How stable is the Mississippi Delta?

Torbjörn E. Törnqvist*
Department of Earth and Environmental Sciences, Tulane University, 6823 St. Charles Avenue, New Orleans, Louisiana 70118-5698, USA
Scott J. Bick†
Department of Earth and Environmental Sciences, University of Illinois at Chicago, 845 West Taylor Street, Chicago, Illinois 60607-7059, USA
Klaas van der Borg
Arie F.M. de Jong
Robert J. Van de Graaff Laboratory, Utrecht University, P.O. Box 80000, NL-3508 TA Utrecht, Netherlands

ABSTRACT

Large deltas are commonly believed to exhibit rapid rates of tectonic subsidence, largely due to sediment loading of the lithosphere. As a result, deltaic plains are prone to accelerated relative sea-level rise, coastal erosion, and wetland loss. Hurricane Katrina's devastation testifies to the severe threat that these processes pose to the Mississippi Delta, but the relative role of tectonics versus other mechanisms causing land subsidence remains elusive. Relative sea-level records derived from basal peat have the potential to quantify differential crustal movements over Holocene time scales with exceptionally high accuracy and precision. Here we present new sea-level index points from two study areas in the southwestern Mississippi Delta that essentially coincide with a recently published detailed relative sea-level record from the eastern part of the delta. Our results show that differential vertical movements among the three study areas have been only ~0.1 mm yr^{-1}. We compare our evidence with a recent sea-level compilation from the Caribbean, to a large extent based on data from areas that are tectonically stable. Our sea-level index points nearly coincide with the Caribbean data, showing surprising tectonic stability for considerable sections of the Mississippi Delta. However, the well-documented high subsidence rates in and near the birdfoot of the Mississippi Delta indicate that different conditions prevail there. The rapid wetland loss in coastal Louisiana is likely due, to a considerable extent, to the compaction of Holocene strata.

Keywords: Mississippi Delta, sea-level change, subsidence, Holocene.

INTRODUCTION

Large deltas are generally believed to be environments that undergo comparatively rapid tectonic subsidence, primarily by means of flexural depression of the lithosphere due to high sedimentation rates (e.g., Morgan, 1970). Because many world deltas are densely populated, there is serious concern about tectonic subsidence as a potential contributor to accelerated relative sea-level (RSL) rise, coastal erosion, and wetland loss (we use the term "tectonic" here in a broad sense, encompassing long-term thermal subsidence as well as subsidence induced by sediment loading, growth faulting, and compaction of pre-Holocene strata). The Mississippi Delta has a long history of investigations that have documented a rapid seaward increase in tectonic subsidence rates, particularly near the present shoreline and around the birdfoot delta (e.g., Russell, 1940; Fisk and McFarlan, 1955; Stanley et al., 1996). In the course of the twentieth century, wetland loss in coastal Louisiana (Fig. 1) has increased to rates as high as 50–100 km^2 yr^{-1} (Gagliano et al., 1981), a severe environmental problem that was placed in the international spotlight by Hurricane Katrina.

Holocene neotectonic activity (e.g., faulting, tilting) is widely recognized as a significant process in many world deltas, such as the Nile (Stanley, 1988), the Ganges-Brahmaputra (Goodbred et al., 2003), the Yangtze (Stanley and Chen, 1993), the Po (Carminati et al., 2003), and the Rhine-Meuse (Törnqvist et al., 1998; Cohen, 2005). Hence, considerable work in deltaic plains has focused on identifying areas of increased tectonic subsidence rates that are particularly sensitive to coastal erosion, flooding, and wetland loss. A detailed understanding of spatial subsidence patterns is paramount to enable future projections of coastal wetland stability in the Mississippi Delta under conditions of accelerated RSL rise.

