Late Quaternary Shelf-Margin Deltas in the Northern Gulf of Mexico: Implications for the Late Quaternary Sea-Level Elevation at the Culmination of the Last Glacial Maximum

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Abstract

New regional seismic-stratigraphic analysis of shelf-margin delta geomorphology at three locations in the northeastern Gulf of Mexico support the Hughes et al. (1981) view that sea-level elevation during the last glacial maximum (as opposed to the magnitude of eustatic rise since the last glacial maximum) was ~90 m below present-day sea level provided that the northeastern sector of the Gulf of Mexico has experienced only isostatic uplift since the last glacial maximum.

Introduction

Numerous lines of evidence show that eustatic levels were significantly lower ~18 Ka BP; i.e., during the last glacial maximum (Shepard, 1973; Hughes et al., 1981; Fairbanks, 1989; etc.). The rapid and large-amplitude sea-level change within Earth’s recent history demonstrate the highly dynamic nature of the cryosphere that has characterized Earth climate systems during at least the last 800 ka (Shackleton and Opdyke, 1973). Despite the young age of the last glacial maximum (LGM), there is considerable uncertainty concerning (1) the exact magnitude of sea-level rise since LGM, and (2) the exact elevation of LGM eustatic levels.

In terms of the magnitude of sea-level rise, Hughes et al. (1981) proposed two scenarios on the basis of global-scale ice volume reconstruction. In their minimum ice-volume estimate, they proposed that sea-level rose by 127 m since LGM. In their maximum estimate, they proposed that sea level rose by 163 m. The disparity between these estimates is due to uncertainty in the height of land-based ice sheets and the degree to which ice-sheet advances were synchronous during the LGM on a global scale. The 36-m difference between the minimum and maximum estimates is substantial and significantly exceeds the ice-volume equivalent attributed to Antarctic ice sheet expansion during the LGM (i.e., ~24 m sea-level equivalent according to Hughes et al., 1981).

On the basis of age/depth relationships of reef-top corals (Acropora palmata) offshore the island of Barbados, Fairbanks (1989) has suggested that sea level rose by ~121±5 m since the LGM. This value is in close agreement with the minimum estimate of Hughes et al. (1981); i.e., 127 m of relative sea-level rise. These two estimates (Fairbanks, 1989; Hughes et al., 1981) are also in relatively close agreement with Shepard’s (1973) estimate of -130 m sea level at the LGM. Shepard’s estimate of post-LGM sea-level rise is based on the worldwide average depth of shelf edges. Yet, it is interesting to note that Shepard also has reported that many margins have shelf-edge depths far greater (>200 m) and shallower (<70 m) than the 130 m global average. Is it that the large range in shelf-edge depth reported by Shepard (1973) represents natural variability in the style of isostatic adjustments for different types of continental margins?

In terms of the exact elevation of LGM sea level, Hughes et al. (1981) recognized that the large volume of water added to the world ocean should induce significant isostatic adjustments. According to Hughes et al. (1981), the water load associated with ~127 m relative sea-level rise (minimum estimate) would cause the ocean floor to be isotastically depressed by ~36 m. In
this scenario, the eustatic rise (e.g., with respect to the center of the Earth) would have been ~91 m. Applying the same reasoning to the Barbados estimate of 121 m eustatic rise suggests that the LGM sea-level elevation would have been ~87 m (i.e., the ocean floor has been isostatically depressed 34 m since the LGM). On a passive continental margin, the isostatic adjustment associated with the post-LGM water load would also have to be balanced against the local loading by delta deposition. In this study, we simply evaluated the geomorphology and stratigraphy of three shelf-margin deltas offshore Alabama and west Florida; i.e., in an area where the shelf-edge depth is shallow (= 100 m), to address the possibility that sea-level elevation during the LGM may have indeed been ~91 m below present-day sea level.

