Evidence for Late Pliocene Deglacial Megafloods from Giant Sediment Waves in the Northern Gulf of Mexico

Zexuan Wang
Western Kentucky University, zexuan.wang278@topper.wku.edu

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EVIDENCE FOR LATE PLIOCENE DEGLACIAL MEGAFLOODS FROM GIANT SEDIMENT WAVES IN THE NORTHERN GULF OF MEXICO

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Master of Science

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Zexuan Wang
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EVIDENCE FOR LATE PLEISTOCENE DEGLACIAL MEGAFLOODS FROM GIANT SEDIMENT WAVES IN THE NORTHERN GULF OF MEXICO

Date Recommended 7/3/2017

M. Royhan Gani, Director of Thesis

Nahid D. Gani

Fredrick D. Siewers

Dean, Graduate School  Date

7/13/17
I dedicate this thesis to my parents.
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Laurentide Ice Sheet outburst floods to the Gulf of Mexico have been mainly documented based on deep-sea cores, especially the megafloods, only during the last several interglacial episodes in the late Pleistocene. The paleoclimatic significance of giant sedimentary structures developed under unconfined Froude-supercritical turbidity currents in subaqueous settings is considerably under-examined. This research extensively documents >20-km-wide and 200-m-thick Plio-Pleistocene giant sediment waves for the first time on the northern Gulf of Mexico continental slope using 3D seismic data, which show waveform morphology in unprecedented detail. The results suggest that such large-scale bedforms were formed under sheet-like unconfined Froude-supercritical turbidity currents as cyclic steps, based on numerical and morphological analyses. Paleohydraulic reconstruction (e.g., flow velocity, discharge, and unit flux), in association with other evidence like geologic age, stable isotope records, and temporal rarity, points out that the responsible Froude-supercritical turbidity currents were most likely triggered by deglacial catastrophic outburst floods during the late Pliocene to early Pleistocene. These flooding events constitute, by far, the oldest record of the glacial outburst floods during the Quaternary Ice Age. The results propose that such pervasive occurrence of large-scale sediment waves are a proxy for catastrophic megaflood events.
Chapter 1. Introduction

The northern Gulf of Mexico serves as a crucial archival site for the upstream Laurentide Ice Sheet meltwater floodings (Figure 1) (Aharon, 2006). Previous identifications of the Laurentide Ice Sheet outburst floods to the Gulf of Mexico focused on the recent surges of meltwater during the last several interglacial episodes in the late Pleistocene based on multiproxy analyses (e.g., siliciclastic grain size, mineral abundance, and the isotope record) of deep-sea cores (Brown and Kennett, 1998; Aharon, 2006; Montero-Serrano et al., 2009). However, the implications of large-scale sedimentary structures that developed under sheet-like Froude-supercritical turbidity currents in subaqueous unconfined settings for ancient deglacial megafloods are under-examined. Sediments accreted under a sustained Froude-supercritical regime by such exceptional discharge events should have great potential to preserve resultant sedimentary structures.

A marine sediment wave is defined by Wynn et al. (2000) as an undulating depositional bedform, generally with tens of meters to a few kilometers in wavelength and several meters in height, generated beneath a current flowing at the seafloor. Large-scale sediment waves generally refer to a wavelength of >300-600 m and a wave height of >5-10 m. Sediment waves originated by Froude-supercritical turbidity currents have been documented extensively by focusing mainly on their recognition, geomorphology, architecture, and formative processes (Lee et al., 2002; Wynn et al., 2000; Cartigny et al., 2011; Gong et al., 2012). Recent flume tank experiments and numerical modelling identified “cyclic steps” as previously unrecognized upper-flow-regime bedforms generated under ultra-powerful Froude-supercritical (Fr >1.5-2) flows bounded by
hydraulic jumps to explain the formation of deep-marine sediment waves (Kostic et al., 2010; Kostic, 2011; Cartigny et al., 2014). Morphology and facies-based recognition of cyclic steps is challenging (Covault et al., 2017) and, thus, poorly documented from the sedimentary record.

**Figure 1. Location map of the study area.** Map of the continental interior of North America during late Pliocene to early Pleistocene shows the study area on the continental slope of the northern Gulf of Mexico, approximate location of shelf margin (black dashed line), shoreline (black solid line), drainage systems of the Mississippi and Tennessee Rivers (blue solid lines), and the Laurentide Ice Sheet (grey area). Laurentide Ice Sheet outburst floods to the Gulf of Mexico were most likely following the drainage systems of Mississippi and Tennessee Rivers.

Source: Modified by the author from Galloway et al. (2000, 2011).
This study revealed a >20-km-wide and 200-m-thick Plio-Pleistocene (~2.9-1.8 Ma) sediment-wave succession on the northern Gulf of Mexico continental slope using 3D seismic data, integrated with biostratigraphic and δ¹⁸O records. The research interpreted this succession to be the first extensive record of a fully-preserved train of cyclic steps formed by sheet-like unconfined hyperconcentrated Froude-supercritical turbidity currents under sustained flow. Such a thick interval of anomalous bedforms in the sedimentary record is likely diagnostic of ancient cataclysmic floods, implying Laurentide Ice Sheet deglacial outburst megafloods.
Chapter 2. Background

2.1. Geological and Paleoclimatic Setting

The Gulf of Mexico basin was created by the oceanic crust spreading between the North American plate and the Yucatan block starting in the middle Jurassic, with an extensive and thick salt accumulation (Galloway, 2008; Galloway et al., 2011). The basin depocenter likely contains as much as a ~20 km-thick succession of upper Jurassic to Holocene strata. The northern Gulf margin has been fed by multiple fluvial systems, of which the Mississippi, Red, and Tennessee Rivers served as the dominate drainage axes spanning from the late-early Pliocene to the Holocene, carrying terrigenous sediments from the North American continent (Figure 1) (Galloway et al., 2000; Galloway et al., 2011). More basinward, the continental slope is characterized by salt domes, which created mini-basins and impacted local slope gradient. Since the early Pliocene, the shelf edge positions upstream of the study area remained almost stable (see Figure 20 in Galloway et al., 2000). However, the shorelines underwent frequent forced regressions, exposing the shelf. This was ascribed to the glacial-induced high-frequency and high-amplitude sea level fluctuations, which allowed a high volume of sediments to be transported directly to the upper slope (Galloway et al., 2000).

