The role of deep processes in late 20th century subsidence of New Orleans and coastal areas of southern Louisiana and Mississippi

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[1] Geodetic leveling observations from Biloxi, MS, to New Orleans, LA, and water level gauge measurements in the New Orleans–Lake Pontchartrain area were analyzed to infer late 20th century vertical motions. These data were used to test the validity of previous subsidence rate measurements and the models that predict the location and causes of subsidence. Water gauges attached to bridge foundations and benchmarks affixed to deep rods that penetrate Holocene strata subsided as much as 0.8 m locally between 1955 and 1995. The observed deep-seated subsidence far exceeds model predictions and demonstrates that shallow processes such as compaction and consolidation of Holocene sediments are inadequate by themselves to explain late 20th century subsidence. Deep-seated subsidence occurring east and north of the normal faults marking the Gulf of Mexico basin margin can be explained by local groundwater withdrawal, and regional tectonic loading of the lithosphere by the modern Mississippi River delta (MRD). Sharp changes in subsidence coincide with strands of the basin margin normal faults. Displacements are consistent with activity and show motions consonant with fault creep. Deep subsidence of the region to the south, including New Orleans, can be explained by a combination of groundwater withdrawal from shallow upper Pleistocene aquifers, the aforementioned lithospheric loading, and perhaps, nongroundwater-related faulting. Subsidence due to groundwater extraction from aquifers ~160 to 200 m deep dominated urbanized areas and is likely responsible for helping to lower local flood protection structures and bridges by as much as ~0.8 m.

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1. Introduction

1.1. Origin of the Modern Landscape of Southeast Louisiana and Southern Mississippi

[2] Twentieth century tide gauges have chronicled the inundation of the northern coast of the Gulf of Mexico and have highlighted the contribution of subsidence to relative sea level rise and landscape change [e.g., *Penland and Ramsey*, 1990; *Turner*, 1991]. The societal cost of inundation by the advancing Gulf of Mexico is immense. It is estimated that over ~77 km^2 (~30 mi^2) of land was lost per year between 1978 and 2000 in south Louisiana alone [*Barras et al.*, 2003]. This "slow motion" disaster has and continues to have major implications for hurricane protection system design, coastal restoration planning, commerce, and energy production.

[3] It is widely held that the current landscape of south Louisiana and environs is due primarily to the interplay of sediment accretion, ocean currents, tides, waves, global sea level rise, subsidence, and human activities. River flooding has built the Mississippi River delta (MRD) by terrigenous sediment deposition and by wetland biologic processes that produce organic matter (Figure 1) [e.g., *Coleman et al.*, 1998; *Delaune et al.*, 1992]. The upward growth of the MRD during Holocene time is evidence that it has accreted sufficiently over the past several thousand years to generally maintain its position with respect to sea level in spite of a slowly rising world ocean and local subsidence. Unfortunately, this natural system was disrupted by humans seeking relief from river flooding and development of new lands for agriculture and settlement [e.g., *Barry*, 1998]. Although 20th century flood control measures have effectively stopped river flooding and maintained Mississippi River navigation for commerce as mandated by the United States Congress, these measures severely reduced the terrigenous sediment and freshwater influx (for wetlands organic sediment production) to the MRD that once balanced the effects of natural subsidence, coastal erosion, and eustatic rise. Although anthropogenic influences may also extend to modern and future eustasy, there is no doubt that local subsidence of the landscape has been accelerated and/or

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augmented by humans expanding their habitat to coastal environments of the northern Gulf of Mexico.

1.2. Subsidence, Measurement Methods, and Controversies

[4] Subsidence is defined as the downward movement of the Earth with respect to a datum or point of reference [*Dokka*, 2006]. It is a condition that can result from many natural and anthropogenic processes, some operating simultaneously. Because subsidence is spatially and temporally variable, it is thus critical to include in any description of subsidence the specific time and space where process observations and measurements pertain.

[5] The paradigm that underpins recent and near future engineering design for coastal protection and restoration in the region is based on subsidence estimates that are mainly century- to millennial-scale averages derived from chronostratigraphic measurements of Holocene sediments [*Louisiana Coastal Wetlands Conservation and Restoration Task Force and the Wetlands Conservation and Restoration Authority* (*LCWCRTF*), 1998; *U.S. Army Corps of Engineers* (*USACE*), 2007]. Some have used these estimates to claim that much of the Louisiana coast has been and continues to be stable in a vertical sense [*Törnqvist et al.*, 2006; *González and Törnqvist*, 2006] and that subsidence is primarily due to consolidation and compaction of Holocene sediments [e.g., *Ramsey and Moslow*, 1987; *Kuecher*, 1995; *Roberts et al.*, 1994; *Roberts*, 1997; *Kulp*, 2000; *Törnqvist et al.*, 2008]. Recent geodetic leveling studies, however, have challenged this paradigm by showing that late 20th century subsidence has not been constant, rather it has been temporally and spatially more variable than can be explained by processes only affecting Holocene sediments [e.g., *Shinkle and Dokka*, 2004; *Dokka*, 2006]. The study by *Shinkle and Dokka* [2004] was performed to assess changes to the National Spatial Reference System and provided velocities on over 2700 benchmarks throughout the south central United States of America. *Dokka* [2006] later showed that subsidence varied over time, but also as a function of depth.

[6] Differences in sampling, measurement methods, and analysis procedures have resulted in two schools of thought regarding the relative contributions of causative process and their aggregate impact on late 20th century subsidence along the northern Gulf of Mexico basin [*Dokka*, 2009]. The overall approach followed by both geologic and geodetic/water level gauge based methods in establishing the subsidence history is similar in several fundamental ways. First, all methods collect field samples to ascertain subsidence through an assessment of their vertical position as a function of time. The quality of the observations depends on the intrinsic precision of the specific methods employed to measure time and space, and on the quality of spatially and temporally precise data used for the establishment of accuracy [*Dokka*, 2009]. Second, because the frequency of sampling associated with geodetic leveling and chronostratigraphic methods are not continuous or uniform through time, the temporal spacing between observations can strongly influence subsidence estimates [e.g., *Meckel*, 2008]. The quantity of observations in the sample space of interest will determine how well we can constrain the subsidence history; the sample space considered in this paper is the late 20th century. Third, the spatial and temporal dimensions of individual samples will define the resolution and limitations of the results. Such values will define the size of the area and time interval over which the measurement should apply. Finally, all methods interpolate between points using simple linear or low order polynomial regression models to complete the establishment of the subsidence history. Our confidence in such interpolations will depend on statistical testing or independent confirmation. Let us now explore how these factors affect the quality of measurements.

[7] There are substantial quantitative and qualitative differences in the precision and accuracy of measurements by different methods [*Dokka*, 2009]. For example, geodetic leveling and water level gauge analysis can provide actual millimeter level observations of late 20th century vertical motion with respect to precise modern data. In this and previous geodetic leveling and tide gauge studies of the region, measurement uncertainties, the dates of surveys, and frequency of observations are well known. The frequency of geodetic leveling surveys was yearly and decadal, whereas water level gauge measurements were measured each day or each month [e.g., *Shinkle and Dokka*, 2004]. The uncertainties associated geodetic leveling observations can thus be described in units of mm yr^{-1} and have been validated by independent measurements that share common sampling time, data, and monumentation [*Dokka*, 2009; *Shinkle and Dokka*, 2004]. In contrast, few if any estimates of 20th century subsidence rates derived from chronostratigraphic studies actually include observations from 20th century materials [e.g., *Kulp*, 2000; *Törnqvist et al.*, 2004, 2006]. Samples from studies in the region have yielded spatial measurements with uncertainties in the meter range. Dating of samples by radiocarbon techniques have typical uncertainties that range from several decades to hundreds of years, with samples separated in time by hundreds and thousands of years [e.g., *Kulp*, 2000; *Törnqvist et al.*, 2004, 2006]. Uncertainties in chronostratigraphic studies can thus be more appropriately described in units of m $century^{-1}$.

[8] The granularity of sampling in space and time constrains our ability to quantify the causative processes of subsidence. For example, a grid of widely spaced samples may be sufficient to document regional subsidence due to loading, but it may be inadequate to capture or even detect the very local effects of a fault or a groundwater well. Geodetic leveling and water level gauge methods have the advantage of being able to measure subsidence at a single point, as well document how subsidence has varied as a function of time [*Dokka*, 2006]. Although water level gauges are limited to points along the coast, such stations are unique for the late 20th century in that they can provide a high frequency record of subsidence; space geodetic techniques can also provide such high frequency data [*Dokka et al.*, 2006]. In contrast, chronostratigraphic studies which use the basal Holocene peat as a surrogate for ancient sea level cannot establish the history of subsidence at a single point or determine how subsidence varied in a region as a function of time [cf. *Törnqvist et al.*, 2004, 2006]. This is because the ever rising Gulf of Mexico through the Holocene has only left behind a single basal peat layer at any location [*Törnqvist et al.*, 2004]. With only one basal peat available, only one measurement at a point is possible. Some have gathered data to reconstruct the subsidence history by

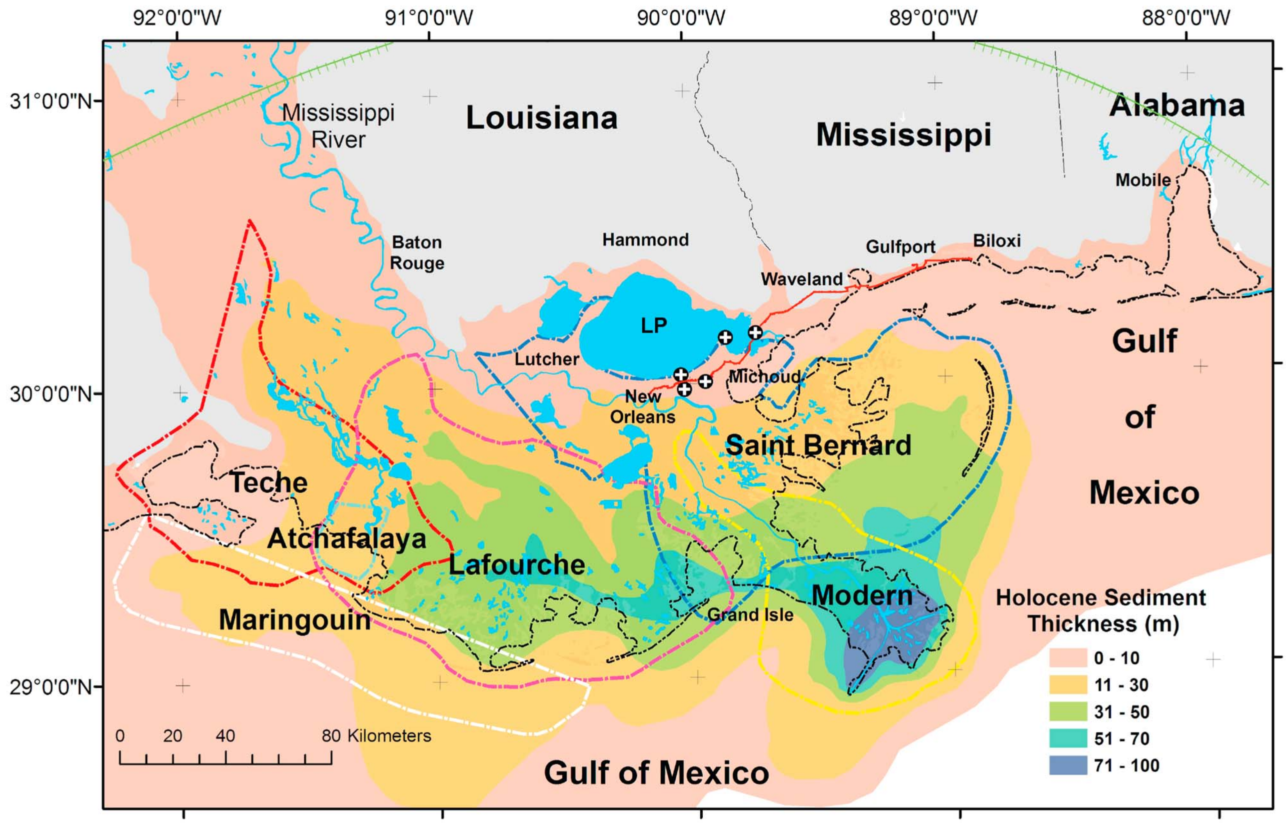

Figure 1. Index map of the southern Louisiana and Mississippi area, emphasizing the location of the depositional lobes and the thickness of the Holocene Mississippi River delta [from *Coleman et al.*, 1998; *Kulp*, 2000]. Hachured green line marks the approximate northern extent (-1 mm yr^{-1} contour) of the subsidence caused by the loads of the delta and rising seas [*Ivins et al.*, 2007]. Location of New Orleans to Biloxi leveling profiles in Figure 3, red solid line. U.S Army Corps of Engineers water level gauges denoted by circles with crosses.

obtaining and analyzing several cores containing a different age basal peat layer in an area. A study of the Lutcher, LA area (~30°03′N, 90°42′W), for example, used several cores distributed over an area of ~4.7 km^2, with peats spanning in age from 3,460 to 7,080 years BP [*Törnqvist et al.*, 2006]. The subsidence measurement, thus, does not reflect change at a point, but rather the integrated subsidence averaged over the footprint of the cores and over the time represented by the cores.

[9] The final step in the construction of a subsidence history typically involves an interpolation of the region between observations using regression analysis. Although space precludes a more complete treatment of regression, one facet deserves mention here. It is noted that the choice of the regression model for the interpolation can have important consequences that can greatly influence subsequent interpretation. In the above example, a near linear model was used to interpolate between ~3,620 years and today [*Törnqvist et al.*, 2006]. It was then concluded that subsidence had been steady and slow through time between observed points [*Törnqvist et al.*, 2006]. No corroborating data were provided, particularly for the late 20th century, when known or suspected anthropogenic drivers such as local groundwater offtake and oil extraction were active. With no direct observations of the position of the peat during the late 20th century, model subsidence rates proposed to be representative of the present can be highly biased by the reliance on prehistoric samples. The result of the imposition of a linear interpolation model is that it tends to smooth away the effects of any short-lived events and processes that may have occurred. The effect of smoothing becomes more profound as the time interval of interpolation increases. In this paper, daily water level gauge measurements provide independent confirmation of the history and rate of subsidence estimated by geodetic leveling at several points.

