Morton, R. A., Buster, N. A., and Krohn, M. D., 2002, Subsurface controls on historical subsidence rates and associated wetland loss in southcentral Louisiana: Transactions Gulf Coast Association of Geological Societies, v. 52, p. 767-778.

Subsurface Controls on Historical Subsidence Rates and Associated Wetland Loss in Southcentral Louisiana

Robert A. Morton,[1] Noreen A. Buster,[1] and M. Dennis Krohn[1]

[1] U.S. Geological Survey, St. Petersburg, FL 33701

Abstract

Two regional releveling profiles and six tide gauges provide a basis for evaluating recent rates of delta plain subsidence in southcentral Louisiana. Analyses of these records demonstrate close correlations among highest historical rates of subsidence, rapid wetland losses, large volume hydrocarbon production, and probable reactivation of deep subsurface faults. Other researchers have demonstrated that the highest geological subsidence rates of the Mississippi delta plain (< 3 mm/yr) correspond closely with the thickest Holocene sediments that fill the underlying incised valley. Within that geologic framework, highest historical subsidence rates (as much as 23 mm/yr) correspond with surface projections of the reactivated Lake Hatch and Golden Meadow fault zones and with individual oil and gas fields. The initial acceleration and subsequent decline in rates of wetland loss in southcentral Louisiana are attributed partly to increased and then possibly decreased rates of subsidence that were related to increased and then decreased rates of fluid production. Decreases in subsurface pore pressures associated with gas production were so large that the state of stress was altered and critically stressed faults were likely reactivated. Subsidence rates in coastal Louisiana associated with natural compaction and dewatering of Holocene deltaic sediments should decrease with time. Therefore historical rates of delta plain subsidence that accelerate and typically exceed geological subsidence rates are most likely influenced by anthropogenic activities, such as subsurface fluid extraction.

Introduction

Recent evidence from the coastal plain of southeast Texas links wetland loss, accelerated subsidence rates, and fault reactivation with long-term (decadal), large volume fluid production in nearby oil and gas fields (White and Morton, 1997; Morton et al., 2001). The links between hydrocarbon production and wetland loss are relatively easy to establish in coastal Texas because (1) the wetland losses are localized, and (2) the natural geological rates of subsidence are low inasmuch as Holocene sediments are thin or absent across much of the coastal plain. In coastal Louisiana (Figs. 1 and 2), it is more difficult to establish possible linkages between deep hydrocarbon production and wetland loss because wetland loss is ubiquitous and caused by many processes and conditions (Coleman and Roberts, 1989; Williams et al., 1994), including a thick sequence of Holocene deltaic sediments (Roberts et al., 1994). Furthermore, the high water content of near-surface sediments in southcentral Louisiana may obscure the presence of surficial faults crossing the delta plain.

Determining whether or not hydrocarbon and water production has contributed to wetland losses involves integrating disparate data sets including isotopic ages of buried peats, geodetic surveys, tide gauge records, subsurface geologic maps, and hydrocarbon production parameters, such as fluid volumes and reservoir pressures. This report summarizes recent analyses of subsidence, reactivated faults, and wetland loss patterns in the Barataria-Terrebonne region primarily between Bayou Lafourche and Bayou Petit Caillou (Fig. 2) where some of the highest rates of historical wetland loss have occurred (Britsch and Dunbar, 1993; 1996).

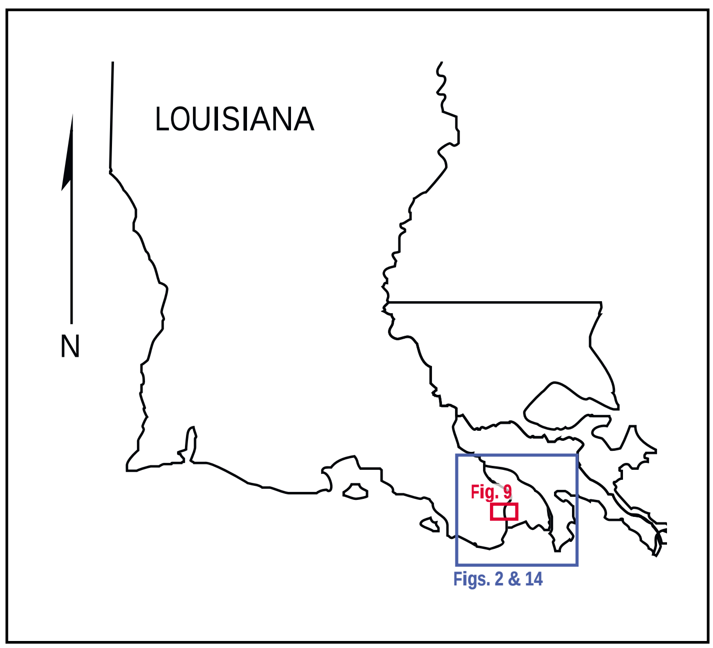

Figure 1. General location of study area in southcentral Louisiana.

