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Early Paleogene Isolation of the Gulf of Mexico from the World's Oceans? Implications for Hydrocarbon Exploration and Eustasy

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ABSTRACT

Deeply incised and backfilled paleocanyons in early Paleogene shelf strata along the western and northern Gulf of Mexico margin attest to large relative sea-level fluctuations, but they predate the accepted age for onset of Cenozoic continental glaciation. Using Pleistocene canyons as a crude yardstick, the scale of these paleocanyons suggests relative sea-level changes at least as large as Pleistocene fluctuations. Therefore, we speculate that water level in the Gulf of Mexico was drawn down while the Gulf was isolated from the world's oceans during the late Paleocene/early Eocene interval. We suggest that the cause for isolation was the progressive collision of the Cuban arc with the Yucatán and Bahamas carbonate platforms, which temporarily closed off the southeastern Gulf of Mexico. In Miocene Mediterranean and Holocene Black Sea examples of marine-basin isolation, evaporation greatly exceeded rainfall and runoff, and our examination of the Gulf of Mexico case suggests that water level may have dropped below the level of the world's oceans at least once by several hundred meters, and possibly much more.

Implications for geology and hydrocarbon exploration in the Gulf may include:

- bypass of enormous quantities of coarse detritus into the deep basin
- seaward collapse of exposed clastic shelf margins
- triggering and/or acceleration of salt evacuation (basinward "squeegee" effect of slumping sediments)

- release of gas hydrates from sediments under shallower and warmer water, thereby contributing to the ~100,000-year-long worldwide Paleocene/Eocene boundary heating event
- development of secondary porosity in both platform and deep-water carbonate sections by dissolution and phreatic diagenesis, e.g., in the Golden Lane/Poza Rica area of Mexico
- hypersalinity and possible sea-bottom stagnation with source-rock deposition in areas that remained marine
- deposition of fine-grained condensed sections (seal and source rock) during flooding period(s) when connection with the world's oceans was reestablished, creating stratigraphic traps at canyon flanks and turbidite reservoirs in the canyons.

Recognition that early Paleogene relative sea-level changes seen in the Gulf may pertain to basin isolation is grounds for treating "eustatic" curves derived for or from the Gulf with suspicion. In addition, catastrophic basinward transfer and collapse of mass near the shelf edges would have caused isostatic unloading (rebound) of shelf margins that was proportional to the mass transfer. In the case of a discreet slumping event, such as the Lavaca "Megaslump" event of south Texas, this effect may have caused uplift of several to a few tens of meters of footwall areas within about 100 km from the slump. Larger downslope movements such as those related to the collective Wilcox fault province would have caused far larger isostatic rebounds on the shelf, perhaps in excess of 100 m if sedimentation did not keep pace with faulting.

A body of circumstantial evidence continues to grow in support of this hypothesis; its potential implications, both academic and commercial, merit further investigation. Integration of information from Cuba, Mexico, the United States, and the Bahamas will be required to fully test the hypothesis.

INTRODUCTION

The margins of the Gulf of Mexico lie in the territorial waters of Mexico, Cuba, and the United States (Figure 1). For political and economic reasons, unified study of circum-Gulf geology and identification of the interrelationships of one subregion with another have been impeded by restrictions on the free flow of data and ideas in the geoscience community. Therefore, there are grounds for proposing new regional hypotheses to explain contemporaneous developments in the Gulf that otherwise might be considered local phenomena only. If a regional, rather than a local, cause for a given phenomenon is supported by existing data, then the implications of the regional cause can be extended to other parts of the Gulf where such developments have not yet been identified.

In this paper, we consider a hypothesis involving physical isolation and drawdown of water level in the Gulf of Mexico (Rosenfeld and Pindell, 2002) that will require the integration of data and ideas from Mexico, Cuba, and the United States to test fully. The existence of late Paleocene/middle Eocene transgressive-regressive cycles and associated enormous incised and backfilled paleocanyons in the northern and western Gulf of Mexico's shelf and slope strata (e.g., Wilcox and Chicontepec Formations) attests to very large-magnitude/short-term relative sea-level fluctuations. However, features approaching this magnitude did not develop again in the Gulf until the Pliocene-Pleistocene, not even at the middle Oligocene eustatic low, and that these features developed prior to the accepted (late Eocene) onset of Cenozoic continental glaciation (Markwick and Rowley, 1998) leads us to hypothesize that water level in the Gulf was drawn down, perhaps intermittently, during period(s) of physical isolation from the world's oceans. We propose that the cause of the isolation was the collision of the Cuban arc with the Yucatán and Bahamas carbonate platforms, which closed off the southeastern Gulf of Mexico/Florida Straits connection in the late Paleocene to early or middle Eocene. In other documented examples of

