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Historical Subsidence and Wetland Loss in the Mississippi Delta Plain

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Abstract

Five representative areas of the Mississippi River delta plain were investigated using remote images, marsh elevations, water depths, sediment cores, and radiocarbon dates to estimate the timing, magnitudes, and relative rates of marsh erosion and land subsidence at geological and historical time scales. In the Terrebonne-Lafourche region of rapid interior-wetland loss, former marshes are now submerged beneath water that averages 0.5 to 1.0 m deep. Most of the permanent historical flooding was caused by rapid subsidence and collapse of the delta plain that occurred during the late 1960s and 1970s. Subsequent erosion of the submerged delta-plain marsh was relatively minor at most of the coring sites.

Widespread nearly simultaneous collapse of marshes across the Mississippi delta plain appears to be unprecedented and not repeated in the geological record of the past 1,000 years. Surface and subsurface data strongly indicate that the rapid subsidence and associated wetland loss were largely induced by extraction of hydrocarbons and associated formation water. Average historical rates of subsidence between 1965 and 1993 were about 8 to 12 mm/yr, whereas average geological rates of subsidence for the past 5,000 years were about 1 to 5 mm/yr. Natural processes such as deep-seated salt migration and fault movement cannot be discounted entirely, but there is no compelling evidence that these processes were responsible for the observed historical changes. Results of this study provide a basis for determining the relative importance of subsidence and shoreline erosion as causes of past wetland loss and for predicting sites and probable mechanisms of future wetland loss. This information should improve the selection of project sites and designs for wetland-loss mitigation and coastal restoration in south Louisiana.

Introduction

The magnitude, rate, and timing of wetland loss in south Louisiana and the identification of the underlying processes that cause historical wetland loss have been high-priority topics of scientific investigation since the 1980s. These issues take on even greater importance and urgency considering that the state is seeking substantial federal funding to restore parts of coastal Louisiana and to compensate for some of the historical wetland loss. There are two major challenges for researchers responsible for providing the scientific data used to formulate public policy regarding wetland loss and coastal restoration in Louisiana. The first is generating subsidence estimates for wetland areas that are not immediately adjacent to benchmarks and tide gauges, which is where subsidence rates have been determined previously. The second challenge is developing accurate models for predicting areas and rates of future subsidence and wetland loss.

This paper addresses the general lack of subsidence estimates away from levee roads and marinas by applying the field and laboratory methods of Morton et al. (2003) to four additional areas of historical wetland loss. The purpose of the study is to examine further the timing and processes involved in subsidence and wetland loss in coastal Louisiana. This was accomplished by: (1) estimating magnitudes of recent subsidence and erosion at these selected areas and (2) comparing the temporal and spatial trends of wetland change to historical trends of subsurface-resource extraction in the same areas.

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Methods

Vibracores and water depths were obtained at the Bay St. Elaine, DeLarge, Pointe au Chien, and Bully Camp study areas (Figs. 1 and 2), where historical wetland loss has been rapid and widespread. Core pairs provided close correlation between delta-plain sediments from the emergent marsh and adjacent open water. Ten additional vibracores had previously been collected from the Madison Bay area (Figs. 1 and 2, and Morton et al., 2003). The cores provided a basis for identifying the predominant sedimentary facies and for selecting stratigraphic contacts and surfaces that could be correlated between cores and used to estimate magnitudes of wetland subsidence and erosion (Table 1). The core locations, descriptions, and photographs, detailed descriptions of historical land-water changes, and histories of nearby resource extraction (oil and gas, sulfur) for the five study areas are reported in Morton et al. (2005).

Water depths at open-water coring sites and along bathymetric profiles were measured from the coring barge with a graduated rod, while the geographic coordinates of each depth measurement were obtained simultaneously with a GPS receiver. Movements of water levels at the coring sites during the field operations were assumed to be comparable to those recorded at nearby tide gauges (Fig. 2, and Morton et al., 2003, 2005). Sub-regional water depths and marsh elevations (Table 1) can be compared only if they are corrected for any local conditions (e.g., tidal stage) that would bias the water-level data. The U.S. Army Corps of Engineers (USACE) New Orleans District and Louisiana Department of Natural Resources (LDNR) operate independent networks of tide gauges located throughout the coastal waters of south Louisiana. The tide gauges at Cocodrie (USACE #76305) and near Montegut (LDNR #TE01-12R) are located less than 20 km from the coring sites (Fig. 2). The Cocodrie gauge was used to correct measured water levels at Bay St. Elaine, Madison Bay, and DeLarge, and the Montegut gauge was used to correct measured water levels at Pointe au Chien and Bully Camp.

