Mississippi Delta subsidence primarily caused by compaction of Holocene strata

TORBJÖRN E. TÖRNQVIST[1*], DAVIN J. WALLACE[1†], JOEP E. A. STORMS[2‡], JAKOB WALLINGA[2§],
REMKE L. VAN DAM[2‖], MARTIJN BLAAUW[2¶], MAYKE S. DERKSEN[2#], CORNELIS J. W. KLERKS[2⋆],
CAMIEL MEIJNEKEN[2**] AND ELS M. A. SNIJDERS[2††]

[1] Department of Earth and Environmental Sciences, Tulane University, 6823 St. Charles Avenue, New Orleans, Louisiana 70118-5698, USA
[2] Department of Physical Geography, Utrecht University, PO Box 80115, NL-3508 TC Utrecht, The Netherlands
[†] Present address: Department of Earth Science, Rice University, Houston, Texas 77251, USA
[‡] Present address: Department of Geotechnology, Delft University of Technology, NL-2600 GA Delft, The Netherlands
[§] Present address: Netherlands Centre for Luminescence Dating, Delft University of Technology, NL-2629 JB Delft, The Netherlands
[‖] Present address: Department of Geological Sciences, Michigan State University, East Lansing, Michigan 48824, USA
[¶] Present address: Shell International Exploration and Production, NL-2280 AB Rijswijk, The Netherlands
[#] Present address: Government Service for Land and Water Management, NL-2500 CG The Hague, The Netherlands
[⋆] Present address: Vestigia Ltd Archaeology and Cultural History, NL-3813 AA Amersfoort, The Netherlands
[**] Present address: ProRail, NL-3500 GA Utrecht, The Netherlands
[††] Present address: Ministry of Housing, Spatial Planning and the Environment, NL-2500 GX The Hague, The Netherlands
[*] e-mail: tor@tulane.edu

Coastal subsidence causes sea-level rise, shoreline erosion and wetland loss, which poses a threat to coastal populations[1]. This is especially evident in the Mississippi Delta in the southern United States, which was devastated by Hurricane Katrina in 2005. The loss of protective wetlands is considered a critical factor in the extensive flood damage. The causes of subsidence in coastal Louisiana, attributed to factors as diverse as shallow compaction and deep crustal processes, remain controversial[2–11]. Current estimates of subsidence rates vary by several orders of magnitude[3,6]. Here, we use a series of radiocarbon-dated sediment cores from the Mississippi Delta to analyse late Holocene deposits and assess compaction rates. We find that millennial-scale compaction rates primarily associated with peat can reach 5 mm per year, values that exceed recent model predictions[5,9]. Locally and on timescales of decades to centuries, rates are likely to be 10 mm or more per year. We conclude that compaction of Holocene strata contributes significantly to the exceptionally high rates of relative sea-level rise and coastal wetland loss in the Mississippi Delta, and is likely to cause subsidence in other organic-rich and often densely populated coastal plains.

It is well established, from studies of both recent[12,13] and ancient[14] coastal strata, that organic-rich deposits (notably peat) undergo rapid compaction, particularly during the earliest stage after formation and burial. Model experiments[15,16] have addressed the compaction of Holocene coastal organic-rich deposits and demonstrated its profound stratigraphic implications, and recent field investigations[17] continue to single out peat compaction as a key control of coastal evolution. Nevertheless, although present-day compaction rates ('shallow subsidence') have been measured in the shallowest subsurface[18], few if any data sets exist that quantify compaction rates (defined here as occurring within the Holocene succession that overlies a comparatively compaction-free Pleistocene basement[5,9]) over timescales longer than a decade or so.