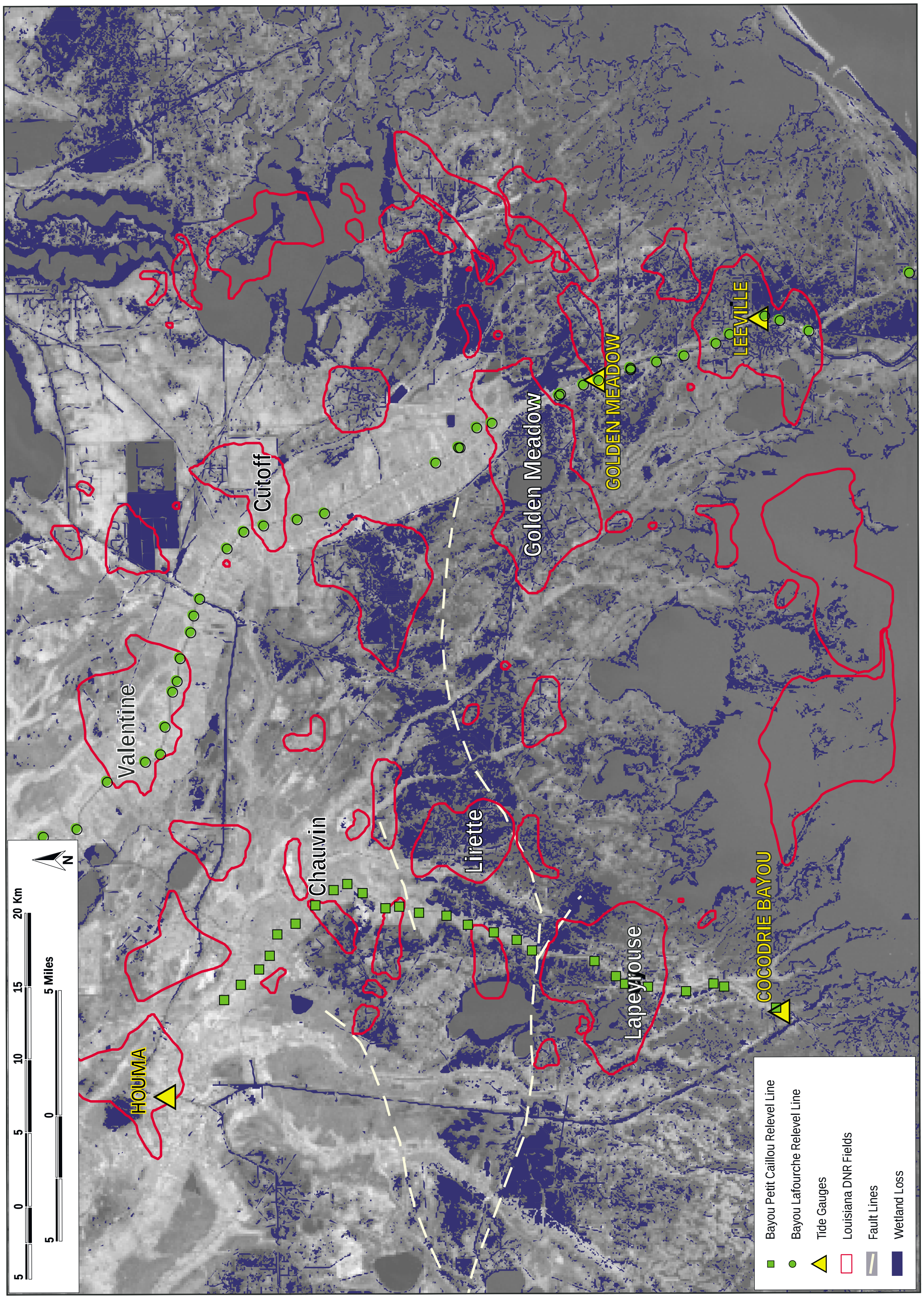

Figure 2. Locations of oil and gas fields, trends of major fault zones, tide gauges, leveling profiles, and areas of wetland loss in southcentral Louisiana. Leveling profiles are from National Geodetic Survey, areas of wetland loss are from Britsch and Dunbar (1996), and fault trends are from Murray (1961) and Kuecher et al. (2001).

Producing Fields And Faults

Petroleum fields in the delta plain of southcentral Louisiana (Fig. 2) produce from relatively thick, interconnected, normally pressured sand reservoirs at depths ranging from 3,000 to more than 16,000 ft. Porous and permeable sand reservoirs at depths exceeding 12,000 ft are the result of rapid creation of accommodation space and attendant basin filling during the middle and late Miocene. The regional basinal subsidence and shelf margin sedimentation were associated with evacuation of salt from the Terrebonne Trough that contributed to salt dome growth in surrounding areas (Diegel et al., 1995).

General locations of the major expansion faults associated with shelf-margin progradation have been well known for decades (Murray, 1961). More recently Kuecher et al. (2001) used seismic profiles to examine the deep-seated fault zones and to vertically project the locations of fault planes that may intersect or be near the delta plain surface (Fig. 2). These shallow fault planes have been reactivated periodically as a result of the overall extensional tectonic stresses in the Gulf Coast Basin, and they are the fault planes most susceptible to reactivation induced by pore-pressure reductions in the subsurface.

Hydrocarbon Production and Formation Pressure Histories

Formation Pressure Gradients

Transient reservoir pore pressures measured periodically in producing wells provide an indirect method of evaluating the potential degree of subsurface stress perturbation associated with the extraction of hydrocarbons and associated formation water. Because formation pressures are depth dependent, a better measure of subsurface pressure change is the final decrease in pressure gradient reported for a particular reservoir. In the Gulf Coast region, normal (hydrostatic) pressure gradients are about 0.465 psi/ft (Dickinson, 1953). As reservoirs are depleted, pore pressure gradients decline, and in some gas wells final pressure gradients before abandonment approach 0.01 psi/ft.

Production and Field Pressure Histories

Hydrocarbon production and pressure histories for several large oil and gas fields in southcentral Louisiana were examined to test the hypothesis that some regional wetland losses were caused by subsidence induced by subsurface fluid extraction. The Valentine, Houma, Lapeyrouse, and Lirette fields were selected for analysis because: (1) substantial data are available for their long periods of production, (2) the fields are near leveling profiles and tide gauges, and (3) the fields are within the regional trend of wetland loss (Fig. 2).

Valentine Field

The Valentine field, discovered in 1936 (Troutman, 1956), is an intermediate depth salt structure that produces from upper and middle Miocene deltaic sand reservoirs at depths from 6,000 to 12,000 ft. The primary reservoirs have produced more than 920 billion cubic feet (Bcf) of gas

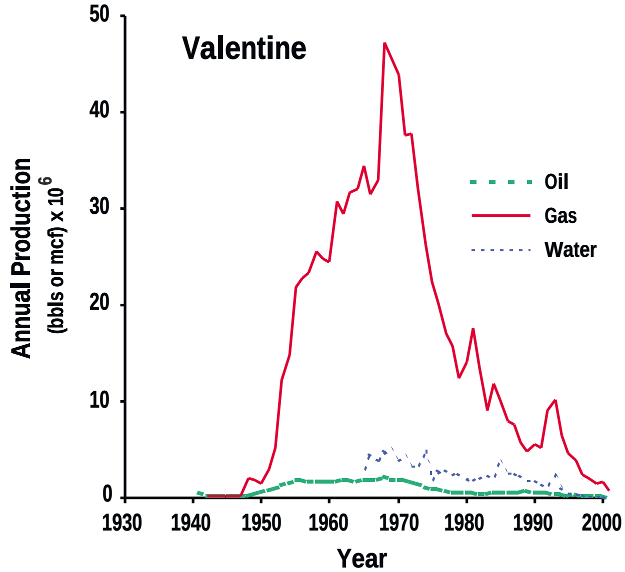

Figure 3. Annual hydrocarbon and water production from the Valentine field, Lafourche Parish, Louisiana. Data are from the Louisiana Department of Natural Resources. Field location is shown in Figure 2.

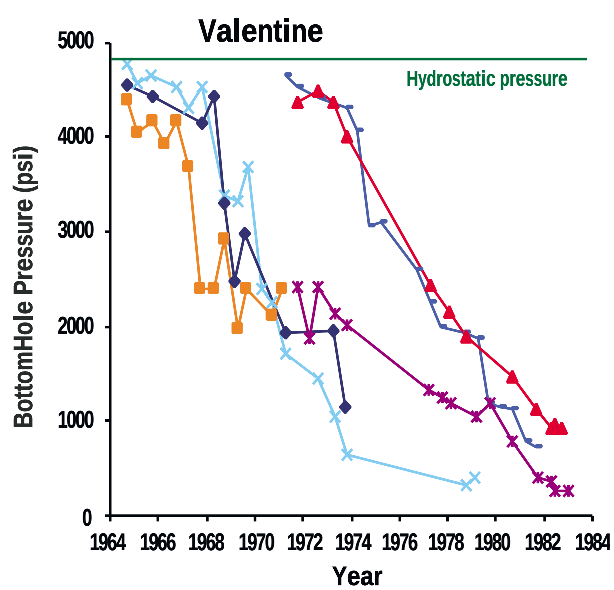

Figure 4. Pressure histories of selected wells in the Valentine field producing from the primary gas reservoirs. Data are from the Louisiana Department of Natural Resources.

along with about 55 million barrels (bbls) of oil and at least 87 million bbls of formation water. Rates of fluid production from the Valentine field (Fig. 3) increased rapidly in the early 1950s, peaked in 1970, and then declined rapidly during the 1970s. Since then annual rates of fluid production have declined and the field is nearly depleted. Reservoir pressures for Valentine and the other fields are only available electronically since 1965, which includes the period of maximum rates of production (Fig. 3). Pressures in the principal gas reservoirs (South Coast 3, Valentine) generally declined 2500 to 4000 psi as production first increased, peaked, and then declined (Figs. 3 and 4). Most of the gas wells produced about 10 to 15 yrs before exceptionally low pressures led to their abandonment.

