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Quantifying large-scale historical formation of accommodation in the Mississippi Delta

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ABSTRACT: Large volumes of new accommodation have formed within the Mississippi Delta plain since the mid-1950s in association with rapid conversion of coastal wetlands to open water. The three-dimensional aspects and processes responsible for accommodation formation were quantified by comparing surface elevations, water depths, and vertical displacements of stratigraphic contacts that were correlated between short sediment cores. Integration of data from remotely sensed images, sediment cores, and water-depth surveys at 10 geologically diverse areas in the delta plain provided a basis for estimating the total volume of accommodation formed by interior-wetland subsidence and subsequent erosion. Results indicate that at most of the study areas subsidence was a greater contributor than erosion to the formation of accommodation associated with wetland loss. Tens of millions of cubic meters of accommodation formed rapidly at each of the large open-water bodies that were formerly continuous interior delta-plain marsh. Together the individual study areas account for more than 440 × 10^6 m^3 of new accommodation that formed as holes in the Mississippi River delta-plain fabric between 1956 and 2004. This large volume provides an estimate of the new sediment that would be needed just at the study areas to restore the delta-plain wetlands to their pre-1956 areal extent and elevations. Published 2010. This article is a US Government work and is in the public domain in the USA.

KEYWORDS: subsidence; erosion; wetland loss; bathymetry; remote sensing; imagery analysis

Introduction

The Mississippi River Delta, one of the largest deltas in the world, was a vast area of sediment accumulation during the late Holocene, and extensive continuous wetlands were the primary subenvironment of the emergent delta plain (Kolb and van Lopik, 1958; Frazier, 1967). For millennia, these extensive biologically productive wetlands were healthy and relatively stable as demonstrated by early field surveys (Russell, 1936) and the oldest topographic maps and aerial photographs (Gagliano *et al.*, 1981; Britsch and Dunbar, 1993). Thick aggradational peats that underlie much of the emergent delta plain also attest to the widespread prolonged existence and accumulation of wetland vegetation (Frazier, 1967; Kosters, 1989); however, the most recent physiographic trend of the delta plain has been replacement of wetlands by open water.

Accommodation is the space available for sediment accumulation as a result of a rise in sea level and/or land subsidence (Jervey, 1988). Accommodation originally referred to the vast space formed within sedimentary basins over millions of years; however, the term also describes space formed over shorter time scales. Historical conversion of coastal-plain wetlands of the northern Gulf of Mexico to open water is an example of accommodation formed at the decadal scale (Morton *et al.*, 2006). In coastal Louisiana, historical accommodation formation (wetland loss) has been so severe that both state and federal agencies have prepared extensive plans to restore wetlands of the Mississippi Delta (National Research Council, 2006). Despite all of the prior analyses of land-water change in the Mississippi Delta, a systematic detailed evaluation of regional historical accommodation formation has not been attempted before because the logistics are complicated and data collection and analyses are time consuming and labor intensive. Consequently there are no estimates of the volume of accommodation that formed in conjunction with rapid wetland loss.

Several studies have documented the development of wetland loss in the Mississippi Delta by period and geographic area (Gagliano *et al.*, 1981; Britsch and Dunbar, 1993; Barras *et al.*, 2008). Although some wetland loss occurred before the mid-1950s, all of the studies have established that the period of extremely rapid wetland loss, which has gained international attention, occurred between the mid-1950s and the mid-1970s. Rapid collapse of the delta plain and formation of holes in the delta-plain fabric were unusual and difficult to explain, considering the antiquity of the delta lobes and prior excellent health and productivity of the emergent wetlands.

The history and causes of wetland loss within the Mississippi Delta plain are of important scientific interest, but our understanding of the relatively rapid morphological changes and conversion of wetlands to open water is incomplete because the depths of the open-water bodies and the areas they encompass have not been systematically documented and reported. We previously documented the sequential development of two-dimensional (2D) (area) accommodation in the Mississippi Delta plain by comparing historical maps and photographs (Morton *et al.*, 2005; Morton *et al.*, 2009b), but we did not have complementary bathymetric data to characterize the one-dimensional (1D) (vertical) accommodation distance, so the evolutionary history of three-dimensional (3D) accommodation (volume) lacked a critical element.

Blum and Roberts (2009) estimated the rate of accommodation formation that will occur above the present surface of the Mississippi Delta plain as a result of future subsidence and sea-level rise. In contrast, our study estimates the accommodation that formed historically below the delta-plain surface as wetlands were transformed to open water. Our study objectives were: (1) to quantify accommodation volume created where wetland loss in the Mississippi Delta was rapid and most extensive, (2) to quantify the primary surficial processes responsible for forming new accommodation in these areas, and (3) to compare the magnitudes of accommodation formed for different delta-plain settings, wetland types, marsh ages, and marsh-sediment properties. These objectives were accomplished by conducting multiple field campaigns involving global positioning system (GPS)-controlled coring operations and bathymetric surveys where wetlands had been converted to open water in the span of a few decades.

Methods

To quantify the 1D (vertical) and 3D (volume) accommodation recently formed in the Mississippi Delta (Figures 1 and 2, Tables I and II), short (<4-m-long) sediment cores, water depths, and water-level measurements were collected at five field areas in the Terrebonne hydrologic basin (Bully Camp, BC; Pointe au Chien, PAC; DeLarge, DL; Madison Bay, MB; Bay St Elaine, BSE) and five field areas in the Barataria hydrologic basin (Ironton, IRN; Bayou Perot, BP; Leeville, LEE; Fourchon, FCN; Caminada, CAM). At those 10 field areas, interior wetlands had rapidly converted to open water after 1956. The field areas were selected after examining historical aerial photographs or satellite images that showed the landscape before conversion to open water and the extant land-water distribution, including emergent-wetland remnants and expanses of unaltered wetlands. The wetland remnants were used as standard references for determining wetland elevations, organic-sediment thicknesses, and the elevations of shallow subsurface stratigraphic contacts that could be correlated in sediment cores across the study area. A hand-held GPS receiver with sub-meter accuracy was used to obtain the positions of all sediment cores, water-depth measurements, and temporary water-level recording stations.

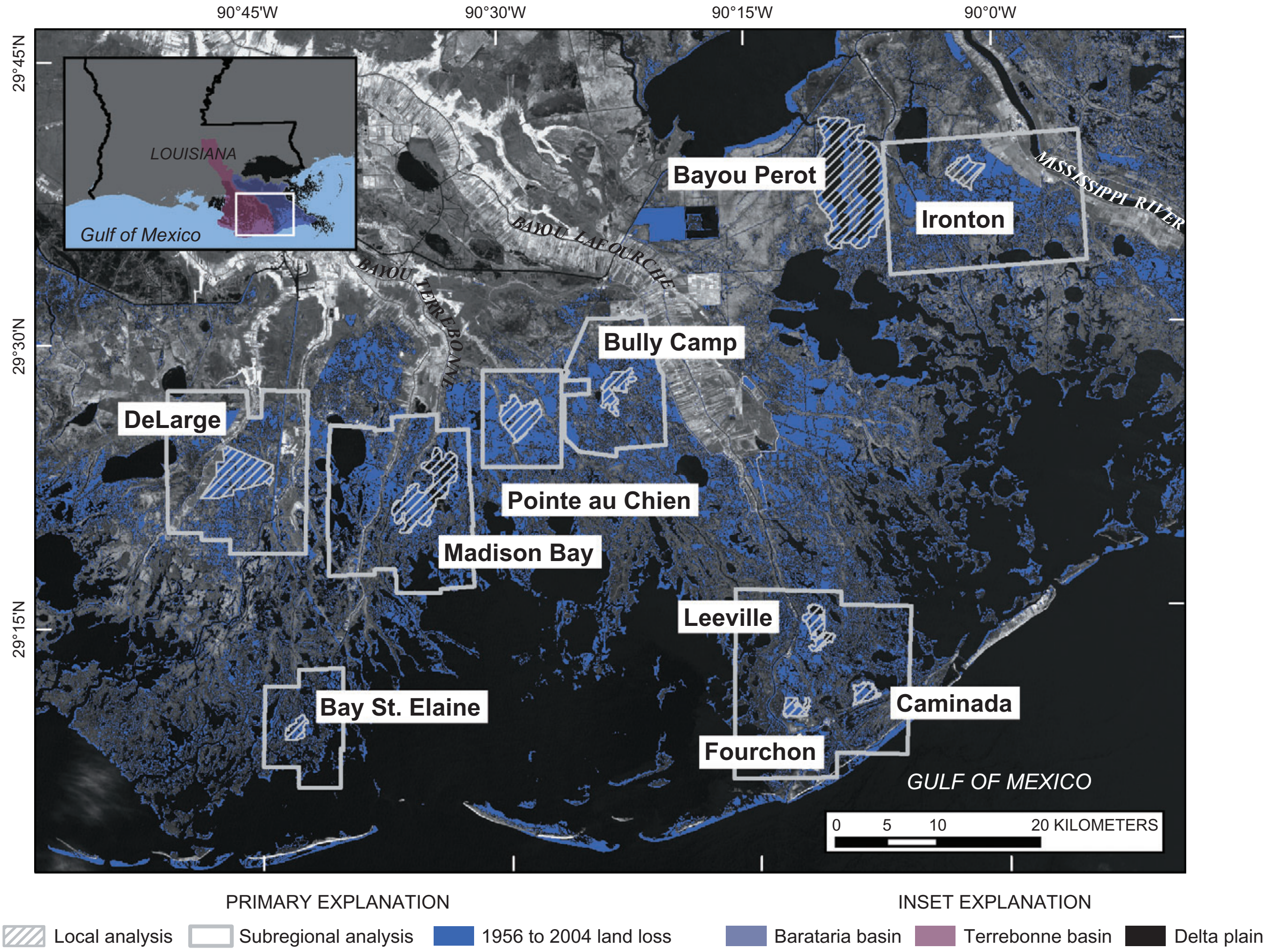

Figure 1. April 16, 2005 Landsat Thematic Mapper (TM) image of the southern Mississippi Delta showing locations of the field-study areas, outlines of areas used in the local and subregional analyses of accommodation formation, and the lateral extent of the delta-plain area.

Sediment cores

Sediment cores were collected where recent rapid wetland loss had occurred to provide close stratigraphic correlation between the remaining emergent wetlands and adjacent open-water sites that were former emergent wetlands. Push cores and vibracores were obtained to determine the thickness and stratigraphy of shallow wetland sediments. Vibracores (Lanesky *et al.*, 1979) provided a continuous stratigraphic record and penetrated below the thick, organic-rich sediments that commonly occur near the wetland surface. Push cores also were used to collect sediments at emergent-wetland sites and in shallow open-water bodies. The push corer (Jowsey, 1966) is designed to minimize sediment compaction and core shortening that commonly occur when unconsolidated water-saturated sediments are cored (Morton and White, 1997). All the cores were split, photographed, and described in detail to identify the predominant sedimentary facies and to select stratigraphic contacts for correlation between those cores that were used to estimate magnitudes of wetland subsidence and erosion (Figure 2, Table I).

