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Dokka, R. K., 2006, Modern-day tectonic subsidence in coastal Louisiana: Geology, v. 34, p. 281-284.

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Modern-Day Tectonic Subsidence in Coastal Louisiana

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ABSTRACT

Subsidence is leading to the slow inundation of communities and wetlands of Louisiana, Mississippi, Texas, and Alabama by the Gulf of Mexico. The prevailing paradigm considers subsidence to be the result of young sediment compaction/consolidation and human activities. This paper describes the results of a test of this theory based on an examination of historic motions of benchmark in the Michoud area of Orleans Parish, LA. This methodology allowed for an assessment of vertical change at different levels over time relative to a precise vertical datum (NAVD88).

Data do not support the current theory on the origins of subsidence by demonstrating that tectonic causes dominate in the study area. During 1969-1971 and 1971-1977, tectonism was responsible for -16.9 mm/yr and -7.1 mm/yr of subsidence, respectively. These contributions account for 73% and 50% of the total subsidence during these intervals. The change in deep subsidence is attributed to renewed motion along a large normal fault (Michoud fault). Over the same time intervals, intermediate depth subsidence due to compaction of Pleistocene to middle Miocene strata was constant (-4.6 mm/yr). Similarly, subsidence due to shallow processes, i.e., sediment compaction and groundwater offtake, was -1.5 mm/yr and -2.5 mm/yr. Subsidence associated with petroleum extraction was not a factor due to the lack of local production.

INTRODUCTION AND HYPOTHESIS TO BE TESTED

Modern subsidence of New Orleans and environs set the stage for the devastation of Hurricane Katrina by lowering the elevations of the land and surrounding levee defenses (Shinkle and Dokka, 2004). It has been long-recognized that areas bordering the Gulf of Mexico (GOM) are subsiding, resulting in slow inundation of the coast (Fig. 1a; e.g., Kolb and Van Lopik, 1958; Holdahl and Morrison, 1974). Subsidence is widely regarded as a near surface effect, being the consequence of shallow sedimentary processes or the result of human activities (e.g., Boesch et al., 1994; Reed and Wilson, 2004). This view has been shaped by the obvious degradation of coastal marshes as well as measurements based on peat chronostratigraphy of samples taken exclusively in wetland areas, and analysis of water level gauges (e.g., Penland and others, 1988; Penland and Ramsey, 1990; Roberts, 1997; Kulp, 2000). Although tectonic processes, e.g., faulting, salt migration, and regional warping due to sediment loading, are widely held to have modified the lithosphere to accommodate as much as 20,000 m of sediments in the GOM (e.g., Worrall and Snelson, 1989), tectonism is rarely invoked as an control on modern subsidence. It is only recently that faulting has been proposed as a significant cause of subsidence (e.g., Gagliano, 1999). Some, however, consider faulting to be human-induced and related to groundwater withdrawal (e.g., Holzer and Gabrysch, 1987) or oil/gas production (e.g., Morton et al., 2002).

In an effort to recalibrate the National Spatial Reference System, Shinkle and Dokka (2004) computed vertical motions on 2710 benchmarks in Louisiana, Mississippi, and adjoining states. Their results indicate that coastal areas have been sinking at higher rates than previously thought and that the area of subsidence extends beyond the wetlands of the Mississippi River’s delta and alluvial valley (Figure 1). Here, benchmark vertical velocities computed from data collected between 1955 and 2005 are used to test the current paradigm that considers subsidence to be largely the result of young sediment compaction and human-related activities.

APPROACH AND GEOLOGIC SETTING

The study area at Michoud, LA (Fig. 1) was selected for three reasons. First, subsidence rates implied by benchmark motions were among the highest in the south-central USA (Shinkle and Dokka, 2004). Second, the area has a wealth of geodetic data, having been surveyed multiple times over the past 50 years. Third, because the area contains an array of closely-spaced benchmarks attached to wells and rods that penetrate to varying levels, subsidence could be determined as a function of depth (see Fig. 2).

