Geophysical Research Letters

RESEARCH LETTER
10.1029/2020GL087213

Abundant Spontaneous and Dynamically Triggered Submarine Landslides in the Gulf of Mexico

Wenyuan Fan[1], Jeffrey J. McGuire[2], and Peter M. Shearer[3]

[1]Department of Earth, Ocean and Atmospheric Science,Florida State University,Tallahassee,FL,USA , [2]U.S. Geological Survey, Earthquake Science Center,Moffett Field,CA,USA , [3]Scripps Institution of Oceanography,UC San Diego,La Jolla,CA,USA

Key Points:
- Abundant submarine landslides were observed in the Gulf of Mexico
- Many of the landslides were dynamically triggered by remote earthquakes
- There is no clear magnitude dependence of the triggering earthquakes

Supporting Information:
- Supporting Information S1

Correspondence to:
W. Fan,
wfan@fsu.edu

Citation:
Fan, W., McGuire, J., & Shearer, P. M. (2020). Abundant spontaneous and dynamically triggered submarine landslides in the Gulf of Mexico. *Geophysical Research Letters*, *47*, e2020GL087213. https://doi.org/10.1029/2020GL087213

Received 23 JAN 2020
Accepted 22 APR 2020
Accepted article online 18 MAY 2020

Abstract

Submarine landslides that occur offshore are common along the U.S. continental margins. These mass wasting events can trigger tsunamis and hence potentially devastate coastal communities and damage offshore infrastructure. However, the initiation and failure processes of submarine landslides are poorly understood. Here, we identify and locate 85 previously unknown submarine landslides in the Gulf of Mexico from 2008 to 2015. Ten of these landslides failed spontaneously while the remaining 75 were dynamically triggered by passing seismic surface waves from distant earthquakes with magnitudes as small as ∼5. Our observations demonstrate ongoing submarine landslide activity in the Gulf of Mexico where dense energy industry infrastructure is present and that the region is prone to secondary seismic hazard despite the low local seismicity rate. Our results should facilitate future investigations to identify unstable offshore slopes, to illuminate dynamic processes of landslides, and perhaps to apply remote detection technology in tsunami warning systems.

Plain Language Summary

Landslides under the ocean are termed submarine landslides. Submarine landslides can pose hazards to coastal communities and offshore infrastructure, including triggering tsunamis and damaging oil platforms, pipelines, and submarine cables. These devastations may further cause environmental damages such as oil spills. Identifying these landslides and understanding their failure processes have both societal significance and intellectual merit. Using 8 years of continuous seismic data, we found 85 previously unknown submarine landslides in the Gulf of Mexico from 2008 to 2015. Ten of these landslides occurred without preceding earthquakes while the remaining 75 were triggered by the passing seismic surface waves from distant earthquakes. Our approach suggests that a remote detection technology for offshore landslides could be applied in tsunami warning systems.

1. Introduction

Submarine landslides reshape seafloor topography and move vast quantities of continental slope material downhill at both active and passive margins (Hampton et al., 1996; Masson et al., 2006). Catastrophic submarine landslides can displace millions of tons of sediment and rock up to hundreds of kilometers (Dingle, 1977). Such mass wasting events can trigger tsunamis and pose significant hazards to coastal communities and seabed infrastructure (Horrillo et al., 2010, 2013; Ten Brink et al., 2008). Smaller landslides that cause no obvious tsunamis have been identified from the seismic surface waves they generate, which have amplitudes comparable to those of M5 earthquakes (Caplan-Auerbach et al., 2001; Dewey & Dellinger, 2008; McAdoo et al., 2000). Pervasive mass wasting events have been identified along the North American margin from bathymetry data (McAdoo et al., 2000). In particular, submarine landslides have been considered as the primary potential source of tsunami generation in the Gulf of Mexico, albeit at a low probability (Horrillo et al., 2010; Pampell-Manis et al., 2016; Ten Brink et al., 2009). However, the kinematic and dynamic processes within submarine landslides are poorly understood because of the challenges in monitoring and observing the failure processes in real time.

Both terrestrial and submarine landslides can be triggered by earthquakes (Johnson et al., 2017; Massey et al., 2018; Meunier et al., 2007) and are commonly spatially close to the triggering earthquakes (Massey et al., 2018; Meunier et al., 2007). The triggering process correlates with mountain or continental slope stability and the local peak ground acceleration (PGA) from the earthquakes (Massey et al., 2018; Meunier et al., 2007). Similar to dynamic triggering of earthquakes, transient strain perturbations from passing seismic waves play a key role in initiating the slope failure of the triggered landslides (Gomberg et al., 2001; Johnson et al., 2017). In contrast to frequently reported dynamic triggering of earthquakes from distant mainshocks, remote dynamic triggering of landslides and submarine landslides has been rarely observed, with detections likely limited by sparsely sampled study sites (Johnson et al., 2017). In the Gulf of Mexico, month-long gravity flows may have been triggered by unknown seismic sources (Tripsanas et al., 2004a). The possibility of remotely triggered submarine landslides without local earthquakes would significantly increase the landslide hazards at both active and passive margins and complicates using flow deposits and seafloor scarps as paleoearthquake proxies, which is only valid when such deposits are triggered by local earthquakes (Goldfinger et al., 2003). However, few direct seismic observations have constrained the triggering process and the relative importance of spontaneous versus dynamically triggered submarine landslides.

Taking the Mississippi River Delta front (MRDF) in the Gulf of Mexico as an example, one of the most well-studied regions for submarine landslides, most studies have relied on collecting data from past landslide deposits (e.g., Maloney et al., 2019; McAdoo et al., 2000). However, we still lack quantitative measures of the frequency and distribution of landslides and an understanding of the local slope stability response to external triggering factors (Maloney et al., 2019). In the MRDF region, regional earthquakes can cause near-source landslides (Coleman & Prior, 1981; Watkins & Kraft, 1978). Observations of additional landslide triggering mechanisms include the following: (1) active salt diapirism has been linked to sediment instability (Martin & Bouma, 1982; Tripsanas et al., 2003, 2004b), (2) high river floods correlate with new mudflow gullies (Coleman & Garrison, 1977, 2004b), and (3) cyclic loading and associated pore-water pressure effects from strong ocean waves (e.g., hurricane-induced ocean waves) can decrease slope stability by both increasing the shear stress acting on sediments and by decreasing the shear strength of the sediments (Henkel, 1970; Pepper & Stone, 2004). However, mudflow activity has been observed offshore Southwest Pass of the Mississippi River during periods without major hurricane activity across the MRDF (2005–2014) or other clear triggering sources (Obelcz et al., 2017). It is unknown whether these unexplained mudflows resulted from steady creep or more episodic flow. It is possible that river floods or small winter storms may have triggered these mudflows, but understanding of the landslide kinematics remains elusive (Maloney et al., 2019).