[10] Although the geodetic leveling measurements of *Shinkle and Dokka* [2004] and *Dokka* [2006] are consistent with temporally similar local and regional tide gauge records, these estimates continue to be controversial to some not only for their differences with subsidence estimates derived from chronostratigraphic studies, but also because they are not congruent with estimates based on late 20th century space-based geodesy [*Meckel*, 2008]. As part of a broader study to better understand the subsidence rate controversy, *Meckel* [2008] compared the results of previous geodetic leveling of *Shinkle and Dokka* [2004] with the values derived from continuous Global Positioning System (cGPS) measurements by *Dokka et al.* [2006] on stations located north of Lake Pontchartrain and radar interferometry (InSAR) measurements in the New Orleans area by *Dixon et al.* [2006]. *Meckel* [2008] concluded that: *"Geodetic rates do not*

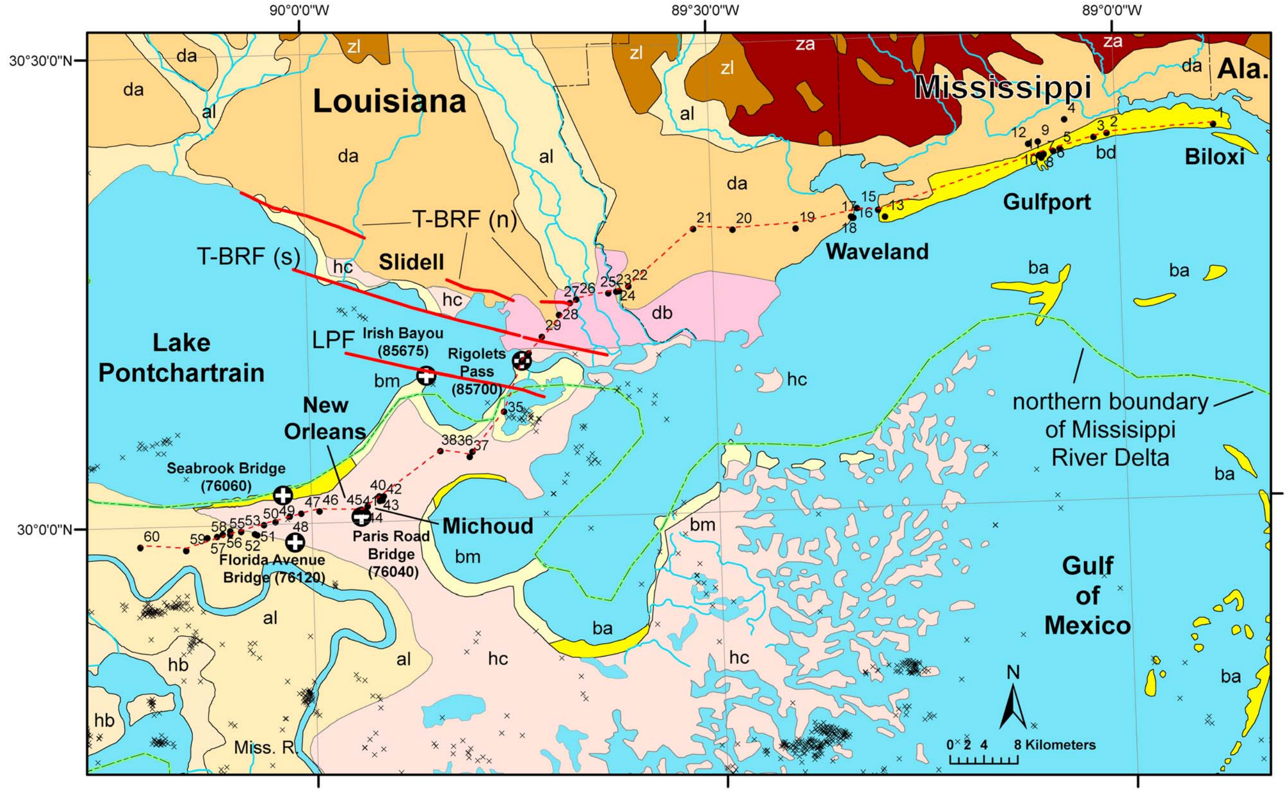

Figure 2. Geologic map and sample localities of study area. Surface materials map from the U.S. Geological Survey. Geodetic leveling survey benchmarks denoted by black dots and numbers; numbers correspond to ID numbers in Table 1. Location of profiles in Figure 3, thin red dashed line. U.S Army Corps of Engineers water level gauges denoted by circles with crosses. Active normal faults of the basin margin shown as thick red lines: Tepatate–Baton Rouge fault (north branch), T-BRF (n); Tepatate–Baton Rouge fault (south branch), T-BRF (s); Lake Pontchartrain, LPF. Northern limit of Saint Bernard delta lobe is noted by green dashed line. Surface materials: al, Holocene and upper Wisconsin age channel and floodplain alluvium; ba, Holocene age barrier island beach deposit composed of shell fragment and shell sand; bd, Holocene age beach deposits composed of sand and dune sand; bm, Holocene age beach deposit composed of mud; da, Pleistocene and Pliocene age coastal plain and marine deposits composed of deltaic sediments; db, Holocene age coastal plain and marine deposits composed of deltaic sediments; hb, Holocene age freshwater coastal marsh peat and clay; hc, Holocene and late Wisconsin age coastal deposits composed of freshwater, brackish water, and (or) saline marsh deposits; za, Decomposition residuum (clays to sand) of Quaternary and Tertiary age on other sedimentary rocks; zl Decomposition residuum (quartz and chert gravel) of Quaternary and Tertiary age. Hydrocarbon wells producing between 1955 and 1995, small black diagonal crosses.

appear to compare well with available InSAR or GPS data, but more rigorous direct comparisons are needed. Measurement accuracy seems unlikely to cause the discrepancy in observed subsidence rate distributions." While seemingly paradoxical, the conclusion by *Meckel* [2008] is quite important because it implies that a comparison of merely rates or vertical motions maybe insufficient to effectively interpret subsidence estimates.

[11] Reappraisal of the area considered by *Meckel* [2008] shows that none the cGPS stations of the region are colocated with the benchmarks of the leveling studies. The closest cGPS station to the level lines of *Shinkle and Dokka* [2004] is in Hammond, LA, and is designated by NGS as, HAMM (30°30′47.05159″N, 90°28′03.42873″W). The most proximal benchmark to HAMM in the *Shinkle and Dokka* analysis is "F 179" (30°32′58″N, 90°28′29″W) and it is ~2.6 km away. It is also noted that the monumentation for each measurement system is set to a different depth and thus record different amounts of subsidence [*Shinkle and Dokka*, 2004]. The benchmarks of the area in question consist mainly of NGS Class C marks that are basically affixed to the top of surface soil [*Shinkle and Dokka*, 2004]; "F 179" is a surface mark resting at the top of the exposed Holocene section. Class C marks are the least stable and typically show more motion than one set in bedrock [*Schomaker and Berry*, 1981]. In contrast, HAMM is on a six-story building that has a foundation that is set in Pleistocene bedrock. Finally, it should be noted that the data do not overlap in time. The area was leveled in 1934, 1960, 1969, 1993 and *Shinkle and Dokka* [2004] computed velocities for the intervals

1934–1960, 1960–1969, and 1969–1993. HAMM has been in operation since 2002. The above discussion demonstrates that comparisons should carefully consider temporal, locational, and monumentation differences between measurement systems.

1.3. Hypotheses to be Tested

[12] Two hypotheses regarding late 20th century subsidence of the New Orleans–southern Louisiana and Mississippi region were tested in this study. First, independent subsidence estimates derived from five local area water level gauge records in the New Orleans–southern Louisiana and Mississippi region were used test the validity of the geodetic leveling-based subsidence estimates of *Shinkle and Dokka* [2004] and *Dokka* [2006] (Figure 2). To facilitate this comparison, a more extensive leveling data set than presented by *Shinkle and Dokka* [2004] and *Dokka* [2006] was assembled from NOAA/National Geodetic Survey (NGS) archives (auxiliary material).[1]

[13] The second hypothesis considered here centers on the identification of the dominant cause(s) of late 20th century subsidence in the region. The physical and chemical processes causing 20th century subsidence along the north central Gulf of Mexico have been attributed to a variety of natural and anthropogenic drivers. Natural processes include sediment compaction and consolidation [*Russell*, 1936; *Kolb and Van Lopik*, 1958; *Roberts et al.*, 1994; *Roberts*, 1997; *Cahoon et al.*, 1995; *Meckel et al.*, 2006, 2007; *Meckel*, 2008; *Törnqvist et al.*, 2008], faulting [*Fisk*, 1944; *Murray*, 1961; *Van Siclen*, 1967; *Veerbeek and Clanton*, 1981; *Kuecher*, 1995; *Heltz and Dokka*, 2004; *Dokka*, 2006], sediment diagenesis [*Roberts et al.*, 1994], and tectonic loading [*Ricketts*, 1872; *Jurkowski et al.*, 1984; *Ivins et al.*, 2007]. Anthropogenic activities that can promote subsidence include groundwater withdrawal [*Kazmann and Heath*, 1968; *Gabrysch*, 1980; *Holzer*, 1981], hydrocarbon extraction [*Holzer and Bluntzer*, 1984; *Mallman and Zoback*, 2007], and accelerated compaction and consolidation of Holocene sediments and organic sediment oxidation due to forced drainage within areas protected by levees [*Snowden et al.*, 1977; *Snowden*, 1984]. Most workers have attributed subsidence to dominantly natural and anthropogenic changes that occur within this lithochronostratigraphic unit [e.g., *Kolb and Van Lopik*, 1958; *Roberts et al.*, 1994; *Kuecher*, 1995; *Kulp*, 2000; *Burkett et al.*, 2003; *Törnqvist et al.*, 2006, 2008]. It has been hypothesized that subsidence is associated (in a statistical sense) with Holocene sediment thickness (Figure 1) [*Roberts et al.*, 1994; *Kulp*, 2000; *Meckel*, 2008] or Holocene sediment/soil type [*Burkett et al.*, 2003]. With few exceptions [e.g., *Cahoon et al.*, 1995; *Dokka*, 2006], previous measurement approaches have been two-dimensional, i.e., x and y, lacking consideration of the vertical variability of subsidence or sufficient sampling that could assess the processes that produce subsidence originating below Holocene sediments. As emphasized by *Törnqvist et al.* [2008], there is a critical need for evidence "that fully separate [Holocene] compaction from other processes contributing to subsidence."

[1]Auxiliary material data sets are available at ftp://ftp.agu.org/apend/jb/2010jb008008. Other auxiliary material files are in the HTML.

[14] To test the hypothesis that late 20th century subsidence is dominated by processes originating in Holocene sediments, we have examined the behavior of water level gauges attached to deep piles of bridges and benchmarks that are connected to steel rods seated in upper Pleistocene deposits. Such a sampling design assured that subsidence measurements would contain no effects due to natural and anthropogenic processes originating within the Holocene section. Our expectation was that the results would shed light on the absolute and relative contributions of known or suspected deep processes such groundwater withdrawal, faulting, pre-Holocene compaction, and lithospheric loading.

2. Methods, Data, and Results

2.1. General Strategy

[15] Geodetic leveling and water level observations are measured with respect to local references and must be linked to a datum or a point of known motion for the measurement of vertical landscape change [e.g., *Dokka*, 2009]. Geodetic leveling of benchmarks attached to deep rods considered here were computed in the manner detailed by *Shinkle and Dokka* [2004] and referenced to the long-standing NOAA/National Ocean Service water level gauge at Grand Isle (East Point), LA (29°15′52″N, 89°57′23″W) [*Shinkle and Dokka*, 2004]. It was reasoned that the relative sea level rise (RSL) at the gauge was dominantly the result of local land subsidence and eustatic sea level rise, along with other lesser effects of an oceanographic, astronomic, and hydrologic nature. The widely accepted 20th century eustatic rise value of 2.0 mm yr^{-1} of *Douglas* [1995] was adopted. The approach was validated by the successful prediction of vertical motions implied by other water level gauges along the Gulf coast [*Shinkle and Dokka*, 2004].

2.2. Data

[16] Late 20th century first-order geodetic leveling data were obtained from the NGS and water level gauge records from the USACE (New Orleans District); the locations of studied benchmarks and water level gauges are shown in Figure 2. Descriptions of data are provided in the auxiliary material, along with spreadsheets used for computations and ancillary information. Statistical computations are based on common statistical methods [e.g., *Hayter*, 2002]. A map depicting Holocene thicknesses in the area, along with the locations of benchmarks and water level gauges analyzed in this study, are shown on Figure 1. Thicknesses were estimated from soil borings and shallow seismic data [*Kolb et al.*, 1975; *Kulp*, 2000]. See auxiliary material for selected maps and cross sections from *Kolb et al.* [1975] showing Holocene sediment thickness relations.

2.2.1. Geodetic Leveling

[17] Geodetic leveling is a well-established, straightforward, but complexly structured method to precisely measure the difference in height between two or more points [e.g., *Vanicek et al.*, 1980]. If the points can be related to a common datum and if the time difference between the two surveys is known, then displacements and velocities of these points can be computed [e.g., *Shinkle and Dokka*, 2004]. To better appreciate how geodetic leveling can be used to measure subsidence, let us review the basic tenants of the method.

[18] First-order geodetic leveling, as well all terrestrial geodetic methods, is initially relative, and arbitrarily assumes that the starting point, the "point of beginning" or POB, has a provisional elevation of "zero." Surveying proceeds to other points in the network to determine relative height differences with respect to the POB. Because the survey ultimately returns to the POB, the degree of misclosure provides a measure of the random and systematic error of the entire network; exacting procedures are required for "geodetic quality" leveling to minimize systematic error [e.g., *Bossler*, 1984]. To put the local, relative measurements into a regional or global context, the network needs to be connected to a datum or reference. Only one point on the network is required, but that point must be independently known. Colleagues have often questioned why *Shinkle and Dokka* [2004] and *Dokka* [2006] used the subsiding gauge at Grand Isle (East Point), LA (~3.9 mm yr^{-1}) to reference leveling surveys instead of a gauge located on presumed stable ground such as at Pensacola, FL (30°24.2′N, 87°12.8′W). There are two answers. The short answer is that the Pensacola tide gauge was never directly connected to the NGS level lines considered in this and previous papers, whereas the Grand Isle (East Point) was. The closest benchmarks of the level lines considered by *Shinkle and Dokka* [2004] are 13.2 km from the Pensacola gauge. Proper comparison requires that they *must* be colocated. The other answer is that even if the Pensacola gauge was part of the network, it would not hold any special status. Recall that only one independently known point on the network is needed, and Grand Isle (East Point) gauge fits that criteria as well as Pensacola.

[19] The most common users of the method are geodetic surveyors who use such observations to establish the initial elevations of a vertical control network. These observed height differences and initial elevations are subsequently modified, typically through a least squares approach, to evenly distribute network error revealed by surveying misclosures. The result is a group of internally well-ordered, "adjusted" elevations that are useful for the establishment of vertical control [e.g., *Zilkoski and Reese*, 1986]. The adjustment process, however, alters the relative vertical positions of the points of the survey such that the "adjusted" elevations no longer retain their statistical independence. Because independence is required of each benchmark in the comparison of two surveys, previous studies in the area [e.g., *Zilkoski and Reese*, 1986; *Burkett et al.*, 2003] that computed subsidence by differencing temporally distinct sets of "adjusted" elevations in the study area must be considered problematic. In contrast, *Shinkle and Dokka* [2004] avoided the independence pitfall by computing vertical displacements from only original field height differences between adjacent points.

[20] Vertical displacements were computed for 60 benchmarks from Biloxi, MS, to Kenner, LA (Figure 2 and Table 1); displacements on an additional 10 benchmarks were computed for surveys in 1991 and 1995 in the Michoud-Chalmette area (29°59′N, 89°57′W; auxiliary material). The original surveys were qualified by NGS as first order, class 1 and 2 [*Bossler*, 1984]; regional surveys in 1955, 1969, 1971, 1977, 1991, and 1993/95, were used to compute displacements that occurred between surveys.

[21] Land motions derived from geodetic measurements such as leveling are influenced by several factors that include: the sampling design of original surveys; the time over which subsidence has been averaged; the accuracy of the reference or datum used to relate measurements; and how the observed point is attached to the Earth. First-order leveling is typically done to support development of geodetic control networks and thus, all of these factors are beyond the control *ex post facto* of geologic users. Geodetic studies have access to spatially and temporally precise vertical data; the local relationship between NAVD88 and the water level data are also known (http://www.ngs.noaa.gov/faq.shtml#GeodeticVSTide). The amount of time between surveys affects the sensitivity of a measurement method for process studies. If the time between measurements is long, the smoothing caused by averaging may eliminate details important for process understanding. For example, the history of daily observations at water level gauges and the short time between the leveling surveys considered here allow for the detection of change of decadal scale processes such as groundwater pumping.

