# PS Basement Controls on Subsurface Geologic Patterns and Near-Surface Geology across the Northern Gulf of Mexico: A Deeper Perspective on Coastal Louisiana*

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## Abstract

Of all the processes that have contributed to the depositional architecture and ongoing subsidence of the Mississippi Delta, tectonic subsidence is probably the least understood. Localized vertical movements in southeast Louisiana are, in part, manifestations of ordered, basin-scale structural patterns that have exercised a profound level of control on all subsequent geological processes including recent coastal environments and ongoing subsidence patterns.

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. Observations from a diverse collection of studies are used to document a framework of fourteen major transfer-fault delimited structural corridors, 25 to 40 miles in width, thought to be 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 the overlying Tertiary cover.

This study incorporates a seismic traverse from a recent proprietary offshore 3-D survey which images offsets in the basement surface corresponding to the transfer faults that trend into southeast Louisiana. Offshore examples illustrate the structural patterns resulting from the interaction of the basement structure, salt systems, and Tertiary faults and can be used as analogs for the subsurface of South Louisiana.

Several examples along the northern Gulf Coast from Florida to southwest Louisiana are used to examine the apparent relationship between the transfer-fault delimited structural corridors and coastal geomorphology. Vertical movements related to these subsurface geologic patterns appear to influence the spatial arrangement of Holocene coastal environments.

Recognition of the ordered arrangement of basement structures, faults and salt systems may provide new insights into the depositional architecture of the Mississippi Delta. Subsurface geologic templates can serve as useful analogs for understanding subsidence patterns and the emerging body of detailed subsidence measurements. Identification of areas of relative geologic stability may influence coastal restoration efforts.

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**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. Observations from a diverse collection of studies are used to document a framework of fourteen major transfer-fault delimited structural corridors, 25 to 40 miles in width, thought to be 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 the overlying Tertiary cover.**

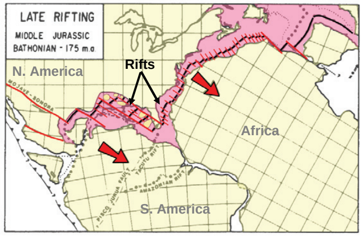
**This study incorporates a seismic traverse from a recent proprietary offshore 3-D survey which images offsets in the basement surface corresponding to the transfer faults that trend into southeast Louisiana. Offshore examples illustrate the structural patterns resulting from the interaction of the basement structure, salt systems, and Tertiary faults and can be used as analogs for the subsurface of South Louisiana.**

**Several examples along the northern Gulf Coast from Florida to southwest Louisiana are used to examine the apparent relationship between the transfer-fault delimited structural corridors and coastal geomorphology. Vertical movements related to these subsurface geologic patterns appear to influence the spatial arrangement of Holocene coastal environments.**

**Recognition of the ordered arrangement of basement structures, faults and salt systems may provide new insights into the depositional architecture of the Mississippi Delta. Subsurface geologic templates can serve as useful analogs for understanding subsidence patterns and the emerging body of detailed subsidence measurements. Identification of areas of relative geologic stability may influence coastal restoration efforts.**

# TECTONIC HISTORY AND BASEMENT FABRIC – GENERAL CONCEPTS AND MODELS

## 1

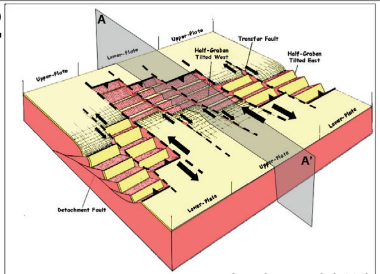



after Klitgord & Schouten (1986)

The geologic story of coastal Louisiana begins with the Triassic-Jurassic breakup of the supercontinent Pangea and the opening of the North Atlantic and Gulf of Mexico.

The structural “grain” of the basement and overlying Mesozoic and Tertiary sediments is, to a large degree inherited from this early rift architecture.

## 2

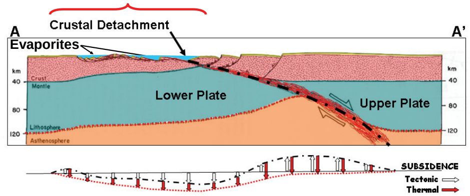



after Lister et al. (1986)

Here is a simple block model of a rifting continental margin. Breakup is characterized by as series of rift basins above alternately dipping crustal detachments which segment the opposing sides into conjugate margins with alternating upper plate and lower plate boundaries as described by Wernicke (1985)

## 3

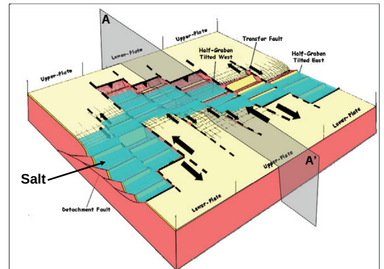
HYPOTHETICAL NORMAL SIMPLE SHEAR OF THE ENTIRE LITHOSPHERE after Wernicke (1985)




This model of a rifting continental margin after Wernicke (1985) approximates the shaded profile A - A’ on the block models to the left and right. The crust and mantle are thinned by a dipping crustal detachment fault. The greatest crustal thinning is above the lower plate and will become the point of continental rupture. The mantle is thinned above the upper plate.

