

OVERVIEW OF THE U.S. NUCLEAR REGULATORY COMMISSION COLLABORATIVE RESEARCH PROGRAM TO ASSESS TSUNAMI HAZARD FOR NUCLEAR POWER PLANTS ON THE ATLANTIC AND GULF COASTS

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ABSTRACT :

In response to the 2004 Indian Ocean Tsunami, the United States Nuclear Regulatory Commission (US NRC) initiated a long-term research program to improve understanding of tsunami hazard levels for nuclear facilities in the United States. For this effort, the US NRC organized a collaborative research program with the United States Geological Survey (USGS) and the National Oceanic and Atmospheric Administration (NOAA) with a goal of assessing tsunami hazard on the Atlantic and Gulf Coasts of the United States. Necessarily, the US NRC research program includes both seismic- and landslide-based tsunamigenic sources in both the near and the far fields. The inclusion of tsunamigenic landslides, an important category of sources that impact tsunami hazard levels for the Atlantic and Gulf Coasts is a key difference between this program and most other tsunami hazard assessment programs. The initial phase of this work consisted of collection, interpretation, and analysis of available offshore data, with significant effort focused on characterizing offshore near-field landslides and analyzing their tsunamigenic potential and properties. In the next phase of research, additional field investigations will be conducted in key locations of interest and additional analysis will be undertaken. Simultaneously, the MOST tsunami generation and propagation model used by NOAA will first be enhanced to include landslide-based initiation mechanisms and then will be used to investigate the impact of the tsunamigenic sources identified and characterized by the USGS. The potential for probabilistic tsunami hazard assessment will also be explored in the final phases of the program.

KEYWORDS:

Tsunami, Landslide, Seismic, Hazard, Nuclear

1. BACKGROUND

In response to the 2004 Indian Ocean Tsunami, as well as the anticipation of the submission of license applications for new nuclear facilities, the United States Nuclear Regulatory Commission (US NRC) initiated a long-term research program to improve understanding of tsunami hazard levels for nuclear power plants and other coastal facilities in the United States. To undertake this effort, the US NRC organized a collaborative research program with researchers at the United States Geological Survey (USGS) and the National Oceanic and Atmospheric Administration (NOAA) for the purpose of assessing tsunami hazard on the Atlantic and Gulf Coasts of the United States. The project work described in this paper represents the combined effort of a diverse group of marine geologists, geophysicists, geotechnical engineers, and hydrodynamic modelers to evaluate tsunami sources that have the potential to impact the U.S. Atlantic and Gulf coasts.

The Atlantic and Gulf Coasts are the focus of this program, both because of the number of existing and proposed nuclear facilities located on these coasts and because many promising research efforts for assessing tsunami

hazard in the Pacific Coast of the United States are already underway as a result of programs outside the US NRC. Tsunami has been long known as a hazard in the Pacific Ocean. However, the 2004 tsunami highlighted the fact the tsunamis can occur in other oceans that are less prepared for this rare phenomenon. Although tsunamis are far rarer along the Atlantic and Gulf of Mexico coastlines, some areas can be highly vulnerable to tsunamis when they do occur because major population centers and industrial facilities are located near the shoreline at low-lying elevations, and often in estuaries. This is in comparison to the Pacific coast where tsunamis are more frequent but the coastline is more sparsely populated and most sections have more topographic relief.

Because the US NRC is interested in understanding hazard associated with the rare large tsunami that may occur over long time periods (in excess of 10,000 years), the research program was developed to investigate both seismic and landslide tsunamigenic sources. It also includes the study and characterization of large sources in the far field, as well as sources in the near field such that all key sources were considered. The study of near-field and far-field tsunamigenic landslides is a key difference between this research program and other tsunami hazard assessment programs, which are typically focused on seismic sources. Although seismic sources are important on the Atlantic and Gulf Coasts, submarine landslides have also historically generated destructive tsunamis and so must be fully investigated in this program. In landslide initiated tsunami, the extent of damaging waves generated by landslides is generally smaller and more localized. However, along coastlines proximal to catastrophic submarine landslides, tsunami run-up can be significant as exemplified by the 1929 Grand Banks tsunami (Newfoundland and Nova Scotia), which likely had a significant landslide-generated component. Less is generally known about submarine landslides as tsunami triggers in comparison to their earthquake counterparts.