2.2. Sediment Wave

A deep-water sediment wave is defined by Wynn et al. (2000) as a large-scale (generally tens of meters to a few kilometers in wavelength and several meters in height), undulating depositional bedform generated beneath a current flowing at, or close to, the seafloor. Using the classification scheme proposed by Wynn and Stow (2002), sediment waves can be divided into four groups: (1) fine-grained, bottom-current-generated; (2) coarse-grained, bottom-current-generated; (3) fine-grained, turbidity current-generated;
(4) coarse-grained, turbidity current-generated. To assign an origin to the sediment waves, several criteria suggested by Wynn and Stow (2002) can be applied: (1) regional depositional setting; (2) wave-shape regularity; (3) wave-crest orientation; (4) interval thickness variation trend; and (5) degree of sinuosity and bifurcation of wave crest. Sediment-wave dimensions summarized by Wynn and Stow (2002) can be applied to estimate grain sizes from sediment-wave morphology when direct measurement of grain size is not possible. For example, (1) fine-grained, turbidity-current-generated sediment waves are up to ~80 m in height and ~7 km in wavelength, and (2) coarse-grained, turbidity-current-generated sediment waves are <10 m in height and <1 km in wavelength.

Formative models for sediment waves include the lee wave model (Flood, 1988), antidune model (Normark et al., 1980), and cyclic step model (Cartigny et al., 2011). The lee wave model suggests that the flow, even though at a low speed due to the weak near-bottom density stratification of the flow, accelerates on the downcurrent flanks to cause less deposition, non-deposition, or erosion, and decelerates on the upcurrent flanks; this leads to the upcurrent migration. This model generally applies to the sediment waves with a bottom-current origin (internal Froude number <0.4). Wynn et al. (2000) proposed that the antidune model (e.g., symmetrical geometry; Kostic, 2011) is most applicable for the observed pattern and mode of formation of sediment waves generated by turbidity currents. Their calculations on the Selvage sediment waves show internal Froude numbers \( F_i \) ranging from 0.5 to 1.9, agreeing well with the antidune existence limits \((0.844<F_i<1.77;\) Allen, 1982\), but too high to fit the lee wave model \((F_i <0.4)\). If antidunes truly form, there should be rapid fallout of sediments from suspension to
preserve their geometry, which can occur under the waning phase of turbidity currents (Skipper, 1971). Kubo and Nakajima (2002) explained that the sediment waves are formed individually downstream of a slope break of the prior waveform, which requires a first slope break to initiate the generation of the first waveform. The upslope migration can be attributed to a higher sedimentation rate on the upslope wave flank (Wynn and Stow, 2002), which is indicative of supercritical flow (Symons et al., 2016). However, the laboratory experiment conducted by Kubo and Nakajima (2002) suggested that the preferential deposition on the upcurrent flank can occur under an out-of-phase subcritical turbidity current (\(F_i < 0.84\)), as long as there is a pre-existing undulating topography causing the blocking (ponding) effect.

Cartigny et al. (2011) and Kostic (2011) argued that cyclic steps provide an alternative formative mechanism for the turbidity-current-generated sediment waves. Parker and Izumi (2000) coined the term “cyclic steps.” Submarine cyclic steps representing another type of morphodynamic instability of supercritical flow were simulated numerically by Kostic and Parker (2006), showing a series of upcurrent-migrating steps, bounded by internal hydraulic jumps. Their geometry can be either symmetrical, upslope asymmetrical or downslope asymmetrical (Kostic, 2011). A review of recent literature shows that some researchers (e.g., Gong et al., 2012) did not incorporate this model in the sediment-wave interpretation, whereas other authors (e.g., Fildani et al. 2006; Lamb et al., 2008; Spinewine et al., 2009; Symons et al., 2016) paid attention to this model in their interpretations. Fildani et al. (2006) and Kostic (2011) noted that cyclic steps are formed as a coherent and quasi-permanent train of longer-wavelength steps that are stabilized by the presence of hydraulic jumps, whereas antidune
processes are ephemeral and generally not sustainable. Fildani et al. (2006) first adopted the concept of net-depositional and net-erosional cyclic steps to assign origins to the sediment waves deposited by flow stripping over the levee of the Shepard Meander of the Monterey Channel. Antidunes (both stable and unstable), chutes-and-pools, and cyclic steps are classified as free-surface-dependent, where the presence of hydraulic jumps (i.e., undular, weak, oscillating, steady, and strong jumps) are required to generate these bedforms (Cartigny et al., 2014).

In this study, the densimetric Froude number is adopted as one of the main criteria to distinguish various supercritical-flow bedforms, owing to the impossibility of observing directly ancient depositional processes. The flume experiment performed by Cartigny et al. (2014) recorded the peak Froude numbers ($F_{r90}$) of stable antidunes, unstable antidunes, chutes-and-pools, and cyclic steps to be 1.31, 1.34, 1.62, and 2.18, respectively, which is indicative of an energy-increasing trend.

