Rift models and the salt-cored marginal wedge in the northern Gulf of Mexico: implications for deep water Paleogene Wilcox deposition and basinwide maturation

James Pindell and Lorcan Kennan
Tectonic Analysis, Ltd., Chestnut House, Duncton
West Sussex, GU28 0LH, UK
Email: jim@tectonicanalysis.com

Abstract

Two primary issues continue to plague geological assessments of the Gulf of Mexico. The first is the common view of “mother salt”, with terms such as “basinward depositional limit” or “onlap limit” of salt being used in reference to the deep Gulf basin without apparent concern for whether or not this limit is depositional. Backstripping techniques clearly show that the crust in the deep Gulf is typical oceanic crust, accreted (crystallized) at about 2.7 km paleo-water-depth, such that this contact cannot be a depositional one if the salt was deposited in shallow water in a basin more or less full to sea level. We argue that the seaward salt limit, even where not reactivated in the Tertiary, is a structural contact formed by salt flow onto oceanic crust. The second is the portrayal of the abyssal plain continuing well north of today’s continental slope prior to the Miocene, and approaching the Sligo-Stuart City carbonate shelf edge (to beneath present-day onshore areas) in the Late Cretaceous. These portrayals appear to presume that the Louann Salt was conveniently “stored” beneath the northernmost abyssal plain (i.e., without bathymetric expression) until the Cenozoic. This paper sets out to revise these long-held concepts, and to replace them with alternatives that explain primary observations in the Gulf much better. We start by assessing the Jurassic rift configuration and its impact on subsequent basin development, which in our view was very different to traditional models. We propose that a “salt-cored marginal sediment wedge” existed between the Sligo-Stuart City carbonate shelf edge and the deep water Wilcox trend which provided a continuous (but perhaps stepped) continental slope, down which Wilcox clastic sediments were free to flow from source to sink without first having to cross hundreds of kilometers of flat abyssal plain to reach their final position. In addition, the analysis hints at a mechanism for the incision of deep canyons (e.g., Yoakum) along the northern and western Gulf shelf margins and leads us to propose a new maturation mechanism in the northern Gulf margin.

Introduction

We highlight the effect that the style of Jurassic rifting and early salt behavior had on Paleogene deposition of units such as the deep water Wilcox in the northern Gulf of Mexico, emphasizing four processes
that are often overlooked but which exercise first-order control on Paleogene aspects of the northern Gulf of Mexico’s petroleum systems:

[1] Asymmetric rifting limited the amount of thermal subsidence in the northern Gulf margin, kept the depositional surface much shallower than is often thought and limiting the thickness of Mesozoic shelf and slope strata prior to Paleogene elasic input and regional failure of an evaporite-cored shelf and slope outboard of the Early Cretaceous shelf edge. At the beginning of the Tertiary, due to movement of the underlying salt, the margin was probably stepped in profile with one or more intraslope plateaus (similar to the seafloor of the Sigsbee salt today) bounded by short slope segments, but the Mesozoic and Paleogene morphology of this marginal wedge of evaporite and sediment is not yet well resolved.

[2] The salt-basement relationship formed in two ways. The first is when salt was being deposited above zones of active basement stretching and/or accretion of oceanic-type crust, such that salt must have been extended and thinned as basement stretching or basalt accretion occurred. We propose that basinward salt movement at this stage was accommodated by gravity-driven deflation where basement stretching had already ceased (landward) and by contemporaneous flow of salt where basement stretching and basalt accretion continued in the center of the Gulf basin. The accommodation space created by this syn-salt stretching/accretion drew in new sea water which evaporated and continuously kept the basin filled with “new” salt, maintaining the depositional surface of the salt basin at sea level, even in the basin’s center. In the zone of continued crustal stretching and basalt accretion, the contact between salt and basement is entirely structural, achieved by continuous lateral flow of the salt toward the central stretching zone of the basin. Because there was no “free face” to the salt during this stage, this contact is not a thrust onto pre-existing basement overlain by water or sediment.

The second way the relationship formed postdated salt deposition (probably early Oxfordian), possibly due to a change to a wetter climate. As seafloor spreading continued, the salt on both sides of the Gulf collapsed basinward toward the site of plate accretion, to produce the thin wedge-shaped relationship that is seen on seismic today and often interpreted as stratal onlap. Our model predicts a maximum salt thickness in the central Gulf was at least 5.5 km and possibly as much as 7 km at this time. Oceanic crust continued to form in the central Gulf after the end of salt deposition and the process of salt-stretching continued until such time as the salt had achieved a relatively stable basinward-dipping wedge shape.

However, late Oxfordian and younger accommodation space above stretching salt was now filled not by new salt, but by sediment and water. In our view, there never was a “basinward limit of mother salt deposition” and there never was emergent basement upland in the central Gulf. The feather edge seen on seismic data was achieved entirely through gravity-driven collapse and spreading of salt. We also observe that a “salt fit” between Yucatán and the US margin never existed, because the end of salt deposition occurred before the US and Mexican salt edges had separated and because there is no particular reason for the end of basinward salt flow over the newly accreted oceanic crust to be synchronous along strike. Indeed, our Yucatán rotation
models suggest that in the eastern and western Gulf the salt edges had separated during the Late Oxfordian, but in the central Gulf, flow continued, and thinned Mexican and US salt remained in contact, until perhaps earliest Tithonian time, some 10 Ma after the end of salt deposition.

[3] Although the morphology and how it changed through time are still poorly defined, the salt-cored marginal sediment wedge formed a basinward sloping surface that filled the gap between the very shallow environments of the Sligo/Stuart City carbonate shelf margin and the abyssal plain in the vicinity of the deep water Wilcox in the deep Gulf. The existence of a broad, gradual slope from the shelf edge to the distant abyssal plain, cored by mobile salt situated structurally higher than the abyssal plain, contrasts with many previously proposed paleogeographic interpretations which carry the abyssal plain environment very close to the Cretaceous carbonate shelf edge (similar in appearance to present-day Florida). Thus, in these previous interpretations, the deep water Wilcox depocenter appears to lie far from the toe of the slope whereas in our view, the Wilcox sands have been deposited at the toe of the slope.

[4] On the shoreward part of the salt-cored marginal wedge, Jurassic and Cretaceous source rocks were deposited in a relatively thin Mesozoic section. Because the marginal wedge sloped basinward, clastic sediments, including the large volumes of the Paleogene, bypassed the wedge and were delivered to the toe of the wedge. Thus, thermal maturation within the marginal wedge setting would likely have been delayed until structurally driven modes of burial took place. Starting in the Paleogene, salt was displaced by local structurally controlled minibasins of clastics bounded by basin-facing and counter-regional growth faults which sole into mother salt or higher salt welds. The effect was to carry initially immature source sections downward into warmer environments atop collapsing hanging walls, whose supradjacent accommodation space was synchronously filled by Wilcox and other Paleogene units. We call this mechanism of maturation the “elevator maturation model”, the effect of which was to form local pods of early maturation until the process became so predominant that the Paleogene began to form a regional depositional unit of great thickness, albeit structurally complex. Farther basinward at the toe of the marginal wedge, maturation by normal burial and thrust mechanisms predominate.

Finally, we speculate that incision of the Paleogene paleo-canyons (e.g., Yoakum) around the northern and western Gulf rim may have been caused by episode(s) of isostatic rebound of the shelf due to downdip basinward shifts of mass in the marginal wedge. In order for this to occur, the shifts in mass must have exceeded that possible by expanded growth faulting alone, where sedimentation keeps pace with accommodation space. Instead, we suspect that downdip shortening and salt inflation exceeded updip extension and salt deflation. Further, these possible basinward shifts in mass may have been triggered by external events such as (1) the Chicxulub impact and associated mega-earthquakes which destabilized the margin, and/or (2) rising Laramide flexural forebulges at the updip (western) edge of the earliest Paleocene slope, thus raising the shelf and tilting the slope basinward. In middle(?) Wilcox time, some of these shifts may have been episodic and large enough to have caused isostatic rebound of the shelf margin and sub-regional relative sea level drops of perhaps 200-400
meters. As a result, rivers flowing into the Gulf at that time (e.g., Yoakum) incised shelf strata to form the canyons.