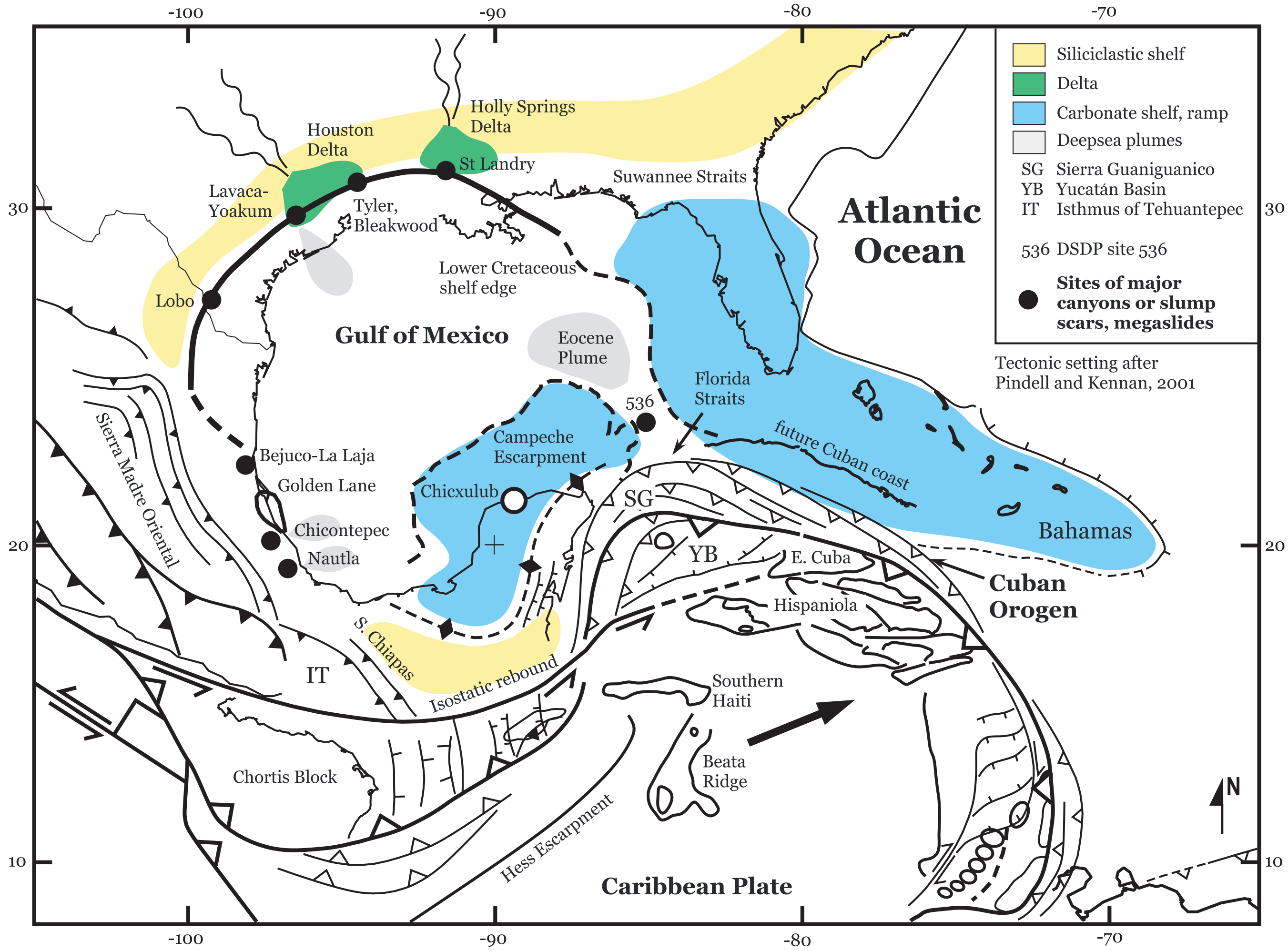
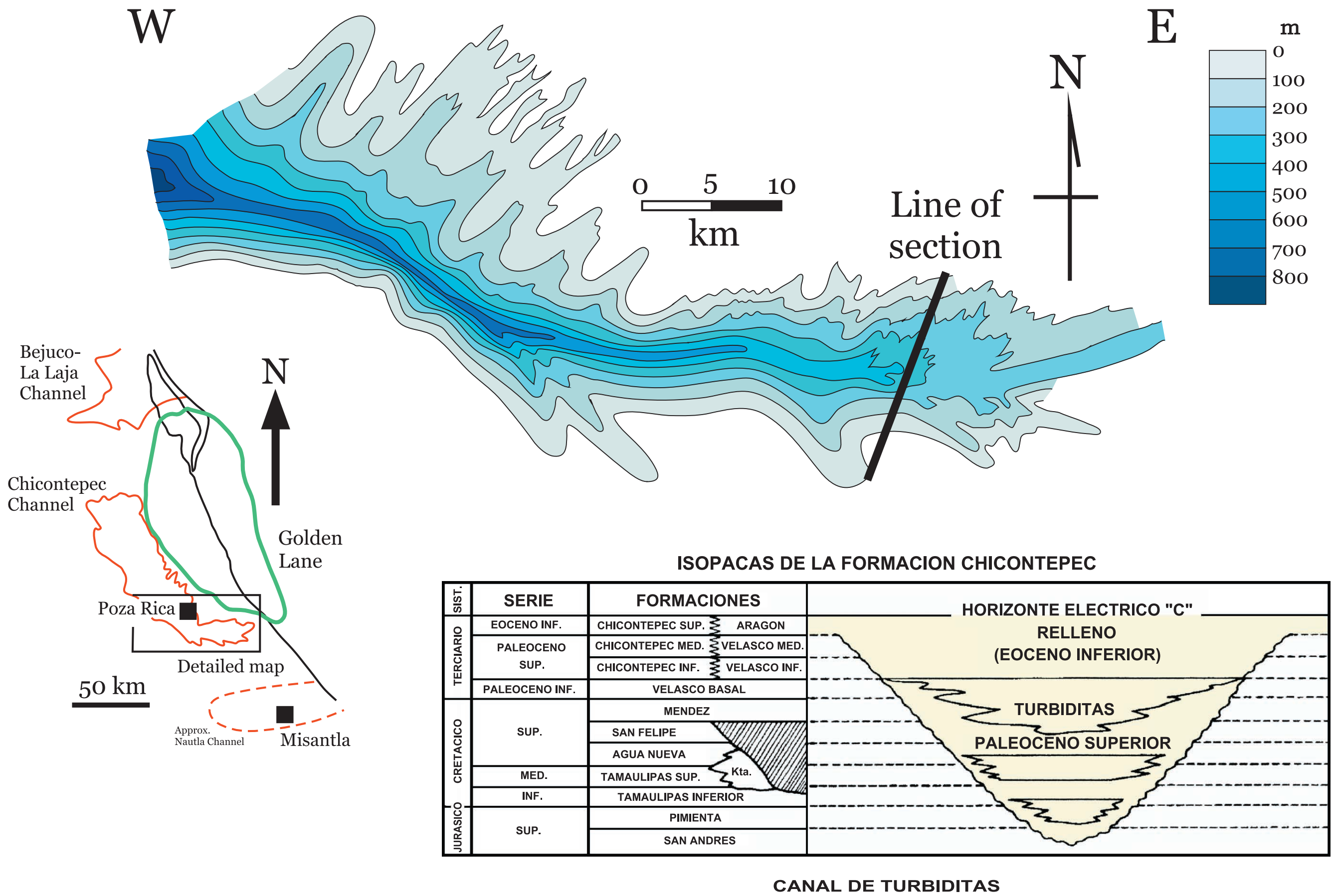


Figure 1. **General map of the tectonic setting of the Gulf of Mexico region at the time of the Paleocene-Eocene boundary (~56 Ma, after Pindell and Kennan, 2001), showing localities noted in the text. Note the way in which the Cuban Orogen blocked the entrance to the Gulf of Mexico.**

marine-basin isolation (the Miocene of the Mediterranean and the Pleistocene/Holocene of the Black Sea), evaporation greatly exceeded fluvial/pluvial input; therefore, drawdown could have been expected in the Gulf of Mexico setting as well.

Two examples of a local phenomenon in the western and northern margins of the Gulf with potentially regional implications are the Chicontepec and Yoakum paleocanyons (Figure 1), where erosion has deeply excavated preexisting Paleocene and older Gulf margin strata. In both these cases, basin-margin strata are incised over distances of 80 km to depths of 1 km or more, while the width of the canyons is only 10 to 15 km. At Yoakum, the incised Paleocene section (lower Wilcox) is sand-rich and was deposited in a shelf rather than slope environment. In contrast, at Chicontepec the pre-canyon Paleocene (turbidites) and older section comprised the continental slope landward of the isolated Tuxpan (Golden Lane) carbonate platform. This canyon was eroded through the entire slope turbidite sequence down into the underlying, already lithified Cretaceous and Jurassic basinal carbonates. The scale and setting of these and other canyons and unconformities suggest to us that the erosive power of subaerial (fluvial) rather than submarine systems was responsible for these remarkable late Paleocene or early Eocene canyons.

Both canyons are backfilled with deep-water sediments (mainly siltstones in Yoakum and turbidites including some channelized sandstones in Chicontepec), which suggests rapid return of the sea that delayed resumption of coarse-grained sedimentation into the canyons. If so, either (1) the entire margin would have had to be uplifted and then lowered rapidly (geologically instantaneously) by as much as 1 km, or (2) hydrologic base level in the Gulf of Mexico



Modified from Pemex, 1999

Figure 2. **Isopach map and cross section of part of the Chicontepec Canyon area, east-central Mexico, modified after Busch and Govela (1978) to show the canyon fill and overspill deposits as the same age (early Eocene). See Figure 1 for general locality.**

fell by perhaps 1 km or more and then rapidly returned to its original level. There is no tectonic reason to suspect, or structural evidence to suggest, that there was uplift along the Texas shelf of anywhere near this magnitude at that time. Similarly, the eastern Mexican Gulf coastal plain and slope were situated in the tectonically loaded Sierra Madre foredeep basin rather than the Sierra Madre hanging wall, and they should have been subsiding rather than rising at that time. Thus, we have examined and compiled circum-Gulf evidence to build a case for one or more rapid and large Paleogene drawdown/flooding cycles in the Gulf through intermittent isolation from the world's oceans when the Cuban Orogen spanned the quasi-oceanic gap between Yucatán and the Bahamas, as outlined below.

