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# Subsidence in the Louisiana Coastal Zone due to Hydrocarbon Production

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## ABSTRACT

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Coastal wetland loss in southern Louisiana poses a great threat to the region's ecologic and economic stability. Wetland loss in the Louisiana Coastal Zone is caused by the interactions of multiple natural and human induced mechanisms, and it has been suggested that subsurface oil and gas production may be a large contributing factor. We model the effect of oil and gas production in Lafourche Parrish, Louisiana on surface subsidence using a first-order leveling line along highway Louisiana 1 to constrain our model. Using geologic and pressure data, we estimate the amount of compaction in modeled reservoirs. We find the subsidence predicted from reservoir compaction is consistent with observations of localized subsidence between 1982 and 1993. Both modeling and observations show that subsidence due to reservoir compaction is a highly localized signal that is not consistent with observations of regional subsidence. Interestingly, while predictions of subsidence from compaction of the reservoir sands fit the observed subsidence in one time epoch, the leveling data shows an increasing rate of subsidence from the 1965-1982 to 1982-1993 epoch – a time when production rates decreased. This indicates the potential for a time-dependent mechanism for production induced subsidence. This work is a critical part in the development of an integrated model of subsidence and wetland loss in southern Louisiana.

**ADITIONAL INDEX WORDS:** *land loss, wetland, oil and gas production*

## BACKGROUND

About 40% of the United States' coastal wetlands are located in Louisiana and land loss in the Louisiana Coastal Zone (LCZ) accounts for 80% of the total coastal wetland loss in the United States since the 1930s. If wetland loss continues at this rate the Louisiana Coastal Wetlands Conservation and Restoration Task Force and the Wetlands Conservation and Restoration Authority (Louisiana Coastal Wetlands Conservation and Restoration Task Force and the Wetlands Conservation and Restoration Authority 1998) estimate the lost public use value to exceed $37 billion by 2050.

In Louisiana, wetland loss is a combination of land subsidence along with eustatic sea level rise, sediment accumulation, erosion, and filling and drainage (BOESCH et al. 1994). Relative sea-level changes result in temporally variable, but spatially constant subsidence patterns along the entire coastal zone (PENLAND et al. 1988; PENLAND and RAMSEY 1990; ROBERTS et al. 1994; SUHAYDA 1987). In areas with minimal tectonic activity tide gauges show a relative sea level change of 2.29 mm/yr (PENLAND et al. 1988). PENLAND et al. (1988; 2000) determined that more than half of the land loss in coastal Louisiana between 1932 and 1990 was related to subsidence, which itself is the combination of multiple mechanisms, both natural and anthropogenic. There is natural subsidence due to compaction of Holocene, Pleistocene, and Tertiary sediments, lithospheric flexure due to the Mississippi delta, and tectonic activity along the regional growth faults. In addition to natural subsidence, there are the anthropogenic effects of subsurface fluid withdrawal, induced faulting due to fluid production, and the absence of sedimentation which enhances the natural compaction signal. These various mechanisms all produce different temporal and spatial signatures. Compaction of Holocene sediments in the Mississippi River delta results in a spatially variable, but temporally constant subsidence pattern (SUHAYDA et al. 1993) and contributes between 0.1 and 1 mm/yr to overall subsidence rates (KOOI and DE VRIES 1998). Lithospheric flexure, as a response to sediment loading, has been shown to lead to geological subsidence rates of 0.05 mm/yr for other portions of the gulf coast (PAINE 1993; SCARDINA et al. 1981). Much of the wetlands losses identified in aerial photographs are on the downthrown sides of growth faults that run along the entire coast and continental shelf, and it has been suggested that the wetland losses are related to natural episodic movement along these faults (DOKKA 2006; GAGLIANO et al. 2003). However, due to the time spanned by aerial photographs and leveling surveys it is impossible determine the component of subsidence due to the faults as opposed to other mechanisms. The subsidence rate from these four mechanisms (~3 mm/yr) is significantly lower than the observed historical subsidence rates of 9 mm/yr to as high as 23mm/yr locally (MORTON et al. 2002). The effect of hydrocarbon production-induced fault reactivation and reservoir compaction on surface subsidence has been investigated as a means of explaining these recent high subsidence rates (MORTON et al. 2001; 2002; 2003b; 2005b; 2005a; 2006; SHARP and HILL 1995; WHITE and MORTON 1997).