2.3. Deglacial Meltwater Megaflood
A glacier outburst flood, also called a jökulhlaup, denotes a flood triggered by a sudden release of water trapped within or behind a glacier. It is characterized by extremely high discharge (Sturm and Benson, 1985). Pleistocene ice-dammed lake outburst floods have been investigated for decades, among which the Lake Missoula flooding in western Montana (~18-14 ka) is one of the best-studied cases (Baker and Bunker, 1985; O’Connor and Baker, 1992; Balbas et al., 2017). The resulting Channeled Scabland shows profound impacts of such catastrophic meltwater floods. Such high-energy, sediment-laden megafloods, when entering a waterbody, can lead to hyperpycnally-generated turbidity currents (Baker, 2002). Some megaturbidite beds were
interpreted to be the products of flood-induced hyperpycnally-generated turbidity currents (e.g., Brunner et al., 1999; Zuffa et al., 2000).
Chapter 3. Methods

3.1. Seismic Interpretation

A high-resolution 3D seismic survey over an area of 635 km$^2$ on the northern Gulf of Mexico continental slope (Figure 1), with an inline and crossline spacing of 12.5 m, was calibrated by wireline logs and interpreted using seismic geomorphological techniques in the IHS Kingdom software. The seismic survey was processed to be zero phased, time migrated, and in American polarity (that is, a positive reflection coefficient, or an increase in acoustic impedance across a bedding interface, is displayed as a peak reflector). Horizons were mapped using manually interpreted seed-lines along peaks and troughs, and with the software’s automatic picking function to fill the gaps between. Analysis incorporated time-depth charts from several wells within the seismic survey to estimate the interval velocity of the sediment-wave succession to be 1,800 to 2,000 ms$^{-1}$. Seismic amplitude and a set of seismic attributes (e.g., dip of maximum similarity) were utilized to investigate the depositional architectures. The interval of interest has a dominant frequency of 13.5 Hz, and vertical resolution and detection limit of 33 m and 8 m, respectively.

3.2. Densimetric Froude Number Estimation

The Densimetric Froude number is a dimensionless ratio of inertial to buoyancy forces in a current that can characterize the flow dynamics. The Densimetric Froude number was calculated based on equation (1) (Bowen et al., 1984, Sequeiros, 2012), and independently verified and constrained by the charts (Figure 2) of Sequeiros (2012) and Cartigny et al. (2013):

$$Fr_d^2 = \frac{\sin \beta}{C_f + \nu}$$

(1)
where \( Fr_d \) is the densimetric Froude number, \( \beta \) is the bed slope angle, \( C_f \) is the drag coefficient and \( E \) is the entrainment coefficient. Using the study area’s slope angle of 2.2°, along with a range of reasonable values for \( C_f \) (5×10^{-4} to 5×10^{-3}; Bowen et al., 1984, Wynn et al., 2000) and \( E \) (5×10^{-4} to 6×10^{-3}; Bowen et al., 1984, Wynn et al., 2000), the calculated densimetric Froude number of the turbidity currents responsible for generating the sediment waves in our study area ranges from 1.9 to 2.5, after additionally constrained by the charts (Figure 2).

### 3.3. Paleohydraulic Reconstruction

Paleohydraulic conditions of the turbidity currents responsible for generating the sediment waves were estimated to reconstruct the flow magnitude in terms of velocity, thickness, discharge, and unit flow flux. Equation (2) defines the densimetric Froude number (\( Fr_d \)) of turbidity currents (Normark et al., 1980, Huang et al., 2009, Sequeiros, 2012, Covault et al., 2017).

\[
Fr_d = \frac{U}{\sqrt{\frac{\rho_{TC} - \rho_W}{\rho_W} gh}}
\]  

(2)

where \( U \) is the depth-averaged flow velocity, \( g \) is the acceleration due to gravity, \( h \) is the depth-averaged flow thickness, \( \rho_{TC} \) and \( \rho_W \) are the densities of turbidity current and ambient water, respectively.
Figure 2. Plots of slope gradient versus the densimetric Froude number ($F_{rd}$). $F_{rd}$ of density/turbidity currents are plotted against the bed-slope gradient (a), showing a positive correlation (red line) (see Sequeiros (2012) for data sources). This shows that the slope gradient of ~0.038 (this study) can lead to the $F_{rd}$ up to 2.7. b, $F_{rd}$ measured and modelled from a variety of methods are plotted against the bed-slope gradient, showing a similar relationship (see Cartigny et al. (2013) for data sources). This shows that the slope gradient of ~0.038 (this study) can lead to the $F_{rd}$ up to 2.4.

Source: (a) Modified from Sequeiros (2012); (b) Modified from Cartigny et al. (2013).

Equation (3) proposed by Normark et al. (1980) demonstrates the relationship between the wavelength of bedforms formed by turbidity currents and the flow velocity.
\[ U^2 = \left[ \frac{gL}{2\pi} \right] \left[ \frac{\rho_{TC} - \rho_W}{\rho_W} \right] \]  

where \( L \) is the wavelength of sediment waves, and \( U, g, \rho_{TC} \) and \( \rho_W \) are as defined previously. The \( \rho_W \) is assumed to be 1.028 g cm\(^{-3}\). Migeon et al. (2000) suggested that sediment waves are always correlated with high sediment input and, hence, it is assumed that the sediment concentration of the turbidity currents ranges from 5\% to 10\% (e.g., high-density turbidity current; Gani, 2004). This leads to the \( \rho_{TC} \) value ranging from 1.11-1.19 g cm\(^{-3}\). Using equation (3), depth-averaged flow velocity responsible for producing the dominant sediment waves (average wavelength 600 m, and maximum wavelength 800 m) is calculated as 9-16 ms\(^{-1}\). Combining equations (2) and (3), the following relation can estimate the flow thickness (Wynn et al., 2000).

\[ h = \frac{L}{2\pi Fr_d^2} \]  

where \( h, L \) and \( Fr_d \) are as defined previously. Using equation (4), the dominant flow thickness is calculated as 15-32 m.

