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Late Quaternary Oyster Shells and Sea-Level History, Inner Shelf, Northeast Gulf of Mexico*

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ABSTRACT

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Oyster (*Crassostrea virginica*) shells collected at nine sites on the Alabama continental shelf in the northeastern Gulf of Mexico have yielded 27 radiocarbon ages between 8,400 and 36,000 yr BP. Ages and water depths of collection sites of these shells are generally consistent with ages and water depths of shells from the U.S. Atlantic shelf. We have evaluated our data against published interpretations of sea-level change over the past 120,000 yr. The nine youngest shells, from six different sites, have age-depth relations consistent with estuarine origins. Older shells (radiocarbon age > 15,000 yr BP) were collected at various depths, some of which are incompatible with their apparent ages and best estimates of late Pleistocene sea levels. Present distribution would seem to require transport of shells over significant distances on the gently sloping shelf. Although their generally good physical condition makes such transport unlikely, shells may have formed lags during transgressive erosion. Furthermore, accuracy of radiocarbon ages is questionable particularly for the older materials in our set, and the significant likelihood of even greater ages for these shells restores the possibility of local origins.

Notable concentrations of mixed-age shells occur at 40 m and 20 m depths. These concentrations are interpreted as lags that document changes in the rate of sea-level rise, and/or the superposition of Holocene and older paleo-estuarine systems. The −40 m lag resulted from a decreased rate of rise in sea level over the period 9,800 to 9,000 yr BP followed by a brief interval of increased rate of rise in sea level. The −20 m lag represents a reworking of pre-Holocene shells and lithified sediments during a subsequent decrease in the rate of rise in sea level postulated at 8,200 to 7,800 yr BP. Both the −40 m and −20 m lags may also be related in depth to interstadial paleo-estuarine deposits dating from 25,000 to 76,000 and 80,000 to 115,000 yr BP, respectively.

ADDITIONAL INDEX WORDS: *American oyster (*Crassostrea virginica*), late Quaternary, sea level, paleoestuaries, cross-shelf transport, radiocarbon dating.*

INTRODUCTION

During the 1960s, investigators attempting to reconstruct late Pleistocene and Holocene sea-level history in the northwestern Gulf of Mexico and along the southeastern U.S. Atlantic coastline depended, to a large degree, on radiocarbon dating of presumed shallow-water or shoreline indicators (CURRAY, 1960, 1965; SHEPARD, 1963; MERRILL *et al.*, 1965; EMERY and GARRISON, 1967; EMERY *et al.*, 1967; MILLIMAN and EMERY, 1968). One of the principal candidates for this approach was the American oyster, *Crassostrea virginica* (GMELIN, 1791), because its habitat is restricted to shallow, brackish-water environments. However, the validity of utilizing relict oyster shells in constructing sea-level curves was challenged by MACINTYRE *et al.* in 1978. Their data indicated that oyster shells, mainly from the Onslow Bay shelf off North Carolina, that were not fixed in place could be subjected to significant post-depositional mixing and landward transport. Therefore, they called into question previous interpretations of sea level that incorporated dates from loose, mobile shells.

Over the past five years, two of the authors (WWS and AWS) have attempted to gain insight into Quaternary sea-level fluctuations in the northeastern Gulf of Mexico by examining the locations and radiocarbon ages of a collection of *Crassostrea virginica* shells from the Alabama continental shelf (SCHROEDER and SHULTZ, 1993). Because the general condition of the shells indicated minimal or no movement along the bottom

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(*personal communication*, DR. ERIC POWELL, Texas A&M University), they assumed that sites on the continental shelf where oysters have been collected represent the original coastal environments and are reasonable approximations of past shoreline locations and sea-level elevations. They concluded that the data can be viewed as supporting an interpretation of fluctuating Holocene sea level (*e.g.*, as shown by CURRAY, 1960), rather than an uninterrupted sea-level rise (*e.g.*, FAIRBANKS, 1989). However, when additional locations and ages of oyster shells collected at previously sampled sites, as well as new sites, on the Alabama and Mississippi shelf are incorporated into their original data set, it becomes evident that a parallel to the situation on the Atlantic shelf occurs on the Alabama-Mississippi shelf. That is, the distribution pattern of some of the relict oyster shells in this area also appears to require post-depositional cross-shelf transport. Alternatively, for both regions, errors in the radiocarbon ages of the older shells (*e.g.*, > 15,000 yr BP in the present study), resulting from contamination by younger carbon, could produce similar age-depth distribution patterns.