We performed a comprehensive search for seismic sources in the Gulf of Mexico and found 85 seismic sources from 2008 to 2015 that excited coherent transcontinental seismic surface waves (Figure 1). These seismic sources are not earthquakes cataloged by the Global Centroid Moment Tensor project (GCMT) (Ekström et al., 2012) or the International Seismological Centre (ISC) (International Seismological Centre, 2013), nor were these sources excited by storms (Supporting Information, Fan et al., 2019). Out of the 85 seismic sources, 10 events occurred spontaneously without obvious preceding earthquakes, while the remaining 75 events occurred immediately or with a short time delay after the passage of surface waves from distant earthquakes, and hence were likely dynamically triggered (Figure 1and Table S1 in the supporting information). Without any other known seismic sources, the paucity of earthquakes and the lack of active faults in the Gulf of Mexico suggest that these 85 well-located seismic events are most easily explained as submarine landslides. In addition, the spatiotemporal correlation between the remote earthquakes and 75 of the events suggests that most of the submarine landslides were dynamically triggered by passing seismic surface waves.

2. Materials and Methods

We applied a novel surface-wave detector based on the Automated Event Location Using a Mesh of Arrays (AELUMA) method to 8 years (2008–2015) of continuous vertical-component long-period seismic data (Figure 1) (de Groot-Hedlin & Hedlin, 2015; Fan et al., 2018), which are primarily from the USArray Transportable Array (Busby et al., 2006). We rely on 20–50 s period Rayleigh waves to detect and locate seismic sources in the Gulf of Mexico (Fan et al., 2018, 2019). Details are discussed in the Supporting Information. Rayleigh waves have been used successfully for detecting and locating unconventional seismic sources, including glacial quakes, landslides, and stormquakes (Ekström et al., 2003; Fan et al., 2019; Tsai & Ekström, 2007). These events commonly have long durations, are depleted in high-frequencies, lack clear seismic arrivals, and have low signal-to-noise ratios (SNR) (Ekström et al., 2003; Shearer et al., 2011; Tsai & Ekström, 2007). These challenges make unconventional seismic sources difficult to detect, and they are commonly missed in standard earthquake catalogs (Ekström, 2006; Shearer, 1994). Our method, which is designed to detect and locate any source of seismic radiation, applies to continuous data and does not require seismic

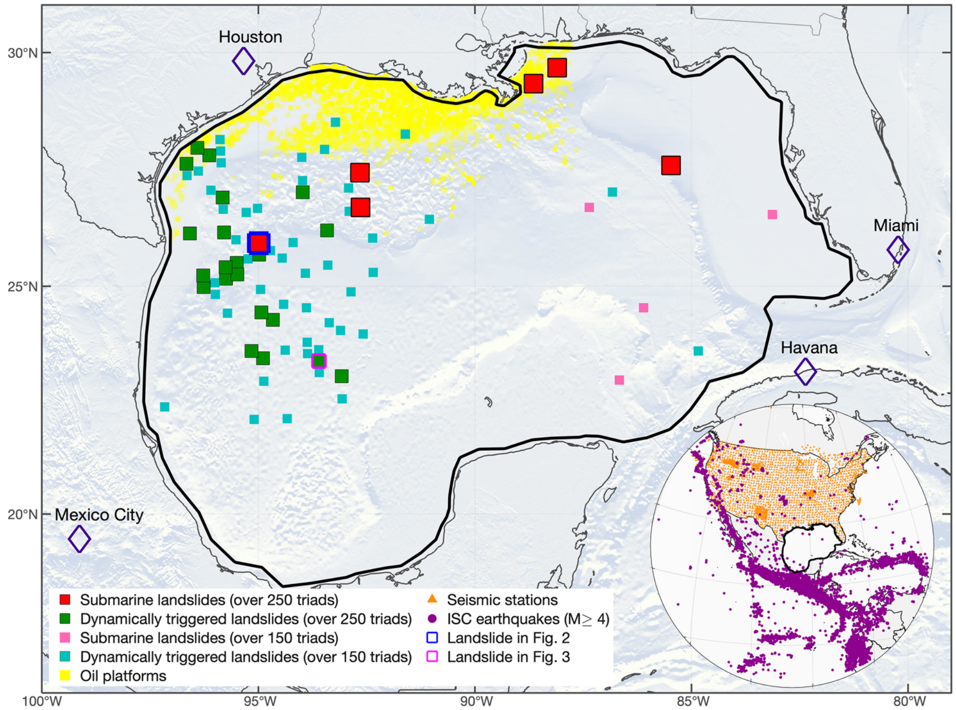

Figure 1. Shaded topographic map showing submarine landslides in the Gulf of Mexico (2008–2015) inferred from seismic observations (this study) and offshore oil platforms. Location estimates for the landslides are shown as squares and the black line outlines the investigated region of the Gulf of Mexico. The insert shows earthquakes reported in the ISC catalog (International Seismological Centre, 2013) with magnitudes greater than 4 (magnitude determined by ISC, NEIC, GCMT, or JMA) from 2006 to 2015, and the U.S. seismic stations are shown as orange triangles, including USArray TA stations, regional networks, and flexible arrays (for details, see the Supporting Information).

phase picks, prior knowledge of source types, or an accurate seismic velocity model (de Groot-Hedlin & Hedlin, 2015; Fan et al., 2018).

The method divides continental-scale seismic arrays into nonoverlapping triangular subarrays (triads) to measure local surface-wave coherence, and then inverts for a source location using the resolved surface-wave propagation directions and arrival times from the triads (e.g., Figure 2) (Fan et al., 2018, 2019). To assure the robustness of the detected submarine landslides, only sources seen by more than 150 triads and having location uncertainty less than 5° are considered in this study (Supporting Information). Six spontaneous submarine landslides and 22 dynamically triggered submarine landslides were located with more than 250 triads (Figure 1), assigned as A and AA quality, respectively, and the remaining events located with more than 150 triads are assigned as B and BB quality, respectively (Table S1). The 85 seismic sources were further screened by visual inspection of aligned USArray records with respect to their epicenters, and all the submarine landslides have coherent transcontinental phases that can be easily identified in the filtered seismograms (e.g., Figure 3c). Our observations are most consistent with seismic waves generated by submarine landslides, as the events are unlikely to be artifacts or S-to-Rayleigh wave scatterers (Supporting Information). We empirically assessed the location uncertainties of the detected seismic sources by using the same approach to locate known regional earthquakes in the Gulf of Mexico and southern Texas (Figure S1). For seismic sources located near the northern Gulf of Mexico, the location uncertainty is less than 50 km for the best cases (Figure S1).

