The dominant processes responsible for subsidence of coastal wetlands in south Louisiana

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Abstract. Wetland loss in coastal areas of Terrebonne and Lafourche Parishes, Louisiana, largely results from two subsurface processes: (1) consolidation of recently deposited Holocene deltaic sediments and (2) active growth faulting. Locally, settlement is high where the thickness of valley fill is great and in broad interdistributary basins where the thickness of consolidation-prone peaty soils is great. The delta cycle is identified as the fundamental sedimentologic unit that constitutes the lower delta plain. Peaty soils from the waning phase of the delta cycle are identified as the deltaic facies most subject to consolidation settlement. Data indicate direct relationships between the thickness of deltaic sediments in individual delta cycles, and the thickness of peaty soils capping these cycles, with present patterns of coastal tract land loss. In addition, active growth faulting is correlated with new areas of interior tract wetland loss. Consolidation and faulting largely explain the curious nature of wetland loss patterns in south Louisiana. Subsidence in The Netherlands has been attributed to similar causes, i.e. thick deposits of consolidation-prone sediments that accumulate on the downthrown sides of basin margin faults.

INTRODUCTION

The study area for this research consists of approximately 4,000 km^2 in Terrebonne and Lafourche

Parishes, Louisiana (Fig. 1). The deltaic wetlands within this study area are currently being converted to open bays at a rate of approximately 80 km^2/yr (Britsch *et al.*, 1991). The subsurface processes contributing to wetland loss in this area are the focus of this research.

RELATIONSHIP OF SUBSURFACE TO SURFACE SUBSIDENCE

During the Late Wisconsinan glacial maxima (±18 ka), eustatic sea levels fell between 90 m (Morton, 1991) and 110 m (Haq, 1995). On the Louisiana Gulf Coast, this sea level lowstand resulted in a deeply incised Mississippi River valley. The net result of this erosion and subsequent valley fill was the removal of a great wedge of consolidated Pleistocene sediments and its replacement by less consolidated materials. Roberts (1985) referred to this as the Holocene Valley Fill and reported on a direct relationship between the thickness of valley fill and radiocarbon-determined rates of subsidence; i.e. thick valley fill equals high rates of subsidence (Fig. 2). A similar relationship was established by Groenewoud *et al.*(1991) in The Netherlands when he correlated increasing rates of subsidence with increasing depth to the base of Quaternary sediments. Subsurface controls on present patterns and rates of land loss are indicated in both studies.

The delta cycle

A major characteristic of modern Mississippi River sediments is the orderly, cyclic repetition of depositional sequences (Coleman *et al.*, 1964; Kolb and Van Lopik, 1958; McIntyre, 1954). A delta cycle is the vertical succession of sediments deposited in response to a delta-building event. Cyclic repetition of deltaic sediments occurs in scales ranging from large delta lobes to small crevasse splays.

One cycle of deltaic sediments is defined as the deltaic sediments accumulated between marine ravinement surfaces, most often measured between successive capping peat sequences (Kuecher, 1994). A model describing relative rises and falls of sea level during the course of deposition of a delta cycle is presented (Fig.3). In this model, relative sea level falls occur when peat deposits are no longer able to vertically accrete at a rate at which the surface is subsiding. Shelly bay muds and prodelta muds deposited at the base of each cycle represent maximum flooding conditions in this vertical assemblage and times during which the surface of the lower delta plain becomes subaqueous and coeval sediments are bioturbated by burrowing organisms. Relative sea level falls occur in the middle of each cycle, times during which the surface of the lower delta plain becomes subaerial and coeval sediments are non-bioturbated. Controls governing wetland loss, therefore, are found at the fundamental level of individual deltaic sequences. Stacks of deltaic sequences (i.e. cycles) constitute the valley fill.

Coastal land loss and subsequent encroachment of the marine environment are conditions endemic to deltaic terranes (Russell, 1936; Morgan, 1973, Coleman *et al.* 1991). Delta abandonment, which occurs on a time scale of approximately 1,000-1,500 yr (Coleman *et al.*, 1991; Coleman *et al.*, 1964) is accompanied by relative sea level rise (i.e. a net rise of sea level due to either the eustatic sea level rising, the land sinking, or a combination of these factors). Data indicate 76% of the relative sea level rise in the Terrebonne delta plain is attributable not to eustatic rise (Ramsey *et al.*, 1989) but to subsidence, which is a downward displacement of the delta plain surface with respect to mean sea level (Penland *et al.*, 1989).

The relationship of the Lafourche Delta with land loss in study area

The Lafourche Delta was constructed between 2.6 and 0.3 ka in a series of four discrete lobes (Fig. 4). Bayou du Large was the major distributary between 2.6 and 1.3 ka, Bayou Terrebonne was the major distributary between 1.3 and 0.8 ka, Bayou Grand Caillou was the major distributary between 0.9 and 0.5 ka, and Bayou Lafourche served as major distributary between 0.7 and 0.3 ka. These lobes are stacked in cross section and constitute a lens-shaped delta sequence atop a transgressive ravinement surface (Fig. 5). In areas where the Lafourche Delta is thick (see location "B" on Fig. 5), subsidence rates appear to be high, and in areas where the Lafourche Delta is thin (see location "A" on Fig. 5), subsidence rates appear to be low.

A likely case for the vertical stack of facies expected on the eastern edge of the Lafourche Delta is provided (Fig. 6). Interdistributary areas (i.e. position "C") are subsiding more rapidly than distributary areas (i.e. position "D"). This phenomenon appears to be due to the consolidation settlement potential of facies present at each respective location. For example, peats (P) and bay muds (BM), which constitute the substrate immediately beneath location "C," settle under self-weight consolidation much more readily than levee (L), beach (B), or distributary mouth bar facies (DMB), which constitute the substrate immediately beneath location "B." Wetland loss appears to be facies-specific at this level of investigation. A re-examination of present patterns of wetland loss in the study area (refer to Fig. 1) indicates that wetland loss is best explained by controls operating at the shallowest levels of investigation. If so, controls on wetland loss could be ordered from those of greatest influence to those of least influence by increasing depth. Thick deposits of near-surface peats and bay muds, therefore, exert more control on subsidence than thick sections of Lafourche Delta, which, in turn, exert more control than thick sections of valley fill.

CONSOLIDATION PROPERTIES OF MODERN DELTAIC SEDIMENTS

Deltaic environments produce distinct sediment types that are laterally and vertically gradational into adjacent environments. The basic facies units that comprise a delta cycle include peat, bay mud, prodelta mud, natural levee silt, splay silt and sand, distributary mouth bar sand, point bar sand, and beach sand (Coleman and Gagliano, 1964). Kuecher (1994) tested seven of these facies types by following procedures outlined in the Annual Book of ASTM Standards (1994) and discovered that each facies type possesses discrete consolidation properties. A review of the methods and results of these consolidation tests can be found in Kuecher (1994; 1993) and Roberts *et al.* (1994).

The consolidation settlement equation is provided below:

Eq. for settlement, S

$$S = \frac{Cc\ \ H}{1 + e_0} \log\left[\frac{(p_0 + \Delta p)}{(p_0)}\right]$$

where
Cc = compression index
H = height, or thickness of subsurface facies <u>or</u> specimen in trim ring
e_0 = void ratio at initiation of loading
p_0 = overburden pressure
Δp = change in pressure during course of test

Included in this equation is a dimensionless number called the compression index, which is the rate factor in the settlement equation. The compression index is defined as the slope on a void ratio versus the log of pressure plot (Das, 1990; Terzaghi, 1943). If the value of the compression index, C_C, is high for a given facies sample, settlement is expected to be high, and vice versa. In lay terms, sediments that deform significantly under load yield high C_C values in consolidation testing. The reverse is also true.