Although only a few years old, this research program has already produced significant results that are currently or will soon be available to the public through a variety of technical publications. These publications include a USGS report to the US NRC (Ten Brink et al, 2007) and multiple articles in a special issue of Marine Geology to be published late 2008 or early 2009 (Barkana et al; Chaytor et al; Geist et al; Lee; Locat et al; Ten Brink et al, 2008). The early research and results discussed in the USGS report were focused on providing sufficient information on the source parameters useful for qualitative assessment of tsunami hazard for the Atlantic and Gulf coasts. This information is currently being used to develop and review tsunami hazard assessments for new nuclear power facilities in the United States. A companion paper in this conference summarizes and discusses in more detail some of the early results of the US NRC program (Kammerer et al, 2008)

2. INITIAL INVESTIGATION OF NEAR-FIELD LANDSLIDE SOURCES IN THE ATLANTIC

In the initial phase of work a significant level of effort was focused on identifying and characterizing offshore near-field landslides and on understanding their regional distribution along the coasts. In this work, efforts were made to consider the impact of varying conditions, such as the effects of glacial periods and sea level changes. Once early results on the location and characterization of offshore landslides was obtained, an effort towards modeling one of the larger slides, the Currituck Slide, was initiated to better understand the tsunami hazard posed by the mapped slides. Before tsunami generation and propagation modeling of the Currituck slide could be undertaken, important properties of the slide, such as flow velocity, needed to be characterized. Work at Laval University included analysis of the dynamic elements of the Currituck slide; and modeling of the slide was undertaken by both Texas A&M University and the USGS. A summary of each of these steps is provided below and a more complete discussion of the results of key research elements is provided in the companion paper in this conference. This early work has also been well documented in the public USGS report (Ten Brink et al, 2007).

2.1 DATA COLLECTION

The first step in the initial investigation of landslides in the Atlantic was the collection and analysis of a large amount of available information useful for the identification and characterization of offshore landslides along the Atlantic coast of the U.S. Multibeam bathymetry, Geologic Long-Range Inclined Asdic (GLORIA) sidescan sonar imagery, a regional grid of high-resolution seismic profiles, and published accounts of sediment cores from

the region was collected (Figure 1). In addition to these data sets, a review of past work studying the geology of the offshore environment, as well as studies of offshore landslides were also collected, reviewed, and summarized. A discussion of the body of previous work is provided in the USGS report (Ten Brink et al, 2007).

