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EASTWARD SHIFT OF DEEPWATER FAN AXES DURING THE MIOCENE IN THE GULF OF MEXICO: POSSIBLE CAUSES AND MODELS

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ABSTRACT

Synthesis of the Gulf of Mexico depositional history reveals a notable eastward displacement of sediment transport in the Miocene. The paleo–Tennessee River system deposited over 9800 ft (3000 m) of sediment south of the fluvio-deltaic input point in available shelf/upper slope accommodation. However, the depositional axis of the MCAVLU (Mississippi Canyon Atwater Valley, and Lund protraction areas) submarine fan system is located more than 150 km (90 mi) east of this depocenter, indicating along shelf/upper slope transport prior to entering the deepwater. This anomaly can be variously explained as a function of salt tectonics or, alternatively, development of strong easterly oceanographic currents.

Evidence for development of intensified, clockwise oceanographic flow in the Miocene has been previously recognized but not linked to this apparent deepwater submarine fan shift. Upper Miocene deepwater fan deposits on the western flank of the Gulf of Mexico Basin, including north-dipping clinoforms, indicate accelerated current flow from the south. In the eastern Gulf of Mexico, seismic stratigraphic analysis shows a major Middle to Upper Miocene unconformity formed on the western Florida platform margin, well below the influence of subaerial erosion processes.

Linking these observations suggests that oceanographic current velocities were probably elevated, and thus may have caused displacement of transport pathways toward the Mississippi Canyon area. Initiation of intensified current flow could be linked with progressive termination of global equatorial flow beginning in the early Miocene.

Implications for deepwater exploration are substantial, given high interest in the Gulf of Mexico Miocene deepwater play and use of source-to-sink reconstructions that often do not consider oceanographic currents.

INTRODUCTION

The Gulf of Mexico is one of the most prolific hydrocarbon-producing basins in the world (Fig. 1), with a Year 2000 Minerals Management Service (MMS) assessment estimating hydrocarbon endowment (discovered and undiscovered reserves) resources in the 100 to 140 BBOE (billion barrels oil equivalent) range in the U.S. (Lore et al., 2001). Consideration of the 'creaming curve,' discovered resources versus time has shown that the basin continues to provide new tiers of discoveries, after diminished success in earlier plays (Snedden et al., 2002).

The Gulf of Mexico Basin is also a natural laboratory of sedimentary processes, from its Mesozoic origin to the Cenozoic evolution into its present-day form as a coastal plain to abyssal plain depositional system (Galloway, 2009a, 2009b). Important new insights into source-to-sink linkages of interior drainage basins to deepwater fans continue to be made (Galloway et al., 2011). The volume and quality of seismic data continues to increase, and we expect significant new ideas to emerge on the basin depositional and structural history. For example, a new perspective on the scale and scope of the Cretaceous/Paleogene boundary event has been recently spurred on by investigation of

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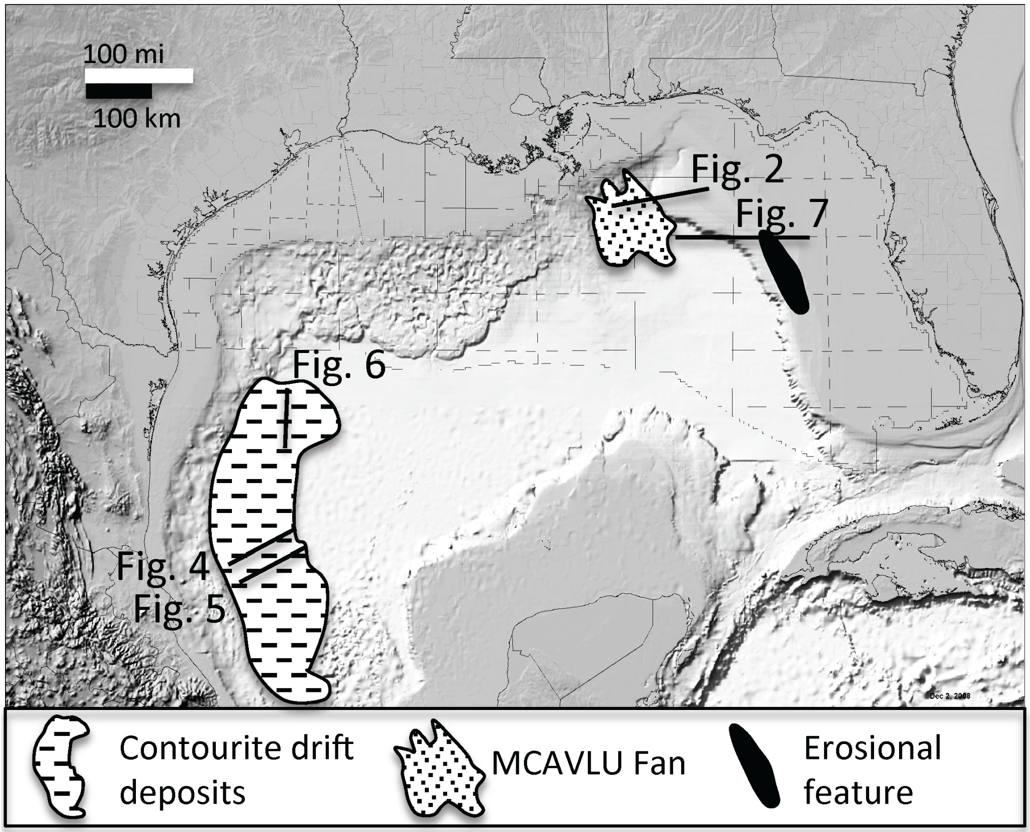

Figure 1. Present-day shaded relief bathymetry map of the greater Gulf of Mexico Basin, showing the location of three areas investigated in this paper. Location of UTIG, ION-Geo, and BOEM released seismic data shown in figures indicated.

industry reflection seismic data from subsalt areas in the deep Gulf of Mexico (Scott et al., 2011).

Synthesis of the Gulf of Mexico depositional history, through the Gulf Basin Depositional Synthesis research project (e.g., Galloway et al., 1998, 2000, 2011), has also yielded other critical questions for scientific investigation. One of these relates to the positioning of the large and thick MCAVLU (for Mississippi Canyon, Atwater Valley, and Lund protraction areas) submarine fan system formed during the Miocene in the central Gulf of Mexico, near Mississippi Canyon. The paleo-Tennessee River system, rejuvenated by uplift of the southern Appalachians in the Miocene, deposited more than 9800 ft (3000 m) of sediment directly south of the fluvial input point in available shelf and upper slope accommodation (Fig. 2). However, the depositional axis of the MCAVLU fan system is displaced more than 90 mi (145 km) to the east of this shelf depocenter, suggesting along slope or shelf edge transport prior to entering the deepwater. The cause of this apparent displacement, either due to structural or depositional processes, remains unclear but there are clues in observations that can be made around the basin.

The purpose of this paper is to first present regional observations of the Miocene from various sites in offshore Mexico and US waters and then to synthesize these into an integrated, basin-scale model that can explain this apparent displacement of the MCAVLU fan system. Alternative models will also be considered in the context of evidence that comes from seismic and well data collected by UTIG and the oil and gas industry over the last 30 years. The findings here are likely to have important implications for understanding the Gulf of Mexico, but also for the Miocene timeframe that is a key phase in the earth's history (Potter and Szatmari, 2009).

METHODS

Data used here is entirely derived from publically released well information from the Bureau of Ocean Energy Management (BOEM, formerly MMS), external publications, University of Texas Institute of Geophysics (UTIG) originally collected seismic data, or seismic donated by various vendors (Galloway et al., 1998, 2000). Compilation of this information is made in light of an understanding of fundamental sedimentological, depositional, and structural processes. This context and the effort to require map-based consistency over a basin-scale ensure that paleogeographic reconstructions are as accurate as possible. These reconstructions have been tested by industry drilling and continue to be updated as new wells and seismic become available. ION-Geo has provided a large gulf-wide 2D seismic grid that also helped in construction of derivative maps in later phases of the project.