3. Results

On 22 September 2013, an A-quality submarine landslide spontaneously occurred in the northern Gulf of Mexico offshore Texas (Figure 2), which we identified as described above and which did not clearly associate with earthquakes or other indigenous sources. The measured surface-wave propagation directions and arrival times captured the coherent transcontinental wavefield excited by the landslide (Figures 2 and S2). The directly measured surface-wave amplitudes at 20-s period suggest a surface-wave

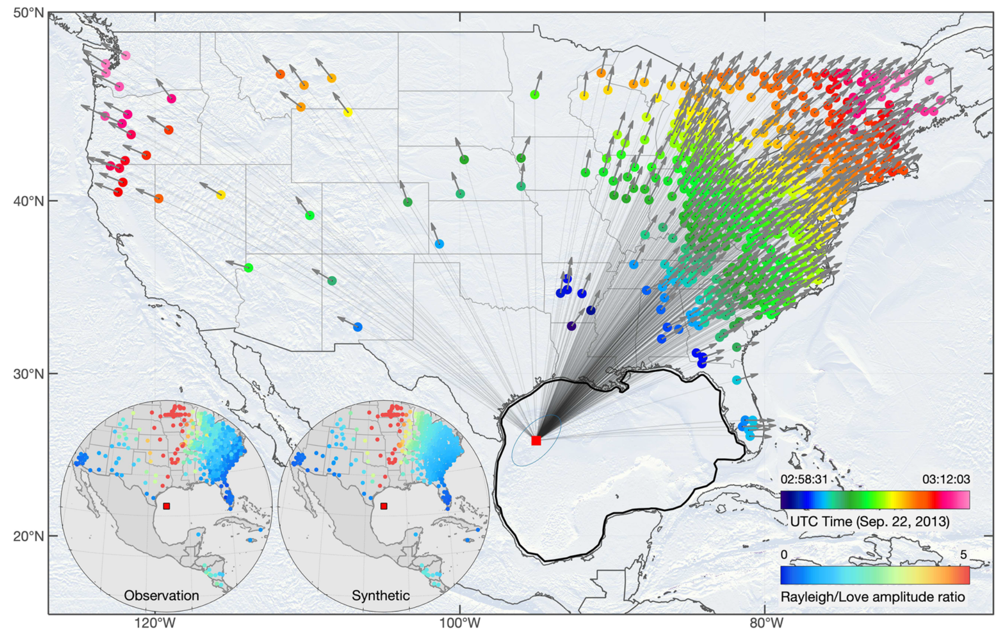

Figure 2. Shaded topographic map showing a spontaneous submarine landslide on 22 September 2013 (red square). The ellipse shows the estimated location uncertainty of the landslide (Fan et al., 2018). The Rayleigh-wave arrival times and propagation directions at each subarray (triad) are shown as the colored dots and arrows. The thin line between the detected submarine landslide and each triad shows the great circle path. The inserts show the observed and synthetic Rayleigh-to-Love amplitude ratios (Supporting Information).

magnitude (Ms) of 3.45. The landslide failure process can be explained by a centroid single-force (CSF) model (Figure S3) (Ekström & Stark, 2013; Tsai & Ekström, 2007). We invert for a CSF model using regional intermediate-period (40–80 s) surface waves, assuming that the source can be simplified as three symmetric boxcar force functions with a fixed duration of 20 s representing forces in the vertical, north, and east directions (Figure S3). The peak amplitude of the centroid force is 1.15×10^{11} N, and the total displaced mass was likely to be 62×10^{9} kg (62 million tons) inferred from an empirical scaling relationship (Ekström & Stark, 2013). If the sediment density is around 1.7×10^{3} kg/m^{3}, this implies displacement of 3.6×10^{7} m^{3} of sediment, which could have covered a region of 1 km^{2} with a thickness of 36 m. The volume of this landslide is smaller than previously reported landslides in the Gulf of Mexico that were identified from the bathymetry data, but landslides with similar volume have been reported along other U.S. margins (McAdoo et al., 2000; Ten Brink et al., 2008). The volume is within the range of typical terrestrial landslides that can efficiently excite seismic surface waves (Ekström & Stark, 2013). To further confirm the source mechanism and rupture dynamics of the submarine landslide, we compared the observed Rayleigh- to Love-wave amplitude ratio with the predicted ratio from the inverted CSF model (Figure 2) and found a good fit to the observed amplitude ratios for stations within 20° epicentral distance at all azimuth (inserts, Figure 2). This submarine landslide is located near a continental slope edge with steep topography, which might have facilitated the gravitational downslope movement (Figures 1 and 2) (Hampton et al., 1996; McAdoo et al., 2000). Another submarine landslide (A quality) occurred on 29 December 2011 offshore Louisiana and can be modeled as a CSF with peak amplitude of 6×10^{10} N, which might have displaced 32×10^{9} kg sediment (Figure S4). Mechanisms of the remaining spontaneous submarine landslides (A and B quality) are unclear due to limited usable data at intermediate periods, although they all excited coherent transcontinental surface waves (e.g., Figure S2).

The 5 January 2009 Gulf of California earthquake (Mw 5.5) is typical of the mainshocks that can trigger submarine landslides in the Gulf of Mexico (Figure 3). The triggered AA-quality landslide occurred 1,547 km away and 435 s after the mainshock, with an occurrence time that coincides with the passage of the mainshock surface waves (~3.6 km/s). The absence of background seismicity near the detected source and the spatiotemporal correlation between the submarine landslide occurrence and the passing surface waves suggests the event was likely near-instantaneously dynamically triggered. The surface-wave packets

