GEOLOGIC IMPLICATIONS OF GEODETIC EVIDENCE OF MAJOR SUBSIDENCE AND INUNDATION OF THE GULF COAST

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INTRODUCTION

It has been long-recognized that the south-central United States of America bordering the Gulf of Mexico (GOM) is actively subsiding, resulting in a slow, yet unrelenting inundation of the coast. This effect has been most apparent in the lower reaches of the alluvial valley of the Mississippi River (MAV) and its Holocene delta in southeast Louisiana where over ~75 km^2 of land has been lost per year over the past 50 years (Barras et al., 1994; Dunbar et al., 1992). This "quiet" disaster has major implications for public safety, ecological systems, and commerce. For example, coastal Louisiana is the site of America's largest and most prolific coastal wetland, the USA's energy heartland, and is home to over 2 million residents who live primarily on narrow, alluvial ridges. Inundation has been linked to a wide range of causes including subsidence of the land, eustatic sea level rise, and sediment starvation of the delta due to construction of flood control levees along the Mississippi River. Most coastal geologists and biologists involved in coastal studies, however, have regarded land loss as a consequence of processes that primarily affect only wetland areas. Furthermore, subsidence has generally been regarded as a near surface effect, being the consequence of shallow sedimentary processes acting on young deposits, i.e., compaction/compaction, and as the result of human activities, e.g., oil and gas extraction, drainage practices, groundwater offtake. The regional tectonic processes that have made it possible for the gulf to accommodate ~20,000 m of sediments since the Jurassic (e.g., Worrall and Snelson, 1989) have rarely been invoked as important controls by recent workers.

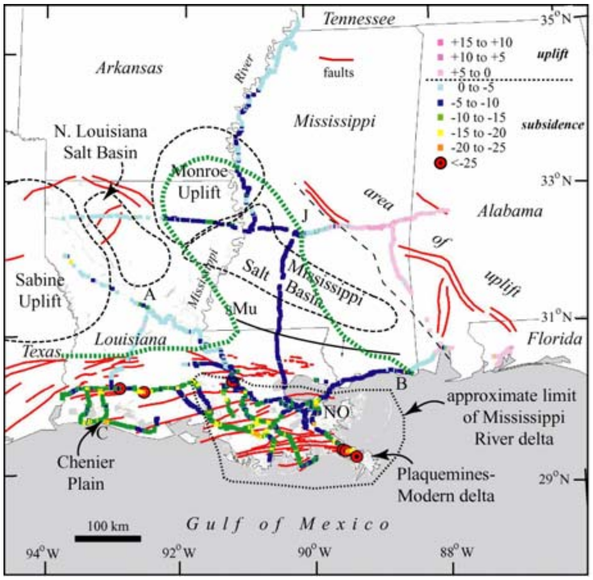


Figure 1. Tectonic map of states bordering the Gulf of Mexico. Colored point symbols are benchmark velocities determined by Shinkle and Dokka (2004). All rates are related to NAVD88. Rates are latest values from a given area and do not represent a single time interval. See Figure 2 for examples of changes in rates over time. Fig. 2 section endpoints: A, Alexandria; B, Biloxi; C, Creole; J, Jackson; NO, New Orleans.

