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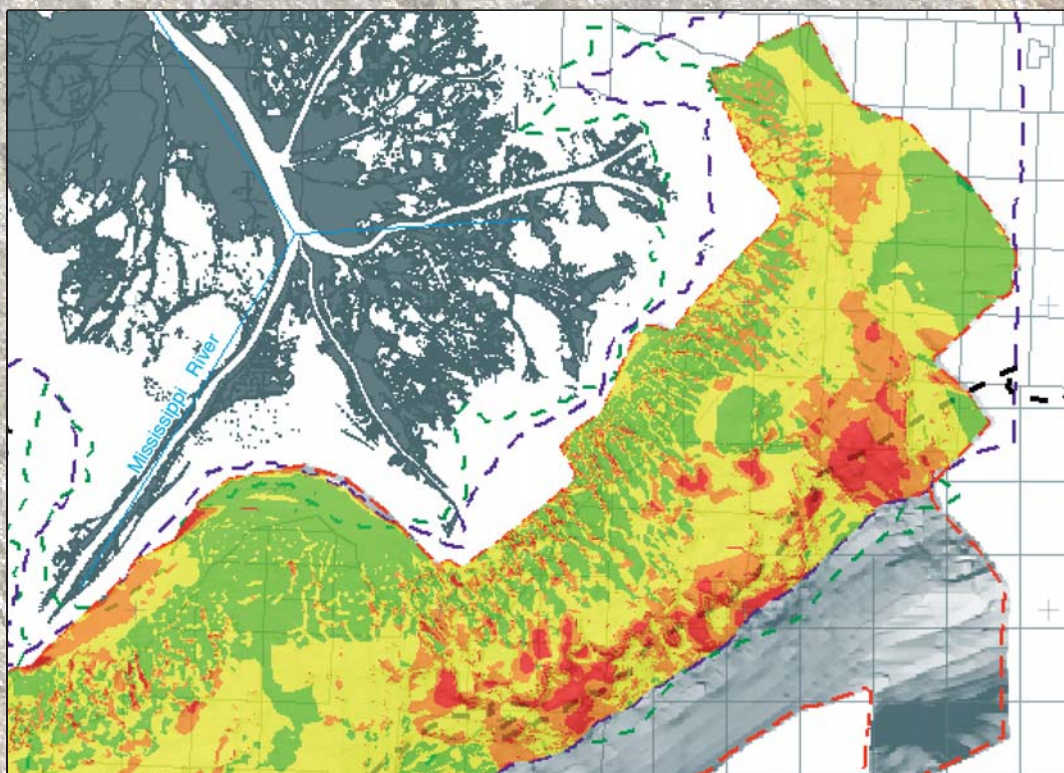
A Pilot Study for Regionally-Consistent Hazard Susceptibility Mapping of Submarine Mudslides, Offshore Gulf of Mexico



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Minerals Management Service
Engineering & Research Branch
381 Elden Steet, MS 4021
Herndon, VA 20170-4817

Submitted by:

William Lettis & Associates, Inc.
1777 Botelho Drive, Suite 262
Walnut Creek, CA 94596

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Christopher Hitchcock, Michael Angell, and Robert Givler
William Lettis & Associates, Inc.
1777 Botelho Drive, Suite 262, Walnut Creek, CA 94596
925/256-6070, hitch@lettis.com

Jim Hooper
Fugro-McClelland Marine Geosciences Inc
6100 Hillcroft Houston, TX 77081
713/369-5574, Jhooper@Fugro.com

ABSTRACT

As part of our pilot MMS-funded project to delineate mudflow failures, sediments susceptible to future slope failure, and areas of relative stability in the Mississippi Delta, we have developed and tested a geomorphology-based approach to map mudflow susceptibility on the sea floor bottom. Our research is designed to provide hazard information for the siting and design of future pipelines and structures. Based on our results for a test area, and interpretation of available datasets for the Mississippi Delta region, the distribution of underwater failures and associated submarine landforms (e.g. mudflow gullies and mudflow lobes) directly reflects the complex interaction between deposition of the Mississippi River and infrequent, but highly influential, impact of waves from large hurricanes. We have used available bathymetric data to delineate areas of relative sea floor stability over the past century, areas of active mudflow transport, and areas of mudlobe deposition. Mudflow transport within the Delta generally occurs within well-defined submarine channels or gullies, spreading out onto the seafloor in deeper water to form overlapping lobes of thick, viscous silty clay. Our mapping delineates the region of mudflow gullies, as mapped by Coleman et al. (1982), as the mudflow transport zone. Local accumulation of sediment coupled with scour during mudflow transport results in highly variable and unstable conditions within the gullies. Semi-stable areas between the mudflow channels locally provide the least hazardous locations for siting of future production facilities and pipeline routing. The zone of overlapping mudlobes located downslope of the gullies is an area of recent deposition vulnerable to mudflow overruns from upslope mudflows. Comparison of our mapping to failures inferred from the post-Hurricane Ivan multibeam bathymetric data for a test area enables us to evaluate the effectiveness of the mapping. Our hazard mapping appears to have adequately characterized areas of greatest net change, including erosion within mudflow channels and deposition within mudlobes, as well as areas of minimal change ('low' hazard) associated with Hurricane Ivan.

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INTRODUCTION

As first recognized during evaluation of the damage caused to offshore oil production in the Gulf of Mexico by Hurricane Camille in 1969, hurricanes have the potential to move massive amounts of sediment on the sea floor. Large-scale wave-induced bottom pressures created by intense hurricanes (such as Camille, Ivan, and Katrina) directly impact the sea floor, causing seafloor failures and mudflow overruns of deep-water regions from upslope sources (Hooper, 1980; Hooper and Suhayda, 2005).

Our pilot project tests the applicability of developing regionally consistent hazard maps that delineate the relative susceptibility of the Mississippi Delta in the Gulf of Mexico to future submarine mudslides. We have developed and applied map-based techniques for delineating the relative susceptibility of underwater slopes to mudslides for the Delta area recently impacted by Hurricanes Katrina and Ivan (Figure 1). Similar to landslide and liquefaction mapping on land, mudflow susceptibility mapping identifies areas vulnerable to submarine failure that may be mitigated by avoidance and/or further investigation and design. Our susceptibility maps are designed, in conjunction with information on hazard opportunity (e.g. recurrence of major hurricanes), to form the regional map framework required to evaluate likely locations of future submarine failures.

BACKGROUND

The Balize delta, or 'birdsfoot delta', is an active depositional delta that began prograding in the Gulf of Mexico over 1,000 years ago (Saucier, 1963). The Balize delta is unique to current and recent deltas formed by the Mississippi River in that it is a 'shelf-stage' delta that has prograded in deep water to near the submarine shelf edge (Roberts, 1997). The delta is supplied with sediment by three major distributary channels (Southwest Pass, South Pass, and Pass A Loutre; Figure 2).

Although partial capture of the Mississippi River flow by the Atchafalaya River has diminished sediment supply to the Balize delta within the last several hundred years (Kesel, 1988; Roberts, 1997), the major river distributaries have grown seaward at an average rate of 100 to 200 ft/yr over the past 150 years (Morgan, 1977). For example, analysis of historic maps of South Pass show that the South Pass bar advanced seaward more than 1 mile between 1867 and 1953 (Lindsay et al., 1984). Deposition rates as high as 1 to 2 ft/yr at the mouths of the distributary channels result in rapid accumulation of low shear strength, low permeability sediment (Coleman et al., 1982; Hooper and Suhayda, 2005).

The submerged delta apron therefore consists of thick, very weak sediments that are inherently unstable and vulnerable to hurricane wave-induced failure (Bea et al., 1975; Hooper, 1980). Rapid sedimentation can change the slope of the seafloor, causing oversteepening in critical areas and loading of the underlying sediments (Lindsay et al., 1984). Associated increased pore-water pressure and buildup of methane gas further makes the accumulated sediment susceptible to failure (Wheland et al., 1978; Roberts, 1997). Even a small change in prevailing conditions (gas content or wave input) can trigger a mudflow. As a result, wave-induced bottom pressures accompanying large

