Journal of Coastal Research	23	3	771–786	West Palm Beach, Florida	May 2007

The Role of Hydrocarbon Production on Land Subsidence and Fault Reactivation in the Louisiana Coastal Zone

Alvin W. Chan* **and Mark D. Zoback**

Department of Geophysics
Stanford University
Stanford, CA 94305-2215, U.S.A.
Alvin.W.Chan@Shell.com
Zoback@pangea.Stanford.edu

ABSTRACT

CHAN, A.W. and ZOBACK, M.D., 2007. The role of hydrocarbon production on land subsidence and fault reactivation in the Louisiana coastal zone. *Journal of Coastal Research,* 23(3), 771–786. West Palm Beach (Florida), ISSN 0749-0208.

We use a simple analytical model of reservoir compaction and a numerical model incorporating both reservoir compaction and fault slip to investigate surface subsidence in the area of the Lapeyrouse Field in southern Louisiana. A releveling survey shows approximately 20 m of elevation change over a 30 years time period that includes the period of extensive oil and gas production from a number of reservoirs at depth. The degree and extent of subsidence estimated from a simple analytical model of compaction predicts approximately half of the elevation change measured from the releveling surveys. Incorporating the impact of compaction-induced slip along the Golden Meadow Fault, located at the northern edge of the Lapeyrouse Field, on surface subsidence still does not account for all of the measured subsidence. Coastal wetland loss is a result of complicated process and it is difficult to isolate the impact of specific mechanisms. This study suggests that land subsidence induced by hydrocarbon production is one of several mechanisms that need to be considered when evaluating localized subsidence and wetland loss in the Louisiana coastal zone.

ADDITIONAL INDEX WORDS: *Land subsidence, fault reactivation, hydrocarbon production, reservoir compaction.*

INTRODUCTION

Coastal wetland loss is caused by complicated interactions between natural and human activities. BRITSCH and DUNBAR (1993) suggested that wetland loss should be defined as vegetated wetlands that change into (i) uplands or drained areas, (ii) nonvegetated wetlands (*e.g.,* mudflats), and (iii) submerged habitats. For coastal wetland to survive in a rapid submerging region, accumulation of both organic and inorganic soils has to keep pace (BRITSCH and DUNBAR, 1993). Extensive areas of salt, brackish, and locally fresh marshes along the coast of northern Gulf of Mexico have been converted to areas of open water and flats in the last 50 years (*e.g.,* BRITSCH and DUNBAR, 1993; PENLAND *et al.*, 2000). The LOUISIANA COASTAL WETLANDS CONSERVATION AND RESTORATION TASK FORCE AND THE WETLANDS CONSERVATION AND RESTORATION AUTHORITY (1998, referred to as COAST 2050 hereafter) reported in 1998 that 40% of the United States' coastal wetland is located in the Louisiana coastal zone; land loss in this region since the 1930s has accounted for 80% of the total coastal land loss in the United States. The loss of wetlands in Louisiana has significant social, economic, and ecological impacts. The coastal zone hosts a large portion of the nation's coastal fisheries and migratory waterfowl population; it also acts as a buffer zone for in-land human population from hurricanes and storms (*e.g.,* FARBER, 1987). With over 2 million residents living in the coastal zone (~46% of the state's population), the severe land loss projected in the next 50 years will cost Louisiana more than $37B (COAST 2050). Using color and infrared aerial photographs, BRITSCH and DUNBAR (1993) show that the 36 km^2/yr wetland loss rate in Louisiana between the 1930s to the 1950s was dominated by shoreline erosion. The statewide land loss rate increased dramatically (>100 km^2/yr) from 1960–80, the majority of the land loss during this time occurred in the interior with local "hotspots" that began as small pockets of open water and progressively expanded into large open water with small vegetated islands. The land loss rate declined back to about 65 km^2/yr in the 1990s. The peak of land loss rate in the 1970s seems to coincide with the peak oil and gas activities in the region (*e.g.,* MORTON, BUSTER, and KROHN, 2002). In this paper, we will examine the impacts of oil and gas production in southern Louisiana on land subsidence and fault reactivations in an attempt to characterize the elevation change experienced in some of the local "hotspots" in the Louisiana coastal zone.

The process of wetland loss is a combination of land subsidence, eustatic sea level rise, sediment supply, erosion, filling, and drainage (BOESCH *et al.*, 1994). However, the extent of wetland loss is not a good indicator of the severity of land

DOI: 10.2112/05-0553 received 29 September 2005; accepted in revision 27 February 2006.

* Present address: Shell International Exploration and Production, Inc., 3737 Bellaire Blvd, Houston, TX 77025, U.S.A.

This work was supported by the U.S. Geological Survey (00HQAG0223-0004) and the Stanford Rock Physics and Borehole Geophysics Project.

subsidence due to the complicated interactions between natural and human activities in both the surface and the subsurface. There are several mechanisms involved in coastal Louisiana that can lead to the submergence of wetlands:

(1) Ongoing consolidation of Holocene sediments of the Mississippi River Delta. This mechanism results in a spatially variable but temporally constant subsidence pattern (*e.g.,* SUHAYDA *et al.*, 1993). In other words, if the sediment consolidation rate is consistence, the amount of land subsidence in the delta will be primarily controlled by the spatial distribution of Holocene sediments. Similar studies on compaction of deltaic sands and shales in other parts of the world, such as the coastal area of the Netherlands, suggest that Holocene sediment compaction may have a first order effect on land subsidence (KOOI, 1997, 2000; KOOI and DE VRIES, 1998) and contribute to a subsidence rate between 0.1 mm/yr and about 1 mm/yr (KOOI and DE VRIES, 1998);

(2) Regional subsidence as a result of lithospheric flexure response to sediment loadings (*e.g.,* SCARDINA, NUNN, and PILGER, 1981) and/or subsidence of Pleistocene and older sediments (*e.g.,* PAINE, 1993). PAINE (1993) suggests that the geological subsidence rate for Pleistocene strata along the Texas coast is consistently at 0.05 mm/yr;

(3) Relative sea-level change results in a temporally variable but spatially constant subsidence pattern across the entire coastal zone (*e.g.,* PENLAND *et al.*, 1988; PENLAND and RAMSEY, 1990; ROBERTS, BAILEY, and KUECHER, 1994; SUHAYDA, 1987). The mean global sea-level rise is estimated to be 12 mm/yr (GOMITZ *et al.*, 1982) and the relative sea-level rise in the Gulf of Mexico is about 23 mm/yr (GOMITZ *et al.*, 1982). The difference (11 mm/yr) between the global and Gulf of Mexico relative sea level rise rates can be attributed to geosyncline downwarping; compaction of Tertiary, Pleistocene, and Holocene deposits; consolidation; subsurface fluid withdrawal; and regional tectonics (PENLAND *et al.*, 1988).

(4) Natural movement on growth faults along the coast and the continental shelf of the Gulf (*e.g.,* GAGLIANO *et al.*, 2003a, 2003b). These studies proposed that the massive land loss in coastal Louisiana is a result of the episodic movement along the east–west trending growth faults along the entire coast. The slip rates are determined using tide gauges and releveling line over a span of 10 to 30 years (GAGLIANO *et al.*, 2003a). However, the long time span between releveling campaigns along with other high frequency signals (*e.g.,* eustatic sea-level changes) recorded by the tide stations, the actual timing (or frequency) of fault slip is extremely difficult to determine. Given a large uncertainties associated with the determining the frequency of slip along faults, the estimated slip rates reported can be uncertain.

(5) Hydrocarbon production-induced fault reactivation (*e.g.,* MORTON, BUSTER, and KROHN, 2002; MORTON, PURCELL, and PETERSON, 2001; MORTON, TILING, and FERINA, 2003; WHITE and MORTON, 1997) and reservoir compaction (*e.g.,* SHARP and HILL, 1995). Studies in other parts of the world have demonstrated that reservoir compaction can have a significant impact on surface subsidence. For instance, up to 10 m of subsidence was observed at Long Beach, California, over the Wilmington oilfield between 1926 to 1967 (*e.g.,* COLAZAS and STREHLE, 1995) and more than 3 m of subsidence at the Ekofisk field in the North Sea during the first 20 years of production (*e.g.,* SULAK, 1991).

While the first four mechanisms suggested a maximum land surface subsidence rate of about 3 mm/yr, the historical rate in some part of Louisiana recorded ranged from 9 mm/yr to as high as 23 mm/yr locally in the past few decades (MORTON, BUSTER, and KROHN, 2002). It is thus apparent that natural processes maybe inadequate to explain the high subsidence rates observed in some parts of coastal Louisiana. Production-induced surface subsidence as a result of reservoir compaction and fault reactivation may have some significant impact locally. The Lapeyrouse Field located in Southern Louisiana (described at length below) was chosen as study site to determine the role of hydrocarbon productions on land surface subsidence.

Human-induced land subsidence along coastal Gulf of Mexico due to subsurface fluid withdrawal was first reported along the Texas coast and has been studied extensively in some areas (*e.g.,* NEIGHBORS, 1981; PRATT and JOHNSON, 1926; SWANSON and THURLOW, 1973). The major cause of human-induced subsidence is the withdrawal of underground fluids, including water, oil, and gas. In the Houston-Galveston area, land subsidence induced by large-scale groundwater withdrawal since 1906 has been up to 3 m (GABRYSCH and COPLIN, 1990) with the "subsidence bowl" formed in the Houston area encompassing more than 10,000 km^2. The implication of elevation changes in coastal wetlands can have dramatic impact on the wetland ecosystem as REED and CAHOON (1993) suggest that a slight decrease in elevation can lead to frequent flooding that can deteriorate vegetation. Erosion due to the loss of vegetation will further accelerate the loss of wetlands in these areas. WHITE and TREMBLAY (1995) reported that wetland loss along the upper Texas coastal area including the Bolivar Peninsula in East Galveston Bay, the Neches River Valley at the head of Sabine Lake and the interfluvial area between the Sabine Lake and the Galveston bay were likely results of hydrocarbon production-induced faulting and subsidence. WHITE and TREMBLAY (1995) reported that the rate of wetland loss has declined since the 1980s due to the dramatic reduction in the rate of groundwater production-induced subsidence as a result of curtailment of groundwater pumpage after the 1970s.