Peat represents the most deformable, compactable facies tested in this study. Peats are organic sediments with very unusual properties. Initial water contents for tested peats in this study ranged from 660-756 wt% water, decreasing to 100-120 wt% water following 8.0 kg/cm^{2}f loading. Initial bulk densities of 1.1-1.2 g/cm^3 are virtually unchanged following the full loading schedule. More importantly, peats never appear to come to equilibrium under load. They continue to deform for years following an induced load in what is called secondary consolidation. A void ratio versus log of pressure plot for one sample of peat (i.e. *Spartina sp.)* is included (Fig. 7). Initial void ratios for peats are high, and the steep slope on this plot indicates peats are highly deformable; this test yielded a C_C value of 4.72. Peaty facies are the suspect facies in wetland loss because of the direct relationship between the thickness of peats and historical patterns of land loss (Kuecher, 1994; Snowdon *et al.*, 1977). Interdistributary areas, which contain nearly all the peaty facies in the study area, are preferentially lost in the decay of wetlands.

By contrast, beach sand represents the least deformable, least compactable facies tested in this study. Initial water contents are in the range of 25-30 wt%, and this range is unchanged following 32.0 kg/cm^2f loading. Beach sands, like all sands and silts tested, deform only slightly upon loading and come to equilibrium (whereby no additional deformation occurs) in a matter of seconds to perhaps a few minutes at maximum. A void ratio versus log of pressure plot for one sample of beach sand is included (Fig. 8). Initial void ratios are very low, and the slope is very low; this test yielded a C_C value of 0.05. Active and relic distributary features, which contain silts and sand, are only marginally influenced by the decay of interdistributaries around them.

Facies subject to high compression indices are peats, prodelta muds, and bay muds. The remaining facies are sand-rich and are not subject to significant consolidation settlement. A summary of the C_C values for various facies tested in this study is provided in Table 1. The range of compression indices between facies types is great and far outweighs the variability of values within the same facies type. Consolidation largely is caused by the self-weight of overlying sediments (Been *et al.*, 1981). Additional testing is recommended.

Utilizing C_C values presented in Table 1, calculations have been made to approximate cumulative settlement at the level of a facies stack within the Lafourche Delta (Kuecher, 1994). Results indicate most settlement occurs in the upper 2-3 m of section, where the thickness of peaty facies is greatest.

DIRECT RELATIONSHIP BETWEEN PEAT SUBSTRATE AND WETLAND LOSS

Numerous vibracores were taken during the course of this study, the majority of which were obtained at water's edge in greater Terrebonne Bay. Contouring the cumulative thickness of near-surface peaty facies in these vibracores (Fig. 9) explains many patterns of coastal tract wetland loss. Of primary interest, thick peat deposits are restricted to interdistributary settings, and these areas are preferentially being lost to the expansion of greater Terrebonne Bay. Second, relic distributaries project well into open water and these contain no appreciable peat. A great thickness of peat may have occupied the mid-bay position, but without data from these areas, a more definitive statement is not possible.

THE ROLE OF SUBCROPPING GROWTH FAULTS IN LAND LOSS

Growth faults are a variety of normal listric faults on the Louisiana Gulf Coast whose movement is contemporaneous with deposition (Hardin *et al.*, 1961). Much is known about growth faults in the deep subsurface, but little is known about whether Louisiana growth faults actually subcrop the surface, or whether these faults are active today. Prior to this study, the relationship between active subcropping growth faults and new areas of interior tract wetland loss was not known.

Growth faults propagate upward through thin sedimentary cover as a series of minor, en echelon faults that constitute a single mapped fault. The association of growth faults to subsurface controls, specifically geopressure, is direct (Hunt *et al.*, 1994), and it is not surprising that deep fluids and gases generated from such zones are transported vertically up these fault planes and into shallow aquifers.

Fault-bound compartments episodically rupture due to the buildup of geopressure (Hunt, 1990; Waples, 1991). Fluid injection up the faults bounding these compartments is likewise episodic (Anderson *et al.*, 1994; Roberts *et al.*, in press). This study proposes that regional growth faults respond to episodic injection in the following fashion: (a) excess fluid is injected into a fault zone from deep, overpressured shale masses, (b) the fault zone becomes lubricated, (c) frictional drag is reduced in the fault zone, and (d) the downthrown block subsides.

Kuecher (1994) mapped the approximate subcropping location of growth faults in eastern Terrebonne and western Lafourche Parishes, Louisiana, utilizing over 3,000 line-kilometers of seismic data provided courtesy of Seismic Exchange, Incorporated (Fig. 10). As per agreement with Seismic Exchange, Incorporated, neither processing parameters nor shotpoint locations will be discussed in referencing these sections. Fault nomenclature was borrowed from an unpublished Pennwell Publishing Company map. Two regional E-W trending regional growth faults, the Lake Hatch Fault and the Golden Meadow Fault (as well as a number of minor faults) were mapped in this exercise.

The Golden Meadow Fault

The Golden Meadow Fault (refer to Fig. 10) is an E-W trending, down to the basin fault. This fault appears to join the Lake Hatch Fault to the west and can be found to the east in the vicinity of Golden Meadow, Louisiana. Interpreted seismic line segment A-A′ (Fig. 11) indicates the fault is a continuous plane to the surface. Vertical offset is mappable below the 2.0 s reflector datum, but it is not easily mapped above 2.0 s because of statics. Kuecher (1994) identified the location of the Golden Meadow Fault, seismically, as well as with core data on both sides of the fault, and concluded that this fault is active in the Holocene sedimentary section.

The Lake Hatch Fault

The Lake Hatch Fault (refer to Fig. 10) is a NE-SW trending, slightly oblique to the basin regional growth fault. This fault appears to join the Golden Meadow Fault to the west and can be found to the northeast in the vicinity of Valentine, Louisiana. Interpreted seismic line segment B-B′ (Fig. 12) indicates the fault is a continuous plane to the surface. Significant vertical displacement is seen at all mapped levels. This fault is probably active in the Holocene sedimentary section. A deep research boring, P-2-91, is projected to the fault's downthrown side.

Relationship of subcropping faults to interior tract wetland loss

A causal relationship between the subcropping location of faults and new areas of land loss has been shown (Kuecher, 1994). New areas of land loss have emerged on the downthrown sides of these growth faults; the relationship is most direct in the western part of the study area. Downthrown sections have been shown to accumulate consolidation-prone sections on downthrown sides (Kuecher, 1994).

Subsidence hotspots have been shown to be related to faults (Kuecher, 1994).

Additional evidence indicating compartmentalization by faults at the surface in this study area is provided in the zonation of vegetation in the lower delta plain (Chabreck *et al.*, 1978, Fig. 13). The approximate boundary between saline marsh vegetation and intermediate marsh vegetation closely matches the trace of the Golden Meadow Fault (refer to Fig. 10). Likewise, the approximate boundary between fresh and intermediate marsh vegetation closely matches the trace of the Lake Hatch Fault (refer to Figure 10). Some component of surface water compartmentalization is accomplished with growth faults. Additional studies are needed.

Detailed salinity and hydrodynamic studies are under way in the Louisiana wetlands. These studies embrace the concepts of compartmentalized water masses and vertical transport of basinal fluids up fault zones (McGinnis *et al.*, 1995).

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FIGURE CAPTIONS

Fig. 1 Study area in Terrebonne and Lafourche Parishes, Louisiana.

Fig. 2 Variations in radiocarbon-determined rates of subsidence with thickness of Holocene Valley Fill (Roberts, 1985).

Fig. 3 Proposed model for relative sea level rises and falls in a typical Mississippi River delta cycle (Kuecher, 1994).

Fig. 4 Chronology of individual delta lobe deposition, Lafourche Delta (Kuecher, 1994).

Fig. 5 Hypothetical W - E cross section across the Lafourche Delta. Legend as follows: BdL = Bayou du Large, BGC = Bayou Grand Caillou, BT = Bayou Terrebonne, BL = Bayou Lafourche. Position "A" represents a thin section of Lafourche Delta. Position "B" represents a thick section of Lafourche

Delta (Kuecher *et al.*, 1993)

Fig. 6 Proposed facies architecture within the eastern side of the Lafourche Delta. Legend: BM = bay mud, P = peat, PD = prodelta mud, DMB = distributary mouth bar, B = beach, CS = channel, and L = levee. Position "C" represents a possible facies stack in a rapidly subsiding interdistributary setting. Position "D" represents a possible facies stack in a slowly subsiding natural levee setting (Kuecher *et al.*, 1993)

Fig. 7 Void ratio versus the log of pressure plot for a modern *Spartina sp.* peaty soil (Kuecher, 1994).