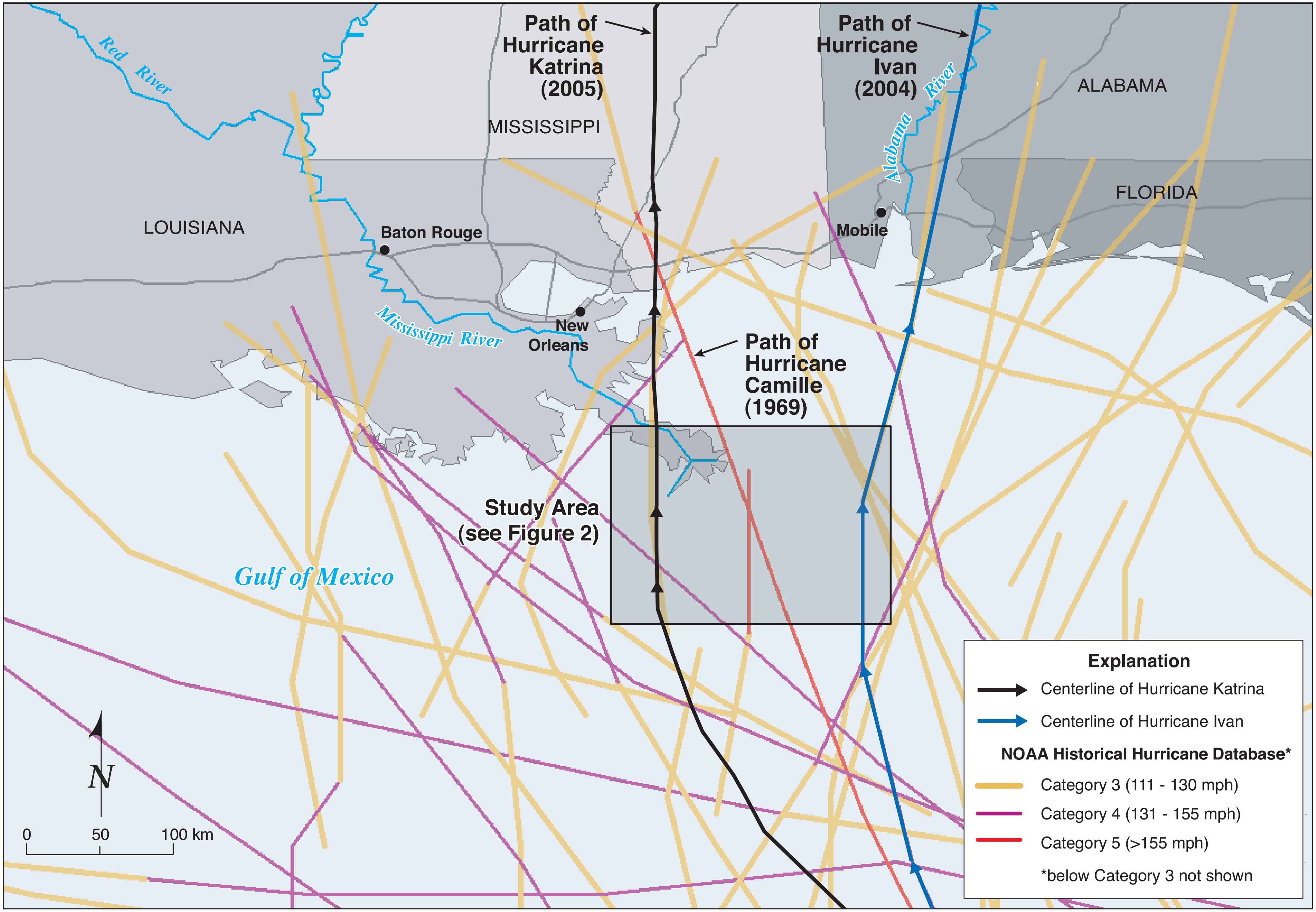

Figure 1. Index map of project area with track lines of historic hurricanes.

1749 MMS Mudflow Hazard

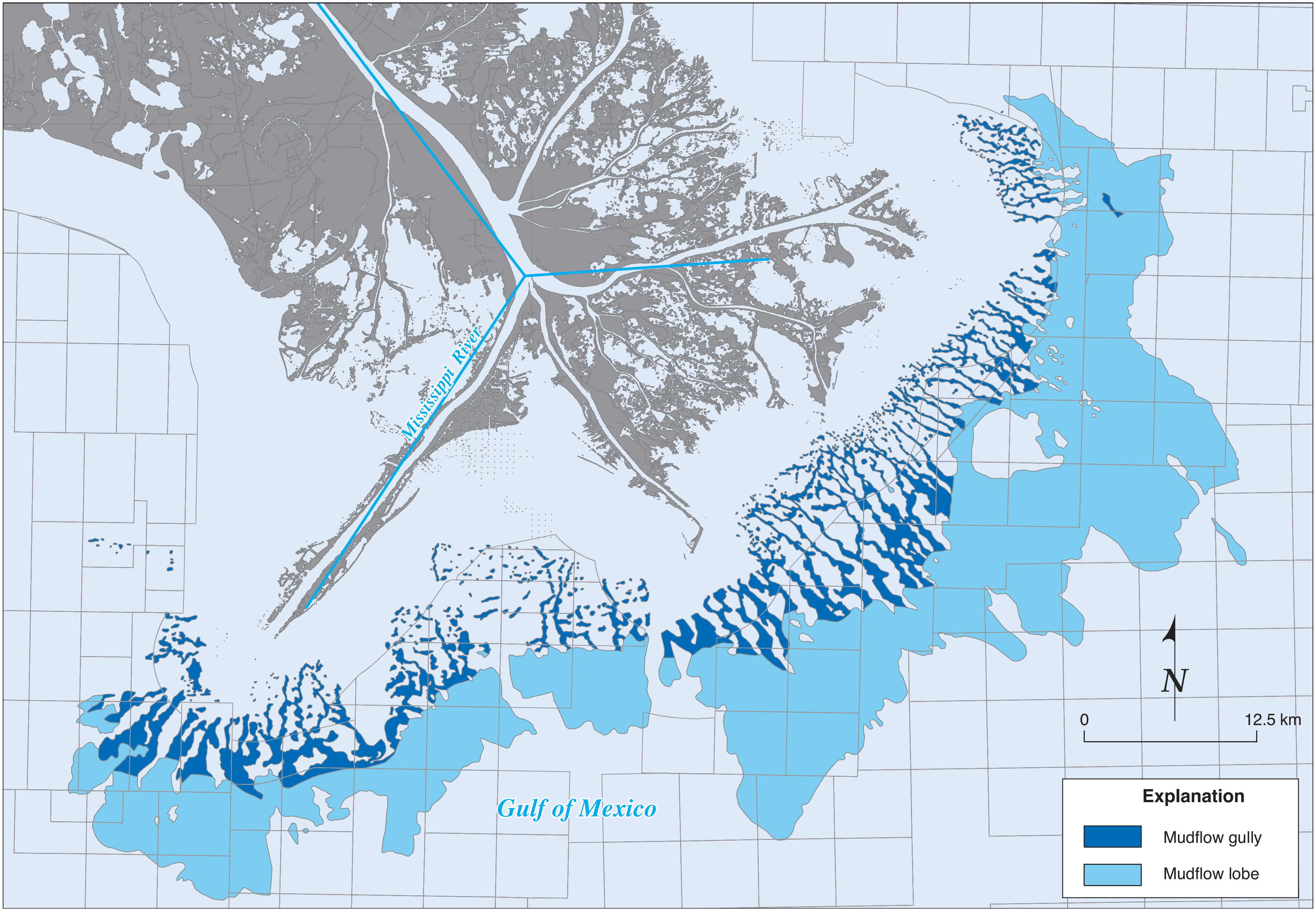

Figure 2. Existing geologic mapping from MMS OFR 80-02 (digitized as part of our pilot study).

hurricanes can cause spectacular failures of the accumulated sediments (Bea et al., 1975; Hooper, 1980; Hooper and Suhayda, 2005).

MUDFLOW HAZARD

Mudflows along the submerged Mississippi Delta apron are part of a complex, dynamic system of sediment transport and deposition developed on the sea floor bottom (Figure 2). Mudflow transport within the Delta generally occurs within well-defined submarine channels or gullies, spreading out onto the seafloor in deeper water to form overlapping lobes of thick, viscous silty clay (Shepard, 1955; Hooper, 1980). We delineate the region of mudflow gullies, as mapped by Coleman et al. (1982), as the "mudflow transport zone" (Figure 3). Local accumulation of sediment coupled with scour during mudflow transport results in highly variable, and unstable, conditions within the gullies.

Semi-stable areas between the mudflow channels locally are vulnerable to failure as mudflow scarps migrate upslope and/or mud channels grow over time, cannibalizing the regions between the active mudflow channels. However, based on our examination of historic bathymetric data, areas between mudflow gullies are surprising stable with low sediment accumulation rates. As such, these areas likely provide the least hazardous locations for siting of future production facilities and pipeline routing.

The mudflow gullies supply a complex zone of overlapping mudlobes in deeper water. The zone of mudlobes, described herein as the "mudlobe deposition zone" (Figure 3), located downslope of the gullies is an area of recent to active deposition vulnerable to mudflow overruns from upslope gullies and mudflows. Localized damage and burial of pipelines and production facilities is well documented in this zone (Coleman et al., 1982; Hooper and Suhayda, 2005).

The distal portion of the mudlobe zone is complicated by the headward migration of salt-related growth faults near the shelf edge (shown on Figure 4). Although a distinctly separate process from that of sediment transport and deposition, long-term displacement on these faults may serve to localize and intensify slope failures. The growth faults, of unknown rates and magnitudes of movement, likely pose additional complexity by interacting with the lower limit of mud lobe deposition. In particular, the faults form an area of relatively steep slopes that appear to bound the seaward terminus of the mudlobe zone.

APPROACH

Mudflows and other submarine slope failures do not occur randomly, but rather typically are localized within areas with a narrow range of geologic and bathymetric characteristics that can be identified and mapped. Multiple criteria predispose underwater slopes to failure including site conditions (e.g. local water depth, slope inclination and aspect, depositional environment, etc.) and material properties (e.g. shear strength, grain size, 'gassy' mud thickness, and sediment age). To evaluate the susceptibility of slopes in the Gulf of Mexico to future failure, these various criteria need to be evaluated, weighted, and integrated into a regionally consistent hazard map.