CHICONTEPEC PALEOCANYON

Although contested by Cantú-Chapa (1985, 2001), the existence of the Chicontepec paleocanyon in the Tampico-Misantla Basin of east-central Mexico (Figure 1) has been described by Busch and Govela (1978), Carillo-Bravo (1980), Busch (1992), and Bitter (1993). The Chicontepec Formation comprises three members: "Lower," "Middle," and "Upper" of Paleocene–lower Eocene age. The Lower and Middle Chicontepec members roughly span the Paleocene and form depositional units in a foreland basinal setting between the Tuxpan (Golden Lane) carbonate platform and the Sierra Madre Oriental thrust front (Figures 1 and 2). Deposition at this time occurred in outer neritic to upper bathyal water depths and was mainly turbiditic in nature. Cut into these, and into deep-water marine carbonate units as old as Jurassic, is a paleocanyon filled with turbiditic sediments of the Upper Chicontepec member. The Upper Chicontepec canyon fill is roughly of Paleocene-Eocene boundary age, but faunal zonation is apparently lacking (Busch and Govela, 1978; Bitter, 1993) as might be expected during rapid infilling after the Gulf reflooded. Overlying this member are the prograding

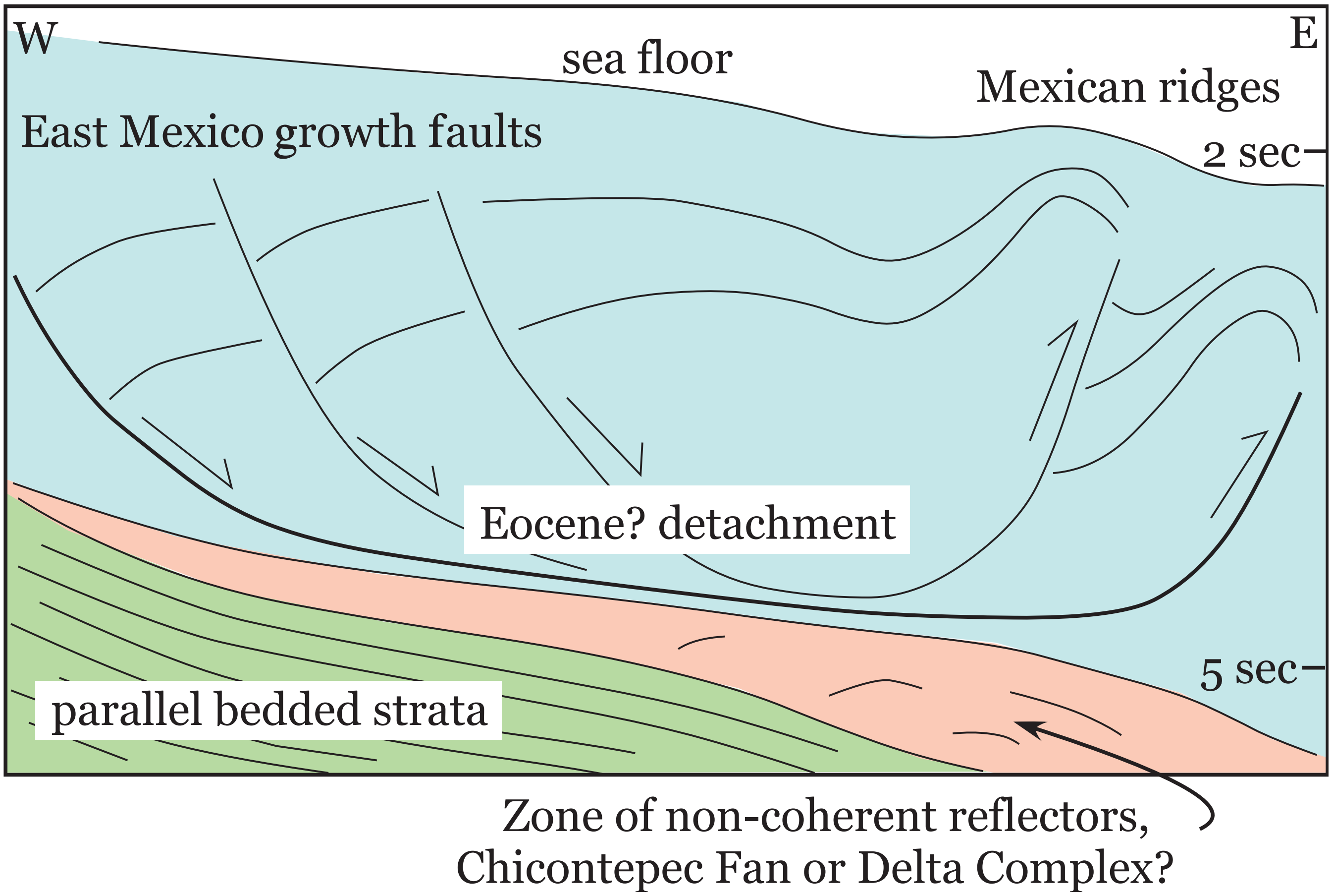


Figure 3. **Schematic seismic section of the eastern Mexican deep-water margin east of the Chicontepec Canyon, drawn from memory of sections presented in presentations at the 2001 Asociación Mexicana de Geólogos Petroleros /AAPG meeting, Veracruz, Mexico.**

littoral and neritic Guayabal and Tantoyuca Formations of middle and upper Eocene age, which represent the first truly shelf setting in the area.

The Chicontepec paleocanyon has relief of at least 1 km, and cuts down to the Late Jurassic San Andrés Formation. Isopachs of the canyon fill increase westward toward the Sierra Madre Oriental thrust front (Figure 2). On this basis, Busch and Govela (1978) considered that current direction was east-to-west during canyon formation. However, if the original surface of the basinal trough dipped eastward on the continental slope as the canyon was cut into it, the same isopach would be produced with west-to-east flow, and we find that this is more in line with regional geology, as did both Cantú-Chapa (1985) and Carillo-Bravo (1980).

Slightly to the south, at the Nautla paleocanyon (also known as San Andres Canyon, as acknowledged by Cantú-Chapa, 2001), 2 km of Chicontepec canyon-fill rests unconformably on Jurassic red beds (Figures 1 and 2; Cantú-Chapa, 2001; Viniegra-O, 1966), suggesting that the canyon cut through the entire marine section above the Santa Ana Massif, which defines basement here. If canyon cutting is the primary reason for the missing Cretaceous and Jurassic section, then the Nautla example would suggest a larger water-level drop in the Gulf than presently documented in Chicontepec. Both canyons cut through the entire Cretaceous section of carbonates and marls. These lithologies are prone to rapid cementation and may have been nearly or fully lithified at the time of late Paleocene or early Eocene of downcutting. Thus, the erosional forces must have been strong and may have taken several tens or hundreds of thousands of years to accomplish.

Offshore, seismic lines show the deep stratal geometry illustrated in Figure 3. A deep, well-bedded, presumed Mesozoic section is overlain by a discontinuously bedded section of probable Paleogene age that underlies the detachment for the Mexican Ridges Fold Belt. The detachment links extensional gravity-driven faults at the top of the slope with compressional folds and thrusts toward the slope-to-basin transition. The middle (subdetachment) section may comprise fans, or perhaps deltas, built of both excavated and bypassed sediment transported into the Gulf of Mexico through the Chicontepec Canyon. The age of this section is poorly constrained at present, but late Paleocene/early Eocene fits the existing constraints, and the great volume of missing Chicontepec strata removed to form the canyon must have been deposited in this area.

Additional anecdotal evidence for large water-level fluctuations in this area is the development of cavernous and other secondary porosities in the Cretaceous reef carbonates of the Golden Lane and basinal carbonate debris in Poza Rica Field that was derived from the Golden Lane reefs. Textures in these strata apparently required flushing by meteoric water downward to depths of at least 2 km, or to about the base of the Chicontepec Canyon (Enos, 1988; Dan Cox, personal communication, 2001). The caverns and finer-scale secondary porosity development may be related to a drastic lowering of the water table, as proposed here, rather than to the very special set of conditions outlined by Enos (1988), who, judging from his comments, may not have been satisfied fully with existing models for understanding this porosity development. Enos (1988) cites Halley et al. (1984) as describing similar circumstances at Deep Sea Drilling Project (DSDP site 536 off northeastern Campeche (Figures 1 and 5A), the location of which also may have been subaerial, or nearly so, for part(s) of the early Paleogene. (Note: Eocene is missing at this locality, according to revised ODSN [Ocean Drilling Stratigraphic Network] range charts.) Like the canyon itself, development of such secondary porosity in the Golden Lane/Poza Rica carbonates may have required a significant time period to develop.