Fig. 8 Void ratio versus the log of pressure plot for a beach sand, BS (Kuecher, 1994).

Fig. 9 Cumulative thickness (m) of peaty sediments in the waning phase of the Lafourche Delta. Note the direct relationship between the greatest thicknesses of peat and areas most impacted by wetland loss. Distributary terranes are relatively unaffected (Kuecher, 1994).

Fig. 10 The seismically mapped location of the Golden Meadow, the Lake Hatch, and other faults interpreted in the study area. Transects of interpreted seismic sections A-A′ and B-B′ are illustrated.

Fig. 11 Interpreted seismic section A-A′ illustrating the character of the Golden Meadow Fault. Reflectors are mapped at approximately 0.8 s, 1.9 s, and 2.9 s.

Fig. 12 Interpreted seismic section B-B′ illustrating the seismic character of the Lake Hatch Fault. Reflectors are mapped at approximately 0.7 s, 1.7 s, and 2.5 s.

Fig. 13 Zonation of vegetation in the Mississippi River lower delta plain (Chabreck *et al.*, 1978).

Table 1 Compression indices for tested deltaic facies

Facies Unit	C_C Value
Peaty facies	4.72
Prodelta mud facies	1.03-2.25
Bay mud facies	0.82
Distributary mouth bar facies	0.12-0.23
Natural levee facies	0.12
Point bar sand facies	0.06
Beach sand facies	0.05

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fig. 8

Fig. 9

Fig. 10

Fig. 11

Fig. 12

Fig. 13

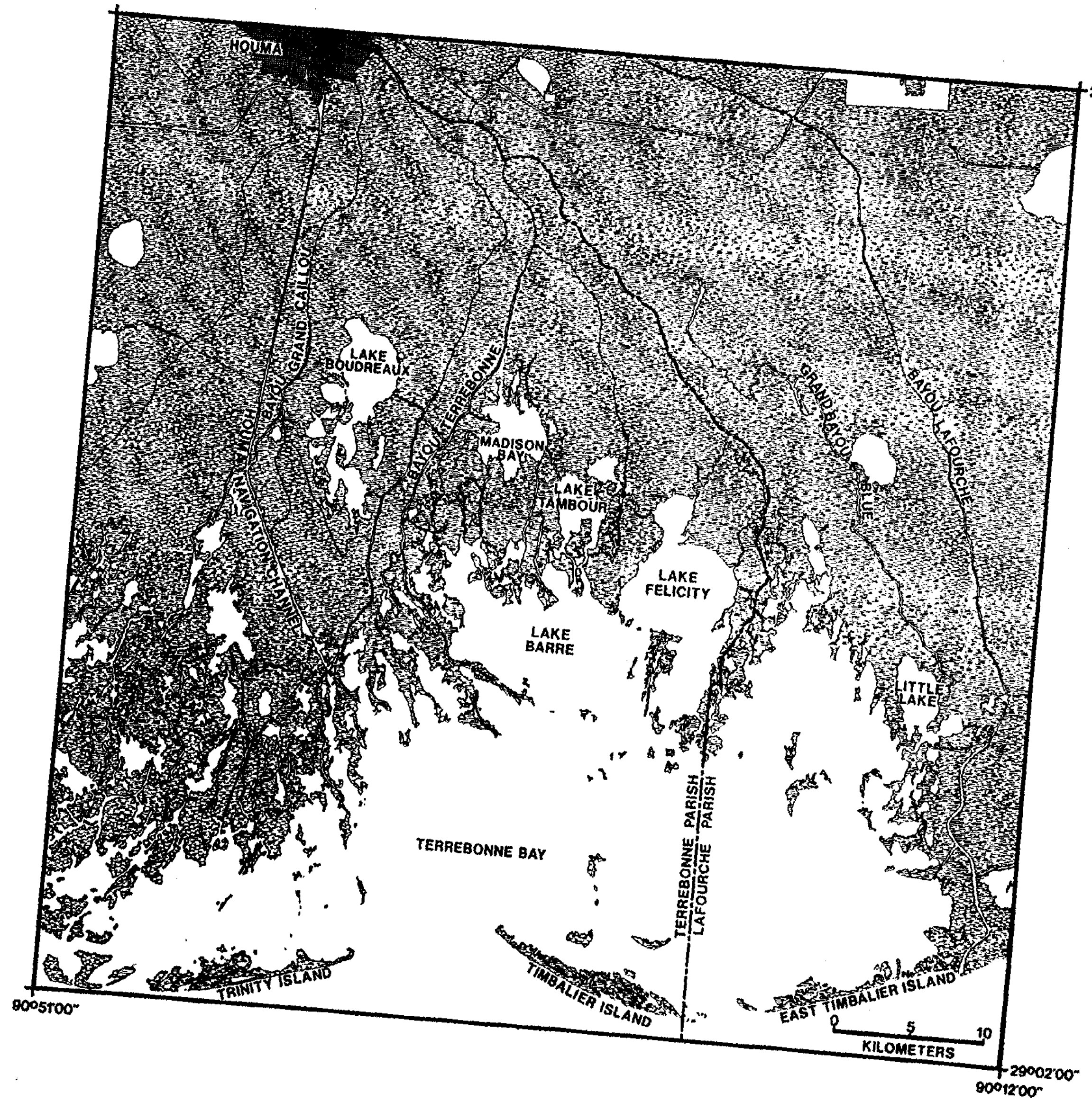

HOUMA
HOUMA NAVIGATION CHANNEL
BAYOU GRAND CAILLOU
LAKE BOUDREAUX
BAYOU TERREBONNE
MADISON BAY
LAKE TAMBOUR
LAKE FELICITY
LAKE BARRE
GRAND BAYOU BLUE
BAYOU LAFOURCHE
LITTLE LAKE
TERREBONNE BAY
TERREBONNE PARISH
LAFOURCHE PARISH
TRINITY ISLAND
TIMBALIER ISLAND
EAST TIMBALIER ISLAND
0
5
10
KILOMETERS
29°36'00"
29°02'00"
90°51'00"
90°12'00"