Earth materials of the area consist of 20-30 m of Holocene deltaic marsh sediments (Fullerton et al., 2003) which overly Pleistocene deltaic deposits containing a regional aquifer at 150-200 m (Dial, 1983). This is underlain by ~10km of mainly Pliocene-Jurassic deltaic and shelf deposits (Bebout and Gutierrez, 1983; McBride, 1998). Subsurface mapping previously identified a large fault, named here the Michoud fault, based on well cut-offs and seismic surveys (Hickey and Sabate, 1972). Sedimentary growth implies that movement along the Michoud fault has been intermittent since Oligocene time (data presented in Bebout and Gutierrez, 1983). A cross-section in McBride (1998) shows a high angle normal fault that is correlated here with the Michoud fault. This fault merges with a low-angle detachment at ~-7 km that is developed along the top of a slightly, south-dipping zone of allochthonous salt and shale. These structures are considered to be related to a regional, south-vergent extensional-contractional complex described by Peel et al. (1995; Fig. 1). Movement of the complex was powered by gravity instabilities created during times of high sedimentation (Peel et al., 1995).

METHODS, DATA AND RESULTS

Geodetic leveling is a highly precise method of determining the difference in height between two points (e.g., Vanicek et al., 1980). Shinkle and Dokka (2004) used 1^{st} order leveling data from the NOAA/National Geodetic Survey and the tide gauge at Grand Isle, LA to compute vertical velocities of benchmarks relative to the North American Vertical Datum of 1988 (NAVD88). Velocities were independently verified through comparison with motions determined by other tide gauges and Global Positioning System base stations. The same method was applied here to compute velocities for the time intervals 1955-1969, 1969-1971, 1971-1977, and 1977-1995 (Fig. 1, Tables DR1[1] and DR2[1]). The Appendix[1] describes the NOAA data sources, methods, and error analysis. Additional leveling was conducted in 2005 using the same NOAA methods (see Appendix[1]).

DISCUSSION

Quantification of Subsidence

Current consensus holds that modern subsidence of the Louisiana coast is the result of compaction and consolidation of young sediments and particular deleterious activities of humans (e.g., Reed and Wilson, 2004). The former is thought to be concentrated in the Holocene delta and alluvial valley of the Mississippi River (e.g., Roberts, 1997). Activities associated with the latter include oil and gas extraction (e.g., Morton et al., 2002), groundwater offtake (e.g., Kazmann and Heath, 1968), and drainage of organic soils (e.g., Kolb and Saucier, 1982). As will be discussed below, these processes although present here and/or elsewhere along the coast, are inadequate to explain the velocity data in the study area. Instead, the data suggest that subsidence here includes a large, deep seated component. An alternative hypothesis is offered below that proposes that this component is related to faulting.

Depth characteristics of studied benchmarks are shown diagrammatically in Figure 2a. This array allowed for the estimation of three components of subsidence: 1) a deep, <-2011 m component that includes a local vertical strain associated with slippage along the Michoud fault and possibly motion associated with regional, tectonic warping (Jurkowski et al, 1984). Both of these processes are likely driven by gravitational instabilities associated with sediment loading of the modern Mississippi River delta on the lithosphere; 2) an intermediate depth component that is due to the compaction of sediments lying between the Quaternary aquifer at ~-170 m and the bottom of the 2011 m well that ends in middle Miocene strata; and 3) a shallow component that occurs from the surface to -170 m. Subsidence here includes the combined effects of groundwater offtake and compaction/consolidation processes in shallow upper Quaternary sediment deposits.

Deep Component: This component is based on the motions of benchmark BH1089. The 2011 m well to which the benchmark is attached penetrates young sediments undergoing natural compaction/consolidation, and oxidation due to drainage projects. The well passes below aquifers where locally large amounts of water have been extracted in the last sixty years (Dial, 1983), and terminates in middle Miocene strata. Thus, the subsidence recorded at BH1089 contains no contribution from any process operating above -2011 m. Studies of regional porosity and bulk density as a function of depth in the GOM suggest that minor compaction continues within strata below the 2011 m well (middle Miocene-Jurassic). Eaton (1969) indicates that sediments at a depth equivalent to that of the bottom of well attached to BH1089 are ~92% compacted. Given the short time intervals considered here, subsidence related to such compaction would likely be small, yet constant over time. Thus, the only contributor to subsidence at BH1089 that cannot be ruled out is tectonic. The tectonic subsidence recorded by

BH1089 was -16.9 mm/yr and -7.1 mm/yr in 1969-1971 and 1971-1977, respectively. Tectonism, therefore, accounts for 73% and 50% of total subsidence in this local area of the footwall during 1969-1971 and 1971-1977, respectively. Finally, the dearth of production wells in the area precludes petroleum extraction as a contributor to subsidence in the area.

