Environ Geol (2006) 50: 261–274
DOI 10.1007/s00254-006-0207-3

ORIGINAL ARTICLE

Robert A. Morton
Julie C. Bernier
John A. Barras

Evidence of regional subsidence and associated interior wetland loss induced by hydrocarbon production, Gulf Coast region, USA

Received: 8 November 2005
Accepted: 30 January 2006
Published online: 23 March 2006

R. A. Morton (✉)
U.S. Geological Survey,
Center for Coastal and Watershed Studies,
St. Petersburg, FL 33701, USA
Tel.: +1-727-8038747
Fax: +1-727-8032032
E-mail: rmorton@usgs.gov
URL: http://www.coastal.er.usgs.gov/gc-subsidence/

J. C. Bernier
ETI Professionals, Inc.,
St. Petersburg, FL 33701, USA

J. A. Barras
U.S. Geological Survey,
National Wetlands Research Center
Coastal Restoration Field Station,
Baton Rouge, LA 70894, USA

Abstract Analysis of remote images, elevation surveys, stratigraphic cross-sections, and hydrocarbon production data demonstrates that extensive areas of wetland loss in the northern Gulf Coast region of the United States were associated with large-volume fluid production from mature petroleum fields. Interior wetland losses at many sites in coastal Louisiana and Texas are attributed largely to accelerated land subsidence and fault reactivation induced by decreased reservoir pressures as a result of rapid or prolonged extraction of gas, oil, and associated brines. Evidence that moderately-deep hydrocarbon production has induced land-surface subsidence and reactivated faults that intersect the surface include: (1) close temporal and spatial correlation of fluid production with surficial changes including rapid subsidence of wetland sediments near producing fields, (2) measurable offsets of shallow strata across the zones of wetland loss, (3) large reductions in subsurface pressures where subsidence rates are high, (4) coincidence of orientation and direction of displacement between surface fault traces and faults that bound the reservoirs, and (5) accelerated subsidence rates near producing fields compared to subsidence rates in surrounding areas or compared to geological rates of subsidence. Based on historical trends, subsidence rates in the Gulf Coast region near producing fields most likely will decrease in the future because most petroleum fields are nearly depleted. Alternatively, continued extraction of conventional energy resources as well as potential production of alternative energy resources (geopressured-geothermal fluids) in the Gulf Coast region could increase subsidence and land losses and also contribute to inundation of areas of higher elevation.

Keywords Wetland loss · Subsidence · Coastal change · Gulf Coast region

Introduction

Wetland losses in the northern Gulf Coast region of the United States are so extensive they represent critical concerns to government environmental agencies and natural resource managers (Boesch et al. 1994). Each year, millions of dollars are spent in coastal Louisiana alone to restore wetlands and to maintain the natural ecosystems that are vital to the Nation's economy (Finkl and Khalil 2005). Coastal wetland losses associated with subsidence can be manifested in two distinctly different ways (Williams et al. 1994). The primary and most extensive losses are caused by sinking of the land surface and subsequent permanent flooding that expands marine and intra-coastal water bodies at the expense of wetland resources. A secondary response is accelerated wetland erosion attributed to lower elevations and thus greater inland penetration of storm waves and overwash. Reduced elevations of coastal wetlands and storm-protection levees increase depths and durations of floods and also increase ecological damage caused by storms. A recent well-documented example of subsidence-aggravated damage was extensive wetland destruction and the flooding of New Orleans, Louisiana as a result of Hurricane Katrina in 2005.

Some areas of wetland loss in the Gulf Coast region coincide with some of the Nation's largest oil and gas fields. However, wetland loss, subsidence, and faulting induced by oil and gas production generally have been discounted because much of the wetland loss occurs in coastal Louisiana where many other factors can contribute to wetland change (Boesch et al. 1994; Williams et al. 1994) and because the complex processes, environmental diversity, and human alterations of the Mississippi delta tend to obscure the links between hydrocarbon production and wetland loss. Beyond these general observations, relatively little is known about the magnitudes and rates of wetland loss near oil and gas fields and their relationship to production histories, fluid compositions, subsurface geology, and near-surface conditions prior to hydrocarbon production.

Land subsidence caused by hydrocarbon production has been documented in many producing basins of the world (Poland and Davis 1972; Van Hasselt 1992; Chilingarian et al. 1995; Nagel 2001; Chilingar and Endres 2005). Despite the widespread recognition of this phenomenon, the potential for subsidence as a result of moderate to deep hydrocarbon production generally has been disregarded in the Gulf Coast region, or remains controversial, because prior studies have produced conflicting results. For example, some prior studies in coastal Louisiana and Texas concluded that production-induced subsidence was minor compared with natural coastal plain subsidence (Boesch et al. 1994; Gagliano et al. 2003; Dokka 2005), or compared to subsidence induced by shallow groundwater withdrawal (Holzer and Bluntzer 1984). Ratzlaff (1982) analyzed regional releveling surveys along the Texas coastal plain and concluded that subsidence was caused mostly by groundwater withdrawal with some contribution from hydrocarbon production. However, Holzer and Bluntzer (1984) examined releveling surveys that were over or close to producing fields and concluded that subsidence induced by oil and gas production was minor compared to regional subsidence of the coastal plain of Texas. Martin and Serdengecti (1984) and Suhayda (1987) came to similar conclusions for coastal Louisiana after using a one-dimensional numerical model to estimate potential magnitudes of subsidence around selected oil and gas fields. These prior studies in coastal Louisiana and Texas drew important scientific conclusions about causes of historical subsidence without examining local subsurface data specifically related to petroleum extraction, or incorporating more appropriate estimates of parameters, such as declines in reservoir pressure, that are used to run the numerical models.

The studies of induced subsidence in the Gulf Coast region demonstrated that reductions in land elevation can occur either directly above the producing formation or several kilometers away from producing wells (Gustavson and Kreitler 1976; Ewing 1985; White and Morton 1997). At some of the investigated sites, the locus of subsidence and land loss was controlled by the coupling between reservoir compaction and slip along growth faults that become active when sufficiently large volumes of fluid (oil, gas, formation water) were removed from the subsurface (Fig. 1). Fluid extraction may cause a decline in pore pressure within the rocks and alter the state of stress near the faults (Geertsma 1973). Thus, both the pattern of hydrocarbon production (reservoir geometries) and fault-plane geometries need to be considered in predicting the location and magnitude of subsidence (A. W. K. Chan, unpublished).

The purpose of this study was to determine if hydrocarbon production contributed to regional subsidence and wetland loss in the Gulf Coast region. This was accom-

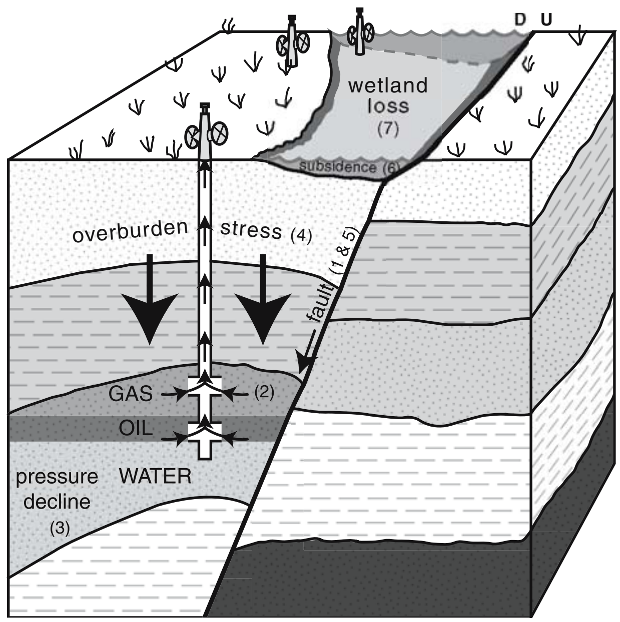


Fig. 1 Sequence of production-related subsurface events that may induce land subsidence and reactivate faults. Prolonged or rapid production of oil, gas, and formation water (2) causes formation pressures to decline (3). This increases the effective vertical stress of the overburden (4), which causes compaction of the reservoir rocks and may cause formerly active faults (1) to be reactivated (5). Either compaction of the reservoir and surrounding strata or slip along fault planes can cause land-surface subsidence (6). Where compaction or fault-related subsidence occurs in wetland areas, the wetlands typically are submerged and converted to open water (7). Figure is not to scale

plished by integrating disparate data sets including: (1) aerial photographs and satellite images depicting the areal extent and timing of wetland loss, (2) subsidence rates derived from geodetic leveling surveys, and (3) production histories of fluids extracted from the same areas where rates of wetland loss and subsidence also were available. Areas of investigation were limited to the southeastern coastal plain of Texas and the Mississippi delta plain where groundwater extraction is negligible, wetlands are extensive, and wetland losses occurred within the broad expanses of formerly continuous marshes. By focusing on interior wetland losses, those associated with shoreline erosion are eliminated or minimized. Understanding the influence of hydrocarbon production on subsidence and wetland changes is important for predicting future wetland conditions and for planning environmental activities such as coastal restoration projects.

