Tectonic control of subsidence and southward displacement of southeast Louisiana with respect to stable North America

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[1] GPS data collected between 1995 and 2006 suggest that southeast Louisiana, including New Orleans and the larger Mississippi Delta, are both subsiding vertically and moving southward with respect to stable North America. Both motions are likely related due to their common tectonic setting. Subsidence in the New Orleans area occurs in part because it is located in the hanging wall of a large listric normal fault system that forms the northern boundary of a 7–10 km thick allochthon that is detached from stable North America. Southward motion of this allochthon relative to stable North America occurs at 2.2 ± 0.6 mm/yr. The average subsidence rate for GPS sites located on the allochthon is 5.2 ± 0.9 mm/yr relative to Earth's center of mass, or ∼7 mm/yr relative to mean sea level. Motion of the allochthon is likely due to the gravity instability created by rapid Holocene sediment deposition in the delta following continental glacial retreat and is facilitated at depth by weak salt horizons. Because New Orleans and other communities of southeastern Louisiana lie atop this active allochthon, future motion of this body should be considered during rebuilding of the region following Hurricanes Katrina and Rita. **Citation:** Dokka, R. K., G. F. Sella, and T. H. Dixon (2006), Tectonic control of subsidence and southward displacement of southeast Louisiana with respect to stable North America, *Geophys. Res. Lett.*, *33*, L23308, doi:10.1029/2006GL027250.

1. Introduction

[2] It is well established that tectonic processes such as faulting, salt evacuation, and load-induced flexure of the lithosphere have played a substantial role in lowering the land surface in the Gulf of Mexico basin over geologic time [*Murray*, 1961; *Worrall and Snelson*, 1989], allowing accumulation of >10 km of largely deltaic and shallow marine sediments since Middle Jurassic time. Nevertheless, modern subsidence in the gulf region is usually described as a near-surface effect, the consequence of shallow sedimentary processes and/or human activities [*Boesch et al.*, 1994; *Gagliano*, 1999; *Reed and Wilson*, 2004]. In particular, faulting and related subsidence is generally attributed to groundwater extraction [*Holzer and Gabrysch*, 1987] or oil and gas production [*Morton et al.*, 2002]. Here, we present new GPS data that reveal both vertical (subsidence) and horizontal (southward translation) motions of New Orleans and the larger Mississippi delta and propose that these motions reflect southward translation of a crustal-scale allochthon encompassing southeastern Louisiana and offshore regions. The data demonstrate that the processes that have made southeastern Louisiana increasingly vulnerable to coastal flooding are continuing and include a regional tectonic component of both vertical and horizontal dimensions.

2. Geological Background

[3] The northern Gulf of Mexico basin is among the most highly studied geological terranes in the world and has provided many examples which serve as the basis for fundamental theories on sedimentation, associated crustal loading, and the nature of normal faulting. Until recently, however, the role of modern faulting has been underappreciated by those studying the factors shaping the region's dynamic landscape. For example, recognition and mapping of faults in the coast based on standard tectonic geomorphologic criteria are difficult because surface materials are composed of generally young, weak, unconsolidated sediments. Thus, proof that well-mapped subsurface faults are currently active and disrupt the surface is elusive. This is compounded by the paucity of historical earthquakes in coastal areas of the northern Gulf of Mexico. This dearth of data has led most investigators to conclude either that there are no active faults in the area, or that faulting, if it occurs, is aseismic [*Holzer*, 1984]. Evidence of active faulting in coastal Louisiana is based wholly on the disruption of roads, bridges, and buildings, and the displacement of benchmarks. Recent earthquakes with magnitudes between 3.0 and 5.2 in both onshore and offshore areas of southeast Louisiana also suggest active tectonic processes (Figure 1).

[4] The Michoud fault (Figure 1) [*Dokka*, 2006] is one of a series of active, generally down-to-the-south, normal faults that marks the northern structural edge of the Gulf of Mexico basin. The Michoud area lies near the northern margin of the Mississippi River delta and is underlain by 20–30 m of Holocene deltaic marsh sediments [*Kolb and Saucier*, 1982; *Fullerton et al.*, 2003] that overly Pleistocene deltaic deposits containing a regional aquifer at 150–200 m depth [*Dial*, 1983]; the Quaternary is in turn underlain by ∼10 km of Pliocene-Jurassic deltaic and shelf sediments [*McBride*, 1998; *Bebout and Gutiérrez*, 1983]. This fault was first detected by sub-surface mapping using fault cut-offs in deep wells and seismic reflection surveys [*Hickey and Sabate*, 1972]. The fault has affected engineered structures locally, but is otherwise lacking in geomorphic expression. Leveling data [*Shinkle and Dokka*, 2004; *Dokka*, 2006] suggest that this fault is active and has had the most displacement of any fault in the region.

