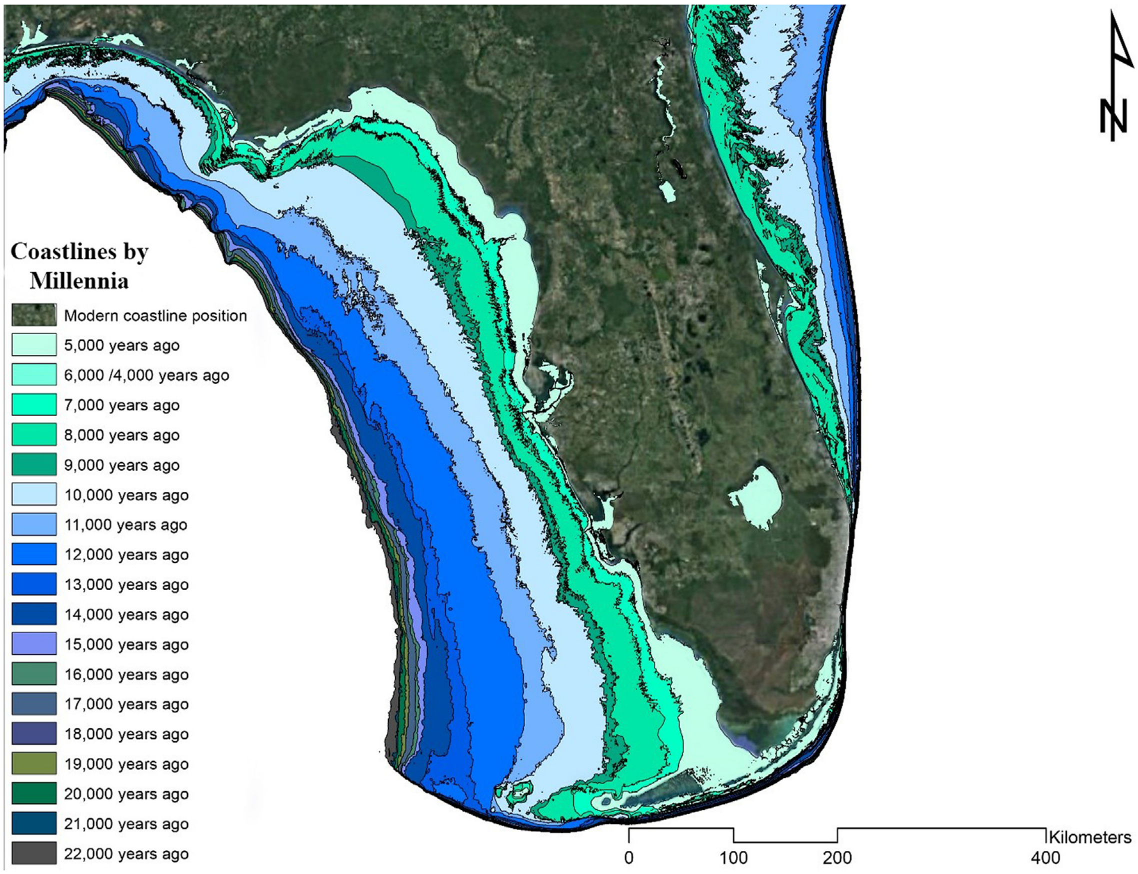

Fig. 3. Approximate location of the coastlines and areas submerged per millennia.