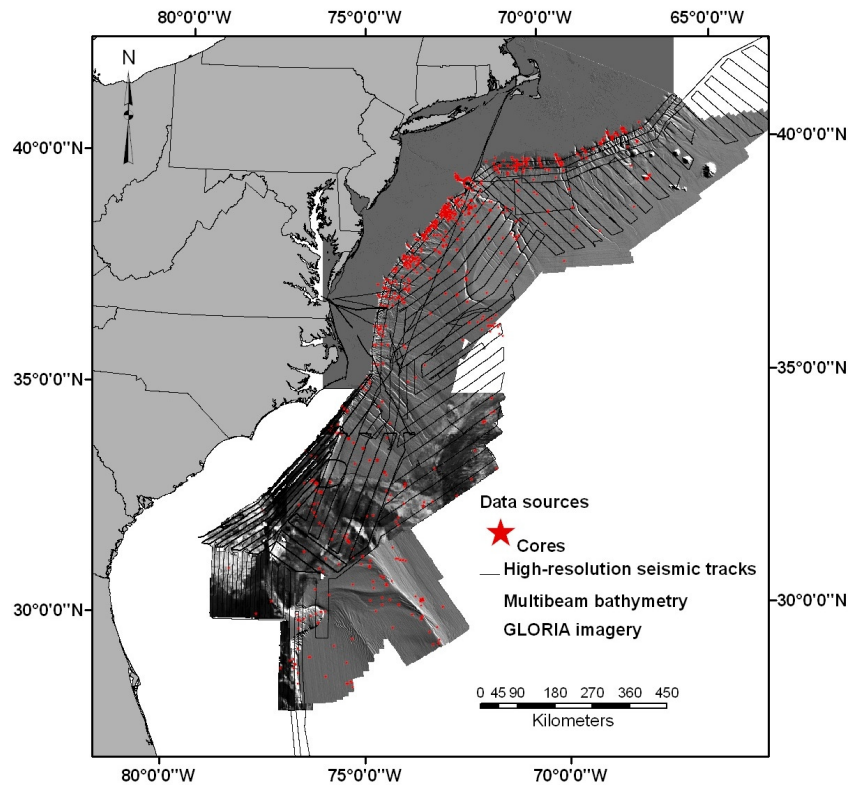


Figure 1 Data Collected for Study of Potential Tsunamigenic Landslides on U.S. Atlantic Coast

Data used in the compilation of the Atlantic coast bathymetry map used in the study were acquired from several sources and vary in age, sounding density, and positional accuracy. The primary data set was acquired by the University of New Hampshire (UNH) (Gardner et al., 2006; Cartwright and Gardner, 2005) and provides near continuous coverage of the U.S. Atlantic margin from the base of the continental slope down to the abyssal plain. These data include gridded bathymetric soundings and mosaiced acoustic backscatter. For sections of the continental slope and rise not covered by the UNH data set, several additional multibeam datasets were used. For areas in which no multibeam soundings were available, sounding data from the National Ocean Service hydrographic database and the NOAA coastal relief model provided bathymetric coverage of the continental slope. Efforts will be made to address some of these data gaps through field studies in future phases of the program. The final map developed for this project covers the ocean floor from the shoreline to depths greater than 5,000 m, between 43.5 and 24 degrees north latitude.

In addition to the acoustic backscatter data from the UNH multibeam surveys, GLORIA sidescan sonar data were used to identify and map landslide features along the U.S. Atlantic continental margin (EEZ-SCAN 87, 1991). Analogue records of 3.5-kHz seismic reflection profiles, co-acquired with the GLORIA sidescan imagery, were used to determine location, geometry, and thickness of landslide features. Although other data sets are available, the acquisition parameters and quality of these data are consistent over the entire area of study, and they provide a relatively clear picture of the upper sedimentary section.

Over 1400 cores have also been collected from the study area off the Atlantic coast, and descriptions of the cores are available. Approximately 1,000 have been visually described, and 145 of them have had general ages

assigned based on faunal content. While the descriptions provided are often brief, they provide a valuable summary of the overall lithology of many of the cores.

2.2 IDENTIFICATION AND CHARACTERIZATION OF LANDSLIDES

The volume and quality of data collected greatly assisted in mapping the distribution and style of surficial submarine landslides along the eastern U.S. margin between the eastern end of Georges Bank and the northern end of the Blake Spur. The near-complete coverage of the Atlantic continental slope and rise by multibeam bathymetry provided a key high-quality and uniform data set that allowed for a more detailed and consistent view and assessment of the geomorphology of submarine landslides than had been possible in the past.