The net result is that the lower plate undergoes greater subsidence than the upper plate. Thus rift valleys are structurally low and become the locus of evaporite deposition.

## 4

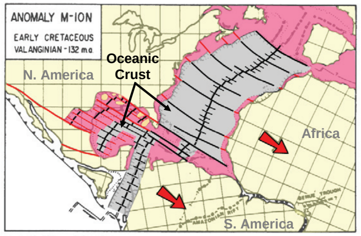



after Lister et al. (1986)

Rift valleys are segmented by transfer faults which form between structural corridors with varying degrees of tectonic extension and exhibit alternating left-lateral and right-lateral offsets.

This early rift architecture probably controlled the distribution and thickness of autochthonous salt (blue).

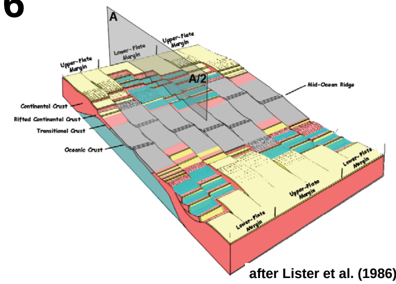
## 5




after Klitgord & Schouten (1986)

Eventually a spreading center formed along the axis of the rift valley and oceanic crust was generated in the wake of the “passive” continental margins.

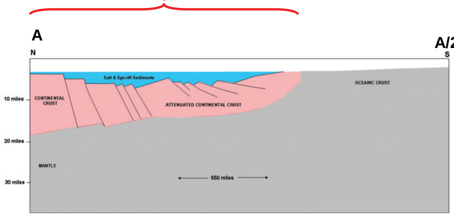
## 6




after Lister et al. (1986)

Our block model now shows a band of oceanic crust between the opposing conjugate margins. The transfer faults that were established in the rift phase merge in some fashion with oceanic transform faults along an irregular continent–ocean boundary.

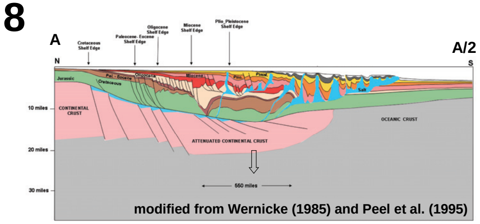
## 7




Late Jurassic

The cross section above approximates the shaded traverse A – A/2 on the block model to the left and might reflect the configuration of the Gulf of Mexico continental margin in the Late Jurassic. Oceanic crust had formed outboard of the rifted continental margin. Salt and syn-rift sediments were deposited across an irregular terrain of attenuated continental crust. (Basement thickness not to scale)

## 8




modified from Wernicke (1985) and Peel et al. (1995)

Present Day

This figure is an artistic combination of a restored Gulf of Mexico seismic profile (modified from Peel et al 1995) and a basement layer modeled after the simple shear model of Wernicke (1985). (basement thickness not to scale)

Sedimentary loading associated with the progradation of successive Mesozoic and Cenozoic depositional sequences has mobilized the salt into allochthonous bodies and caused the basement to subside.

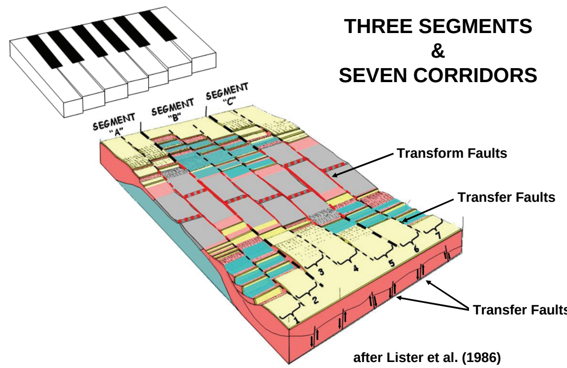
## 9

In the simplified model at right, the basement is a complex mosaic of variably attenuated continental crust, intruded volcanics, and oceanic crust. The continental margin is partitioned into three segments (A-C) and seven corridors. The segments correspond to alternating upper-plate and lower plate margins based on the simple shear model of Wernicke (1985). Among the most fundamental, but overlooked elements of this fabric are the transfer fault zones. Transfer faults segment the continental margin into corridors (1-7) thought to be characterized by varying degrees of extension, crustal attenuation, and tectonic subsidence.

It is suggested that the patterns of subsidence across the northern Gulf Coast are controlled by a similar basement fabric.

Transfer-fault delimited structural corridors should be expected to have a differential response to sedimentary loading, perhaps behaving like articulated piano keys as shown at right. Because the basement structure also controls the distribution of autochthonous salt, the arrangement of allochthonous salt systems and associated faults and salt withdrawal basins will also reflect this fabric.