Criteria for recognizing induced subsidence and fault reactivation

Temporal and spatial coincidence of wetland loss and hydrocarbon production

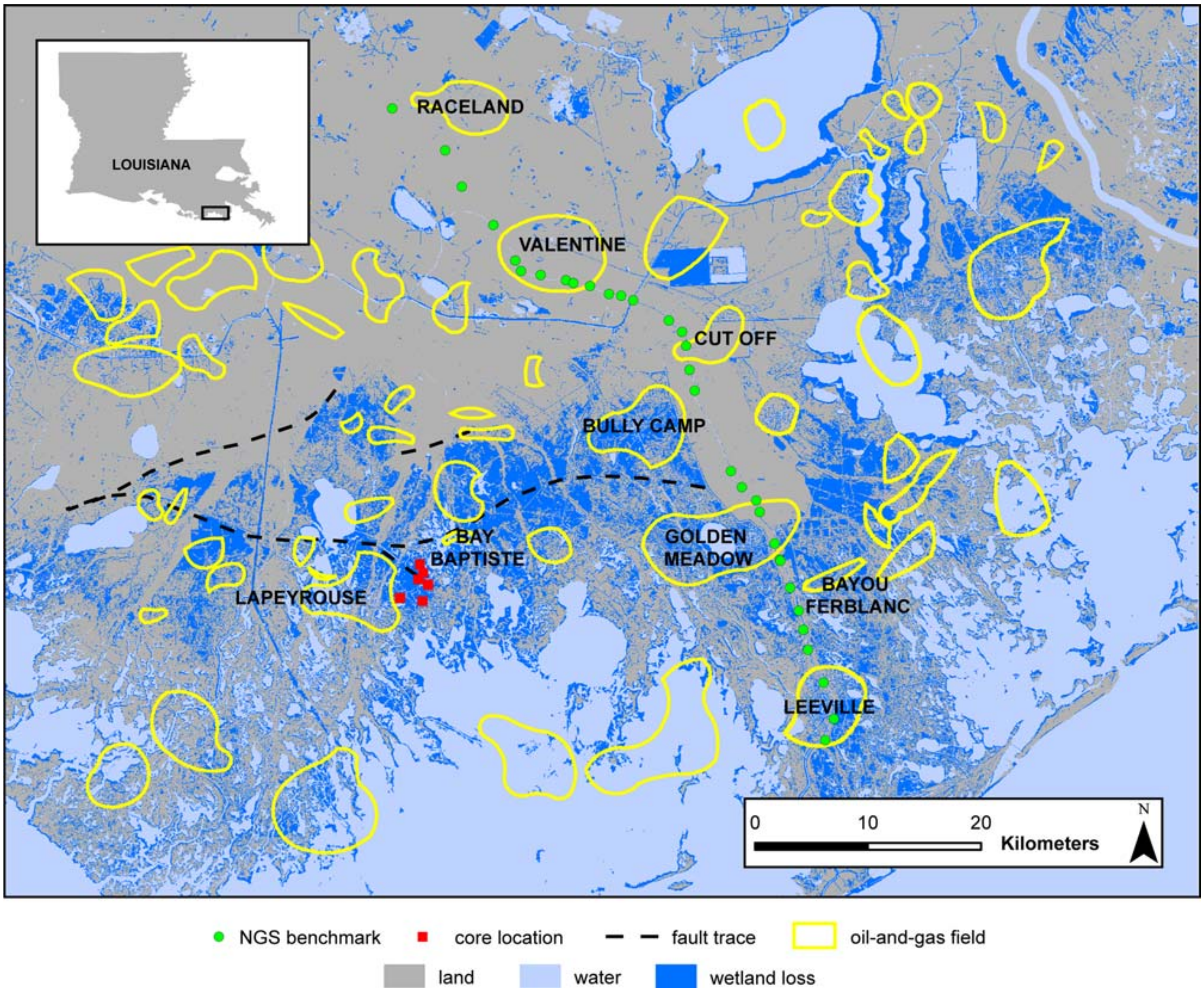


Fig. 2 Map of south Louisiana showing data sets near and along Louisiana Highway 1 between Raceland and Leeville, including locations of benchmarks along Louisiana Highway 1 (*green circles*), oil and gas fields, wetland losses, and cores from the Madison Bay study area (*red squares*). Fault projection from Kuecher et al. (2001); wetland losses from Morton et al. (2005); outlines of producing fields modified from Morton and Purcell (2001)

Wetland losses or fault reactivation typically are attributed to induced subsidence when the area and timing of wetland losses and fault movement coincide with advanced stages of hydrocarbon production. Production-induced subsidence in the Gulf Coast region was first reported in the mid 1920s at the Goose Creek field near Houston, Texas (Pratt and Johnson 1926). Subsidence at Goose Creek of about 1 m was enough to convert an upland to open water. Subsequent studies linking subsidence and hydrocarbon production in the coastal plain of southeast Texas were also limited to individual fields (Ewing 1985; Sharp and Hill 1995) or focused on only a few fields (White and Morton 1997; Morton et al. 2001).

Field-based investigations of wetland losses in the Mississippi delta focused initially on direct surficial effects of resource extraction such as excavation of drilling sites and associated access channels (Scaife et al. 1983) and indirect effects such as alterations of marsh hydrodynamics (frequency and duration of inundation), alterations in water circulation patterns, and changes in water quality (Boesch et al. 1994; Williams et al. 1994). Other studies explained wetland losses in terms of biogeochemistry and plant physiology that included saltwater intrusion, water logging, and sulfide concentration in the roots (DeLaune and Pezeshki 1994; Mendelssohn and McKee 1988). These investigations, which actually identified symptoms of subsidence and permanent inundation, did not consider subsurface geological processes that would cause subsidence. Only recently have there been analyses of subsurface data (volumes and rates of fluid production, reservoir structure, magnitudes and rates of pressure reduction) that would provide a direct basis for testing the hypothesis that hydrocarbon production has contributed significantly to regional subsidence and interior wetland loss in the Gulf Coast region (Morton et al. 2001, 2005; A. W. K. Chan, unpublished).