Fig. 1

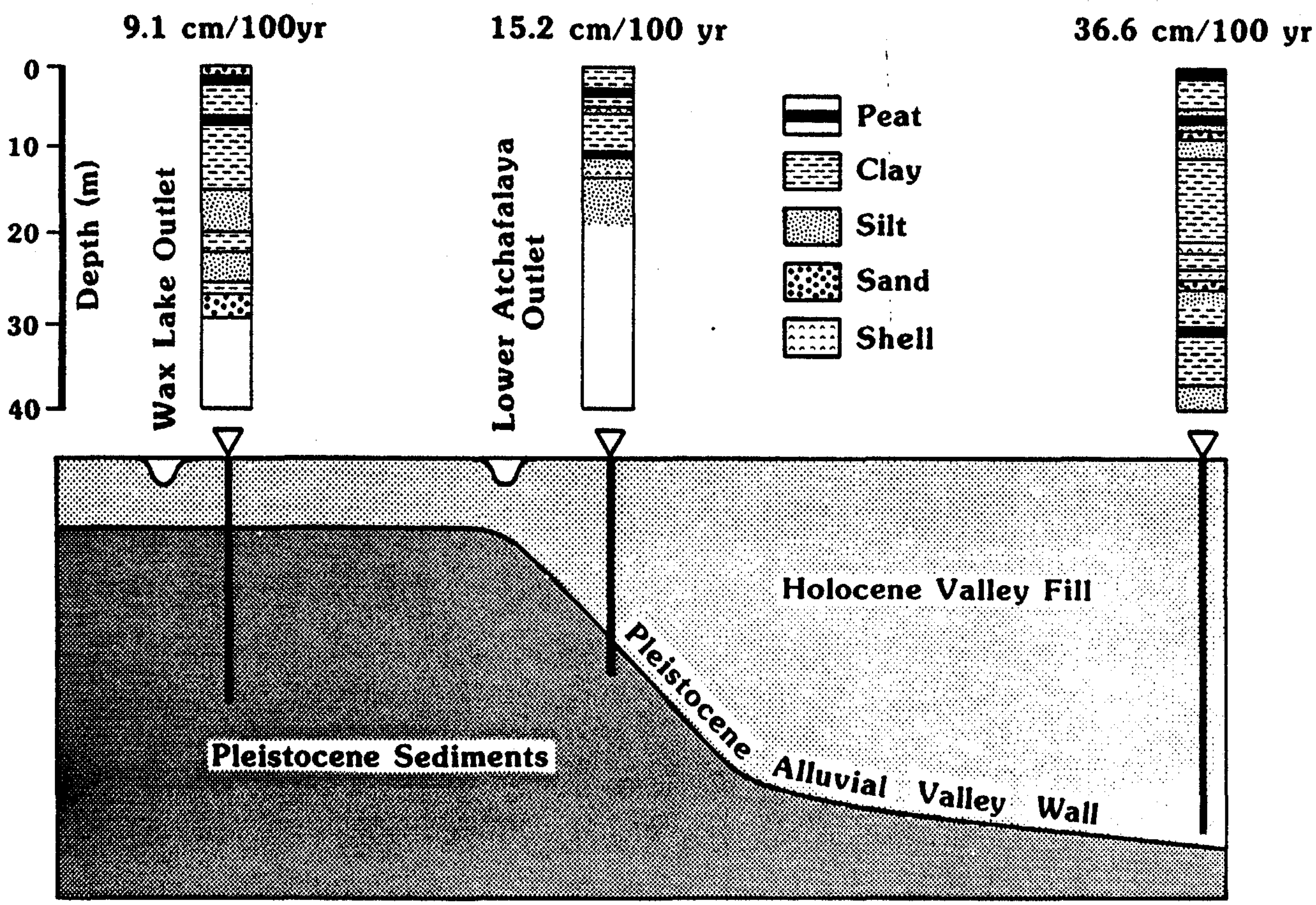
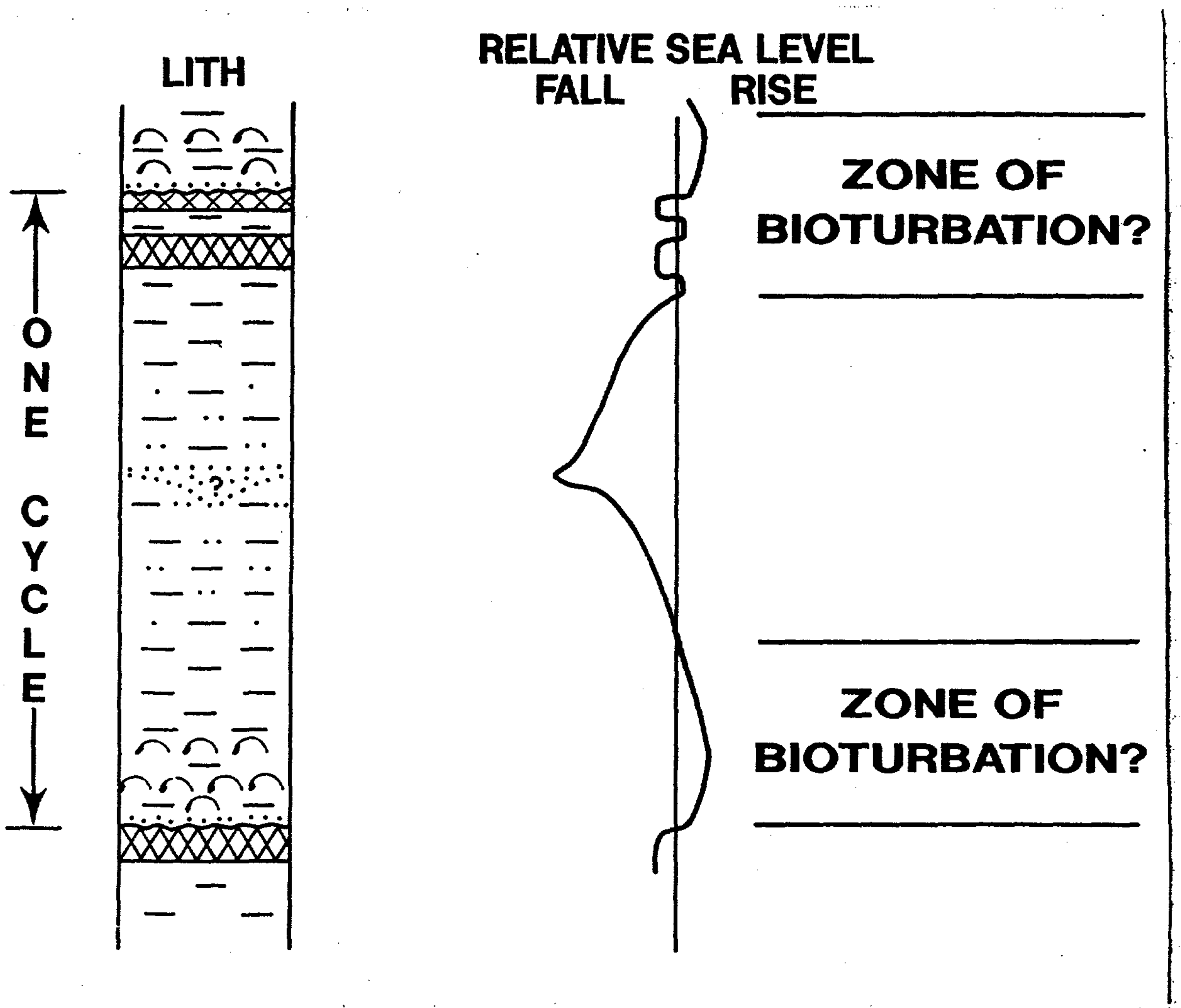
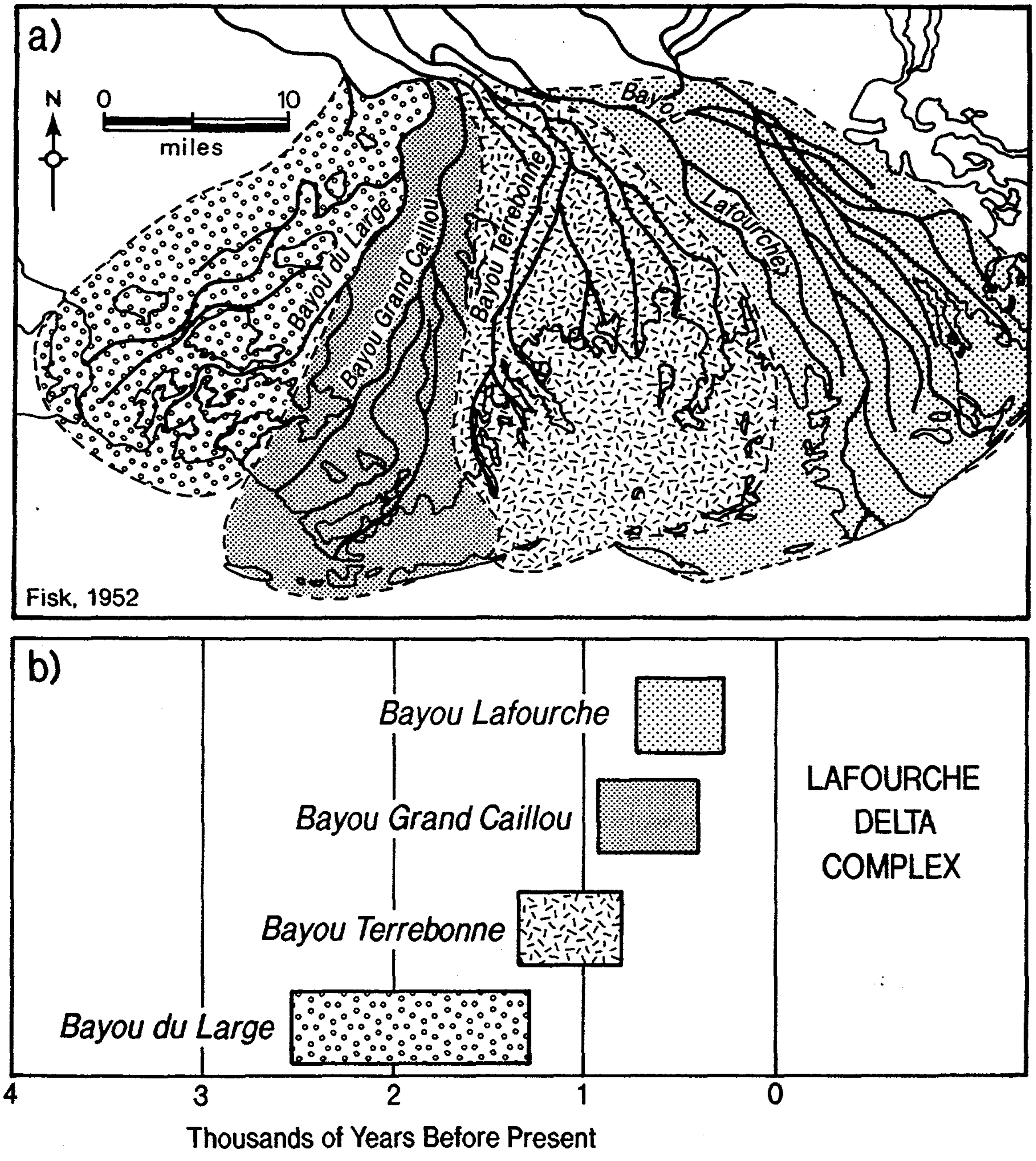