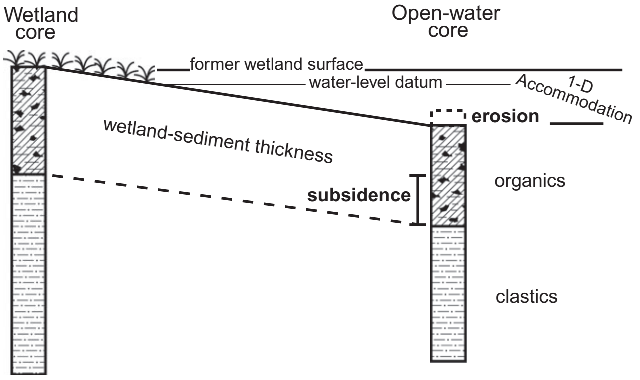

Figure 2. Conceptual diagram showing thicknesses of organic sediments, elevations of the organic-clastic correlation horizon, and the subsidence and erosion components contributing to 1D accommodation. Modified from Morton *et al.* (2009a).

Water-level measurements and bathymetric surveys

Wetland elevations and water depths in adjacent open-water bodies that were former wetlands can be compared only if

Table I. Measured 1D accommodation and calculated components of subsidence and erosion at core sites in the Mississippi Delta plain

Core	Accommodation (cm)	Erosion (cm)	Subsidence (cm)
Ironton (IRN)			
02v	35	–16	51
03v	73	13	60
04v	89	77	12
05Bv	80	41	39
06v	70	35	35
10v	52	42	10
11v	70	48	22
12v	95	58	37
13v	75	33	42
14v	84	70	14
16v	40	38	02
Bayou Perot (BP)			
01v	178	157	21
02v	194	181	13
03v	202	113	89
04v	194	34	160
05v	174	117	57
06v	145	74	71
10v	62	–6	68
14v	122	100	22
Bully Camp (BC)			
01A	95	6	89
02A	94	26	68
03	57	–2	59
04	184	35	149
05	99	3	96
Pointe au Chien (PAC)			
01A	77	–13	90
02A	73	10	63
03	94	14	80
04	74	–01	75
06	87	08	79
Madison Bay (MB)			
01	70	–10	80
02	79	27	52
03	94	28	66
04	138	63	75
05	122	42	80
06	88	24	64
DeLarge (DL)			
01A	81	2	79
Bay St Elaine (BSE)			
01	84	deposits	129
02	58	–15	73
05	56	–7	63
Leeville (LEE)			
03v	73	65	8
04v	122	94	28
05v	91	26	65
06v	90	97	–07
09v	77	52	25
10v	61	09	52
13v	69	72	–03
Fourchon (FCN)			
02v	39	25	14
03v	111	71	40
04v	100	22	78
05v	91	43	48
06v	89	72	17
07v	58	41	17
10v	55	–11	66
11v	96	14	82
Caminada (CAM)			
02v	95	81	14
05v	91	53	38
07v	104	71	33
08v	69	44	25
10v	67	59	08
14v	49	51	–02
16v	47	45	02

Note: Negative erosion values indicate sediment deposition relative to the wetland-sediment thickness in the standard marsh core. Negative subsidence values, implying uplift, are most likely a result of core compaction or minor errors in measurements.

Table II. Geological setting and accommodation dimensions for 10 study areas within the Mississippi River Delta plain

Study area	Geological setting	Average marsh elevation (cm)	Average water depth rod (cm)	Average water depth bathy (cm)	Average 1D accommodation (cm)	Local 2D Accommodation (km^2)	Local 3D Accommodation (10^6 m^3)	Subregional 2D Accommodation (km^2)	Subregional 3D Accommodation (10^6 m^3)
Ironton	Levee flank	28	48	–	76^a	3·6	2·7	79·2	60·2
Bayou Perot	Channel	51	145	–	196^a	26·8	52·5	26·8	52·5
Bully Camp	Upper delta plain	42	252	82	124	5·8	7·2	49·6	61·5
Point au Chien	Upper delta plain	35	48	43	78	9·6	7·5	47·8	37·3
Madison Bay	Upper delta plain	28	73	88	116	13·2	15·4	84·3	97·8
DeLarge	Upper delta plain	32	53	–	85^a	16·0	13·6	58·5	49·8
Bay St Elaine	Lower delta plain	49	20	–	69^a	2·1	1·4	21·3	14·7
Leeville	Lower delta plain	33	55	64	97	4·3	4·2	^{b}	^{b}
Fourchon	Lower delta plain	40	46	36	76	2·8	2·1	^{b}	^{b}
Caminada	Beach ridge	32	46	43	75	2·5	1·9	^{b}	^{b}
Caminada headland	Lower delta plain				83	9·6	8·2	85·1	70·4
							Total	452·6	444·2

Note: Average marsh elevations and water depths are referenced to NAVD88. Average 1D accommodation values include more points than the core sites listed in Table I. Local 2D (area) and 3D (volume) values describe the accommodation formed between 1956 and 2004 by historical wetland loss closest to the core sites. The larger subregional 2D (area) and 3D (volume) accommodation values include the landscape beyond bathymetric control, but where wetland loss occurred at the same time and in the same marsh type. –, Indicates not available.

[a] Limited number of rod measurements.

[b] Included in Caminada headland estimates.

they are corrected for time-dependent local fluctuations (e.g. tidal stage or wind-driven variations) that would influence water levels. Accommodation formation was evaluated by referencing all wetland elevations and water depths to the North American Vertical Datum of 1988 (NAVD88). During the initial field operations, water depths were measured with a graduated tape or rod while the time and geographic position of each depth measurement were obtained simultaneously with a GPS receiver. Water levels measured at the field areas were adjusted to NAVD88 using water levels recorded at the same time at nearby gauges operated by the Louisiana Department of Natural Resources (LDNR), US Army Corps of Engineers (USACE), and US Geological Survey (USGS). In addition, wetland elevations obtained from field measurements at each of the study areas were supplemented using published elevations at Coastwide Reference Monitoring System sites (CRMS; Louisiana Department of Natural Resources, 2009) within the same general area.

Preliminary field results provided 1D magnitudes of the new accommodation and estimates of the respective contributions of subsidence and erosion. Subsequent bathymetric surveys were conducted for the six largest water bodies that were former interior wetlands (Bully Camp, Pointe au Chien, Madison Bay, Leeville, Fourchon, and Caminada) to provide more extensive spatial coverage and more accurate 1D estimates of local accommodation (Table II). The bathymetric surveys employed a small, shallow-draft boat equipped with a high-resolution, 200-kHz, single-beam acoustical transducer coupled with a survey-quality GPS receiver. A survey-quality GPS receiver also was located at a nearby benchmark that served as a reference base station during the bathymetric surveys. Post-processed GPS horizontal positions of the base station, which were obtained from the National Geodetic Survey (2008), were applied to the boat-antenna and water-depth positions, and USGS internal software was used to reference the water depths to NAVD88. For each bathymetric survey, the point data (latitude, longitude, and water depth) were converted into a 3D raster surface in ArcMap 9.2 using the natural neighbors gridding algorithm. Grid cell size was 10 m for all the bathymetric surveys except for Caminada, where the cell size was 5 m because of greater data density and a smaller study area.

Repeated water-depth measurements

At six of the field areas, water depths were initially measured by rod in 2002, 2003, 2006, or 2007 and were later measured by acoustical bathymetric surveys either in 2004 or in 2008. Comparing elevation differences along reoccupied transects (Figures 3 and 4) provides estimates of both apparent and real changes in water depths. Considering the accuracy of both surveying methods, the smallest differences in water depths of a few centimeters (Figures 3B, 3C, and 4B) are likely apparent water-depth changes, whereas differences of decimeters to meters are probably actual water-depth changes (Figure 3A).

Apparent water-depth changes are attributed to different measurement techniques and horizontal differences in instrument position. Water depths initially were measured with a graduated rod that provided single values with lower precision than the continuously recording transducer. In addition, at soft-sediment sites, the rod could have penetrated fluid mud, yielding greater than actual water depths, or fluid mud could have reflected or attenuated acoustical energy of the transducer, yielding shallower than actual water depths. Furthermore, horizontal differences in instrument position between the first

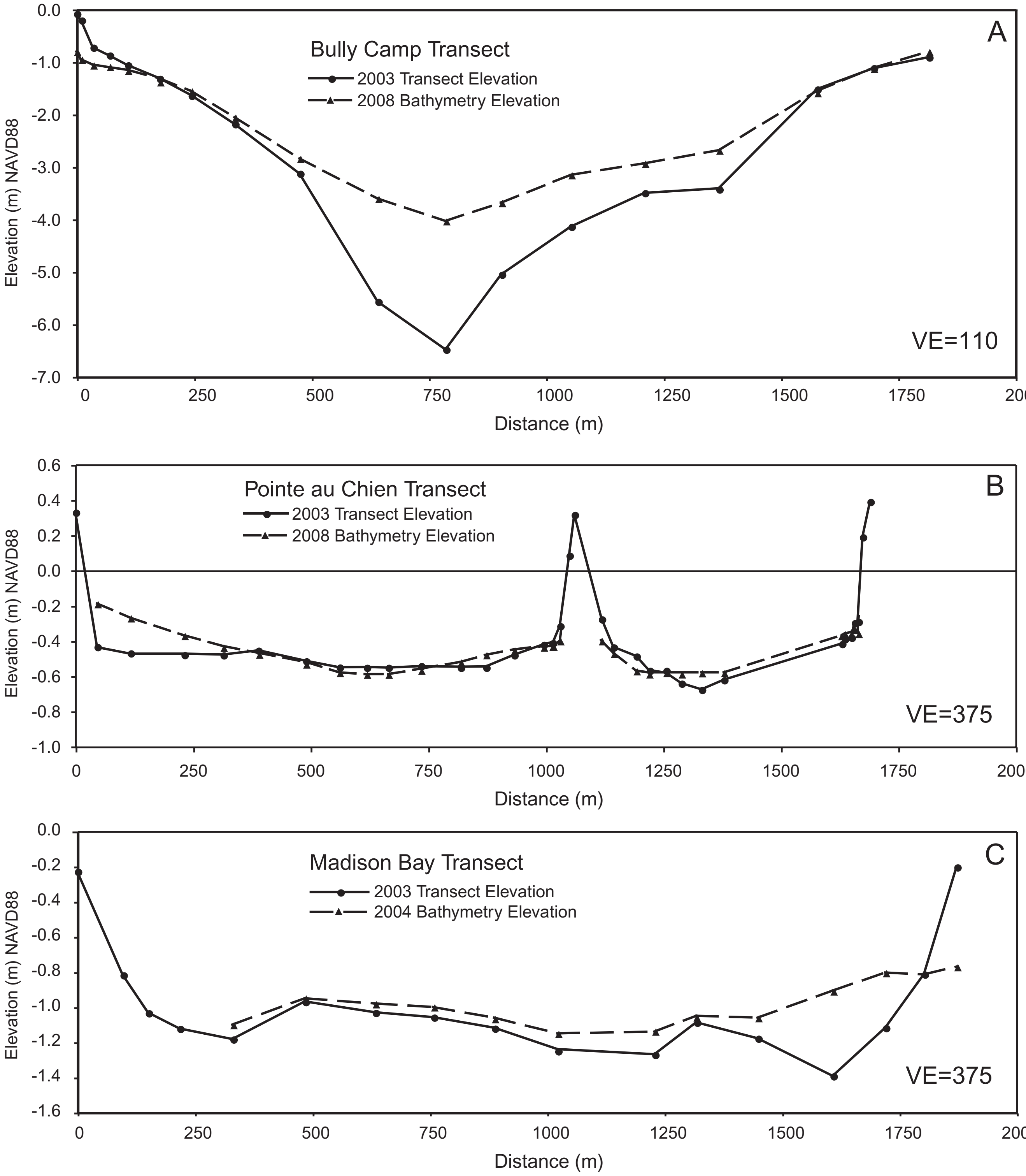

Figure 3. Repeated water-depth profiles at the (A) Bully Camp, (B) Pointe au Chien, and (C) Madison Bay study areas showing differences related to different surveying techniques and actual changes in water depth.