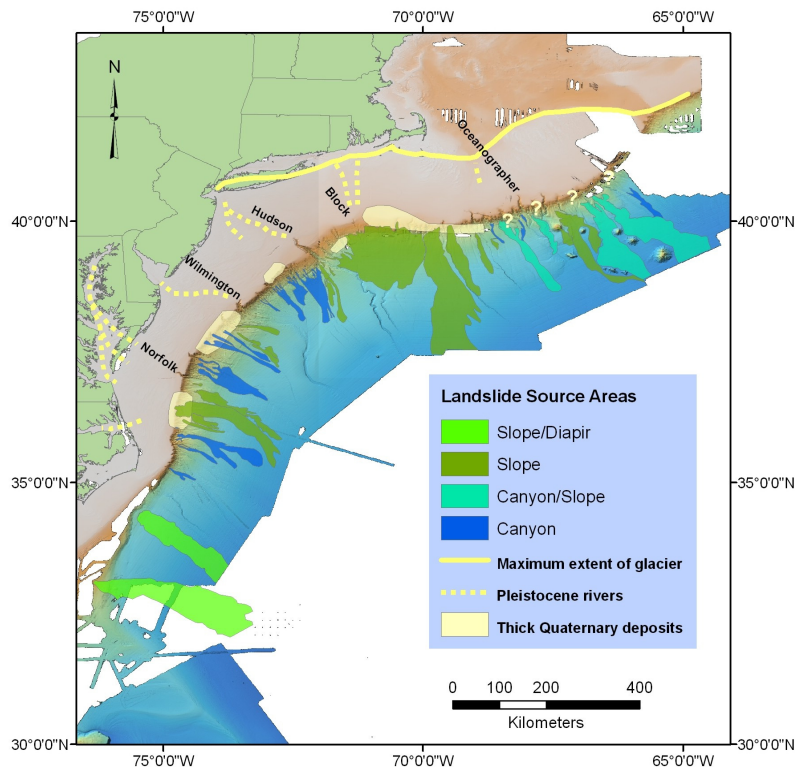


Figure 2 Initial Map of Landslide Source Areas Along the U.S. Atlantic Coast

The mapping of these landslide-affected areas was broken into several steps. The first step was to identify any scarps of significant size around and within landslide source areas. Scarps were easily identified in shaded-relief and slope maps derived from the bathymetric data. Next the areas affected by landslides were outlined. Depending on availability, a mix of shaded-relief imagery, backscatter imagery from the multibeam system, and GLORIA imagery were used. The final step was to merge the thickness information derived from subbottom profiles with the interpretation of the sea-floor imagery to distinguish the erosional and depositional sections of the landslide. The volumes of the source areas of mapped and potential slides of various sizes and differing geologic settings (e.g. submarine canyons or the open slope) were calculated.

This mapping indicates that landslides along the U.S. Atlantic margin initiate predominantly in two morphologic settings, canyon (heads and sidewalls) and on the open continental slope (Figure 2). The canyon-sourced failures often have several canyons feeding a single deposit, and the deposits are smaller than those derived from the open slope. As a result, they are unlikely to cause tsunami events. Open-slope failures commonly originate on the middle and lower slope in 800-2,200 m depths. These landslides extend farther offshore, are thicker, and have

considerably larger volumes than their canyon derived counterparts. As a result of the large volumes of material that sometimes fail, open slope-sourced slides are considered to have the most potential to initiate tsunami (Murty, 2003). However, a significant volume of material may also be mobilized in landslides associated with areas of salt diapirism as well. From the modeling of source volumes of individual scarps along the margin, we see that three regions (off Georges Bank, Currituck area, and in the Carolina Trough) have had a history of, and potential for, large volume failures. With the current data, it is difficult to determine if landslides on the southern New England slope involve large volumes of material per event, or if the region is dominated by smaller, but more numerous landslides.

2.3 CARRITUCK LANDSLIDE ASSESSMENT AND MODELING

In order to gain an initial understanding of the implications of the mapped landslides on the tsunami hazard along the Atlantic coast, a study to characterize and perform hydrodynamic modeling of the Currituck landslide was undertaken. This work also showed the potential for the methods employed. Tsunami magnitude depends strongly upon the size of the slide and how the landslide moves as it fails and flows. Therefore, the first step was to determine the parameters needed for the tsunami generation and propagation modeling. This work had significant challenges because the initial geometry of the material was not known, it was unclear if there had been a single event or multiple events, and the properties of the geologic material were not well characterized. During this work several issues were considered and the researchers endeavored to answer the following multiple lines of inquiry. Ultimately a possible initial velocity and acceleration of the failed mass was developed from the mobility analyses.

Once estimates of the important landslide parameters had been developed, preliminary hydrodynamic modeling of the slide was conducted for the purpose of determining the range of possible near-shore wave heights and understanding the possible impact of the continental shelf. Considerations of bottom friction and non-linearity were included in this work. This study was undertaken early in the program and played an important role for the US NRC because the modeling allowed staff to understand the general implications of the initial landslide mapping results. It also helped to scope and focus the organization of the broader research program.