Despite the strong interest in quantifying tectonic subsidence rates in large deltas, relatively few of such studies have been carried out. Previous investigations (e.g., Stanley, 1988; Stanley and Chen, 1993; Stanley and Warne, 1993; Carminati et al., 2003) typically estimated subsidence rates with millimeter per year accuracy and precision. The resolving power of these studies was limited either by assumptions about the timing of the onset of deltaic deposition, by uncertainties in the sea-level relationship of ^{14}C dated materials, and/or by the use of data prone to compaction of Holocene strata. Recent advances on several fronts (notably the advent of direct accelerator mass spectrometry [AMS] ^{14}C dating of sea-level indicators and global positioning system [GPS] based elevation measurements) offer new opportunities for unprecedented accuracy and precision in quantifying deltaic neotectonics (e.g., Cohen, 2005), as much as an order of magnitude better (~0.1 mm yr^{-1}) than previous studies. Here we present new high-resolution RSL data to measure the subsidence of the Pleistocene basement in different parts of the Mississippi Delta, suggesting that con-

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*E-mail: tor@tulane.edu.
†Present address: UNAVCO, Inc., 1600 Chicago Avenue, Suite R5-R7, Riverside, California 92507-2069, USA.

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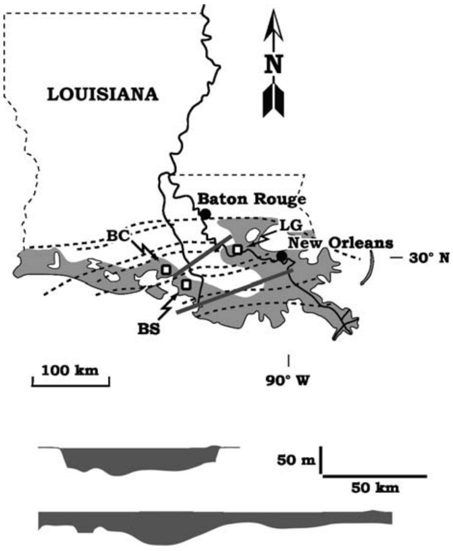

Figure 1. Location map; areas undergoing coastal wetland loss are shaded (after Van Beek and Meyer-Arendt, 1982). Dashed lines indicate principal growth-fault systems (after Murray, 1961) and two cross sections show thickness of topstratum, roughly equivalent to Holocene cover (after Fisk and McFarlan, 1955). Note different structural position of study areas, plus different thickness of nearby Holocene sediment loads. cal—calendar; LG—Lutcher-Gramercy area; BC—Bayou Cypremort area; BS—Bayou Sale area.

siderable sections of this large depocenter are surprisingly stable.

METHODS

The strategy followed involves the comparison of RSL data from three separate study areas. The thrust of our analysis is that, given spatially uniform eustatic and glacio-hydro-isostatic signals (e.g., Mitrovica and Milne, 2002), any contrasts between RSL curves can be attributed to differential tectonic subsidence rates. Our approach is based on the use of basal peat samples as sea-level indicators, adhering to the rationale that the initial Holocene transgression of the highly consolidated Pleistocene basement of the Mississippi Delta results in onlap by a peat-forming wetland. Peat formation begins as soon as the water level rises above the land surface, and provided that this water level can be related unequivocally to sea level, extremely detailed RSL records unaffected by compaction of Holocene strata can be obtained. Building on the pioneering work by Chmura et al. (1987) and a recent sea-level study in the eastern Mississippi Delta (Törnqvist et al., 2004), we use the carbon isotope signature of basal peat plant remains as a proxy for paleosalinity. Brackish to saline marsh vegetation is dominated by C_4 taxa with distinctly heavier $\delta^{13}C$ values than freshwater C_3 plants. This provides us with a tool to verify whether peat accumulation was directly controlled by sea-level rise.

The Gulf of Mexico is an exceptionally favorable setting for obtaining high-resolution Holocene RSL data because of its microtidal regime with a present-day spring tidal range in coastal Louisiana <60 cm, commonly ~40 cm. Salt-marsh peat is common in the Mississippi Delta, providing sensitive sea-level indicators that formed within the <30 cm zone between mean high water (MHW) and mean sea level (MSL). Samples were collected by means of hand coring and plant macrofossils were extracted from the basal peat samples for AMS ^{14}C measurement.

Given our focus on vertical movements, accurate and precise elevation measurements of sampling sites are of utmost importance. Similar to our previous work we used a combination of differential GPS measurements and optical surveying with an electronic total station. Our methodology with respect to the construction of error boxes of sea-level index points (i.e., ^{14}C age calibration procedures and vertical error estimates) is identical to that followed in Törnqvist et al. (2004); further details can be found there.