Peat is abundant in the Mississippi Delta and compaction has frequently been invoked as a major contributor to land subsidence and relative sea-level (RSL) rise[19]. A significant recent contribution in this context entailed stochastic modelling[5,9], suggesting that present-day compaction rates in the Mississippi Delta are probably <3 mm yr^{-1}, substantially lower than rates of RSL rise that are locally as high as $\sim$10 mm yr^{-1} over the past century[19]. However, model calculations have yet to be verified with field data that accurately quantify compaction rates over Holocene timescales. Although subsidence rates in the Mississippi Delta have been determined by a variety of methods[2–6,8,11,20], no observational studies currently exist that fully separate compaction from other processes contributing to subsidence. Such evidence is critical to (1) gain a better understanding of subsidence mechanisms and rates so as to ultimately increase the predictive power of numerical models; and (2) obtain baseline data for coastal management, including coastal restoration projects.

The present contribution relies on $>$100 shallow boreholes (mostly up to $\sim$15 m in depth) from a study area located around Bayou Lafourche (Fig. 1), a precursor of the Mississippi River. Previous work[21] established the late Holocene stratigraphy in this area, consisting of widespread (commonly clayey) wood peat overlain by silty to clayey fluvial overbank deposits sourced from Bayou Lafourche. Thus, an extensive peat-forming bald cypress swamp was draped with clastic material of variable thickness. Radiocarbon dating of the top of organic deposits in a detailed cross-section (Fig. 2) yielded consistent ages of 1,500 ^{14}C yr BP (ref. 21). A further ^{14}C sample (Elmfield I–1, 1,700 ± 20 ^{14}C yr BP) verified the age of this transition in a different part of the study area (Fig. 1). Collectively, the near-isochronous nature of

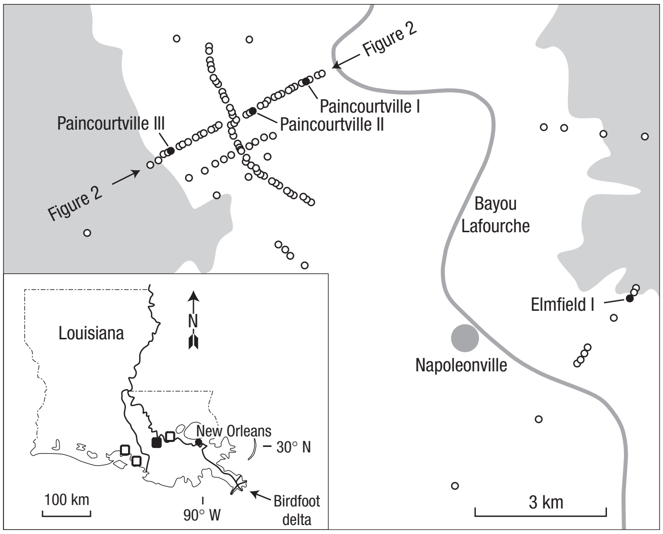

Figure 1 Map of the study area. Boreholes used for the compaction analysis are indicated by open circles. Filled circles are named core sites that were ^{14}C dated. Swamps are indicated by grey shading. Sample Elmfield I–1, UCIAMS-37154, 1,700 ± 20, coordinates: 694.320E/3314.280N/+2.0, depth: 402–404 cm, material dated: one *Taxodium distichum* cone fragment. The inset map shows the location of the study area (filled square); open squares are areas from which compaction-free RSL data were collected[6,7].