Houma Field

Since its discovery in 1945 (Troutman, 1956), the Houma field has produced more than 851 Bcf of gas, 7 million bbls of oil, and 21 million bbls of water primarily from middle Miocene deltaic sand reservoirs. Hydrocarbons are trapped in a faulted anticline with fault displacement being down-to-the basin (south). Most of the production in the Houma field comes from reservoirs between 10,000 and 16,000 ft deep. The history of fluid production from the field (Fig. 5) follows a slightly erratic path that includes an initial acceleration in production in the late 1950s, an intermediate acceleration in the late 1960s and early 1970s, and a final period of production decline beginning in the early 1970s.

Lapeyrouse and Lirette Fields

The Lapeyrouse field has been producing from multiple upper Miocene deltaic sand reservoirs at depths ranging from about 6,000 to 16,000 ft since its discovery in 1941. The principal reservoirs (Exposito, Bourg, Pelican, and Duval) produce primarily gas (Braunstein, 1965) with subordinate volumes of liquid hydrocarbons and formation water. Annual rates of fluid production in the field increased rapidly after 1956, peaked in 1970, and have generally declined since then (Fig. 6). Total fluid production at Lapeyrouse has exceeded 624 Bcf of gas, 18 million bbls of oil, and 39 million bbls of water.

Most pore pressures in the Lapeyrouse reservoirs are normal except in the Pelican reservoir (Fig. 7) at about 15,000 ft, but other reservoirs at 15,000 ft have normal pressure gradients. Pore pressures in the Exposito reservoir declined steadily between 1965 and 1978 (Fig. 7) in response to the relatively rapid rates of gas production (Fig. 6). Plots of pressure histories for the Bourg, Pelican, and Duval reservoirs also show the same general trends with pressure reductions of 4,000 to 6,000 psi being common (Fig. 7).

Pore pressure reductions in the Lapeyrouse reservoirs may have reactivated a nearby fault. To investigate this possibility, pressure gradient reductions in 44 wells in the Lapeyrouse field were calculated by taking the difference between the initial and final reported reservoir pressures and dividing by the depths of production (perforation depths). Values for pressure gradient reduction ranged from 0.026 to 0.42 psi/ft and are distributed so that the

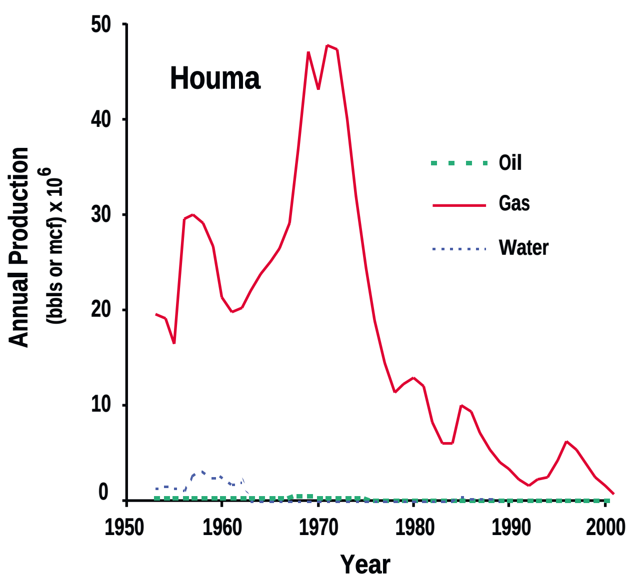

Figure 5. Annual hydrocarbon and water production from the Houma field, Terrebonne Parish, Louisiana. Data are from the Louisiana Department of Natural Resources. Field location is shown in Figure 2.

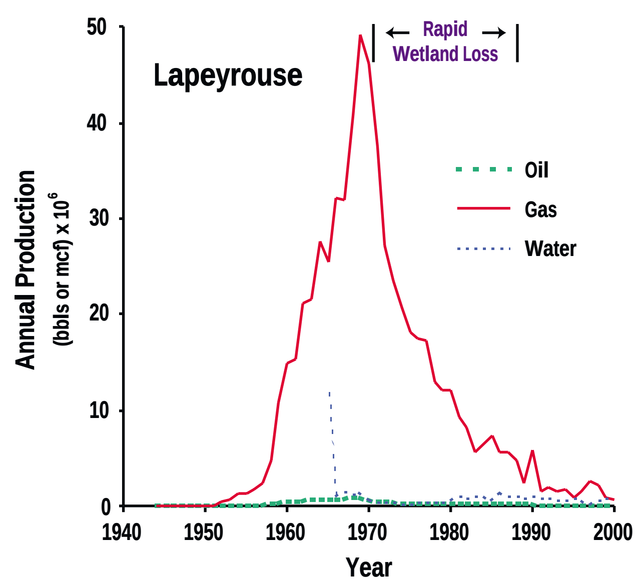

Figure 6. Annual hydrocarbon and water production from the Lapeyrouse field, Terrebonne Parish, Louisiana. Data are from the Louisiana Department of Natural Resources. Field location is shown in Figure 2.

