The Texas mud blanket:
Understanding fine-grained sediment flux in the NW Gulf of Mexico
during the previous transgression

By

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The evolution and source of the Texas Mud Blanket (300 km$^3$) was determined from 26 new radiocarbon dates and from ~3000 km of 2D seismic data. Sediment flux (km$^3$/ka) was calculated from this combined dataset. XRD reveals its origins are mostly from the Colorado and Brazos Rivers.

Between LGM and 17 ka, sediments filled the deepest accommodation behind a productive reef trend. 17-9 ka was a time of rapid eustatic rise (~7 mm/year) and low sedimentation (flux= 0.4 km$^3$/ka). At ~9 ka, sediment flux to the mud blanket increased to 41 km$^3$/ka because of ravinement of Brazos and Colorado deltas. By ~5.5 ka, Texas was experiencing a climatic optimum, which reduced sediment supply from local rivers. During the last 3.5 ka the mud blanket received 172 km$^3$ of fine-grained Colorado and Brazos sediments. The most pronounced trend is the anti-correlation of mud blanket growth and rates of eustatic rise.
ACKNOWLEDGEMENTS

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Members of John's lab (Davin Wallace, Rodrigo Fernadez, Tyler Smith, Alex Kirshner, Brad Michalchuck, and Kristy Milliken) gave generously of their time, scientific expertise, friendship, and personal advice, and to them I am indebted. I have learned much from many other students, and faculty members, and I am grateful for their association and friendship.

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Most importantly, I need to thank my wife Laura and my son Benjamin who have been ever patient, supportive, and loving through late nights, long absences, busy weekends, and all in all a long couple of years. This would not have been possible without them.
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THE HOLOCENE TEXAS MUD BLANKET: A RECORD OF MAJOR CHANGES IN
SEDIMENT DELIVERY AND REDISTRIBUTION

Robert W. R. Weight, John B. Anderson and Rodrigo Fernandez

ABSTRACT

The Texas Mud Blanket (TMB) is a large (~300 km$^3$) depocenter that formed after the last (LGM – MIS 2) eustatic lowstand on the central Texas shelf, an area where no large rivers occur. The evolution of the TMB is determined from 26 new radiocarbon dates and from ~3000 km of high-resolution 2D seismic data. Sediment flux (km$^3$/ka) was calculated from this combined dataset. XRD analysis reveals that the origin of sediments accumulated in the TMB are mainly local, coming mostly from the Colorado and Brazos rivers, with the Mississippi River having been a secondary source.

A large depression between the MIS 3 shoreline on the west and a linear reef trend on the east created accommodation for the TMB. The ancestral Colorado and Rio Grande deltas are the northern and southern boundaries, respectively. Between LGM and ~17 ka, terrestrial and lagoonal sediments filled the deepest parts of the depocenter. From ~17 to ~9 ka was a time of rapid eustatic rise and low sedimentation (flux= 0.4 km$^3$/ka). At ~9 ka, sediment flux to the mud blanket dramatically increased to 41 km$^3$/ka. During this time, older, falling stage Brazos and Colorado deltas were being ravened,
producing an estimated 61 km$^3$ of sediment, of which an estimated 58.3 km$^3$
was silt and clay and contributed to growth of the TMB. By ~5.5 ka, Texas was
experiencing maximum temperature and minimum precipitation for the
Holocene, which led to a reduction in sediment accumulation in the TMB.
During the last 3.5 ka the mud blanket experienced remarkable growth,
having accumulated 172 km$^3$ of sediment, accounting for 57% of its volume.
Mineralogical data indicate that most of this sediment that comprises the TMB
was derived from the Colorado and Brazos rivers and did not vary
significantly over the time of its evolution. This calls for a dramatic increase
in the sediment yields of these rivers during the late Holocene, which is best
explained by a more variable climate at this time and elimination of
accommodation space within the river valleys as they were filled to capacity.

INTRODUCTION

Sources of terrigenous sediment supply to marine basins vary throughout a eustatic
cycle. The simplest models predict increased sediment input during the falling
portion of the cycle culminating in a lowstand (Van Wagoner et al., 1988). These
models further predict a decrease in terrigenous sediment supply during the
transgression to maximum highstand. In the NW Gulf of Mexico there are two
exceptions to this model: the Mississippi River delta and the Texas Mud Blanket
(TMB). Due to its large drainage basin and deglacial drainage history, the Mississippi
River has had sufficient sediment supply to overcome the effects of sea level rise and
prograde deltaic sediments out to the shelf edge. The TMB, on the other hand, is
located on the Texas shelf adjacent to only low discharging rivers with small
drainage basins. Sediments from these rivers have been mostly deposited within
their incised valleys. With no direct fluvial input to this large (300 km$^3$) depocenter,
the question looms, what is the source of the TMB?

Curry (1960) first documented the TMB and proposed the process by which a
convergence of longshore currents created a seaward return flow over the central
Texas shelf and supplied sediment to the TMB. He further argued that marine
erosion during transgression-remobilized sediments eroded from both the Rio
Grande and the Mississippi deltas and that these sediments were transported to the
north and to the west, respectively. Van Andel and Poole (1960) went a step further
showing on their surficial sediment distribution map recycled Rio Grande and
Brazos and Colorado sediments in the location of the mud blanket.

Shideler (1977, 1978) first mapped the TMB using sand/mud ratios from surface
grab samples and shallow cores. He also identified a regionally persistent bottom
nepheloid layer in the water column directly above the mud blanket, which he
attributed to sediment re-suspension (Shideler, 1981). He proposed a conceptual
model of southward and offshore transport of both palimpsest Brazos/Colorado
sediments and modern sediments resting above relict Rio Grande sediments. He
concluded that sediment is also delivered to the shelf by ebb-tidal currents flowing
from the inlets of Matagorda Bay (Pass Cavallo), Corpus Christi Bay (Aransas Pass),
proposed both the ancestral Rio Grande delta and the Colorado delta as potential
sources for the TMB. In view of a band of fine-grained terrigenous sediments along the outer shelf and slope that extends from the Mississippi delta to the south Texas shelf (Van Andel, 1960), Balsam and Beeson (2003) conclude that, “some fine-grained Mississippi sediment is transported as far west as the south Texas coast.” This is in conflict with Davies and Moore (1970), who argued that Mississippi sediments only extend slightly west of the Sabine River and no farther. This is supported by the fact that Holocene sediments decrease in thickness from east to west across the western Louisiana and east Texas continental shelves (Wellner et al., 2004; Abdulah et al., 2004). This does not, however, rule out the possibility that substantial amounts of suspended sediment is delivered to the mud blanket from offshore, including possibly the Mississippi River.