From the above, we envisage the following: At the end of Middle Chicontepec time, water level in the Gulf was drastically lowered by more than the preexisting water depth of the Chicontepec Trough, possibly by up to 1 km or more, for a significant period of time. One or more rivers flowing either out of or along the front of the growing Sierra Madre Oriental flowed toward the Gulf and excavated the Chicontepec and Nautla Canyons throughout the Paleocene-age Lower and Middle Chicontepec clastics, Cretaceous carbonates, and, ultimately, Jurassic strata (Figure 2). This was accomplished by fluvial erosion rather than by submarine processes, as other studies have assumed. The river(s) carried clastic detritus from the rising Sierra Madre out onto the slope of the Gulf of Mexico, probably into a deltaic and ultimately a submarine fan depositional environment (Figure 3). At about the Paleocene-Eocene boundary, or perhaps just into the lower Eocene, water level in the Gulf returned to normal, presumably by breaching of the land barrier at the Cuban Orogen (see Climate, Regional Drainage Patterns, and Gulf–World's Oceans Connections), and the Upper Chicontepec was deposited rapidly as canyon fill derived from the adjacent Sierra Madre Oriental. This environment of rapid deposition involved much reworking of existing material, hence the irresolvable faunal zonation.

YOAKUM AND SOUTHEASTERN TEXAS/ NORTHEASTERN MEXICO MARGIN

Both megaslumps and canyons are associated with the Wilcox Formation in southern Texas and northernmost Mexico (Figures 1 and 4). The Lobo and Lavaca megaslumps formed in the late Paleocene mainly in areas of thick, prograded clastic deltaic deposits of Paleocene age (e.g., Houston Delta; Galloway et al., 1991, 2000). The slumps likely comprise material from the poorly consolidated shelf-slope break.

Downcutting into the Lavaca megaslump, as well as headward into the shelf for some 80 km northwest of the slumped zone, is the Yoakum paleocanyon (Figure 4). The Yoakum Canyon is similar to the Chicontepec Canyon in that it has about 1 km of relief, has sides sloping up to 30°, and has canyon fill of fine-grained sediment that spilled over the canyon limits (Figure 4). It is potentially important that this canyon cuts through other than basinal (trough) strata because it strongly suggests that the canyon-forming process was subaerial rather than submarine. Indeed, Galloway et al. (1991, p. 263) write: "Wilcox canyon fills include (1) a lower onlap fill, which consists largely of disorganized slump and debris-flow deposits, but locally contains sandy channel fills and turbidite mounds. . .'' We suggest that the debris-flow and sandy channel fills may indicate a subaerially eroding canyon with slumping walls and a river in the thalweg. We further speculate that a major paleocanyon also may exist under the lower Río GrandeValley, with the Lobo megaslump representing slides that formed along its walls or at its headward extremity.

Other examples of canyons in the world with this magnitude of incision and distance of headward erosion across a shelf are rare; not even the Quaternary Hudson, Mississippi, or La Jolla Canyons reach this

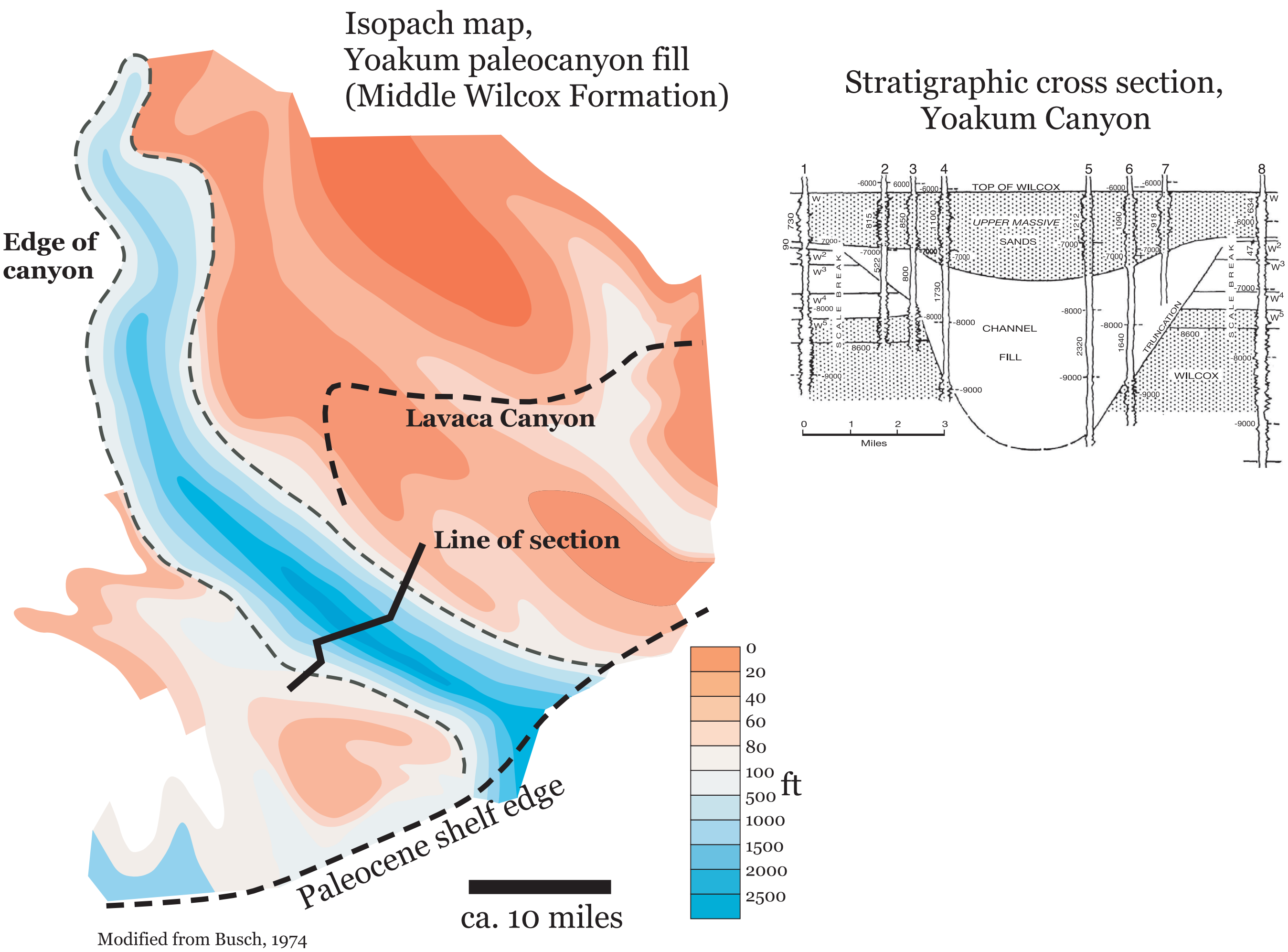


Figure 4. **Isopach map and cross section of the Lavaca megaslump and Yoakum paleocanyon area, Texas, modified after Busch (1974). See Figure 1 for general locality. Note that the paleocanyon cuts into shelf strata northwest of the Lavaca megaslumps, such that the isopach here approximates a paleostructure map and attests to the fact that the canyon was nearly flat with little gradient at its base.**

scale on the shelf. The Hudson Canyon, formed during an obvious and significant glacial drawdown, has a length of only 15 km on the shelf in contrast to 80 km for Yoakum. The Mississippi Canyon is somewhat wider than Yoakum Canyon, in a predominantly slope setting, and is more clearly of a submarine slump origin (Prather et al., 1998). The La Jolla Canyon lies in an active strike-slip setting and probably should not be used in such comparisons. In the case of the Nile and Rhone Rivers, gullies and canyons incising the shelf and even more landward sections (Ryan and Cita, 1978; Barber, 1981) developed during the Messinian salinity crisis when water level in the Mediterranean fell by more than 2 km (Butler et al., 1995). We believe that current strength in the marine environment would be insufficient to cause such magnitudes of incision on the shelf , and we find it difficult to envision how canyon flanks in unconsolidated material could approach 30° slopes in an active-marine environment known otherwise to be a site of longshore drift.