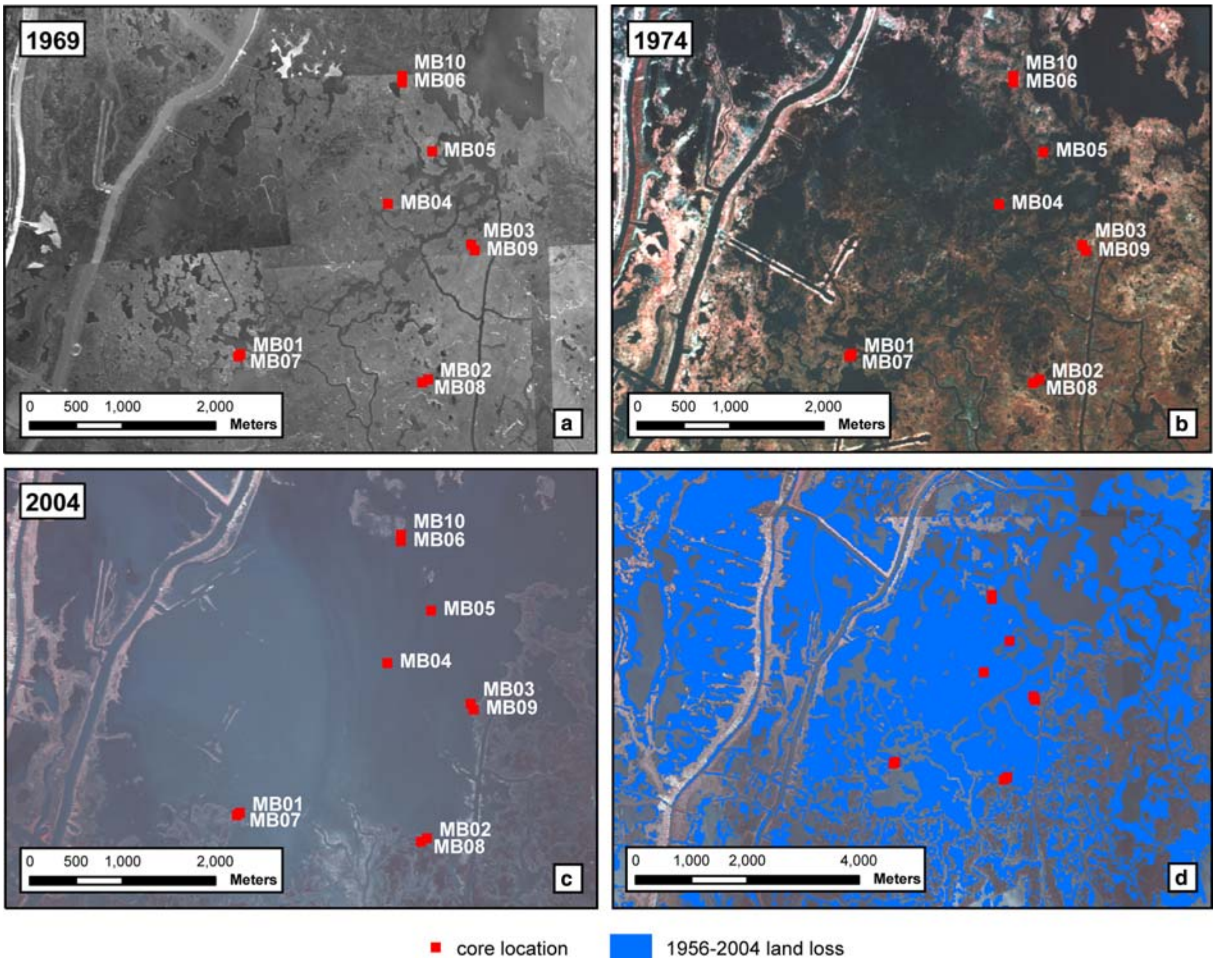


Fig. 3 Locations of sediment cores and stratigraphic cross-sections from the Madison Bay area superimposed on pre- and post-subsidence aerial photographs taken in (**a**) 1969, (**b**) 1974, and (**c**) 2004. (**d**) 1956–2004 wetland loss at Madison Bay and the surrounding area superimposed on the 2004 image. The photos show that wetlands above the field were healthy and continuous in 1969, but deteriorated and had converted mostly to open water by 1974. The rapid changes likely were caused by induced subsidence and fault reactivation resulting from hydrocarbon production. Modified from Morton et al. (2005)

Patterns of subsidence, which led to wetland replacement by open water similar to those in Texas, also were documented in south Louisiana as part of a series of sub-regional studies of subsidence and wetland loss in the Mississippi delta plain. Those studies analyzed wetland loss and fluid production histories for more than 50 oil and gas fields (Morton et al. 2002, 2005) with unpublished analyses of more than 200 fields as corroborating evidence. The opening of Madison Bay, Louisiana, near the Lapeyrouse Field, provides an example of the relative timing and typical surficial changes that occurred throughout the delta plain where wetland loss was most rapid and most extensive between 1969 and 1974 (Figs. 2, 3). As shown in Fig. 4, there was

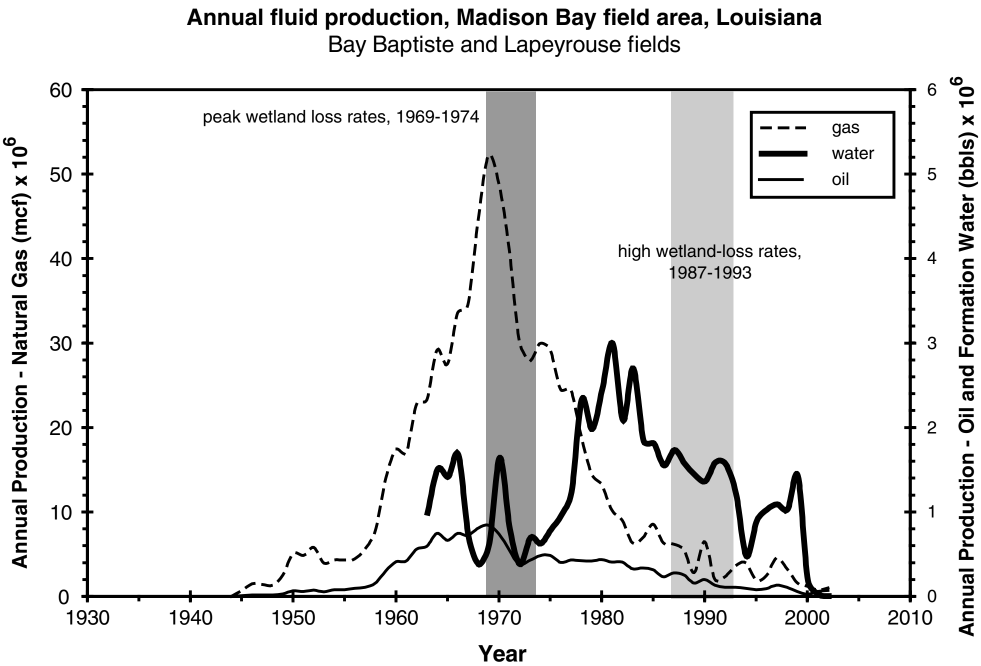


Fig. 4 Cumulative hydrocarbon production in the Lapeyrouse and Bay Baptiste Fields, Louisiana from 1944 to 2002. Compare production history with changes in wetlands observed in air photos at nearby Madison Bay (Fig. 3). Production data from the Louisiana Department of Natural Resources and the PI/Dwights PLUS database (IHS Energy 2003). Wetlands began rapidly disappearing after the field began rapidly producing large volumes of hydrocarbons in the 1960s. Wetland loss generally slowed when hydrocarbon production rates declined. Wetland loss also was rapid in the late 1980s and early 1990s following a peak period of formation water production. Modified from Morton et al. (2005)

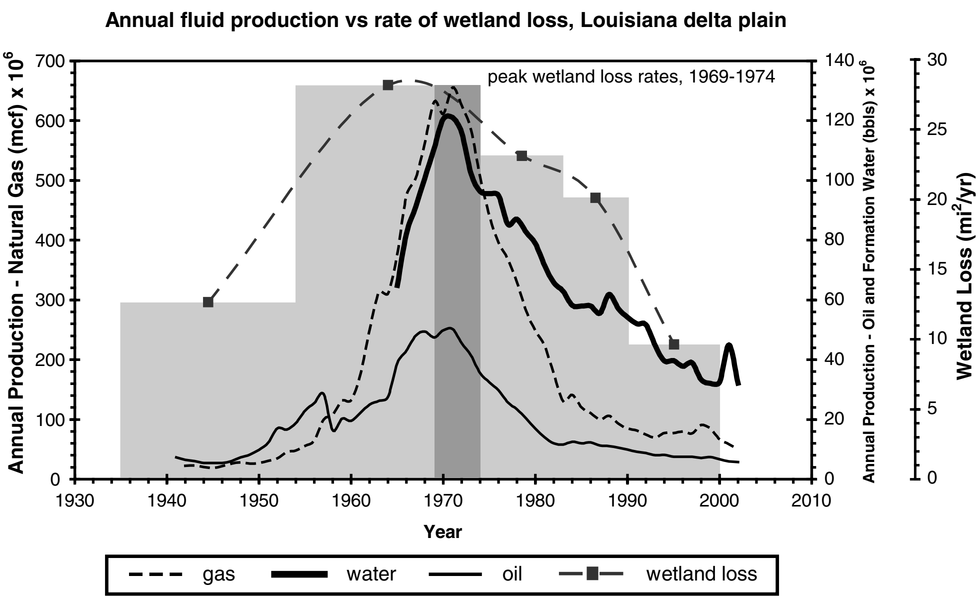


Fig. 5 Composite histories of fluid production from oil-and-gas fields and wetland loss in south Louisiana. Production data from the Louisiana Department of Natural Resources and the PI/Dwights PLUS database (IHS Energy 2003). Wetland loss values were determined by Britsch and Dunbar (1993) and John Barras (unpublished data). These historical data, integrated across the delta plain, show close temporal and spatial correlations between rates of wetland loss and rates of fluid production. From Morton et al. (2005)

a hiatus of about 25 years between the onset of production and the first visible evidence of surface disturbance and wetland loss.

Temporal and spatial correlations between wetland loss and hydrocarbon production also can be tested at a sub-regional scale by comparing the combined annual rates of fluid extraction for fields in the Mississippi delta plain with average annual rates of wetland loss for the same area (Fig. 5). Rates of wetland loss in the 1990s and early 2000s were slower than when the wetlands collapsed between the 1960s and 1980s. The deceleration in rates of wetland loss, which corresponds with the rapid decline in hydrocarbon production, could signal a reduction in the underlying rates of subsidence.