9.1 cm/100yr
15.2 cm/100 yr
36.6 cm/100 yr
0
10
20
30
40
Depth (m)
Wax Lake Outlet
Lower Atchafalaya Outlet
Peat
Clay
Silt
Sand
Shell
Holocene Valley Fill
Pleistocene Alluvial Valley Wall
Pleistocene Sediments

Fig. 2



LITH
ONE CYCLE
RELATIVE SEA LEVEL
FALL
RISE
ZONE OF BIOTURBATION?
?
ZONE OF BIOTURBATION?

Fig. 3



a)
N
0
10
miles
Bayou
Lafourche
Bayou du Large
Bayou Grand Caillou
Bayou Terrebonne
Fisk, 1952
b)
Bayou Lafourche
Bayou Grand Caillou
Bayou Terrebonne
Bayou du Large
LAFOURCHE
DELTA
COMPLEX
4
3
2
1
0
Thousands of Years Before Present

Fig. 4

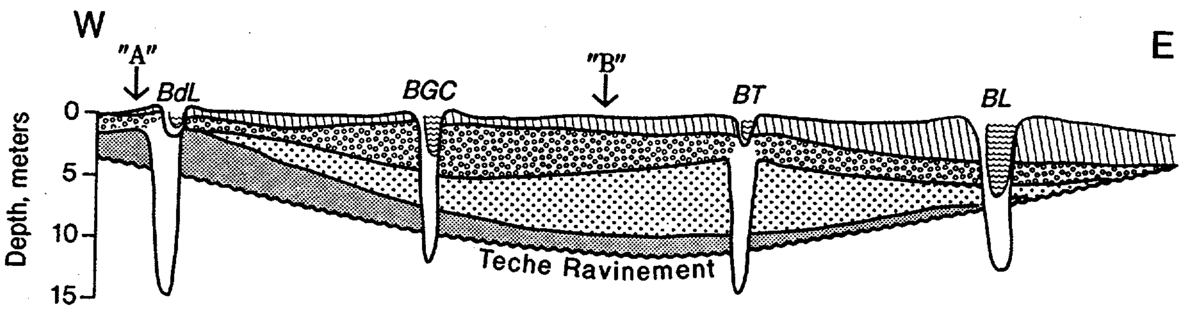


Fig. 5

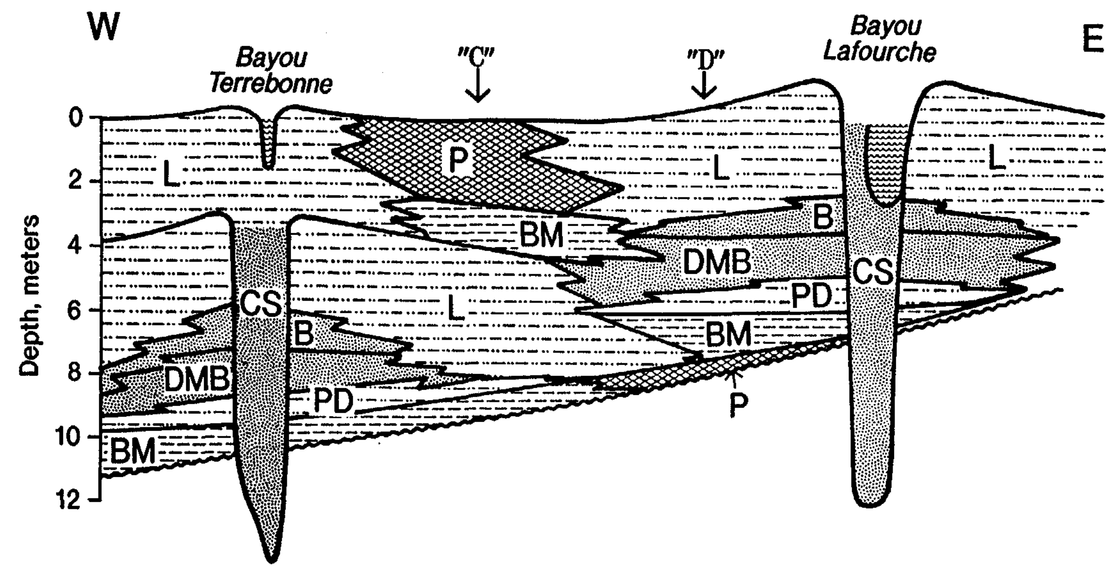
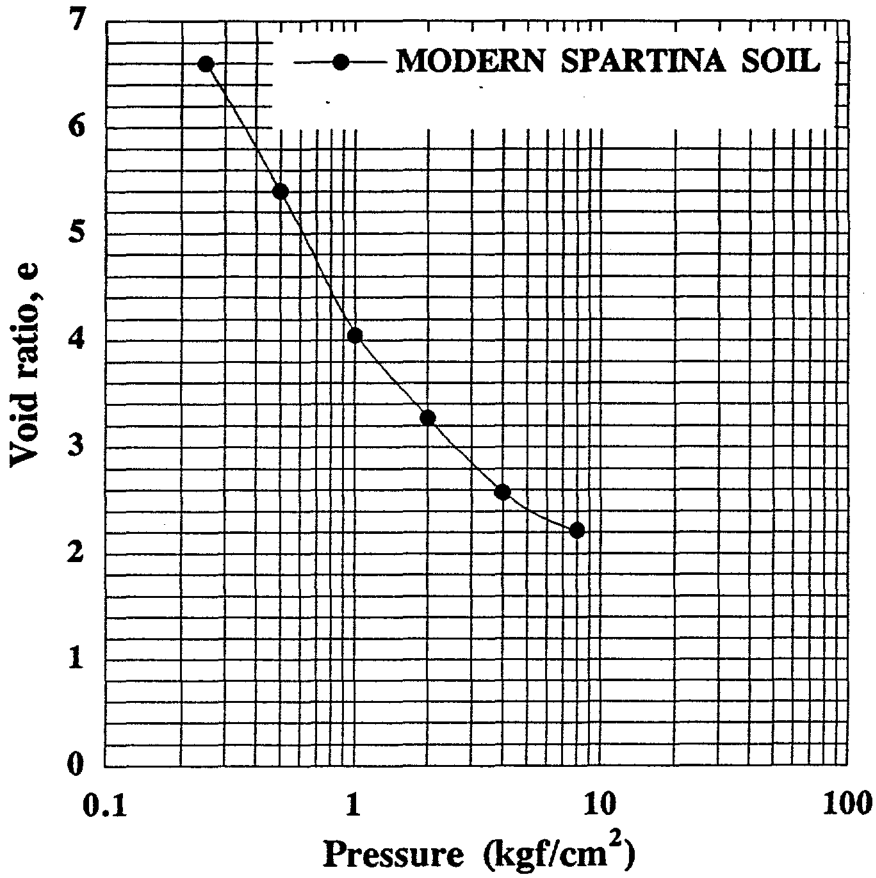