Asymmetric rifting of the northern Gulf footwall and implications for paleobathymetry

Pindell et al. (1986), Marton and Buffler (1994), Pindell and Kennan (2001), and Pindell (2002) have advocated asymmetric rifting in the Gulf of Mexico, in which the U.S. side is the footwall and northwest Yucatán the hanging wall. Figure 1 depicts the geometry and lithospheric configuration of the basin from on onset of rifting in the Early Jurassic (Fig. 1A), through the end of rifting and the onset of ocean crust formation (Fig. 1B) to normal ocean spreading in the central Gulf by Late Jurassic time (Fig. 1F). Note that in the asymmetric model, maximum crustal stretching occurs in the north, but maximum lithospheric extension occurs in the south. Because crustal stretching in the northern Gulf (footwall) far exceeds upper mantle stretching, creation of syn-rift accommodation space greatly exceeded long-term post-rift thermal subsidence. Thus, the rift facies (red beds and evaporites) appears to be far thicker than the post-rift Mesozoic marine section in the northern Gulf; furthermore, the post-rift Mesozoic marine section may be far thinner than has often been thought. Conversely, the Yucatán side of the Gulf shows little syn-rift subsidence but significantly more thermal subsidence; basement can be drilled beneath upper Jurassic marine strata, but the Early Cretaceous carbonate section is substantially thicker (McFarlan and Menes, 1991).

Because of this reduced long term thermal subsidence on the footwall side of the Gulf, the syn-rift section (red beds and evaporite) will subsequently remain structurally higher than is predicted by uniform stretching models such as that of McKenzie (1978). Furthermore, if the evaporite section on the footwall setting of little upper mantle thinning had filled the syn-rift basin to sea level, which seems clear in the Gulf, then the depositional surface on top the evaporite may remain much higher (perhaps as much as 3 km, Fig. 2) than oceanic crust over time, unless the salt thins by early basinward collapse to nearly zero thickness.

Along the northern Gulf margin, this principle of reduced thermal subsidence would be manifested by the maintenance of a relatively shallow drowned shelf that extended well south of the present day coastline offshore. Data from several wells hint at such a drowned shelf. For instance, at Norton (Garden Banks 754) the thickness from salt to a neritic Aptian section is only 300 m, and top Paleocene at 600 m above salt is apparently deposited at bathyal (500-1000 m) water depth (D. Jarvie, Humble, pers. comm., 2002; Minerals Management Service, 2007). Also, immature kerogen in the Jurassic section (Ro 0.3-0.6) shows that the area was never deeply buried. Of course, Norton may have been buoyed up above a salt swell or diapir and bounded by deep minibasins, but there are other wells (e.g., Showboat; Dohmen et al., 2002) which show a similarly slow apparent subsidence history (Minerals Management Service, 2007), and which more importantly show preservation of outer shelf environments into the Cretaceous and bathyal environments into the Paleogene even beyond the present-day shelf slope break. The consistently shallow water depths and thin stratigraphy from Norton means that it cannot have started deep and shallowed as flanking sedimentation built up from the basin.
Figure 1 A-C. Sequential cross-sections showing the evolution of the Gulf of Mexico from the onset of asymmetric rifting to the transition to proto-ocean crust formation (in the form of seaward dipping reflectors, or SDR’s, and, possibly, sheeted dykes emplaced below earliest salt).

Figure 1 D-F. Sequential cross-sections showing the transition from subsalt emplacement of proto-ocean crust in the central Gulf to true submarine emplacement of typical oceanic crust no earlier than middle Oxfordian time.
floor; it and bathymetry of surrounding areas has always been shallow. Although the subsidence history of Norton itself may be misleading, there cannot have been massive seafloor relief during the Paleogene and, thus, the proposed shelf drowned to only bathyal depths appears likely to be a regional and not simply a local feature.

Furthermore, given that regional seismic lines (e.g., Mount et al., this volume; Radovich et al., this volume) suggest a regional Mesozoic to Wilcox thickness of no more about 3-4 km below this ca. 1000 m paleobathymetric datum from Norton, the top of the salt at Wilcox time must have been no more than about 4-5 km deep, whereas oceanic crust just south of the present day salt canopy at this time was about 7.5 km deep (Fig. 2). When combined with a variety of basement types and subsidence models, this in turn implies that at least 4-7-5 km of salt cored the slope beneath Norton even as late as Wilcox time; the unlikely minimum basement depth below Norton is about 8-9 km, and the most likely (given recent seismic data and the present day basement depth) is about 11-12 km, compared to 15-16 km today.

These simple calculations are the basis for our proposal that the relatively shallow drowned shelf around the northern Gulf margin was cored by thick salt. Deeper than normal shelves by Wilcox time, we propose the term “salt-cored marginal wedge”, as described further later. In deep-water Cretaceous penetrations, we see that paleo-water depths had only reached upper bathyal (<1000 m) by the Maastrichtian. Thus, although it was progressively deepening, the salt-cored marginal wedge can be shown to have persisted into the Cenozoic as much shallower than the abyssal plain perhaps as far out as the northern Garden Banks area. Figure 2 shows what may be an extreme case, where Norton is relatively close to its present position. If it was in some way (we await the publication of suitable seismic) rafted into place, the inferred 1000 m paleo-depths may have been farther north than shown and the slope between Norton and the abyssal plain may have been closer to 1° than 2°. The position of the toe of the slope, in our view was located where we see a dramatic drop-off in the relief of inflated salt-cored folds to the south, not far north of Kaskida (see Fig. 5 of Lewis et al., this volume) and near Baja (see Fig. 5 of Winker, this volume).

How might this the salt-cored marginal wedge deepen with time? If we backstrip the regional Mesozoic sediment (ca. 3-5 km) from the Norton Wilcox datum (ca. 1000 m), the basement rises and the top of salt rises from ca. 4-5 km to ca. 2-2.3 km, making the perhaps unreasonable assumption that salt thickness remains constant. This apparent driving tectonic subsidence from end salt time (ca. 158 Ma) to Wilcox time (ca. 55 Ma) is only 70% of what we would expect if the area were underlain by middle Jurassic basaltic crust (see below) and is consistent with the asymmetric rifting model (Tectonic Analysis, unpublished flexural subsidence calculations). Forward models working from a template like that of Figure 1 are able to keep the driving tectonic subsidence to no more than about 800 m by the Aptian, and as a result the sediment thickness between salt and the Aptian (about 300m, possibly about 450 m if decompacted) provide for an Aptian water depth of less than 600 m at Norton even without salt inflation.

If the salt in the Norton area inflated, then basement subsidence would be higher. If the salt deflated as Mesozoic sediment was deposited (quite likely – see Mount et al., this volume), then basement subsidence could be lower than 2-2.3 km calculated. One conclusion quickly revealed by these calculations is that, when salt is
Figure 2. (A) true-scale, and (B) vertical exaggerated semi-schematic cross-section from the Cretaceous shelf edge through Norton to the abyssal plain showing the well constraints on bathymetry of the salt-cored marginal sediment wedge and shape of the lower slope.

Figure 3. Reconstruction of the salt basin at the end of salt deposition, underlain by rifted continental crust to the south and north and by "proto-oceanic" crust in the basin center, south of today's shelf edge. Salt is up to 7.5 km thick. This "salt-fit" map matches the rear of the basement step-up (see Figs. 7 and 8) rather than salt edges, unlike previously published models. Modified from Pindell and Kennan (2006).
present, conventional backstripping may tell us little or nothing about underlying subsidence history or basement type.

Another possible subsidence mechanism is probably basinward salt flow or creep induced by flexing of the basement surface downwards towards the rapidly subsiding oceanic crust outboard of the salt. This could cause the upper portions of the marginal wedge to deflate and flow basinward, leading to early salt tongues that spread towards the basin center over pre-existing Jurassic or Early Cretaceous sediments and which provide the detachment for the earliest fold belts underneath the younger Sigsbee Canopy (Frank Peel, pers. comm., 2001; Moore et al., 2002). The stable Sligo-Stuart City carbonate shelf edge may also relate to Mesozoic salt movement. This shelf edge is continuous and not broken up as might be expected if movements of underlying salt had occurred during or after its Aptian (and younger) deposition. We consider that any salt lying originally along this belt had flowed basinward by Aptian time, leaving behind a salt weld only, and an overlying stable substrate on which the carbonate shelf edge developed. Thus, we show the base of the Mesozoic section under the Cretaceous shelf edge as slightly deeper than the average top salt in Figure 2.