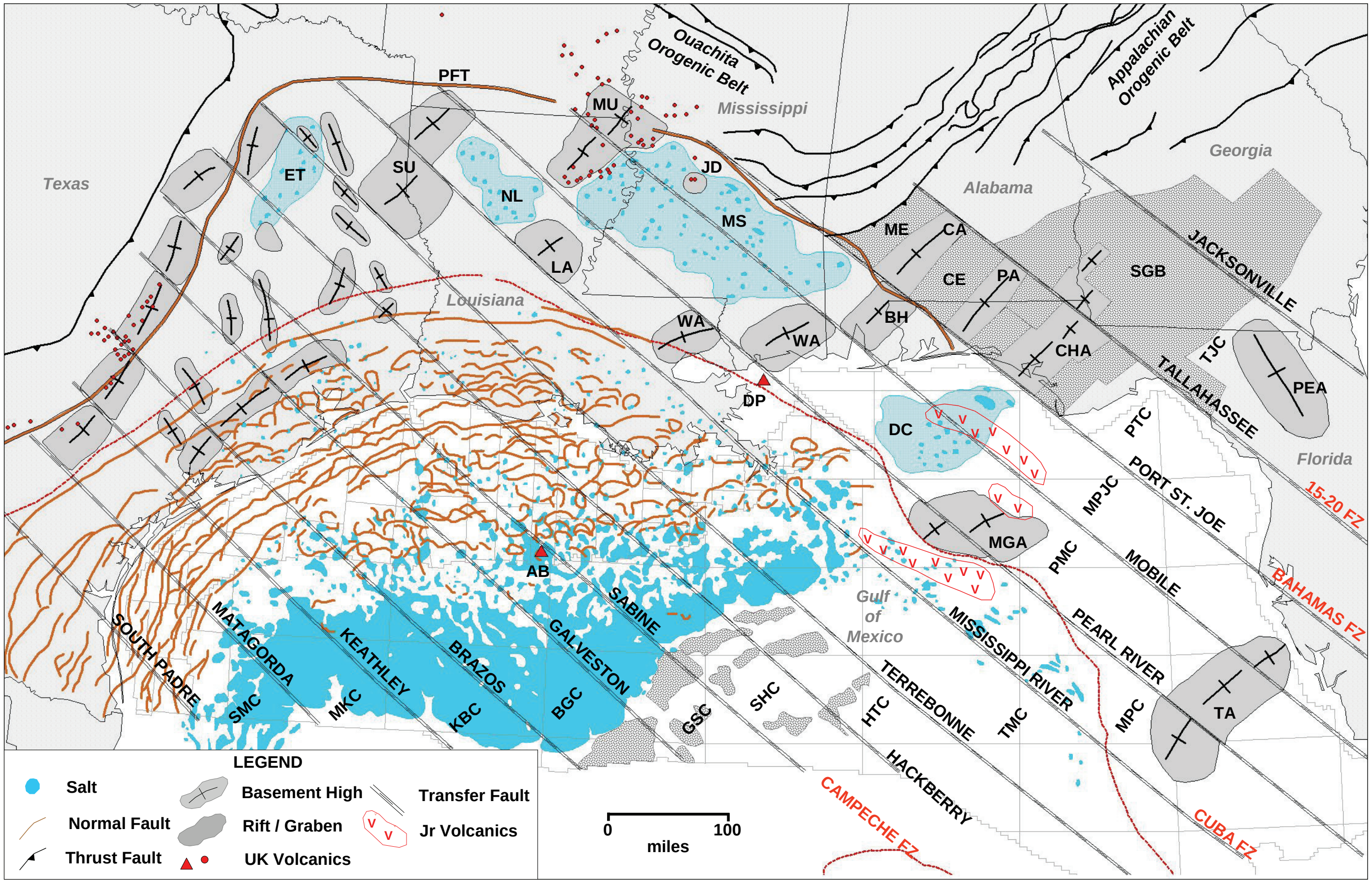
THREE SEGMENTS & SEVEN CORRIDORS




after Lister et al. (1986)

# MAJOR TRANSFER FAULT ZONES OF THE NORTHERN GULF OF MEXICO

## Selected Structural Features of the Northern Gulf of Mexico Basin

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The arrangement of structural elements across the northern Gulf of Mexico suggests the continental margin is segmented by fourteen "major" northwest-southeast trending transfer fault zones related to Mesozoic rifting. The map to the left shows the generalized transfer faults trends identified in this study, as well as the prominent structural features of the intervening structural corridors.

Major structural arches, embayments, rifts, and salt basins are all generally arranged within structural corridors delimited by the 14 major transfer faults. These corridors are thought to be characterized by varying degrees of extension, crustal attenuation and tectonic subsidence. 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. The corridors are more finely segmented by minor transfer fault trends (not shown) which also exhibit regular and predictable lateral and vertical offsets that are reflected in overlying Tertiary cover.

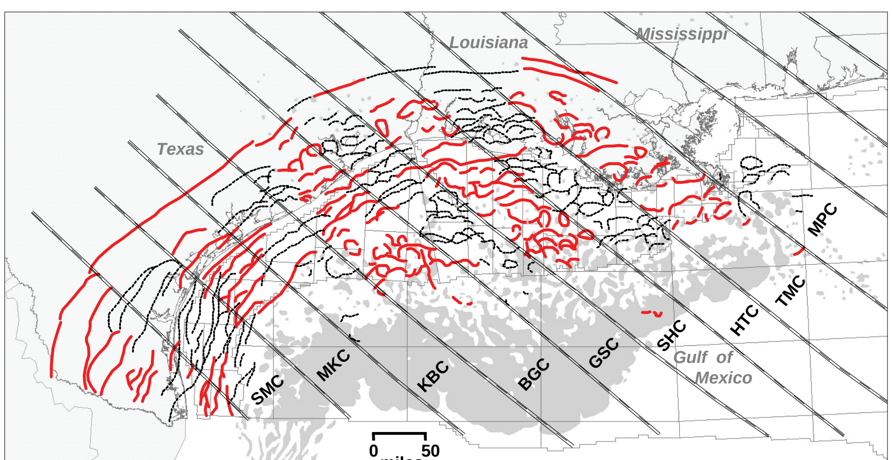
The transfer fault zones shown here have been generalized from numerous observations in the literature. There is considerable local variation in their azimuth. For a complete bibliography, the reader is referred to Stephens (2009).

