Basement Controls on Subsurface Geologic Patterns and Coastal Geomorphology across the Northern Gulf of Mexico: Implications for Subsidence Studies and Coastal Restoration

Bryan P. Stephens

U.S. Department of the Interior, Minerals Management Service,
1201 Elmwood Park Blvd., New Orleans, Louisiana 70123-2394

ABSTRACT

Several causes of subsidence in the Gulf Coast in general, and southeast Louisiana in particular, have been identified. These include sediment loading, compaction of Holocene sediments, subsurface faulting, salt withdrawal, and fluid extraction. Recent geodetic leveling studies suggest much of the subsidence is tectonic in nature and related to movement along Tertiary fault systems. This paper suggests that an ordered basement structure has also exercised a profound level of control on all subsequent geological processes including recent coastal environments and ongoing subsidence.

The arrangement of structural elements across the northern Gulf of Mexico suggests the continental margin is segmented by northwest-southeast trending transfer fault zones related to Mesozoic rifting. Major transfer faults segment the continental margin into structural corridors approximately 25 to 40 mi in width, characterized by varying degrees of extension, crustal attenuation, and tectonic subsidence. The corridors are more finely segmented by minor transfer fault trends which also exhibit regular and predictable lateral and vertical offsets that are reflected in overlying Tertiary cover.

Mesozoic and Tertiary faults, salt systems, and shelf margins are segmented along the same transfer-fault delimited corridors. Variations in sediment thickness suggest that the transfer faults have influenced deposition throughout the history of the basin. Modern seismicity demonstrates ongoing activity along these deep crustal boundaries.

Gulf Coast topographic and bathymetric trends appear to be sympathetic to the basement structure as reflected by stream courses, incised valleys and offshore sediment fairways. The shape of the coastline and distribution of coastal barriers and spits also conform to lateral and vertical offsets along underlying transfer fault zones.

Recognition of the ordered arrangement of basement structures, faulting and salt systems can help coastal scientists better understand the emerging body of detailed subsidence measurements and guide future lines of inquiry. Identification of areas of relative geologic stability may influence coastal restoration efforts.

INTRODUCTION

This paper expands on the previous work of Stephens (2001), which described a series of basement-controlled structural corridors delineated by northwest-southeast trending transfer faults beneath the modern abyssal plain and outer continental shelf of offshore Louisiana. This study incorporates a seismic traverse from a

Stephens, B. P., 2009, Basement controls on subsurface geologic patterns and coastal geomorphology across the northern Gulf of Mexico: Implications for subsidence studies and coastal restoration: Gulf Coast Association of Geological Societies Transactions, v. 59, p. 729-751.

recent proprietary offshore 3D survey that images offsets in the basement surface corresponding to the transfer faults that trend into southeast Louisiana. Observations from a diverse collection of studies are used to document a framework of transfer-fault delimited corridors across the northern Gulf of Mexico and illustrate the influence of transfer faults on depositional systems and structural styles throughout the geologic history of the basin. Finally, the apparent relationship between the transfer-fault delimited structural corridors and the arrangement of Holocene coastal environments of the northern Gulf Coast is examined.

TECTONIC SETTING

The Atlantic and Gulf coasts of North America are situated along "passive" continental margins created during the Triassic-Jurassic breakup of the supercontinent Pangea. Continental rifting was accompanied by deposition of red-beds and interbedded volcanics in a series of Triassic to Jurassic basins spanning the Atlantic Margin from Canada to the South Georgia Basin (SGB) (Fig. 1). Triassic rifting in the Gulf of Mexico Basin was followed by marine incursion during the middle to late Jurassic resulting in deposition of the Louann Salt in the East Texas Salt Basin (ET), North Louisiana Salt Basin (NL), Mississippi Salt Basin (MS), and Desoto Canyon Salt Basin (DC) (Fig. 1). Autochthonous salt beneath the Gulf Coast and northern Gulf of Mexico was probably deposited within discrete rift basins above thin transitional crust. However, details of the rift architecture are masked by the thick Tertiary sedimentary section and allochthonous salt. Rifting is thought to have been followed by a Jurassic drift phase during which oceanic crust formed through seafloor spreading at the basin center. Details of the tectonic evolution of the basin remain uncertain, including the structural configuration of the base-

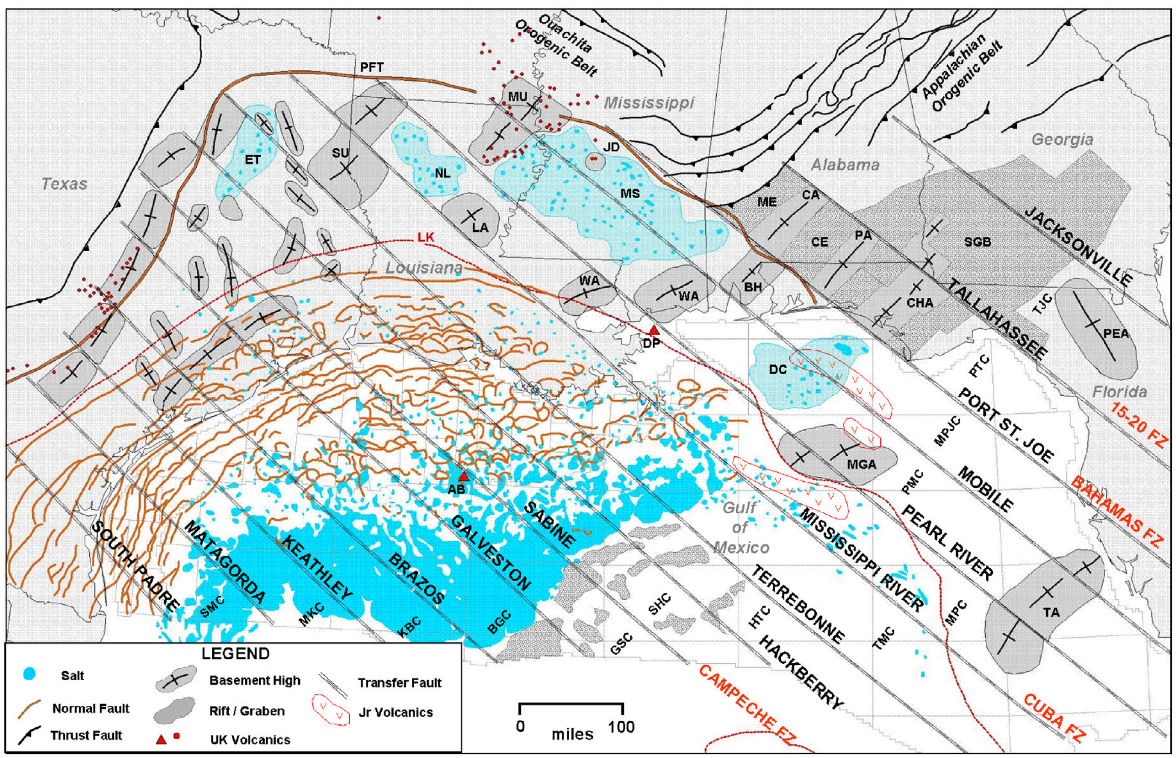

Figure 1. Selected structural features of the northern Gulf of Mexico Basin. Basement structures and rifts after Muehlberger (1992), Goldhammer (1999), Klitgord and Schouten (1986), Sartain and See (1997), Miller (1982), and Stephens (2001). Salt after Simmons (1992), Lopez (1995), and Muehlberger (1992). Faults after Diegel (1995), Muehlberger (1992), and Klitgord and Schouten (1986). Jurassic volcanics after Imbert and Philippe (2005). Cretaceous volcanics after Braunstein and McMichael (1976), Rezac and Tieh (1980), and Muehlberger (1992). See text for discussion.

ment, amount of intraplate deformation, extent of oceanic crust and translation of the Yucatan Block. For more detailed treatment the reader is referred to Klitgord and Schouten (1986), Salvador (1987, 1991), Pindell and Kennan (2001), Post (2005), and Fillon (2007).

The Gulf of Mexico Basin experienced a period of renewed tectonism during the Laramide Orogeny (Late Cretaceous to Early Tertiary), including rejuvenation of the Sabine Uplift (SU) (Fig. 1) and the Monroe Uplift (MU) (Fig. 1), as well as widespread volcanism. Progradation of Tertiary depositional sequences beyond the Lower Cretaceous shelf edge produced a succession of shelf margin growth faults and mobilized the Louann Salt into allochthonous salt bodies (Fig. 1). The historical coastal landscape of southern Louisiana was formed over the past 10,000 years or so through deposition and reworking of Holocene delta lobes of the Mississippi River during the transgression and current sea-level highstand that followed the close of the Wisconsinian glacial period.

PREVIOUS WORK

Central to the current thesis is the view that rifted continental margins are segmented by margin-normal transfer fault zones. Figure 2 is a 3D block diagram of a rifted continental margin modified after Lister et al. (1986). In this simplified model, the margin is partitioned into three segments and seven corridors. The segments correspond to alternating upper-plate and lower-plate margins based on the simple shear model of crustal detachment of Wernicke (1985). The segments are more finely partitioned by transfer fault zones into corridors characterized by varying degrees of crustal extension. Alternating horsts and salt-filled graben within the corridors of the lower-plate margins are offset from one another across the transfer faults. Transfer faults, which are established during the rifting phase of continental breakup, propagate outward, and merge in some manner with

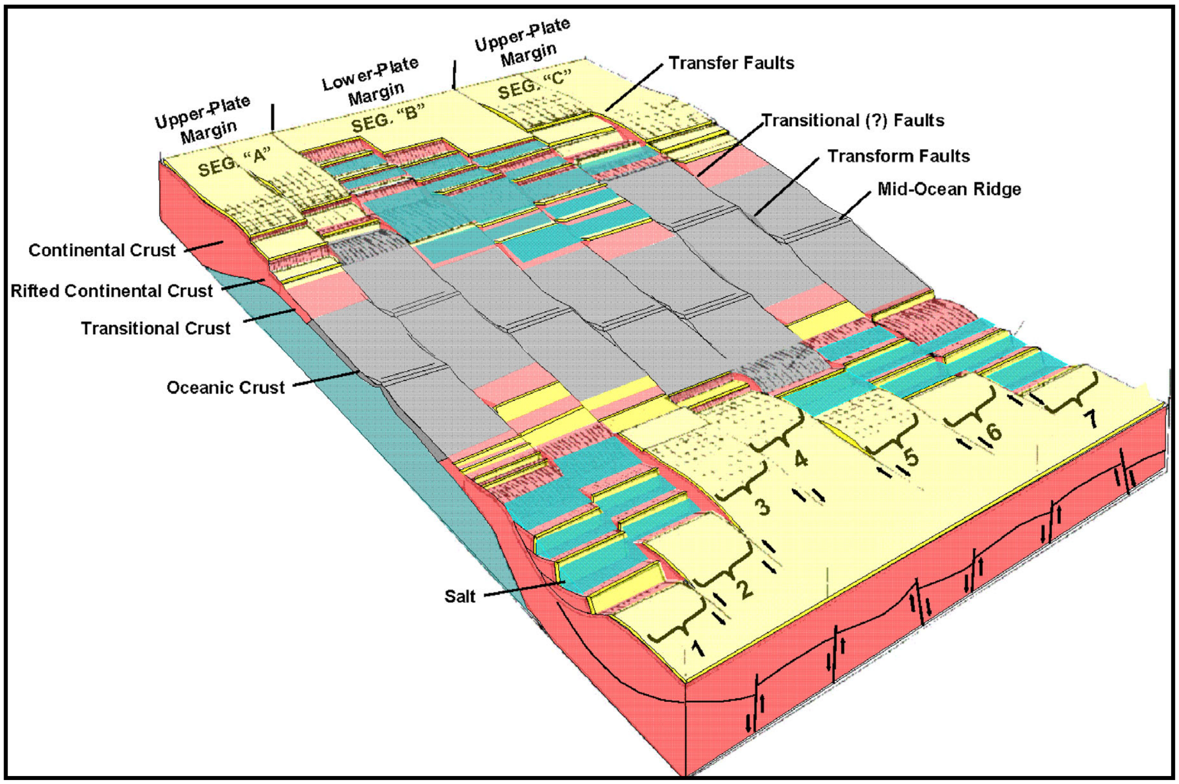

Figure 2. Three-dimensional crustal model of a passive continental margin (modified after Lister et al., 1986). Margin partitioned into three upper-plate/lower-plate segments (A-C) and seven structural corridors (1-7). See text for discussion.

oceanic transform faults as continental rupture culminates in the formation of oceanic crust (Sykes, 1978; Stephens, 2001).