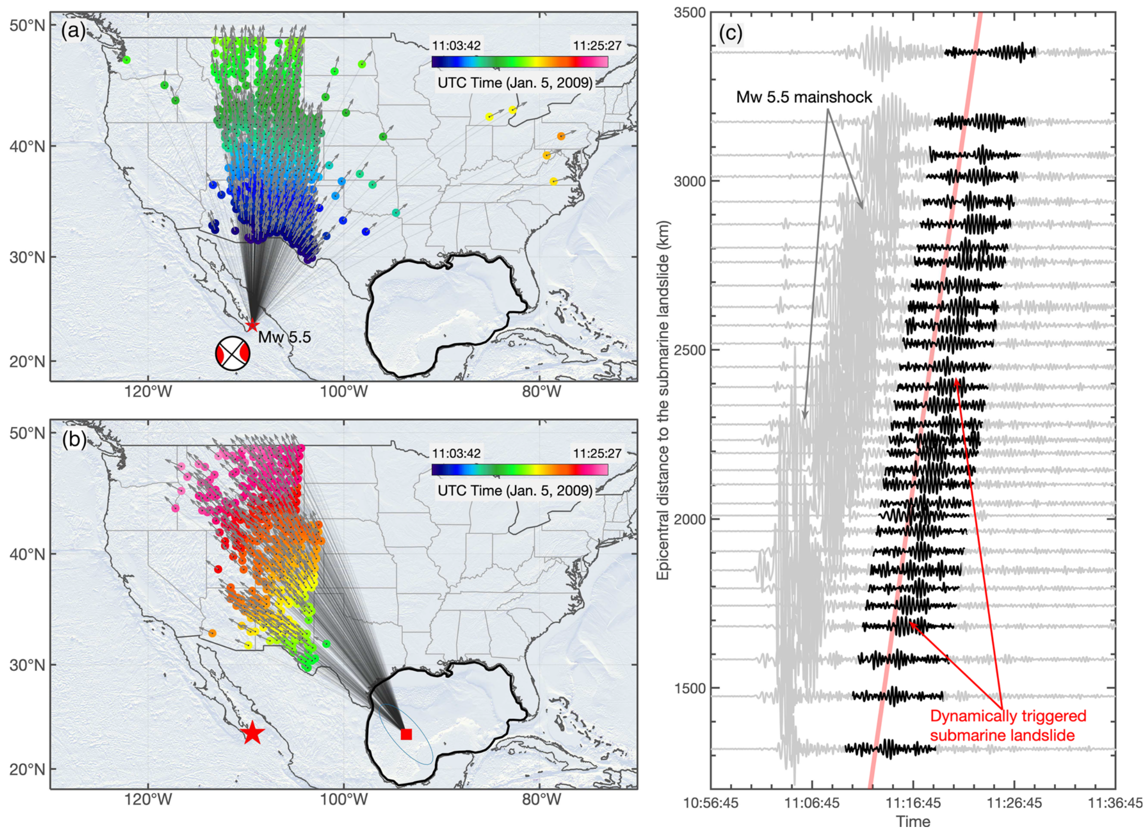

Figure 3. A submarine landslide dynamically triggered by the 5 January 2009 Gulf of California earthquake (Mw 5.5). The Rayleigh wave arrival times and propagation directions of the triggering earthquake (a) and the dynamically triggered submarine landslide (b) are shown as the colored dots and arrows. (c) A record section of self-normalized bandpass-filtered (20–50 s) waveforms aligned with the epicenter of the submarine landslide in (b). The records are randomly selected from the stations to cover a wide range of epicentral distances. The red line shows a 3.5 km/s reference move-out velocity. The gray and black signals are waves from the triggering and triggered events, respectively, and the arrows point out example surface wave packets of the triggering (gray) and triggered (red) events.

of the triggered submarine landslide are well separated from the mainshock surface waves and can be easily identified from the aligned traces, confirming the robustness of our detection (Figure 3c). Occasionally, multiple submarine landslides can be triggered by one mainshock (Figure S5). For example, the 10 January 2010 offshore Northern California earthquake (Mw 6.5) triggered two submarine landslides in the Gulf of Mexico, and the earthquake-submarine landslide sequence caused over 30 minutes of ground motion at stations along the U.S. west coast (Figures S5A–S5C). Another example is the May 28 2009 offshore Mexico earthquake (Mw 5.3), which caused a similar cascading process in the Gulf of Mexico (Figures S5D–S5F). It is interesting that these landslide-triggering mainshocks are moderate-magnitude earthquakes thousands of kilometers away, as studies of dynamic triggering of earthquakes typically involve larger and/or closer mainshocks. It is possible that ground motions near the triggered submarine landslides were strongly amplified by local geological structures and topography, which might have led to the observed slope failures (Johnson et al., 2017).

In total, 75 submarine landslides in the Gulf of Mexico were dynamically triggered by 65 remote earthquakes from 2008 to 2015 (Figure 4, Table S1). These distant earthquakes were within 40° of the Gulf of Mexico, and concentrated along the Pacific and North American plate boundary spanning a wide range of latitude (inserts, Figure 4). The triggered landslides cluster in the northwestern corner of the Gulf of Mexico, where local seafloor topography is highly heterogenous with numerous locally steep regions around diapirs and basins possibly created by tectonics in conjunction with the mobile salt layer offshore Texas (Figure 1) (McAdoo et al., 2000). Comparing the triggering distance to triggering time, all the detected submarine landslides occurred after the passage of *S*-waves (median triggering velocity 2.6 km/s) and are most likely triggered during or after the passage of the surface waves (e.g., 3 km/s, Figures 4 and S6). These observations indicate that the landslides were triggered either near-instantaneously or triggered with a short delay time