Unlike coastal Texas, the link between subsurface fluid withdrawal and subsidence-induced wetland loss in coastal Louisiana is more difficult to establish because wetland loss is widespread and caused by many processes and conditions (*e.g.,* COLEMAN and ROBERTS, 1989; WILLIAMS, PENLAND, and ROBERTS, 1994). The relationship between hydrocarbon production and Louisiana coastal wetland loss is poorly understood. Only a few authors have investigated the potential impact of oil and gas production on subsidence in this region (*e.g.,* BOESCH *et al.*, 1994; COLEMAN and ROBERTS, 1989; MORTON, PURCELL, and PETERSON, 2001; SUHAYDA, 1987). Most of the authors prior to MORTON *et al.* (2001) concluded that subsidence caused by hydrocarbon production in coastal Louisiana is negligible due to the depth of the reservoirs or that the subsidence affect only the immediate area and do not affect the wetland on a regional scale. However, as MORTON, PURCELL, and PETERSON (2001) pointed out, these con-

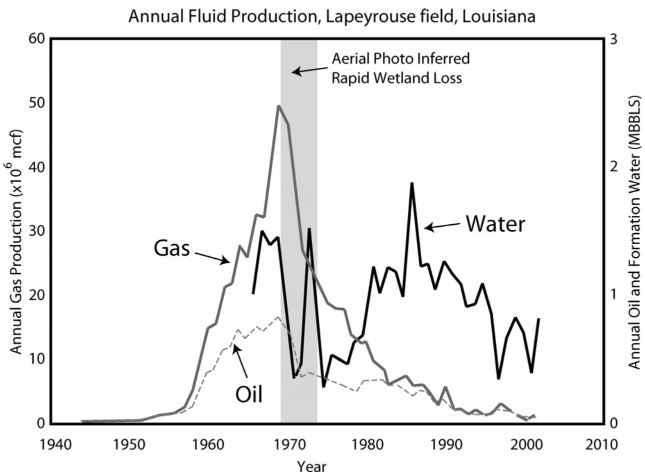

Figure 1. Cumulative annual production data for Lapeyrouse Field (after Morton *et al.*, 2002).

clusions regarding minimal impacts of hydrocarbon production were neither based on subsurface data from the producing fields nor any numerical or analytical models that incorporate the physical changes of the formations associated with depletion and the corresponding stress changes. Using core samples and releveling data, MORTON, BUSTER, and KROHN (2002) demonstrated that the changes in the historical surface subsidence rates in certain part of coastal Louisiana appear to correspond with the hydrocarbon production rates in those areas (Figure 1). The appearance of some surface fault traces after the 1970s also led them to propose the potential of fault reactivation as a contributor of surface subsidence. To investigate the validity of the proposal by MORTON, BUSTER, and KROHN (2002), we will use both analytical and numerical models to examine and demonstrate the implications of reservoir depletion on surface subsidence in the vicinity of the Lapeyrouse Field.

In situ stress and pore pressure measurements along with the constitutive laws will be analyzed in the context of a formalism termed Deformation Analysis in Reservoir Space (DARS) to estimate the change in porosity (or volumetric strain) as a result of production (see detailed discussion of DARS by CHAN, 2004; ZOBACK, CHAN, and ZINKE, 2001). Combining the estimated strains and the geometry of the reservoirs, the amount of reservoir compactions can be determined. We then use both analytical and numerical methods to analyze the impact of compaction on surface subsidence. Using an analytical method for single disc-shaped reservoirs (GEERTSMA, 1973), we estimate the magnitude of surface subsidence based solely on reservoir compaction. By addressing the problem numerically, surface subsidence is estimated based on realistic reservoir shapes along with the location and magnitude of production-induced fault slip. These results are then compared with the actual releveling data.

PRODUCTION-INDUCED LAND SURFACE SUBSIDENCE

Analytical and numerical models have been proposed since the 1970s in an attempt to relate surface subsidence with oil and gas production. Based on a simple nucleus-of-strain concept based on thermoelastic theory, GEERTSMA (1973) estimated the surface subsidence as a response to the production-induced compaction of a disc-shaped oil and gas reservoir at depth (see Appendix). VAN HASSELT (1992) studied the Groningen gas field in the Netherlands with several two-dimensional models and successfully demonstrated that the GEERTSMA (1973) solution can be used for estimating production-induced land surface subsidence. He also validated the predicted subsidence by field observations and showed that the results were comparable to those from a more complicated finite element method. GEERTSMA (1973) assumed a constant formation compressibility and linear stress-strain relationship throughout the entire half-space. However, this is not representative of weak sand reservoirs in the Gulf of Mexico that show some elastic–viscoplastic deformation during depletion (CHAN, 2004; CHAN, HAGIN, and ZOBACK, 2004).

The GEERTSMA (1973) solutions stated that the magnitude of surface subsidence, u_Z, is a function of pressure change, ΔP_P, in the reservoir, the compressibility, c_m, and Poisson's ratio, ν, of the material, such that:

$$u_z(r, 0) = -2c_m(1 - \nu)\Delta P_P H A(\rho, \eta) \quad (1)$$

where ρ and η are dimensionless parameters and can be defined as $\rho = r/R$ and $\eta = D/R$. D, H, and R are the depth, thickness, and the radius of the reservoir, respectively. The solution for A is a linear combination of the elliptic integrals of the first, second and third kind (see Appendix). To incorporate a more complicated rheology to the GEERTSMA (1973) solution, we replaced $-2c_m(1 - \nu)\Delta P_P H$ in Equation 1 with reservoir compaction, ΔH, estimated from the DARS analysis such that:

$$u_z(r, 0) = \Delta H A(\rho, \eta) \quad (2)$$

This modification allows us to use the DARS formalism to estimate the amount of compaction that may occur in each individual reservoir and translate the results to surface subsidence as a function of pressure and/or time by super-positioning the effects from all reservoirs.

Without considering the impact of background regional subsidence (which we cannot independently constraint), we examine whether such a simple analytical model can generate a local subsidence profile of the same order of magnitude as the observed elevation changes. Since the physical properties of the reservoirs are heterogeneous and cannot be fully modeled by circular discs with uniform thickness, we do not expect to capture characteristics of the observed elevation changes in fine detail.

PRODUCTION-INDUCED FAULT REACTIVIATION

Extensive studies on induced-seismicity as a result of subsurface fluid injection and withdrawal have been conducted since the 1960s (*e.g.,* BARANOVA, 1999; DAVIS, NYFFENEGGER, and FROHLICH, 1995; DOSER, BAKER, and MASON, 1991; EVANS, 1966; GRASSO, 1992; GRASSO and WITTLINGER, 1990; MCGARR, 1991; MEREU *et al.*, 1986; PENNINGTON *et al.,* 1986; RALEIGH, HEALY, and BREDEHOEFT, 1976; SEGALL,

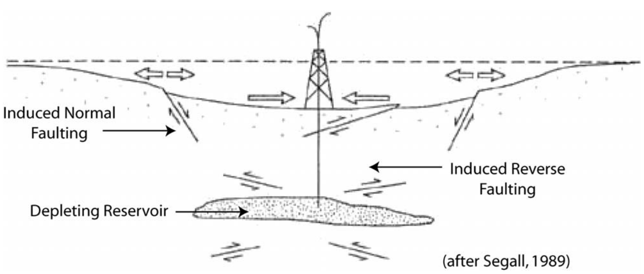

Figure 2. Schematic cross section of deformation surrounding a depleting reservoir (after Segall, 1989).

1985, 1989, 1992). Most of these studies demonstrated that the number of seismic events in the proximity of producing oil or gas field increases significantly after production or injection began. It is well documented that mechanical instability induced by fluid injection is related to the increase of pore pressure which allows slip on pre-existing faults by lowering the effective normal stress (e.g., EVANS, 1966; RALEIGH, HEALY, and BREDEHOEFT, 1976). Based on this argument, the reduction of pore pressure as a result of production should inhibit faulting. However, observations and studies of seismic events around different oil and gas fields around the world suggested that depletion will result in a change in stress around the reservoir that may encourage slip on faults outside of the reservoir (*e.g.,* BARANOVA, 1999; DAVIS, NYFFENEGGER, and FROHLICH, 1995; DOSER, BREAKER, and MASON, 1991; GRASSO and WITTLINGER, 1990; MCGARR, 1991; MEREU *et al.*, 1986; PENNINGTON *et al.,* 1986; SEGALL, 1985, 1989, 1992).

Using poroelastic theory with an assumption of an ellipsoidal reservoir embedded in an elastic medium, SEGALL (1985, 1989, 1992) calculated stress changes surrounding a hydrocarbon reservoir induced by reduction of pore pressure inside the reservoir. The stress changes can result in fault reactivation in the proximity of the reservoir (Figure 2) leading to reverse faulting above and below the reservoir while normal faulting occurring near the edge of the reservoir.

While the Segall solution analytically calculates stress changes and the potential of fault reactivation in the vicinity of the depleting reservoir, the impact of the compaction of an irregular shaped reservoir on a non-planar fault surface is best estimated using numerical modeling. Therefore, we use the Poly3D software developed by THOMAS (1993) to examine the impact of hydrocarbon production on a fault located outside of the depleting reservoir. Instead of coupling pore pressure history with surface subsidence and fault slip as in the analytical solutions, we apply compactions determined from the DARS formalism for each individual reservoir as a boundary condition. Driven by reservoir compaction, Poly3D is used to determine the location and magnitude of slip along the fault surface. We model the compacting reservoir as a planar discontinuity surface embedded in an elastic medium. With our interest mainly focused on deformation above the reservoir, we only consider the top surface of the structure and displace the surface downward uniformly to simulate compaction based on the calculated values. In other words, compaction in Poly3D is simulated by negative displacement of the planar surface along the z-axis. Assuming the fault surface is free of traction and is able to slip in any direction within the fault plane (*i.e.,* no opening or closing of the fault), the magnitude and location of slip induced by reservoir compaction can be estimated. In reality, fault surfaces may not be traction-free, it is a reasonable assumption since growth faults in the coastal area are active and constantly slipping (KUECHER *et al.*, 2001). As a result, the estimate from Poly3D represents the maximum slip that can occur on the fault plane due to reservoir deformation.

LAPEYROUSE FIELD, LOUISIANA

The Miocene-aged Lapeyrouse Field is located west of Madison Bay in the Terrebonne Parish in Southern Louisiana (Figure 3). Both geological and historical subsidence rates have been published for this region. Carbon dating of sediment cores in the Madison Bay area suggest that the Holocene sediments had an average subsidence rate of 1.4 mm/yr for the last 500 years (FRAZIER, 1967); ROBERTS, BAILEY, and KUECHNER, 1994) reported that the average rate of subsidence in the region was about 2.7 mm/yr for the last 5000 years. These results are comparable to the tide gauge measurements at Houma prior to 1962 when the measured subsidence rate averaged about 0.7 mm/yr (PENLAND *et al.*, 1988). However, the historical subsidence rate in the Madison Bay area seems to have increased significantly since 1962: PENLAND *et al.* (1988) reported 19.4 mm/yr of subsidence at the Houma tide gauge between 1962 and 1982; subsidence rates estimated from surface elevation table (SET) measurements (CAHOON, DAY, and REED, 1999) and recent sediment cores (MORTON, TILING, and FERINA, 2003) are about 23 mm/yr. Moreover, two regional leveling lines are available in this area with the Bayou Petit Calliou Relevel Line transecting the Lapeyrouse Field (MORTON, BUSTER, and KROHN, 2002). Based on the Bayou Petit Calliou relevel line, MORTON, BUSTER, and KROHN (2002) reported that the highest local subsidence rate of 9.3 mm/yr within the Madison Bay wetland loss “hotspot” coincides spatially with the nearby Lapeyrouse Field. While the cause of the different estimates of subsidence rate from the core and releveling data remain unclear, the observed subsidence at Madison Bay is significantly higher than subsidence estimated from relative sea-level change and/or natural sediment compactions in the region. MORTON, TILING, and FERINA (2003) proposed that the occurrence of the Madison Bay hotspot might be related to hydrocarbon production at the Lapeyrouse Field and the potential movement of the Golden Meadow Fault Zone located north of Madison Bay. Figure 4 shows the general locations of all the gas wells drilled within the Lapeyrouse area. The square boxes are the station locations for the 1993 Bayou Petit Calliou relevel line. MORTON, BUSTER, and KROHN (2002) observe 4–25 cm of subsidence over the Lapeyrouse Field between 1966 and 1993 (Figure 5). MORTON, BUSTER, and KROHN (2002) also suggested that the dramatic elevation change near station M might be related to movement of the Golden Meadow Fault. Note that the leveling survey pub-