Subsidence related to subsurface fluid withdrawal in the Gulf of Mexico region was first recognized along the Texas coast (NEIGHBORS 1981; SWANSON and THURLOW 1973). In the

Houston-Galveston area subsidence rates of up to 120 mm/yr greatly exceeded the natural subsidence rates estimated to be up to 13 mm/yr. Gabrysch and Copland (1990) found that the rapid subsidence rates and subsidence of up to 3 m was induced by large-scale groundwater withdrawal forming a large subsidence bowl. Subsidence of this magnitude in coastal wetland areas where elevations rarely exceed 3 m above sea level, and thus even slight decreases in elevation can lead to frequent flooding which can devastate the ecosystem.

In Louisiana it has been more difficult to link wetland loss to fluid withdrawal as both are pervasive throughout the region and the land loss is likely caused by many interacting processes and conditions. Previously, many authors felt that oil and gas production would only cause local subsidence and be small due to the depth of production and thus have little affect on regional wetland loss. (Boesch et al. 1994; Coleman and Roberts 1989; Suhayda 1987). However, Morton et al. (2001) found that periods of rapid wetland loss corresponded to times of high oil and gas production and inferred that this may indicate that the fluid production was driving the wetland loss. We can use the analytical method developed by Geertsma (1973) to model the role that hydrocarbon production at depth has on the observed surface subsidence and resulting land loss in the LCZ.

## METHOD

The Geertsma solution is an analytical model for estimating the surface deformation due to the depletion of an idealized reservoir of radius R at depth D (Geertsma 1973). The Geertsma solution calculates the vertical and radial components of surface displacement from:

$$u_z(r,0) = -2C_m(1-\nu)\Delta pHR\int_0^\infty e^{-D\alpha}J_1(\alpha R)J_0(\alpha r)d\alpha \qquad (1)$$

$$u_r(r,0) = 2C_m(1-\nu)\Delta pHR\int_0^\infty e^{-D\alpha}J_1(\alpha R)J_1(\alpha r)d\alpha$$

Where $u_z$ is the vertical displacement and $u_r$ is the radial displacement for a reservoir of radius R at depth D and thickness H. $C_m$ is the compaction coefficient of the reservoir, ν is the Poisson ratio, Δp is the change in pore pressure, r is the distance from the center of the reservoir on the surface, and $J_0$ and $J_1$ are Bessel functions. We can define the change in height of the reservoir as:

$$\Delta H = \int_0^H C_m(z)\Delta p(z)dz \quad (2)$$

However, $C_m$ as defined by Geertsma is not an appropriate estimate of the compaction coefficient as it is assumed to be the same throughout the entire half space as opposed to the reservoir having a different compaction coefficient than the surrounding medium. Instead, we estimate ΔH using Deformation Analysis in Reservoir Space (DARS) (Chan and Zoback 2002; Chan 2004) which incorporates the bottom hole pressure decline, an elastic-plastic end cap constitutive law for reservoir sands developed for an off shore Gulf of Mexico reservoir, and a generalized stress path for the Gulf of Mexico.

A generalized Geertsma solution is shown in Figure 1 which allows for a first-order estimation of surface displacements for reservoirs of various sizes and depths. The shallower the reservoir is the larger and more localized the surface signal is. However, even for deep reservoirs where the surface signal is broader the deformation is still limited to within approximately three reservoir radii.