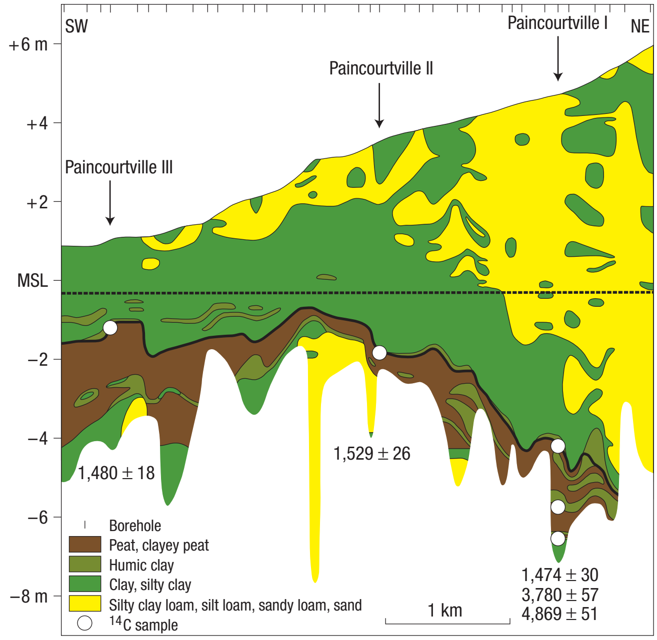

Figure 2 Cross-section perpendicular to Bayou Lafourche near Paincourtville, Louisiana. For location see Fig. 1. The thick dashed horizontal line is the reconstructed position of the peat-forming swamp surface at the beginning of activity of Bayou Lafourche, assumed to be ∼40 cm above the coeval mean high tide level (further explanation in text). The thick solid line is the position of this surface after compaction. Ages are in conventional ^{14}C years BP (Before Present = 1950 AD). The three youngest ages were derived from a total of eight subsamples that provided nearly identical results. Calibration yields an age of 1,400 calendar years before field data collection[21]. MSL = present-day mean sea level.

transitions such as the one considered here[22] plus the fact that peat-forming swamps are essentially flat topographic features with decimetre-scale microtopography, presents an exceptional opportunity to measure the deformation of this surface and to quantify rates of differential compaction. Whereas the age of this surface enables us to address millennial-scale processes, it is sufficiently young that compaction is unlikely to have long ago run its course, which would lead to grossly underestimated compaction rates. For our analysis, we selected evidence from a larger database of ∼250 boreholes and only used sites (Fig. 1) with an unequivocal transition from Bayou Lafourche overbank deposits to underlying wood peat, with the latter usually >30 cm in thickness.

We analysed the relationship between overburden thickness and compaction rate, on the basis of the following rationale. Recently collected compaction-free basal peat data from the Mississippi Delta[6,7] show that mean sea level was about 1 m below present around the beginning of activity of Bayou Lafourche. The peat-forming swamp in our study area must have been located at or above mean high tide level, ∼30 cm above coeval mean sea level (on the basis of the present-day tidal range). As our study area is well landward of the shoreline (currently >100 km, but probably substantially less ∼1,400 years ago), we must take into account the gentle slope of the (ground)water table that grades to sea level[23]. Using a gradient of 1.0–1.5 cm km^{-1} on the basis of the present-day slope of the lowermost reaches of the Mississippi and Atchafalaya rivers, we estimate the elevation of the swamp in our study area at ∼40 cm above the contemporaneous mean high tide level. Thus, we calculate compaction rates with respect to a surface at −30 cm relative to present mean sea level (Fig. 2). The uncertainties in the above assumptions have been incorporated in our calculations, but it is important to note that they have a minor impact on the overall outcome of the analysis. The appeal of this approach is that by tying our measurements to a nearby compaction-free RSL record derived from basal peat that accumulated immediately on the comparatively stable Pleistocene basement, we rule out other variables that contribute to subsidence but affect both data sets equally (that is, long-wavelength tectonic and isostatic processes associated with ice, water and sediment loading or unloading). No evidence exists for significant fault systems between our study area and the area where the majority of the RSL data was obtained, ∼30 km to the east. In other words, we have fully isolated the compaction component.

Our analysis (Fig. 3) suggests a striking linear relationship between compaction rate and overburden thickness. It is likely that this mainly involves secondary consolidation (sometimes referred to as creep) that is particularly prominent in peat, because the primary consolidation stage characterized by a rapidly decreasing permeability is believed to be very short[24]. The regression line that describes the relationship between compaction rate and overburden thickness does not intersect the origin. An explanation for this is that a considerable portion of the data set is affected by strata underlying the peat. Figure 2 shows a subsurface sand body (constituting a buried alluvial ridge) in the central part of the cross-section that has led to a thinner overlying peat bed and reduced compaction rates. We have identified all data points with positive evidence for such conditions (Fig. 3); removing these data would result in a gentler slope of the trend line.