The location of the continent-ocean boundary in the deepwater Gulf of Mexico and the nature and geometry of the crust, particularly in the areas beneath and beyond the Sigsbee Salt Canopy, remain unresolved. For alternative views see Imbert and Philippe (2005) or Pindell & Kennan (2009).

MAP REFERENCES & KEY:

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). Structural arches include the Sabine Uplift (SU), Monroe Uplift (MU), LaSalle Arch (LA), Jackson Dome (JD), Wiggins Arch (WA), Baldwin High (BH), Conecuh Arch (CA), Pensacola Arch (PA), Chattahoochee Arch (CHA), Peninsular Arch (PEA), Middle Ground Arch (MGA) and Tampa Arch (TA). Grabens include the Manilla Embayment (ME), Conecuh Embayment (CE), and South Georgia Basin (SGB). Salt Basins (light blue) include East Texas (ET), North Louisiana (NL), Mississippi (MS) and Desoto Canyon (DC). Also noted are the Gulf Coast Peripheral Fault Trend (PFT) and the Lower Cretaceous shelf edge (LK).

## Segmentation of Gulf Coast Tertiary Faults within Transfer-Fault Delimited Structural Corridors

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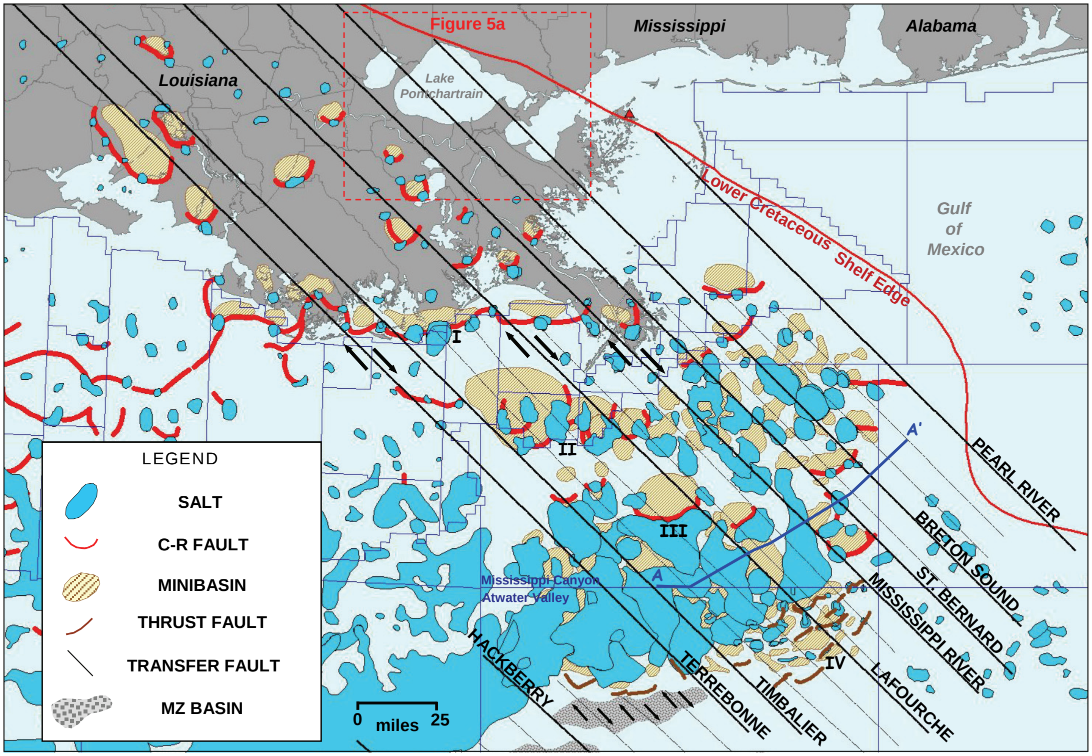
The trend of each of the major transfer faults traversing the Texas and Louisiana coasts can be discerned from the segmentation of Tertiary fault trends. The map to the left is an unconventional presentation of the generalized "first-order" Tertiary fault trends of Diegel et al. (1995). Individual fault segments have been colored according to the corridor that contains their approximate center point. Alternating red and black colors were chosen for visual effect. 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 SOUTHEAST LOUISIANA AND ADJACENT WATERS