Chan and Zoback (in press) extended the observations of Morton et al. (2002) by adding numerical and analytical models, which incorporated physical changes in the formations associated with depletion and the resulting stress changes, to estimate surface subsidence due to oil and gas production in the Lapeyrouse field in Terrebonne parish and the potential for induced slip along the nearby Golden Meadow Fault. They used changes in reservoir pore-pressure to model the role of reservoir compaction on surface subsidence and compared this to observations of elevation change along a leveling line that transects the study area. Surface subsidence predicted by only compaction of the reservoirs did not fully explain the subsidence observed along the leveling line, thus Chan and Zoback (in press) then created a numerical model to determine the effect that the compacting reservoirs have on the nearby Golden Meadow Fault. They were able to show that depletion of oil and gas reservoirs in the Lapeyrouse field can have a significant impact on surface subsidence and fault slip locally; however, they were still not able to fully reproduce the subsidence observed along the leveling line. One of the limitations of this local study is that the Golden Meadow Fault lies to the north of the modeled reservoirs and the Lapeyrouse field whereas in much of the LCZ the large fields are cut by the regional faults or there is production on both the upthrown and downthrown sides of the fault. The findings of Chan and Zoback (in press) indicate that subsurface fluid withdrawal is a mechanism that needs to be seriously considered when modeling subsidence in the LCZ, and that future modeling should be more regional in order to incorporate it with other subsidence mechanisms and to accurately assess its impact on the regional subsidence picture.

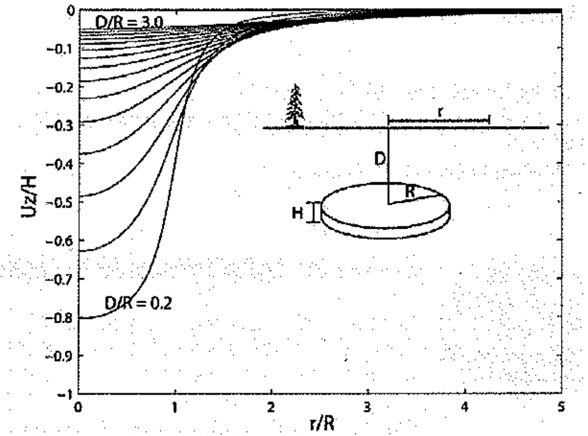

Figure 1: Generalized Geertsma (1973) model for reservoirs of varying radius and depth ratios. The shallower the reservoir the more pronounced the surface signal. As the reservoirs become deeper the surface signal becomes broader, but becomes only about as large as three reservoir radii.

## STUDY AREA

In this work we extend the work of Chan and Zoback (in press) by building a more regional model of subsidence due to hydrocarbon production in Lafourche Parrish, Louisiana. This is an ideal location because there is a first-order leveling line along Louisiana Highway 1 (LA 1) from Grand Isle in the south to Racelend in the north, with multiple time epochs and recently re-calculated rates, which crosses multiple large oil and gas fields and regional growth faults (Figure 2)(Shinkle and Dokka 2004). In addition, this is an area where small amounts of subsidence can have a large impact as of the region has elevations of between 1 and 4 meters above sea level, and at no place does is get above 5 meters. In addition, LA 1 is the only hurricane evacuation route for the estimated 80,000 residents in southern Lafourche Parrish including Port Fourchon, Louisiana's southernmost port, and an important port for oil and gas. Much of this road is built on levees within the wetlands or on small areas of land surrounded by wetlands. There are also numerous wetland restoration projects in this area making it critical that we understand the mechanisms causing subsidence and wetland loss so that restoration efforts can be carried out effectively.

