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REVISITING SUBMARINE MASS MOVEMENTS ALONG THE U.S. ATLANTIC CONTINENTAL MARGIN: IMPLICATIONS FOR TSUNAMI HAZARDS

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Abstract

Interest in the generation of tsunamis by submarine mass movements has warranted a reassessment of their distribution and the nature of submarine landslides offshore of the eastern U.S. The recent acquisition and analysis of multibeam bathymetric data over most of this continental slope and rise provides clearer view into the extent and style of mass movements on this margin. Debris flows appear to be the dominant type of mass movement, although some translational slides have also been identified. Areas affected by mass movements range in size from less than 9 km^2 to greater than 15,200 km^2 and reach measured thicknesses of up to 70 m. Failures are seen to originate on either the open-slope or in submarine canyons. Slope-sourced failures are larger than canyon-sourced failures, suggesting they have a higher potential for tsunami generation although the volume of material displaced during individual failure events still needs to be refined. The slope-sourced failures are most common offshore of the northern, glaciated part of the coast, but others are found downslope of shelf-edge deltas and near salt diapirs, suggesting that several geological conditions control their distribution.
Keywords: bathymetry, seismic reflection, side scan, sediments, Quaternary.

1. Introduction and Background

Since the 1929 earthquake near the Grand Banks offshore of Nova Scotia, Canada (Heezen and Ewing, 1952), it has been realized that submarine landslides contribute to shaping passive continental margins. A full appreciation of the importance of this process was delayed several decades until bathymetric, sub-bottom profiling, and seafloor imaging techniques were sufficiently advanced to allow systematic mapping of large portions of continental margins. The importance of submarine mass movements was confirmed after completion of the systematic mapping of this margin by GLORIA in 1987. We have used available multibeam bathymetry, GLORIA sidescan sonar imagery, a regional grid of high-resolution seismic profiles, and published accounts of sediment cores to map the distribution and style of surficial landslides along the U.S. Atlantic margin between the eastern end of Georges Bank and the Blake Spur (Fig. 1). The near-complete coverage of the U.S. Atlantic continental slope and rise by multibeam bathymetry provides a uniform dataset and a more detailed and consistent view of the geomorphology of submarine landslides than had been available in the past. Here we review the distribution and style of submarine landslides along the continental margin, and speculate on the geologic conditions that have influenced their distribution.

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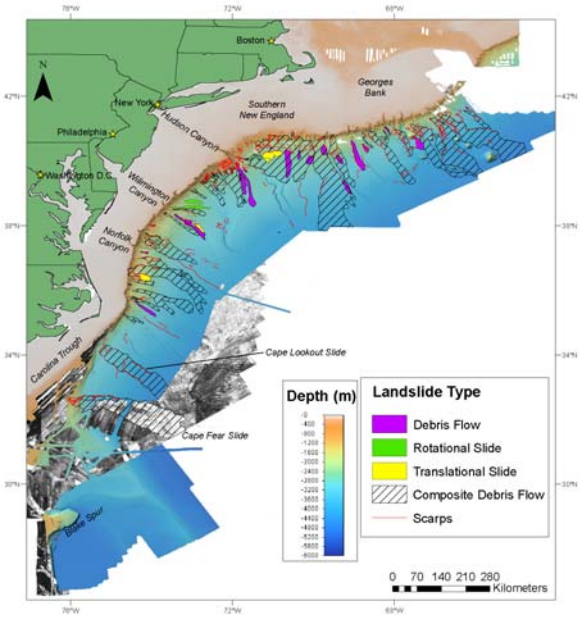

Figure 1. Distribution of different landslide types along the US Atlantic continental slope and rise between the eastern end of Georges Bank and the Blake Spur, overlain on the regional bathymetry compilation. GLORIA sidescan data (black and white) can be seen over areas where there is sparse or no multibeam bathymetry data available.

Studies of individual landslides along the U.S. Atlantic margin first appeared in 1960s (e.g., Uchupi, 1967) and continued through the 1980s (see Embley and Jacobi (1986) and Booth (1993) and numerous references therein). The first regional synthesis of landslide distribution was compiled by Embley (1980) using echo-sounder profiles and cores, with subsequent regional compilations benefiting from the collection of additional local (e.g., O'Leary, 1996; Popenoe and Dillon, 1996) and regional (Booth *et al.*, 1988; Pratson and Laine, 1989) data. Booth *et al.* (1993) provided a summary of landslide distribution and attributes and the first tabulated information on the dimensions of these features, characteristics of the source areas, and style of failure.

