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Invited review article

Mississippi River subaqueous delta is entering a stage of retrogradation

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ABSTRACT

The subaqueous delta of the Mississippi River, the largest river system in the conterminous U.S., has entered a stage of retrogradation caused by multiple natural and anthropogenic activities. Since the 1950s, the suspended sediment load of the Mississippi River has decreased by ~50% due primarily to the construction of > 50,000 dams in the Mississippi basin. The impact of this decreased sediment load has been observed in subaerial environments, but the impact on sedimentation and geomorphology of the subaqueous delta front has yet to be examined. To identify historic trends in sedimentation patterns, we compiled bathymetric datasets, including historical charts, industry and academic surveys, and National Oceanic and Atmospheric Administration hydrographic data, collected between 1764 and 2009. The progradation rate (measured at the 10 m depth contour) of Southwest Pass, which receives 69% of the suspended sediment load reaching Head of Passes, has decreased from ~67 m/yr between 1874 and 1940 to ~26 m/yr between 1940 and 1979, with evidence of further deceleration from 1979 to 2009. At South Pass and Pass a Loutre, the delta front has entered the destructive phase, with the 10 m contour retreating at rates > 20 m/yr at both passes since 1979. Advancement of the delta front also decelerated in deeper water (in some areas out to ~180 m depth). Except locally, where mudflow lobes are advancing, deeper contours show a pattern of decreasing progradation rate between 1874–1940 and 1979–2005 time periods. Furthermore, based on differences measured between available bathymetric datasets, the sediment accumulation rate across the delta front decreased by ~73% for the same period. The retention rate of Mississippi River sediment on the delta front ranged from 67 to 81% for the time periods assessed, with total sediment load stored on the delta front equal to 317 ± 54 Mt/yr from 1874 to 1940, 145 ± 25 Mt/yr from 1940 to 1979, and 87 ± 15 Mt/yr from 1979 to 2005. We document for the first time that the Mississippi River delta front has entered a phase of retrogradation, which will likely be accelerated by future upstream activities that divert a portion of the sediment load to the upper delta for coastal protection and restoration projects. The decline of the subaqueous Mississippi River Delta has critical implications for biogeochemical cycling, subaqueous mass wasting, and sediment dispersal to the coastal ocean.

1. Introduction

Deltas are an important part of the source-to-sink pathway where terrestrial sediments are dispersed into the marine environment. Transport and deposition of sediment within and away from the delta are important for global carbon cycling, marine ecosystems, pollutant dispersal, and natural resources. Recent research on global deltas has shown that anthropogenic impacts to river systems are influencing patterns of sediment distribution at the river mouth (e.g., Bergillos et al., 2016; Blum and Roberts, 2009; Couvillion et al., 2011; Fan et al., 2006; Yang et al., 2017). Here, we examine changes in sedimentation patterns on the subaqueous Mississippi River delta, which is formed where the Mississippi River empties into the northern Gulf of Mexico (Fig. 1). The Mississippi River is ranked seventh in the world in both water discharge and suspended sediment load (Milliman and Meade, 1983; Meade, 1996) and the Mississippi River delta is one of the most

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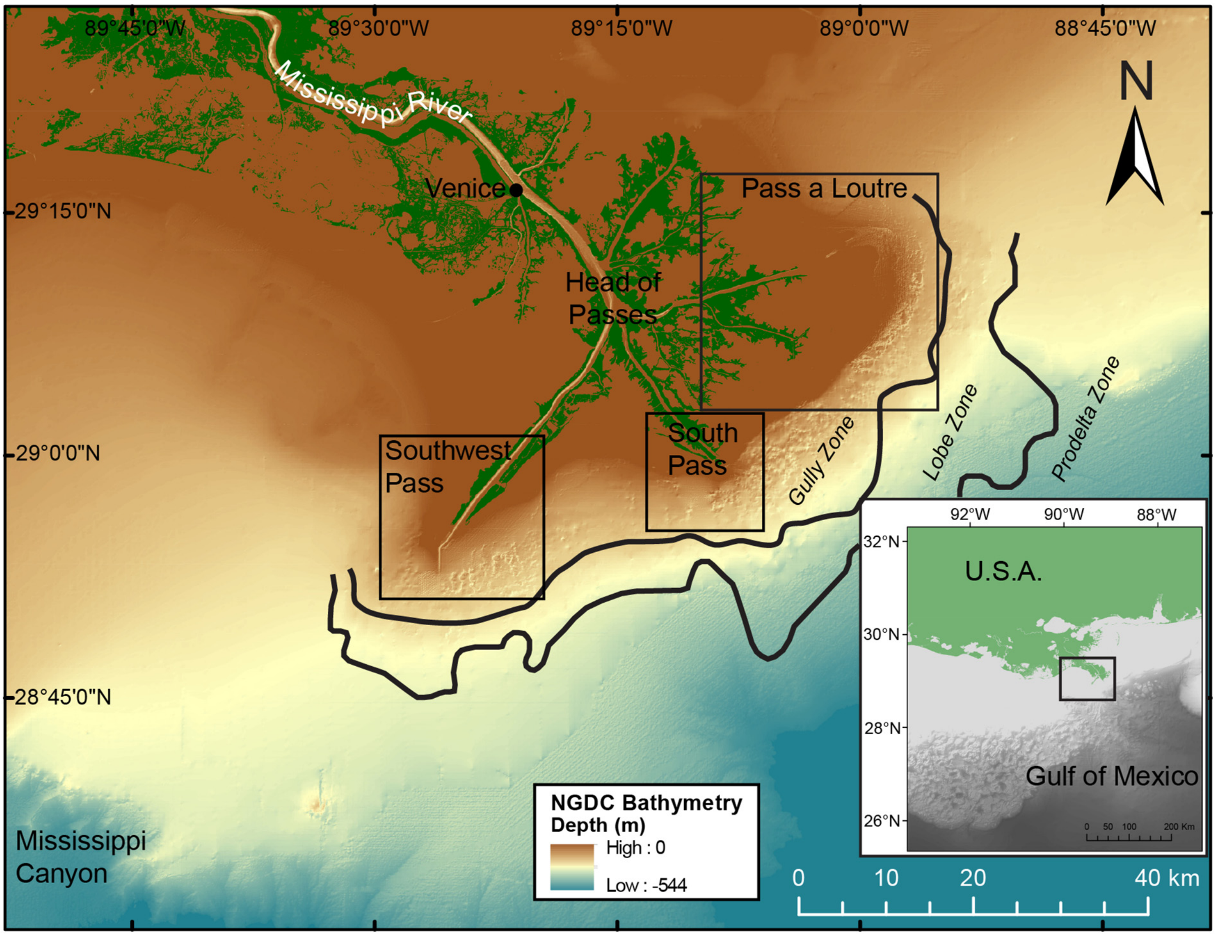

Fig. 1. Overview map of the Mississippi River delta showing major passes and offshore bathymetry (Love et al., 2012). Black lines represent the boundaries between the mudflow gully, mudflow lobe, and prodelta zones, which are labeled Gully Zone, Lobe Zone, and Prodelta Zone and italicized. Three small black boxes highlight the three major passes, which are the study areas in Fig. 4. Inset shows regional map with black box over delta location.

well studied and recognizable deltas in the world (Bentley et al., 2016).

Recent studies have shown extensive land loss (4877 km^2 between 1932 and 2010) in the subaerial deltaic plain of southern Louisiana (Couvillion et al., 2011), which has been mainly attributed to construction of flood-protection levees disconnecting the river from the deltaic plain and a decline in Mississippi River sediment load (Kesel, 1988; Keown et al., 1986). Wetland-loss rates are estimated at 50–100 km^2/yr (Gagliano et al., 1981), with 25% of the 1932 deltaic land area lost through 2010 (Couvillion et al., 2011). This poses a threat to communities along the north-central Gulf of Mexico coast, energy and navigation infrastructure, fisheries, commerce, and the extensive wetland ecosystem of the delta region (Twilley et al., 2016). Clearly, anthropogenic modifications to the Mississippi River are impacting the delta, but little is known about the extent of these impacts on the subaqueous portion of the delta. Furthermore, the subaqueous delta front is an area of extensive sediment instability (e.g. Coleman et al., 1980) and upstream modifications may affect submarine landslide activities due to changes in sedimentation rates and patterns of sediment consolidation.

In order to assess trends in sedimentation rates and patterns on the subaqueous delta front, we examined historic datasets and show that the delta is entering a stage of decelerated and negative growth. Sediment transport pathways transition from land to sea across deltas and understanding both the marine and terrestrial delta environments will provide insight into the processes that control delta sedimentation and morphology.