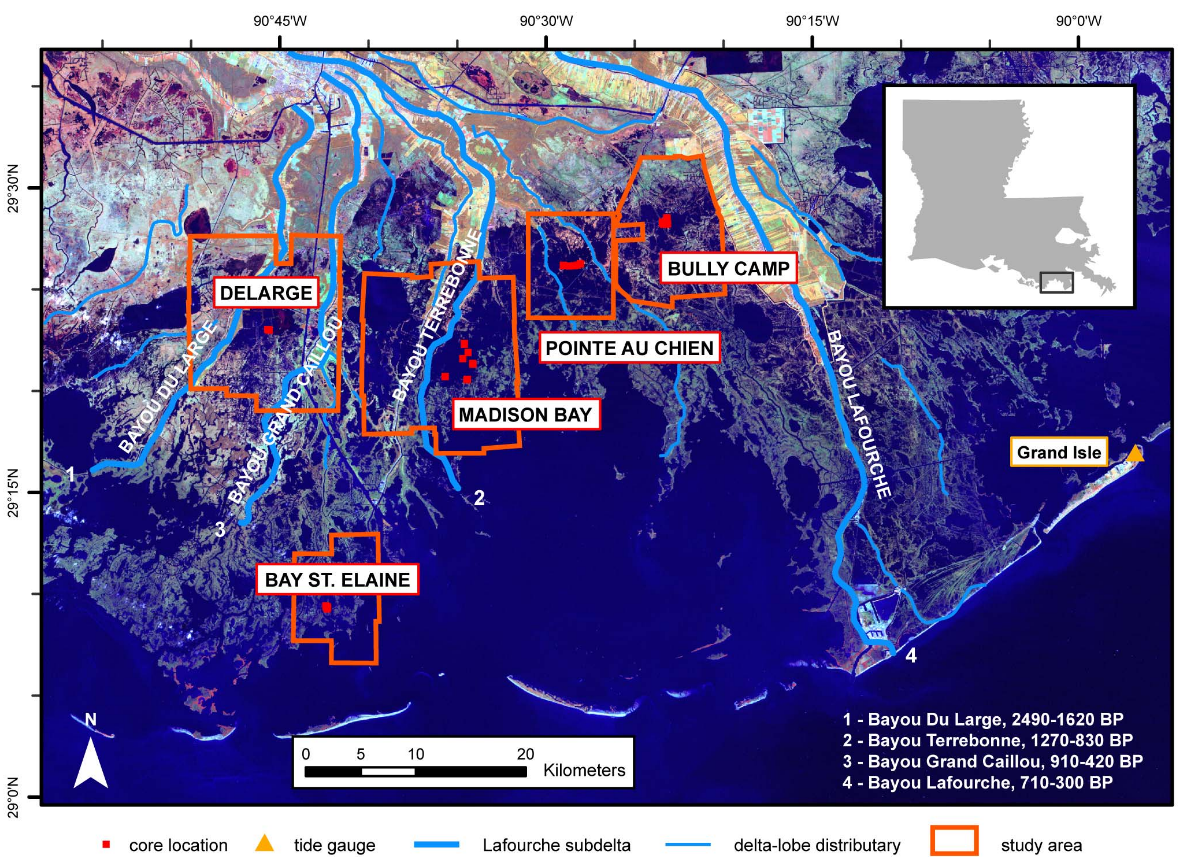

Figure 1. Regional map of south-central Louisiana showing locations of coring sites and subdeltas of the Lafourche delta system. Geologic ages of the Lafourche subdeltas after Penland et al. (1988). Landsat TM 5 image acquired Nov. 7, 2004. The RGB visual display uses bands 4 (near-infrared), 5 (mid-infrared), and 3 (visible red).

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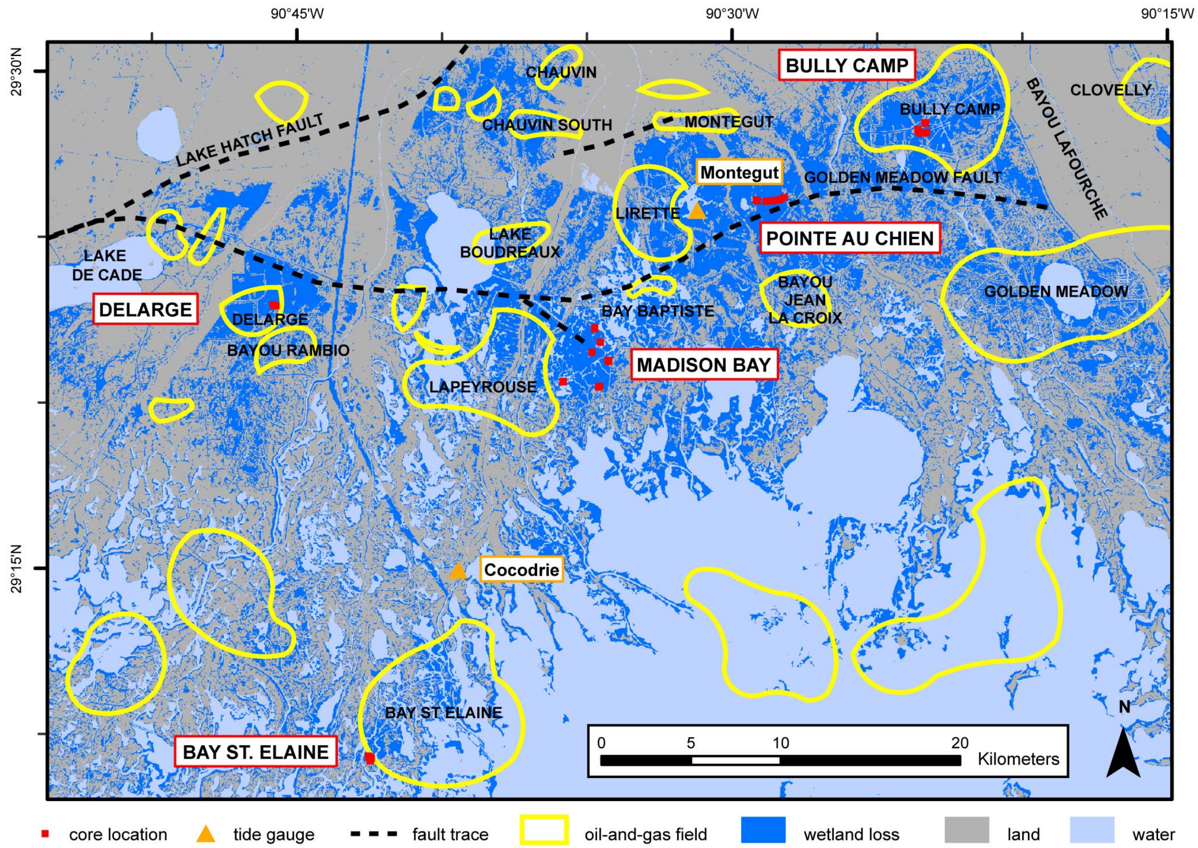

Figure 2. Regional map of south-central Louisiana showing locations of coring sites, the USACE Cocodrie tide gauge, the LDNR Montegut tide gauge, and the distribution of wetland losses (1956-2004) relative to producing oil-and-gas fields and potentially active faults. Land-water classification and wetland loss from Morton et al. (2005). Fault projection from Kuecher et al. (2001).

Beta Analytic, Inc. (Miami, FL) conducted isotopic analyses of peat samples from the vibracores and provided radiocarbon ages (^{14}C) and the corresponding ^{13}C values for the remains of former delta-plain marshes (Table 2). Ranges and means of ^{13}C ratios for the fresh, intermediate, brackish, and saline marshes of the Barataria Basin (Chmura et al., 1987) were used to interpret the types of marshes recovered in the vibracores.

Average long-term geological rates of delta-plain subsidence can be inferred from burial histories of peats, using depths of peat below the surface and the ^{14}C peat ages (Penland et al., 1988; Roberts et al., 1994; Kulp and Howell, 1998). Results of those calculations (Tables 3 and 4) can also be expressed as average long-term geological rates of sediment aggradation. For this report, burial histories of peats are expressed as subsidence rates rather than rates of sediment aggradation.

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Table 1. Core depths and NAVD88 elevations of stratigraphic markers correlated between core pairs. The most prominent markers are contacts between predominantly organic and predominantly clastic sediments. Positive marsh-minus-water (M-W) depth-difference values indicate erosion, and negative M-W depth-difference values indicate sediment accumulation. M-W elevation-difference values represent estimated subsidence. Core locations are presented in Morton et al. (2005).