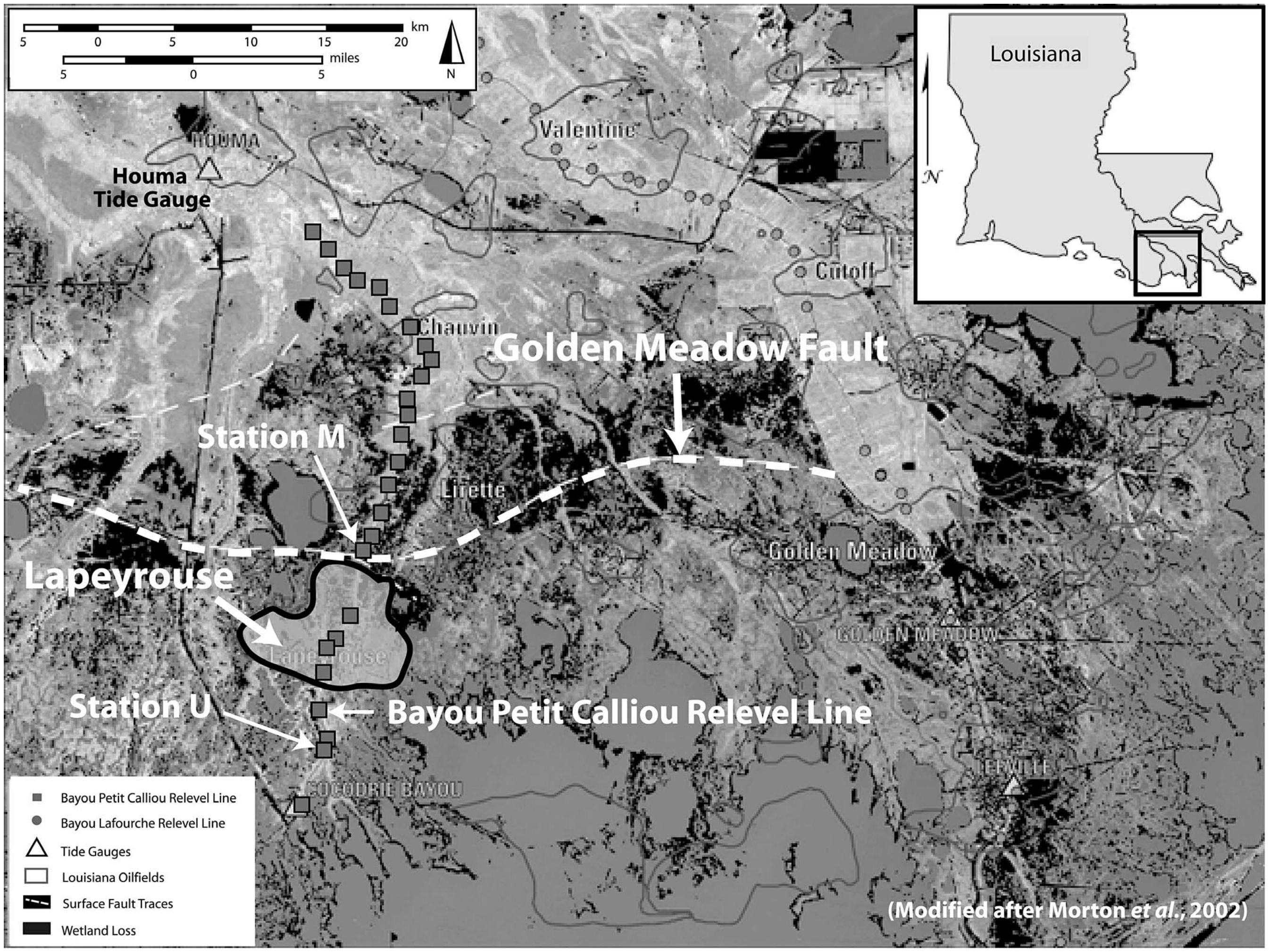

Figure 3. Regional aerial photograph of the study area (modified after Morton *et al.*, 2002).

lished by MORTON, BUSTER, and KROHN (2002) represents the relative vertical elevation changes with respect to the first bench mark of the Bayou Petit Calliou relevel line. If the first benchmark is not located in a stable region but is also subsiding, the result from this relevel survey will underestimate the actual magnitude of vertical elevation changes. Thus, background regional subsidence will not be captured in the relative elevation changes. However, since the primary focus of this study is to examine the local effect of hydrocarbon production on subsidence, the releveling data is adequate to demonstrate the relative elevation changes induced by fluid withdrawal in the subsurface. To evaluate the impact of hydrocarbon production on subsidence locally, we adjust our predicted elevation changes with respect to the southernmost station of the available releveling line, referred as Station U in this paper, used by MORTON, BUSTER, and KROHN (2002). We chose to change the reference station along Bayou Petit Calliou relevel line (MORTON, BUSTER, and KROHN, 2002) to avoid potential complications due to production north of the Lapeyrouse Field.

Production at the Lapeyrouse Field began in the 1950s and accelerated in the 1960s with a peak of production of about 1.6 million barrels per year in the 1970s (Figure 1) (MORTON, BUSTER, and KROHN, 2002). Cumulative gas production at the Lapeyrouse Field is about 624 billion cubic feet while cumulative oil production is about 18 million barrels. Four sand formations, the Exposito, Bourg, Pelican, and Duval, are examined in this study. All of these sands are primarily gas producers and the formations are generally clean, fine-grained sand with excellent initial porosity and permeability (STICKER, 1979). There is no known salt diapir near the field and most of the producing sands are stacked anticlinal structures bounded by the Golden Meadow Fault Zone in the north. We have selected this site because of the extensive gas production in the 1970s (Figure 1) that might have lead to a significant amount of subsidence in the area through reservoir compaction and its proximity to the Madison Bay hot spot. Stress changes as a result of production may also enhance the potential of fault movement in the adjacent Golden Meadow Fault Zone. The Bayou Petit Calliou Relevel Line

Figure 4. A close up aerial photograph of the Lapeyrouse Field.

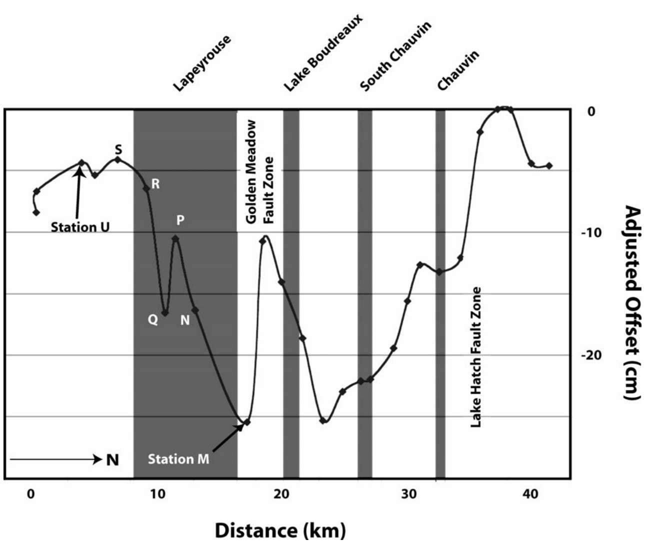

Figure 5. Relevel line along the Bayou Petit Calliou showing elevation changes between 1966 and 1993 (after Morton *et al.*, 2002).

will be used as a quantitative control on the amount of elevation change in the area (Figure 5) and will be compared to the predictions of the analytical and numerical models.

Figure 6 illustrates how we used the corrected bottom-hole pressures (BHP) for the Pelican sand to identify potential subcompartments (or flow barriers) between wells. If the wells are located within the same compartment, the pressure history should be on the same trend as pressure declined as a whole unit between the wells. However, the pore pressure reduction trends observed in Pelican sand follow three separated paths implying the existence of flow barriers between the wells. In order to determine if such compartmentalization has any relationship to the physical structure of the reservoir, we superimpose the well locations along with the structural contour map onto the aerial photographs (Figure 7). The simplified contour map in the composite diagram is modified based on a number of documented structural maps filed at the Department of Natural Resource, Louisiana, in Baton Rouge. Compartments inferred from the pore-pressure histories for the Pelican sand are indicated on the composite diagram and correspond extremely well with the fault blocks identified from the structural map: Fault Block I consists of

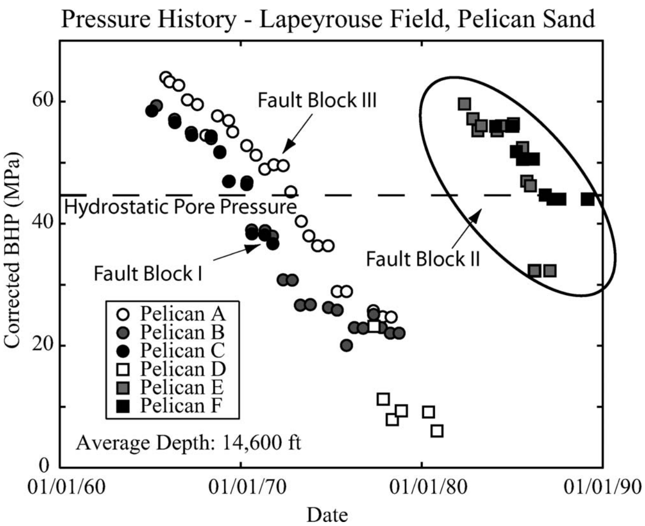

Figure 6. Pressure history plot for the Pelican sand.

wells B, C and D, wells E and F are located within fault block II and well A seems to be located in a separate fault block from the rest of the wells. As a result, these faults may have prevented fluid from migrating laterally between the blocks.

Reservoir Compaction and Land Surface Subsidence

To estimate the impact of oil and gas production in the four producing sands at Lapeyrouse on surface subsidence, it is essential to estimate the amount of reservoir compaction in the formations. However, without proper rock mechanics data, we must assume the producing sands at Lapeyrouse behave similarly to Field "X" in the Gulf of Mexico (CHAN, 2004; CHAN, HAGIN, and ZOBACK, 2004). Field "X" is a Miocene-aged sand reservoir located on the continental shelf in the Gulf of Mexico near the Louisiana coast. We make this assumption based on the age of the formation and that both are located in the same deltaic basin. Because applying laboratory data from a different field is not ideal, the predictions presented here need to be used with caution.