survey (rod) and second survey (transducer) could have resulted in apparent water-depth changes. The nearly systematic shallower depths recorded by the bathymetric surveys (Figures 3C, 4A–4C) may be related to conversion of GPS heights above the ellipsoid to NAVD88 vertical elevations.

Large water-depth changes within an accommodation area are attributed to sediment erosion and deposition associated with hurricanes that affected coastal Louisiana between the 2003 and 2008 survey dates. The most significant short-term bathymetric change was partial filling of the hole at Bully Camp (Figure 3A). The pre-2008 water-depth reduction of more than 2 m was most likely a result of sediment redistribution across the delta plain in 2005 by Hurricanes Katrina and Rita. Both were major (Category 3) hurricanes that impacted the study areas (Barras, 2007a, 2007b).

Areas of accommodation

The 2D (area) accommodation that formed in the Mississippi Delta plain between 1956 and 2004 was estimated for (1) the local areas of wetland loss where water-depth measurements and cores were collected, and (2) the surrounding subregional

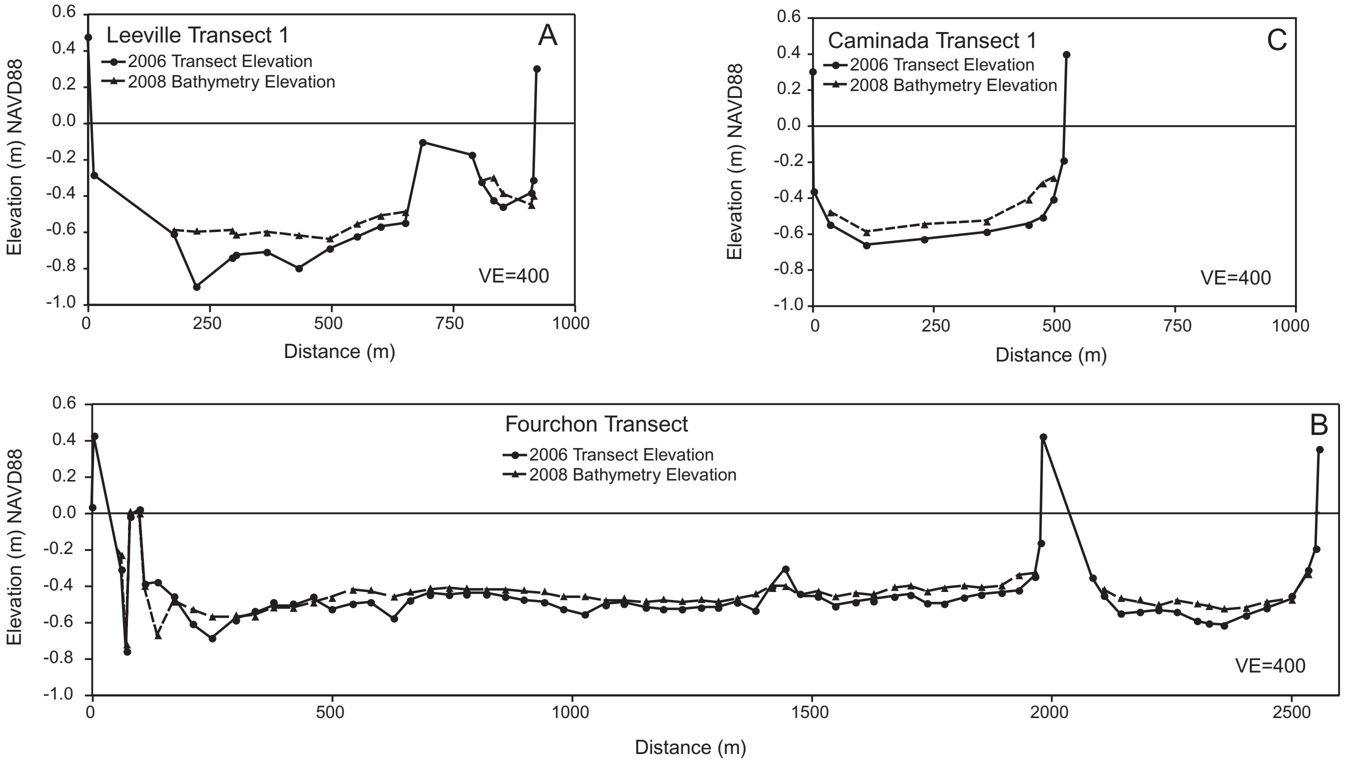

Figure 4. Repeated water-depth profiles at the (A) Leeville, (B) Fourchon, and (C) Caminada study areas showing differences related to different surveying techniques and actual changes in water depth.

areas of related wetland loss. Because the bathymetric surveys included areas that were pre-existing water bodies, the surveyed 2D extent would overestimate the 2D areas of new accommodation. Morton *et al.* (2005) and Barras *et al.* (2008) described the aerial photographic and Landsat Thematic Mapper (TM) satellite imagery land-water classifications and geographic information system (GIS) methods that were used to generate the land-change dataset from which the historic 2D accommodation was calculated.

For those study areas where bathymetric surveys were conducted, the georeferenced shoreline used to process the bathymetric data was also used as the accommodation clipping mask for the local 2D area. For the study areas without full bathymetric surveys, the local clipping mask was created to bound the coring basin and adjacent open-water areas to mimic the area that would have been included if the study area had been surveyed. The subregional 2D accommodation clipping mask was defined by the coverage of aerial photographs used for the 1956 to 2004 land-change analysis conducted by Morton *et al.* (2005) or determined for this study. The historical imagery for the Caminada headland study areas (LEE, FCN, CAM) overlaps, so a single subregional area was defined that includes all three local study areas (Figure 1, Table II). Minor volumes of additional accommodation may have formed between 2004 and when the bathymetric surveys were conducted in 2008, but those volumes would not significantly alter the study results because the rates of subsidence and wetland loss at the field study areas were low (Barras *et al.*, 2008; Morton and Bernier, 2010; Morton *et al.*, 2009b).

Wetland subsidence and erosion

We estimated 1D accommodation that formed within interior delta-plain wetlands and apportioned the new space to either subsidence or erosion (Table I), which are the two processes primarily responsible for historical formation of accommodation. Subsidence and erosion were calculated using the formulas of Morton *et al.* (2009a) that compare the elevations and vertical offsets of stratigraphic contacts correlated between adjacent cores (Figure 2). The estimated magnitudes of subsidence and erosion between emergent-wetland cores and adjacent open-water cores assume that wetland-sediment thicknesses and stratigraphic positions of correlation markers are nearly uniform across horizontal distances of tens to hundreds of meters. The amount of vertical erosion at an open-water core site is equal to the difference in wetland-sediment thickness between a wetland core and an adjacent open-water core (Figure 2). The amount of subsidence at an open-water core is equal to the elevation difference of a correlated stratigraphic marker between two adjacent cores. The estimates of subsidence and erosion at an open-water location also equal the 1D accommodation created by the land-water change, which is the difference between the former wetland elevation and the existing water depth (Figure 2). Average 1D accommodation values in Table II generally are larger than those calculated from values in Table I because the Table I values are limited to measurements only at the core sites, whereas the water-depth values in Table II include deeper measurements in the open-water bodies beyond the core sites.

One-dimensional accommodation measurements (Table I) can be highly accurate because they only involve the difference between marsh elevations and water depths (Figure 2). The average 1D accommodation for each study area (Table II) is the sum of average marsh elevation and average water depth. Unlike estimates of subsidence and erosion, accommodation values are not subject to errors caused by sediment compaction during coring or imprecision introduced by gradational stratigraphic contacts, nor are they affected by the position or uncertainties in NAVD88.

Isotopic analyses

To test if ages of the basal marshes influenced the volume of recently formed accommodation, sediment samples were

Table III. Average radiocarbon age and physical characteristics of marsh sediments at each study area in the Mississippi Delta

Study area	Average marsh ^{14}C age (cal. years BP)	Average marsh thickness (cm)	Average organic content (%)	Average bulk density (g/cm^3)
Ironton	775	120	45	0·16
Bayou Perot	2650	327	38	0·19
Bully Camp	825	126	39	0·21
Pointe au Chien	850	111	39	0·22
Madison Bay	855	186	26	0·25
DeLarge	965	110	19	0·27
Bay St Elaine	710	124	14	0·45
Leeville	520	141	No data	
Fourchon	470	93	21	0·40
Caminada	600	120	39	0·21

collected from the base of the first (oldest) marsh peat just above the contact between clastic and organic sediments in selected cores. Peat samples selected for isotopic analysis from the Terrebonne basin were submitted to Beta Analytic, Inc., whereas those from the Barataria basin were submitted to the National Ocean Sciences Accelerator Mass Spectrometry (AMS) Facility at the Woods Hole Oceanographic Institution. The laboratories provided radiocarbon ages (^{14}C) and the corresponding δ^{13}C values for the remains of former delta-plain marshes. Reported conventional radiocarbon ages were calibrated to calendar years before present (cal. years BP) (Table III) using the program OxCal 4.1 (Bronk Ramsey, 2009), which includes the INTCAL04 atmospheric corrections of Reimer *et al.* (2004). Multiple samples were dated for the oldest marsh at most of the study areas, so a single value representing the average of the median calibrated ages was used to establish the general marsh depositional history for each area.