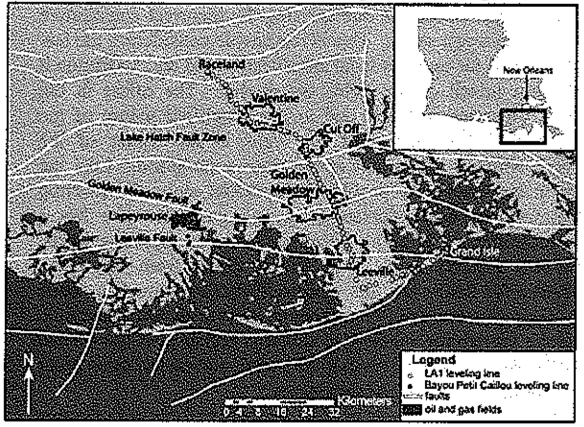

Figure 2: Regional map showing the major oil and gas fields of Leeville, Golden Meadow, Cut Off, Valentine, and Lapeyrouse, the leveling lines used in CHAN AND ZOBACK (in press) (black circles) and this study (white circles), and the regional faults as white lines.

SHINKLE AND DOKKA (2004) recently recalculated elevation rate changes for a network of leveling lines throughout Louisiana, including the leveling line along LA 1. There are multiple epochs of leveling data, but here we present only the elevation changes between 1982 and 1993. The elevation changes shown in Figure 3 are all relative to the station at Grand Isle which is where the line was started, and this base station is tied to a tide gauge and GPS station at the Coast Guard Station. The error bars represent the error in measuring elevation at each location along with the error accumulated along the leveling line. The entire line shows a regional subsidence signal on the order of 5-8 cm, with regions of higher subsidence. These areas of higher subsidence correlate well with the Leeville, Golden Meadow, Cut Off, and Valentine oil and gas fields, and the inferred location of the regional growth faults.

The regional map only shows the major oil and gas fields that the leveling line along LA 1 crosses, however oil and gas fields are pervasive through southern Louisiana and the region of high rates of land loss. This, along with the observation that periods of wetland loss correlated well with periods of high fluid production (MORTON et al. 2002), leads to the two key questions that motivate this research: 1) is the subsidence signal higher over the oil and gas fields? and 2) does the rate of subsidence correlate with the rate of oil and gas produced?

We use well logs and pressure data over the same time period as the leveling data (in this case 1982-1993) from the Leeville, Golden Meadow, and Valentine oil and gas fields to identify reservoir compartments and estimate the amount of reservoir compaction due to production. The radius of the idealized reservoir is determined by making the reservoirs large enough to encompass all the wells in the same compartment without overlapping any other compartments. For compartments with only one well we center the idealized reservoir on the well by default. All three fields began producing between the 1920s and 1940s and produce from intermediate depth (6000'-12000')mid to late-Miocene sands. Production in this area peaked in the 1970s and then declined rapidly. Valentine is the only field directly associated with a salt structure; in this case the reservoirs are all along the flank of an intermediate depth salt dome. Figure 4 shows the idealized reservoirs at all depths used for the Geertsma model in map view. The model estimates the surface subsidence signal expected due to the depletion of all the modeled reservoirs over the time period of interest.

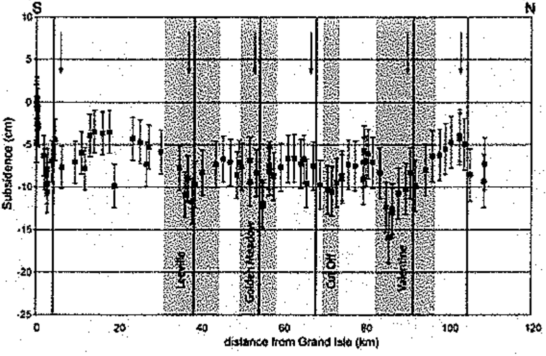

Figure 3: Leveling line between Grand Isle in the south and Racelend in the north showing subsidence in cm for between 1982 and 1993. All elevation changes are relative to Grand Isle. Grey boxes indicate the aerial extent of the 4 major oil and gas fields the leveling line crosses and dark gray lines represent the inferred surface locations of the regional normal faults with arrows indicating downthrown side. Notice the localized regions of subsidence that coincide with the oil and gas fields and the faults.

