Cenozoic Structural Evolution and Tectono-Stratigraphic Framework of the Northern Gulf Coast Continental Margin

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Abstract

The Cenozoic structural evolution of the northern Gulf of Mexico Basin is controlled by progradation over deforming, largely allochthonous salt structures derived from an underlying autochthonous Jurassic salt. The wide variety of structural styles is due to a combination of (1) original distribution of Jurassic and Mesozoic salt structures, (2) different slope depositional environments during the Cenozoic, and (3) varying degrees of salt withdrawal from allochthonous salt sheets. Tectono-stratigraphic provinces describe regions of contrasting structural styles and ages. Provinces include (1) a contractional foldbelt province, (2) a tabular salt-minibasin province, (3) a Pliocene–Pleistocene detachment province, (4) a salt dome–minibasin province, (5) an Oligocene–Miocene detachment province, (6) a lower Oligocene–Vicksburg detachment province, (7) an upper Eocene detachment province, and (8) the Wilcox growth fault province of Paleocene–Eocene age.

Within several tectono-stratigraphic provinces, shale-based detachment systems, dominated by lateral extension, and allochthonous salt-based detachment systems, dominated by subsidence, can be distinguished by geometry, palinspastic reconstructions, and subsidence analysis. Many shale-based detachments are linked downdip to deeper salt-based detachments. Large extensions above detachments are typically balanced by salt withdrawal.

Salt-withdrawal minibasins with flanking salt bodies occur as both isolated structural systems and components of salt-based detachment systems. During progradation, progressive salt withdrawal from tabular salt bodies on the slope formed salt-bounded minibasins which, on the shelf, evolved into minibasins bounded by arcuate growth faults and remnant salt bodies. Associated secondary salt bodies above allochthonous salt evolved from pillows, ridges, and massifs to leaning domes and steep-sided stocks.

Allochthonous salt tongues spread from inclined salt bodies that appear as feeder faults when collapsed. Coalesced salt tongues from multiple feeders formed canopies, which provided subsidence potential for further cycles of salt withdrawal. The Sigsbee escarpment is the bathymetric expression of salt flows that have overridden the abyssal plain tens of kilometers since the Paleogene. The distribution and palinspastic reconstruction of Oligocene–Miocene salt-based detachments and minibasins suggest that a Paleogene salt canopy, covering large areas of the present onshore and shelf, may have extended as far as the Sigsbee salt mass.
INTRODUCTION

New concepts, seismic data, and hydrocarbon exploration in deeper water led to a revolution in the understanding of Cenozoic tectonics of the northern Gulf of Mexico continental margin in the 1980s. In particular, recognition of allochthonous salt bodies combined with quantitative palinspastic reconstruction changed the prevailing view of the northern Gulf of Mexico Basin from a passive margin with vertical rooted salt stocks and masses with intervening steep growth faults, to a complex mosaic of diachronous detachment fault systems and variously deformed allochthonous salt sheets.

The modern history of Gulf Coast structural studies as expressed in published literature began with the recognition of the Sigsbee escarpment as a salt overthrust at the toe of the slope (Amery, 1969). The profound significance of this observation was first considered by Humphris (1978), who proposed large-scale basinward flow of salt and subsequent withdrawal by downbuilding of slope sediments deposited on top of the moving salt mass. In the same volume (Bouma et al., 1978), which represents a turning point, Martin (1978) reviewed the stratigraphic and structural framework of the Gulf Coast with the contemporary understanding of margin progradation over autochthonous Louann salt with attendant rooted vertical stocks and steep growth faults apparently related to flow of deeply buried shale and salt masses. An allochthonous salt canopy in Iran (Jackson and Cornelius, 1985) was recognized at a time when the petroleum industry was interpreting allochthonous salt wings and sheets on seismic reflection profiles of the outer shelf and slope, offshore Louisiana.

In 1989, many of these interpretations and concepts of Gulf Coast salt tectonics were presented, including several contributions from industry (GCS SEPM 10th Annual Conference in 1989). In the same year, Worrall and Snelson (1989) used quantitative palinspastic reconstructions to show how Humphris’ (1978) model for basinward salt flow applied to large-scale growth fault systems of the Texas shelf, and Jackson and Cramez (1989) discussed the recognition of salt welds on allochthonous and autochthonous salt. Sumner et al. (1990) described the three-dimensional structure of minibasins developed by Pliocene–Pleistocene evacuation of allochthonous salt derived from counter-regional (northward-dipping) feeders on the Louisiana outer shelf. Diegel and Cook (1990) and Diegel and Schuster (1990) used structural reconstructions incorporating subsidence analysis to constrain the geometry and thickness of evacuated allochthonous salt in the onshore and shelf of Louisiana even in areas where shallow salt bodies are no longer present. Studies of Gulf Coast salt tectonics since then have focused in areas of relatively recent hydrocarbon exploration efforts in the outer shelf and upper slope (e.g., Huber, 1989; West, 1989; Wu et al., 1990; Seni, 1992; Rowan et al., 1994). In this chapter, we show that the new concepts are equally applicable to coastal and inner shelf areas.

Figure 1—Structural summary map of the northern Gulf of Mexico Basin. Black areas are shallow salt bodies. Tick marks are on the downthrown side of major growth faults: black = seaward dipping; red = landward dipping (counter-regional); blue = thrust faults.
Typically, reviews of Gulf Coast salt structures (e.g., Martin, 1978; Worrall and Snelson, 1989) begin with a description of the low-relief structures at the updip basin margin, proceed to the high-relief salt stocks of coastal Louisiana, and then describe the more complex leaning stocks and allochthonous salt wings and sheets of the outer shelf and slope. That approach is logical based on the evolutionary deformation sequences described by Trusheim (1960) and Seni and Jackson (1983) for progradation across autochthonous salt, which thickens into the axis of relatively simple cratonic basins. However, the scale and complexity of the Gulf Coast continental margin are more clearly understood by proceeding in the opposite direction, from the abyssal plain to the coastal areas. This inverse approach has the advantage of using shallow and well-imaged structures on the modern slope as analogs for the early history of structures that are now more fully developed and deeply buried beneath neritic and continental sections. This approach also allows us to revisit the less recently studied but still actively explored areas of the inner shelf and onshore Gulf Coast and to provide a consistent and comprehensive tectono-stratigraphic framework of the Gulf Coast from a modern perspective.

In this chapter, tectono-stratigraphic provinces are defined and described. We analyze the evolution and origin of these provinces with the aid of selected palinspastic reconstructions of two-dimensional cross sections, deep-structure maps, and subsidence analysis. The similarity of structures in the more basinward provinces to reconstructed structures farther landward provides additional analogs for determining the early history of the older structures. The relationships between adjacent provinces are discussed when appropriate. Finally, alternative palinspastic reconstructions of a transect from the Cretaceous margin to the modern abyssal plain in western Louisiana are presented to address the overall Cenozoic structural evolution of the basin. The Chapter Appendix describes the reconstruction and subsidence analysis methodologies and the inferred salt budget and magnitude of salt dissolution during the Cenozoic.

TECTONO-STRATIGRAPHIC PROVINCES

Overview

Construction of a regional framework of Gulf Coast structure entails several difficulties. These include the great three-dimensional complexity of the structures, the large variability along strike as well as landward and basinward, and the uncertainty of deep structures in many areas that are not well imaged by contemporary seismic methods. Only the first-order structures are adequately reflected on a structural summary map (Figure 1), which does little to reflect the deep structure and genetic relationships.

A tectono-stratigraphic province map (Figures 2, 3) illustrates eight distinct regions defined by contiguous
areas of similar structural style. The eight nongenetic provinces discussed here are (1) a contractional foldbelt province at the toe of slope, (2) a tabular salt–minibasin province on the slope, (3) a Pliocene–Pleistocene detachment province on the outer shelf, (4) a salt dome–minibasin province, (5) an Oligocene–Miocene detachment province onshore and on the shelf, (6) an Oligocene Vicksburg detachment province onshore Texas, (7) an upper Eocene detachment province, and (8) the Wilcox growth fault province of Paleocene–Eocene age.

The province map is necessarily a poor representation of the structural complexity at multiple levels, and particularly on the slope, many reasonable subdivisions are possible to reflect some of the significant changes in structural style and degree of structural development in this active structural environment. Also, the nature and origin of middle slope contractional belts on the Texas slope (Figure 1) are not discussed in this chapter. The primary subdivision of the shelf and onshore areas is that between provinces dominated by listric growth faults soling on subhorizontal detachments and the large salt dome–minibasin province. The salt dome–minibasin province can be further subdivided geographically into updip, eastern, and mid-shelf sectors. The individual detachment provinces are distinguished by age of expanded section, but we also interpret a fundamental genetic distinction between those detachments that are salt welds (Pliocene–Pleistocene and Oligocene–Miocene detachment provinces) and those that are purely sliding surfaces not directly related to salt withdrawal. In addition, many of the structures in the tabular salt–minibasin province of the slope represent earlier stages of structural evolution than the more structurally evolved provinces on the shelf and onshore.