Marsh-sediment attributes

To evaluate if accommodation was controlled partly by sediment attributes, measurements were obtained for wetland-sediment thickness (Figure 2), organic content, and bulk density. Wetland-sediment thickness typically was measured in three to four cores from the remnant emergent-marsh sites at each study area (Morton *et al.*, 2005; Morton *et al.*, 2009b) and the average marsh thickness for the study area was calculated. Marsh-sediment organic content and bulk-density measurements were obtained from the CRMS site nearest each study area. They represent the average of six measurements, each at 4-cm increments for the upper 24 cm of sediment (Louisiana Department of Natural Resources, 2009). Relying on nearby CRMS sites for marsh-soil properties is not as exact as having analyses for sediments from the study areas, but considering the comparable geologic settings and spatial coverage of the CRMS sites, the data are considered to be adequate for the intended purpose.

Historical Accommodation Formation

The 10 study areas encompassed a spectrum of geological settings (Figure 1, Table II) including: (1) an upper delta-plain levee flank of the Mississippi River (Ironton), (2) a pre-existing upper delta-plain interior channel (Bayou Perot), (3) four upper delta-plain interdistributary areas (Bully Camp, Pointe au Chien, DeLarge, and Madison Bay), (4) three lower delta-plain interdistributary areas (Bay St Elaine, Leeville, and Fourchon), and (5) a lower delta-plain beach-ridge margin area (Caminada). The Bully Camp, Pointe au Chien, DeLarge, and Madison Bay areas were located within the prominent east-west regional trend where historical wetland loss was greatest (Figure 1), and the Bully Camp and Bay St Elaine areas were over or near former mines that produced sulfur from shallow salt-dome caprocks using the Frasch-solution process.

For the six largest study areas (Bully Camp, Pointe au Chien, Madison Bay, Leeville, Fourchon, and Caminada), 3D accommodation (Table II) was estimated by integrating water depths from acoustical bathymetric surveys, emergent-marsh elevations, and GIS-derived areas of open water that were former marsh. In contrast, water-depth surveys at Ironton, Bayou Perot, DeLarge, and Bay St Elaine consisted only of rod measurements along a few short transects that included a limited number of data points. For those four field areas, 3D accommodation estimates are first approximations based on average water depths and marsh elevations applied to the subregional open-water area where wetland loss occurred at the same time and in the same delta-plain setting (Table II). Extrapolation of average 1D accommodation estimates from the local area to the subregional area is justified because the average water depths determined with rod measurements compared favorably with average water depths derived from more precise bathymetric surveys (Table II). An exception is at Bully Camp where the average rod water depth was biased because of a deep hole above the former sulfur mine. There the average water depth derived from the bathymetric survey was a better estimator of water depths beyond the surveyed area.

Upper delta-plain levee-flank

A nearly continuous brackish to intermediate marsh (average thickness 120 cm) formed the upper delta-plain levee flank at Ironton in the 1950s. Although some wetland loss occurred between 1956 and 1978 (Britsch and Dunbar, 1993), most of the accommodation formed after 1978 (Barras *et al.*, 2008). At Ironton, marsh elevations (average 28 cm) were substantially lower than at other nearby upper delta-plain marshes, indicating prior subsidence of the reference marsh surfaces. Water depths where marsh formerly existed increased toward the center of the open-water area (Figure 5A), but water depths (average 48 cm) generally were similar to or shallower than the other upper delta-plain areas, possibly because the accommodation was relatively young.

The 1D accommodation at Ironton (average 76 cm) was formed by both delta-plain erosion and subsidence. Magnitudes of both components spanned relatively large ranges (Table I), but erosion averaged about 40 cm and subsidence averaged about 29 cm. Furthermore, erosion exceeded subsidence at

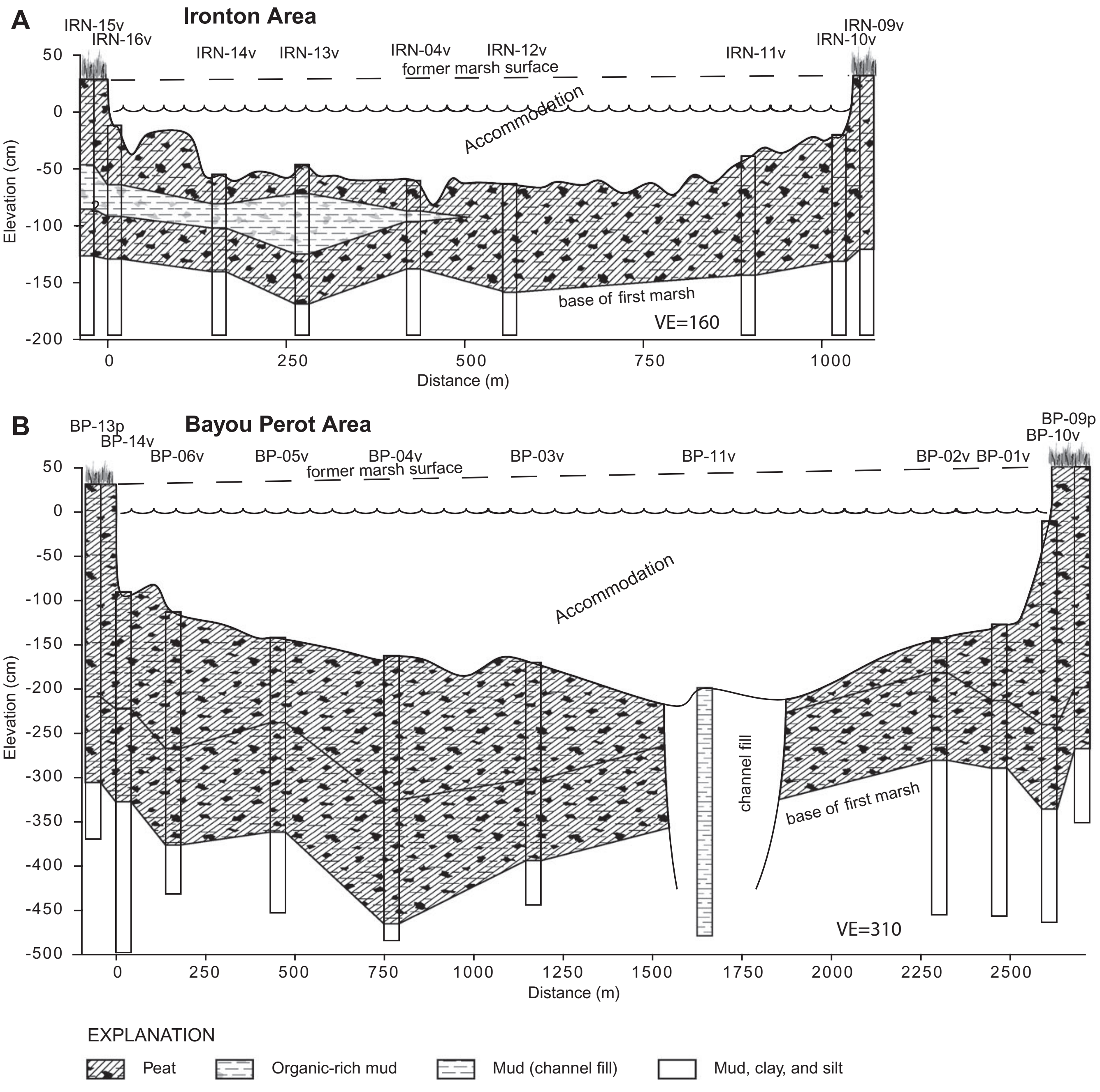

Figure 5. Combined bathymetric profiles (rod measurements) and stratigraphic cross-sections for marsh and open-water core sites illustrate the magnitude of accommodation (in centimeters) at the (A) Ironton and (B) Bayou Perot study areas.

most of the open-water coring sites (Figure 5A, Table I). On the levee flank, the local 3D accommodation ($2{\cdot}7 \times 10^6$ m^3) was smaller than that at the other upper delta-plain areas (Figure 6). In contrast, the subregional 3D accommodation ($60{\cdot}2 \times 10^6$ m^3) was equal to or greater than that at most of the other upper delta-plain areas because it was so widespread.

Upper delta-plain channel

An 1891 topographic map shows Bayou Perot as a small meandering channel connecting two large lakes; consequently, tidal and meteorological forces have driven water continuously through Bayou Perot for at least 120 years. Since 1956, most of the historic wetland loss near Bayou Perot occurred along its shores as the channel widened (Barras, *et al.*, 2008). The hydrologic setting prompted Penland *et al.* (2000) to classify the wetland loss as erosion by channel flow. Much of the historic accommodation along the shores of Bayou Perot formed before 1978, but the channel margins continued to retreat systematically after 1978. However, it was unclear if shoreline retreat was caused by wave and current erosion of the banks, submergence and retreat associated with subsidence, or a combination of both processes. Water depths where the marsh surface previously existed progressively increased toward the former channel position, coinciding with the zones of sequential historical wetland loss (Figure 5B).

Swarzenski *et al.* (1991) classified the brackish marsh adjacent to Bayou Perot as non-floating 'quaking' marsh, indicating a condition transitional between floating marsh and fast-land marsh. Marsh sediments at Bayou Perot were by far the oldest and thickest (average thickness 327 cm) compared to those at the other study areas (Tables II and III). Marsh eleva-

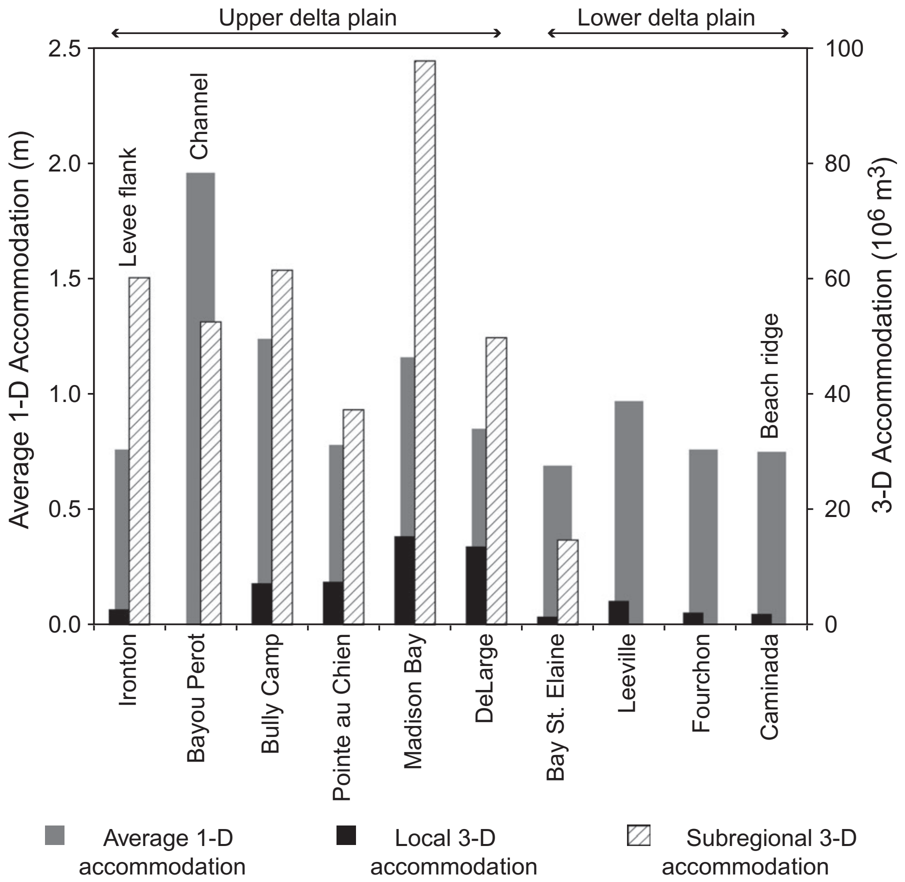

Figure 6. Comparison of 1D and 3D accommodation measurements at the 10 study areas.

tions on the west and east banks of Bayou Perot were 31 and 51 cm, respectively. This substantial elevation difference was likely a result of greater historical subsidence on the west side of the bayou. Subsidence accounted for as much as 160 cm of marsh submergence on the western side, whereas it accounted for 68 cm or less on the eastern side (Table I, Figure 5B).