estimates of the elevation of submerged paleoshorelines to ± 5 m. Samples from the first 8000 years (22,000 to 14,000 cal BP) of the curve are coral samples that represent the lowest possible elevation of the sea-level. At 22,000 cal BP, sea-levels are approximately −125 to −130 m below modern sea-levels (bmsl). From 22,000 to 17,000 cal BP, sea-levels begin to steadily rise to −110 m bmsl. From 16,800 to 14,700 cal BP, there is a gap in sea-level data. This gap precedes meltwater pulse (MWP) 1A, estimated to start by 14,500 cal BP, making it difficult to discern the sea-level response in the Gulf of Mexico (Fairbanks, 1989). The Bchron model gives a more precise location of the paleo-coastline during this period by calculating the probability of its location using the known dates. By 14,700 cal BP, water levels had risen to −94 m bmsl and continued to rapidly rise 24 m to −70 m bmsl by 13,800 cal BP. The transgression rate slows after MWP 1A and the onset of the Younger Dryas, yet levels continue to rise 10 m to −60 m bmsl over the next 2400 years from 13,800 to 11,200 cal BP. MWP 1B is identified as starting at 11,200 cal BP, where sea-levels rise 20 m to −40 m bmsl in 400 years. After 10,800 cal BP, rates of sea-level rise slow and increase to −18 m bmsl by 8400 cal BP. At 8000 cal BP, MWP 1C begins, and sea-level rises 10 m to −8 m bmsl by 7200 cal BP. After the end of MWP 1C, sea-levels progressively rise to modern levels by 2500 cal BP (Figs. 2, 4 and 5).

8. High stands and low stands

Several researchers have inferred intervals of higher than present sea-level in the Gulf of Mexico during the mid to late Holocene (Blum et al., 2001; Morton et al., 2000; Otvos, 2004). The datasets indicate two high stands between 6300 and 4700 and 2000 to 1200 cal BP. Differentiation of the dated samples based on their environment of formation demonstrates that samples that indicate high stands are shellfish or foraminifera from the western Gulf. The lack of corroborating evidence from other marine samples, such as mangroves or corals, suggests the possibility that there were, in fact, no high stands in the Gulf and that the shellfish have been redeposited, giving the facade of a high stand. All manner of sea-level proxy data should be express in the presence of high stands or sea-level reversals, including coral, mangrove, and salt marsh deposits across the Gulf of Mexico. Since the LGM, there does not appear to be any major clusters of sea-level data that indicate a substantial reversal of more than 5 m in sea-level until the later Holocene. There appears to be a regression centered at 4000 cal BP, which is indicated by the coral, freshwater, and shellfish datasets. The shellfish, however, can be problematic for the aforementioned reasons. Four of the seven elkhorn coral samples collected during this period were living well below the modern 5 m water-mark. Additionally, during the same time period, freshwater samples were collected 1–2 m below previously indicated sea-levels. The archaeological record may also reflect the 4000 cal BP regression event. Several coastal sites in Florida and Texas were abandoned during the same period of the regression (Saunders and Russo, 2010; Ricklis et al., 1991, 2005). This abandonment may have been a demographic shift toward the newly re-exposed coastal landscape and the associated resources (Sassaman et al., 2016).

The results of the Bchron chronology curve utilizing the unedited coral dataset was remarkably close to the linear regression curve (see Figs. 4 and 5). A convergence test was conducted as part of an output function of the program. The model had a mean rate P-value of 0.49, concluding that the null hypothesis (i.e., the model was not significantly affected by sampling errors within the dataset) could not be rejected (Wasserstein and Lazar, 2016). Bchron also has an output function that presents the quintile (5-quantiles) of predicted ages by depth on the probability bell curve **(see** Table 4**).** The output divides the probability distribution of date ranges at 10-m intervals of depth into percentages of the distribution. The columns moving left to right at