Intermediate Component: This component is based on the difference in benchmark motions between the 2011 m well (BH1089) and three adjacent water wells (BH1088, BH1090, BH1091) that penetrate to depths between -170 and -178 m; for comparison, the average velocity of the three wells was used. The intermediate component includes subsidence effects that occur in Pleistocene to middle Miocene strata. Compaction is the only likely process operating in this interval. During 1969-1971 and 1971-1977, intermediate depth compaction was constant and contributed -4.6 mm/yr to the total subsidence.

Shallow Component: This category includes contributions from processes that occur from the surface (BH1087) down to the bottom of the aforementioned water wells (~0 to -178 m; Fig. 2). Processes that could contribute include Holocene-Pleistocene compaction/consolidation, organic soil oxidation due to drainage projects, and groundwater offtake in the deep aquifer that are tapped by the water wells. The contribution of the shallow component was essentially constant over time: -1.5 mm/yr and -2.5 mm/yr during 1969-1971 and 1971-1977, respectively. The stability of water levels over this time (Dial, 1983) suggests that groundwater offtake effects may have been small.

Integration of geologic and geodetic data suggests that tectonic subsidence is most likely related to slip along and strains associated with the Michoud fault. Two lines of evidence suggest that the Michoud fault was active between 1969 and 1995 and had significant slip and non-permanent vertical strains that affected areas beyond the Michoud area. First, benchmarks of the hanging wall near the fault, i.e., BH1084, BH1083, show significantly more subsidence than nearby footwall counterparts, i.e., BH1088, BH1087, BH1090, BH1089, BH1091 (~-39 mm/yr compared to ~-21 mm/yr, respectively [1969-1971], and ~23 mm/yr compared to ~11 mm/yr, respectively [1971-1977]). We can rule out changes due to shallow and deep compaction because these processes would not be expected to vary significantly over the short time intervals considered here. Subsidence due to groundwater extraction could certainly increase with time due to increases in offtake. Studies by Dial (1983), however, document that offtake from the main aquifer in the region actually declined slightly from ~1968 to 1982 and that the annual water levels at well OR-78 (to which BH1088 is attached) remained constant. It is proposed, therefore, that relative differences in subsidence between blocks of the Michoud fault generally reflect fault motion. Assuming that the slip vector was oriented 180° and plunging 70°, the observed relative vertical motion implies the following slip rates: 24 mm/yr (1969-1971) and 15 mm/yr (1971-1977). Figure 3 suggests that normal slip ended between 1995 and 2005 and was followed by small retrograde motion. The second line of evidence involves the recognition of the marked difference in behavior of the two fault blocks during deformation. As shown on Figure 2, subsidence of the hanging wall progressively slowed with time following initiation. In contrast, the footwall shows a behavior similar to elastic unloading. After initial slip during 1969-1971 in which the hanging wall is removed from a small part of the footwall, subsidence of footwall slowed significantly (1971-77). This was followed during 1977-1995 by more rapid subsidence. Relations in Shinkle and Dokka (2004) show that vertical motions were not uniform across the footwall but rather displayed a pattern suggestive of a relative up then down oscillation following fault initiation.

Comparison with Previous Subsidence Estimates

Measurements of subsidence inferred from benchmarks from the Michoud area are substantially different than previous estimates. Gagliano (1999) created a regional map showing areas of supposed similar subsidence character to support planning efforts by the State of Louisiana in their effort to stem coastal land loss. In the Mississippi River delta plain (including the Michoud area), the mapping units were primarily based on leveling data along natural levee ridges from the most recent epoch of record and other methods in other areas. No vertical datum was specified in order to accurately relate measurements collected with different methods. The Michoud area was classified to be an area of low subsidence, i.e., 0 to 0.3 m/100 yr. In comparison, subsidence indicated by benchmark motions reported in this study during 1969-1971 was 8 to 14 times the rates of Gagliano (1999). The discrepancy between the geodetic rates provided here and previous estimates can be understood through a review of the methods employed and the quality of vertical datum used to reference measurements.