3. INVESTIGATION OF FAR FIELD TSUNAMIGENIC LANDSLIDES IN THE ATLANTIC

The research related to far field tsunamigenic landslides, has focused on collecting information and assessing the potential impact to the U.S. Atlantic and Gulf coasts. Numerous debris deposits from landslides have been identified in the literature along the Canadian, European and African coasts of the Atlantic Ocean and a number of possible source areas were considered in detail for this program. These areas include the Canary Islands, the Mid-Atlantic Ridge, the glaciated margins of northern Europe and Canada, the Scotia margin immediately NE of the U.S. border, the northern European margin, and the Puerto Rico trench. In many cases, evidence of tsunamis from landslides were found, although the effects were often highly localized as is common for landslide-initiated tsunamis. The USGS report provides information on both historical tsunamis and proposed modeling parameters for these areas.

Perhaps the most publicized hypothesized hazard is that of a possible collapse of Cumbre Vieja, a volcano on the Canary island of La Palma (Ward and Day, 2001). As envisioned by Ward and Day, a flank collapse of the volcano may drop a rock volume of up to 500 km³ into the surrounding ocean. The ensuing submarine slide is further hypothesized to generate a strong tsunami with amplitudes of 25 m in Florida. In the time since the initial work was published, significant work by other researchers has been undertaken to look at their assumptions. A review of all associated work was undertaken for this program and it was concluded that the danger to the U.S. Atlantic coast from the possible collapse of Cumbre Vieja is exaggerated. Mader (2001) pointed out that Ward and Day's assumption of linear propagation of shallow water waves is incorrect, because it only describes the geometrical spreading of the wave and neglects dispersion effects. A more rigorous hydrodynamic modeling by Gisler et al. (2006), confirms Mader's criticism. Their predicted wave amplitude for Florida is between 1 and 77

cm. A fuller discussion is provided in the USGS report and the potential impact of a collapse of Cumbra Vieja will be further studies by NOAA as part of this project.

4. INITIAL INVESTIGATION OF TSUNAMIGENIC LANDSLIDES IN THE GULF OF MEXICO

This project has also started investigating the potential for tsunamigenic landslides in the Gulf of Mexico. The Gulf of Mexico is a small, geologically diverse ocean basin that includes three distinct geologic provinces: a carbonate province, a salt province, and canyon to deep-sea fan province. Currently the work in this area is not as advanced as the assessment in the Atlantic. However, early work investigating landslides undertaken by this project and others that indicates that submarine landslides have occurred in each of the three provinces, although they vary in style and size among these different provinces. Landslides also have been shown to be active throughout much of the history of this basin, including in the Quaternary Period, up to the present. Submarine landslides have been studied in the Gulf of Mexico in the past for two reasons: first they can pose a hazard to offshore platforms and pipelines and second, when more deeply buried they can serve either as hydrocarbon reservoirs or barriers in reservoirs depending on their composition. The threat of submarine landslides as a generator of tsunamis has not previously been addressed for the Gulf of Mexico region. However, the existing literature describing the distribution and style of submarine landslides that have occurred in the Gulf of Mexico during the Quaternary has been reviewed for this program and is summarized in the USGS report. The review focused on landslides that have occurred in on the continental slope and rise in the Gulf of Mexico; with much of the discussion focused on the part of the basin within the U.S. Exclusive Economic Zone (EEZ) due to the availability of a greater number of publications from this region. Research is on-going in this area.

5. IDENTIFICATION AND CHARACTERIZATION OF SEISMIC SOURCES THAT MAY IMPACT THE ATLANTIC OR GULF COASTS

5.1 Sources in the Atlantic Ocean

Earthquake-generated tsunamis generally originate by the sudden vertical movement of a large area of the seafloor during a large magnitude earthquake. Such movement is generated by reverse or thrust faulting, most often in subduction zones. The Atlantic Ocean basin is generally devoid of subduction zones or potential sources of large reverse faults. The two exceptions are the Hispaniola-Puerto Rico-Lesser Antilles subduction zone, where the Atlantic tectonic plate subducts under the Caribbean plate, and the enigmatic zone of large earthquakes west of Gibraltar. These two earthquake source areas were investigated, an evaluation of their tsunamigenic potential was undertaken, and the potential for impact to the U.S. coastline by resulting tsunami was considered.