STUDY AREAS AND RESULTS

The results of Törnqvist et al. (2004) for the Lutcher-Gramercy area between New Orleans and Baton Rouge serve as the reference data set. That investigation already suggested more stability of the Pleistocene basement than expected, which might be a partial result of the fact that the Lutcher-Gramercy area is located relatively far inland (Fig. 1). For comparison, the flexure zone in the Nile Delta that separates stable from subsiding areas is found only 15–45 km landward of the shoreline (Stanley and Warne, 1993). Thus, our new data were obtained from localities that are much closer to the coast in the southwestern Mississippi Delta and structurally downdip from the Lutcher-Gramercy area, near distributaries known as Bayou Cypremort and Bayou Sale, respectively. All study areas are in the vicinity of substantial, yet variable (30–60 m thick) Holocene sediment loads (Fig. 1).

Elevations were obtained with reference to National Geodetic Survey (NGS) benchmarks L043 (Bayou Cypremort area) and T168 (Bayou Sale area), both classified as stability category C, defined by the NGS as ''may hold, but of the type commonly subject to surface motion.'' The benchmark used previously in the Lutcher-Gramercy area (BJ3747) is of the more reliable stability category B. We carried out simultaneous differential GPS measurements during 2–3 consecutive days (6 h per day) to obtain elevation data for the three NGS benchmarks with respect to the North American Vertical Datum 88, using the GEOID99 model. As discussed in more detail by Bick (2005), the elevation differences of the NGS benchmarks in the three study areas were corroborated by the GPS surveys within 3 cm. The purely gravimetric G99SSS geoid model provides elevation differences for the three benchmarks that are similar to those of the GEOID99 model within 17 cm. This shows that these NGS benchmarks are sufficiently robust for our purposes, and thus that any differences between sea-level index points from the three study areas can be attributed to long-term vertical movements.

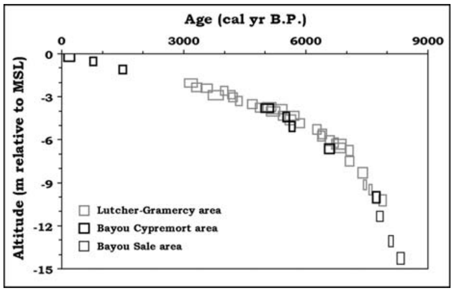

Figure 2. Sea-level index points (error boxes) from Lutcher-Gramercy (after Törnqvist et al., 2004), Bayou Cypremort, and Bayou Sale areas (MSL—mean sea level; cal—calendar). Error boxes are defined such to incorporate rise of mean sea level with at least 95% probability. For location of study areas see Figure 1.

Underpinning our analysis is a database of ~200 cores from the Bayou Cypremort area and ~20 cores from the Bayou Sale area. Detailed cross sections were constructed so as to select sampling sites for basal peat ^{14}C dating (see GSA Data Repository[1]). While basal peat is not continuous in either study area, it is much more common near Bayou Cypremort, where it was encountered in a depth range from near present MSL to ~10 m below MSL. In the Bayou Sale area, suitable basal organics only occur at depths >11 m below MSL. All samples were collected from the very base of organic-rich facies immediately overlying a weakly developed paleosol that caps highly consolidated (mostly Pleistocene) strata.

Figure 2 shows a plot of the sea-level index points from the Lutcher-Gramercy area (Törnqvist et al., 2004), plus the new data from the Bayou Cypremort and Bayou Sale areas. Several of the dated herbaceous charcoal samples have $\delta^{13}C$ values heavier than $-20‰$ (see footnote 1), suggesting that they likely derive from *Spartina* spp. Thus, we infer that peat formation occurred within the intertidal zone.

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[1] GSA Data Repository item 2006115, cross sections and radiocarbon data, is available online at www.geosociety.org/pubs/ft2006.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA.