In this article, we will present new data on distributions and ages of oyster shells from the northeastern Gulf of Mexico. As with the previously published material on relict oyster shells, these data show some strong relationships to late Pleistocene and Holocene sea-level curves, as well as some radiocarbon ages and locations that are clearly misfits relative to expected paleocoastal settings. We will discuss multiple possible origins of oyster-shell accumulations, including *in situ* shell accumulations representing paleoestuarine oyster reefs, displaced shells resulting from cross-shelf transport, and shell lags resulting from vertical displacement. These results will, in turn, be examined in light of potential errors in radiocarbon age determinations (*e.g.*, OLSSON, 1968; STAPOR and TANNER, 1973). By themselves these interpretations do not necessarily suggest anything particularly new regarding the mechanisms or prevalence of shell reworking. However, closer examination suggests patterns that may have wider significance, particularly in regard to increasing evidence for relatively rapid changes in the rate of rise of sea level. This discussion is admittedly speculative and offers no definitive answers to this complex problem. Our hope, however, is that such an examination will help to focus renewed attention on those associations that may prove to be informative in future integrative studies of shelf paleogeography.

SETTING

The study area encompasses most of the continental shelf in the westernmost section of the northeastern Gulf of Mexico. This shelf province, adjacent to Mississippi, Alabama, and the northwest panhandle of Florida, is a triangular, gently sloping region (Figure 1). It is bounded on the west by the Mississippi River delta system and to the east by the De Soto Canyon. Seaward the shelf break ranges in depth from 60 to 100 m. Most of the shelf is covered by the Mississippi-Alabama-Florida (MAFLA) sand sheet (DOYLE and SPARKS, 1980). This sandy facies has been viewed as a product of mixing of sediments flushed from coastal embayments, eroded from the older St. Bernard lobe of the Mississippi River delta, dispersed westward from the Florida shelf, and locally reworked from palimpsest Pleistocene deposits (MAZZULLO and BATES, 1985). Other locally important shelf features include regions of shell gravels and shell banks, often composed of disarticulated oyster shells, as well as low- to high-relief, hard-substrate deposits and structures (LUDWICK and WALTON, 1957; LUDWICK, 1964; SCHROEDER *et al.*, 1988, 1989; SHULTZ *et al.*, 1990; SAGER *et al.*, 1992).

METHODS

Figure 1 depicts the sites on the Alabama-Mississippi shelf where shells of the American oyster *Crassostrea virginica* were obtained for this study. Shells were collected by conventional surface-ship trawling and dredging operations and by divers utilizing Scuba. As in previous studies, special attention was paid to correctly identifying all of the specimens in our collections. Of particular concern was the possible misidentification of adult *Ostreola equestris* (SAY, 1834), a subtidal species, as small *C. virginica*. After conferring with Dr. Eric Powell at Texas A&M University, we are confident that all shells submitted for analysis were *C. virginica*. Figure 2 illustrates examples of typical relict oyster shells collected from the Alabama-Mississippi shelf.

The physical condition of the shells selected for radiocarbon dating varied; some were nearly pristine while others displayed slightly rounded edges, suggesting limited horizontal displacement, and some were corroded with small borings, suggesting prolonged exposure (Figure 2). Nonetheless,

