Modern-day tectonic subsidence in coastal Louisiana

Roy K. Dokka Center for GeoInformatics and Department of Civil & Environmental Engineering, Louisiana State University, Baton Rouge, Louisiana 70803, USA

ABSTRACT

Subsidence is leading to the slow inundation of communities and wetlands of Louisiana, Mississippi, Texas, and Alabama (United States) by the Gulf of Mexico. The prevailing paradigm considers subsidence to be the result of young sediment compaction and/or 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, Louisiana. This methodology allowed for an assessment of vertical change at different levels over time relative to a precise vertical datum (North American Vertical Datum of 1988, NAVD88). Data do not support the current theory on the origins of subsidence; they demonstrate 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.

Keywords: tectonic subsidence, Louisiana, Gulf of Mexico, Michoud fault.

INTRODUCTION AND HYPOTHESIS

Modern subsidence of New Orleans (Louisiana, United States) 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 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 et al., 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 Gulf of Mexico (e.g., Worrall and Snelson, 1989), tectonism is rarely invoked as a 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 to oil and 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 delta and alluvial valley (Fig. 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, Louisiana, (Fig. 1) was selected for three reasons. First, subsidence rates implied by benchmark motions were among the highest in the south-central United States (Shinkle and Dokka, 2004). Second, the area has a wealth of geodetic data, having been surveyed multiple times over the past 50 yr. 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–

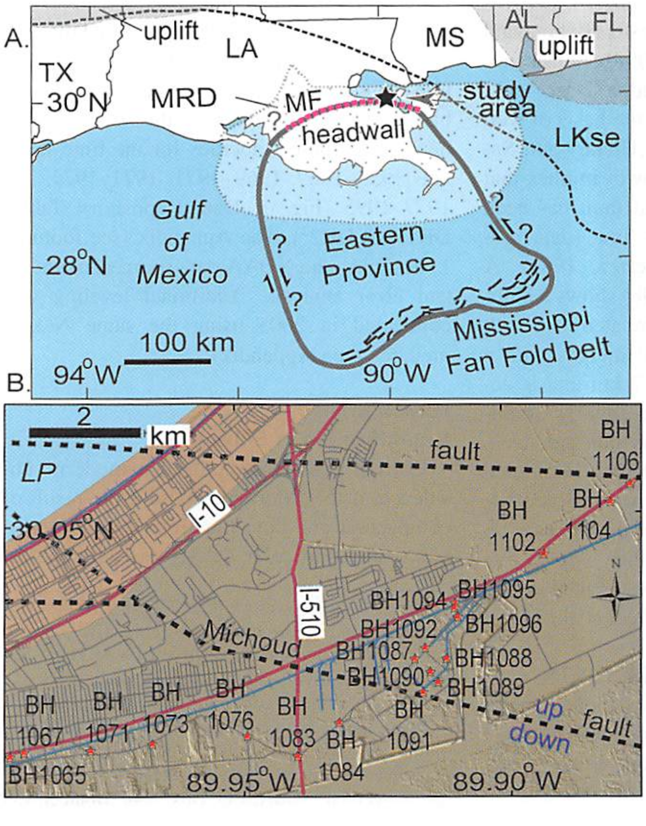

Figure 1. A: Index map of south Louisiana showing regional features and location of study area (star). Entire region with exception of areas labeled "uplift" have undergone late twentieth century subsidence (Shinkle and Dokka, 2004). Michoud fault (MF) is updip projection of fault mapped in subsurface by Hickey and Sabate (1972). Coupled extensional-contractional complex (Eastern Province) is from Peel et al. (1995). MRD—Mississippi River delta; Lkse—Late Cretaceous shelf edge. B: Location map showing benchmarks considered in this report. Benchmarks are marked with National Oceanographic and Atmospheric Administration–National Geodetic Survey identification code, e.g., BH1089 (Table DR2; see footnote 1). LP—Lake Pontchartrain.

Geology; April 2006; v. 34; no. 4; p. 281–284; doi: 10.1130/G22264.1; 3 figures; Data Repository item 2006059.