Precision, accuracy, and practical range of methods: Geodetic leveling is demonstrably the most accurate and precise method commonly used to measure modern subsidence, i.e., today ±human lifetime. Leveling can measure sub-millimeter vertical changes that occur over short periods, i.e., days, resulting in a resolution of mm per year or better. Furthermore, subsidence measured by leveling in the region has been independently validated by other methods (e.g., Shinkle and Dokka, 2004). In contrast, estimates based on peat chronostratigraphy average changes in position of a peat horizon over hundreds to thousands of years (e.g., Kulp, 2000). Yearly to decadal changes such as measured here are beyond the resolution of peat chronostratigraphy methods. Furthermore, the accuracy of previous studies has not been verified independently using other methods of comparable or superior resolution. Other studies using inland water level gauges failed to account for uncorrelated effects such as changes to the surface hydrology (e.g., canal building, drainage projects) and climatic changes to the watershed (freshwater input, wind patterns, etc.; Penland and Ramsey, 1990; Turner, 1991).

Vertical Datum: This paper provides the first depth dependent analysis of subsidence of the gulf coast region within the context of a spatially and temporally precise vertical datum. All previous attempts to measure subsidence in south Louisiana except Shinkle and Dokka (2004) employed an imprecise vertical datum to reference measurements. Unfortunately, failure to use a precise vertical datum such as NAVD88 has several unintended negative consequences. First, by using a datum that does not extend beyond the subsiding area to a point of vertical stability (or to a point of known motion), all measurements will be in error by the amount that the "reference" point is actually moving. Studies that use a local, informal datum will thus underestimate, or even neglect entirely any regional component (e.g., Jurkowski et al., 1984; Kuecher et al., 2001; Morton et al., 2002). Second, the use of an areally restricted datum like sea level precludes users from defining the spatial limits of subsidence. If one cannot access the datum during measurement, no meaningful measurement can be made. Thus, studies using water level gauges or peat chronostratigraphy that rely on sea level as a datum were unable to detect subsidence in areas beyond the coast. In contrast, the use of NAVD88 explains why Shinkle and Dokka (2004) were able to measure subsidence of benchmarks well beyond the limits of the delta and alluvial valley of the Mississippi River (Fig. 1a). Finally, different areas with subsidence measurements based on locally contrived datums cannot be compared. Previous attempts to map subsidence regionally using disparate data have yielded unsatisfactory results (cf. Gagliano [1999] with Shinkle and Dokka [2004]). This statement also holds for studies that relied on sea level as a vertical datum to reference measurements, i.e., water level gauges and peat chronostratigraphy. It is now recognized that the elevation of sea level is not the same everywhere and that its position has changed globally over recent time (e.g., Miller and Douglas, 2004). Thus, any local measurement that is related to sea level is uncertain. Problems are compounded for studies using peat chronostratigraphy because this method relies on unconfirmed ancient positions of sea level.

CONCLUSIONS

The following conclusions were reached in this study of 1st order geodetic leveling data collected between 1955 and 2005 in Michoud area of coastal Louisiana:

1. Three, depth related subsidence components were identified and quantified based on the array of benchmarks set at different depths and measured multiple times. Measurements from 1955 to 1995 were made with respect to a precise vertical datum (NAVD88).
2. Data do not support the prevailing theory that modern subsidence is due solely to shallow sedimentary processes and the activities of humans. Instead, relations suggest that motions contain a large deep-seated component that is argued to be of tectonic origin. Tectonic subsidence in the area reached its maximum during 1969-1971 (-16.9 mm/yr) when it constituted 73% of the total subsidence. Subsidence coincided with an interval of rapid slip (23.7 mm/yr) along the Michoud fault, a regional, down-to-the-south normal fault. Between 1971 and 1977, slip on the fault slowed to 15 mm/yr and the tectonic contribution to total subsidence dropped to 50%. Additional leveling across the fault trace in 2005 suggests that normal fault motion ended between 1995 and 2005. An intermediate depth component due to compaction of sediments was constant over these time intervals (-4.6 mm/yr). Subsidence related to shallow processes, i.e., compaction of surface sediments and groundwater offtake, was also essentially constant over time: -1.5 mm/yr and -2.5 mm/yr during 1969-1971 and

1971-1977, respectively. The lack of production wells in the area precludes oil and gas extraction as a contributor to subsidence in the area.