The toe-of-slope contractional foldbelt provinces include the Perdido foldbelt of Oligocene age in Texas (Blickwede and Queffelec, 1988; Weimer and Buffler, 1992) and the Mississippi Fan foldbelt of Miocene–Pliocene age in eastern Louisiana (Weimer and Buffler, 1992; Wu et al., 1990). These salt-floored fold and thrust systems apparently formed at the basinward margin of autochthonous salt. Note that these systems are of different ages and separated geographically by a wide zone lacking known contractional deformation. (See the above references for more information on these provinces.)

The tabular salt–minibasin province is characterized by extensive salt sheets with intervening deep-water sediment-filled minibasins. Most of these minibasins form bathymetric lows today. The Pliocene–Pleistocene detachment province includes areas of evacuated allochthonous salt along detachments for listric growth faults as well as remnant allochthonous or “secondary” salt domes and wings in the area of the Pliocene–Pleistocene shelf margin depocenters. The salt dome–minibasin province is characterized by salt stocks and intervening shelf minibasins bounded by large-displacement, arcuate, and dominantly counter-regional growth faults. This province is diachronous: structures and related depocenters range

Figure 3—Structural summary map of the northern Gulf of Mexico Basin. Tectonostratigraphic provinces are color coded as in Figure 2 and faults as in Figure 1.
in age from Eocene to Pleistocene updip to the modern shelf margin. The Oligocene–Miocene detachment province is large and complex but is characterized by listric down-to-the-basin growth faults that sole in the Paleogene section. The Oligocene Vicksburg detachment system in onshore Texas contains sand-prone Vicksburg deltaic sediments greatly expanded by a listric down-to-the-basin fault system that soles in Eocene Jackson shales. The upper Eocene detachment province includes several listric detachment-based fault systems expanding the upper part of the Eocene section. In the Paleocene–Eocene Wilcox growth fault province in southern Texas are found the oldest major growth fault systems downdip of the middle Cretaceous margin. Like the upper Eocene fault systems, the geometries of these systems are variable along strike, with listric faults either soling directly on the autochthonous Louann salt or in the upper Cretaceous section before stepping down to the Louann level. A more complete description and analysis of the individual provinces follow.

Tabular Salt–Minibasin Province

The tabular salt–minibasin province covers most of the continental slope along the northern Gulf of Mexico margin, stretching from Mexico to eastern Louisiana between the shelf margin and the Sigsbee escarpment at the toe of the slope. Although much variability is present in this large region, allochthonous salt tongues or “tabular” salt with intervening sediment-filled minibasins represent its dominant structural style (Figure 3). We use the term tabular salt to refer to laterally extensive salt bodies with flat tops. The term salt sheet refers to allochthonous salt with a subhorizontal top and base, and salt wing means a less extensive allochthonous salt body with a demonstrable base.

The bathymetry of the modern Louisiana slope reflects the profound influence of salt tectonics and sedimentation in the deep-water environment (Figure 4). First-order features include the prominent Sigsbee escarpment, the expression of a large salt body overriding the abyssal
plain, the Mississippi Canyon, and the upper part of the Mississippi Fan.

The western Keathley Canyon area and the southern part of the eastern Keathley Canyon and Walker Ridge are underlain by a contiguous canopy of coalesced allochthonous salt (Figure 4). The western part is covered by a thin sedimentary cover forming nascent polygonal minibasins above allochthonous salt and separated by crestal grabens on salt ridges. The southern Keathley Canyon and Walker Ridge area, just landward of the escarpment, is underlain by tabular salt near the seafloor (Figure 5). The dominant features of the central part of the Louisiana slope are the deep and currently sediment-starved minibasins surrounded by interconnected shallow salt bodies.

Isolated salt bodies and interconnected minibasins surrounded by arcuate growth fault systems also occur in eastern Green Canyon and western Atwater areas (Figure 4), where recent sedimentation has reduced the bathymetric relief relative to areas farther west. Areas northeast of Mississippi Canyon are dominated by erosion, large slides, and isolated allochthonous salt bodies forming bathymetric highs with distinct convex outlines. Slope minibasins expressed as bathymetric lows commonly contain sediments greater than 6 km thick either symmetrically or asymmetrically ponded in basins tilted southward (Figure 6).

In general, there is a gradual transition from isolated minibasins surrounded by contiguous salt in the lower slope to isolated salt bodies surrounded by interconnected fault-bounded minibasins near the shelf margin. This transition reflects progressive deformation during progradation of the margin across allochthonous salt. A seismic profile in the middle slope shows an early stage of sedimentation above allochthonous salt. A perched basin in Figure 7 is beginning to subside into the salt, whereas faults with seafloor expression indicate a contemporaneous sliding downslope. Normal faults occur at the northern end, and reverse faults occur at the southern end.

A profile (Figure 8) just to the north of Figure 7 shows the result of progradation of the shelf margin across the northern end of another allochthonous salt body. Shelf strata, expanded on listric growth faults, forced evacua-
tion of the northern end of the salt body to form a weld connected to a south-leaning salt massif. Strata within the basin thin rapidly onto the massif and show evidence of erosion. Normal faults occur at the south end of the basin where reverse faults similar to those in Figure 7 may have been present. The updip salt weld represents the updip portion of the Pliocene–Pleistocene detachment province.

Pliocene–Pleistocene Detachment Province

Sumner et al. (1990, p. 48) divided the Pliocene–Pleistocene detachment province into separate regions of “organized” and “disorganized” roho systems. The organized systems occur in the western and eastern parts of the area and are underlain by extensive salt welds, or rohos. The disorganized systems occur in the central area where a combination of residual salt wings, evacuation surfaces, and windows between salt bodies forms a more complex structure.

We restrict the term roho to the characteristic discontinuous, high-amplitude seismic reflections caused by remnant salt along welds (Jackson and Cramez, 1989), also called salt-evacuation surfaces or salt-withdrawal surfaces. We also refer to the Pliocene–Pleistocene salt-withdrawal structures of the outer shelf as roho systems, after Sumner.

Figure 6—Slope minibasins, offshore Louisiana. Two deep basins are separated by a shallow basin perched above allochthonous salt. Events marked “M” are multiple reflections. See Figure 2 for location.

Figure 7—Seismic profile from the middle slope of Louisiana. Down-to-the-south normal faults at the north end are linked to thrust structures at the south end. Sliding perched basin is beginning to subside into shallow salt (green). See Figure 2 for location.
Figure 8—Seismic profile from the shelf edge of Louisiana. Shelf margin sedimentation and associated listric growth faults collapsed the north end of a salt body to produce a weld (green) just south of a counter-regional salt feeder. The southern end of the salt body remains near the seafloor with shelf margin sediments onlapping and thinning onto the southern flank.

Figure 9—Uninterpreted (top) and interpreted (bottom) seismic profile across an organized roho system, western Louisiana outer shelf, showing roho reflections along the detachment for Pliocene–Pleistocene listric growth faults. A north-dipping counter-regional salt feeder is interpreted at the north end of the subhorizontal salt weld (green). Pl A, B, C = three successive Pliocene–Pleistocene levels. See Figure 2 for location.
et al. (1990), but choose the more general genetic term salt-withdrawal fault system or salt-based detachment system for similar structures without roho reflections. Organized roho areas of the outer shelf show large amounts of extension by listric down-to-the-basin growth faults that expand Pliocene–Pleistocene sediments above the salt welds (Figure 9). Although some contractional structures exist locally, they do not balance the cumulative extensions. Palinspastic reconstruction suggests that extension is balanced by withdrawal of tabular salt originally present near the seafloor (Figure 10). (See Chapter Appendix for more details on reconstruction methods.)

Another reconstructed example from the Pliocene–Pleistocene detachment province illustrates the complete collapse of a shelf-margin minibasin onto a salt weld (Figures 11, 12). The former north-dipping thinning wedge of sediment is now collapsed to form a complexly faulted turtle structure above the salt weld. The evolution of the toe of the former salt mass includes possible initial thrusting, followed by inversion into a counter-regional extensional fault during deformation of the salt massif into salt domes along the counter-regional faults.

In the last two examples (Figures 10, 12), we reconstructed the top of salt by undoing growth fault motions and flattening to a reasonable seafloor constrained by the position of the paleoshelf margins. The base of salt in the reconstructions is only inferred from the minimum structural relief above the salt through time. Diegel and Cook (1990) and Rowan (1994) presented strategies for incorporating subsidence analysis to independently constrain salt thicknesses through geologic time. This technique (see Chapter Appendix), combined with the structural reconstructions, is a powerful tool in deducing the early history of more deeply buried structural systems of the inner shelf and onshore areas. The large salt-withdrawal component of subsidence, estimated by backstripping in southern Louisiana, provides a solution to the long-standing problem of how space was created for thick Cenozoic shallow water deposits late in the history of a passive margin initiated in Jurassic time (see Chapter Appendix).

**Oligocene–Miocene Detachment Province**

The Oligocene–Miocene detachment province covers most of the modern slope and parts of coastal onshore Texas and Louisiana (Figures 2, 3). This is a region of large-displacement, dominantly down-to-the-basin listric growth faults that sole on a regional detachment above the Paleogene section. The updip limit of the detachment is irregular and crosses the more linear trends of the Oligocene and Miocene depocenters (e.g., Winker, 1982).
Figure 11—Interpreted seismic profile showing basinward-thinning strata above the Pliocene–Pleistocene salt weld, western Louisiana outer shelf. See Figure 2 for location.