HYPOTHESIS

We hypothesize the following: A significant lowering of the Gulf's base level at about the Paleocene-Eocene boundary was responsible for development of the canyon and megaslump features. However, dating uncertainties allow that the numerous canyons (Figure 1) may not be of exactly the same age; thus, more than one cycle of drawdown affecting different places may have occurred. As initial drawdown took place, the shelf became exposed, and the first event was the primarily subaqueous failure of large segments of the basin margin, represented by the Lavaca and other megaslumps. As water level was drawn down farther, either in the same or in subsequent events, the original fluvial systems responsible for the deltas at which the slumping took place cut more deeply through the shelf and upper slope strata and, in the case of Lavaca, through material that had already slumped basinward (Figure 4). We consider the apparent lack of significant gradient in the floors of both the Chicontepec and Yoakum paleocanyons (Figures 2 and 4) to support the fluvial interpretation of their origin, in contrast to submarine canyons cut by relatively dense turbidity currents that normally require a relatively steep gradient in order to gain the necessary energy to become and remain erosive. As water level rose again, the canyons were backfilled with generally fine-grained sediments that eventually overtopped the original canyon walls. Concerning the backfilling, we pose the question: What could have caused the change from such drastic canyon erosion to such rapid canyon infilling if the margin had remained submarine the entire time? The answer does not appear to be an accelerated influx of sediment, as the canyon fill is very fine to silty; we suggest that a rapid return to a submarine environment was responsible.

Following the first episode of infilling, further large basinward shifts in facies with notably rapid downcutting and incision of various magnitudes, all followed by rapid flooding events (fine-grained transgressive tongues), are recorded in the Upper Wilcox, Queen City, Sparta, and Yegua Formations (Galloway et al., 1991). Because their ages pre-date the accepted time of initial Tertiary continental glaciation (Markwick and Rowley, 1998), we speculate that these cycles of very large relative sea-level change may have been driven by at least one period of isolation (evaporative drawdown of hundreds of meters) and reconnection (rapid flooding) of the Gulf with the world's oceans as topographic relief in the Cuban Orogen was breached (see the following section), rather than being caused by worldwide eustatic cycles.

CLIMATE, REGIONAL DRAINAGE PATTERNS, AND GULF–WORLD'S OCEANS CONNECTIONS

In order for water level in the Gulf to fall below global eustatic levels, the Gulf must have been physically isolated from the world's oceans, and evaporation must have exceeded total river input and precipitation. Although the Gulf was linked during the Late Cretaceous to the world's oceans across epicontinental and deeper channel systems via the Western Interior Seaway, the Suwannee Straits of northern Florida, the Isthmus of Tehuantepec of southern Mexico, and the southeastern Gulf of Mexico/Florida Straits, by the Late Paleocene, all of these connections, except for the southeastern Gulf/Florida Straits, had been interrupted as a result of long-term eustatic fall and local tectonic developments (Ziegler and Rowley, 1998; Galloway et al., 2000; Pindell, 1993; Johnson and Barros, 1993). Thus, if Cuba blocked the Florida Straits and Yucatán Channel in the Paleogene, as suggested here, then the potential exists for the Gulf to have been isolated at about the late Paleocene. In this event, we note that the paleolatitude of the Gulf has remained within the latitudinal band of 15°–25°N since the Paleocene, certainly in a zone of high evaporation potential. Further, relief in the Sierra Madre Oriental probably reached its maximum in the late Paleocene–middle Eocene (Suter, 1987), possibly causing a rain-shadow effect along the western margin of the Gulf. Major late Paleocene–middle Eocene rivers did enter the Gulf of Mexico from the Laramide foreland (Galloway et al., 2000) but, in our opinion, would not have been able to replace the water lost to evaporation. In Mexico, catchment areas were limited by the rising Sierra Madre Oriental. Given this high evaporation potential, and using the Mediterranean Messinian crisis as an analogue (where rivers such as the Rhone and Nile were unable to overcome evaporation), we are confident that the late Paleocene–middle Eocene setting for the Gulf of Mexico at the time of the Cuban blockage of the southeastern Gulf was generally conducive to evaporative drawdown.

With regard to Cuba and the southeastern Gulf, the Cuban island arc is understood to have collided with the northeastern Yucatán and Bahamas passive margins in the late Paleocene to middle Eocene (Iturralde-Vinent, 1994), such that the Cuban Orogen (and the adjacent Bahamas and Yucatán platforms) is capped by a strong middle Eocene subaerial unconformity (Pardo, 1975; Pzolzyckowski, 1999; Ball et al., 1985). However, it is unclear whether the arc collision and subjacent imbrication of shelf strata from Yucatán to the Bahamas across the southeastern Gulf of Mexico gap attained sufficient and continuous bathymetric/topographic statement to close off the Gulf of Mexico during and, possibly, for some time after the collision. We believe that the observations at the Chicontepec and Yoakum Canyons provide evidence that the Cuban thrust belt did, in fact, seal off the Gulf, as depicted in Figure 1. Further, there is no reason to assume that the Gulf was not sealed off, perhaps intermittently, during the progressive collision.

More direct evidence that the Cuban Orogen closed off the mouth of the Gulf comes from seismic sections in this area (Figure 5A) that show late Eocene strata commonly resting above a strongly erosional hiatus that often cuts down to middle Cretaceous levels and, along the northeastern Yucatán margin, to deformed basement. Although the basement is not well defined here, Figure 5B shows that an undeformed late Eocene and younger section rests on a deformed substratum (Rosencrantz, 1990). We envision that at least one, and possibly several post-drawdown flooding episode(s) in the Gulf created this scoured surface and that the late Eocene and younger age of the overlying section defines the period following the activity of strong, erosive currents. Similarly, Figures 5C, 5D, and 5E also show the effect of severely erosive bottom currents. In these sections and others, hiati at the Paleocene-Eocene boundary, as well as within the late middle to late Eocene, have been noted (Angstadt et al., 1983; ODSN, 2001).

Finally, we note the existence of a deep-sea fan located to the northwest of the Florida Straits (Figure 1; ''Eocene Plume''). We suggest that the fan comprises material eroded from the Cuban Orogen and the Paleogene unconformities in the Florida Straits. It would be surprising if such a fan did not exist in this location, given the volume of material that apparently was eroded from the Straits during potentially catastrophic refilling of the Gulf once the barrier was breached.

The sequence of events during arc collision in the Florida Straits/Yucatán Channel is as follows (after Pindell and Kennan, 2001). The Cuban forearc migrated with sinistral transpression to the north-northeast along the eastern Yucatán margin during the Maastrichtian to middle Eocene (Figure 1). During this transpression, the western Cuban fold-thrust belt of the Sierra Guaniguanico (Jurassic-Paleocene shelf and slope strata derived from the eastern Yucatán margin) was imbricated ahead of the Cuban arc rocks and was carried toward the Bahamas for ultimate collision (Pindell, 1985; Hutson et al., 1998; Iturralde-Vinent, 1994). Likewise, a southern Bahamian slope-and-shelf section was imbricated ahead of the arc as it converged upon the Bahamas (Hempton and Barros, 1993). Figure 1 suggests that the imbricated fold belt spanned and blocked the Florida Straits and Yucatan Channel starting in the late Paleocene, precisely when the Chicontepec and Yoakum Canyons were cut, and just before the culmination of the Cuban convergence with the Bahamas (note the final middle Eocene position of the northern Cuban coastline in Figure 1). However, upon that culmination, Pindell and Kennan (2001) argue that the collision was accompanied by the dropping off of the subducted, south-dipping proto-Caribbean slab beneath Cuba, which predictably should have led to 1 or 2 km of early or early–middle Eocene isostatic rebound of the entire Cuban Orogen, operating over a flexural wavelength of about 300 km across the orogen. This development either could have enhanced the original late Paleocene blockage of the mouth of the Gulf or caused additional blockages into the Eocene.