This paper presents results from an investigation aimed at resolving the uncertainty about the origin of the TMB. This is done using high-resolution seismic data, radiocarbon age control, and mineralogy. We address the following questions: When did the TMB form? How has it evolved in space and time? How have accumulation rates and sediment volumes varied on the central Texas continental shelf during the last transgression? What have been the roles of eustasy, climate, antecedent topography, and of transgressive processes in reworking and redistributing sediments?
BACKGROUND

The TMB is located on the central and southern portions of the Texas continental shelf, in the northwestern Gulf of Mexico. It is located within a bathymetric embayment between the ancestral deltas of the Rio Grande River to the south, and the Colorado River to the northeast (Fig. 1). The lower portion of the TMB fills a depression between the MIS 3 shoreline on its landward margin and a series of reefs on its basinward margin (Figs. 1, 2). These reefs began to form prior to 21,500 calendar years BP (Bright and Rezak, 1976; Belopolsky and Droxler, 1999). They kept up with rapid sea-level rise during the first half of the deglaciation and appear to have stopped growing during the Younger Dryas, 12,000 to 11,000 years BP, which was a short return to colder/glacial conditions (Belopolsky and Droxler, 1999; Flower et al., 2004). The reefs are partially buried by the TMB.

Anderson et al. (2004) point out that depositional variability along the Texas shelf is controlled by sediment supply variations from one fluvial system to the next. These variations are, in turn, controlled by differences in drainage basin size, geology, and climate, as well as by antecedent topography. Table 1 shows the variability in sediment supply of northwest Gulf of Mexico rivers to exemplify these differences. The largest discharging rivers, from the largest to the smallest, are the Mississippi River, the Rio Grande River, the Brazos River, and the Colorado River. Adjacent to the TMB there are several small rivers that contribute sediment to the margin. These include the Lavaca, Guadalupe, San Antonio, Aransas-Mission (not in table 1), and Nueces rivers. The small sediment discharge of these rivers has been
insufficient to allow them to fill their valleys and form delta’s on the shelf (Simms et al., 2006a). Therefore, during the last sea-level cycle this region has remained an inter-deltaic setting dominated by shoreline/shoreface processes (Rodriguez et al., 2001). Additionally, the NW Gulf of Mexico has experienced several climate fluctuations during deglaciation and transgression (Poore et al., 2003). These fluctuations have resulted in significant variations in sediment supply to the basin (Anderson et al., 2004).

**TABLE 1. DRAINAGE BASIN SIZE, DISCHARGE, MODERN SEDIMENT FLUX, AND VALLEY CLASSIFICATION FOR TEXAS RIVERS AND MISSISSIPPI RIVER**

<table>
<thead>
<tr>
<th>River</th>
<th>Drainage Basin (km²)</th>
<th>Modern Discharge (m³/sec)</th>
<th>Sediment flux (metric t/y)</th>
<th>Valley Classification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rio Grande</td>
<td>339,936</td>
<td>(1)123</td>
<td>(1)20,000,000</td>
<td>Overfilled</td>
</tr>
<tr>
<td>Nueces</td>
<td>44,030</td>
<td>(3)40</td>
<td>(7)680,000</td>
<td>Underfilled</td>
</tr>
<tr>
<td>San Antonio</td>
<td>11,059</td>
<td></td>
<td></td>
<td>Underfilled</td>
</tr>
<tr>
<td>Guadalupe</td>
<td>15,644</td>
<td>(1)75</td>
<td></td>
<td>Underfilled</td>
</tr>
<tr>
<td>Lavaca</td>
<td>6,061</td>
<td>(3)21</td>
<td></td>
<td>Underfilled</td>
</tr>
<tr>
<td>Brazos</td>
<td>118,362</td>
<td>(1)226</td>
<td>(1)16,000,000</td>
<td>Overfilled</td>
</tr>
<tr>
<td>Colorado</td>
<td>114,995</td>
<td>(1)81</td>
<td>(3)4,039,000</td>
<td>Overfilled</td>
</tr>
<tr>
<td>San Jacinto</td>
<td>10,308</td>
<td>(1)730</td>
<td>(2)6,196,000</td>
<td>Underfilled</td>
</tr>
<tr>
<td>Trinity</td>
<td>46,620</td>
<td></td>
<td></td>
<td>Underfilled</td>
</tr>
<tr>
<td>Sabine</td>
<td>25,537</td>
<td>(1)510</td>
<td>(1)750,000</td>
<td>Underfilled</td>
</tr>
<tr>
<td>Neches</td>
<td>25,900</td>
<td></td>
<td></td>
<td>Underfilled</td>
</tr>
<tr>
<td>Mississippi</td>
<td>3,238,000</td>
<td>(5)18,379</td>
<td>(5)200,000,000</td>
<td>Overfilled</td>
</tr>
</tbody>
</table>

Notes: (1) Milliman and Syvitski, 1992 (2) Seaber et al., 1987 (3) USGS, 2003 (4) Shepard, 1953 (5) Meade, 1995 (6) Simms et al., 2006a

During the last sea-level fall (MIS 5e through MIS 2), Texas rivers incised into the shelf, and at lowstand the shoreline was located 80-225km seaward of the present-day coast in -90 to -120 meters water depth (Simms et al., 2007a). Suter and Berryhill (1985) mapped the lowstand erosion surface (sequence boundary) on the central Texas shelf and recognized a broad topographic depression on the outer
shelf. They proposed that this depression formed as incised valleys of central Texas rivers merged into one shoreline parallel-incised valley. Conversely, Eckles et al. (2004) and Simms et al. (2007a) stressed that the width and depth of the outer shelf depression was too great to be entirely a product of fluvial incision, further noting that seismic facies and drill core from the depression show no evidence of fluvial deposition (Fig. 2). As sea-level rose, a vast lagoon occupied the outer shelf depression (LeBlanc and Hodgson, 1959; Belopolsky and Droxler, 1999).