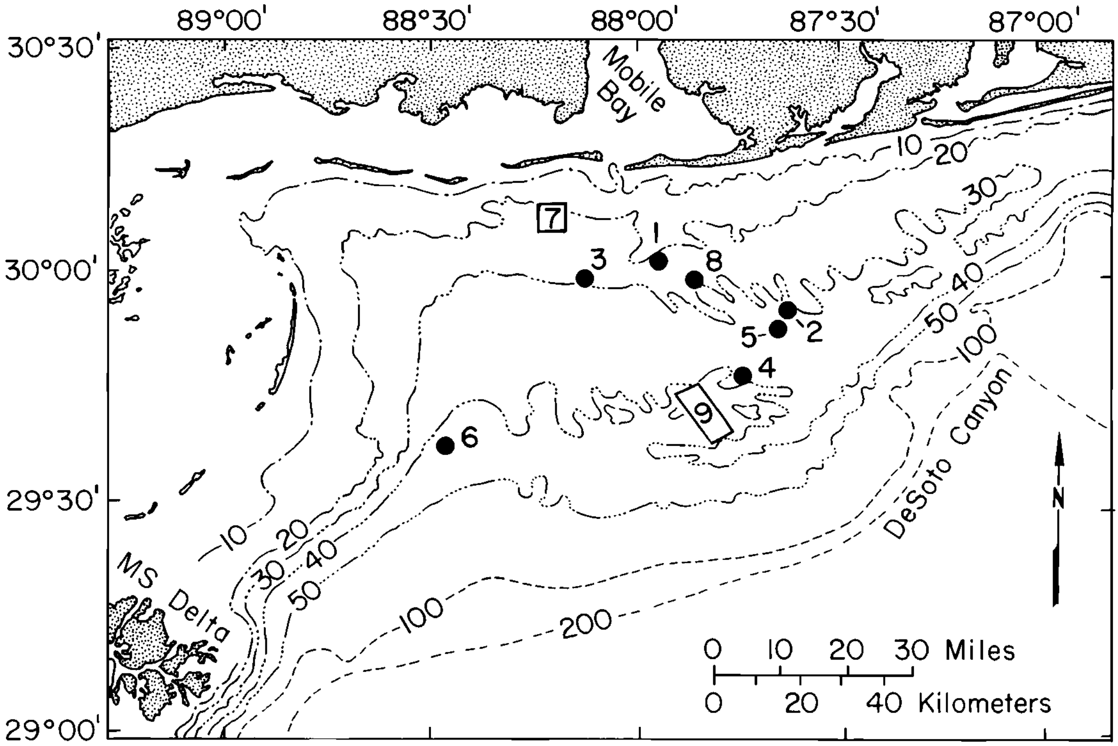

Figure 1. Index map of the westernmost section of the continental shelf in the northeastern Gulf of Mexico, showing sites where relict *Crassostrea virginica* oyster shells were collected for this study. See Table 1 for detailed information.

all appeared to consist of solid nacreous lamellar shell material and were initially judged to be mineralogically unaltered. Surface encrustations and leached exterior layers were removed by acid etching prior to extraction of carbon for analysis. Radiocarbon dating analyses were performed by Beta Analytic Inc., Coral Gables, Florida, USA.

All sample ages discussed in this article are uncorrected apparent radiocarbon ages, calculated as years before present (A.D. 1950) using a radiocarbon half-life of 5568 years and 95% of the activity of NBS oxalic acid as modern standard. We recognize that radiocarbon age determinations are subject to serious errors, particularly for relatively old samples. Discussion of errors will follow presentation of the results.

RESULTS

Oyster shells were collected from nine sites on the Alabama-Mississippi continental shelf (Figure 1). These sites occur from 17 to 68 km south of the present-day shoreline in water depths of 18 to 43 m. Oyster shells are apparently widespread on the shelf, and the sites sampled are almost certainly not the only such occurrences. Nonetheless, these sites are distinct in that they are surrounded by areas where comparable efforts failed to reveal oyster shells. From a total collection of over 170 shells, 27 were submitted for radiocarbon age determination. Most of the nine sites were represented by multiple shells but for three sites only single shells were dated.

Ages obtained ranged from 8,480 ± 90 yr BP to 35,620 ± 770 yr BP (Table 1). The overall age distribution is strongly bimodal (Figure 3), with one cluster of nine ages in the range 8,400 to 11,000 yr BP and another cluster of 12 ages in the range 26,500 to 31,000 yr BP. Only five shells have ages between 11,000 and 26,500 yr BP, and a single age greater than 31,000 yr BP was obtained. The maximum depth from which shells were recovered in this study is 42.7 m at site 9.

Figure 2. Examples of relict *Crassostrea virginica* (Gmelin) oyster shells from the Alabama continental shelf.

The younger cluster of ages (8,400 to 11,000 yr BP) comprises three dated shells from Site 1, one of the two shells from Site 4, two shells from Site 6, as well as the single shells from Sites 2, 3, and 5. Present depths below mean sea level for these sites range from 24.7 to 26.8 m for Site 1, 28.9 to 33.5 m for Site 2, 29.3 to 31.1 m for Site 3, 33.5 to 37.8 m for Site 4, 33.5 to 36.6 m for Site 5, and 40.0 to 40.9 m for Site 6 (Table 1 and Figure 3).

The older cluster of ages (26,500 to 31,000 yr BP) is associated primarily with shells from Site 7, from which 8 out of 10 shells analyzed have ages in this time period. Depth for this site is 18.7 to 23.5 m below present mean sea level. Similar ages were also obtained for shells from Site 8 at a depth of 27.5 m. In addition, one shell each from Sites 4 and 9 yielded ages in this range, representing depths of 36.6 to 37.8 m and 37.9 to 38.4 m, respectively (Table 1). Ages between 11,000 and 26,500 yr BP consist of one of the ten shells from Site 7, and four out of five shells from Site 9. Site 7 also yielded one shell with radiocarbon age greater than all others, 35,620 yr BP. Depths for Site 7 are 19.2 to 20.1 m, while depths for Site 9 are 37.9 to 42.7 m.

DISCUSSION

Late Pleistocene sea-level fluctuations, first identified in the 1960s, have been considerably refined by more recent studies (*e.g.*, CHAPPELL and SHACKLETON, 1986). Although details remain controversial, the persistent general pattern indicates strongly that the present inner continental shelf (water depth < 40 m) was in all likelihood above sea level for at least 14,000 years prior to 10,000 yr BP (Figures 4 and 5). Similarly, at some earlier time or times (at least 25,000 yr BP), sites at a present depth >25 m were submerged during one or more "late Pleistocene" interstadial highstands (Figures 4 and 5). Oysters are not expected to have been alive in areas exposed above sea level during lowstand, and given the limited depths of Gulf Coast estuaries, oysters are not expected to have flourished at paleodepths greater than ap-

Table 1. *Crassostrea virginica from Alabama continental shelf. See Figure 1 for site locations.*