Figure 12—Reconstruction of depth-converted seismic profile based in part on seismic profile in Figure 11. Basinward-thinning strata above the weld restore to an onlapping configuration on the south flank of a presently evacuated salt body. Reconstruction by the MESH method (see Chapter Appendix). Pl. A, B, C = three successive Pliocene–Pleistocene levels.
Another characteristic of this province is the great thickness of deltaic sediments above the detachment, usually exceeding 5 km.

Depth conversion of an interpreted seismic profile (Figures 13, 14) from onshore southern Louisiana illustrates the magnitude of the subsidence problem in this province. Wells have penetrated Miocene neritic sediments as deep as 6 km below sea level. This remarkable stacking of deltaic sandstone reservoirs helps make southern Louisiana one of the world's great petroleum provinces. Thermal and isostatic subsidence alone cannot account for more than 6 km of shallow-water sediment deposited in the late Tertiary on a passive margin where rifting occurred in the Jurassic, but subsidence can be balanced isostatically with salt withdrawal (see Chapter Appendix). This technique for estimating salt withdrawal also accounts for rotation and translation of fault blocks; in this and other examples from the Oligocene–Miocene detachment, extensional faulting does not account for the large subsidence anomalies.

Estimated salt thicknesses using the method in the Chapter Appendix are used in the alternative reconstructions (Figures 15, 16) of the southern Louisiana cross section (Figure 15). Although this technique estimates the amount of salt withdrawal, it does not locate the level of the evacuation surface. End-member models show that either salt was withdrawn from the autochthonous Louann level (Figure 15) or the detachment for listric growth faults represents a salt weld that formerly contained a thick, allochthonous salt body (Figure 16).

We prefer the allochthonous model for several reasons. (1) Salt penetrations occur along the Oligocene–Miocene detachment in western Louisiana. (2) The geometries resemble those above the shallower Pliocene–Pleistocene detachment systems, and we know of no example of a listric detachment formed in response to a rolling fold of salt beneath several kilometers of deep-water sediments. (3) The thinning wedge above the detachment suggests a collapsed onlap similar to examples from the outer shelf described previously. (4) Sub-detachment counter-regional faults provide a means for extrusion of the Louann salt to the level of the Oligocene seafloor. Finally, (5) it seems
mechanically unlikely that a thick salt layer would remain undeformed beneath kilometers of sediments that thicken into counter-regional growth faults of pre-Oligocene age.

The detachment system discussed in the previous example extends across a large part of coastal Louisiana and Texas and comprises the Oligocene–Miocene detachment province. Also, similar deep penetrations of Miocene deltaic sediments are well known across the entire area. Geometric analogs to known salt-based detachment systems of the Pliocene–Pleistocene depocenters, as well as palinspastic reconstructions and subsidence analysis, imply that large areas of the shelf may have been underlain by allochthonous salt sheets that were evacuated by progradation of the Miocene deltaic margin. This scenario probably applies even in parts of the Oligocene–Miocene detachment province in western Louisiana and Texas, where few shallow salt domes occur. We interpret this entire province to be a salt-based detachment with salt emplacement at an allochthonous level in the Paleogene and subsequent salt evacuation during progradation of the late Oligocene–late Miocene shelf margin.

A regional seismic profile from western Louisiana illustrates the scale of the Oligocene–Miocene detachment system in an area where the detachment is relatively shallow and well imaged (Figure 17). Sub-detachment strata, seismically correlated to Eocene and Cretaceous rocks penetrated updip, are well imaged. A marked discordance occurs along the detachment: sub-detachment strata extend across the entire profile with relatively even thickness, whereas deltaic units above the detachment are greatly expanded but thin rapidly basinward to be replaced by successively younger strata. This pattern of expansion and thinning reflects the progressive evacuation of allochthonous salt during progradation of the shelf. Two wells are shown on this profile where reported salt penetrations occur at the level of detachment, basinward of sub-detachment counter-regional structures that may have acted as feeders for allochthonous salt. The map distribution of these feeders (Figure 18) suggests multiple sources for a probably extensive Paleogene salt canopy that is now reduced to a weld.

The irregular landward edge of the Oligocene–Miocene detachment system in southeastern Texas and Louisiana corresponds to the landward limit of the con-
tinuous salt canopy on the Paleogene slope. The age of earliest evacuation of the canopy also varies with its updip extent. Landward reentrants in the canopy edge were the earliest evacuated areas, and basinward promontories were evacuated later. The earliest evacuation corresponds to early Frio deltaic deposition in the early Oligocene of central Louisiana. But just to the east, the detachment reaches only as far landward as the present coast within the early Miocene depocenters.

**Salt Dome–Minibasin Province**

The salt dome–minibasin province (Figures 2, 3) is divided geographically into updip, eastern, and mid-shelf sectors. All of the sectors share the same structural style that defines this nongenetic province—salt stocks and intervening shelf minibasins bounded by large-displacement, arcuate, and dominantly counter-regional growth faults. Unlike the mid-shelf sector, the updip and eastern sectors are composed of isolated structural systems surrounded by areas of relatively simple structure.

**Updip and Eastern Sectors**

The landward edge of the Oligocene–Miocene detachment is interpreted as the updip limit of a continuous Paleogene salt canopy, but isolated allochthonous salt bodies occur in the updip and eastern sectors of the salt dome–minibasin province. Dominantly down-to-the-basin listric growth faults of the detachment province formed in areas of extensively coalesced allochthonous salt, but isolated minibasins rimmed by arcuate faults and flanking salt domes formed during evacuation of isolated allochthonous salt bodies of the updip and eastern sectors of the salt dome–minibasin province.
Palinspastic reconstruction of a cross section through coastal southeastern Louisiana illustrates the structural evolution of the eastern sector of the province (Figure 19). The present-day cross section shows a minibasin bounded on the south by a large displacement counter-regional fault and bounded on the north by a smaller displacement down-to-the-south growth fault. Both of these faults sole within the Paleogene section, well above the Jurassic salt horizon. South-leaning salt domes occur along the counter-regional fault east and west out of the plane of section (Schuster, 1995). The soling horizon connects the shallow counter-regional fault to a deeper counter-regional fault to form a stepped-counter-regional system (Schuster, 1993, 1995).

The large apparent extension above the soling horizon is much greater than the extension in the Mesozoic and Paleogene section. The section is balanced by including an isolated salt body at the soling horizon. This structure evolved in two distinct phases: (1) extrusion of an allochthonous salt body near the seafloor in Paleogene time followed by (2) evacuation of that salt body to form a minibasin floored by a salt weld and bounded by salt-withdrawal faults and leaning salt domes along the counter-regional fault (Figure 19).

Two distinct structural styles—salt-based detachments and stepped counter-regional fault systems—formed during shelf margin progradation in southern Louisiana. Where the allochthonous salt coalesced to form a continuous canopy, salt-based detachment systems developed. Conversely, where the salt bodies were isolated, salt-floored minibasins and marginal salt domes formed. The modern Louisiana slope is a direct analog for the
Figure 17—Interpreted seismic profile across the Oligocene–Miocene detachment province and mid-shelf salt domes–minibasin province. Strata above the salt detachment form a series of expanded wedges that thin basinward above more isopachous sub detachment Eocene and older strata, which are deformed by counter-regional faults. Well symbols indicate wells that penetrate salt at the level of detachment. Pl = lower Pleistocene, UM = upper Miocene, MM = middle Miocene, LMA and LMB = lower Miocene, UF = Oligocene upper Frío, MF = Oligocene middle Frío, E = Eocene, UK = Upper Cretaceous, and LK = Lower Cretaceous. See Figure 2 for location. This vertically exaggerated profile is shown at true scale in Figure 35 (folded insert).
Paleogene slope before deformation of allochthonous salt. The modern bathymetry (Figure 4) shows the outlines of isolated allochthonous salt in the easternmost Louisiana slope and a more continuous canopy to the west.

**Mid-Shelf Sector**

The structural style of the mid-shelf sector of the salt dome–minibasin province is similar to the updip and eastern sectors of the province. The mid-shelf minibasins generally contain younger deltaic sediments, and the deep structure is obscured by deep burial. Unlike the more isolated fault systems of the updip and eastern sectors, the counter-regional faults of the mid-shelf sector form a linked network across much of the shelf. Also, although characterized by a different structural style than the Oligocene–Miocene detachment province, this sector is probably genetically related to it.

Salt-based detachment systems terminate basinward either in minibasins bounded by counter-regional faults or in thrust complexes related to the forward edge of a salt sheet (e.g., Sumner, 1990; Schuster, 1995). In the former case, salt domes occur around the edges of the minibasins, most commonly along the counter-regional faults. The reconstruction of the previous onshore example (Figure 16) shows the evolution of the basinward margin of a salt massif into a minibasin bounded by a counter-regional fault and associated salt dome.