To understand the magnitude and extent of subsidence induced by reservoir compaction, we first use the modified Geertsma method assuming no faulting will be triggered as

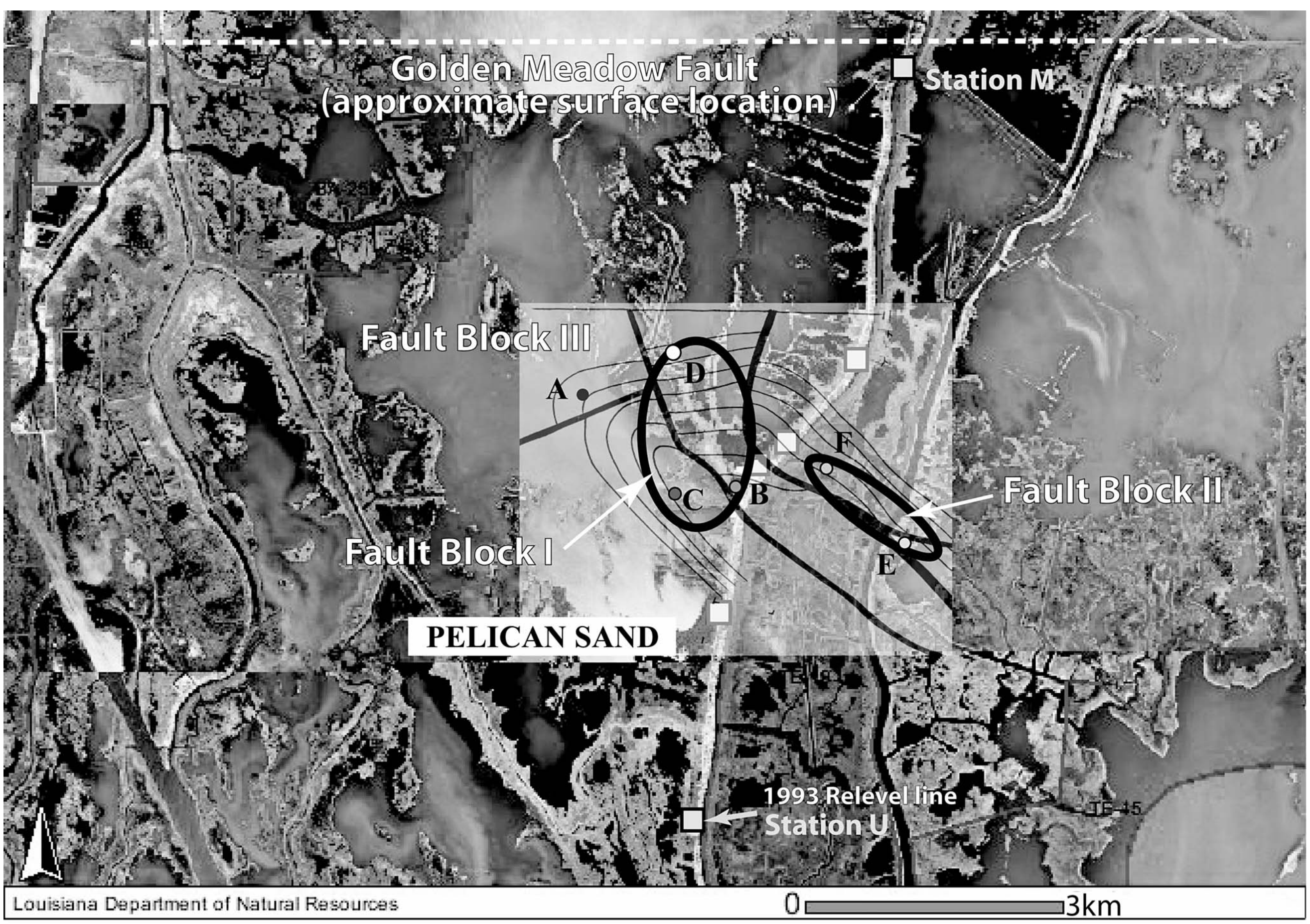

Figure 7. Composite diagram showing the structural map for Pelican Sand along with the wells overlaying the aerial photographs.

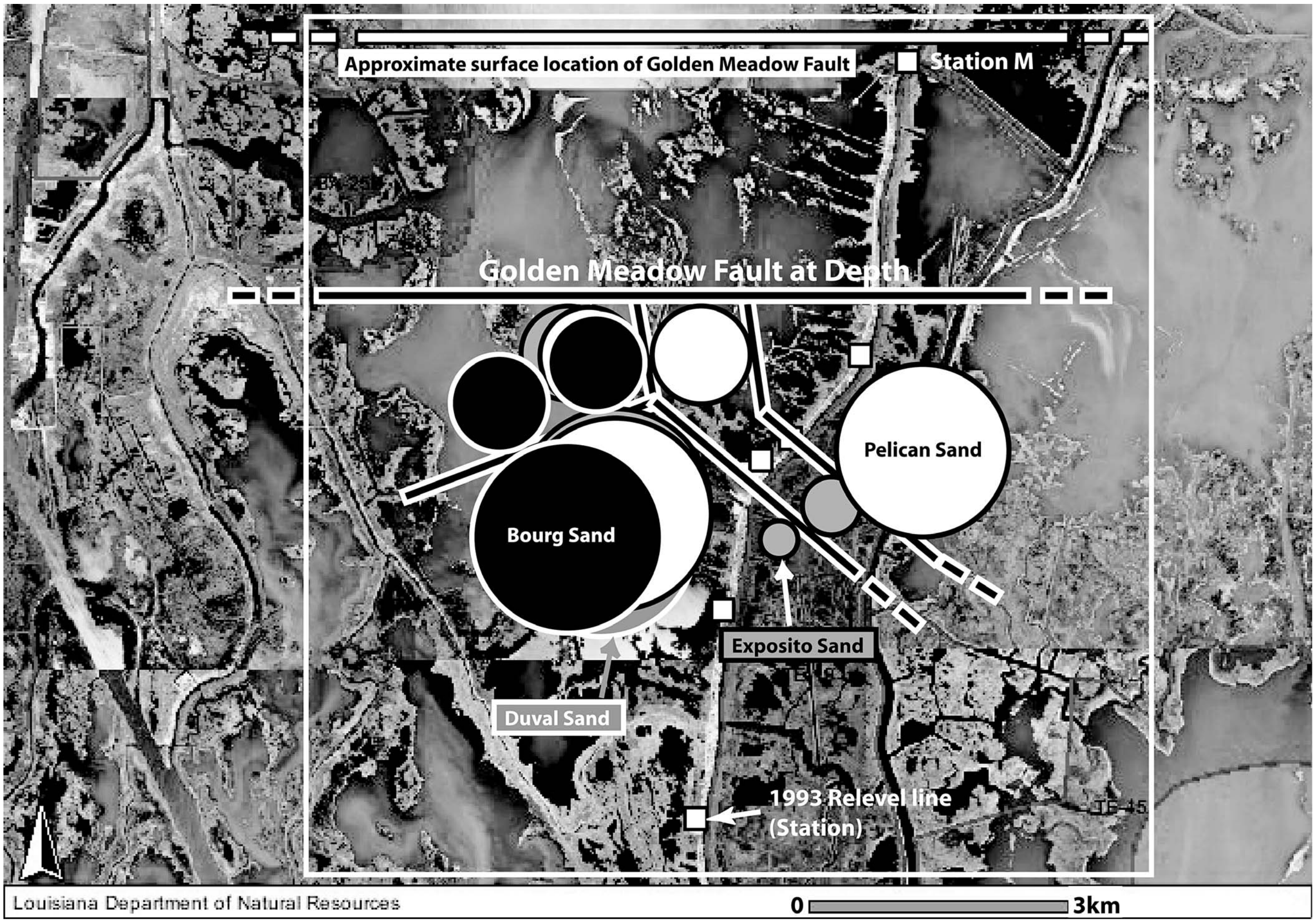

Figure 8. Map view of the circular-disc reservoirs used in the Geertsma solution for estimating the impact of reservoir compaction on surface subsidence.

a result of depletion. The existence of subcompartments in the producing sands suggests that it is possible to treat the individual fault blocks separately. Since the thickness of the reservoirs in Lapeyrouse is relatively small compare to the depth of the sands, the variation in thickness of these sands should only have minimal impact on surface deformation. As a result, we create a number of circular discs with uniform thickness at different depths to represent the individual reservoirs of interest (Figure 8). The color code represents the different formations while the size of the disc is set to encompass all the wells that are identified as in the same pressure compartment (or fault block) from the pressure history data. As all of these reservoirs are relatively thin (average thickness of 10 m) with respect to their depth (average of 4.5 km in depth), the uncertainties associated with the size of the discs created should had minimal impact on the estimated vertical elevation change locally and only a slight influence on the lateral extent of the surface subsidence bowl (see Appendix).

While stress changes as a result of depletion (also known as depletion stress path) can affect the nature of reservoir deformation and the amount of compaction induced by depletion, no such measurements are available in the Lapeyrouse Field. A general depletion stress path of 0.54 that is representative of the Gulf of Mexico offshore fields (Chan, 2004) is used for the Lapeyrouse Field. Using the estimated stress changes along with the equations derived by Zoback, Chan, and Zinke (2001), we estimated the degree of porosity loss and compaction that happens in each reservoir as a result of production from the elastic rheology derived for Field "X" by Chan, Hagin, and Zoback (2004). Substituting the amount of compaction into the modified Geertsma solution, a map of surface deformation is produced (Figure 9). By changing the degree of reservoir compaction it will change the surface subsidence predictions proportionally. Figure 9D shows that the total amount of subsidence (relative to station U) predicted over the center of the bowl (~8 cm) using an elastic compaction curve under predicts the observed subsidence of about 15 cm. Moreover, the large amount of subsidence of benchmark M (located near the Golden Meadow fault [Figures 5 and 7]) is not matched at all, and will be addressed in the context of possible depletion-induced slip below.

Figure 10 further compares the observed subsidence over the Lapeyrouse Field (heavy line) with the subsidence bowl

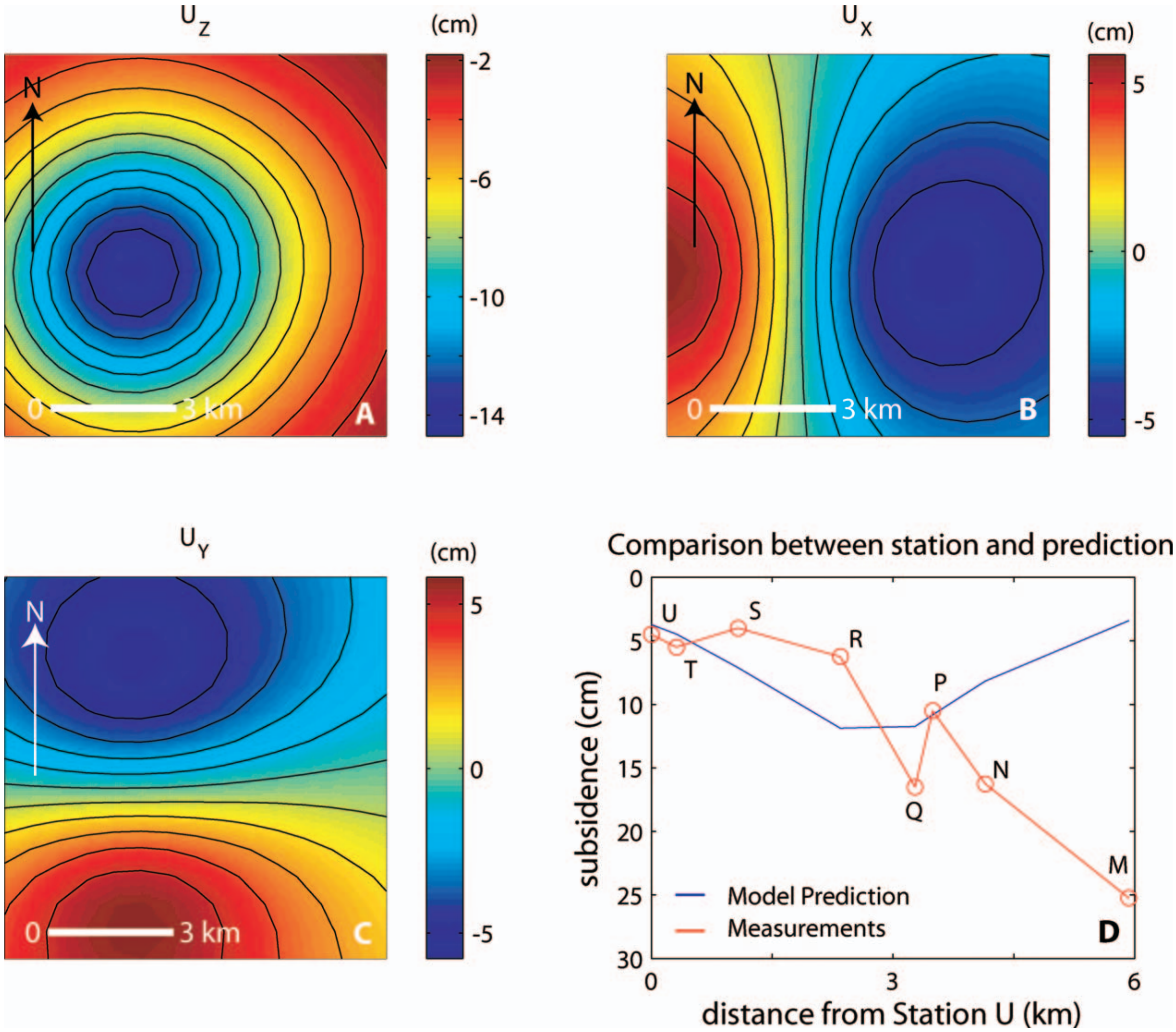

Figure 9. Results from the Geertsma solution based on an elastic-viscoplastic rheology.