Structural accommodation of syn-rift salt deposition

Reconstructions of plate motions in the Gulf of Mexico region indicate that the US and Mexican salt were deposited in a single basin until early Oxfordian time (Fig. 3). The basement of this basin beneath the salt in the Early Oxfordian comprised extended continental crust and possibly some form of transitional or oceanic-type basaltic crust in its central part. The position of a transition to basaltic crust beneath the salt is the subject of debate, with some authors (e.g., Imbert and Philippe, 2005) place it close to the US coast, some place it beneath the present-day shelf edge (Marton and Buffler, 1994), and more conservative models place it close to the edge of salt except under the Sigsbee salt canopy, where it may lie about 150 km north of the Sigsbee Escarpment (e.g., Pindell et al., 2000). Sediment back-stripping (Tectonic Analysis, 2006) and seismic refraction studies (Marton and Buffler, 1994) indicate that south of the present-day shelf edge the crust has effectively oceanic physical properties (density, velocity, heat flow, subsidence history), and may comprise intensely extended continental crust, probably with a substantial component of magma intrusion, or basalt, perhaps in the form of sheeted dykes or sills at or below the salt. Furthermore, the ca. 15 km of sediment (e.g., Radovich et al., this volume) south of the present-day shelf edge is hard to explain unless the basement is essentially oceanic (even depth dependent extension models cannot subside basement faster than oceanic crust).

Between rifting in the early Jurassic and the transition to accretion of proto-oceanic subsalt crust, 300-500 km (increasing west) of motion between Yucatán and North America had occurred by the time salt deposition ended in the early or middle Oxfordian. The majority of this strain took place over some 10 million years in the Middle Jurassic (e.g., Pindell, 1985; Marton and Buffler, 1994). Unless salt deposition took place only at the end of this period of extension or accretion, at least the older portions of the salt must also be extended, along with the underlying crust. However, in that case, the Gulf would have been the site of an
enormous and very deep lake or interior seaway, for which evidence is lacking. Thus, we infer that the Gulf evaporite was deposited during some of the intra-continental extension or accretion of subsalt proto-oceanic crust, perhaps over some 10 million years. Furthermore, evaporite, specifically halite, is the predominant lithology that filled the accommodation space created by the crustal extension because the arid, intra-continental, Mid-Jurassic climate apparently was not conducive to other types of sediments entering the Gulf. Thus, in the areas of early salt deposition, we expect it to have undergone large magnitude syn-depositional extension.

We assume that (1) evaporite is primarily a shallow water deposit; (2) subsidence and evaporation draws a continuous supply of sea water from one or more marine connections across the surface of the basin at near zero depositional depth; and (3) this is a steady state process that persists until the climate becomes wetter or a fundamental change in paleogeography takes place (e.g., tectonic termination of basin isolation). Where crust and early salt are being stretched, and extension is causing local salt necking, subsidence may have been faster than in adjacent areas. Deep-water salt deposition may be possible for very short periods, but salt deposition can happen so fast that such a setting would quickly fill, making the process transient; high evaporation rates can keep the accommodation space filled and ensure that the depositional surface remains effectively flat and near sea level.

In a widening evaporite basin, the salt-basement interface will be a structural rather than a depositional contact. The structure may be of at least two types. One is a discrete standard detachment fault, where the salt mass has actually slid across exhumed footwalls of the extending basement (or red bed) surface. A second type of structural contact with basement may be far more important for understanding basement-sediment relations in the Gulf of Mexico. The contact may be brought about by the “rolling” of salt onto a pre-existing surface, with little discrete shear, as the salt flows laterally to match underlying extension of pre-existing basement or intrusion of new basaltic, oceanic-type, crust. If the contact with basement has less strength than the interior of the salt (perhaps strengthened by enclosed sediment), it may show discrete, larger magnitude, shearing. With Yucatán separating from North America more or less northwest to southeast, and the basin confined to the west (Mexico) and east (Florida), strain in the salt is essentially biaxial. The rolling movement of salt into the center of the basin, where extension or accretion was concentrated, continually deflates the depositional surface, providing accommodation space for more salt.

We estimate the subsalt depth of the extending/accreting crust onto which this salt flowed during its extension at approximately 5.5-6 km. An early to middle Oxfordian reconstruction (Fig. 3) shows that Mexican and US salts more than overlap at this time, and there this no indication in geophysical data that the outer “mother salt” is underlain by a significantly mechanically different type of crust. Thus, basalt extrusion could not have been submarine prior to the middle Oxfordian. More or less normal oceanic-type crust of near zero age is typically accreted at about 2.6 km water-depth implying that the isostatic balance between a brim-full salt basin (density ca. 2.2 g/cc) and basaltic proto-oceanic crust lies at ca. 5.5 km (Fig. 3). We suggest that this is the minimum salt thickness in the central Gulf at the end of salt deposition. Because highly stretched and/or intruded crust at least as far north as the present-day shelf edge would have undergone some thermal subsidence by this
time (about 0.5-0.8 km) the original maximum thickness of salt could be as high as 7±0.3 km (in reasonable agreement with, for example, Diegel et al., 1995; Peel et al., 2005; McBride, 1998).

Salt flow towards the central Gulf after the end of salt deposition

A fundamental change in basin configuration occurred when evaporation and salt deposition waned and ceased. No more salt was added to balance the formation of oceanic crust and extension of salt in the basin center; the basin could no longer fill to sea level and necking of salt there would attempt to form a salt chasm or crack (Fig. 4; Pindell, 2002). However, steep “chasm walls” could not be preserved within salt of low shear strength. As before, lateral flow continued to roll more salt onto the young oceanic crust as it was created, with the most rapid flow occurring within the zone of the attempted salt chasm, where lateral pressure gradient was highest. The depositional surface of the zone of necking progressively deepened, forming a very broad, low-gradient V-shaped groove down the Gulf’s central axis of stretching. Accommodation space above the stretching salt was filled with water and, possibly, sediment. Towards the bottom of the V-shaped groove, salt continued to creep basinward onto progressively emplaced oceanic crust, until the flanks of the “chasm” were very gentle indeed. At some point, the necking salt mass approached gravitational equilibrium, possibly buttressed from further creep by early sediment fill within the groove of the early deep Gulf, meaning that the internal strength of the evaporite was able to maintain some critical dip angle defining the top of the deflating salt wedge. Basinward creep would then slow or stop completely, until some later event (e.g., mega-earthquakes, basin margin uplift, or thermal doming, reactivated it at a later time. Note that only after the opposing salt edges have pulled apart is it possible for sediment to be deposited on basaltic crust. Until this time, any sediment is deposited on stretching but subsiding salt and will itself stretch as salt continues to flow into the center of the basin.

The Red Sea (Fig. 5) may be a good analog for the Oxfordian Gulf of Mexico during its transition from stretching salt basin to site of submarine seafloor spreading. In some places, salt-cored margins are separated by a seafloor spreading center in the center of relatively steep-sided “chasms”. Salt glaciers can be seen in Red Sea seismic lines (Neil Mitchell, pers. comm., 2007) flowing basinward from the margins out onto the early oceanic crust. Along strike from these windows into oceanic crust, there are areas where the salt-cored slope continues to collapse from both sides of the basin and bury the oceanic spreading center. Because the Red Sea is so young and narrow, it is not clear what kind of slopes will eventually survive to support the flanking salt margins, but it is clear that, for several millions of years at least, salt-cored slopes can maintain significant gradients.

The contact where salt flowed onto the basaltic oceanic crust basement surface as it formed, although structural, looks depositional on seismic data because the salt accommodated to the shape of the underlying basement surface perfectly and because there appear to be no sediments between salt and basement (unlike the case of Cretaceous and younger salt tongues). The leading edge of the necking salt is often very thin, perhaps flattened by the overlying sediment, and thus it superficially looks like an onlap relationship with basement (e.g., Fig. 6 of Trudgill et al., 1999) and gives the misleading impression that the central Gulf was the site of a
Figure 4. (A) The onset of seafloor spreading required the attempted creation of a central Gulf “Salt Chasm” as plate divergence continued in the absence of active salt deposition. In this model, we show highly stretched continental crust beneath the salt, and show the onset of basalt intrusion coinciding with the end of salt deposition. (B) This is our preferred variation on the model, in which sub-salt basaltic crust intrusion starts several million years before the end of salt deposition. Salt thickness is definitely controlled by the isostatic balance of salt and new basalt (ca. 5.5-7 km). Only this thickness of salt explains bathymetric relief in the Paleocene Gulf and allows basement to be deep enough at Oxfordian time that it can subside to its present 16 km depth.