This evolutionary scenario is also evident when comparing typical dip cross sections in sequence from the lower slope to onshore (Figure 20). The lower slope example (Figure 20a) shows extensive allochthonous salt near the seafloor; the upper slope example (Figure 20b) shows the initiation of subsidence where basinward sliding is accomplished by a linked slip system of down-to-the-basin normal faults at the landward end of the salt body and basinward-directed thrusts at the basinward end. The shelf margin example (Figure 20c) shows complete collapse of the landward part of the salt body to form a weld beneath listric normal faults and onlap onto a south-leaning asymmetric salt massif similar to the second stage in previous reconstructions of both the Pliocene–Pleistocene and Oligocene–Miocene salt-based detachments (Figures 12, 16). The outer shelf example (Figure 20d) shows complete evacuation of an allochthonous salt body by formation of a counter-regional fault at the southern end. The inner shelf example (Figure 20e) is geometrically similar to the outer shelf example except that it is more deeply buried. It is also similar to the reconstructed onshore example (Figure 16).

The salt dome–minibasin style of structure occurs in isolation within areas of discrete allochthonous salt bodies, as in the updip and eastern sectors of the province, but it also occurs as the basinward part of many salt-based detachment systems. It is likely that the mid-shelf sector of the salt dome–minibasin province bears this relation to the adjacent Oligocene–Miocene detachment. If the Oligocene–Miocene and mid-shelf provinces are related this way, then the large minibasins in the mid-shelf area may also be floored by allochthonous salt at the Paleogene level rather than being rooted directly to the Jurassic Louann salt horizon. The interpreted regional seismic profile in Figure 17 shows the relationship between the Oligocene–Miocene salt-based detachment and the mid-shelf sector of the salt dome–minibasin province. This profile was chosen to avoid salt domes, but the large counter-regional faults at the southern end of the section are linked to salt domes out of the plane of the section (Figure 3).
Figure 19—Reconstruction of a stepped counter-regional system formed by evacuation of an isolated allochthonous salt body (Schuster, 1995). UM = upper Miocene, MM = middle Miocene, LM = lower Miocene, Pg = Paleogene. See Figure 2 for location.
Oligocene Vicksburg Detachment System

Palinspastic Analysis and Comparison with Salt-Based Detachments

Not all detachments in the northern Gulf of Mexico Basin are salt-withdrawal fault systems. A large shale-based detachment system is recognized onshore in southern Texas in the lower Oligocene Vicksburg productive trend (e.g., Honea, 1956; Combes, 1993) (Figures 2, 21). The well-imaged detachment surface is about 700 m below the top of the Eocene Jackson shale, which is often penetrated along the detachment. Although this fault system shares a superficial similarity to the salt-withdrawal detachment systems previously discussed, it is geometrically distinct. The superficial similarities include the presence of expanded deltaic sediments above listric normal faults that sole into a subhorizontal detachment surface.

The profound differences are apparent in reconstructed depth cross sections (compare Figures 22, 23). In this shale-based detachment system, the expanded sequences are younger landward in contrast to salt-based examples (Figures 10, 12, 16, 23), where expanded sequences prograde basinward. The base of the reconstructed sediments remains sub-horizontal in the shale-based example, unlike the characteristic basinward onlap configuration in reconstructed salt-based detachment systems. Growth faults above salt-based detachments generally become younger basinward, but reconstructions of the Vicksburg detachment indicate periodic landward backstepping of the active growth fault. Extension increases with age above the Vicksburg detachment’s conveyor belt. In contrast, in salt-withdrawal systems such the Oligocene–Miocene detachment system, a wave of extension moves basinward with the prograding depocenter such that all the faulted strata, regardless of age, are extended about the same amount, but at different times. Above salt-based detachments a zone of extension in the upper slope and outer shelf progrades along with the margin. Older growth faults are stranded on the shelf rather than continuously translated along the detachment by cumulative extension recurring at the head of the fault system, as in the Vicksburg fault system.

Unlike the salt-withdrawal fault systems, the shale-based Vicksburg detachment is an example of extreme extension. The oldest units in the Vicksburg example (Figure 22) were translated horizontally more than 16 km, with all the extension accumulated across a fault zone 2.4 km in restored horizontal width (over 600% extension). In contrast, the oldest sediments in the salt-withdrawal example (Figure 23) show about 3.2 km of horizontal translation distributed over a zone of faulting 16 km wide in the reconstructed state (about 20% extension). Salt withdrawal during extension resulted in about 2.1 km of vertical motion, or about 70% of the horizontal extension in the Louisiana example. About 1.2 km of vertical motion during extension occurred in the Vicksburg example, or only about 7% of the horizontal movement.

Numerous reconstructions, including those presented here, indicate that salt-withdrawal and shale-based detachment systems can be distinguished using palinspastic reconstruction independent of confirming evidence such as salt penetrations. Unambiguous reconstructions are, however, dependent on the availability of reliable biostratigraphic control. Reconstructions are only diagnostic back to the age of the deepest reliable stratigraphic correlation across the fault system. In the absence of deep well control with reliable biostratigraphic markers, interpretations of fault system evolution are as speculative as the correlations. Large changes in speculative correlation across growth faults result in radically different reconstructed geometries. Correlations based solely on seismic character across large growth faults are often misleading or completely useless. In the absence of deep biostratigraphic control, apparently conservative correlations (i.e., minimized fault displacements) tend to make reconstructed salt-withdrawal systems appear to be shale-based slide systems.
Relationship of Vicksburg Detachment System to Oligocene–Miocene Detachment Province

Because of the limited dip extent of the cross section, the previous Vicksburg reconstruction (Figure 22) does not address downdip compensation of extension. The relationship to the next youngest extensional fault system of Oligocene Frio age, however, is similar to the relationship of a perched Miocene detachment system to the Oligocene–Miocene master detachment on the Texas shelf (Figure 24). The perched detachment overlies a deeper detachment that extends basinward beneath younger extensional fault systems.

Reconstruction of the perched detachment (Figure 25) shows extreme extension and a lower Miocene geometry similar to the Vicksburg example, with no indication of allochthonous salt at the perched level. The restored onlapping wedge geometry of the subperched detachment section (Figure 25, Oligocene) suggests that salt withdrawal occurred at this deeper but still allochthonous level. This model is consistent with the previously presented interpretation that the Oligocene–Miocene detachment represents an extensive, time-transgressive salt weld.

The relationship of the Vicksburg detachment to the Oligocene–Miocene detachment beneath expanded Frio sediments may be similar. We know of one cored salt penetration at the level of detachment for Frio growth faults in onshore southern Texas that is hundreds of kilometers distant from known shallow salt domes along strike. The extreme extension in these sections is probably taken up by a reduction in the length of salt near the seafloor. Although the timing of the Perdido folds is appropriate for some of the updip extensional fault systems, the magnitude and duration of contraction are insufficient for balancing the updip extensional fault systems (Worrall and Snelson, 1989).

Wilcox Fault Province of Southern Texas

Description

The oldest Tertiary growth fault system in the northern Gulf of Mexico Basin is the Paleocene–Eocene Wilcox fault system (Figure 2). Although this system varies greatly along strike, its base is relatively shallow and well imaged in southern Texas (Figure 26). The deep structure of the southern Texas Wilcox fault system is unlike those previously discussed. The most prominent feature of the trend is the great expansion (more than tenfold) of Wilcox deltaic strata confined to narrow depotrysts. These
Depotroughs are also characterized by the apparent absence of Cretaceous strata, which are well imaged outside the troughs (Figure 26). The landward edge of the troughs is the locus of the complex Wilcox growth fault system, which expands the upper Wilcox section by about a factor of ten. The complex imbricate fan of down-to-the-basin growth faults merges downward into major fault planes that sole at the Jurassic Louann salt level, apparently directly overlain by Paleogene strata. The basinward edge of the Eocene-filled depotroughs is bounded by counter-regional faults that extend to the Louann salt level and have Cretaceous strata on their footwalls.

**Palinspastic Analysis and Alternative Interpretations**

The reconstruction of part of this profile (Figure 26) shows the creation of space for the Wilcox depotrough by collapse of an autochthonous Mesozoic salt massif (Figure 27). The width of these massifs at the end of the Cretaceous is not constrained by the reconstruction, which shows a maximum Tertiary extension model with minimum width of the Cretaceous salt massifs. The opposite end-member, pinning the basinward Mesozoic block at the eastern end of the section, is also geometrically admissible, resulting in wide salt massifs and no net extension in the Tertiary. In either case, this reconstruction...
does not address the formation of the salt walls in Cretaceous time. The two possibilities are (1) thinning of the Lower Cretaceous cover by post depositional extension in the Late Cretaceous, or (2) syndepositional growth throughout the Cretaceous without extreme extension. The first mechanism has been proposed for the evolution of similar salt–depotrough structures in the Kwanza Basin (Verrier and Castello-Branco, 1972; Duval et al., 1992; Lundin, 1992; Vendeville and Jackson, 1992b).

Arguments in favor of the extensional model (not shown) include documentation of the mechanism by physical modeling (Vendeville and Jackson, 1992a,b) and the generally isopachous nature of the Lower Cretaceous strata. The extensional hypothesis, however, requires basinward sliding of at least 40 km, and no contractional structures of the appropriate age and magnitude are known to exist. Extreme extension could be compensated by large contraction of salt width in the downdip salt
basin or by a hidden thrustbelt beneath the salt on the poorly known Texas slope. Although there are extensional structures in the Lower Cretaceous section, the irregular shape of the collapse edge (Figures 28, 29) suggests that extension alone may not account for the origin of the salt walls.