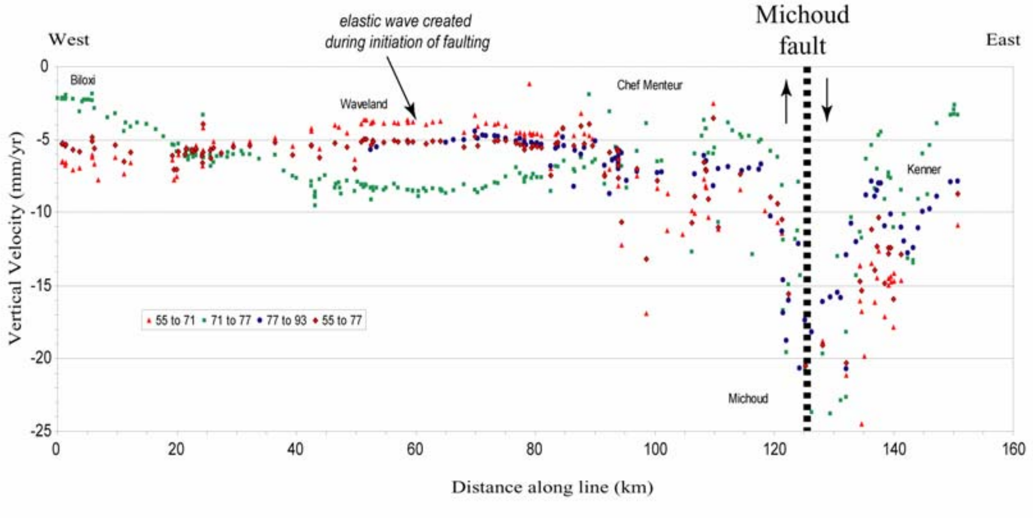
This paper briefly explores the geological implications of a new, regional vertical velocity data set based on 1st order geodetic leveling measurements on benchmarks and tidal records recently published elsewhere by Shinkle and Dokka (2004). In an effort to assess the accuracy of the National Spatial Reference System in the region, Shinkle and Dokka computed vertical motions on 2710 benchmarks throughout Louisiana, Mississippi, and coastal areas of Alabama and Florida were indexed to the North American Vertical Datum of 1988 (NAVD88). Below, these rates are compared with previous values, and it is concluded that modern subsidence has occurred at substantially higher rates than previously thought and that subsidence occurs far beyond the wetlands of the Mississippi River delta (MRD; Figure 1). The data do not support the widely held contention that modern subsidence is the result of merely young sediment compaction/consolidation and human related activities such as oil and gas extraction. The data instead demonstrate that subsidence has multiple natural and human-induced causes that include a large tectonic component and locally, a substantial fault component.

GEODETICALLY DERIVED VERTICAL VELOCITIES

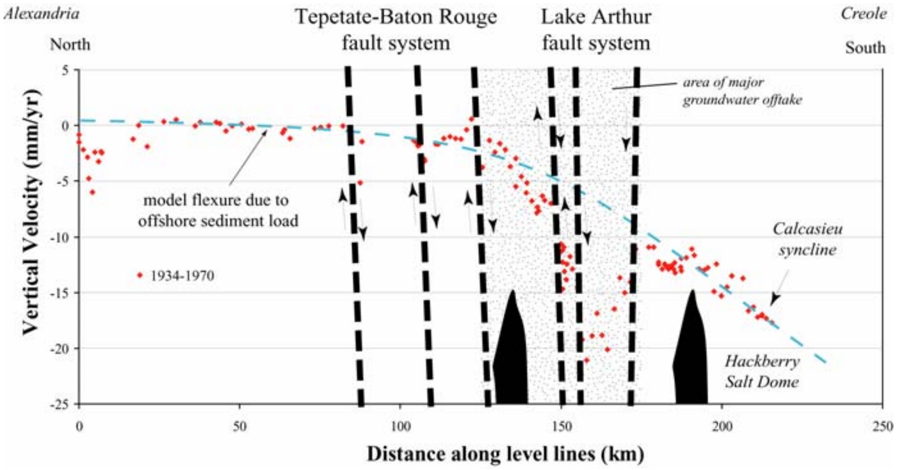
Figure 1 shows some of the vertical velocities computed by Shinkle and Dokka (2004) using NOAA data archives from ~1920-1995. Readers are urged to consult that paper for details on methods and assumptions. This map shows the latest rates at all benchmarks and thus does not represent a single interval of time. In contrast, Figure 2 shows several sections through the region and depicts motions over specific time intervals.