Figure 5. Red Sea (map rotated 90° to a more “Gulf-like” orientation) as an analog for the Oxfordian Gulf of Mexico after the onset of submarine oceanic crust formation. Like the Red Sea, the Gulf has: (1) a central belt of normal oceanic crust, flanked by salt-bearing rifted margins; (2) a central deep bathymetric chasm between shallower salt-cored shelves which have not (yet) collapsed and (3) at least one area in which salt has continued to flow basinward over basaltic crust, with salt on both sides of the basin remaining in contact. The “Afar Triangle”, a subaerial portion of “quasi-oceanic” crust, is not a good analog for the Gulf because no subsidence mechanism can get it as deep as Gulf basement today (see Fig. 6). Note the locations which may be analogous to those of Baha and Norton in the Gulf of Mexico.
possibly subaerial basement surface (*e.g.*, Cole *et al.*, 2001) that was onlapped from the north between Oxfordian and Early Cretaceous time. Some simple backstripping calculations (Fig. 6) demonstrate that this was definitely not the case: the oceanic basement in the Gulf is perfectly normal and was emplaced at about 2.7 km paleo-water depth. The salt feather edge near Baha and elsewhere is a structural relationship formed in deep water, and not near a paleo-shoreline. This view explicitly predicts that the strata immediately above the salt pinch-out are abyssal plain shales.

Simple isostatic balance calculations also provide an important insight into basement-salt relationships during this salt-necking process. We observe on seismic lines, from Texas, Louisiana, and Mexico, that there is a step-up of about 2-2.5 km in basement height more or less coincident with a dramatic basinward thinning of the salt (Fig. 7; see also Fig. 5 of Winker, this volume), beyond which sediment rather than salt overlies apparently normal oceanic crust. Calling the top of this step-up the continent-ocean-boundary (COB) is problematic, not only because there is no clear fit between the Mexican and US margins but also tends to assume that crust landward of this line is attenuated continent rather than basaltic.

Figure 8 presents a model first published by Pindell (2002) in which:

- “Oceanic crust” is initially emplaced beneath pre-existing salt at about 5.5 km.
- There is no implied time relationship between the end of salt deposition and the onset of basaltic crust formation.
- Once salt deposition eventually ceases, salt is allowed to stretch and collapse basinward as sea floor spreading continues, so as not to develop a very steep-walled, unstable salt chasm. We envisage a more modest slope of 1-2° degrees to the edge of the separated salt, although in the short term (5-10 Ma?) steeper slopes of up to 5° may have persisted, as in the Red Sea.
- The isostatically compensated depth of oceanic crust emplacement rises basinward as the salt collapses and thins basinward (*i.e.*, the ratio of salt to water in the isostatic balance drops), becoming submarine under an increasing depth of water, until it reaches zero thickness at a water depth of *ca.* 2.6 km. The gradient on the basement step appears to be typically about 4-5°.
- Where basinward creep of salt continued longer, the landward slope of the basement step-up is lower and in the most extreme case (central Gulf) may be almost imperceptible, which in turn leads to misinterpretation of the nature of the basement-salt relationship.
- Oceanic crust basinward of the step up to the toe of the collapsed salt wedge is emplaced horizontally at *ca.* 2.6 km.
- The buttressing effect of sediment in the oceanic tract between the collapsed salt toes and mantling the salt-cored slope eventually strengthens it enough to end basinward salt collapse. Within a few tens of kilometers from the salt toe, salt may be close to its original thickness of 5.5-7 km.
SUBSIDENCE MODEL: \( D = X + t^{1/3} \) (\( D \) = basement depth to basement, \( X \) is initial water depth, \( t \) is time)

For an Iceland or Afar like crust, \( X = 0 \) (whereas normal oceanic crust has \( X = 2.6 \) km)

In the Gulf, \( t \) (age) = 134–160 Ma (±144), thus \( t^{1/3} = 12 \) km, and tectonic subsidence is \( 12/3 = 4 \) km.

For every km of sediment added, basement subsides 70% and paleobathymetry shallows by 30%.

<table>
<thead>
<tr>
<th>Thought experiment results:</th>
<th>0 km</th>
<th>1 km</th>
<th>2 km</th>
<th>3 km</th>
<th>4 km</th>
<th>5 km</th>
<th>6 km</th>
<th>7 km</th>
<th>8 km</th>
<th>9 km</th>
<th>10 km</th>
<th>11 km</th>
<th>12 km</th>
<th>13 km</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Sediment</td>
<td>4 km</td>
<td>4.7 km</td>
<td>5.4 km</td>
<td>6.1 km</td>
<td>6.8 km</td>
<td>7.5 km</td>
<td>8.2 km</td>
<td>8.9 km</td>
<td>9.6 km</td>
<td>10.3 km</td>
<td>11.0 km</td>
<td>11.2 km</td>
<td>12.4 km</td>
<td>13.1 km</td>
</tr>
<tr>
<td>Top of Basement Water Depth</td>
<td>4 km</td>
<td>3.7 km</td>
<td>3.4 km</td>
<td>3.1 km</td>
<td>2.8 km</td>
<td>2.5 km</td>
<td>2.2 km</td>
<td>1.9 km</td>
<td>1.6 km</td>
<td>1.3 km</td>
<td>1.0 km</td>
<td>0.7 km</td>
<td>0.4 km</td>
<td>0.1 km</td>
</tr>
</tbody>
</table>

At known water depth in Gulf, basement would be only 5-6 km and sediment thickness only 1-2 km.

For perfect results every time.... simply add water!

At known basement depth and sediment thickness in the Gulf, water depth would be near sealevel.

Figure 6. A simple backstripping and subsidence calculation (equation from Parsons and Sclater, 1978) shows that the crust in the central Gulf cannot have originally formed near sea level. Basement reaches its present depth due to the combination of thermal subsidence and sediment loading. Thermal subsidence of Late Jurassic oceanic crust can be no more than 4 km. If it started at sea level no more than about 3 km of sediment can be added to get present-day bathymetry, but basement can be no deeper than about 7 km. Similarly, starting at sealevel we can recreate central Gulf basement depth if we add about 12 km of sediment, but this would result in bathymetry of only a few hundred meters. Only if basement started at ca. 2.6 km water depth can we easily recreate both bathymetry (> 3 km) and basement depth (ca. 12 km outboard of salt in Walker Ridge).

Figure 7. North-south seismic section (line-drawing from real data, courtesy of Shell E&P) in northeast Gulf, showing transitional continent-ocean boundary as well as basement step-up and collapsed(?) or stretched salt wedge, at the edge of normal ocean crust. True ocean crust morphology is relatively flat. Low amplitude undulations, when mapped in detail, are typical of ocean spreading fabrics.
Once salt creep has ended, we are left with anomalously shallow salt-cored bathymetry, because the 5.5-7 km original salt thickness cannot have fully collapsed within the known salt limits. This concept contrasts dramatically with the models of, for instance, Ings et al. (2004) who create bathymetry similar to that proposed here, but only by prograding enormous thicknesses of sediment, perhaps 2-3 times thicker than known Mesozoic in the Garden Banks and Keathley Canyon areas.

This simple model clearly needs further testing. For instance, new PSDM seismic data may allow us to better assess the relative volumes of salt and Mesozoic sediment beneath the younger canopies. It implies relatively simple and testable relationships between some first order features on seismic lines and the process of transitioning from subsalt basaltic crust to true submarine oceanic crust. In particular, it provides a solution to the “salt fit” problem.

There is no particular reason for basinward creep of salt to cease synchronously along strike; indeed, it probably persisted longest in the central Gulf. For example, an earliest Tithonian (ca. 148 Ma) reconstruction by Pindell and Kennan (2006) has the seismically constrained toe of mother salt beneath the Sigsbee Escarpment (US) and Sigsbee Knolls (Mexico) only just about to separate, the gap between salt toes in the western Gulf is ca. 200 km, and in the eastern Gulf is ca. 100 km. Thus, there is no easy way to match the salt edges on the US and Mexican sides of the Gulf to make an end salt deposition map. However, because the end of salt deposition and the onset of salt-thinning is synchronous across the Gulf, the landward edge (not the basinward edge used in most published maps) of the step-up must be the same age everywhere, effectively giving us a true “salt-fit isochron” with which we can make a more accurate early Oxfordian fit between Yucatán and North America (Fig. 3).