We make no attempt to define the number or duration of times when the Gulf was isolated from the world's oceans, but judging from the geology of the Florida Straits, we are confident that by the late Eocene, the Cuban Orogen had been downcut in one or more places (e.g., Yucatán and/or Nicholas Channels) to a sufficient depth that the marine connection probably was never broken again. Angstadt et al. (1983) make the point that the Eocene unconformity west of Cuba and in the Nicholas Channel seems to be unique and cannot be related to the ''normal'' range of sea-level fluctuations. The Eocene erosional event is obvious, while a supposedly much larger Oligocene eustatic sea-level fall is not represented by an unconformity. Today, water depths in the Yucatán and Nicholas Channels are about 2 km and just less than 1 km, respectively, and we find that the present structural levels of the Eocene unconformities in these areas are in line with expected amounts of subsidence since the Eocene, given the various aspects of the setting. Further, the area between western Cuba and Yucatán (Yucatán Channel) was transtensionally widened and deepened toward the end of Cuba's migration toward the Bahamas (Rosencrantz, 1990; Pindell and Kennan, 2001), subsequent to the period of canyon cutting (and proposed marine isolation) in the Gulf.

The strongest single piece of evidence for rapid refilling of a lowered Gulf of Mexico is the canyon in the Straits of Florida whose thalweg presently lies 3,000 m below sea level (Figure 5D). This canyon was cut through Paleocene strata into Lower Cretaceous rocks. The likely mechanism for this event is the flow of ocean water into a drawn down Gulf of Mexico on one or more occasions when the barrier

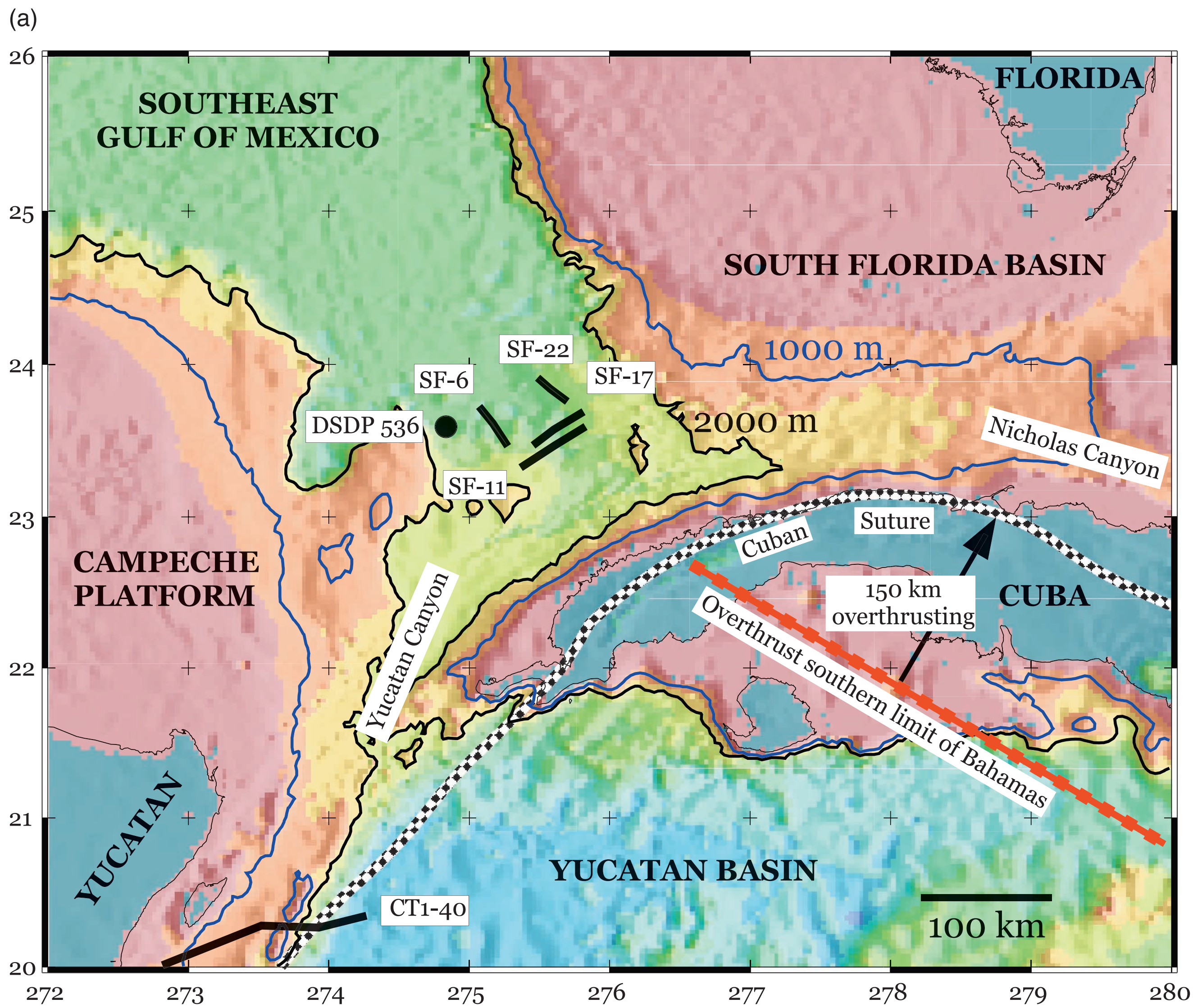


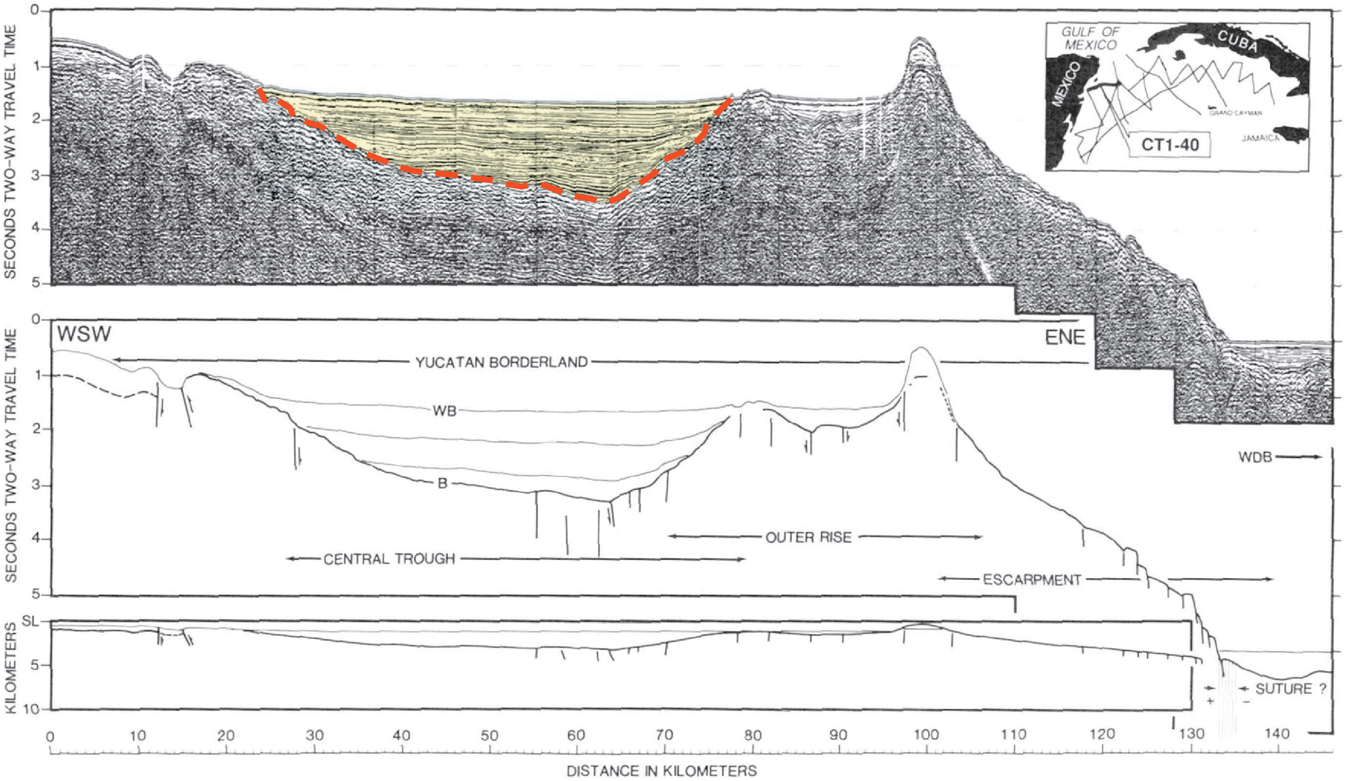
Figure 5. (A) Map of the southeastern Gulf of Mexico/Yucatán Channel/Florida Straits area, showing locations of representative seismic sections that show the early Paleogene unconformities that we suggest were produced by current scour during flooding events in the Gulf of Mexico. Seismic lines are modified after Angstadt et al. (1983), Rosencrantz (1990), and Marton and Buffler (1999). Bathymetry is from Smith and Sandwell (1997). (B) Seismic section CT1-40 across the pull-apart zone of the eastern Yucatan margin. Location is shown in Figure 5A (From Rosencrantz, 1990). (C) Seismic line SF-6B showing incised Paleogene and Cretaceous strata buried by younger sediments. Location is shown in Figure 5A (From Marton and Buffler, 1999). (D) Seismic line SF-17, location shown in Figure 5A (from Marton and Buffler, 1999) showing canyon incised into Cretaceous strata, which we consider was initially cut in the Paleogene. TB = top Berriasian; LK = Lower Cretaceous; MCSB = ''Mid-Cretaceous Sequence Boundary,'' suspected by us to be top Cretaceous; UK-C = Upper Cretaceous–Cenozoic. Vertical exaggeration about 10 at sea bottom.