predicted from the Geertsma solution shown in Figure 9D, but presents this comparison for several different constitutive laws that would result in differing amount of compaction in the various disc-shaped reservoirs shown in Figure 8. These constitutive laws were discussed at some length by CHAN (2004), CHAN, HAGIN, and ZOBACK (2004), and HAGIN and ZOBACK (2004). As shown, utilizing the generalized compaction law of YALE *et al.* (1993) under predicts the amount of subsidence in the middle of the compaction bowl even more, whereas the elastic–viscoplastic compaction law for completely uncemented sands presented by CHAN (2004) and HAGIN and ZOBACK (2004) somewhat over predicted the amount of subsidence over the reservoir.

Reservoir Compaction and the Potential of Fault Reactivation

The misfit at Station M in Figure 10 and the proximity of the survey station to the approximate location of the surface trace of the Golden Meadow Fault Zone suggest that subsidence measured at Station M may be influenced by the movement along the Golden Meadow Fault. We utilized Poly3D to numerically estimate the impact of reservoir compaction in Lapeyrouse on the Golden Meadow Fault. Utilizing a seismic study across the Lapeyrouse Field by KUECHER *et al.* (2001), the shape of all the reservoirs (modified after STICKER, 1979) and the Golden Meadow Faults were digitized for the numerical models (Figure 11). While the producing sands are anticlinal structures and some of the individual reservoir blocks are dipping gently to the southwest, we assume all the reservoirs are horizontal in the model for simplicity.

To estimate the maximum amount of compaction-induced fault slip along the Golden Meadow Fault on surface subsidence, we assume the fault is traction-free. In other words, the Golden Meadow Fault can slip freely along its surface without any restrictions. Figure 12 compares the effect of

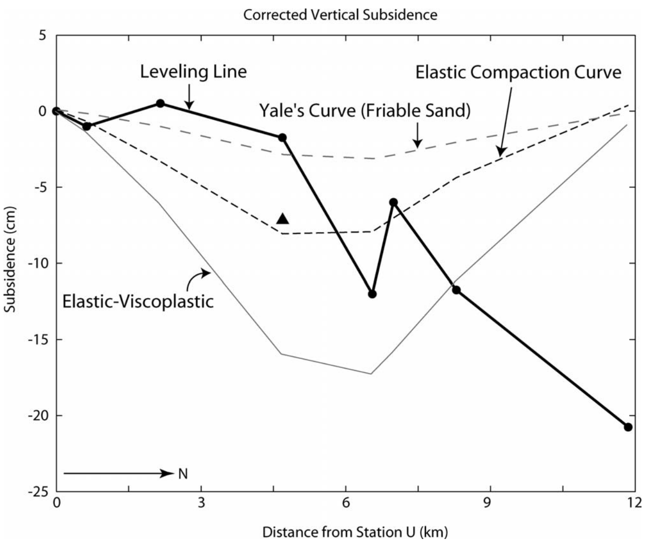

Figure 10. The impact of rheology of the producing sand on the magnitude of the predicted surface subsidence.

Golden Meadow Faults on surface subsidence. Note that when the fault is locked (*i.e.,* no displacement allowed), surface subsidence is controlled by reservoir compaction and yields a similar result to that of the Geertsma solution (Figure 9A). The slight difference between the subsidence bowls of Figures 9 and 12 is due to the shape of the reservoirs: all the reservoirs are disc-shaped in the Geertsma solution while the reservoirs are irregular shaped in the numerical model. The occurrence of fault slip along the Golden Meadow Fault significantly alters the shape of the subsidence bowl especially in the vicinity of the fault. The result shown in Figure 12B is the maximum subsidence that can occur with the influence of production-induced slip on the Golden Meadow Fault. The slip distribution along the Golden Meadow Fault varies spatially (Figure 13) due to the location of the reservoirs and the shape of the fault. As the Golden Meadow Fault is modeled as a discontinuity in the elastic half space, deformation on the southern side of the fault will not translate to the other side.

Comparing the predicted subsidence with the Geertsma method and the releveling line as in Figure 10, it is apparent that the occurrences of compaction-driven fault slip along the Golden Meadow Fault changes the prediction of the vertical elevation change across the Lapeyrouse Field (Figure 14). Slip on the fault as a result of reservoir compaction provided extra vertical elevation change at Station M in the two cases examined. For the elastic case, compaction-driven slip on the fault resulted in an additional 6 cm of elevation change at Station M; an additional 10 cm of elevation change is predicted when the reservoirs are assumed to be totally unconsolidated. Although the generalized compaction curve for unconsolidated sands provides larger estimated elevation changes at Station M, it also overestimates the magnitude of subsidence in the center of the bowl.

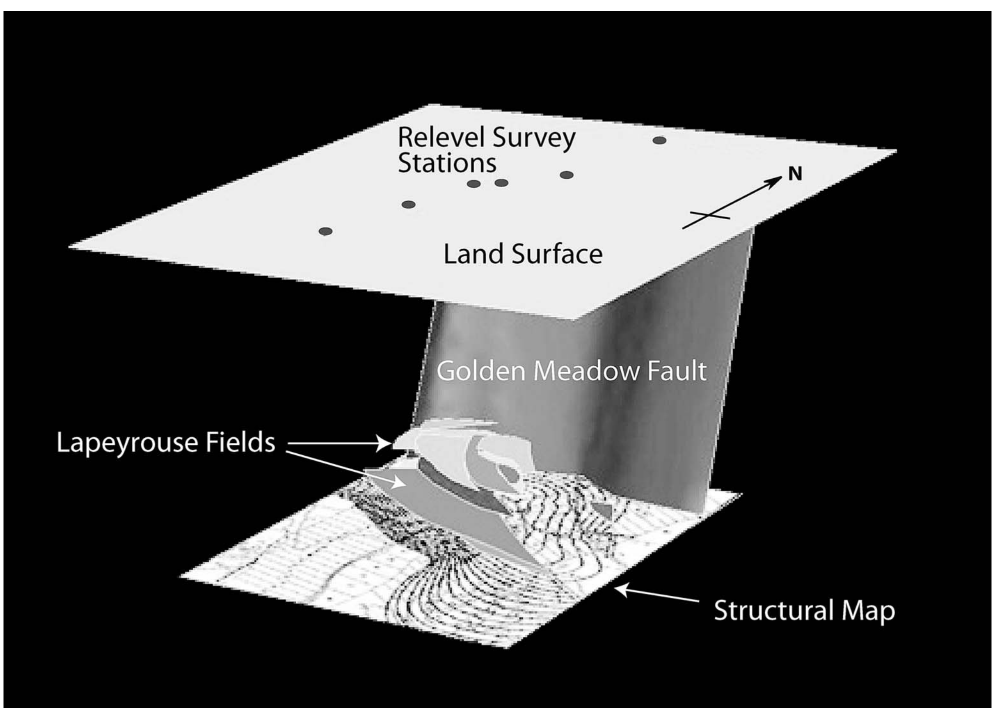

Figure 11. A perspective view of the simplified Lapeyrouse Field and the Golden Meadow Fault created based on actual structural map. **For color version of this figure, see page 675.**

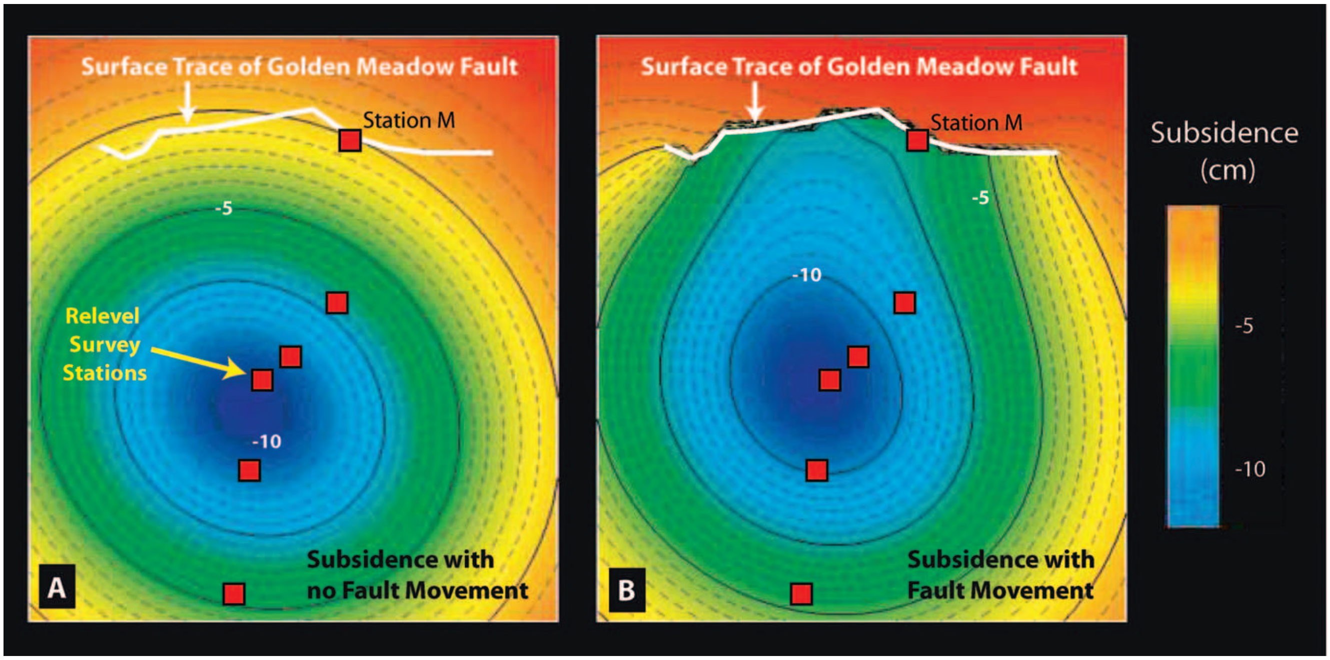

Figure 12. Estimated surface subsidence for a locked fault.