[22] The nature of how a monument is physically connected to the Earth determines the amount of the total vertical motion it can record [e.g., *Dokka*, 2006]. Examples of monuments include: shallow-founded infrastructure such as sidewalks, concrete culverts, stainless steel rods of varying lengths, and bridge abutments atop piles that penetrate into the Earth. Piles supporting bridges in the region are driven to a depth sufficient to provide adequate friction for support of vertical dead weight loads and uplift resistance due to wind loads (Burton Kemp, former District Geologist, USACE (New Orleans), written communication, 2010). The depth to which the monument penetrates into the Earth marks the upper limit of the subsurface where vertical change can originate. For example, because no significant dimensional change is expected along the vertical length of steel-reinforced concrete piles supporting a bridge, it is reasonable to assume that the observed vertical motion of the benchmark reflects changes between the bottom of the piles and the center of the Earth. Furthermore, any vertical motion that has occurred above the bottom of the monument is not recorded.

[23] All monuments of this study were set at a depth that was below the base of local Holocene deposits (Table 1). This was confirmed by examination of installation records (NGS datasheets, (http://www.ngs.noaa.gov/cgi-bin/datasheet.prl), soil boring logs [*Kolb et al.*, 1975], review of as-built construction drawings of bridges and other massive structures, e.g., large building foundations and seawalls, and field examination to confirm that some monuments are set directly into Pleistocene deposits. This study also includes several benchmarks that are attached to deep set water well casings (~180 m) and an ~2000 m injection well casing (Waste Well 2; Table 1); the water well casings terminate in upper Pleistocene sands, whereas the injection well penetrates into middle Miocene strata [*Dokka*, 2006]; Waste Well 2 is located at 30°01′23″N, 89°54′46″W. Thus, it is reasonable to conclude that all deep set benchmark and water level gauge data considered here do not contain any effect of compaction, consolidation, or oxidation of Holocene sediments.

[24] Figure 3a shows that all benchmarks from all surveys subsided between 1969 and 1995; similar results can be seen in Figure 3b (1955–1993/95). The narrow belt of generally

Table 1. Summary of Vertical Displacements Inferred From Geodetic Leveling Surveys on Deep Set Benchmarks From Biloxi, MS to New Orleans, LA[a]

ID[b]	NGS Benchmark	Distance From U 189 (km)	Depth and Soil Type[c]	Displacement (mm)							Error 95% CI
				1955–1969	1955–1971	1955–1977	1955–1993/1995	1969–1971	1969–1977	1969–1993/1995	
2	S 234	12.6	20.4					−15.7	−35.9		2.1
3	F 215	14.3	ms-b					−15.9	−36.7		2.4
4	Y 234	17	ms-b, QP					−13.4	−48.4		2.8
5	R 191	18.5	ms-b	−74.60	−90.4	−120.2		−15.8	−45.6		3.0
6	Q 191	19.4	ms-b	−93.07	−108.3	−141.3		−15.2	−48.2		3.2
7	P 191	20.6	ms-b	−71.94	−83.1	−118.3					3.4
8	N 191	20.8	ms-b	−65.33	−76.1	−110.0		−10.8	−44.7		3.4
9	K 191	20.8	ms-b, QP	−73.55	−85.2	−119.5					3.4
10	M 191 RESET 1963	21	ms-b					−10.2	−46.7		3.5
11	W 214	21.1	22.4					−11.3	−43.5		3.5
12	F 191	21.9	ms-b, QP	−74.31	−84.9	−124.3					3.6
13	U 190	40.7	ms-p	−59.70	−58.5	−104.6					6.7
14	EAST	42.2	ms-br, QP	−74.89	−77.9	−123.2					7.0
15	WEST	44.8	ms-br, QP	−58.00	−51.9	−101.2					7.4
16	V 234	45.5	ms-br, QP					3.1	−45.9		7.5
17	T 190	45.6	ms-b, QP	−49.26	−46.1	−94.6		3.2	−45.4		7.5
18	874 7438 TIDAL 2	45.7	ms-b, QP	−49.51	−50.9	−98.5		−1.4	−49.0		7.5
19	A 215	52.4	26.8, QP					−1.3			8.6
20	A 235	59.8	26.8, QP					−4.7			9.9
21	C 215	64.5	31.7, QP					3.1	−46.4	−108.7	10.6
22	H 122	74.7	ms-br, QP	−54.39	−60.9	−100.6	−169.9	−3.3	−47.6	−114.1	12.3
23	EAST PEARL RIVER	75.9	ms-br, QP	−54.48	−61.3	−105.9	−175.4	−6.8	−52.0	−121.5	12.5
24	A 193	76.3	29.3, QP					−10.0	−54.4	−127.5	12.6
25	EAST MIDDLE BOLT	77.3	ms-br, QP	−53.86	−61.7	−104.3	−177.1	−7.9	−51.0	−123.8	12.7
26	WEST PEARL BRIDGE	81.1	ms-br, QP	−56.64	−62.0	−101.1	−178.0	−5.3	−44.9	−121.9	13.4
27	ST 646	82	690, QP					−0.6	−37.7	−112.0	13.5
28	B 193	83.9	29.3					−5.7	−47.7	−126.5	13.8
29	D 193	87.2						−3.3	−39.8	−109.1	14.4
30	S 156	89.7	ms-br	−86.40	−100.0	−114.8	−241.5	−13.6	−28.6	−155.3	14.8
31	J 92	90.8	ms-br	−68.74	−78.2	−109.7	−187.4	−9.4	−41.3	−119.1	15.0
32	HUEY LADTD	90.8	ms-br	−70.97	−80.8	−113.7		−9.8	−43.2		15.0
33	C 193	91	21.9					−9.6	−43.5	−123.8	15.0
34	OR 179 WELL	91.1	742					−10.4	−42.7		15.0
35	E 193	97.4	19.5					−15.3	−52.5	−155.3	16.0
36	F 193	103.4	17.1					−20.8	−46.8		17.0
37	R 153	104.1	ms-br	−101.33	−120.2	−142.5	−242.2	−18.9	−41.5	−131.7	17.2
38	C 189	107.6	20.7					−16.8	−36.9	−133.5	17.7
39	OR 78 WELL	116.2	172.2					−46.0	−134.0		19.1
40	W 152	116.6	ms-b	−195.71	−239.8	−330.8	−597.6	−44.1	−136.2	−377.7	19.2
41	OR 79 WELL	116.6	178.6					−37.6	−106.0		19.2
42	WASTE WELL 2	116.6	2012					−32.4	−78.8	−259.4	19.2
43	OR 80 WELL	117	179.8					−39.7	−111.7		19.3
44	F 189	118.5	24.4					−75.5	−244.7	−560.2	19.5
45	D 276	119.4	ms-br					−74.9	−204.7	−467.7	19.7
46	227 RESET	124.4	9.8					−46.2	−126.0	−358.7	20.5
47	B 276	126.4	ms-br					−39.5	−102.0	−260.7	20.8
48	B 3130	127.9	ms-br	−199.13	−243.2	−311.2		−44.1			21.1
49	S 152	129.7	ms-br	−169.93	−203.4	−233.1	−357.9	−33.4	−63.5	−176.5	21.4
50	P 193	131.1	36.6					−29.5	−53.8	−169.0	21.6
51	TEST	132.4	22.9	−187.65	−221.8			−34.1			21.8
52	F 156	132.6	ms-br	−181.99	−216.5	−260.7	−424.5	−34.5	−79.3	−227.5	21.8
53	Y 147	133.8	ms-br					−36.8	−97.8	−275.3	22.0
54	281 LAGS RESET 1952	135	ms					−45.5	−128.2		22.2
55	K 189	135.2	31.7					−36.6			22.3
56	P 188	136	ms-br					−37.3	−91.5	−254.9	22.4
57	L 188	136.7	ms-br					−30.3	−64.3	−209.9	22.5
58	U 147	138.4	ms-b					−27.7	−58.0	−200.5	22.8
59	M 188	141.3	ms-br					−26.6	−43.1	−156.3	23.3
60	B 147	146.7	ms-f					−29.8			24.2

[a]Data from National Geodetic Survey/NOAA; Silver Spring, MD. All displacement values are in mm.

[b]U 189 is 1.

[c]Depth of penetration of steel rods or foundation into the Earth. Depth in m. Soil type at surface is Holocene, except where noted as QP, Pleistocene Prairie Complex. Other monument types: ms, massive structure, with varieties; br, bridge abutment; f, foundation; p, pier.

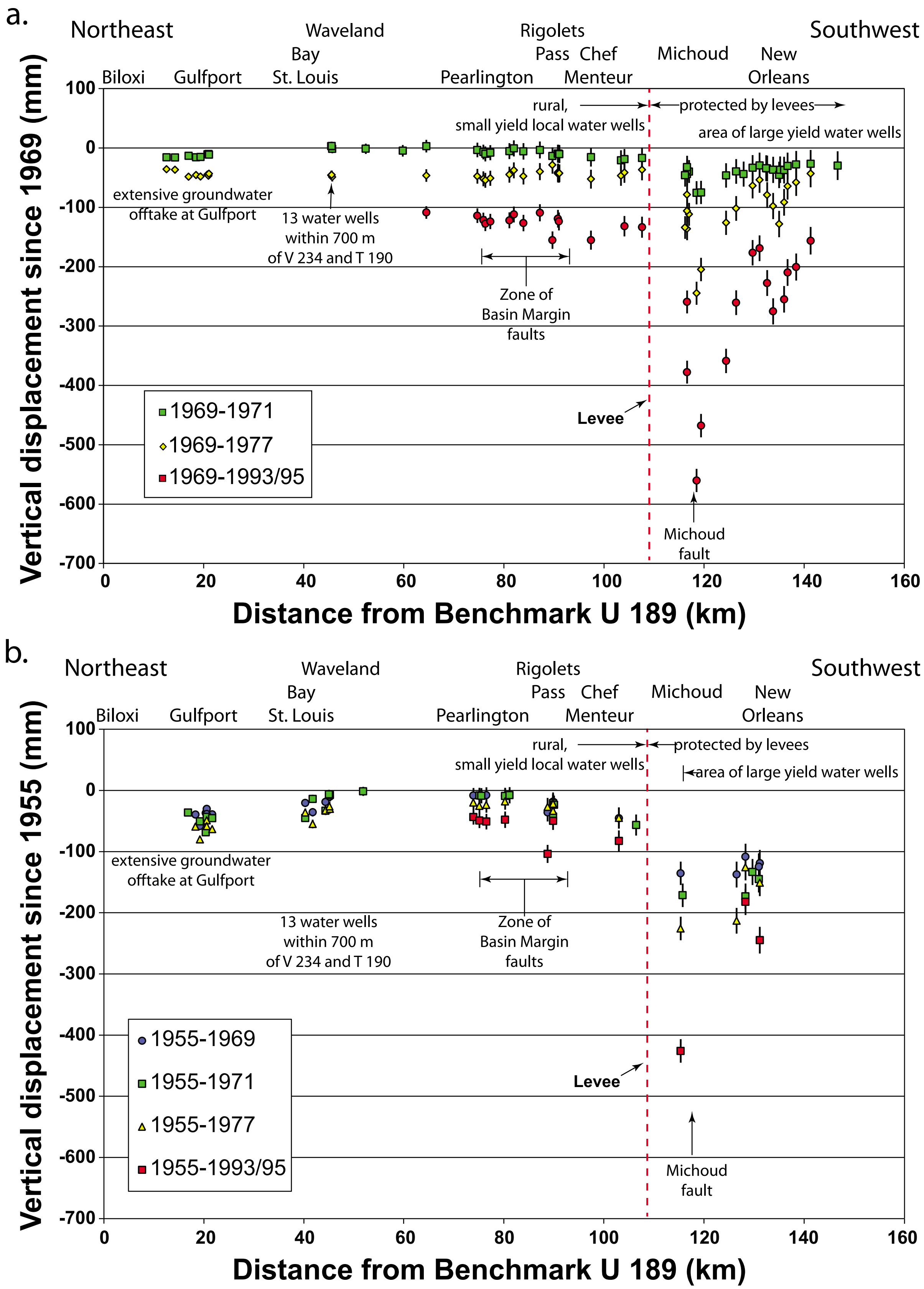

Figure 3. Vertical displacements of National Geodetic Survey/NOAA benchmarks attached to deep rods and piles derived from first-order leveling surveys from Biloxi, MS, to New Orleans, LA. Locations of benchmarks in profile are shown on Figure 2. Data provided in Table 1. (a) Surveys from 1969, 1971, 1977, and 1993/95. (b) Surveys from 1955, 1969, 1971, 1977, and 1993/95. See text for discussion.

Table 2. Water Level Gauges of the New Orleans–Lake Pontchartrain Region[a]

Gauge Name	Description of Location	Latitude and Longitude	Time Range Recorded
76040	The Intercoastal Waterway (IWW) at the Paris Road Bridge	30°00′22″N, 89°57′23″W	1959–2007
76060	The Inner Harbor Navigation Canal (IHNC) at the Seabrook Bridge	30°01′53″N, 90°02′04″W	1962–2005
76120	Inner Harbor Navigation Canal (IHNC) at the Florida Avenue Bridge	29°58′08″N, 90°02′04″W	1944–2003
85675	Lake Pontchartrain at Irish Bayou	30°09′16″N, 89°51′21″N	1959–2000
85700	Lake Pontchartrain at the Rigolets Pass Bridge	30°10′05″N, 89°44′12″W	1961–2001

[a]Operated by the United States Army Corps of Engineers, New Orleans District.

south dipping normal faults of the Gulf of Mexico basin margin [*Murray*, 1961] is also shown in Figure 3 and marks the divide separating the generally slow subsiding Mississippi coast from the more rapidly sinking Lake Pontchartrain–Mississippi River delta area (Figure 2). These faults include the Tepatate–Baton Rouge [*Sneed and McCulloh*, 1984] and Lake Pontchartrain fault systems [*Kolb et al.*, 1975; *Lopez et al.*, 1997] (Figures 2 and 3).

[25] The greatest amounts and sharpest local increases in subsidence detected by leveling occur in the Michoud area of eastern New Orleans (Figure 3). Here, the total subsidence of benchmarks between 1955 and 1995 was nearly ~0.6 m. Subsidence of areas north and east of the belt of faults that mark the basin margin steadily decreases gradually toward Biloxi in all surveys (Figure 3). Small spikes in subsidence also occur near the Mississippi communities of Gulfport, Bay St. Louis, and Pearlington.