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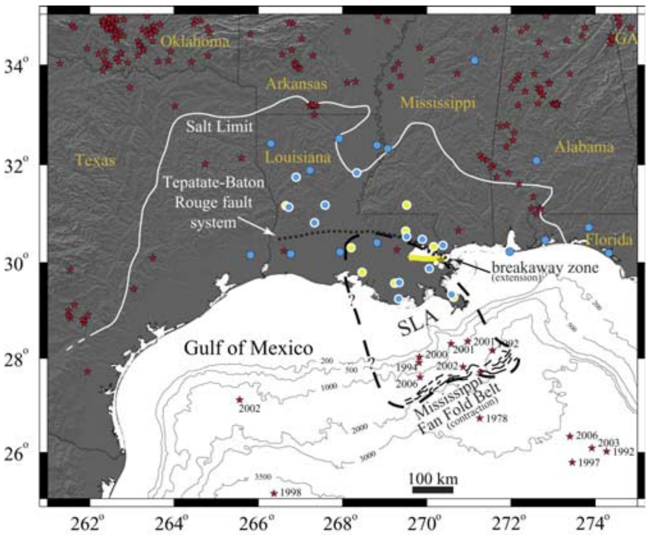

Figure 1. Map of GPS sites in Louisiana superimposed on a shaded relief map: continuous sites (cyan), episodic sites (yellow). Sites with white border are plotted in Figure 2 (see Table S1 of the auxiliary material). White line labeled "Salt Limit" shows northern limit of sub-surface salt layers. Boundary of southeast Louisiana allochthon (SLA) shown as heavy black dashed line; based largely on the south vergent, coupled extensional-contractional system of *Peel et al.* [1995]. Actual detached area may extend into Texas. Mississippi Fan Fold Belt is a zone of folded Holocene sediments undergoing contraction synchronous with south translation of SLA and extension in breakaway zone. Breakaway zone marked by Michoud fault (yellow line), but is likely more complex and includes more northerly faults belonging to the Tepatate-Baton Rouge system. This system marks the approximate northern edge of lithosphere thinned during Jurassic rifting of the Gulf of Mexico [*Worrall and Snelson*, 1989]. Earthquakes 1978–2006 (red stars), source is U.S. Geological Survey, http://neic.usgs.gov/neis/epic/epic.html. Bathymetric contours are in meters.

[5] Seismic reflection data [*McBride*, 1998] indicate that the Michoud fault merges with a regional detachment at ~7 km depth developed along the top of a gently south-dipping layer of allochthonous salt and shale [*Diegel et al.*, 1995; *Peel et al.*, 1995]. *Peel et al.* [1995] recognized that the upper crust in southeast Louisiana, as well as similar terranes to the west, detached and translated southward during late Miocene to Quaternary time. The detachment "daylights" within the Gulf of Mexico, near the base of the Mississippi fan. Active motion of the allochthon above the detachment was inferred on the basis of the folding of young sediments at the base of the fan, the Mississippi Fan fold belt [*Peel et al.*, 1995] (Figure 1).

3. GPS Data

[6] The GPS data represent a mix of episodic observations (EGPS) lasting several days every one to two years from 1997 to 2005, and continuously observed sites (CGPS) with 2–11 years of data (Figure S1 and Table S1 of the auxiliary material).[1] The EGPS sites consist of rods 14–30 m deep, whereas the CGPS sites are mostly on masonry buildings founded on bedrock or pile-driven foundations up to 37 m deep. Data were analyzed using the methods described in the work of *Sella et al.* [2002], but aligned to global reference frame IGb00. Motion of the stable North American plate is defined by a least squares inversion of the IGb00 velocities for 124 CGPS sites located in North America away from any known deformation including that caused by glacial isostatic adjustment [*Sella et al.*, 2006]. None of the sites used in this study were part of the 124 stable sites. Vertical component uncertainties are larger than horizontal uncertainties, probably reflecting the influence of the variably humid troposphere. East uncertainties tend to be larger than north uncertainties because we have not resolved the carrier phase cycle ambiguities. Nevertheless, there is a clear distinction between the horizontal and vertical velocities of sites located north of the Michoud and Tepatate-Baton Rouge faults (stable North America) versus sites located to the south (Figure 2).