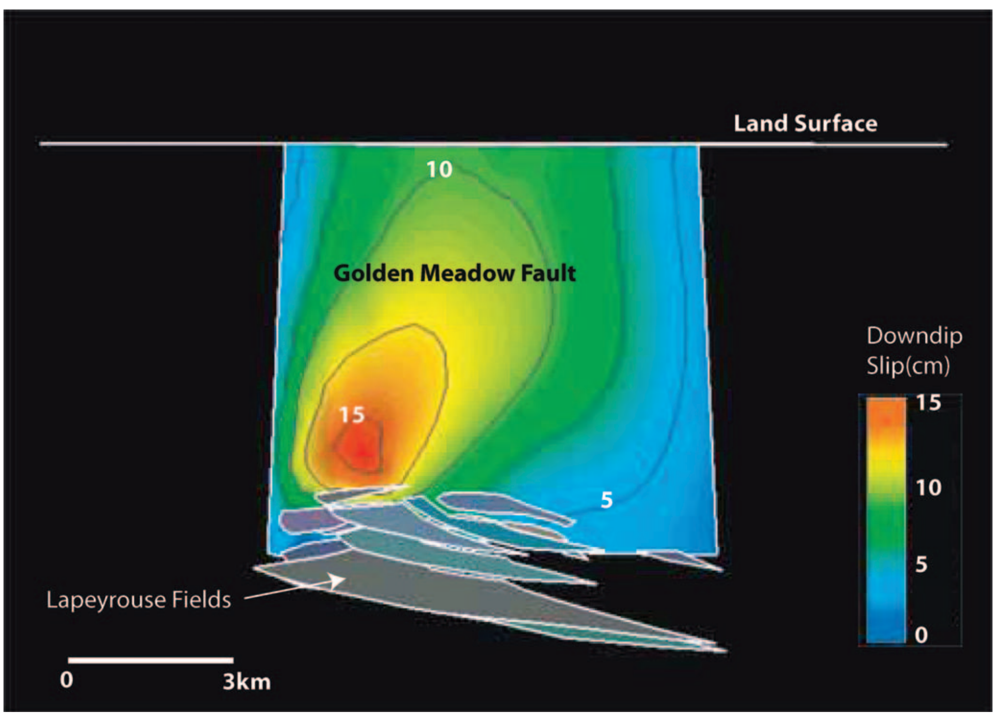

Figure 13. Slip distribution along the Golden Meadow Fault.

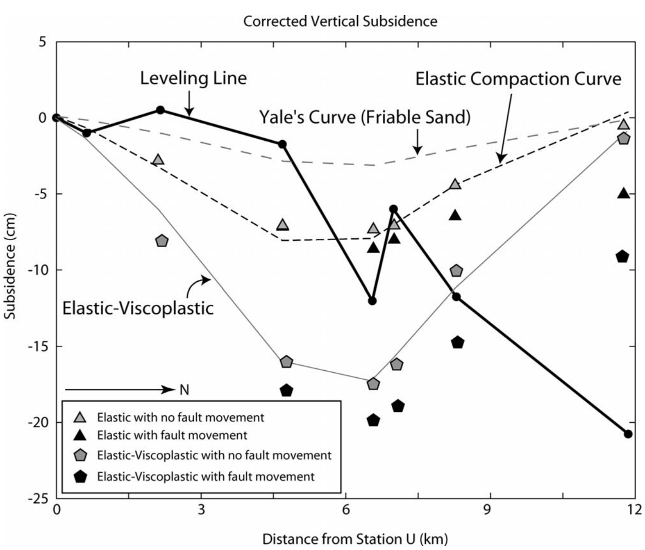

Figure 14. Comparison of the predicted subsidence from the analytical and numerical model with the observed subsidence measured by releveling.

DISCUSSION

In the analysis above, we considered only compaction and compaction-related fault slip on the vertical elevation changes. Movement along regional growth faults was often ignored in our study, PENLAND *et al.* (2002) report that 54% of wetland loss in coastal Louisiana is related to land subsidence but attributed only ~1% of land loss to faulting (at a single location: the Empire Fault in the Balize Delta). Conversely, GAGLIANO *et al.* (2003a,b) suggested that wetland loss was primarily the result of slip along regional growth faults that are linked to the Oligocene-Miocene detachment surface at depth of over 6 km. They also proposed that the massive land loss in the Terrebonne Trough was a result of movement along the regional faults as a result of the subsurface salt migration towards the Gulf of Mexico creating an onshore extensional zone. Using aerial photographs, they identified more than one hundred surface fault traces and concluded that most of these fault traces are related to subsurface faults. Since most of the wetland loss located near the surface trace of these major faults, GAGLIANO *et al.* (2003a,b) concluded that fault movements along these growth faults have been occurring throughout the Quaternary and the sudden loss of wetland in the 1960s is just a result of sediment deprivation from the Mississippi River that accentuates surface signatures. They also suggested that fault movement along these active growth faults are episodic and are not uniform across the fault regionally. Based on surface elevation changes, they concluded that the rate of vertical movement along active faults ranged from 1.5 mm/yr to 12.2 mm/yr. Unfortunately, these rates of movement are estimated without separating effects from any other potential contributors to fault movements, as a result, the fault movement rates proposed by GAGLIANO *et al.* (2003a,b) cannot be used as the background slip rate for the regional growth faults since they include the combined effects of natural and human-induced fault movement plus other mechanisms mentioned in previous sections.

If the regional growth faults located in the coastal Louisiana are active and have natural episodic movements, it is fair to assume that fault movement occurs when the stress acting on the fault surface reaches a threshold stress. After fault slip, the accumulated stress is released and the fault is locked again until stress builds up to the threshold stress again. Since most growth faults in coastal Louisiana are active, the relatively large stress change induced by reservoir compaction due to hydrocarbon production may have an impact on the frequency of slip along these growth faults (CHAN, 2004).

Although we have illustrated that fluid withdrawal can cause surface subsidence in the coastal wetlands, a number of outstanding issues remain for future investigations:

(1) The predicted severity of compaction-induced subsidence in the area of the Lapeyrouse Field is 5–10 cm and highly localized over the field. The significance of this degree of subsidence for wetlands loss needs to be evaluated.
(2) The affect of production-induced fault slip at depth is to alter the shape of the subsidence bowl but not to significantly increase the maximum amount of subsidence. The poor fit of calculated subsidence to that apparently observed at station M, maybe the result of production to the north of the Golden Meadow fault or that the Golden Meadow fault was naturally slipping in that area.
(3) We isolated the Lapeyrouse Field in this study to illustrate the potential impact of hydrocarbon production on surface subsidence in a local scale. To fully consider the role of hydrocarbon production from the many oil and gas fields in southern Louisiana, it will be necessary to evaluate production-induced subsidence in the context of the multiple subsidence mechanisms that may be operative in the region.
(4) We illustrated that reservoir rock properties have an important influence on the estimated amount subsidence. It would be valuable to conduct detailed rock mechanics experiments using representative samples from the reservoirs in the region for future modeling.

It is important to have as much reliable data on vertical elevation changes in the region as possible to test various hypotheses related to subsidence and wetlands loss. Such data could come from repeating surveys on the existing first-order level lines, from GPS or InSAR observations.

CONCLUSIONS

Utilizing both simple analytical and numerical models, the relationship between subsurface hydrocarbon production, land surface subsidence and fault reactivation has been investigated in the Louisiana Coastal Zone. The Lapeyrouse Field located in the Terrebonne Parish was chosen as the study site due to its proximity to the Madison Bay land loss hotspot and because it is bounded by a major regional growth fault in the north. Although there are some uncertainties as-

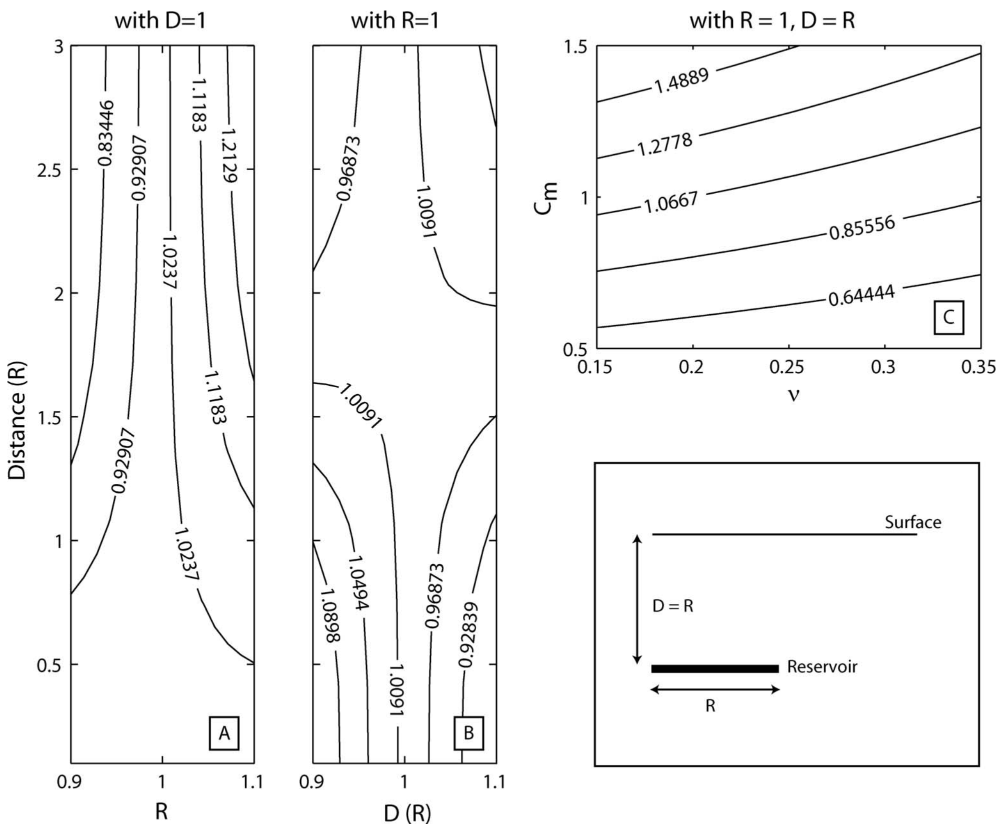

Figure 15. Sensitivity of the estimated subsidence due to uncertainties associated with different parameters for a shallow reservoir.

sociated with the severity of reservoir compaction estimated due to massive fluid withdrawal in Lapeyrouse, the predicted subsidence based on the Geertsma solution yields a comparable result to the measured elevation change from releveling surveys. The similarity between the simple Geertsma solution and surface elevation measurements suggests that subsurface hydrocarbon production has some influence on surface deformation. However, compaction-induced subsidence cannot fully capture the subsidence profile near the Golden Meadow Fault. Using a more complicated numerical model based on Poly3D, we have demonstrated how reservoir compaction may have encouraged slip along the Golden Meadow Fault. The estimated elevation change as a result of compaction-induced fault slip only contributes about 35% of the actual measured elevation change. It is uncertain if this misfit is caused by the uncertainties associated with the modeling (such as rock properties, reservoir geometries and interaction among faults) or other human and/or natural processes. Regardless, using both simple analytical and numerical models with limited information, we have demonstrated that hydrocarbon production can introduce surface subsidence (and to some extent fault slip) on the order of the observed surface elevation change locally.