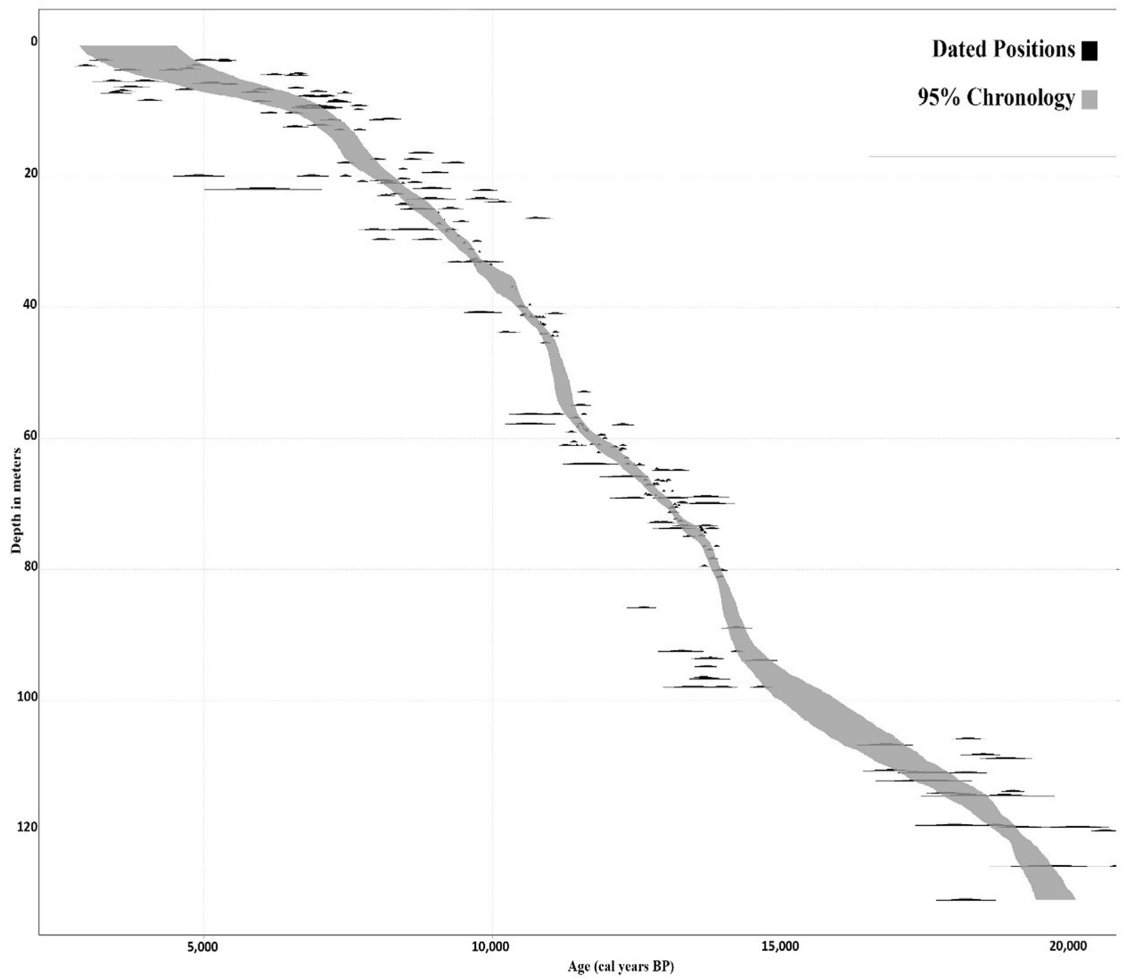

Fig. 4. Bchron 95% chronology for 290 unedited coral samples.

a given depth encompass 99.7% of the probability distribution for the dates. Areas where the linear regression and Bchron models differed by more than 10 m, such as 14,700 to 16,700 cal BP, are due to a lack data points altogether, yet the Bchron model was able to estimate the probability of the location of the missing data to within a 5 m depth range.

The Bchron model also validated the new editing methods utilized in the 2019 curve for identifying outliers. The results of the chronology model show that a sea-level curve utilizing linear regression can be a viable method, provided the editing of outliers, yet Bchron surpasses linear regression model when large areas of data are missing. One drawback with the Bchron program is the necessity of calculating depth accumulations over a large region. This makes elkhorn coral a valuable proxy for the Gulf of Mexico region. Sea-level curves for coastal regions outside of the elkhorn coral habitat range must identify a similarly well-constrained proxy or utilize a linear regression model.