[7] Figure 2a shows the north velocity component relative to stable North America for the available GPS data in Louisiana plotted as a function of latitude. The area north of the Michoud fault and Tepatate-Baton Rouge fault system exhibits no significant motion relative to stable North America (mean north velocity and standard error 0.3 ± 0.2 mm/yr). The area to the south yields south-directed velocities in the range of −2.2 ± 0.6 mm/yr (Table S1 of the auxiliary material), rates comparable to present-day east-west extension in the central and eastern Basin and Range province [e.g., *Bennett et al.*, 1998; *Dixon et al.*, 2000]. These sites also subsided at an average of −5.2 ± 0.9 mm/yr, whereas most sites north of the Michoud fault and Tepatate-Baton Rouge fault system show no significant vertical motion (mean vertical velocity and standard deviation −0.1 ± 0.5 mm/yr; Figure 2b).

[8] The GPS data are consistent with earlier leveling data indicating that subsidence in south Louisiana is more pronounced south of the Michoud and Baton Rouge faults [*Shinkle and Dokka*, 2004; *Dokka*, 2006]. Areas north of this belt of normal faults can be considered part of the stable continental interior, whereas all GPS sites to the south show combined southward motion and subsidence. *Gan and Prescott* [2001] noted southward movement of several CGPS sites in the Mississippi embayment (average rate 1.7 ± 0.9 mm/yr) that is statistically equivalent to our result. However, the limited number of sites available for the earlier study precluded definition of a boundary for this motion.

[9] Marine water gauge data along coastal Louisiana indicate relative sea level rise, reflecting a combination of land subsidence and global sea level rise [*Penland and Ramsey*, 1990; *Shinkle and Dokka*, 2004]. Global average sea level rise is ~2 mm/yr [*Miller and Douglas*, 2004], relatively slow compared to the land subsidence rate measured here and in other recent studies of coastal Louisiana [*Shinkle and Dokka*, 2004; *Dokka*, 2006; *Dixon et al.*, 2006]. Relative to sea level, the land surface south of the Michoud fault and Tepatate-Baton Rouge fault system is

[1]Auxiliary material data sets are available at ftp://ftp.agu.org/apend/gl/2006gl027250. Other auxiliary material files are in the HTML.

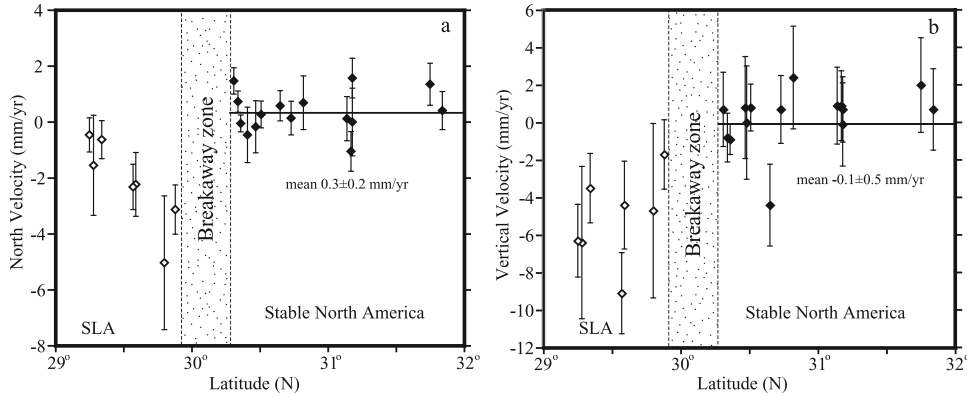

Figure 2. (a) North and (b) vertical components of GPS site velocities for sites with white border in Figure 1, plotted as a function of latitude. North component is relative to stable North America [*Sella et al.*, 2006]. Vertical stippled zone is approximate location of breakaway zone. Open diamonds are sites located south of fault; solid diamonds are sites north of fault. Error bars for individual data are 1 standard deviation. Horizontal line depicts the mean of GPS data for areas north of breakaway zone.

moving downward at an average rate of ∼7 mm/yr (GPS subsidence + 2 mm/yr eustatic rise).

4. Discussion

[10] GPS data provide two important insights into the nature of the landscape change that has made coastal Louisiana increasingly vulnerable to storm surge. First, the on-going landscape modification is not only occurring in the vertical dimension, but also involves lateral change. The current paradigm considers that most landscape change occurs in the vertical dimension, and is largely the product of compaction of Holocene sediments and anthropogenic activities [*Boesch et al.*, 1994; *Gagliano*, 1999; *Reed and Wilson*, 2004]. Second, because our study used benchmarks attached to deep set rods (EGPS) or buildings founded on pilings (CGPS), our measurements contain little or no contribution from compaction of surficial Holocene sediments. Coupled with the general absence of groundwater withdrawal in southeast Louisiana, the existing paradigm does not explain the motions revealed by our study.