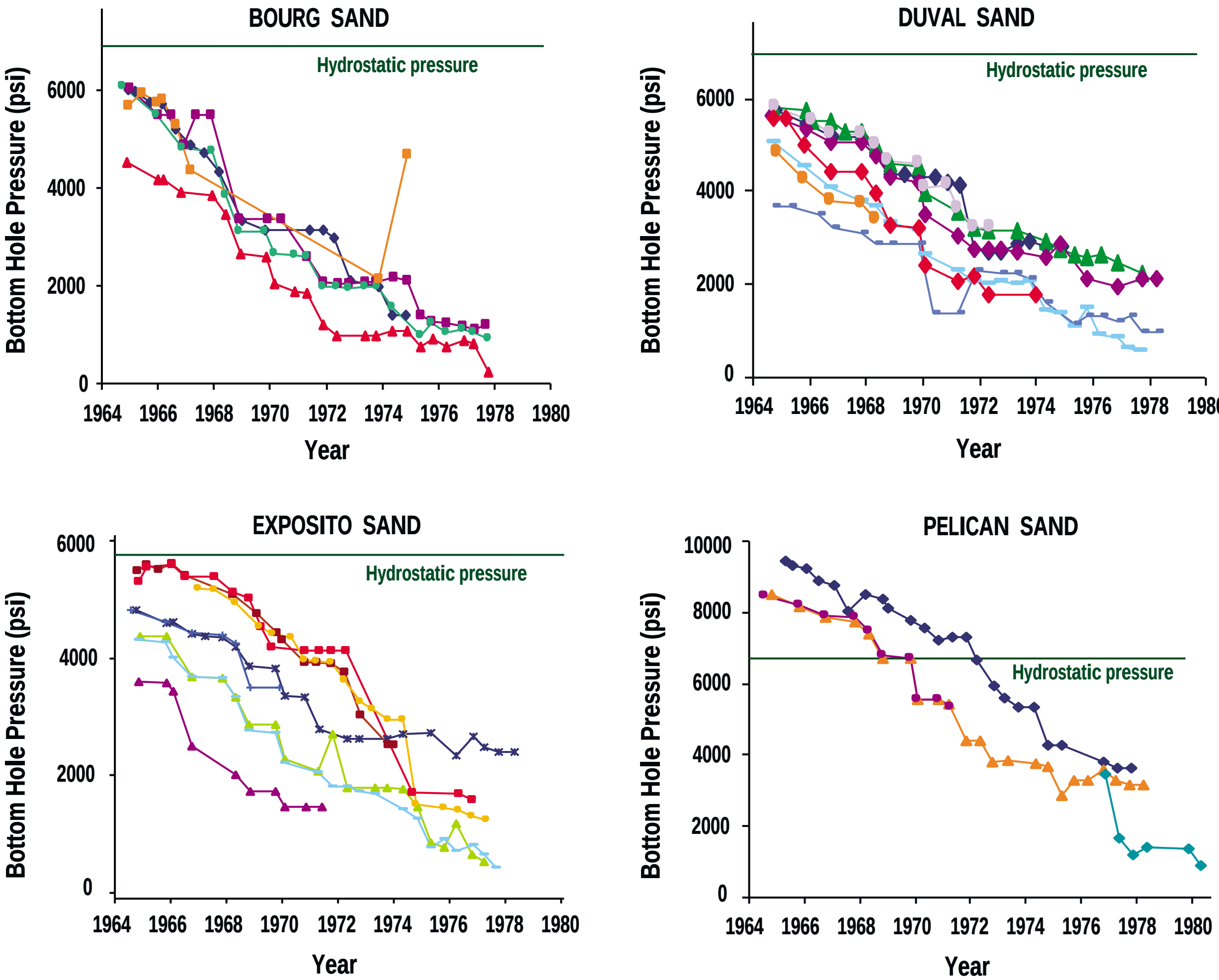

Figure 7. Pressure histories of selected wells producing from the Bourg, Exposito, Duval, and Pelican reservoirs in the Lapeyrouse field, Terrebonne Parish, Louisiana. Data are from the Louisiana Department of Natural Resources.

median is between 0.15 and 0.2 psi/ft (Fig. 8). A map of highest pressure-gradient reductions delineates a northwest-southeast trend (Fig. 9) that coincides with the crest of the anticline structure. The anticline, which is the reservoir trap, formed by rollover on the downthrown side of a large growth fault that is part of the Golden Meadow fault zone (Fig. 2). Although it is unlikely that extremely low post-production pore pressure gradients could be sustained indefinitely, the large differences in pressure gradients at depth might cause master faults that were critically stressed to pass the threshold of failure and begin to move.

The Lirette field (Fig. 2) is another large gas charged area close to the Lapeyrouse field that produces from the same stratigraphic intervals as the Lapeyrouse field, but is on the upthrown side of the Golden Meadow fault zone. Discovery of the Lirette field in 1937 was aided by the surficial expression of gas seeps (Troutman, 1956). The seeps indicate that before commercial development began, fluids were migrating vertically along deep fault planes that intersect the subsurface gas reservoirs. The Lirette field produces gas from Miocene reservoirs at depths ranging from 5,500 to 12,000 ft (Braunstein, 1967). Early gas production was erratic, but gradually increased until the late 1960s when it increased rapidly for a few years and then declined rapidly during the 1970s (Fig. 10). Subsurface fluid production from Lirette reservoirs totals about 1.3 trillion cubic

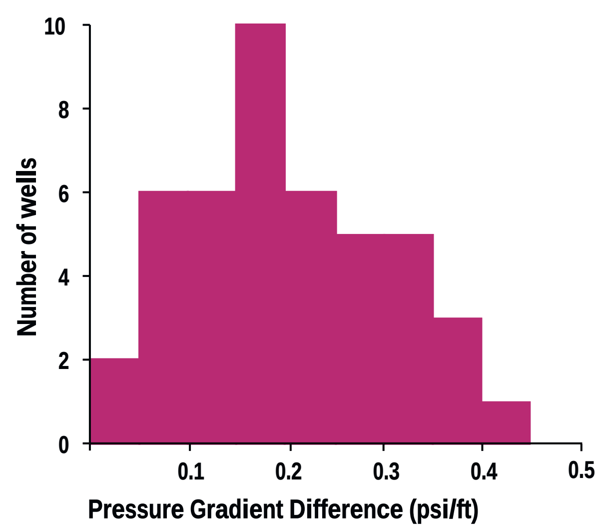

Figure 8. Distribution of pressure gradient differences between the initial pressures and final pressures reported for 44 gas wells in the Lapeyrouse field.

feet (Tcf) of gas, 18 million bbls of oil, and 59 million bbls of formation water.

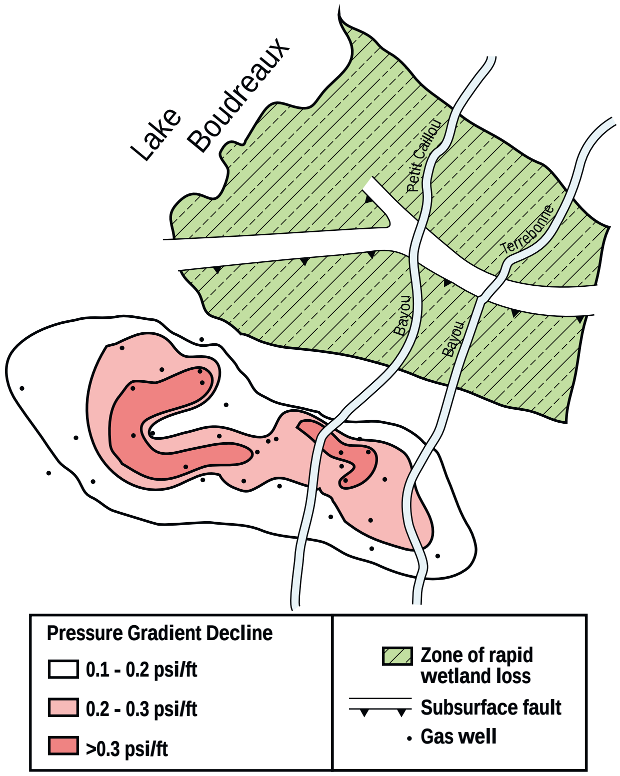

Figure 9. Locations of gas wells in the Lapeyrouse field and associated reductions in reservoir pressure gradients, subsurface trace of the major down-to-the-basin fault controlling the structure of the Lapeyrouse field (Sticker, 1979), and patterns of rapid wetland loss between 1974 and 1990 near Madison Bay (Britsch and Dunbar, 1996).