Sea-level rise since LGM is well constrained for the northwestern Gulf of Mexico (Milliken et al., 2008). During the Early Holocene rates of rise averaged 4.1 mm/yr. However, by about 7,000 years ago the rate of rise slowed and the Brazos and Colorado rivers began to form deltas on the inner shelf (Abdulah et al., 2004). Since ~4,000 years ago sea-level has been rising at a rate of 0.4 to 0.6 mm/yr (Milliken et al., 2008). During this phase of slow rise the Colorado, Brazos, and Rio Grande rivers virtually filled their onshore valleys with sediment (Simms et al., 2006a; Taha and Anderson, 2008, unpublished data), while smaller rivers with lower sediment input were flooded to create bays.

Subsidence has had a primary influence on stratigraphic architecture, while tectonics has exerted only a secondary influence (Anderson et al., 2004). Subsidence rates vary along the NW Gulf margin but in general shows a linear increase in the offshore direction, with rates of a few cm/ka at the coast and about 100 cm/ka at the shelf break (Anderson et al., 2004). Tectonic influences include both salt and
shale diapirism, and sediment load induced growth faulting (Ewing and Antoine, 1966; Woodbury et al., 1973; Cartwright et al., 1998).

Satellite images like the one shown in Figure 3a provide clear evidence that suspended sediments are distributed widely across the northern Gulf of Mexico, largely under the influence of wind-driven currents. Circulation patterns on the continental shelf are mainly driven by prevailing southeast winds (Fig. 1). The dominant oceanographic feature is a counter-clockwise gyre created by strong westward coastal currents and by an eastward current that moves along the shelf break (Cochrane and Kelly, 1986). Between September and May, the near shore limb of this gyre moves west and southward towards south Texas. The current reverses and moves to the north during summer months. A loop current that enters through the Yucatan Strait and exits via the Florida Straits is the most obvious oceanographic feature of the central Gulf of Mexico (Sionneau et al., 2008; Fig. 3b). Anti-cyclonic rings separate from this loop current and move to the west. Additionally, a zone of coastal convergence of longshore currents occurs in central Texas (McGowan et al., 1977; Cochrane and Kelly, 1986; Oey, 1995).

**METHODS**

**CORE ANALYSIS**

Nine platform boring cores (MI 652, MU A-10, PN A-69, BA 538, BA 399, BA A-39, EI 68, ST 52, and MU 759) used for this study were provided by Fugro McClelland
Engineering (Fig. 1). They are labeled according to their offshore block name because exact coordinate locations were not provided. The cores are incomplete sub-samples of complete cores. Core descriptions, including gross lithology, color, shell content, and sediment stiffness were provided with the cores. Grain size analysis was done on samples from cores MU A-10, MI 652, and MI 652 using a Malvern, Mastersizer 2000 laser analyzer. In some cases, grain size was used in conjunction with grain size versus density plots of Hamilton and Bachman (1982) to calculate a range of possible densities. This was done in order to make rough comparisons between modern fluvial sediment discharge and sediment volumes. Grain size was also used in understanding the mineralogical variations in our X-ray diffraction (XRD) results.

**SEISMIC ANALYSIS**

Between 1990 and 1996, 3050 km of single channel 2D seismic data was acquired on the central Texas shelf using Rice University's research vessel *R/V Lone Star* (Fig. 1). The seismic data was collected using a 15 in³ water gun and was digitally recorded using an Elics Delph 2 recording system. Basic processing was done using ProMax. Vertical resolution is approximately 1 m (Banfield and Anderson, 2004; Eckles et al., 2004). Onlap, downlap, toplap and erosion truncations were used to interpret key surfaces.

A depth conversion velocity of 1807 m/s was calculated from cores where a distinct lithologic boundary corresponded to the MIS 2 sequence boundary (SB). This
velocity was then used to tie seismic and core data. Occasionally block locations are several km’s away from the nearest seismic line. This could result in a potential correlation error. However, given the planar nature of the seismic reflections within the TMB, this error is thought to be minimal.

**FLUX CALCULATION**

Equations for calculating sediment flux from modern rivers are provided by Milliman and Syvitski (1992), Mulder and Syvitski (1996), Syvitski and Morehead (1999), and Syvitski and Milliman (2007). These equations allow for comparisons of modern suspended load discharge and a variety of variables. Comparisons are made with the past using cores and by calculating mass accumulation rates (MAR) based on dry bulk densities (DBD) of sediments. This accounts for compaction and allows for comparison of calculated values with equated sediment yield predictions from modern fluvial suspended sediment discharge (Carter et al., 2002). This method is useful in area’s where little or no seismic data is available and up-scaling from cores must be done. However, in area’s where adequate seismic data is available, volumes may be calculated directly. These volumes more closely constrain the amount of sediment accumulated because they represent two or three dimensions rather than up-scaled one-dimensional values. For this study the term flux is used to denote depth converted sediment volumes per unit time.
C-14 DATING

AMS radiocarbon dates from several cores provides a chronostratigraphic framework for the TMB. Radiocarbon ages from cores were used to bracket seismic reflections to specific time periods, creating a robust age model for the evolution of the TMB through time. Carbonate samples were analyzed at the UC Irvine KCCAMS facility following the procedures outlined in Santos et al. (2007). Because fully articulated and in-tact shells were scarce, the shell material dated included a variety of species (Table 2). Our dates were augmented using results from Banfield and Anderson (2004) and Eckles et al. (2004), who obtained dates using only foraminifera (Table 2). Their dates plot within the trends observed in our radiocarbon dates. Dates greater than ~40 ka are considered "radiocarbon dead" and establish a time significant lower bounding surface for the TMB. Radiocarbon dates were calibrated using the method of Stuiver and Polach (1977), with Calib 5.0.1 (Stuiver and Braziunas, 1993). Corrections were applied based on the Marine04 database. This database assumes a global ocean and applies an ~400 year correction.
**XRD ANALYSIS**

Whole rock and clay mineral X-ray diffraction (XRD) analyses were performed on 30 samples at K/T GeoServices, Inc. Randomly oriented clay mounts were created by vacuum depositing, centrifugally size fractionated (<4 micron equivalent spherical diameter) suspensions. These were exposed to ethylene glycol vapor for more than 24 hours. The whole rock and clay mineral aggregate mounts were analyzed using a
Siemens D500 automated powder diffractometer equipped with a copper X-ray source (40kV, 30mA) and a scintillation X-ray detector. Whole rock samples were analyzed over an angular range of five to sixty degrees two theta at a scan rate of one degree per minute using a sample spinner to reduce the effects of preferred orientation. The glycol solvated, oriented clay mounts were analyzed over an angular range of two to thirty-six degrees two theta at a rate of one degree per minute.