2. Background

Since post-Last Glacial Maximum sea-level rise decelerated ~7 ka (thousands of years before present, where present is 1950 CE), the Mississippi River has been building land off the southern Louisiana coast in a series of delta complexes, switching depo-center location due to upstream avulsions every ~1–1.5 k.y. (Frazier, 1967; Tornqvist et al., 1996; Blum and Roberts, 2012). Deposition on the currently active Plaquemine-Balize complex began ~1.2 ka (Tornqvist et al., 1996) and has deposited sediment > 100 m thick on the shelf (Coleman and Roberts, 1988; Kulp et al., 2002), building out almost to the shelf edge. The distinctive "birdfoot" shape of the modern active subaerial delta has been used as an end-member for fluvially dominated deltas, where the supply of sediment is high and there is relatively small influence of waves and tides (Galloway, 1975; Wright, 1985).

Sediment from the Mississippi River enters the Gulf of Mexico through multiple distributaries that comprise the "birdfoot" including, from west to east, Southwest Pass, South Pass, and Pass a Loutre (Fig. 1). The estimated annual sediment load from the Mississippi River is ~210 Million tons per year (Mt/yr) with ~80% of the total load represented by fine silt and clay in suspension (Milliman and Meade, 1983), but much of this sediment load is sequestered in the lower reaches of the river before entering the Gulf of Mexico. For example, during water years 2008–2010, only 19% of the total suspended sediment load of the river measured at Tarbert Landing reached the major passes entering the Gulf of Mexico (Allison et al., 2012). Sediment load is lost from the main Mississippi River channel through outlets and diversions between Baton Rouge and Head of Passes (e.g., Bonnet Carre

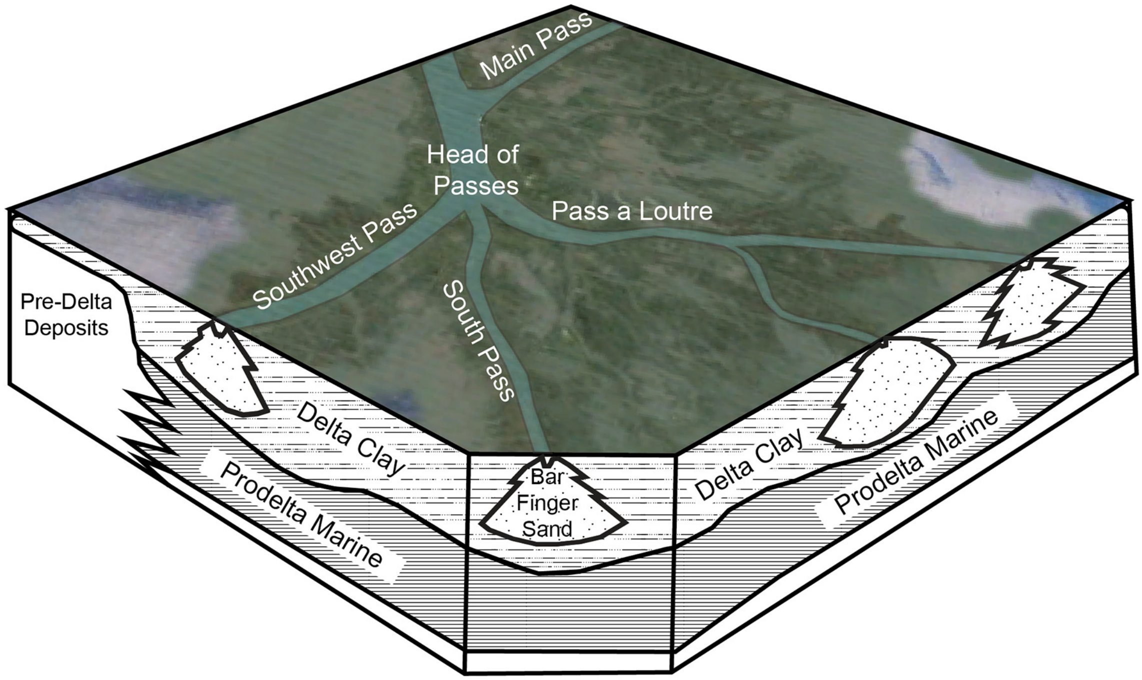

Fig. 2. Diagram depicting sub-seafloor geology of the MRDF, modified from Fisk (1961). Bar finger sands are deposited along the distributary mouths and clays are deposited away from the mouth bars. The delta sediments are built out over prodelta marine clays.

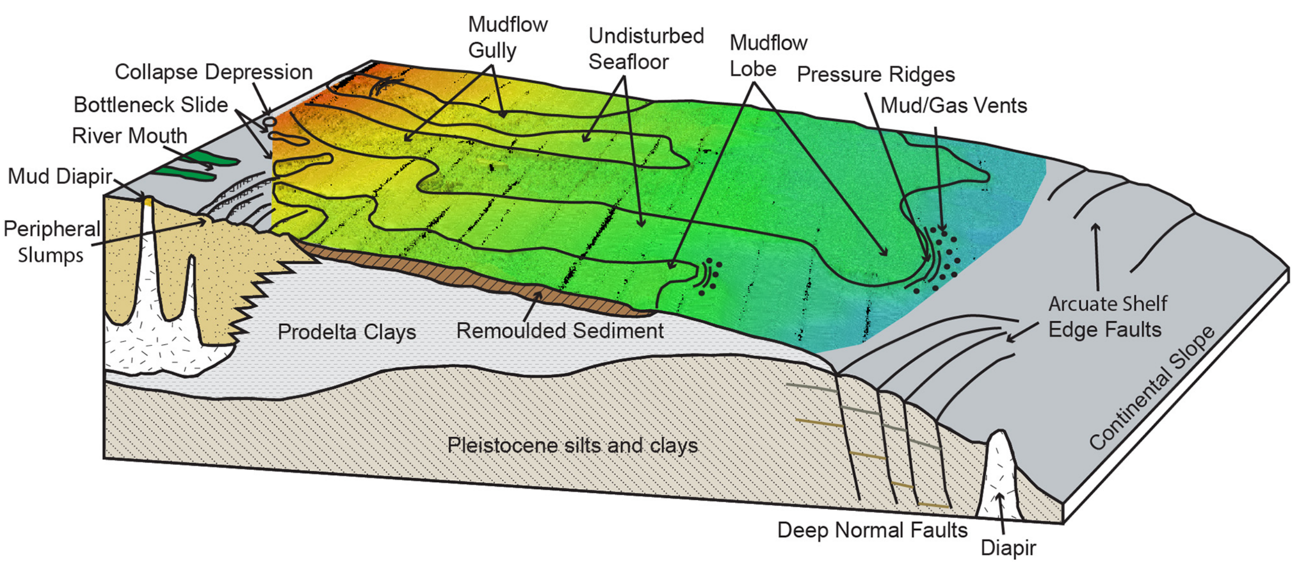

Fig. 3. Block diagram showing major instability features as defined by Coleman et al. (1980) with rainbow shaded bathymetry from Walsh et al. (2006), varying from ~15 m in red to about 60 m in blue. Cross section and deeper features not drawn to scale. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Spillway, West Bay, Baptiste Collette) and further sediment is sequestered through channel aggradation in the river's lower reaches (Allison et al., 2012; Bentley et al., 2016). For water years 2008–2010, of the sediment load reaching Head of Passes, the distribution of suspended sediment load transported through each distributary is approximately 69% Southwest Pass (20.8 Mt/yr), 15% South Pass (4.7 Mt/yr), and 16% Pass a Loutre (4.8 Mt/yr) (Allison et al., 2012).

On the birdfoot delta, distributary channels are lined by natural levees and distributary mouth bars form at the termination of each pass in the Gulf of Mexico (Fig. 2, Fisk, 1961). Due to rapid sedimentation, the distributary mouth bars, along with the channel and natural levees, have prograded into the Gulf of Mexico at variable rates that have exceeded 100 m/year at Southwest Pass (Fisk, 1961; Gould, 1970; Prior and Coleman, 1982). Beyond the subaerial delta, the subaqueous delta front (also known as the clinothem foreset, [sensu Slingerland et al., 2008]) extends to the outermost shelf to water depths of up to ~200 m. Measurements of sedimentation rates on the delta front range from less than a centimeter per year at distances beyond 17 km from Southwest Pass in > 100 m water depth (Ruttenberg and Goni, 1997) to > 1 m/yr immediately adjacent to distributary mouths (Coleman et al., 1991). As a fine-grained dispersal system, the Mississippi River delta has previously been defined by rapid rates of sediment accumulation proximal to the river mouth (Walsh and Nittrouer, 2009).