2.2.2. Water Level Gauges

[26] Daily 8 A.M. records from five U. S. Army Corps of Engineers (USACE) gauges in the New Orleans–Lake Pontchartrain region (Figures 1 and 2; http://www.mvn.usace.army.mil/eng/edhd/wcontrol/wcmain.asp) were used to reconstruct local water level rise histories and to infer local subsidence between 1959 and 2008; we limit the time range from near 1960 to the end of 1995 for vertical motion comparisons with benchmarks. The gauge names, location, coordinates, and the time range recorded are listed in Table 2 and include: 76040, The Intercoastal Waterway (IWW) at the Paris Road Bridge (1959 to 2007); 76060, The Inner Harbor Navigation Canal (IHNC) at the Seabrook Bridge (1962 to 2005); 76120, The IHNC at the Florida Avenue Bridge (1944 to 2003); 85675, Lake Pontchartrain at Irish Bayou (1959 to 2000); and 85700, Lake Pontchartrain at the Rigolets Pass Bridge (1961 to 2001). The data are generally continuous through time, except for a few gaps of days, weeks, and sometimes months. Raw and processed data, along with a report detailing data handling procedures used by the USACE (New Orleans District) are provided in the auxiliary material.

[27] Examination of each of the raw data sets (auxiliary material) shows discontinuities stemming from deliberate changes in the vertical position of the gage zero mark with respect to nearby vertical control monuments. These alterations were performed by the USACE so that the "zero"

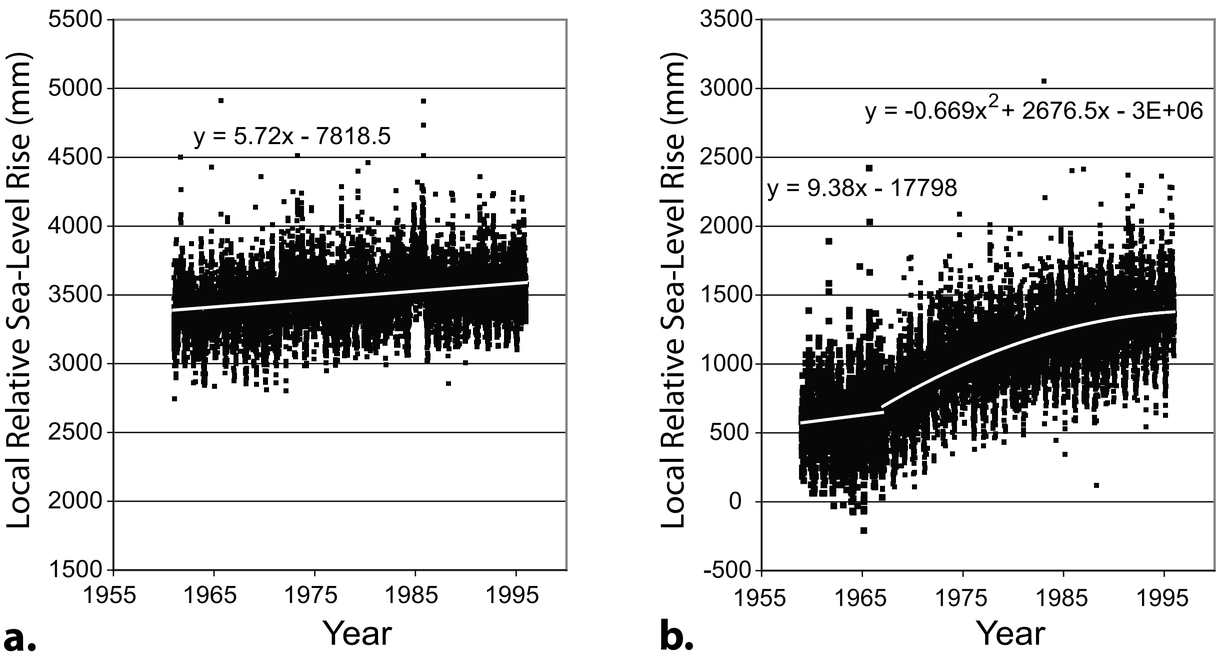

Figure 4. Differing late 20th century sea level rise histories at selected USACE water level gauges in the New Orleans–Lake Pontchartrain area: (a) Rigolets Pass Bridge (85700). (b) Paris Road Bridge (76040). The linear rise rate at Rigolets Pass Bridge was +5.7 mm yr^{-1}. Removal of the eustatic rise rate of 2.0 mm yr^{-1} [*Douglas*, 1995] indicates an average subsidence rate of −3.7 mm yr^{-1} at the gauge. The Paris Road Bridge gauge shows markedly more rapid sea level rise over the same time. See text for discussion.

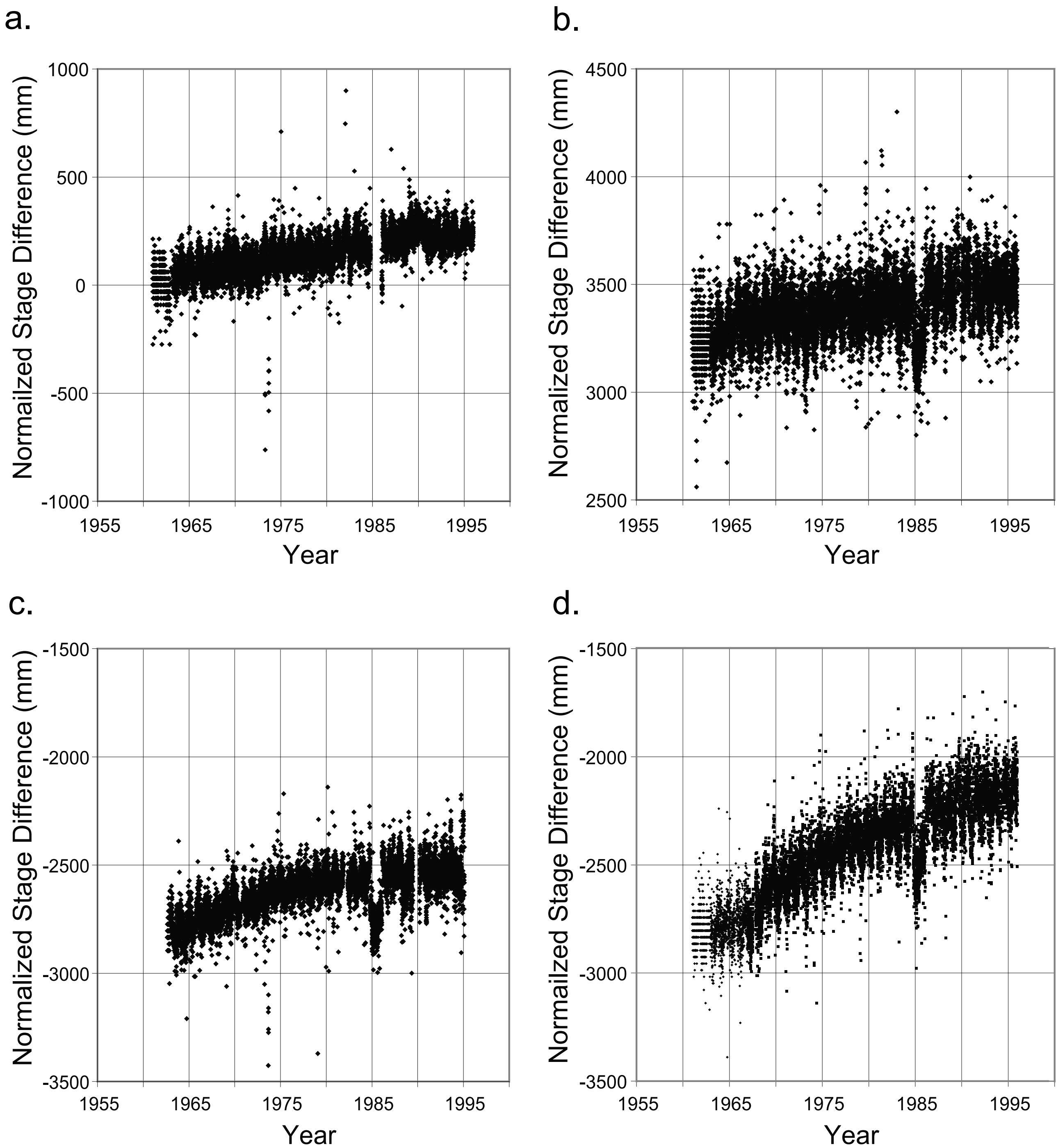

Figure 5. Time series of water level gauges of the New Orleans area which have been differenced against the USACE gauge at Rigolets Pass (85700). (a) Lake Pontchartrain at Irish Bayou (85675); (b) the IHNC at the Florida Avenue Bridge (76120); (c) the Inner Harbor Navigation Canal (IHNC) at the Seabrook Bridge (76060); (d) the Intercoastal Waterway (IWW) at the Paris Road Bridge (76040). See Figure 2 and Table 2 for locations and text for discussion.

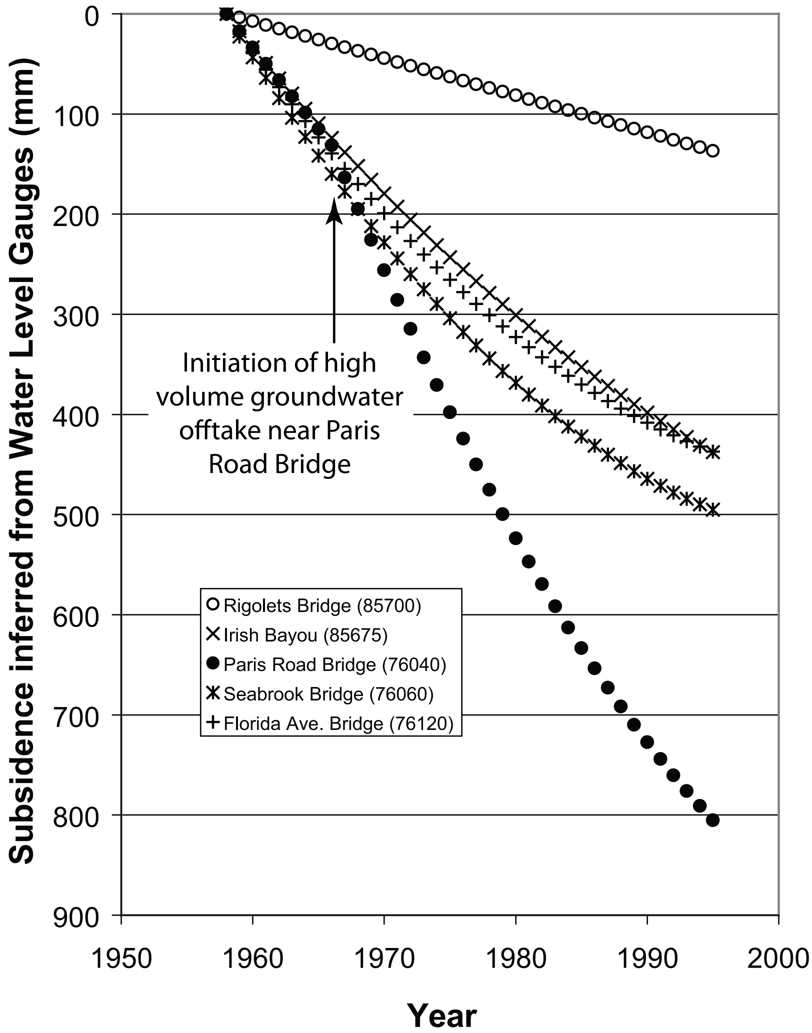

Figure 6. Subsidence histories inferred from USACE water level gauges in the New Orleans–Lake Pontchartrain area. Based on differenced water level time series at area gauges with subsidence at Rigolets Pass Bridge added back. See text for explanation.

of the gage would correspond to the "zero" of a particular epoch of a vertical geodetic datum. Fortunately, these adjustments of the gage are documented in the gage inspection records together with the explanatory notes in the "Stages and Discharges" books kept by the USACE (New Orleans District). The record of gauge changes allowed for creation of continuous, normalized data sets of daily, 8 A.M. stage readings that were then used to compute monthly means. The loss of data at the Rigolets Pass Bridge (30°10′05″N, 89°44′12″W) gauge at various times in 1985 produced anomalous spikes in all differenced time series. These anomalies, however, did not significantly affect the interpretation of the time series. Inspection of the adjusted water level time series shows that the greatest RSL change in the area occurred at gauge 76040 (Paris Road Bridge; 30°00′22″N, 89°57′23″W) and the least at gauge 85700 (Lake Pontchartrain at Rigolets Pass Bridge) (Figure 4); the other gauge histories are included in auxiliary material.

[28] Water level gauges record the combined effects of many processes including eustatic rise, local land subsidence, local and regional climatic factors, local hydrologic effects, and oceanographic processes, i.e., tides and currents [e.g., *Zervas*, 2001]. Several common techniques were employed to remove these effects. Differencing of local gauge data against a reference gauge, i.e., subtracting one time series from another, removes many common effects such as eustatic rise, regional climatic and oceanographic processes, e.g., weather cycles, tides and currents. Differencing, however, also removes the common subsidence components at each gauge. A complimentary approach is time averaging, whereby a regression model is fit to the differenced, time series in order to smooth away any short-lived hydrologic phenomena, e.g., storm surges.

[29] All time series were differenced against the Rigolets Pass Bridge gauge (85700). The gauge was chosen as the local reference gauge because it showed the least RSL and was constant over the late 20th century (Figures 4 and 5). Differencing removed other common oceanographic and hydrologic influences, but retained a portion of the local vertical motion signal. However, to use the gauges to estimate subsidence, the vertical motion removed by differencing with gauge 85700 needed to be restored. This was accomplished by adding back the local subsidence at Rigolets Pass Bridge that was derived from previous leveling; benchmark "J 92"

(30°10′05″N, 89°44′12″W) is attached to the bridge and its subsidence rate was used (Table 1) [*Shinkle and Dokka*, 2004]. This value was chosen to maintain consistency with regional leveling estimates. The "J 92" subsidence value was added back to all gauges (Figure 6).

[30] Water levels at all gauges rose continuously, but not uniformly in the study area between 1959 and 1995 (Figure 5). Also, the subsidence histories inferred from these gauges are similar to the geodetic leveling results, suggesting that land sinking was continuous, but spatially variable between 1959 and 1995 (Figures 3 and 6). Over this time, the locus of high subsidence shifted from central New Orleans eastward to the Michoud area. With the exception of the gauge at the Rigolets Pass Bridge which has remained constant over time, water level rise and associated subsidence have declined over this time at all stations.

[31] The subsidence implied by the Rigolets Pass Bridge gauge (85700) was the least, and showed a constant -3.7 mm yr^{-1} change throughout this time interval (Figure 6). Data from all of the other gauges except the Paris Road Bridge near Michoud are similar in that they can be best described by a simple, exponential decay curve (Figure 6). From 1959 to 1966, subsidence rates at the Florida Avenue Bridge (29°58′08″N, 90°02′04″W) and Seabrook Bridge (30°01′53″N, 90°02′04″W) gauges ranged from ~21 to ~16 mm yr^{-1}. By 1995, rates at both gauges had slowed to ~5 mm yr^{-1}. Subsidence rates at the Irish Bayou on Lake Pontchartrain gauge (30°09′16″N, 89°51′21″N) between 1959 and 1966 ranged from ~14 to ~15 mm yr^{-1}, and had slowed to ~7 mm yr^{-1} by 1995. In contrast, the Paris Road Bridge gauge (76040) subsided at constant rate of ~16 mm yr^{-1} during the interval 1959–1966. In 1967, however, the rate of local subsidence suddenly increased to ~32 mm yr^{-1}, as water levels rapidly increased at the Parish Road Bridge gauge. The rate of subsidence then declined exponentially, reaching a rate of ~16 mm yr^{-1} in 1995. Over the interval 1959–1995, the Paris Road Bridge gauge subsided nearly 0.3–0.4 m more than the other three New Orleans area gauges. Leveling data show a similar pattern that suggests that the circa 1967 spike in subsidence was spatially confined to the local area near the Paris Road Bridge (Figures 2 and 3).