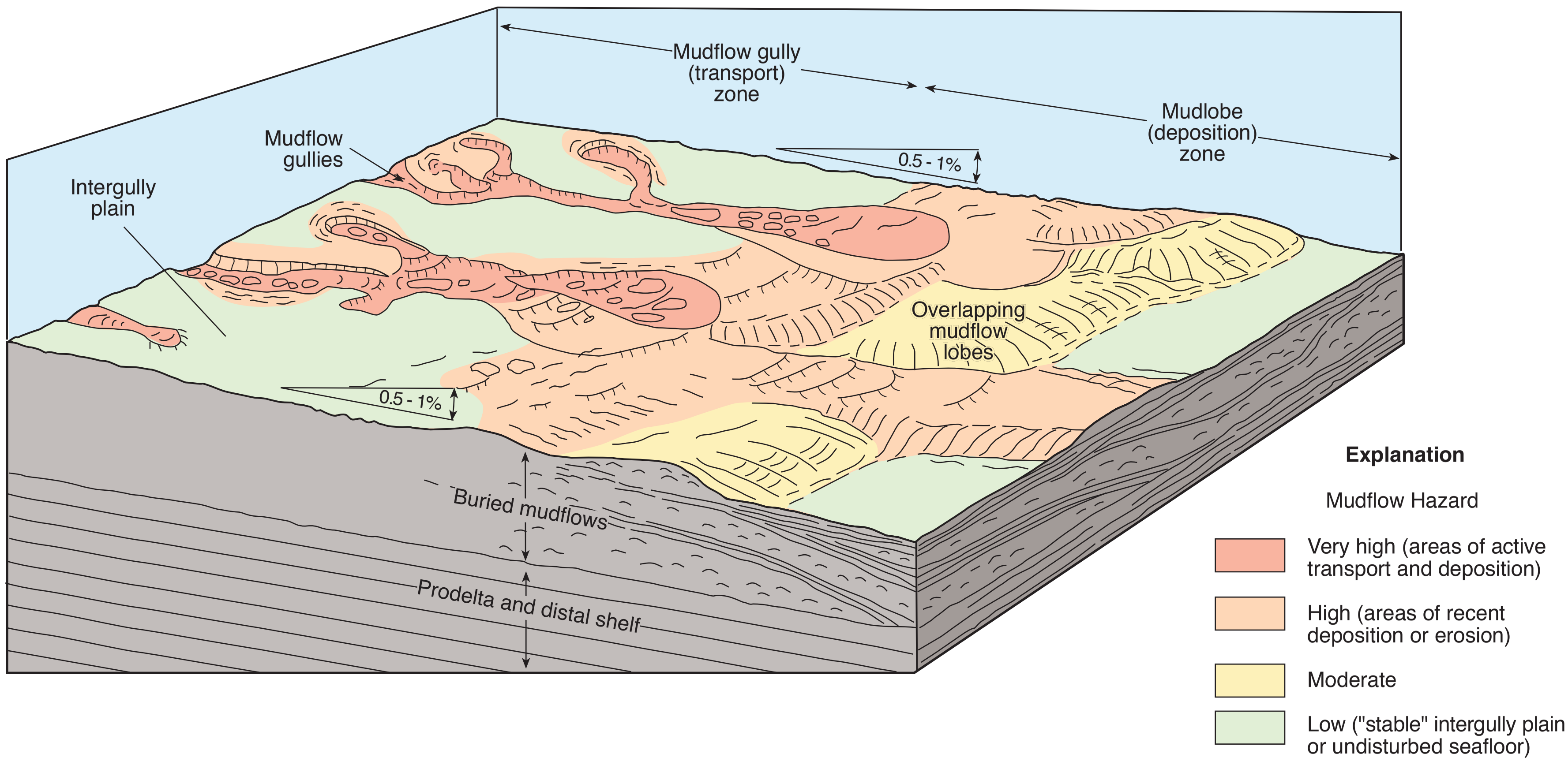

Figure 3. Delta-front landforms and relative mudslide hazard (after Hooper, 1980)

For this pilot project, mudflow hazard was evaluated for the Mississippi Delta region by ranking the relative contribution of various geologic, slope, and bathymetric properties to obtain an integrated hazard map. We have applied methods developed on shore for evaluating the distribution of possible landsliding and liquefaction in response to large earthquakes (e.g. Keefer and others, 1998; Hitchcock et al., 1999; Pike et al., 2001). Adapted to the unique geologic environment of the Delta, these mapping techniques are applicable to mapping of mudflow hazard in the Gulf of Mexico.

Geographic information systems (GIS) technology enables sophisticated, numerical-based mapping of slope failure susceptibility, whether submarine or subaerial (e.g. Pike et al., 2001). We have compiled and incorporated available datasets in a common GIS map layer format. Using a criteria matrix, we ranked key factors that influence submarine stability by assigning point scores for map units (rate of change, slope, and geologic unit) in each map layer (Figure 4). The point scores within a series of derivative GIS map layers are summed in a single interpretative map layer depicting mudflow susceptibility.

The data compilation and evaluation process involved the following steps: (1) compilation of available bathymetric data and development of a composite bathymetric base map; (2) development of derivative map layers that depict rates of change of the sea floor (deposition and erosion) from historic bathymetric maps; (3) development of a submarine slope gradient map from bathymetric data; (4) digitization of available geologic mapping and tectonic structures from Coleman et al. (1982) to create a geologic map layer; (5) revision of the geologic map layer to incorporate independent geologic interpretation of multibeam bathymetric data; (6) interpretation of correlations between mudflow locations and density, sediment characteristics, and slope to develop a mudflow susceptibility criteria matrix; (7) derivation of a point score system for integration of map units for each map layer, and (8) integration of the map layers with summation of associated point scores for each layer to develop a derivative mudflow susceptibility map. Below we discuss the data and methods used to develop the susceptibility map and interpret the relative contribution of various criteria for each map layer.

Geologic Map Layer

Geologic mapping of submarine features on the seafloor provides valuable information and context for identifying and delineating the processes associated with mudflow failure, transport, and deposition. Important geologic factors influencing the susceptibility of mud deposits to slope failure include the genesis (source), composition, and age of seafloor sediment. For this project, polygons of map units derived from MMS OFR 80-02 (Coleman et al., 1982) were digitized into a geologic map layer (Figure 5). The digitization process is described in more detail in metadata accompanying the map files provided on the accompanying data DVD. In addition, interpretation of multibeam bathymetric data allowed revision and updating of mudlobe features in the mudlobe deposition zone. This mapping was included as part of the final geologic map layer.

Regionally consistent, geomorphic-based mapping of the sea floor bottom allows extrapolation of available site-specific data on material properties data. Geologic units,

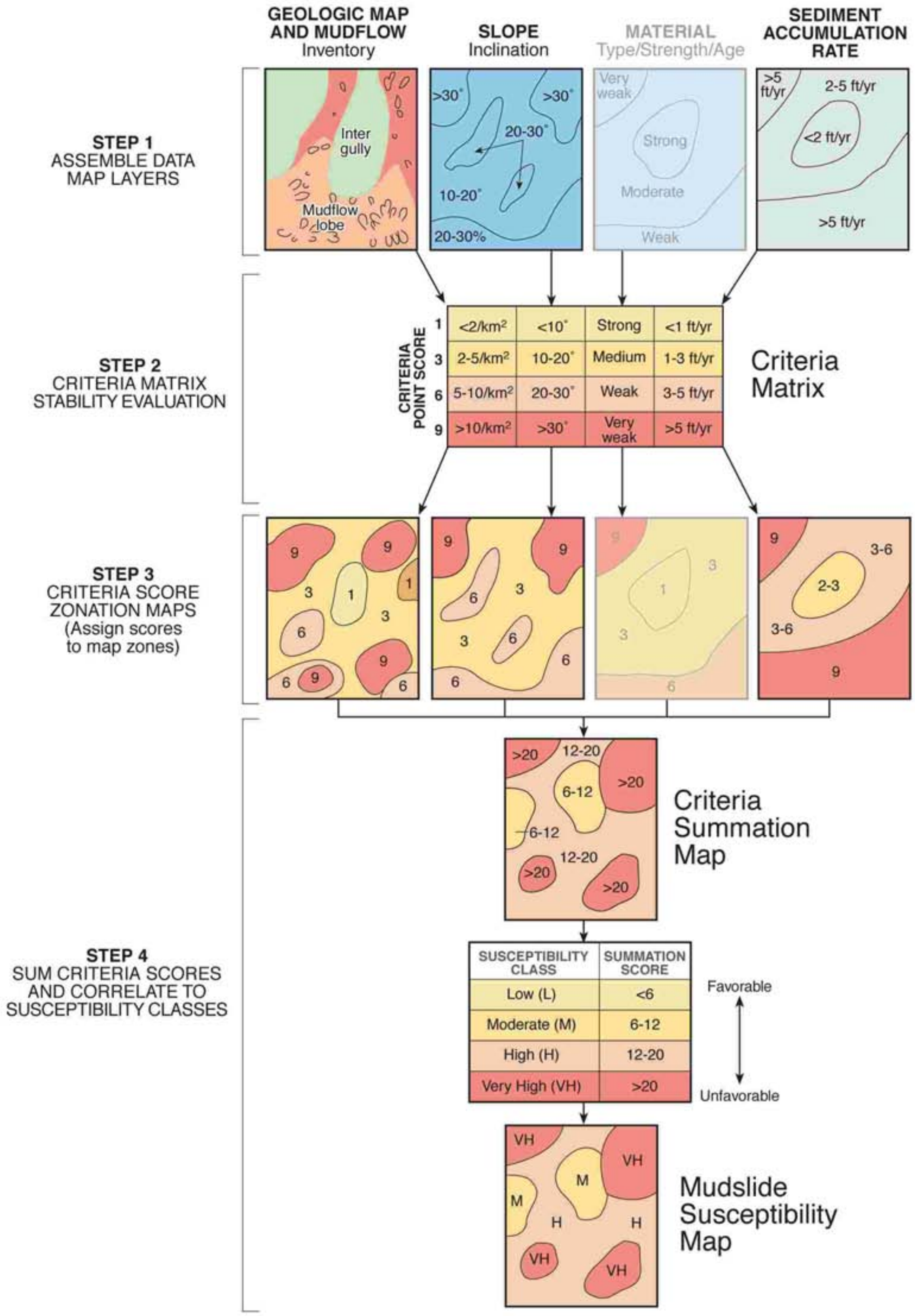

Figure 4. Conceptual diagram showing criteria matrix based mapping approach.