Seafloor mapping of the delta front has identified a complex morphology attributed to subaqueous mass movements. Prominent features were mapped and described by Coleman et al. (1980) and include collapse depressions, bottleneck slides, mudflow gullies, and mudflow lobes (Fig. 3). Overall, the slope of the delta front ranges from 0.1° to

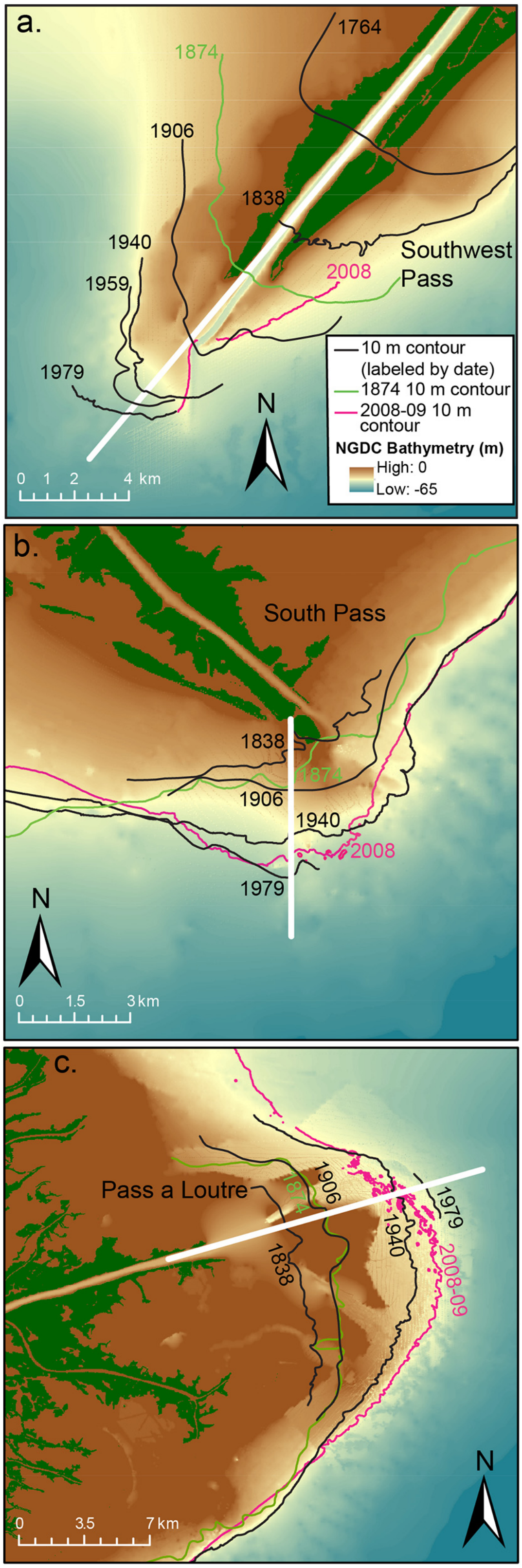

Fig. 4. Map of the passes of the Mississippi River delta showing historical progradation of the 10 m depth contours through time. See Fig. 1 for locations. Green line represents 1874 data, pink line represents 2008–2009 data, and black lines represent all other years (see labels). Progradation rates are calculated along the white lines. a. Southwest Pass. 2008–2009 data are not available across the white line in NOAA DEMs. The most recent nautical chart (NOAA, 2011) was used to measure progradation during the most recent time interval. The chart indicates that the area is a dredged material dump site, and therefore contours may not reflect natural progradation. b. South Pass, c. Pass a Loutre. Data sources: 1838 and 1906 from NOAA nautical charts (NOAA, 1838, 1906); 1764 and 1959 from Gould (1970). 1874, 1940, and 1979 from Coleman et al. (1980); 2009 data from NOAA Hydrographic survey DEMs (NOAA, 2009). The NOAA northern gulf coast 1 arc-second DEM is colored and shaded as background (Love et al., 2012). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

2.2°, but is mostly < 1.5° (Coleman et al., 1980). Seafloor morphology indicates that mass wasting is pervasive across the delta front and that several mechanisms of instability are operating to create a wide array of complex morphologic features. Hurricane waves have been identified as a triggering mechanism for failures on the delta front that result in damage to offshore infrastructure (Bea, 1971; Henkel, 1970). However, recent work has demonstrated that smaller waves from events of ~annual return period may also be important triggers of failures (Obelcz et al., 2017). Rapid sediment accumulation and under-consolidation are important factors in seafloor instability (Coleman and Garrison, 1977; Lee et al., 2007) and changes to rates and patterns of sediment accumulation could impact stability and failure susceptibility.

Measurements of suspended sediment load in the lower Mississippi River show a decline of over 70% since 1850, with the largest decrease (~50%) occurring since ~1950, which is mostly attributed to the building of dams on major Mississippi River tributaries, particularly on the Missouri River (Keown et al., 1986; Kesel, 1988; Meade and Moody, 2010; Blum and Roberts, 2012). The pre-dam total suspended load of the Mississippi River at Tarbert Landing, MS was ~400–500 Mt/yr (Kesel, 1988; Blum and Roberts, 2009; Bentley et al., 2016), which was reduced to ~130 Mt/yr from 1970 to 2013 (Bentley et al., 2016). In addition to upstream dams, the Atchafalaya River is also capturing water and suspended sediment from the Mississippi River. The Mississippi River intercepted the Red River in the 15th century, creating the Mississippi River distributary, the Atchafalaya River (Fisk, 1952; Aslan et al., 2005). From 1900 to 1950, the percent discharge of the Mississippi River flowing into the Atchafalaya distributary increased from ~6% to ~25% (Fisk, 1952). Since the 1960s, the Old River Control Structure has maintained the flow to the Atchafalaya, including the Red River contribution, at 30% of the Mississippi-Red Rivers combined flow, although actual amounts vary annually between 15 and 29% (Mossa, 1996). The decline in sediment load in the lower Mississippi River since the 1950s, along with reduction in overbank flows due to levee construction, has contributed to loss of wetlands in southern Louisiana (Kesel, 1988), and may also influence trends in sediment distribution in the subaqueous delta.

Some evidence for a decline in subaqueous delta accumulation associated with the drop in Mississippi sediment load has been observed previously, but only in a limited number of sediment cores taken from offshore Southwest Pass. In this area, Allison et al. (2007) documented a decline in mass accumulation rate (MAR) from two sediment cores of 235% and 273% that occurred around 1946 based on ^{210}Pb analysis. The MAR decline was also associated with a decrease in the burial rate of particulate organic carbon (POC). Although other cores across the subaqueous front were analyzed, the pattern of MAR decline was not observed due to bioturbation and sediment focusing, and earlier work also did not identify the MAR decline at ~1950 (Eadie et al., 1994; Corbett et al., 2006; Allison et al., 2007). The primary objective of this study is to assess trends in sedimentation patterns of the delta front over a larger spatial scale during a time period (1764–2009) where the Mississippi River system has undergone major anthropogenic modifications.

3. Methods

An overview of our methods and estimates of uncertainty is provided here, with more detailed analytical methods outlined in the