Semi quantitative determinations of whole-rock mineral amounts were done utilizing integrated peak areas (derived from peak-decomposition / profile-fitting methods) and empirical reference intensity ratio (RIR) factors determined specifically for the diffractometer used in data collection. The total phyllosilicate (clay and mica) abundance of the samples is determined on the whole-rock XRD patterns using combined \{00l\} and \{hkl\} clay mineral reflections and suitable empirical RIR factors.

XRD patterns from glycol-solvated clay-fraction samples were analyzed using techniques similar to those described above. The relative amounts of phyllosilicate minerals were determined from the patterns using profile-fitted integrated peak intensities and combined empirical and calculated RIR factors. Determinations of mixed-layer clay ordering and expandability was done by comparing experimental diffraction data from the glycol-solvated clay aggregates with simulated one dimensional diffraction profiles generated using the program NEWMOD written by R. C. Reynolds (Walker, 1993).
RESULTS

SEISMIC ANALYSIS

Parallel seismic reflections of the TMB onlap landward, and downlap seaward unless onlapping reefs (Fig. 2). The transgressive surface is marked by back-stepping reflections and the MIS 2 SB is defined by toplap and truncation below, and by downlap and onlap above (Fig. 2). These surfaces merge on the inner shelf and form the base of the TMB. The TMB is bounded by MIS 3 shoreline deposits on the inner shelf (Eckles et al. 2004), and on the outer shelf by the MIS 2 shoreline with reefs resting above these deposits (Fig. 2). This topography is accentuated in the south by faults. The TMB is bounded by the Colorado Delta to the north and the Rio Grande Delta to the south (Fig. 1). The TMB's stratigraphic relationship to these deltas is quite different. The sandy Rio Grande Delta is characterized by steep clinoforms with distinct topset delta reflections (Fig. 4). The TMB reflections onlap the Rio Grande Delta showing a diachronous relationship. Conversely, reflections of the Colorado Delta appear to inter-finger with reflections of the TMB (Fig. 5).

Evidence of transgressive ravinement is widespread and has completely removed the down-dip portions of incised valleys of the central Texas rivers (Simms et al. 2007a; Fig. 2).

In the study area, a velocity of 1500 m/s or 1525 m/s was previously used to convert two-way travel time to depth for Late Pleistocene and Holocene strata (Abdulah et al., 2004; Banfield and Anderson, 2004; Eckles et al., 2004). However,
using this velocity for the Holocene section resulted in miscorrelation of the sequence boundary identified by radiocarbon dates (Simms et al., 2007a) and the sequence boundary identified in seismic records (Fig. 6). For this reason, an independent test was developed in order to calculate the actual velocity of TMB sediments. Four cores that penetrate a prominent MIS 3 shoreline deposit on the inner shelf (Eckles et al., 2004) were used for this analysis. Each shows a sharp downward change from mud to sand at the SB. Velocities were calculated using the depth to this lithologic boundary and the two-way travel time from seismic data. The resulting average velocity of 1807 m/sec aligns the seismically-derived and radiocarbon-derived sequence boundaries (Fig. 6). This value is in the range of velocities expected for modern sediments with similar mean grain sizes (Hamilton and Bachman, 1982).

**RADIOCARBON DATES**

In order to build a robust chronostratigraphic framework for the TMB, 26 new radiocarbon ages were added to 6 existing ages from Eckles et al. (2004) and Banfield and Anderson (2004), (Table 2). Ages in calendar years BP were plotted against sample depth below the sea floor in order to reveal accumulation rates (MU A-10) and relative accumulation rates (MI 652 and PN A-69 plotted for comparison with MU A-10 rates) for each core location (Fig. 7a). Sample 57 from core MU A-10 is the only radiocarbon date that is significantly out of sequence (Table 2). This is attributed to down-hole contamination associated with the coring process. Therefore, this sample was not included in accumulation rate calculations. Four
distinct accumulation rate trends were observed using linear regressions of the age versus depth plot for core MU A-10 (Fig. 7a). A 0.2 mm/year rate was calculated between the oldest viable dates of ~17 ka BP and ~9 ka BP. From ~9 ka BP to ~5.5 ka BP the rate increases one order of magnitude to 2.0 mm/year. Between ~5.5 ka BP and ~3.5 ka BP there is gap in age data with a rate of accumulation of 0.3 mm/year. The most recent trend from ~3.5 ka BP to ~1 ka BP shows a 20-fold increase from the initial rate of .2 mm/year to 4.3 mm/year. Core MI 652 shows a similar increase in accumulation between 4 and 3 ka BP (Fig. 7a). Radiocarbon ages from core PN A-69 show a relatively continuous, gradually increasing trend in accumulation rates through time (Fig. 7a). Thus, the age-depth plots of all three cores show an overall increasing rate of accumulation through time contrasting the overall decreasing rate of sea level rise (Fig. 7b). Core MU A-10 provides an age model to estimate the ages of seismic reflections across the TMB (Fig. 8). Ages from cores MI 652 and PN A-69 provide additional age control to test the time significance and correlation of seismic reflections.

**SEDIMENT FLUX**

A single age model based on radiocarbon dates from core MU A-10 was used to estimate sediment flux back to ~20 ka (estimated age of LGM based on data compilations of Arz et al., 2007). The age model was applied to the depth corrected seismic reflections in order to create time surfaces and stratigraphic units. In this manner, seismic surfaces were used to estimate unit volumes, create isopach maps of these units (Fig. 9), and conduct sediment flux calculations. The limitations of this
method is that gaps in radiocarbon ages, and seismic reflections missing at one location but seen elsewhere in TMB, result in poorly constrained values. Despite these limitations, the results are reasonable except for a single time gap (~5.5 to ~3.5 ka BP) and edge effects on both the young and old ends of the dataset. In some cases, these problems necessitated combining the volumes of two or more time surfaces, which limited the resolution for these time periods (Table 3).