One-dimensional accommodation at Bayou Perot (average 196 cm) was the largest of all the study areas (Figure 6) because it had the greatest water depths (Table II). Field measurements indicate that the 1D accommodation consisted primarily of channel-bank erosion, which substantially exceeded subsidence at most of the core sites (Table I). Half to nearly all of the accommodation at former emergent-marsh sites was attributable to erosion of the organic-rich marsh-sediment section. The field data at Bayou Perot focused on channel enlargement and not on minor areas of wetland loss in the surrounding marshes. Therefore, for our purposes the local and subregional 3D accommodation estimates ($52{\cdot}5 \times 10^6$ m^3) are the same, and the 3D accommodation is comparable to that at other upper delta-plain areas (Figure 6).

Upper delta-plain interdistributary areas

When it was surveyed in 2008, the Bully Camp area was characterized by isolated remnants of brackish marsh (average thickness 126 cm) in an open-water setting (Figures 7A and 8A). Wetland loss, which initiated prior to 1956, originally resulted from extensive dredge and fill activities associated with oil-field development and later sulfur extraction (Morton *et al.*, 2005). By the middle 1960s, water was ponding on the marsh surface in future loss locations. By 1974, interior wetland loss was substantial, and by 1990 nearly all of the former wetlands were open water. Marsh elevations at BC-01B and BC-02B (Figure 7A) were 55 and 49 cm, respectively, which were slightly higher than at the other study areas. However, the elevation at BC-03 on a drowned marsh remnant was –8 cm, probably because of differential subsidence. A depression more than 6 m deep (Figures 3A and 8A) at the center of the historically formed accommodation coincided with subsidence over the salt-dome caprock where sulfur was extracted.

One-dimensional accommodation estimates at Bully Camp (average 124 cm) indicate that subsidence was the predominant component (average 92 cm). Apparently the remnant marsh at BC-03 had differentially subsided, considering that the base of the marsh was 51 and 59 cm lower than at BC-02B and BC-01B, respectively. By comparison, erosion at most open-water locations was 35 cm or less (Table I). Local volumetric accommodation at Bully Camp was $7{\cdot}2 \times 10^6$ m^3 (Table II), whereas the subregional accommodation volume was $61{\cdot}5 \times 10^6$ m^3. Both local and subregional volumetric estimates of accommodation were some of the highest of all of the areas investigated (Table II and Figure 6).

The most rapid wetland loss at Pointe au Chien (Figure 7B) occurred between 1969 and 1974. When the area was surveyed in 2008, only isolated patches of brackish marsh (average thickness 111 cm) remained surrounded by open water (Figure 8B). Where cores were collected, marsh elevations (average 35 cm) and water depths (average 48 cm) were typical for this upper delta-plain setting.

Across the Pointe au Chien area, 1D accommodation (average 78 cm) and magnitudes of subsidence (average 77 cm) were nearly identical. The highest marsh elevations coincided with the areas of least subsidence. Erosion estimates

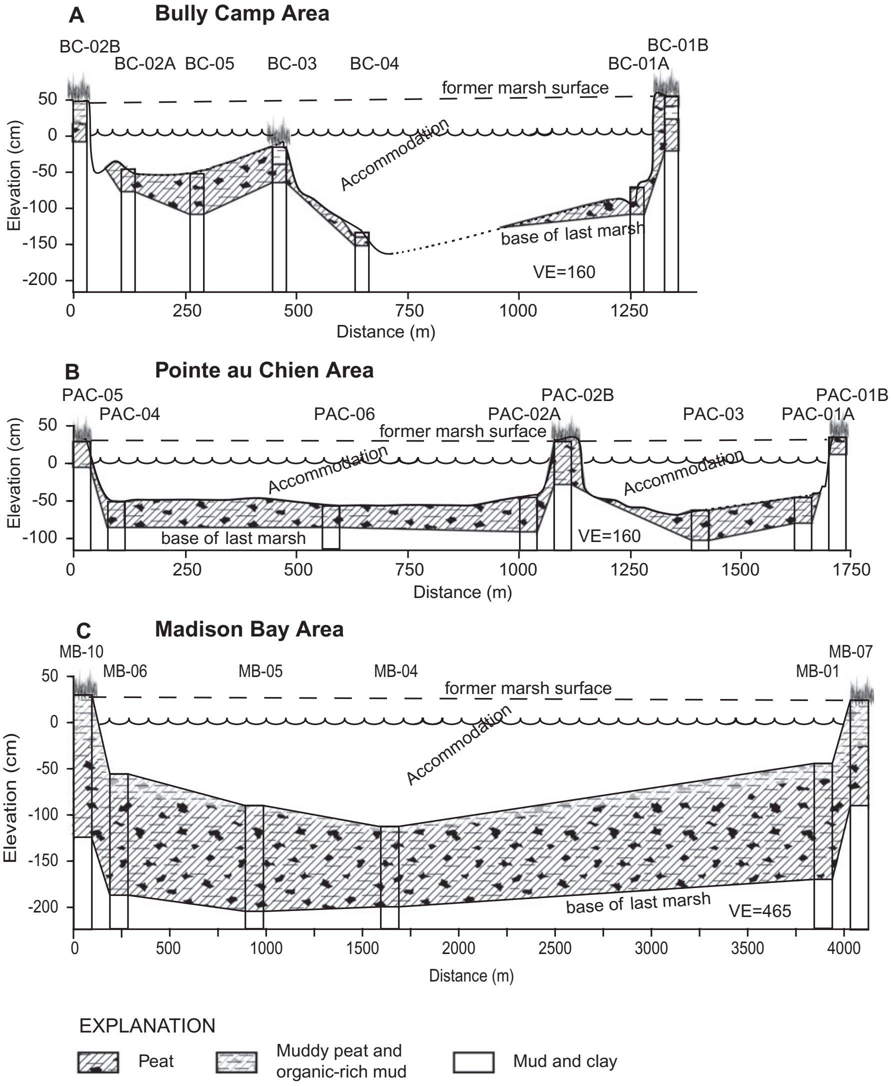

Figure 7. Combined bathymetric profiles (rod measurements) and stratigraphic cross-sections for marsh and open-water core sites illustrate the magnitudes of accommodation (in centimeters) at the (A) Bully Camp, (B) Pointe au Chien, and (C) Madison Bay study areas.

at open-water locations were imprecise because marsh-sediment thicknesses across the area were variable. Despite the imprecision, erosion of the marsh surface at open-water coring sites was minor (average 10 cm) compared to magnitudes of subsidence (Figure 7B, Table I). The local 3D accommodation at Point au Chien ($7{\cdot}5 \times 10^6$ m^3) was approximately half of that at the other upper delta-plain areas except at Bully Camp (Figure 6, Table II), and the subregional 3D accommodation ($37{\cdot}3 \times 10^6$ m^3) also was substantially less than at the other upper delta-plain areas primarily because of a smaller area and shallower water depths.

Before 1956, the Madison Bay area was characterized by broad expanses of dense saline to brackish marsh with a network of small, widely spaced tidally influenced creeks. Later it became a hotspot with one of the highest decadal rates of delta-plain wetland loss (Reed, 1995). At Madison Bay, marsh sediments were substantially thicker (average thickness 186 cm) and marsh elevations were significantly lower (average 28 cm) than at most other delta-plain areas (Table II), perhaps because of prior subsidence. In contrast, water depths where marsh formerly existed (Figure 7C) were substantially deeper (average 88 cm) than at other delta-plain areas (Table II).

Accommodation at Madison Bay (Table I, Figures 7C and 8C) formed as widespread areas of drowned marsh in the 1950s to 1970s that eventually became permanently submerged. During submergence, the water bodies enlarged and finally coalesced to produce large areas of open water. One-dimensional accommodation (average 116 cm) was caused primarily by subsidence. Subsidence was least around the open-water margin (average 59 cm), whereas subsidence near the center (cores MB-04 and MB-05) was about 75 cm (Figure 7C). Overall, the field measurements indicate that subsidence was twice as important as erosion (average 30 cm) in forming accommodation at Madison Bay. The local 3D accommodation at Madison Bay ($15{\cdot}4 \times 10^6$ m^3) was the largest at any study area except for Bayou Perot, and subregional 3D accommodation ($97{\cdot}8 \times 10^6$ m^3) was the largest of any of the study areas regardless of geologic setting (Figure 6).