Providing that the lateral along-strike extent of the sediment waves is >20 km, which corresponds to the flow width, the discharge and unit flux (i.e., flux per unit width) for a single flow event are estimated, using the following equations (5) and (6), to be 3×10\(^6\) m\(^3\)s\(^{-1}\) (10 km\(^3\)/h) to 1×10\(^7\) m\(^3\)s\(^{-1}\) (40 km\(^3\)/h) and 140-510 m\(^2\)s\(^{-1}\), respectively.

\[ Q = w \times h \times U \]  

\[ q = \frac{Q}{w} \]  

where \( Q \) is the flow discharge, \( q \) is the unit flow flux, \( w \) is the flow width, \( h \) and \( U \) are as defined previously.
3.4. Biostratigraphic Record

Geological ages of the studied succession were constrained by the planktonic and benthic foraminifera, and calcareous nannoplankton markers from wells drilled in the study area, which are compiled by Bureau of Ocean Energy Management (BOEM, 2017). The last appearance datums (LADs) of these fossils were adopted to provide a regionally correlatable, widely-used, and well-dated chronostratigraphic framework of the Gulf of Mexico.

3.5. Oxygen Isotope ($\delta^{18}O$) Record

This research analyzed the benthic $\delta^{18}O$ records of Lisiecki and Raymo (2005) that were based on globally-distributed cores, and the planktonic $\delta^{18}O$ records of Joyce et al. (1990, 1993) that were derived from the Ocean Drilling Program (ODP) hole 625B in the Gulf of Mexico, which is just ~100 km away from the study area. These $\delta^{18}O$ data serve as proxies for global ice volume changes and the Gulf of Mexico meltwater discharge history, respectively.
Chapter 4. Results

4.1. Seismic Geomorphology

Figure 3 shows a 200-m-thick Plio-Pleistocene sediment-wave succession on the continental slope (~2.2° slope angle) of the northern Gulf of Mexico. The biostratigraphic markers (BOEM, 2017) constrain the interval age between ~1.8 and ~2.9 Ma (Figure 4).

![Seismic profile](image)

Figure 3. **Along-slope seismic profile.** Seismic cross section (a) perpendicular to the wave-crests shows the sediment-wave succession, for which the seismic interval velocity is 1,800 to 2,000 ms⁻¹. Three mapped horizons (A-C) are highlighted (b). The biostratigraphic data constrain their ages to 2.44 Ma, 2.5 Ma, and 2.9 Ma, respectively (see Figure 4 for details). Between horizons A and C, the sediment waveforms are more acoustically reflective and traceable with a lower angle of climb, indicating more active sediment build-up by turbidity currents. In contrast, the waveforms overlying horizon A are more acoustically transparent with a higher angle of climb, indicating that hemipelagic/pelagic drapings were more dominant than turbidity-current deposition. Source: Created by the author from BOEM (2017).
Figure 4. Seismic cross section showing the age constraints of the sediment waves using biostratigraphic data from wells A and B. Biostratigraphic markers at well A (Figure 7) include *Sphaeroidinella dehiscens* acme "A" (1.02 Ma), *Pseudoemiliania lacunosa* "C" acme (1.02 Ma), *Calcidiscus macintyrei* (1.6 Ma), *Sphaeroidinella dehiscens* acme "B" (1.6 Ma), *Discoaster brouweri* (1.93 Ma), *Globorotalia miocenica* (2.39 Ma), *Discoaster surculus* (2.49 Ma), *Discoaster tamalis* (2.8 Ma), *Globorotalia multicamerata* (2.98 Ma), and *Sphenolithus abies* (3.57 Ma). In addition, biomarker *Globoquadrina altispira* (3.13 Ma) at well B (Figure 7) provides independent age information. Both foraminiferal planktic and benthic and calcareous nannoplanktic markers are used.

Source: Created by the author from BOEM (2017).

The study interval is located southeastward of the Mississippi Delta and southward of the Mobile Bay (Figure 1). The sediment-wave field covers a minimum of ~200 km², likely extending beyond the seismic coverage, with trains of more than 30 generally parallel bedforms (Figures 5, 6 and 7). The base of the sediment-wave succession lies 0.4-0.5 s TWT below the present-day sea floor, which has a water depth ranging from 950-1,250 m. The individual waveform exhibits a wavelength between 200 and 800 m (550 m in average) and a wave-height between 3 and 15 m (7 m in average) (Figure 3). Their dimensions decrease both upslope and downslope from the center of the field (Figure 5). The crestlines are straight or slightly sinuous and oriented northeast-southwest, generally aligned perpendicular to the regional slope (Figures 5 and 7). A 10-
degree rightward deflection of the wave crests orientation likely exhibits the Coriolis effect on fast-moving flows along the slope (Figure 5). The sediment waves have steeper up-current flanks than down-current flanks (Figure 6). They exhibit an up-current migrating pattern (that is, up-current climb; Figure 3), with more deposition on the up-current flanks whereas less deposition or even erosion on the down-current flanks.