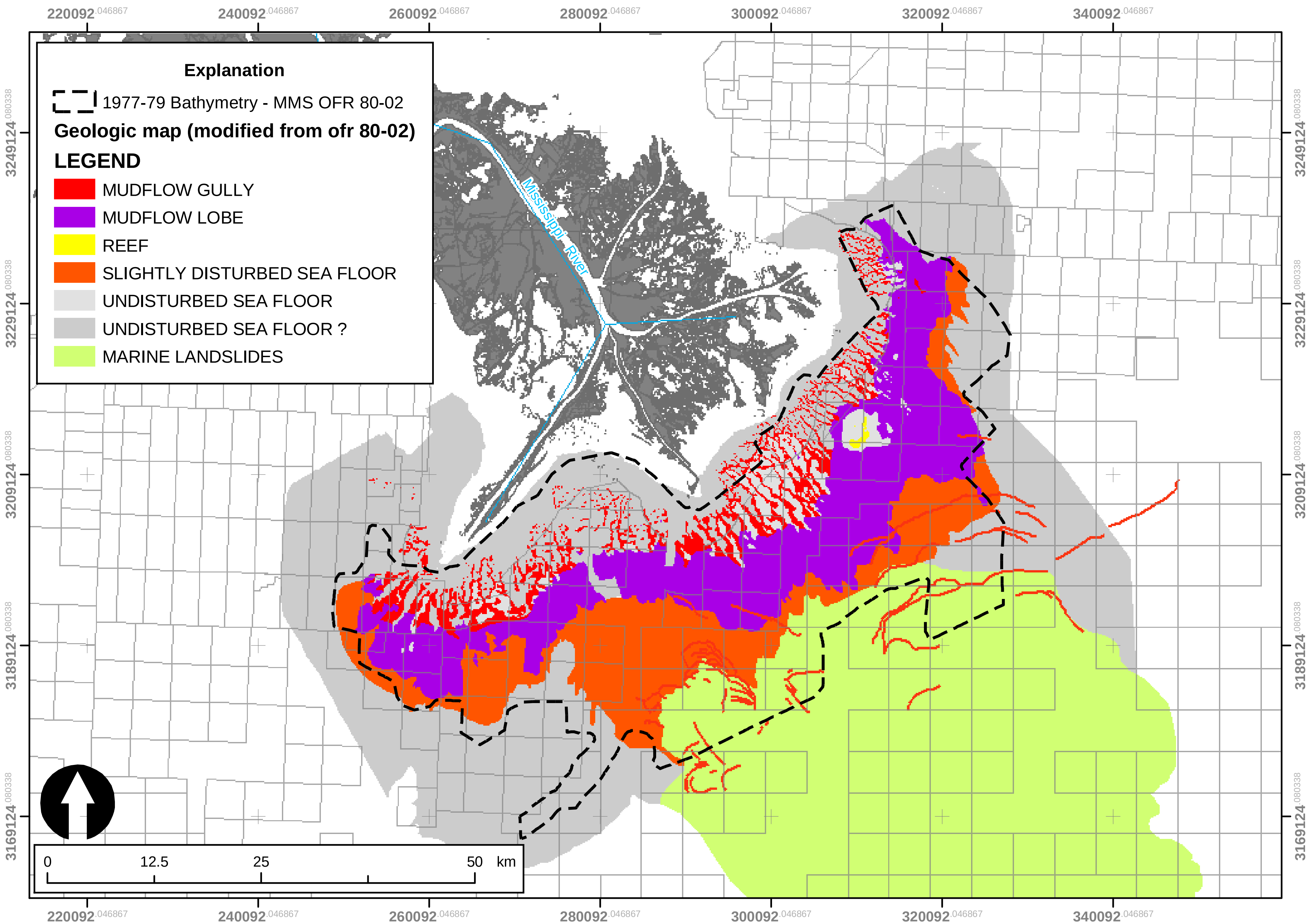

Figure 5. Geologic and geomorphic map of site region (modified from MMS OFR 80-02).

mapped on the basis of depositional environment and relative age, are particularly useful for estimating properties of sediment in areas that lack subsurface data. In particular, age of the sediment following its last failure episode is a major material factor controlling future failure (Hooper, 1980; Hooper and Suhayda, 2005). The younger the deposit, the more likely it is to fail in the next large storm. For example, mudlobes created by failures triggered by Hurricane Ivan are now full of excess pore pressure and likely will be producing gas for the next few tens of years. They are much more susceptible to future or renewed failure during the next hurricane season. Meanwhile, mudlobes that didn't fail during recent storms, including Hurricanes Ivan and Katrina, will continue to strengthen (due to continued consolidation and thixotropy) and become even more resistant to future hurricanes (Hooper and Suhayda, 2005).

Sediment age is a geologic attribute that can be determined and mapped using geomorphic mapping techniques. Relative ages of underwater landforms are derived based on the relative positions of sediments (e.g. the law of superposition with younger sediments covering older ones), interpretation of active depositional environments (e.g. pelagic vs. mudlobe, deltaic, etc.), and evaluation of relative geomorphic expression of landform surfaces. In the absence of a comprehensive digital borehole and material properties database, comparison of bathymetric data over time is used to map changes in the seafloor bottom, including mudslide failures (depressions in the sea floor) and creation of new mudlobes (additions to the sea floor). This mapping is combined with geomorphic mapping of seafloor landforms to classify the recency of mudslide movement and mudlobe deposition. For example, mudflow channels with rough surfaces typically have moved recently (i.e., within a year or two). Thus, detailed mapping provides information on the age and, indirectly, relative strength of stored sediment.

Table 1 shows the relative mudflow failure susceptibility characteristics of the various geologic units and accompanying point score. Based on relative age and activity, mudflow gullies typically are most active areas of sediment transport on the seafloor and are assigned the highest hazard point score. Mudflow lobes are areas of recent deposition vulnerable to mudflow overruns from upslope mudflows, and thus also relatively high hazard. Older marine landslides are lower hazard, as is slightly disturbed seafloor. Areas of undisturbed seafloor, as mapped by Coleman et al. (1982), have the lowest associated hazard and point score.

Table 1. Contribution to mudflow hazard based on geologic map unit (map units from Coleman et al., 1982).

Geologic Map Unit	Point Score	Hazard
Mudflow Gully	4	High
Mudflow Lobe	3	↑
Marine Landslides	2	
Slightly disturbed seafloor	1	
Undisturbed seafloor	0	Low

Compilation and Analyses of Bathymetric Data

Compiled bathymetric data forms the basis for performing interpretive analyses of past submarine failures and likely future locations susceptible to failure. Bathymetric data provides valuable information used to delineate submarine landforms, including individual mudflows, and derive seafloor slope. Also, this information is required to determine areas of relative stability and long-term patterns of sediment transport and deposition. In particular, comparison of bathymetric surveys from different time periods provides information on changes in the seafloor bottom over time. Sediment accumulation and erosion rates derived from comparison of bathymetric surveys allow for interpretation of locations, amounts, and frequency of mass movement on the seafloor (Coleman et al., 1982).

The study area in the Mississippi Delta is unique in that a historic record, supported by detailed bathymetric data, exists of the sea floor over the past 140 years. Bathymetry in 1874 was compiled and drafted by Coleman et al. (1982) from maps that span the period 1872 to 1874 and incorporated copies of original soundings. Coleman et al. (1982) also provide maps of 1940 and 1977-1979 bathymetry.

As part of data compilation for this project, we digitized the bathymetric mapping compiled in map form by Coleman et al. (1982) and supplemented this published mapping with more recent, publicly available multibeam bathymetric data (as shown in Figure 6; Table 2). Bathymetric data was digitized from contours on paper-based bathymetric maps compiled by Coleman et al. (1982). In addition, raw bathymetric data from the NOAA multibeam survey was gridded and used to develop composite slope and shaded relief maps for interpretation (Figure 6). Full descriptions of the bathymetric data digitized for this project, along with representative figures showing the extent and resolution of the bathymetric map layers, are provided within accompanying metadata.

Table 2. Sources of bathymetric data used in this study.

Year	Source	Analyses Performed
1872-1874	Map 2 from Coleman et al. (1982)	Digitized contours, derivation of slope map, shaded relief
1940	Map 3 from Coleman et al. (1982)	Digitized, derivation of slope map, shaded relief
1977-1979	Map 4 from Coleman et al. (1982)	Digitized, derivation of slope map, shaded relief
1989	NOAA multibeam data	Processed grid data, slope map, shaded relief

From the compiled bathymetric map layers, "residual" seafloor relief map layers were constructed by subtracting bathymetric elevations, in grid format, of more recent surveys from older surveys. The residual map layers were prepared to identify areas of net seafloor change, including areas of net loss (erosion or incision) and gain (deposition). If it is assumed that change in the relative seafloor depth is a response to erosion,