### Methods

For shelf-edge depth to be meaningful in terms of estimating sea-level elevation during the LGM, there are at least three questions that must be addressed: (1) Is the present-day shelf-edge geomorphology a consequence of the sea-level elevation at the LGM lowstand? (2) If so, what is the exact relationship between shelf-edge elevation and sea-level elevation? And (3) has the elevation of the shelf-edge elevation changed significantly since the LGM?

The Alabama-west Florida outer continental shelves and upper slopes have been selected because regional high-resolution seismic studies have been previously conducted (Bart and Anderson, in press; McKoewn et al., in press). Bart and Anderson (in press) identified two shelf-margin delta sequences offshore Pensacola and Mobile bays. The shelf-margin deltas exhibit relatively distinct offlap breaks (i.e., the transition between the topset and the foreset). Seismic correlation from these depocenters (unit 2 from Bart and Anderson, in press) to age control at MP303 occurred at 20 msec to account for the main energy arrival. We made our assumption that the source wavelet is ~45 msec in duration. The first arrival is weak and the majority of the wave energy occurs at 20 msec below the sea surface. The seismic source was towed from the port side and the streamer was towed from the starboard side of the Lone Star R/V. The separation between the source and the receiver was ~5 m. The direct arrival shows that the magnitude of relative sea-level rise was ~120 m.

1. Shelf-margin deltas offshore Mobile and Pensacola (i.e., unit 2 depocenters from Bart and Anderson, in press) and offshore Apalachicola (i.e., Unit 2 from McKoewn et al., in press) were deposited during the culmination of the LGM.

2. The water depth at the offlap break of Unit-2 shelf-margin deltas was ~10 m during the LGM (Bart and Ghoshal, 2003). [We defined the offlap break as the change from a gently dipping topset to a steeply dipping foreset. On the basis of our ongoing analyses of the modern Mississippi delta lobe (Bart and Ghoshal, 2003), we tentatively proposed that the average water depth of the offlap break was ~10 m.]

3. The magnitude of relative sea-level rise was ~120 m.

4. Post-LGM subsidence and ravinement was minimal.

The Alabama-west Florida and Apalachicola seismic grids were acquired in three field seasons (1994, 1996, and 1997) from the Lone Star R/V, using a single-channel streamer and 15 cubic inch water-gun source operated at 2000 pounds/square inch. Shipboard navigation was via differential GPS mode. The seismic source was suspended from a surface float that placed the seismic tool at approximately two feet below the sea surface. The seismic source was towed from the port side and the streamer was towed from the starboard side of the Lone Star R/V. The separation between the source and the receiver was ~5 m. The direct arrival shows that the source wavelet is ~45 msec in duration. The first arrival is weak and the majority of the wave energy occurs at 20 msec below the first arrival. We made our assumptions on the main energy peak and thus we subtracted 20 msec to account for the main energy arrival.
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occurring 20 msec later than the first energy arrival. We used a velocity of 1500 m/sec to convert twp-way travel time to water depth. To ensure that the seismic travel times were accurate, we calibrated the seismically predicted sea-floor times against the water depths predicted from a Fruno bottom profile onboard the Lone Star R/V as well against the bathymetric charts.