Site	Oyster	Location: Lat (N)	Location: Long (W)	Depth (m)	Uncorrected Radiocarbon Age (yr BP)	Collection Method
1	1	30°00.5′	87°57.3′	26.8	8,480 ± 90	Scuba
	2	30°00.9′	87°57.1′	24.7–25.9	9,040 ± 90	dredge
	3	30°00.9′	87°57.1′	25.0–25.9	9,650 ± 110	dredge
2	1	29°55.4′	87°30.7′	28.9–33.5	8.980 ± 80	dredge
3	1	29°55.6′	88°03.4′	29.3–31.1	9,360 ± 80	dredge
4	1	30°47.0′	87°45.6′	33.5–36.6	10,290 ± 130	dredge
	2	30°45.2′	87°43.8′	36.6–37.8	27,070 ± 730	dredge
5	1	29°52.7′	87°32.1′	33.5–36.6	10,820 ± 150	dredge
6	1	29°38.1′	88°26.9′	40.0–40.9	10,100 ± 120	trawl
	2	29°38.1	88°26.9′	40.0–40.9	10,860 ± 120	trawl
7	1	30°04.5′	88°13.6′	19.8–20.4	29,760 ± 710	dredge
	2	30°04.5′	88°13.6′	19.8–20.4	29,550 ± 410	dredge
	3	30°03.9′	88°13.2′	22.9–23.5	28,450 ± 550	dredge
	4	30°04.7′	88°12.0′	19.5–20.7	28,730 ± 330	trawl
	5	30°04.7′	88°11.9′	19.2–20.1	19,860 ± 150	dredge
	6	30°04.6′	88°11.9′	19.2–20.4	35,620 ± 770	trawl
	7	30°04.6′	88°11.9′	18.7–20.1	27,410 ± 600	dredge
	8	30°05.3′	88°12.0′	18.9–20.1	28,370 ± 390	dredge
	9	30°05.2′	88°11.9′	19.2–19.8	31,000 ± 380	trawl
	10	30°05.2′	88°11.9′	19.2–19.8	27,940 ± 450	trawl
8	1	29°59.5′	87°48.1′	27.5	26,530 ± 270	Scuba
	2	29°59.5′	87°48.1′	27.5	30,760 ± 460	Scuba
9	1	29°38.3′	87°51.6′	37.9–41.9	22,700 ± 160	trawl
	2	29°38.3′	87°51.6′	37.9–41.8	19,690 ± 150	trawl
	3	29°37.2′	87°51.0′	38.1–42.7	21,310 ± 150	trawl
	4	29°37.2′	87°51.0′	38.1–42.7	15,240 ± 90	trawl
	5	29°41.8′	87°55.5′	37.9–38.4	29,060 ± 310	trawl

proximately 15 m. Thus, shells whose ages and depths of origin closely match inferred sea levels are consistent with expectations. However, age-depth points which are significantly above or below the sea-level curves (Figure 3) require additional explanation. We will consider both transport of shells from their original locations of origin and errors in obtaining and interpreting radiocarbon ages as hypothetical factors in such problems.

Errors in radiocarbon ages are most likely to cause underestimation of age. We assume that estuarine waters in which oysters lived did not contain significantly lowered initial amounts of radiocarbon (*e.g.*, from fluvial interaction with old carbon in carbonate rocks) which would result in increased apparent age. Contamination of shells by younger and therefore more active carbon may result in radiocarbon ages that are significantly younger than ages as determined by other methods. Although we initially felt that the consistency of ages in our older group supported their validity, we recognize that consistent, low-level contamination would yield the same pattern. We must be cautious in accepting as accurate any pre-Holocene ages, particularly ages greater than 15,000 years.

One group of shells, from Sites 1, 2, 3, 4 (the younger of the two shells), 5, and 6, have ages between 8,400 and 11,000 yr BP and were recovered from depths of 25 to 40 m (Figure 3). These shells can be attributed to paleo-estuarine conditions, and are consistent with established sea-level chronology (*i.e.* requiring little or no cross-shelf transport either shoreward or seaward).

Most shells from Site 9 and one shell from Site 7 were significantly shallower than expected from their apparent ages (15,240 to 22,700 yr BP). If these ages are accepted and if the sea-level curve of Curray (1965) is taken as an upper limit of actual sea-level before 20,000 yr BP, then these shells would appear to require significant shore-

