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Wetland Losses Related to Fault Movement and Hydrocarbon Production, Southeastern Texas Coast

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ABSTRACT

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Time series analyses of surface fault activity and nearby hydrocarbon production from the southeastern Texas coast show a high correlation among volume of produced fluids, timing of fault activation, rates of subsidence, and rates of wetland loss. Greater subsidence on the downthrown sides of faults contributes to more frequent flooding and generally wetter conditions, which are commonly reflected by changes in plant communities (*e.g., Spartina patens* to *Spartina alterniflora*) or progressive transformation of emergent vegetation to open water. Since the 1930s and 1950s, approximately 5,000 hectares of marsh habitat has been lost as a result of subsidence associated with faulting. Marshes have expanded locally along faults where hydrophytic vegetation has spread into former upland areas.

Fault traces are linear to curvilinear and are visible because elevation differences across faults alter soil hydrology and vegetation. Fault lengths range from 1 to 13.4 km and average 3.8 km. Seventy-five percent of the faults visible on recent aerial photographs are not visible on photographs taken in the 1930's, indicating relatively recent fault movement. At least 80% of the surface faults correlate with extrapolated subsurface faults; the correlation increases to more than 90% when certain assumptions are made to compensate for mismatches in direction of displacement. Coastal wetlands loss in Texas associated with hydrocarbon extraction will likely increase where production in mature fields is prolonged without fluid reinjection.

ADDITIONAL INDEX WORDS: *Coastal erosion, remote sensing, coastal wetlands, salt marsh, land subsidence.*

INTRODUCTION

Along the northwestern Gulf of Mexico, significant oil and gas reserves coincide with the Nation's most extensive and productive coastal wetlands. Direct wetland losses caused by excavation of drilling sites, construction of canals, and installation of pipelines by the petroleum industry are easily observed and have been documented as a primary environmental impact (TURNER and CAHOON, 1988). Less obvious but equally destructive are wetland losses associated with subsidence and faulting induced by oil and gas production. This study extends the work of WHITE and TREMBLAY (1995) who reported wetland losses along four faults on the Texas Coast, by examining in more detail the number of faults affecting wetlands, documenting changes in marsh vegetation along active faults, determining relationships between surface faults and subsurface faults, and describing histories of fault movement and fluid production.

Hundreds of faults offset Quaternary sediments and intersect the land surface along the southeast Texas Gulf Coast (VERBEEK, 1979). There is evidence that many faults have become active during the past few decades as a result of the withdrawal of water, oil and gas (VAN SICLEN, 1967; GUSTAVSON and KREITLER, 1976; VERBEEK and CLANTON, 1981). Wetland losses along surface faults have been documented (WHITE *et al.,* 1985; MORTON and PAINE, 1990; WHITE and TREMBLAY, 1995; WHITE and MORTON, 1995), but the extent, timing, and probable causes of the fault activity have not been fully investigated. In this study, 40 faults that intersect coastal wetlands on the upper Texas coast were identified, mapped, and examined using aerial photographs (Figure 1). Primary objectives of this investigation were to document the locations and lengths of surface faults intersecting coastal wetlands, to determine historical activity of the faults, and to examine the relationship between fault movement, underground fluid production, and wetland changes.

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METHODS

Most surface faults analyzed in this paper were initially identified as part of a wetlands mapping effort of the Texas Coastal Zone (WHITE *et al.,* 1985 and 1987). Faults were identified primarily on photographs taken in 1979, from which the fault traces were optically transferred to USGS 7.5 minute topographic base maps.

Faults crossing wetlands are traceable on aerial photographs due to slightly lower elevations on the faults' downthrown* sides creating contrasting moisture regimes and veg-

* The terms "downthrown" and "upthrown" sides of a fault indicate relative movement along the fault plane. Accordingly, use of the term upthrown refers to a relative and not absolute displacement, or uplift, along the fault.

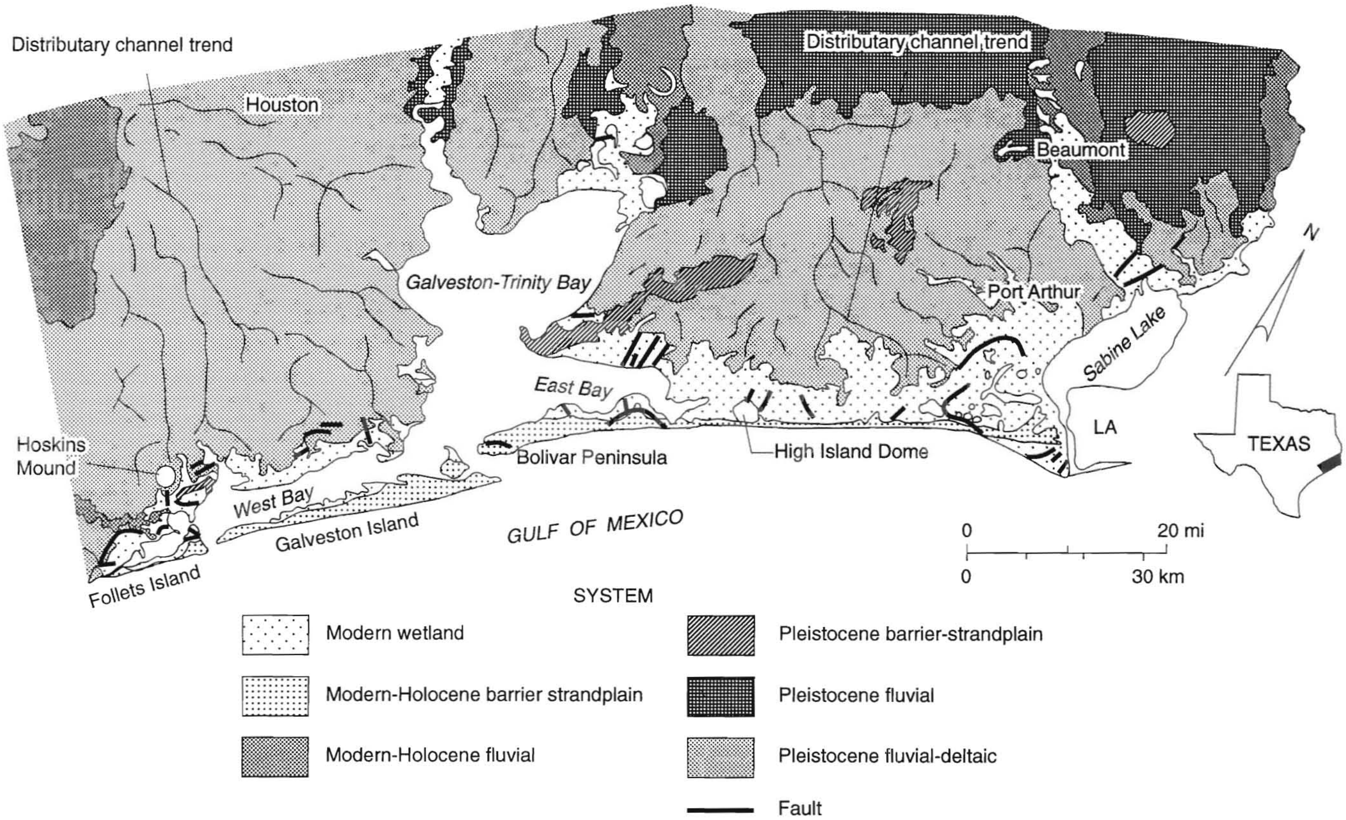


Figure 1. Distribution of surface faults intersecting wetlands on the upper Texas Coast. Thirty-six of the 40 faults are shown in this figure; the remaining four are to the southwest. Coastal deposition systems modified from FISHER *et al.* (1972, 1973).

etation communities that highlight the fault traces (Figures 2 and 3) (CLANTON and VERBEEK, 1981; WHITE *et al.,* 1985). Sequential aerial photographs were used to determine when a fault first became visible and traceable at the land surface and to examine the subsequent progressive changes in vegetation and moisture conditions along the fault. The principal imagery examined to define fault traces and changes along the trace were aerial photographs taken in 1930, 1956, 1979, and 1989–1993. In selected areas, these photographs were supplemented with 1940's, early 1950's, and 1960's vintage photographs. The trace of each fault was classified as (0) not visible, (1) faintly visible, or (2) distinctly visible. Faults that were distinctly visible and traceable on more recent photographs, but only partly traceable on older photographs were assigned two visibility classes, such as 0 to 1.