W
E
Bayou Terrebonne
"C"
"D"
Bayou Lafourche
Depth, meters
0
2
4
6
8
10
12
L
P
BM
B
DMB
CS
PD
L
BM
B
DMB
PD
BM
P

Fig. 6



MODERN SPARTINA SOIL
Void ratio, e
7
6
5
4
3
2
1
0
0.1
1
10
100
Pressure (kgf/cm2)

Fig. 7

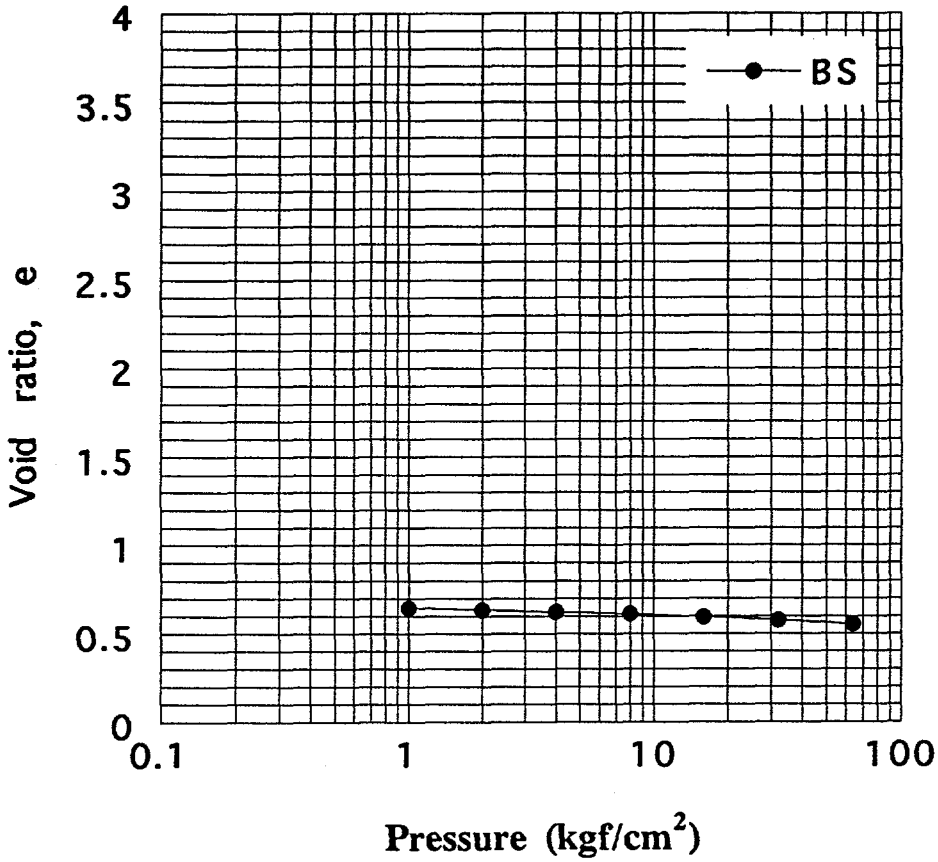


Fig. 8

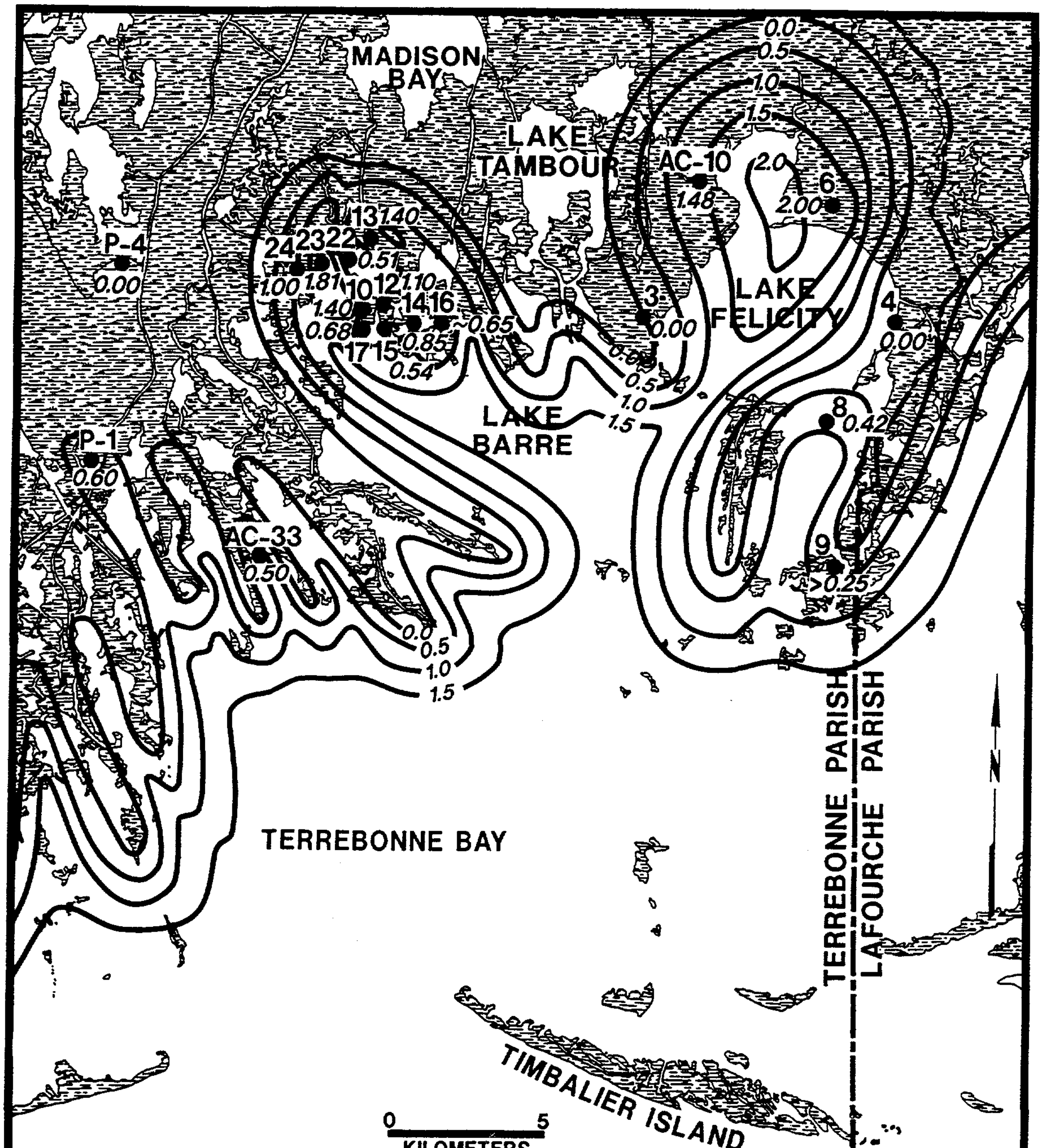

MADISON BAY
LAKE TAMBOUR
LAKE FELICITY
LAKE BARRE
TERREBONNE BAY
TIMBALIER ISLAND
TERREBONNE PARISH
LAFOURCHE PARISH
P-4
0.00
P-1
0.60
AC-33
0.50
AC-10
1.48
6
2.00
3
0.00
4
0.00
8
0.42
9
>0.25
24
23
22
13
1.40
0.51
1.00
1.81
10
12
1.10
14
16
1.40
0.68
17
15
0.85
0.54
0.65
0.0
0.5
1.0
1.5
2.0
N
0
5
KILOMETERS