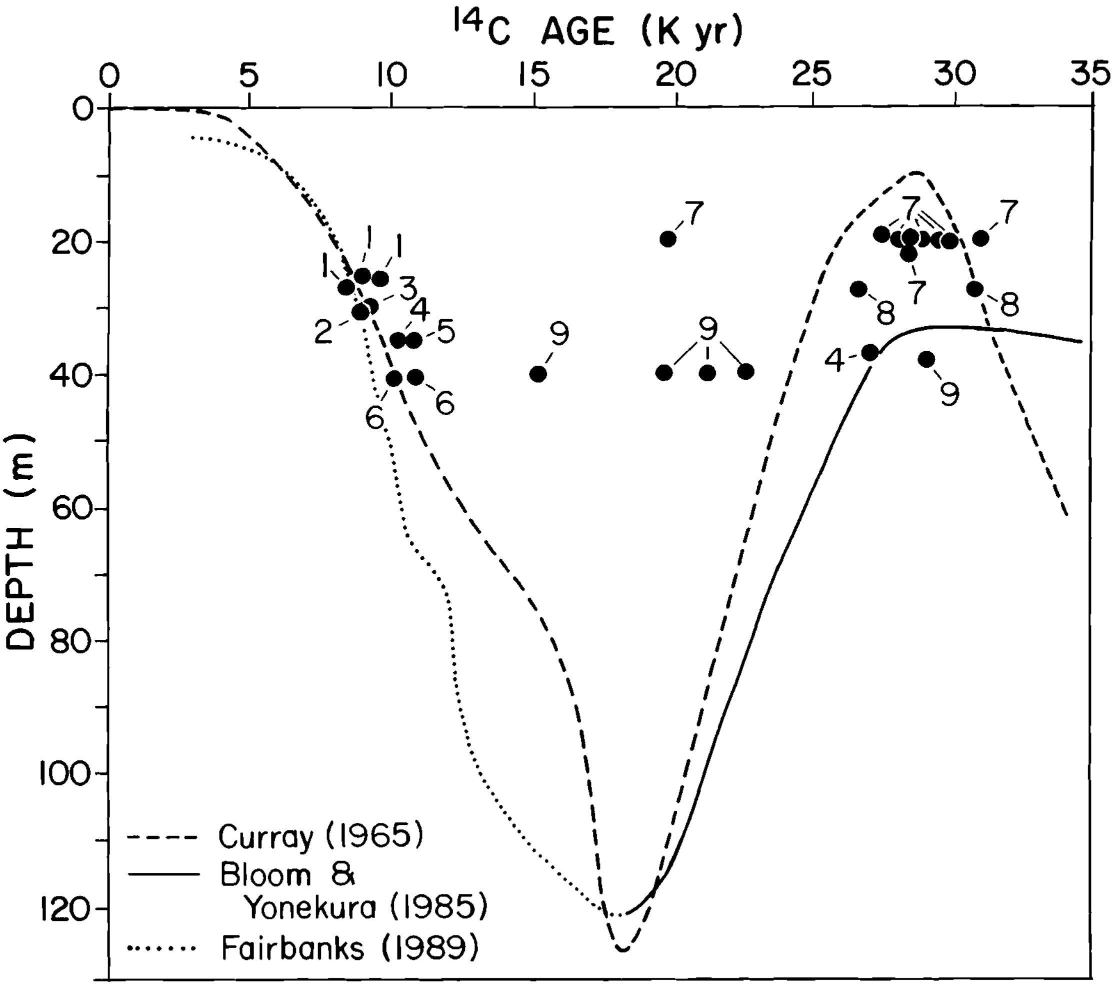

Figure 3. Plots of depth and radiocarbon age for oyster shells collected in this study. Each point represents an individual shell, and numbers correspond to sampling sites (see Figure 1 and Table 1). Note: The Fairbanks (1989) curve is based on radiocarbon ages adjusted for local seawater $\Delta^{14}C$ (minus 400 yr) and local uplift (34 cm kyr^{-1}).

ward transport; the four shells at Site 9 would have been moved upward by 20 m to 70 m in elevation over horizontal distances of 24 to 35 km, and the single shell at Site 7 would have been moved upward over 90 m in elevation over a distance of 90+ km. This is a serious discrepancy and may be difficult to reconcile even with exceptional storm-wave transport, particularly in light of the physical conditions of the individual shells which suggest only limited horizontal displacement. Alternatively, if some or all of the apparent ages are significantly younger than the true ages of the shells, then relations to paleo-sea-levels are completely unconstrained and no direct inferences may be drawn about transport of shells.

The oldest shells (apparent ages >25,000 yr BP), were collected at depths near or below the −10 m highstand inferred by CURRAY (1965) but above the −35 m sea level identified by BLOOM and YONEKURA (1985) at 26,000 to 30,000 yr BP. Accepting for the moment both the sea-level curve of CURRAY (1965) and our oyster-shell ages as accurate, these data are generally in agreement. Any discrepancies in the direction of shells deeper than expected from CURRAY (1965) could be explained by transport of shells from their sites of origin.