We find compaction rates up to 5 mm yr^{-1} and argue here that these values are probably conservative. First, rates have been averaged over 1,200–1,600 years, yet it is highly improbable that they were constant over such a long time span. Indeed, it is conceivable that proximal overbank aggradation was initially rapid[25] and that compaction rates followed suit (that is, rates

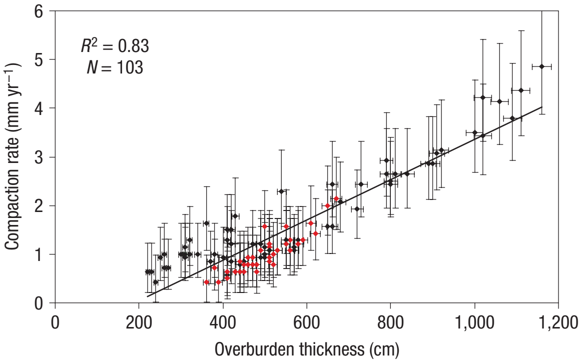

Figure 3 Relationship between overburden thickness and compaction rate. Data points in red represent sites with positive evidence for reduced compaction due to a subsurface sand body (other data points represent sites for which such evidence was not available, yet such conditions cannot be ruled out). For the overburden thickness (horizontal axis), a 2% error was used to account for non-vertical drilling (error increases with depth). For the compaction rates (vertical axis), an error of ±40 cm was applied for land-surface elevation (derived from topographic maps), ±40 cm for the inferred reference (ground)water level at −30 cm, plus the 2% error for depth measurement. The sum of these errors was calculated as $\sqrt{(e_1^2 + e_2^2 + \cdots + e_n^2)}$. In addition, a ±200 yr error was incorporated for the age of the clastic–organic transition.

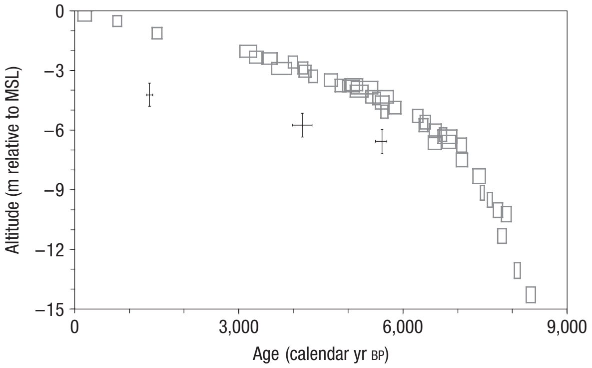

Figure 4 Comparison of compaction-prone and compaction-free ^{14}C samples. Three ^{14}C-dated wood peat samples from core Paincourtville I (see Fig. 2) plotted versus a compaction-free RSL record[6] represented by grey error boxes, mainly based on data obtained ∼30 km east of the Bayou Lafourche study area. The RSL record was derived from basal peat samples that accumulated immediately on the consolidated Pleistocene basement. Both data sets are affected equally by eustatic sea-level rise, glacio-hydro-isostasy, tectonic subsidence (including subsidence due to deltaic sediment loading) as well as compaction of pre-Holocene strata. Unlike the RSL record, the three samples from core Paincourtville I were in addition affected by compaction of underlying Holocene deposits.