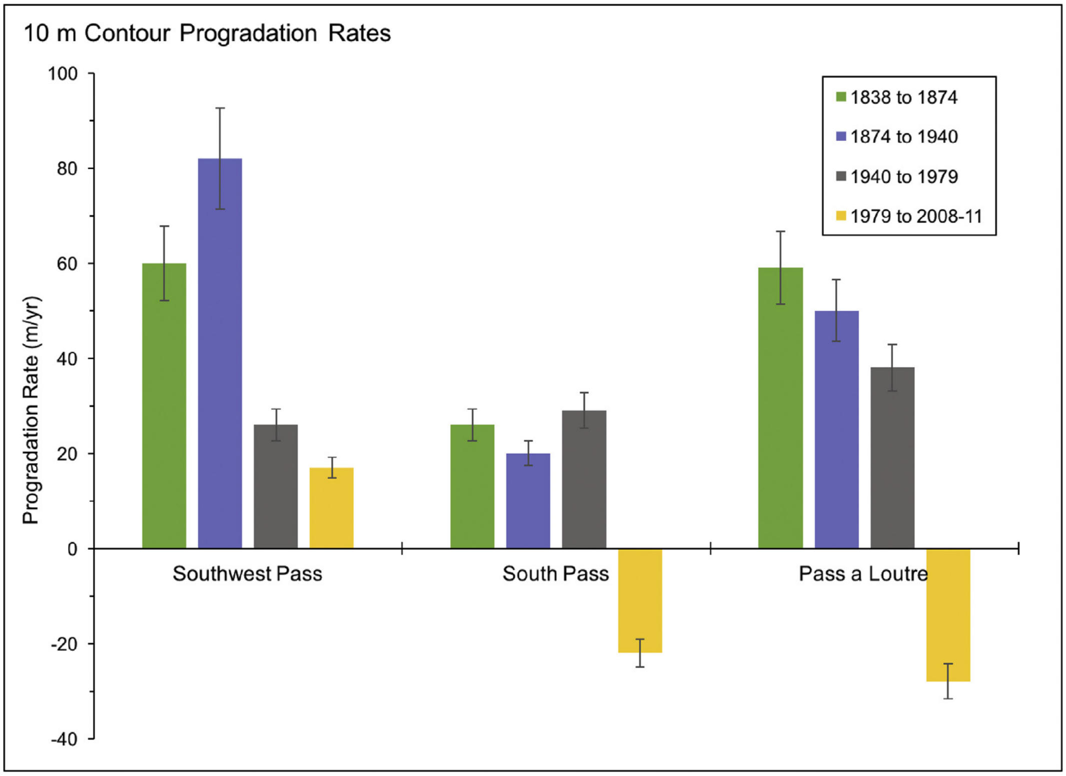

Fig. 5. Progradation rate of the 10 m contour measured at Southwest Pass, South Pass, and Pass a Loutre during four different time intervals (shown in the legend). Negative progradation rates indicate retrogradation of contour lines. Error bars reflect 13% uncertainty. Datasets of various ages between 2008 and 2011 were used to calculate progradation rate for the most recent time interval due to lack of a recent regional dataset. For Southwest Pass the interval is 1979–2011, for South Pass it is 1979–2008, and for Pass a Loutre it is 1979–2008–09, as the most recent dataset was collected over the course of two years.

Supplementary materials.

We compiled bathymetric datasets from the Mississippi River delta front into an Environmental Systems Research Institute (ESRI) Geographic Information System (GIS) ArcMap project. These datasets include historic nautical charts, National Oceanic and Atmospheric Administration (NOAA) hydrographic surveys, and academic and industry surveys that range in age from 1764 to 2009. A list of datasets and sources is provided in Table S1. The oldest nautical charts were georeferenced in ArcMap using geographic landmarks and latitude and longitude readings where available. Due to differences in horizontal datums and projection methods, there is some uncertainty in this process, but a best fit was achieved by using multiple control points. Condrey et al. (2014) evaluated the accuracy of professional coastal latitude and longitude estimates (by government navigators and pilots) for the 18th and 19th centuries in this region, and found the error in this period to be generally < 2%, compared to modern known positions.

Bathymetric data used herein were collected using a wide range of methods (lead line to multibeam sonar) and different vertical datums, with varying degrees of completeness in metadata describing conditions. As such, there are uncertainties in the data that must be considered when making comparisons between datasets. Overall, we identify the major sources of bathymetric depth uncertainty as follows (Fig. S1). (1) Tidal range is < 1 m (t_u), and comparable to the degree of coastal setup/setdown under strong winds (NOAA station no. 8760922, Pilot Station East on Southwest Pass). (2) Uncertainty in the vertical datum (v_u) used for reference is estimated at ~2 m (as per NOAA, 2016). (3) Uncertainty from sound speed variations in water are greater, and vary with depth, temperature, and salinity. To establish a likely range of uncertainty from sound speed, average sound speeds were determined for water at temperatures of 10° and 25 °C and salinity at 17.5 and 35 psu, assuming 50% to 0% freshwater (0 psu) vs. seawater (35 psu). This yielded a sound speed (SS) range of 1468–1534 m/s (Medwin, 1975). Two-way travel times (TWT) were calculated for maximum and minimum values, which were then differenced. Depth uncertainty (U) was calculated as: $U = (TWT_{max} - TWT_{min})\ SS_{max}$, yielding depth uncertainties from sound speed of 2.3 m at 25 m depth, 6.7 m at 75 m depth, and 11.2 m at 125 m depth. Total error was estimated to be the square root of the sum of squares for all sources of error, yielding total uncertainty of 3.2, 7.1, and 11.4 m for 25 m (12.8%), 75 m (9.4%), and 125 m (9.1%). We assume that this depth-dependent uncertainty is of the same order as uncertainties from manual soundings, but that is difficult to assess. All uncertainty estimates for calculated seafloor change are reported at the maximum value of 13%.

Progradation rates were determined by measuring the distance between a chosen depth contour for datasets of different ages. The measured distances were divided by the age range between the two datasets, giving an average progradation rate across that time interval (Fig. S2 and Table S2). A straight and continuous line was drawn approximately perpendicular to contour lines extending across each of the datasets and all measurements were taken along this line (white line in Fig. 4). Vertical profiles were also compared between different datasets using the ArcGIS profiling tool. Because contours were derived from bathymetric soundings, we apply the maximum total bathymetric uncertainty estimate (13%) to these rates as well.

Maps of seafloor change were generated by differencing datasets, clipped to the area where they overlap, and volume changes were calculated using ArcMap's cut-fill tool. Seafloor change rates were determined by dividing the change in sediment volume by the area of and time span between the two datasets (Table S3). Sediment volume was converted to sediment mass using a bulk density of 1.51 ± 0.17 g/cm^3, based on a sediment density of 2.7 g/cm^3 and a range in sediment porosity of 0.6–0.8 (Johns et al., 1985; Keller et al., 2016) (Table S3). Additional uncertainty from bathymetric data of ~13% yields a total uncertainty of ~17%, based on the square root of the sum of squares for

Table 1
Progradation rates of the Mississippi River Delta Front

Southwest Pass

Contour (m)	Progradation Rate (m/yr) 1874-1940	1940-1979	1979-2005/09/11*	Facies
10	82 ± 11	26 ± 3	17 ± 2	Collapse Depression Zone
20	68 ± 9	40 ± 5	9 ± 1	Collapse Depression/ Bottleneck Slide Zone
40	90 ± 12	29 ± 4	-2 ± 0.3	Gully Zone
60	NA	35 ± 5	-3 ± 0.4	Undisturbed/ Interlobe, near gully-lobe transition
80	NA	16 ± 2	28 ± 4	Lobe/Pro-Delta Zone

South Pass

Contour (m)	Progradation Rate (m/yr) 1874-1940	1940-1979	1979-2008-09*	Facies
10	20 ± 3	29 ± 4	-22 ± 3	Collapse Depression Zone
20	29 ± 4	13 ± 2	-10 ± 1	Gully Zone
40	34 ± 4	26 ± 3	NA	Gully Zone
140	15 ± 2	10 ± 1	8 ± 1	Lobe Zone
180	3 ± 0.4	14 ± 2	12 ± 2	Lobe Zone

Pass a Loutre

Contour (m)	Progradation Rate (m/yr) 1874-1940	1940-1979	1979-1997/ 2008-09*	Facies
10	50 ± 7	38 ± 5	-28 ± 4	Collapse Depression Zone
20	60 ± 8	24 ± 3	-10 ± 1	Gully Zone
40	67 ± 9	9 ± 1	-11 ± 1	Lobe Zone
60	44 ± 6	8 ± 1	-9 ± 1	Lobe Zone
80	42 ± 5	13 ± 2	-24 ± 3	Lobe Zone
100	59 ± 8	29 ± 4	-54 ± 7	Lobe Zone

All values display 13% bathymetric uncertainty
*Due to the lack of a recent regional bathymetric dataset, multiple datasets were used to determine progradation during the most recent time period. For Southwest Pass: 10 m = 2011; 20 and 40 m = 2009; 60 and 80 m = 2005. For South Pass: 10 and 20 m = 2008; 140 and 180 m = 2009. For Pass a Loutre: 10 m = 2008-09 (data collection spanned both years); 20100 m = 1997.

both uncertainty terms.