The insightful work of Adams (1989, 1993, 1997) suggested that the Texas Gulf Coast was underlain by a series of horsts and graben offset by northwest-southeast “transform” faults and that this inherited Triassic fabric controlled the depositional thickness of the Louann Salt, subsequent allochthonous salt systems, and dip-oriented sediment fairways in the overlying Tertiary section. A series of similar papers were produced by workers from the University of Texas and Texas A&M University that collectively established a nomenclature for a series of northwest-southeast trending “segments” and “corridors” delimited by transfer faults across the northern Gulf of Mexico (Watkins et al., 1996). Watkins et al. (1995) applied the models of Wernicke (1985) and Lister et al., (1986) to explain the large-scale asymmetry of salt systems across the greater Gulf of Mexico Basin. Bradshaw and Watkins (1995) presented a model for the Texas shelf similar to that of Adams (1993).

Recent studies of faulting and subsidence in the coastal zone have recognized several possible causes of subsidence and wetland loss. None, however, have recognized the ordered structural framework within which these processes operate. Lopez (1991) and Lopez et al. (1997) identified active faults in Lake Pontchartrain based on 2D reflection seismic data and historical vertical offsets of bridges and trestles. Gagliano et al. (2003) have documented the surface expression of over 100 faults in southeast Louisiana and identified submergence of wetlands on the downthrown side of east-west trending growth faults as the primary cause of land loss. However, they do recognize seven northwest-southeast trending faults or lineaments. Morton et al. (2002) used leveling profiles and tide gauge records from south-central Louisiana to infer that historical subsidence and wetland loss were spatially and temporally correlated with volumes and rates oil and gas production. Regional transects generated from geodetic leveling surveys by Shinkle and Dokka (2004) have revealed that the subsiding region extends beyond the modern Mississippi Delta, from eastern Texas to Florida, and as far north as Memphis, Tennessee. Other researchers (e.g. Tornqvist et al., 2006) have concluded that subsidence related to compaction of Holocene sediments is the primary cause of wetland loss in coastal Louisiana.

MAJOR TRANSFER FAULTS OF THE NORTHERN GULF OF MEXICO

Fourteen “major” transfer fault trends are identified in this study for the northern Gulf of Mexico. The following section discusses evidence for each of the major transfer faults and prominent structural features of the intervening structural corridors as depicted in Figure 1.

The Jacksonville Transfer Fault

The Jacksonville Transfer Fault (JTF) is the northwestward extension of the Jacksonville Fracture Zone of Klitgord and Schouten (1986). The trajectory of the JTF along the northeast flank of the South Georgia Basin (SGB) (Fig. 1) was documented by Sartain and See (1997).

The Tallahassee Transfer Fault

The Tallahassee Transfer Fault (TTF) is the northwestern extension of the 15 Degree – 20 Minute Fracture Zone of Klitgord and Schouten (1986). The TTF forms the southwest margin of the South Georgia Basin (SGB) and separates it from the Chattahoochee Arch (CHA) and Apalachicola Embayment to the southwest (Sartain and See, 1997). The trace of the TTF is also evident on the subcrop map of the sub-Zuni surface published by Barnett (1975). The northwestward projection of the TTF intersects the White River Fault Zone of Fisk (1944).

The Port St. Joe Transfer Fault

The Port St. Joe Transfer Fault (PSJTF) is the northwestern extension of the Bahamas Fracture zone of Klitgord & Schouten (1986). The trace of the PSJTF is also evident on the subcrop map of the sub-Zuni surface published by Barnett (1975) and subsequent interpretations by Miller (1982) and Smith (1983). The PSJTF parallels the traces of the Pickens-Gilbertown and Pollard-Foshee fault systems in southern Alabama. The northwestward projection of the PSJTF aligns with the Arkansas River Fault Zone of Fisk (1944) and the Alabama-Arkansas Fault System of Thomas (1988). The PSJTF was recognized by Smith (1983) as the Jay Fault, by Christenson (1990) as the "Florida Lineament," by MacRae and Watkins (1996) as the "Florida-Bahamas Transfer Fault," and by Kinsland (1984) as the "North American Transcontinental Transfer Fault." Thomas (1991) related the PSJTF to an earlier Paleozoic feature, the Alabama-Oklahoma Transform. The PSJTF forms the southeastern margin of the Port St. Joe – Tallahassee Corridor (PTC) (Fig. 1), which includes, from northwest to southeast, the Manilla Embayment (ME), Conecuh Arch (CA), Conecuh Embayment (CE), Pensacola Arch (PA), Chattahoochee Arch (CHA), and Apalachicola Embayment. Basement control on salt deposition and Mesozoic stratigraphy in this area was recognized by Wilson, (1975), Dobson and Buffler (1991), and Prather (1992), and is discussed in later sections. The PSJTF forms the northeastern flanks of the Desoto Canyon Salt Basin (DC), Baldwin High (BH), Mississippi Salt Basin (MS), and Monroe Uplift (MU) shown on Figure 1.

The Mobile Transfer Fault

The Mobile Transfer Fault (MOTF) has also been referred to as the Sunniland Fracture Zone (Mitchell-Tapping et al., 1999). The MOTF appears to bisect the Desoto Canyon Salt Basin. MacRae and Watkins (1993a, 1993b) present 2D seismic time-structure map on the base of salt or equivalent (BSE) surface that shows a step or flexure that parallels the inferred trace of the MOTF. Coincident with this BSE flexure is a package of seaward dipping reflectors (SDRs) thought to be subaerial basalt flows of Jurassic age (Imbert, 2005) possibly related to the Central Atlantic Magmatic Province (CAMP) (Hames et al., 2003; Post, 2005). The northwestern projection of the MOTF passes near the Jackson Dome (JD) in central Mississippi and extends through the Monroe Uplift in northeastern Louisiana and aligns with the Ouachita River Fault Zone of Fisk (1944). The truncation edge of the Ferry Lake Anhydrite beneath the Mid-Cretaceous Unconformity on the southern flank of the Monroe Uplift is highly angular with northwest-southeast trending segments (Johnson, 1958) that closely follow the trajectories of the Mobile and Pearl River transfer faults. The trend of the MOTF near the Alabama Coast was recognized by Jamieson et al. (1998). It has been suggested that the Mud Hole Warm Water Spring of offshore Florida is associated with the Sunniland Fracture Zone (Mitchell-Tapping et al., 1999), which corresponds to the MOTF.

The Pearl River Transfer Fault

The Pearl River Transfer Fault (PRTF) follows the southwestern flank of the Desoto Canyon Salt Basin (DC) and parallels the Lower Cretaceous shelf edge (LK), passing near the Upper Cretaceous Door Point (DP) Volcano (Fig. 1). Onshore, the northwestward projection of the PRTF forms the southwest flanks of the eastern Wiggins Arch (WA), Mississippi Salt Basin (MS), and Monroe Uplift (MU), as well as the northeast flanks of the LaSalle Arch (LA), North Louisiana Salt Basin (NL), and Sabine Uplift (SU). The PRTF was first recognized by name by MacRae and Watkins (1996). Turner (2001) recognized Mesozoic strike-slip faults in northeast Texas along the northwestward projection of the PRTF that he referred to as the "South Florida Shear Zone."

The Mississippi River Transfer Fault

The Mississippi River Transfer Fault (MRTF) aligns with the Cuban Fracture Zone of Klitgord and Schouten (1986) and the Red River Fault Zone of Fisk (1944). The MRTF parallels the Mississippi River through the modern delta, and the Red River through central and northwestern Louisiana. The northwestward projection of the Mississippi River Transfer fault aligns with the western flanks of the Wiggins Arch (WA), North Louisiana Salt Basin (NL), and LaSalle Arch (LA), and also bisects the Sabine Uplift (SU).

The Terrebonne Transfer Fault

The trace of the Terrebonne Transfer Fault (TTF) in the offshore Gulf of Mexico was identified from the distribution of minibasins, allochthonous salt systems, and segmentation of counter-regional fault trends

(Stephens, 2001). The TTF is aligned with the Five Island Trend of salt domes in south-central Louisiana (Fisk, 1944). The northwestward projection of the TTF generally coincides with the western flank of the Sabine Uplift (SU) and the northeastern flank of the East Texas Salt Basin (ET) (Fig. 1).

The Hackberry Transfer Fault

The Hackberry Transfer Fault (HTF) was identified by Stephens (2001) based on the configuration of the basement surface and the arrangement of Mesozoic basins beneath the abyssal plain. The northwestward projection of the HTF passes just east of Hackberry Dome in southwest Louisiana, then along the southwest flank of the Sabine Uplift (SU) and the northeast flank of the East Texas Salt Basin (ET) (Fig. 1). Details of the HTF in southwestern Louisiana are developed in later sections.

The Sabine Transfer Fault

The Sabine Transfer Fault (STF) was recognized by Simmons (1992), extending from the Ouachita front, across the Texas Gulf Coast and shelf, and through the Sigsbee Salt Canopy. The STF aligns with the Campeche Fracture Zone (Fig. 1) of Klitgord and Schouten (1986), and is the most prominent of the transfer faults beneath the abyssal plain (Stephens, 2001). The STF trends through Green Knoll, just outboard of the Sigsbee Salt Canopy, and near an outcropping of Cretaceous basalt at Alderdice Bank (AB). The STF also marks the pronounced change from relatively continuous shale-detachment faults on the Texas Shelf to an abundance of salt related counter-regional faults on the southwest Louisiana Shelf (Diegel et al., 1995).

The Galveston Transfer Fault

The Galveston Transfer Fault (GTF) was recognized by Huh et al. (1996) based on offsets of rift basins, faults, and allochthonous salt/shale systems beneath the Texas shelf. The northwestward projection of the GTF aligns with offsets in basement highs and faults identified by Goldhammer (1999) beneath the central Texas Gulf Coast and along the Peripheral Fault Trend (Fig. 1)

The Brazos Transfer Fault

The Brazos Transfer Fault was identified by Simmons (1992) extending from the Ouachita front, across the Texas Gulf Coast and shelf, and through the Sigsbee Salt Canopy. The northwestward projection of the GTF aligns with offsets in basement highs and faults identified by Goldhammer (1999) and passes through a cluster of Cretaceous volcanic features near its intersection with the Peripheral Fault Trend (PFT) (Fig. 1).

The Keathley Transfer Fault

The Keathley Transfer Fault (KTF) has not been previously named, but is here aligned with one of the inland basement faults of Goldhammer (1999). The actual location may be slightly to the southwest, closer to the Alaminos Canyon, and may dictate the eastern margin of the Perdido Foldbelt. Trudgill et al. (1999) interpreted three northwest-southeast transfer faults segmenting the Perdido Foldbelt within the Matagorda-Keathley Corridor (MKC) (Fig. 1).

The Matagorda Transfer Fault

The Matagorda Transfer was previously identified by Bradshaw and Watkins (1995) beneath the Texas Shelf. Its northwestward projection aligns with basement structures of Goldhammer (1999) and is associated with Cretaceous volcanism along the Peripheral Fault Trend (PFT) (Fig. 1).

The South Padre Transfer Fault

The South Padre Transfer Fault (SPTF) has not been previously named, and is not well constrained, but can be discerned from segmentation of tertiary fault systems as discussed in the next section.

EXPRESSION OF TRANSFER FAULTS IN TERTIARY FAULTS AND SALT SYSTEMS

The trend of each of the major transfer faults traversing the Texas and Louisiana coasts can be discerned from the segmentation of Tertiary fault trends. Figure 3 is an unconventional presentation of the generalized "first-order" Tertiary fault trends of Diegel et al. (1995). Individual fault segments have been colored according to the corridor that contains their approximate center point. Alternating red and black colors were chosen for visual effect, and the black faults are dashed for visibility on gray-scale prints. Very few faults span more than one of the structural corridors delimited by "major" transfer faults. The few that do span multiple corridors may be further segmented at a level not resolvable on the original small-scale figure of Diegel et al. (1995). Faults are more finely segmented by minor transfer faults not depicted on this figure, but developed in the next section. This segmentation tends to be subtle in areas of shale detachments, but more pronounced in areas underlain by mobile salt.