decreased through time). Second, whereas Bayou Lafourche had already been abandoned when it was dammed in 1904, it must have become largely inactive well before that time. Thus, the duration of increased overburden loading due to active sedimentation (probably associated with high compaction rates) was probably significantly shorter than what is assumed here. Third, our study area overlies <40 m of Holocene, compaction-prone sediments[26]. Considerable portions of the Mississippi Delta are underlain by much thicker Holocene successions. For example, thicknesses are >100 m in the birdfoot delta (Fig. 1) that is characterized by exceptionally rapid deformation rates of buried prodelta deposits, as reflected by widespread mud diapirism[27]. On the basis of the above considerations, we estimate that compaction rates in the Mississippi Delta of 10 mm yr^{-1} or more are within the realm of possibilities, but only locally, under the right combination of circumstances and over timescales shorter (for example, 10^2 yr) than the time span considered above. However, within the study area, present-day compaction rates are probably well below 5 mm yr^{-1}.

As noted above, differential compaction due to subjacent lithological variability is a significant factor. For instance, studies in the Rhine–Meuse Delta, The Netherlands[28], provide an example of >6 m of differential compaction that could be related to a subsurface sand body. Following Bloom[13], we measured compaction rates for three ^{14}C-dated peat samples at one locality (Paincourtville I; Fig. 2) and compared their position with time-equivalent basal peat that did not experience Holocene compaction (Fig. 4). We find that all three samples have been vertically displaced by a minimum of 2 m (the deepest sample) to more than 3 m (the shallowest sample). Thus, even the base of the peat bed was displaced by at least 2 m, demonstrating considerable compaction of underlying strata.

Although compaction has long been recognized as an important process contributing to Mississippi Delta subsidence and RSL rise[18–20], direct measurements of compaction rates over timescales longer than a decade that rule out other variables have not been available, either from coastal Louisiana or elsewhere. Stochastic modelling[9] has identified peat beds alternating with relatively permeable clastic deposits, a condition not unlike that in our study area, as particularly compaction-prone facies successions. Nevertheless, assuming an age of basal (<40 m deep) Holocene deposits in our study area of 10 kyr (ref. 26), maximum probable modelled present-day compaction rates[5] barely exceed 1 mm yr^{-1}. Much higher compaction-dominated subsidence rates (6.4 mm yr^{-1}) have recently been reported for the New Orleans metropolitan area for a three-year time interval[4], although the premier driving force in that case is artificial drainage rather than overburden loading.

Although on one hand our findings show that (peat) compaction rates are particularly rapid in the uppermost 10–15 m, we note that compaction of deeper Holocene strata is also significant. This has important implications for geodetic studies of modern land-surface motions, as it cautions against inferring tectonic mechanisms (including faulting) from any such observations that are not firmly anchored in a highly consolidated Pleistocene basement[8,11]. In this context, we draw attention to the fact that the three continuous global positioning system stations that exhibit the highest subsidence rates in coastal Louisiana[8] are all located on Holocene successions that are at least twice as thick as the depth of their monuments.

Given that high compaction rates are probable in thick organic-rich successions, long-term success of coastal restoration requires a high proportion of clastic sediment, provided that adverse compaction effects due to overburden loading can be minimized. Our findings have considerable implications for proposed coastal restoration efforts that involve the creation of new river diversions to transfer water and sediment into areas that have experienced wetland loss in the past century[29]. Although recent work[30] has implicated that a predominantly riverine sediment supply should be capable of maintaining and rebuilding coastal wetlands, the effectiveness of diversions will depend heavily on the architecture of underlying Holocene strata that dictates compaction rates and their spatial variability. Our cross-section (Fig. 2) provides a vivid example of how thick peat beds can accommodate large volumes of sediment ($\sim$35% of the total volume of overbank deposits in this case), leading to reduced net surface-elevation gain. Clearly, successful coastal restoration will only be achievable if it is underpinned by a detailed understanding of subsurface sedimentary architecture. Our findings also suggest that only diversions considerably larger than the ones that have been experimented with so far are likely to be effective[29], because high sediment fluxes are required to offset shallow compaction that will remain a factor even under the best of circumstances.

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Correspondence and requests for materials should be addressed to T.E.T.

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