to the Gulf was breached. Subsequent sedimentation in this area has been slow, and ocean currents have kept this canyon free of younger sediments.

ISOSTATIC CONSIDERATIONS

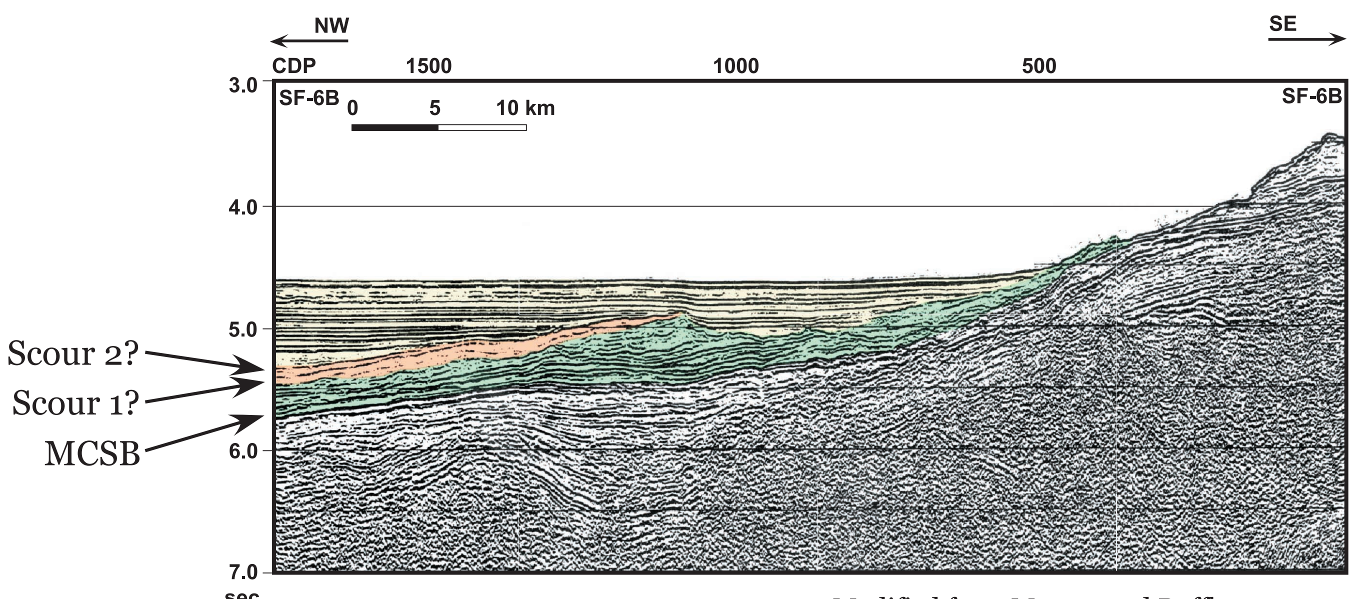
The isostatic response of the lithosphere due to water drawdown and flooding in the Gulf is potentially a very important process in the story. For every kilometer of water removed from the Gulf by evaporation, the lithosphere will isostatically rebound by about one third of that, say 300 m. For the Gulf's margins, such rebound will become progressively less in the landward direction, where original water depths were less than 1 km. But the flexural rigidity of the crust still will cause rebound of the margins, perhaps by 100 m (~330 feet) at the shelves.

(b)



From Rosencrantz, 1990, Tectonics

(c)



Modified from Marton and Buffler, 1999

Figure 5. (cont.).

This carries some implications. First, once started, evaporation would tend to enhance the isolation of the Gulf by uplift of the Gulf's margins, making them less likely to be breached. Second, existing rivers in the northern and western Gulf floodplain would respond to this marginal uplift by incising the outer shelf on their way to the lowered Gulf. Third, if the Gulf was isolated from the world's oceans, the

(d)

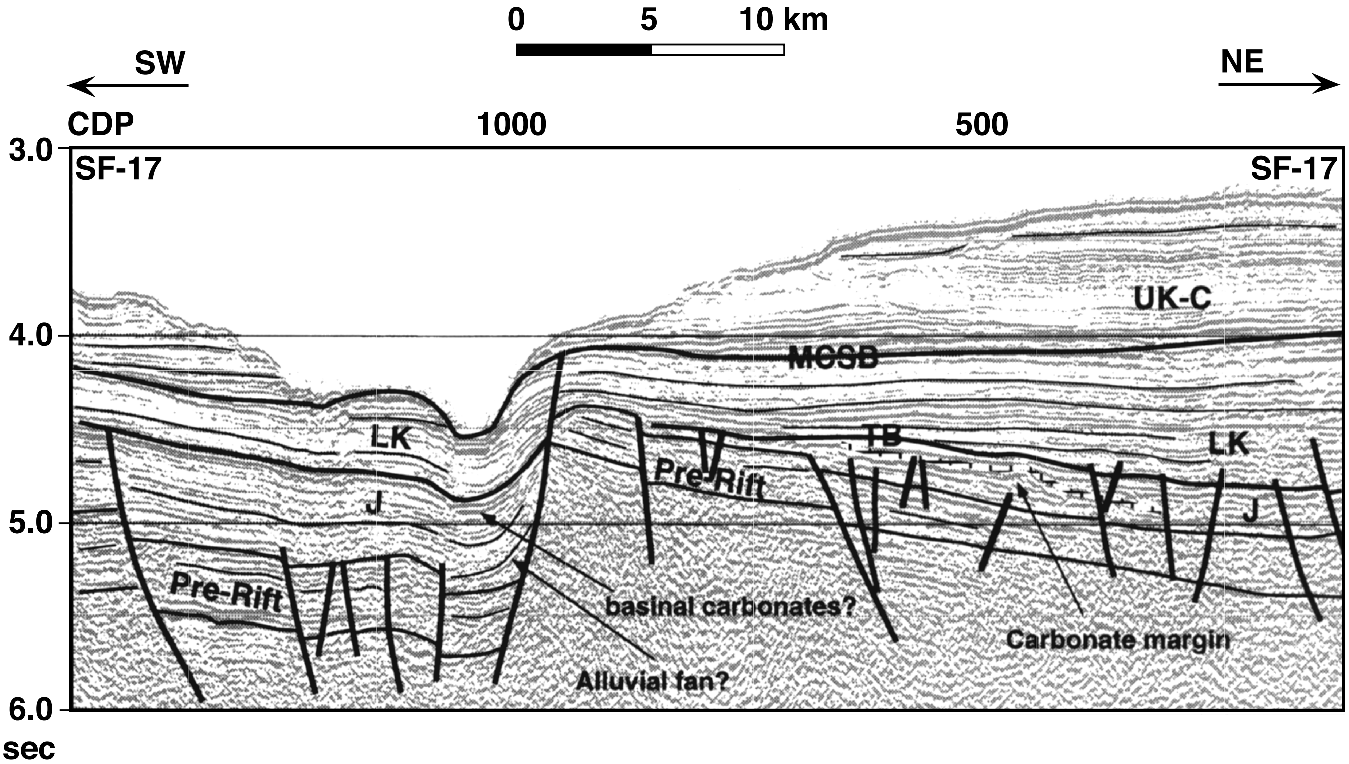


Figure 5. (cont.).