			Base Last Marsh		Base First Marsh	
Core ID	Core location	Core Elevation (cm NAVD88)	Depth in Core Barrel (cm)	Elevation (cm NAVD88)	Depth in Core Barrel (cm)	Elevation (cm NAVD88)
Bay St. Elaine Area						
composite BSE-04	marsh	49			105	-56
BSE-05	water	-7			112	-119
difference (M-W)		56			-7	63
composite BSE-04	marsh	49			105	-56
BSE-01	water	-35			150	-185
difference (M-W)		84			-45	129
BSE-01	water	-35			150	-185
composite BSE-03	marsh	50			96	-46
difference (M-W)		85			-54	139
BSE-02	water	-8			111	-119
composite BSE-03	marsh	50			96	-46
difference (M-W)		58			-15	73
Madison Bay Area						
MB-10	marsh	30	153	-123	198	-168
MB-06	water	-58	129	-187	175	-233
difference (M-W)		88	24	64	23	65
MB-10	marsh	30	153	-123	198	-168
MB-05	water	-92	111	-203	134	-226
difference (M-W)		122	42	80	64	58
MB-10	marsh	30	153	-123	198	-168
MB-04	water	-108	90	-198	134	-242
difference (M-W)		138	63	75	64	74
MB-01	water	-46	125	-171	186	-232
MB-07	marsh	24	115	-91	192	-168
difference (M-W)		70	-10	80	6	64
MB-05	water	-92	111	-203	134	-226
MB-09	marsh	17	146	-129	168	-151
difference (M-W)		109	35	74	34	75
MB-03	water	-77	118	-195	131	-208
MB-09	marsh	17	146	-129	168	-151
difference (M-W)		94	28	66	37	57
MB-02	water	-59	134	-193	151	-210
MB-08	marsh	20	161	-141	180	-160
difference (M-W)		79	27	52	29	50

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Table 1. (Cont.) Core depths and NAVD88 elevations of stratigraphic markers correlated between core pairs. The most prominent markers are contacts between predominantly organic and predominantly clastic sediments. Positive marsh-minus-water (M-W) depth-difference values indicate erosion, and negative M-W depth-difference values indicate sediment accumulation. M-W elevation-difference values represent estimated subsidence. Core locations are presented in Morton et al. (2005).

Core ID	Core location	Core Elevation (cm NAVD88)	Base Last Marsh: Depth in Core Barrel (cm)	Base Last Marsh: Elevation (cm NAVD88)	Base First Marsh: Depth in Core Barrel (cm)	Base First Marsh: Elevation (cm NAVD88)
DeLarge Area						
DL-01B	marsh	32	30	2	110	-78
DL-01A	water	-49	28	-77	97	-146
difference (M-W)		81	2	79	13	68
Pointe au Chien Area						
PAC-05	marsh	33	41	-8		
PAC-04	water	-41	42	-83		
difference (M-W)		74	-1	75		
PAC-05	marsh	33	41	-8		
PAC-06	water	-54	33	-87		
difference (M-W)		87	8	79		
PAC-05	marsh	33	41	-8		
PAC-02A	water	-41	46	-87		
difference (M-W)		74	-5	79		
PAC03-05	marsh	33	41	-8		
PAC03-02B	marsh	32	56	-24		
difference (05-02B)		1	-15	16		
PAC-02A	water	-41	46	-87	114	-155
PAC-02B	marsh	32	56	-24	99	-67
difference (M-W)		73	10	63	-15	88
PAC-02B	marsh	32	56	-24	99	-67
PAC-03	water	-62	42	-104	129	-191
difference (M-W)		94	14	80	-30	124
PAC03-02B	marsh	32	56	-24	99	-67
PAC03-01B	marsh	39	26	13	103	-64
difference (01B-02B)		7	-30	37	4	3
PAC-03	water	-62	42	-104	129	-191
PAC-01B	marsh	39	26	13	103	-64
difference (M-W)		101	-16	117	-26	127
PAC-01A	water	-38	39	-77	110	-148
PAC-01B	marsh	39	26	13	103	-64
difference (M-W)		77	-13	90	-7	84
Bully Camp Area						
SM-02B	marsh	49	59	-10	93	-44
SM-02A	water	-45	33	-78	80	-125
difference (M-W)		94	26	68	13	81
SM-02B	marsh	49	59	-10	93	-44

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Table 1. (Cont.) Core depths and NAVD88 elevations of stratigraphic markers correlated between core pairs. The most prominent markers are contacts between predominantly organic and predominantly clastic sediments. Positive marsh-minus-water (M-W) depth-difference values indicate erosion, and negative M-W depth-difference values indicate sediment accumulation. M-W elevation-difference values represent estimated subsidence. Core locations are presented in Morton et al. (2005).

Core ID	Core location	Core Elevation (cm NAVD88)	Base Last Marsh Depth in Core Barrel (cm)	Base Last Marsh Elevation (cm NAVD88)	Base First Marsh Depth in Core Barrel (cm)	Base First Marsh Elevation (cm NAVD88)
SM-05	water	-50	56	-106	92	-142
difference (M-W)		99	3	96	1	98
SM-02B	marsh	49	59	-10	93	-44
SM-03	marsh	-8	61	-69	103	-111
difference (02B-03)		57	-2	59	-10	67
SM-02B	marsh	49	59	-10	93	-44
SM-04	water	-135 *	24 *	-159	51 *	-186
difference (M-W)		184	35	149	42	142
SM-04	water	-135	24 *	-159		
SM-01B	marsh	28 **	46 **	-18		
difference (M-W)		163	22	141		
SM-01A	water	-67	40	-107		
SM-01B	marsh	28 **	46 **	-18		
difference (M-W)		95	6	89		

*excluding 5-cm recent sand deposition

**excluding uppermost 27-cm recent (muddy) marsh deposition

Historical Subsidence and Erosion of Delta-Plain Marshes

Methods of estimating subsidence and erosion

Magnitudes of marsh subsidence and erosion were estimated by comparing the elevations and vertical offsets (Table 1) of sediment surfaces and stratigraphic contacts correlated between adjacent core pairs. The relative subsidence and erosion between emergent marsh and open-water cores assumes that marsh-sediment thickness and stratigraphic positions of correlative contacts are uniform over short distances (tens to hundreds of meters). The amount of erosion at the open-water core site is equal to the difference in marsh-sediment thickness between the open-water core and the adjacent marsh core. The amount of subsidence at the open-water core is equal to the elevation difference between the correlated stratigraphic markers between the two adjacent cores. To be precise, the core sections being correlated must not be deformed (shortened), and the erosion and subsidence estimates must equal the vertical displacement between the cores (Table 1). This technique provides a minimum estimate of total subsidence because there is no measurement of the absolute amount of historical subsidence of the marsh surface relative to some standard vertical datum. Stated another way, the former marsh preserved beneath open water has subsided more than the adjacent emergent marsh, but the emergent marsh also has subsided some unknown amount.

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Table 2. Radiocarbon ages and carbon-isotope data for organic samples. Core locations are presented in Morton et al. (2005).