Age control, which is fundamental to any basin-scale mapping and reconstruction effort, is provided by a large number of industry and Deep Sea Drilling Program (DSDP) wells that have penetrated Miocene strata in the Gulf of Mexico (Galloway, 1998). A typical Gulf of Mexico well may penetrate as many as 20 different biostratigraphic datums which have temporal resolution of better than 1 m.y. (Wornardt, 2001; Snedden and Liu, 2011). These control points are extrapolated from well control via seismic correlation. The seismic correlations for this study are largely based upon deepwater seismic data (outside of the salt canopy region) where seismic data quality is high (Galloway et al., 2000). On the western Florida platform margin, additional age control is provided by shallow cores, boreholes, and dredge samples described in Mullins et al. (1986, 1987, 1988), Mitchum (1978), and Freeman-Lynde (1983).

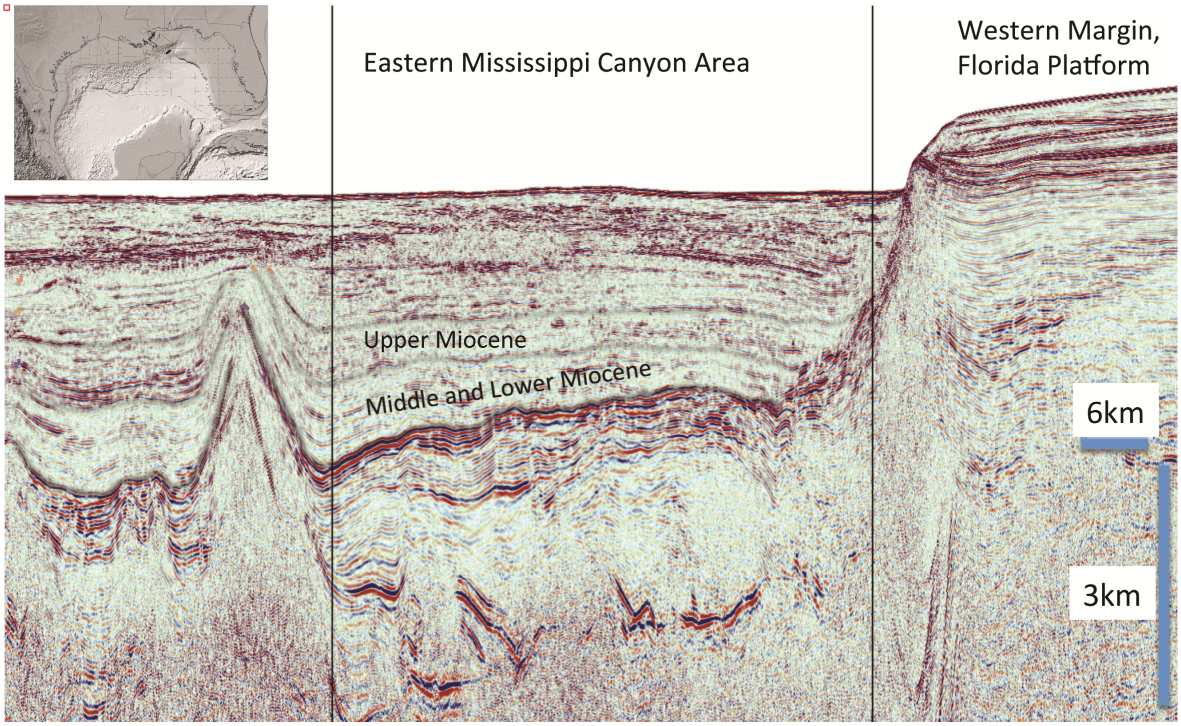

Figure 2. Seismic depth-converted section extending across eastern portion of Mississippi Canyon protraction area to western margin of the Florida Platform. Seismic line is courtesy of ION-Geo. Inset shows approximate line location.

REGIONAL OBSERVATIONS

Observations are from three key areas (Fig. 1) of the Gulf of Mexico Basin: 1) northeastern Gulf of Mexico, the location of an apparent offset between Miocene sediment source/pathway and ultimate depositional sink; 2) eastern Mexico deepwater, where 300 ft (90 m) scale Miocene-age dipping, shingled seismic reflections are present; and 3) western Florida platform and margin, where evidence of significant Middle Miocene erosional truncation, first noted by Mullins et al. (1987) is reexamined (Fig. 2). These seemingly unrelated observations are linked in a synthesized basin-scale model and later evaluated against alternative explanations. The three areas are first described in a series of paleogeographic reconstructions from Early Miocene to Early Pliocene.

Paleogeographic Reconstructions

The Early Miocene marks a transition into Basin-and-Range extension that reorganized the Rocky Mountain drainage systems (Galloway et al., 2011), as well as adjacent areas, and thus changed the paleogeography of the Gulf of Mexico Basin (Fig. 3A). Ancestors of the modern Mississippi, Red, and Rio Grande Rivers developed, with related to sediment load, climate, and discharge. Paleogeographic reconstruction of the Lower Miocene 1 (LM1) shows limited submarine fan development, as only modest amounts of sand traversed the continental slopes in front of the main fluvio-deltaic depocenters (Galloway et al., 2000). One exception is a small deepwater fan system formed in the southeast portion of the Mississippi Canyon protraction area.

The bulk of sediment derived from terrestrial source terrains was stored in shelf depocenters, including a wide, wave-dominated shore zone system known as the Oakville Bar (Galloway et al., 2000). In addition, a wide shelf with an absence of submarine canyons may have limited the amount of sediment delivered to the deepwater. The axis of the depocenter was located to the northeast of the paleo-Rio Grande fluvio-deltaic system, perhaps an early indication of strong alongshore currents. In eastern Mexico, two submarine fan systems were introduced, a product of renewed orogenic activity in Mexico. Along the northeastern Mexico shelf, a wave-dominated shore zone system developed across the foundered Norias fluvio-deltaic system of the Oligocene (Rodriguez, 2011). The western Florida margin saw limited siliciclastic sediment input across the shallow carbonate platform, a pattern that persisted for much of the Miocene (Fig. 3A).

Reconstruction of the Lower Miocene 2 (LM2, latest Early Miocene) shows a different pattern, with large, sand-prone submarine fans initiated in the northeast portion of the Gulf of Mexico, between the modern Mississippi delta and the Florida platform margin (Fig. 3B). The apices of these submarine fans display a substantial easterly offset from the principal fluvial axes of the paleo-Mississippi and paleo–Red River fluvio-deltaic depocenters, a separation of at least 90 mi (150 km). This is the first major period of bypass of sand into the deep Gulf of Mexico, since the Early Eocene timeframe when the extensive Wilcox submarine fan was deposited (Combellas and Galloway, 2006). In Eastern Mexico, a large submarine fan system with mounding in its inner fairway developed with a northeasterly orientation (Galloway et al., 2000). These submarine fans were the result of increased uplift and erosion of the Mexican landmass that deposited outboard into the deepwater, along with loading and destabilization of the narrow, eastern Mexican shelf (Rodriguez and Mann, 2011).

Early Middle Miocene (MM–H) paleogeographic reconstructions show the Tennessee fluvio-deltaic system entering the Gulf of Mexico Basin with rejuvenation of the southern Appalachians (Poag and Sevon, 1989; Boettcher and Milliken, 1994;