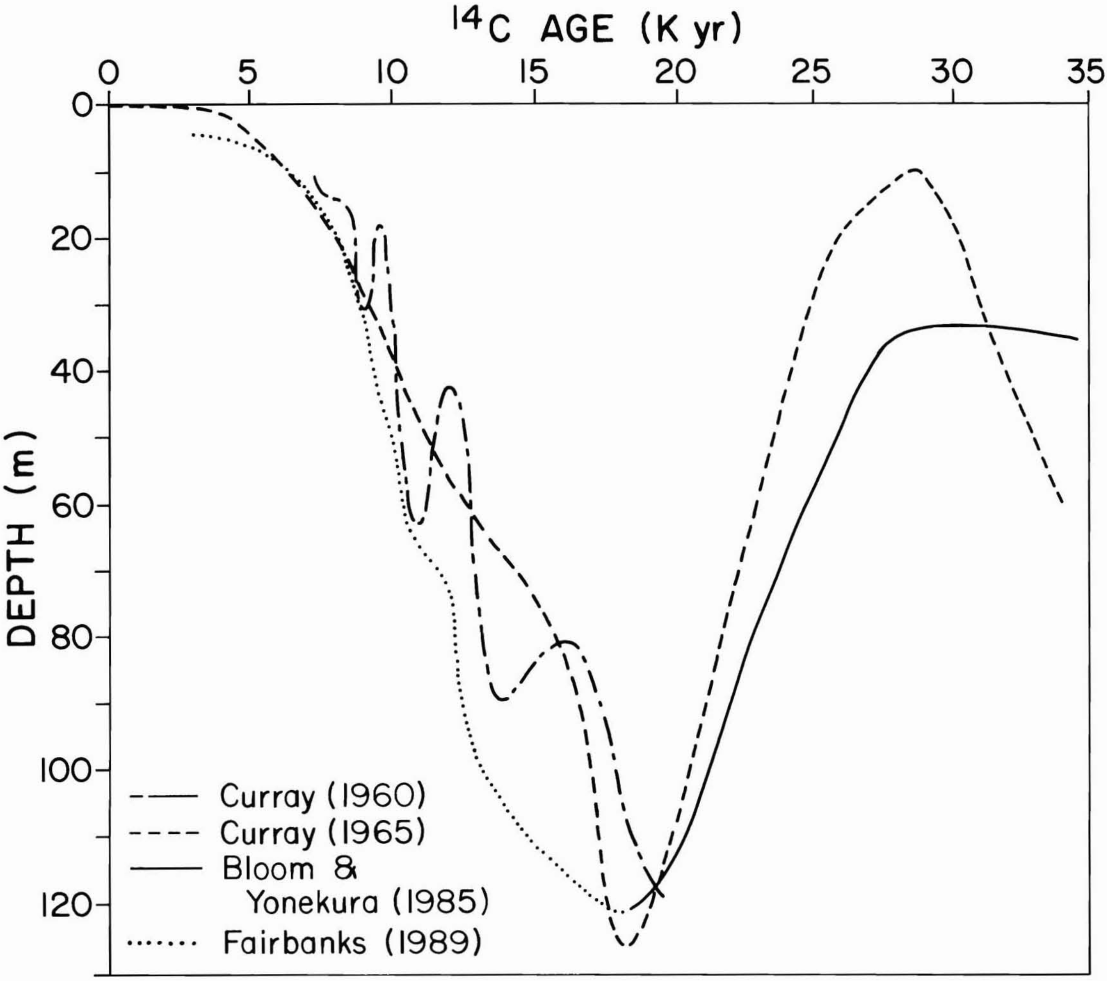

Figure 4. Compilation of latest Pleistocene-Holocene sea-level curves.

Such transport might include: (1) storm-surge ebb, (2) cross-shelf transport by falling sea level and/or fluvial incision, and (3) vertical displacement or erosional lowering with little significant lateral or cross-shelf movement. These processes may be difficult to differentiate using only distributional evidence. Fluvial dispersal might allow shells of the same age to be found at several depths; however, this pattern is not evident from our data. Furthermore, the relatively good physical condition of the shells argues against long distances of transport by either fluvial or storm-event currents. The tendency of some sites, especially six and seven, to contain shells of varying ages at the same depth is consistent with origins as a lag. The alternative case that these older shells were accurately dated and are taken as having come from sites above sea level according to the curve of BLOOM and YONEKURA (1985), transport of these shells to higher elevations appears necessary. As discussed above, this situation is problematic and difficult to explain reasonably. Finally, if the ages themselves are suspect, then all such specific inferences regarding paleogeography of shells are speculative.

It is apparent that specific depth ranges comprise most of the "problem" shell ages. These depths, centered around 20 and 40 m in our da-