GEOLOGIC OBSERVATIONS

Examination of the spatial distribution of moving benchmarks in the context of their geologic setting provides important insights into processes governing subsidence. First, the most obvious observation is that subsidence occurs far beyond the areal limits of the deltaic plain (Fig. 1 and 2). This is in marked contrast with the prevailing view that considers subsidence to be: 1) concentrated in the modern Holocene delta (MRD) and the alluvial valley of the Mississippi River (MAV); and 2) is primarily the result of local sediment compaction and consolidation (e.g., Saucier, 1994, Roberts, 1997). Subsidence rates gradually decline away from the northern and eastern limits of the MRD in Louisiana, reaching zero velocities in northeastern Mississippi and Alabama. Beyond these areas, velocities are positive indicating uplift. North of the MRD (north shore of Lake Pontchartrain), velocities are negative and gradually decline to the north. They peak briefly near the Southern Mississippi “uplift” but subsidence continues far to north along the MAV to near southwestern-most Tennessee (Fig. 1); the “uplift” is actually an actively forming antiform that is subsiding relative to NAVD88. At the latitude of Vicksburg, an area of subsidence centered at Tallulah, LA, is flanked to the east and west by uplifted areas. This may be due to the load of the Quaternary sediments in the MAV. To the west, rates remain high across both the coastal Chenier Plain and Cajun Prairie of southwestern Louisiana (Fig. 1). Previous studies indicate that subsidence continues west along the Texas gulf coast (Holdal and Morrison, 1974). In southwestern Louisiana, rates increase sharply south of the Tepatate fault system (Heltz and Dokka, 2004). Relations in the area show a strong association of fault slip to groundwater offtake as a function of time. As the volume of water pumping increased markedly in from the early 1950s through the mid 1980s, so did the motion on local normal faults. Both processes slowed *a)*


West
elastic wave created
during initiation of faulting
Michoud
fault
East
Biloxi
Waveland
Chef Menteur
Kenner
Michoud
Vertical Velocity (mm/yr)
0
-5
-10
-15
-20
-25
▲ 55 to 71 ● 71 to 77 ● 77 to 93 ◆ 55 to 77
0
20
40
60
80
100
120
140
160
Distance along line (km)

b)


Alexandria
North
Tepetate-Baton Rouge
fault system
Lake Arthur
fault system
Creole
South
area of major
groundwater offtake
model flexure due to
offshore sediment load
◆ 1934-1970
Calcasieu
syncline
Hackberry
Salt Dome
Vertical Velocity (mm/yr)
5
0
-5
-10
-15
-20
-25
0
50
100
150
200
250
Distance along level lines (km)

c)

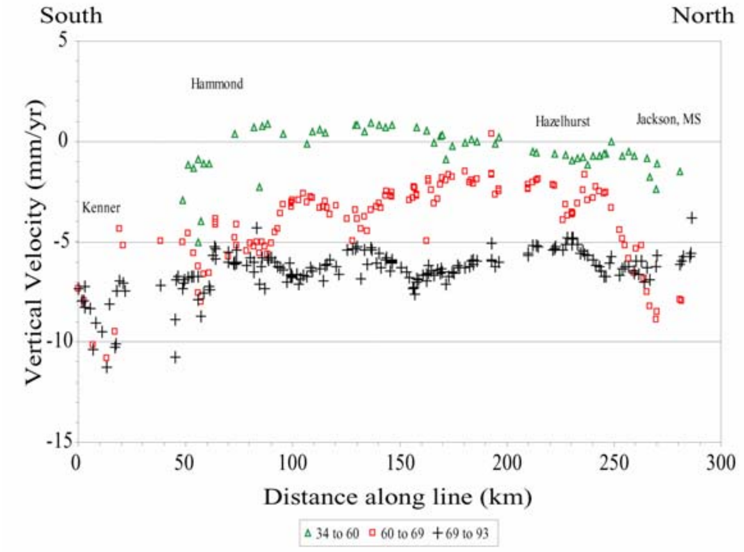

South
North
Hammond
Hazelhurst
Jackson, MS
Kenner
Vertical Velocity (mm/yr)
5
0
-5
-10
-15
0
50
100
150
200
250
300
Distance along line (km)
△ 34 to 60 □ 60 to 69 + 69 to 93