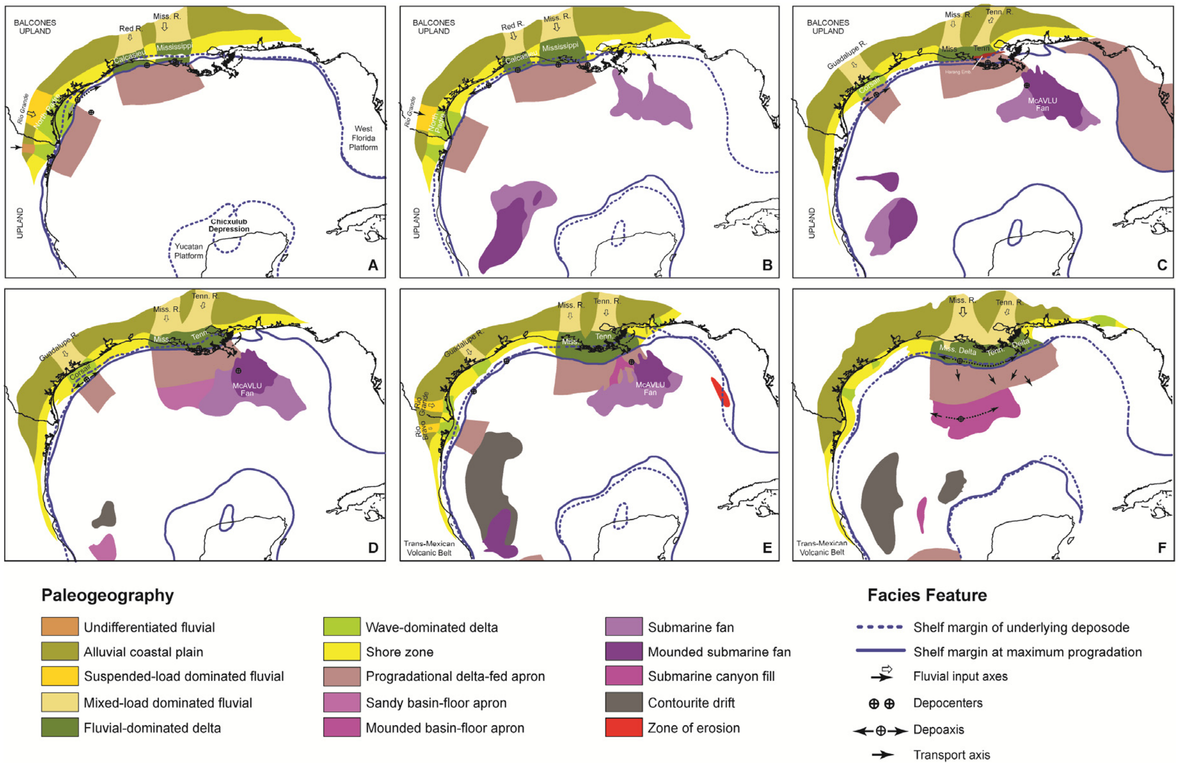

Figure 3. Paleogeographic reconstructions of the Gulf of Mexico Basin. A, Lower Miocene 1 (LM1) seismic sequence F; B, Lower Miocene 2 (LM2) seismic sequence G; C, Middle Miocene (MM) seismic sequence H; D, Middle Miocene (MM) seismic sequence K; E. Upper Miocene (UM) seismic sequence K; and F, Pliocene basal (PB1) 1 seismic sequence L.

Galloway et al., 2011) and decline of the Red River system (Fig. 3C). In spite of this new input, mapping shows a continuation of this pattern of offset fan and fluvio-deltaic axes in the Mississippi Canyon protraction area. This large fan system, now called the MCAVLU is a major reservoir in the deep Gulf of Mexico, with significant gross thicknesses in excess of 6500 ft (1900 m) (Combellas-Bigott and Galloway, 2006) (Fig. 2). During this timeframe, a prominent collapse system, called the Harang embayment of Louisiana (Fig. 3C), formed as a function of shelf-margin retreat and erosion in front of the Tennessee delta depocenter, a considerable distance northwest of the MCAVLU fan system (Combellas-Bigott and Galloway, 2006). Submarine fan development in Mexico also persisted during a period of continued uplift and erosion of the Mexican landmass.

Interpretation of the later Middle Miocene paleogeography (MM–I) shows a continuation of this fan system, and the apparent displacement of fan and fluvio-deltaic feeder systems (Fig. 3D). Re-entrainment of sand from deltaic depocenters and transport to the east along the slope or shelf edge must be invoked to explain sand developed in abyssal plain fans of the MCAVLU system. Mapping also shows the emergence of a small ‘contourite drift complex’ in deepwater Mexico, also recognized by Rodriguez (2011), as will be described in a subsequent section.

The Late Miocene reconstruction (UM–K, Fig. 3E) shows a major increase of the overall deepwater fan area in the Louisiana deepwater, outside of the Mississippi Canyon protraction area (Galloway et al., 2000). Lateral compensation is thought to be the main cause, as earlier bypass axes and minibasin corridors persisted (Combellas-Bigott and Galloway, 2006), but additional channelization in the area in front of the Tennessee fluvio-deltaic system probably contributed to fan expansion. Seismic mapping indicates that the ‘contourite drift’ area had reached its maximum extent in the Mexican deepwater area, anchored on its southern end by a submarine mound. The mounded submarine fan located in offshore Veracruz was the result of increased uplift and erosion of the Trans-Mexican volcanic belt that deposited sediments outboard into the Mexican deepwater (Rodriguez and Mann, 2011). The reconstruction also shows development of a large erosional zone on the seafloor of the Florida platform margin (Fig. 3E) that is thought to be roughly Middle Miocene in age (Mullins et al., 1987; see discussion in a subsequent section).

By the time of the Miocene-Pliocene transition, classical submarine fan deposition had declined in the central Gulf of Mexico, transitioning into a broad basin floor apron in western Louisiana (Fig. 3F). The large contourite drift field of Mexican waters is also thought to continue, though a second contourite drift field developed to the west, closer to the Yucatan Platform (Fig. 3F). It is uncertain whether erosion or a non-deposition occurred on the western Florida platform margin, as the Pliocene overlies the Middle Miocene here (Mullins et al., 1987).

Comparison of the six paleogeographic reconstructions shows the temporal evolution of MCAVLU submarine fan system (Figures 3A–3F). Although the fluvio-deltaic pathways are well documented, the apparent slope transport and bypass to the east, up to 90 mi (150 km) from the deltaic depocenters, is striking. Explanation for this apparent offset of the source to sink system requires a full comprehension of the basin evolution and discussion of observations in two other areas: Eastern Mexico deepwater and the western Florida platform margin.

Eastern Mexico Deepwater

The eastern portion of Mexico includes several basins that have accommodated Miocene sedimentation. On the north, extending up and across the US/Mexico international border, is the Burgos Basin, a southern continuation of the Rio Grande embayment. The Burgos Basin has both onshore and offshore components. Hernandez-Mendoza et al. (2008) used PEMEX reflection seismic data to map Tertiary-age packages and show a correlation between the Veracruz and Laguna Madre-Tuxpan basins to the south. Mapping terminated at the present-day 1600 ft (500 m) isobath. Other pertinent seismic analyses are described from the Laguna Madre-Tuxpan area (Ambrose et al., 2005) and Veracruz basins (Jennette et al., 2003).

Further basinward, UTIG shot widely spaced, regional 2D seismic data in the mid-1970s (Fig. 1). Some of these lines have been reprocessed using new algorithms (e.g. Hartwig et al., 2012), but the relatively shallow Miocene section described here has good reflectivity and seismic character on original sections. The bulk of the observations described below are derived from UTIG 2D seismic data.

The Gulf Basin Depositional Synthesis research project (GBDS) seismic horizons discussed here have been mapped basin wide and generally correspond to maximum flooding horizons or sequence boundaries close to marine biostratigraphic markers, which represent condensed sections (Galloway et al., 1998) (Table 1). These can be compared with chronostratigraphic designations for both local and global usage (Snedden and Liu, 2011). The GBDS seismic horizon and chronostratigraphic designations do not use absolute ages that change with timescale modifications. These horizons can be generally compared with Hernandez-Mendoza et al. (2008) and Jennette et al. (2003), though there is some variation between the two studies in age assignments reflecting both time scale changes and use of different biostratigraphic markers.

Seismic Observations

The coeval Miocene section found in deepwater off of eastern Mexico contains a series of hummocky, oblique, and shingled to parallel seismic clinoform reflections, per terminology of Mitchum et al., 1977) (Figs. 4–6). Rodriguez (2011) interpreted these shingled seismic reflections in offshore Mexico as contourite drifts, current modified deepwater deposits such as observed in offshore New Zealand (Lu and Fulthorpe, 2004). Seismic lines normal to shelf isobaths, and to depositional and structural dip, show that these shingled clinoforms dip to the north and northeast (Fig. 4). These terminate eastward (paleoseaward), as dips decrease progressively, into a series of horizontal, parallel, and continuous reflections. To the west, the seismic clinoform interval continues into the folds of the Mexican Ridges, thinning progressively landward. Here, these commonly merge into migrating wavy reflections. A clinoform set boundary is present between two of the Mexican Ridges (Fig. 5). Using interval velocities derived from analogous near-surface sediments (1848 m/sec, East Breaks Basin of Beaubouef and Friedman [2000]), the clinoform interval ranges in thickness from 420 to 820 ft (130 to 250 m), thinning both landward and seaward. The clinoform packages are bounded at the base by reflection ‘5,’ corresponding to the top of GBDS basin center seismic sequence MM–I or Late Middle Miocene in age (Table 1). The upper surface, where clinoforms change to wavy-bedded reflections, appears to coincide with GBDS seismic horizon “3” or top of the GBDS Basin center sequence UM–K, which is dated as Latest Miocene (Galloway et al., 2000) (Table 1). As discussed earlier, these horizons are based upon industry well and age control, with seismic correlations using UTIG and industry seismic data.