Shallow stratigraphic offsets

Correlation of shallow stratigraphic markers in adjacent sediment cores provides a basis for determining the relative magnitudes of subsidence and subsequent erosion of the wetland surface (Fig. 6). The former marsh sediments preserved beneath open water have subsided more than the adjacent subaerial marsh sediments, but the entire area including the subaerial marsh has subsided some unknown amount. Thus, subsidence estimates away from benchmark control are minimums because there are no measurements of the total amount of historical subsidence compared to some standard vertical datum. In Fig. 6, the correlated beds have been displaced downward between 50 and 65 cm compared to the adjacent marsh surface. Preservation of most of the delta plain marsh beneath about a meter of water and the timing of the greatest wetland loss (1969–1974) demonstrate that subsidence was rapid. The imagery analysis and core pairs taken near the land/water interface show that ero-

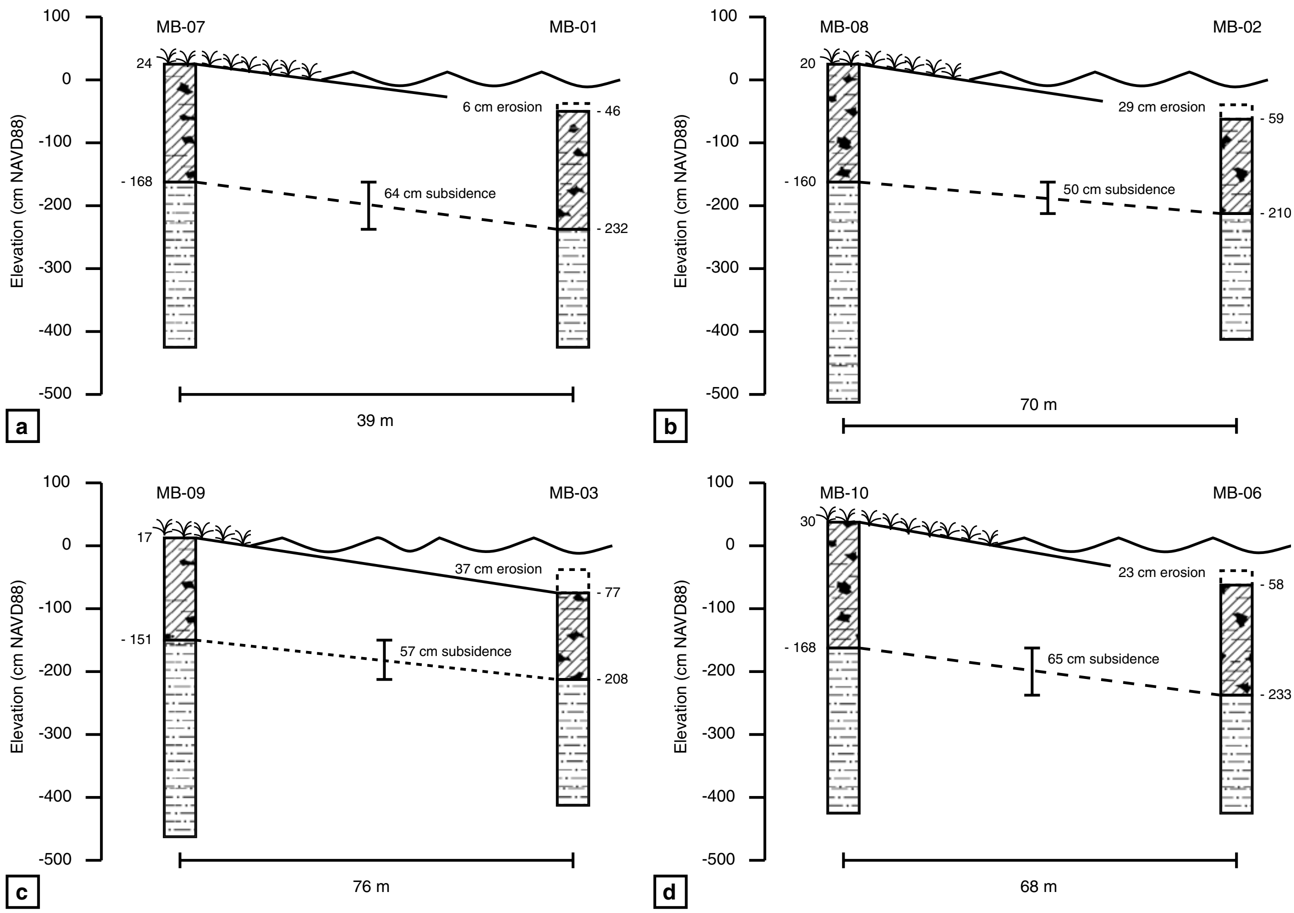


Fig. 6 Stratigraphic correlations for marsh and open water core pairs MB07-MB01 (**a**), MB08-MB02 (**b**), MB09-MB03 (**c**), and MB10-MB06 (**d**) illustrate the magnitude of subsidence and wetland erosion (in cm) at the Madison Bay wetland-loss hotspot. The upper stratigraphic unit represents the peat and organic mud facies, whereas the lower unit includes the clastic sand and mud facies. Locations shown in Fig. 3. Modified from Morton et al. (2003)

sion is only a minor process converting interior wetlands to open water, and subsidence is largely responsible for the conversion. At most of the open water sites that formerly were continuous emergent marsh, surveyed water depths were greater than the thickness of the delta plain marsh. This physical relationship is clear evidence that wetland loss resulted from subsidence because it is impossible to erode to those depths and still preserve some of the marsh deposits. Erosion of the former marsh sediments at most Madison Bay core sites ranges from 6 to 37 cm and averages about 20 cm (Fig. 6). Overall, the stratigraphic correlations indicate that subsidence is responsible for about two thirds of the differences between marsh elevations and water depths, whereas erosion is responsible for the other third. Therefore, subsidence has been twice as important as erosion in altering the landscape at Madison Bay. In other parts of the Mississippi delta plain where interior wetland loss was greatest, magnitudes of subsidence, timing of wetland loss, and correlation of those processes with hydrocarbon production were similar to those conditions recorded at Madison Bay (Morton et al. 2005).

Substantial declines in reservoir pressures

When oil, gas, and associated formation water are extracted from the subsurface, the natural pressures and pressure gradients in the formation are reduced (Poland and Davis 1972; Mes 1990; Chilingarian et al. 1995). If large volumes of fluids are produced faster than the rate of recharge, then the decreases in formation pressure at depth (Fig. 7) increase vertical effective stresses around the reservoir (Fig. 1). The increased overburden stresses cause reservoir compaction, which can be transmitted through the overburden to the surface as subsidence (Geertsma 1973).

Kreitler et al. (1990) reported large-magnitude, widespread depressurization beneath the Texas coastal plain in the 1.2–2.4 km depth range as a result of production of hydrocarbons and associated brines. Pressure gradients calculated by Kreitler et al. (1990) from bottom-hole pressure measurements in thousands of wells were substantially below expected normal hydrostatic pressure gradients within the depths of fluid production. The wide distribution of sub-hydrostatic pressures indicated that depressurization was regional and not just around the large fields.

Similar examples of regional depressurization were obtained for fields in south Louisiana by analyzing pressure histories for more than 200 wells from several fields distributed throughout the Mississippi delta plain