Fig. 9

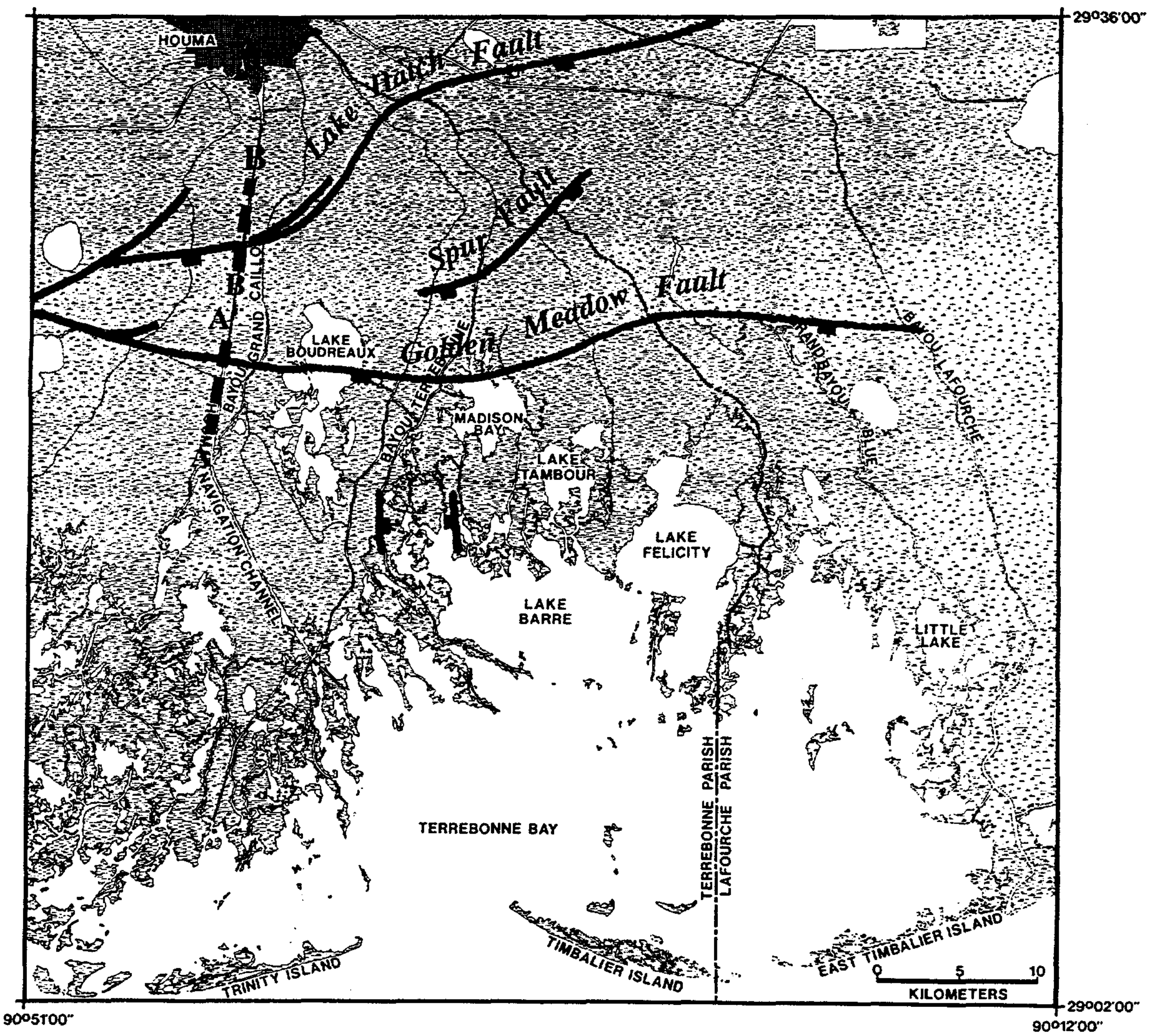

29°36'00"
HOUMA
Lake Hatch Fault
Spur Fault
Golden Meadow Fault
B
B
A
A
BAYOU GRAND CAILLOU
NAVIGATION CHANNEL
LAKE BOUDREAUX
BAYOU TERREBONNE
MADISON BAY
LAKE TAMBOUR
LAKE FELICITY
LAKE BARRE
BAYOU BLUE
BAYOU LAFOURCHE
LITTLE LAKE
TERREBONNE PARISH
LAFOURCHE PARISH
TERREBONNE BAY
TRINITY ISLAND
TIMBALIER ISLAND
EAST TIMBALIER ISLAND
0
5
10
KILOMETERS
29°02'00"
90°51'00"
90°12'00"