3. Discussion

3.1. Validation of Previous Geodetically Derived 20th Century Subsidence Measurements

[32] Subsidence estimates inferred from daily observations of late 20th century water levels from the New Orleans area are similar in magnitude, timing, and spatial distribution to the results computed from first-order leveling surveys [*Shinkle and Dokka*, 2004; *Dokka*, 2006]. Both estimates indicate that as much as ~0.6–0.8 m of deep-seated subsidence occurred between ~1955 and 1995 (Figures 3a and 6). In contrast, the estimates presented here for only the deep component of subsidence are ~8 to 50 times higher than the Holocene chronostratigraphy-based model of *Kulp* [2000]; that model predicts <16 mm of total subsidence, i.e., shallow and deep, in the area over the same time interval.

[33] Two water level gauges of this study were used to test the hypothesis regarding the accuracy of the vertical velocities derived from late 20th century geodetic leveling surveys by *Shinkle and Dokka* [2004] and *Dokka* [2006]. The first test used the gauge at the Rigolets Pass Bridge (85700) that was colocated with benchmark "J 92" (Figure 2). This gauge was selected for two reasons. First, the gauge is attached to the same deep pile–founded bridge to which NGS Benchmark "J 92" was attached. The vertical motion history of "J 92" has been well documented through the late 20th century because it has been part of previous, long-line, NGS first-order leveling surveys that were tied to the long-standing National Ocean Service/NOAA water level gauge at Grand Isle (East Point), LA [*Shinkle and Dokka*, 2004]. Second, the subsidence history of the Rigolets Pass Bridge could be estimated independently from the local water level history. The subsidence rate at the Rigolets Pass gauge between 1961 and 1995 was estimated to be -3.7 mm yr^{-1} after accounting for the aforementioned eustatic rise from the total RSL record (-5.7 mm yr^{-1}; Figure 4). The subsidence estimate at the gauge is similar to the -4.9 mm yr^{-1} value derived from geodetic leveling at "J 92" (Table 1) [*Shinkle and Dokka*, 2004]. The small, 1.2 mm yr^{-1} difference is well within the allowable error for the 142 km long, first-order geodetic leveling survey between Grand Isle and Rigolets Pass [*Dokka*, 2006]. These results, therefore, confirm the vertical motion estimates set forth by *Shinkle and Dokka* [2004] and *Dokka* [2006].

[34] A second test of the accuracy of vertical velocities of *Shinkle and Dokka* [2004] and *Dokka* [2006] was performed using the water level gauge attached to the Paris Road Bridge (76040). Colocated on the piles of this major structure are two NGS benchmarks, "B 387" (30°00′24″N, 89°56′20″W and "V 371" (30°00′14″N, 89°56′19″W). Geodetic leveling surveys in 1991 and 1995 implied an average subsidence rate of -17.5 mm yr^{-1}. This rate matched closely the subsidence rate implied by the water level gauge for the same time interval, -15.9 mm yr^{-1}. Again, because the observed difference is small, the vertical velocities of *Shinkle and Dokka* [2004] and *Dokka* [2006] are thus confirmed.

[35] Subsidence estimates of the New Orleans area presented here exceed those previously presented by *Burkett et al.* [2003]. In addition to the methodological issue described above, this difference is the result of an untenable assumption originally made by *Zilkoski and Reese* [1986], and later by *Burkett et al.* [2003], when referencing their data. They assumed that subsidence at benchmark "J 92" affixed to the Rigolets Bridge was zero and calculated subsidence at other benchmarks accordingly; it should be noted that *Zilkoski and Reese* [1986] recognized that if "J 92" was not stable, all points in the network would be in error. The contemporary motion of "J 92" as demonstrated in this study clearly invalidates the assumption of stability. This suggests that the subsidence rate estimates of *Burkett et al.* [2003] are biased by -4 to -5 mm yr^{-1}, the amount of the subsidence rate at "J 92" inferred by geodetic leveling and water level gauge analysis.

3.2. Implications for Causation

[36] Data presented here implying large late 20th century vertical motions of geodetic leveling monuments and water level gauges set into upper Pleistocene strata invalidate the widely held view that late 20th century subsidence is dominated by processes originating in Holocene sediments [e.g., *Ramsey and Moslow*, 1987; *Kuecher*, 1995; *Roberts et al.*, 1994; *Roberts*, 1997; *Kulp*, 2000; *Törnqvist et al.*,

2008]. Full appreciation of modern subsidence, especially for engineering design of future flood protection systems and ecosystem restoration, requires consideration of shallow and deep processes caused by natural and anthropogenic drivers. The following discussion centers on the identification of the dominant cause(s) of late 20th century subsidence in the study area.

[37] It is assumed that late 20th century vertical motions of deep set monuments of south Louisiana and Mississippi reported here are due to the integrated effect of multiple natural and anthropogenic processes. The processes that are considered have been reported previously in the literature and include regional isostatic subsidence produced by Quaternary sediment and water loading (Figure 1) [*Jurkowski et al.*, 1984; *Ivins et al.*, 2007; *Syvitski et al.*, 2009], faulting [e.g., *Kolb et al.*, 1975; *Dokka*, 2006; *Dokka et al.*, 2006], pre-Holocene sediment compaction [*Edrington et al.*, 2008], and groundwater pumping [*Kazmann and Heath*, 1968]. Subsidence due to oil and gas extraction has been considered elsewhere in south Louisiana [*Mallman and Zoback*, 2007], but its potential impact here is negligible given the limited production in the area (Louisiana Department of Natural Resources, http://sonris-www.dnr.state.la.us/www_root/sonris_portal_1.htm).

[38] We can also eliminate from consideration any process that produces change within Holocene sediments because all of the monuments to which the benchmarks and water level gauges are attached are founded in Pleistocene deposits. Previous analysis of subsidence in the New Orleans area by *Burkett et al.* [2003], for example, used many of the same benchmarks included in this study but did not consider subsidence variation as a function of monumentation depth. Subsidence was assumed to be related to Holocene soil type and geology. A geographical information system (GIS) approach was used to search for possible associations. Unfortunately, all of the benchmarks attached to deep monuments used by *Burkett et al.* [2003] penetrated the Holocene section and thus contain no influences from processes originating within Holocene soils. The importance of the third dimension in the interpretation of subsidence will be discussed further below.

[39] The general approach followed here in assessing the causes of deep vertical motions first involved comparisons with models of sediment and water loading. Because the subsidence effect due to regional loading is uncertain [*Ivins et al.*, 2007], a range of effects were considered using values and spatial patterns predicted or implied by previous models. This was followed by consideration of predicted subsidence caused by compaction of sub-Holocene deposits. Further analysis was conducted in light of local geologic and hydrologic observations.

3.2.1. Deflection of the Lithosphere by Sediments and Water Loads

[40] It has been long suspected that large masses of sediments deposited on the Earth's surface such as the Holocene Mississippi River delta (MRD) are sufficient to deform the lithosphere [*Ricketts*, 1872; *Russell*, 1936; *Jurkowski et al.*, 1984; *Ivins et al.*, 2007]. Simple 2-D flexure modeling by *Jurkowski et al.* [1984] demonstrated the physical plausibility of sediment and water loading as a driver of late 20th century subsidence in the study area. Recently, 3-D Maxwell viscoelastic modeling by *Ivins et al.* [2007] provided additional insights into the areal distribution of load-induced subsidence. Although modeling by *Ivins et al.* [2007] has been useful in validating the plausibility of subsidence by sediment and water loading, uncertainties associated with model input requirements, i.e., the structure and physical properties of the crust and mantle and the spatial and temporal details of sediment loading, preclude the creation of any single quantitative model that can be tested by late 20th century measurements.

[41] Others have argued against the importance of such regional isostatic effects, noting that the net Holocene sediment accumulation is small in more upstream portions of the delta and contending that sediment compaction there is sufficient to explain long, time-averaged subsidence rates implied by peat chronostratigraphy [*Törnqvist et al.*, 2006; *González and Törnqvist*, 2006]. However, by ignoring the effects of loading, opponents of load-induced flexure must also accept that the elastic, upper, part of the lithosphere is sufficiently strong to prevent any deformation caused by the combined load of the 120 m of delta and marine sediments and late Quaternary sea level rise; alternatively, flexure could be retarded if the underlying mantle is quite viscous.

[42] One way that these disparate views can be compared and thus tested, centers on how each model regards the strength of the elastic crustal lithosphere and the viscosity of the underlying mantle. Implicit in the model of *Törnqvist et al.* [2006] is a strong and rigid elastic lithosphere and/or a highly viscous mantle. In contrast, the *Jurkowski et al.* [1984] and *Ivins et al.* [2007] models predict flexure of an elastic lithosphere due to the loading. This is accompanied by slow viscous flow of the underlying mantle as it deforms to accommodate the repositioning of the overlying elastic upper layer. Because of lithosphere's finite strength and elasticity, the area of the flexure will extend beyond the limits of the load.

[43] The aspect of the *Ivins et al.* [2007] model that is useful in our comparison is its prediction that subsidence would not be restricted to the footprint of the load, i.e., the Mississippi River delta, but instead should be expected to continue beyond the delta boundary and gradually die away (Figure 1). The broadening of the signal beyond the load footprint is considered to be the result of time-dependent diffusive viscous creep in the mantle and to elastic stress diffusion in the crust [*Ivins and Wolf*, 2008]. This reduction of downward vertical displacement away from the delta is observed in the geodetic leveling data (Figure 3) as well as in the previous tide gauge analyses of *Penland and Ramsey* [1990] and *Turner* [1991]. The model of *Ivins et al.* [2007] is also consonant with the tide gauge at Pensacola where it correctly predicts that the subsidence rate is effectively zero.

[44] On this basis, it is proposed that a small, but significant portion of the late 20th century deep-seated subsidence recorded by geodetic leveling and water level gauges in the study area is most likely caused by load-induced subsidence. The precise amplitude of this effect remains uncertain, but the physics of the situation seemingly demand that it not be zero everywhere as implied by the *Törnqvist et al.* [2006] model. A more rigorous comparison will be possible when sediment and water load fluxes and lithospheric mechanical parameters are better constrained. Reevaluation of the *Ivins et al.* [2007] model suggests that more realistic subsidence rate results can be achieved by reducing the

sediment flux to better match observations and by assuming a weaker and thinner elastic upper lithosphere and/or a less viscous upper mantle. Until then, the *Törnqvist et al.* [2006] model cannot be rejected outright. However, if such a model is to be considered plausible, evidence for a very strong lithosphere and/or very viscous mantle must be provided. Such a model must also account for the declining subsidence rates from the area north of the basin margin faults along the Mississippi coast to western Florida coast where stable ground is reached. Small subsidence differences observed in the leveling data across this area are spatially associated with local groundwater wells (Mississippi Department of Environmental Quality) and may be related to withdrawal. South of the basin margin faults, loading is clearly insufficient to explain all vertical motions. Below, we examine the contribution of other known processes.

3.2.2. Basin Margin Faults

[45] Two major basin margin faults that border the Gulf of Mexico traverse the study area and include the Tepatate–Baton Rouge fault system (T-BRF) [*Murray*, 1961; *Sneed and McCulloh*, 1984], and the Lake Pontchartrain fault system (LPF) [*Kolb et al.*, 1975; *Lopez et al.*, 1997]. Both are east-west striking, down-to-the-south, normal fault systems (Figure 2). Figure 7 is a digital elevation model of the north shore of Lake Pontchartrain showing fault line scarps and other landforms associated with these active faults.

[46] The T-BRF is actually a system of faults and can be traced from the north shore of Lake Pontchartrain westward to the floodplain of the Mississippi River (Figures 2 and 7a). The surface expression of the T-BRF is typically a series of right-stepping, down-to-the-south monoclinal steps developed in gently south dipping, largely semilithified Quaternary terrace deposits (Figure 7b). The most obvious expression of the fault in the study area is an E-W fault line scarp that passes near the intersection of U.S. 90 and U.S. 190 (30°13′40″N, 89°40′41″W) [*Kolb et al.*, 1975]. The footwall exposed here contains apparently uplifted Pleistocene Prairie Complex. Another strand of the T-BRF that was detected in this study occurs between Prevost Island (30°11′34″N, 89°42′43″W) and Rigolets Pass (Figures 2 and 7). This strand, referred to here as the T-BRF (south branch), occurs along the eastern projection of a previously unnamed fault mapped by *Lopez et al.* [1997]. *Kolb et al.* [1975] and *Lopez et al.* [1997] both used shallow seismic methods to locate and map the same fault in Lake Pontchartrain (Figure 2); this fault, the Lake Pontchartrain fault, cuts through the lake and passes just north of Irish Bayou and southwest of Rigolets Pass (Figure 2).

[47] Previous studies have disagreed on whether these two fault systems are currently active in the study area. *Kolb et al.* [1975] used closely spaced borings to claim that the Holocene-Pleistocene contact was undisturbed in the vicinity of the both the T-BRF and the LPF. In contrast, *Lopez et al.* [1997] proposed that both the LPF and the T-BRF (south branch) were active based on late 20th century vertical deformation observed on local bridges; *Lopez et al.* [1997] was mute on the activity of the T-BRF (north branch). Geodetic leveling data presented here on benchmarks that straddle each of the faults show differential motions that are consistent with active faulting as described by *Lopez et al.* [1997] (Table 3). The magnitude and sense, i.e., down-to-the-south, motion along the Lake Pontchartrain fault observed by *Lopez et al.* [1997] are also supported by differential behavior of the Rigolets and Irish Bayou water level gauges (Table 3 and Figure 5a). The gauge data also suggest that fault throw, i.e., differential vertical component of displacement, was constant in much of late 20th century time, an observation consistent with fault creep. Creep is often associated with Gulf Coast normal faults [e.g., *Holzer and Gabrysch*, 1987]. However, noncreep behavior cannot be ruled out given the 1987 Irish Bayou earthquake, an event thought to have occurred on the Lake Pontchartrain fault [*Lopez et al.*, 1997].

[48] In summary, first-order geodetic leveling and water level gauge data are consistent with previous field observations by *Lopez et al.* [1997] that normal faults of the basin margin are down to the south and currently active. Along with the Lake Pontchartrain fault, both northern and southern strands of the Tepatate–Baton Rouge fault are active. Although the amount of subsidence resulting from faulting was small and generally restricted to narrow (10s of m) zones at the fault, the confirmation of present-day activity is important from a geohazards standpoint.

3.2.3. Sediment Compaction and Consolidation

[49] Compaction and consolidation are fundamental natural processes that affect sediments after deposition [e.g., *Fowler and Yang*, 1998; *Meckel*, 2008]. These processes are regarded by most workers to be the primary cause of subsidence in the region [e.g., *Ramsey and Moslow*, 1987; *Kuecher*, 1995; *Roberts et al.*, 1994; *Roberts*, 1997; *Törnqvist et al.*, 2008]. These processes result in rearrangement of sediments through the expulsion of intergranular air (compaction) and water (consolidation) and leads to significant dimensional change, densification, and porosity changes over time. *Ramsey and Moslow* [1987] attributed 80% of the observed relative sea level rise in coastal Louisiana to "compactional subsidence." Several workers have related the magnitude of observed subsidence to the local thickness of the Holocene section [e.g., *Roberts et al.*, 1994; *Kuecher*, 1995; *Reed*, 1995; *Kulp*, 2000]. Modeling, however, suggests that natural compaction and consolidation-related subsidence over short intervals such as the late 20th century can only explain a few mm per year of modern day subsidence in south Louisiana [*Meckel et al.*, 2006]. In contrast, compaction and consolidation of Holocene sediments can be greatly accelerated by forced drainage of areas protected by levees [e.g., *Snowden et al.*, 1977; *Snowden*, 1984]. Because the deep set monuments used in this study bypass shallow sediments, subsidence contributions from natural and anthropogenic compaction and consolidation of Holocene sediments are not relevant here. Our concern regarding natural compaction is thus limited to subsidence effects that have occurred in older materials.