<table>
<thead>
<tr>
<th>#</th>
<th>Seismic Surfaces</th>
<th>Volume (km$^3$)</th>
<th>Volume %</th>
<th>Cumulative %</th>
<th><strong>Calculated Age (Years BP)</strong></th>
<th>Flux (km$^3$/ka)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Sea Floor</td>
<td>31.0</td>
<td>10.3%</td>
<td>100.0%</td>
<td>*</td>
<td>*37.9</td>
</tr>
<tr>
<td>2</td>
<td>Blue3</td>
<td>22.0</td>
<td>7.3%</td>
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<tr>
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<tr>
<td>17</td>
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<td>2.9%</td>
<td>165.2%</td>
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<td>8.7%</td>
<td>173.9%</td>
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*Indicates surfaces missing sufficient Radiocarbon and/or depth control at MU A-10 site in order to assign it an age
**Age calculations were made using linear regression equations from accumulation rate plot of core MU A-10
*0 years is used as the young age for flux calculation
*20,000 y is used as the old age for flux calculation

The results were plotted against time and sea-level, and combined with a chart of the timing of climatic events that could potentially affect TMB sedimentation (Fig. 10). The resulting flux data is grouped into five units of time based on sediment flux trends. The first unit spans ~20 to ~17 ka BP and the flux is 22.4 km$^3$/ka (Fig. 10, Table 3). This is the least constrained unit using the oldest viable date obtained in the TMB (Table 2) and a reasonable approximation of LGM time (Estimated as 20 ka BP based on data compilations of Arz et al., 2007), and therefore represents an
average flux for the deposits filling the back-reef depression prior to ~17 ka BP. Unit 2 sediment flux is moderately constrained from ~14.7 to ~9 ka BP at 0.4 km$^3$/ka (Fig. 10, Table 3). This same flux was extended to ~17 ka BP based on the 0.2 mm/year accumulation trend (~17 to ~8.8 ka BP; Fig 7a), and the distinctness of its sediments (red mud with abundant shell material and foraminifera). Unit 3 (~9 to ~5.5 ka BP) shows two orders of magnitude increase in flux from 0.4 km$^3$/ka to 41.1 km$^3$/ka that gradually declines until ~5.5 ka BP (Fig. 10, Table 3). A low sedimentation rate (0.3 mm/year, Fig. 7a) resulted in a hiatus (0.0 km$^3$/ka) from ~5.5 to ~3.5 ka BP (Fig. 10; Table 3). This hiatus or very slow sedimentation rate produced Unit 4. The final period of high flux (~3.5 ka BP to present) is Unit 5 (Fig. 10, Table 3). This youngest unit records the highest flux for the TMB, reaching 78.8 km$^3$/ka between ~1.8 and ~1.4 ka BP. From ~1.4 ka BP to present the flux is poorly constrained because of limited sampling of the upper 4 meters of core MU A-10.

XRD

X-ray diffraction analysis was performed on 30 samples (Table 4). Sixteen samples are from TMB cores MU A-10, MI 652, and PN A-69. Fourteen of the samples are control samples for comparing TMB mineralogy to that of its potential sources. Five of these samples were taken from red fluvial clays of the transgressive Rio Grande delta plain (LM Cores 2, 4, 26, 30, 32; Fig. 1), five samples are from the Maringouin and Teche lobes of the Mississippi delta (Cores EI 68 and ST 52; Coleman et al., 1998; Fig. 1), and four samples are from Brazos/Colorado transgressive delta's (Cores BA A39, BA 399, BA 538; Abdulah et al., 2004; Fig. 1).
The result is a mineralogical fingerprint for each of the rivers. Samples from each location plot together based on their relative abundances of plagioclase; 23-28% (Rio Grande), 13-17% (Mississippi), 8-13% (Brazos and Colorado), with the TMB samples plotting from 10-13%. TMB samples plot within the range of Brazos and

Relative proportions of quartz, plagioclase, and potassium feldspar were used to create a QPK ternary diagram, which reflects mineralogical maturity of sediments (Fig. 11, Table 5). This diagram reveals that the Rio Grande samples are the most immature, the Brazos and Colorado samples are the most mature, and the Mississippi samples overlap slightly with both the Rio Grande and the Brazos/Colorado samples (Dickinson and Suzcek, 1979; Fig. 11). To further distinguish between samples from different geographic locations, relative proportions of quartz, plagioclase, and total clays were compared (Fig. 11, Table 5).
Colorado delta samples. Rio Grande samples show little similarity to TMB samples (Fig. 11). A few samples from the TMB plot close to, but do not overlap with, a single sample (XRD # 26) from the Mississippi delta (Fig. 11) indicating a possible Mississippi sediment source. However, these samples are outliers within each population. These data do not conclusively rule out a Mississippi River source, but they clearly indicate that the dominant sediment sources are the Brazos and Colorado rivers.

### Table 5. XRD Relative Abundances for QPK and QPClay Ternary Diagrams

<table>
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<th>XRD#</th>
<th>Sample ID</th>
<th>Depth (m)</th>
<th>Quartz</th>
<th>Plagioclase</th>
<th>K-Spar</th>
<th>TOTAL</th>
<th>Quartz</th>
<th>Plagioclase</th>
<th>Total Clays</th>
<th>TOTAL</th>
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The Q/P/Clay diagram also reveals a spread in values between quartz and total clays for the TMB samples and for each individual fluvial population (Fig. 11). This is interpreted to result, in part, from variations in physical sorting. This hypothesis was tested using a clay-rich sample (fine grained end-member, 6μm graphic mean grain size) and an adjacent sand-rich sample (coarse grained end-member, 87μm graphic mean grain size) from an interbedded sand and clay unit, of core MI 652. XRD analysis showed that all of the remaining TMB samples plot between the grain size end-members (Fig. 11). Many of the TMB samples are higher in total clays and lower in quartz relative to the Brazos and Colorado samples (Fig. 11). This is interpreted to result from winnowing or reworking Brazos and Colorado sediments that were subsequently transported to the TMB.