Relative sea level rise through time is also a factor in the uncertainty of observed seafloor change. If we assume a current rate of 13 mm/yr relative sea level rise at the Mississippi River delta front (including 3 mm/yr eustatic sea level rise (IPCC, 2014) and 10 mm/yr subsidence (Jankowski et al., 2017; Tornqvist et al., 2008)), seafloor change maps would reflect an underestimate of seafloor accretion of 13 mm/yr. The 10 mm/yr subsidence rate of Jankowski et al. (2017) and Tornqvist et al. (2008) includes shallow subsidence occurring in the upper 5–10 m of Holocene sediment. Additionally, the shallow subsidence rates were calculated from coastal wetlands containing peat deposits, but modeling results show that prodelta mud is characterized by slower compaction than peat (Meckel, et al., 2007). Therefore, we assume that the 10 mm/yr subsidence rate is appropriate to account for seafloor elevation change due to compaction. The influence of relative sea level rise could also impact calculations of progradation rate. If we assume a 0.5° slope (based on 1979 bathymetric dataset from Coleman et al., 1980), horizontal rates of contour retreat would be ~1.49 m/yr. Rates of seafloor change and progradation observed in these datasets are in the tens of centimeters and tens of meters range, respectively, suggesting

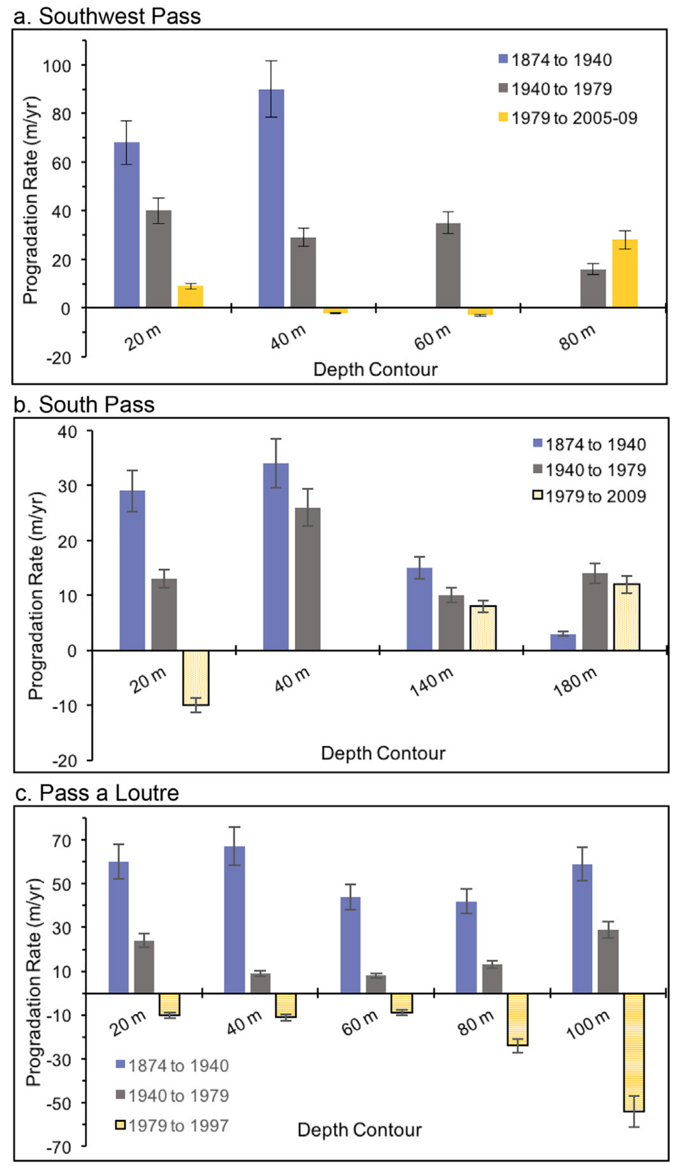

Fig. 6. Rates of offshore delta progradation measured at various depth contours (labeled) at a. Southwest Pass, b. South Pass, and c. Pass a Loutre. Negative progradation rates indicate retrogradation of contour lines. Error bars reflect 13% uncertainty. In A. datasets of various ages between 2005 and 2009 were used to calculate progradation rate for the most recent time interval due to lack of a recent regional dataset.

that the influence of relative sea level rise on seafloor change is minor. Furthermore, measured changes in progradation exceed the ~13% uncertainty that we attribute to our methods (Figs. 5 and 7).

4. Results

4.1. Distributary mouth bar progradation (10 m contour)

Distributary mouth bar progradation rates have declined at Southwest Pass, South Pass, and Pass a Loutre from the time period 1838–1874 to the period 1979–2008/09 (Figs. 4 and 5). Measured at the 10 m contour interval, these rates have changed from 60 to 9 m/yr, 26 to −22 m/yr, and 59 to −28 m/yr, respectively (Table 1 and Fig. 5; negative values reflect retrogradation). Between these time intervals, progradation rates have varied, but the most recent time interval shows a pronounced decrease in rate, with transgression of South Pass and Pass a Loutre from 1979 to 2009 (Figs. 4b, c, and 5). Progradation rates during pre- and post-1940 periods for Southwest Pass are 67 and 23 m/

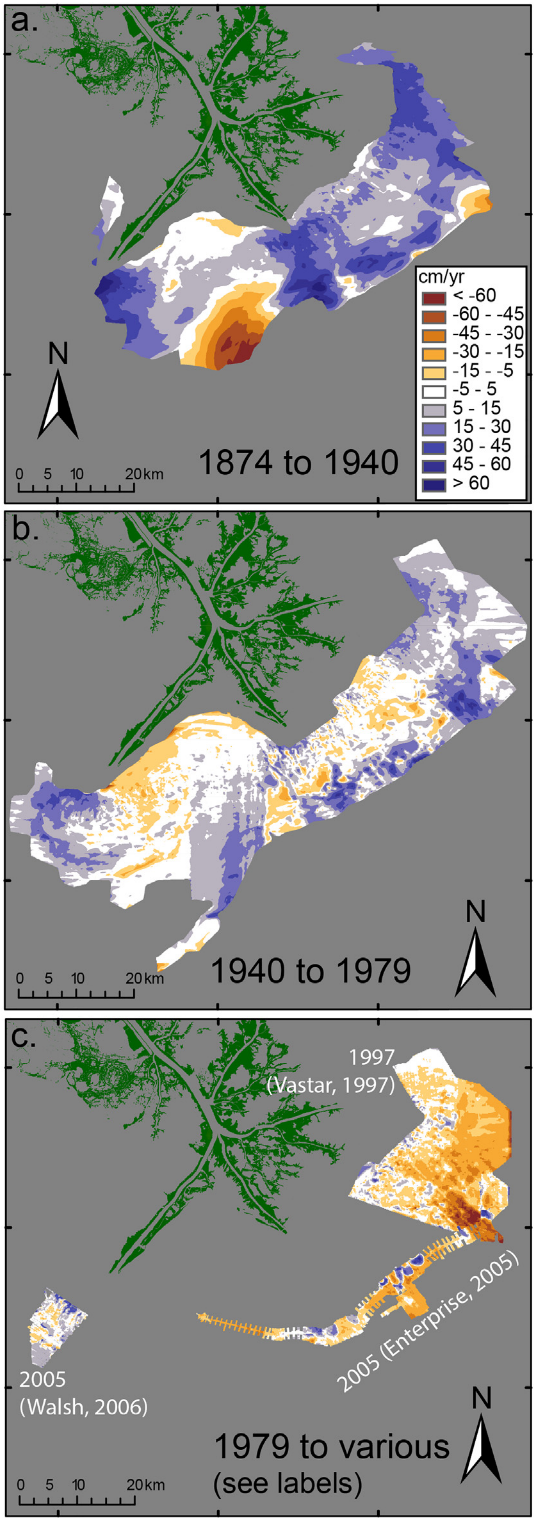

Fig. 7. Difference of depth maps showing seafloor change rates during selected time periods. Color bar in a. is also used in b. and c. Negative values (warm colors) indicate decreased seafloor elevation and positive values (cool colors) represent increased seafloor elevation. Data for 1874, 1940, and 1979 are from Coleman et al. (1980). Data for c. are from Walsh et al. (2006), Enterprise (2005) and Vastar (1997). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

yr, for South Pass are 22 and − 12 m/yr, and for Pass a Loutre are 53 and 9 m/yr, respectively. These measured changes all exceed the ~13% uncertainty that we attribute to our methods.

4.2. Offshore progradation (> 10 m contour)

Although synchronous datasets are not available for the areas offshore each of the passes, measurements of progradation rates for contours deeper than 10 m were also calculated where possible (Fig. 6, Table 1). At Southwest Pass, we measured a decline in progradation rate at the 20 m, 40 m, and 60 m contours, but an increase in progradation rate at the 80 m contour. Based on mapping and interpretation offshore Southwest Pass done by Coleman et al. (1980), at depths from 20 to 60 m, the delta front is characterized by mudflow gullies and undisturbed sediment, but the 80 m contour is located within the mudflow-lobe zone (Figs. 1 & 3). At South Pass, we observed a decline in progradation rate at the 20 m, 40 m, and 140 m contour through time. The progradation rate at the 180 m contour is variable, but shows an increase in progradation rate from the earliest to most recent time periods. At Pass a Loutre, there has been a decline in progradation rate measured at the 20 m, 40 m, 60 m, 80 m, and 100 m contour, with all contours now transgressing. At South Pass and Pass a Loutre, the 20 m and 40 m contours are within the mudflow-gully zone while the deeper contours are within the mudflow lobe zone (Coleman et al., 1980) (Figs. 1 and 3).