Details of the geometry of Wilcox growth faults are controlled by the salients and reentrants in the collapse edge of the Cretaceous strata onto the Louann salt horizon. At the northeastern end of the map area, the large Wilcox depotorough abruptly terminates but is replaced northward by a separate trough that is offset to the west. At the southern end of the map area, the eastern margin of the trough is not mapped, but the western edge has an abrupt offset that overlies the position of a basement wrench fault system (Figure 30). These steep basement faults offset the base of Louann salt and are possibly coeval with Louann deposition. Additional displacement on these faults formed a northwest-trending anticline during Paleocene deformation of the Sierra Madre and Coahuila foldbelts in northeastern Mexico.

The irregular edges of the troughs do not match well, suggesting either that the Lower Cretaceous deep-water equivalent deposits onlapped existing salt walls or that complex internal deformation has greatly altered the shape of these edges. The blunt terminations, in particular, are difficult to restore without intervening salt bodies or large tear faults. Northwest-trending offsets may represent different initial positions of Cretaceous salt walls rather than large tear faults. The different initial positions could be caused by original salt thickness changes across Jurassic wrench faults. On the downdropped side of these faults, thicker salt farther landward might result in formation of a salt wall farther updip on that side of the fault.

Whatever their origin, collapse of large autochthonous salt walls created space for Wilcox depotoroughs and related growth fault systems. The southern Texas deep structure, possibly basement controlled, is distinctly different from the isolated counter-regional withdrawal basins beneath the Oligocene–Miocene detachment offshore western Louisiana (Figure 18). Although large salt walls existed on the Cretaceous slope in southern Texas, isolated pillows or diapirs, which later became feeders for allochthonous salt, existed in southern Louisiana. Similar salt walls may have existed in the Louisiana Wilcox trend as well, and sub-detachment withdrawal basins may occur beneath the Texas shelf.

Figure 24—Interpreted seismic profile (top) and detailed drawing (bottom) across the Oligocene–Miocene detachment province on the south-central Texas shelf. The middle Miocene perched detachment (center) is interpreted as an analog for the Vicksburg shale-based detachment; it is connected downdip to the deeper Oligocene–Miocene detachment interpreted as an extensive salt weld. UM = upper Miocene, MM = middle Miocene, LM = lower Miocene, OL = Oligocene. See Figure 2 for location.
Relationship to Oligocene–Miocene Detachment Province

A true-scale regional reconstruction (Figure 31) across the onshore part of the central Texas Gulf Coast shows the nature of the transition from the Wilcox depotroughs to the Oligocene–Miocene detachment system. In this part of Texas, the imbricate fan of the Wilcox fault system has widened to form a perched detachment above Upper Cretaceous strata, but it still roots into a broad depotrough with most, if not all, of the Mesozoic section absent above the autochthonous Louann salt horizon. This depotrough is overlapped by a younger Eocene perched detachment that may terminate in a poorly known depotrough beneath thick Eocene shales. The seaward end of that trough is interpreted to be the feeder system for allochthonous salt subsequently evacuated by progradation of the Oligocene Frio shelf margin. Again, the width of the salt walls is unconstrained by the reconstructions of the late Eocene and Late Cretaceous.

PROVINCE RELATIONSHIPS ALONG WESTERN LOUISIANA TRANSECT

The limitations of subregional reconstructions are apparent from the Texas examples just presented, in which salt-bounded blocks of sediment are not laterally constrained by reconstruction and the relative magnitudes of extension and salt reduction are not determined. Inclusion of salt withdrawal in cross section reconstruction produces an extra degree of freedom compared to typical thrust belt reconstructions. Although the backstripping approach is a powerful way to reconstruct syn-depositional structures, the results are completely dependent on the stratigraphic correlations. There are no geometric rules for deducing the deep structure of salt-withdrawal fault systems with nonrigid footwalls. Accurate reconstruction of these systems is dependent on seismic geometries and stratigraphic correlations. The requirement to choose a composite profile that minimizes...
Diegel and Schuster (1990) presented two such regional reconstructions. One is in the eastern Gulf through the isolated systems of the eastern part of the salt dome–minibasin province (Figure 19 is extracted from that reconstruction; see also Schuster, 1995, this volume). The other one is in western Louisiana (Figure 32) and is discussed here and is reconstructed in Figures 33, 34, and 35 (folded insert). The western Louisiana transect is in the center of the basin and crosses (1) the Wilcox fault system, (2) an upper Eocene fault system, (3) the onshore salt dome–minibasin province, (4) the Oligocene–Miocene detachment system and related mid-shelf salt dome–minibasin province, (5) a Pliocene–Pleistocene organized roho system, and (6) the tabular salt–minibasin province of the slope.

The reconstructed western Louisiana cross section has the advantages of being in the complex central part of the basin and being relatively well imaged at deep levels. Still, it is important to separate well-constrained parts of this section from speculative parts without reliable seismic geometries and correlations. To separate interpretation from speculation, we include two types of cross sections: (1) an interpreted seismic profile and depth-converted frame cross section showing only reliable correlations and seismic geometries (Figure 35 [enclosure]) and (2) speculative, alternative cross sections completed to the pre-Louann basement (Figures 33–35).

Description

The Cretaceous carbonate margin and Louann salt horizon are imaged at the northern end of the profile. The profile crosses the Wilcox fault system, which terminates in a laterally extensive depotrough. This depotrough is bounded on the south by counter-regional faults and associated south-leaning salt domes of the updip sector of the salt dome–minibasin province. A small upper Eocene fault system overlies this trough. This laterally discontinuous detachment system is a relatively superficial structure within the depotrough and is therefore not subdivided from the updip sector of the salt dome–minibasin province in Figures 2 and 3. The landward edge of the Oligocene–Miocene detachment is overlain by expanded middle Oligocene Frio deltaic strata. Successive younger late Oligocene–early Miocene depocenters occur basinward, and a middle Miocene depocenter is located in the mid-shelf sector of the salt dome–minibasin province.

High-amplitude continuous seismic reflectors correlated to Cretaceous and Eocene chalks persist beneath the Oligocene–Miocene detachment and are deformed into counter-regional fault-bounded minibasins (see Figure 18). The Oligocene–Miocene detachment surface is not imaged beyond the salt dome–minibasin province. Southward, the roho-based Pliocene–Pleistocene fault systems continue to the salt massifs at the shelf edge. Well control indicates that this shallow detachment overlies middle Miocene strata. Presently, the roho reflection along the detachment represents the effective base of reliable seismic geometries in this area. The slope portion of
the profile crosses a tabular salt body without an imaged base, as well as two deep minibasins updip of the salt mass that extends southward to the Sigsbee escarpment. Flat-lying abyssal plain strata are clearly imaged for 70 km under the Sigsbee salt mass. There is no fold and thrust belt at the toe of the slope here. Small structures within the depth-converted subsalt reflections may be small contractional structures or artifacts of the approximate depth conversion assuming vertical ray paths beneath thick salt.

Figure 27—Reconstruction of the southern Texas Wilcox fault system above autochthonous salt (black). This end-member model assumes large extension during Wilcox deposition, but a continuum of models, trading the width of Upper Cretaceous salt walls for Tertiary extension, is geometrically possible. LK = Lower Cretaceous, UK = Upper Cretaceous, UWx = Upper Eocene Wilcox. Sea water is stippled. Reconstruction is by the MESH method.
Figure 28—Shaded relief map of the structure on a Lower Cretaceous horizon, southern Texas. Lower Cretaceous strata are absent from prominent depotroughs for Wilcox deposition. Bracket symbols indicate generalized traces of Tertiary growth faults. LK = Lower Cretaceous. See inset map for location.
Regional Palinspastic Analysis: Alternative Models

Two alternative speculative sections based on the frame section were restored to investigate end-member scenarios for the evolution of the north-central Gulf of Mexico Basin (Figures 32, 33, 35 [enclosure]). Model I (Figure 33) extrapolates the base of the Sigsbee salt mass directly to the Louann level, as suggested by Worrall and Snelson (1989). In this model, the base of the mid-slope tabular salt body is also rooted to the autochthonous Louann level. Likewise, speculative feeder systems for the Pliocene–Pleistocene róho systems are shown rooted directly to the autochthonous salt. The updip, better constrained part of the cross section is the same in both models. Model II (Figures 34, 35 [enclosure]), also consistent with the frame section, differs from model I in extending the Paleogene weld of coastal Louisiana beneath the outer shelf and slope to connect to the base of the Sigsbee salt mass. In model I, the Sigsbee salt overthrust was initiated by the end of the Cretaceous; it began later in model II at about the same time as other extrusions farther landward.