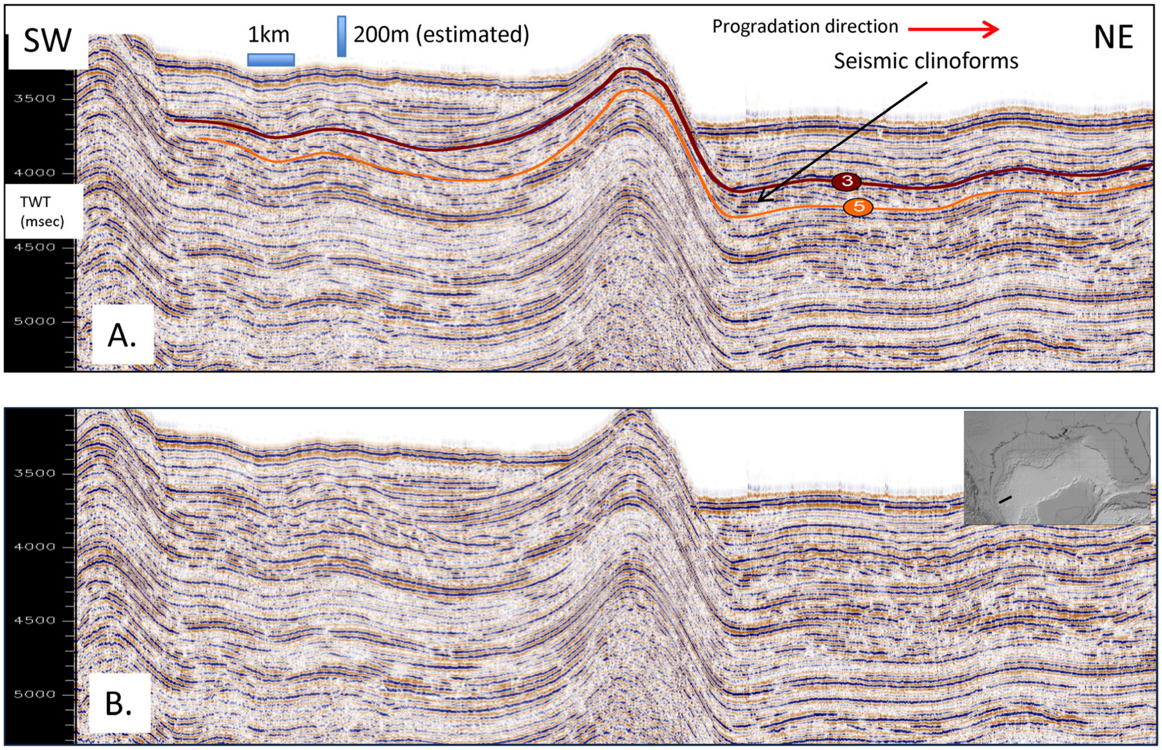

Figure 4. UTIG seismic line GLG–24: (A) Interpreted time section showing clinoform packages in Miocene strata of the eastern Mexico deepwater. GBDS seismic horizons are discussed in text and Table 1. Outermost structure of the Mexican Ridges is located in center of figure. (B) Uninterpreted time section with inset showing approximate location of seismic line.

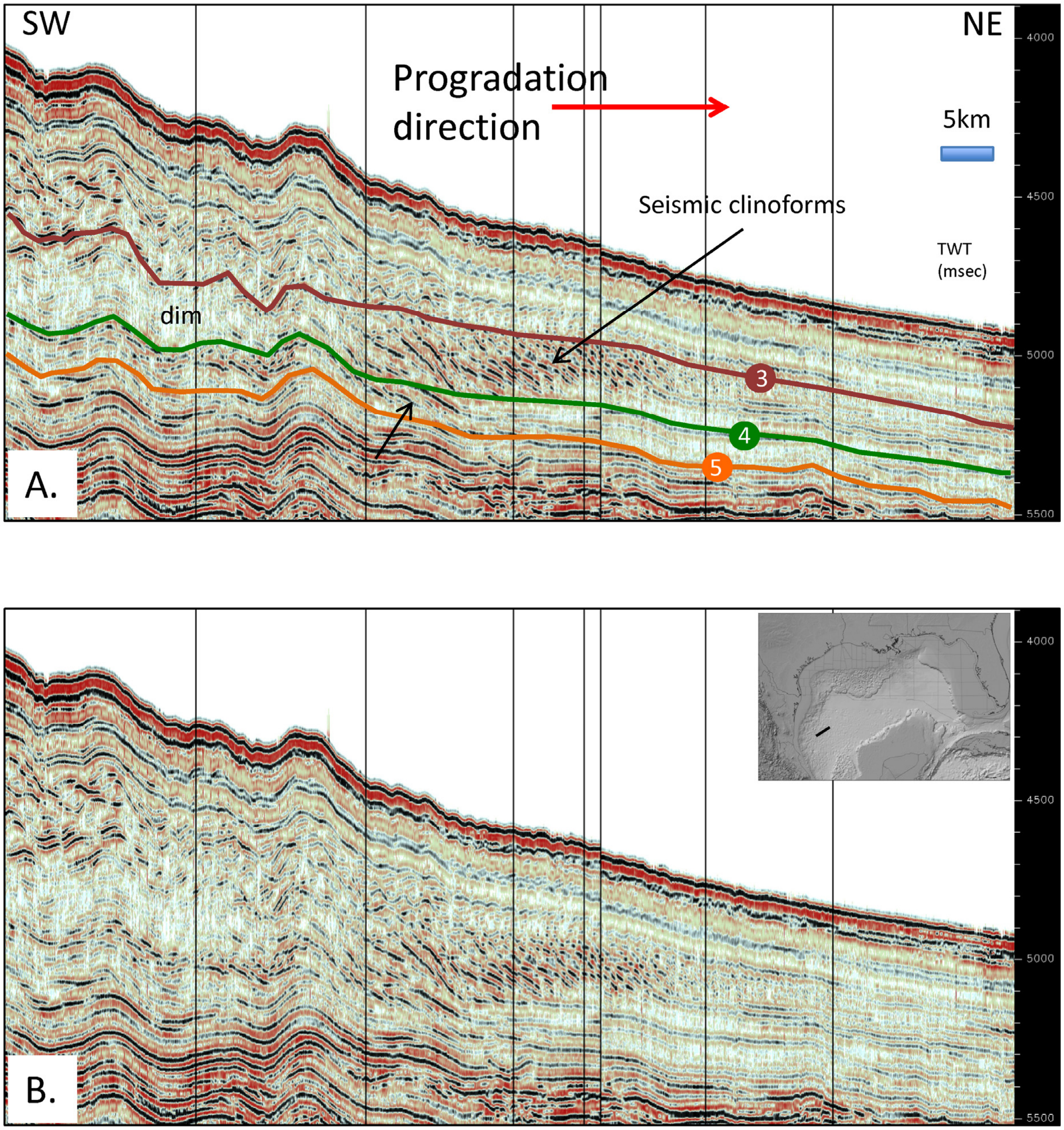

Figure 5. UTIG seismic line 16–1–5–6: (A) Interpreted time section showing clinoform packages in Miocene strata of the eastern Mexico deepwater. GBDS seismic horizons are discussed in text and Table 1. (B) Uninterpreted time section with inset showing approximate location of seismic line.

Lines located further north, with orientations subparallel to depositional and structural strike, show a more complex stratigraphy (Figs. 5 and 6). A prominent reflection and change in seismic internal geometry coincides with reflection '4,' corresponding with the Top of GBDS basin center sequence UM–J which is Late Miocene in age by correlation to U.S. wells (Table 1).

On Line WG–b–1, a mound-shaped feature with double downlap stratal termination transitions to the north, first as parallel seismic clinoforms dipping northward, and then as near-horizontal, continuous reflections (Fig. 6). The feature overlies GBDS seismic reflection '5,' corresponding to the top of GBDS basin center sequence MM–I, which has been dated in US wells as Late Middle Miocene (Table 1). However, there is a clear asymmetry to reflection geometries, as clinoform reflections dipping to the south are absent on the south end of the seismic mound. Above reflection 4, reflections are sub-horizontal, showing slight dip increases nearing reflection terminations into seismically dim zones with channel-like cross-sectional profiles. Line WG–1–b shows two seismically dim mounds, each with flanking, north-dipping shingled clinoform seismic reflections (Fig. 6).