Severe weather and restricted access limited the data collected at DeLarge. Where emergent brackish marsh formerly existed (average thickness 110 cm), water depths ranged from 47 to 71 cm and averaged about 53 cm (Figure 9A). Minor wetland loss occurred between 1956 and 1969, whereas major wetland loss occurred between 1969 and 1974. An extensive network of man-made canals and associated embankments of dredged material compartmentalized the area of wetland loss. By 1978, wetland loss near the coring site was extensive, with only isolated marsh patches remaining in an open-water setting. The northern boundary of complete

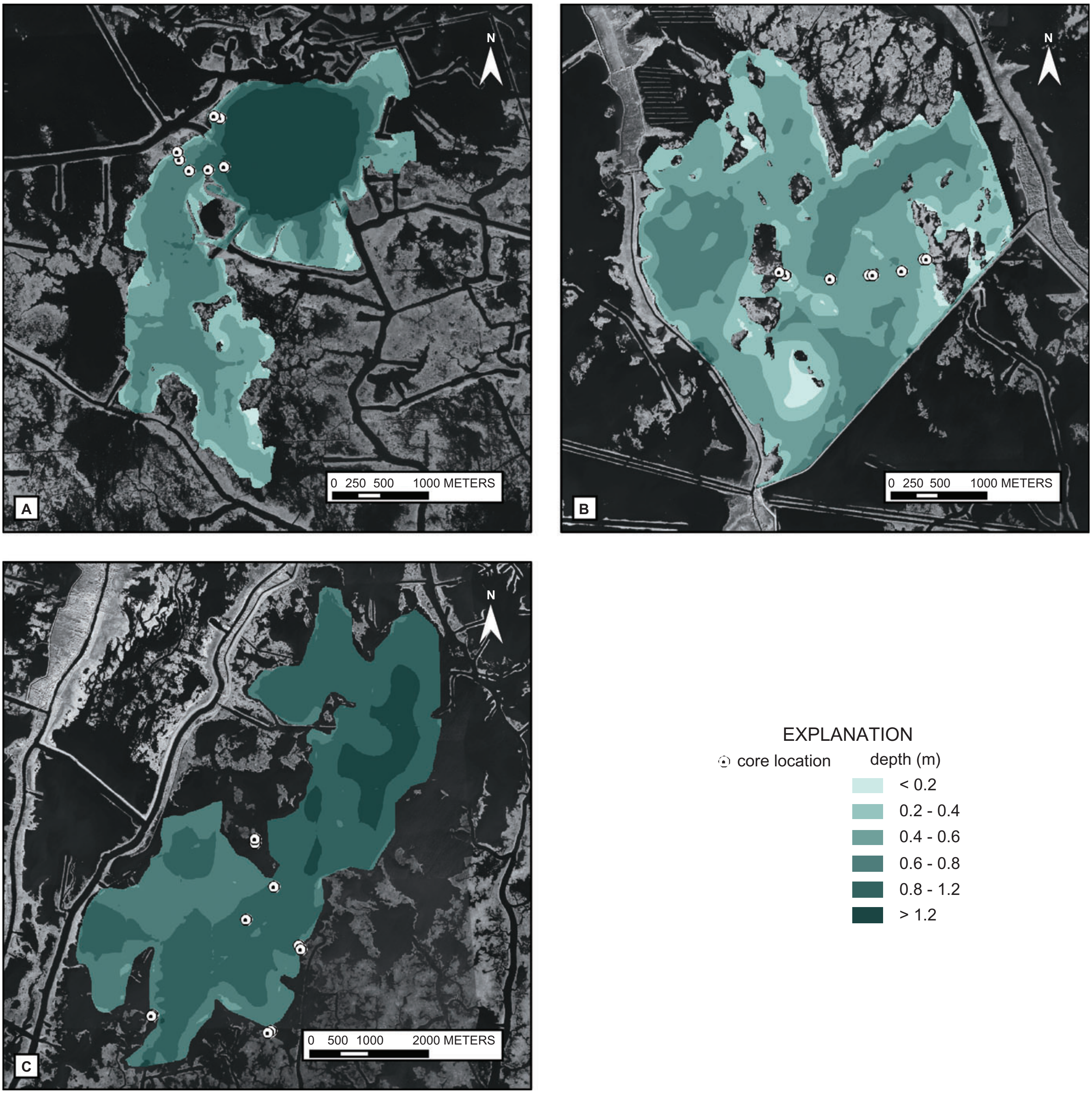

Figure 8. Results of the (A) Bully Camp, (B) Pointe au Chien, and (C) Madison Bay acoustical bathymetric surveys with superimposed core locations.

wetland loss approximately coincided with the projected surface trace of the Golden Meadow Fault (Kuecher *et al.*, 2001). Stratigraphic correlation indicates that 1D accommodation of 81 cm was created mostly by subsidence (79 cm), whereas surficial erosion was minor (2 cm). A short bathymetric profile indicated that average 1D accommodation was 85 cm, slightly greater than the value obtained from the core data. The local and subregional 3D accommodation estimates at DeLarge ($13{\cdot}65 \times 10^6$ m^3 and $49{\cdot}8 \times 10^6$ m^3, respectively) are comparable to those measured at other upper delta-plain areas where subsidence exceeded erosion (Figure 6).

Lower delta-plain areas

The Bay St Elaine study area occupied a marginal marine setting where a dense network of tidal channels and ponds disrupted the saline marsh (average thickness 124 cm). Interior wetland loss began with dredging access canals for hydrocarbon and sulfur production wells and mostly occurred before 1978. The wetland loss was concentrated north of a marsh-edge lineation that had the characteristic surface expression of a subsurface fault. However, high-resolution geophysical surveys by Roberts *et al.* (2008) showed no fault-related stratigraphic offsets beneath the marsh lineation.

At Bay St Elaine, average marsh elevations were moderately high (average 49 cm), but water depths where marsh formerly existed were extremely shallow (average 20 cm). According to the field data, accommodation formed primarily as a result of subsidence rather than erosion (Table I). However, 1D accommodation (average 69 cm) was less than subsidence (average 88 cm) because of subsequent sediment deposition, including replacement of the upper marsh section by channel fill (Figure 9B and Table I). Compared to the other study areas,

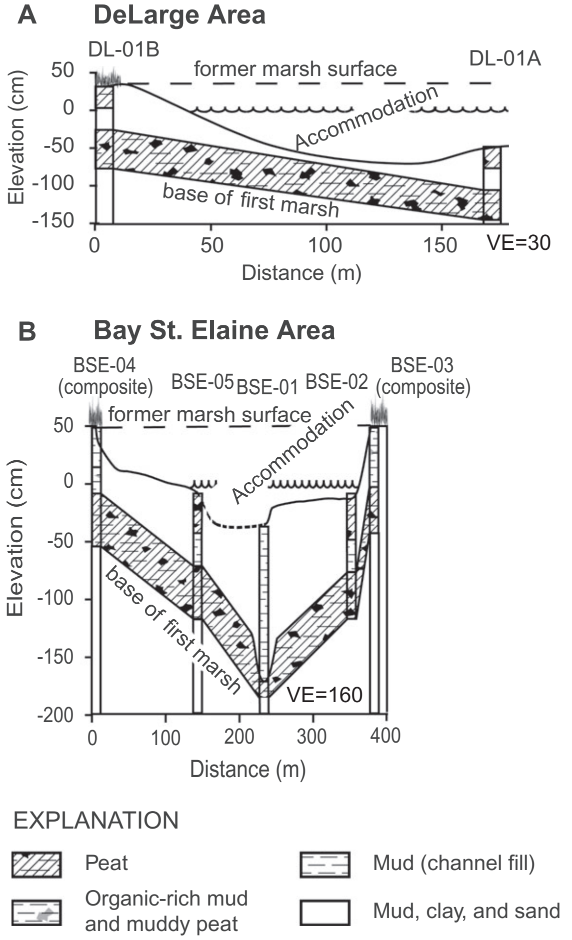

Figure 9. Combined bathymetric profiles (rod measurements) and stratigraphic cross-sections for marsh and open-water core sites illustrate the magnitudes of accommodation (in centimeters) at the (A) DeLarge and (B) Bay St Elaine study areas.

the local and subregional 3D accommodation estimates for Bay St Elaine (1·4 and 14·7 × 10^6 m^3, respectively) were the smallest regardless of the geologic setting (Figure 6) because the area was small and water depths were shallow.

In 2008, the formerly continuous, emergent saline marsh that dominated the 1950s Leeville landscape was mostly open water with a remnant fringe of emergent marsh (average thickness 141 cm). Most of the wetland conversion to open water (Figures 10A and 11A) occurred between 1978 and 1990. Marsh elevations at Leeville generally were low (average 33 cm), but water depths were moderate (average 64 cm) compared to the other areas (Table II). These parameters combined to generate the largest average 1D accommodation (average 97 cm) and local 3D accommodation (4·2 × 10^6 m^3) of all the lower delta-plain areas (Table II, Figure 6). The processes forming accommodation were constrained spatially with erosion exceeding subsidence in most of the Leeville area except around core sites LEE-05v and LEE-10v, where subsidence exceeded erosion (Table I, Figure 10A).

At the Fourchon study area, saline emergent marsh was nearly continuous in the early 1950s, except near core FCN-11, which was located in a pre-existing pond. Interior-marsh disintegration continued from the late 1950s through the late 1970s, but accelerated in the 1980s. By 1990, the present landscape was established, and little land loss occurred after 2001. Compared to the other delta-plain areas, the marsh elevations at Fourchon were moderately high (average 40 cm) but water depths were relatively shallow (average 36 cm), and marsh sediments were comparatively thin (average 93 cm). Water depths were slightly deeper on the western side of the core transect and where permanent water has persisted around core site 11 (Figures 10B and 11B). Together, the 1D accommodation associated with land-water changes averaged 76 cm (Table II). In general, the physical setting controlled which process was responsible for creating the accommodation. Subsidence exceeded erosion at most of the open-water coring sites, whereas erosion exceeded subsidence at most of the marsh-edge coring sites (Figure 10B). Local 3D accommodation at Fourchon (2·1 × 10^6 m^3) was the second smallest of all the delta-plain areas (Table II, Figure 6).

At the Caminada study area, the conversion of formerly continuous saline emergent marshes (average thickness 120 cm) to water occurred primarily after 1978. By 2001, there was more water than land, and by 2004 almost all of the formerly emergent marsh between the core sites and the beach-ridge complex was open water (Figure 11C). Marsh elevations were relatively low (average 32 cm), and water depths were relatively shallow (average 43 cm) but consistent across the area that was formerly emergent marsh (Figures 10C and 11C). One-dimensional accommodation (average 75 cm) was created mostly by erosion, which was substantially greater than subsidence at all of the coring locations (Table I). Average marsh-sediment erosion was 60 cm, whereas average subsidence was only 15 cm. Local 3D accommodation at Caminada was 1·9 × 10^6 m^3, which was consistent with local 3D accommodation at the other lower delta-plain areas but substantially smaller than at the upper delta-plain areas (Figure 6).

Subregional 3D accommodation was not determined for the individual study areas at Leeville, Fourchon, and Caminada (Table II) because of their proximity to one another (Figure 1). Instead the individual areas were combined for the Caminada headland, where the 3D accommodation was measured as 70·4 × 10^6 m^3 (Table II). This volume was second in magnitude only to the subregional volume at Madison Bay (Figure 6).