[11] A tectonic model is proposed that explains the new data as well as previous geologic and geophysical observations. Present-day vertical and horizontal motions of southeast Louisiana revealed by GPS are consistent with a regional coupled extensional-contractional complex such as originally proposed by *Peel et al.* [1995]. Driven by gravitational instability caused by massive sediment deposition and loading at the edge of the continent and sea level rise, such structural complexes involve the synchronous development of a surface zone of extension by high-angle normal faults within the breakaway zone as well as a zone of contraction marked by folding and thrust faulting at the toe (Figure 3). These zones are physically and kinematically linked at depth by a low-angle detachment fault rooted in low strength salt and shale. We term this detached and south-southeast moving terrane, the *South Louisiana allochthon* (*SLA*).

[12] Seismic reflection profiling and well data indicate the overall structure of the SLA (Figure 3). The zone of normal faults where the SLA has separated from stable North America, termed here the breakaway zone, consists of a zone of high-angle, down-to-the-south, listric normal faults that merge at depth with a sub-horizontal detachment fault. Faults of the breakaway zone include the Michoud, faults of the Tepatate-Baton Rouge system, and unnamed faults (Figures 1 and 3). One such unnamed fault was associated with the 1987 Irish Bayou earthquake [*Lopez*, 1991]. Although the spacing of our GPS sites does

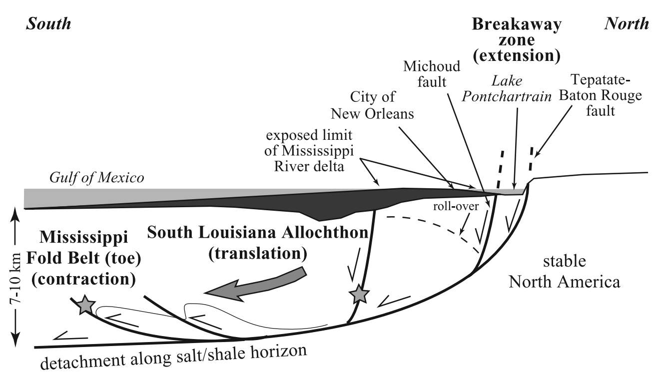

Figure 3. Cartoon depicting the regional scale, extensional-contractional complex comprising the south Louisiana allochthon (adapted from *Peel et al.* [1995]). The system is driven by loading due to late Quaternary deposition of the Mississippi River delta (black shaded area) and eustatic sea level rise. Southward translation of the south Louisiana allochthon with respect to stable North American plate is accompanied up dip by extension in the breakaway zone by normal faulting, and down dip by contraction in the Mississippi fold belt. Non-uniform horizontal motions implied by GPS observations and earthquakes suggest that the allochthon is only partially intact. Tectonic subsidence along faults of the breakaway zone occurs because of downward motion of the hanging wall, and local reverse drag. Reverse drag is the consequence of translation along a curved fault plane and results in a rollover antiform. Local subsidence is due to the integrated effects of regional isostasy, faulting, sediment compaction, dewatering, and fluid withdrawal. Small arrows show relative fault motions.

not allow us to resolve displacements on individual faults of the breakaway zone, previous leveling data suggest that the Michoud fault and eastern strands of the Tepatate-Baton Rouge fault system are dominant [*Dokka*, 2006; *Shinkle and Dokka*, 2004]. Subsidence associated with the Michoud fault and the Tepatate-Baton Rouge fault system suggests that the breakaway zone may experience higher rates of subsidence than other parts of the allochthon. Because faulting exerts control of Holocene sediment deposition, faults also contribute indirectly to the other major subsidence process, compaction of Holocene sediments.

[13] Seismic imaging [*McBride*, 1998] and well data suggest that the SLA is ~7–10 km thick and rooted in salt and shale. Horizontal vectors implied by the GPS observations (Table S1 of the auxiliary material) exhibit a range of azimuths, and are not consistent with simple southward translation as might be expected for a rigid block. We propose two, non-mutually exclusive explanations: (1) the dispersion reflects uneven translation of a fractured, semi-intact allochthon; and/or (2) sufficient observations have not yet been made to reduce measurement uncertainty.

[14] Although the northern Gulf of Mexico basin is generally regarded as aseismic, over 20 earthquakes have occurred since 1978 and almost all are located within the areal limits of the allochthon (Figure 1). The events range in magnitude from 3.0 to 5.2, and generally occur at depths of 5–10 km (available at http://neic.usgs.gov/neis/epic/epic.html).