[50] Estimation of the amount of late 20th century subsidence that can be attributed to compaction/consolidation of pre-Holocene sediments and rocks is challenging because of the lack of direct observation of the processes. One approach, described by *Edrington et al.* [2008], used a standard decompaction technique to model long-term compaction and subsidence rates for strata residing above a middle Miocene horizon in the Michoud area. They estimated that the entire stratigraphic section considered, including the Holocene, had compacted between 704 and

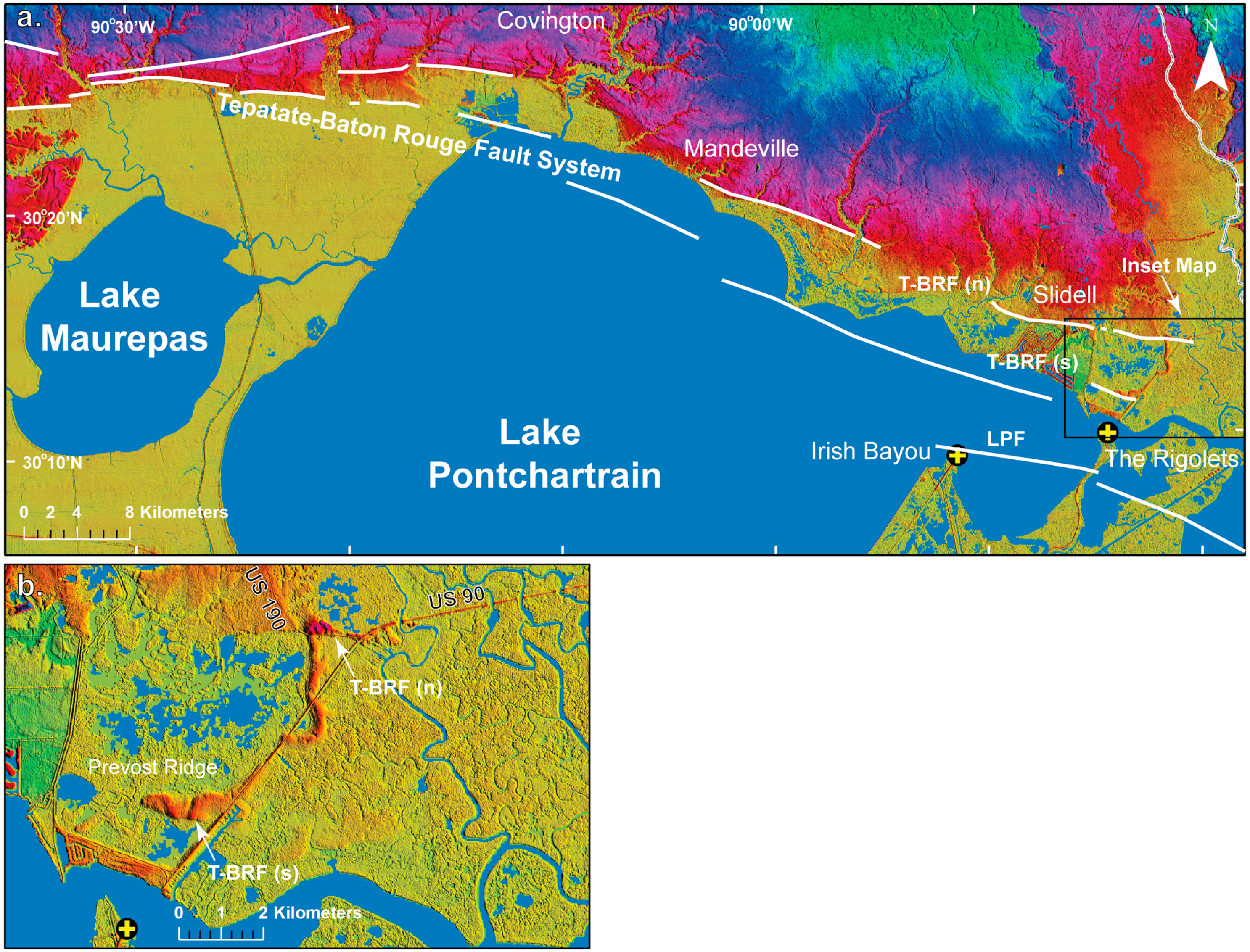

Figure 7. (a) Regional LiDAR digital elevation model draped over relief map that highlights the geomorphic expression of the Tepatate–Baton Rouge fault from Baton Rouge to Lake Pontchartrain and the Lake Pontchartrain fault system. Note that geomorphic features associated with the faults are not fault scarps, but are instead narrow, monoclinal steps in the topography. The low cohesion of surface materials and the humid climate do not support the formation and preservation of surface fractures. (b) Local fault line scarps associated with the aforementioned faults in eastern St. Tammany Parish, Louisiana.

Table 3. Fault Throw on Basin Margin Faults

Fault	Previous Observations	This Paper[a]
Tepatate–Baton Rouge (north branch)	Not active during Holocene [*Kolb et al.*, 1975]	No differential vertical movement between BMs ST 646 and B 193
Tepatate–Baton Rouge (south branch)	2.5–5 cm between 1990 and 1996 [*Lopez et al.*, 1997]	Differential vertical movement between E3175 and T156: ~3 cm (1955–69); ~1 cm (1971–77); no data (1977–95).
Lake Pontchartrain	7.5–10 cm between 1986 and 1996	Difference between water gauges 85675 and 85700 (Figure 5a) was 6.5 cm between 1986 and 1996

[a]Quantitative differences between *Lopez et al.* [1997] and this paper are likely the result of sampling differences and sample spacing.

914 m over this ~10 million year interval, with a computed mean compaction rate of 0.0704–0.0914 mm yr^{-1}. While such an estimate might be congruent with our intuition that Pleistocene to middle Miocene age sediments should be well compacted after >10,000 years of burial, such long-term average rates inaccurately conveys a level of spatial and temporal resolution that is beyond the limits of measurement tools used to produce them. Timing relations used by *Edrington et al.* [2008] were based on micropaleontological analysis and dimensional change determined from well logs, methods that have uncertainties of thousands of years and a meter and more, respectively. If seen in this light, the late 20th century proportion of the total compaction of pre-Holocene sediments measured by *Edrington et al.* [2008] is essentially zero.

3.2.4. Deep-Seated Vertical Motions at Michoud

[51] *Dokka* [2006] presented vertical motion data on a benchmark named "Waste Well 2" located at Michoud that showed that vertical motion was apparently steady between 1969 and 1995, averaging −9.5 mm yr^{-1}. "Waste Well 2" is unique in the region because it is attached to a well casing set to a depth of >2000 m, and thus avoids the effects of shallow natural and anthropogenic processes originating in Holocene sediments, as well as deep processes such as groundwater pumping. Because "Waste Well 2" also sits within a broad, NW trending boundary that separates two areas that have subsided differently during the late 20th century, it was reasoned that the motion of "Waste Well 2" was of tectonic origin and related to a broad fault zone that *Dokka* [2006] termed, the Michoud fault. The involvement of processes operating well below producing aquifers further suggested that recent motion was perhaps associated with of one of the many WNW striking faults previously mapped in the subsurface [*Hickey and Sabate*, 1972].

[52] *Dokka* [2006] provided geodetic leveling evidence for only ~300 mm of differential vertical displacement on a pair of benchmarks straddling the broad Michoud fault. *Edrington et al.* [2008] also claimed that the Michoud fault was of limited significance because their subsurface projection of the fault did not cut a middle Miocene microfossil horizon located ~2000 m beneath the benchmarks at Michoud. While the *Edrington et al.* [2008] measurements lack the resolution to test for the ~300 mm of displacement documented by *Dokka* [2006], the stratigraphic constraint discussed by *Edrington et al.* [2008] does suggest that the Michoud fault has had little, pre-late 20th century motion. Thus, relations of *Edrington et al.* [2008] cannot rule out the possibility that small, modern fault motions have occurred above the Miocene marker or continue into the deeper subsurface as proposed by *Dokka* [2006].

[53] While no data or information has yet been put forth that can invalidate *Dokka*'s [2006] contention that motions of the deep "Waste Well 2" benchmark may be of tectonic origin, the explanation is clearly inadequate because it assumed that all motion was fault related and failed to consider the effects of the aforementioned sediment and water loading. Motions related to loading would be expected to explain perhaps as much as −2 to −5 mm yr^{-1} of the −9.5 mm yr^{-1} observed at the "Waste Well 2" benchmark between 1969 and 1995. More work is clearly needed to resolve the remaining unexplained subsidence. Below, it is proposed that groundwater withdrawal from producing aquifers may be responsible for modern upper level motion along the Michoud fault.

3.2.5. Groundwater Withdrawal

[54] Large residual vertical displacements remain in the greater New Orleans area after accounting for the effects of basin margin faulting, deep compaction, and regional loading by the Holocene MRD and late Quaternary sea level rise. Groundwater withdrawal has been long suspected of contributing to subsidence in the New Orleans area [*Kazmann and Heath*, 1968]. *Meckel* [2008] recently examined the gross quantities of groundwater withdrawn from parishes in southeast Louisiana during the late 20th century and speculated that withdrawal might explain subsidence in some areas. Although *Meckel* [2008] performed no detailed analysis of pumping records to prove such an assertion, the interpretation is plausible and important to consider given that: 1) the magnitude of the residuals is large and similar to those associated with groundwater withdrawal elsewhere along the Gulf Coast [e.g., *Holzer*, 1981]; and 2) evidence for other possible drivers are lacking, e.g., the potential effect of hydrocarbon production is limited to a small oil field south of the Lake Pontchartrain fault (30°06′54″N, 89°44′12″W) (Figure 2). Subsidence in this area, however, is no different than surrounding areas where hydrocarbon production is absent. Below, additional evidence is presented that strengthens the notion that groundwater withdrawal is the likely cause of the residual vertical motions.

[55] Independent evidence supports the hypothesis that groundwater withdrawal was responsible for much of the late 20th century deep subsidence and RSL rise in the New Orleans area. First, there is a spatial association between areas of large subsidence and areas populated with high-yield groundwater wells (data obtained from http://www.dotd.louisiana.gov/intermodal/wells; Figures 8 and 9). Second, the timing of initiation of a more rapid phase of subsidence and

Figure 8a. Map of the Michoud-Chalmette, LA area, highlighting the Paris Road bridge area (Inset). Shown are the USACE water level gauge 76040 (black circle with yellow cross), benchmarks with names (magenta circles with black crosses), and high yield water wells (green dots, with yield in gallons per minute) at the adjacent Entergy New Orleans, Inc. power station at Michoud. Water is used in electricity production at three generators and wells have supplied ~9000 gallons per minute since 1967; first two generators were installed in 1957 and 1963.

water level rise near Michoud (Figure 6) corresponds with the date when local high yield wells were put into service. Third, as subsidence and RSL rise in the New Orleans area slowed between 1970 and 1995, the water levels in a regional monitoring well stabilized (Figure 10).

[56] Figure 9 is a map showing total local subsidence values and the location and water yield values in the New Orleans area. The easternmost part of New Orleans is rural and contains small yield groundwater wells that support individual households. To the southwest, high subsidence values were encountered on benchmarks that are well inside (~8 km) leveed areas and near high yield water wells (Figures 3 and 9). The local subsidence consequences of groundwater withdrawal are well illustrated by relations at and near the Paris Road Bridge near Michoud, site of water level gauge 76040 (Figure 8). Four water wells located

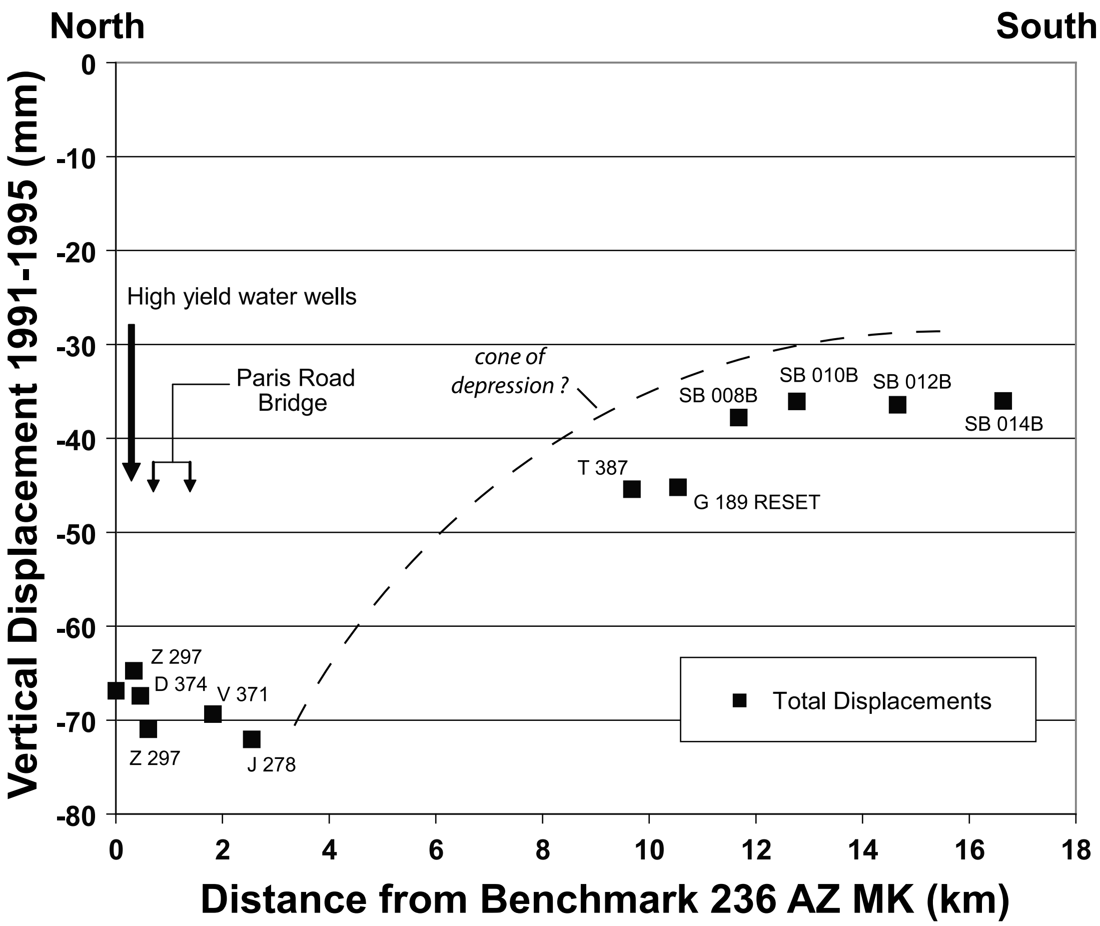

Figure 8b. Profile across the area showing 1991–1995 vertical displacements of deep rod benchmarks and their proximity to water wells near the northern end of the Paris Road Bridge. See text for discussion.

within 300 m of the gauge were established between 1955 and 1962. Each well has yielded between 1,645 and 2,020 gallons per minute in subsequent years (http://www.dotd.louisiana.gov/intermodal/wells; Figure 8a) in support of power generation for the City of New Orleans; the site is referred to as the "Entergy Michoud Power Plant" (30°00′29″N, 89°56′14″W). Figure 8b is a profile across the area that shows that the locus of 1991–1995 motions of deep rod benchmarks is also centered on the area of the high yield wells. Approximately 70 mm of subsidence occurred during this interval (Figure 8b). Subsidence of deep set benchmarks decreased to the south away from the high yield wells in a pattern reminiscent of a "cone of depression" (Figure 8b). Timing relations at the 76040 gauge also shows an sharp increase in water level in mid-1967 (Figure 6), the time of start-up of the last and largest generator at the power plant [*Sprehe*, 2005]; another large yield drinking water well located 2.7 km to the WNW came online near the beginning of 1967 and may have also contributed to the sharp change.