ACKNOWLEDGMENTS

Supported by grants from the National Science Foundation (9725330 and 0220288). Helpful reviews were provided by S. Boss, T. Dixon, T. Meckel, K. Shinkle, and an anonymous reviewer.

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FIGURE CAPTIONS

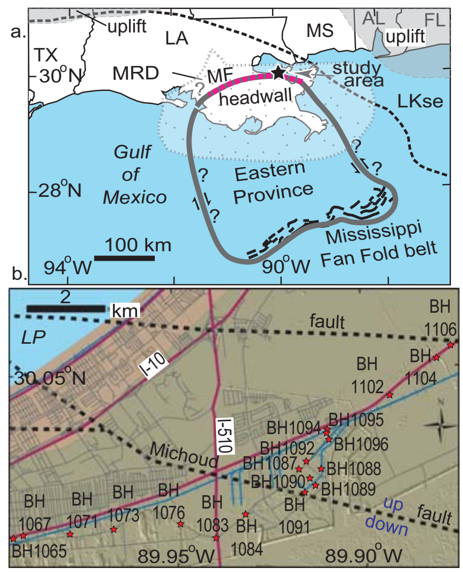
Figure 1. a. Index map of south Louisiana showing regional features and location of study area (star). Entire region with exception of areas labeled “uplift” have experienced late 20th century subsidence (Shinkle and Dokka, 2004). MF, Michoud fault. Michoud fault is updip projection of fault mapped in the subsurface by Hickey and Sabate (1972). Coupled extensional-contractional complex (Eastern Province) of Peel et al. (1995). MRD, Mississippi River delta. LKse, Late Cretaceous shelf edge. b. Location map showing benchmarks considered in this report. Benchmarks marked with NOAA/National Geodetic Survey identification code, e.g., BH1089 (Table DR2[1]). LP, Lake Pontchartrain.

Figure 2. a. Diagrammatic cross-section showing nature of benchmarks near Michoud, LA. Benchmarks with associated rods are shown to length. Water wells, with attached benchmarks:

OR-78, BH1088; OR-79, BH1090; OR-80, BH1091. Note: well casing attached to benchmark BH1089 not shown to scale. Stratigraphy generalized from Dial (1983) and Bebout and Gutierrez (1983). b. Corresponding NAVD88 related vertical velocities in mm/yr (Table DR2[1]). Errors explained in Appendix[1].

Figure 3. Cumulative displacement of benchmarks straddling the Michoud fault as a function of time. Data and methods provided in Appendix[1]. All level lines indexed to BH1104. Note that relative fault motion stopped between 1995 and 2005. Data suggest that retrograde motion on the fault has occurred recently.

[1] GSA Data Repository item 2006##, Appendix, is available online at www.geosociety.org/pubs/ft2005.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA..



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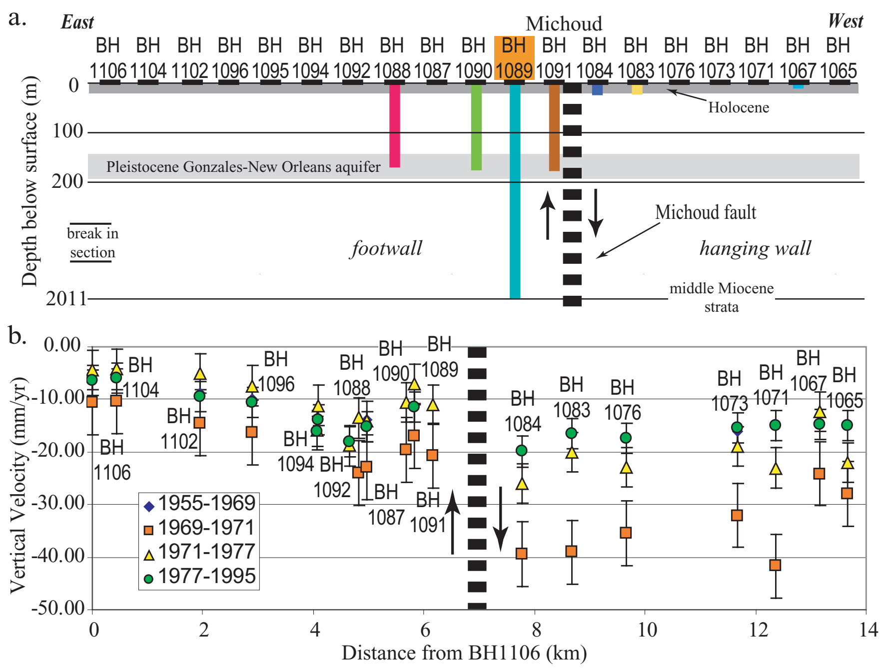