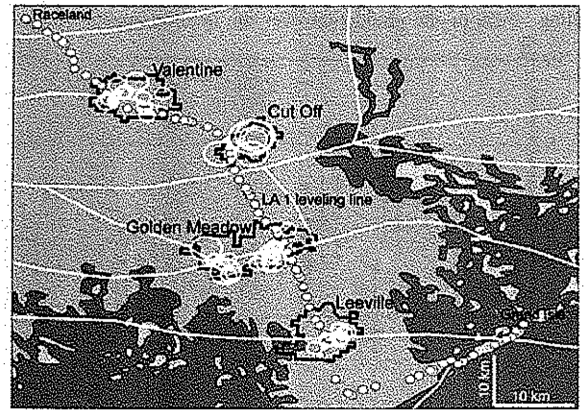

Figure 4: Map of modeled area with LA 1 leveling line in white circles, regional faults in white, important oil and gas fields outlined in black, and modeled reservoirs at various depths as white discs.

## RESULTS

Figure 5 shows the results of the Geertsma model for compacting reservoirs in the Leeville, Golden Meadow, and Valentine oil and gas fields in map view for production between 1982 and 1993. Significant subsidence bowls are identifiable over all three fields with maximum predicted subsidence of approximately 10 cm over the 11 year time period. It is notable that despite the depth of the reservoirs (~6000'-12000') the signals remain localized over the producing fields.

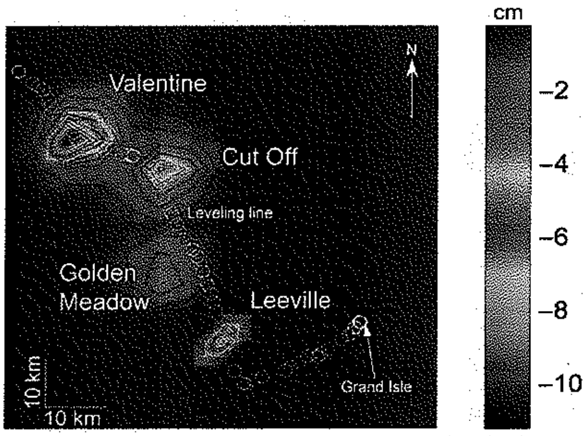

Figure 5: Map view of model results. Leveling line is show as white circles, magnitude of subsidence between 1982 and 1993 in cm. The subsidence bowls are localized over each of the oil and gas fields and have maximum subsidence of about 10 cm.

In Figure 6 we compare the subsidence observed along the leveling line with what is predicted by Geertsma in the same locations. In order to remove some of the regional signal present in the leveling data we show the changes in elevation relative to the station marked by the large square as opposed to Grand Isle. This allows us to identify approximately 5 cm of regional subsidence over the 11 year time period as noted by the dashed line. The model results are shown as the solid line. The model fits the observed subsidence at Leeville and Cut Off within the errors of the leveling data. At Golden Meadow the model greatly under predicts the observed subsidence. This is likely due to only modeling ~50% of the production over the time of interest and most of these reservoirs are located off the transect of the leveling line. At Valentine the model over predicts the observed subsidence which could be due to using the incorrect constitutive law for the reservoir sands. This is reasonable considering the law was developed for samples from an offshore field and Valentine it the furthest inland of the fields we model. The offset in the modeled Valentine signal is due to the simplified nature of the reservoirs and the placing of the wells at the center of the reservoir, which is likely not an accurate assumption. Like the results in map view, the profile of the model along the leveling line shows that while depleting oil and gas reservoirs has a substantial effect; it is highly localized over the depleting fields. There also appears to be little to no effect from the faults transecting the fields, but this will be further examined in future work. Going back to the first motivating questions, we find that in Lafourche Parrish the subsidence signal is higher over the oil and gas fields, but it is a highly localized signal, and on the same order of magnitude as the regional subsidence.