remaining water itself would rebound with the lithosphere, and the net lowering of the Gulf's water level relative to the world's oceans would be one-third less than the actual amount of water lost in the Gulf. Finally, all of these considerations would have been reversed once water began to reflood the Gulf: specifically, the floor and margins of the basin would have subsided under the load of additional water, leading to pronounced marine transgression across the formerly exposed and incised shelves. Such onlap sections (mostly shale) include the Big Shale, Yoakum, Reklaw, Weches, Cook Mountain, and Moody's Branch Formations (Galloway et al., 2000).

DISCUSSION

Our hypothesis provides a unifying mechanism for diverse phenomena of Paleogene age that either already have been observed, or are as yet unexamined, in Cuban, Mexican, and U.S. waters. These include (1) the subaerial(?) exposure of circum-Gulf continental shelves and upper slopes; (2) severe canyon incision into shelves and slopes (Yoakum and Chicontepec); (3) massive slumping of clastic continental shelf/slope sections (Lavaca) on a scale not approached again in the Gulf until the Pleistocene; (4) transfer of load by mass wasting and deposition, possibly driving massive salt evacuation ahead of the migrating clastic wedge; (5) deep karsting and porosity development in exposed carbonate margins; (6) high volumes of sediment bypass and progradation into the deep Gulf basin, including the possibility of deltaic deposition on the Paleogene continental slope; and (7) severe deep-sea scour along the flank of the Cuban Orogen.

Flooding episode(s) in the basin would have resulted in rapid backfilling of the canyons with "transgressive" fine-grained, seal- and locally source-prone sediments, which would logically spill beyond the canyon walls due to the isostatic loading effect of the flood on the shelves (Upper Chicontepec Formation in Chicontepec Canyon, and Big Shale/Middle Wilcox [not exactly clear, in our opinion] in Yoakum Canyon). Also, severe erosion along the paths of seawater reentry (Nicholas and Yucatán Channels, Florida Straits) is expected, with the associated transportation of southerly-derived clastic detritus into the deep southeastern Gulf of Mexico.

It might be expected that progressive Cuban uplift would block the Gulf and that the eventual breaching of the barrier would lead to only a single isolation event that was perhaps prolonged. However, the timing of the drawdown episode(s) (late Paleocene–early Eocene) preceded the culmination of the Cuban Orogeny (middle Eocene). Thus, the Cuban Orogen was dynamically growing during drawdowns; therefore, it is possible that multiple barriers were created and breached during final suturing, thereby producing repeated isolation events in the Gulf. Ultimately, the two key parameters that mattered most were (1) the continuity of the orogen from the Bahamian to the Yucatán "Eocene" unconformities, and (2) the elevation of this growing orogen relative to eustatic sea level on its southeastern side. Considering that both thrust-belt development as well as the dropping off of the proto-Caribbean slab during suturing probably caused kilometric magnitudes of uplift, the creation of a land bridge from the Bahamas to Yucatán would not be surprising. Subsidence and erosion along the transcurrent fault system between the Yucatán Block and Cuba in the Yucatán Channel probably led to permanent barrier failure in the latest (early to middle Eocene) stages of the Cuban Orogeny.

Concerning eustasy, possible intermittent Paleogene isolation of the Gulf of Mexico may have caused cyclical transgressive-regressive cycles in the Gulf that have previously been interpreted as large-magnitude worldwide eustatic fluctuations. Because these large-magnitude/short-term cycles predate the accepted onset of Cenozoic continental glaciation in the late Eocene, we would treat Paleocene–middle Eocene relative sea-level histories derived for or from the Gulf margins with a high degree of suspicion. Potential drawdown/flood cycles include Lower Wilcox/Big Shale; Middle Wilcox?/Yoakum Shale; Upper Wilcox/Reklaw Shale; Queen City/Weches formations; Sparta/Cook Mountain formations; and Yegua-Cockfield/Moodys Branch formations. Thus, the Gulf of Mexico should not be used as a laboratory for defining global eustatic changes for early Paleogene. Since at least late Eocene deposition of the Jackson Formation and equivalent units, the Gulf appears to us to have remained connected to world's oceans. As continental glaciation is known to have operated since the late Eocene, we accept that the Jackson and subsequent progradational sand wedges (such as the Frio Formation) in the Gulf may relate genetically to glacioeustasy. The large volume of Frio sandstones is presumably related to erosion of the Eocene Laramide uplifts, after the subjacent Laramide foredeep basins were filled, and to the onset of basin and range tectonics in the U.S. and Mexican Cordillera.

We propose a mechanism similar to the Messinian desiccation of the Mediterranean for large, short-term, early Paleogene relative water-level fluctuations in the Gulf of Mexico, a basin that has been used extensively in the determination of Cenozoic relative sea-level charts. In Pindell (1998, p. v) the question was posed: "Why don't relative sea level charts change in ***style*** as we go back beyond the Late Eocene earliest onset of Cenozoic continental glaciation?" Are there **two** primary drivers for large, short-term fluctuations operating today, one of which is unknown but that operated alone prior to the late Eocene? If our drawdown/flood hypothesis for the early Paleogene of the Gulf of Mexico is correct, we will need to ignore the Gulf of Mexico for calibration of eustatic charts for the early Paleogene.

If the relative fall(s) in the Gulf's water level proposed in this paper exceeded typical post-middle Eocene eustatic falls, our hypothesis, if correct, carries the following implications for hydrocarbon exploration:

- one or more ubiquitous circum-Gulf unconformities matching the time(s) of lowered water level, with Paleocene to middle Eocene paleosols on the shelves and upper continental slopes
- exposure and karsting of exposed carbonate platforms (Florida, Yucatán, Córdoba, Tuxpan, Tamaulipas Arch, etc.)
- deeply incised, silt and fine-grained turbidite-filled canyons with stratigraphic trapping potential cut along other river systems feeding the Gulf that are not yet well documented (Tyler, Bleakwood, St. Landry, Nautla; Figure 1), and possibly in the Rio Grande Embayment
- slumping and landsliding of exposed canyon walls and poorly consolidated upper-slope deposits in areas other than the documented Lavaca megaslump
- fluvial thalweg deposits comprising braided channels and sandbars on the floors of subaerially eroded canyons during periods of lowered water level.
- a major paleocanyon analogous to the Nile paleocanyon of the Mediterranean Sea should exist under the present day Rio Grande. In this case, the anomalous block faulting of Paleocene strata within a narrow strip along the U.S.–Mexican border (the Lobo trend) would be due to gravitational failure along the canyon's rapidly propagating headwall. The downdip paleocanyon may

have been large enough to nucleate the Eocene to Oligocene Vickburg Embayment depocenter.

- extensive Paleocene to middle Eocene sandy lowstand deltas and basin slope, and floor fans basinward of the subaerial canyon systems. Such deposits could provide important hydrocarbon reservoirs and migration pathways from deep maturation "kitchens." We note that the Chicontepec Formation is saturated with hydrocarbons (Bitter, 1993), possibly due to its physical contact with the Upper Jurassic source rocks at the base of the canyon.
- deposition and preservation of both algal- and land plant–dominated organic debris (oil and gas–prone) during the lowstand interval in basinal deposits laid down under a stratified column of hypersaline brine, and accumulation of oil-prone source material in the condensed section(s) following reconnection with the world's oceans.

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