The distinctiveness of a fault trace can be influenced by soil moisture at the time the photographs were taken (VERBEEK and CLANTON, 1981). In general, we concluded that variations in moisture conditions during wetter periods should produce fault-normal variations in soils and vegetation that persist, making the faults visible on photographs even during drier periods. For example, faults traceable on 1930 photographs, which were taken during a period of higher than normal rainfall, were equally traceable on 1956 photographs, which were taken during a drought.

The link between surface faults and subsurface faults has been reported by many researchers (WEAVER and SHEETS, 1962; VAN SICLEN, 1967; REID, 1973; KREITLER, 1978; VERBEEK, 1979; VERBEEK and CLANTON, 1981). In this study, surface and subsurface faults were correlated by extrapolating subsurface faults shown on structure maps (from GEOMAP Co. and other sources) to the surface generally at angles between 45 and 80° (QUARLES, 1953; BRUCE, 1973; REID, 1973; GUSTAVSON and KREITLER, 1978).

Locations of surface faults and directions of throw were compared to the locations of oil and gas fields to determine the geographic relationship of the faults to the fields. A distance of 5,000 m was used as an estimate of geographic proximity between surface faults and producing fields. Faults may be activated greater distances than this from some fields if production from multiple fields causes regional depressurization and subsidence (EWING, 1985; GERMIAT and SHARP, 1990; PAINE, 1993).

FAULT DISTRIBUTION, MOVEMENT, AND RELATION TO SUBSURFACE FAULTS

Distribution

Forty faults intersecting wetlands were identified and mapped between Sabine Lake and Matagorda Bay (Figure 1).

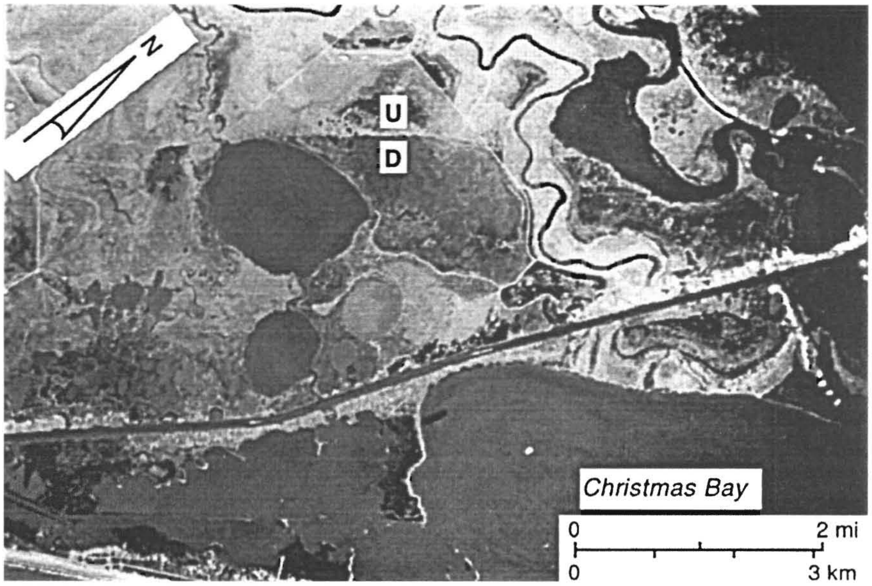


Figure 2. Active coastal plain fault in the Brazoria National Wildlife Refuge inland from Follets Island (Figure 1). D = downthrown side, U = upthrown side. NASA photograph taken in 1979.

Faults are scattered throughout this region and affect wetlands that have developed on Pleistocene deltaic and thin Holocene marsh deposits on the mainland, and Holocene barrier and flood-tidal delta deposits on the islands and peninsulas (FISHER *et al.,* 1972). Four parallel faults forming a graben, which is defined at the surface by wetter conditions and lower marshes, were mapped on the inland margin of East Bay (Figure 1). VERBEEK and CLANTON (1981) mapped five faults in this area, one of which was identified in shallow high-resolution seismic reflection profiles. Inland from Follets Island, there are nine faults, most of which have a NE strike. Several of these faults appear to be associated with the salt dome Hoskins Mound. In general, faults are linear to curvilinear, and their traceable lengths range from 1 to 13.4 km (Table 1).

Fault Movement

Most of the faults (about 75%) exhibited recent surface expression during the last six decades, with the majority appearing since the 1950s. Of the 40 faults mapped on recent aerial photographs, only 10 (25%), were visible on photographs taken in the 1930s (Table 1). By the early- to mid-1950's, 26, or approximately 65%, were identifiable on aerial photographs. Many of the faults identified on 1930s and 1950's photographs, however, were only faintly traceable and would not have been easily recognized without prior knowledge of the fault locations. By 1979, all but one of the 40 faults could be located and traced on aerial photographs. Distinctiveness of fault traces was due primarily to extensive replacement of emergent vegetation by open water along the downthrown side.

Surface and Subsurface Faults

Geological structures in the Gulf Coast Basin that influence near-surface coastal plain sediments formed as a result of gravity-driven tectonism involving tensional stresses and sediment mobilization. The dominant features are large expansion faults (growth faults), salt diapirs, and withdrawal basins. Late Cenozoic structural history of the region includes several stages of faulting and reactivation of older faults caused by episodic movement of salt and deep-water shale as well as shifting sites of diapirism. The regionally extensive expansion faults in the subsurface are aligned northeast-southwest, which is parallel to the present-day coast.

Subsurface faults are high-angle normal faults that have increased throw with depth, and an angle that commonly steepens toward the earth's surface (VAN SICLEN, 1967; YERKES and CASTLE, 1969; BRUCE, 1973, KREITLER, 1978; SHEETS, 1979; VERBEEK and CLANTON, 1981). Subsurface faults were extrapolated to the surface at angles generally ranging from about 45° to 80°. Most faults in this study had a best fit at angles of between 60° and 70° (Table 1).

Sixty percent of the mapped faults can be correlated with extrapolated faults shown on subsurface structure maps. The correlation of surface faults with subsurface faults increases to 80% if only those faults with adequate subsurface control for fault identification are considered. Sixteen surface faults have an excellent to good correlation with subsurface faults in terms of location, orientation, and direction of vertical displacement, and eight exhibit at least some properties that correlate with subsurface faults. Four of the faults have reverse throws relative to nearby subsurface faults. Considering these as correlative brings the total out of the 30 with

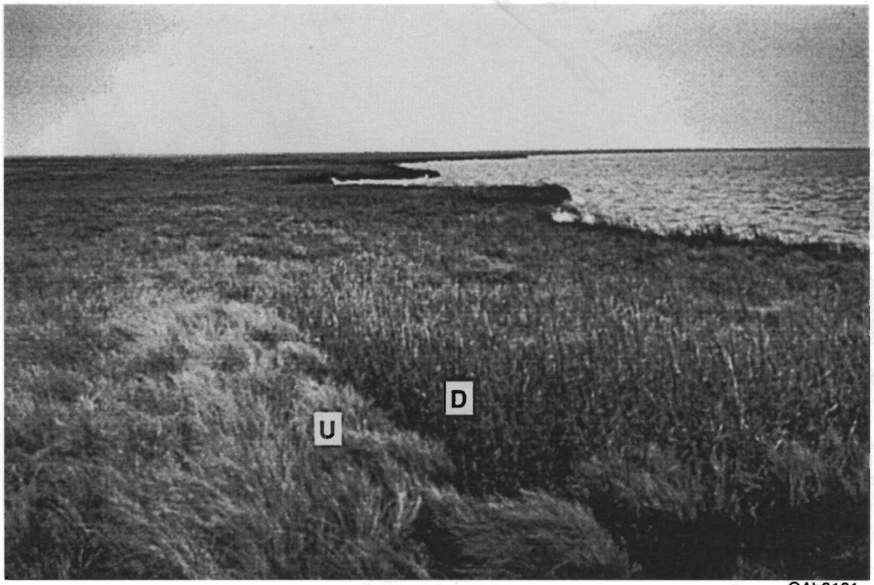


Figure 3. Field view of fault shown in Figure 2. Vegetation changes from *Spartina patens* on the upthrown side to *Spartina alterniflora* on the downthrown side. The change in vegetation is a result of lower elevations and more frequent flooding on the fault's downthrown side.

adequate subsurface control to 28, or 93%, that can be correlated with subsurface faults.

Surface faults can have an apparent reverse throw relative to their subsurface equivalent for several reasons. First, the direction of movement along a fault at the surface can be locally opposite to the throw of the major fault plane at depth because of a rotational component associated with fault movement. This phenomenon commonly occurs along normal faults associated with salt domes and shale ridges in the Gulf Coast Basin (MARTIN JACKSON, 1995, *personal communication*). Second, movement at the surface across a fault can be in a reverse direction to the original displacement along the fault (BELL, 1991).