Results

Offlap Break Elevations Offshore Pensacola and Apalachicola

On the northeastern Gulf of Mexico outer continental shelf, regional seismic-stratigraphic correlations and mapping demonstrate that the offlap breaks of discrete shelf-margin deltas define the shelf-edge offshore Mobile and Pensacola bays (Bart and Anderson, in press) and offshore Apalachicola (McKoewn et al., in press). The locations of the LGM depocenters are shown on Figure 1. Between the Mobile and Pensacola depocenters, the shelf edge is defined by older shelf-margin deltas (Bart and Anderson, in press). Offshore Mobile Bay, the Unit-2 shelf-margin delta laps down on a surface that we infer is correlative to surface 10; i.e., the OIS 3 maximum flooding surface (defined by Sydow and Roberts (1994) from the Main Pass 303 drill site) (Fig. 2a). At this location, Unit 2 has a maximum thickness of 200 msec. The offlap-break elevation of Unit 2 delta is at 115 msec (~85 m) below sea level. The prograding-wedge foresets exhibit either toplap or termination near the sea floor on the outer shelf at a surface. The profile also shows deeper units, Unit-6 and Unit-7 prograding wedges, which are found across the study area. The upper bounding surfaces dip slightly in an offshore direction, and the top of the Unit-2 prograding wedges defines the sealfloor on the outer shelf and upper slope. On the middle shelf, a 30 to 40 msec thick shelf-perched unit, Unit-1, laps down and buries Unit-2. Faint discontinuous reflectors within Unit-1 suggest low-angle progradation to the south and southeast. At its basinward edge, Unit-1 has an irregular taper before it pinches out at a depth of 105 msec (~80 m). The landward edge of Unit-1 extends beyond the limits of the study area. On the upper slope, strata onlap the foresets of the prograding wedges.

Regional correlations show that a shelf-margin depocenter south of Pensacola Bay is stratigraphically equivalent to the Mobile depocenter (Bart and Anderson, in press). Seismic profile 47 (Fig. 2b) shows the stacking of the Unit-2 shelf-margin delta offshore Pensacola. At this location, Unit-2 has a maximum thickness of 100 msec. The Unit-2 offlap break has an elevation of ~100 msec (75 m) below sea level. On the outer shelf, the shelf perched unit, Unit-1, overlies the Unit-2 prograding wedge and pinches out at a water depth of ~80 msec (60 m). Unit-6 and -7 prograding wedge strata underlie the inner shelf.

Seismic profile APL-03 (Fig. 2c) shows the Unit-2 prograding delta offshore Apalachicola, Florida. Unit-2 has a maximum thickness of 80 msec. The top of the unit is a fluvial incision topset surface that can be correlated to the inner shelf where it truncates older strata. The wedge-shaped Unit-2 shelf-margin delta is confined to the outer shelf. Unit-2 morphology locally defines the shelf-edge (Fig. 1). The water depth at the offlap break is ~120 msec (~90 m) (Fig. 2c). Delta clinoforms in Unit 2 grade from shingled and oblique parallel to oblique tangential seaward. Locally, sigmoidal clinoform geometries are preserved associated with delta lobe switching and progradational centers.

Discussion

Although our visual method of choosing the position of the offlap break on 2-D profiles was not highly precise, the results clearly showed that Unit-2 offlap breaks were well above 120 m water depth. Moreover, seismic correlation demonstrates that the offlap break of Unit-2 deltas only locally defined the shelf edge (Fig. 2). Elsewhere, the shelf edge was defined by older shelf-margin deltas. If offlap breaks formed in a water depth of 10 m (Bart and Ghoshal, 2003), and if the Unit-2 shelf-margin deltas were deposited during the LGM, the LGM sea-level elevation might have been 65 m to 80 m below present sea level (Table 1), which would be significantly shallower than the generally accepted estimate of eustatic rise since LGM (i.e., the ~120 m estimate from Fairbanks, 1989). The relative shallow depths of offlap breaks observed offshore Alabama and west Florida suggested at least three possibilities: (1) Unit-2 shelf-margin del-
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tares were deposited before or after the LGM when sea level was higher. (2) The Alabama/west Florida shelf-edge region experienced isostatic uplift. Or (3) The LGM sea-level elevation was indeed significantly less than 120 m. In this following section, we consider these possibilities.

How Well is the LGM Age of Unit-2 Shelf-Margin Deltas Constrained?