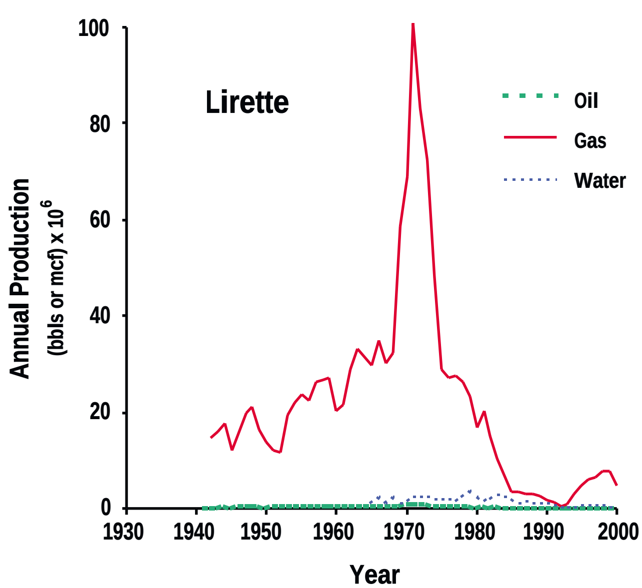

Figure 10. Annual hydrocarbon and water production from the Lirette field, Terrebonne Parish, Louisiana. Data are from the Louisiana Department of Natural Resources. Field location is shown in Figure 2.

Patterns And Rates Of Delta Plain Subsidence

Historical Subsidence Rates

Recent subsidence rates of the lower delta plain in southcentral Louisiana can be estimated directly using precise elevation differences at benchmarks calculated by the National Geodetic Survey, and indirectly using water levels recorded at tide gauges operated by the U.S. Army Corps of Engineers. Analyses of similar historical records have been presented previously (Hodahl and Morrison, 1974; Penland et al., 1988), but not in the context of deep subsurface fluid withdrawal and reservoir pressure changes that might influence those surface records. The releveling data are especially useful for evaluating recent subsidence rates because the geodetic surveys follow the natural levees of the distributary channels (Fig. 2). The levees of the delta distributaries are composed of dense sediments that have been subaerially exposed for long periods and are not subject to high rates of natural subsidence, such as might be associated with the oxidation and compaction of adjacent delta plain peats and interdistributary muds. The releveling lines also provide the densest surficial control for accurately evaluating recent subsidence rates across the delta plain.

The original leveling surveys represent benchmark elevations that are referenced to a base station. Changes in surface elevation recorded by subsequent surveys are also referenced to the base station that is assumed to be stable, but may be unstable. For example, if the base station subsided more than adjacent benchmarks, then the differences in elevation would appear to be no change at the base station and positive vertical ground movement (uplift) at the adjacent benchmarks. To avoid the appearance of anomalous uplift in a subsiding province, elevation differences were adjusted by subtracting the maximum positive difference from the remaining benchmark values. This adjustment lowers the profile the same amount as the apparent uplift, preserves the relative motions from one benchmark to another, but shifts the zero datum (no apparent change) to the benchmark that before adjustment exhibited the highest positive change. This adjustment may still incorrectly indicate stability at a benchmark that may have subsided, but the overall trend is likely to be more accurate because it provides an estimate of the subsidence at the base station. Before adjustment, both the Bayou Lafourche and Bayou Petit Caillou releveling data (Fig. 2) exhibited anomalous uplift at the benchmarks adjacent to the base stations; consequently both data sets were adjusted by - 45.97 and - 59.56 mm respectively. Each adjustment is probably a minimum that represents a more accurate portrayal of the profile considering that the delta plain is subsiding (Holdahl and

Morrison, 1974).

Bayou Lafourche Relevel Line

The most extensive releveling data along Bayou Lafourche represent elevation changes at benchmarks surveyed in 1965 and again in 1982. Adjusted magnitudes of subsidence ranged from 15 to 158 mm and averaged about 84 mm (Fig. 11). Equivalent rates of subsidence ranged from 0.9 to 9.4 mm/yr and averaged about 5 mm/yr. Zones of faster or slower subsidence closely correspond respectively to faults or producing fields, and to interfield areas. For example, benchmarks recording the highest rates of subsidence were near the Lake Hatch and Golden Meadow fault zones, or Valentine, Cutoff, Golden Meadow, and Leeville fields (Figs. 2 and 11). Compared to surrounding areas, subsidence rates were slower between the Valentine and Cutoff fields, and between the Cutoff and Golden Meadow fields (Fig. 11).

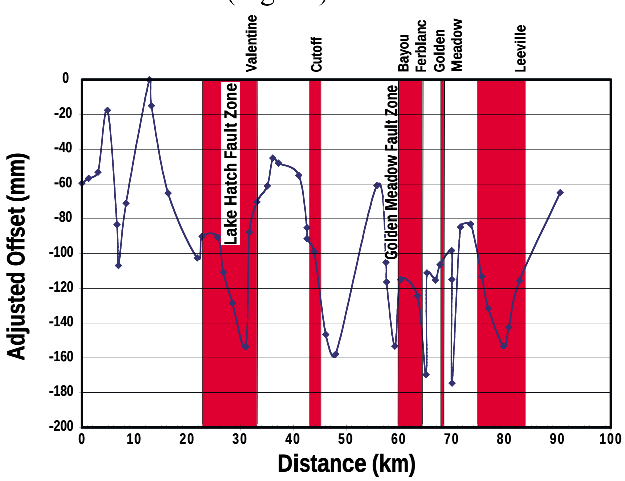

Figure 11. Relevel line along Bayou Lafourche showing adjusted offset in surface elevations between 1965 and 1982. Original data are from the National Geodetic Survey. Profile location is shown in Figure 2.

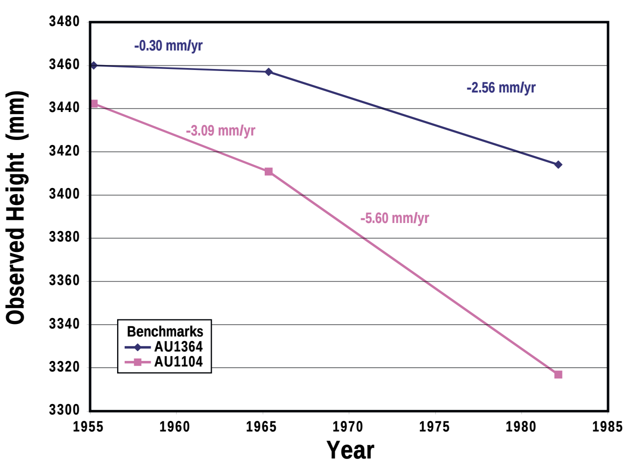

Figure 12. Magnitudes and rates of subsidence between 1955 and 1965, and between 1965 and 1982 measured at benchmarks over the Valentine field, Lafourche Parish Louisiana. Original data are from the National Geodetic Survey. Field location is shown in Figure 2.

Leveling surveys in 1955, 1965, and 1982, which included two benchmarks over the Valentine field, permit comparison of ground movement for two consecutive periods (Fig. 12). The land subsided during both periods, but the rate of subsidence accelerated substantially during the second period (1965-1982). Furthermore, the period of accelerated ground subsidence over the Valentine field coincided with the period of accelerated and maximum rates of fluid production (Fig. 3).