Coastal wetland loss is a result of complicated interactions between natural processes and human activities; it is difficult to isolate the impact of one specific mechanism from another. The study presented in this paper suggests that production-induced land subsidence is one of the many mechanisms that should not be ignored when evaluating wetland loss in the Louisiana Coastal Zone. Detailed studies and modeling incorporating other mechanisms are required in order to accurately assess the interaction between these mechanism and their cumulative contributions to surface subsidence. While wetland loss is widespread in southern Louisiana, hydrocarbon production is capable of causing localized deformation in the vicinity of the producing reservoirs. The degree to which production from the many fields in the area has contributed to widespread wetlands loss is still unknown.

ACKNOWLEDGMENTS

The authors would like to thank Bob Morton for his insightful discussion on the potential of hydrocarbon production induced land subsidence in Louisiana and his comments on the manuscript. We would also like to acknowledge Daniel Ashford from the Louisiana Department of Natural Resources, Ellen Mallman and Tricia Floria from Stanford University for their help at different stage of this project. We also like to thank Professors Gary Mavko, Amos Nur and Margot Gerritsen for their suggestions on the original manuscript.

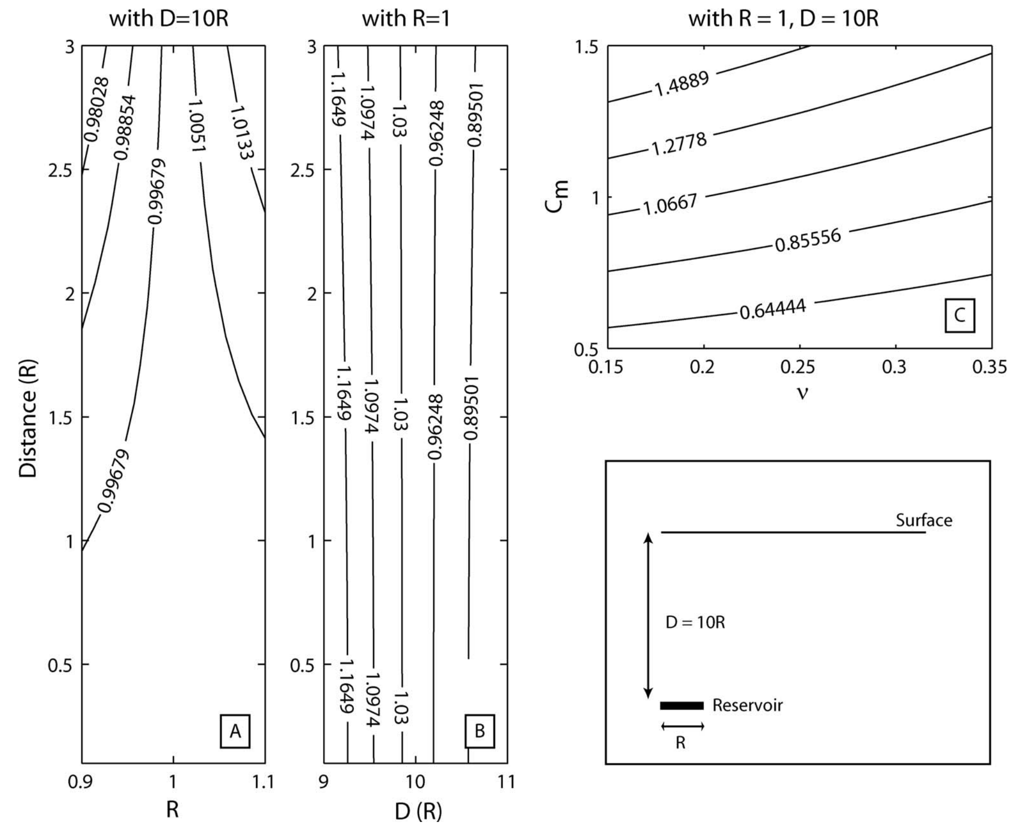

Figure 16. Sensitivity of the estimated subsidence due to uncertainties associated with different parameters for a deep reservoir.

LITERATURE CITED

Baranova, V.; Mustaqeem, A., and Bell, S., 1999. A model for induced seismicity caused by hydrocarbon production in the Western Canada sedimentary basin. *Canadian Journal of Earth Sciences,* 36, 47–64.

Barras, J.A.; Bourgeois, P.E., and Handley, L.R., 1994. Land Loss in Coastal Louisiana: 1956–1990. National Wetlands Research Center Open File Report 94-01.

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

Britsch, L.D. and Dunbar, J.B., 1993. Land loss rates: Louisiana Coastal plain. *Journal of Coastal Research,* 9, 324–338.

Cahoon, D.R.; Day, J.W., Jr., and Reed, D.J., 1999. The influence of surface and shallow subsurface soil processes on wetland elevation; a synthesis. *Current Topics in Wetland Biogeochemistry,* 3, 72–88.

Chan, A.W., 2004. Production-Induced Reservoir Compaction, Permeability Loss and Land Surface Subsidence. Stanford, California: Stanford University, Ph.D. thesis, 176p.

Chan, A.W.; Hagin, P.N., and Zoback, M.D., 2004. Viscoplastic deformation, stress and strain paths in unconsolidated reservoir sands (Part 2): field application using Dynamic DARS analysis. Presented at Gulf Rock 2004, the 6th North American Rock Mechanics Symposium (NARMS), Houston, TX June 6–9, 2004. ARMA/NARMS 04-568.

Colazas, X.C. and Strehle, R.W., 1995. Subsidence in the Wilmington oilfield, Long Beach, California, USA. *In*: Chilingarian, G.V. (ed.), *Subsidence due to Fluid Withdrawal.* Amsterdam: Elsevier Science, pp. 285–336.

Coleman, J.M. and Roberts, H.H., 1989. Deltaic coastal wetlands. *Geologie en Mijnbouw,* 68, 1–24.

Davis, S.D.; Nyffenegger, P.A., and Frohlich, C., 1995. The 9 April 1993 earthquake in south-central Texas: was it induced by fluid withdrawal? *Bulletin of Seismological Society of America,* 85(6), 1888–1895.

Doser, D.I.; Baker, M.R., and Mason, D.B., 1991. Seismicity in the War-wink gas field, Delaware Basin, West Texas, and its relationship to petroleum production. *Bulletin of the Seismological Society of America,* 81(3), 971–986.

Eason, G.; Noble, B., and Sneddon, I.N., 1954. On certain integrals of Lipschitz-Hankel type involving products of Bessel functions. *Philosophical Transaction, Royal Society of London,* A247, 529–551.

Evans, D.M., 1966. The Denver area earthquakes and the Rocky Mountain Arsenal Disposal Well. *Mountain Geologist,* 3, 23–36.

Farber, S., 1987. The value of coastal wetlands for protection of property against hurricane wind damage. *Journal of Environmental Economics and Management,* 14(2), 143–151.

Frazier, D.E., 1967. Recent deltaic deposits of the Mississippi River; their development and chronology. Symposium on the geological history of the Gulf of Mexico, Antillean-Caribbean region. *Transactions—Gulf Coast Association of Geological Societies,* 17, 287–315.

Gabrysch, R.K. and Bonnet, C.W., 1975. Land-surface subsidence in Houston-Galveston region, Texas. *Texas Water Development Board Report 188,* Austin: Texas, 19p.

Gabrysch, R.K. and Coplin, L.S., 1990. Land-surface Subsidence Resulting from Ground-water Withdrawals in the Houston-Galveston Region, Texas, Through 1987. U.S. Geological Survey Report of Investigations No. 90-01, Washington, D.C., 53p.

Gagliano, S.M.; Kemp, E.B., III; Wicker, K.M.; Wiltenmuth, K.S., and Sabate, R.W., 2003a. Neo-tectonic framework of southeast Louisiana and applications to coastal restoration. Transactions of the 53rd Annual Convention of the Gulf Coast Association of Geological Societies and the Gulf Coast Section SEPM 2003, Baton Rogue, Louisiana, October 22–24, 2003, LIII, 262–272.

Gagliano, S.M.; Wicker, K.M.; Wiltenmouth, K.S., and Kemp, E.B., III, 2003b. Active Geologic Faults and Land Change in Southeastern Louisiana. Prepared for the U.S. Army Corps of Engineers, New Orleans District, Contract No. DACW 29-00-S-0034. Coastal Environments, Inc. Baton Rouge, Louisiana 70802.

Geertsma, J., 1973. Land subsidence above compacting oil and gas reservoirs. *Journal of Petroleum Technology,* June 1973, 734–744.

Gomitz, V.; Lebedeff, S., and Hansen, J., 1982. Global sea level trends in the past century. *Science,* 215, 1611–1614.

Grasso, J.R. 1992. Mechanics of seismic instabilities induced by the recovery of hydrocarbons. *Pure and Applied Geophysics,* 139, 507–533.

Grasso, J.R. and Wittlinger, G., 1990. Ten years of seismic monitoring over a gas field. *Bulletin of the Seismological Society of America,* 80(2), 450–473.

Hagin, P.N. and Zoback, M.D., 2004.Viscous deformation of unconsolidated reservoir sands (Part 2): Linear viscoelastic models. *Geophysics,* 69, 742–751.

Jaeger, J.C. and Cook, N.G.W. 1969, *Fundamentals of Rock Mechanics.* Methuen and Co. Ltd.: London, 515p.

Kooi, H., 1997. Insufficiency of compaction disequilibrium as the sole cause of high pore fluid pressure in pre-Cenozoic sediments. *Basin Research,* 9, 227–241.

Kooi, H., 2000. Land subsidence due to compaction in the coastal area of The Netherlands: the role of lateral fluid flow and constraints from well-log data. *Global and Planetary Change,* 27, 207–222.

Kooi, H. and de Vries, J.J., 1998. Land Subsidence and hydrodynamic compaction of sedimentary basins. *Hydrological Earth System Science,* 2, 159–171.

Kuecher, G.J.; Roberts, H.H.; Thompson, M.D., and 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. *Environmental Geosciences,* 8(2), 77–94.

Louisiana Coastal Wetlands Conservation and Restoration Task Force and The Wetlands Conservation and Restoration Authority, 1998. *Coast 2050: Toward a Sustainable Coastal Louisiana.* Louisiana Department of Natural Resources: Baton Rouge, LA. 161p.

McGarr, A., 1991. On a possible connection between three major earthquakes in California and oil production. *Bulletin of the Seismological Society of America,* 81(3), 948–970.

Mereu, R.F.; Brunet, J.; Morrissey, K.; Price, B., and Yapp, Y., 1986. A study of the microearthquakes of the Gobles oil field area of Southwestern Ontario. *Bulletin of the Seismological Society of America,* 76(5), 1215–1223.

Morton, R.A.; Buster, N.A., and Krohn, M.D., 2002. Subsurface controls on historical subsidence rates and associated wetland loss in south central Louisiana. *Gulf Coast Association of Geological Societies Transactions,* 52, 767–778.

Morton, R.A.; Purcell, N.A., and Peterson, R., 2001. Field evidence of subsidence and faulting induced by hydrocarbon production in Coastal Southeast Texas. *Gulf Coast Association of Geological Societies Transactions,* 51, 239–248.

Morton, R.A.; Tiling, G., and Ferina, N., 2003. Primary causes of wetland loss at Madison Bay, Terrebonne Parish, Louisiana. *USGS Open File Report* 03-60.

Neighbors, R.J., 1981. Subsidence in Harris and Galveston counties, Texas. *In*: Johnson, A.I. (ed.), *Legal, Socio-Economic and Environmental Significance of Land Subsidence in the United States.* American Society of Civil Engineering Journal of the Irrigation and Drainage Division, 107(IR2), 161–174.