## Selected Structural Features of Southeastern Louisiana

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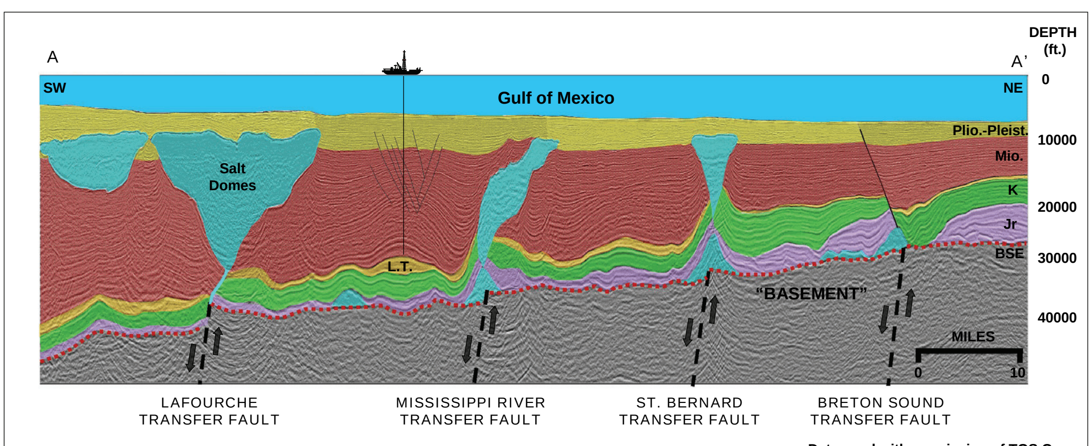
The map to the left illustrates selected structural elements of southeast Louisiana and adjacent waters. Allochthonous salt (dark blue) in the Mississippi Canyon and Atwater Valley Areas is after Stephens (2001, Fig. 8). Other offshore salt locations are after Simmons (1992) and Muehlberger (1992). Onshore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

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 (IV) 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. 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 analogs.

## Seismic Evidence of Transfer Faults: 3-D Seismic Profile – Southeastern Mississippi Canyon Area

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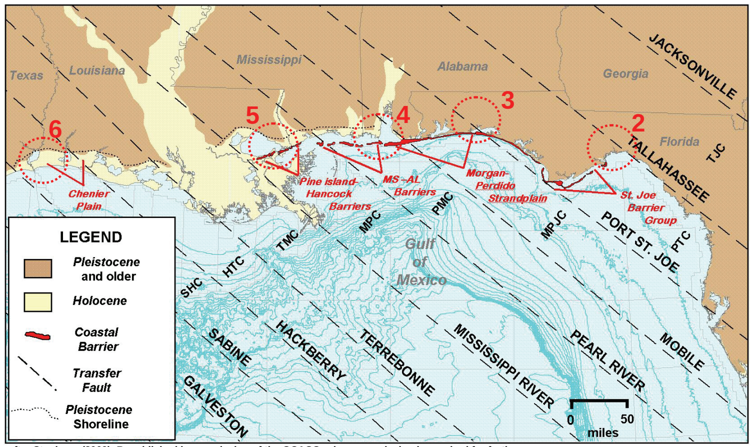
The seismic profile to the left was extracted from a recently acquired depth-migrated 3-D seismic survey in the Mississippi Canyon area and is presented with permission of TGS Corp. (see map above for line location). The basement surface beneath the salt canopy is thought to be equivalent to the “base of salt or equivalent” (BSE) surface of MacRae and Watkins (1996) and is stepped along the inferred transfer fault trends. 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 (LT) 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 ten miles.

# 1 EXPRESSION OF TRANSFER FAULTS IN COASTAL GEOMORPHOLOGY

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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 structural corridors. 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 pattern is more evident in southern Louisiana if the early Holocene shoreline, as approximated by the Pleistocene outcrop, is considered. 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 figures 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.

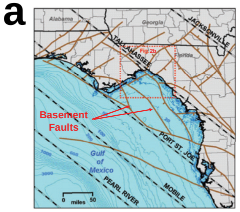
## 2 The Tallahassee Transfer Fault and the Wakulla River

Figure 2a shows the basement fault trends of the Big Bend Area of Florida (after Barnett, 1975) and the major transfer fault zones of this study. The prominent southwest-facing shorelines and bathymetric inflections showing deepening to the southwest are generally aligned with the interpreted transfer fault zones.

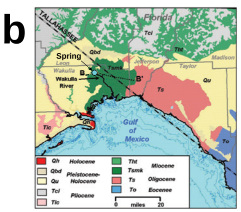
Figure 2b is a Geologic map of the Woodville Karst Plain and the Wakulla River area. The pink and green areas are Oligocene and Miocene limestones that are relatively high-standing above the up-thrown side of the Tallahassee Transfer Fault. Wakulla Springs, which is the largest first-magnitude spring in Florida, emerges here and flows southeast, parallel to the trend of the Tallahassee Transfer Fault.