The LGM age of the Unit-2 deltas is not well constrained and additional chronostratigraphic data are needed to confirm this fundamental assumption. For example, in one possible scenario, Unit-2 shelf-margin deltas might have been constructed during a stillstand of the overall transgression after sea-level elevation already had undergone a significant rise. This possibility is discounted because we observe no onlap between Unit-2 and the underlying strata. In addition, if the Barbados sea-level curve (Fairbanks, 1989) is indeed valid and our assumption concerning the relationship between offlap break elevation and sea-level elevation is correct, then Unit-2 depocenters may have been built and abandoned during the rapid transgression between ~10.5 Ka BP and ~12 Ka BP (Libby years of the radiocarbon scale); i.e., from ~8.5 Ka BP and ~12.5 Ka BP). Moreover, the regional extent of Unit-1 strata offshore Mobile and Pensacola bays on the middle continental shelf suggests that Unit-1 represents a transgressive systems tract; i.e., the first major back-step of the coastal plain. The depositional pinchout of Unit-1 landward of the shelf edge also shows that the shallow elevation of the Unit-2 offlap break is not a consequence of aggradation of sediment during the transgression and highstand.

Why Have the Alabama and West Florida Margins Not Experienced Significant Isostatic Depression Since the LGM?

As is the case for most ocean-basin passive margins, the Louisiana and Texas continental shelf edge is located well into the basin and thus overlies either transitional continental crust or oceanic crust. The large volumes of sediments offshore Louisiana and Texas might thermally weaken the underlying lithosphere in two ways: (1) A thick sediment blanket would insulate the underlying lithosphere and thus retard its cooling; and (2) The heavy load of sediments would depress the base of the lithosphere into regions of higher temperatures. In contrast, due to the relatively small influx of clastics to the northeastern Gulf of Mexico during the Cenozoic, the shelf edge offshore Alabama and west Florida does not extend far into the basin. Thus, the shelf edge in this sector of the Gulf Basin probably overlies relatively cool and unattenuated continental crust. If these lines of reasoning are accepted, the thermally weakened lithosphere offshore Texas and Louisiana probably would experience greater magnitudes of isostatic adjustment associated with new loads (e.g., water loads during post-LGM sea-level rise) than the cooler lithosphere offshore Alabama and west Florida. The shallow shelf edges observed in the northeastern Gulf of Mexico may be a consequence of lower subsidence associated with the small sediment loads on the relatively strong continental crust.

The passive-margin tectonic setting of the northeastern Gulf of Mexico (and other mature passive margins) are distinctly different from that of Barbados, the solitary emergent part of a large accretionary prism at the juncture of two converging oceanic plates; i.e., Atlantic plate subducting below the Caribbean plate. Given this difference in plate tectonic settings (and the underlying rheology), the Barbados margin (an oceanic setting) probably responds to loading (by either sediment and/or water) quite differently than do passive continental margins like the northern Gulf of Mexico. From a theoretical perspective, loading of continental lithosphere should induce more isostatic depression than would similar loading of oceanic lithosphere. If this assumption is correct, offlap-break elevations on passive continental margins (i.e., Alabama and west Florida)
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should be deeper than the elevation of the shallow-water strata observed offshore Barbados. The actual offlap-break elevations are the reverse of what we observe. This dilemma (the shallow elevation of offlap breaks offshore Alabama and west Florida) suggests to us that the northeastern sector of the Gulf of Mexico has experienced minimal isostatic depression and may in fact have experienced isostatic uplift.

Is it Possible That the Northeast Sector of the Gulf of Mexico has Undergone Isostatic Uplift?

The shallow water depths of Unit-2 offlap breaks today suggest that the area may have experienced significant isostatic uplift. Moreover, the 20 m range in offlap-break elevations (-65 to -85 m) is relatively large (if the formation of Unit-2 offlap breaks from these three study areas was indeed coeval) suggesting that uplift across the region may have been variable. We discount the possibility that there have been significant differentials in the rates of transgressive ravinement because the three shelf-margin deltas evaluated have similar orientations with respect to approach of prevailing winds from the southeast. Moreover, the 20-m differential in Unit-2 offlap-break elevations probably is not due to large-scale lateral variations in subsidence because the study areas are beyond the influence of growth faulting and thick mobile salt.