Paine, J.G., 1993. Subsidence of the Texas coast: inferences from historical and late Pleistocene sea levels. *Tectonophysics,* 222, 445–458.

Penland, S. and Ramsey, K.E., 1990. Relative sea-level rise in Louisiana and the Gulf of Mexico: 1908–1988. *Journal of Coastal Research,* 6, 323–342.

Penland, S.; Ramsey, K.E.; McBride, R.A.; Moslow, T.F., and Westphal, K.A., 1988. *Relative Sea Level Rise and Subsidence in Louisiana and the Gulf of Mexico*: Louisiana Geological Survey, Baton Rouge, Louisiana, 65p.

Penland, S.; Wayne, L.; Britsch, L.D.; Williams, S.J.; Beall, A.D., and Butterworth, V.C., 2000. Process classification of coastal land loss between 1932 and 1990 in the Mississippi River Delta Plain, Southeastern Louisiana. *USGS Open File* 00-418.

Penland, S.; Williams, S.J.; Britsch, L.D., and Beall, A.D., 2002. Geologic classification of coastal land loss between 1932 and 1990 in the Mississippi River Delta Plain, southeastern Louisiana. *Transactions of the Gulf Coast Association of Geological Societies,* 52, 799–807.

Pennington, W.D.; Davis, S.D.; Carlson, S.M.; DuPree, J.D., and Ewing, T.E., 1986. The evolution of seismic barriers and asperities caused by the depressuring of fault planes in oil and gas fields of south Texas. *Bulletin of the Seismological Society of America,* 76, 939–948.

Pratt, W.E. and Johnson, D.W., 1926. Local subsidence of the Goose Creek oil field (Texas). *Journal of Geology,* 34(7), 577–590.

Raleigh, C.B.; Healy, J.H., and Bredehoeft, J.D., 1976. An experiment in earthquake control at Rangely, Colorado. *Science,* 191, 1230–1237.

Reed, D.J. and Cahoon, D.R., 1993. Marsh submergence vs. marsh accretion: interpreting accretion deficit data in coastal Louisiana. *In*: Magoon, O.T., Wilson, W.S., Converse, H., and Tobin, L.T. (eds.), *Coastal Zone '93, Proceedings of the Eighth Symposium on Coastal and Ocean Management.* New York: American Society of Civil Engineers, pp. 243–257.

Roberts, H.H.; Bailey, A., and Kuecher, G.J., 1994. Subsidence in the Mississippi River Delta; important influences of valley filling by cyclic deposition, primary consolidation phenomena, and early diagenesis. Forty-fourth annual convention of the Gulf Coast Association of Geological Societies, American Association of Petroleum Geologists and the Forty-first annual convention of the Gulf Coast Section of the Society of Economic Paleontologists and Mineralogists, 44, 619–629.

Scardina, A.D.; Nunn, J.A., and Pilger, R.H., Jr., 1981. Subsidence and flexure of the lithosphere in the North Louisiana salt basin. *EOS, Transactions,* American Geophysical Union, 62(17), 391.

Segall, P. 1985. Stress and subsidence resulting from subsurface fluid withdrawal in the epicentral region of the 1983 Coalinga earthquake. *Journal of Geophysical Research,* 90, 6801–6816.

Segall, P., 1989. Earthquakes triggered by fluid extraction. *Geology,* 17, 942–946.

Segall, P. 1992. Induced stresses due to fluid extraction from axisymmetric reservoirs. *Pure and Applied Geophysics,* 139, 535.

Sharp, J.M., Jr., and Hill, D.W., 1995. Land subsidence along the northeastern Texas Gulf coast: effects of deep hydrocarbon production. *Environmental Geology,* 25, 181–191.

Sticker, E.E., 1979. Geology and Reservoir Analysis of the Lapeyrouse Field, Terrebonne Parish, Louisiana. New Orleans, Louisiana. University of New Orleans, Master's thesis, 68p.

Suhayda, J.N., 1987. Subsidence and sea level. *In*: Turner, R.E., and Cahoon, D.R. (eds.), Causes of Wetland Loss in the Coastal Central Gulf of Mexico, Volume II: Technical Narrative. OCS Study/MMS 87-0120. New Orleans: Louisiana: Minerals Management Service, pp. 187–202.

Suhayda, J.N.; Bailey, A.; Roberts, H.H.; Penland, S., and Kuecher, G., 1993. Subsidence properties of Holocene sediments: South Louisiana. *Coastal Zone '93 New York,* New York: American Society of Civil Engineering, 1215–1229.

Sulak, R.M., 1991. Ekofisk: the first 20 years. *Journal of Petroleum Technology,* 43(10), 1265–1271.

Swanson, R.L. and Thurlow, C.I., 1973. Recent subsidence rates along the Texas and Louisiana coasts as determined from tide measurements. *Journal of Geophysical Research,* 78, 2665–2671.

Thomas, A.L., 1993. Poly3D: A Three-Dimensional, Polygonal Element, Displacement Discontinuity Boundary Element Computer

Program with Applications to Fractures, Faults and Cavities in the Earth's Crust. Stanford, California: Stanford University, Master's thesis, 69 p.

VAN HASSELT, J.PH., 1992. Reservoir compaction and surface subsidence resulting from oil and gas production: a review of theoretical and experimental research approaches. *Geologie en Mijnbouw,* 71, 107–118.

WHITE, W.A. and MORTON, R.A., 1997. Wetland losses related to fault movement and hydrocarbon production, Southeastern Texas coast. *Journal of Coastal Research,* 13, 1305–1320.

WHITE, W.A. and TREMBLAY, T.A., 1995. Submergence of wetlands as a result of human-induced subsidence and faulting along the upper Texas Gulf Coast. *Journal of Coastal Research,* 11, 788–807.

WILLIAMS, S.J., PENLAND, S., and ROBERTS, H.H., 1994. Processes affecting coastal wetland loss in the Louisiana deltaic plain. *In*: WILLIAMS, S.J. and CICHON, H.A. (eds.), *Processes of Coastal Wetlands Loss in Louisiana.* U.S. Geological Survey Open File 940275, pp. 21–29.

YALE, D.P.; NABOR, G.W.; RUSSELL, J.A.; PHAM, H.D., and YOUSEF, M., 1993. Application of variable formation compressibility for improved reservoir analysis. SPE 26647.

ZOBACK, M.D.; CHAN, A.W., and ZINKE, J., 2001. Production-induced normal faulting. Proceedings of the 38th US Rock Mechanics Symposium, DC Rocks 2001, Washington D.C., 7–10 July 2001, 157–163.

APPENDIX: THE GEERTSMA METHOD

For a disc-shaped reservoir of thickness H and radius R at depth D, GEERTSMA (1973) estimated the effect of production on surface subsidence based on a nucleus-of-strain concept. The reservoir is modeled as an "isolated volume of reduced pore pressure in a porous or non-porous but elastically deforming half-space with traction free surface" (GEERTSMA, 1973). Based on poroelastic theory, subsidence due to a uniform pore pressure reduction, ΔP_P, can be treated as the displacement perpendicular to the free surface as a result of the nucleus of strain for a small but finite volume, V, such that:

$$u_z(r, 0) = -\frac{1}{\pi}c_m(1-\nu)\frac{D}{(r^2+D^2)^{3/2}}\Delta P_P V \qquad (A.1)$$

$$u_r(r, 0) = +\frac{1}{\pi}c_m(1-\nu)\frac{r}{(r^2+D^2)^{3/2}}\Delta P_P V \qquad (A.2)$$

where c_m is defined as the formation compaction per unit change in pore-pressure reduction, and Poisson's Ratio, ν. Assuming both c_m and ν are constant throughout the entire half space, the amount of subsidence caused by a producing disc-shaped reservoir at depth can then be estimated by integrating the nucleus-of-strain solution over the reservoir volume:

$$u_z(r, 0) = -2c_m(1-\nu)\Delta P_P HR\int_0^\infty J_1(R\alpha)J_0(r\alpha)e^{-D\alpha}\,d\alpha \qquad (A.3)$$

$$u_r(r, 0) = +2c_m(1-\nu)\Delta P_P HR\int_0^\infty J_1(R\alpha)J_1(r\alpha)e^{-D\alpha}\,d\alpha \qquad (A.4)$$

J_0 and J_1 are Bessel functions of the zero and first order respectively. EASON *et al.* (1954) evaluate integrals involving products of Bessel functions. The general form of such integrals is noted as:

$$I(\mu, \nu; \lambda) = \int_0^\infty J_\mu(at)J_\nu(bt)e^{-ct}t^\lambda\,dt \qquad (A.5)$$

Introducing the dimensionless parameters $\rho = r/R$ and $\eta = D/R$, Equations A.3 and A.4 can be simplified as

$$u_z(r, 0) = -2c_m(1-\nu)\Delta P_P HA(\rho, \eta) \qquad (A.6)$$

$$u_r(r, 0) = 2c_m(1-\nu)\Delta P_P HB(\rho, \eta) \qquad (A.7)$$

where $A = RI(1, 0; 0)$ and $B = RI(1, 1; 0)$. The solutions for A and B are linear combinations of the elliptic integrals of the first, second and third kind (EASON *et al.,* 1954).

$$A = I(1, 0; 0) = \begin{cases} -\frac{k\eta}{4\sqrt{\rho}}F_0(m) - \frac{1}{2}\Lambda_0(p, k) + 1 & (\rho < 1) \\ -\frac{k\eta}{4}F_0(m) + \frac{1}{2} & (\rho = 1) \\ -\frac{k\eta}{4\sqrt{\rho}}F_0(m) + \frac{1}{2}\Lambda_0(p, k) & (\rho > 1) \end{cases} \qquad (A.8)$$

$$B = I(1, 1; 0) = \frac{1}{k\sqrt{\rho}}\left[\left(1 - \frac{1}{2}k^2\right)F_0(m) - E_0(m)\right] \qquad (A.9)$$

where $m = k^2 = \rho/[(1-\rho)^2 + \eta^2]$ and $p = k^2\{(1-\rho)^2 + \eta^2\}/[(1-\rho)^2 + k^2]$. F_0, E_0, and Λ_0 are the completed elliptic integrals of the first, second kind, and the Heuman's Lambda function, respectively.

Figures 15 and 16 demonstrate the sensitivity of the estimated subsidence due to uncertainties associated with R, D, c_m, and ν. Figure 15A shows that a 10% change in the radius of the disc-shaped reservoir could yield a 20% uncertainty in the estimated subsidence for a shallow reservoir (*i.e.,* $D \approx R$). A 10% change in D could results in a 10% change in the estimated subsidence (Figure 15B). Uncertainty related to Poisson's Ratio is relatively insignificant, but the estimated surface subsidence appears to be directly proportional to the uncertainty associated with compressibility (Figures 15C and 16C). However, if the reservoir is significantly deeper (*i.e.,* $D > 10R$), the impact of the size of the disc on surface subsidence is less than 2% (Figure 16A).

As Geertsma noted, rate and degree of pore pressure reduction in any gas reservoir depends on the permeability distribution within the reservoir, locations of the wells and the production rate. The analytical solution presented by GEERTSMA (1973) is limited to a disc-shaped reservoir. However, the Geertsma method could still be used for an irregular-shaped reservoir by replacing integration to summation of the effect of nuclei of strain over the reservoir volume.