The relationship between subsurface and surface faults is exemplified on Bolivar Peninsula near the Caplen field, where two subsurface faults that intersect lower Miocene strata at about 1,800 m have an excellent correlation with surface faults at extrapolated angles of approximately 65° (EWING, 1985).

CHANGES IN EMERGENT VEGETATION ACROSS FAULTS

Field observations and marsh transects indicate that vegetation communities change across faults as a result of elevation differences on the upthrown and downthrown sides. For example, along a topographic transect across a fault inland from Follets Island (Figure 1), plant communities on the upthrown side, which is about 25 cm higher than the downthrown side, change from an irregularly flooded high marsh of *Spartina spartinae* and *Spartina patens,* to a more frequently flooded low marsh of *Spartina alterniflora, Distichlis spicata,* and *Salicornia* sp. (Figure 4). Soils also vary from the upthrown to downthrown sides, reflecting a change in the frequency of flooding and plant species composition (Table 2). Similar changes occur across faults in back-island salt marshes on Bolivar Peninsula. Field observations in May 1991 indicated that vegetation communities on the topographically higher upthrown sides of faults contained more *Spartina patens* and *Distichlis spicata* than the downthrown sides, which supported larger stands of *Spartina alterniflora* and patchy areas of *Scirpus maritimus, Distichlis spicata,* and *Spartina patens.*

Differences in plant communities across faults appear to be related to a successional change in vegetation as subsidence and associated relative sea-level rise increase the depth, frequency, and duration of flooding on the downthrown sides of faults. Because *Spartina alterniflora* can withstand more frequent flooding than *Spartina patens* and *Distichlis spicata* (ADAMS, 1963; CHABRECK, 1972; WEBB and DODD, 1978; GLEASON and ZIEMAN, 1981; MENDELSSOHN and MCKEE, 1988a; NAIDOO *et al.,* 1992), a gradual replacement of these higher marsh species by *Spartina alterniflora* is expected. In a salt marsh in North Carolina, ADAMS (1963) attributed the replacement of portions of a maritime forest (*Juniperus virginiana*) by *Spartina alterniflora* to a relative rise in sea level. If fault-related subsidence and relative sea-level rise continue at rates that surpass rates of marsh sedimentation, eventually water depths and frequency of inundation will exceed even that which *Spartina alterniflora* can tolerate (MENDELSSOHN and MCKEE, 1988b) and all emergent vegetation will be replaced by open water.

These types of successional changes are occurring on the downthrown sides of faults crossing Bolivar Peninsula. Aerial photographs taken in the 1930's do not reveal the faults. Veg-

Table 1. *Length, historical development and angle of extrapolation of surface faults intersecting wetlands, upper Texas Coast.*

Fault Number	Informal Fault Name	Fault Length (km)	Fault Visibility 1930 Photo	Fault Visibility 1956 Photo	Fault Visibility 1979 Photo	Fault Visibility Late 1980s–1990s Photos	Approximate Angle of Extrapolation Between Surface and Subsurface Faults (degrees)
1	Orange	1.0		0*	2	2	75
2	Neches Valley W	5.0	0	0	2	2	45
3	Neches Valley E	5.5	0	0	2	2	40
4	Texas Point E	1.6	0	0	2	2	
5	Texas Point C	1.8	0	0	0	2	
6	Texas Point W	3.7	0	1	2	2	
7	Blind Lake	10.8	0	0	2	2	
8	Clam Lake N	6.1	0	0	2	2	60
9	Clam Lake E	7.5	0	0	0–1	2	90
10	Star Lake	3.6	0	0	2	2	70
11	Mud Lake	2.9	0	1	2	2	68
12	High Island E	3.9	0	2	2	2	
13	High Island N	1.1	0	0	2	2	45
14	Robinson Lake E	3.0	0	0	2	2	69
15	Robinson Lake EC	5.0	0	0–1	2	2	68
16	Robinson Lake WC	1.0	0	0–1	2	2	64
17	Robinson Lake W	4.6	0	0	2	2	64
18	Bolivar Fan E–W	13.4	0	0–2	2	2	65
19	Bolivar Fan N	2.3	0	0–1	2	2	65
20	Flake	2.4	2	2	2	2	80
21	Point Bolivar	1.8	2	2	2	2	80
22	Gordy Marsh	2.5	0–1	0–1	2	2	75
23	Lost Lake	1.5	0	2	2	2	
24	Jones Bay	3.1	0	2	2	2	38
25	Hitchcock N	4.0	2	0–2	2	2	50
26	Hitchcock C	4.0	1	1	2	2	
27	Hitchcock S	2.6	0	1	2	2	70
28	Chocolate Bay N	3.2	0	0–1	2	2	64
29	Chocolate Bay C	6.6	1	1	2	2	79
30	Chocolate Bay S	5.1	0–1	2	2	2	54
31	Hoskins Mound	1.5	0	2	2	2	45
32	Mud Island N	1.2	0	0–1	2	2	45
33	Mud Island S	2.0	0–1	1	2	2	
34	Christmas Bay	2.7	2	2	2	2	
35	Salt Lake	12.5	2	1–2	2	2	83
36	Slop Bowl	4.2	0	1	2	2	
37	Bryan Mound	1.8	0	0–1	2	2	
38	Cedar Lakes	2.0	0	0	1–2	2	75
39	Dead Caney Lake	1.8	0	0–1	2	2	
40	Boggy Bayou	2.2	0	0	0–2	2	?

Total length of faults = 152.2 km, Average length = 3.8, Mode = 1.8.
* Visibility of faults on aerial photographs: 0 = not visible, 1 = faintly visible, 2 = distinctly visible.

etation appears to be primarily that of a topographically high irregularly flooded marsh characterized by *Spartina patens* and *Distichlis spicata*. By the 1950's, the faults are visible, and formerly high marshes located on the downthrown sides had become partly replaced by low regularly flooded *Spartina alterniflora* marsh, and open water. By 1979, there was additional local replacement of high marsh by low marsh, but the most significant and widespread change was that from marsh to open water.

Succession and loss of emergent vegetation in this area are attributed more to inundation than to increases in salinity. Estuarine salinities in East Bay, for example, average approximately 10–15 ppt (MARTINEZ 1973, 1974, 1975), which is within the tolerance range of salinities for most of the above listed species (PENFOUND and HATHAWAY, 1938; CHABRECK, 1972; MENDELSSOHN and MCKEE, 1988a). Salinity may play a roll in the succession, however, as *Spartina patens* is less tolerant of increasing salinities than *Spartina alterniflora* (PEZESHKI *et al.,* 1987; MENDELSSOHN and MCKEE, 1988a; NAIDOO *et al.,* 1992).

The progressive historical changes toward more extensive flooding, permanent inundation, and loss of wetlands on the downthrown sides of faults (Figure 5) is an indication of active fault movement. Approximately 5,000 hectares of emergent vegetation have been converted to open water as a result of fault-related subsidence since the 1930's and 1950's (Table 3). About 70% of the loss has occurred in the Neches River Valley in association with two faults that cross the valley

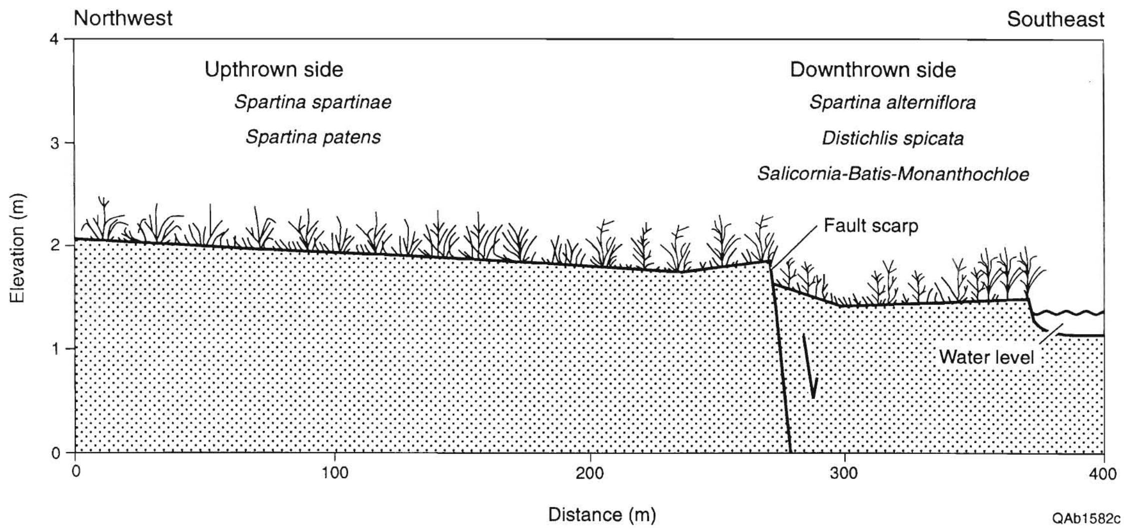


Figure 4. Topographic profile across an active fault (Figure 3) showing relative elevations and plant communities that occur on each side of the fault. Lower elevations of approximately 25 cm on the downthrown side of this fault are reflected in a topographically lower marsh community. From WHITE and PAINE (1992).