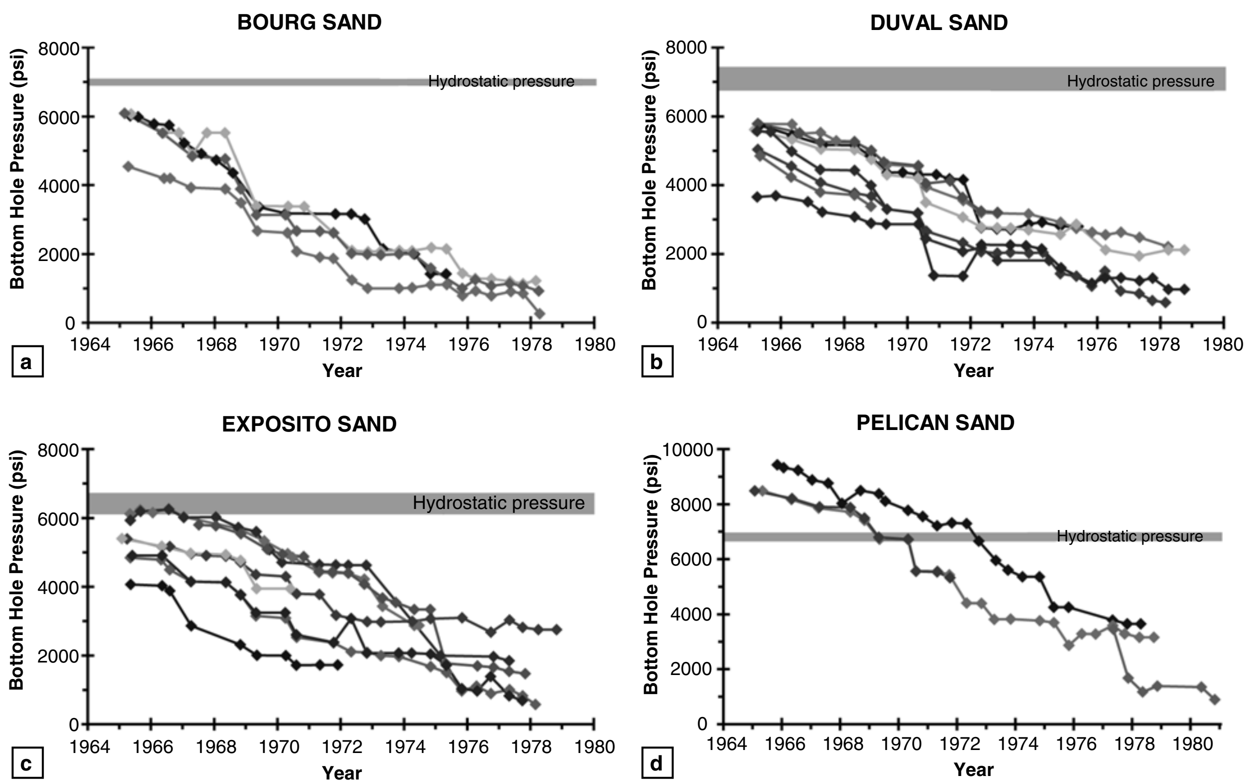


Fig. 7 Pressure histories of selected wells producing from the (**a**) Bourg, (**b**) Exposito, (**c**) Duval, and (**d**) Pelican reservoirs in the Lapeyrouse Field, Terrebonne Parish, Louisiana. Pressure data from the PI/Dwights PLUS database (IHS Energy 2003). Rapid declines in subsurface pressures like those graphed can lead to increased overburden stress, compaction of the strata, reactivation of faults, and land-surface subsidence. Modified from Morton et al. (2002)

(Morton et al. 2002 and unpublished data). Although fluid production is concentrated within and near the field areas, the impact of pressure decline extends beyond the individual fields. Where multiple fields are producing from the same strata, regional depressurization can cause subsidence and wetland losses in areas between the fields. Consequently, induced subsidence is not spatially constrained to the land surface directly above producing fields (Figs. 2, 8).

Coincident displacement of surface and deep subsurface faults

Throughout the Gulf Coast region there are many deep faults that serve as structural traps for hydrocarbons. Only a few faults of the primary fault systems extend upward to shallow depths, where they may intersect the surface (Fig. 1 and Kuecher et al. 2001; Gagliano et al. 2003). If the pressure drop in the producing formation is sufficiently large, then the subsurface state of stress is altered and faults that are near the threshold of failure may be reactivated and begin to move (A. W. K. Chan, unpublished).

Ewing (1985), White and Tremblay (1995), and Morton et al. (2001) showed how near-surface faults were reactivated around a few producing fields in Texas following a rapid acceleration in rates of hydrocarbon production. Comparison of aerial photographs to structure contour maps of the deep producing reservoirs show that the surface fault traces have the same orientation and sense of displacement as much deeper faults that are part of the structural trap for hydrocarbons (Fig. 8). However, the surface fault traces did not become apparent until production had lasted several decades and the rate of production accelerated (White and Morton 1997; Morton et al. 2001). Similar results are obtained for the Mississippi delta plain when histories of fault expression (Kuecher et al. 2001; Gagliano et al. 2003) are compared to the production histories for nearby oil and gas fields. When the fault is active, the land area on the downthrown side of the fault subsides near the fault plane (Fig. 9). Depending on the depth and angle of the fault, the induced subsidence and associated wetland loss may occur several kilometers away from the producing wells (Fig. 8) rather than directly above the producing reservoirs.

Accelerated subsidence rates

Subsidence rates for the Gulf Coast region estimated for Pleistocene and Holocene sediments provide a basis for comparing subsidence rates between geological and historical time scales. This comparison can be used to determine if historical subsidence rates are comparable to or greater than those expected from natural processes operating in the sedimentary basin. Paine (1993) used radiocarbon ages and elevations of Pleistocene strata and global sea-level data to estimate average geological (10^5 years) subsidence rates of 0.02–0.05 mm/year for the central Texas coastal plain. Similarly, Penland et al. (1988), Roberts et al. (1994), and M. A. Kulp (unpublished) all used radiocarbon ages and depths of peat deposits to estimate subsidence rates in the Mississippi delta for the past few thousand years. Analyses of Penland et al. (1988) yielded subsidence rates that ranged from 1 to 5 mm/year and averaged 2 mm/year; those of Roberts et al. (1994) yielded rates that ranged from 3 to 5 mm/year and averaged 4 mm/year. The most extensive database of

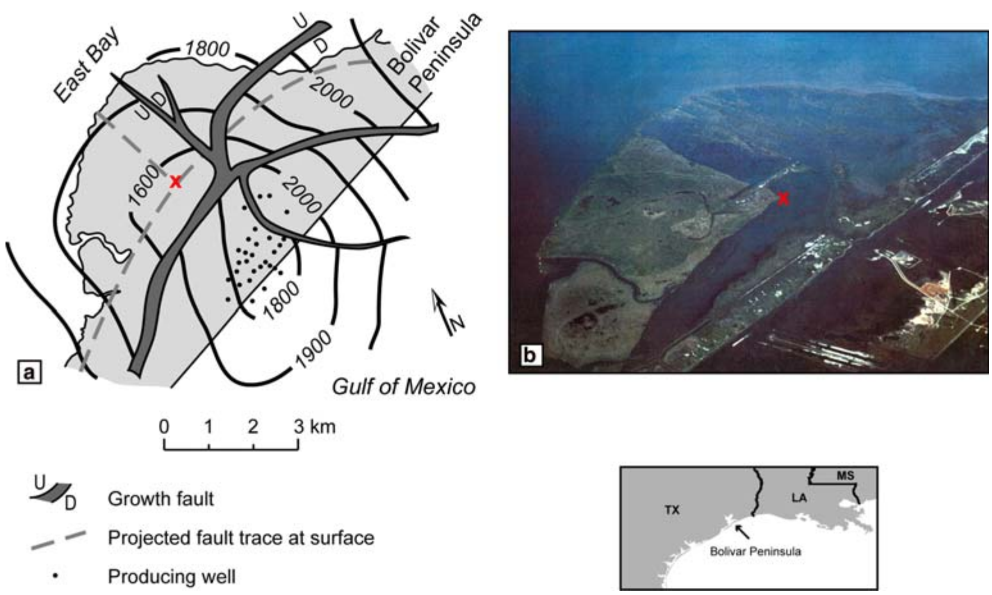
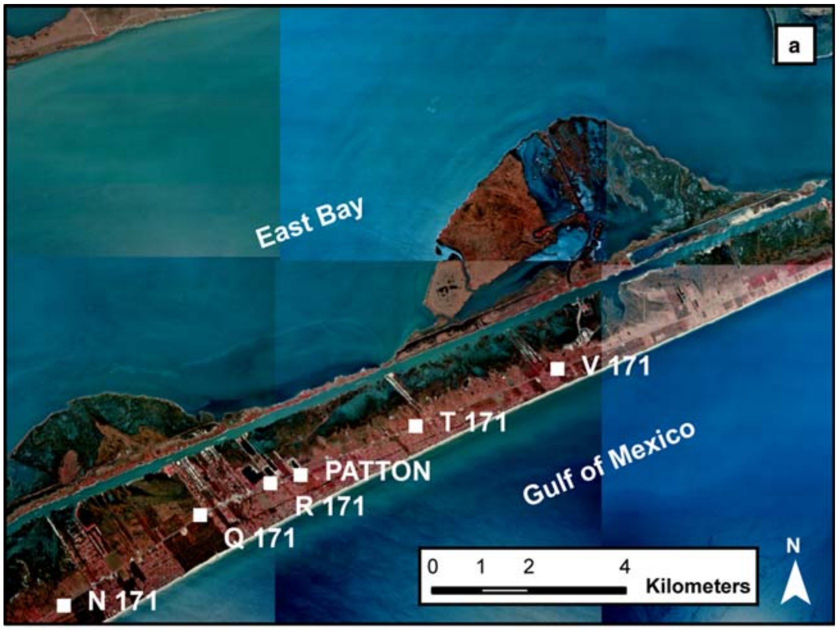


Fig. 8 (**a**) Subsurface structure at Caplen Field, Texas including fault traces at the depth of hydrocarbon production. Comparing projected fault traces at the surface with an aerial photograph (**b**) of the same area shows that recent subsidence along the faults was responsible for wetland loss. Contours in meters below sea level