Discussion

Subsidence and erosion

Results of our study indicate that most of the historical accommodation associated with land-area changes in the central and eastern Terrebonne hydrologic basin (Tables I and II) formed before 1978 primarily as a result of subsidence, whereas accommodation in the western and central Barataria hydrologic basin formed after 1978 and was a result of either primarily erosion, or the nearly equal contribution of subsidence and erosion. Although erosion generally was greater than subsidence in the Barataria basin, the erosion likely was enhanced by initial subsidence that lowered the marsh surface to a position where it was susceptible to subsequent erosion by storm waves. At Bayou Perot, channel-bank erosion exceeded subsidence, but subsidence was greater on the west side of the bayou than on the eastern side. Lower marsh elevations on the west side of Bayou Perot are consistent with land-surface subsidence induced by deep hydrocarbon production from the Delta Farms field complex (Morton *et al.*, 2009b). Moreover, the magnitudes of delta-plain subsidence at Bayou Perot were equal to or greater than the largest magnitudes of subsidence measured at any study area (Table I). Subsidence probably enhanced the current-driven erosion by lowering the delta plain and subjecting a larger surface area to stronger currents.

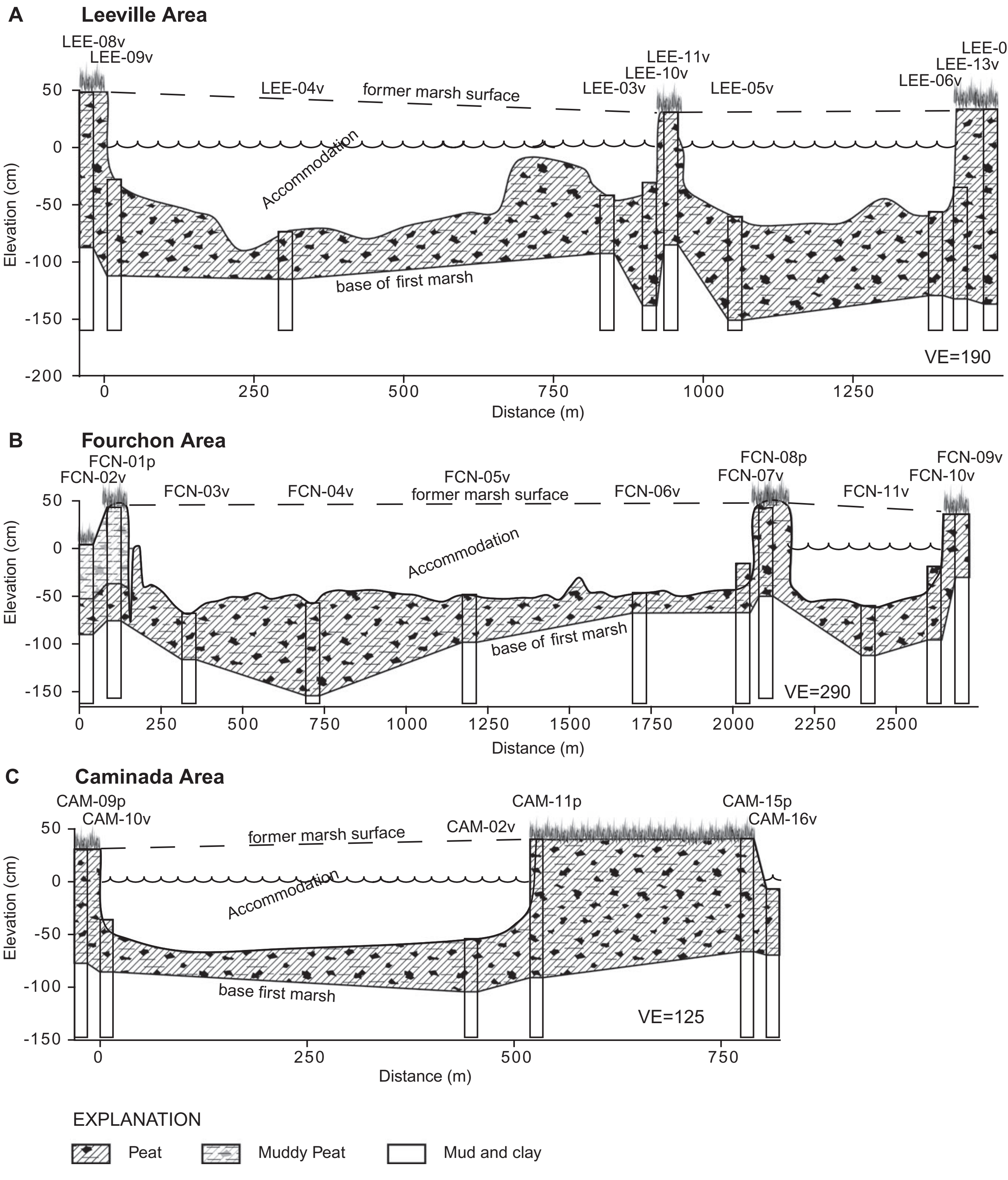

Figure 10. Combined bathymetric profiles (rod measurements) and stratigraphic cross-sections for marsh and open-water core sites illustrate the magnitude of accommodation (in centimeters) at the (A) Leeville, (B) Fourchon, and (C) Caminada study areas.

The results also indicate that accommodation formed in the upper delta plain was greater than that formed in the lower delta plain (Figure 6), and subsidence was more important than erosion in forming the upper delta-plain accommodation. Subsidence associated with sulfur mining contributed substantially to accommodation formation at Bully Camp but not at Bay St Elaine, which was about 4 km from the locus of sulfur extraction.

At all the study areas, peat or organic-rich sediments were recovered in the open-water cores where continuous emergent marshes formerly existed (Figures 5, 7, 9, and 10). Furthermore, extant water depths generally were greater than the thicknesses of the organic-rich marsh sediments. This physical relation is clear evidence that subsidence contributed to accommodation formation, because it is physically impossible to erode to those depths and still preserve some of the marsh deposits.

Extant emergent-marsh elevations were significantly lower where subsidence was greatest, such as at Madison Bay, DeLarge, and in the marsh-island remnants of Pointe au Chien and Bully Camp. Low marsh elevations at Ironton and on the west side of Bayou Perot (Table II) also indicate that those

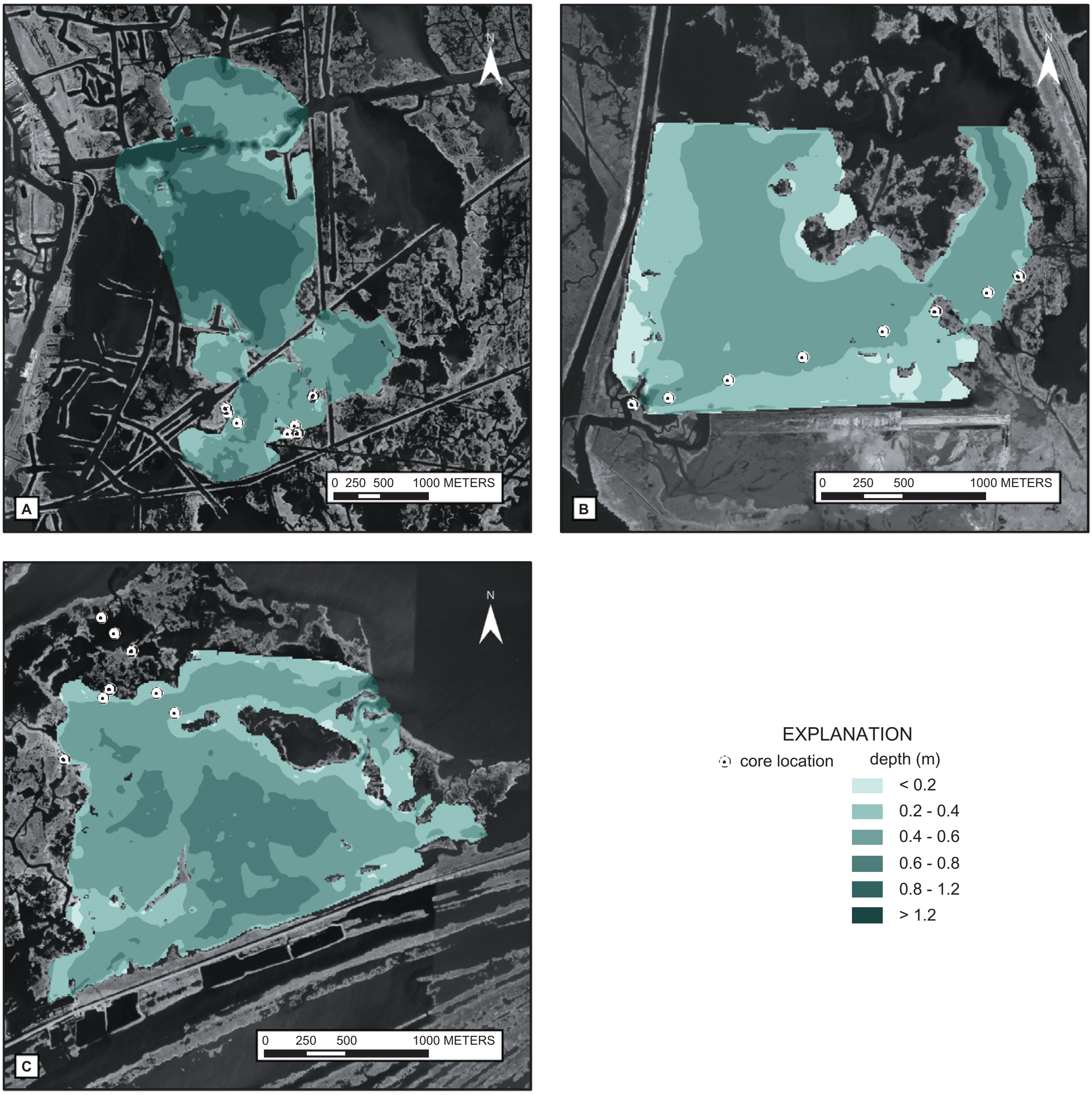

Figure 11. Results of the (A) Leeville, (B) Fourchon, and (C) Caminada acoustical bathymetric surveys with superimposed core locations.

areas were lowered by subsidence. Drowned marsh is an intermediate stage in the progression from emergent wetlands to open water. Spatial analyses of historical imagery identified patterns of delta-plain submergence, including water-body enlargement, marsh breakup, and essentially uniform drowning of large sections of marsh (Morton *et al.*, 2005; Morton *et al.*, 2009b). The history of drowned marsh confirms that subsidence initially was the primary process responsible for interior accommodation formation and not erosion.

In both cross-section and plan views, the areas of accommodation are roughly bowl shaped with water depths increasing away from the marsh (Figures 5, 7, 8, 9, 10, and 11). For some areas, such as Bayou Perot, the water-depth gradient clearly is a function of the age of the accommodation with the oldest space coinciding with the greatest water depths. For most of the other areas, the water-depth gradient coincides with the magnitude of subsidence or erosion.

Marsh age

At upper delta-plain interdistributary areas, marshes generally have persisted for a thousand years or more, whereas marshes of the lower delta plain are only a few hundred years old (Frazier, 1967; Kosters, 1989; Morton *et al.*, 2005; Morton *et al.*, 2009b). Because of these chronostratigraphic relations, the oldest middle-to-upper delta-plain marshes are substantially older than the oldest lower delta-plain marshes (Table III).