Core ID	Sample Depth (cm)	Stratigraphic Horizon	Conventional Age (BP)	$\delta^{13}C$ (‰)
		Bay St. Elaine Area		
BSE-01	146-147	base first marsh	820 ± 40	-25.6
BSE-02	73-74	top first marsh	400 ± 40	-23.4
BSE-02	110-111	base first marsh	850 ± 40	-26.6
BSE-04	21-22	top first marsh	320 ± 40	-24.6
BSE-04	71-72	base first marsh	680 ± 40	-24.8
BSE-05	37-38	base last marsh	200 ± 40	-13.9
		Madison Bay Area		
MB-02	133-134	base last marsh	840 ± 40	-26.0
MB-02	145-146	top first marsh	940 ± 40	-25.6
MB-02	150-151	base first marsh	930 ± 40	-25.8
MB-04	107-108	top intermediate marsh	720 ± 40	-26.6
MB-04	113-114	base intermediate marsh	700 ± 40	-27.0
MB-04	133-134	base first marsh	960 ± 40	-26.7
MB-07	114-115	base last marsh	600 ± 40	-25.8
MB-07	186-187	top first marsh	980 ± 40	-26.3
MB-07	191-192	base first marsh	950 ± 40	-26.5
MB-09	46-47	base recent marsh	150 ± 40	-14.1
MB-09	145-146	base last marsh	680 ± 40	-26.7
MB-09	167-168	base first marsh	920 ± 40	-26.3
MB-10	152-153	base last marsh	660 ± 40	-26.4
MB-10	197-198	base first marsh	970 ± 40	-26.5
		DeLarge Area		
DL-01A	26-27	base last marsh	510 ± 40	-27.4
DL-01A	56-57	top first marsh	840 ± 40	-26.4
DL-01A	95-96	base first marsh	1050 ± 40	-26.9
		Pointe au Chien Area		
PAC-01A	109-110	base first marsh	900 ± 40	-27.2
PAC-01B	25-26	base last marsh	280 ± 40	-26.1
PAC-02A	91-92	top first marsh	930 ± 40	-27.3
PAC-02A	112-113	base first marsh	980 ± 40	-28.0
PAC-02B	55-56	base last marsh	430 ± 40	-26.2
PAC-03	99-100	first marsh	940 ± 40	-27.4
PAC-03	128-129	base first marsh	950 ± 40	-19.4
		Bully Camp Area		
SM-01B	27-28	base recent marsh	90 ± 40	-26.3
SM-01B	72-73	base last marsh	420 ± 40	-27.4
SM-02B	58-59	base last marsh	450 ± 40	-26.5
SM-02B	85-86	top first marsh	860 ± 50	-27.0
SM-02B	92-93	base first marsh	900 ± 40	-27.3

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Table 3. Minimum subsidence rates inferred from minimum aggradation rates based on marsh thickness (interval rate) and sample depth (depth rate). Core locations are presented in Morton et al. (2005).

Core ID and Sample Depth (cm)	Stratigraphic Horizon	^{14}C Age (BP)	Marsh Thickness (cm)	Interval Rate (mm/yr)	Sample Depth (cm)	Depth Rate (mm/yr)
Bay St. Elaine Area						
BSE-01-146/147	base first marsh	820			147	1.8
BSE-02-073/074	top first marsh	400	38	0.8	74	1.9
BSE-02-110/111	base first marsh	850			111	1.3
BSE-04-021/022	top first marsh	320	51	1.4	54	1.7
BSE-04-071/072	base first marsh	680			105	1.5
BSE-05-037/038	base last marsh	200			38	1.9
Madison Bay Area						
MB-02-133/134	base last marsh	840			134	1.6
MB-02-145/146	top first marsh	940			145	1.5
MB-02-150/151	base first marsh	930			151	1.6
MB-04-107/108	top intermediate marsh	720			108	1.5
MB-04-113/114	base intermediate marsh	700			114	1.6
MB-04-133/134	base first marsh	960			134	1.4
MB-07-114/115	base last marsh	600			115	1.9
MB-07-186/187	top first marsh	980			187	1.9
MB-07-191/192	base first marsh	950			192	2.0
MB-09-046/047	base recent marsh	150			47	3.1
MB-09-145/146	base last marsh	680	100	1.9	146	2.1
MB-09-167/168	base first marsh	920			168	1.8
MB-10-152/153	base last marsh	660			153	2.3
MB-10-197/198	base first marsh	970			198	2.0
DeLarge Area						
DL-01A-026/027	base last marsh	510			27	0.5
DL-01A-056/057	top first marsh	840	40	1.9	57	0.7
DL-01A-095/096	base first marsh	1050			96	0.9
Pointe au Chien Area						
PAC-01A-109/110	base first marsh	900			110	1.2
PAC-01B-025/026	base last marsh	280			26	0.9
PAC-02A-091/092	top first marsh	930	22	4.4	92	1.0
PAC-02A-112/113	base first marsh	980			113	1.2
PAC-02B-055/056	base last marsh	430			56	1.3
PAC-03-099/100	first marsh	940			100	1.1
PAC-03-128/129	base first marsh	950			129	1.4
Bully Camp Area						
SM-01B-027/028	base recent marsh	90			27	3.0
SM-01B-072/073	base last marsh	420	46	1.4	73	1.7
SM-02B-058/059	base last marsh	450			59	1.3
SM-02B-085/086	top first marsh	860	8	2.0	86	1.0
SM-02B-092/093	base first marsh	900			93	1.0

*depth to contact from composite core description for BSE-04
**thickness excludes the overlying recent marsh

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Table 4. Rates (mm/yr) of sediment accumulation (sed) and inferred rates of subsidence (sub) for the Terrebonne and Barataria Basins estimated from isotopic ages (< 5000 BP) and direct field measurements (feldspar marker).

Method	Type	Period	Range (mm/yr)	Mean (mm/yr)	Reference
marker	sed	years	n/g	22	Rybczyk and Cahoon, 2002
^{137}Cs	sed	decades	11 - 17	13*	Hatton et al., 1983
^{137}Cs	sed	decades	3 - 10	7**	Hatton et al., 1983
^{137}Cs	sed	decades	6 - 8	7	DeLaune et al., 1985
^{14}C	sub	centuries	1 - 16	6	Penland et al., 1988
^{14}C	sub	centuries	3 - 7	5	Roberts et al., 1994
^{14}C	sub	centuries	0.5 - 4	2	this study, Table 3
^{14}C	sub	millennia	1 - 5	2	Penland et al., 1988
^{14}C	sub	millennia	3 - 5	4	Roberts et al., 1994
^{14}C	sub	millennia	0.1 - 8	1	Kulp and Howell, 1998

n/g = not given
*levee
**back marsh

Pointe au Chien area

The Pointe au Chien (PAC) study area (Figs. 1 and 3) was selected to represent the results presented by Morton et al. (2005) because, in many respects, it is similar to the other four delta-plain settings. Extant marsh elevations at PAC range from 32 to 39 cm above the North American Vertical Datum of 1988 (NAVD88), and water depths where marsh formerly existed range from 24 to 68 cm and average about 48 cm below NAVD88 (Fig. 4).

The Pointe au Chien study area is located within an east-west regional trend of historic wetland loss that extends from Lake De Cade to Bayou Lafourche (Fig. 2). Wetland loss at PAC is nearly complete, with isolated marsh patches surrounded by open water. Much of the wetland loss occurred between 1969 and 1974 (Fig. 3). There is no obvious surface expression of faults or other structures controlling patterns of wetland loss, although the projected surface trace of the Golden Meadow fault (Kuecher et al., 2001) occurs to the south of the core sites (Fig. 3D).

Six stratigraphic units were identified in the PAC cores: (1) dark olive-gray peat, (2) gray to olive-gray, massive to laminated mud, (3) olive-gray to black peat, (4) gray to olive-gray or black, massive to laminated mud and organic mud, (5) olive-gray to gray, massive to laminated silt, sand, and/or mud, and (6) olive-gray laminated mud and sand. The unit 3 peat represents the first subdelta marsh.