To determine if the rate of subsidence correlates with the rate of oil and gas produced we begin by examining the subsidence rates for both epochs of leveling data and compare that to the fluid production rates. Figure 7 shows the subsidence rate, in mm/yr, along the LA 1 leveling line for the two leveling epochs of 1965-1982 (blue squares) and 1982-1993 (red squares). It is apparent that subsidence rates have almost doubled along the entire line in the second time epoch (1982-1993). If the change in subsidence rate was due solely to changes in fluid production it would be expected that the production rate of fluids in the four major fields crossed by the leveling line would also increase in the second time period. However, for all four fields the production of fluids decreased in the second time epoch while the subsidence rate increased as is illustrated in Figure 8 for Leeville. This indicates that there may be a time dependent subsidence mechanism that is

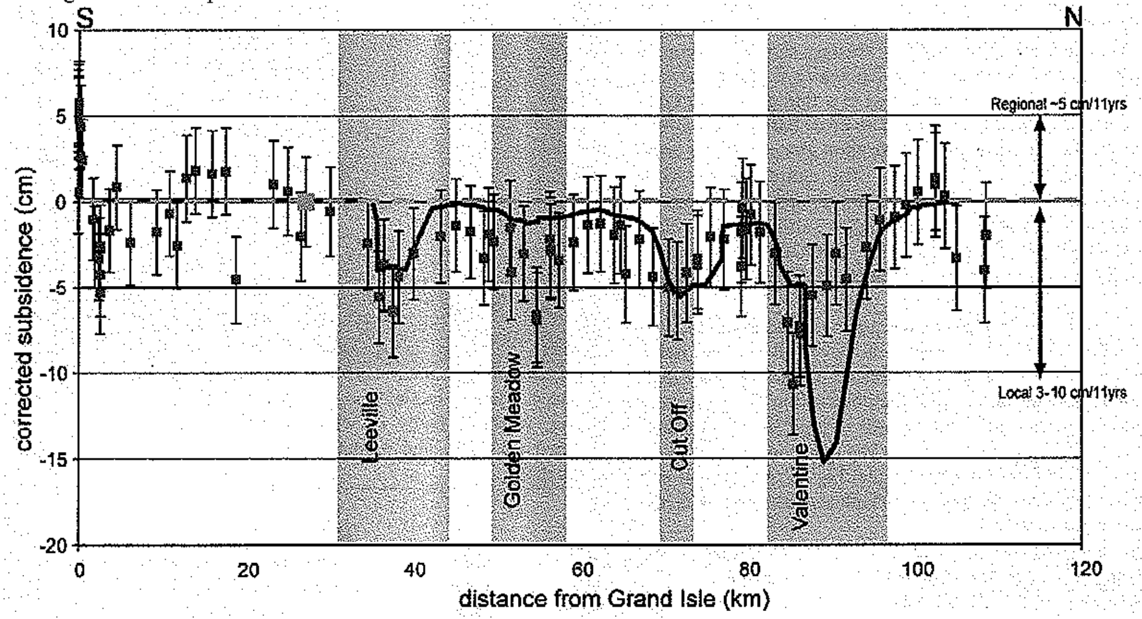

Figure 6: Comparison of subsidence model (solid line) to leveling data relative to station marked by the large square. Important oil and gas fields are shown in grey boxes. Dashed line indicates the approximate regional subsidence observed along the entire line. Compaction of reservoirs in the Leeville, Golden Meadow, Cut Off, and Valentine fields add an additional 3-10 cm of localized subsidence to the regional signal.