(Figure 6). Additional wetland losses totaling almost 900 hectares have occurred along faults in salt marshes on Bolivar Peninsula and in brackish marshes to the northeast (WHITE and TREMBLAY, 1995).

In some areas, differential subsidence along faults has resulted in an expansion of marshes rather than a loss of marshes. Marsh expansion is due to more frequent inundation and the spread of hydrophytes into areas previously characterized by prairie grasses. An example of this type of change occurred along an active fault that crosses Gordy Marsh near the eastern shore of Trinity Bay (Figure 7). This fault could not be clearly discerned on aerial photographs taken in 1930 nor in the 1950s, but by 1963, the fault had a distinct trace because of wetter conditions on the downthrown southeast side. By 1970 and 1979, the fault was even more distinct and wetlands, as interpreted on aerial photographs, had expanded. From the 1950's to 1989, marsh area increased by 275 hectares on the downthrown side of the fault (WHITE *et al.*, 1993).

Table 2. *Types and characteristics of soils located on the upthrown block and downthrown block of a fault crossing the Brazoria National Wildlife Refuge. From Crenwelge* et al. (1981).

UPTHROWN BLOCK:
Surfside Clay
Level saline soil-rarely flooded
Water table < 0.6 m during winter
Salty prairie vegetation
90% *Spartina spartinae*
DOWNTHROWN BLOCK:
Harris Clay
Level saline marsh soil
Water table < 0.5 m
Typically 50% *Spartina patens*
25% *Disticlis spicata*
10% *Paspalum vaginatum*
10% *Scripus americanus*
Harris-Tracosa Complex
Broad tidal marsh areas
45% Harris Clay, 40% Tracosa Mucky Clay
Water table < 0.5 M
Depressions containing water
Tracosa Soils—*Ruppia maritima* in depressions
Where vegetated—90% *Spartina alterniflora*

A scenario of vegetation succession similar to the irregularly to regularly flooded marshes can be envisioned for the prairie to marsh conversion as the frequency of flooding increases on the downthrown sides of faults. Prairie grasses near Gordy Marsh are dominated by *Spartina spartinae,* with other scattered species including *Schizachyrium scoparium, Paspalum lividum, Setaria geniculata* (CROUT, 1976; HARCOMBE and NEAVILLE, 1977). Marshes are characterized by *Spartina patens, Spartina spartinae, Distichlis spicata, Scirpus maritimus, Phragmites australis,* and locally *Spartina alterniflora,* among other species (CROUT, 1976; HARCOMBE and NEAVILLE, 1977; BENTON *et al.,* 1979; and WHITE *et al.,* 1985). As the area of prairie grasslands became more frequently inundated, there was a corresponding change in vegetation types from prairie species to marsh species. Vegetation and soil types are similar to those shown in Table 2.

SURFACE FAULTS AND OIL AND GAS PRODUCTION

Subsidence associated with the withdrawal of underground fluids such as ground water, oil, and gas has been reported in many parts of the world (BELL, 1988) including the Gulf Coast Basin (GABRYSCH, 1969; POLAND and DAVIS, 1972; MARTIN and SERDENGECTI, 1984). Some early examples of subsidence and faulting associated with oil and gas produc-

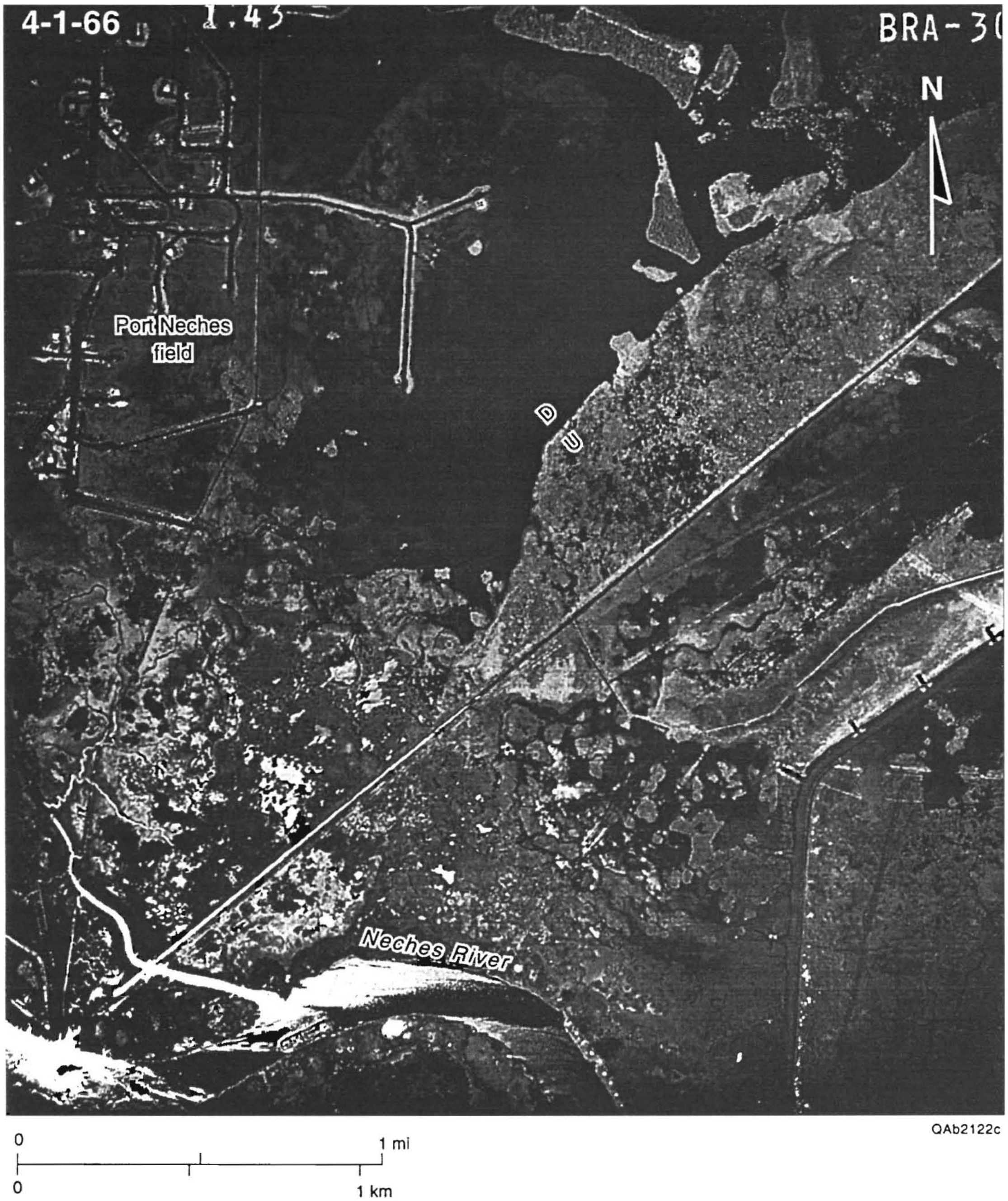


Figure 5. Neches River valley fault as shown on aerial photograph taken in 1966 by the U.S. Department of Agriculture. D = downthrown side, U = upthrown side. This is the westernmost fault shown in Figure 6.

tion are the Goose Creek field in the Houston area, and the Saxet field in the Corpus Christi area (PRATT and JOHNSON, 1926; GUSTAVSON and KEITLER, 1976; HILLENBRAND, 1985). There is evidence that production from at least 18 oil and gas fields located on the Texas coastal plain has caused subsidence, some of which occurred along active faults (KREITLER, 1978; VERBEEK and CLANTON, 1981; EWING, 1985; KREITLER *et al.*, 1988; HOLZER, 1990; WHITE and TREMBLAY, 1995). Surface faults associated with three fields examined in detail in this paper were reported by WHITE *et al.* (1985) and EWING (1985) (Caplen field), and WHITE and TREMBLAY (1993) (Clam Lake and Port Neches fields).