Bayou Petit Caillou Relevel Line

Comparison of leveling profiles along Bayou Petit Caillou illustrates variable magnitudes and rates of subsidence between 1966 and 1993 (Fig. 13). Between the Lake Hatch fault zone and the Lapeyrouse gas field, adjusted magnitudes of subsidence ranged from 41 to 254 mm and averaged about 173 mm. Equivalent rates of subsidence ranged from 1.5 to 9.4 mm/yr and averaged about 6.4 mm/yr. Some of the local subsidence variability correlates closely with the locations of faults and petroleum fields. For example, the zones of least subsidence coincided with the interfield area south of Houma/Bourg and the non-productive area south of the Lapeyrouse field (Figs. 2 and 13). Relatively high subsidence rates were associated with the Lake Hatch and Golden Meadow fault zones (Fig. 13).

Interior Tide Gauge Records

Penland et al. (1988) reported average rates of relative sea-level rise at tide gauges throughout coastal Louisiana including six interior gauges between Bayou Lafourche and Bayou Petit Caillou (Fig. 14). Except for the record at the Houma gauge (1946 to 1983), water-level records were limited to the period between 1957-69 and 1982-83. Tide gauge records for the 1960s-1980s period document

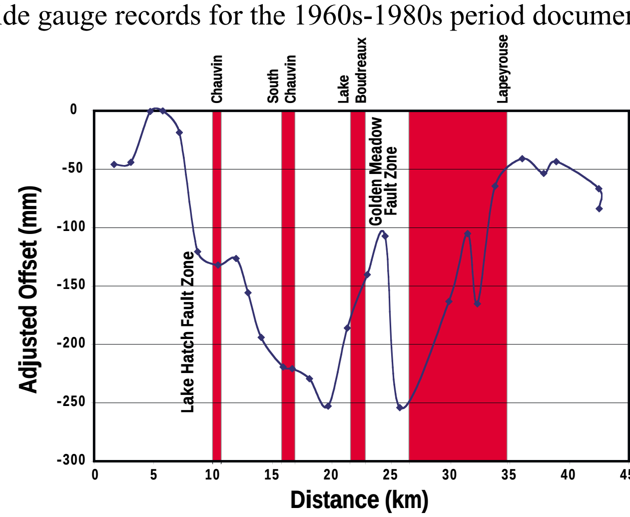

Figure 13. Relevel line along Bayou Petit Caillou showing adjusted offset in surface elevations between 1966 and 1993. Original data are from the National Geodetic Survey. Profile location is shown in Figure 2.

a general seaward decrease in submergence rates (Fig. 14); highest submergence rates (23.3 mm/yr) were recorded at the Golden Meadow gauge. This general trend is adequate for a first approximation of delta plain subsidence, but it does not provide the same level of detail as the releveling profiles (Figs. 11 and 13).

Penland et al. (1988) reported that average rates of relative sea-level rise at the Houma gauge increased rapidly from 0.7 mm/yr (1946-1962) to 19.4 mm/yr (1962-1982). Inspection of the actual water level record at Houma (Penland et al., 1988) shows relative sea-level stability before 1960, and rapid submergence of the delta plain between the mid 1960s and the mid 1970s. The Houma gauge is within the limits of fluid extraction from the Houma field (Fig. 2), and the delta plain submergence recorded by the gauge correlates well with the hydrocarbon production history. The pre-1960 period of relative sea-level stability corresponds to a stage of low initial production (Fig. 5), whereas the period of rapid relative sea-level rise (subsidence) corresponds to a stage of accelerated production.

Geological Subsidence Rates

Roberts et al. (1994) reported subsidence rates in the Terrebonne region spanning periods from a few hundred to several thousand years. The geological rates of subsidence, estimated from burial depths and radiocarbon ages

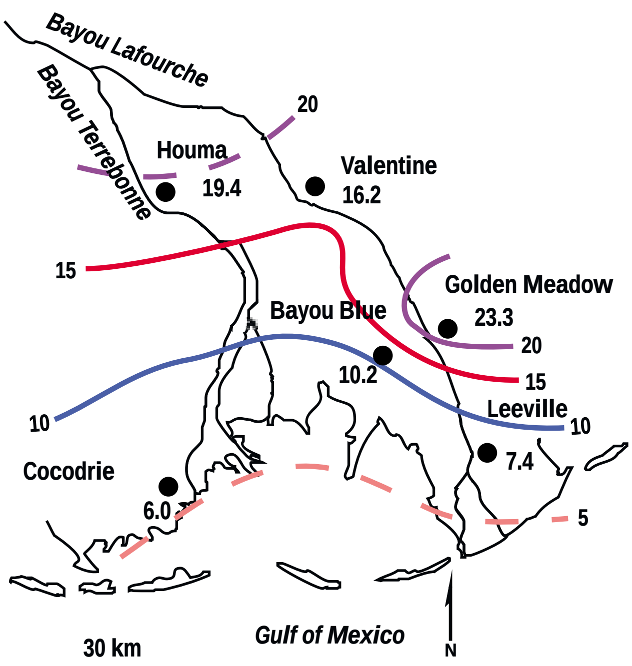

Figure 14. Historical rates of delta plain submergence recorded at interior tide gauges operated by the U.S. Army Corps of Engineers in Terrebonne and Lafourche Parishes. Rates of submergence (mm/yr) are from Penland et al. (1988).

of peats within two deep borings (P-1-90, P-2-91), were independently consistent; which tends to validate their scientific accuracy. Average subsidence rates were 4.0 and 4.3 mm/yr respectively during the past 10 to 15 thousand years, whereas they averaged 2.7 and 2.8 mm/yr respectively during the past 5,000 yrs. Higher rates of subsidence for the older period undoubtedly reflect the combination of delta-plain subsidence and eustatic sea-level rise that occurred before sea level became relatively stable about 5,000 yrs ago. The calculated rates of subsidence for the past 5,000 yrs (< 3 mm/yr) were used to avoid confusing the eustatic signal with actual subsidence.

Comparison of Subsidence Rates

The ages of buried peats, elevation differences from releveling surveys, and water level records in southcentral Louisiana yield three different rates of delta plain subsidence. The geological rates of subsidence are less than 3 mm/yr, whereas the historical subsidence rates are as much as 9 mm/yr or 23 mm/yr, depending on whether the rates are derived from releveling surveys or tide gauge records. Average adjusted rates of subsidence computed for the Cocodrie relevel line are generally lower than those computed for the Leeville line. The apparent differences in subsidence velocities are probably an artifact of the time elapsed between surveys. The longer 27-year period of the Cocodrie profile, compared to 17-year period for the Leeville profile, would explain the slower subsidence rates especially if the true rates of subsidence decreased during the longer period.

Patterns Of Historical Wetland Loss

Regional Patterns

Interior wetland losses in the Barataria-Terrebonne region are concentrated in a shore parallel zone (Fig. 2) that roughly corresponds to the transition from saltwater to brackish water marshes (Britsch and Dunbar, 1996; Penland et al., 2000). This general east-west trend is interrupted by narrow, roughly north-south bands of no wetland loss that coincide with higher elevations along the natural levees of both major and minor distributaries. Higher delta-plain elevations inland (north) of the wetland-loss zone have minimized or prevented additional wetland losses even though those areas also have subsided. Throughout coastal Louisiana, some of the interior wetland loss was caused directly by canal construction (Turner, 1997). South of the zone of interior wetland losses, saltwater marshes surrounding open water have been destroyed primarily as a result of wave and current action and attendant shoreline erosion (Penland et al, 2000). The east-west band of interior wetland loss (Fig. 2) also coincides with the zone of highest subsidence rates recorded at the releveling profiles (Figs. 11 and 13) and tide gauges (Fig. 14), and overlies the trend of prolific hydrocarbon fields producing from moderately deep Miocene sand reservoirs.