Radiocarbon ages and carbon-isotope ratios of peat samples indicate that freshwater plants established the first marsh at PAC about 950 BP. The duration of this wetland is uncertain because the ages of samples near the top of the peat are within the error range of ages from the base of the peat (Fig. 4). After the first marsh was flooded, as much as 50 cm of mud was deposited before the last marsh was established about 300 to 400 BP. Since then, long-term rates of marsh aggradation have averaged about 1 mm/yr (Table 3).

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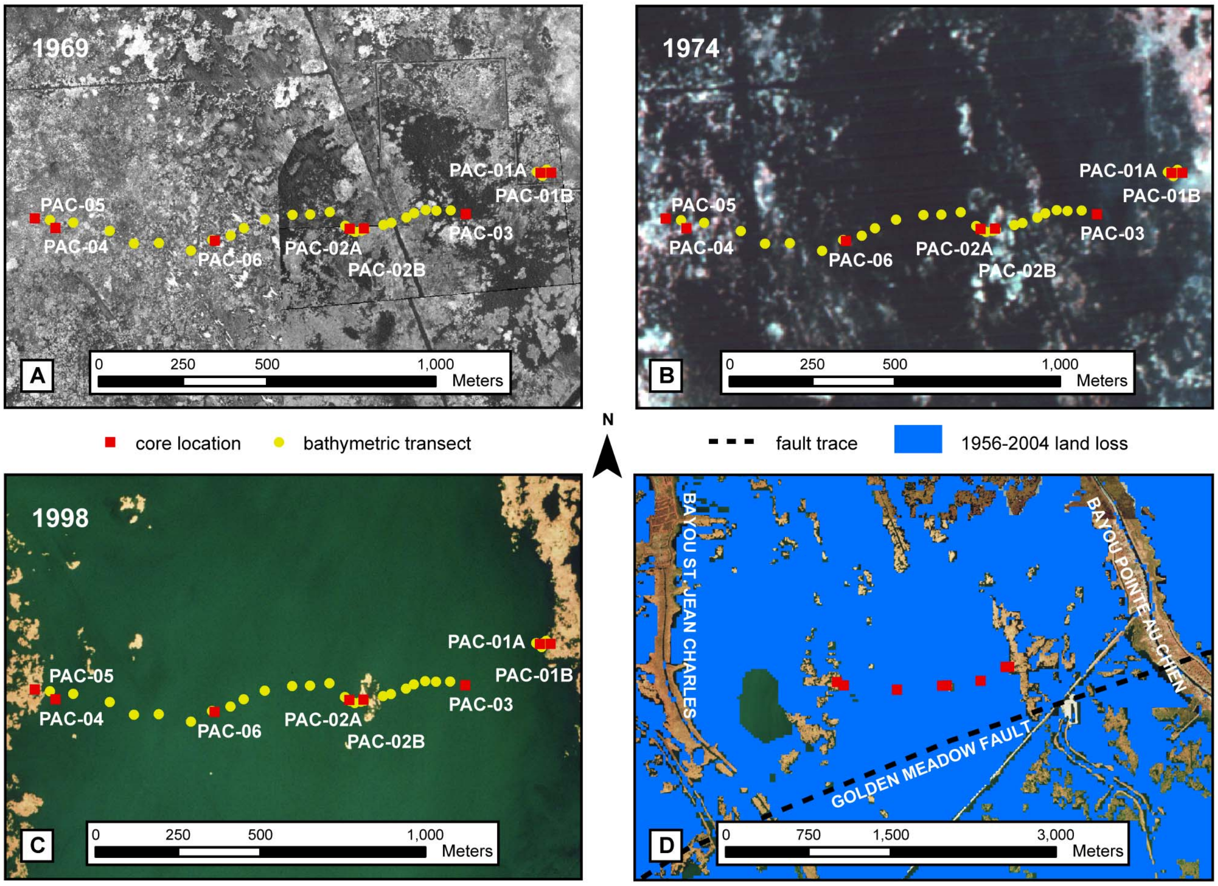

Figure 3. Locations of sediment cores and sediment-surface profiles from the Pointe au Chien area superimposed on aerial photographs taken in (A) 1969, (B) 1974, and (C) 1998. (D) 1956-2004 wetland loss at Pointe au Chien and the surrounding area superimposed on the 1998 image. The 1998 DOQQ imagery was obtained from the Louisiana Oil Spill Coordinator's Office (LOSCO).

The magnitudes of land subsidence are similar across the Pointe au Chien area of wetland loss (Fig. 4), and the highest marsh elevations coincide with the areas of least subsidence. Analysis of marsh cores PAC-01B and PAC-05 suggest that the base of the last marsh was near NAVD88 before the area subsided. Consequently, comparisons of open-water cores with marsh core PAC-02B may underestimate total subsidence because the marsh remnant at core PAC-02B has subsided more than the adjacent emergent marsh. Core PAC-02B has subsided 16 to 37 cm relative to the adjacent marsh at cores PAC-01B and PAC-05. Subsidence at the open-water sites ranged from 75 to 117 cm and averaged about 88 cm (Table 1). The variable thickness of marsh sediments across the Pointe au Chien area makes estimates of erosion at the open-water sites imprecise. Nevertheless, erosion of the last marsh surface ranged from 0 to 14 cm, which is minor compared to magnitudes of subsidence.

Patterns of wetland loss in the Pointe au Chien area do not coincide with the projected extent of any single oil-and-gas field, but the area of wetland loss is surrounded by the Bayou Jean la Croix, Lirette, and Montegut fields (Fig. 2). Initial discovery of gas in the 1920s at Lirette was attributed to surface seeps, whereas deep hydrocarbons at Lirette were discovered in 1937 (Troutman, 1956) and at Montegut in 1957 (Silvernail, 1967). These fields produce from rollover anticline structures associated with a family of growth faults (Piaggio, 1961; Lyons, 1982). Peak hydrocarbon production from these fields occurred between 1965 and 1980 (Fig. 5). The combined cumulative production through 2002 from the three fields was 35.2 million bbls of oil, 1.7 Tcf of gas, and 103 million bbls of water. Regional depressurization of subsurface reservoir strata may be a contributing factor to surface subsidence in this area. The projected surface trace of the Golden Meadow Fault extends through the southern zone of