4.3. Vertical seafloor change

The difference-of-depth map for 1874 to 1940 shows seafloor-change rates expressing an overall increase in seafloor elevation from 1874 to 1940, especially near the mouths of the major passes of the delta (Fig. 7a, Table 2). There are two areas in deeper water between Southwest Pass and South Pass, and southwest of Pass a Loutre that show significant decreases in seafloor elevation from 1874 to 1940. It is possible that these are real features, but the original Coleman et al. (1980) 1874 contour map shows much less detail (smoother contours) compared to the 1940 and 1979 contour maps, particularly in deeper water, possibly reflecting poor data coverage in those areas. The total volume change between 1874 and 1940 was calculated to be a gain of $\sim +10.1 \pm 1.3\,km^3$ and an average seafloor change rate of $+12.0 \pm 1.6$ cm/yr over the mapped area (Table 2 and Table S3).

The difference of depth map for 1940 to 1979 shows seafloor change rates varying between areas with losses and gains of seafloor elevation (Fig. 7b). The gains occur mostly offshore the mouths of the major Passes of the delta and in the mudflow lobe zone, while the losses are primarily in shallower waters and between the Passes. The total volume change between 1940 and 1979 was calculated to be a gain of $\sim +3.8 \pm 0.5\,km^3$ and an average seafloor change rate of $+5.5 \pm 0.7$ cm/yr over the mapped area (Table 2 and Table S3).

Although there has not been a more recent bathymetric survey encompassing the entire subaqueous delta than Coleman et al.'s (1980) 1979 survey, we did compare the 1979 dataset to several smaller, more recent surveys collected for academic research and the oil and gas industry (Fig. 7c). These surveys included a 1997 survey offshore Pass a Loutre (covering $\sim 456\,km^2$), a 2005 survey along the mudflow lobe zone south of South Pass ($\sim 139\,km^2$), and a 2005 survey offshore from Southwest Pass ($\sim 63\,km^2$). The total volume change between 1979 and each of these surveys was a loss of $\sim -1.2 \pm 0.16\,km^3$, a loss of $\sim -0.4 \pm 0.05\,km^3$, and a gain of $\sim +0.1 \pm 0.01\,km^3$, respectively. The average seafloor change rates were -14.4 ± 1.9 cm/yr, -10.4 ± 1.4 cm/yr, and $+3.3 \pm 0.4$ cm/yr, respectively (negative values indicate loss) (Table 2 and Table S3).

Because the majority of sediment entering the Gulf of Mexico through the birdfoot delta is transported through Southwest Pass, we also looked more closely at the datasets available from the region offshore, which should be near the active depo-center for the delta front (Fig. 8). In this area, we observed an increase in seafloor elevation from 1940 to 1979 over most of the seafloor with some areas, mostly in the deepest water, experiencing little to no change. Over the same area, from 1979 to 2005, we observe a more heterogeneous pattern of

Table 2
Seafloor change rates of the Mississippi River Delta Front

Calendar Years	Average Seafloor Change Rate (cm/yr)[1,2]	Equivalent Sediment Load (Mt/yr)[1,3]	Percent Change from Previous Time Period (%)	Delta Front Sediment Retention Rate[4]	Datasets
1874-1940	12 ± 1.6	317 ± 54		70%	Coleman et al., 1980
1940-1979	5.5 ± 0.7	145 ± 25	-54	81%	Coleman et al., 1980
1979-1997	-14.4 ± 1.9	-382 ± 65	-363		1979 (Coleman et al., 1980); 1997 (Vastar Resources, Inc., 1997 from Guidroz, 2009)
1979-2005	-10.4 ± 1.4	-276 ± 47	-290		1979 (Coleman et al., 1980); 2005 (Enterprise Products Partners, LLC, 2005 from Guidroz, 2009)
1979-2005	3.3 ± 0.4	87 ± 15	-40	67%	1979 (Coleman et al., 1980); 2005 (Walsh et al., 2006)
1979-1997/ 2005	-11.9 ± 1.5	-315 ± 54	-317		1979 (Coleman et al., 1980); 1997 and 2005 (Vastar Resources, Inc., 1997; Enterprise Products Partners, LLC, 2005; Walsh et al., 2006)

[1] Constrained only to area overlapping with Walsh et al. (2006) survey
[2] Using total area of Coleman's 1979 survey (1753000000 m^2)
[3] Assuming bulk density of 1.51 g/cm^3
[4] Assuming uncertainty of 17%

seafloor change with some areas losing elevation and others gaining. The areas with highest seafloor elevation gain are closest to the mouth of Southwest Pass, within some mudflow lobes, and in the deepest part of the survey area. The average rate of change for the area was ∼ +17.4 ± 2.3 cm/yr from 1940 to 1979 and ∼ +3.3 ± 0.4 cm/yr from 1979 to 2005. A vertical profile through this region confirms overall accretion from 1940 to 1979 with more variable seafloor change from 1979 to 2005 (Fig. 9).

4.4. Volume estimates

For each of the difference-of-depth comparisons described in the previous section, we calculated an approximate equivalent sediment load that would be needed to account for the measured volume change (Table 2 and Table S3). We first applied the average sedimentation rate for each time frame to an area of 1753 km^2, which is the area covered by the 1940 to 1979 difference of depth map, to obtain a total sediment volume for the delta front (Fig. 7). A uniform area was used so that comparisons could be made between each time frame. Results show that the sediment load deposited between 1874 and 1940 was 317 ± 54 Mt/yr. For 1940 to 1979 the rate was 145 ± 25 Mt/yr. The only dataset that showed net gain in volume after 1979 was the Walsh et al. (2006) 2005 survey offshore from Southwest Pass. Using the average seafloor change rate from that survey, we calculated 87 ± 15 Mt/yr accumulation rate across the delta front. However, given that the difference-of-depth maps from offshore South Pass and Pass a Loutre showed an overall decrease in sediment volume, that value is likely an overestimate.

5. Discussion

Based on our observations of decreased growth, we conclude that the Mississippi River subaqueous delta is entering a stage of decline. This decline could be caused by anthropogenic alterations to the Mississippi River system. The sediment load reaching the Mississippi River delta has declined since the 1950s, primarily due to dam construction within the Mississippi River basin (Kesel, 1988). At Tarbert Landing, suspended sediment load decreased significantly between 1950 and 1967, followed by a more gradual decline from 1967 to 2007 (Kesel, 1988; Meade and Moody, 2010; Bentley et al., 2016). This decline is coincident with our observations of decreased progradation and accumulation on the delta front (Figs. 6 & 10).

The vertical seafloor change observed across the entire delta front shows a decline in accumulation through time. In two of the most recent difference-of-depth maps (1979 to 1997 (Arco) and 1979 to 2005 (Enterprise)) (Fig. 7c), we calculated a decrease in seafloor elevation at rates of −14.4 ± 1.9 cm/yr and − 10.4 ± 1.4 cm/yr, respectively. These estimates greatly exceed the assumed rate of 13 mm/yr of seafloor elevation decrease due to subsidence and eustatic sea level rise. Some of this difference is likely due to the limited spatial extent of the datasets and the heterogeneity of accumulation patterns across the delta front. For example, we are missing data from immediately offshore South Pass where higher rates of seafloor accretion were observed in the earlier difference-of-depth maps. The data offshore Southwest Pass does show overall seafloor accretion during the most recent time period. Localized high rates of seafloor loss could be related to submarine landslide dynamics with expected deepening in mudflow gullies and accretion in mudflow lobes. The high average rates of seafloor loss across the delta front that exceed 13 mm/yr also suggest that sediment of the delta front is being remobilized and transported out of the delta-front zone.