Transfer Faults and Corridors of Southeastern Louisiana and Adjacent Waters

Figure 4 illustrates selected structural elements of southeast Louisiana and adjacent waters. Allochthonous salt (dark blue) in the Mississippi Canyon and Atwater Valley areas is after Stephens (2001, his Figure 8). Other offshore salt locations are after Simmons (1992) and Muehlberger (1992). Onshore salt locations are after Lopez (1995). Counter-regional (north-dipping) fault systems (red) are after Schuster (1995), Diegel (1995), Stephens

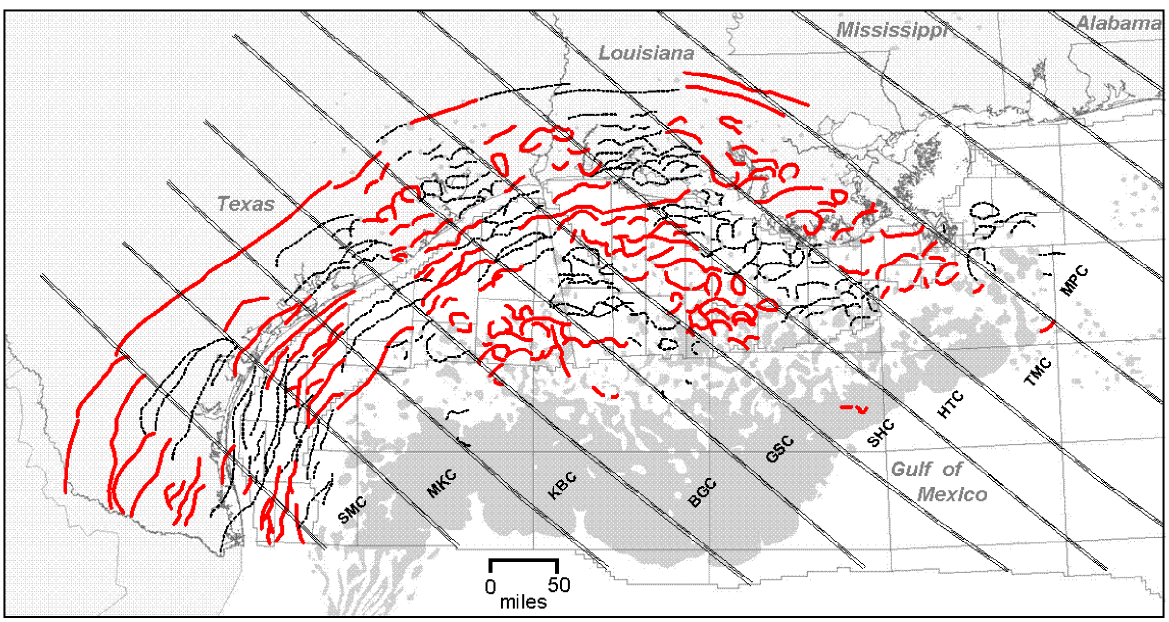

Figure 3. Tertiary faults of the Northern Gulf of Mexico after Diegel (1995): Faults alternately colored red and black by structural corridor to illustrate segmentation of successive fault systems along transfer fault trends. Offshore salt (gray) after Simmons (1992) and Muehlberger (1992). See text for discussion.

(2001) and Geomap Company (1983). Salt withdrawal minibasins (cream) are after Frye and Grimes (1970), Seglund (1974), Geomap Company (1983), and Stephens (2001). Thrust faults (brown) are after Stephens (2001). The Terrebonne–Mississippi River Corridor (TMC) is further segmented by the Timbalier, Lafourche, and four other unnamed "minor" transfer faults that can be projected into southeast Louisiana (Fig. 4). Stephens (2001) inferred the transfer faults of the TMC from the distribution of minibasins, allochthonous salt systems, and segmentation of counter-regional fault trends. Counter-regional faults are associated with salt feeders and salt welds that sourced the south-leaning diapirs and tabular salt bodies. The Terrebonne Trough (I), Bourbon Dome (II) and Tubular Bells (III) counter-regional fault trends generally traverse the TMC from west to east. However, each is highly segmented and systematically offset in a right-lateral sense across the inferred transfer faults (Fig. 4). Salt withdrawal basins associated with the counter-regional faults are filled with thick Miocene depositional sequences and are similarly delimited by the underlying transfer fault trends. The areas on the up-thrown sides of the counter-regional fault systems are relatively stable structural highs, and are characterized by a thinner Miocene section. Outboard of the Sigsbee Salt Canopy, the Mississippi Fan Fold Belt and the Mesozoic basins of Stephens (2001) are similarly segmented and right-laterally offset. The Mississippi River – Pearl River Corridor (MPC) is further segmented by the St. Bernard, Breton Sound, and three unnamed "minor" transfer faults (Fig. 4). The northwestward projections of the transfer faults of Mississippi Canyon into southeastern Louisiana are generally consistent with the "transforms" of Adams (1997). Details of the onshore extensional fault systems were not available. However, the recognized counter-regional faults and salt withdrawal minibasins are of a comparable scale to the transfer-delimited offshore analogues.

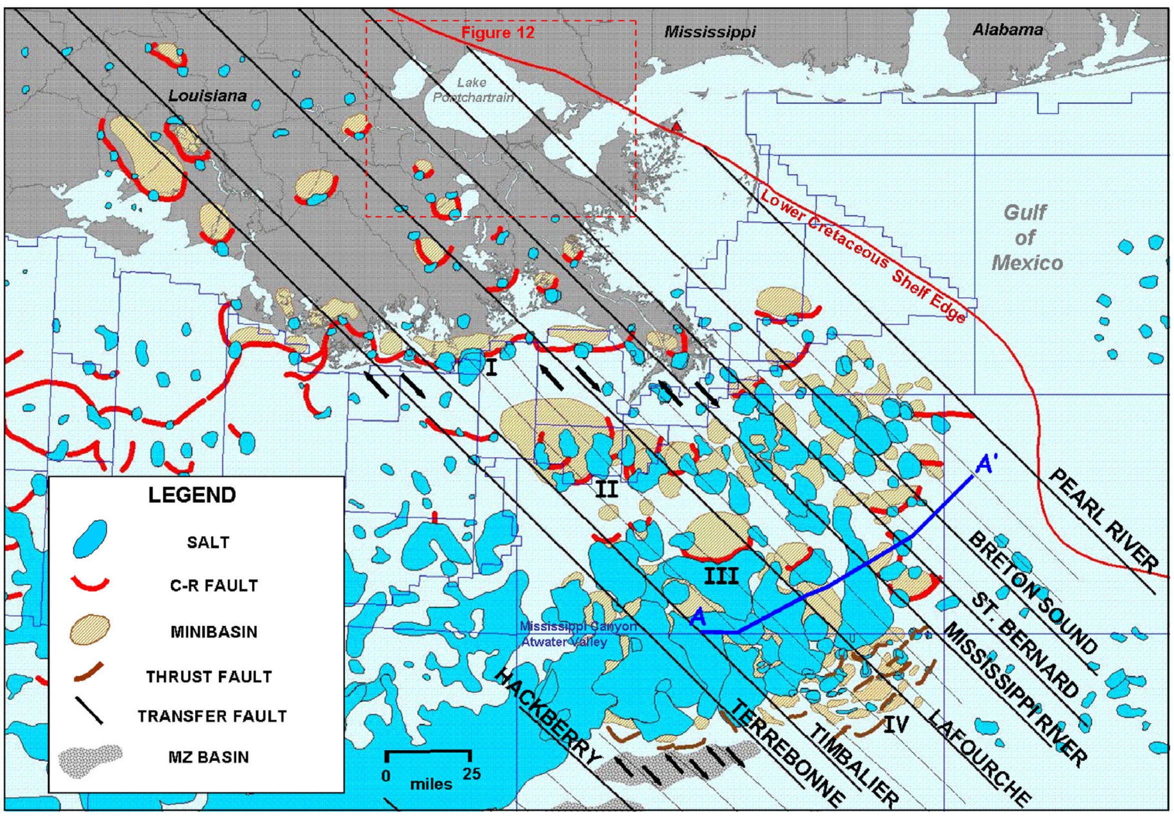

Figure 4. Structural "collage" of southeastern Louisiana and adjacent waters after Stephens (2001). Offshore salt after Simmons (1992) and Muehlberger (1992). Onshore salt after Lopez (1995). Counter-regional faults after Diegel (1995) and Schuster (1995). Onshore minibasins after Seglund (1974), Frye and Grimes (1970), and Geomap Company (1983). Box indicates area of Figure 12. See text for discussion.

Seismic Evidence of Transfer Faults

Stephens (2001) interpreted the basement structure beneath the abyssal plain of the north central Gulf of Mexico as a series of Mesozoic horsts and graben offset by northwest-southeast trending transfer faults. He argued that the projection of these transfer faults beneath the salt canopy and shelf could be discerned by the arrangement of structural elements in the Tertiary cover, but presented no seismic evidence of the transfer faults beneath the salt canopy. Recently acquired depth-migrated 3D seismic surveys reveal a "basement" surface beneath the salt canopy that is stepped along the inferred transfer fault trends (Fig. 5). The basement surface is thought to be equivalent to the BSE surface of MacRae and Watkins (1996). Five remnant autochthonous salt pillows are present above the BSE surface on the subject line. The Jurassic (Jr) stratigraphy to the east of the St. Bernard Transfer Fault can be tied to well control, but is increasingly speculative to the southwest. The top of the Cretaceous section (K) is a reliable seismic reflector throughout the area. From northeast to southwest there is approximately 25,000 ft of relief on the Cretaceous surface. The lower Tertiary section (L.T.) is condensed. The Miocene section (Mio.) thickens from 6600 ft in the northeast, to over 26,500 ft in the southwest, in proportion to the relief on the Cretaceous surface. Thickening of the Miocene section proceeds in a stepwise fashion within structural corridors, which are partitioned by allochthonous salt bodies and extensional faults that are vertically aligned with the underlying transfer faults. The top of the Miocene section deepens by only 3600 ft across the traverse and exhibits localized relief associated with salt movement, including turtle-structure anticlines and uplift over diapirs. The Plio-Pleistocene section thickens from 2300 ft to 8800 ft from northeast to southwest, but gains elevation by 2900 ft. This enigmatic shallowing to the southwest is a manifestation of depositional relief on the Mississippi Fan. Note that the lateral offsets between the transfer faults, at depths below 30,000 ft, and the near-surface expression of associated allochthonous salt bodes and faults can be as much as 10 mi.

EXPRESSION OF TRANSFER FAULTS IN COASTAL GEOMORPHOLOGY

The coastline of the northeastern Gulf of Mexico is partitioned into a series of alternating south-southeast and southwest facing segments that correspond to the transfer-fault delimited corridors discussed in the previous sections (Fig. 6). The general shoreline pattern from the Texas-Louisiana border to the Big Bend area of Florida is a series of southeast facing shorelines separated by right-lateral excursions across the underlying transfer fault trends. Southwest facing shorelines are aligned with the northwest-southeast trending transfer fault zones. This

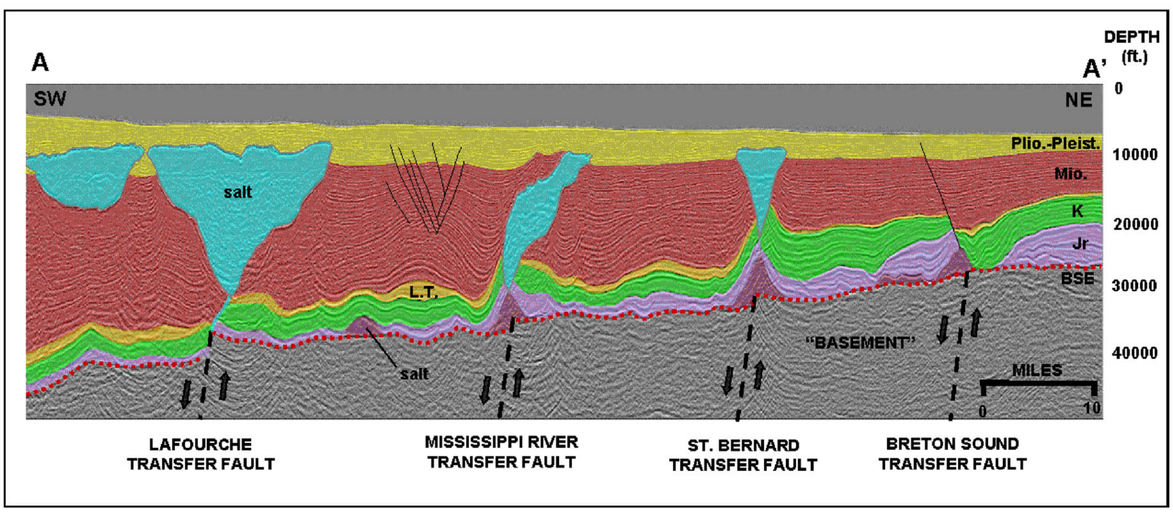

Figure 5. 3D seismic depth line from southeastern Mississippi Canyon Area showing gross Mesozoic and Tertiary stratigraphy, as well as locations of major transfer fault zones. See text for discussion. Line location shown on Figure 4. Seismic data courtesy of TGS.

pattern is more evident in southern Louisiana if the early Holocene shoreline, as approximated by the Pleistocene outcrop, is considered (Fig. 6). Barrier spits such as the St. Joe Peninsula and the Fort Morgan Peninsula are situated off the southwest flanks of protruding erosional headlands at the farthest reaches of the southwest-facing shoreline segments. During the early Holocene, prior to deposition of the Mississippi Delta, what is now the northeastern shore of Lake Pontchartrain was just another of the southwest facing shorelines. The Pine Island – Hancock Barrier Trend was similarly situated off the southwest flank of an erosional headland in southeastern Mississippi. The following sections present localized subsurface evidence for several of the major transfer faults and examine the manifestations of the deep structure in patterns of coastal depositional systems and geomorphology.