The U.S. Atlantic continental margin rifted asynchronously from south to north during the Mesozoic (Klitgord *et al.*, 1988). Salt deposition probably was extensive during early stages of continental margin formation, but only in the Carolina Trough offshore of North and South Carolina did salt domes form (Dillon *et al.*, 1982; Fig. 1). During the early Middle Jurassic a nearly continuous carbonate platform and barrier reef system formed that stretched northward from the Bahamas to the Canadian margin (Poag, 1991). Deposition during the Cenozoic was primarily siliciclastic sediments (Poag and Sevon, 1989) except during the Eocene when calcareous chalk was deposited along much of the margin (Weed *et al.*, 1974). The Quaternary saw large volumes of sediment eroded from the North American continent by glacial processes, with deposition by large river systems along the Georges Bank shelf edge (Schlee and Fritsch, 1982) and along the southern New England shelf. Beyond the extent of glaciers, the large river systems that underlie the

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present Hudson, Delaware, and Chesapeake estuaries extended across the shelf with shelf-edge deltas built off the Virginia and Delaware coasts, while the Hudson Canyon system transferred sediment to a deep-sea fan (Poag and Sevon, 1989).

3. Methods

3.1 BATHYMETRY

Data used in the compilation of the U.S. Atlantic margin bathymetry map 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) in support of the U.S. Law of the Sea Study (Gardner et al., 2006) and provides near continuous coverage of the U.S. Atlantic margin from the base of the continental slope down to the abyssal plain (~ 1500-m and 5000-m). Several additional multibeam data sets collected by ships from Woods Hole Oceanographic Institution, Lamont-Doherty Earth Observatory, and the National Oceanographic and Atmospheric Administration (NOAA) were used in several areas where there were no UNH data. In areas where multibeam soundings were not available sounding data from the National Ocean Service hydrographic database and the NOAA coastal relief model provided bathymetric coverage of the continental slope.

3.2 GLORIA SIDESCAN

In addition to the acoustic backscatter data from the UNH multibeam surveys, GLORIA sidescan sonar data collected in 1987 (EEZ-SCAN 87, 1991) were used to identify and map landslide features. These data provide near total coverage of the sea floor within the study area at a pixel resolution of 50-m, from the shelf edge out to 200 nm from shore.

3.3 SEISMIC REFLECTION PROFILES

Analogue records of 3.5 kHz seismic reflection profiles, co-acquired with the GLORIA sidescan data, helped 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.

3.4 CORES

Over 1400 cores have been collected from the study area, and descriptions of the cores are available from the National Geophysical Data Center core repository database. Of these, approximately 1000 have been visually described, and 145 of them have had general ages assigned based on faunal content. While many of the descriptions are brief they provide a valuable summary of the overall lithology of the cores.

3.5 DATA ANALYSIS

The mapping of landslide affected areas was broken into several steps. The first step was to identify scarps around and within landslide source areas. Scarps showed clearly in shaded-relief and slope maps derived from the bathymetric data. Second, using shaded-

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relief bathymetry, backscatter mosaics, and GLORIA imagery, the areas affected by landsliding were outlined. Most landslide areas have a high-backscatter signature on the sidescan and multibeam imagery. In the southern part of the study area, offshore of the Carolinas, where the multibeam coverage was incomplete, the extent of the landslide areas was based on the GLORIA imagery alone (Fig. 1). Composite slides were differentiated from individual, single event slides based on the presence of more than one headwall scarp and multiple deposit lobes. Third, the thickness of landslide deposits were measured on sub-bottom profiles. In some cases the thickness of the deposit was clearly imaged, however in others a highly-reflective seafloor did not allow sub-bottom penetration, and in some cases the base of the deposits may have been deeper than could be penetrated by the profiling system. These data and interpretations were incorporated into a GIS where the volumes of landslide deposits were calculated based on estimates of the average thickness of the deposit and its areal extent, while the volumes of source areas of a subset of the mapped slides were calculated using the bathymetry and an interpolated smooth-surface technique reported by ten Brink *et al.* (2006).

4. Results

Fifty-five landslide areas were mapped between the eastern end of Georges Bank and the Blake Spur, from the shelf-slope break, down to the abyssal plain (Fig. 1). This number is considerably less than the 179 tabulated by Booth *et al.* (1988; 1993), which is due to our ability to better define the larger landslide complexes and resolve their composite nature with the new bathymetry. The types of landslides were interpreted from the morphology of the deposits as well as from their internal character, and we use the classification scheme presented by Locat and Lee (2002) to describe them. Rotational slides, translational slides, and debris flows were identified, and their distribution is shown in Figure 1. Debris flows were by far the most common type identified and originate from clearly defined headwall scarps and failure surfaces, extending as much as 200 km downslope. Many of the debris flows have several scarps in the source area suggesting they consist of multiple failures rather than a single event or retrograde slumping. Identified rotational slides predate a thick section of younger sediment, which onlaps the slide toes. Translational slides were identified on the multibeam bathymetry as slabs often with a toe that appears to have undergone some disintegration. Headwall scarps were clearly defined and, in the observed cases, indicate a short translation distance.