The 2019 Gulf of Mexico sea-level curve developed during this research is capable of locating paleo-coastline to within ± 5 m of water depth (see Figs. 4 and 5). The new editing methods identified n = 178 outliers versus the n = 12 identified by Balsillie and Donoghue (2004) methods. By decreasing the envelope of acceptance from 75 m to 10 m and using statistical and linear regression models, this research improved the accuracy of predicting paleo-coastlines since the LGM.

9. Conclusion

Nearly 40% of the modern global population currently live within 100 km of the coastline (Neumann et al., 2015). Lower than modern sea-levels spanning 115,000 years extended global coastal plains onto the continental shelves, increasing habitable land by 13% (168 million km^2) globally during maximum regression (Lambeck et al., 2002). The use of the coastal environment for subsistence extends far into human antiquity. The coastal plain environments have played a role in both the physical and cultural development of modern humans (Marean, 2010), yet archaeological research deep on the continental shelf is only in its infancy in the US. The global archaeological record is missing vital information concerning the cultural development and migrations of human populations in coastal environments during the last glacial period (115,000–11,500 cal BP). Answering vehemently debated questions such as ‘Where did the first Americans originate?’ ‘How did they arrive on the continent?’ and ‘How did rapid landscape inundation impact coastal adaptations during meltwater pluses?’ are further complicated by the lack of research on such an important landscape.

This model was created for the exploration and identification of submerged pre-contact coastal sites in the Gulf of Mexico to begin filling in the gaps of the archaeological record. Predictive modeling of submerged coastal sites on Florida's western continental shelf requires precise locations of paleo-coastlines, a thorough understanding of coastal geological processes, the ability to identify fluvial and karst features in sub-bottom profile data, and knowledge of local cultural history (Faught, 2018). The crux of this research is to create a comprehensive dataset designed for researchers to locate, identify, and investigate submerged coastal sites. Using these models, researchers can now precisely target offshore locations where coastal sites may occur. Focusing on locations where coastal regions were quickly transgressed during meltwater pulses should contain the highest probability of intact