**DISCUSSION**

Radiocarbon age control, seismic data, accumulation rates, flux calculations, and mineralogy provide a framework from which the evolution and source of the TMB can be discussed. For purposes of discussion, the stratigraphic section is divided into five sediment flux units and their corresponding time intervals: Unit 1 (~20 to ~17 ka), Unit 2 (~17 to ~9 ka), Unit 3 (~9 to ~5.5 ka), Unit 4 (~5.5 to ~3.5 ka), and Unit 5 (~3.5 ka to present. Figure 10 also summarizes some of the main depositional events that occurred in the northern Gulf of Mexico during the time the TMB formed.
UNIT 1 (~20 to ~17 ka) - Initial marine inundation

Relative sea-level rise in the northwestern Gulf of Mexico was influenced by glacio-
hydro-isostasy, which resulted in submergence of the outer part of the central Texas
shelf at a time when global sea level was still at a lowstand (Simms et al., 2007b)
(Unit 1, Fig. 10). The southern part of the study area was initially flooded at ~20 ka,
followed by submergence of the shelf depression situated between the MIS 3 and
MIS 2 shorelines (Fig. 2, 9). Coraline algae, which dates back to ~21.5 ka (Rezak et
al., 1985; Belopolsky and Droxler, 1999), suggests reefs were established on highs
associated with the MIS 2 shoreline while Unit 1 was being deposited (Fig. 9). Beach
sands with a shallow marine foraminiferal assemblage, observed in core MU 759,
indicate that the shoreline existed near this location during Unit 1 deposition (Fig. 1,
9). The setting at that time may have been similar to the mixed siliciclastic-
carbonate system of modern-day Belize, with reefs growing on old siliciclastic
shorelines (Ferro et al., 1999). The deepest portions of estuaries in the south (Fig.
2b) and the back-reef depression in the north (Fig. 2a) were filled with sediments
(Fig. 9) that indicate transitional, from terrestrial to marine, conditions. This is
supported by the dominance of lighter carbon isotopes in sediments resting just
above the MIS 2 SB that gradually shifts to heavier isotopic values upward in the
section of core MUA-10 (Eckles et al., 2004). The sediment flux for this unit (22.3
km³/ka) represents 22% of the total volume of the mud blanket (Fig. 10, Table 3).
However, the lack of radiocarbon dates older than 17 ka, and the possibility of non-
marine sediments in the lower portion of the section, limit the precision of the
sediment flux associated with this unit.
UNIT 2 (~17 to ~9 ka) - Rapid sea level rise and slow TMB growth

The sediments from this unit consist of biogenic-rich red mud, which is markedly different from the siliciclastic-dominated olive-grey mud in younger TMB sediments. The red color and high concentration of shell material suggests low siliciclastic input (Potter et al., 2005). Sediment flux (0.4 km$^3$/ka; Fig. 10) and sedimentation rate (0.2 mm/year; Fig. 7) calculations support these sedimentological observations. The >63 µm size fraction is dominated by foraminifera composed of an open shelf assemblage. This indicates that by ~17 ka the back-reef area had been flooded with marine waters, with sedimentation occurring mostly in two separate depocenters in the northern and southern parts of the TMB (Fig. 9).

Radiocarbon ages from the reefs indicate that they were still living at the time of deposition of Unit 2, at least until ~12.3 ka (Rezak et al., 1985). Siliciclastic sediment flux remained low (0.4 km$^3$/ka; Fig. 10) before and after ~12.3 ka. This suggests that if the reefs died between ~12.3 to ~9 ka BP their demise was unrelated to TMB sedimentation and was caused by other mechanisms (Belopolsky and Droxler, 1999).

From ~12 to ~9 ka, the Brazos and Colorado rivers constructed large fluvial-dominated deltas on the shelf (MIS 2 to MIS 1 deposits, Abdulah et al., 2004; Fig. 9) indicating a period of increased sediment supply to the shelf by both rivers (Anderson et al., 2004). This increase was possibly associated with a period of climate instability and associated shifting between cool/wet and warm/dry
conditions (Fig. 10). The sediment flux to the TMB remained low during this time, so sediments from the Brazos and Colorado rivers was mostly deposited in the deltas to the north. This was a period of rapid sea-level rise (7.1 mm/year, Fig. 10), which implies a correlation between delta growth and creation of accommodation via sea-level rise, but anti-correlation with TMB formation.

UNIT 3 (~9 to ~5.5 ka) - Rapid TMB growth

By ~9 ka, the present day barrier islands of the central Texas coast began to form, beginning with Mustang Island (Simms et al., 2006b) and the Brazos and Colorado deltas switched from fluvial-dominated to wave-dominated deltas (Abdulah et al., 2004). These deltas (Abdulah et al., 2004) formed broad bathymetric highs that extended ~50 km seaward of the shoreline. During this same time period there was increased floodplain sequestration of sediment in both the Brazos and Colorado drainage basins (Waters and Nordt, 1995; Taha and Anderson, 2008). There were two factors that resulted in increased floodplain storage at this time. First, the climate became increasingly arid during the mid-Holocene (Fig. 10), which simultaneously increased sediment load and decreased stream competence resulting in floodplain deposition (Waters and Nordt, 1995). Secondly, floodplain aggradation occurred as sea-level rose (Taha and Anderson, 2008). During this time, smaller Texas rivers, such as the Trinity, Lavaca and Nueces rivers, were flooded to create Galveston Bay, Matagorda Bay and Corpus Christi Bay, respectively (Anderson et al., 2008; Maddox et al., 2008; Simms et al., 2008). A transgressive Rio Grande delta also existed on the shelf, although its location is poorly constrained.
(Banfield and Anderson, 2004). Hence, all indications are that sediment supply to
the shelf should have decreased during this time. However, this was the time of
rapid growth of the TMB. We estimate that 58.3 km$^3$ of sediment was delivered to
the TMB during this time interval. The most likely source for this sediment was from
transgressive ravinement of existing shelf deposits, especially the Brazos and
Colorado deltas.

The efficiency of transgressive ravinement has varied during the previous
transgression depending on both the rate of sea-level rise and changes in the shelf
profile (Swift, 1975). Using the sea level curve of Simms et al. (2007b) and the MIS 2
erosion surface (Simms et al., 2007a) allowed estimates of sediment flux through
transgressive ravinement to be calculated. The results revealed a two-order of
magnitude increase in flux between ~9 and ~8 ka, with a gradual reduction in flux
to almost zero by ~6 ka (Fig. 10).