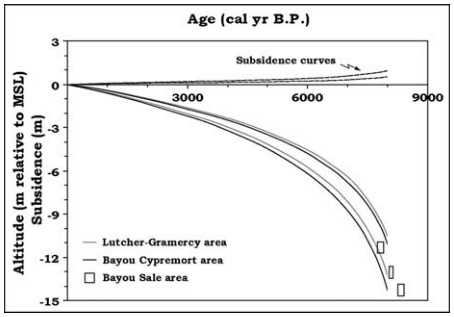

Figure 3. Regression analysis of data from Figure 2, featuring upper and lower bounds for data sets from Lutcher-Gramercy (gray lines) and Bayou Cypremort (black lines) areas. cal—calendar. Equation is of form AGE = P1 × exp(–P2 × ALTITUDE), applied to upper right and lower left corners of error boxes in Figure 2. All regression lines have r^2 of 0.99 or better; for further details see Bick (2005). Also indicated are three Bayou Sale area sea-level index points that are largely consistent with error envelopes defined by regression analysis. Upper part of graph shows difference between two upper and two lower regression lines, providing subsidence curves for Bayou Cypremort area relative to Lutcher-Gramercy area. MSL—mean sea level.

The error boxes from all three study areas show a common coherent pattern that can be mathematically described by an exponential function, as was demonstrated previously for the Lutcher-Gramercy data set (Törnqvist et al., 2002). We carried out a least squares regression analysis for the Lutcher-Gramercy and Bayou Cypremort areas, both of which had a sufficient amount of data for this purpose. Our regression analysis (Fig. 3) took into account the errors of the sea-level index points by means of a separate calculation, for both study areas, of exponential curves fitted to the upper right and lower left corners of the error boxes. The obtained error envelopes represent a highly conservative reconstruction of RSL rise, because the corners of the error boxes represent 95% confidence limits in both the horizontal (age) and vertical (altitude) dimensions (cf. Törnqvist et al., 2004).

The difference between the upper and lower regression lines for the two study areas is shown in Figure 3 by means of two subsidence curves. These curves indicate vertical differences of <1 m at 8000 calendar (cal) yr B.P. This translates into averaged subsidence rates of the Bayou Cypremort area, relative to the Lutcher-Gramercy area, of 0.06–0.12 mm yr^{-1}. Given the large overlap between the two envelopes, we could even entertain the slight possibility that the Lutcher-Gramercy area subsides relative to the Bayou Cypremort area. Because we only have a few relatively old sea-level index points from the Bayou Sale area, regression analysis was not feasible for this data set. However, the three error boxes are not offset relative to the error envelopes for the two other study areas. In addition, the youngest of the three Bayou Sale samples corresponds in age to the oldest sea-level index points from the other two study areas, and plots only ~1 m lower, translating into only a slightly higher rate of subsidence (~0.1 mm yr^{-1}). Thus, differential crustal movements among the three study areas are extremely small, and the growth-fault system between the Bayou Cypremort and Bayou Sale areas (Fig. 1) has seen limited activity during the past ~8 k.y.

DISCUSSION AND CONCLUSIONS

There is considerable controversy about the primary causes of subsidence and wetland loss in coastal Louisiana. Many investigators have favored compaction of Holocene strata (e.g., Penland and Ramsey, 1990), fluid withdrawal from the deeper subsurface (e.g., Morton et al., 2003), growth-fault activity (e.g., Kuecher et al., 2001), or combinations thereof. However, a recent geodetic study based on high-resolution leveling data (Shinkle and Dokka, 2004) has argued for present-day subsidence rates of 10–15 mm yr^{-1} in the Mississippi Delta and 5–10 mm yr^{-1} in much of the states of Louisiana and Mississippi, extending as far inland as Memphis, Tennessee. This would imply very high subsidence rates of the Pleistocene surface.

The finding that our three study areas exhibit such strikingly similar tectonic histories for at least the past ~8 k.y. leaves the question open whether they simply happen to subside at nearly equal, yet rapid rates. Therefore, we compared our RSL data with sea-level records from elsewhere. Toscano and Macintyre (2003) published an extensive compilation of RSL data from the Caribbean, based on coral (*Acropora palmata*) and mangrove (*Rhizopora mangle*) peat data. They inferred a composite RSL trend curve for the Caribbean region, consisting of a smooth line that separates coral data that must have formed below MSL from the mangrove data that must have formed between MSL and MHW. Much of their data derive from settings (e.g., Florida, Bahamas, Belize) that are widely believed to be tectonically very stable, in particular over Holocene time scales. We compared our data with their RSL curve (Fig. 4) and find that they essentially coincide. Toscano and Macintyre (2003) stressed the uncertainties in their data set due to the coverage of a very large area with inherent spatial variation of both tectonics and isostasy. Nevertheless, only considering Caribbean basal peat data does not allow the trend curve to be shifted upward, so it is unlikely that any difference between our data and the Caribbean record can be ascribed to this. The similarity between the data from the Mississippi Delta and the Caribbean supports the notion that glacio-isostatic forebulge collapse associated with the melting of the Laurentide Ice Sheet extends to northernmost South America, consistent with geophysical modeling by Milne et al. (2005).