Four large tsunamigenic earthquakes have occurred in the Atlantic Ocean west of Gibraltar in the last 300 years. However, there is no simple tectonic model for this area that explains the generation of these earthquakes. As a result, promising work undertaken to determine the source parameters of the 1755 Lisbon earthquake is of particular interest. A variety of past studies have hypothesized various sources for this earthquake, which is known to have caused a tsunami around much of the Atlantic Ocean. However, prior to this project there had not been an attempt to fit cross-ocean tsunami reports of the 1755 Lisbon earthquake to any of the proposed fault sources. As part of this program, modeling of various sources is being undertaken to try to determine a viable source location and geometry that predicts the many records of tsunami impacts from the earthquake.

5.2 Sources in the Caribbean

The 2004 magnitude 9.2 Sumatra-Andaman earthquake was a surprise from a geologic and tectonic perspective in that it occurred along a highly oblique subduction zone, where the convergence rate is low, and where very large earthquakes were thought unlikely to occur. Many of the tsunamigenic fault zones in the Caribbean and

Atlantic are characterized by similar tectonics and may have higher hazard than has been previously predicted. In particular, a major concern was raised about the Puerto Rico trench, because a tsunami initiating here has a potential impact on the U.S. East Coast. The USGS has recently carried out extensive fieldwork in the Puerto Rico trench to understand the tectonics of the area. As a result, researchers on the US NRC project were able to rapidly provide an evaluation for this source. As part of this analysis, tsunami propagation from several different large-magnitude earthquakes in the Caribbean was modeled to estimate deep ocean tsunami amplitudes offshore U.S. Atlantic and Gulf coasts. A range of tsunami amplitudes is determined based on natural variations in slip distribution patterns expected for large magnitude earthquakes along plate boundaries in the Caribbean. This work is ongoing and has been useful for providing general hazard information to the US NRC.

A series of large earthquakes with mostly thrust motion took place in the eastern half of northern Hispaniola between 1946 and 1953. One of the events in 1946 was accompanied by a destructive local tsunami. In contrast to the Puerto Rico trench, a larger vertical motion is expected for a given magnitude of slip on portions of the Hispaniola trench. It is unclear, whether the western part of the subduction zone would rupture in a single earthquake and how far west the rupture would extend. Modeling is needed to determine if the U.S. Atlantic coast would be protected from tsunamis generated in this subduction zone by the Bahamas banks which are near sea level and act as obstructions to tsunami wave propagation.

5.2 Sources in the Gulf of Mexico

The Gulf of Mexico basin is devoid of subduction zones or potential sources of large reverse faults. However, the Caribbean basin contains two convergence zones whose rupture may affect the Gulf of Mexico, the North Panama Deformation Belt and the Northern South America Convergent Zone. Hydrodynamic modeling is needed to evaluate the role of the Yucatan straits (between Cuba and the Yucatan Peninsula) in modifying the propagation of tsunamis into the Gulf of Mexico, though some initial modeling has been initiated.

6. UPCOMING ACTIVITIES

As part of the second phase of the program, which is currently underway, the USGS will conduct field investigations in key locations for the purpose of obtaining new data useful for determining tsunami hazard assessment of nuclear facilities. The USGS is also continuing investigations into assessing landslide potential in the Gulf of Mexico, determining the source of the 1755 Lisbon earthquake, and a variety of other topic of interest.

Simultaneously, the MOST tsunami generation and propagation model used by NOAA is currently being enhanced to include landslide-based initiation mechanisms and is being validated with case studies, including the 1958 Lituya Bay megatsunami. The enhanced MOST model will be used to investigate the tsunamigenic sources identified and characterized by the USGS, with the goal of creating an estimation of deterministic tsunami hazard levels for the full length of Atlantic and Gulf Coasts. This information may ultimately be developed into a map of deterministic tsunami hazard for these coastlines and will be of direct benefit to the US NRC efforts to assess tsunami hazard at coastal facilities.

The potential for developing tools and data to undertake probabilistic tsunami hazard assessments (PTHA) will also be a key focus of later phases of the research program. PTHA will require an understanding of the frequency of different initiating events. Some areas in which the US NRC is likely to initiate additional work in the coming years relates to understanding the timing of the submarine landslides identified in the Atlantic. One example is careful age dating on cores recovered from within and adjacent to mapped landslides. In the companion paper in this conference, information on the result of ongoing work, some of which is leading to PTHA is provided.

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