Bathymetric highs are particularly susceptible to ravinement. For example, research
on the 1929 Brazos wave-dominated delta, which extended offshore into 20 meters
of water, was removed in less than three decades (Rodriguez et al., 2000). Assuming
a -10 meter depth of transgressive ravinement, the current depth of ravinement for
central Texas (Rodriguez et al., 2001), ravinement of the Colorado and Brazos deltas
would have removed an estimated 61.0 km$^3$ of sediment. This is very close to the
amount (58.3 km$^3$) of sediment that accumulated in the TMB during this time (Fig.
10; Table 3). The rapid increase in sediment flux from 0.4 to 41.1 km$^3$/ka at ~9 ka
BP (Fig. 10; Table 3) is thus explained by ravinement and cannibalization of deltas.
As the shoreline continued to migrate landward, these sediment sources were gradually depleted and the sediment flux decreased until the deltas were overstepped by the advancing shoreline.

UNIT 4 (~5.5 to ~3.5 ka) - Climatic optimum and TMB hiatus

Between ~5.5 and ~3.5 ka, there was a significant reduction in sediment flux in the TMB, which corresponds to a prolonged warm/dry climate interval known as the climatic optimum (Fig. 10), (Nordt et al., 1994) that likely caused a reduction in sediment flux from rivers. Research on the upper Colorado River valley indicate that after the shift to a drier climate at ~5.0 ka BP flood magnitudes decreased (Blum et al., 1994). In the Brazos fluvial valley, floodplain aggradation shifted to the northern reaches of the valley after ~5 ka (Taha and Anderson, 2008). Hence, both the Colorado and Brazos rivers delivered less sediment to their lower valleys and potentially to the Gulf during the Holocene climatic optimum.

UNIT 5 (3.5 ka to present) - Climate controlled deposition

After a pause in TMB growth between ~5.5 and ~3.5 ka (Fig. 10), there was a phase of rapid growth. By this time, the Brazos River had filled its onshore accommodation (Taha and Anderson, 2008) and this is likely to have been the case for the Colorado River. Smaller Texas rivers have continued to fill their bays with sediments. Yet, the TMB experienced its most rapid growth (Fig. 10).
The total volume of Unit 5 \((172 \text{ km}^3)\) is 57% of the total TMB, which equates to a discharge from \(10.0 \times 10^7\) to \(1.50 \times 10^7\) metric tons/year (Fig. 10). The only river with a modern discharge with this order of magnitude is the Mississippi River and the amount required to account for the TMB flux at this time is equal to about 50-75% of its modern discharge (Table 1). Despite this, the mineralogical data support a Brazos/Colorado source (Fig. 11). Furthermore, there is no connection between the Late Holocene lobe switching events of Mississippi Delta and the TMB, as might be expected if the Mississippi were a major sediment source (Coleman et al., 1998). If the sediment sources were the Brazos and Colorado rivers, their discharge would need to have been more than eight times their combined present-day discharge. Anderson et al., (2004) estimated an order of magnitude increase in sediment supply of these rivers during the falling stage.

Perlmutter et al., 1998) showed that sediment flux is greatest when prolonged dry periods are followed by periods of increased precipitation. This is supported by Fraticelli’s (2006) work on the modern Brazos Delta, and is likely the cause of this last period of increased sediment flux. After the Middle Holocene warm and dry climate maximum (~4.5 to ~6 ka, Nordt et al., 1994), climate conditions in central Texas became more variable (Toomey et al., 1993; Humphrey and Ferring, 1994; Nordt et al., 1994, 2002; Fig. 10). There is little agreement on the exact timing of these variations. However, it is agreed that the main shift to cool/wet conditions occurred sometime between ~4 and ~2.5 ka (Fig. 10). Despite a lack of agreement as to the magnitude and timing of millennial-scale climate oscillations of the late
Holocene, this climate variability appears to have resulted in the high and somewhat variable sediment flux of Unit 5 (Fig. 10).

During this most recent period of increased sediment supply to the TMB, fine-grained sediments derived mostly from the Brazos and Colorado Rivers have been winnowed by coastal currents and delivered to the TMB, while sands have been deposited in coastal settings. Thus, from ~3.5 ka to the present, sediment transport to the TMB has been dominated by longshore coastal currents and offshore wind-driven currents, as proposed by Curay (1960), and Shideler (1978, 1979).

CONCLUSIONS

1. The Texas mud blanket (TMB) has mostly accumulated in a mid-to-outer shelf depression that is situated between the MIS 3 and MIS 2 shorelines. Deposition was mostly confined by the ancestral Colorado Delta to the north and the Rio Grande Delta to the south. Reef growth on the MIS 2 shoreline enhanced the eastern margin of the depocenter. In the south, faulting has deepened the shelf depocenter.

2. XRD data reveal that the Brazos and Colorado rivers were the dominant sediment sources of the TMB, with the Mississippi River having served as a secondary source.

3. Five sediment flux units observed in the TMB record variations in the dominant controls on sedimentation; antecedent topography, rates of eustatic rise,
efficiency of transgressive ravinement, and climate-controlled sediment delivery from rivers.

4. From ~20 to ~17 ka there was a transition from terrestrial to marine sedimentation with shallow marine and possibly fluvial sediments having filled the deepest accommodation. By ~17 ka, a mixed siliciclastic/carbonate depositional system was established. A new shoreline had developed on the landward side of the depocenter and a series of reefs were growing on the ancestral MIS 2 shoreline. Marine foraminifera in sediments of this age indicate a back-reef depocenter that was open to marine waters.

5. Low sediment flux to the TMB occurred from ~17 to ~9 ka. During this time, sea level rose at its highest rate of ~7mm/year, which corresponds to a phase of Colorado and Brazos delta growth that was most pronounced from ~12 to ~9 ka. Hence, sediments appear to have been sequestered in shelf deltas that largely escaped transgressive ravinement.

6. From ~9 to ~5.5 ka was a period of rapid growth of the TMB related to the ravinement of both falling stage and transgressive Brazos and Colorado deltas. As these sediment sources were depleted, sediment flux decreased.