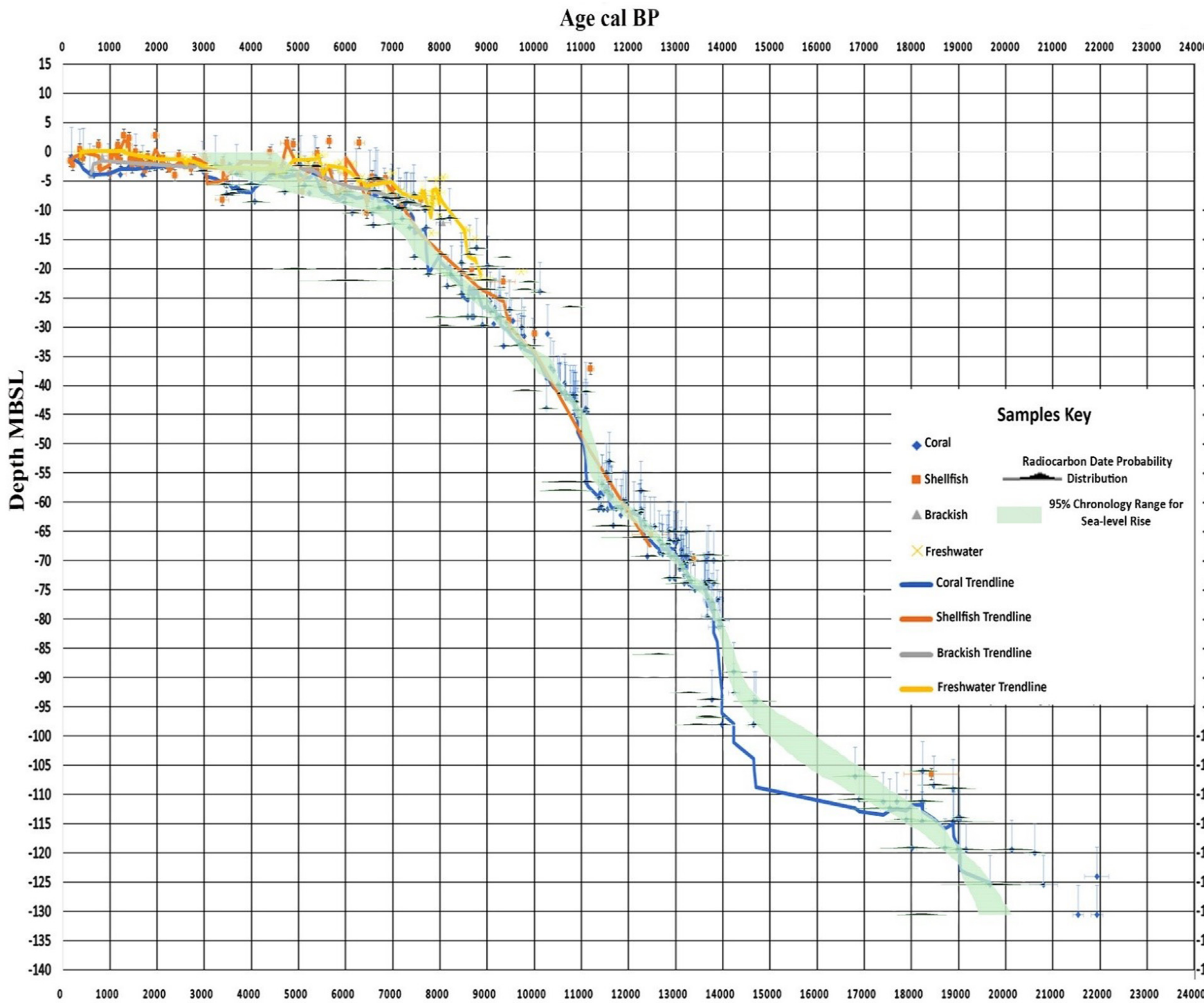

Fig. 5. 2019 Gulf of Mexico sea-level curve with Bchron overlay.

Table 4
Quantiles of predicted ages by depth.

Depth in Meters	2.5%	10%	50%	90%	99.7%
0	2946.9	3399.8	4324	4511.1	4593
10	6679.8	6747.9	6899	7036	7166
20	7851	7923	8064	8183	8314
30	9266.9	9315	9422	9545	9630
40	10,428	10,465	10,522	10,574	10,640
50	11,037	11,079	11,149	11,237	11,336
60	11,631	11,667.9	11,760	11,852	11,970
70	12,924	12,958.9	13,043	13,102	13,151
80	13,789.9	13,826.9	13,887	13,928	13,974
90	14,116	14,157	14,257	14,373	14,528
100	15,027	15,173	15,486	15,807	16,193
110	16,827	16,975.9	17,272	17,567	17,838
120	18,722	18,805	18,948	19,068	19,253
130	19,355	19,460	19,693	19,970	20,274

sediments and minimally disturbed sites. These regions fall within ranges from 100 to 70 m, 60 to 40 m, and 20 to 10 m in depth.

Until global submerged coastal plains are investigated for Late Pleistocene and Early Holocene archaeological sites, the story of human history will be missing a vital part of the narrative. Littoral landscapes play a major role in the Holocene archaeological record since sea-levels stabilized. Archaeological surveys on the submerged landscape will begin to answer questions about human interaction with the coastlines during the largest sea-level increase in modern human history. These answers lay waiting on distant shorelines, currently drowned on the continental shelf.

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I, Shawn Joy, disclose that I have no financial and/or personal relationships with other people or organizations that could inappropriately influence (bias) my work.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.quaint.2019.07.023.

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