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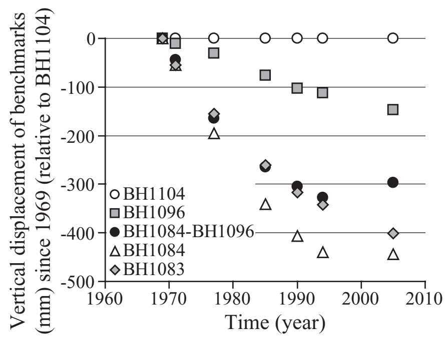

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Data Repository Item 2006##

APPENDIX

Sources of Data for Vertical Velocity Computation

Vertical velocities of benchmarks relative to NAVD88 were calculated using the methods described in Shinkle and Dokka (2004). This involved the integration of several epochs of 1st order geodetic leveling data, as well as the relative sea level rise recorded at the long-standing tide gauge at Grand Isle, LA (East Point), and the global eustatic sea level rise. These latter two components were used to establish a linkage to the North America Vertical Datum of 1988 (NAVD88). Data and information regarding leveling data can be obtained at from the National Geodetic Survey at www.ngs.noaa.gov. A summary of leveling data sources and error constraints are provided below in Table DR1. Tide gauge data from Grand Isle, LA are available from the National Ocean Service www.nos.noaa.gov. Analysis of data from this tide gauge is provided in Shinkle and Dokka (2004). The vertical velocities cited in this paper (Table DR2) differ slightly from Shinkle and Dokka (2004) in that here a consensus value of 2.0 mm/yr for eustatic sea level rise is used (Miller and Douglas, 2004). Shinkle and Dokka (2004) used a value of 1.25 mm/yr that corresponded to the mean of the largest mode of rise estimates.

An additional leveling survey was conducted by Mr. Blake Amacker, Mr. Jordan Heltz, Mr. Clifford Mugneir, Mr. Imtiaz Hossain, and Dr. Roy K. Dokka of the Louisiana Spatial Reference Center to determine if differential motion along the Michoud fault was continuing as of January 05, 2005. Four benchmarks (BH1104, BH1096, BH1084, and BH1083) were surveyed using the same 1st order methods employed during the collection of the NGS data. BH1104 and BH1096 occur in the fault's footwall, whereas BH1084 and BH1083 are situated in the hanging wall. Additional NGS 1st order leveling surveys from 1985 (NGS Line L24903-2) and 1990 (NGS Line L25283-1) were included in this analysis. Each survey was indexed to BH1104 (set to 0 mm). The results are shown in Figure 3 and Table DR3 and suggest that motion along the Michoud fault likely ceased between 1995 and 2005.

Error Analysis

In order to relate changes in height differences revealed by leveling to a common datum, Shinkle and Dokka (2004) referenced each leveling epoch, i.e., survey, to the same benchmark (AT0688) located adjacent to the tide gauge. It was assumed that changes in elevation at that NAVD88 benchmark over time were equal to the relative sea level rise recorded by the tide gauge minus the eustatic component (Shinkle and Dokka, 2004). This seems reasonable considering that the tide gauge is longstanding (>20 years) and generally the product only by marine influences (Shinkle and Dokka, 2004). All changes revealed by leveling in the region were related to that single benchmark where its elevation could be established at any time in the context of NAVD88. Thus, assessment of the total maximum error (σ_{total}) at benchmarks in the study area relative to NAVD88 would involve the estimation of the uncertainties associated with each component measurement: the vertical displacement implied by pairs of leveling runs separated by a known time span (l), the vertical displacement at the point of beginning located at the water level gauge at Grand Isle-East Point (g), and the eustatic (e) sea level change. Uncertainties were estimated by calculating the error for each constituent measurement and then combining them according to the general law of error propagation (e.g., Borradaile, 2003). The combined uncertainty is expressed by,

$$\sigma_{total} = ((\sigma_e)^2 + (\sigma_g)^2 + (\sigma_l)^2))^{½} \qquad (1)$$