7. A period of low sedimentation rates and a hiatus in TMB growth from ~5.5 to ~3.5 ka corresponds to the warm and dry conditions of the Holocene Climatic Optimum (~4.5 to ~6.0 ka, Nordt et al., 1994) and sequestration of fluvial sediments in onshore valleys.
8. The final episode of TMB growth (~3.5 ka-present) is associated with high frequency climate oscillations of this time period. During this time, approximately 57% of the total TMB volume accumulated.

9. The most pronounced trend in the evolution of the TMB is the anti-correlation between its evolution and rates of sea-level rise. This indicates that efficiency of transgressive ravinement and sediment production by this process is closely regulated by rates of transgression.

10. One of the most surprising outcomes of this study is the shear volume and extraordinarily high flux rates associated with TMB growth during the last 3.5 ka. The order of magnitude increase in volumes and flux provokes a desire to include a higher-discharge source like the Mississippi River to help contribute to the huge volumes of sediment observed over this time interval. However, the mineralogical data suggest a dominantly Brazos/Colorado source. For these rivers to be the major suppliers of sediment to the shelf, pronounced changes in transport efficiency and/or sediment supply must have occurred during the late Holocene because a decreased rate of transgression resulted in transgressive ravinement being of little importance after 6 ka. A change in oceanographic circulation could have increased transport efficiency to the TMB by changing the location of convergence and offshore flow. Still, an increase in sediment supply of these rivers, likely caused by more variable climate, was necessary to provide the order-of-magnitude increase seen at this time.
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REFERENCES


Figure 1. Important geographic and paleogeographic features within the study area. The larger inset map shows seismic lines, cross section lines (labeled with a letter) and the -120 bathymetry contour, which generally corresponds to the shelf break. Seismic lines in text are labeled with a number. The plot of shelf gradients (small inset) illustrates that Central Texas is a ramp between two relatively flat shelves with distinct shelf breaks. Core locations are shown as white boxes with a corresponding label. Laguna Madre cores are shown in the smaller inset map. Mississippi delta lobe locations are from Coleman et al. (1998). Brazos and Colorado delta locations are from Suter and Berryhill (1985), and from Abdulah et al. (2004). Locations of the Rio Grande delta's are from Suter and Berryhill (1985), and from Banfield and Anderson (2004). Reef locations are from Rezak et al. (1985), modified from Belopolsky and Droxler (1999).
Figure 2. Interpreted and uninterpreted seismic lines 4 and 1 (see figure 1 for locations) illustrating a prominent erosion surface (Transgressive surface of ravinement) that defines an outer shelf depression in which the TMB accumulated. Also shown are the locations of cores PN A-69 and MI 652.
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Figure 3. (a) Satellite image showing general westward transport of suspended sediments in the northern Gulf of Mexico. (b) Circulation patterns in the Gulf of Mexico. Black arrows indicate mean currents. Dashed arrows show migration Loop Currents, Loop Current Rings (LCR), and Cyclonic Rings (CR). (From Sionneau et al., 2008). Also shown is the coastal convergence zone from McGowen et al. (1977).
Figure 4. Interpreted and uninterpreted seismic lines 5 and 2 showing stratigraphic relationship between the mud blanket and the Rio Grande delta (See figure 1 for locations). Mud blanket reflections are parallel and show a strong onlapping relationship with the surface of the delta.
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Figure 5. Interpreted and uninterpreted, strike-oriented seismic line 6 illustrating the relationship between the TMB and the Colorado Delta (See figure 1 for location). Note inter-fingering of the delta and TMB, and truncation of delta topset beds.
Figure 6. Results from seismic velocity test using core MU A-10 and surfaces from seismic line # 3 (see Figure 1 for core and seismic line locations). A velocity of 1807 m/sec more accurately places the sequence boundary above the radiocarbon dead dates.
Figure 7. A- Age-depth plots for three cores (MU A-10, MI 652, and PN A-69) and accumulation rates for core MU A-10 based on linear regressions. B- Mud blanket age-depth plot for core MU A-10 and the northern Gulf of Mexico sea level curve for the last ~9 000 years from Milliken et al., 2008). Note inverse relationship between mud blanket rate of accumulation and the rate of sea level rise.
Figure 7. A- Age-depth plots for three cores (MU A-10, MI 652, and PN A-69) and accumulation rates for core MU A-10 based on linear regressions. B- Mud blanket age-depth plot for core MU A-10 and the northern Gulf of Mexico sea level curve for the last ~9 000 years from Milliken et al., 2008). Note inverse relationship between mud blanket rate of accumulation and the rate of sea level rise.
**Figure 8.** Ten prominent seismic reflections correlated between core sites with radiocarbon dates used for subdividing the TMB into units for volume and sediment flux calculations (For core locations see figure 1).
Figure 9. (a) Unit 1 (20-17 ka) isopach map and TMB isopach superimposed on stage 2 erosion surface from Simms et al. (2007a). (b) Unit 2 (17-9 ka) isopach map. (c) Unit 3 (9-5.5 ka) isopach map and TMB. (d) Unit 5 (5.5 ka to present) isopach map. Shorelines are based on Simms et al. (2007b) sea level curve. Delta locations are based on Banfield and Anderson (2004), Abdulah et al. (2004), and Suter and Berryhill (1985).
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Figure 10. Central Texas shelf sediment flux in relation to sea-level and records of Texas climate change. The sea level curve is from Simms et al. (2007b). Ravinement flux is calculated using the area between shorelines at 1000-year intervals (for the area bounded by 26.5° N in the south, to 95° W in the east), and assuming a -10 m depth of ravinement (Rodriguez et al., 2001). Sediment discharge was calculated from TMB flux and mean grain size (Table 4) using grain size versus density plots of Hamilton and Bachman (1982) to make comparisons between modern fluvial sediment discharge (Table 1) and TMB flux. Sediment discharge is shown as white symbols showing the time period (x-axis) and the range of discharge (10^6 metric t/year) values (y-axis) based on the range of grain sizes observed in TMB sediments.
Figure 11. QPK and QPClay ternary diagrams illustrating differences between sediments of the Rio Grande (RG), Brazos/Colorado (B/C), and Mississippi (M) drainage basins. The QPClay diagram plots total clays with the Q and P proxy for maturity. The Q and total clay relationship is largely controlled by variations in grain size variations.