[15] The modern southerly motion of the SLA documented by decadal-scale GPS observations is similar to long, time-averaged geological rates of horizontal translation of the area when averaged since post-middle Miocene time. *McBride* [1998] documents 21.3 km of southward translation of strata above the South Timbalier salt sheet (south of GPS station LMCN, Figure 1) since 8.8 Ma, giving a long-term average rate of 2.4 mm/yr. Of course, rates averaged over long time intervals do not detect important details of geologic processes that may occur at annual or decadal timescales. Given that processes causing subsidence and lateral translation are at least partially physically linked, the high rates of subsidence documented for the Michoud fault in 1969–1977 [*Dokka*, 2006] may have also been accompanied by higher translation rates of the SLA.

[16] Creation of coupled extensional-contractional complexes such as the SLA along the northern Gulf of Mexico basin has generally coincided with intervals of high sediment influx delivered by rivers during periods of eustatic rise [*Worrall and Snelson*, 1989]. The voluminous sedimentation creating the Holocene delta of the Mississippi River and its alluvial valley began after the major retreat of Holocene glaciers from central North America [e.g., *Roberts*, 1997]. Significant loading of the lithosphere by the current delta and alluvial valley and sea level rise is relatively recent and thus its isostatic consequence (subsidence) has not yet been fully realized [*Jurkowski et al.*, 1984; *Ivins et al.*, 2005]. The instability is exacerbated by the location of the depocenter on an unstable, mobile substrate of salt and shale. The northern boundary of the SLA and the southern limit of stable North America in this region corresponds approximately to a line separating the North American craton from lithosphere thinned during Jurassic rifting [*Worrall and Snelson*, 1989] (Figure 1). Proximal areas to the north are stable, even though they are underlain by salt (Figure 1). Thus the combination of sediment loading and weak sub-surface salt strata combine to promote motion of the SLA.

[17] Previous explanations for the causes of modern faulting along the Gulf Coast have emphasized groundwater and petroleum extraction [*Holzer and Gabrysch*, 1987; *Morton et al.*, 2002]. Although applicable in some areas such as Houston-Galveston, the groundwater extraction explanation is untenable for southeast Louisiana (and SLA) because groundwater withdrawal is minimal, due to severe saltwater intrusion [*Kazmann and Heath*, 1968; *Baumann et al.*, 2006]. Areas of southeast Louisiana where water is heavily pumped are north of the Baton Rouge fault (breakaway zone) and areas to the west. Although groundwater related subsidence has been observed north of the fault [*Wintz et al.*, 1970], the relative sense of motion across the fault is opposite to that of the down-to-the-south Baton Rouge fault [*Dokka and Kebede*, 2003]. Recently, oil and gas extraction has been advanced as a major cause of fault activation and subsidence in south Louisiana. However, magnitudes and patterns of late 20th-century subsidence [*Shinkle and Dokka*, 2004] do not coincide with oil fields as predicted. Motion and subsidence near the Michoud fault, the region's most active fault, are unrelated to petroleum extraction due to the lack of local production [*Dokka*, 2006].

[18] The size, internal structure, and kinematics of the southeast Louisiana allochthon are generally similar to other extensional complexes driven by gravitational instabilities (e.g., early Miocene detachment systems of the southwestern USA [*Dokka et al.*, 1998] and large volcanic edifices [e.g., *Ward*, 2001; *Cervelli et al.*, 2002]). One major difference, however, is that whereas friction-controlled (stick-slip) behavior is often important for crustal materials of extensional terranes and large volcanoes, the rheological behavior of salt is quite different, facilitating ductile, aseismic deformation along the detachment fault. Salt enters the ductile deformation regime at temperatures of less than 100°C [*Davis and Engelder*, 1985] and becomes quite weak. Down-hole temperature measurements [*Bebout and Gutiérrez*, 1983] indicate that 100°C is encountered at a depth of about 3.2 km in the study area, well above the 7–10 km detachment depth. Salt rheology thus likely exerts critical control on the motion of the SLA, enabling it to move more or less continuously and with few earthquakes along its detachment. We therefore suspect that earthquakes in the SLA are not associated with the detachment, but instead reflect internal deformation within the allochthon. We do not anticipate that the SLA should move as a coherent body.

[19] Lateral translation and associated tectonic subsidence of southeast Louisiana is not unexpected given the geologic history of the Gulf of Mexico basin. However, this mobility has been overlooked in studies aimed at understanding the modern landscape. Expanding accurate measurements of both subsidence and lateral motions and recognizing their variable rate over short time frames are critical for understanding their underlying causes and for designing an appropriate flood protection strategy for the vulnerable landscape.

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