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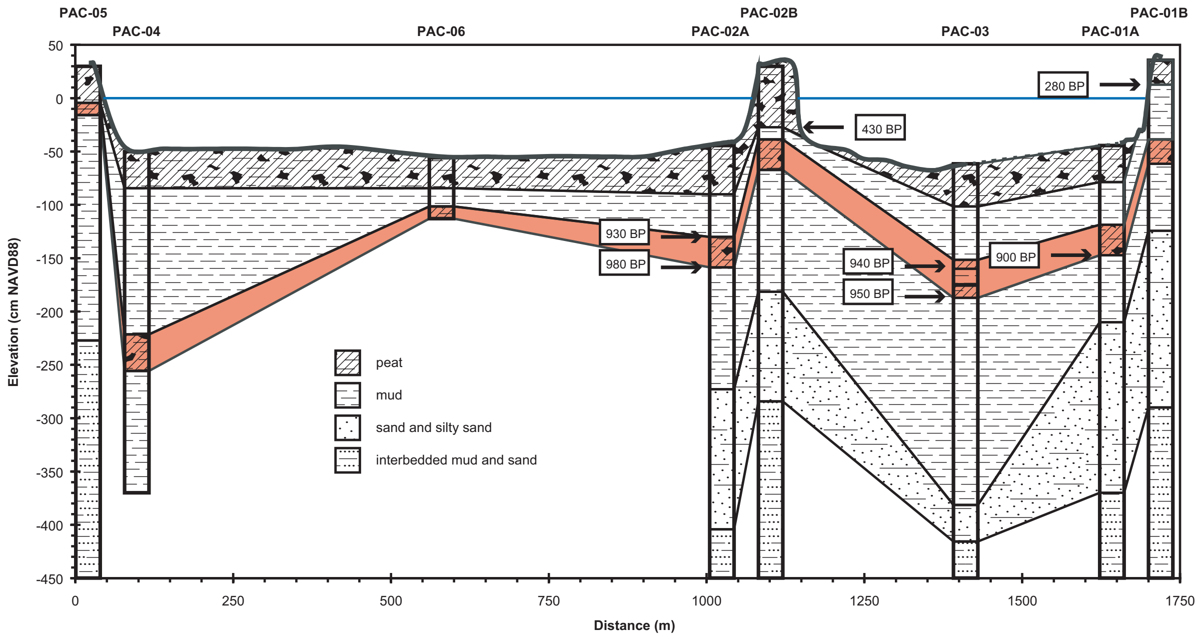

Figure 4. Combined bathymetric profile and stratigraphic cross section for marsh and open-water cores illustrate the magnitude of subsidence and wetland erosion (in cm) at the Pointe au Chien area. Locations shown in Figure 3, 200x vertical exaggeration.

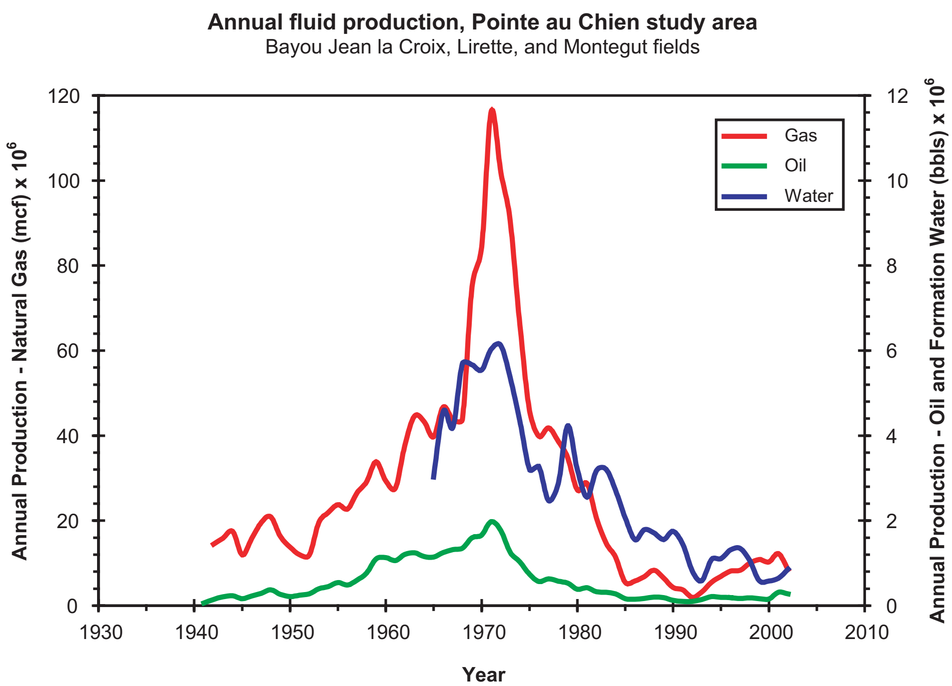

Figure 5. Annual fluid production through 2002 from the Bayou Jean la Croix, Lirette, and Montegut fields in Terrebonne Parish. Data from the Louisiana Department of Natural Resources and the PI/Dwights PLUS database (IHS Energy Group, 2003).

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greatest wetland loss between Bayou Terrebonne and Bayou Pointe au Chien (Fig. 2), but spatially it does not appear to correlate with any limits to wetland loss. The projected surface trace of the Lake Hatch spur fault, however, approximates the northern boundary of extensive wetland loss.

Geological and Historical Rates of Subsidence

Geological subsidence rates

Rates of vertical sediment accumulation have been used as a proxy for subsidence rates based on the assumption that the accommodation space necessary for vertical sediment accumulation (aggradation) was provided by subsidence regardless of the specific process (crustal loading, sediment compaction, fault activation). For wetland sediments and static sea-level conditions, this assumption appears to be valid as a first approximation. The condition of constant sea level equivalent to modern sea level is not difficult to achieve for recent periods, such as decades or a few centuries, but would not be a reasonable assumption for periods encompassing several millennia. To avoid potential inaccuracies associated with eustatic fluctuations, only published subsidence rates for periods less than 5,000 years were included in the comparison (Table 4). Geological rates of subsidence calculated for this study range from 0.5 to 4.4 mm/yr (Table 3) and average about 2 mm/yr (Table 4).

Historical subsidence rates

Historical changes in land elevation relative to a standard vertical datum can be measured directly from controlled benchmarks or inferred from long-period tide-gauge records (Holdahl and Morrison, 1974). Both of these methods have been used to approximate subsidence rates in south Louisiana (Penland et al., 1988; Morton et al., 2002). Shinkle and Dokka (2004) re-analyzed historical leveling data along Bayou Lafourche and Bayou Petit Caillou and calculated revised subsidence rates between 1965 and 1993. The spatial trends of the revised subsidence rates (Fig. 6) are identical to those presented by Morton et al. (2002); however, they also allow comparison of subsidence rates for two periods (Fig. 6). Within the context of generally increased subsidence in a seaward direction, highest rates of subsidence coincided locally with faults and producing oil-and-gas fields. Between the fields and faults, subsidence rates were lower. There is no evidence of uplift across the known salt domes (Valentine, Bully Camp, and Leeville) that would indicate historical dome growth. From 1965 to 1982, subsidence rates between Raceland and Leeville ranged from 1.6 to 12.0 mm/yr and averaged about 7.6 mm/yr. From 1982 to 1993, subsidence rates ranged from 8.2 to 18.9 mm/yr and averaged about 12.1 mm/yr. Although subsidence rates accelerated between the two periods, the spatial order of higher and lower rates was maintained, indicating that subsidence is strongly controlled by subsurface geological processes.