[57] The proposed dominance of groundwater withdrawal-related subsidence in the New Orleans area during much of the late 20th century is further supported by the record at a regional USGS monitoring well (OR-175; 30°05′26″N, 89°46′36″W). This well is located just east of Michoud (Figure 9) and documents monthly observations of the elevation of the water surface in the well from 1963 to the present (Figure 10). The record shows that groundwater surface at OR-175 declined exponentially from at 1963 to the early 1980s. Steep decline occurred between 1963 and ~1981, with the sharpest drop beginning at ~1967 and lasting until 1970. The timing of the most severe decline of the water levels in OR-175 is consistent with the changes observed at surface water level gauges and deep set benchmarks (Figures 3 and 6).

[58] The concomitant slowing of decline of the major regional water table (Figure 10), deep subsidence (Figures 3 and 6), and RSL rise (Figure 4) in the region through the 1980s and 1990s suggests a diminution of the influence by groundwater withdrawal on subsidence, particularly in the New Orleans area west of Michoud from ca. 1981 to present. Water level gauge records for the late 1990s and early 2000s (Figure 5) and the regional USGS groundwater monitoring well (Figure 10) suggest that, with the exception of the Michoud area (including the vicinity of the Paris Road bridge), groundwater withdrawal may only be a minor influence on 21st century deep subsidence. This change in the regional pattern and magnitude of deep subsidence, and

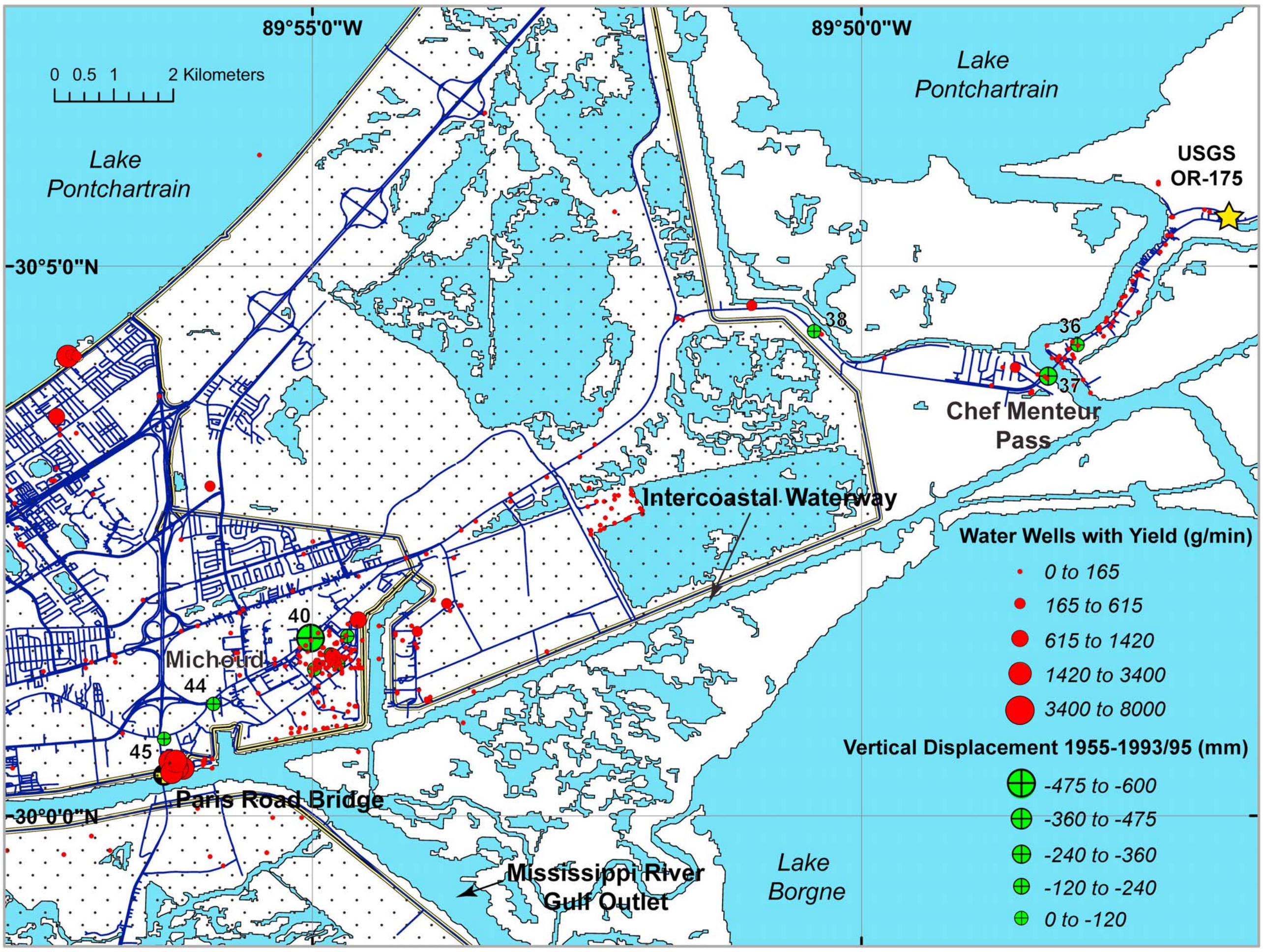

Figure 9. Map of New Orleans area showing water wells with yield rates (red circles). Also shown are deep set benchmarks and their 1955–1995 vertical displacements inferred from geodetic leveling (green circles with crosses); selected benchmarks labeled with ID number keyed to Table 1. Stippled pattern denotes areas protected by federal levees and floodwalls (yellow/black line). Star (yellow) is the location of U.S. Geological Survey observation well OR-175 considered in Figure 10.

the shifting of the locus of deep subsidence to Michoud area is supported by 2003–2005 InSAR measurements of *Dixon et al.* [2006] (Figure 11).

3.2.6. Groundwater Withdrawal-Related Faulting in New Orleans

[59] Several areas of the coast along the northern Gulf of Mexico that have been affected by subsidence due to groundwater withdrawal have also experienced related surface fracturing, reactivation of preexisting faults, and related surface deformation [e.g., *Holzer and Gabrysch*, 1987]. In the Houston, TX area, such features often have obvious geomorphic expression and have been detected in the field and on remotely sensed data [e.g., *Gabrysch*, 1980; *Buckley*, 2000]. Relative motions have been measured with land and space-based geodetic techniques [e.g., *Norman and Elsbury*, 1991; *Holzer and Gabrysch*, 1987; *Buckley*, 2000]. Fracturing and deformation can be caused by: 1) differential groundwater offtake at nearby wells; 2) offtake in areas with preexisting structures that reactivate; and 3) offtake from several wells in an area where aquifers have complex and variable stratigraphy. Given that groundwater-related subsidence has been significant in the study area, it is logical to assume that fracturing and deformation may also have occurred. Below, evidence is presented that suggests that groundwater withdrawal has resulted in fault motion and deformation in central and eastern New Orleans.

3.2.6.1. Michoud Fault

[60] *Dokka* [2006] proposed the existence of the Michoud fault based on a marked change in vertical velocity of a series benchmarks in the Michoud area. It was assumed to be related to NW striking normal faults previously mapped in the subsurface. The proposed location and orientation of the surface trace of the fault in the work of *Dokka* [2006] is supported by the pattern of subsidence revealed in 2003–2005 InSAR data (Figure 11) [*Dixon et al.*, 2006]. Motions between 1969 and 1995 suggested that the Michoud fault was a broad zone of down-to-the-southwest shear. Such a broad pattern of near surface deformation is consistent with a fault that encounters low-cohesion materials in their upper reaches. Such materials cannot sustain a single fracture but instead promote the diffusion of shear that is manifest in the topography as a monoclinal steps or sag.

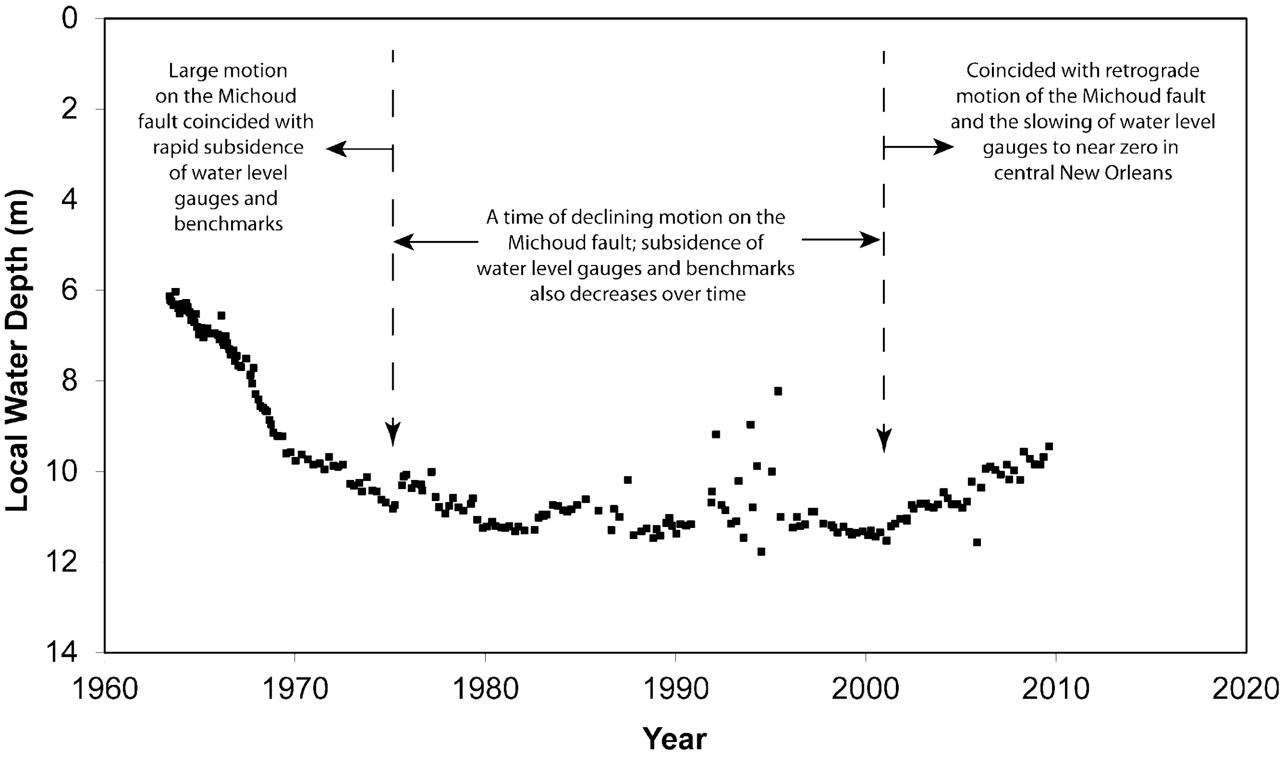

Figure 10. Water level history at U. S. Geological Survey observation well OR-175 located ~3.8 km northeast east of Chef Menteur Pass. Its coordinates are 30°04′4.2″N, 89°48′15.6″W. Points represent monthly observations. See Figure 9 for location and text for discussion.

[61] Differential vertical motions near the Michoud fault were originally considered by *Dokka* [2006] to be unrelated to groundwater pumping because of the apparent stability of regional groundwater levels and reports by local officials that pumping had been minimal in the Michoud area in late 20th century time. Although evidence presented above allows for the possibility that the Michoud fault is rooted below producing aquifers and that a portion of its total motion may be due to deeper tectonic processes, reexamination of previous relations in light of new data and information suggests that much of the observed differential vertical motion may indeed be related to water pumping of the regional aquifer.

[62] Evidence supporting the hypothesis that late 20th century motions on the Michoud fault are related to groundwater withdrawal is circumstantial and centers on two key observations. First, vertical motions inferred from geodetic leveling surveys show that the southwestern fault block (hanging wall) of the NW striking Michoud fault moved down relative to its footwall between 1969 and 1995. Subsequent surveys, however, showed that the sense of motion on the fault had reversed sometime between 2000 and 2005 [*Dokka*, 2006]. InSAR permanent scatter velocities based on 2003–2005 radar data from *Dixon et al.* [2006] show a pattern of vertical motions that is consistent with the apparent retrograde behavior of the adjacent fault blocks in the Michoud area (Figure 11). These data suggest that the northeastern side of the Michoud fault subsided on average ~2.5 mm yr^{-1} faster than the formerly downthrown southwestern block fault during 2003–2005.