The area of landslides was measured using the GIS, and ranged from 9 to 15,241 km^2 with a mean of 1,880 km^2. The water depth of the source area for landslides was identified as the shallowest scarp upslope of the landslide area. Where the bathymetry coverage was adequate (33 of the 55 landslides), the depth of measured headwall scarps ranged from 92 to 3,263 m with a mean depth of 1,630 m; 50% of the scarps occurred on the middle and lower slope in 1,200-2,250 m water depths. The relief could be measured on 45 of the headwall scarps: 75% had less than 100 m relief. The toe of the landslide deposits occurred in water depths greater than 2,126 m, with a mean depth of 3,101 m. The thickness of landslide deposits, where they could be measured, ranged from 5 to 70 m (Fig. 2), with a mean thickness of approximately 20 m. The volumes of sediment contained within landslide deposits ranged from 0.05 to 392 km^3, with many of the large slides comprised of several smaller deposits. The largest landslide complexes occur off the southern New England region (190 and greater than 392 km^3) and in the Carolina

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Trough area (114 and 150 km^3). By contrast, most of the landslides between Hudson and Norfolk Canyons have deposit volumes less than 10 km^3 (Fig. 2).

The volumes of 34 mapped landslides source excavation areas calculated from the bathymetry only were found to be between 0.06 km^3 and 179 km^3. Although only a subset of those currently identified was used in these calculations, they are a representative of the full range of landslide types in the region. The largest volumes calculated are associated with the extensive slope-sourced landslides off Georges Bank and southern New England, and south of Cape Hatteras. The smallest source volumes were those found within the canyon systems; both canyon head and canyon side-wall sources.

Although numerous core and surficial sediment samples have been recovered from shelf, slope, and rise of the U.S. Atlantic margin, little information is available on the age of the landslides described herein. Of the few reliable dates that are available, we see that most failures are older than 10,000 yr BP (Embley, 1980; Prior *et al.*, 1986; Popenoe *et al.*, 1993), with only one failure with a Holocene age (Embley, 1980). The Pliestocene age of the sediment comprising the landslide deposits indicates that the failure process removed only a relatively thin surficial skin rather than cutting deeply into older strata under the continental slope (Fig. 3).

5. Discussion

Compared with previous regional studies of the distribution and size of major submarine landslides along the U.S. Atlantic margin (e.g., Booth *et al.*, 1988; 1993; Hance, 2003), the availability of high-resolution multibeam bathymetry significantly improves resolution and interpretation of these features. As a result, although we report a smaller number of mass movement features, we have been able to better define the extent and thickness of individual and composite landslides, which in most cases incorporate a number of the singular features described by previous investigators. As Booth et al. (1988) first observed, we note two distinct source areas for landslides: submarine canyons (headwalls and sidewalls) and the open continental slope. The importance of the distinction between these two types is the difference in magnitude of the individual landslides, and hence their tsunami generating potential. Open-slope sourced landslides have deposits that can exceed 200 km^3, and although many are composite features, we see source area excavations that exceed 100 km^3. By contrast, the canyon-sourced landslide deposits rarely exceed 10 km^3, with source area excavations less than 1 km^3.

The spatial distribution of landslides along the U.S. Atlantic margin is, in part, controlled by the underlying geology. Landslides are the most common, tend to be largest and of the open slope-sourced nature, offshore of areas where Quaternary sediment is thickest on the outer shelf and upper slope (Fig. 3). Nearly 60% of the area affected by landslides occurs offshore of the thick Quaternary shelf deposits of the Georges Bank, southern New England, and Virginia areas. These three areas are also regions where the older strata underlying the slope dip sub-parallel to the gradient of the present slope (Uchupi, 1967; Uchupi and Emery, 1967; Rona, 1969; McGregor, 1981; O'Leary, 1986), and display failure surfaces suggestive of sliding along bedding planes. The two large landslide areas in the Carolina Trough are controlled by different geological processes. They are sourced near salt domes and both the tectonic activity of the salt domes (Dillon *et al.*, 1982;