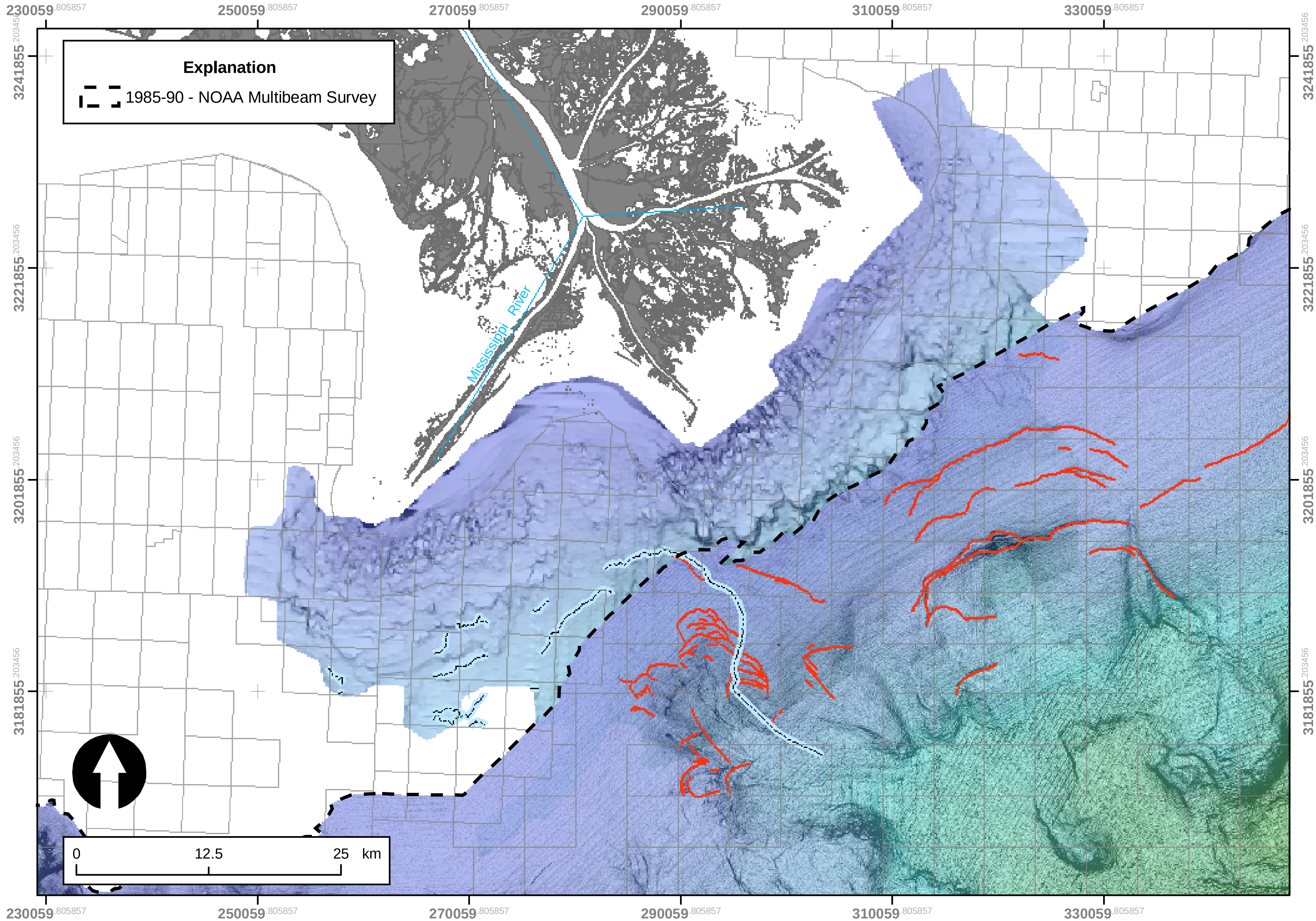

Figure 6. Composite Bathymetric map (1977-1990) illustrating locations of bathymetric profiles.

sedimentation, or perhaps tectonic displacement (above regional salt structures), then the residual map layers document the loci, amounts, and rates of seafloor change associated with the processes.

Rates of change (in feet per year) were derived from the difference between 1874 and 1940 bathymetric surveys (Figure 7), a time period of 66 years, and between the 1940 and 1977-1979 surveys (Figure 8), a period of 35 to 37 years. Rates of change were derived by dividing the total amount of change between two grid points by the time between the two surveys of interest. The final sedimentation rate map layer used in construction of the mudflow susceptibility map layer was obtained by subtracting the 1940 bathymetric map from the 1977 bathymetric map and dividing residual values by 37 years to obtain sediment accumulation/erosion rates. The resulting sedimentation rate map was binned into a series of categories (high to low sediment accumulation) and assigned relative hazard point scores (Table 3).

Table 3. Contribution to mudflow hazard from sediment accumulation and erosion rates (based on rate of change derived from comparison of historic bathymetric data).

Rate of Change (feet/year)	Change in Sea Floor Depth	Point Score	Hazard
-2 to -2.5	Decrease – very high	9	High
-1 to -2	Decrease - high	9	↑
-0.5 to -1	Decrease - moderate	6	
-0.25 to –0.5	Decrease - low	3	
0 to –0.25	Decrease –very low	1	Low
0 to 0.25	Increase – very low	1	Low
0.25 to 0.5	Increase - low	2	
0.5 to 1	Increase - moderate	3	
1 to 2	Increase - high	6	↓
> 2	Increase –very high	9	High

Slope Gradient Map

Although very gradual compared to hillslopes on land, submarine slopes play a large role in underwater stability in the Mississippi Delta region. Slopes exhibiting marginal static stability, and areas of past submarine failure, are usually the most susceptible to hurricane-induced failure. Oversteepened slopes in previous mudflow headscarps, sides of mudflow gullies, and disrupted mudlobe masses are particularly prone to failure.

As part of our mudslide susceptibility mapping, we developed a slope gradient map layer using digital bathymetric data derived from 1977-1979 bathymetric maps, the most detailed and laterally extensive public dataset available (Figure 9). The slope map derived from the 1977-79 dataset is similar to that derived from the 1940 bathymetric dataset. The slope-gradient map layer was derived using a third-order, finite difference, center-weighted algorithm. Based on a direct correlation between slope and hazard, we assign the greatest point score, associated with the greatest mudflow hazard, to the steeper slopes (Table 4).

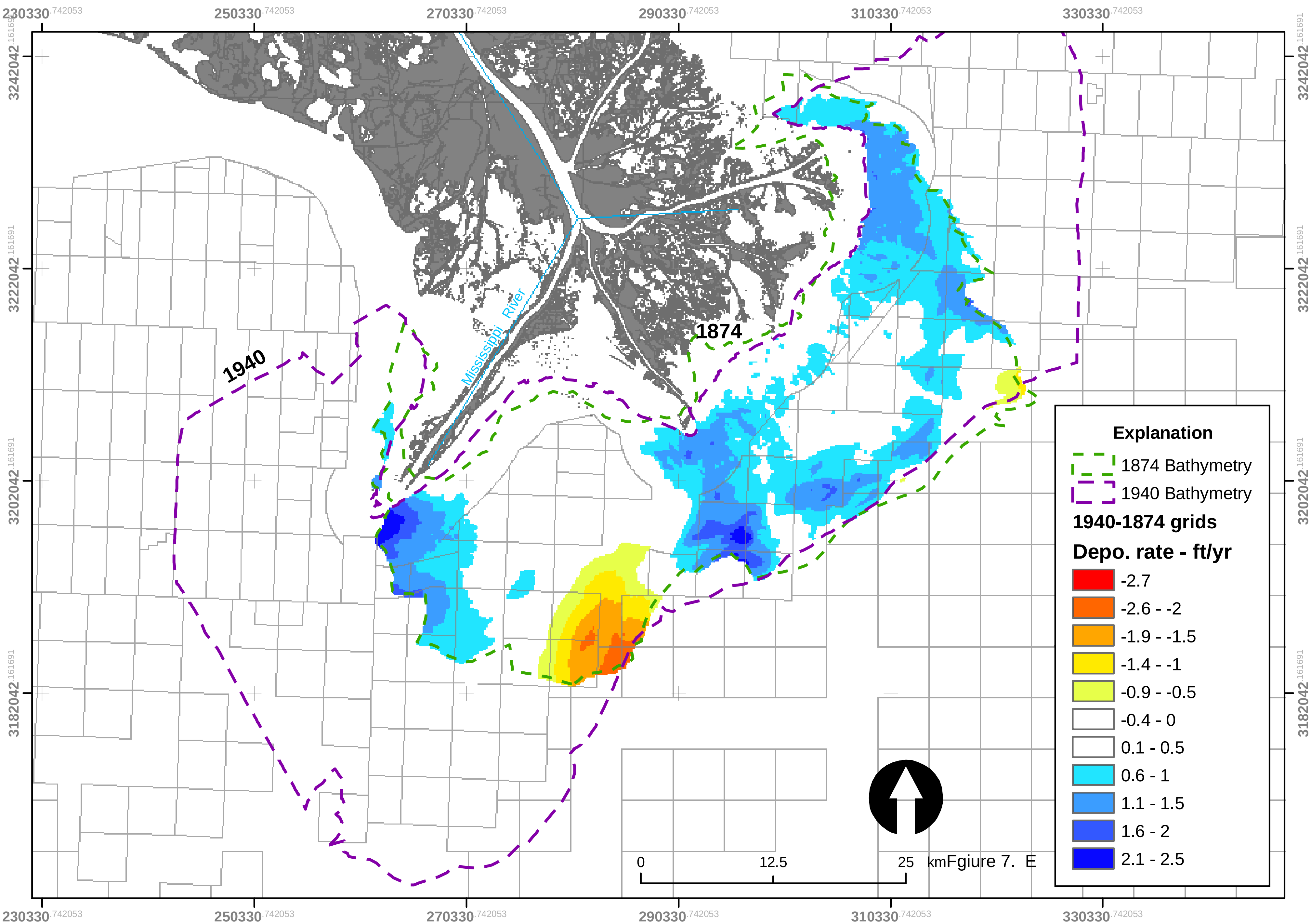

Figure 7. Residual map of seafloor change from 1874 to 1940.