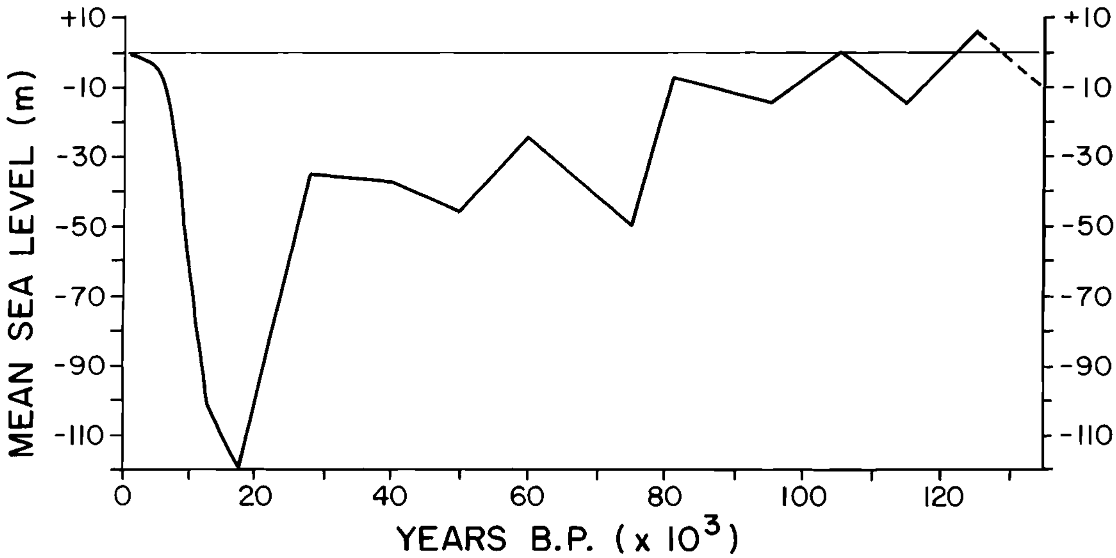

Figure 5. Late Quaternary sea-level curve from glacioeustatic records (modified from TOSCANO and YORK, 1992).

taset, appear to contain lags in which shells of varying ages are mixed. Although our data by themselves do not necessarily provide a compelling case for favored depths, other studies help support this pattern. Stations on the mid-Atlantic U.S. continental shelf from which oyster shells were recovered are most numerous in the 35 to 40 m range (MERRILL *et al.*, 1965). Atlantic shells with radiocarbon ages in the range of 13,000 to 18,000 yr BP are with few exceptions from depths of 20 to 40 m (MACINTYRE *et al.*, 1978). Arguments raised against long distances of transport for these shells (MACINTYRE *et al.*, 1978; EMERY *et al.*, 1979) have been used to question the lowstand sea level inferred at depths of 100 to 130 m (MILLIMAN and EMERY, 1968) and to suggest that shelf topography precluded transport from depths below 80 m.

Materials associated with oyster shells at Site 7 provide evidence in support of erosion and lagging. Collections at this site yielded not only oyster shells but also two types of rocks. These rocks, described in detail elsewhere (SCHROEDER *et al.*, 1988; HOWARD, 1990), are generally rounded, pebble- to cobble-sized and variably encrusted with living benthic fauna. Rock types include calcite-cemented sandstone and mudstone inferred to have been formed at or near the sediment-water interface and siderite-cemented sandstone and mudstone inferred to have been formed in anoxic sediment, perhaps a few meters below the sediment-water interface. The formation of siderite nodules and clasts in their present oxic environment is highly unlikely; these materials must have been exhumed sometime after lithification. The presence of this mixture of materials is entirely consistent with erosion of sediment, possibly a few meters thick, that formerly overlaid the present seafloor surface. This erosion would have resulted in a lag deposit of larger, less mobile particles including rocks and shells.

Growing evidence for more complicated changes in sea level since the late Wisconsinan lowstand comes from data on *in situ* shelf deposits, ^{234}U-^{230}Th dating of corals by thermal ionization mass spectrometry, and high-resolution seismic stratigraphy. *In situ* shelf deposits, including saltmarsh peat, beach coquina, and *Crassostrea virginica* shells in lagoonal sediment suggest that sea level during the last transgression was at least 30 m shallower than indicated by previous sea-level curves (BLACKWELDER *et al.*, 1979). The Younger Dryas event, a cooling episode between 11,000 to 10,000 yr BP when the climate of northern Europe returned to near-glacial conditions for a few hundred years, has been intensively investigated (*e.g.*, DANSGAARD *et al.*, 1989; FAIRBANKS, 1989; BROECKER and DENTON, 1990). Rate of sea-level rise, revealed in ^{14}C and ^{234}U-^{230}Th dated corals from

Barbados and Papua New Guinea, appears to have been very low in the Younger Dryas interval (BARD *et al.*, 1990; EDWARDS *et al.*, 1993). Furthermore, seismic-reflection profiles for Quaternary deposits on the Texas inner shelf suggest as many as five stillstands in the last 10,200 years (SIRINGAN, 1993). In short, evidence appears to be mounting for an unsteady rate of rise in glacioeustatic sea level.