Figure 2c is a cross section through Wakulla Springs based on three shallow boreholes reinterpreted after Rupert (2001). Deepening of the Oligocene Suwanee Limestone and thickening of the Miocene St. Marks Formation suggest down-to-the-southwest motion on the Tallahassee Transfer Fault during the Tertiary. It is suggested that the fracture systems feeding the spring and the course of the river are controlled by this deep structural trend.

a




b

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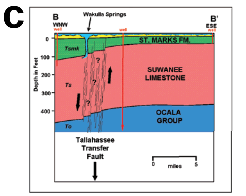
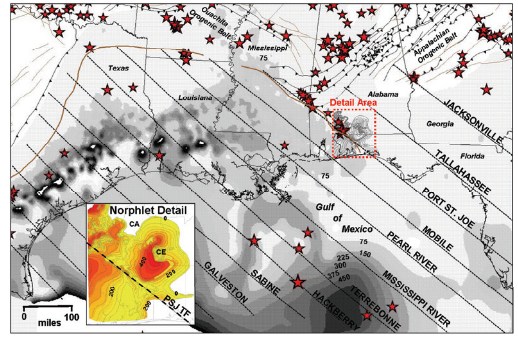



Figures 2 a, b, & c after Stephens (2009), Republished by permission of the GCAGS, whose permission is required for further use.

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

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The Port St. Joe Transfer Fault is perhaps the best place to demonstrate recurring movement along transfer faults throughout the geologic history of the basin.

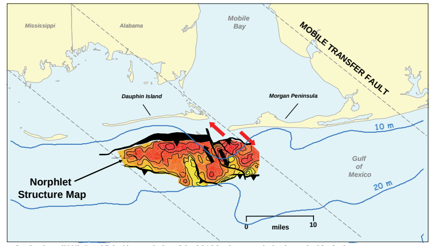
The inset colorfill map is an isopach of the Jurassic (~160 mya) Norphlet Formation in the Conecuh Embayment area (after Prather, 1992). Reds are thick and yellows are thin. The Norphlet is over 400 feet thick in the Conecuh Embayment (CE), but is juxtaposed across the Port St. Joe Transfer Fault to a Norphlet thin. The Norphlet is thin to absent over the Conecuh Arch (CA) but is juxtaposed to a Norphlet thick across the transfer fault. The transfer fault is evident in the early horst and graben topography that controlled the depositional thickness of the Norphlet Sandstone.

The gray-scale background map is a Lower Wilcox Accumulation Rate Map for the Lower Tertiary from approximately 55 to 58 million years ago (after Fillon et al., 2005). The accumulation rate increases from white to dark gray. Note the linear transition to 75 ft/my that aligns with the Port St. Joe Transfer Fault. This pattern suggests down-to-the-southwest motion on the Port St. Joe Transfer Fault during Lower Tertiary time.

The red stars are modern earthquake epicenters for the period from 1973-2000 (USGS, Mueller et al., 1997). Note the 12 earthquakes aligned with the Port St. Joe Transfer Fault through Mississippi and southwest Alabama. These earthquakes had magnitudes of 3 to 4.9 with calculated depths between 16,400 ft. and 33,000 ft. which would be within the “basement”.

Note that all three of these datasets are a aligned with a prominent northwest-southeast trending shoreline segment. Clearly, the Port St. Joe Transfer Fault was active in the Mesozoic, active in the Lower Tertiary, and continues to be active today.

## 4 Jurassic Structure and the Mobile Bay Area

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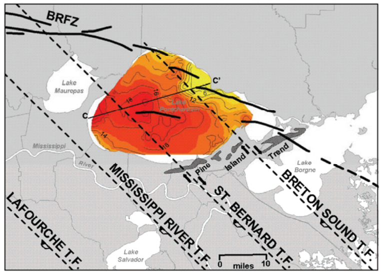
The trace of the Mobile Transfer Fault is thought to trend along the eastern shore of Mobile Bay. The apparent right-lateral offset between Dauphin Island and the Morgan Peninsula it thought to reflect down-to-the-southwest motion on an un-named minor transfer fault. The same right-lateral offset is mimicked by the subsurface fault pattern of the Jurassic Norphlet Formation at a depth of approximately 21,000' (after Story, 1998).

The apparent lateral offset of the barrier islands does not reflect ongoing strike-slip motion on basement faults, but rather a lateral translation of the shoreface because of down-to-the-southwest vertical motion on the transfer fault. This down-to-the-southwest movement is also manifested in the right-lateral excursions of the 10m and 20m bathymetric contours.

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

a

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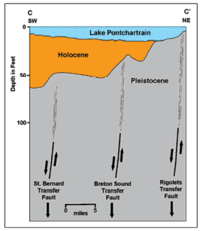


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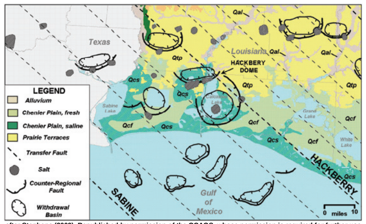
Near-surface structural and depositional features of the Lake Pontchartrain Basin appear to be influenced by down-to-the-southwest vertical motion on the Breton Sound, St. Bernard, and Mississippi River transfer faults.

The color-fill map (Figure 5a) of the depth to the top of the Pleistocene (after Kidinger et al., 1997) steps down from northeast to southwest in good correspondence to the underlying transfer-delimited corridors (red areas are deepest and yellow areas are shallowest). It is suggested that the stepped profile of the Pleistocene surface on the geologic cross-section (Figure 5b, after Kidinger et al., 1997) is an indication of down-to-the-southwest movement on the underlying transfer faults.