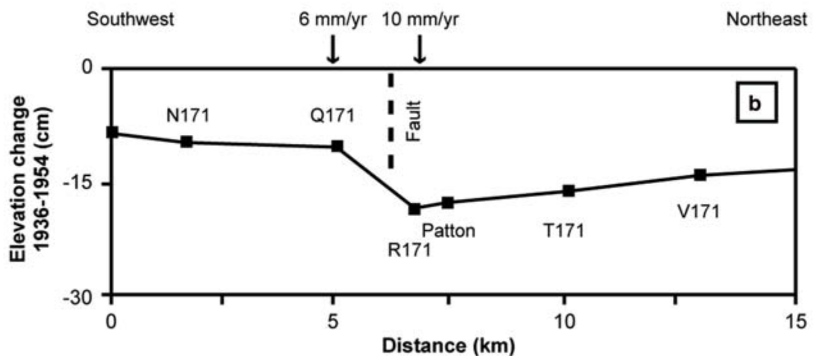


Fig. 9 (**a**) Location of benchmarks and (**b**) releveling profile along State Highway 87 that crosses a reactivated deep subsurface fault near Caplen, Texas. Compare with Fig. 8. Releveling profile from White and Morton (1997)

radiocarbon dates for the Mississippi delta (M. A. Kulp, unpublished) yielded subsidence rates that ranged from 0.1 to 8 mm/year and averaged about 1 mm/year.

As expected, regional geological subsidence rates are higher in the Louisiana coastal plain because Holocene sediments are relatively thick compared to the Texas coastal plain where Holocene sediments are thin. From a theoretical viewpoint, subsidence rates of geologically young deposits should be high initially as pore water is expelled from the sediments and the sediments compact. Following the initial rapid compaction, subsidence rates should decline exponentially. This principle was illustrated for Holocene Mississippi delta sediments by M. A. Kulp (unpublished) who plotted calculated subsidence rates for the past 6 ky. The plot showed that the trend of subsidence rates decayed exponentially with time to about 2 mm/year after about 2 ky.

Historical subsidence rates are calculated from elevation changes at benchmarks, which are periodically resurveyed by the National Geodetic Survey. Some releveling surveys in the Gulf Coast region are located along roads that cross the structural grain of the Texas coastal plain (Holzer and Bluntzer 1984; Paine 1993) and the Mississippi delta plain (Shinkle and Dokka 2004), and they also pass through or near producing fields (Figs. 2, 9, 10). Comparing data from first-order leveling surveys provides a basis for determining magnitudes and rates of subsidence for the intervening period. Analysis of leveling data from surveys in 1965, 1982, and 1993 along Louisiana Highway 1 between Raceland and Leeville (Fig. 10) shows that (1) subsidence rates were substantially higher near producing fields and faults than between the fields, and (2) subsidence rates accelerated between the first and second periods of measurement. In this sub-region subsidence rates between 1965 and 1982 ranged from 1.6 to 12.0 mm/year and averaged about 7.6 mm/year, whereas between 1982 and 1993 they ranged from 8.2 to 18.9 mm/year and averaged about 12.1 mm/year.

Another way of detecting induced subsidence around producing fields is by comparing observed recent rates of subsidence with rates established for natural subsidence

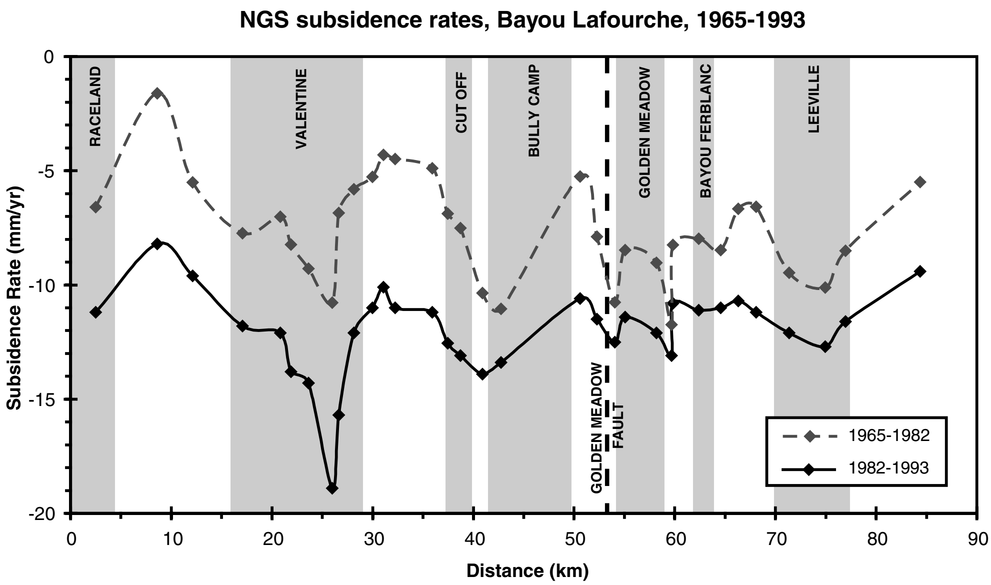


Fig. 10 Plots of historical subsidence rates along Bayou Lafourche calculated by the National Geodetic Survey from releveling of benchmarks (Shinkle and Dokka 2004). Benchmark locations shown in Fig. 2. The *plots* show a close spatial correlation between highest subsidence rates, hydrocarbon-producing fields (delineated in *gray*), and the projected intersection of the Golden Meadow fault zone. They also show that subsidence rates accelerated between 1965–1982 and 1982–1993. Modified from Morton et al. (2005)

in the same region. For example, Morton et al. (2001) estimated a minimum short-term subsidence rate for the Port Neches field in Texas during the period of maximum production. The estimated subsidence rate of 30 mm/year is three orders of magnitude higher than the geological subsidence rates for the coastal plain estimated by Paine (1993). Accelerated rates of subsidence in south Louisiana can also be demonstrated by comparing geological and historical rates. The average historical subsidence rate in the Mississippi delta of 12 mm/year (Shinkle and Dokka 2004) is roughly an order of magnitude higher than average geological rates of subsidence reported by Penland et al. (1988) and M. A. Kulp (unpublished).

Higher than expected historical subsidence rates in coastal Louisiana and Texas are occurring over older (Tertiary and Quaternary) deposits that should have already compacted. In fact, the geotechnical properties of Pleistocene and older deposits beneath the coastal plains and continental shelf of Texas and Louisiana show that they are overcompacted for their burial depths because of repeated subaerial exposure during lowstands in sea level (Fisk and McClelland 1959; Bernard et al. 1962). Because historical subsidence rates are substantially higher than geological subsidence rates in coastal Texas and Louisiana, and because historical subsidence rates in the Mississippi delta plain accelerated (Fig. 9), there must be another geophysical explanation for these trends that are inconsistent with those predicted by compaction theory alone.

Subsidence prediction

Numerical models used to predict subsidence caused by subsurface fluid withdrawal commonly are inaccurate (Van Hasselt 1992; Rhett 1998) and they tend to underestimate observed induced subsidence (Nagel 2001; A. W. K. Chan, unpublished). This is because the subsurface processes are still poorly understood and the fluid-production models typically focus only on depletion and pressure reduction in the primary reservoirs of a single field. Therefore, numerical models are not considered applicable for estimating future reductions in land elevation in the Gulf Coast region. In the absence of a reliable numerical model, qualitative and semi-quantitative predictions can be made on the basis of subsidence measurements at benchmarks without regard for the underlying mechanisms. Subsidence magnitudes and trends derived from tide-gauge measurements are less reliable than elevation surveys because water-level records contain decadal trends (Hicks 1968; Douglas et al. 2001) that reflect external forces not related to land-elevation changes.

Predicting subsidence rates for the Gulf Coast region currently is limited to inferences based on historical data, because rates since 1993 are not available and NOAA GPS Continuously Operating Recording Stations (CORS) throughout the region have not been gathering data long enough to determine extant local rates. Two approaches to subsidence prediction are possible using the historical (pre-1993) data. One is a quantitative temporal analysis of subsidence rates to determine the average rates and trend for a sub-region that are then projected into the future (Shinkle and Dokka 2004) without consideration of the underlying processes. Another method of qualitatively predicting future subsidence trends is by analogy using a case study of induced subsidence where the geological conditions and driving forces are similar to those in the area of interest. A well-known example in the Gulf Coast region is the Houston–Galveston area in Texas where subsidence and fault reactivation were induced by industrial and municipal groundwater withdrawal (Galloway et al. 1999). Induced subsidence was so severe around Houston that in 1975 the Texas legislature established a subsidence district and regulatory policies to discourage groundwater pumping and to encourage conversion to surface-water supplies. Extensometer measurements around Houston (Kasmarek et al. 1997), obtained as part of the subsidence-management program, show that where rates of groundwater withdrawal were greatly reduced, subsidence either slowed dramatically or stopped (Fig. 11, Pasadena to Texas City), but where high rates of groundwater withdrawal continued, subsidence also continued at high rates (Fig. 11, Addicks). This example of induced subsidence is applicable to the subsidence issues in south Louisiana because the Gulf Coast Basin framework geology and subsurface processes are similar, and long-term, large-volume fluid production histories are well established in both sub-regions.