Older sets of seismic clinoforms, also with north to northeast dips, are present in the sequence between GBDS seismic horizon '5' and '6' (Table 1). Horizon '6' relates to the top of GBDS basin center sequence MM–H which is Middle Miocene in age. Older clinoform packages may be present but would be located well within the Mexican Ridges, where structural complexity has obscured imaging these features.

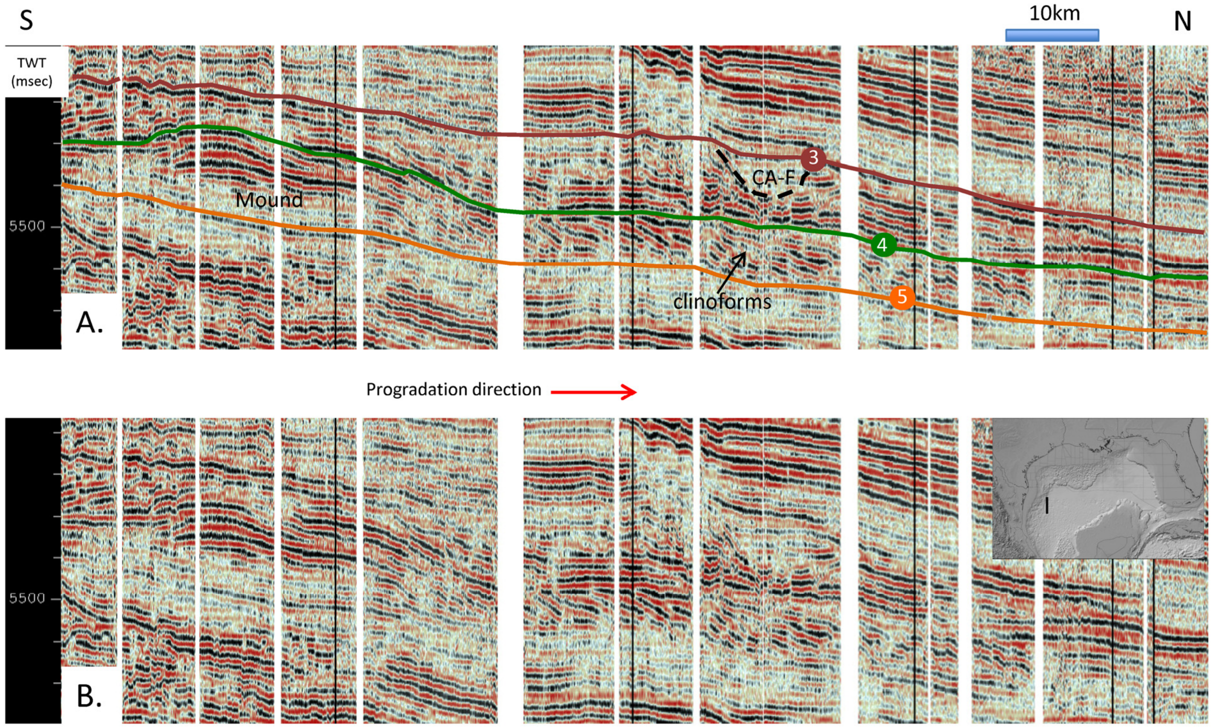

Figure 6. UTIG seismic line WG–1–b: A. Interpreted time section showing clinoform packages in Miocene strata of the eastern Mexico deepwater. GBDS seismic horizons are discussed in text and Table 1. Note mound-like seismic feature and interpreted channel-fill (CA-F). B. Uninterpreted time section with inset showing approximate location of seismic line.

Table 1. Seismic and chronostratigraphic horizons.

GBDS Seismic Horizon	GBDS Basin Center Sequence	Chronostratigraphic Designation	Approximate Age
3	Top UM–K	Me1_mfs	Near Miocene/Pliocene stage boundary
4	Top UM–J	Tor1_mfs	Late Miocene
5	Top MM–I	Tor1_sb	Late Middle Miocene
6	Top MM–H	Ser2_mfs	Middle Miocene
7	Top LM2–G	Lan1_mfs	Latest Early Miocene

Interpretation

Seismic clinoforms are generally interpreted as indications of shelf-phase delta migration (<300 ft; 100m scale) or larger (>300–650 ft; 100–200m) continental margin progradation and aggradation (Mitchum et al., 1977). However, these clinoforms are located at 55 to 110 mi (80 to 190 km) from the mapped coeval shelf-edge of the Miocene (Hernandez-Mendoza et al., 2008; Galloway et al., 2000). Paleowater depths in this area are likely to have been bathyal (>1500 ft; 450 m) at this time (Rodriguez, 2011).

The strike line illustrated in Figure 6 shows a prominent mound-like feature analogous to deepwater fans penetrated elsewhere in the Gulf of Mexico and globally (Nelson et al., 2008). The asymmetric distribution of seismic clinoforms flanking this mound, with south-dipping, shingled reflections being absent, points to some process modifying the mound following emplacement. One explanation could be strong bottom currents eroding the mound and transporting material to the north. At the very least, submarine mound shifting was more pronounced to the north than the south.

It is well known that strong deepwater contour currents can modify and, in fact, build large sediment deposits, so called ‘drift’ deposits (Mullins et al., 1980; Lu and Fulthorpe, 2004). A variety of geometries are produced, ranging from erosional features like gullies, furrows, deflation surfaces, erosional channels (moats) to depositional features like mounds, dunes and sediment waves (Viana et al., 2007). Seismic clinoforms of this scale have not, to date, been recognized as being produced by modern contour currents but one could argue that Miocene conditions were substantially different than the present day. The Miocene is a well-known time period of changing oceanographic conditions as a function of closing ocean gateways (Potter and Szatmari, 2009) that could accelerate bottom flow in some areas. The Miocene is also a time of rapid changes in ice volume, sea levels, and climate, all leading to oceanic current variations, a pattern also observed in the Holocene (c.f. Voekler et al., 2006; Toucanne et al., 2007).

Muddy sediment waves are present in younger (<5 Ma), near-surface sediments in the immediate vicinity (Behrens, 1994) but clearly have a different form (wavy) and orientation (southerly) than the Miocene clinoforms described here. However, there is an obvious upward transition from the seismic clinoforms into the wavy geometries described by Behrens (1994), suggesting a similar dynamic process (see Figure 5, in the interval above GBDS reflection 3).

The upper seismic reflection package seen on Line WG–1–b (Fig. 6) could be viewed as a channel-fill (CA-F) and levee (bright continuous reflections) system. Analogs might include the modern Bryant Fan of the central Gulf of Mexico (Nelson et al., 2008). The measured channel width is remarkable (>8 km) but the line of section may be oblique to the paleotransport direction.

Comparison of paleogeographic maps for the key units shows the size of the interpreted contourite drift deposit varies temporally, increasing progressively from the Middle Miocene into the Upper Miocene, and then declining in the Pliocene (Figs. 3D–3F). The transition observed on Line WG–1b (Fig. 6) showing the seismic clinoforms being replaced by geometries suggestive of channel-levee systems, implying that downslope processes have begun to be more prominent than along shelf transport. A similar evolution was noted in the Canterbury Basin Miocene section (Lu and Fulthorpe, 2004).

The volume of sediment moved or deflected by these postulated deepwater currents is substantial, but the area of accelerated current flow thought to form contourites in the Atlantic ocean seaward of the Mediterranean outflow point is comparable in scale if not larger (Toucanne et al., 2007). In addition, large fields of contourites have been recognized in Brazilian deepwater settings (Masse et al., 1998).

Although well bores have not, to the authors' knowledge, penetrated the section of interest, there is a prominent unconformity present in wells drilled to the south. The upper part of the Middle Miocene is truncated in wells in the Campeche Sound, with three planktonic foraminifera zones missing (Salazar Medina, 2001). It is interesting to consider the possibility of accelerated current flow causing erosive reentrainment of previously-deposited sands during the timeframe coeval with the deepwater mounds and flanking, north-dipping seismic clinoforms in Eastern Mexico deepwater areas. Alternatively, tectonic uplift associated with convergence of Yucatan and the Chortis block could be responsible for the observed erosional gap (Rodriguez, 2011).