[63] The second line of evidence is the apparent association in time of changes in water levels observed in the regional USGS groundwater monitoring well near Michoud with changes in the rates of deep subsidence during the late 20th century (Figure 10). Water levels in this well declined along an approximately exponentially decaying path from ~1964 to ~2001 (Figure 11). Such a decaying decline is similar in form to the subsidence of the area inferred from water level gauges (Figure 6) and geodetic leveling (Table 1) during the same interval. The most rapid decline of groundwater levels occurred between, 1964 and ca. 1975 and generally coincided with the time interval of most rapid differential displacement of benchmarks straddling the Michoud fault [*Dokka*, 2006], as well as the time of most rapid subsidence measured by leveling and the water level gauges (Figures 4 and 6). Falling water levels in the well during 1964–1975 also coincided with the time of major urban development and groundwater pumping in the Michoud area. While water levels in the monitoring well fluctuated from year to year during the interval ~1975 to ~2001, the average water level rise was very low (Figure 11). With the exception of the Rigolets Pass gauge that remained constant, subsidence also slowed at all USACE New Orleans area water level gauges during this same time interval (Figure 6). Measurements at water level gauges 76040 and 76120 of the central New Orleans area suggest that subsidence had nearly stopped by ca. 2001. This diminution of subsidence in the more western environs of the study area, i.e., central New Orleans, over last 25 years of the 20th century was likely the consequence of reduced groundwater pumping, perhaps driven by changes in water policy following the publication of *Kazmann and Heath* [1968]. They analyzed mid-20th century groundwater offtake in central New Orleans and warned of

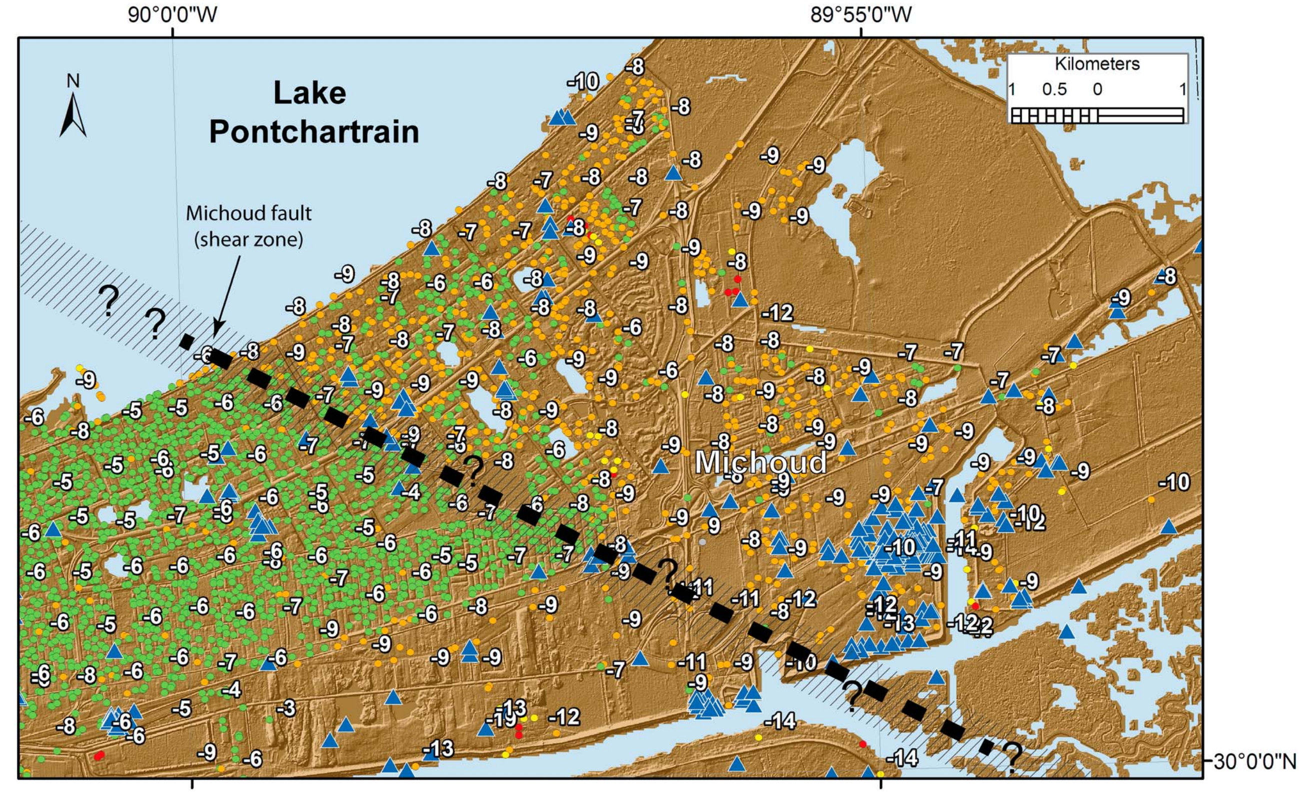

Figure 11. Map of the Michoud area of New Orleans showing vertical velocities derived from InSAR analysis of *Dixon et al.* [2006]. The heavy dashed black line is the Michoud fault of *Dokka* [2006]; this fault is probably best described as a shear zone (black ruled zone). InSAR velocities for 2003–2005, in mm yr^{-1}: red dots, <−17; yellow, −17 to −13; orange, −13 to −7; green, −7 to 0; blue triangles, water wells. Field investigation showed that InSAR permanent scatterers in the area correlate mainly with reflecting surfaces on single-story homes. It has been standard construction practice in New Orleans since the 1950s to build such homes on pilings that completely penetrate Holocene deposits (C. Mugnier, personal communication, 2010). Because the monumentation of the InSAR is similar to both leveling and water level gauge measurements, the results are comparable. See text for discussion.

the subsidence hazard posed by continued groundwater pumping. *Dokka* [2006] showed that motion along the Michoud fault had also ceased near 2001. After ~2001, water levels in the monitoring well began to rise and have continued to do so to the present (Figure 11). This broadly coincided with time of reversal of vertical motions along the Michoud fault [*Dokka*, 2006] (Figure 11). The reversal of motion on the Michoud fault beginning near 2001 can be explained as the consequence of declining groundwater offtake in areas of New Orleans west of Michoud and continued water pumping at Michoud and environs. The continuing rising water levels in the monitoring well and the apparent stabilization of surface water levels at gauges 76060 and 76120 suggests the possibility that groundwater-related subsidence no longer occurs in some areas of central New Orleans. Continued monitoring of groundwater levels and area surface water gauges, coupled with measurements of vertical motions by InSAR, and continuously operating GNSS reference stations are needed to validate this trend.

3.2.6.2. Gentilly Fault

[64] LiDAR-based digital elevation model (DEM) maps suggest the existence of an arcuate-shaped surface fault in the Gentilly neighborhood (29°59′47″N, 90°03′40″W) of the central New Orleans area (Figure 12); the literature contains no record of active surface faults in the area [e.g., *Kolb et al.*, 1975]. Although the area is highly urbanized, field investigations of the Gentilly fault (new name) support this interpretation (Figures 12b and 12c). The lineament seen in the LiDAR data correspond in the field with narrow fracture zones in broken streets and sidewalks and distorted roof lines of houses. The positions of the Holocene-Pleistocene contact in shallow borings [*Kolb et al.*, 1975] straddling the Gentilly fault are consistent with the general sense of down-to-the-south offset suggested by the LiDAR data.

3.3. The Role of Anthropogenic Subsidence

[65] While geologic history and the results of this study suggest that deep-seated natural processes such as loading and faulting have been persistent in time, and constitute significant contributors to overall subsidence of the area, it is the activities of humans, e.g., groundwater withdrawal, that have been the dominant, deep-seated cause of landscape change in the late 20th century. The effectiveness of humans as agents of geological change in the fragile MRD and

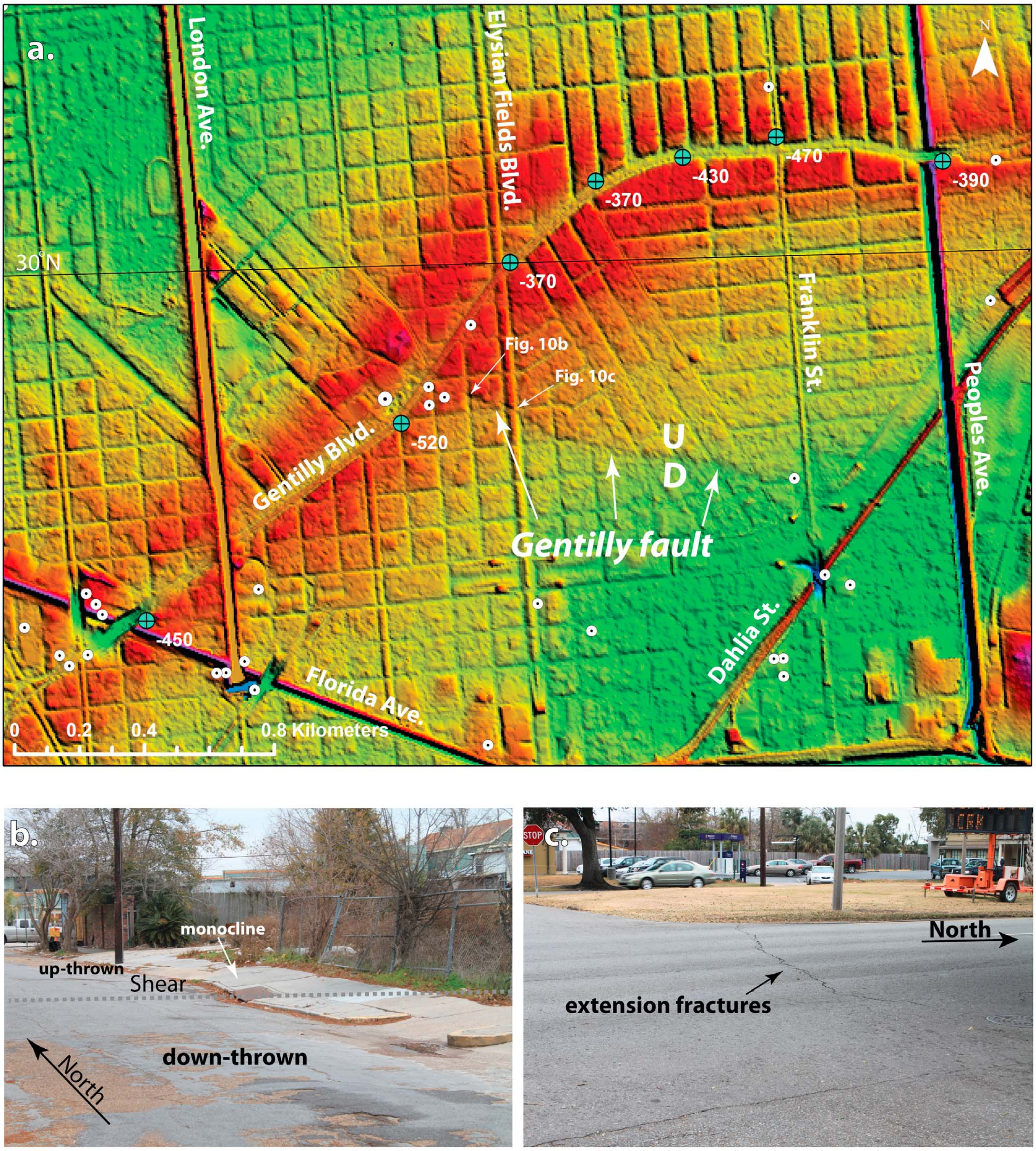

Figure 12. (a) LiDAR relief map of the Gentilly neighborhood of the City of New Orleans showing surface fracturing associated with the Gentilly fault. Range of elevations: red, >2 m; orange, 2 m to 0 m; yellow, 0 to −2 m; green, −4 to −6 m. Symbols: U, up-thrown block; D, down-thrown block; Blue green circles with crosses, benchmarks with 1955–1995 vertical displacement (mm); White circles with black dots, water wells. (b and c) Field photographs of surface fractures observed on LiDAR relief map. Locations of photographs are shown in Figure 12a. See text for discussion.

adjoining coastal lands should not be surprising considering that the entire landscape has been highly manipulated in the interests of agriculture, urbanization, and river flood mitigation for nearly 300 years [e.g., *Barry*, 1998; *Colten*, 2005]. When the additional subsidence due to desiccation, oxidation, and accelerated compaction of shallow sediments within leveed communities and farms [e.g., *Snowden et al.*, 1977; *Snowden*, 1984] are added to the deep components documented in this paper, the dominance of anthropogenic change cannot be denied. Such change has had particular impact on enhancing the vulnerability of this low-lying land to flooding from severe storms, as was observed in 2005 during Hurricane Katrina. One of the few places where the protection system was overtopped by surge was at the Paris Road Bridge [*National Institute of Standards and Technology*, 2006], the site of greatest subsidence in the area and a place where large amounts of groundwater has been withdrawn.

[66] Unfortunately, future projections of subsidence and landscape changes that underpin hurricane protection for New Orleans and other population centers [*USACE*, 2007] (http://www.mvn.usace.army.mil/pdf/hps_verticalsettlement.pdf), as well as for coastal restoration planning for coastal Louisiana [*LCWCRTF*, 1998] (www.lacoast.gov/Programs/2050/MainReport/report1.pdf) have not integrated highly precise late 20th century geodetic and water level data that are tied to temporally and spatially precise data. If allowed to stand, the underestimation of subsidence in this vulnerable land may have devastating human and ecosystem consequences in the near future as RSL rise and hurricane landfalls continue.

4. Conclusions

[67] The following conclusions were reached in this study of late 20th century geodetic leveling and water level gauge data from coastal Mississippi-Lake Pontchartrain-New Orleans area:

[68] 1. Subsidence estimates from water gauges attached to major bridges yield similar results to geodetic measurements of benchmarks affixed to deep rods set in upper Pleistocene sedimentary deposits. All monuments show that the entire sampling area subsided during the late 20th century, with the maxima occurring in the New Orleans area. Subsidence in the Michoud area of New Orleans exceeded 0.8 m between 1955 and 1995; local sea levels in the region rose between ~0.2 and ~1.0 m. Subsidence markedly decreases away from urbanized areas and north of the belt of active basin margin normal faults. Subsidence gradually decreases to the east and north along upland terraces and coastal Mississippi. Subsidence inferred from water level gauges colocated with benchmarks confirms the accuracy of the previous vertical motion estimates of *Shinkle and Dokka* [2004] and *Dokka* [2006].

[69] 2. Because all monuments in this study are set in upper Pleistocene, semilithified sediments, and thus, lack mechanical coupling to Holocene sediments, subsidence estimates presented here do not contain the contributions of shallow processes such as natural or man-induced compaction, consolidation, and oxidation-related decomposition of Holocene sediments. The amount of deep-seated subsidence observed is 8 to 50 times higher than the total subsidence indicated by previous estimates. These observations contradict the current geological paradigm that asserts that natural compaction of Holocene sediments is the dominant cause of subsidence in the region. Full accounting of the total late 20th century subsidence must, therefore, include shallow and deep-seated components.

[70] 3. Deep subsidence of the Mississippi coast that occurs east and north of the basin margin faults can be explained by a combination of: a) regional loading of the lithosphere by the modern Mississippi River delta and late Quaternary sea level rise; and b) local groundwater withdrawal. Although the amplitude of deformation predicted by loading models is presently poorly constrained, the predicted lateral extent of load-induced subsidence fits well with observed subsidence implied by benchmarks and regional water level gauges; data suggest that the lateral effect extends as far east as Pensacola, FL.

[71] 4. Sharp, local changes in subsidence coincide with the known traces of strands of the basin margin normal fault system. While not major contributors to regional subsidence, these active faults are important for the geohazards they pose. The Lake Pontchartrain fault and the south strand of the Tepatate–Baton Rouge fault system show several cm of relative vertical displacement during the late 20th century; displacement histories are apparently constant over time, suggesting a creep mechanism. The north strand of the Tepatate–Baton Rouge fault system showed no motions during the time interval considered.

[72] 5. The magnitude of deep subsidence in urban New Orleans is too large to be explained by any combination of faulting, deep compaction, and lithospheric loading. Based on spatial and temporal relations, it is proposed that this residual subsidence is largely due to local and regional groundwater withdrawal from shallow aquifers. Groundwater extraction in urbanized areas has likely been responsible for lowering local flood protection structures and bridges in the area by as much as 0.8 m since ~1960. The loci of maximum subsidence coincide with areas of large yield water wells that tap regional aquifers ~160 to 200 m deep. The time following installation of new high volume water wells near the Paris Road Bridge in the late 1960s, for example, was followed by the rapid subsidence of the bridge and surrounding area, and local water level rise. Water pumping is also suspected to be responsible for recent surface fracturing in central and eastern New Orleans. However, local subsidence at Michoud that occurs at depths >1.8 km below producing aquifers suggests that regional faulting may also be operative.

[73] 6. Subsidence in the eastern New Orleans area in the late 20th century has been dominated by mainly anthropogenic drivers. Unfortunately, current hurricane protection and coastal restoration planning for the New Orleans and coastal Louisiana–Mississippi region are based on long, time-averaged subsidence rate estimates that do not reflect modern motions established by geodetic methods and water level gauge measurements. In the interest of public safety, these plans need immediate reconsideration in light of the data presented here.

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