The Houston–Galveston subsidence data demonstrate that when the human activities inducing subsidence slow or stop, then subsidence rates decelerate or return to the very slow background rates (few mm/year) that are caused by natural geological processes within the sedimentary basin. Given the geological similarities between coastal Louisiana and coastal Texas, significant reductions in subsidence rates are expected in the Mississippi delta because the rates of subsurface-fluid withdrawal that are largely responsible for the rapid induced subsidence have markedly declined (Fig. 5). This prediction is based on the assumption that hydrocarbon production will continue to decline rather than increase, as might occur if large, deep-gas fields are discovered.

Discussion

Whether the high rates of historical subsidence and associated interior wetland loss in the Gulf Coast region are natural or induced by fluid production is still controversial. Gagliano et al. (2003) concluded that historical subsidence and wetland losses in south Louisiana were caused naturally by sediment loading, salt evacuation, and gravity gliding. All of these processes are known to be responsible for the overall tectonic regime of the Gulf Coast Basin, but Gagliano et al. (2003) presented no evidence to substantiate their claim that the recent timing (post-1960s) and accelerated rates of subsidence in the Mississippi delta were attributable to natural salt migration and fault reactivation. They also did not consider that (1) major decreases in formation pore pressure, such as those reported by Morton et al. (2002) around hydrocarbon producing fields in south Louisiana, have the same effect as sediment loading (increased vertical effective stress), or that (2) changes in subsurface stress induced by fluid withdrawal are capable of accelerating movement of potentially active faults (A. W. K. Chan, unpublished). Gagliano et al. (2003) also argued that the 1964 Alaskan earthquake was largely responsible for the timing of fault reactivation in south Louisiana, again without presenting any scientific evidence of transitory changes in subsurface stress that

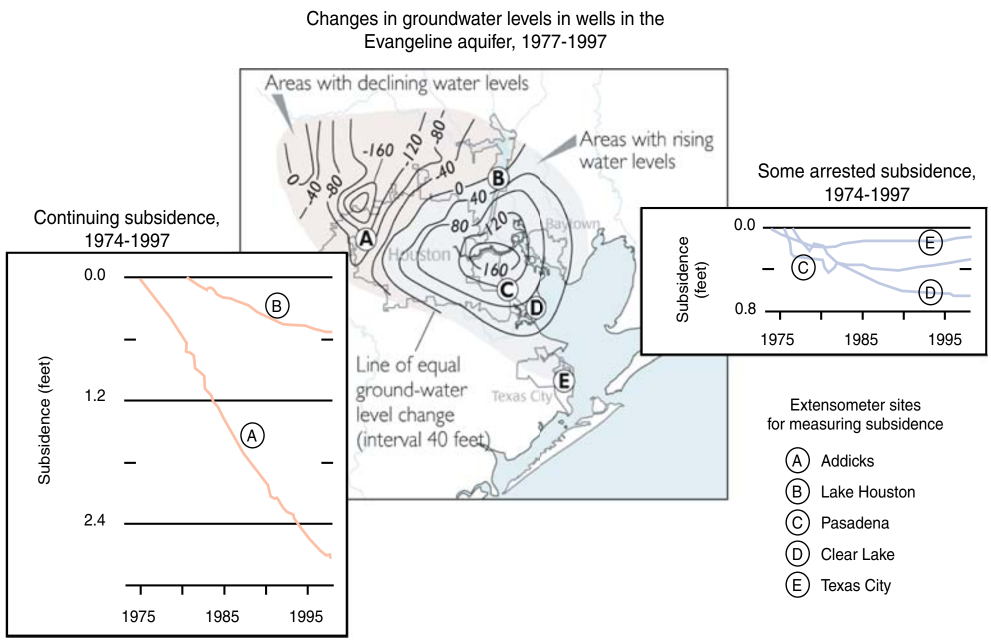


Fig. 11 Land-surface subsidence trends in the Houston–Galveston area related to groundwater withdrawal. From Kasmarek et al. (1997)

would support their speculation. The 1964 Alaskan earthquake was not felt in Louisiana, although seiches were generated in water bodies by the passing surface wave (Stevenson and McCulloh 2001). Perhaps more important is the fact that the massive interior wetland losses in the delta plain were mostly initiated more than 5 years after the 1964 Alaskan earthquake (Fig. 3 and Morton et al. 2005).

Historical subsidence rates are substantially higher than geological subsidence rates in the Gulf Coast region (Paine 1993; Morton et al. 2002, 2005). One explanation for this observation is that natural faulting and subsidence were extremely active in the 1970s and 1980s at the same time when surficial processes were being monitored and the monitoring methods were able to measure the vertical movement. Another explanation is that subsidence and/or fault activation have been accelerated by subsurface resource extraction. More than 150 quadrillion ft^3 of natural gas and nearly 20 trillion barrels of oil have been produced from the coastal fields of Texas and Louisiana since the 1920s (Morton and Purcell 2001). At least an additional 20 trillion barrels of formation water have also been produced as a common practice to prolong hydrocarbon recovery in mature fields. Historical records indicate that in most fields, substantially more formation water is produced than oil (Figs. 4, 5).

The question of natural or induced causes applied to subsidence also can be applied to the issue of fault reactivation. What natural processes would cause so many faults across the coastal plain of Texas and the Mississippi delta plain to reach the threshold of failure at the same instant in geological time? A reasonable explanation is that fault reactivation was accelerated by the large volumes of produced fluids, the consequent reductions in subsurface pressure gradients, and attendant changes in stress fields around the faults. Detailed radiocarbon dating of shallow subsurface peats in the Mississippi delta plain (Morton et al. 2005) does not show prior evidence for abrupt, regional submergence and burial of the wetlands like what is occurring today. Instead, the chronology of peat formation and submergence was related to delta-lobe switching (Penland et al. 1988; Morton et al. 2005).

Conclusions

Production-induced subsidence, fault movement, and wetland loss are indicated if the following situations co-occur: (1) large wetland areas become open water at the same time and in the same places as hydrocarbons are produced, (2) wetland sediments near producing fields subside rapidly beginning a few years to a decade after production rates accelerate, (3) the cumulative volumes of fluids produced cause large, rapid declines in subsurface pressures, (4) surface faults reactivated after initial production have the same orientation and direction of displacement as subsurface faults near the producing reservoirs, and (5) subsidence rates measured near the fields during production are substantially higher compared to those in surrounding areas or compared to geological rates of subsidence. Each condition by itself does not directly link wetland loss, subsidence, and hydrocarbon production, but together they are compelling evidence of causality.

If historically high subsidence rates in the Gulf Coast region were largely induced by fluid production, then future rates of subsidence likely will follow a similar pattern. If current production trends continue, then significant reductions in local subsidence rates are expected because the rates of subsurface-fluid withdrawal largely responsible for the rapid induced subsidence have markedly declined. Moreover, fault movement likely has already relieved the stress differential created by subsurface pressure reductions, and the state of stress has returned to near-equilibrium conditions. If this is true, then continued subsidence related to fault reactivation would not be expected because the subsurface perturbations caused by peak fluid production have passed. Alternatively, if deep gas is discovered in the Gulf Coast region and extraction of conventional energy resources continues, or if there is large-scale, long-term production of geopressured–geothermal fluids (Lombard 1985), then subsidence and land losses would likely increase unless reservoir-management techniques are implemented to control the induced subsidence.

There is a need for (1) assessing cumulative subsidence since production began in coastal areas, (2) evaluating environmental impacts of secondary hydrocarbon recovery methods, and (3) developing engineering technologies that would minimize future subsidence. These objectives can be achieved by investigating the areal extent and rates of subsidence around producing fields, correlating rates of subsidence and land losses with reservoir parameters (cumulative production, fluid composition, pressure histories), examining the influence of geologic framework and structural style on subsidence, exploring rock deformation theories for explanations of subsidence and recurrent fault movement, and developing predictive environmental impact models that can be applied to other coastal regions where high volume fluid production is anticipated.

Acknowledgements We thank Noreen Buster and Ginger Tiling for assistance in compiling some of the data and Russell Peterson and Betsy Boynton for assistance in preparing the illustrations. We also thank Tip Meckel and Jim Flocks for their critical reviews that improved the content and clarity of the paper.