Western Florida Platform and Margin

The western Florida margin developed in the early Cretaceous, as a carbonate-rimmed platform built upon the sharp boundary between thick transitional and thin transitional crust in the northeastern Gulf of Mexico (Dobson and Buffler, 1997). Today, a relatively shallow, flat platform (<980 ft; 300m) drops to deep depths (>6500 ft; 2000 m) over a few km (1 to 2 mi) distance (Fig. 2). The thick (>10 km) Tertiary succession of the Mississippi Canyon area is represented on the Florida platform by a relatively thin (<980 ft; 300 m) succession dominated by Miocene and younger strata (Missimer, 1999). Much of the thin Tertiary section is composed of carbonates and evaporites, with limited siliciclastic input (Mitchell-Tapping, 2002). The modern bathymetry of platform and steep slope was established in the Miocene and reflects Loop Current flow that winnows bottom sediments on the outer shelf and slope and creates a hard ground at depths of 650 to 1300 ft (200 to 400 m) water depth (Mullins et al., 1987).

Seismic stratigraphic investigation of the Florida platform margin reveals a prominent unconformity of Middle Miocene age, first noted by Mitchum (1978). Shallow seismic surveys (Fig. 7) show truncation of Miocene sigmoidal clinoforms (termed Sequence II by Mullins et al. [1987, 1988]) and overlay by slope front-fill, onlapping strata (Sequence I). The zone of truncated reflections was mapped in one area as spanning 6 by 85 mi (10 by 140 km). This erosion was attributed to increased flow velocities of the paleo–Loop Current due to tectonically induced closure of the Isthmus of Panama (Mullins et al., 1987).

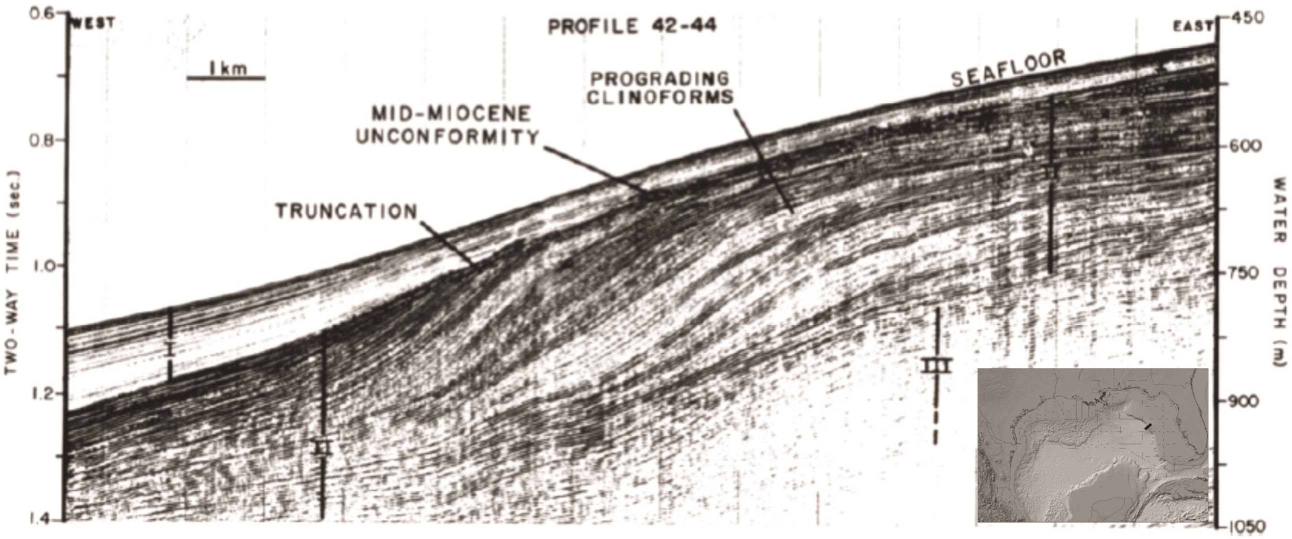

Figure 7. Portion of older seismic reflection profile 42–44 across Florida Platform margin, showing truncation of sigmoidal clinoforms, interpreted to represent erosion by accelerated Loop currents in Middle Miocene (modified after Mullins et al., 1987). Inset shows approximate section location.

Seismic Observations and Interpretations

Seismic data posted on the web by BOEM facilitates reexamination of Mullins et al. (1987)'s Middle Miocene-age unconformity. Line M85–08 is regional east-west seismic section just north of Mullins et al. (1987) original study area (Fig. 8). Observations of stratal terminations and seismic character allow direct comparison with Mullins et al. (1988) six seismic stratigraphic units (I to VI) (Table 2) on this regional seismic line.

Sequence VI can be carried to the top of the Florida escarpment, showing high amplitude reflections with prominent relief, characteristic of carbonate-dominated lithologies. Mullins et al (1988) suggested a Middle Cretaceous age, based upon dredge samples (Freeman-Lynde, 1983).

Sequence V downlaps westward upon Sequence VI, a stratal relationship also observed by Mullins et al. (1988). Similarly, the seismic character is more subdued than overlying or underlying units, but has good continuity and relatively low seismic frequency (Fig. 8A). Mullins et al. (1988) viewed this unit as Late Cretaceous in age, based upon correlation with the seismic stratigraphic analysis of Mitchum (1978).

Sequence IV is a thin unit of variable amplitude character showing some truncation at the contact with underlying Sequence V (Fig. 8A). The low frequency and discontinuity of reflections were also noted by Mullins et al. (1988) but the unit is considerably thinner in this area. The age of this unit is most problematic, given the Eocene to Campanian ages suggested by Mullins et al. (1988) and Mitchum (1978). It would therefore span the K/Pg boundary unit, a time of considerable synsedimentary disturbance and removal and reorganization around the Gulf of Mexico related to the Chicxulub bolide impact (Rodriguez, 2011; Scott et al., 2011).

Sequence III exhibits high-amplitude, high-continuity reflections that downlap onto Sequence IV. Correlation updip on the Florida Shelf shows the reflection continuing below a large acoustically dim seismic package (Fig. 8B). Further south, this seismic sequence shows similar downlap onto Mullins et al.'s (1988) Sequence IV. Comparable variations in seismic character, from continuous, moderate amplitude to diverging, high amplitude to chaotic reflections, are also seen in this sequence. Based upon correlation with coring described in Mitchum (1978) and Mullins et al. (1987), an age range of Oligocene to Early Miocene has been suggested (Mullins et al., 1988). No other biostratigraphic data is available to better constrain the interpretations.

Sequence II has two seismic units apparent on Line M85–08. The basal unit, here called IIB by analogy with Mullins et al. (1988), lies below a surface of truncation on the seaward margin of the Florida platform. A seismic unit exhibiting discontinuous to chaotic reflections lies unconformably above this unit (blue line in Figure 8) and is termed IIA by analogy with Mullins et al. (1988). The seismic surface separating sequence IIA and IIB shows remarkable similarity with the large truncation surface interpreted as a submarine slide (slump scar) by Mullins et al. (1988). The regional extent of this Miocene submarine slide surface is well-documented (Mullins et al. 1986, 1987, 1988), and is mapped for over 60 mi (100 km). The chaotic appearance of IIA may reflect failure products of the mass wasting at the over steepened paleoslope. Regionally, Unit IIB continues eastward to large-scale clinoform packages, also seen in areas to the south, indicating major carbonate shelf progradation (Mullins et al., 1988). Mullins et al. (1987) recognized onlap and truncation associated with the surface separating IIA and IIB, suggested it equates to an unconformity caused by accelerated oceanic cur-