In turn, because the edge of continental basement is clear on the Yucatán side of the Gulf, we can propose a line for the “salt fit isochron” under the Sigsbee salt canopy, close to the north side of the Keathley Canyon and Walker Ridge protraction areas. This is the absolute farthest south possible limit of attenuated continental crust in this area, and farther south the “basement” beneath “mother salt” must be basaltic and the basement-salt relationship must be structural. The basement step always seems to coincide with a dramatic northward thickening of salt where it can be seen on seismic, and in turn we note that salt-cored detachment folds increase dramatically in vertical relief above and north of the step, as we would expect. We note with interest that our proposed position for the “salt fit isochron” under the Sigsbee salt canopy coincides with a belt of salt structures (Zarra et al., this volume) that appears to be northern limit of layer cake Mesozoic to Paleocene stratigraphy drilled at Kaskida (Lewis et al., this volume).

Figure 9 summarizes the relationships between salt and basement, and the possible bathymetry above the salt not long after the separation of the US and Yucatán salt edges (Oxfordian-Kimmeridgian boundary time, ca. 154 Ma) in the western and eastern Gulf. Figure 10 shows an outline map view of the northern Gulf of Mexico after salt edge separation in the western and eastern Gulf. We suggest that landward of the salt-cored slope,
Figure 8. Shape of Kimmeridgian “Salt Chasm. Emplacement of oceanic-type crust is controlled isostatically.
From this basic premise we can infer that IF: 1) salt column was ca. 5.5 km thick at the onset of collapse (i.e. top salt at sea level); 2) salt collapsed over newly emplaced ocean crust towards the center of the basin on both sides of Gulf until either sediment in the center of the basin, or covering the salt was able to buttress it enough to halt its movement; 3) regrading of the slope only occurred landward as far as needed to balance basinward flow while maintaining a slope of probably not much less than 1° and not more than 2° (i.e. areas A = B and C = D) and; 4) there was no dissolution of salt during or after collapse, THEN: 1) the early salt chasm may have started ca. 55-60 km wide, with top-salt gradients of ca. 5° (as in Red Sea) but “rapidly” (5 Ma?) graded to lower gradients (ca. 1.5° as shown here); 2) if Oxfordian-Kimmeridgian strata part-filled the chasm, then the Challenger seismic unit will be flat-bedded and parallel-layered, burying the early chasm fill, but will thin landward once it encounters the salt cored slope (not far north of Baha, Kaskida?); and 3) because the salt did not deflate to the horizontal, there area between the Cretaceous slope and the central Gulf may have had significant bathymetric relief, about 3-4 km above the contemporaneous basin floor and 1-2 km below the Late Cretaceous and Early Tertiary shelf edge known from onshore areas. The Red Sea analog has persisted since the Late Miocene indicating that salt-cored relief steeper than we infer for the Gulf can persist for 10-15 Ma. It seems reasonable that much lower gradients could persist for perhaps as much as 50-100 Ma after salt deposition ended.

Figure 9. Implications of a Red Sea model for the Gulf of Mexico and other salt margins: Salt bathymetry will not be flat and will not be entirely predictable, but the initial “brim-full” salt volume requires there to be substantial salt-cored bathymetric relief inboard of collapsed margins. Present-day salt edges will not be isochrons along the salt edge, or on opposing margins. Also, restorations of salt-involved cross-sections should not assume top salt is flat (most do), and should use a deeper original source layer. The transition from mostly stretched continental crust to mostly basalt in the form of sheeted dykes took place from 5-10 Ma before the end of salt deposition and was gradational. By end salt time (ca. 158 Ma) there was no stretched continental crust close to the center of the basin, and the step-up which results from thinning salt, and its replacement with water and sediment is probably more or less isochronous but difficult to define. Our interpretation indicates that the feather edge of salt is always in structural relationship with underlying salt, and that there is no necessary one to one relationship between salt and continental crust. This figure illustrates several possible relationships: (1) updip, salt may onlap north as result of thermal subsidence; (2) salt on actively faulting thin continental crust; (3) salt on subsalt intruded basalt, before the end of salt deposition; (4) salt necking and flowing toward the center of the basin, above basalt, after the end of salt deposition; 5) thin salt tongues or glaciers, the younger ones climbing over the first sediments deposited directly onto new oceanic crust.
water depth is probably not more than 1000 m as outlined above. From shelf to deep basin, we suggest paleobathymetry might be stepped, not unlike the Sigsbee canopy today.

The slope from this area of anomalously shallow bathymetry to the true basin floor was probably located somewhere in the Norton (Garden Banks) area. Oxfordian to Tithonian strata probably mantled the salt-cored marginal wedge. However, because basinward salt flow continued to at least late Oxfordian time, and possibly to Tithonian time in the central Gulf, these sediments would not form a continuous blanket, but would be stretched as salt flowed, possibly setting up a pattern of mini-basins sinking into the salt in Late Jurassic and Cretaceous time as suggested by sequentially restored cross-sections (e.g., Diegel et al., 1995; Mount et al., this volume). In detail, a Cretaceous view of the area of shallow bathymetry would probably show a complex array of minibasins and salt walls, in which plateau-crossing canyons feed sediment directly into the deep basin center simply to Keathley Canyon and others today. The persistence of shallower than expected bathymetry will have a profound influence on Wilcox deposition, some 90-100 Ma later, as discussed below.

This view is in marked contrast to the model of Imbert and Philippe (2005) who explicitly assumed the salt would behave as a viscous fluid, deflate, and maintain a flat top as ocean crust formation continued in the Gulf (Fig. 11). Eventually, a point is reached when the oceanic spreading center, at a depth of ca. 2.6 km emerges through the deflating salt. The model has several insuperable flaws:

- The emergence of the oceanic spreading center should be synchronous throughout the Gulf, but it appears in fact to vary by up to 10 Ma.

- Their work explicitly continues basaltic crust as far north as the Houston magnetic anomaly (too far north in our view), but does not use a starting 5.5-7 km starting salt thickness in their salt-thinning model, as such a basement requires. A simple salt-fit cross-section of the Gulf has some 2000 km² of salt on the North American side. If this deflated to 2.6 km depth, the salt edges on the US and Mexican side would separate no sooner than about 140 Ma, at least 8-15 Ma too late and the salt pinchout would be farther south than observed by about 150 km in the west, 100 km in the east, and 50 km in the central Gulf.

- The model implies a dramatic drop in bathymetry south of the Cretaceous shelf edge. Although similar to conventional paleobathymetric models for the Gulf (e.g., Galloway et al., 2000), this model provides no viable explanation for the shallow paleobathymetry observed in the Norton well and others (unless they rafted in some 350-400 km from the north?).

After a hiatus, deep salt tongues spread out across thin sediments deposited above basalt. These tongues often form the detachment for younger fold belts (e.g., Atwater fold belt, Moore et al., 2001), and may also be the root zone for much younger diapers or salt pillows (e.g., Sigsbee Knolls, Yucatán).
Figure 10. Map showing the proposed salt-cored slope and marginal sediment wedge at Late Oxfordian time, extending out at least as far as the continent-ocean boundary transition zone (dark green dash) beneath the present-day shelf edge. Through the Cretaceous, salt collapse allows retreat of the outer slope break only to about the outer part of the green zone, such that the pink zone marks the true continental slope down to the basin floor. The edge of the area of shallow bathymetry may be indicated by the Norton well see text for details. Similarly, the Paleogene Wilcox sands were probably deposited at the toe of the slope close to the pink-grey boundary. In this model, thick and laterally continuous Wilcox sands might not be found much farther north than they have been. More northerly subsalt areas may instead show Wilcox sands in minibasins and turtles which are not necessarily connected.