Comparison of subsidence rates

Short-term historical rates of geological processes are commonly higher than the long-term average rates of those same processes, and subsidence rates are no exception. The important question to answer is whether the temporal differences are related to actual differences in the driving forces, or whether they are simply related to timing of the observations or sampling frequency. Some geological processes, such as fault slip, are intermittent, and their instantaneous rates may be very high, but the duration is short and the frequency of recurrence is low. These processes typically produce low long-term average rates of change. High instantaneous rates measured for these processes cannot be sustained indefinitely; therefore, those rates should not be extrapolated for predictive purposes. For example, if the historical rates of subsidence had persisted for the past 1,000 years, the Mississippi delta would have been deeply inundated long ago.

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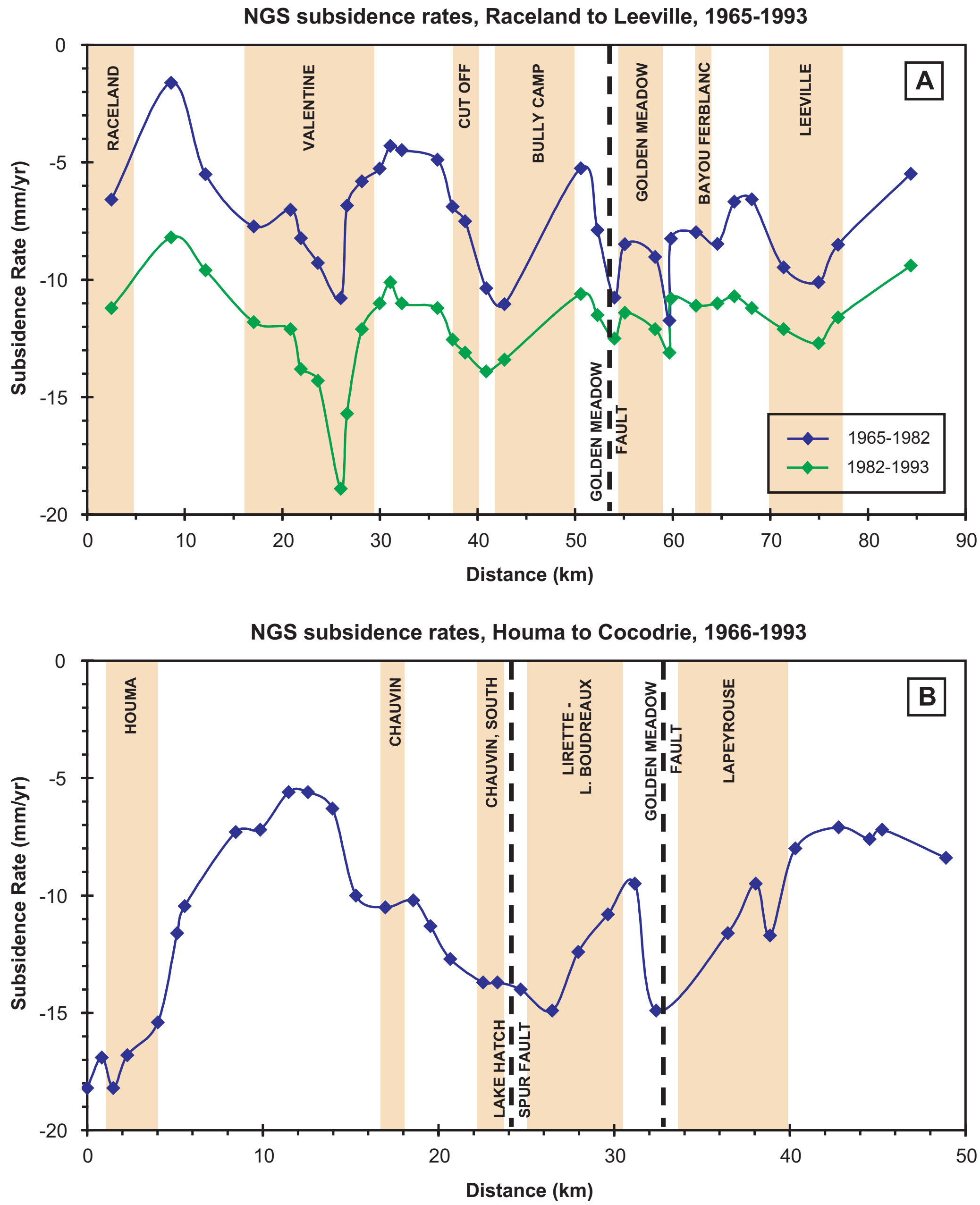

Figure 6. Plots of historical subsidence rates along (A) Bayou Lafourche and (B) Bayou Petit Caillou calculated by the National Geodetic Survey from re-leveling of benchmarks (Shinkle and Dokka, 2004). The plots show a close spatial correlation between highest subsidence rates, hydrocarbon-producing fields (delineated in tan), and the projected intersection of deep faults. They also show that subsidence rates accelerated between 1965-82 and 1982-93. Modified from Morton et al. (2002). Revised subsidence rates provided by Kurt Shinkle (NGS).

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Historical subsidence rates are roughly an order of magnitude higher than geological subsidence rates (compare Fig. 6 and Table 4). One explanation would be that natural faulting and subsidence are active at a time when monitoring is being conducted, and the methods of detection can resolve and measure the movement. Another explanation is that the rates actually are much higher than normally would be expected because subsidence and/or fault activation have been induced by subsurface-resource extraction.

Whether the high rates of historical subsidence and associated wetland loss are natural or induced is still somewhat controversial. Gagliano et al. (2003) concluded that historical subsidence and wetland losses in south Louisiana were caused naturally by sediment loading, salt evacuation, and gravity gliding. All of these processes are known to be responsible for the overall tectonic regime of the Gulf Coast Basin, but Gagliano et al. (2003) presented no evidence to substantiate their claim that the recent timing (post-1960s) and rates of subsidence south of New Orleans were attributable to natural salt migration and faulting. They also did not consider that (1) major decreases in formation pore pressure, such as those reported by Morton et al. (2002) around hydrocarbon producing fields in south Louisiana, have the same effect as sediment loading, or that (2) changes in subsurface stress induced by fluid withdrawal are capable of accelerating movement of potentially active faults (Chan, 2005). Gagliano et al. (2003) also argued that the 1964 Alaskan earthquake was largely responsible for the timing of fault reactivation in south Louisiana, again without presenting any scientific evidence of transitory changes in subsurface stress that would support their speculation. The 1964 Alaskan earthquake was not felt in Louisiana, although seiches were generated in water bodies by the passing surface wave (Stevenson and McCulloh, 2001). Perhaps more important is the fact that the massive wetland losses in the delta plain (Figs. 2 and 7) were mostly initiated more than 5 years after the 1964 Alaskan earthquake.

Significant reductions in subsidence rates are expected in the Terrebonne-Lafourche Basins because the rates of subsurface-fluid withdrawal that were largely responsible for the rapid induced subsidence have markedly declined (Fig. 7). Moreover, whatever contribution fault reactivation may have made, fault movement likely has already relieved the stress differential created by subsurface pressure reductions, and the state of stress has returned to near-equilibrium conditions. If this is true, then additional subsidence related to fault reactivation would not be expected because the subsurface perturbation caused by peak fluid production has passed (Fig. 7).