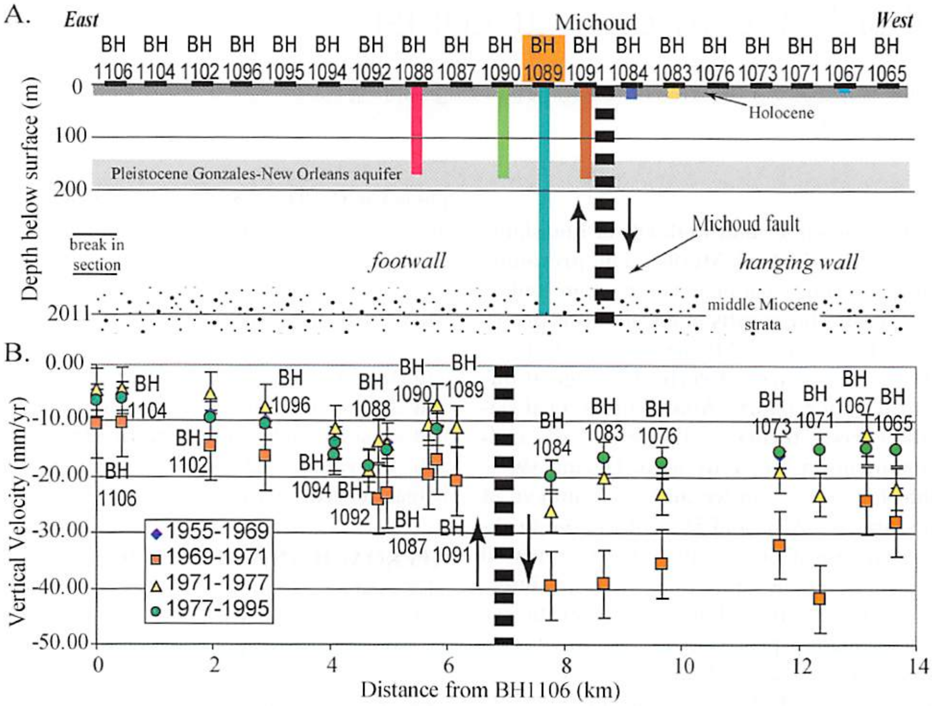

Figure 2. A: Cross section showing nature of benchmarks near Michoud, Louisiana. Benchmarks with associated rods are shown to length. Water wells and attached benchmarks: OR-78, BH1088; OR-79, BH1090; OR-80, BH1091. Well casing attached to benchmark BH1089 is not shown to scale. Stratigraphy is generalized from Dial (1983) and Bebout and Gutierrez (1983). B: Corresponding NAVD88 related vertical velocities (in mm/yr). Errors are explained in Appendix; see also Table DR2 (see footnote 1).

30 m of Holocene deltaic marsh sediments (Fullerton et al., 2003), which overlie Pleistocene deltaic deposits containing a regional aquifer at 150–200 m (Dial, 1983). This is underlain by ~10 km of mainly Pliocene–Jurassic deltaic and shelf deposits (Bebout and Gutierrez, 1983; McBride, 1998). Subsurface mapping previously identified a large fault, named the Michoud fault, on the basis of well cutoffs 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 first-order leveling data from the National Oceanographic and Atmospheric Administration (NOAA)–National Geodetic Survey and the tide gauge at Grand Isle, Louisiana, 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; Data Repository Tables DR1 and DR2[1]). The Appendix (see footnote 1) describes the NOAA data sources, methods, and error analysis. Additional leveling was conducted in 2005 using the same NOAA methods (see Appendix).

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). 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. I offer an alternative hypothesis proposing that this component is related to faulting.

Depth characteristics of studied benchmarks are shown 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 is associated with slip 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 is due to the compaction of sediments between the Quaternary aquifer at ~−170 m and the bottom of the 2011 m well that ends in middle Miocene strata. (3) A shallow component occurs from the surface to −170 m. Subsidence here includes the combined effects of groundwater offtake and compaction and/or 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 and/or consolidation, and oxidation due to drainage projects. The well passes below aquifers where locally large amounts of water have been extracted in the past 60 yr (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 Gulf of Mexico suggest that minor compaction continues within strata below the 2011 m well (middle Miocene–Jurassic). Eaton (1969) indicated that sediments at a depth equivalent to that of the bottom of the 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

---

[1] GSA Data Repository item 2006059, Table DR1 (NOAA data used in the study), Table DR2 (vertical velocities of benchmarks relative to NAVD88), Table DR3 (relative vertical motions of benchmarks near the Michoud fault), and the Appendix (data sources, methods, and error analysis), is available online at www.geosociety.org/pubs/ft2006.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA.