Madison Bay Hot Spot

One of the most dramatic and least understood losses of interior wetlands in southcentral Louisiana occurred near Madison Bay (Figs. 2 and 9). The history of this rapid marsh loss was chronicled for 7 consecutive periods between 1941 and 1990 (Reed, 1995), but the processes causing rapid deterioration of the wetlands were unclear (DeLaune et al., 1994) considering that only a few dredged canals crossed the deteriorating marsh (Reed, 1995). From the early 1940s to the late 1960s wetland changes were minor, whereas wetlands deteriorated rapidly between 1969 and 1978.

Several lines of converging evidence indicate that rapid subsidence and conversion of wetlands to open water near Madison Bay were caused primarily by reduction of surface elevations associated with hydrocarbon production and probable fault reactivation. The most compelling evidence is the repeated leveling surveys along Bayou Petit Caillou (Fig. 13), which show that the broad regional zone of historical wetland losses essentially coincided with the zone of maximum land surface subsidence (Fig. 2). Additional evidence of subsidence comes from aerial photographs of the region (not presented) that show that widths of the subaerial levees along Bayou Terrebonne and Bayou Petit Caillou are wider both north (upstream) and south (downstream) of where the land loss is greatest. These local differences in levee morphology indicate that post-depositional elevations are lower where the levees are narrow and land loss is high. Other evidence pointing to induced subsidence and fault movement comes from comparing decreases in reservoir pressure gradients and subsurface fault displacement and orientation in the Lapeyrouse field, with the pattern of wetland loss near Madison Bay (Fig. 9). That comparison shows that the area of rapid wetland loss coincides with the downthrown side of the major reservoir fault where the fault plane would likely intersect the surface.

Discussion And Conclusions

Wetland scientists have conducted numerous studies designed to explain historical wetland changes across the Mississippi delta plain. Many of these studies focused on biogeochemistry and plant physiology emphasizing surficial processes and the responses of wetland plants to increased flooding and eventual water logging (Nyman et al., 1993; Reed, 1995 among others), or to construction of canals and associated altered hydrology including saltwater intrusion (Turner, 1997). Many of the biogeochemical processes that have been cited frequently as causes of wetland loss in southcentral Louisiana (water logging, peat collapse, salt stress, sulfide concentrations) are probably correct, but they are also symptoms of subsidence, and they would all be initiated or accelerated by high rates of subsidence that exceed marsh sediment aggradation.

Some wetland studies recognized that subsidence was responsible for submergence and prolonged flooding, but the subsidence was attributed to processes such as compaction of Holocene deltaic sediments (Nyman et al., 1993) or cyclical deterioration of delta lobes (Wells and Coleman, 1987) that operate on geological time scales. Subsidence rates in coastal Louisiana associated with natural compaction and dewatering of Holocene deltaic sediments should decrease with time; therefore historical rates of delta plain subsidence that accelerate and typically exceed geological subsidence rates are most likely influenced by anthropogenic activities, such as subsurface fluid extraction.

Subsidence induced by subsurface fluid withdrawal has been de-emphasized in discussions of factors causing wetland loss probably because the linkages are so poorly documented. Although some studies mention oil and gas production as possibly contributing to wetland loss, most concluded that those relationships are either insignificant, or the impacts of production induced subsidence are more local than regional (Suhayda, 1987; Coleman and Roberts, 1989; Boesch et al., 1994). Prior conclusions regarding minimal impacts of deep hydrocarbon production on wetland loss were either based on no subsurface data, or the results of numerical models that did not adequately address the altered states of stress in the subsurface related to large volume fluid withdrawal.

The recent systematic decrease in rates of wetland loss across the delta plain (Fig. 15) has not been adequately explained. These trends reported by Britsch and Dunbar (1993), which were verified by Barras et al. (1994), were unexpected because previous analyses of wetland losses had shown increased rates of loss for each subsequent period (Gagliano et al., 1981; VanBeek and Meyer-Arendt, 1982). Speculation that the rates of wetland loss decreased because the total area of wetlands had diminished (Reed, 1995) was not supported by scientific evidence linking the trends to the primary causes of wetland loss summarized by Boesch et al. (1994). If induced subsidence and fault reactivation are major contributors to historical wetland

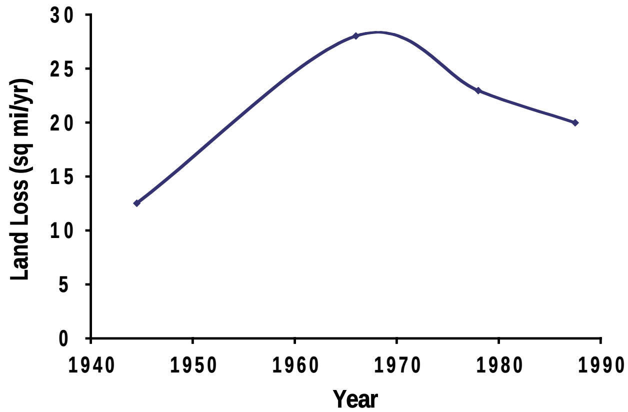

Figure 15. Historical rates of wetland loss across the delta plain of southeastern Louisiana. From Britsch and Dunbar (1993).

loss in the Barataria-Terrebonne region, then the decline in wetland loss (Fig. 15) could be related to decreased rates of subsidence associated with decreased rates of hydrocarbon production (Figs. 3, 5, 6, and 10).

Although the time series data (wetland loss, subsidence, fluid production) are not perfectly synchronized, there are temporal and spatial trends that correlate so closely that causal relationships are suggested. For example, the recent changes in elevations and water levels in the lower delta plain document an acceleration in rates of submergence followed by a period of lower submergence rates. The temporal history of coastal land loss in the delta plain follows a similar pattern (Fig. 15). A significant fact is that nearly half of the coastal land loss in Louisiana (1930-1990) occurred between 1956 and 1974 (Britsch and Dunbar, 1993).

The histories of hydrocarbon production (Figs 3, 5, 6, and 10) and pore-pressure reductions (Figs. 4 and 7) show that the highest subsidence rates corresponded to or closely followed the maximum rates of fluid extraction. Similarly, the decreased rate of wetland loss follows the decreased rates of hydrocarbon production. Direct wetland losses associated with oilfield canal construction have a history that closely parallels fluid production, but canal construction would not cause subsidence, which is the primary process underlying historical submergence and permanent inundation of the delta plain. Stress perturbations within the producing formations introduced by the rapid fluid extraction and attendant declines in pore pressures would lead to subsurface adjustments, such as reservoir compaction and probable movement along fault planes, that would translate to land surface subsidence. However, after the maximum stress perturbations are accommodated, then near equilibrium conditions would be reached and the rates of subsidence would decrease.