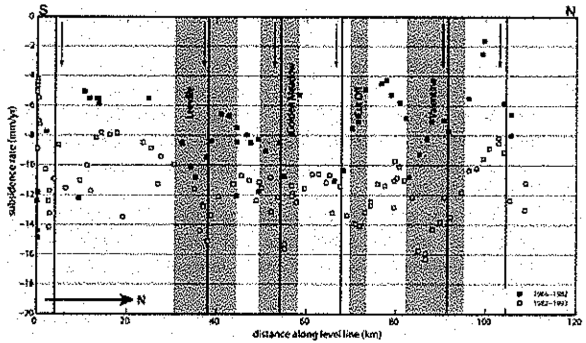

Figure 7: Subsidence rate along LA 1 leveling line for two time-epochs: 1965-1982 (filled squares) and 1982-1993 (hollow squares). Subsidence rate increases over the entire line in the second time epoch.

not being modeled by the simple Geertsma model with an elastic-plastic constitutive law. There are multiple mechanisms that may explain this discrepancy between the production and subsidence rates, including that the reservoirs undergo time-dependent compaction (CHAN et al. 2004), and that the reservoir bounding shales are compacting due to the decrease in reservoir pressure. As the pore pressure decreases in the reservoir due to production the difference in pressure between the reservoir and the sealing shale increases the effective stress on the shales causing them to dewater over longer time periods. This is the same mechanism as that used to explain the delayed subsidence following water production observed in California's San Joaquin Basin (POLAND et al. 1975). In addition, that the subsidence rate is higher everywhere in epoch 2 suggests a regional process as opposed to the local signal expected from oil and gas production.

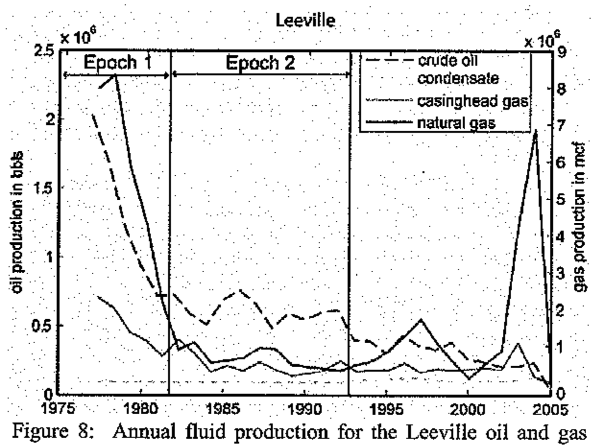

Figure 8: Annual fluid production for the Leeville oil and gas field. Production is lower in the second time epoch when subsidence rates are higher indicating that either fluid production is not responsible for the increase in subsidence rate, or there is a time dependent deformation due to the fluid production that is not modeled in the simple elastic-plastic Geertsma solution. Similar results are seen for the Golden Meadow, Cut Off and Valentine fields.

## DISCUSSION

This work is an important extension of previous work attempting to identify the mechanisms responsible for subsidence in the LCZ. Most previous studies correlating fluid withdrawal with regional subsidence have been largely qualitative (MORTON et al. 2001; 2002; 2003b; 2003a; 2005b; 2005a; 2006). Generally these researchers simply compared aerial photographs to identify submerged regions regardless of the mechanism that caused the submergence. Leveling data was only used to show the rate of subsidence and that the regions of increased subsidence rate correlate with the oil and gas fields. MORTON et al. (2006) observe that wells in the Lapeyrouse field show marked pressure declines to substantially sub-hydrostatic levels, and that this along with observations in Texas of regional depressurization from fluid withdrawal causes them to conclude that the depressurization due to hydrocarbon production in the LCZ must also be leading to a regional depressurization. However, examination of bottom hole pressure data from multiple fields in the LCZ by CHAN AND ZOBACK (in press) and this study show that the producing reservoirs are highly compartmentalized such that depressurization caused by production in one well may not have any effect on the pressures in adjacent or nearby wells. Due to this compartmentalization more detailed pressure data and modeling needs to be used to determine the role of fluid withdrawal on regional depressurization and subsidence. The generalized Geertsma model shown in Figure 1, along with the modeled results in Figures 5 and 6, indicates that with reservoirs of a finite diameter the surface subsidence due to fluid withdrawal highly local, and can't explain the entire regional subsidence signal.