The angle of climb (that is, up-current migration angle) with respect to the bed slope was calculated as a proxy for sediment wave build-up activity, meaning that the higher the angle of climb, the more aggradational a waveform and less active a flow (Howe, 1996). The sediment waves between horizons B and C (Figure 3) migrate upstream with an angle of climb of 3.9°, which is comparable to that of the Orinoco sediment-wave field (2°-3.8°; Ercilla et al., 2002), indicating active deposition by flows. In contrast, the angle of climb is 11.3° above horizon A (Figure 3), indicating dominant hemipelagic/pelagic sedimentation. The up- and down-current flanks are characterized by high and low seismic amplitude, respectively (Figures 3, 5, and 7). The sediment-wave interval above horizon B exhibits well-layered, paralleled and continuous seismic reflectors, in contrast to the underlying relatively discontinuous seismic reflectors associated with truncations of down-current flanks (Figure 3).

4.2. Formative Mechanism of Sediment Waves

Gravity driven soft-sediment deformational origin can be easily ruled out by their up-current migration and differential deposition across each waveform (Wynn et al., 2000). A variety of genetic depositional processes such as turbidity currents, contour currents and hemipelagic/pelagic drappings, together with formative models such as antidune (Normark et al., 1980), lee wave (Flood, 1988), and cyclic step (Cartigny et al., 2011) are
considered to explain the observed depositional architectures and seismic signatures. A number of criteria were used to interpret formative mechanisms, including orientation of wave crests, angle of climb, reflection amplitude contrast, densimetric Froude number, and cross-sectional morphology of the sediment wave.

Figure 5. Reflection amplitude and dip-of-maximum-similarity maps of horizon B using the 3D seismic data. The seismic amplitude map of horizon B (Figure 3) exhibits an alternating high and low amplitude pattern (a). These high and low reflectivities are associated with up- and down-current flanks, respectively. The dip-of-maximum-similarity map of horizon B highlights the geomorphology of the wave field in planview. Wave crests are broadly parallel (b).

Source: Created by the author.
Figure 6. 3D perspective view of horizon B. Wavy geometry of a train of sediment waves is demonstrated in 3D amplitude maps of horizon B (Figure 3), showing an asymmetrical shape with steeper up-current flanks.
Source: Created by the author.

The slope-parallel wave crests (Figure 5) that formed in a deep-marine condition below the shelf edge indicate their downslope-flowing turbidity-current origin. Especially between horizons A and C, the sediment waves exhibit a large reflection-amplitude
contrast across waveforms along with a low angle-of-climb. Hemipelagic/pelagic drapings were dominant in the overlying acoustically-transparent interval.

![Seismic amplitude maps of horizons A and C](image)

**Figure 7. Seismic amplitude maps of horizons A and C.** Horizon C marks the onset of sediment wave deposition (a). Horizon A marks the transition between active sediment build-up dominated by turbidity currents and background sedimentation dominated by hemipelagic/pelagic drapings (b). See Figure 3 for horizon definitions.

Source: Created by the author

We estimated the densimetric Froude number, a dimensionless ratio of inertial to buoyancy forces in a current, of the responsible turbidity currents falling between 1.9 and 2.5. Sequeiros (2012) pointed out that, given the same slope angle, the smoother the bed and heavier the suspended sediments and the higher the densimetric Froude number. Considering the muddy flat-slope environment and the likely hyperconcentrated turbidity currents, the densimetric Froude number in this research is likely underestimated. Cartigny et al. (2011) schematically illustrated the evolution of bedforms with increasing densimetric Froude numbers (Figure 8). The flume experiment performed by Cartigny et al. (2014) measured the peak densimetric Froude numbers (Fr90) of stable antidunes, unstable antidunes, chutes-and-pools, and cyclic steps to be 1.31, 1.34, 1.62, and 2.18,
respectively, indicating an energy-increasing trend. Dorrell et al. (2016) suggested that Froude number >1.5-2 is associated with chutes-and-pools and cyclic steps.

Fildani et al. (2006) and Kostic (2011) suggested that cyclic steps are formed as a coherent and quasi-permanent train of longer-wavelength steps that are stabilized by the presence of hydraulic jumps, whereas antidune processes are ephemeral and not sustainable. Antidunes have a symmetrical geometry (Kostic, 2011) whereas cyclic steps have a broad range of symmetry including symmetrical and upslope- or downslope-asymmetrical geometries (Cartigny et al., 2011). Thus, we interpreted our giant sediment waves as cyclic steps developed under ultra-Froude-supercritical turbidity currents, since they record a higher densimetric Froude number (1.9 to 2.5), and exhibit a longer chain, longer wavelength and highly asymmetrical geometry.

**Figure 8. Charts showing bedforms formed under various Froude numbers.** The chart (a) summarizes lower- and upper-flow regime bedforms including dunes, antidunes, and cyclic steps based on migration direction, geometry, and scale. The chart (b) shows the Froude number of each bedform. Source: Modified from Cartigny et al. (2011).
4.3. Paleohydraulics

Paleohydraulic reconstruction, mainly based on bedform wavelengths, densities of turbidity current and ambient water, and densimetric Froude numbers, suggests that the turbidity currents that deposited these cyclic steps were exceptionally immense and powerful. The depth-averaged flow velocity and flow thickness can reach 16 ms\(^{-1}\) and 32 m, respectively. The depth-averaged flow velocity (9-16 ms\(^{-1}\)) and flow thickness (15-32 m), when integrated with the minimum flow width (~20 km), yield minimum peak discharge and unit flux values of \(3 \times 10^6\) m\(^3\)s\(^{-1}\) (10 km\(^3\)/h) to \(1 \times 10^7\) m\(^3\)s\(^{-1}\) (40 km\(^3\)/h) and 140-510 m\(^2\)s\(^{-1}\), respectively, for a single flow event. Although crude and subject to uncertainties, the paleohydraulic calculations provided here, especially the paleodischarge, are likely correct to an order of magnitude.
Chapter 5. Discussion