The Tallahassee Transfer Fault and the Wakulla River

Figure 7 depicts the "basement" faults of the Big Bend region of Florida after Barnett (1975). The fault pattern is characterized by northeast-southwest and northwest-southeast trends. Two northwest-southeast trending down-to-the-southwest faults are aligned with the Tallahassee and Port St. Joe transfer faults and with prominent southwest-facing shorelines. Note also the pronounced inflections in the bathymetric contours that are interpreted to reflect down-to-the-southwest vertical movement along the Pearl River and Mobile transfer faults.

The Wakulla River and Wakulla Springs appear to be structurally controlled by the TTF. Figure 8 is a geologic map of the Wakulla River area (see Figure 7 for location). The river is sourced by Wakulla Springs, the largest first-magnitude spring in the state of Florida, and flows southeast into the Gulf of Mexico. The river and spring are situated within the Woodville karst plain which formed within the Oligocene Suwanee Limestone and the Miocene St. Marks Formation (Rupert, 1988). The outcrops of the Suwanee Limestone (Ts) and St. Marks Formation (Tsmk) are generally situated on a high block to the northeast and upthrown to the TTF (Fig. 8). Figure 9 is a geologic cross section through Wakulla Springs and across the TTF re-interpreted after Rupert (1988). It is suggested that the thickening of the St. Marks Formation and the structurally low position of the Suwanee

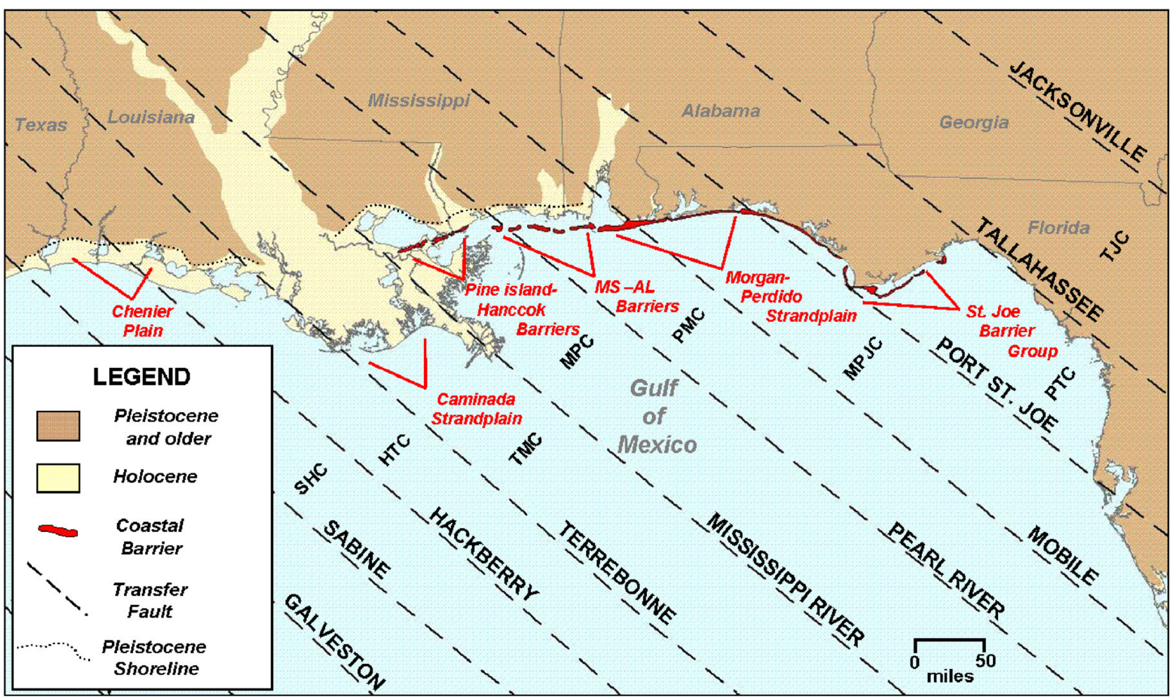

Figure 6. Holocene barrier complexes and shorelines of the northeastern Gulf Coast after Otvos (1978, 2005) and their relationship to transfer-fault delimited structural corridors. See text for discussion.

Limestone to the west of the TTF reflects movement of the TTF during the Miocene and that fracturing associated with this movement may have influenced the karst system. It is further suggested that ongoing vertical movement and resultant topography across the TTF controls the course of the river.

Movement on the Port St. Joe Transfer Fault through Geologic Time

The Port St. Joe Transfer Fault (PSJTF) is perhaps the best place to demonstrate recurring movement along transfer faults throughout the geologic history of the Gulf of Mexico Basin. Figure10 combines a Norphlet (Jurassic) isopach map, Lower Wilcox (Paleocene) accumulation rate map, and locations of historical earthquakes

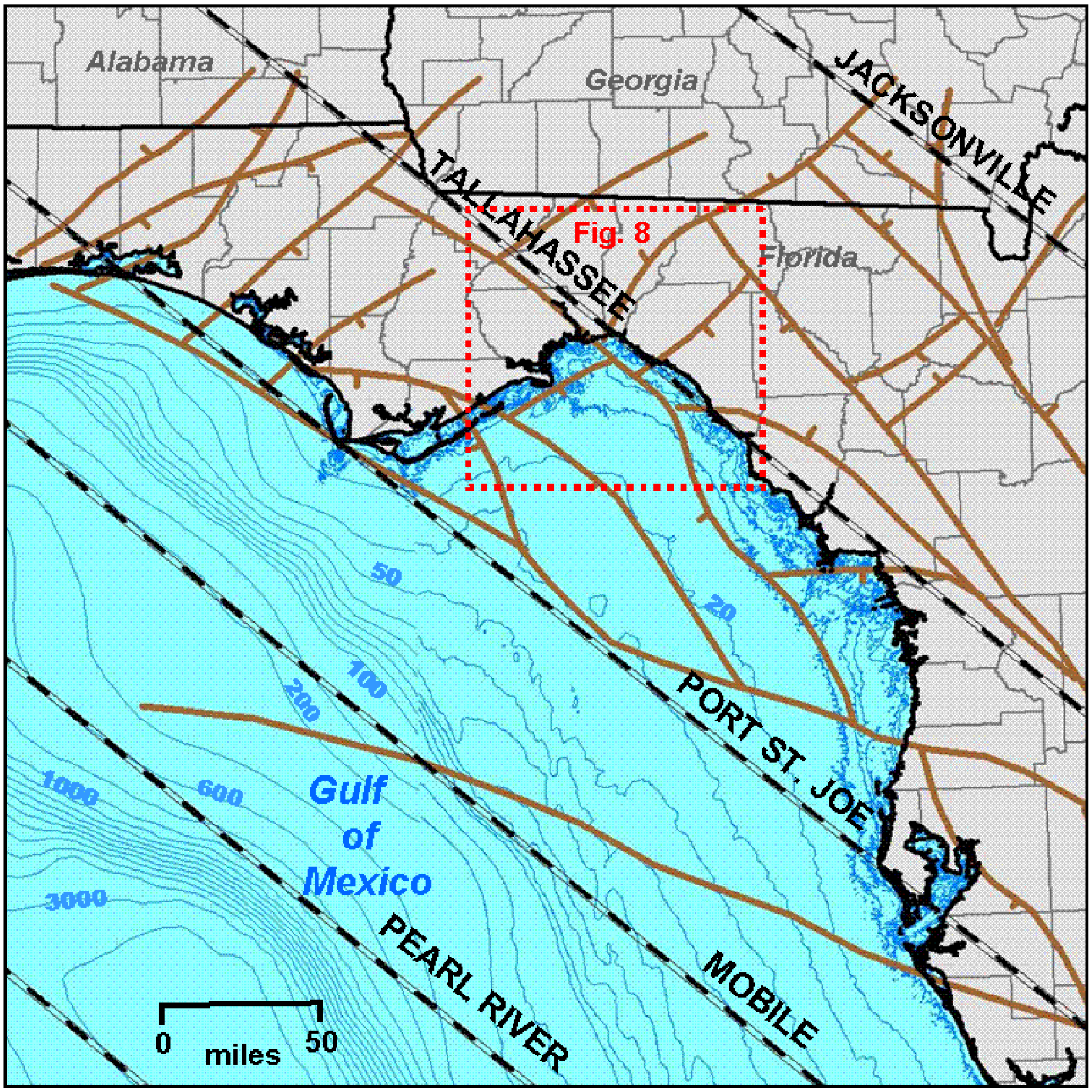

Figure 7. Basement faults of central Florida after Barnett (1975) and their relationship to transfer fault trends. Box indicates area of Figure 8. See text for discussion.

to demonstrate movement during Jurassic time, early Tertiary time, and continuing to the present. The inset map is an isopach of the Jurassic Norphlet Sandstone after Prather (1992). To the northeast of the PSJTF, the Norphlet is over 400 ft thick in the Conecuh Embayment (CE) but is absent over the Conecuh Arch (CA). The PSJTF is manifested as a prominent northwest-southeast lineament across which the Conecuh Embayment is juxtaposed to a Norphlet thin. The Conecuh Arch is juxtaposed across the PSJTF to a Norphlet thick. The gray-scale background map represents the Lower Wilcox (58.0-55.2 Ma) accumulation rate after Fillon et al. (2005). Note the linear trend in the accumulation rate map coincident with the Port St. Joe Transfer Fault, corresponding to 75 ft per million yr. This suggests down-to-the-southwest vertical motion across the PSJTF during the Early Tertiary. The red stars are a subset of historical earthquakes for the period 1973-2000. Note the twelve earth-