In both models, most of the salt structures evolved into leaning stocks by the end of Eocene Wilcox deposition. In model I, the Sigsbee salt mass was up to 3.7 km thick with more than 60 km of overthrust. The northernmost salt body on the section remained constrained by shelf margin deposition into a possibly overhung stock near the paleoshelf margin. The entire profile to the south was in the bathyal environment at this time. Although the

Additional seismic observations support the continuation of the base of the Sigsbee salt above a Paleogene horizon as in model II. On the frame section, the base of the Sigsbee salt body cuts down to the level of Eocene(? ) abyssal plain strata before being obscured by a deep basin, but seismic profiles just west of the cross section show that the base of the Sigsbee salt body extends an additional 30 km northward, subparallel to and above flat-lying Eocene(?) and older strata (Figure 36). Although the details of the speculative parts of both sections are conjectural, several aspects of the reconstructions (described below) lead us to favor model II. Both models restore to a similar structural style at the end of Cretaceous time: low-relief asymmetric salt bodies developed under a pelagic cover. At the northern end of the section, a thicker Cretaceous section updip of a salt massif reflects basinward flow of autochthonous salt into the massif. Initiation of these salt structures is not addressed by the reconstructions. In model I, the Sigsbee salt overthrust was initiated by the end of the Cretaceous; it began later in model II at about the same time as other extrusions farther landward.

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Figure 31—Reconstruction of a regional cross section across the Wilcox, upper Eocene, and Frio fault systems, onshore central Texas. The Wilcox fault system is perched above autochthonous salt (black). The Frio-age growth faults are interpreted to sole into an evacuated Paleogene canopy now forming the Oligocene–Miocene salt-based detachment that continues offshore (Figure 24). LK = Lower Cretaceous. See Figure 2 for location.
Figure 32. Five times vertically exaggerated frame section (showing only reliable correlations and observed seismic geometries) across western Louisiana, from the Lower Cretaceous margin to the abyssal plain. A true-scale section is shown in Figure 35 (folded insert). Salt is shown in black. WxFS = Wilcox fault system, SDMB = salt dome–minibasin province, OMB = Oligocene–Miocene detachment province, PPD = Pliocene–Pleistocene detachment province, TSMB = tabular salt–minibasin province, LK = Lower Cretaceous, UK = Upper Cretaceous, P-E = Paleocene–Eocene, UE = upper Eocene, LO = lower Oligocene, UO = upper Oligocene, LM, LMB, LMA = lower Miocene, MM = middle Miocene, UM = upper Miocene. See Figure 2 for location.
Figure 33—Speculative cross section for model I and reconstruction based on frame section (Figure 32). Reduced and squeezed from true-scale original; only selected stages are shown. Salt is shown in black. Base of Sigsbee salt mass is connected directly to the autochthonous Louann salt layer. This model is rejected in favor of model II (Figures 34, 35). Reconstruction is by the PREP method.
Figure 34—Speculative cross section for model II and reconstruction based on frame section (Figure 32). Reduced and squeezed from true-scale original; only selected stages are shown. Salt is shown in black. This model, which we prefer, connects the base of the Sigsbee allochthonous salt to the Paleogene canopy level. Reconstruction is by the PREP method.
Figure 36(a)—Comparison of seismic profiles across the Sigsbee salt body (green), southwestern Louisiana slope. Profile used for the frame section and reconstructions (Figures 32, 33, 34, 35) shows the base of the Sigsbee salt sheet reaching as deep as a reflector tentatively correlated to the Eocene (top of brown interval).
Figure 36(b)—Profile farther northwest shows the base of salt (green) continuing above through-going Eocene(?) and older abyssal plain strata (brown interval) for an additional 30 km northward. Apparent structure on the base of salt and subsalt strata is due to the velocity contrast of salt and sediment. E = Eocene, K = Cretaceous. See Figure 2 for locations.
The present-day section in model II appears more complicated than that in model II by inclusion of an additional level of allochthonous salt, model II is simpler in the restored upper Eocene section. In model II, the extrusion of allochthonous salt began over the entire bathyal part of the section, with the precursor to the Sigsbee salt mass forming as the most basinward of these flows. In model I, extrusion occurred only from the slope feeders that were updip of the imaged Paleogene detachment. Other salt bodies (excluding the Sigsbee salt) remained constrained into leaning stocks, even though they were in the same environment.

By middle Frio time, the salt canopy in model II was complete, but some salt was still at the autochthonous level. The middle Frio marked the end of about 25 m.y. of relatively low rates of sedimentation in the Louisiana Gulf Coast that followed Eocene Wilcox deposition. This interval, almost as long as all the remaining Oligocene, Miocene, and Pliocene combined, is probably represented by less than 600 m of sediment beneath the western Louisiana shelf. The exact timing of the extrusion of salt during this condensed interval is unconstrained. Initiation and coalescence of salt flows did not necessarily occur precisely at the same time throughout the basin.

In model I, the Paleogene salt extrusion occurred only on the upper half of the slope. Salt remained at the autochthonous level on the lower slope. Although there is no direct evidence for a Paleogene canopy on the lower
slope, as in model II, it is likely that sedimentation rates were even lower in this more distal position. Thus, any existing stocks were less constrained by sedimentation and more likely to flow into allochthonous sheets near the seafloor.

In late Oligocene time, middle Frio deposition represented the renewal of clastic progradation that continues to the Recent. In both models, Frio deltaic sedimentation began to prograde across the completely coalesced salt canopy, and the first major salt-based detachment faulting began. In model II, several minibasins formed over the canopy on the slope. The age of initiation and the geometry of these postulated minibasins are unconstrained, and the interpretation shown in model II is only one of several possible scenarios. The ages of the basins could be synchronous, younging to the south, or more irregular, depending on deep-water sediment dispersal patterns. In model I, the lower slope remained a relatively sediment-starved region with continued downbuilding of sediment between old salt stocks.

The structures initiated in Oligocene Frio time continued through Anahuac, early-middle Miocene in both models. The Paleogene salt evacuation surface was created by deltaic progradation and related listric growth faulting that progressively collapsed the salt canopy. The Sigsbee salt body continued to grow and override abyssal sediments. In model I, autochthonous rooted diapirs continued downbuilding, and in model II, minibasins continued to deepen on the slope. In the early Miocene of both models, a large minibasin in the modern mid-shelf region inverted to become a faulted turtle structure above allochthonous salt. In model I, the basinward end of the canopy formed a Sigsbee-like salt overthrust that climbed section and overrode Frio–middle Miocene slope sediments.

Salt withdrawal from the autochthonous level is a possible alternative to the Paleogene canopy indicated in both models I and II for present-day coastal Louisiana and the inner shelf. The implications of autochthonous solution include collapse of onlap onto a large rolling fold within the 4-km-thick subdetachment stratigraphy (Figure 37). There are several arguments against this autochthonous salt model. (1) It is inconsistent with allochthonous salt penetrations onshore and (2) inconsistent with mapped subdetachment salt-collapse structures (Figure 18). (3) It is unlikely that thick salt would remain undeformed beneath 4 km of Cretaceous–Eocene sediments until Oligocene time. (4) Although geometrically admissible, it is unlikely that a shale-based gravity slide would develop over a detachment surface dipping steeply landward, and (5) it is also unlikely that the 4-km-thick subdetachment section could be deformed by a rolling fold mechanism requiring folding and unfolding. Finally, (6) the salt-based detachment model is preferred because analogs in the Pliocene–Pleistocene trend are well known whereas no example of a rolling fold and backward-sloping detachment is known to us.

A possible objection to the regionally extensive Paleogene canopy proposed in model II is that many areas, particularly the western Louisiana inner shelf, are devoid of salt domes or other remnant shallow salt. However, salt-withdrawal fault systems are not always associated with remnant shallow salt, and large areas of salt evacuation may be difficult to recognize. Both models I and II imply efficient salt evacuation by lateral flow and/or dissolution. Although there is abundant remnant shallow salt in the central Louisiana Pliocene–Pleistocene detachment province offshore, considerably less is present in the same province offshore western Louisiana, where the salt-based detachment is also documented by drilling. In the East and West Cameron outer shelf in this province, there is a region of about 80 km dip extent and 65 km strike extent underlain by a salt weld without shallow secondary salt domes present (Figure 3). In another example in southern Texas, a salt interval was cored at the level of detachment for Frio growth faults in southern Texas, where the nearest salt dome is 80 km away in an older fault system and the nearest known shallow salt in the same age fault system is over 300 km away. These results challenge the dogma that the distribution of salt domes in a basin reflects the distribution of original salt deposition.

By late Miocene time, thin salt flows formed in the upper slope of both models I and II. In model I, this salt had sources at both the autochthonous and allochthonous Paleogene levels. In model II, this salt was fed entirely from allochthonous salt at the allochthonous Paleogene level. By Pliocene time in both models, additional shallow salt flows formed farther down dip. These flows coalesced on this line of section to form an organized roho system, but farther east toward the depocenter, flows were constrained by higher sedimentation rates and remained isolated to form a disorganized roho system. In model II, the flows rooted to the evaporating Paleogene canopy. As the Miocene flows continued to inflate, the updip parts were deformed and evacuated by Pliocene sediments at the prograding shelf edge. From Pliocene to Recent time, allochthonous salt extruded in the Miocene–Pliocene was largely evacuated into domes out of the plane of section and basinward by continued progradation of the shelf margin depocenters. Both models imply significant loss of salt from the plane of the section, partly due to accumulation in salt domes out of the plane, but probably largely due to dissolution (see Chapter Appendix).

The four main differences in tectono-stratigraphic evolution highlighted by the alternative reconstructions of models I and II are given in Table 1.