We suggest that changes in rate of sea-level rise during the Holocene transgression may have contributed to the complicated distribution of oyster shells on the inner shelf. If some of the concentrations of oyster shells are to be accepted as lags rather than as *in situ* deposits, we would wonder both how they formed and how they remained to the present. We speculate that sea-level rise may produce a transgressive lag of great extent on a smoothly sloping shelf but that a lag at a specific depth requires a slower rate of rise in sea level or a stillstand, if not a sea-level fall. Preservation of such a lag without deposition of overlying sediment during continued sea-level rise would require a reduced rate of shoreface erosion or a rapid landward advance of the shoreface; these conditions suggest a rapid rate of rise in sea level following formation of a lag. The assemblage at 40 m (Figure 3) includes shells as young as 10,100 yr BP and may be related to a period of decreased rate of rise in sea level. The best documented event of this type is the Younger Dryas episode around 11,000 to 10,000 yr BP, which was followed by a brief, rapid rise in sea-level (FAIRBANKS, 1989; EDWARDS *et al.*, 1993). However, the Younger Dryas episode corresponds to sea levels in the range of 62–68 m below present sea level and thus is probably not related to the 40 m shell deposit. Another significant decrease in the rate of sea-level rise is noted at 9,800 and 9,000 yr BP (see Figure 3 in EDWARDS *et al.*, 1993) when sea level was in the range of 37–52 m below present sea level. Just as in the Younger Dryas episode, this decreased rate in rise of sea-level is followed by an increased rate in rise, albeit modest in amplitude and not entirely documented. Subsequent variations in the rate of rise of sea-level (SIRINGAN, 1993) may have contributed to the formation of other degradational lags such as the one involving shells and lithified sediments at Site 7 at 20 m depth around 8,000 yr BP (Figure 4). Interestingly, the sea-level history proposed over thirty years ago by CURRAY (1960) included considerable complexity over these same ranges of age and depth (Figure 4), though other workers tended to favor a more monotonic sea-level curve for the Holocene.

The foregoing model assumes a topographically smooth shelf on which effects of sea-level change are played out. The nature and distribution of togography on the MAFLA shelf is in some locations at odds with this assumption; Pleistocene estuaries on the shelf (BALLARD and UCHUPI, 1970; SCHROEDER and SHULTZ, 1993) may have left some bay-barrier topography during the glacial maximum and lowstand. Relict barrier features would tend to influence the development of transgressive estuaries and preservation of their deposits. Protected estuarine sites suitable for development of oyster reefs might form preferentially atop older bay-barrier systems even during steady sea-level rise. Breaching or overtopping of the barrier during continued sea-level rise would allow rapid landward shift of the site of active shoreface erosion across the relatively level bay-top and would permit mixing of shells of various ages over considerable cross-shelf distances. This superposition of Holocene and older bay-barrier systems can therefore provide an alternative explanation for mixed-age lags at specific depths, even if varying rates of sea-level rise are discounted. We feel that both phenomena are independently documented and may well have acted together. Recognition of this complexity is important in assessing both paleogeographic and geochronologic interpretations.

SUMMARY

American oyster (*Crassostrea virginica*) shells collected at nine sites on the Alabama continental shelf in the northeastern Gulf of Mexico have yielded 27 radiocarbon ages between 8,400 and 36,000 yr BP. Ages and water depths of collection sites of these shells are generally consistent with ages and water depths of shells from the U.S. Atlantic shelf. Some shells appear to represent *in situ* estuarine deposits, whereas others have radiocarbon ages that appear inconsistent with origins near late Pleistocene sea levels. We feel that uncertainties in accuracy of radiocarbon ages greater than 15,000 yr, together with the generally good physical condition of the shells, provide no compelling evidence for long-distance cross-shelf transport of shells.

The nine youngest shells, from six different sites, have age-depth relations consistent with estuarine origins. The radiocarbon ages of older shells are problematic; while some can be tied to particular sea-level curves, many are from depths above postulated sea levels during late Pleistocene glacial conditions (Figure 3). Given the likelihood of significant errors in radiocarbon ages, such that true ages of these shells may be much greater than their radiocarbon ages, and the independent interpretation of sea levels that would be compatible with oyster habitat near these locations between 25,000 and 115,000 yr BP (Figure 5), we feel that a call for significant cross-shelf transport, either seaward or landward, is unwarranted. Nonetheless, we feel that reworking and erosion of estuarine deposits, with resultant lagging of shells, are likely to have occurred.

Notable concentrations of mixed-age shells occur at 40 m and 20 m depths. We interpret these concentrations as lags documenting changes in rate of sea-level rise and/or the superposition of Holocene and older paleo-estuarine systems. The 40 m lag either resulted from a decreased rate of rise in sea level over the period 9,800 to 9,000 yr BP followed by a brief interval of increased rate of rise in sea level; or it is a combination of Holocene estuarine deposits and paleo-estuarine deposits from interstadial sea levels around −40 m dating from 25,000 to 76,000 yr BP (Figure 5; CHAPPELL and VEEH, 1978). The 20 m lag represents a reworking of pre-Holocene shells and lithified sediment during a subsequent decrease in the rate of rise in sea level postulated at 8,200 to 7,800 yr BP; it may overlie interstadial paleoestuarine deposits from the period between 80,000 and 115,000 yr BP (Figure 5).

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