Figure 2. Selected vertical velocity profiles across the south-central United States highlighting areas of historic subsidence; data from Shinkle and Dokka (2004). See Fig. 1 for locations. a) Biloxi, MS to Kenner, LA (near New Orleans). Major episode of subsidence beginning near 1969 is associated with initiation of major slip along Michoud fault in east New Orleans. Aseismic but protracted interval of strain release is suggestive of a "slow earthquake" that is not yet complete (period >35 yrs!). Note also apparent elastic wave generated in area east of fault (amplitude = ~5 cm, wavelength = ~135 km) during strain release event. b) Subsidence between Alexandria to Creole, LA between 1938-1970. Analysis of groundwater offtake records and fault slips strongly imply a causative relationship. These data show that most subsidence and fault motion stopped in the late 1980s when groundwater offtake was abruptly curtailed (Heltz and Dokka, in preparation, 2005). Removal of the groundwater effect, however, leaves a residual subsidence that increases steadily towards the south. This suggests that large, ~6km thick, Pleistocene loads that lie offshore (e.g., Worrall and Snelson, 1989) have not yet been fully compensated. c) Kenner, LA to Jackson, MS. Some local vee-shaped velocity anomalies are associated with groundwater offtake of shallow aquifers (e.g., near Jackson).

abruptly in the late 1980s. In contrast, much of west-central and northwest Louisiana has been stable. Near Baton Rouge, rates abruptly slow north of the Denham Springs fault.

Second, examination of benchmark velocities as a function of time shows that motions have not been linear through time. This suggests that multiple natural and human-induced processes area at work and that some processes have varied through time. Because some of these and other processes are probably unpredictable, e.g., faulting related strains, politically driven human responses to subsidence, eustatic sea level rise, modeling future subsidence and resultant inundation of areas by the Gulf of Mexico will be unsatisfying.

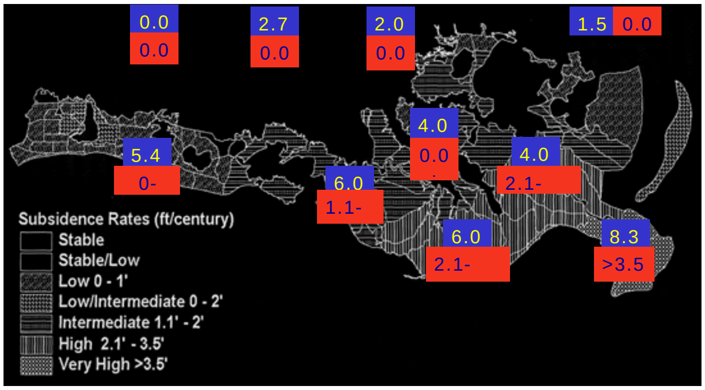


Figure 3. Generalized subsidence rates from wetland areas (Gagliano, 1999) with rates from adjacent land areas implied by geodetic study of Shinkle and Dokka (2004).

The third observation is that subsidence rates based on benchmarks in coastal Louisiana are 2 to 50 times higher than estimates based on peat deposits (Fig. 3); these estimates are the primary basis for the prevailing view on the cause of coastal inundation and land loss (se excellent discussion in Gagliano, 1999). Subsidence in the delta plain is most rapid in the youngest delta lobe (Plaquemines-Modern or “Birds-foot” delta) where: 1) recent sediment accumulation and associated compaction rates are greatest; 2) normal faulting is most active; and 3) sediments are least compacted and consolidated. The greatest surprise in the geography of subsidence occurs, however, in southwest Louisiana. Here, peat chronostratigraphic estimates suggest that only slight subsidence (~0.03 m/century) occurs, whereas benchmark velocities rates are 1.0-2.4 m/century (10-24 mm/yr). The final observation is that differential motion between benchmarks straddling fault-line scarps or surface projections of subsurface normal faults of the region support the notion that many of these faults are indeed active today and contribute to subsidence and resultant inundation. The Michoud fault, shown on Figure 2a, is an excellent example.

IMPLICATIONS FOR COASTAL PUBLIC POLICY

Mitigation strategies to help wetlands areas have been developed (see www.americaswetlands.org). Such strategies, however, cannot help the subsiding land areas of the coast where people live and work. Higher levees are needed now.

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