Evidence from this study demonstrates that the primary factor causing accelerated interior wetland loss in southcentral Louisiana between the 1950s and 1970s was accelerated subsidence and probably fault reactivation induced by rapid, large volume production of hydrocarbons (primarily gas) and formation water. Available tide gauge and hydrocarbon production data suggest that the post-1970s deceleration in rates of wetland loss across the delta plain may be related to post-1970s reductions in subsidence rates, but the land elevation data are currently inadequate to unequivocally make that conclusion. Additional releveling surveys or analysis of additional water level data will be necessary to determine if rates of induced subsidence have decreased since rates of hydrocarbon production have decreased. Knowing past and present causes and rates of subsidence in southcentral Louisiana are imperative for predicting future wetland conditions, evaluating restoration options, and managing the ecosystem and associated natural resources.

Acknowledgments

We thank Greg Ferrara for managing data layers in the Geographic Information System, Betsy Boynton for preparing the final figures, and Katherine Koepsell (NGS) for providing releveling data. Editorial comments by Virginia Burkett and Jack Kindinger improved the paper.

References

Barras, J.A., P.E. Bourgeois, and L.R. Handley, 1994, Land loss in coastal Louisiana 1956-1990: U.S. Geological Survey Open File Report 94-01, 4 p.

Boesch, D.F., M.N. Josselyn, A.J. Mehta, J.T. Morris, W.K. Nuttle, C.A. Simenstad, and D.J.P. Swift, 1994, Scientific assessment of coastal wetland loss restoration and management in Louisiana: Journal of Coastal Research Special Issue No. 20, 103 p.

Braunstein, J. (ed.), 1965, Oil and gas fields of southeast Louisiana: New Orleans Geological Society, v. 1, 195 p.

Braunstein, J. (ed.), 1967, Oil and gas fields of southeast Louisiana: New Orleans Geological Society, v. 2, 189 p.

Britsch, L.D., and J.B. Dunbar, 1993, Land-loss rates Louisiana coastal plain: Journal of Coastal Research, v. 9, p. 324-338.

Britsch, L.D., and J.B. Dunbar, 1996, Land loss in coastal Louisiana, Terrebonne Bay: U.S. Army Corps of Engineers, Technical Report GL-90-2, Map 6, 1:125,000.

Coleman, J.M., and H.H. Roberts, 1989, Deltaic coastal wetlands: Geologie en Mijnbouw, v. 68, p. 1-24.

DeLaune, R.D., J.A. Nyman, and W.H. Patrick Jr., 1994, Peat collapse, ponding, and wetland loss in a rapidly submerging coastal marsh: Journal of Coastal Research, v. 10, p. 1021-1030.

Dickinson, G., 1953, Geologic aspects of abnormal reservoir pressures in Gulf Coast Louisiana: American Association of Petroleum Geologists Bulletin, v. 37, p. 410-432.

Diegel, F.A., J.F. Karlo, D.C. Schuster, R.C. Shoup, and P.R. Tauvers, 1995, Cenozoic structural evolution and tectono-stratigraphic framework of the northern Gulf Coast continental margin, *in* M.P.A. Jackson, D.G. Roberts, and S. Snelson, eds., Salt tectonics: a global perspective: American Association of Petroleum Geologists Memoir 65, p. 109-151.

Gagliano, S.M., K.J. Meyer-Arndt, and K.M. Wicker, 1981, Land loss in the Mississippi River deltaic plain: Gulf Coast Association of Geological Societies Transactions, v. 31, p. 295-300.

Hodahl, S.R., and N.L. Morrison, 1974, Regional investigations of vertical crustal movements in the U.S., using precise relevelings and mareograph data: Tectonophysics, v. 23, p. 373-390.

Kuecher, G.J., H.H. Roberts, M.D. Thompson, and I. Matthews, 2001, Evidence for active growth faulting in the Terrebonne delta plain, south Louisiana: Implications for wetland loss and the vertical migration of petroleum: Environmental Geosciences, v. 8, p. 77-94.

Morton, R.A., N.A. Purcell, and R.L. Peterson, 2001, Field evidence of subsidence and faulting induced by hydrocarbon production in coastal southeast Texas: Gulf Coast Association of Geological Societies Transactions, v. 51, p. 239-248.

Murray, G.E., 1961, Geology of the Atlantic and Gulf Coast Province of North America: Harper and Brothers, New York, 692 p.

Nyman, J.A., R.D. DeLaune, H.H. Roberts, and W.H. Patrick Jr., 1993, Relationship between vegetation and soil formation in a rapidly submerging coastal marsh: Marine Ecology Progress Series, v.96, p. 269-279.

Penland, S., K.E. Ramsey, R.A. McBride, J.T. Mestayer, and K.A. Westphal, 1988, Relative sea-level rise and delta-lain development in the Terrebonne Parish region: Louisiana Geological Survey, Coastal Geology Technical Report No. 4, 121 p.

Penland, S., L. Wayne, L.D. Britsch, S.J. Williams, A.D. Beall, and V.C. Butterworth, 2000, Process classification of coastal land loss between 1932 and 1990 in the Mississippi River delta plain, southeastern Louisiana: U.S. Geological Survey Open File Report 00-418, map with text.

Reed, D.J. (ed.), 1995, Status and trends of hydrologic modification, reduction in sediment availability, and habitat loss/modification in the Barataria-Terrebonne estuarine system: Barataria-Terrebonne National Estuary Program Publication No. 20, 338 p.

Roberts, H.H., A. Bailey, and G.J. Kuecher, 1994, Subsidence in the Mississippi River delta – Important influences of valley filling by cyclic deposition, primary consolidation phenomena, and early diagenesis: Gulf Coast Association of Geological Societies Transactions, v. 44, p. 619-629.

Sticker, E.E., 1979, Geology and reservoir analysis of the Lapeyrouse Field, Terrebonne parish, Louisiana: unpub. MS thesis, University of New Orleans, New Orleans, Louisiana.

Suhayda, J.N., 1987, Subsidence and sea level, *in* R.E. Turner, and D.R. Cahoon, eds. Causes of Wetland Loss in the Coastal Central Gulf of Mexico: Minerals Management Service OCS Study MMS87-0120, v. II Technical Narrative, p. 187-202.

Troutman, A., 1956, The oil and gas fields of Southeast Louisiana: Five Star Oil Report, Inc., Houston, TX., 342 p.

Turner, R.E., 1997, Wetland loss in the northern Gulf of Mexico: Multiple working hypotheses: Estuaries, v. 20, p. 1-13.

VanBeek, J.L., and K.J. Meyer-Arendt, 1982, Louisiana's eroding coastline: Recommendations for protection: Louisiana Department of Natural Resources Baton Rouge, Coastal Management Division, 49 p.

Wells, J.T., and J.M. Coleman, 1987, Wetland loss and the subdelta life cycle: Estuarine, Coastal, and Shelf Science, v. 25, p. 111-125.

White, W. A., and R. A. Morton, 1997, Wetland losses related to fault movement and hydrocarbon production, southeastern Texas coast: Journal of Coastal Research, v. 13, p. 1305-1320.

Williams, S.J., S. Penland, and H.H. Roberts, 1994, Processes affecting coastal wetland loss in the Louiisiana deltaic plain: American Society of Civil Engineers Coastal Zone '93, p. 211-219.