Other modifications to the delta could influence the subaqueous delta morphology. For example, jetties were built on both Southwest Pass and South Pass to maintain the channel for ship traffic. The Southwest Pass jetties were completed to their current extent by 1914, according to nautical charts (NOAA, 1914), and the South Pass jetties were completed by 1878 (Corthell, 1880). There does not appear to be a major change in progradation of these passes during the period immediately following jetty construction from 1874 to 1940. Other impacts to the distributary mouths include dredging and filling operations that are ongoing near Southwest Pass (Clark et al., 2013). Nautical charts that include bathymetry data up to 1924 (NOAA, 1925) show navigation structures that began directing ship traffic to the south out of the mouth of Southwest Pass and the 1965 nautical chart (NOAA, 1925) is the first that shows a dredged channel turning to the south. Prior to this, traffic had been directed to the southwest. The 1965 chart does not show other dredging or dumping in the immediate vicinity of Southwest Pass, but oil platforms start to appear north of the pass. The 1976 nautical chart (NOAA, 1976) shows the area around Southwest and South Passes designated as "Spoil Area". This area extended ∼3 km out from the river on both sides of Southwest Pass and ∼5 km southwest from the jetties. The 1978 chart (NOAA, 1978) shows an area ∼11 km^2 immediately seaward of the mouth of Southwest Pass marked as "dump site", for dredged material. The 10 m contour for Coleman's 1979 dataset does not intersect this area. It is possible that these modifications have altered the morphology and progradation rate at the distributary mouth bars, but the presence of spoil and dump sites would tend to increase the apparent progradation rate, rather than decrease it, as is observed. Alternatively, if the sediment that would naturally have been delivered to the delta front is being dredged from the channels and

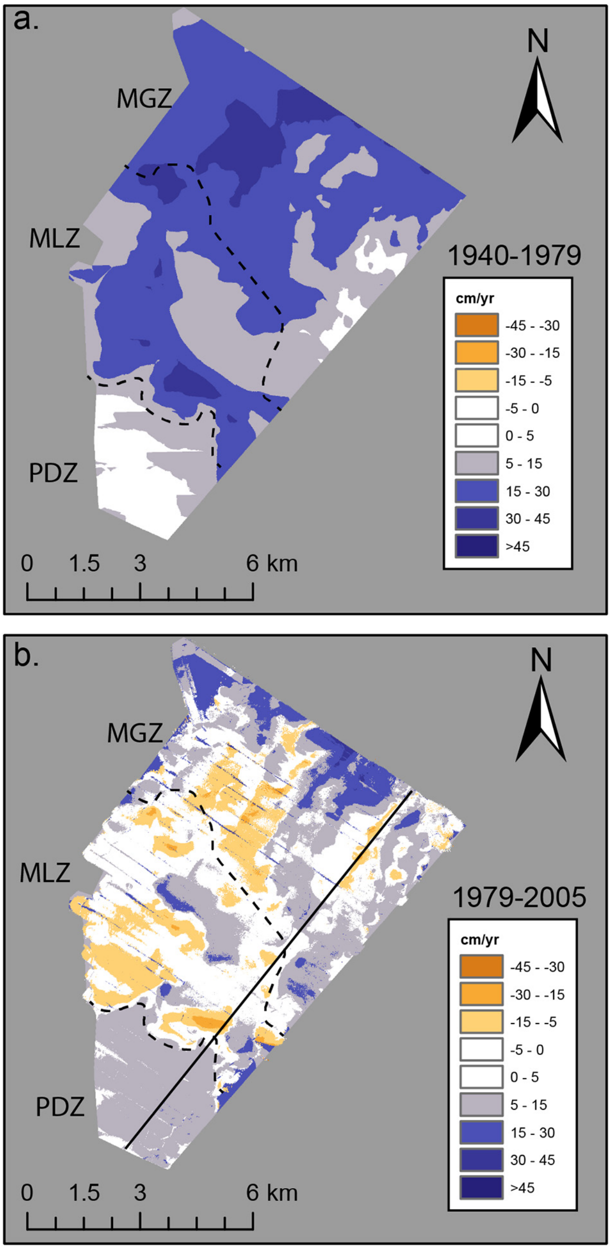

Fig. 8. Difference of depth maps showing seafloor change rate offshore Southwest Pass (location coincides with Walsh, 2005 survey in Fig. 6c). Negative values (warm colors) indicate decreased seafloor elevation and positive values (cool colors) represent increased seafloor elevation. Data for 1940 and 1979 are from Coleman et al. (1980). Data for 2005 are from Walsh et al. (2006). Black line marks profile location for Fig. 9. Dashed black lines separate the mudflow gully zone (MGZ), mudflow lobe zone (MLZ), and prodelta zone (PDZ). (For interpretation of the references to color in this figure legend, the reader is referred to the online version of this chapter.)

deposited outside the delta front, a decreased progradation rate would result. Nevertheless, the decline in progradation rate and sediment accumulation observed in deeper water on the delta front suggest that the driver of subaqueous delta decline is greater than changes to the distributary mouths.

The decline of the subaqueous delta could also be a function of the natural advance of the delta into increasing water depths. As the delta has grown into deeper water, toward the shelf edge, more sediment is required to fill the accommodation and continue to build the delta outward. Models have demonstrated this pattern of brief progradation followed by delta retreat without external forcing (Muto and Steel, 1992). However, we find the timing of reduced progradation rates and offshore accumulation observed in our datasets (Fig. 6), combined with earlier sediment core evidence of a coincident decline at ~1950 (Allison et al., 2007), to be convincing evidence that anthropogenic alterations to the Mississippi River system are consistent with subaqueous delta decline.

The offshore progradation rates and difference of depth maps suggest that the delta is also experiencing an overall decline in deeper waters. At Southwest Pass and South Pass, progradation rates of contours within the mudflow gully zone have decreased and rates within the mudflow lobe zone have increased. This suggests that the advance of the delta into the Gulf of Mexico is slowing, but the decline has not yet resulted in cessation of mudflow activity on the delta front. The increased progradation rate within the mudflow lobe zone shows that mudflow lobes continue to advance into deeper water of the prodelta zone. This pattern is also observed in the difference of depth maps offshore Southwest Pass and South Pass between 1979 and 2005 (Fig. 8c). Mudflow lobes are clearly identified as areas of accretion in both areas. However, at Pass a Loutre, the pattern of mudflow lobe advance is not observed. The contours offshore Pass a Loutre are retrograding at all depths, including the mudflow lobe zone (Table 1) and we do not observe well defined mudflow lobe advance in the difference-of-depth map (Fig. 8c). This does not necessarily indicate a cessation of mudflow activity in the area, but does suggest that mudflow activity is not sufficient to advance delta lobes into deeper water. Alternatively, there could be advancing mudflow lobes offshore Pass a Loutre at deeper depths within the mudflow lobe zone where we lacked sufficient data coverage to measure seafloor change.

The decline of the Mississippi River subaqueous delta has important implications for subaqueous mass wasting, sediment transport to the deep sea, global biogeochemical cycling, and improving our understanding of the role of deltas in a source-to-sink context. In terms of mudflow hazard, our data show that the seafloor within the mudflow lobe zone continues to advance offshore Southwest and South Passes, despite an overall decline in progradation at shallower depths. This suggests that mudflows are still active in the areas offshore Southwest Pass and South Pass despite the reduction in sediment accumulation. This is confirmed by recent data from offshore Southwest Pass (Walsh et al., 2006; Keller et al., 2016; Obelcz et al., 2017) and known damage to offshore infrastructure during recent hurricanes (Thomson et al., 2005; Nodine et al., 2007; Guidroz, 2009). Although we did not observe evidence for mudflow lobe advance offshore Pass a Loutre, mudflows during Hurricanes Ivan (2004) and Katrina (2005) did result in pipeline damage offshore Pass a Loutre (Nodine et al., 2007). Both hurricanes occurred after our most recent dataset used to measure offshore progradation and seafloor change. Rapid sediment accumulation is often cited as a driving mechanism for submarine landslides (Lee et al., 2007), particularly for the Mississippi River delta front (e.g., Coleman and Garrison, 1977). Evidence of mudflow lobe accretion from our data show that submarine mass wasting is still active within the mudflow lobe zone despite reduced rates of sediment accumulation, suggesting a more complex set of forcing mechanisms are active on the delta front.