The current research considered several scenarios to understand the triggering mechanism of the powerful Froude-supercritical flows responsible for producing the giant sediment waves at the seabed: (1) Confined turbidity currents within submarine channels and associated currents spilled over the levees; (2) Volcanic blasts; (3) Salt-movement-induced slope failures; (4) Debris flows or mass transport processes; and (5) Land-derived sheet flood events. In the upstream area of the sediment waves, no submarine channel, paleo-volcano, salt dome, or debris flow/mass transport complexes were observed (Figure 5). This suggests that the flows that deposited the sediment waves were unlikely to be triggered by scenarios 1-4. Notably, the large lateral extent of such bedforms (Figure 5) points to a linear source of sediment supply, most likely linked to land-derived sheet flood events.

Land-derived sheet flood events generally include seasonal floods (e.g., cyclone-induced floods (Alexander and Fielding, 1997); monsoons (Ventra et al., 2015); and glacial outburst floods (Brown and Kennett, 1998; Shaw and Lesemann, 2003; Montero-Serrano et al., 2009). Several lines of evidence support that the laterally-extensive and giant sediment waves (that is, cyclic steps) analyzed were mostly likely the product of catastrophic glacial outburst megafloods with unparalleled magnitude.

The first evidence is stratigraphic sparsity (that is, one-time-occurrence out of a total of >5-km-thick Eocene-to-recent section) and great thickness (100-200 m) of the sediment-wave interval. Typically, the repetitive and short-lived nature of seasonal floods cannot account for such temporally-limited existence and exceptional thickness, whereas
the low-frequency yet high-magnitude catastrophic meltwater floods are capable of producing stratigraphically sparse megabeds.

The second evidence is paleohydraulics of the responsible flows. Table 1 shows peak discharge magnitudes and flow velocities of catastrophic glacial outburst floods, non-catastrophic meltwater floods, modern glacial-dammed lake floods, and seasonal river floods/hyperpycnal flows, as well as observed velocities of regular turbidity currents from various locations around the world. Notably, the estimated flood peak discharge (3×10⁶ to 1×10⁷ m³s⁻¹) responsible for generating the sediment waves in this research is of the same order of magnitude as catastrophic glacial outburst megafloods, which is two-to-three orders of magnitude greater than that of the other types of events (Table 1). Meinsen et al. (2011) and Shaw and Lesemann (2003) argued that only glacial outburst megafloods are capable of generating such large discharge (that is, >10⁶ to 10⁷ m³s⁻¹). The unit-discharge (140 to 510 m²s⁻¹) estimated in this study is also in good agreement with the estimated unit-discharge of 100 to 600 m²s⁻¹ in the Livingstone Lake flood produced by glacial outburst (Shoemaker, 1995). Likewise, the calculated velocity (9 to 16 ms⁻¹) of the turbidity currents that generated the sediment waves in this study falls within the velocity range of catastrophic glacial outburst floods, which is one-or-two orders of magnitude greater than the real-time observed velocities of normal turbidity currents (Table 1). Although the peak velocity during the Lake Missoula glacial-outburst flood, as estimated in the river, was up to 30 ms⁻¹ (Baker and Costa, 1987), which was double the maximum velocity calculated in the current study, greater resistance by ambient water and weak confinement of sheet flow likely contributed to this deceleration in the present case.
Table 1. Paleo hydraulic estimations of historic and prehistoric flood events and direct velocity observations of turbidity currents.