Figure 11. Salt deflation model of Imbert and Philippe (2005). This model does not (1) predict a salt-cored platform or slope, even though the starting point is similar to our model (Figure 4); (2) fit the likely age of end salt deposition (just pre-Norphlet) relative to seafloor in the Perdido or East Gulf areas; (3) predict, in our view, enough salt in the cross-section. The model predicts a “salt-fit” water depth to top salt of about 2.6 km which does not agree with well paleontologic data and predicts a ca. 2.6 km bathymetric drop from a shelf edge developing just up-dip from the salt edge, whereas we suggest an upper slope dropping not more than 1 km to a salt-cored platform or, with a further drop much farther out into the Gulf (north of Kaskida and Baha) to the ultimate basin floor, not unlike the Sigsbee platform and escarpment today. This model also predicts a maximum post-deflation salt thickness of about 3.5 km, about half of that predicted by our calculations. Finally, if we apply our starting salt thickness (5.5-7 km in contrast), this model would predict that the oldest oceanic crust to emerge through the thinned salt would be of Early Cretaceous age, compared Oxfordian-Kimmeridgian.
The salt-cored marginal wedge; inclined slope to the deep water Wilcox

The mainly Jurassic processes outlined above created a northern Gulf margin by the end of Jurassic time that comprised a shallow water shelf in today’s onshore (generally underlain by the landward fringe of salt), deepening gradually basinward to a somewhat drowned and perhaps intermittently deflating, salt-cored “shelf” setting beneath today’s outer coastal plain and offshore (Bossier Shale realm). By middle Cretaceous time, this salt-cored shelf was still neritic in places and by latest Cretaceous was still not more than 500-1000 m deep. While Norton, and perhaps other wells, have thin Mesozoic sections that are probably not representative (600 m compared to 3-4 km), it is unlikely that there was more than a few hundred meters of bathymetric relief on this drowned shelf. These offshore depositional thins may have been zones of salt inflation due to continued salt movements, but they were probably not much shallower than the bulk of the shelf. Basinward flow of salt from beneath the future position of the Aptian-Albian carbonate shelf edge probably took place as a result of basinward tilting of the basement surface. Very little salt remained in place in the “shelf edge belt” by the Aptian, and this lack of salt probably played a key role in allowing the stable shelf edge to form.

Salt flow may have been episodic and could have inflated salt masses or pillows in the Norton area if the basinward motion is not transferred all the way to the salt limit in the deep Gulf. Only very small volumes of salt tongues or glaciers are present above submarine sediment above oceanic crust, so this mechanism of “salt leakage” probably cannot accommodate much basinward salt flow from updip to closer to the shelf edge. Similarly, we know of no well-defined Cretaceous or Late Jurassic toe folds.

By the end of the Cretaceous, the US side of the Gulf comprised a very broad salt-cored marginal wedge of strata outboard of the Sligo-Stuart City shelf edge, which dropped at the “upper shelf edge” to upper bathyal depth over a broad area (perhaps 350 km or more) before dropping again to the abyssal plain. Seismic lines (Reid, 1983) over the Cretaceous shelf edges in Louisiana, show top Cretaceous dropping not more than about 1 km from the shelf edge, suggesting that this area is not similar to Florida or Yucatán, although many conventional models seem to assume a very abrupt drop to the abyssal plain, conveniently just beyond the limit of good seismic data (masked by young basins and salt features). From well data, it is clear that the true continental slope (lower bathyal zone) and rise in fact lay far offshore, somewhere in the southern Garden Banks area (Fig. 10).

The Tuscaloosa fans, deposited in an upper slope setting, occur at the interface of the carbonate shelf edge and the top of the marginal wedge (Fig. 12). They may have been trapped here if excess accommodation space was created as a result of local basinward salt flow, possibly driven by underlying volcanic doming (Salvador, 1991) and basinward basin tilting in this area at this time. Because the top of salt within the marginal wedge is probably 3-4 km higher than the toe of salt and possibly higher than the depositional surface of the abyssal plain (Fig. 2) it probably took only moderate basement tilting or seismicity to cause local basinward downhill readjustment of the slope of the salt-cored marginal wedge which might focus deposits such as the Tuscaloosa fans.
Figure 12. Descriptions of Woodbine and Tuscaloosa deposition and associated volcanism and angular unconformities suggest a significant phase of salt mobility in mid-Cenomanian time, probably aided by thermal uplift onshore, basinward tilting of the basement surface, and by the fact that the “salt-cored” slope is already probably stretched and lower than the Lower Cretaceous shelf edge in his area to start with. Given the revised younger age for Challenger/MCSB as top Cretaceous (e.g., Winker, this volume), pulling up all underlying age estimates, this phase could define when the “deep salt” allochthon crept southward over earliest basin strata in the Mississippi Fan/Atwater fold belt area (Frank Peel, pers. comm.; Moore et al., 2001).

Figure 13. Setting of the northern Gulf Margin prior to Wilcox slumping of the outer shelf. Note the dramatic contrast between the traditional view of paleobathymetry (red) and our salt-cored marginal wedge model (blue). Bathymetric profiles are compared in Figure 14. Wilcox clastics may have been coursed directly to the abyss or indirectly via perched mini-basins and secondary slope canyons and may be found intraslope and toe of slope fans.
One such episode may have occurred at the end of the Cretaceous, triggered by the Chicxulub meteorite impact. Such a basinward collapse in the Houston Embayment area may have provided the incentive for lower Wilcox basinward sliding (Lobo megaslide) updip and may have focused initial deposition of expanding lower Wilcox section. We suspect that long wavelength basinward flow of salt is driven by the readjustment of the slope of the salt-cored marginal wedge to basement tilt or shaking, and not driven by updip sediment loading, which seems to form relatively narrow expanding rollover sections and cause the initial eruption from earliest Eocene time on (but not before) of salt canopies (e.g., Diegel et al., 1995; Peel et al., 1995) not far south of the Wilcox expanders. We further suspect that only when much of the mother salt has evacuated into canopies and the Wilcox growth faults link down to a thin salt detachment (Radovich et al., this volume), rather than getting lost in a thick salt mass (Fig. 2), does expansion drive the earliest discrete fold belts beneath the canopies (“Bajo Foldbelt” of Radovich et al., this volume), probably after the end of Wilcox deposition.

Conventional paleogeographic models (e.g., Galloway et al., 2000; Galloway and Ganey-Curry, 2003) typically show sandy Wilcox restricted to growth-faulted delta sections, and shale-prone deep Gulf of Mexico would be shale-prone (Zarra, this volume). Furthermore, the models commonly show the toe of the Wilcox slope in the vicinity of the present-day coastline. Thus, the presence of thick sandy Wilcox about 350 km basinward is a surprise, and not easily explained (e.g., Meyer et al., 2005). The proposed salt-cored marginal wedge may have played a key role in the transportation of Paleogene clastics to the basin floor along a trend that exactly mimics the toe of the slope we had independently predicted. If there is a continuous, albeit gentle, basinward slope on top of the salt-cored marginal wedge, and particularly if this is somewhat incised by one or more canyons such as we see today, turbidity currents and mass flows could transfer sediment to the deep-water Wilcox trend, without the need for horizontal transfer across an intervening swath of flat abyssal plain that appears on many paleogeographic maps. Figure 13 shows schematic Paleocene bathymetry and possible depositional trends according to this model and a schematic cross section of that paleogeography is shown in Figure 14.

Our model makes some testable predictions that may be critical in future subsalt exploration:

• If the toe of the slope lay not far north of the known deep Wilcox sand, then strata of this age should start to thin to the north. Limited published seismic suggests this may be the case. For instance, Meyer et al. (2005) show thickness of Mesozoic in Baha-2 about 0.5-1sec thinner than at Baha-1 and farther south (Trudgill et al., 1999).

• We expect Wilcox sands to break up on the slope into incised canyon fills rather than unrestricted fan lobes, unlike the generalized broad upper fan suggested by the published paleogeographic maps (Meyer et al., 2005; Zarra et al., this paper).

• We expect thick, continuous deep-water Wilcox, expected in the “traditional view”, to be absent in the area between the present-day coast and the slope close to the Garden Banks-Keathley Canyon boundary. Rather, any Wilcox sand in this area should be restricted to minibasins similar to those we see today. Seismic data (Radovich et al., this volume) and cross-sections (Mount et al., this volume) suggest that
Figure 14. Cross-section based on Figure 13, showing the contrast in paleobathymetric profile between a “traditional” slope model and our “salt-cored marginal wedge model,” which puts the main drop to the abyssal plain at least 300 km farther basinward. We propose that the toe of the wedge is not far north of the known deep Wilcox (e.g., Kaskida and Baha). Some Wilcox sand may have been trapped in mini-basins above the wedge, and canyons analogous to Keathley Canyon and Alaminos Canyon may have played a role in transporting sand out to the abyssal plain.