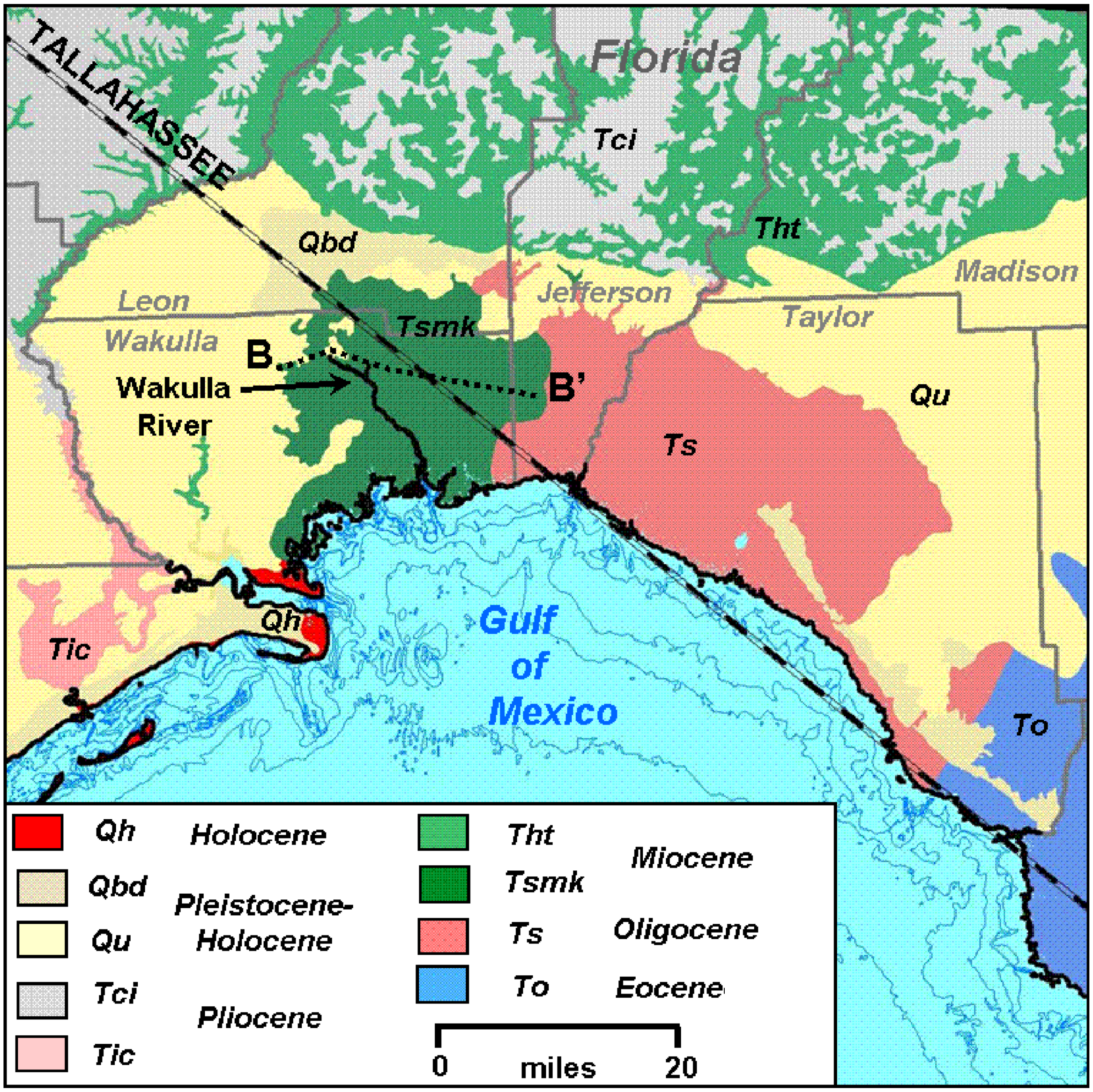

Figure 8. Geologic map of the Big Bend area of Florida after Scott et al. (2001), showing the relationship of the surface geology and the course of the Wakulla River to the Tallahassee Transfer Fault. Map location shown in Figure 7. See text for discussion.

quakes clustered along the trace of the PSJTF through east-central Mississippi and southwestern Alabama (Mueller et al., 1997). These earthquakes had magnitudes of 3 to 4.9 with calculated depths between 16,400 and 33,000 ft, which would be within the "basement." Clearly the PSJTF is still active. Also note the alignment of each of these datasets with a segment of northwest-southeast trending Gulf of Mexico shoreline.

Jurassic Structure and the Mobile Bay Area

The northwestward projection of the Mobile Transfer Fault from offshore is thought to be associated with the topographically-high eastern shoreline of Mobile Bay (Fig. 11). The Holocene coastal barriers of southern Alabama appear to be segmented and offset in a right- lateral sense across minor transfer faults of the Pearl River – Mobile Corridor. The inland projections of these transfer faults were recognized by Fisk (1944). The inset map in Figure 11 is a 3D seismic depth map of the Jurassic Norphlet Sandstone after Story (1988). The Norphlet

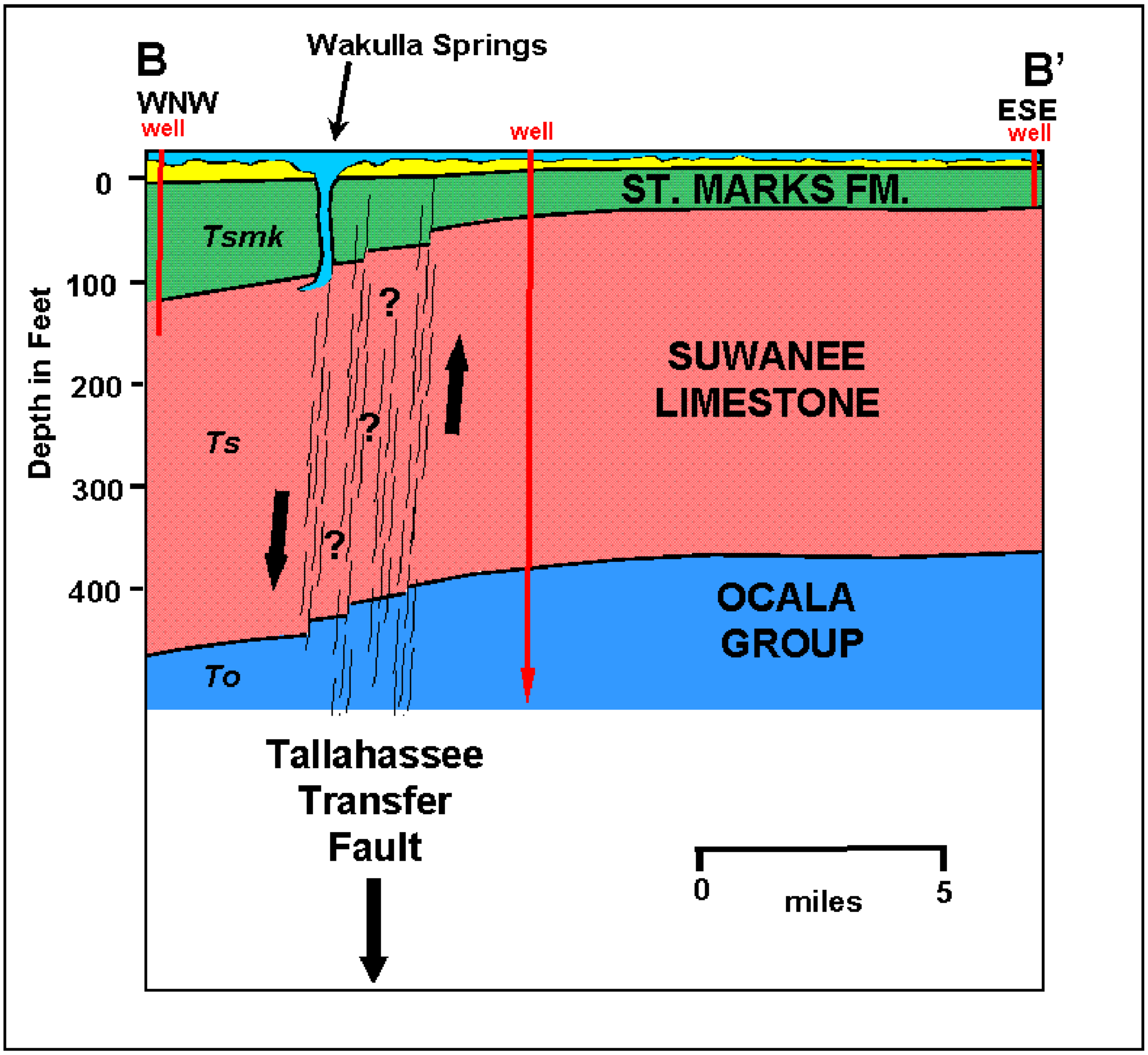

Figure 9. Geologic cross section of the Wakulla Springs area reinterpreted after Rupert (1988). Line location on Figure 8. See text for discussion.

produces gas from salt-related structural highs (red) at depths around 21,000 ft, within a graben. The widths of the Norphlet graben and Dauphin Island both appear to coincide with a structural corridor delimited by the minor transfer fault trends interpreted on Figure 11. Note that the northern boundary fault of the Norphlet graben was interpreted by Story (1988) to be offset by a right-lateral strike-slip fault. This right-lateral offset is mimicked by Dauphin Island and the Morgan Peninsula.

Transfer Faults and Near-Surface Geology of the Lake Pontchartrain Basin

Near-surface structural and depositional features of the Lake Pontchartrain Basin appear to be influenced by the Breton Sound, St. Bernard, and Mississippi River transfer faults. Figure 12 depicts the depth to the top of the Pleistocene surface after Kidinger et al. (1997), the Baton Rouge Fault Zone (BRFZ) after Lopez (1991) and the outline of the Holocene Pine Island Barrier Trend after Flowers and Isphording (1990). The Pleistocene surface steps down to the southwest along a northwest-southeast trending flexure that parallels the projection of the Breton Sound Transfer Fault. Figure 13 is a geologic cross section across the Lake Pontchartrain Basin re-interpreted after Kidinger et al. (1997). The stepped relief on the Pleistocene surface is interpreted to be a manifestation of vertical offset on the Breton Sound and St. Bernard transfer faults, either along faults, as recognized by Lopez (1991) or as displacement along subseismic fracture zones in the relatively unconsolidated upper Tertiary section. The northeastern (southwest-facing) shore of Lake Pontchartrain is interpreted to overlie the Rigolets Transfer Fault, which is the first unnamed transfer fault to the northeast of the Breton Sound Transfer Fault on Figure 4. The northwestward projection of the Rigolets Transfer Fault was recognized by Fisk (1944). The

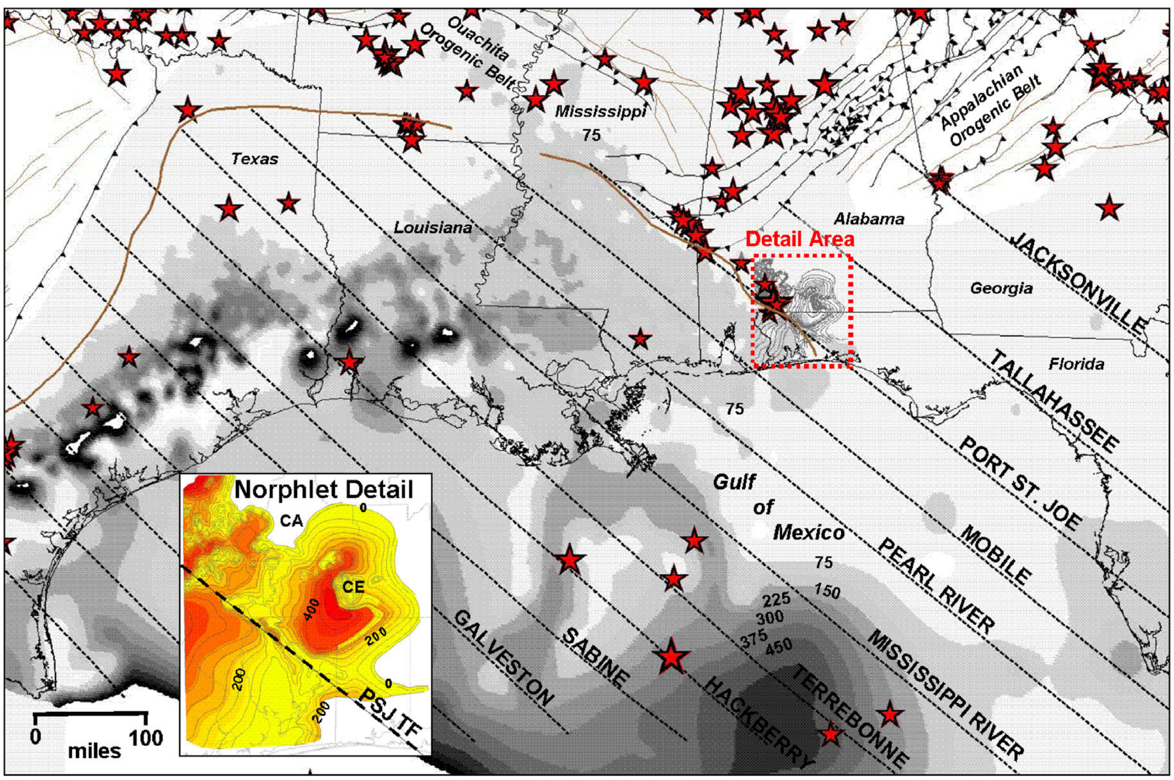

Figure 10. Sediment accumulation rate (gray-scale) of the Lower Wilcox (58.0-55.2 Ma) depositional sequence after Fillon et al. (2005). Norphlet isopach map (inset) after Prather (1992). Red stars are recorded earthquakes for the period 1973-2000 from the U.S. Geological Survey (Mueller et al., 1997). Faults of the Appalachian-Ouachita Orogenic Belt from Muehlberger (1992). See text for discussion.