In summary, model II is favored mainly for two reasons. First, seismic observation of the base of salt subparallel to Paleogene horizons on the mid-slope is consistent with model II. Second, although the present-day structure is simpler in model I, the restored Oligocene structure is simpler in model II, and there is no apparent reason to restrict salt extrusion to only the upper part of the Paleogene slope.
DISCUSSION AND CONCLUSIONS

Our current understanding of the structural evolution of the northern Gulf of Mexico Basin is based on improved seismic imaging, deep structural mapping, palinspastic analysis using biostratigraphic correlations, and an analog approach that uses developing structures on the modern slope to understand the early history of older structures on the shelf and onshore. There are still large areas of the basin where the deep structure is obscure and reliable correlations are impossible. In these areas, interpretations and reconstructions are necessarily speculative. Improved imaging and analysis have changed our understanding of Gulf Coast evolution, and it is reasonable to assume that these advances will continue.

The use of modern and Pliocene–Pleistocene analogs for the early history of older structures, although striking in many cases, may be limited by dramatic changes in sedimentation rates and styles of deep-water sediment dispersal through time. Palinspastic reconstructions results are limited by lack of adequate seismic imaging and stratigraphic correlations in many areas. Reconstructions typically provide viable alternative evolutionary scenarios but not unique solutions. Salt-withdrawal estimates based on backstripping are limited by uncertainties in paleowater depths and residual tectonic subsidence (an error in water depth produces twice the error in salt withdrawal, and an error in tectonic subsidence produces 2.8 times the error; see Chapter Appendix and Figure A-1). Other sources of error include uncertainties in densities, velocities, and deformation histories, as well as unaccounted flexural effects and complexities in the thermal history of the margin due to rapid sedimentation and complex salt structures. Subsidence analysis for salt withdrawal is useful for finding first-order phenomena such as distinguishing salt-based from shale-based detachment systems, but it is unlikely to be a sensitive indicator of paleobathymetry or sea level changes.

Large-scale salt withdrawal provides a solution to the long-standing problem of production of accommodation space for extremely thick deltaic sections in the Cenozoic. Our observations and analyses argue for large-scale evacuation of a Paleogene salt canopy that extended across most of the margin, from the present onshore to the present middle slope, from southern Texas to central Louisiana. We interpret salt-withdrawal features updip and to the east of this canopy as more isolated structures rooted to the autochthonous level or as isolated allochthonous salt bodies not coalesced into a canopy. The location of this transition is not well known to us in many areas. Younger allochthonous salt structures in the outer shelf and upper slope from southern Texas to central Louisiana are tentatively interpreted to be rooted to this older allochthonous level rather than the autochthonous level. This scenario is probably misleading in its simplicity. The complexity, variety, and three-dimensional nature of structures in the region present many additional problems.

The tectono-stratigraphic provinces described here are nongenetic, but we have presented interpretations of their origins and interrelationships. Although subject to refinement and realignment of boundaries, the provinces may remain useful first-order divisions even as new data become available and new concepts are developed. The variation in structural style from the salt dome–minibasin province to the salt-based detachment provinces is interpreted in two ways. Salt domes and related counter-regional fault-bounded minibasins occur either as (1) a downdip component of the fully evolved salt-based detachment system (mid-shelf sector) or as (2) evacuated allochthonous salt bodies that never coalesced into an extensive sheet (updip and eastern sectors).

The variation in structural style from the tabular salt–minibasin province to the salt dome–minibasin province is probably a difference in the extent of salt withdrawal, with basins on the slope surrounded by tabular salt evolving into fault-bounded basins flanked by residual salt domes, mainly on the shelf. The presence of contractual structures at the toe of allochthonous salt bodies may also be due to the extent of salt withdrawal, with early contractual systems developed on the slope inverting to become large-displacement counter-regional faults on the shelf. Variation within the Pliocene–Pleistocene roho systems, from organized to disorganized areas, remains unexplained. The comparison of sub-detachment structure beneath the Oligocene–Miocene detachment (Figure 18) and the deep structure beneath the southern Texas Wilcox fault system (Figure 28) highlights the influence of Mesozoic salt structures, and possibly pre-Louann structures, in determining the style and geometry of Tertiary growth fault systems.

Worrall and Snelson (1989) noted a difference in structural style between the Louisiana and Texas parts of the Oligocene–Miocene detachment province, with more linear faults typical of Texas and more arcuate fault patterns in Louisiana. This difference is quantitative rather than qualitative. Similar structures occur on both sides of the

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The tectono-stratigraphic provinces described here are nongenetic, but we have presented interpretations of their origins and interrelationships. Although subject to refinement and realignment of boundaries, the provinces may remain useful first-order divisions even as new data become available and new concepts are developed. The variation in structural style from the salt dome–minibasin province to the salt-based detachment provinces is interpreted in two ways. Salt domes and related counter-regional fault-bounded minibasins occur either as (1) a downdip component of the fully evolved salt-based detachment system (mid-shelf sector) or as (2) evacuated allochthonous salt bodies that never coalesced into an extensive sheet (updip and eastern sectors).

The variation in structural style from the tabular salt–minibasin province to the salt dome–minibasin province is probably a difference in the extent of salt withdrawal, with basins on the slope surrounded by tabular salt evolving into fault-bounded basins flanked by residual salt domes, mainly on the shelf. The presence of contractual structures at the toe of allochthonous salt bodies may also be due to the extent of salt withdrawal, with early contractual systems developed on the slope inverting to become large-displacement counter-regional faults on the shelf. Variation within the Pliocene–Pleistocene roho systems, from organized to disorganized areas, remains unexplained. The comparison of sub-detachment structure beneath the Oligocene–Miocene detachment (Figure 18) and the deep structure beneath the southern Texas Wilcox fault system (Figure 28) highlights the influence of Mesozoic salt structures, and possibly pre-Louann structures, in determining the style and geometry of Tertiary growth fault systems.

Worrall and Snelson (1989) noted a difference in structural style between the Louisiana and Texas parts of the Oligocene–Miocene detachment province, with more linear faults typical of Texas and more arcuate fault patterns in Louisiana. This difference is quantitative rather than qualitative. Similar structures occur on both sides of the
state line, but perched detachments are more common and extensive in Texas, whereas regional fault trends are more arcuate in Louisiana. Even within the “linear” fault trends of Texas and western Louisiana, detailed mapping usually shows linear fault systems to be composed of complexly nested arcuate faults. Worrall and Snelson (1989) attributed these differences to the dominance on the Texas shelf of Tertiary strandplain and barrier island depositional environments as contrasted to the alluvial and deltaic environments more typical of offshore Louisiana.

It is unlikely that geologically rapid shifts of depositional environment on the shelf would radically change the geometry of an active fault system that spans dozens of sequences and began in the slope environment. We suggest a slight modification of this concept. Perhaps the style of deposition initially deforming allochthonous salt on the slope is the most important factor determining the ultimate structural style, even though changes in depositional style on the slope are likely to be related to different depositional styles on the shelf (e.g., line sources or point sources for deep-water deposition related to differing shelf environments). The origin of perched detachments may also be linked to the presence of shales likely for detachment, such as the Jackson and Anahuac shales of Texas.

The extent and origin of the toe-of-slope foldbelts are also not well known. Foldbelts may be entirely absent in some areas or perhaps merely obscured by allochthonous salt overriding the basinward depositional limit of autochthonous salt. The timing of the known foldbelts does not appear to correlate in a simple way to the timing of updip extension, which persisted throughout the Cenozoic (compare Peel et al., 1995). Perhaps changes in slope or reduction of deep salt, which compensates for most of the extension, are important.

A final question raised by this discussion is the uniqueness of northern Gulf Coast allochthonous salt structures. Extensive allochthonous salt, including salt canopies, is reported from few salt basins (e.g., Great Kavir, Jackson and Cornelius, 1988; Jackson et al., 1990; Isthmian salt basin, southern Mexico, Correa Perez and Gutierrez y Acosta, 1983). Are Gulf Coast style allochthonous salt structures more common, but unrecognized, or are the scale and complexity of salt-related structures in the Gulf Coast unique?

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Chapter Appendix

Reconstruction Techniques

Two reconstruction techniques were used to restore syndepositional faulting in this study: the proprietary PREP computer program described by Worrall and Snelson (1989) and a proprietary finite-element program called MESH (Diegel and Cook, 1990). This finite-element technique preserves area, accounts for decompaction, and minimizes the shape change within fault blocks. The horizontal component of unfaulted bed length is preserved, and footwalls are not assumed to be rigid. The method used for each reconstruction is noted in the captions. Paleobathymetric slopes are assumed to be constant through time with respect to the position of the prograding shelf margin, with a maximum slope of 1.5°. Because of the probability of three-dimensional flow and dissolution, salt area is not preserved. Instead, salt thicknesses through time are estimated from a one-dimensional isostatic calculation described below and by Diegel and Cook (1990).

Subsidence and Salt Withdrawal

A fundamental problem of Gulf Coast geology is to explain the great thickness of shallow water Tertiary strata on a Mesozoic passive margin. Barton et al. (1933, p. 1457) clearly recognized the problem early in the history of Gulf Coast exploration:

The Gulf Coast geosyncline arouses isostatic meditation. ... Isostatically, the Gulf Coast geosyncline must be, and for a long time must have been, negatively out of equilibrium. Subsidence continued, however, and presumably must have increased the lack of isostatic equilibrium, as the progressive depression of the basement has increased the negative gravity anomaly. The movement, therefore, has been the reverse of what would be expected from the theory of isostasy.