Despite the widespread recognition of this phenomenon, the potential for significant wetland losses as a result of moderate to deep hydrocarbon production has generally been disregarded because in many old sedimentary basins, the mag-

Table 3. *Loss in marsh area along several faults identified in Table 1. Note that most of the reported losses occurred between the 1950's and late 1970's, which suggests that this is a conservative estimate of the total loss. Losses have likely increased along faults in these areas and in other areas.*

Location	Loss (hectares)	Date of Photos
Neches River valley	3,500	1956 to 1978
Bolivar Fan	600	1956 to 1979
Clam Lake	275	1956 to 1987
Chocolate Bay S	190	1930 to 1979
Jones Bay	120	1956 to 1992
Lost Lake	95	1950's to 1989
Gordy Marsh	45	1950's to 1979
Total	4,825	

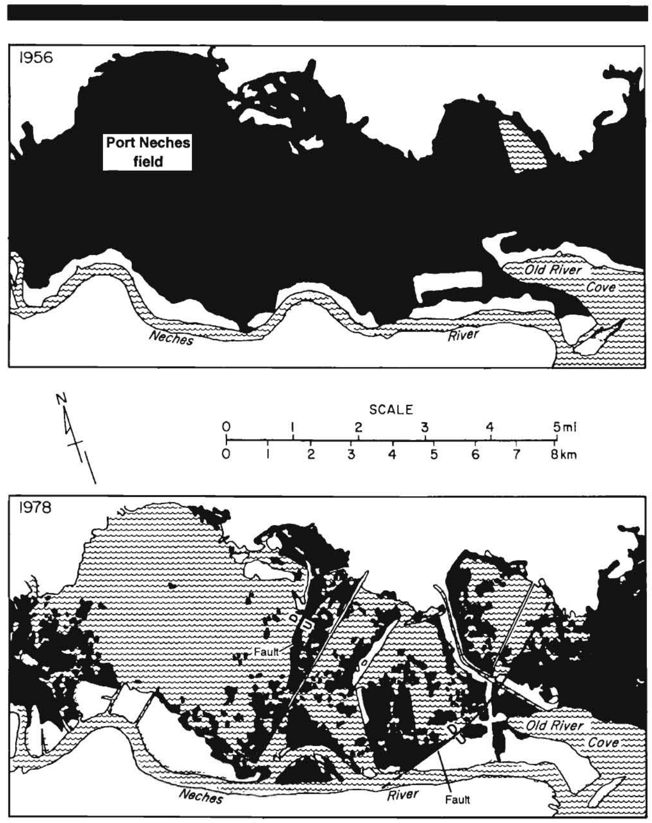
nitude of compaction strain associated with hydrocarbon production was small (GEERTSMA, 1973). This is not the case in relatively young sedimentary basins where large volumes of hydrocarbons and formation water are produced at moderate depths.

According to summaries presented in CHILINGARIAN *et al.* (1995), induced subsidence depends primarily on production depth, areal extent and thickness of reservoir, consolidation state of reservoir and overburden, heterogeneity of sediment column, and volume and rate of produced fluids. Tertiary reservoirs and overlying strata of the Gulf Coast Basin where subsidence is pronounced are typically shallow to moderately deep, moderately thick (multiple pay zones) and areally extensive, unconsolidated, interbedded sandstones and mudstones with high *in-situ* porosities (MORTON and GALLOWAY, 1991). These sediments are highly compressible and subject to compaction as a result of fluid withdrawal.

Oil and gas reservoirs of the Gulf Coast are compartmentalized by sealing faults that create permeability boundaries and limit lateral flow of fluids. Because the reservoirs are confined by faults that prevent drainage from adjacent strata, large-volume fluid production results in greatly reduced pore pressures and increased shear stresses. In the absence of direct subsurface measurements, cumulative fluid production is a leading indicator of reduced pore pressures and increased shear stresses within the reservoir.

Previous studies in the Gulf Coast Basin demonstrate that land surface subsidence commonly occurs several kilometers away from producing wells rather than directly above the producing formation (GUSTAVSON and KREITLER, 1976; EWING, 1985; MORTON and PAINE, 1990). The locus of subsidence and wetland loss is controlled by the coupling between reservoir compaction and slip along the faults. The induced subsidence and wetland losses are concentrated along faults that become active when sufficiently large volumes of fluid (oil, gas, formation water) are removed from the subsurface. Fluid extraction causes a decline in pore pressure within the rocks and alters the state of stress near the faults. Thus, both the pattern of hydrocarbon production and the three-dimensional geometries of faults need to be considered in predicting the location and magnitude of wetland losses.

It may be possible to prevent significant faulting and subsidence through appropriate engineering design before the reservoirs are developed. For example, subsidence resulting



Map Unit	1956		1978		Net Change*	
	Acres	Hectares	Acres	Hectares	Acres	Hectares
Water	2,560	1,037	11,070	4,483	+8,510	+3,446
Marsh	15,740	6,375	6,330	2,564	−9,410	−3,811

* Loss of additional 900 acres (365 hectares) of marsh primarily due to spoil disposal.

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Figure 6. Changes in the distribution of wetlands between 1956 and 1978 in the Neches River valley at the head of Sabine Lake. Differential subsidence along the faults crossing the valley have contributed to the conversion of emergent vegetation to open water. D = downthrown side, U = upthrown side. Modified from WHITE *et al.* (1987).

from groundwater withdrawal is virtually arrested when pumpage does not exceed rates of recharge (GABRYSCH and COPLIN, 1990). There is evidence that subsidence associated with oil and gas production can be arrested by pressure maintenance programs. The Wilmington field in California is a well known example. After production began in 1936, the field subsided approximately 9 m until 1966, when the surface finally became stable as a result of a water injection program that was begun in 1957 (YERKES and CASTLE, 1969). Water injection repressurized the producing formations halting subsidence and causing local rebound (YERKES and CASTLE, 1976). Implementation of pressure maintenance programs early in the production history of a reservoir could

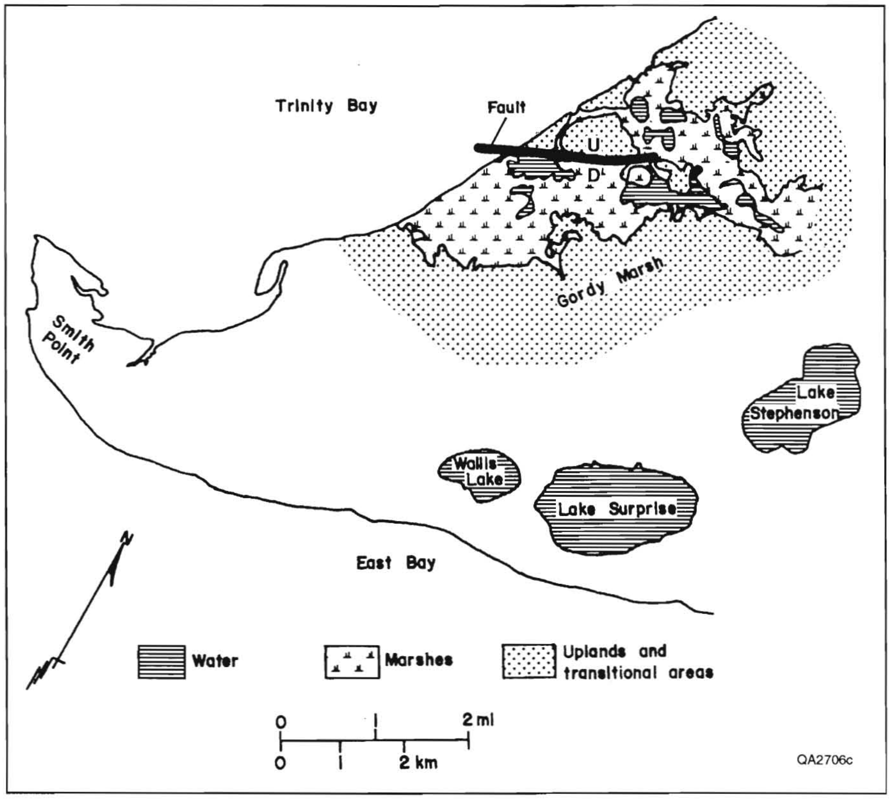

Figure 7. Simplified illustration of fault that intersects Gordy Marsh on the southern margin of Trinity Bay (Figure 1). Marshes and ponded water characterize the downthrown side (D) of the fault. From White *et al.* (1985).

reduce formation compaction, inhibit faulting and subsidence at the surface, and mitigate or eliminate the loss of wetlands.

Geographic Association between Surface Faults and Oil and Gas Fields

In this study, 29 (about 70%) of the surface faults are within 5,000 m of an oil and gas field and have an orientation and direction of throw that suggests an association with the field. Only 21 fields (53%), however, have both a close geographic association with faults and production history (for example, year of discovery) that suggest that oil and gas production could be responsible for the faults initial appearance at the surface. Nevertheless, the progressive loss of wetlands along many of the faults indicates recent fault movement may be related to oil and gas production even though the faults were present before production began. In some cases fault movement may be related to regional extensional subsidence associated with large-volume regional fluid production from more distant fields.