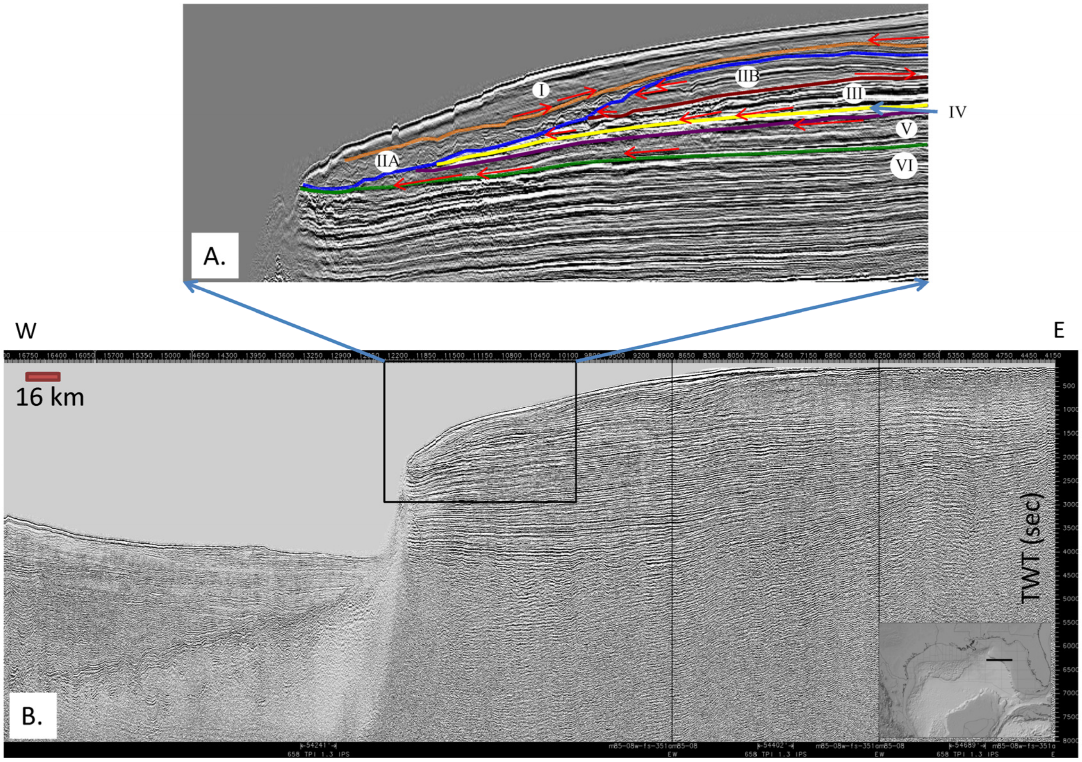

Figure 8. MMS released seismic line M85–08: A. Interpreted portion of margin showing seismic intervals I to VI (Table 2), which are comparable to seismic sequences of Mullins et al. (1988). B. Uninterpreted larger section with inset showing approximate location of seismic line.

Table 2. Florida platform margin seismic horizons.

Sequence No.	Seismic Character	Possible Age	Source
I	Slope-front fill seismic geometry	Latest Miocene to Pliocene	Mullins et al. (1987, 1988)
IIA	Discontinuous to chaotic reflections onlap onto IIB	Middle Miocene	Mullins et al. (1987)
IIB	Truncation above, parallel continuous. Clinoforms to east.	Miocene	Mullins et al. (1986, 1987, 1988)
III	High amp., cont. downlap onto Sequence IV	Oligocene to early Miocene	Mullins et al. (1986, 1987, 1988)
IV	Variable amplitude character	Eocene (?) to Campanian (?)	Mitchum (1978)
V	Truncation above, downlap below	Late Cretaceous (?)	Mullins et al. (1988)
VI	High ampl. cont.	Mid-Cretaceous	Freeman-Lynde (1983)

rents in the latest Middle Miocene (Fig. 7). Erosion under the Brazil current, a western intensification of Atlantic oceanic currents, has produced similar erosion on the shelf edge to upper slope (Duate and Viana, 2007).

Sequence I has variable thickness, reflecting depositional topography of the underlying Sequence IIB. The change from large-scale clinoforms to a slope-front fill seismic geometry was also observed to the south (Mullins et al., 1987), where Mullins et al. (1988) suggested this unit as Latest Miocene to Pliocene in age.

Although the correlations described above are tentative and need further calibration with future drilling, the remarkable similarity with the seismic stratigraphy of Mullins et al. (1988) is compelling. The observation of a pronounced truncation and onlap surface separating early Miocene and Latest Miocene strata (IIA/IIB boundary of Figure 8) is also a key to the regional to basinal story. It is coeval with the age of the current-modified fan deposits in Eastern Mexico and the apparent displacement of the MCAVLU fan in Mississippi Canyon protraction area (GBDS horizons 3 to 5 of Table 1).

BASIN SCALE SYNTHESIS AND INTERPRETATION

Observations from Miocene strata described above from three separate areas in the Gulf of Mexico may be linked in a basin-scale synthesis and viewed in the context of a time of considerable global change. Evidence of apparently synchronous, current-modified deepwater fan systems in eastern Mexico, displaced shelf bypass sand transport pathways in the central Gulf of Mexico, and erosion on the western margin of the Florida platform points to a possible common control.

One controlling process could be the intensification of oceanic currents in the Miocene, beginning in Latest Early Miocene (LM2) and continuing until the Pliocene/Miocene boundary, around 5 Ma (Fig. 3). The acceleration of current flow could comprehensively explain observations of coeval current modification of deepwater fans, and construction of parallel, north-dipping clinoform reflections in the northeastern Mexico offshore area (Fig. 9). In the Northeast Gulf of Mexico, it is possible that strong bottom flow moved sediment from the Tennessee and Mississippi fluvio-deltaic depocenters along the shelf edge to a slope entry point 60 to 90 mi (100 to 150 km) to the east. Further east toward Florida, a generally sand-starved area in the Miocene (Galloway et al., 2000), these strong currents caused major erosion of the platform margin and created an unconformity between Miocene and Pliocene strata.

Alternative Models for MCAVLU Submarine Fan Offset

Alternative models can explain the seismic geometries, regional thickness trends, and erosional evidence separately in each area but none provide a basin-scale model linking all these observations. For example, deposition of the thick MCAVLU fan system in the Mississippi Canyon protraction area is clearly facilitated by salt evacuation and creation of accommodation. However, it well known that sediment input and progradation drives salt movement (Peel et al., 1995), so the easterly-shifted sediment pathways must have been well established by the time of initial salt evacuation in the Mississippi Canyon area. Obviously, salt evacuation in Mississippi Canyon would have little effect upon Mexico or Florida.

A major slope failure, termed the Harang embayment of Louisiana, could have played a role in funneling sediment to the deepwater, as suggested by Combellas-Bigott and Galloway (2006). However, the Harang embayment developed, filled, and healed within a relatively short timeframe (largely MM–H), while observed displacement of the MCAVLU fan system both preceded and followed its brief existence (Galloway et al., 2000).

Regional uplift in the Late Miocene has been suggested as a cause of development of a long basinward slope that in turn opened accommodation space with seaward migration of the salt canopy (Jackson et al., 2011). This may have shifted the focus of sedimentation from the Tennessee fluvio-deltaic depocenter eastward to the Mississippi Canyon area. However, we would expect the effects of this Miocene uplift on sedimentation to be broadly distributed across the Gulf of Mexico and not confined to the depositional axis localized on the Mississippi Canyon protraction area. Affects of the Miocene uplift are absent in Florida (Mullins et al., 1988) and or limited in the northern Mexico offshore region (Hernandez-Mendoza et al., 2008) with most uplift centered upon the Veracruz region near the Trans-Mexican volcanic belt (Rodriguez, 2011).

Of course, the confluence of several of the factors above probably played a role in the apparent easterly offset of the MCAVLU submarine fan system. Development of a structural grain (due to salt stocks and canopies), a minibasin corridor trending NE–SW, and strong oceanic currents carrying sediment toward the east probably contributed to the net sediment flux into the MCAVLU fan system. It is also important to consider the input of wave-reworked sediment stored in the shore zone system to the east of the Tennessee fluvio-deltaic axis, which may have resulted in higher net sand in the MCAVLU system than observed elsewhere (Combellas-Bigott and Galloway, 2006).