The geologic history of delta-plain development was derived from the spatial distribution of calibrated ^{14}C ages of the first marsh deposits. The ^{14}C ages cluster into three groups: older than 1000 cal. years BP, 1000 to 750 cal. years BP, and less than 750 cal. years BP (Table III). The oldest marsh was established between the Mississippi River and Bayou Lafourche (Figure 1) about 2650 cal. years ago. This marsh, which currently is beneath Bayou Perot, is substantially older than any of the other marshes and represents deposition associated with an older delta lobe (Frazier, 1967). The next oldest marsh was deposited at DeLarge (965 cal. years BP) between Bayou DeLarge and Bayou Grand Caillou, and developed progressively at Madison Bay (855 cal. years BP) along Bayou Terrebonne and then at Bay St Elaine (710 cal. years BP) as the delta lobe prograded seaward. The first marsh development between Bayou Terrebonne and Bayou Lafourche (Figure 1), which occurred at Pointe au Chien (850 cal. years BP) and Bully Camp (825 cal. years BP), formed at the same time as the marsh at Madison Bay (855 cal. years BP) and about 100 years after the marsh at DeLarge. Along lower Bayou Lafourche, the first marshes formed sequentially several hundred years later at Caminada (600 cal. years BP), Leeville (520 cal. years BP), and Fourchon (470 cal. years BP).

There is a moderate correlation (R^2 = 54%) between local accommodation volume, average calibrated marsh age, and inferred geologic setting of the oldest marsh peat at each study area (Figure 12A). In general, the largest local 3D accommodation formed on the oldest upper delta-plain marshes (Madison Bay, DeLarge) and the smallest local 3D accommodation formed on the youngest lower delta-plain marshes (Fourchon, Caminada, Bay St Elaine). However, there is no statistically significant correlation between subregional accommodation volume, average marsh radiocarbon age, and inferred geologic setting even when the anomalously old marsh age at Bayou Perot is eliminated (Figure 12B).

Marsh physical properties

The magnitude of accommodation formed at each study area may have been determined partly by the physical properties of the surrounding marsh sediments and how the soil properties influenced delta-plain subsidence and erosion. For example, mud partings in the organic-rich sediments are more common in upper delta-plain settings, such as at Bayou Perot and Ironton, than in lower delta-plain settings such as at Leeville, Fourchon, and Caminada, where the accumulation of peat at most coring sites was essentially uninterrupted. Considering the geological conditions at Bayou Perot and Ironton, prolonged periods of organic accumulation punctuated by periods of clastic invasion may have been caused by two different physical processes: (1) episodic overbank flooding of a distributary channel associated with storm events or seasonal flooding, and/or (2) periodic submergence of the delta plain.

In general, there is a well-established inverse correlation between marsh-sediment organic content and bulk density (Manrique and Jones, 1991; Guntenspergen *et al.*, 1995) owing to the decrease in mineral matter as organic content increases. That same correlation also is evident in the south Louisiana marsh-sediment data (Table III).

For the Mississippi delta-plain study areas, there are good correlations between average marsh-sediment thickness and 1D and 3D accommodation ($R^2 = 0{\cdot}86$ and $R^2 = 0{\cdot}89$, respectively); however, both correlations are strongly biased by the thickest marsh and largest accommodation at Bayou Perot (Figure 13A). Without the data point at Bayou Perot, the correlation between average marsh-sediment thickness and either local or subregional volume of accommodation is much weaker.

There is a good correlation ($R^2 = 0{\cdot}81$) between average bulk density and local 3D accommodation except at Bay St Elaine and Fourchon, where accommodation is low but bulk density is high (Figure 13B, Table III). However, there is only a weak inverse correlation ($R^2 = 0{\cdot}32$) between average bulk density and subregional 3D accommodation, and no significant correlation between average bulk density and 1D accommodation. Furthermore, there is no statistically significant correlation between average organic content and 1D, local 3D, or subregional 3D accommodation. The lack of correlation for some of these parameters and subregional accommodation may be partly a function of the minimum bounding areas that were arbitrarily defined by the availability of photography.

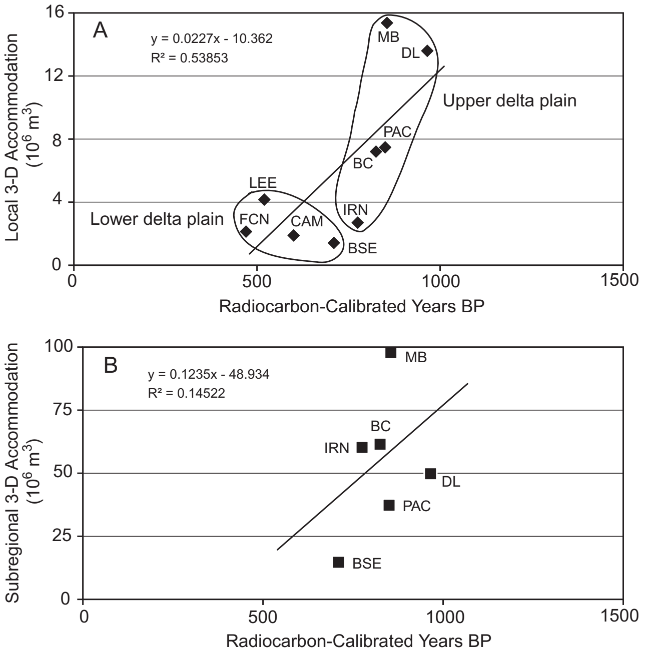

Figure 12. Calibrated radiocarbon age of the first delta-plain marsh versus accommodation volume at the (A) local and (B) subregional scales.

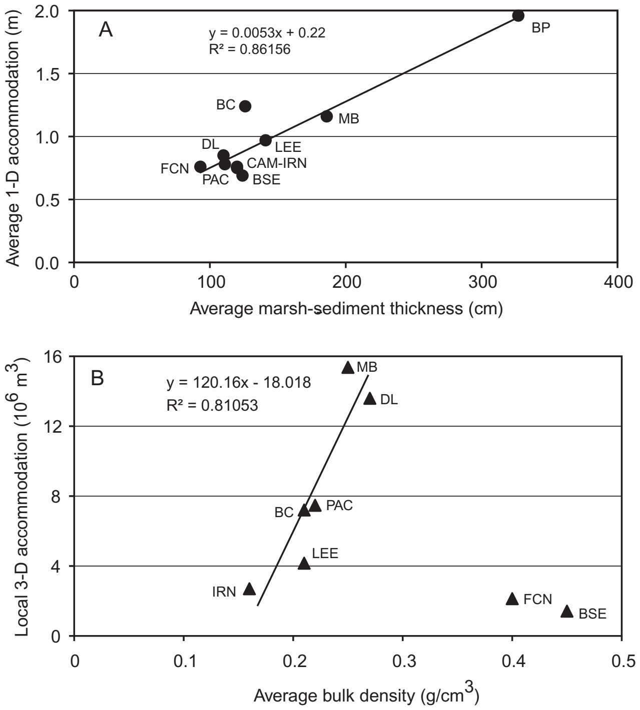

Figure 13. Comparison of marsh-sediment physical properties and accommodation vertical dimensions and volumes.

Conclusions

Marsh elevations, stratigraphic data, and water depths in the Mississippi Delta plain indicate that historical land-area changes were products of both marsh-sediment erosion and land subsidence. Subsidence exceeded erosion at most of the upper delta-plain marsh areas that are now open water, except at Ironton and Bayou Perot. At the lower delta-plain areas of Leeville, Fourchon, and Caminada, the subsidence-erosion predominance was variable depending on core location. Three-dimensional accommodation generally was least at lower delta-plain areas where erosion typically was greater than subsidence. An exception was at the lower delta-plain area of Bay St Elaine, where subsidence contributed substantially more to accommodation formation than erosion. Differential subsidence rates over short distances have led to local variations in submergence-induced land loss versus erosion-induced land loss. For example, rapid delta-plain collapse led to greater preservation of the organic sediments and greater water depths within the areas of newly formed accommodation. In contrast, slow subsidence of the delta plain led to higher rates of surficial marsh erosion, thinner preserved sections of organic sediments, and shallower water depths in the areas of newly formed accommodation. The slowly subsiding marshes are consistent with the areas of wet marsh that were tracked sequentially on satellite imagery.

The importance of historic delta-plain subsidence to initiating accommodation formation is underscored by the facts that: (1) all the study areas have undergone some subsidence, and (2) the erosion component is totally contained within the peat section and does not penetrate beneath the peat-clastic contact regardless of peat thickness (Figures 5, 7, 9, and 10). The physical properties of the marsh sediments (thickness, organic content, and bulk density) partly influenced the dimensions or volume of new accommodation. In general, the older marsh deposits have higher organic content, and they generated larger local 3D accommodation.

Blum and Roberts (2009) estimated future volumes of accommodation in the Mississippi River Delta based on projected rates of sea-level rise and subsidence, and expected extent of delta plain inundation. In contrast, we have reported the accommodation volumes that historically formed in the delta plain at 10 study areas as a consequence of land subsidence and surface erosion. Therefore the accommodation values generated by the two studies are not directly comparable. We estimated that more than 444×10^6 m^3 of accommodation (Table II) formed within the study areas in the Mississippi Delta plain after 1956. This large volume provides a measure of new sediment that would be needed just at the study areas to restore the delta-plain wetlands to their pre-1956 condition. Furthermore, the volume of accommodation at the study areas is only a fraction of the total volume of accommodation associated with delta-plain wetland loss between 1956 and 2004 (Figure 1). For example, the subregional accommodation at the study areas encompass 452·6 km^2 (Table II), which is only 19·4% of the 2333·5 km^2 total land-loss area in the delta plain between 1956 and 2004 (Barras *et al.*, 2008), or 2·2% of the 20 551 km^2 total area in the delta plain (Barras *et al.*, 2008). If water depths in the areas of accommodation formation are similar to those in the areas surveyed, then the total accommodation formed between 1956 and 2004 in the delta plain could be more than five times the volume measured at the study areas, or about $2{\cdot}2 \times 10^9$ m^3.

Our retrospective analysis cannot be used to predict future accommodation formation in the Mississippi Delta plain because the rate of land-to-water conversion has not followed a predictable trend and has markedly declined during the past 30 years (Barras *et al.*, 2008). Furthermore, the historical formation of delta-plain accommodation was not driven entirely by natural processes that would be expected to persist in the future and provide a scientific basis for empirical extrapolation (Morton and Bernier, 2009). Considering past events, present circumstances, and expected future conditions, we anticipate that rates of future accommodation formation will be low except for wetland loss associated with episodic storm impacts. Other than drowning the delta plain and making the area more susceptible to storm impacts, it is uncertain how future sea-level rise will impact rates of accommodation formation in the Mississippi Delta.

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