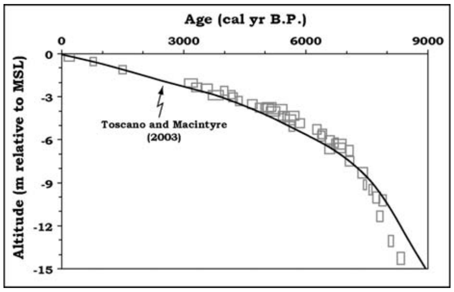

Figure 4. Comparison of all sea-level index points from Mississippi Delta (gray boxes) with Caribbean relative sea-level curve (Toscano and Macintyre, 2003). MSL—mean sea level; cal—calendar.

We conclude that the Pleistocene basement in significant sections of the Mississippi Delta may be much more stable than is commonly believed, and our data are in conflict with the extremely high subsidence rates advocated by Shinkle and Dokka (2004). Furthermore, our evidence strongly suggests that fault-induced subsidence rates as high as 16.9 mm yr^{-1} in the New Orleans area, as inferred by Dokka (2006), must have been limited to the brief time interval that his geodetic data capture, and cannot have played any significant role earlier during the Holocene. The implication of this is, at least for the areas that we have studied, that subsidence of the land surface and associated wetland loss is likely caused, to a large extent, by the compaction of Holocene strata (cf. Penland and Ramsey, 1990). However, the difference (up to two orders of magnitude) between our data and the geodetic data makes it hard to explain such high compaction rates, particularly in areas with relatively thin Holocene covers. In this context, it should be noted that many other factors (e.g., dredging of canals) influence wetland loss.

Many world deltas for which rapid and/or complex tectonic subsidence has been documented are located nearby or within active (Nile) or failed (Rhine-Meuse) rifts, in foreland basins (Po), or in other tectonically active settings (Ganges-Brahmaputra). The Mississippi Delta is surrounded by a thermally mature passive margin characterized by extremely slow subsidence rates (0.05 mm yr^{-1} or less along the central coast of Texas; Paine, 1993), only slightly less than the rates inferred from our study areas. Isopach maps of Pliocene–Pleistocene deposits (Woodbury et al., 1973) suggest that average subsidence rates in our study areas during the past 3 m.y. have been 0.25 mm yr^{-1} or less. These slightly higher values may be related to the gradual seaward shift of the principal depocenter to a position near the present shelf edge during this time interval.

Conditions are likely to be very different in and near the birdfoot of the Mississippi Delta. The Holocene succession in this area is >100 m thick (e.g., Coleman and Roberts, 1988; Stanley et al., 1996). Coleman (1981) ascribed these exceptional thicknesses to rapid dewatering and deformation of underlying Pleistocene strata, as reflected by the widespread presence of mud diapirs. In their visionary paper, Fisk and McFarlan (1955) speculated on the relative role of mantle flow versus adjustment within the sedimentary crust as causes of subsidence. Although it remains to be determined which factor is most significant, we favor the latter. Contrary to our study areas where Pleistocene strata were subaerially exposed for tens of thousands of years during the last glacial, their offshore marine counterparts continue to undergo dewatering today. Our results are strikingly consistent with the work by Fisk and McFarlan (1955) that inferred a dramatic seaward flexure of the Pleistocene basement, most of which is downdip of our study areas. The possibility of active growth faulting in these areas cannot be excluded, and RSL data from such localities could elucidate whether this pattern can be corroborated. Nevertheless, our current findings indicate that considerable areas in coastal Louisiana that are currently subject to rapid wetland loss (Fig. 1) are surprisingly tectonically stable.

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