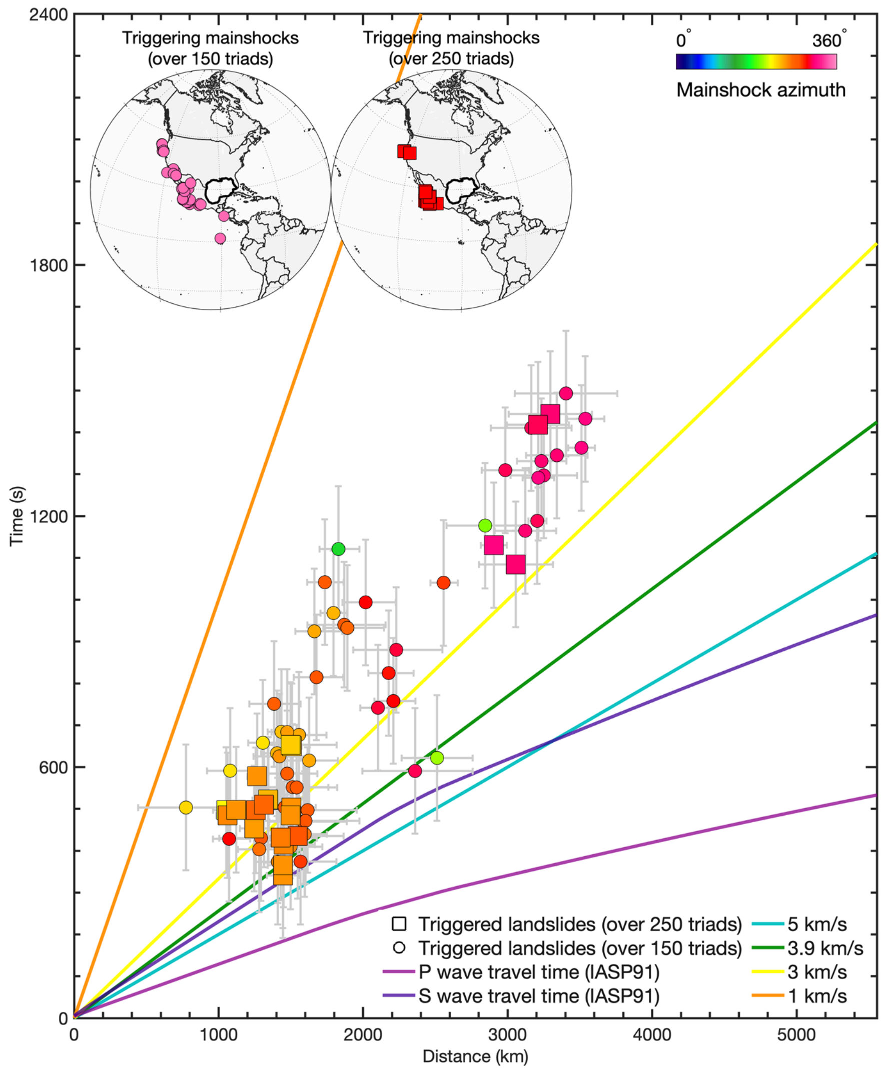

Figure 4. Time versus distance plot of the triggered submarine landslides. Twenty-two triggered landslides (AA quality) are shown as squares, and 53 triggered landslides (BB quality) are shown as circles. The landslides are colored by the azimuth of their triggering earthquakes. The gray bars show the triggering distance uncertainties and 150 s reference uncertainty in triggering time (Table S1). The inserts show the locations of the triggering earthquakes. The *P*- and *S*-wave arrival times are from the IASP91 velocity model (Kennett & Engdahl, 1991).

of less than tens of minutes, although the lack of near-field in situ observations hampers detailed differentiation of these two triggering types. Triggering distance uncertainty for a given triggered submarine landslide is evaluated by assessing distances from the mainshock to the nearest and furthest points on its uncertainty ellipse (Figure 4, Table S1). Our surface-wave detector determines the event time after solving for the event location (Fan et al., 2019); therefore, the estimated event time and location are not independent. Given that the maximum location uncertainty of the detected triggered landslides are less than 521 km, we take 150 s (assuming a 3.5 km/s surface-wave speed) as a reference uncertainty range for all the triggered submarine landslides (Figure 4) (Fan et al., 2019). Given this uncertainty, we do not analyze possible triggering pairs that are spatially separated by less than 6° to assure the robustness of our temporal correlations and interpretations. However, local earthquake triggering has been reported by previous studies (Meunier et al., 2007; Massey et al., 2018; Ten Brink et al., 2009). Our current observations do not exclude other types of triggering processes such as local earthquake triggering or high river floods, but focus on previously underrecognized submarine landslides that are dynamically triggered by distant earthquakes.

4. Discussions and Conclusions

The 65 remote triggering earthquakes have diverse source characteristics, including all three types of focal mechanisms (strike-slip, reverse, and normal faulting earthquakes), magnitudes ranging from Mw 4.9 to Mw 7.3, and centroid depths ranging from 12 to 69 km (Figure S6, Table S1). In addition, the triggering mainshocks occur at a wide range of azimuths from the Gulf of Mexico (Figure 4). We observe more moderate-magnitude triggering earthquakes than large-magnitude earthquakes, which is consistent with the Gutenberg-Richter law. This observation indicates that distant moderate-size earthquakes might have similar triggering potential to large earthquakes in causing submarine landslides in the Gulf of Mexico. Fifty-one triggering earthquakes are strike-slip earthquakes, and the triggered submarine landslides are commonly located within the maximum radiation-lobe of either Rayleigh or Love waves of these earthquakes. A large portion of these strike-slip earthquakes are from the Rivera Fracture Zone, the Gulf of California, and the Mendocino Fracture Zone (Figure 4, Table S1). The median magnitude of the triggering earthquakes is Mw 5.4, and we do not observe the triggering earthquake magnitude clearly increasing with triggering distance (Figure S6). Intriguingly, there is an absence of triggered events following remote $M \geq 8$ earthquakes, including the 2010 Maule earthquake, the 2011 Tohoku earthquake, and the 2012 Indian Ocean earthquakes, which have dynamically triggered earthquakes globally. One possible explanation is that our approach may have missed potentially triggered slides when the mainshock waveform durations were long and masked over the landslide waveforms (Fan et al., 2018; Johnson et al., 2017). Alternatively, these $M \geq 8$ earthquakes may have not triggered any events in the region because the peak dynamic strain is not the only triggering threshold modulating the triggering behavior. For example, the frequency of the passing surface waves may be a key parameter controlling the process and strong short-period (~30 s) surface waves may be required for the landslide destabilization process (Brodsky & Prejean, 2005), favoring short-to-intermediate triggering distances (Figure 4).

Given that the triggering occurs at distances of over 1,000 km (Figure 4), the predicted dynamic triggering stresses in this study are relatively small, likely less than 0.1 MPa, although we do not have in situ measurements of the wavefield within the low rigidity sediments. The stress perturbations are significantly smaller than those that trigger large-scale landslides in near-earthquake regions (Meunier et al., 2007; Massey et al., 2018; Ten Brink et al., 2009). For example, using high-frequency peak spectral acceleration values and considerations of the failure strength of continental slope sediments, Ten Brink et al. (2009) found that large-scale submarine landslides would only be triggered within ~10 km of a M5.5 and ~50 km of a M7 earthquake, respectively. The contrast in triggering distance range for remote and near-earthquake landslides suggests that the triggering mechanisms are likely different for remote versus local triggering. However, it is currently unclear whether this difference in sensitivity results from different frequency content of the triggering waves, different size landslides, or different regional geologic settings (e.g., U.S. Atlantic margin vs. the Gulf of Mexico). Future in situ seafloor-based ground motion observations and marine geophysical surveys would be necessary to clarify the ground motions and hence dynamic stress perturbations induced by both distant and nearby earthquakes, enabling quantitative modeling of the slope failure processes in the Gulf of Mexico.

Evidence of slope failure is extensive on the margin of the Gulf of Mexico (McAdoo et al., 2000). Compared to the U.S. margin along the east and the west coasts, geomorphic features suggest that the largest near-U.S. submarine landslides by an order of magnitude occurred on the Texas slope in the Gulf of Mexico (McAdoo et al., 2000; Ten Brink et al., 2008). In addition, many very large failures have occurred in Mississippi Canyon province and the largest submarine landslide there covers 5,509 km^2 of seafloor (McAdoo et al., 2000). Most of these identified submarine landslides are dated to over 7,500 years ago, and submarine landslide activity may have been decreasing since the last glacial period (Goodwin & Prior, 1989). However, on 10 February 2006, a mysterious seismic source (Ms 5.3) occurred offshore southern Louisiana, which was likely a submarine landslide (Dewey & Dellinger, 2008; Ten Brink et al., 2008). The 1929 Grand Banks landslide is another example showing the potential for significant submarine landslides (Fine et al., 2005; Mosher & Piper, 2007). Submarine landslide activity triggered by remote earthquakes has been found in offshore Cascadia, although the triggered landslides did not generate clear seismic signals (Johnson et al., 2017). Our observations suggest that submarine landslide activity is active throughout much of the Gulf of Mexico.