MORTON et al. (2006) suggest that since the most rapid period of wetland loss in the LCZ correlates well with the period of highest fluid production, and that as production decreases so will the subsidence such that in the future subsidence due to fluid withdrawal will likely be a decreasing problem. However, they also observe the acceleration of subsidence rate along LA 1 from the 1965-1982 to the 1982-1993 leveling epochs which we have shown is actually a time when the production rates were decreasing. These two points contradict each other, or indicate that another mechanism not addressed by MORTON et al. (2006) is driving the increased subsidence rate.

In addition to subsidence being driven by fluid withdrawal, some authors argue for a tectonic component of subsidence in the LCZ (DOKKA 2006; GAGLIANO et al. 2003). DOKKA (2006) specifically argues that some, if not all, of the subsidence signal in the LCZ is due to natural movement along the regional growth faults. DOKKA chooses a study area near the identified Michoud fault near New Orleans where the lack of oil and gas wells along with the magnitude of subsidence observed indicate that the observed subsidence signal is driven by a large, deep-seated, tectonic component, and that other subsidence mechanisms are inadequate to explain the observed subsidence (2006). While the Michoud fault may have a strong influence on the local subsidence in DOKKA's (2006) study, many other locations in the LCZ either show evidence of production induced faulting (CHAN and ZOBACK in press) or no strong signal of fault movement (this study). So, while natural movement along regional growth faults is a mechanism that needs to be considered and included in modeling subsidence in the LCZ, it seems that the dominating signal is highly spatially varying.

Fluid withdrawal is one of many mechanisms that contribute to subsidence in the LCZ. Other researchers are modeling the effect of compaction of Holocene sediments (MECKEL et al. 2006), lithospheric flexure due to the loading of the Mississippi Delta, and natural movement of the regional growth faults (DOKKA 2006). These studies illustrate that at any given location in the LCZ these different subsidence mechanisms will have varying influences on the local subsidence signal. Thus, one simple model of subsidence will be inadequate to explain the spatial and temporal variability of subsidence in the LCZ. Future work would benefit greatly from lab data for on-shore reservoir samples to constrain the constitutive laws, more and better pressure data including possible pressure recoveries after production has ended, better surface data from either long-term, permanent GPS stations or InSAR, and more detailed finite-element modeling. Any study of wetland loss and its impact on the local ecosystem will benefit greatly from an accurate, spatially variable model that accounts for all important mechanisms of land subsidence, including subsidence related to reservoir compaction and induced fault movement.

## CONCLUSIONS

Using bottom hole pressure data, a constitutive law for Gulf of Mexico sands, and a generalized Gulf of Mexico stress path we modeled the effect fluid withdrawal in the Leeville, Golden Meadow, Cut Off, and Valentine oil and gas fields had on the regional subsidence between 1982 and 1993. We then compared it to what was observed along the first order leveling line along LA 1 in Lafourche Parrish, Louisiana. We find that the observations of localized subsidence of ~3-10 cm over the modeled fields between 1982 and 1993 is consistent with what is theoretically expected from reservoir compaction. The amount of localized subsidence over the fields is comparable to the regional signal of ~ 5 cm over the same 11 years. The subsidence due to reservoir compaction is highly localized over the oil and gas fields, whereas regional subsidence is seen everywhere. In this location, induced fault slip will likely contribute only a small amount to the localized subsidence, and the signal is within the error of the leveling data. Compaction due to fluid withdrawal in the Leeville, Golden Meadow, Cut Off, and Valentine fields does have an effect on localized subsidence, but can not account for the entire observed regional subsidence signal. In addition, acceleration of subsidence rates from the 1965-1982 to the 1982-1993 leveling epochs while production rated decreased indicates that there is a time-dependent component due possibly to compaction of shales after production, or another un-modeled regional subsidence signal. In order to accurately model subsidence in the Louisiana Coastal Zone reservoir compaction due to fluid withdrawal must be integrated with other more regional subsidence mechanisms, such as compaction of Holocene sediments and lithospheric flexure, to create an integrated model of subsidence.

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