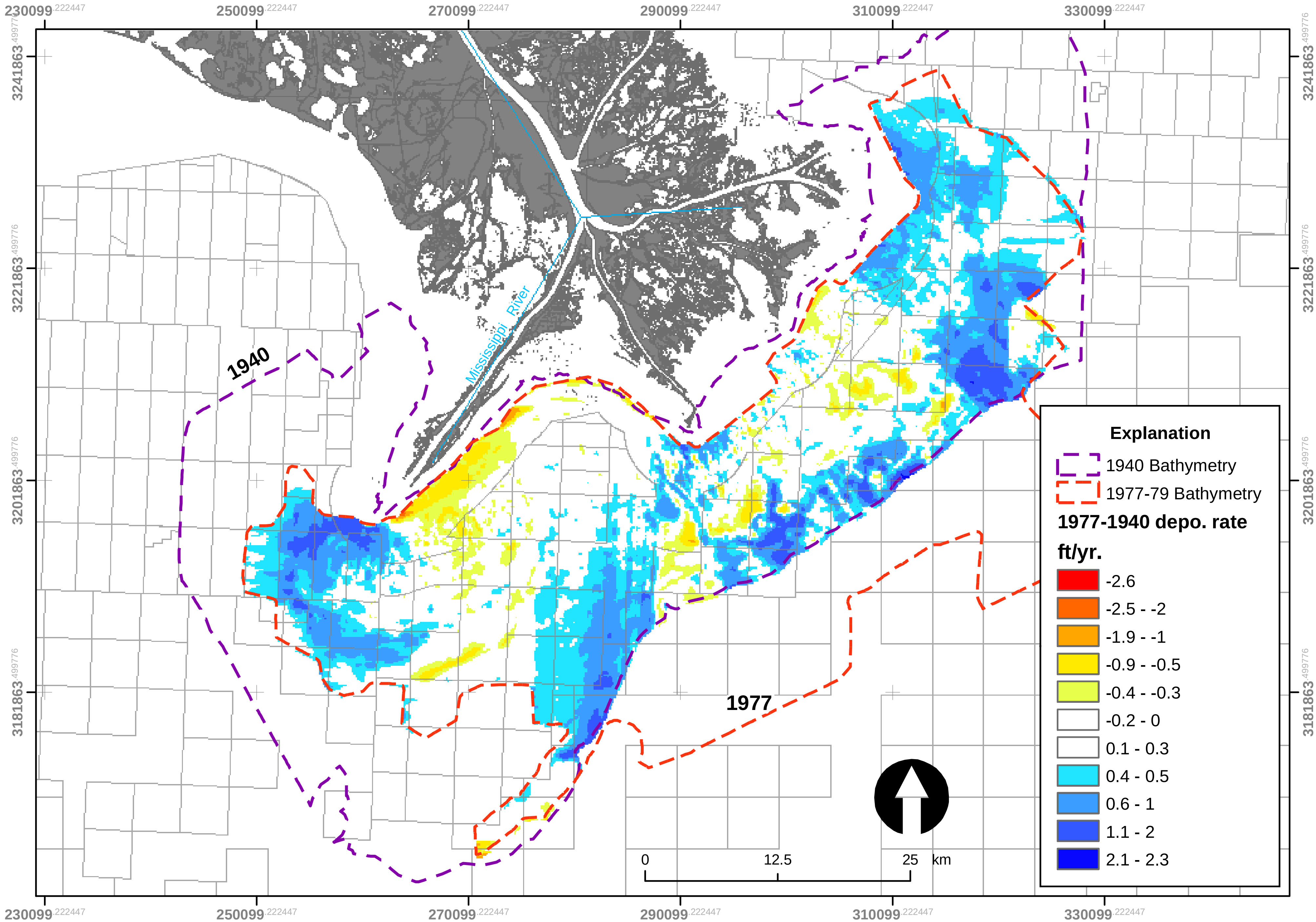

Figure 8. Residual map of seafloor change from 1940 to 1977-79.

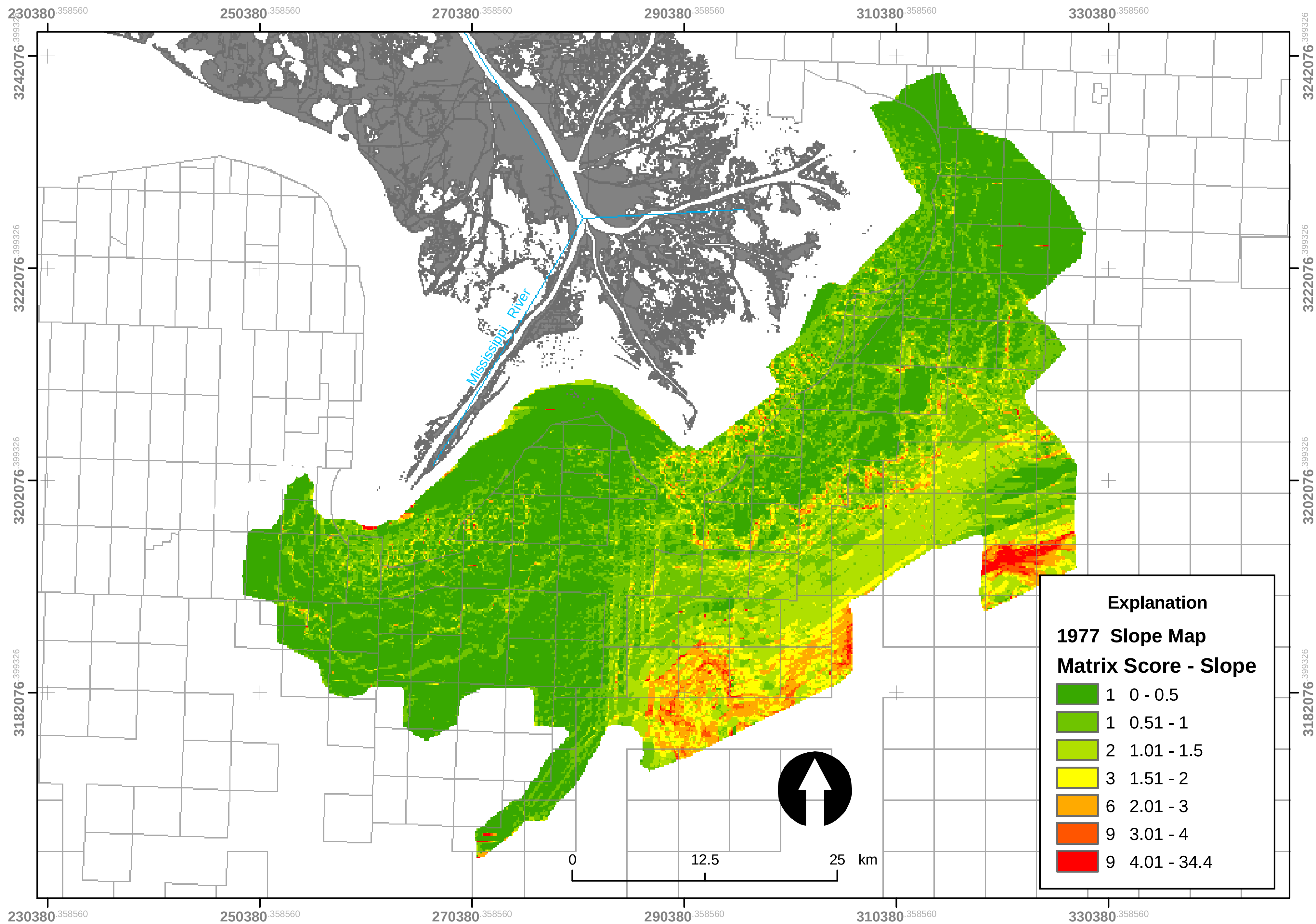

Figure 9. Slope map derived from 1977-1979 bathymetry.

Table 4. Contribution to mudflow hazard from seafloor slope.

Slope (degrees)	Point Score	Hazard
>4°	9	High
3° - 4°	9	↑
2° - 3°	6	
1.5° - 2°	3	
1° - 1.5°	2	
0° - 1°	1	Low

GIS-based Integration of Map Layers

GIS was used to compile existing data into a common database, and to develop derivative hazard maps by map layering techniques. The final landslide susceptibility classifications were defined by the Criteria Matrix (Figure 4), as derived from the sum of each input map's point score (Table 5). The individual weights of the input data were calibrated based on comparison with areas of known mudflow failures. These mudflow classifications, based on the cumulative point scores, were used to construct a regional mudflow susceptibility map (Plate 1).

Table 5. Mudflow susceptibility map classes with associated cumulative point scores derived from input map layers.

Cumulative Point Score	Mudflow Susceptibility
9 - 30	Very High
6 - 9	High
3 - 6	Moderate
0 - 3	Low

RESULTS

Ultimately the *potential* for future damaging mudflows depends on not only the *susceptibility* of slopes to failure but also the *opportunity* for waves input from future large hurricanes to exceed a specified threshold level required for initiation of mudslides. In order to evaluate potential locations and amounts of mudsliding over a future period of interest, and during extreme triggering events like hurricanes, mudslide susceptibility mapping must be combined with site-specific geotechnical information as well as potential storm intensity input and return interval risk. However, in absence of this detailed information and based on examination of available regional data, we have taken the initial step of delineating areas of relative sea floor stability, active mudflow transport, and mudlobe deposition.

Our final liquefaction map (shown on Plate 1) depicts areas of relative susceptibility to mudflow failure and related change, i.e. local erosion or burial. Areas of 'low' mudflow susceptibility (score 0-3) likely are relatively stable but may be impacted by minor or sparsely distributed mudflows with minimal hazard to built structures. Areas of 'moderate' susceptibility (score >3-6) likely will experience localized, minor seafloor changes and/or sediment transport with minimal impacts to the built environment. Areas of 'high' mudflow susceptibility (score >6-9) likely will have extensive mudflows triggered during winter storms or by hurricanes producing new large mudflow deposits. Mudflows may impact and damage built structures. Areas of 'very high' mudflow susceptibility (score >9) will likely have extensive mudflows triggered during winter storms or by hurricanes along with associated submarine slope failures on steep slopes. Built structures may be damaged by mudflow transport and deposition of new mudflows.

Areas of Greatest Instability

Interestingly, areas of the greatest net change in the sea floor appear to have been centered in roughly the same locations over the past 120 years. Major areas of net sediment accumulation are located off the main distributaries (shown in red on Figures 7 and 8). These areas have progressed seaward with the development of the distributaries but are directly connected to deposition at the mouths of the distributaries. Major and minor mudflow gullies appear to have remained in relatively the same locations over the same time periods, with relatively minor lateral shifts.

The deposition zone, located downslope of the gullies is an area of net change with recent to active deposition. A northeast-trending zone of sediment accumulation present offshore of South Pass from 1874 to 1977 (Figure 7 and 8), coincides with a region of relatively steep slopes formed by the front of young mudlobes. The high slopes and high-rates of deposition suggest the mudlobe deposition zone should be considered a high hazard area as existing and new infrastructure may be damaged by future mudflows. In particular, localized damage and burial of pipelines and production facilities is possible due to mudflow overruns from upslope gullies and mudflows.