The Gulf of Mexico is a geologically complex ocean basin with thick sediment and the observed submarine landslides are likely associated with rapid sediment accumulation and complex seafloor topography with high internal pore pressures (Divins, 2003; Harry Roberts et al., 2000; Lee et al., 1996; Roberts, 1996; Weimer & Dixon, 1994). Mechanically, slides occur when the driving shear stress exceeds the resisting shearing strength, allowing gravitational force to facilitate material transport downslope coupled with internal deformation of the slide. To effectively generate seismic energies, our observed submarine landslides likely slid rapidly along a basal detachment fault beneath a relatively rigid sediment block (Hampton et al., 1996; Masson et al., 2006; Dewey & Dellinger, 2008; Ten Brink et al., 2008). Mechanisms facilitating spontaneous submarine landslides might be overly steep slopes, overpressurization from sedimentation and compaction, gas hydrate dissociation, presence of weak oil layers, or groundwater or oil seepage (Hampton et al., 1996; Locat & Lee, 2002; Masson et al., 2006). The observed dynamic triggering is likely enhanced by thick sediment and complex local bathymetry in the Gulf of Mexico (Gomberg, 2018; Johnson et al., 2017). Geologic structures such as sedimentary basins and topographic ridges may cause strong site amplification, which is likely influenced by earthquake radiation patterns, specific path-site characteristics, and the local geometry and orientation of the structure (Gomberg, 2018). For example, thick sediment may cause long-duration resonances in passing surface waves and greatly amplified local ground motion (Johnson et al., 2017; Gomberg, 2018). Prolonged strong ground motion might lead to cyclic fatigue and enhanced shear failure, causing accumulation of plastic strain and excessive shearing-induced pore fluid pressure, which would effectively reduce the material strength and eventually cause landslides (Biscontin et al., 2004; Meunier et al., 2007; Talling et al., 2014; Wang, 2007). In addition, laboratory experiments have shown that sediment permeability can be enhanced by strong ground motion, which might have further assisted the triggering process (Biscontin et al., 2004; Kokusho & Kojima, 2002). These factors are testable if we have in situ ground motion observations. Currently, the closest nearby broadband stations are in southern Texas, and are too far away and in significantly different geological materials to be a reliable representation of the ground motion in the unconsolidated sediments of the Gulf of Mexico. A future OBS deployment would be highly valuable to understand the dynamic triggering processes, and identify different triggering thresholds.

In addition to radiating coherent transcontinental seismic surface waves, landslides can deform as slowly as centimeters per day without radiating much seismic energy (Hampton et al., 1996; Masson et al., 2006; Delbridge et al., 2016). Therefore, our observations likely represent a minimum measure of submarine landslide activity in the Gulf of Mexico, and we might have missed many slowly deforming submarine landslides. Whether they occur spontaneously or are triggered dynamically by earthquakes, rapidly moving submarine landslides can pose a tsunami hazard for communities along the Gulf of Mexico coast (Ten Brink et al., 2009). In addition, submarine landslides may damage or demolish offshore infrastructure like oil platforms or pipelines (Figure 1), leading to economic loss and possible environmental damage (Bea et al., 1983; Sterling & Strohbeck, 1973). For example, a well in offshore Louisiana (Taylor Energy) was damaged by a submarine landslide and has been continuously leaking for 15 years since 2004 (MacDonald, 2019). Today, offshore drilling programs are expanding into deep water, including the Western Planning Area offshore southern Texas (Orr et al., 2018), where we have observed pervasive submarine landslides. These regions are vulnerable to the hazard posed by triggered landslides whether or not those landslides radiated seismic energy themselves. In addition, our method can be used to detect and locate dynamically triggered terrestrial landslides. The successful detection and location of submarine landslides in the Gulf of Mexico proves the effectiveness of our method and suggests that it has potential to be adapted for real-time hazard monitoring purposes. Future studies in the region to identify unstable slopes and to improve locations of seismically detectable submarine landslides are critical and would facilitate planning efforts to reduce the foreseeable risks posed by such events.

Data Availability Statement

The seismic data were provided by Data Management Center (DMC) of the Incorporated Research Institutions for Seismology (IRIS). The facilities of IRIS Data Services, and specifically the IRIS Data Management Center, were used for access to waveforms, related metadata, and/or derived products used in this study. IRIS Data Services are funded through the Seismological Facilities for the Advancement of Geoscience and EarthScope (SAGE) Proposal of the National Science Foundation under Cooperative Agreement EAR-1261681. The earthquake catalogs were downloaded from the Global Centroid Moment Tensor project (GCMT) (Ekström et al., 2012), and the International Seismological Centre (ISC) (International Seismological Centre, 2013). The AELUMA code can be obtained on request through the IRIS data service product website

(last accessed 13 November 2019). The data used in the study are publicly available at the DMC (last access 01/23/2020). The detected landslide locations are in the Supporting Information.

Acknowledgments
We would like to thank Dr. Hayes, Dr. Tsai, Dr. Gomberg, Dr. Hickman, Dr. Parsons, Dr. ten Brink, and an anonymous reviewer for their constructive suggestions, which have led to improvements in our paper. This work was partially supported by National Science Foundation grant OCE-1833279.

References

Bea, R. G., Wright, S. G., Sircar, P., & Niedoroda, A. W. (1983). Wave-induced slides in South Pass block 70, Mississippi Delta. *Journal of Geotechnical Engineering*, *109*(4), 619–644.

Biscontin, G., Pestana, J., & Nadim, F. (2004). Seismic triggering of submarine slides in soft cohesive soil deposits. *Marine Geology*, *203*(3-4), 341–354.

Brodsky, E. E., & Prejean, S. G. (2005). New constraints on mechanisms of remotely triggered seismicity at Long Valley Caldera. *Journal of Geophysical Research*, *110*, B04302. https://doi.org/10.1029/2004JB003211

Busby, R. W., Vernon, F. L., Newman, R. L., & Astiz, L. (2006). Earthscope's USArray: Advancing eastward. *EOS Transactions American Geophysical Union*, *87*(52). Fall Meet. Suppl., Abstract U41B-0820

Caplan-Auerbach, J., Fox, C. G., & Duennebier, F. K. (2001). Hydroacoustic detection of submarine landslides on Kilauea volcano. *Geophysical Research Letters*, *28*(9), 1811–1813.