The northeast sector of the Gulf of Mexico outer continental shelf may be experiencing isostatic uplift owing to the much larger volume of sediment loading the basin the west offshore Texas and Louisiana. The shelf-margin deltas considered in this study are 180 km, 250 km, and 350 km east of the modern Mississippi River delta (Fig. 1). It is possible for example, that the Alabama and west Florida outer continental shelf is elevated as part of a peripheral bulge. If LGM sea-level elevation was ~90 m (Hughes et al., 1981), then a 65-m elevation of the Unit-2 offlap break offshore Pensacola would have to have been uplifted 25 m since LGM (i.e., an average uplift rate of 1.38 mm/a during the past 18 Ka). In one possible scenario, the Pensacola-sector of the northeastern Gulf of Mexico (where the Unit-2 offlap break is shallowest) corresponds to the crest of the peripheral bulge whereas the flanks to the east (Apalachicola sector) and west (Mobile-Bay sector) (where corrected depth of Unit-2 offlap breaks are deeper, 70 m and 85 m, respectively) would have experienced isostatic uplift at slightly slower rates (e.g., 1.11 mm/a and 0.28 mm/a, respectively). If high rates of uplift also affected the coastal zone during the Holocene, there should be geologic evidence of elevated shoreline features onshore. We know of no such studies indicating such. Detailed geomorphic modeling and geomorphologic studies and are needed to evaluate further this possibility.

Our preliminary investigation favors the minimum estimate proposed by Hughes et al. (1981); i.e., that the LGM sea level was ~91 m lower than today only provided that the Alabama/west Florida outer continental shelf region has experienced significant isostatic uplift. We acknowledge that there is considerable uncertainty involved in our evaluation. Our ongoing studies are aimed at conducting more detailed and quantitative analyses of the important questions concerning the nature and magnitude of sea-level change and lithospheric response since the LGM.

Conclusions

On the basis of a regional seismic-stratigraphic analysis of shelf-margin deltas in the northeastern Gulf of Mexico, we favor the Hughes et al. (1981) view that the sea-level lowstand elevation was ~90 meters below present-day sea level. We tentatively propose that the northeastern sector of the Gulf of Mexico has undergone isostatic uplift associated with the large-volume sediment load to the west. The 20-m differential between offlap-break elevations of LGM shelf-margin deltas offshore Pensacola Bay and Apalachicola respectively may correspond to the crest and flank of the peripheral bulge associated with large volume sediment loads to the west. In this scenario, deeper offlap-break elevations observed offshore Texas, Louisiana and Mississippi may be a consequence of high subsidence associated with loading of thermally weakened lithosphere underlying those regions. We acknowledge that additional data and modeling are needed to confirm these tentative hypotheses.
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References


Table 1. Elevations of Unit-2 shelf edge elevations with respect to present-day sea-level offshore A. Mobile, Alabama, B. Pensacola, Florida and C. Apalachicola, Florida. The 10-m correction to the observed elevations of offlap breaks is based on the assumption that offlap breaks formed in 10-m water depths (Bart and Ghoshal, 2003).

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Figure 1. Study area location map showing drainage basins, surface geology, bathymetry, and seismic grids offshore Mobile Bay, Pensacola Bay and Apalachicola.
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Figure 2. (A) Interpreted line drawing of dip-oriented seismic segment of Profile 5 showing prograding wedges Units 2, 6, 7, and shelf-perched Unit-1 on the outer continental shelf offshore Mobile Alabama. (B) Interpreted line drawing of Profile 47 showing the coeval Unit-2 prograding wedges offshore Pensacola, Florida. A shelf-perched unit, Unit-1, caps the prograding-wedge at the outer shelf. (C) Interpreted line drawing of Profile APL03 showing the Unit-2 prograding wedge offshore Apalachicola, Florida. The transgressive systems tract is condensed at this location.