The distal portion of the mudlobe deposition zone is bounded the headward migration of salt-related growth faults near the shelf edge. The shelf edge may serve, in part, to limit the seaward, downslope migration of the mudlobe depositional system. Although a distinctly separate process from that of sediment transport and deposition, long-term displacement on these faults cause local steepening of submarine slopes that may serve to intensify slope failures.

Areas of Relative Stability

Our approach focused on delineating and ranking areas of greatest historic change for the Mississippi Delta area as part of our map-based evaluation of portions of the seafloor with the highest likelihood of future failure. However, equally important, there are areas of the seafloor that apparently are relatively stable over time and thus likely much less susceptible to future failure.

Areas of relative seafloor stability are marked by low sediment accumulation/erosion. Due east of South Pass is a region of minor sediment accumulation (-0.5 to 0.5 ft/yr.) in the 1940/1874 sediment accumulation map (Figure 7). This region also has low to moderate sediment accumulation and erosion in the 1977/1940 map (Figure 8). We believe these regions of relative stability are representative of regions located between mudflow gullies. The 1977/1940 residual map (Figure 8) illustrates south-southeast-trending zones of erosion, which maybe evacuated mudflow gullies (e.g. regions of active mudflow transport to the mudlobe front). Areas of relative stability located between active mudflow gullies likely primarily consist of older sediment. The gully interfluves are associated with low mudflow hazard, with the exception of localized margin erosion and minor mudflow overflow, and are more viable locations for siting pipelines and other structures.

Although locally associated with mud transport and associated high mudflow hazard, major and minor mudflow gullies appear to have remained in relatively the same locations over the same time period, with minor lateral shifts. In particular, the residual map derived from the difference between the 1977-79 and 1940 bathymetric data sets highlighted distinct south-southeast-trending zones of net seafloor loss, which coincide with mapped mudflow gullies (e.g. regions of active mudflow transport to the mudlobe front). This could reflect either total sediment bypass, or sequential erosion and deposition during mudflow transport events. If erosion and subsequent deposition impact the same reaches of a channel during single events, the net change is very low.
In striking contrast, areas of seafloor instability are marked by high rates of sediment loss or accumulation. Not surprisingly, major areas of sediment accumulation are located off the main distributaries. These areas have increased in size and progressed seaward with the development of the distributaries.

The mudlobe deposition zone consists of northeast-trending zone of high-rate sediment accumulation present offshore of South Pass. The mudlobe zone coincides with a region of oversteepend high slopes formed by the front of young mudlobes, located downslope of the active gully transport zone. Net seafloor deposition associated with the mudlobe zone is focused in roughly the same area from 1874 to 1977-1979.

Salt-related growth faults near the shelf edge may serve, in part, to limit the seaward, downslope migration of the mudlobe depositional system. Long-term displacement on these faults likely causes local steepening of submarine slopes that may serve to intensify slope failures and limit downslope migration of the mudlobe front.

Calibration of Mudflow Susceptibility Mapping with Post-Hurricane Ivan Multibeam Bathymetry

Comparison of our preliminary susceptibility mapping to failures inferred from the post-Hurricane Ivan multibeam bathymetric data (e.g. Figure 10) enables us to evaluate the effectiveness of the mapping. This information is used to calibrate the utility of the pilot mudflow susceptibility mapping and identity what key parameters may influence locations of future mudflows. The calibration process is essential to determine if the mapping approach is valid, if the results are overly conservative, and what other factors or datasets might be required to produce more accurate hazard assessment.

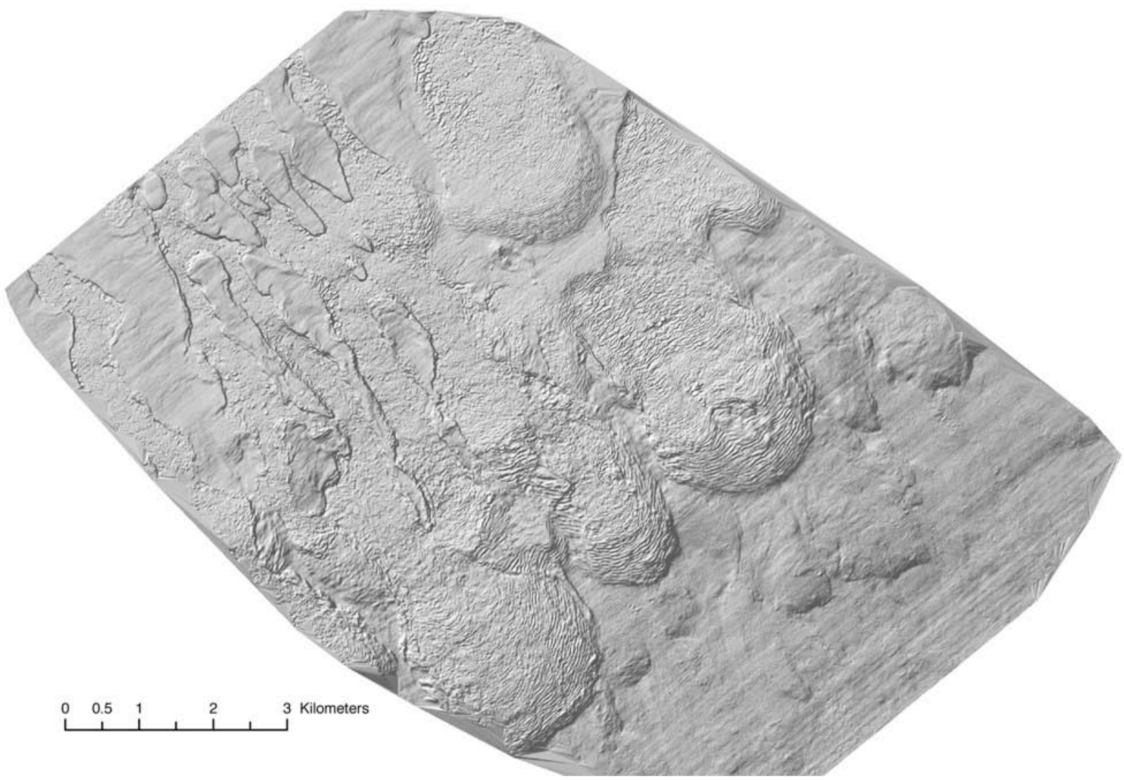

Figure 10. Post-Hurricane Ivan multibeam dataset.

Multibeam data collected within a portion of the mudlobe area after Hurricane Ivan (Figure 10), before Hurricanes Katrina and Rita, document distinct seafloor changes between the 1977-1979 bathymetric surveys and 2004, a period of 25 to 27 years (Figure 11). Unfortunately, the absence of seafloor surveys immediately before Hurricane Ivan precludes determination of what portion of the changes are directly attributable to the hurricane.

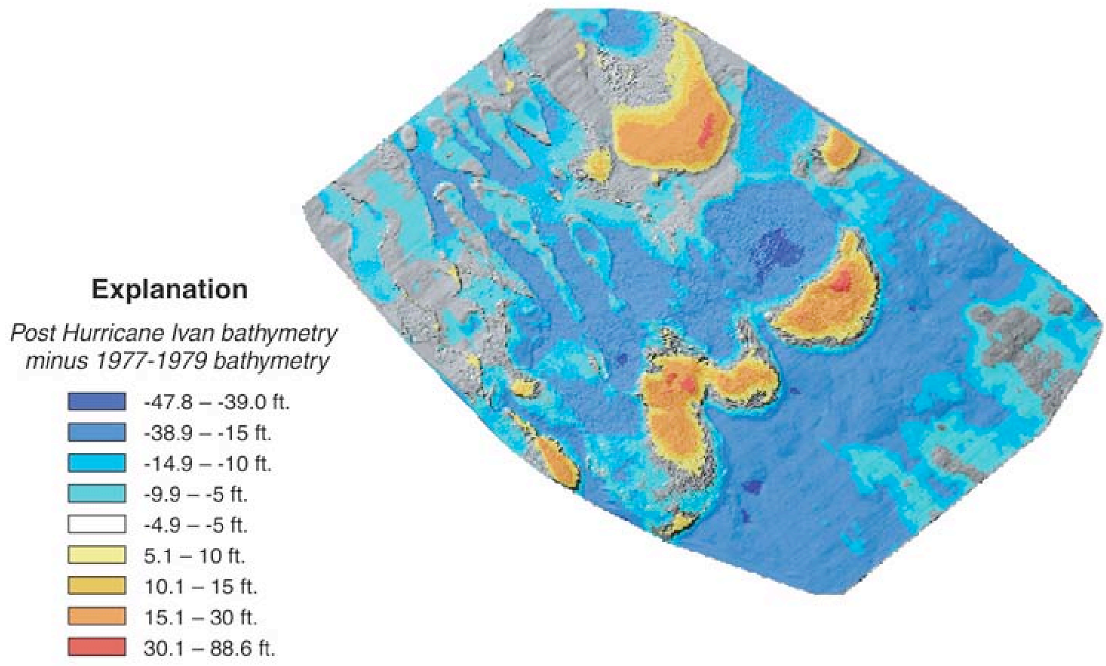

Figure 11. Net change in the seafloor determined from post-Hurricane Ivan multibeam dataset (represents change over a 25 to 27 yr period, including Hurricane Ivan related movement).

Based on interpretation of the post-Ivan bathymetry, areas of net seafloor erosion are most closely associated with mudflow gullies (Figure 11). These gullies appear to have been emptied between 1977-79 and 2004, with the intervening gully interfluves relatively unchanged over the same time period. Net seafloor loss also is closely associated with downslope failure of large mudlobes, in 300 to 400 feet of water, with net deposition within the mudlobe front. Failure of the mudlobes appears to consist primarily of downslope slumping with net loss in the uphill portion of the mudlobe and net deposition downslope. This deposition consists of mudlobe overflow onto older mudlobes, causing oversteepended mudfront slopes.