Coleman, J. M., & Garrison, L. E. (1977). Geological aspects of marine slope stability, northwestern Gulf of Mexico. *Marine Georesources & Geotechnology*, *2*(1-4), 9–44.

Coleman, J. M., & Prior, D. B. (1981). Subaqueous sediment instabilities in the offshore Mississippi River Delta: Section 5. AAPG Special Volumes, 1–53.

de Groot-Hedlin, C. D., & Hedlin, M. A. (2015). A method for detecting and locating geophysical events using groups of arrays. *Geophysical Journal International*, *203*(2), 960–971. https://doi.org/10.1093/gji/ggv345

Delbridge, B. G., Bürgmann, R., Fielding, E., Hensley, S., & Schulz, W. H. (2016). Three-dimensional surface deformation derived from airborne interferometric UAVSAR: Application to the Slumgullion Landslide. *Journal of Geophysical Research: Solid Earth*, *121*, 3951–3977. https://doi.org/10.1002/2015JB012559

Dewey, J. W., & Dellinger, J. A. (2008). Location of the Green Canyon (offshore southern Louisiana) seismic event of February 10, 2006, U.S. *Geological Survey Open-File Report*, *31p*, 2008–1194.

Dingle, R. (1977). The anatomy of a large submarine slump on a sheared continental margin (SE Africa). *Journal of the Geological Society*, *134*(3), 293–310.

Divins, D. (2003). *Total Sediment Thickness of the World's Oceans & Marginal Seas*. Boulder CO: NOAA National Geophysical Data Center.

Ekström, G. (2006). Global detection and location of seismic sources by using surface waves. *Bulletin of the Seismological Society of America*, *96*(4A), 1201. https://doi.org/10.1785/0120050175

Ekström, G., Nettles, M., & Abers, G. A. (2003). Glacial earthquakes. *Science*, *302*(5645), 622–624. https://doi.org/10.1126/science.1088057

Ekström, G., Nettles, M., & Dziewoński, A. (2012). The global CMT project 2004–2010: Centroid-moment tensors for 13,017 earthquakes. *Physics of the Earth and Planetary Interiors*, *200*, 1–9.

Ekström, G., & Stark, C. P. (2013). Simple scaling of catastrophic landslide dynamics. *Science*, *339*(6126), 1416–1419.

Fan, W., de Groot Hedlin, C. D., Hedlin, M. A. H., & Ma, Z. (2018). Using surface waves recorded by a large mesh of three-element arrays to detect and locate disparate seismic sources. *Geophysical Journal International*, *215*(2), 942–958. https://doi.org/10.1093/gji/ggy316

Fan, W., McGuire, J. J., de Groot-Hedlin, C. D., Hedlin, M. A., Coats, S., & Fiedler, J. W. (2019). Stormquakes. *Geophysical Research Letters*, *46*, 12,909–12,918. https://doi.org/10.1029/2019GL084217

Fine, I., Rabinovich, A., Bornhold, B., Thomson, R., & Kulikov, E. (2005). The Grand Banks landslide-generated tsunami of November 18, 1929: preliminary analysis and numerical modeling. *Marine Geology*, *215*(1-2), 45–57.

Goldfinger, C., Nelson, C. H., Johnson, J. E., & Party, S. S. (2003). Holocene earthquake records from the Cascadia subduction zone and northern San Andreas fault based on precise dating of offshore turbidites. *Annual Review of Earth and Planetary Sciences*, *31*(1), 555–577.

Gomberg, J. (2018). Cascadia onshore-offshore site response, submarine sediment mobilization, and earthquake recurrence. *Journal of Geophysical Research: Solid Earth*, *123*, 1381–1404. https://doi.org/10.1002/2017JB014985

Gomberg, J., Reasenberg, P., Bodin, P. L., & Harris, R. (2001). Earthquake triggering by seismic waves following the Landers and Hector mine earthquakes. *Nature*, *411*(6836), 462.

Goodwin, R. H., & Prior, D. B. (1989). Geometry and depositional sequences of the Mississippi Canyon, Gulf of Mexico. *Journal of Sedimentary Research*, *59*(2), 318–329.

Hampton, M. A., Lee, H. J., & Locat, J. (1996). Submarine landslides. *Review of Geophysics*, *34*(1), 33–59.

Harry Roberts, J. C., Hunt Jr, J., & Shedd, W. (2000). Surface amplitude mapping of 3D-seismic for improved interpretations of seafloor geology and biology from remotely sensed data. *Gulf Coast Association of Geological Societies Transactions*, *50*, 495–503.

Henkel, D. (1970). The role of waves in causing submarine landslides. *Geotechnique*, *20*(1), 75–80.

Horrillo, J., Wood, A., Kim, G.-B., & Parambath, A. (2013). A simplified 3-D Navier-Stokes numerical model for landslide-tsunami: Application to the Gulf of Mexico. *Journal of Geophysical Research: Oceans*, *118*, 6934–6950. https://doi.org/10.1002/2012JC008689

Horrillo, J., Wood, A., Williams, C., Parambath, A., & Kim, G. (2010). Construction of Tsunami Inundation Maps in the Gulf of Mexico. Report Award Number: NA09NWS4670006, National Tsunami Hazard Mitigation Program (NTHMP), National Weather Service Program Office, NOAA.

International Seismological Centre (2013). On-line Bulletin, Int. Seis. Cent., Thatcham, United Kingdom, http://www.isc.ac.uk. Latest access 04/14/2020.

Johnson, H. P., Gomberg, J. S., Hautala, S. L., & Salmi, M. S. (2017). Sediment gravity flows triggered by remotely generated earthquake waves. *Journal of Geophysical Research: Solid Earth*, *122*, 4584–4600. https://doi.org/10.1002/2016JB013689

Kennett, B., & Engdahl, E. (1991). Traveltimes for global earthquake location and phase identification. *Geophysical Journal International*, *105*(2), 429–465.

Kokusho, T., & Kojima, T. (2002). Mechanism for postliquefaction water film generation in layered sand. *Journal of Geotechnical and Geoenvironmental Engineering*, *128*(2), 129–137.

Lee, G. H., Watkins, J. S., & Bryant, W. R. (1996). Bryant canyon fan system: an unconfined, large river-sourced system in the northwestern Gulf of Mexico. *AAPG bulletin*, *80*(3), 340–357.

Locat, J., & Lee, H. J. (2002). Submarine landslides: Advances and challenges. *Canadian Geotechnical Journal, 39*(1), 193–212.

MacDonald, I. R. (2019). Underwater mudslides are the biggest threat to offshore drilling, and energy companies aren't ready for them. The Conversation, March 11.