Fig 10

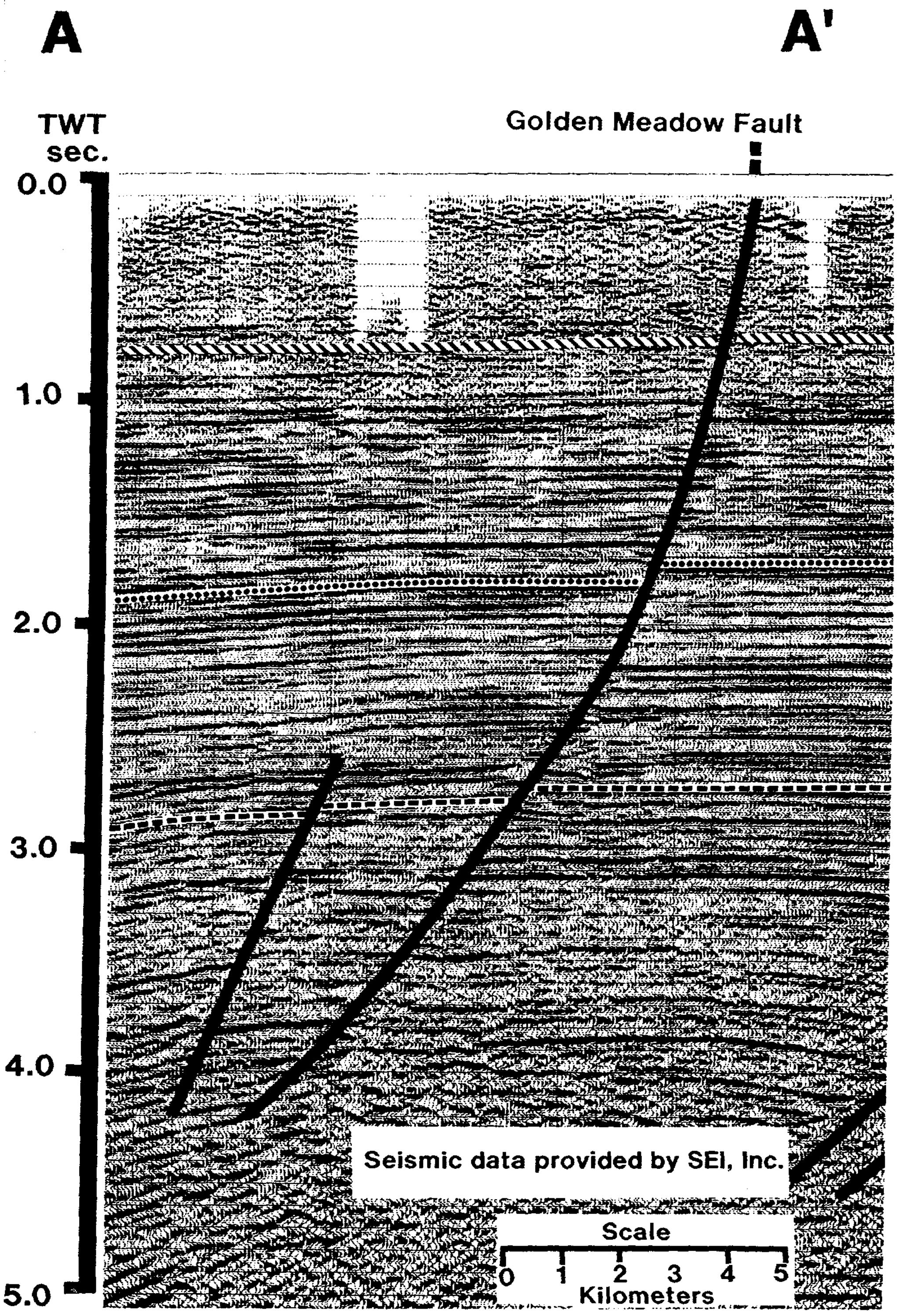
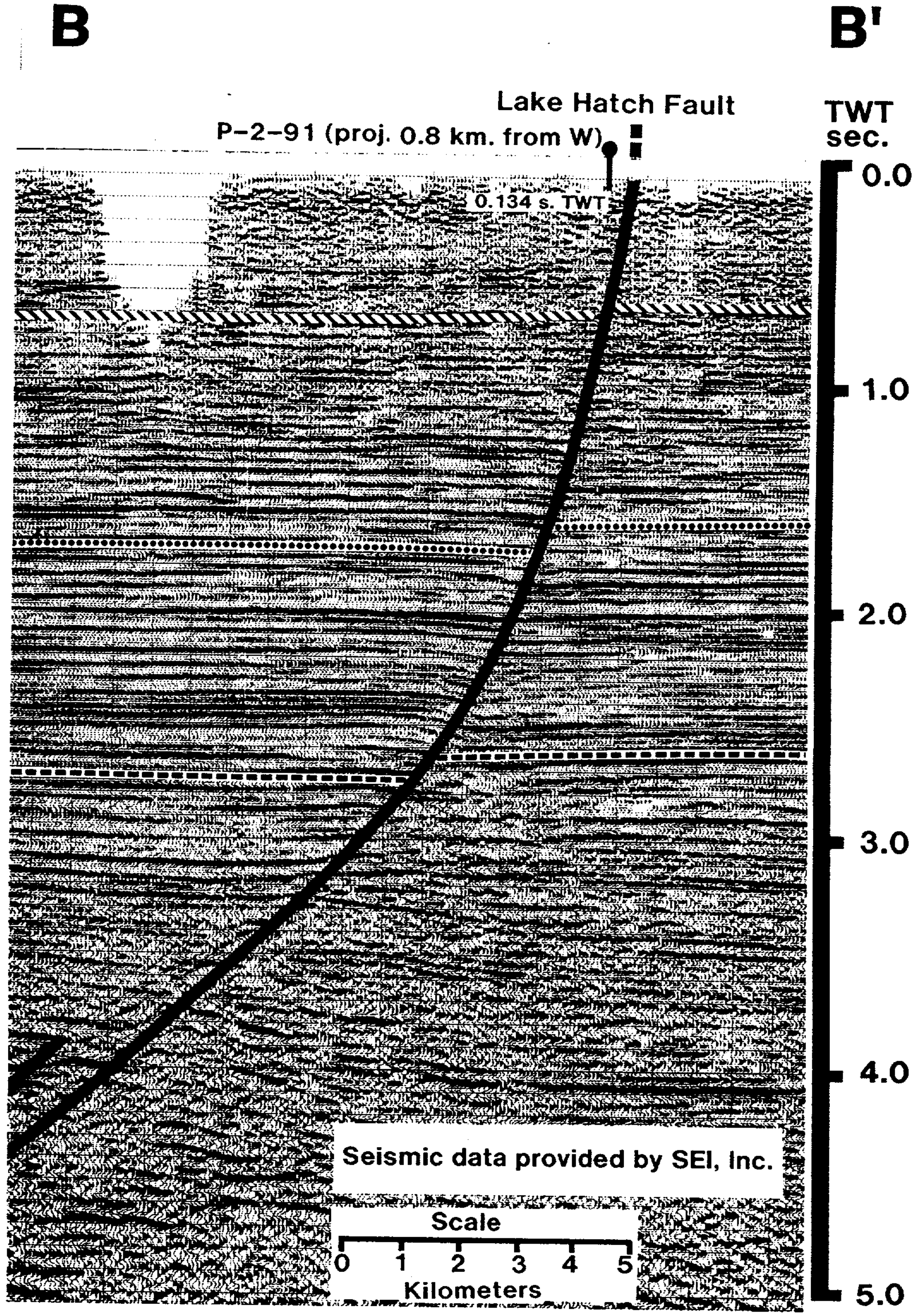

A
A'
TWT
sec.
Golden Meadow Fault
0.0
1.0
2.0
3.0
4.0
5.0
Seismic data provided by SEI, Inc.
Scale
0 1 2 3 4 5
Kilometers

Fig. 11



B
B'
Lake Hatch Fault
P-2-91 (proj. 0.8 km. from W)
0.134 s. TWT
TWT
sec.
0.0
1.0
2.0
3.0
4.0
5.0
Seismic data provided by SEI, Inc.
Scale
0 1 2 3 4 5
Kilometers

Fig. 12

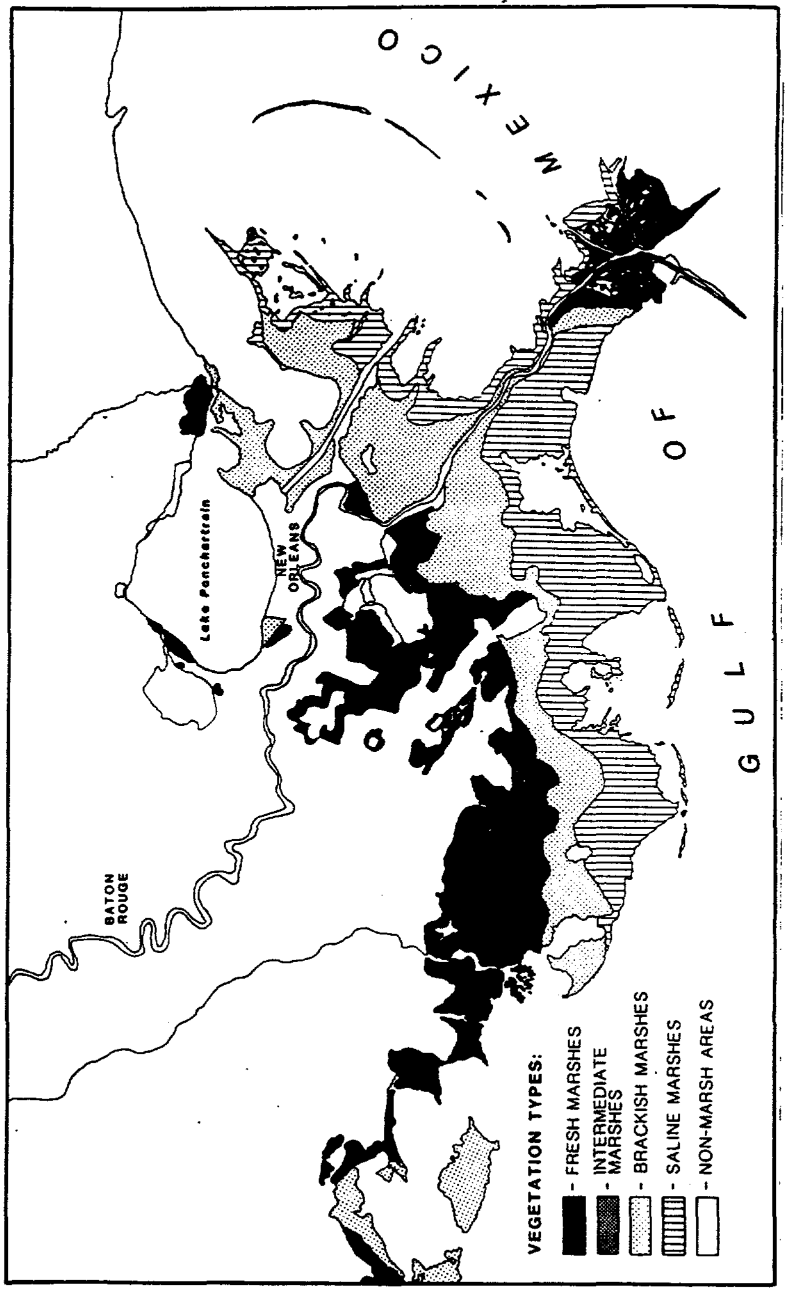

GULF OF MEXICO
Lake Ponchartrain
NEW ORLEANS
BATON ROUGE
VEGETATION TYPES:
- FRESH MARSHES
- INTERMEDIATE MARSHES
- BRACKISH MARSHES
- SALINE MARSHES
- NON-MARSH AREAS

Fig. 13