Our hazard mapping appears to have adequately characterized areas of greatest net change, including erosion within the mudflow channels and deposition within the mudlobes, as well as areas of minimal change ('low' hazard) associated with Hurricane Ivan (Figure 12). However, the mudflow hazard susceptibility mapping did not capture the large mudflow in the northern portion of the map that apparently occurred during Hurricane Ivan. The 1977-79 bathymetric data did not have sufficient detail to identify the front of this mudlobe.

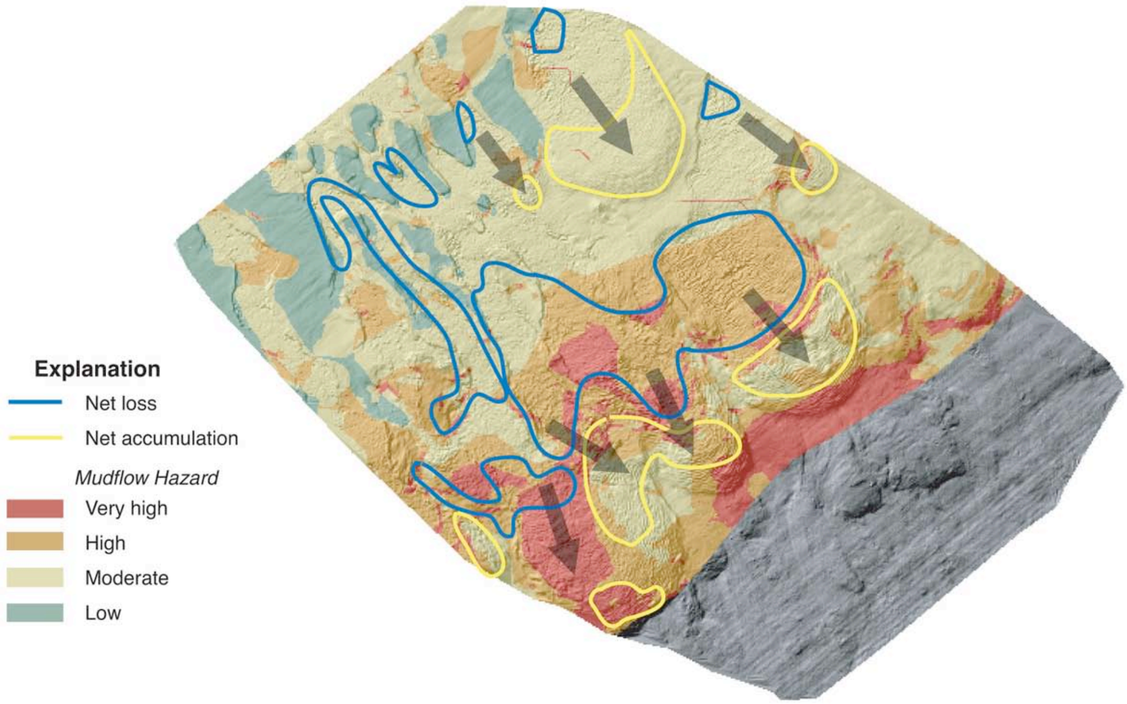

Figure 12. Comparison of areas of net seafloor accumulation and loss derived from post-Hurricane Ivan multibeam dataset with mudflow hazard map derived from 1977-1979 geologic mapping and bathymetric data provided in Coleman et al1. Arrows show inferred directions of mass movement.

Alternatively, this failure may reflect the absence of the mudlobe on the 1977-79 bathymetry, i.e. the mudflow post-dates the 1977-79 bathymetry and may have been directly caused as a new mudlobe by Hurricane Ivan. Future study is required to examine whether mudflow failure that results in the creation of a new mudlobe without the presence of pre-existing morphology may not be readily identifiable using our geomorphic-based mapping approach. If true, this would suggest that incorporation of additional information into the mudflow susceptibility mapping, including geotechnical boring data, would produce more robust hazard maps.

Our mapping adequately characterizes the largest mudflow lobes that have moved since 1977-79 and which present the largest hazard. Comparison of bathymetric surveys performed in 1977-79 and 2004 show that these large flows are migrating downslope. However, our mapping approach does not currently account for the hazard posed to downslope areas overrun by the larger mudflows. Thus, our mapping underestimates the hazard for areas with a mudlobe forming upslope (areas in center of Figure 12 with net accumulation in yellow). Our revised hazard mapping technique incorporates the calculated rate of mudlobe advance to delineate a distance downslope of the active mudlobes as a very high hazard area.

DISCUSSION

Results of our pilot study to develop, test, and apply methods for preparing mudflow susceptibility maps of the Gulf of Mexico in areas impacted by Hurricane Ivan have generally validated our hazard mapping approach with several key exceptions that has required rethinking of some of our assumptions and weighting of the available data sets. We originally envisioned that landslide susceptibility maps for mudflow hazard in the Gulf would incorporate four main input components: 1) mudflow density, 2) slope percent, 3) material strength (incorporating age of mudflow material), and 4) 'gassy' mud thickness. Of these factors, we have found that material strength, as determined from available borehole and geophysical data, is highly variable within mudflow deposits. Sediment strength can vary significantly, both laterally and with depth. In addition, Hooper and Suhayda (2005) show that sediment strength likely varies with time with local strengthening of mud deposits following degassing associated with mudflow deposition. Therefore it is difficult to derive diagnostic characteristics for recent or active mudflows.

Geologic mapping by Coleman et al. (1982) has provided the context for regional and site-specific studies over the past twenty-three years. This published mapping, and accompanying bathymetric datasets, provides the basis for our pilot study. However, with deposition rates of 1 to 2 ft per year and mudlobe front advance into the Gulf of over 2.7 miles between the first submarine survey in 1874 and most recent published survey in 1979-80, much has changed in the submarine environment since the mapping published by Coleman et al. (1982).

Comparison of post-Ivan bathymetric data with pre-Ivan data for a test area allows us to determine locations where the sea floor changed and mudflows likely were caused by Hurricane Ivan. This information is used to calibrate the pilot mudflow susceptibility map provided with this report and examine what key parameters may influence locations and density of future mudflows. The calibration process is essential to determine if the mapping is overly conservative or accurately captures the distribution and density of past mudflows. In addition, comparison of the susceptibility mapping to actual failures will enable us to evaluate whether additional parameters need to be incorporated into the mudslide hazard matrix or the mapping procedure.

Implications for Predicting Future Mudflows

Mudflow susceptibility mapping depicting the vulnerability of sediments on the sea floor bottom is the necessary first step in producing maps that can be used to predict and avoid infrastructure damage. However, mudflow susceptibility mapping, if it is to be useful for risk applications, must include the collection and interpretation of the site and material parameters required to evaluate wave-induced bottom pressure effects from future hurricanes. In addition, in order to quantitatively evaluate the potential locations and movements of mudflows over a future period of interest and during extreme triggering events like hurricanes, mudflow susceptibility mapping needs to be combined with potential storm intensity input and return interval risk. By integrating storm intensity, direction, and return interval it may be possible to produce probabilistic hazard maps that realistically predict probable locations of mudslide failures during future hurricanes, similar to those currently available on land for earthquake-related liquefaction and landsliding (e.g. Keefer et al., 1998).

One of the most important factors in evaluating possible future mudslide failures is the direction of approach of a hurricane to the delta region. The direction of approach of a hurricane to the region is critical as it determines the wave direction. Wave direction likely is not a critical factor for the major mudlobe features in water depths of 300-450 ft because there is an open exposure to wave from many southerly directions. However, in shallower water, mudflow channels contain very weak sediment that absorbs wave energy, cuts wave heights, filters the wave period spectrum, and generally protects upslope areas from otherwise destructive waves.

The orientation of the mudflow gullies therefore likely plays an important role in the impact of large hurricanes on the Delta. Because mud channels are generally oriented downslope (with exceptions), waves that pass across the channels severely impact these channels, while the semi-stable zones lying between the channels may be relatively unaffected (Hooper, 1980; Hooper and Suhayda, 2005). Thus, one of the most important factors in evaluating possible future mudflow failures is the direction of approach of a hurricane to the delta region.

SUMMARY

As part of our pilot MMS-funded project to delineate mudflow failures, sediments susceptible to future slope failure, and areas of relative stability in the Mississippi Delta, we have developed and tested a geomorphic-based approach to map mudflow susceptibility on sea floor bottom. We have developed, and applied, techniques for delineating the relative susceptibility of underwater slopes to mudflows. Based on our results to date for a test area, and examination of available datasets for the Mississippi Delta region, the distribution of submarine landforms (e.g. mudflow gullies and mudflow lobes) and associated underwater failures is not accidental but rather directly reflects the complex interaction between deposition of the Mississippi River and infrequent but highly influential impact of waves from large hurricanes. Based on comparison with post Hurricane Ivan bathymetric data, our map of mudflow hazard accurately characterized relatively high hazard associated with mudflow channels and the areas of greatest net change as the highest hazard.

The mudlobe deposition zone, located downslope of the active transport zone of gullies, is an area of net seafloor change with recent to active deposition. Relatively steep slopes, high rates of change, and historic damage to pipelines and structures suggest the mudlobe deposition zone should be considered a high hazard area with the potential for future mudflows and mudlobe movement. In particular, localized damage and burial of pipelines is possible due to mudflow overruns from upslope gullies and mudflows.
Our preliminary hazard mapping provides a framework for inclusion and interpretation of recent and future bathymetric and geotechnical data.

Our mapping approach can be used on a regional basis to highlight relative mudflow hazard or, by incorporating high-resolution bathymetric data, to evaluate site-specific hazard for pipeline routing and siting of future production facilities. Future work includes incorporation of available geotechnical information and mudflow modeling results by other researchers to refine and improve the predictability of mudflow hazards on the Mississippi Delta seafloor.

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