Maloney, J. M., Bentley, S. J., Xu, K., Obelcz, J., Georgiou, I. Y., Jafari, N. H., & Miner, M. D. (2019). Mass wasting on the Mississippi River subaqueous delta. *Earth-Science Reviews*, *200*, 103001. https://doi.org/10.1016/j.earscirev.2019.103001

Martin, R. G., & Bouma, A. H. (1982). Active diapirism and slope steepening, northern Gulf of Mexico continental slope. *Marine Georesources & Geotechnology*, *5*(1), 63–91.

Massey, C., Townsend, D., Rathje, E., Allstadt, K. E., Lukovic, B., Kaneko, Y., et al. (2018). Landslides triggered by the 14 November 2016 Mw 7.8 Kaikōura earthquake, New Zealand. *Bulletin of the Seismological Society of America*, *108*(3B), 1630–1648.

Masson, D., Harbitz, C., Wynn, R., Pedersen, G., & Løvholt, F. (2006). Submarine landslides: Processes, triggers and hazard prediction. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *364*(1845), 2009–2039.

McAdoo, B., Pratson, L., & Orange, D. (2000). Submarine landslide geomorphology, US continental slope. *Marine Geology*, *169*(1-2), 103–136.

Meunier, P., Hovius, N., & Haines, A. J. (2007). Regional patterns of earthquake-triggered landslides and their relation to ground motion. *Geophysical Research Letters*, *34*, L20408. https://doi.org/10.1029/2007GL031337

Mosher, D. C., & Piper, D. J. W. (2007). Analysis of multibeam seafloor imagery of the Laurentian Fan and the 1929 Grand Banks landslide area. In V. Lykousis, D. Sakellariou, & J. Locat (Eds.), Submarine mass movements and their consequences, *Advances in Natural and Technological HazardsResearch* (Vol. 27). Dordrecht: Springer. https://doi.org/10.1007/978-1-4020-6512-5_9

Obelcz, J., Xu, K., Georgiou, I. Y., Maloney, J., Bentley, S. J., & Miner, M. D. (2017). Sub-decadal submarine landslides are important drivers of deltaic sediment flux: Insights from the Mississippi River Delta front. *Geology*, *45*(8), 703–706.

Orr, R., Hammerle, K., & Frye, M. (2018). Development of the 2019-2024 national oil and gas leasing program on the united states outer continental shelf. in 2018 AAPG International Conference and Exhibition.

Pampell-Manis, A., Horrillo, J., Shigihara, Y., & Parambath, L. (2016). Probabilistic assessment of landslide tsunami hazard for the northern Gulf of Mexico. *Journal of Geophysical Research: Oceans*, *121*, 1009–1027. https://doi.org/10.1002/2015JC011261

Pepper, D. A., & Stone, G. W. (2004). Hydrodynamic and sedimentary responses to two contrasting winter storms on the inner shelf of the northern Gulf of Mexico. *Marine Geology*, *210*(1-4), 43–62.

Roberts, H. H. (1996). Surface amplitude data: 3D-seismic for interpretation of sea floor geology (Louisiana slope). *Gulf Coast Association of Geological Societies Transactions*, *46*, 353–362.

Shearer, P. M. (1994). Global seismic event detection using a matched filter on long-period seismograms. *Journal of Geophysical Research*, *99*(B7), 13,713–13,25. https://doi.org/10.1029/94JB00498

Shearer, P. M., Walter, F., & Fricker, H. A. (2011). Seventeen Antarctic seismic events detected by global surface waves and a possible link to calving events from satellite images. *Journal of Geophysical Research*, *116*, B06311. https://doi.org/10.1029/2011JB008262

Sterling, G. H., & Strohbeck, E. (1973). The failure of the South Pass 70B platform Hurricane Camille. in Offshore Technology Conference, Offshore Technology Conference.

Talling, P. J., Clare, M. L., Urlaub, M., Pope, E., Hunt, J. E., & Watt, S. F. (2014). Large submarine landslides on continental slopes: geohazards, methane release, and climate change. *Oceanography*, *27*(2), 32–45.

Ten Brink, U. S., Lee, H. J., Geist, E. L., & Twichell, D. (2009). Assessment of tsunami hazard to the US east coast using relationships between submarine landslides and earthquakes. *Marine Geology*, *264*(1-2), 65–73.

Ten Brink, U., Twichell, D., Geist, E., Chaytor, J., Locat, J., Lee, H., et al. (2008). Evaluation of tsunami sources with the potential to impact the US Atlantic and Gulf coasts, U.S. Geological Survey Administrative report to the US Nuclear Regulatory Commission 300.

Ten Brink, U., Twichell, D., Lynett, P., Geist, E., Chaytor, J., Lee, H., et al.(2009). Regional assessment of tsunami potential in the Gulf of Mexico. U.S. Geol. Surv. Admin. Rep to the National Tsunami Hazard Mitigation Program.

Tripsanas, E. K., Bryant, W. R., & Phaneuf, B. A. (2004a). Depositional processes of uniform mud deposits (unifites), Hedberg Basin, northwest Gulf of Mexico: New perspectives. *AAPG Bulletin*, *88*(6), 825–840.

Tripsanas, E. K., Bryant, W. R., & Phaneuf, B. A. (2004b). Slope-instability processes caused by salt movements in a complex deep-water environment, Bryant Canyon area, northwest Gulf of Mexico. *AAPG Bulletin*, *88*(6), 801–823.

Tripsanas, E. K., Bryant, W. R., Prior, D. B., & Phaneuf, B. A. (2003). Interplay between salt activities and slope instabilities, Bryant Canyon area, northwest Gulf of Mexico. In J. Locat, J. Mienert, & L. Boisvert (Eds.), Submarine mass movements and their consequences, *Advances in Natural and Technological Hazards Research* (Vol. 19). Dordrecht: Springer. https://doi.org/10.1007/978-94-010-0093-2&urluscore;34

Tsai, V. C., & Ekström, G. (2007). Analysis of glacial earthquakes. *Journal of Geophysical Research*, *112*, F03S22. https://doi.org/10.1029/2006JF000596

Wang, C.-Y. (2007). Liquefaction beyond the near field. *Seismological Research Letters*, *78*(5), 512–517.

Watkins, D. J., & Kraft Jr, L. M. (1978). Stability of continental shelf and slope off Louisiana and Texas: Geotechnical aspects: 4. character of the sediments.

Weimer, P., & Dixon, B. (1994). Regional sequence stratigraphic setting of the Mississippi fan complex, northern deep Gulf of Mexico: Implications for evolution of the northern gulf basin margin. In *Submarine fans and turbidite systems: Sequence stratigraphy, reservoir architecture and production characteristic, GCSEPM Found 15th Ann Res Conf*, pp. 373–381.