Barton et al. (1933) were correct in noting that isostatic loading could not account for Gulf Coast subsidence and suggested that basement subsidence was caused by yielding of the crust beneath the sediment load to form a “geosyncline.” They concluded their argument (p. 1458) with a note of uncertainty about this interpretation, however:

The surface in the Gulf Coast seems to have remained nearly at sea-level. ... The subsidence, therefore, seems more probably to be the effect of the sedimentation and to have tended to compensate it. But the subsidence can not be the effect of a movement toward isostatic equilibrium under the effect of the extra load of the sediments. ... [The subsidence] seems more easily explainable not as an effect of the sedimentation but of some dynamic cause. ... But the close equivalence of subsidence and sedimentation is not so easily explained by such a dynamic cause.

Thermal and isostatic subsidence alone cannot account for over 6 km of shallow water sediment deposited in the upper Tertiary on a passive margin where rifting occurred in the Jurassic. The rate of thermal subsidence of a passive margin decreases exponentially with time and is also proportional to crustal attenuation, where oceanic crust represents a maximum thermal subsidence case (Parsons and Sclater, 1977; McKenzie, 1978; Le Pichon and Sibuet, 1981; Sawyer, 1985). Therefore, by comparison with the North Atlantic (Williams, 1975; Sawyer, 1985) and with theoretical subsidence histories (McKenzie, 1978; Le Pichon and Sibuet, 1981), a reasonable maximum for the excess subsidence (as defined in Figure A-1) since rifting is about 2.3 km (equal to ~3.2 km
Figure A-1—One-dimensional isostatic balance including salt withdrawal and paleobathymetry. Excess subsidence is defined by $Y'$. 

Weight Column A = Weight Column B 
$W = (0.92)Z - (1.98) \Delta w_d - (2.83)Y'$

Figure A-2—Magnitude of the subsidence problem in southern Louisiana. Backstripping of 6 km of sediments (column A) requires about 2.7 km of change in water depth (column B). Using a reasonable estimate of 200 m change in water depth still leaves 1.4 km of unaccounted excess subsidence (column C) that could be balanced by 400 m of excess thermal subsidence and 4 km of salt withdrawal (column D).
of conventional tectonic subsidence, including a hypothetical water column). Significant thermal subsidence continued for about 150 m.y. after rifting, but the bulk of this subsidence occurred in the first 100 m.y., with an exponential decline. Even a linear distribution of the total excess subsidence over 150 m.y. suggests that 400 m is a conservative estimate for the maximum excess thermal subsidence since the end of the Oligocene on the Gulf Coast margin.

For the post-Oligocene subsidence to be the result of isostatic loading, a top Oligocene water depth of about 2700 m would be necessary (Figure A-2), but we know from interpretation of depositional environments and faunal picks that this area was on the continental shelf at that time. Even given crude approximations of densities and ignoring decompaction, the magnitude of this discrepancy is impressive. Additional space created by a component of thermal subsidence is also insufficient to account for this subsidence. Using salt withdrawal as an unknown and using an estimated paleowater depth, a simple one-dimensional Airy isostatic model estimates the magnitude of salt withdrawal (Figure A-1). A plot of the total subsidence and backstripped subsidence as a function of age highlights the profound subsidence anomaly in Miocene time (Figure A-3). As noted by Barton et al. (1933), this subsidence anomaly migrates basinward with the prograding depocenters (Figure A-4). Salt withdrawal is the "dynamic mechanism" sought by Barton. Thick Louann salt, deposited in the Mesozoic, in effect stored the early subsidence of the basin for reuse by the prograding Cenozoic clastic margin that displaced the weak salt.

The backstripping technique (Steckler and Watts, 1978) can also be applied to deformed cross sections. Rather than using thicknesses from a single well, we reconstructed the fault motions above the detachment and measured changes in overburden thickness accounting for lateral translation and rotation of fault blocks. Estimated salt thickness was then added to the reconstruction (see Figures 15, 16). Although this technique estimates the amount of salt withdrawal, it does not locate the level of the evacuation surface. Two possible models are that the salt was withdrawn from the autochthonous Louann level (Figure 15) or that the detachment for listric growth faults represents a salt weld that formerly contained a thick, allochthonous salt body (Figure 16).

We prefer the allochthonous model for several reasons. (1) Salt penetrations occur along the Oligocene–Miocene detachment in western Louisiana. (2) The geometries resemble those above the shallower Pliocene–Pleistocene detachment systems, and we know of no example of a listric detachment formed in response to a rolling fold of salt beneath several kilometers of deep-water sediments. (3) The thinning wedge above the detachment suggests a collapsed onlap similar to the previous described examples from the outer shelf. (4) Subdetachment counter-regional faults provide a means for extrusion of the Louann salt to the level of the Oligocene seafloor. Finally, (5) it seems mechanically unlikely that a thick salt layer would remain undeformed beneath thousands of meters of sediments that thicken into counter-regional growth faults of pre-Oligocene age.
Salt Budget and Dissolution

Thick accumulations of shallow-water sediments and presumed lack of significant tectonic subsidence indicate that a large amount of salt-withdrawal subsidence has occurred in the Gulf Coast basin. Certainly a large component of lateral flow of salt is reflected in the Sigsbee salt mass. Although the Sigsbee salt body along the reconstructed profile may not be representative regionally, its area above the Paleogene level is about 320 km², which corresponds to an average salt thickness of 1100 m over the 290-km length of the section from the head of the Oligocene–Miocene detachment to the updip end of the Sigsbee salt mass. This area of salt accounts for less than half of the original 2.4-km salt thickness estimated from subsidence analysis using the method discussed previously. Shallow salt bodies out of the plane of the section probably account for a small part of the remainder, with dissolution completing the salt balance.

Although downbuilding relative to sediments is necessary to explain the height of Gulf Coast salt stocks, evidence of structural truncation and caprock indicates that there has also been considerable upward flow compensated by dissolution. Accumulation of anhydrite residue in caprock implies that thousands of feet of salt have been removed from the crests of onshore salt domes (Goldman, 1933). This interpretation is also supported by the truncation of vertical foliation observed in shallow salt mines (Balk, 1949, 1953; Hoy et al., 1962; Kupfer, 1962). Bennett and Hanor (1987) attributed increased formation water salinity in the vicinity of Welsh salt dome, onshore southern Louisiana, to active dissolution. They estimate that a minimum of 6 km³ of salt was dissolved into the present formation waters. Although salt was penetrated at 2050 m depth at Welsh, no caprock was reported. Seni and Jackson (1983), on the basis of withdrawal basin volume, estimated that almost half of the mobilized salt of the East Texas salt basin was dissolved (380 km³ of a total volume of 800 km³). Caprock, although common in East Texas, is not thick enough to account for all of this volume loss. Seni and Jackson (1983) inferred that the loss occurred by erosion and dissolution at the seafloor rather than solely by circulating groundwater.

Evidence of salt dissolution is not limited to the onshore area. Average Gulf Coast formation waters are more than four times more saline than seawater, and many authors believe this is because of salt dissolution (for review, see Hanor, 1983). If halite is exposed to seawater, either directly by uplift and erosion, sea level drop, or extrusion or indirectly by contact with flowing pore water, it will dissolve. Although caprock is only reported from 5 of 77 cored offshore salt domes (Halbouty, 1979), one of the Eureka cores in the upper slope encountered 36 m (117 ft) of anhydrite caprock above a salt massif (Lehner, 1969). This amount of caprock would require a minimum of about 2300 ft (700 m) of anhydrite caprock above a salt massif (Lehner, 1969). This amount of caprock would require a minimum of about 2300 ft (700 m) of salt dissolution (assuming an average 5% anhydrite content of Louann salt). Manheim and Bischoff (1968) reported salinity gradients approaching saturation in formation waters encountered by Eureka core holes near salt bodies in the upper slope and interpreted these gradients as indicators of active slope salt dissolution. At least one slope minibasin is known to have a stable brine pool (Trabant and Presley, 1978). This brine occurrence was discovered when pore waters in research cores were found to be eight times more saline than seawater.
Salt dissolution is undoubtedly occurring in other parts of the slope even though the seafloor structure does not always allow stable brine pools to form. Burk et al. (1969) reported caprock in core recovered from the Challenger Knoll in the Sigsbee abyssal plain. Apparently, circulating meteoric water is not necessary for salt dissolution to occur. Caprock on the shelf may be periodically exposed at the seafloor by extrusion or sea level fluctuations and removed by erosion. The allochthonous Sigsbee salt mass overrode the abyssal plain sediments with its upper surface at or near the seafloor throughout the entire Cenozoic era. Similarly, an extensive Paleogene salt canopy extruded near the sea floor would have provided the opportunity for large amounts of dissolution in the past. Without an impermeable pelagic mud drape, we might expect cumulative dissolution to be more extensive than implied by the reconstructions presented here (compare Fletcher et al., 1995, in this volume).