VERBEEK and CLANTON (1981) and HOLZER and BLUNTZER (1984) concluded that differential subsidence and fault activation from hydrocarbon production in the Houston area is relatively minor compared to that associated with extensive volumes of groundwater withdrawal. Most of the faults analyzed in this study, however, are in areas that should not be significantly affected by groundwater pumpage.

Hydrocarbon Production, Fault Activity, and Associated Wetland Losses

To determine possible relationships between hydrocarbon production and surface fault activity promoting wetland loss, we investigated production histories of three moderately large oil and gas fields that have a geographic association with surface faults. All three fields, Port Neches, Clam Lake, and Caplen (Figure 8), are associated with deep-seated salt domes (FISHER *et al.,* 1972, 1973; MUSOLFF, 1962). Production histories of the three fields are somewhat similar in that each was discovered before 1940, production is from Miocene and Oligocene reservoirs, and cumulative oil production in each exceeds 19 million barrels. Surface faults correlate well with subsurface faults, and formerly extensive marshes have been converted to open water on the downthrown sides of the faults. Surface environments where the fields are located include the alluvial valley of a major river, an interfluvial coastal plain marsh and a barrier island (Figure 8).

Port Neches Field

The Port Neches field is located in the Neches River valley near the head of Sabine Lake (Figure 8). Cumulative hydrocarbon production has exceeded 25 million barrels of oil and 40 billion ft^3 of gas since discovery of the field in 1929 (Figure 9). If associated fields (Port Neches, North, South, and West)

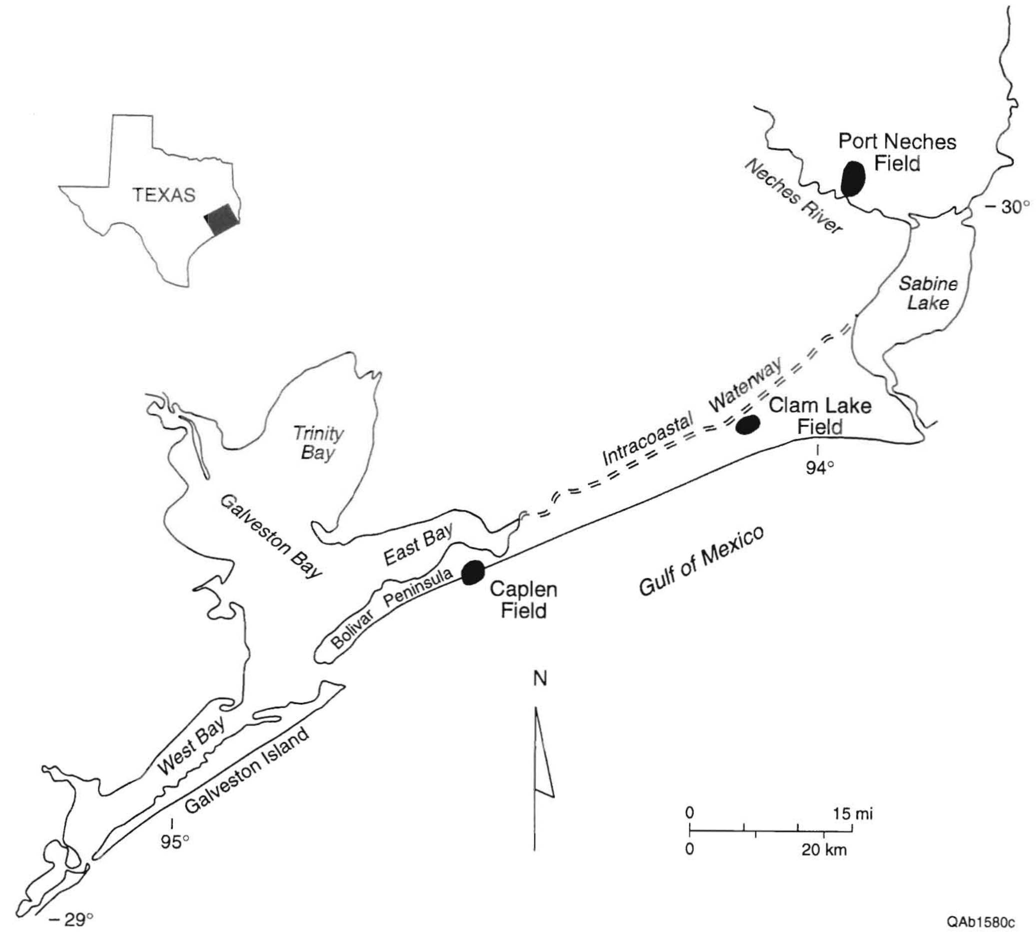

Figure 8. Locations of Port Neches, Clam Lake, and Caplen oil and gas fields. Wetland loss around these fields has exceeded 4,500 ha since 1956.

are included, cumulative oil production exceeds 33 million barrels, and gas production 500 billion ft^3. Production in the Port Neches field is from average depths of about 1,800 m (TEXAS RAILROAD COMMISSION, 1994). Annual production records show rapid acceleration in gas production in the late 1950's, with production falling precipitously after 1959 (Figure 9). Oil production peaked in the early 1950's and gradually declined through the 1980's.

Traces of two surface faults mapped east of the Port Neches field (Figure 6) were not visible on photographs taken in the 1930's or mid-1950's, but were visible on photographs taken in the 1960's (Figure 5). Between 1956 and 1978, almost 3,500 hectares of wetlands in the Neches River valley were replaced by open water and shallow subaqueous flats (WHITE *et al.,* 1987). These extensive losses occurred primarily on the downthrown side of the faults that border the field (Figures 5 and 6), indicating that differential subsidence over the field contributed to the loss of wetlands.

Complications arise in attributing all the wetland losses in the Neches River valley to subsidence because other processes can contribute to wetland loss. Among those processes are dredging and filling of wetlands, which can cause direct and indirect losses, and construction of upstream dams and reservoirs that can reduce the supply of fluvial sediments that nourish and maintain wetlands. The spatial and temporal relationships among oil and gas production, fault activation, and wetland loss are compelling evidence that there is a causal relationship between hydrocarbon production and differential subsidence across the mapped faults.

Clam Lake Field

The Clam Lake field, which is located in the interfluvial area between Sabine Lake and East (Galveston) Bay (Figure 8), was discovered in 1937. Since discovery, it has produced more than 21 million barrels of oil and 4 billion ft^3 of gas (Figure 10) at depths ranging from 700 m to 2,000 m (WILLIAMS, 1962). The field is centered on a salt dome with complex subsurface faulting, including a major north-south striking fault downthrown on the west side toward the field (WILLIAMS, 1962). Extrapolation of this fault to the surface at an angle of approximately 60° matches well with a surface fault that is traceable over a distance of about 6 km (Figure 11). The fault trace was not visible on aerial photographs in 1930

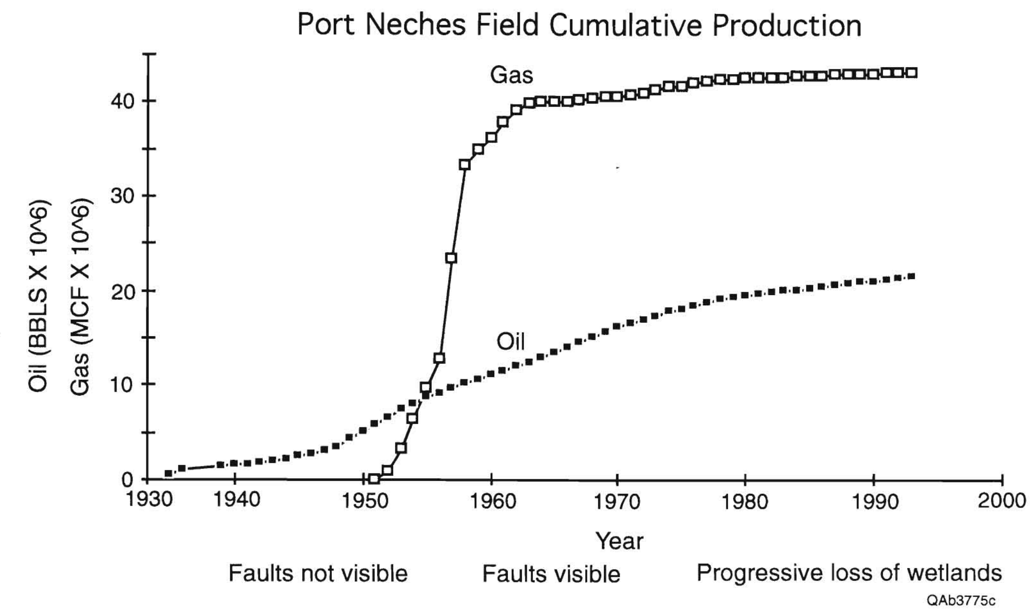

Figure 9. Cumulative production of oil and gas from the Port Neches field located in the Neches River valley. Surface faults downthrown toward the field are not visible on aerial photographs taken in the mid-1950's but are visible by the mid-1960's after cumulative gas production had reached 40 billion ft^3. Production volumes are from the Texas Railroad Commission.