References

Bernard HA, LeBlanc RJ, Major CF (1962) Recent and Pleistocene geology of southeast Texas. In: Geology of the Gulf Coast and central Texas and guidebook of excursions. Houston Geol Soc, pp 175–224

Boesch DF, Josselyn MN, Mehta AJ, Morris JT, Nuttle WK, Simenstad CA, Swift DJP (1994) Scientific assessment of coastal wetland loss restoration and management in Louisiana. J Coast Res Spec Issue 20

Britsch LD, Dunbar JB (1993) Land-loss rates Louisiana coastal plain. J Coast Res 9:324–338

Chilingar GV, Endres B (2005) Environmental hazards posed by the Los Angeles Basin urban oilfields: an historical perspective of lessons learned. Environ Geol 47:302–317

Chilingarian GV, Donaldson EC, Yen TF (1995) Subsidence due to fluid withdrawal. Developments in Petroleum Science 41, Amsterdam Elsevier Science

DeLaune RD, Pezeshki SR (1994) The influence of subsidence and saltwater intrusion on coastal marsh stability: Louisiana Gulf coast, USA. J Coast Res Spec Issue 12, pp 77–89

Dokka RK (2005) The effects of active normal faulting on the modern-day subsidence of southern Louisiana. Abstracts with Programs Geological Society of America 37, p 12

Douglas BC, Kearney MS, Leatherman SP (2001) Sea level rise; history and consequences. International Geophysics Series 75

Ewing TE (1985) Subsidence and surface faulting in the Houston–Galveston area, Texas related to deep fluid withdrawal. In: Dorfman MH, Morton RA (eds) Geopressured geothermal energy, Proceedings of the Sixth U.S. Gulf Coast Geopressured Geothermal Energy Conference. Pergamon Press, New York, pp 289–298

Finkl CW, Khalil SM (2005) Saving America's wetlands: strategies for restoration of Louisiana's coastal wetlands and barrier islands. J Coast Res Spec Issue 44

Fisk HN, McClelland B (1959) Geology of continental shelf off Louisiana: its influence on offshore foundation design. Bull Geol Soc Am 70:1369–1394

Gagliano SM, Kemp EB, Wicker K, Wiltenmuth K, Sabate RW (2003) Neotectonic framework of southeast Louisiana and applications to coastal restoration. Trans Gulf Coast Assoc Geol Soc 53:262–272

Galloway D, Jones D, Ingerbritsen SE (1999) Land subsidence in the United States. U.S. Geological Survey Circular 1182

Geertsma J (1973) Land subsidence above compacting oil and gas reservoirs. J Petrol Tech 25:734–744

Gustavson TC, Kreitler CW (1976) Geothermal resources of the Texas Gulf Coast-environmental concerns arising from the production and disposal of geothermal water. University of Texas at Austin, Bureau of Economic Geology Geological Circular 76–7

Hicks SD (1968) Long-period variations in secular sea level trends. Shore Beach 36:32–36

Holzer TL, Bluntzer RL (1984) Land subsidence near oil and gas fields, Houston, Texas. Ground Water 22:450–459

IHS Energy Group (2003) PI/Dwights Plus U.S. Production Data on CD. Available from IHS Energy Group, 15 Iverness Way East, D205, Englewood, CO 80112

Kasmarek M, Coplin LS, Santos HX (1997) Water-level altitudes 1997, water-level changes 1977–1997, and 1996–1997, and compaction 1973–1996 in the Chicot and Evangeline aquifers, Houston–Galveston region, Texas. U.S. Geological Survey Open-file Report 97–181

Kreitler CW, Akhter MS, Donnelly ACA (1990) Hydrogeologic hydrochemical characterization of Texas Frio Formation used for deep-well injection of chemical wastes. Environ Geol Water Sci 16:107–120

Kuecher GJ, Roberts HH, Thompson MD, Matthews I (2001) Evidence for active growth faulting in the Terrebonne delta plain, south Louisiana: implications for wetland loss and the vertical migration of petroleum. Environ Geosci 8:77–94

Lombard DB (1985) Geopressured geothermal brines—a resource for the future. In: Dorfman MH, Morton RA (eds) Geopressured geothermal energy, Proceedings of the Sixth U.S. Gulf Coast Geopressured Geothermal Energy Conference. Pergamon Press, New York, pp 3–7

Martin JC, Serdengecti S (1984) Subsidence over oil and gas fields. In: Holzer TL (ed) Reviews in Engineering Geology VI, pp 23–34

Mendelssohn IS, McKee KL (1988) Spartina alterniflora die-back in Louisiana: time-course investigation of soil waterlogging effects. J Ecol 76:509–521

Mes MJ (1990) Ekofisk reservoir pressure drops and seabed subsidence. In: Proceedings of 22nd Offshore Tech Conf, pp 373–387

Morton RA, Purcell NA (2001) Wetland subsidence, fault reactivation, and hydrocarbon production in the U.S. Gulf Coast region. U.S. Geological Survey Fact Sheet FS-091–01

Morton RA, Purcell NA, Peterson RL (2001) Field evidence of subsidence and faulting induced by hydrocarbon production in coastal southeast Texas. Trans Gulf Coast Assoc Geol Soc 51:239–248

Morton RA, Buster NA, Krohn MD (2002) Subsurface controls on historical subsidence rates and associated wetland loss in southcentral Louisiana. Trans Gulf Coast Assoc Geol Soc 52:767–778

Morton RA, Tiling G, Ferina NF (2003) Primary causes of wetland loss at Madison Bay, Terrebonne Parish, Louisiana. U.S. Geological Survey Open-file Report 03–60

Morton RA, Bernier JC, Barras JA, Ferina, NF (2005) Rapid subsidence and historical wetland loss in the south-central Mississippi delta plain: likely causes and future implications. U.S. Geological Survey Open-file Report 2005-1216. (http://www.pubs.usgs.gov/of/2005/1216)

Nagel NB (2001) Compaction and subsidence issues within the petroleum industry: from Wilmington to Ekofisk and beyond. Phys Chem Earth 26:3–14

Paine JG (1993) Subsidence of the Texas coast: inferences from historical and late Pleistocene sea levels. Tectonophysics 222:445–458

Penland S, Ramsey KE, McBride RA, Mestayer JT, Westphal KA (1988) Relative sea-level rise and delta-plain development in the Terrebonne Parish region. Louisiana Geological Survey Coastal Geology Tech Rept 4

Poland JF, Davis GH (1972) Land subsidence due to withdrawal of fluids. In: Man and his physical environment, Readings in environmental geology. Burgess Publ. Co., pp 77–90

Pratt WE, Johnson DW (1926) Local subsidence of the Goose Creek oil field. J Geol 34:577–590

Ratzlaff KW (1982) Land-surface subsidence in the Texas coastal region. Texas Dept of Water Resources Rept 272

Rhett DW (1998) Ekofisk revisited: a new model of Ekofisk reservoir geomechanical behavior. SPE/ISRM Eurock '98 1:367–375

Roberts HH, Bailey A, Kuecher GJ (1994) Subsidence in the Mississippi River delta—important influences of valley filling by cyclic deposition, primary consolidation phenomena, and early diagenesis. Trans Gulf Coast Assoc Geol Soc 44:619–629

Scaife WW, Turner RE, Costanza R (1983) Coastal Louisiana recent land loss and canal impacts. Environ Manage 7:433–442

Sharp JM Jr, Hill DW (1995) Land subsidence along the northeastern Texas Gulf Coast: effects of deep hydrocarbon production. Environ Geol 25:181–191

Shinkle KD, Dokka RK (2004) Rates of vertical displacement at benchmarks in the lower Mississippi Valley and the northern Gulf Coast. National Oceanic and Atmospheric Administration Tech Rept 50

Stevenson DA, McCulloh RP (2001) Earthquakes in Louisiana. Louisiana Geological Survey Public Information Series 7

Suhayda JN (1987) Subsidence and sea level. In: Turner RE, Cahoon DR (eds) Causes of Wetland Loss in the Coastal Central Gulf of Mexico, vol II Technical Narrative, Minerals Management Service OCS Study MMS87-0120, pp 187–202

Van Hasselt JP (1992) Reservoir compaction and surface subsidence resulting from oil and gas production. Geol Mijnbouw 71:107–118

White WA, Morton RA (1997) Wetland losses related to fault movement and hydrocarbon production, southeastern Texas coast. J Coast Res 13:1305–1320

White WA, Tremblay TA (1995) Submergence of wetlands as a result of human-induced subsidence and faulting along the upper Texas Gulf coast. J Coast Res 11:788–807

Williams SJ, Penland S, Roberts HH (1994) Processes affecting coastal wetland loss in the Louisiana deltaic plain. Am Soc Civil Eng Coast Zone '93, pp 211–219