Baton Rouge Fault Zone (BRFZ) does not parallel the deep transfer fault trends, but rather intersects them obliquely. It is suggested that the segmentation of BRFZ is a reflection of the deep transfer faults.

The Holocene age Pine Island Barrier Trend (Otvos, 1978) also appears to be segmented and exhibits right-lateral offsets across the St. Bernard and Breton Sound transfer faults (Fig. 12). These transfer faults are known from the offshore seismic profile (Fig. 5) to exhibit down-to-the-southwest vertical offset. Assuming that the Pine Island Barriers were deposited on a structurally high trend, slight differential subsidence across these deep basement faults comparable to the observed relief on the Pleistocene surface would cause the right stepping offsets of the early Holocene shoreline. Note also that the larger lakes Pontchartrain and Borgne span multiple corridors, but are somewhat segmented. However, the widths of lakes Maurepas and Salvador are generally delimited by the width of the underlying corridors. The large-scale meanders of the Mississippi River to the south of Lake Pontchartrain seem to be confined within the corridor delimited by the Mississippi River Transfer Fault and the Breton Sound Transfer Fault.

Transfer Faults, Subsurface Structure, and Coastal Environments of the Chenier Plain

The shape of the southwest Louisiana coastline, distribution of coastal environments and size and location of inland lakes appear to closely coincide with subsurface structural patterns arranged within transfer-fault delimited corridors. The geologic map of southwest Louisiana (Fig. 14) is after Snead and McCulloh (1984). Locations of counter-regional faults and salt withdrawal basins of Paleocene through Oligocene age are after Diegel et al. (1995) and Seglund (1974). Down-to-the-basin normal faults and lateral fault families associated with the salt withdrawal basins, as well as regional growth faults associated with shale detachments are not shown. The Hackberry Transfer fault of Stephens (2001) skirts the northeastern shore of Calcasieu Lake and the eastern flank of

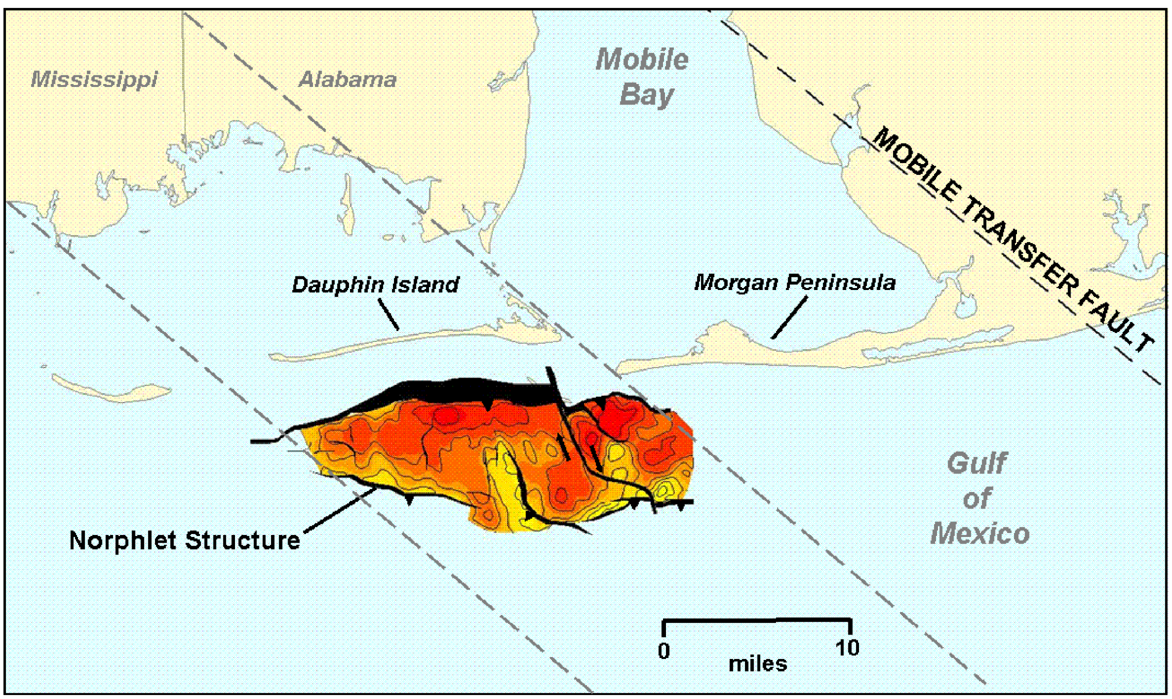

Figure 11. Norphlet Sand (Jurassic) form-line structure map of the Mobile Bay Area after Story (1998). Note arrows showing relative sense of offset along interpreted right-lateral strike-slip fault and similar right-lateral offset of the Dauphin Island and Morgan Peninsula barriers. See text for discussion.

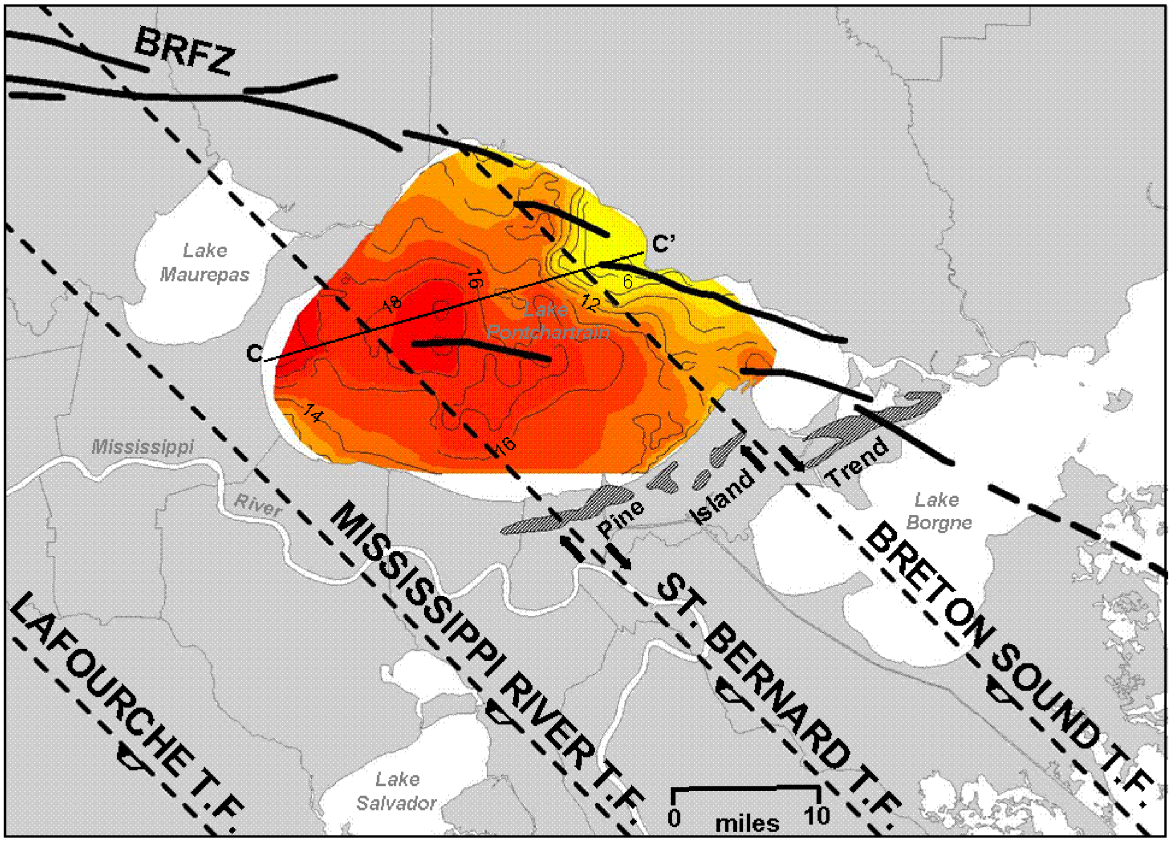

Figure 12. Near-surface structural and depositional features of the Lake Pontchartrain Basin. Depth to the top of the Pleistocene (color-filled contours in ft) after Kidinger et al. (1997). Baton Rouge Fault Zone (BRFZ) after Lopez et al. (1997). Pine Island Barrier Trend after Flowers and Isphording (1990). Map location shown on Figure 4. See text for discussion.

Hackberry Dome and its associated counter-regional fault system. The Sabine Transfer Fault and several unnamed minor transfer faults are also shown. The trends of these transfer faults can be discerned from stream courses and surface fracture trends, and were recognized by Fisk (1944).

The widths of counter regional fault systems and minibasins, including the Hackberry and Calcasieu Lake counter-regional systems, correspond to the widths of the underlying transfer fault delimited structural corridors. Seglund (1974) recognized that Calcasieu Lake was situated over a salt withdrawal basin. Sabine Lake, Grand Lake, and White Lake are of similar dimensions to the underlying structural corridors. The freshwater marsh areas (Qcf) of the chenier plain appear to be located on the up-thrown sides of the counter-regional faults, and above structural highs between the withdrawal basins. Saline marsh (Qcs) and open water areas are situated above salt withdrawal basins. The large right-lateral excursion of the coastline across the Hackberry Transfer Fault results in a southwestward-facing shore line analogous to the previously discussed transfer-aligned shorelines of Lake Pontchartrain, Mobile Bay, and the Florida Panhandle.

DISCUSSION AND CONCLUSIONS

Although poorly understood, transfer faults appear to be among the most fundamental and persistent geologic features of the basin (Stephens, 2001). There appears to be a large scale (25 to 40 mi) organization of Gulf of Mexico structural provinces, coastal systems, and shoreline segments corresponding to the structural corridors

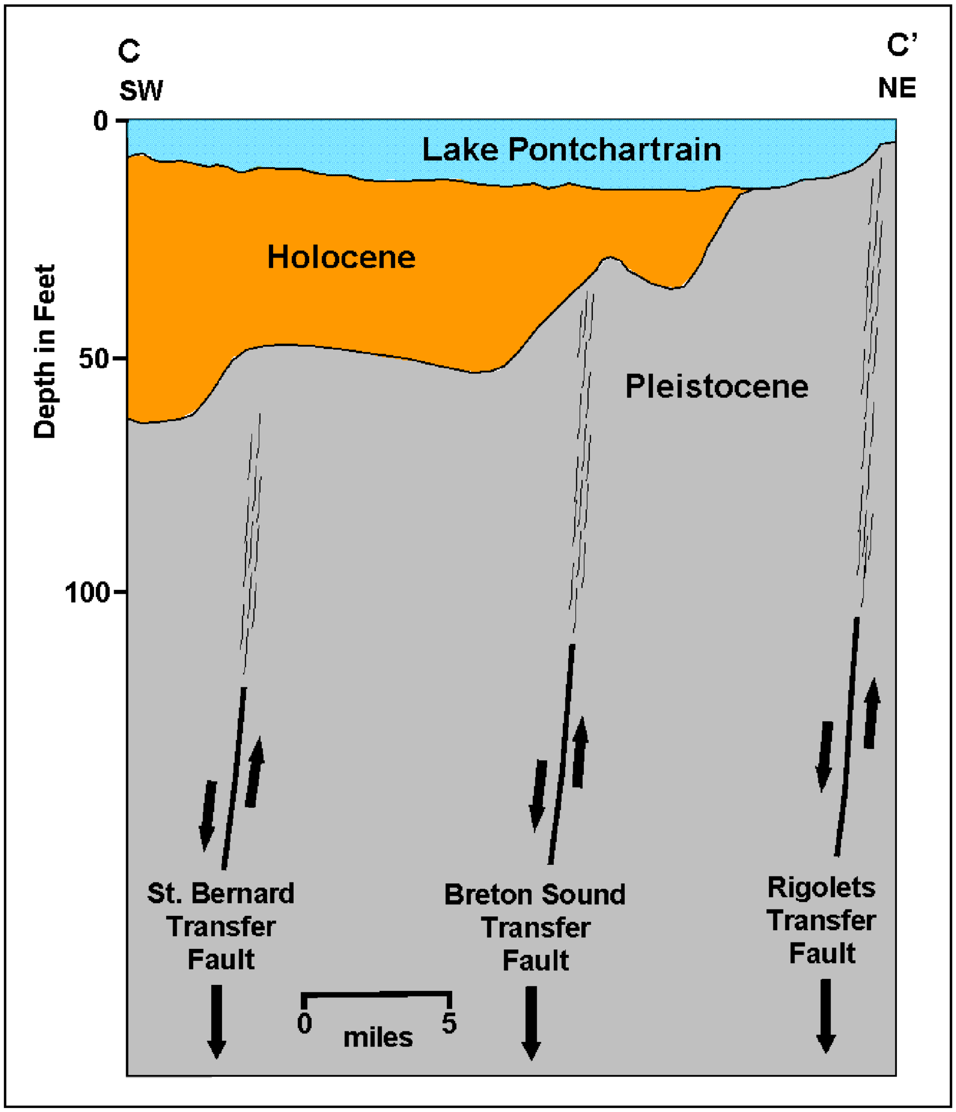

Figure 13. Geologic cross section of the Lake Pontchartrain Basin reinterpreted after Kidinger et al. (1997). Relief on Pleistocene surface interpreted to be from vertical offset along faults and subseismic fractures associated with basement transfer fault trends. Line location shown on Figure 11. See text for discussion.