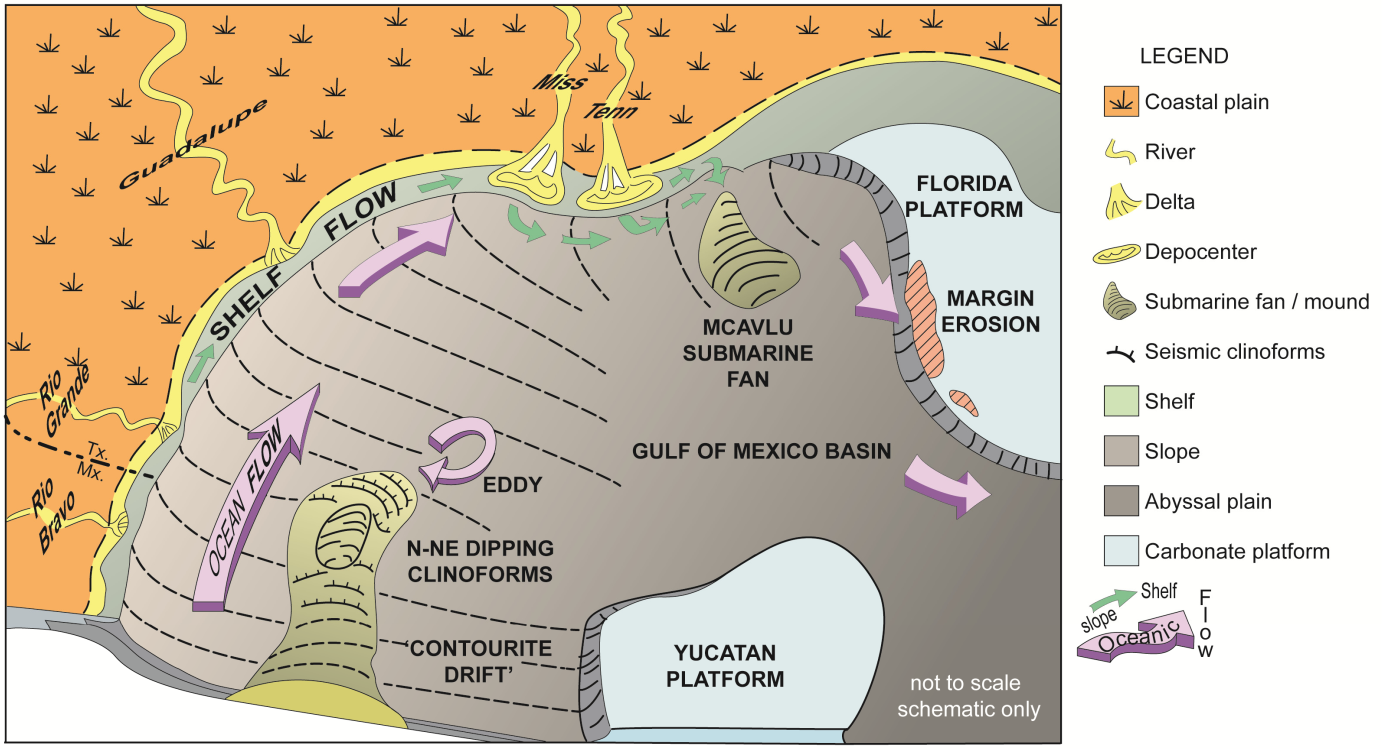

Figure 9. Schematic diagram illustrating interpreted basin paleogeography and paleocirculation in Middle to Upper Miocene. Accelerated deepwater current flow in the Miocene may be responsible for modification of submarine fans in Mexico deepwater, easterly displacement of MCAVLU fan in central Gulf of Mexico, and erosion on the western Florida platform. Not drawn to scale.

GLOBAL DRIVERS AND TIMING

The Miocene is a time of great change, from plate reorganization, closing and opening of oceanic gateways, major shifts in paleoclimate, depositional transitions, and considerable structural evolution (Potter and Szatmari, 2009). One important associated process was the progressive reduction of global equatorial flow starting in the latest Oligocene and culminating with the joining of North and South America across the Isthmus of Panama in the Miocene to Pliocene timeframe (Kuhnt et al., 2004; Coates et al., 1992). It has been suggested that shallowing began around 13 Ma (Middle Miocene) and closure of the Central American Seaway was completed around 3.5 Ma (Pliocene) when the modern Gulf Stream took form (Potter and Szatmari, 2009; Lawver et al., in press).

Termination of the greenhouse equatorial current system has been the subject of recent numerical models and simulations, as it affected both ocean and terrestrial realms (Nisancioglu et al., 2003; Herold et al., 2010). There is some evidence that shoaling was episodic, with a major uplift of the sill to a depth of 3200 ft (1000 m), effectively shutting off deep bottom water (North Atlantic Deepwater) movement from Atlantic to Pacific oceans around 12 to 13ma (Duque-Caro, 1990; Nisancioglu et al., 2003). This approximates GBDS interval MM–I, which contains seismic reflection patterns typical of contourite current erosion and deposition (Fig. 3D). Apparent offset of the MCAVLU submarine fan system commenced earlier when intensification of Gulf of Mexico Loop currents followed closures in the Pacific and Mediterranean Sea and the change in global oceanic flow patterns (Omta and Dijkstra, 2003; von der Heydt and Dijkstra, 2005)

The complete closure of the Central American Seaway by the Pliocene does not easily explain the termination of the MCAVLU fan offset and the establishment of a broad submarine apron directly south of the Tennessee and Mississippi fluviodeltaic systems (Fig. 3F). Rather, evolution of the slope into a more rugose terrain with salt stocks, pillows, minibasins and a greater degree of channelization may have played a role, as well as termination of salt lateral migration versus vertical movement. Lu and Fulthorpe (2004) suggested that major contourite deposition in the Canterbury Basin of New Zealand terminated when downslope processes began to dominate over along slope transport.

The clockwise current motion hypothesized here for the Miocene (Fig. 9) resembles, at least kinematically, the present-day Loop Current of the Gulf of Mexico (Leipper, 1970; Welsh and Inoue, 2000). Current meters moored in the deepwater Gulf of Mexico have measured persistent (>1–5 days) near-bottom transport velocities under the present-day Loop Current exceeding 20 cm/sec (8 in/sec) (Hamilton, 1990). This is sufficient to generate the necessary shear stress to entrain and transport the very fine to fine sand typically found in Gulf of Mexico Miocene reservoirs (Snedden et al., 1988). Miocene current velocities may have exceeded modern transport speeds by analogy with the Gulf Stream which is thought to have experienced episodic, elevated current strength during discrete periods of glacial ice expansion in the Miocene and Pliocene (Kaneps, 1979). Current speeds under the modern Gulf Stream have been measured as high as 47 cm/sec (18.5 in/sec) in water depths exceeding 2500 m (8200 ft) (Betzer et al., 1974).

Like the modern Loop Current, the Miocene system may have spun off eddies or other rotary currents into smaller areas (c.f. Maul et al., 1974) (Fig. 9). Although cyclonic (anticlockwise) flow associated with the Loop Current has been observed in current meter records (Hamilton, 1990), modeling suggests that anticyclonic rings may also form (Welsh and Inoue, 2000). Comparison of paleogeographic reconstructions in the Gulf of Mexico suggests at least two additional anti-cyclonic (clockwise) rotating current systems may have existed in the Miocene-Pliocene time frame. The small deepwater fan system located in the far eastern portion of the Mississippi Canyon protraction area (Fig. 3A) could relate to a small but intense eddy centered here. A similar eddy positioned in the deepwater of eastern Mexico could be responsible for development of a pair of contourite drift fields mapped there (Fig. 3F).

CONCLUSIONS

Local and regional studies of the Gulf of Mexico have yielded important clues to the deepwater paleocirculation during the Miocene yet few have attempted a comprehensive, basin-scale synthesis incorporating all the observations:

In Eastern Mexico offshore, reconnaissance 2D seismic data exhibits evidence of submarine fan systems modified by northerly flowing deepwater bottom currents and genesis of north-dipping parallel, shingled, oblique to parallel seismic reflections;

This occurs roughly at the same time as initiation of the laterally offset MCAVLU abyssal plain fan system, as deduced from paleogeographic reconstructions using industry seismic and well data;

Nearly synchronous erosion of the western margin of the Florida platform also supports the idea of intensified oceanic currents, as earlier suggested by Mullins et al. (1987).

Future work including numerical modeling studies of Gulf paleocirculation would better constrain the timing of acceleration and deceleration of the Miocene current flow in the Gulf of Mexico, a predecessor of the modern Loop Current. This paper will hopefully support more detailed modeling and provide a more comprehensive picture of a critical time in the earth's history.

It may also lead to better subsurface prediction of sand-prone reservoir fairways. Current work on source-to-sink reconstructions does not presently incorporate oceanic flow in prediction of submarine fan geometry or location (Somme et al., 2009). Our work, as well as recent insights from Brazil and other areas (Shanmugam, 1993; Duate and Viana, 2007; Mutti and Carminatti, 2012) suggests that along slope flow and current modification of deepwater fan systems may be underappreciated.

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