−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. The dearth of production wells in the area precludes petroleum extraction as a contributor to subsidence in the area.

Intermediate Component. The intermediate 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), including Holocene-Pleistocene compaction and/or 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 nonpermanent vertical strains that affected areas beyond the Michoud area. First, benchmarks of the hanging wall near the fault, i.e., BH1084 and BH1083, show significantly more subsidence than nearby footwall counterparts, i.e., BH1088, BH1087, BH1090, BH1089, and BH1091 (~−39 mm/yr compared to ~−21 mm/yr, respectively [1969–1971], and ~23 mm/yr compared to ~11 mm/yr, respectively [1971–1977]). Changes due to shallow and deep compaction can be ruled out 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 ca. 1968 to 1982 and that the annual water levels at well OR-78 (to which BH1088 is attached) remained constant. I propose 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 in 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 was removed from a small part of the footwall, subsidence of footwall slowed significantly (1971–1977). This was followed during 1977–1995 by more rapid subsidence. Relations in Shinkle and Dokka (2004) showed 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.

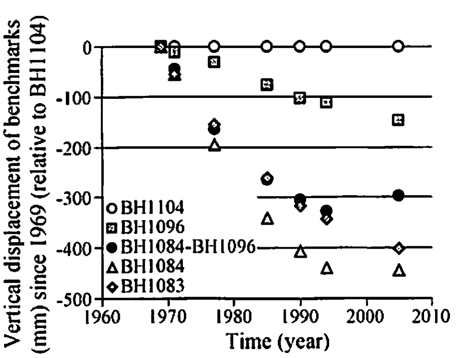

Figure 3. Cumulative displacement of benchmarks straddling Michoud fault as function of time. Data and methods are provided in Appendix (see footnote 1). All level lines indexed to BH1104. Note that relative fault motion stopped between 1995 and 2005. Data suggest that retrograde motion on fault has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

Comparison with Previous Subsidence Estimates

Measurements of subsidence inferred from benchmarks from the Michoud area are substantially different from 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., 0–0.3 m/100 yr. In comparison, subsidence indicated by benchmark motions reported in this study during 1969–1971 was 8–14 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 plus/minus human lifetime. Leveling can measure submillimeter vertical changes that occur over short periods, i.e., days, resulting in a resolution of millimeters per year or better. Furthermore, subsidence measured by leveling in the region was 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 (e.g., freshwater input, wind patterns; Penland and Ramsey, 1990; Turner, 1991).

Vertical Datum

This paper provides the first depth-dependent analysis of subsidence in the Gulf of Mexico coast region within the context of a spatially and temporally precise vertical datum. All previous attempts to measure subsidence in south Louisiana, except that of 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). 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, and 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

I reached the following conclusions in this study of first-order geodetic leveling data collected between 1955 and 2005 in the 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

This work was supported by grants from the National Science Foundation (9725330 and 0220288). S. Boss, T. Dixon, T. Meckel, K. Shinkle, and an anonymous reviewer provided helpful reviews.

REFERENCES CITED

Bebout, D.G., and Gutiérrez, D.R., 1983, Regional cross sections, Louisiana Gulf Coast: Baton Rouge, Louisiana Geological Survey Folio Series 6, 10 p.

Boesch, D.F., Josselyn, M.N., Mehta, A.J., Morris, J.T., Nuttle, W.K., Simenstad, C.A., and Swift, D.J.P., 1994, Scientific assessment of coastal wetland loss, restoration and management in Louisiana: Journal of Coastal Research, v. 10, special issue no. 20, 103 p.

Dial, D., 1983, Groundwater data for the Mississippi River parishes in the greater New Orleans area, Louisiana: U.S. Geological Survey Water Resources Basic Records Report 11, 20 p.

Eaton, B.A., 1969, Fracture gradient prediction and its application in oilfield operations: Journal of Petroleum Technology, v. 22, p. 1353–1360.

Fullerton, D.S., Bush, C.A., and Pennell, J.N., 2003, Map of surficial deposits and materials in the eastern and central United States: U.S. Geological Survey Geological Investigations series I-2789.

Gagliano, S.M., 1999, Faulting, subsidence and land loss in coastal Louisiana, *in* Coast 2050: Toward a sustainable coastal Louisiana, the appendices: Baton Rouge, Louisiana Department of Natural Resources, p. 21–70.