Uncertainties associated with leveling are due to random and systematic errors accumulated along the entire line of survey (e.g., Vanicek et al., 1980). Analyses of leveling errors are not benchmark specific, but instead reflect the integrity of the survey line as a whole. The geodetic leveling data used here are classified as 1st order, class II or better by the National Geodetic Survey/NOAA, and thus have passed stringent quality and accuracy requirements (Bossler, 1984). The high precision of 1st order leveling is due in large part to the exacting procedures that help minimize systematic and random error accumulation (e.g., Vanicek et al., 1980). For data to be classified as 1st order, class II, the maximum propagated standard deviation of elevation difference in millimeters (σ_l) between survey control points obtained from the least squares adjustment can be stated as,

$$\sigma_l = 0.7 * (b)^{1/2} \quad (2)$$

where b is defined as the elevation difference accuracy. The elevation difference accuracy is the relative elevation error between a pair of control points that is scaled by the square root of their horizontal separation traced along existing level routes; the units of b are (mm)/ $\sqrt{d}$ (km), where d is the length of the leveled line. Starting with zero error at the point of beginning, progressive measurements result in the accumulation of error along the line, reaching a maximum at the end of the line. Because error accumulates and increases along the length of a leveling line, the error on an individual benchmark can be estimated based on its distance from the starting point along the level line. Table DR1 shows the error statistics for all level lines presented in this paper.

Uncertainties associated with the water level gauge also include the error related to the estimation of eustatic sea level rise. Recent consensus hydrographic and satellite altimetry estimates put the mean global increase in sea level at 1.5-2.5 mm/yr (Miller, and Douglas, 2004). If we equate this range to a 2 sigma estimate, then the standard deviation of the estimate of this component is ±0.50 mm/yr = σ_e. The standard error of the regression of the monthly mean sea levels for the Grand Isle-East Point tide gauge is ±0.97 mm/yr = σ_o (Shinkle and Dokka, 2004). Table DR2 provides 2σ errors for each benchmark velocity in the study.

Errors associated with the vertical displacements computed over the short level lines that straddle the trace of the Michoud fault (Fig. 3) are provided in Table DR3. The smaller uncertainties reflect the short distance between endpoints of the surveys (3.755 km). Because in this case only local relative movements adjacent to the Michoud fault were of interest, only errors associated with leveling were included.

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TABLE DR1. NATIONAL GEODETIC SURVEY/NOAA LEVELING DATA SOURCES USED TO COMPUTE VELOCITIES OF BENCHMARKS IN MICHOUD AREA*

Time interval (NGS lines used)	Number of Common Benchmarks	Length of Common Line (km)	Starting/Ending Benchmarks[†]	Maximum σ for two lines (mm)[§]	Maximum σ of Vertical Velocities (mm/yr)**
1955-1969 (L15414/A -L21664/2)	118	131.3	BH0398/AU0413	11.34	0.81
1969-1971 (L21664/2-L22314)	223	144.9	BH0848/AU0520	11.90	6.22
1971-1977 (L22314-L24133/21)	118	85.7	BH1193/AU0413	9.20	1.43
1971-1977 (L22314-L24133/22)	109	66.3	BH0397/BH1194	8.1	1.20
1971-1977 combined (L22314- L24133/21 & L24133/22)	227	158.2	BH0397/AU0413	12.45	1.92
1977-1995 (L24133/21- L25424/2)	61	57.0	BH1167AU0413	7.47	0.43

[*]Leveling data from National Geodetic Survey/NOAA.
[†]National Geodetic Survey permanent identifier code for benchmarks
[§] Describes the maximum standard deviation over the entire double run for two lines allowable under NGS 1st order class 2 specifications.
**Estimated value of two standard deviation uncertainty of relative vertical velocity that could have accumulated along the line.