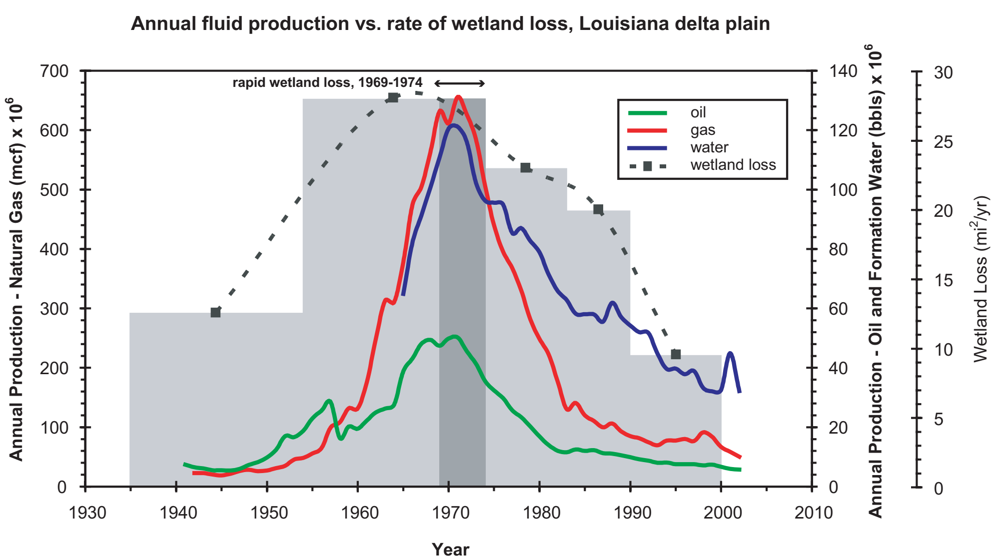

Figure 7. Composite histories of fluid production from oil-and-gas fields and wetland loss in south Louisiana. Production data from the Louisiana Department of Natural Resources and the PI/Dwights PLUS database (IHS Energy Group, 2003). Wetland loss values were determined by Britsch and Dunbar (1993) and John Barras (personal communication, 2005). These historical data, integrated across the delta plain, show close temporal and spatial correlations between rates of wetland loss and rates of fluid production.

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Conclusions and Implications

Historical wetland losses in the Mississippi delta plain have been classified on the basis of morphology and interpreted physical processes (Penland et al., 2000a, 2000b). Wetland losses around the margins of interior water bodies were attributed to shoreline erosion based on the inferred erosional capability of storm waves and field observations of local marsh erosion. Results of our study indicate that most of the wetland losses around open-water bodies at the coring sites are due to subsidence, and erosion is only a minor process contributing to the conversion of wetlands to open water. At most of the open-water sites that were formerly continuous emergent marsh, extant water depths are greater than the thickness of the delta-plain marsh. This physical relation is clear evidence that wetland loss resulted from subsidence, because it is impossible to erode to those depths and still preserve some of the marsh deposits. Emergent-marsh elevations, used as the standard for subsidence estimates, are significantly lower where subsidence has been greatest, such as at Madison Bay and the marsh-island remnants of Pointe au Chien and Bully Camp. The magnitudes and similarities of subsidence around the perimeters of water bodies that were former marshes provide compelling evidence that the subsidence is not largely related to fault reactivation, because it is not geologically reasonable to infer a fault between each emergent-marsh and open-water core pair. The similarities of subsidence magnitudes across the delta plain, regardless of position relative to a fault plane, are further evidence that recent subsidence is not locally fault controlled.

Lithologic and chronostratigraphic similarities of peat deposits from Bay St. Elaine, DeLarge, Pointe au Chien, and Bully Camp indicate that processes that influenced the organic accumulation and influx of clastic sediments operated over large portions of the delta plain, and not just locally. This implies that fault reactivation is not a likely mechanism to explain the alternating deposition of peat and mud several hundred years ago. Furthermore, there is no unequivocal evidence of a fault influencing the thickness or number of peat beds at any of the coring sites. This includes Bay St. Elaine, where cores were deliberately taken across the marsh-water lineament that appears to be the surface expression of a fault. The fault may have moved recently, but there is no evidence of recurrent motion in the recent geologic past that has resulted in stratigraphic expansion, which is typical of an active growth fault that moves frequently.

The types of core data and imagery used by Gagliano et al. (2003) and Morton et al. (2002, 2003, 2005) are similar, and yet their interpretations with regard to past and future subsidence and wetland loss are quite different. These differences are not academic, because they have profound implications with regard to predicting future subsidence and its impact on coastal-restoration projects. Gagliano et al. (2003) attributed the historical subsidence and wetland loss to natural processes deep within the Gulf Coast Basin that are random and unpredictable as to future occurrences. In contrast, Morton et al. (2002, 2003, 2005) concluded that historical subsidence and wetland loss was primarily induced by fluid withdrawal, and therefore the future impacts are qualitatively predictable.

Results from this study confirm that the most likely explanation for historical wetland losses in south-central Louisiana is regional subsidence and local fault reactivation induced by hydrocarbon production. There is no compelling evidence of historical salt dome growth in the area before, during, or after the period of rapid subsidence and the pore-pressure reduction in the reservoirs is equivalent to sediment loading across the delta plain. Furthermore, it is clear that offsets in stratigraphic marker beds observed in shallow cores taken in marsh and adjacent open-water sites are a result of subsidence, not fault slip. There is no evidence that such widespread instantaneous subsidence occurred in the past few thousand years as a result of natural deep-basin processes (sediment loading, salt migration, gravity gliding).

The results of this study give guidance to future research directions and the development of datasets that could facilitate resource-management decisions and coastal-restoration planning efforts in south Louisiana. The conclusion that some interior water bodies are expanding as a result of subsidence rather than shoreline erosion needs to be tested systematically in the field. Shoreline erosion seems to be an intuitively correct explanation for water-body expansion where fetch and water-body orientation with respect to predominant wind directions are sufficient to generate erosive waves. This hypothesis can be tested easily by taking core pairs around the perimeters of some of the largest water bodies. Also, there are several wetland-loss mitigation sites where riprap was used to dampen wave energy, but the shore-

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line continued to retreat. Elevation profiles and cores taken landward of the riprap would offer a way of determining which processes were primarily responsible for the wetland loss and shoreline retreat. If shoreline erosion is not the primary cause of water-body expansion, then hard structures may not be an appropriate method of mitigating wetland loss at those sites.

Monitoring the rates and trends of delta-plain subsidence is necessary for accurately predicting future subsidence rates. Evaluating the relative vulnerability of coastal-restoration projects to potential subsidence is an objective of state officials who are charged with the responsibility of managing coastal resources. In the absence of a sophisticated numerical model for predicting subsidence, historical subsidence records can serve as indicators of regions of higher and lower risk. This approach becomes even more powerful when the subsurface processes causing subsidence are known and future trends can be predicted.

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