Hickey, M., and Sabate, R., eds., 1972, Tectonic map of Gulf coast region, U.S.A.: Tulsa, Oklahoma, Gulf Coast Association of Geological Societies and American Association of Petroleum Geologists, Scale 1:1,000,000.

Holdahl, S.R., and Morrison, N.L., 1974, Regional investigations of vertical crustal movements in the U.S., using precise relevelings and mareograph data: Tectonophysics, v. 23, p. 373–390, doi: 10.1016/0040-1951(74)90073-0.

Holzer, T.L., and Gabrysch, R.K., 1987, Effect of water-level recoveries on fault creep, Houston, Texas: Ground Water, v. 25, p. 392–397.

Jurkowski, G., Ni, J., and Brown, L., 1984, Modern uparching of the Gulf coastal plain: Journal of Geophysical Research, v. 89, p. 6247–6262.

Kazmann, R., and Heath, M., 1968, Land subsidence related to ground-water offtake in the New Orleans area: Gulf Coast Association of Geological Societies Transactions, v. 18, p. 108–113.

Kolb, C., and Saucier, R., 1982, Engineering geology of New Orleans, *in* Leggett, R., ed., Case histories in engineering geology, no. 5: Boulder, Colorado, Geological Society of America, p. 75–93.

Kolb, C., and Van Lopik, J., 1958, Geology of the Mississippi River deltaic plain, southeastern Louisiana: U.S. Army Corps of Engineers Waterways Experiment Station Technical Report 3-483, 120 p.

Kuecher, G.J., Roberts, H.H., Thompson, M.D., and Matthews, L., 2001, Evidence of active growth faulting in the Terrebonne delta plain, south Louisiana: Implications for wetland loss and the vertical migration of petroleum: Environmental Geosciences, v. 8, p. 77–94, doi: 10.1046/j.1526-0984.2001.82001.x.

Kulp, M., 2000, Holocene stratigraphy, history, and subsidence of the Mississippi River delta region, north-central Gulf of Mexico [Ph.D. thesis]: Lexington, University of Kentucky, 283 p.

McBride, B.C., 1998, The evolution of allochthonous salt along a megaregional profile across the northern Gulf of Mexico Basin: American Association of Petroleum Geologists Bulletin, v. 82, no. 5B, p. 1037–1054.

Miller, L., and Douglas, B.C., 2004, Mass and volume contributions to 20th century global sea level rise: Nature, v. 428, p. 406–409, doi: 10.1038/nature02309.

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

Peel, F.J., Travis, C.J., and Hossack, J.R., 1995, Genetic structural provinces and salt tectonics of the Cenozoic offshore U.S. Gulf of Mexico: A preliminary analysis, *in* Jackson, M.P.A., et al., eds., Salt tectonics: A global perspective: American Association of Petroleum Geologists Memoir 65, p. 153–175.

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

Penland, S., Ramsey, K.E., McBride, R.A., Mestayer, T., and Westphal, K.A., 1988, Relative sea level rise and delta-plain development in the Terrebonne Parish region: Coastal Geology Technical Report no. 4: Baton Rouge, Louisiana Geological Survey, 120 p.

Reed, D., and Wilson, L., 2004, Coast 2050: A new approach to restoration of Louisiana coastal wetlands: Physical Geography, v. 25, p. 4–21.

Roberts, H.H., 1997, Dynamic changes of the Holocene Mississippi River Delta Plain: The delta cycle: Journal of Coastal Research, v. 13, p. 605–627.

Shinkle, K., and Dokka, R.K., 2004, Rates of vertical displacement at benchmarks in the lower Mississippi Valley and the northern Gulf Coast: National Oceanic and Atmospheric Administration Technical Report 50, 135 p.

Turner, R.E., 1991, Tide gauge records, water level rise, and subsidence in the northern Gulf of Mexico: Estuaries, v. 14, p. 139–147.

Vanicek, P., Castle, R., and Balaza, E., 1980, Geodetic leveling and its applications: Reviews of Geophysics, v. 18, p. 505–524.

Worrall, D.M., and Snelson, S., 1989, Evolution of the northern Gulf of Mexico, with emphasis on Cenozoic growth faulting and the role of salt, *in* Bally, A.W., and Palmer, A.R., eds., The geology of North America; an overview: Boulder, Colorado, Geological Society of America, Geology of North America, v. A, p. 97–138.

Manuscript received 21 September 2005
Revised manuscript received 2 December 2005
Manuscript accepted 11 December 2005

Printed in USA