The Pine Island Barrier Trend extended westward from an erosional headland in southwestern Mississippi to enclose Lake Pontchartrain during the early Holocene. Note that the Pine Island trend is segmented with apparent right lateral offsets that are generally aligned with the underlying transfer fault zones. It appears that down-to-the-southwest vertical motion on the transfer fault zones influenced the depositional topography, causing lateral translation of the shoreface environment and barrier islands. This is analogous to the previous example from Dauphin Island, Alabama. The location and size of other wetland lakes, as well as the course of the lower Mississippi River appear to correspond to the underlying transfer-delimited structural corridors.

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

a

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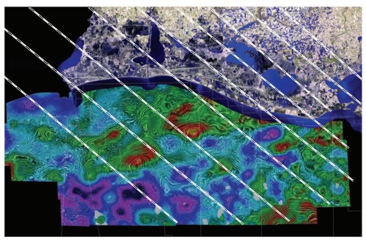
This Geologic Map of southwest Louisiana (after Snead & McCulloh, 1984) has been modified with selected subsurface geologic features including counter-regional faults after Diegel et al. (1995), salt after Lopez (1995), and salt withdrawal basins after Seglund (1974). Coastal environments include freshwater marsh in light green and salt marshes in bluish-green. Note that the saltwater marshes and lakes are underlain by salt withdrawal basins. Freshwater marshes are situated above subsurface structural highs on the up-thrown side of counter-regional faults. The Hackberry Transfer Fault passes just to the east of Hackberry dome and its associated counter-regional fault system and salt withdrawal basin. Note that the width of coastal lakes coincides with the width of the underlying transfer-delimited corridors. Coastal environments and the coastline itself are regularly offset in a right lateral sense across the transfer faults.

b



The north half of Figure 6b is a satellite image of southwest Louisiana showing coastal wetlands and lakes. The southern half of the image is a horizontal slice from a regional 3-D seismic survey at a depth of approximately 11,000 feet (Fairfield advertisement – AAPG Explorer, June 2005). The concentric outlines of dipping strata within the offshore salt withdrawal minibasins (red) are readily apparent. In between the withdrawal basins are structural highs which are relatively stable and would be expected to undergo a lesser degree of subsidence. Note the similarity of pattern and scale between the offshore subsurface minibasins and the coastal lakes.

# SUBSURFACE STRUCTURAL MODEL & ASSOCIATED SUBSIDENCE PATTERNS FOR SOUTHEAST LOUISIANA AND ADJACENT WATERS

**Block diagrams A-D (right) depict a generalized structural model for the area of southeast Louisiana and adjacent waters shown on the map below. The model is highly vertically exaggerated and relative scales are inaccurate.**

**Figure A is a schematic representation of the underlying basement structure, depicted as a series of horsts and graben (rifts) partitioned into six structural corridors by right-lateral transfer faults. Attenuation of the continental crust is thought to increase from east to west, such that each successive corridor is thinner and will undergo greater isostatic adjustment when loaded by sediments. Within each corridor, rifts are presumed to be underlain by thinner crust than the intervening horsts.**

**Figure B depicts the original distribution of autochthonous salt (blue), which was probably a direct reflection of the rift architecture. Salt abundance and thickness increases from east to west and is highly variable.**

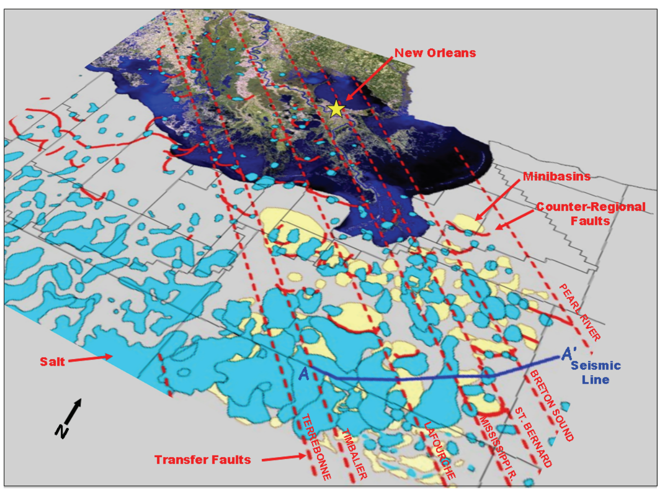
**Figure C is a simplified illustration of the allochthonous salt systems and associated faulting resulting from sedimentary loading and salt mobilization. Autochthonous salt has been largely evacuated from the rift basins to form a variety of allochthonous salt bodies (blue). Counter-regional (generally north-dipping) faults and salt welds (red) are the feeders for south-leaning salt diapirs. Down-to-the-basin growth faults (brown) form in response to the accommodation space created by the evacuating salt. The overall result is a series of salt withdrawal "minibasins" arranged within transfer-fault delimited structural corridors in similar fashion to the underlying rift architecture.**