Figure 15. “Elevator” model for maturation by basin formation within a salt-cored marginal wedge. Note that the thickness of sediment shown on the slope may be highly exaggerated; in many areas it may be a zone of bypass.
mini-basin formation probably started during the Late Jurassic. Thus, turtles derived from these minibasin fills could encapsulate complete petroleum systems and be attractive exploration targets if well-imaged and within economic reach of the drill.

**Implications for hydrocarbon maturation**

The proposed salt-cored marginal wedge has some first order implications for petroleum systems. First, Jurassic and Cretaceous source rocks have been deposited on top of the wedge in neritic to upper bathyal water depths and have little chance for deep burial until the tectonic events of the Tertiary. Our model, and limited seismic data, indicate that maximum burial of Late Cretaceous source rocks is no more than about 3-4 km prior to the Eocene, so that they are unlikely to be mature by that time. This view is in dramatic constrast to models such as those of Ings et al. (2004) which use salt no more than 1 km thick and can only build significant bathymetric relief by using a prograding sedimentary wedge two to three times thicker than observed in the Gulf. Likewise, the Cretaceous is so starved in the deep abyssal Gulf, especially given that the Challenger reflector is now known to be top Cretaceous rather than mid-Cretaceous (Dohmen et al., 2002; Minerals Management Service, 2007), that there is little chance of burial related Cretaceous maturation there either.

Second, on the southward sloping salt-cored marginal wedge, regional Paleogene deposition could not have buried the Mesozoic source rocks to maturation depths without strong structural control. Burial mechanisms for the Mesozoic section on the marginal wedge involve the physical lowering of the section downward into the deeper, and hotter, levels of the salt-cored wedge. One such mechanism pertains to mini-basins where salt was evacuated from beneath a swath of Mesozoic section such that the section physically dropped, thereby becoming buried by “syn-mini-basin” clastics. In this view, it is not that salt rose dramatically around a deep Mesozoic section; instead, a shallow Mesozoic section was lowered into deep salt. Another mechanism relates to Wilcox and younger growth-fault bounded half-grabens, in which the Mesozoic section has collapsed basinward as part of the hanging walls, moving adjacent to progressively warmer parts of of the growth-fault footwalls as the grabens grow. Figure 15 schematically shows these mechanisms, which we call “elevator mechanisms”. They are of initially local significance for maturation, the effect of which is to put immature source rock sections adjacent to hotter sections of the marginal wedge’s core. The close relationship between oil and salt should not be surprising. Thus, not only could mini-basins contain an entire petroleum system, with Mesozoic source rocks and Paleogene clastics/seals and their own maturation mechanism, but maturation would be delayed until the onset of Paleogene (or Neogene depending on position) structure and sedimentation. Eventually, the mini-basins and half grabens coalesce to form a more complete Paleogene cover on the Mesozoic section. Lateral and oblique heat flow from footwalls to collapsed hanging walls is an important process in the overall maturation story. Along the toe of the marginal wedge, and within the abyssal plain, maturation by more traditional, regionally significant sedimentary burial or overthrusting, is expected.
Speculation on the origin of the Paleogene circum-Gulf paleo-canyons

We now move from observation and modeling to speculation in regard to the near-Paleocene-Eocene boundary incised paleo-canyons such as Hardin, Yoakum, and Chicontepec. Despite one of us being integral in the development of the Paleogene water level drawdown hypothesis (Rosenfeld and Pindell, 2003), the speculation that we make here assumes that no such event occurred in the Gulf of Mexico. It also presumes that the rates and magnitudes of eustatic change (Dewey and Pitman, 1998) prior to the late Eocene or early Oligocene re-establishment (after a hiatus since the Triassic) of polar/continental glaciation (Markwick and Rowley, 1998) were too small to generate the paleo-canyons, which are on a scale apparently unique to the Gulf until the Pleistocene when eustatic falls probably were large enough to cut deep canyons. Our speculation represents a “third way” to produce the canyons.

Any basinward shift of mass within the salt-cored sediment wedge will cause thinning of the salt and sediment underlying the upper slope. This will be accompanied by a geologically instantaneous rebound of the underlying basement. The larger the basinward shift of mass and loss of material from the upper slope, the larger the rebound. We can estimate realistic magnitudes as follows. If we consider a position in the upper slope where vertical thickness is reduced by structural detachment or salt deflation, and model this in an one-dimensional Airy fashion, where water replaces the structurally displaced sedimentary section, the local rebound will be about 50-70% of the thickness of the displaced section, and the local bathymetry (in the absence of new sedimentary section) will end up about 30-50% deeper than it was at the outset. In the case of salt, which has a density about mid-way between water and mantle, the rebound is 50%. The rebound is > 50% if the sediment wedge is on average denser than salt, and less if it is on average less dense than salt.

In a pure 1-D Airy model, this underlying basement uplift would not cause uplift at the adjacent shelf margin because it would only apply locally. Similarly if we remove a thickness of sediment over a significant area, the basement beneath that area may rebound by about 50-70% of the thickness removed. However, this rebound would not affect the shelf up dip from the area in which unloading and rebound occurred because the Airy model implicitly gives the basement no lateral strength; uplift and subsidence are strictly local effects. The shelf would only rebound if material was actually removed from the shelf itself.

However, if we consider a more physically-reasonable flexural model, in which loading spreads basement subsidence over an area wider than the load, then we see that any isostatic uplift that occurs due to unloading is similarly spread across the flexural half-wavelength, which may be 300 km or more, depending on the elastic thickness of the basement in the area being modeled. Weaker crust, with reduced elastic thickness has a shorter flexural wavelength and rebounds in a way which is closer to the Airy approximation.

Thus, basement uplift beneath the marginal wedge will be slightly less than 50-70% of the thinning of the overlying sediment, but there will also be uplift in the upper slope and adjacent shelf if the shelf is within the flexural half wavelength of the section removed. This uplift of the shelf will occur even though there may have been no reduction in sediment thickness on the shelf itself. If much of the marginal wedge along its strike shifts
basinward and thins synchronously or nearly so, then the rebound calculated in a 2-D flexural model will approximate the uplift in three dimensions (analogous to, for example, 2.5-D gravity modeling). As in the 2-D case, isostatic rebound of the basement under the wedge will somewhat less than 50-70% of the thickness of the displaced section, but it will cause a landward-decreasing uplift over a distance of the flexural half wavelength along a considerable length of the shelf.

In short, if 1 km of section underlying the upper slope is displaced far enough basinward and is not replaced by new sediment in the shelf/upper slope position, then shelf uplift on the order of 100-200 m is possible, and the rate at which this happens corresponds to the rate of basinward shift in mass, which could be quite rapid (< 1 m.y.). In turn, there is a positive feedback loop as the erosional removal of sediment from the shelf unloads it further leading to further rebound. We expect this process to be of minor importance compared to the shift of mass within the marginal wedge, but it may become significant if material is removed from a significant length of the shelf (see, for example, McGinnis et al., 1993). Such a shelf uplift would appear in the sequence stratigraphic record along the margin as a major relative sea level fall of a similar magnitude to Plio-Pleistocene sealevel changes, but it has nothing to do with eustasy and only affects some or part of one margin.

We know that basinward shift of pre-Eocene strata occurs, as shown by the Wilcox extensional fault systems, but is there also a corresponding net basinward shift of mass? Conventionally, it is assumed that sedimentation within growth fault basins in the shelfal updip position is the driver for sediment detachment and downslope creep, pushing marginal wedge sediments down the slope. Analog models certainly show that progradation of a basinward tapering sediment wedge can trigger salt or shale movement (e.g., Ge et al., 1997; McClay et al., 1998). In these models, both horizontal and vertical maximum stresses are positive, but the vertical stress due to sediment loading is sufficient to overcome the confining effect of the sediments beyond the prograding wedge, triggering normal faulting in an updip position (where maximum vertical stress is greater than maximum horizontal stress) and toe thrusting in a downdip position (where the overburden is thinner, vertical stress is lower and becomes smaller than maximum horizontal stress). Downdip of the normal faults, stresses within the marginal wedge are compressional. In this case, the magnitude of isostatic rebound is small, because the density of growth basin fill is not much less than that of the pre-basin strata.