<table>
<thead>
<tr>
<th>Type</th>
<th>Location/Event</th>
<th>Flow Velocity (ms⁻¹)</th>
<th>Peak Flow Discharge (m³s⁻¹)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turbidity current monitoring</td>
<td>Multiple locations (n=15; e.g., Yellow River, Lake Superior, Santa Clara River)</td>
<td>0.05 to 0.5</td>
<td>-</td>
<td>Sequeiros (2012)</td>
</tr>
<tr>
<td>Seasonal river flood</td>
<td>Amazon River</td>
<td>2</td>
<td>3 × 10⁵</td>
<td>Baker and Costa (1987)</td>
</tr>
<tr>
<td></td>
<td>Yangtze River</td>
<td>11.8</td>
<td>1 × 10⁵</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Katherine River</td>
<td>7.5</td>
<td>6 × 10⁵</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Mississippi River</td>
<td>2</td>
<td>3 × 10⁴</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pecos River</td>
<td>12</td>
<td>2.7 × 10⁴</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Rakaia River</td>
<td>5 to 6</td>
<td>5.6 × 10⁷</td>
<td>Browne (2002)</td>
</tr>
<tr>
<td>Hyperpycnal flow</td>
<td>Multiple locations (n&gt;100; e.g., Yukon River, Apalachicola River, Potomac River)</td>
<td>-</td>
<td>3.6 × 10³ to 5.7 × 10⁵</td>
<td>Mulder and Syvitski (1995)</td>
</tr>
<tr>
<td></td>
<td>Tulesequah, British Columbia</td>
<td>-</td>
<td>1.6 × 10⁴</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Summit, British Columbia</td>
<td>-</td>
<td>3.2 × 10⁵</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Abdukagor, Mountainous Badakhshan</td>
<td>-</td>
<td>1 × 10³</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Lake George, Alaska</td>
<td>-</td>
<td>1 × 10⁴</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Russell Fjord, Alaska</td>
<td>10 to 11</td>
<td>1.1 × 10⁷</td>
<td>Mayo (1989)</td>
</tr>
<tr>
<td></td>
<td>Strandline Lake, Alaska</td>
<td>-</td>
<td>5 to 6 × 10⁵</td>
<td>Sturm et al. (1987)</td>
</tr>
<tr>
<td></td>
<td>Grímsvötn, Iceland</td>
<td>2.2 to 2.8</td>
<td>5.7 × 10⁴</td>
<td>Snorrason et al. (2002)</td>
</tr>
<tr>
<td></td>
<td>Yarkand River, Xinjiang</td>
<td>-</td>
<td>8.5 × 10⁵</td>
<td>Xiangsong (1992)</td>
</tr>
<tr>
<td>Non-catastrophic glacial meltwater flood</td>
<td>Hudson Strait</td>
<td>-</td>
<td>2 × 10⁴</td>
<td>Marshall and Clarke (1999)</td>
</tr>
<tr>
<td></td>
<td>Lake Agassiz flood</td>
<td>-</td>
<td>5 × 10⁴ to 3 × 10⁵</td>
<td>Teller et al. (2002)</td>
</tr>
<tr>
<td>Catastrophic glacial outburst flood</td>
<td>Lake Missoula flood</td>
<td>12</td>
<td>1.9 × 10⁶ to 2.1 × 10⁷</td>
<td>Baker and Bunker (1985); Baker and Costa (1987); O’Connor and Baker (1992)</td>
</tr>
<tr>
<td></td>
<td>Livingstone Lake flood</td>
<td>2 to 10</td>
<td>6 × 10⁹ to 6 × 10⁹</td>
<td>Shaw et al. (1989)</td>
</tr>
<tr>
<td></td>
<td>Labrador Sea flood</td>
<td>-</td>
<td>1.5 × 10⁶</td>
<td>Shaw and Lesemann (2003)</td>
</tr>
<tr>
<td></td>
<td>Labyrinth, western Dry Valleys</td>
<td>11 to 15</td>
<td>1.6 to 2.2 × 10⁶</td>
<td>Lewis et al. (2006)</td>
</tr>
<tr>
<td></td>
<td>Siberian Altai Mountains flood</td>
<td>-</td>
<td>1 × 10⁷</td>
<td>Herget (2005)</td>
</tr>
<tr>
<td></td>
<td>Chuya-Kuray Lakes, Altai</td>
<td>20 to 45</td>
<td>1.6 to 1.8 × 10⁷</td>
<td>Baker et al. (1993); Rudoy (2002)</td>
</tr>
<tr>
<td></td>
<td>Lake Agassiz-Ojibway flood</td>
<td>-</td>
<td>5.2 × 10⁶</td>
<td>Teller et al. (2002)</td>
</tr>
<tr>
<td></td>
<td>Lake Weser flood</td>
<td>10 to 12</td>
<td>1.3 × 10⁶</td>
<td>Meinsen et al. (2011); Winsemann et al. (2011)</td>
</tr>
<tr>
<td>This study</td>
<td>-</td>
<td>9 to 16</td>
<td>3 × 10⁶ to 1 × 10⁷</td>
<td>-</td>
</tr>
</tbody>
</table>

Source: Compiled by the author.
The third evidence is geologic age and isotope records. The inception age of the early Northern Hemisphere glaciation agrees well with the depositional age of the sediment waves. Based on the LR04 stack of benthic $\delta^{18}O$ records (Figure 9) of Lisiecki and Raymo (2005) that were collected from globally distributed deep-sea cores, the time span of $\sim$2.9 to $\sim$1.8 Ma brackets multiple glacial cycles ranging from marine isotope stage 65 to Gauss 11. They are characterized by high-amplitude interglacial-glacial $\delta^{18}O$ variations, indicating that deglacial megafloods were likely triggered by severe temperature changes. Similarly, the planktonic $\delta^{18}O$ records of Joyce et al. (1990, 1993) derived from the Ocean Drilling Program (ODP) hole 625B in the Gulf of Mexico (Figure 10), which is just $\sim$100 km away from the current study area, exhibit several large $\delta^{18}O$ negative anomalies bounded by Discoaster tamalis (2.8 Myr) and Discoaster brouweri (1.93 Myr), evidencing isotopically-light glacial meltwater influx to the Gulf of Mexico passing our study area. Based on stable isotope analysis, Keigwin (1987) suggested that the prominent $\delta^{18}O$ maxima in the Mammoth Paleomagnetic Event (M2) marks a minor glacial advance prior to the onset of ice-rafting in the North Atlantic at $\sim$2.4/2.5 Ma (Shackleton et al., 1984). These deglacial megafloods were likely following the initiation of continental ice accumulation during the early ice age associated with this M2 glaciation. Evidence of glacier expansion as early as 3.6 to 3.4 Ma to the mid-latitude zone has been presented by Gao et al. (2012) from James Bay Lowland in Canada. Thus, the current research ascribes the unconfined Froude-supercritical turbidity currents depositing the large-scale sediment waves (that is, wavelength >300 to 600 m and wave-height >5 to 10 m, according to the statistical analysis of Symons et al., 2016) discussed here to catastrophic glacial outburst floods. A number of outburst floods have to be
invoked to account for such a thick (200 m) interval of sediment waves. Pulses of deglacial megafloods, resulting from ice dam collapsing (O’Connor and Baker, 1992) or ice lift-off (Shoemaker, 1992), yielded a great amount of sandy sediments in the northern Gulf of Mexico (Galloway et al., 2000), through hyperpycnally-generated, hyper-concentrated turbidity currents. A relatively narrow shelf allowed the turbidity currents to reach the shelf-slope break and re-accelerate along the steep slope. Once generated, this research speculates that these floods likely followed the Mississippi and Tennessee river drainage system, based on three arguments: (1) ~90% of the North American meltwater discharged into the Gulf of Mexico via the Mississippi River during the last deglaciation (Licciardi et al., 1999); (2) The current study area is located close to the Mississippi and Tennessee river mouths; and (3) the Mississippi River dominated the sediment input from the mid-continent to the northern Gulf during the early Pliocene to the Holocene (Galloway et al., 2000).