**Figure D illustrates the expected patterns of relative subsidence resulting from this subsurface structural configuration. Basement-related tectonic subsidence increases from east to west across successive structural corridors. Within corridors, the areas underlain by minibasins (red) are the products of the greatest overall subsidence because of the combined effects of thin crust, salt evacuation, thicker sediment load, and more compaction. Intervening structural highs experience less overall subsidence (orange-yellow) because they are underlain by thicker crust and a relatively thin sedimentary column and thus undergo less tectonic subsidence and compaction. There may be localized uplift above some salt domes. Down-to-the-basin and counter-regional faults separate more rapidly subsiding minibasins from relatively stable areas. The arrangement of right-stepping structural highs and more rapidly subsiding minibasins compares favorably with the patterns of coastal barriers and lakes in south Louisiana as discussed in previous sections.**

**The subsidence patterns described above may also approximate the relative topography of the late Pleistocene surface onto which the Holocene Mississippi Delta was deposited. Incised valleys may have preferentially followed major transfer fault zones, which would have been down-to-the-southwest topographic and bathymetric inflections. The Timbalier Channel and the Mississippi Canyon (not shown), which are offshore extensions of the Wisconsinian incised valley of the Mississippi River, appear to follow the trace of the Terrebonne Transfer Fault. The Mississippi River in southeast Louisiana is aligned with the Mississippi River Transfer Fault.The sub-lobes of the Mississippi Delta may have gravitated toward the subsiding minibasins.**

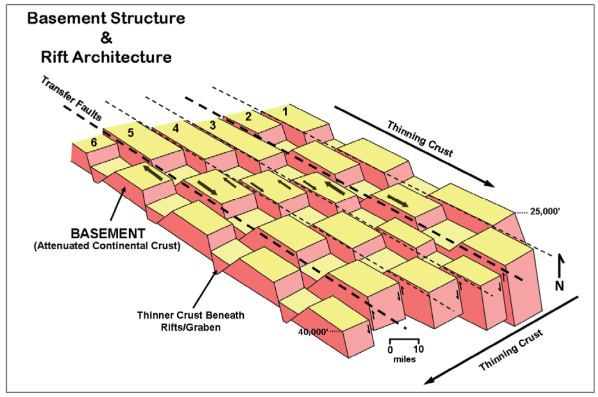
**The examples presented demonstrate a clear relationship between coastal depositional systems and subsurface structural patterns. Subsidence rates vary continuously in space and time and may change abruptly, but predictably, across discrete structural boundaries. An understanding of the structural order 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.**

**Recognition of the ordered arrangement of basement structures, faults and salt systems may provide new insights into the depositional architecture of the Mississippi Delta. Subsurface geologic templates can serve as useful analogs for understanding subsidence patterns and the emerging body of detailed subsidence measurements. Identification of areas of relative geologic stability may influence coastal restoration and protection efforts.**

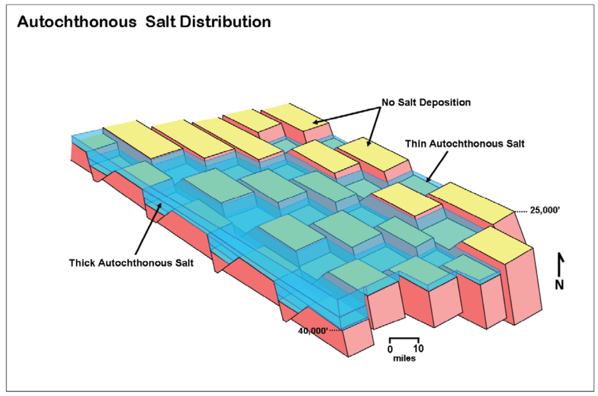



**Perspective view of southeast Louisiana showing transfer fault zones (red dashed lines), counter-regional faults (solid red), allochthonous salt (light blue) and salt withdrawal Minibasins (cream)**

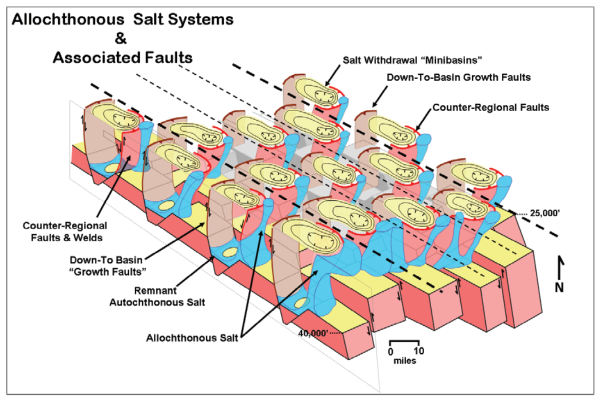
**A**



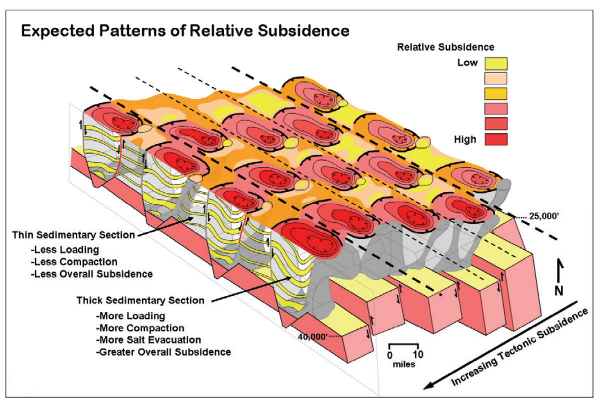

**B**




**C**




**D**



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