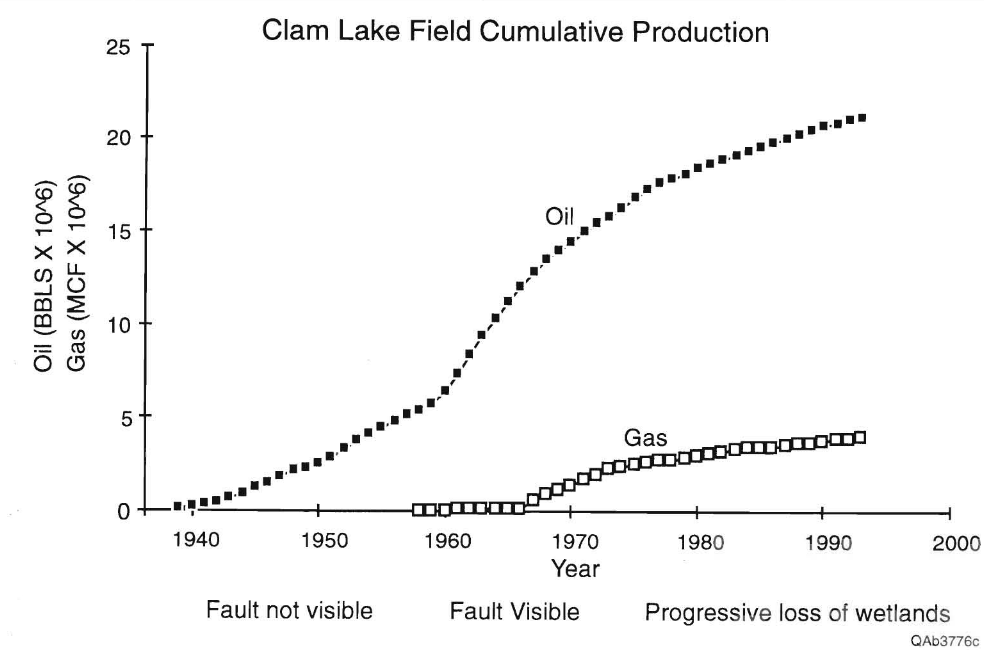

Figure 10. Cumulative production of oil and gas from the Clam Lake field. A surface fault downthrown toward the field was not visible in 1956 but was distinctly visible in 1966 after broad areas of emergent vegetation were replaced by open water on the downthrown side of the fault. Cumulative oil production exceeded 12 million barrels in 1966. Production volumes are from the Texas Railroad Commission.

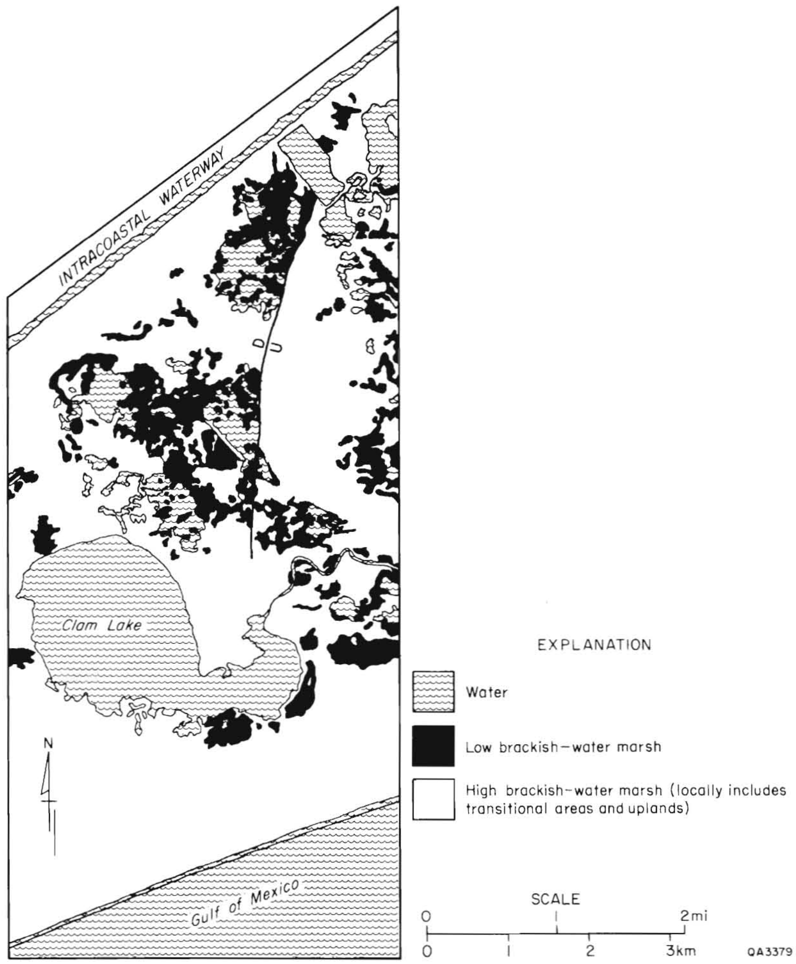

Figure 11. Fault and associated marshes and water features near Clam Lake (Figure 8) in the McFadden National Wildlife Refuge. From WHITE *et al.* (1987).

and 1956, but is distinctly visible on photographs taken in 1966 and later. The fault intersects brackish-water marshes and its visibility is accentuated because of ponded water and low marshes on the downthrown side of the fault (Figure 11). Between 1956 and 1987 approximately 275 hectares of marsh was converted to open water primarily on the downthrown side of the fault (WHITE and TREMBLAY, 1995).

Fault movement between 1956 and 1966 correlates well with annual oil production (Figure 10). Production gradually increased from 1937 to 1958, after which there was a rapid rise in production from 1958 to 1963 followed by a decline. Cumulative oil production through 1964 exceeded 10 million barrels (Figure 10). A second fault in this area was not clearly visible on 1978 photographs but is very distinct on 1989 photographs, indicating activation or accelerated movement during the past two decades.

Caplen Field

Production from the Caplen field is primarily from lower Miocene reservoirs at depths of 2,100 to 2,200 m (EWING, 1985). After its discovery in 1939, oil production reached a peak in the mid-1950s when annual production exceeded 600,000 barrels (TEXAS RAILROAD COMMISSION records). Between 1943 and 1979, annual production fluctuated between 300,000 and 600,000 barrels a year, declining at a relatively uniform rate after 1970. Gas production increased in the late 1950's and 1960's, with casinghead gas reaching a peak between 1968 and 1971, and non-associated gas reaching a peak in the early 1980's. Production of both oil and gas declined after 1980. Apparently most of the production comes from a strong water drive, and records from the Railroad Commission of Texas indicate a total fluid production, including formation water, of 30–40 million barrels to 1985 (EWING, 1985).