Using our estimated equivalent sediment loads, we calculated retention rates for sediment on the delta front as a ratio of delta front accumulation to Mississippi River sediment load. Retention rates are 70% from 1874 to 1940, 81% from 1940 to 1979, and 67% from 1979 to 2005 (Table 2). These values are fairly consistent through time, but seem high compared to measured deposition to accumulation ratios of 7–18 from sediment cores west of the delta (Corbett et al., 2004), which indicate significant removal of sediment from the delta front through re-working after deposition. Furthermore, using the sediment loads at Tarbert Landing does not take into account the amount of sediment deposited along the lower reaches of the river, and exiting the river from outlets upstream of Head of Passes; this total amount has been shown to be relatively high. Bentley et al. (2016) documented substantial channel-floor aggradation in the Mississippi River between New Orleans and Head of Passes. Allison et al. (2012) showed that for water

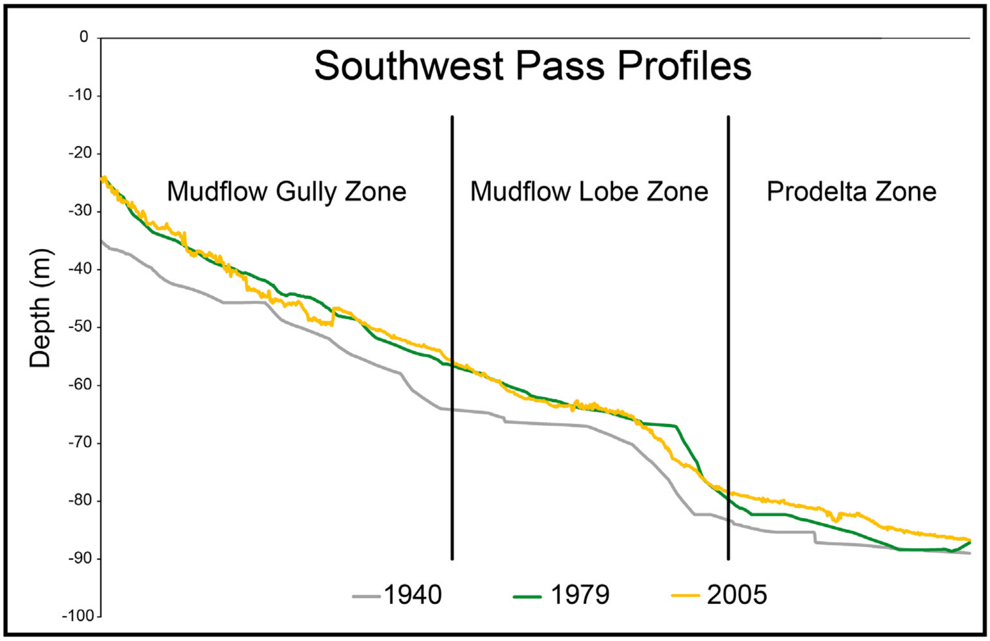

Fig. 9. Vertical profiles offshore Southwest Pass. Profile location shown in Fig. 9.

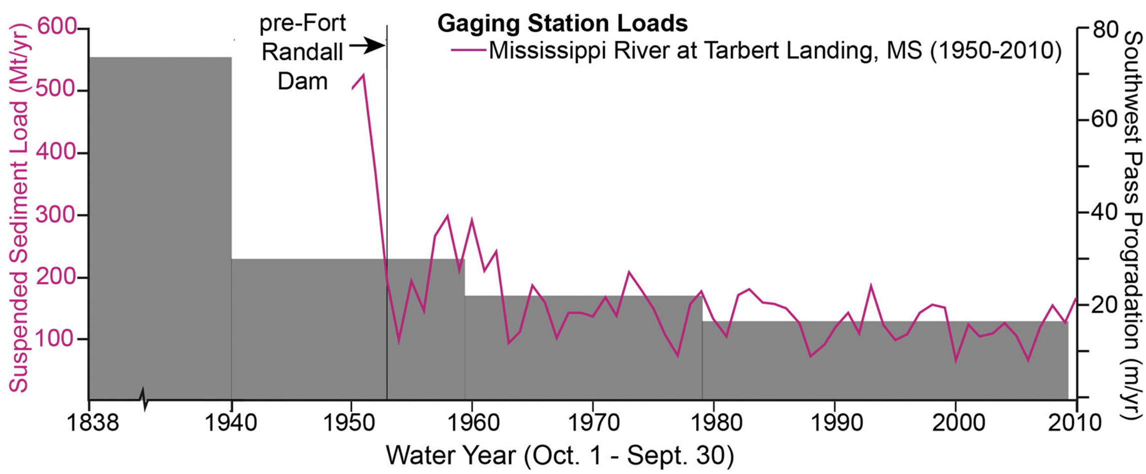

Fig. 10. Suspended sediment load of the Mississippi River as measured at Tarbert Landing (pink) compared with measured progradation rates of Southwest Pass (gray). Mt/yr = Million tons per year. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

years 2008–2010, the total suspended sediment load at Tarbert landing was 157 Mt/yr, but the amount entering the Gulf of Mexico through the three major passes combined was only 30.3 Mt/yr. If the percent of sediment deposited between Tarbert Landing and the Gulf of Mexico has consistently been similar to that measured by Allison et al. (2012), our calculated equivalent sediment loads would be higher than the amount of sediment delivered through the three main passes. For the most recent period, our calculated sediment load of 87 ± 15 Mt/yr is based on extrapolation of seafloor change offshore Southwest Pass to the entire delta front. Southwest Pass receives the majority of sediment load compared to South Pass and Pass a Loutre and so we have likely overestimated the overall sediment volume on the delta front during this time period. For the earlier periods, it appears that either our estimates are too high, or that a higher percentage of sediment at Tarbert Landing reached the Gulf of Mexico from 1874 to 1979. Major flood events could be responsible for a significant delivery of sediment to the subaqueous delta and water years 2008–2010 did not include a major flood event. Additionally, river systems are dynamic and natural spatial and temporal variability in sediment discharge may not be reflected in the short 2008–2010 time period that was measured.

In terms of biogeochemical cycling, rivers are responsible for bringing freshwater and terrestrial sediment to the coastal ocean, where carbon cycling is an important process. It is estimated that carbon burial on continental margins amounts to 80–85% of the global total (Berner, 1982; Hedges and Keil, 1997). Allison et al., 2007 showed localized reduction in MAR at ~1950 in two sediment cores collected near Southwest Pass, but they did not observe the same pattern in other sediment cores across the delta front due to bioturbation and sediment focusing. Our work effectively shows that the observed reduction in MAR offshore Southwest Pass is pervasive across the delta front region. Associated with the reduced MAR, Allison et al. (2007) also measured a decline in TOC decrease with depth, synchronous with the decline in MAR at ~1950, indicating that the riverine lithogenic flux is directly proportional to POC burial rate in the oxic areas of the Mississippi River delta front. Therefore, we expect reduced POC burial rates across the entire delta front coincident with anthropogenic alterations to the Mississippi River system.

Pathways of sediment delivery to the subaerial delta from offshore regions during hurricanes have been identified as an important source of inorganic sediment for southern Louisiana wetlands (Turner et al., 2006; Smith et al., 2015). Although the region we analyzed in this research is likely too far offshore to be an important sediment source for landward delivery, it does show that patterns of offshore sediment accumulation have been impacted by anthropogenic and natural forcing. There are likely similar impacts to more shallow regions of the subaqueous delta, which should be considered when calculating sediment budgets for the region. The delta's onshore and offshore systems are connected and further research into the evolving patterns of subaqueous sediment transport and distribution are warranted.

Studies have shown that other major river systems worldwide have experienced declines in sediment load due to anthropogenic changes upstream (e.g., Syvitski et al., 2005). For example, the sediment load of the Yellow River (Huang He) has declined by ~90% over the past 60 years (Wang et al., 2016) and the Yangtze sediment load has decreased by ~70% since the 1950–1960s (Xu et al., 2007). These major Asian rivers, along with the Mekong and Ganges-Brahmaputra discharge 50–70% of their sediment load to the sea with half of that amount accumulating near the river mouth and the remainder transported to distal depocenters (Liu et al., 2009). Our estimates of retention rate for the subaqueous Mississippi River delta suggest a higher percentage of sediment is retained adjacent to the river mouth compared to the Asian rivers, perhaps reflecting different oceanographic conditions between the regions (e.g., the Mekong, Yangtze, and Ganges-Brahmaputra are characterized by higher tidal range (Walsh and Nittrouer, 2009)). Our results also show that upstream decline in suspended sediment is coincident with decreased accumulation on the subaqueous delta, a pattern that is likely occurring on the many river systems that have undergone changes in sediment load due to anthropogenic forcing. These changes could have significant impacts to global patterns of sediment dispersal to the coastal ocean.

6. Conclusions

1. The subaqueous Mississippi River delta is entering a stage of decline consistent with the reduction in suspended sediment load of the river caused by anthropogenic modifications.
2. Despite reduced sediment accumulation across the delta front, submarine mass wasting is still active and poses a hazard to offshore infrastructure.
3. Given patterns of anthropogenic modifications to river systems worldwide, we expect other major delta systems are entering decline, which has implications for delta ecosystems and global biogeochemical cycling.
4. During the time period from 1979 to the early 2000s, high average rates of seafloor loss across the delta front suggest that the delta front is a temporary depocenter for fluvial sediments, with subsequent transport out of the region.

Supplementary data to this article can be found online at https://doi.org/10.1016/j.margeo.2018.03.001.

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