This is the first study to recognize extensive, large-scale sediment waves (that is, cyclic steps) in the Gulf of Mexico deep-marine records, and reveal their paleoclimatic implications linked to the catastrophic glacial outburst megafloods. Unlike land-based evidence (e.g., erosional drumlins, rhythmites, “giant current ripples”, giant bars) for glacial outburst megafloods, which are subject to subsequent erosions, marine-based evidence has a higher preservation potential due to pelagic/hemipelagic dr apings and higher depositional rates.
Figure 9. The LR04 benthic δ\textsuperscript{18}O stack based on 57 globally-distributed δ\textsuperscript{18}O records. Large peaks, marking increased abundance of \textsuperscript{18}O, denote glacial maxima, whereas large troughs denote glacial minima. The timing of the sediment-wave deposition suggests that multiple glacial cycles from marine isotope stage 65 to Gauss 11 (marked by dashed rectangular) likely triggered the deglacial megafloods that produced the sediment waves. Note that labelled numerical numbers and letters denote marine isotope stages. Paleomagnetic time-scale is provided for age reference.
Source: Modified from Lisiecki and Raymo (2005).
The planktic δ\(^{18}\)O records from the northeastern Gulf of Mexico, and associated biostratigraphic markers from the Ocean Drilling Program hole 625B. For the Pliocene and early Pleistocene, negative δ\(^{18}\)O anomalies greater than 1.3‰, as interpreted by Joyce et al. (1990, 1993), was resulted from the discharge of isotopically-light glacial meltwater from the Mississippi River to the Gulf of Mexico. Using the same biomarkers (that is, Discoaster tamalis and Discoaster brouweri) as time constraints, a series of large negative δ\(^{18}\)O excursions exist during the time of deposition of our sediment waves. This suggests that influx of \(^{18}\)O-depleted meltwater passed through our study area (~90 km away from hole 625B) from the Mississippi River. FAD and LAD denote first appearance datum and last appearance datum, respectively.

Source: Modified from Joyce et al. (1990, 1993).
Although glacial deposits as old as 3.5 Ma have been identified as part of the Northern Hemisphere Ice Age (e.g., Gao et al., 2012), all the documented glacial outburst floods are younger than middle-to-early Pleistocene (Baker and Bunker, 1985; Shaw et al., 1989; Bjornstad et al., 2001; Froese et al., 2003; Meinsen et al., 2011). Therefore, the megaflood events presented here constitute, by far, the oldest record of glacial outburst floods during the Quaternary ice age.

Notably, some large-scale sediment waves formed by unconfined turbidity currents (excluding volcanic-induced and slope-failure-induced flows, and channel-levee spillovers) reported previously also show good temporal correlations with the Quaternary ice age, such as the ones from the Barra fan at Rockall Trough corresponding to the Late Glacial-Bølling/Allerød interstadial (Howe, 1996), upper-Pleistocene-to-lower-Holocene bedforms from the “Humboldt Slide” at the northern California continental slope (Lee et al., 2002), Holocene bedforms from the continental shelf off the Icy Bay and Malaspina Glacier (Lee et al., 2002), and the upper-Pliocene-to-upper-Pleistocene sediment waves on the Landes Plateau in the Aquitaine continental slope off the Bay of Biscay (Faugères et al., 2002). This current research proposes the pervasive deposition of large-scale sediment waves as a proxy for glacial outburst floods. Future studies should investigate this proxy further.
Chapter 6. Conclusions

This is the first detailed study of large-scale Plio-Pleistocene sediment waves on the continental slope, northern Gulf of Mexico. The study interpreted such bedforms formed under unconfined Froude-supercritical turbidity currents as cyclic steps. Paleohydraulic reconstruction, in association with other evidence such as geologic age, stable isotope records, thickness and temporal rarity, suggests that the Froude-supercritical turbidity currents were triggered by glacial outburst megafloods. Whereas previous studies of the Laurentide Ice Sheet deglacial megafloods to the Gulf of Mexico have focused on recent interglacial episodes relying on deep-sea cores, this study provides new insights on the paleoclimatic implications of the large-scale sediment waves formed under unconfined turbidity currents linked to older Laurentide Ice Sheet megafloods.

Although it is widely accepted that the Northern Hemisphere glaciation started around ~2.5 Ma (Prell, 1984), the giant sediment waves in this study lend credibility to the hypothesis that the Northern Hemisphere glaciation likely started earlier, triggering megafloods to the northern Gulf of Mexico. These megaflood events represent, by far, the oldest record of glacial outburst floods during the Quaternary ice age.
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Appendix A-1. Seismic frequency spectrum of the sediment-wave interval showing that the dominant frequency is ~13.5 Hz and the bandwidth ranges from 8 to 78 Hz. Source: Created by the author.
Appendix A-2. Chart showing interval velocity (one-way) versus two-way travel time below sea floor, using time-depth charts from several wells within our seismic survey. Source: Created by the author.
Appendix A-3. 3D perspective view of the 3D seismic survey used in this study.
Source: Created by the author.