TABLE DR2. VERTICAL VELOCITIES COMPUTED ON BENCHMARKS OF THE MICHOUD, LA AREA*

PID[†]	Location		Distance from BH1106 (km)[§]	Vertical velocity (mm/yr)								Benchmark attached to:**
	Latitude (ºN)	Longitude (ºW)		1955-1969	±2s	1969-1971	±2s	1971-1977	±2s	1977-1995	±2s	
BH1106	30.055	89.876	0			-10.60	6.19	-4.39	3.79	-6.31	2.89	headwall
BH1104	30.052	89.88	0.43			-10.41	6.19	-4.27	3.79	-5.95	2.89	headwall
BH1102	30.044	89.893	1.94	-8.81	3.03	-14.44	6.18	-5.05	3.79	-9.52	2.89	headwall
BH1096	30.034	89.909	2.9	-9.94	3.03	-16.25	6.18	-7.40	3.79	-10.57	2.89	0.1
BH1095	30.035	89.909	4.07					-15.92	3.78	-16.11	2.88	concrete post
BH1094	30.035	89.909	4.09					-11.13	3.78	-13.85	2.88	concrete post
BH1092	30.029	89.915	4.66					-18.83	3.78	-18.01	2.88	0.1
BH1088	30.026	89.911	4.81			-24.02	6.17	-13.53	3.78			well, -170m
BH1087	30.027	89.917	4.97	-13.98	3.03	-23.00	6.16	-14.18	3.78	-15.25	2.88	rod, -2m
BH1090	30.024	89.914	5.67			-19.62	6.16	-10.52	3.78			well, -176m
BH1089	30.023	89.913	5.82			-16.88	6.16	-7.14	3.78	-11.41	2.88	well, -2011m
BH1091	30.022	89.916	6.17			-20.73	6.16	-11.08	3.78			well, -178m
BH1084	30.017	89.932	7.77			-39.36	6.15	-26.04	3.77	-19.93	2.88	rod, -24m
BH1083	30.011	89.939	8.67			-39.08	6.14	-19.97	3.77	-16.61	2.88	concrete pier
BH1076	30.015	89.949	9.67			-35.44	6.14	-22.93	3.77	-17.43	2.88	building
BH1073	30.014	89.967	11.67	-16.15	3.02	-32.06	6.13	-18.93	3.76	-15.33	2.87	concrete post
BH1071	30.013	89.978	12.37			-41.73	6.12	-23.02	3.76	-15.02	2.87	concrete post
BH1067	30.013	89.991	13.17			-24.13	6.12	-12.27	3.76	-14.70	2.87	rod, -9.8m
BH1065	30.013	89.996	13.67			-28.03	6.12	-22.12	3.76	-15.06	2.87	concrete post

Note: Motions relative to North American Vertical Datum of 1988. Data form basis of Figure 2. The Michoud fault occurs between BH1091 AND BH1084.
*Methods based on Shinkle and Dokka (2004). See Table DR2 for sources of data and analysis of errors.
[†]Permanent identifier (PID) of benchmark (National Geodetic Survey/NOAA).
[§]Benchmarks are aligned approximately from ENE (BH1106) to WSW (BH1065).
**Information from NOAA data sheets (http://www.ngs.noaa.gov/cgi-bin/datasheet.prl)

TABLE DR3. CUMULATIVE DISPLACEMENTS (MM) OF SELECTED BENCHMARKS ACROSS THE MICHOUD FAULT RELATIVE TO BENCHMARK BH1104 SINCE 1969

Year*	BH1083	±2σ	BH1084	±2σ	BH1096	±2σ	BH1104	±2σ	BH1084-BH1096	±2σ
1969	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1971	-54.940	3.837	-55.480	3.578	-11.190	2.669	0.000	0.000	-44.290	1.386
1977	-155.710	3.837	-195.210	3.578	-31.270	2.669	0.000	0.000	-163.940	1.386
1985	-260.770	3.837	-340.420	3.578	-75.900	2.669	0.000	0.000	-264.520	1.386
1990	-317.140	3.837	-406.970	3.578	-102.680	2.669	0.000	0.000	-304.290	1.386
1994	-342.220	3.837	-439.800	3.578	-112.160	2.669	0.000	0.000	-327.640	1.386
2005	-401.285	3.837	-444.380	3.578	-147.330	2.669	0.000	0.000	-297.050	1.386
Distance from BH1104 (km)	3.755		3.266		1.817		0.000		1.449	

*Leveling data from National Geodetic Survey/NOAA. 1969, line L21664/2; 1971, line L22314; 1977, line L24133/21; 1985, line L24903/2; 1990, line L25283/1; 1994, line L25517/1. Data for 2005 from Louisiana Spatial Reference Center.