delimited by the 14 major transfer fault trends (Fig. 6). More highly extended corridors underlain by thinner crust would be expected to undergo a greater degree of isostatic adjustment under subsequent sedimentary loads. The stepped profile of the basement surface and corresponding thickening of the Tertiary section visible on the 3D seismic profile (Fig. 5) across southeastern Mississippi Canyon Area are evidence of this process. Vertical movements, perhaps associated with differential isostatic adjustments across transfer faults, appear to be directly reflected in topographic and bathymetric trends. It has long been recognized that the courses of major rivers are structurally controlled (e.g., Potter, 1978). Fisk (1944) recognized the effects of deep structural movements on river and stream courses throughout the Mississippi Valley. Stephens (2001) demonstrated an alignment of modern deep-water sediment fairways of the abyssal plain with the deep basement structure. Rivers were probably

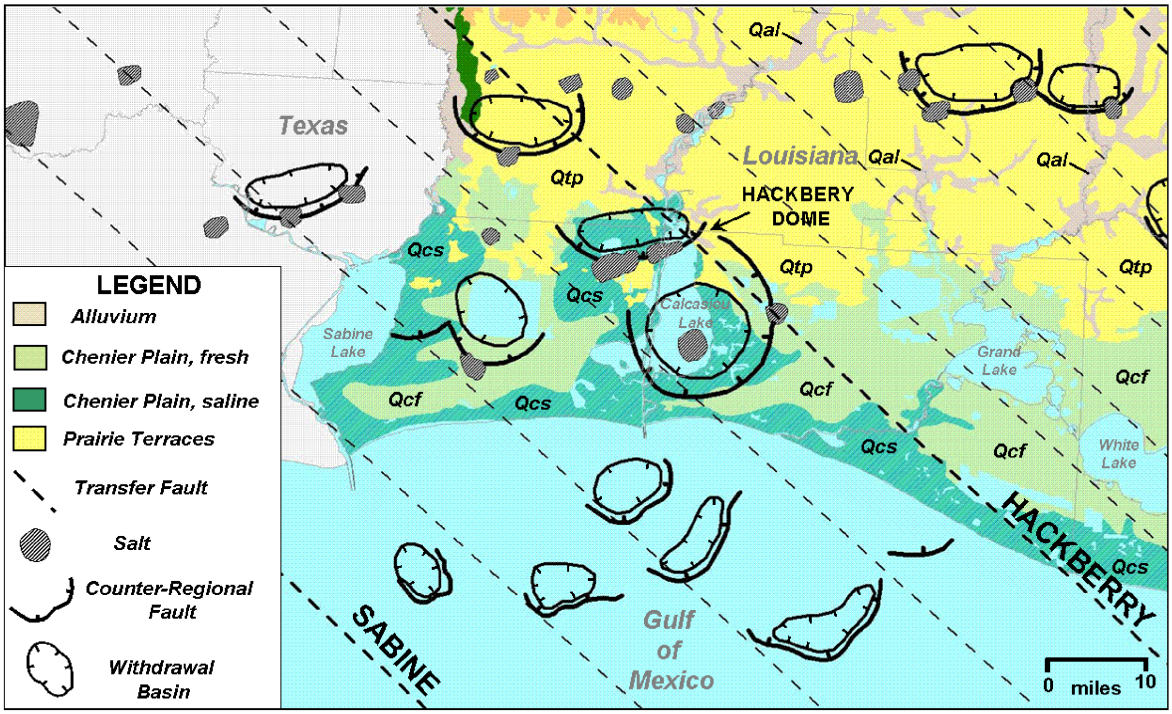

Figure 14. Geologic map of southwestern Louisiana after Snead and McCulloh (1984) with selected subsurface geologic features. Counter-regional faults after Diegel et al. (1995). Salt after Lopez (1995). Salt withdrawal basins after Seglund (1974). See text for discussion.

more likely to follow the transfer fault trends during relative low stands of sea level, when the incised valleys would have skirted the flanks of transfer delimited structural highs. The manifestations of the subsurface structural patterns in the distribution of coastal environments are less apparent during high stands of sea-level because of high sedimentation rates, particularly near deltaic depocenters. Thus the protrusion of the Holocene delta of the Mississippi River beyond the Pleistocene shoreline masks the conformance of south Louisiana to the overall structural pattern.

Superimposed on the pattern of basement-related differential subsidence across the major structural corridors, is the finer (10 mi) partitioning of faults and salt systems within the post-rift section by minor transfer faults (e.g., Figs. 4 and 14) as described by Adams (1993, 1997) and Bradshaw and Watkins (1995). The patterns of ongoing adjustment of the basement, combined with patterns of salt withdrawal, sediment compaction and faulting in the post-rift section have produced a landscape of continuously varying subsidence rates through space and time. Fisk and McFarlan (1955) debated whether downwarping of the Mississippi Delta was the product of isostatic adjustment of the basement to sedimentary loading, or due to adjustments within the post-rift section, and favored the former. Tornqvist et al. (2006) revisited the question and favored the latter. The examples presented here provide ample evidence that both processes are operating in a highly ordered pattern within the context of the plate-tectonic theory that was not yet accepted in Fisk's time. Paradoxically, even though high sedimentation rates associated with deltaic depocenters may mask the patterns of tectonic subsidence, the actual rates and magnitudes of tectonic subsidence may be greater in those areas because of increased sediment loading, salt mobilization, faulting and compaction. The Holocene delta plain of the Mississippi River has been able to substantially, but not completely, outpace subsidence. Active lobes of the Holocene Mississippi River Delta have been able to aggrade, but, once abandoned, quickly succumb to subsidence. The effect of isolating the Mississippi Delta from its sediment sources through levying will be to quickly unmask the patterns of naturally-occurring, structurally-controlled vertical subsidence that proceeds unabated.

A cursory comparison to the data of Shinkle and Dokka (2004) suggests that differential vertical movements across the major transfer fault zones described in this paper are reflected in modern subsidence rates. The examples presented demonstrate a clear relationship between coastal depositional systems and subsurface structural patterns. Subsidence rates vary continuously in space and time and may change abruptly, but predictably, across discrete structural boundaries. An understanding of the structural order of the subsurface geologic framework is essential to interpreting the growing body of detailed subsidence measurements. Before the magnitude of human-induced causes of subsidence, such as hydrocarbon extraction, can be assessed, the natural variations outlined above must be understood. The configuration of the coastline and relative topography of the Gulf Coast are products of ongoing vertical movements that have operated through the geologic history of the basin. The locations of relatively high-standing features, such as coastal barriers are likely determined by deep structural trends and are relatively fixed. More rapidly subsiding areas are likely to persist through space and time. A subsurface structural model, calibrated with detailed subsidence measurements is likely to be good predictor of future subsidence patterns.

ACKNOWLEDGMENTS

The opinions presented here are solely those of the author, and do not reflect the position of the Minerals Management Service. TGS Corporation is gratefully acknowledged for permitting the use of the seismic line presented in Figure 5. The author would like to thank Richard Fillon of the Earth Studies Group, for providing the Wilcox accumulation rate data used in Figure 10, and for his encouragement over the years to "get some of these ideas out there."

REFERENCES CITED

Adams, R. L., 1989, Effects of inherited pre-Jurassic tectonics on the Gulf Coast: American Association of Petroleum Geologists Bulletin, v. 73, p. 325-326.

Adams, R. L., 1993, Effects of inherited pre-Jurassic tectonics on the U.S. Gulf Coast: Gulf Coast Association of Geological Societies Transactions, v. 43, p. 1-9.

Adams, R. L., 1997, Microbasin analysis of south Louisiana: An exploration model, Or: Hutton and Lyell were wrong!: Gulf Coast Association of Geological Societies Transactions, v. 47, p. 1-12

Barnett, R. S., 1975, Basement structure of Florida and its tectonic implications: Gulf Coast Association of Geological Societies Transactions, v. 25, p. 122 -142.

Bradshaw, B. E., and J. S. Watkins, 1995, Mesozoic and Cenozoic salt migration pathways in offshore Texas, northwestern Gulf of Mexico: Proceedings of the 16th Annual Gulf Coast Section of the Society of Economic Paleontologists and Mineralogists Foundation Bob F. Perkins Research Conference, Houston, Texas, p. 13-23.

Braunstein, J., and C. E. McMichael, 1976, Door Point: A buried volcano in southeast Louisiana: Gulf Coast Association of Geological Societies Transactions, v. 26, p. 79-80.

Christenson, G., 1990, The Florida lineament: Gulf Coast Association of Geological Societies Transactions, v. 40, p. 99-115

Diegel, F. A., D. C. Schuster, J. F. Karlo, R. C. Shoup, and P. R. Tauvers, 1995, Cenozoic structural evolution and tectono-stratigraphic framework of the northern Gulf Coast continental margin, *in* M. P. A. Jackson, D. G. Roberts, and S. Snelson, eds., Salt tectonics: A global perspective: American Association of Petroleum Geologists Memoir 65, Tulsa, Oklahoma, p. 109-151.

Dobson, L. M., and R. T. Buffler, 1991, Basement rocks and structure, northeast Gulf of Mexico: Gulf Coast Association of Geological Societies Transactions, v. 41, p. 191-206.

Fillon, R. H., 2007, Mesozoic Gulf of Mexico Basin evolution from a planetary perspective and petroleum systems implications: Petroleum Geoscience, v. 13, p. 105-126.

Fillon, R. H., P. N. Lawless, and A. S. Waterman, 2005, Paleocene-Eocene deposystems and evolution of the Gulf of Mexico Basin petroleum system: Gulf Coast Association of Geological Societies Transactions, v. 55, p. 195-222.

Fisk, H. N., 1944, Geological investigation of the alluvial valley of the lower Mississippi River: Mississippi River Commission, Vicksburg, Mississippi, 78 p.

Fisk, H. N., and E. McFarlan, Jr., 1955, Late Quaternary deltaic deposits of the Mississippi River, *in* A. Poldervaart, ed., Crust of the Earth: Geological Society of America Special Paper 62, Boulder, Colorado, p. 279-302.

Flowers, G. F., and W. C. Isphording, 1990, Environmental sedimentology of the Pontchartrain estuary: Gulf Coast Association of Geological Societies Transactions, v. 40, p. 237-250.

Frye, M. G., and W. H. Grimes, 1970, Bay Marchand–Timbalier Bay–Caillou Island salt complex, *in* M. Halbouty, ed., Geology of giant fields: American Association of Petroleum Geologists Memoir 14, Tulsa, Oklahoma, p. 277-291.

Gagliano, S. M., E. B. Kemp, III, K. M .Wicker, K. S. Wiltenmuth, and R. W. Sabaté, 2003, Neo-tectonic framework of southeast Louisiana and applications to coastal restoration: Gulf Coast Association of Geological Societies Transactions, v. 56, p. 262-276.

Geomap Company, 1983, Generalized geological subsurface structure map, *in* L. L. McCormick and R. S. Kline, eds., Oil and gas fields of southeast Louisiana, v. III: New Orleans Geological Society, Louisiana, p. X, scale 1:950,400.

Goldhammer, R. K., 1999, Mesozoic sequence stratigraphy and paleogeographic evolution of northeast Mexico, *in* C. Bartolini, J. L. Wilson, and T. F. Lawton, eds., Mesozoic sedimentary and tectonic history of north-central Mexico: Geological Society of America Special Paper 340, Boulder, Colorado, p. 1-58.

Hames, W. E., J. G. McHone, P. R. Renne, and C. Ruppel, 2003, Introduction, *in* W. E. Hames, J. G. McHone, P. R. Renne, and C. Ruppel, eds., The Central Atlantic Magmatic Province: Insights for fragments of Pangea: American Geophysical Union Geophysical Monograph 136, Washington, D.C., p. 1-16.