Two surface faults that cross the barrier island are not visible on aerial photographs taken in 1930, but portions of the faults are traceable on photographs taken in 1952. A benchmark releveling survey along Bolivar Peninsula indicates differential subsidence across a fault in this area from 1936 to 1954 (Figure 12). By 1950, cumulative production had

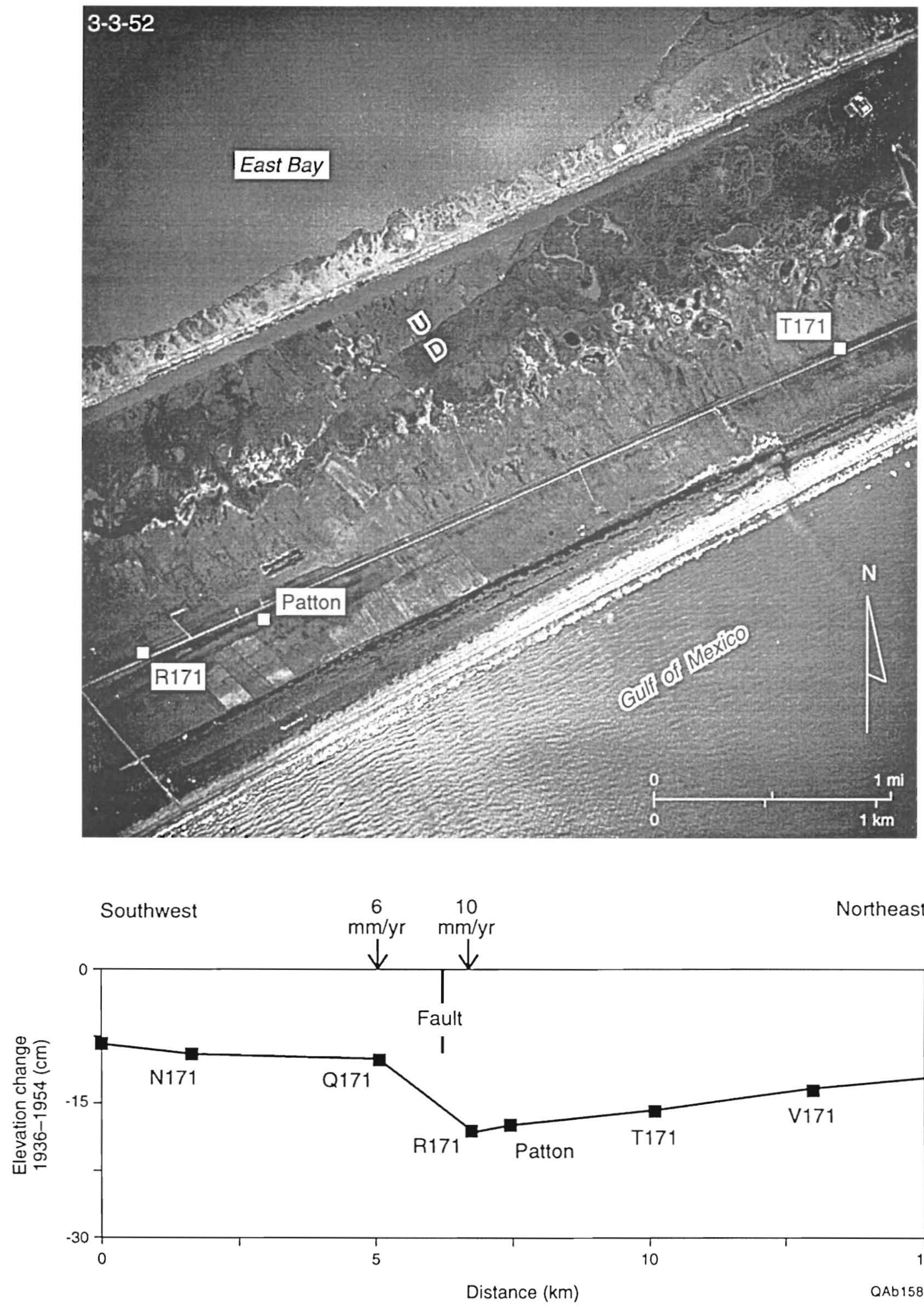

Figure 12. Aerial photograph and land-surface subsidence profile showing fault on Bolivar Peninsula near Caplen field (Figure 8). Land-surface subsidence profile is based on bench mark leveling surveys in 1936 and 1954 along State Highway 87. Projection to the southwest of the fault shown in the aerial photograph indicates it should cross the highway between bench marks R171 (shown in the photograph) and Q171, which is located out of the photograph to the southwest. Increased rates of subsidence at R171 indicates that it is on the downthrown side (D) of the fault and Q171 is on the upthrown side (U). Profile from Charles W. Kreitler, unpublished data.

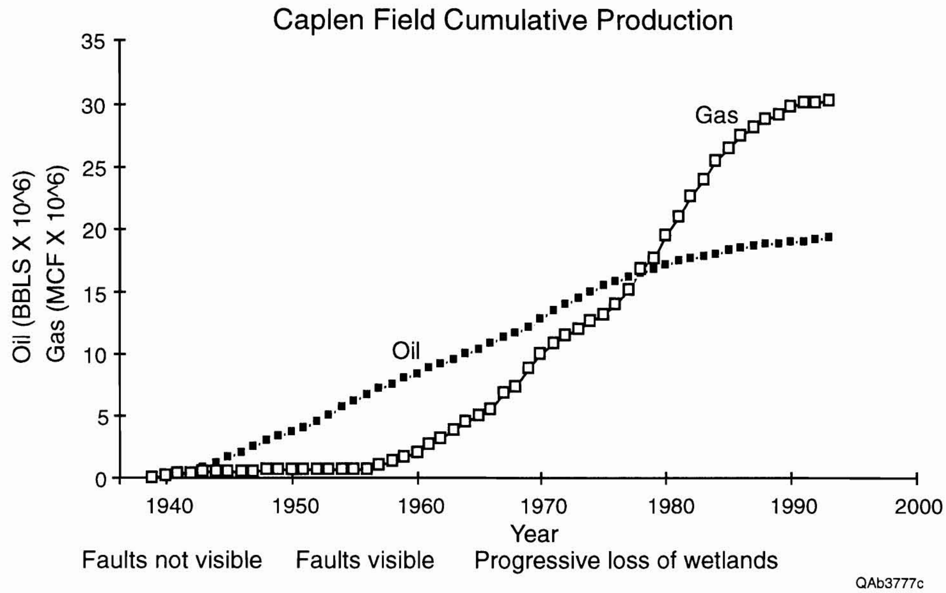

Figure 13. Cumulative production of oil and gas from the Caplen field (Figure 8). Surface faults near the field were not visible in 1930 but were visible in the 1950's. Since the 1950's, there has been an expanding loss of wetland emergent vegetation on the faults downthrown sides. Production volumes are from the Texas Railroad Commission.

reached about 3.7 million barrels of oil and 647 million ft^3 of gas (Figure 13). The faults are more pronounced on photographs taken in the 1970's and 1980's, as areas of open water expanded at the expense of marshes. Approximately 600 hectares of marsh were converted to open water between the 1950s and 1989 (WHITE and TREMBLAY, 1995). This wetland loss coincides with annual gas production that peaked in the late 1960s to early 1980s. As with the Port Neches and Clam Lake Fields, the spatial and temporal relationships between oil and gas production, faulting, and marsh loss support EWING'S (1985) conclusion of a causal relationship between fluid production and fault movement. Much larger fluid volumes produced from reservoirs at High Island salt dome (Figure 1) may have caused regional depressurization and subsidence that in turn contributed to reactivation of several faults along the northern margin of East Bay (EWING, 1985).

CONCLUSIONS

Recent artificially induced fault movement has resulted in the loss of large wetland areas on the southeastern Texas Gulf coast. Air photo analysis of 40 faults illustrate extensive replacement of emergent vegetation by open water along many of these faults. Upland and wetland response to fault movement is a time-dependent progression toward wetter conditions and eventually permanent inundation. Successional changes in wetlands may proceed from initial dense stands of topographically high marsh characterized by species such as *Spartina patens* and *Spartina spartinae,* to low, regularly flooded marsh dominated by *Spartina alterniflora*. Continued subsidence and associated relative sea-level rise forms isolated ponds and shallow subaqueous flats, and eventually larger, coalescing ponds and open water. This expansion of open water on the downthrown sides of faults has contributed to the loss of approximately 5,000 hectares of wetland emergent vegetation since the 1930's and 1950's. Locally, however, differential subsidence along faults has resulted in an expansion of wetlands into areas previously mapped as uplands.

Land-surface subsidence and coastal wetland loss are not only caused by shallow groundwater extraction, but can also be caused by hydrocarbon production at depths of more than 2,000 m. Subsidence in many areas is focused along surface faults.

Approximately 75% of the observed faults have been activated in recent decades. There is a close correlation between history of fluid production and history of fault movement. Production data from two fields indicate that fault movement was initiated during the first 10 to 20 years of production after about 5 million bbls of oil had been extracted. In a third field, large volumes of gas production appear to have triggered fault movement. Once faults are activated, wetland losses continue throughout the production period of the field. Documented wetland losses are greatest around moderately large fields that have produced more than 19 million bbls of liquids during a period of about 40 years.

Continued large-volume extraction of conventional energy resources as well as anticipated production of alternative energy resources (geopressured-geothermal fluids) and methane dissolved and entrained in formation water in the Gulf Coast region will only increase existing subsidence and wetland losses or cause inundation of areas that are currently stable unless techniques are developed to control the induced subsidence.

The long history of fluid production, subsidence, and wetland loss in the Gulf Coast region provides a basis for managing reservoirs in other coastal plain settings throughout the world where large oil and gas fields are being produced beneath valuable wetlands.

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