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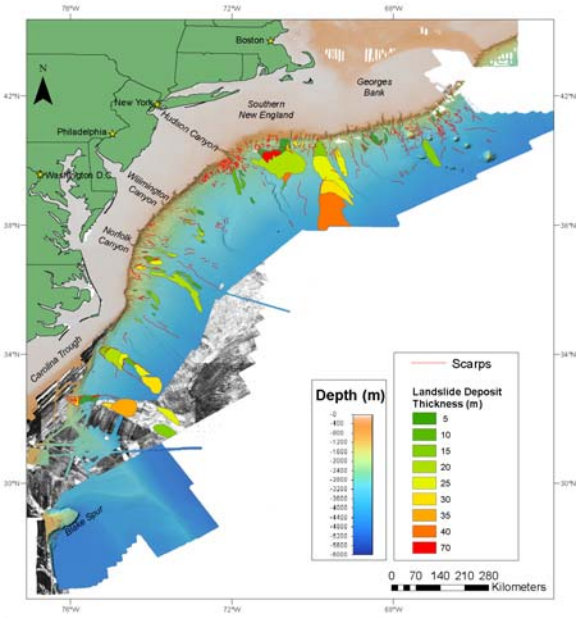

Figure 2. Thickness of landslide deposits mapped using 3.5-kHz profiles. Some were too thin to be resolved by these profiles and others had surface returns that attenuated the signal did not allow penetration to the base of the deposit.

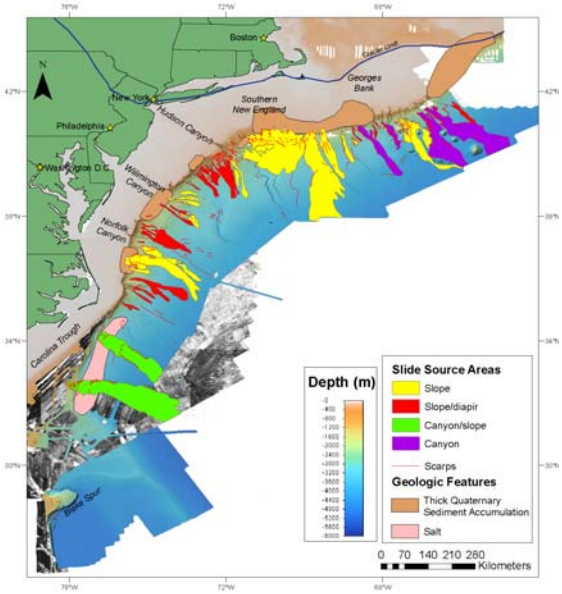

Figure 3. Map showing the distribution of landslides by source area and their relationship to regions of Quaternary sediment accumulation and salt diapirism. The largest landslides have open-slope source areas (in the Carolina Trough area they are associated with salt domes). The landslides off Georges Bank appear to have contributions from both canyon and open-slope sources.

Popenoe et al., 1993) and hydrate destabilization (Carpenter, 1981) have been suggested as the triggering mechanisms for these failures. Landslides covering the remainder of the continental margin are off areas where Quaternary deposits at the shelf-edge are thin and older strata underlying the slope are nearly horizontal rather than having a dip sub-parallel to the seafloor and account for only 16% of the total landslide area of the margin. Therefore, other than localized tectonic mechanisms, rapid sediment accumulation rates during the Quaternary (Poag and Sevon, 1989) and the dipping nature of the subsurface strata may be the reason why sediments on parts of the margin are more prone to failure, given the appropriate triggering mechanism.

Using the classification of Locat and Lee (2002), we find the dominant mass movement modes to be debris flows, translational and rotational slides, which in most cases are now found together as part of larger, multiphase composite deposits. In part, the reason for this may be because the bulk of the sediment that makes up the mass-wasting deposits was Quaternary in age and largely unconsolidated to semi-lithified, and could not be transported large distances without undergoing disintegration. The height of scarps in most landslide source areas have less than 75 m relief indicating that in most places only the Quaternary section (Poag and Sevon, 1989) is being removed.

Using the new bathymetry compilation we find that the open slope-sourced slides are larger both in the area of failure and overall volume of per-event failed material, and as such, are the dominant means of rapid margin modification (Fig. 3). Because of the large volumes of material that can fail during an individual or retrogressive open slope-sourced slide, these are considered to have the most potential to initiate tsunami along the U.S. Atlantic margin. The regions off the glaciated New England margin, a shelf-edge delta system off southern Virginia, and the Carolina Trough area, appear to have a history of these large volume failures, and therefore greatest potential as landslide-induced tsunami source zones.

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