On the other hand, should we presume that all basinward movement of the marginal wedge is driven and recorded by Wilcox extensional basins? What if the basinward movement of the marginal wedge takes the form of an enormous collapse or mass-wasting process? In this case, rather than being driven by addition of prograding sediment, the marginal wedge may collapse under its own weight. We do not expect the salt-cored marginal wedge to be particularly stable. Although we believe that substantial relief persisted into the Paleogene, the presence of Jurassic and Cretaceous salt tongues indicates more than one previous episode of basinward collapse. We envisage a metastable marginal wedge, buttressed by layered sediment above (without dramatic lateral thickness changes that might trigger salt movement) and in the basin to the south. The wedge probably became increasingly likely to fail through time due to the effects of both thermal subsidence and sediment loading tilting the basement below the salt, and the sediments above the salt, towards the basin.
Several events could trigger the basinward collapse of the marginal wedge, including mega-earthquakes associated with the Chixulub impact and also possibly the progradation of only relatively small amounts of sediment, just enough to destabilize the wedge. In contrast to the “conventional” view, where progradation drives salt motion from the rear, the basinward collapse of the marginal sediment wedge results in extension rather than compression within the salt core of the marginal wedge and in true tensional horizontal stress in the sediment mantling the wedge, such that no large vertical loading is needed to drive the growth of normal faults. “Wedge-pull”, rather than “sedimentary-push” may be the initial mechanism for a major basinward shift of mass. In this case, the extensional faults may pre-date growth sedimentation and there may be significant relief on the seafloor towards the upper slope. There may also be extensional faults across much of the width of the failing slope, not concentrated only where sediment progradation is occurring. On many of the margins that we have studied we see that gravitational failure often begin with counter-regional faulting rather than by basin-facing failure. Counter-regional faults expel material from beneath the slope and are thus particularly effective at shifting mass basinward. Down-to-the-basin normal faulting appears to re-establish equilibrium once the counter-regionals have begun their slope-oversteepening effect. Figure 16 shows how this process might work, together with deflation of salt beneath the upper slope, to drive flexural rebound of the shelf, resulting in incision.

It seems that there is a bias in most analog and numerical models of salt deformation (flat basement, large magnitude sediment progradation) which has obscured the possible importance of this basinward tilting and wedge metastability process. Of recently published models, only Fort et al. (2004) seem to explicitly build a model that starts with a tilted basement and a variety of sediment blanket geometries.

In the case of the Gulf of Mexico, the marginal wedge we propose is perhaps 400-500 m wide, from shelf and upper slope to lower slope and the basin floor. Thus, if the salt deflates on the upper shelf, and this is balanced by salt flow or shortening at the toe of the slope, the process is effectively transferring mass 400-500 km from the upper slope to the basin floor. This is far beyond the flexural half wavelength of the underlying basement, and means that the shelf and upper slope can no longer “see” this shifted mass.

The result is the same as if we had eroded hundreds of metres or more from the entire upper slope, the inevitable effect of which is substantial rebound of the upper slope and adjacent shelf. This then triggers canyon incision, particularly if the starting water depth on the shelf is less than the magnitude of the rebound. Thus, we consider that the Wilcox shelf and upper slope half grabens could be the eventual response to, rather than the cause of, basinward lateral or downdip shift of the salt-cored marginal wedge. Wilcox growth wedges of clastic sediment may have been filling accommodation space created by deflation of the salt beneath the upper slope.

It may be difficult to prove if net basinward shift of mass is sufficient to drive isostatic rebound in the late Paleocene and/or early Eocene. Can we balance sections well enough to make the necessary calculations? Probably not, but it may be worth assessing the process in greater detail than it has been to date. Whether or not it is the cause of the circum-Gulf Paleogene canyons, this mechanism is yet another variable that makes the isolation of eustatic sea level from relative sea level curves nearly impossible.
Figure 16. Semi-schematic cross-sections showing the effect of basinward shifting of mass in the salt-cored marginal wedge. A) Thinning of the stratigraphic section under the slope is balanced by salt-inflation or folding at the toe of the slope, possibly ahead of a major counter-regional fault. B) The basement responds to unloading by rebounding, and flexure ensure that this rebound (albeit reduced) is felt by the shelf, where incision occurs and the shoreline regresses basinward.
Conclusions

A well-constrained basement type and subsidence model, combined with recently published seismic and well data, suggests that:

- Thermal subsidence in the northern Gulf may have been reduced compared to “normal” attenuated rifted crust.
- Only normal oceanic crust emplaced at ca. 2.6 km beneath water can explain the combination of water depth and sediment thickness in the Gulf. Although depth-dependent stretching models can drive subsidence faster than McKenzie-type stretching models, they cannot produce faster subsidence than the oceanic model and do not allow the crust of the central Gulf to subside to its present depth if it started at or near sea level.
- At the time of the end of salt deposition, salt was about 5.5 km thick in the center of the Gulf salt basin, and may have thickened to perhaps 7.5 km beneath the present-day shelf-slope break.
- Total cross-sectional area of US salt in a north-south profile was about 2000 km², indicating that 30-75% of salt, depending on location, dissolved mainly during late Paleogene and younger canopy migration.
- Salt-thinning and flow over contemporaneously erupted oceanic crust occurred after the end of salt deposition. The isostatic balance between basalt, thinning salt, and deepening water explains the observed basement step-up north of the edge of “mother salt.” The lower edge of this step-up provide a better “salt fit isochron” than plate rotation models, which attempt to match present day salt edges.
- Everywhere in the deep central Gulf the relationship of “mother salt” to basement is structural, not depositional, and the oceanic basement immediately beneath thinned salt, particularly under the Sigsbee Canopy, may be as much as 10-15 Ma younger than the salt which appears to “onlap” south onto it.
- The volume of salt in the Gulf could not have deflated to a horizontal surface within its present limits; it was simply too thick. Instead, there must have been significant relief on a “salt-cored marginal wedge” of sediment which lay between the Cretaceous shelf edge and the abyssal plain, the latter of which we suggest did not extend much farther north than northern Keathley Canyon. The model is supported by water depth estimates from published wells.
- In practice, salt must have some finite strength (note Sigsbee Escarpment), perhaps as a result of intra-salt contamination (anhydrite?, carbonates?, clastics?) or other rocks (basalt intrusions?) or the carapace of mantling post-salt sediment. It does not behave as an ideal viscous fluid. The Red Sea analogue shows that salt-cored bathymetric relief can be maintained for greater than 10 Ma.
- Intermittent basinward flow of the salt within this marginal wedge was probably caused by adjustments in response to basement tilt and possibly large magnitude earthquakes, which would be expected from a meteorite impact.
The marginal wedge, with its paleo-continental slope far south of today’s shoreline, probably played a key role in the deposition of deep-water Wilcox sands and has first order impact on Paleogene sediment distribution and maturation in the subsalt in the Garden Banks and Green Canyon areas and farther north. Traditional paleobathymetric models do not easily explain the presence of thick Wilcox sands in the Keathley Canyon and Walker Ridge areas.

The salt-cored marginal wedge model requires 2 to 3 km less Late Jurassic and younger strata to explain the observed paleobathymetry in many wells. The section at Norton started shallow and remained shallow and can not have been pumped up as a diapir or salt wall between flanking basins, in which case it would start deep and become shallower rather than starting very shallow and deepen slowly. The Mesozoic section is generally thinner than expected in traditional basin models and, as a result, maturity is delayed and petroleum prospectivity may be improved. Source rock and oil-typing data do not indicate that the salt-cored wedge compromised source rock quality.

The salt-cored margin proposed here may have been meta-stable and prone to basinward creep and gradient reduction. Associated basinward shifts in mass may have been enough to drive relative sea level changes in the surrounding margins, enough to locally influence sedimentation and possibly enough to play a role in cutting the larger canyons.

Acknowledgements

We thank Tony Watts, Walter Pitman, Peter Tauvers, and Fred Diegel for gravity and subsidence modeling, access to data, and discussions on many of the issues discussed in this paper.

References


Dohmen, T. E., 2002, Age dating of expected MCSB seismic event suggests that it is the K/T boundary, GCAGS Transactions, v. 52, p. 177-180.


Pindell, J., 2002, How deep was the Late Jurassic Gulf of Mexico?, Offshore Magazine, v. 62 (Feb 2002), p. 60, 62, 63, 100.
Radovich, B. J., C. D. Connors, and J. D. Moon, 2007, Deep imaging of the Paleogene, Miocene structure and stratigraphy of the western Gulf of Mexico using 2D pre-stack depth migration of mega-regional onshore to deep water, long-offset seismic data : GCSSEPM Foundation 27th Annual Bob F. Perkins Research Conference, this volume.