Huh, S., J. S. Watkins, R. Kadande, R. Fiduk, S. Bryant, K. E. Silver, B. E. Bradshaw, F. Xue, and J. Xi, 1996, Regional structure and tectonics of the Texas shelf, *in* J. O. Jones and R. L. Freed, eds., Structural framework of the northern Gulf of Mexico: Gulf Coast Association of Geological Societies Special Publication 80, Austin, Texas, p. 39-52.

Imbert, P., 2005, The Mesozoic opening of the Gulf of Mexico: Part 1, evidence for oceanic accretion before, during and after salt deposition: Proceedings of the 25th Annual Gulf Coast Section of the Society of Economic Paleontologists and Mineralogists Foundation Bob F. Perkins Research Conference, Houston, Texas, p. 1119-1150.

Imbert, P., and Y. Phillippe, 2005, The Mesozoic opening of the Gulf of Mexico: Part 2, integrating seismic and magnetic data into a general opening model: Proceedings of the 25th Annual Gulf Coast Section of the Society of Economic Paleontologists and Mineralogists Foundation Bob F. Perkins Research Conference, Houston, Texas, p. 1151-1189.

Jamieson, G., J. F. Karlo, and R. C. Shoup, 1998, Tectonic provinces of the northern Gulf of Mexico, *in* R. Shoup, J. Watkins, J. Karlo, and D. Hall, eds., Integration of geologic models for understanding risk in the Gulf of Mexico: American Association of Petroleum Geologists Hedberg Research Conference, Galveston, Texas, p. 1-8.

Johnson, O. H., Jr., 1958, The Monroe Uplift: Gulf Coast Association of Geological Societies Transactions, v. 8, p. 24-26.

Kidinger, J. L., S. J. Williams, S. Penland, J. G. Flocks, and P. Connor, 1997, Holocene geologic framework of Lake Pontchartrain Basin and lakes of southeastern Louisiana: Gulf Coast Association of Geological Societies Transactions, v. 47, p. 635-638.

Kinsland, G. L., 1984, Basement structure of the Gulf Coast, interpretation of gravity anomalies supported with structural, magnetic, and seismic data: Gulf Coast Association of Geological Societies Transactions, v. 34, p. 85-94.

Klitgord, K. D., and H. Schouten, 1986, Plate kinematics of the central Atlantic, *in* P. R. Vogt and B. E. Tucholke, eds., The geology of North America, v. M: The western North Atlantic region: Geological Society of America, Boulder, Colorado, p. 351-378.

Lister, G. S., M. A. Etheridge, and P. A. Symonds, 1986, Detachment faulting and the evolution of passive continental margins: Geology, v. 14, p. 246-250.

Lopez, J. A., 1991, Origin of Lake Pontchartrain and the 1987 Irish Bayou earthquake: Proceedings of the 11th Annual Gulf Coast Section of the Society of Economic Paleontologists and Mineralogists Foundation Research Conference, Houston, Texas, p. 103-110.

Lopez, J. A., 1995, Salt tectonism of the Gulf Coast Basin: New Orleans Geological Society, Louisiana, scale 1:1,560,000.

Lopez, J. A., S. Penland, and J. Williams, 1997, Confirmation of active geologic faults in Lake Pontchartrain in southeast Louisiana, Gulf Coast Association of Geological Societies Transactions, v. 47 p. 299-303.

MacRae, G., and J. S. Watkins, 1993a, Basin architecture, salt tectonics and Upper Jurassic structural development, Desoto Canyon Salt Basin, northeastern Gulf of Mexico: Proceedings of the 13th Annual Gulf Coast Section of the Society of Economic Paleontologists and Mineralogists Foundation Research Conference, Houston, Texas, p. 9-20.

MacRae, G., and J. S. Watkins, 1993b, Basin architecture, salt tectonics, and Upper Jurassic structural styles, Desoto Canyon Salt Basin, northeastern Gulf of Mexico: American Association of Petroleum Geologists Bulletin, v. 77, no. 10, p. 1809-1824.

MacRae, G., and J. S. Watkins, 1996, Desoto Canyon Salt Basin: Tectonic evolution and salts structural styles: Gulf Coast Association of Geological Societies Transactions, v. 46, p. 53-61.

Miller, J. A., 1982, Structural control of Jurassic sedimentation in Alabama and Florida: American Association of Petroleum Geologists Bulletin, v. 66, p. 1289-1301.

Mitchell-Tapping, H. J., J. R. Bellucci, W. Graham, and T. J. Lee, 1999, Mud hole: A unique warm-water submarine spring located offshore southwestern Florida: Gulf Coast Association of Geological Societies Transactions, v. 49, p. 370-383.

Morton, R. A., N. A. Buster, and M. D. Krohn, 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 .

Muehlberger, W. R., 1992, Tectonic map of North America, southeast and southwest sheets: American Association of Petroleum Geologists, Tulsa, Oklahoma, scale 1:5,000,000.

Mueller, C., M. Hopper, and A. Frankel, 1997, Preparation of earthquake catalogs for the national seismic-hazard maps: Contiguous 48 states: U.S. Geological Survey Open-File Report 97-464, <http://pubs.usgs.gov/of/1997/464/> Accessed July 24, 2009.

Otvos, E. G., 1978, New Orleans-south Hancock Holocene barrier trends and origins of Lake Pontchartrain: Gulf Coast Association of Geological Societies Transactions, v. 33, p. 337-355.

Otvos, E. G., 2005, Numerical chronology of the late Quaternary Gulf Coastal Plain; barrier evolution and an updated Holocene sea-level curve: Gulf Coast Association of Geological Societies Transactions, v. 55, p. 629-641.

Pindell, J., and L. Kennan, 2001, Kinematic evolution of the Gulf of Mexico and Caribbean: Proceedings of the 21st Annual Gulf Coast Section of the Society of Economic Paleontologists and Mineralogists Foundation Bob F. Perkins Research Conference, Houston, Texas, p. 193-220.

Post, P. J., 2005, Constraints on the Interpretation of the origin and early development of the Gulf of Mexico Basin: Proceedings of the 25th Annual Gulf Coast Section of the Society of Economic Paleontologists and Mineralogists Foundation Bob F. Perkins Research Conference, Houston, Texas, p. 1016-1061.

Potter, P. E., 1978, Significance and origin of big rivers: Journal of Geology, v. 86, p. 13-33.

Prather, B. E., 1992, Evolution of a late Jurassic carbonate/evaporate platform, Conecuh Embayment, northeastern Gulf Coast, U.S.A.: American Association of Petroleum Geologists Bulletin, v. 76, p. 164-190.

Rezak, R., and T. T. Tieh, 1980, Basalt on Louisiana outer shelf: Transactions of the American Geophysical Union, v. 61, p. 989.

Rupert, F. R., 1988, The geology of Wakulla Springs: Florida Geological Survey Open File Report 22, Tallahassee, 18 p.

Salvador, A., 1987, Late Triassic-Jurassic paleogeography and origin of Gulf of Mexico Basin: American Association of Petroleum Geologists Bulletin, v. 71, p. 419-451.

Salvador, A., 1991, Origin and development of the Gulf of Mexico basin, *in* A. Salvador, ed., The geology of North America, v. J: The Gulf of Mexico Basin: Geological Society of America, Boulder, Colorado, p. 389-444.

Sartain, S. M., and B. E. See, 1997, The South Georgia Basin: An integration of Landsat, gravity, magnetics and seismic data to delineate basement structure and rift basin geometry: Gulf Coast Association of Geological Societies Transactions, v. 47, p. 493-498.

Schuster, D. C., 1995, Deformation of allochthonous salt and evolution of related salt-structural systems, Eastern Louisiana Gulf Coast, *in* M. P. A. Jackson, D. G. Roberts, and S. Snelson, eds., Salt tectonics: A global perspective: American Association of Petroleum Geologists Memoir 65, Tulsa, Oklahoma, p. 177-198.

Scott, T. M., K. M. Campbell, F. R. Rupert, J. D. Arthur, T. M. Missimer, J. M. Lloyd, J. W. Yon, and J. G. Duncan, 2001, Geologic map of the state of Florida: Florida Geological Survey, Tallahassee, scale 1:750,000.

Seglund, J. A., 1974, Collapse-fault systems of Louisiana Gulf Coast: American Association of Petroleum Geologists Bulletin, v. 58, p. 2389-2397.

Shinkle, K., and R. K. Dokka, 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.

Simmons, G. R., 1992, The Regional distribution of salt in the northwestern Gulf of Mexico: Styles of emplacement and implications for early tectonic history: Ph.D. dissertation, Texas A&M University, College Station, 180 p.

Smith, D. L., 1983, Basement model for the panhandle of Florida: Gulf Coast Association of Geological Societies Transactions, v. 33, p. 203-208.

Snead, J. I., and R. P. McCulloh, 1984, Geologic map of Louisiana: Louisiana Geological Survey, Baton Rouge, scale 1:500,000.

Stephens, B. P., 2001, Basement controls on hydrocarbon systems, depositional pathways, and exploration plays beyond the Sigsbee Escarpment in the central Gulf of Mexico: Proceedings of the 21st Annual Gulf Coast Section of the Society of Economic Paleontologists and Mineralogists Foundation Bob F. Perkins Research Conference, Houston, Texas, p. 129-158.

Story, C., 1998, Norphlet geology and 3-D geophysics of Fairway Field Mobile Bay, Alabama, *in* 3-D seismic case histories from the Gulf Coast Basin: Gulf Coast Association of Geological Societies Special Publication, Austin, Texas, p. 123-129.

Sykes, L. R., 1978, Intraplate seismicity: Reactivation of preexisting zones of weakness, alkaline magmatism, and other tectonism post dating continental fragmentation: Reviews of Geophysics and Space Physics, v. 16, p. 621-688.

Thomas, W. A., 1988, Early Mesozoic faults of the northern Gulf Coastal Plain in the context of opening of the Atlantic Ocean, *in* W. Manspeizer, ed., Triassic-Jurassic rifting (developments in geotectonics 22): Elsevier Scientific Publishing Co., New York, p. 463-476.

Thomas, W. A., 1991, The Appalachian-Ouachita rifted margin of southeastern North America: Geological Society of America Bulletin, v. 103, p. 415-431.

Tornqvist, T. E., S. J. Blick, K. van der Borg, and A. F. M. deJong, 2006, How stable is the Mississippi Delta?: Geology, v. 34, no. 8, p. 697-700.

Trudgill, B. D., M. G. Rowan, C. J. Fiduk, P. Weimer, P. E. Gale, B. E. Korn, R. L. Phair, W. T. Gafford, G. R. Roberts, and S. W. Dobbs, 1999, The Perdido Fold Belt, northwestern deep Gulf of Mexico, part 1: Structural geometry, evolution and regional implications: American Association of Petroleum Geologists Bulletin, v. 83, p. 88-113.

Turner, J. R., 2001, Evidence for strike-slip faulting in the Smackover Formation of northeast Texas and south Arkansas and its geological implications: Gulf Coast Association of Geological Societies Transactions, v. 51, p. 339-347.

Watkins, J. S., G. MacRae, and G. R. Simmons, 1995, Bipolar simple-shear rifting responsible for distribution of mega-salt basins in Gulf of Mexico, *in* C. J. Travis, H. Harrison, M. R. Hudec, B. C. Vendeville, F. J. Peel, and B. F. Perkins, eds., Salt, sediment, and hydrocarbons: Proceedings of the 16th Annual Gulf Coast Section of the Society of Economic Paleontologists and Mineralogists Foundation Bob F. Perkins Research Conference, Houston, Texas, p. 297-305.

Watkins, J. S., W. R. Bryant, R. T. Buffler, and staff and students of the Gulf of Mexico Structural and Stratigraphic Synthesis Project (GMS3), 1996, Structural framework map of the northern Gulf of Mexico, *in* J. O. Jones, and R. L. Freed, eds., Structural framework of the northern Gulf of Mexico: Gulf Coast Association of Geological Societies Special Publication, Austin, Texas, p. 95-98.

Wernicke, B., 1985, Uniform-sense normal simple shear of the continental lithosphere: Canadian Journal of Earth Sciences, v. 22, p. 108-125.

Wilson, G. V., 1975, Early differential subsidence and configuration of the northern Gulf Coast Basin in southwest Alabama and northwest Florida: Gulf Coast Association of Geological Societies Transactions, v. 25, p. 196-206.