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Review article

Assessment of tsunami hazard to the U.S. Atlantic margin

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ABSTRACT

Tsunami hazard is a very low-probability, but potentially high-risk natural hazard, posing unique challenges to scientists and policy makers trying to mitigate its impacts. These challenges are illustrated in this assessment of tsunami hazard to the U.S. Atlantic margin. Seismic activity along the U.S. Atlantic margin in general is low, and confirmed paleo-tsunami deposits have not yet been found, suggesting a very low rate of hazard. However, the devastating 1929 Grand Banks tsunami along the Atlantic margin of Canada shows that these events continue to occur. Densely populated areas, extensive industrial and port facilities, and the presence of ten nuclear power plants along the coast, make this region highly vulnerable to flooding by tsunamis and therefore even low-probability events need to be evaluated.

We can presently draw several tentative conclusions regarding tsunami hazard to the U.S. Atlantic coast. Landslide tsunamis likely constitute the biggest tsunami hazard to the coast. Only a small number of landslides have so far been dated and they are generally older than 10,000 years. The geographical distribution of landslides along the margin is expected to be uneven and to depend on the distribution of seismic activity along the margin and on the geographical distribution of Pleistocene sediment. We do not see evidence that gas hydrate dissociation contributes to the generation of landslides along the U.S. Atlantic margin. Analysis of landslide statistics along the fluvial and glacial portions of the margin indicate that most of the landslides are translational, were probably initiated by seismic acceleration, and failed as aggregate slope failures. How tsunamis are generated from aggregate landslides remains however, unclear. Estimates of the recurrence interval of earthquakes along the continental slope may provide maximum estimates for the recurrence interval of landslide along the margin. Tsunamis caused by atmospheric disturbances and by coastal earthquakes may be more frequent than those generated by landslides, but their amplitudes are probably smaller. Among the possible far-field earthquake sources, only earthquakes located within the Gulf of Cadiz or west of the Tore-Madeira Rise are likely to affect the U.S. coast. It is questionable whether earthquakes on the Puerto Rico Trench are capable of producing a large enough tsunami that will affect the U.S. Atlantic coast. More information is needed to evaluate the seismic potential of the northern Cuba fold-and-thrust belt. The hazard from a volcano flank collapse in the Canary Islands is likely smaller than originally stated, and there is not enough information to evaluate the magnitude and frequency of flank collapse from the Azores Islands. Both deterministic and probabilistic methods to evaluate the tsunami hazard from the margin are available for application to the Atlantic margin, but their implementation requires more information than is currently available.

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1. Introduction

The U.S. Atlantic margin is well suited for the study of low-probability high-risk tsunami events. The margin is vast (2500 km long) and includes a variety of morphological features, sediment types and depositional environments, allowing us to investigate salient parameters that are relevant to hazard assessment. Tsunamis generated by submarine landslide are a significant component of the tsunami hazard to the U.S. Atlantic margin. The first and largest part of this review article describes recent work aimed at understanding submarine landslides, their temporal and spatial distributions along the U.S. Atlantic margin and their relationships to earthquakes, in an effort to quantify their probability of occurrence. This focus stems from the observation of numerous submarine landslide scars along the Atlantic margin and the 1929 Grand Banks landslide tsunami, the only known major tsunami to cause significant damage to locations along the Atlantic coast of North America (Fine et al., 2005). The second part of the article reviews the state-of-knowledge of other sources that have the potential to generate trans-Atlantic or local tsunamis. These include earthquake-generated tsunami sources from the Azores–Gibraltar plate

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boundary, the Puerto Rico Trench, and the northern Cuba fold-and-thrust belt, volcanic flank collapse and large landslides in the eastern Atlantic Ocean, and local earthquake and meteo-tsunamis (tsunamis caused by atmospheric pressure disturbances). The third part of the paper reviews recent developments in deterministic and probabilistic approaches to assessing tsunami hazard. The discussion raises several fundamental questions regarding the assessment of landslide tsunamis along the U.S. Atlantic margin.

2. Tsunami hazard from local landslide sources

2.1. The U.S. Atlantic Margin & characteristics of submarine landslides

2.1.1. Physiography of the U.S. Atlantic margin

The Atlantic margin of the U.S. extends from the Straits of Florida in the south to Georges Bank in the north. The margin continues northeastward offshore Nova Scotia and Newfoundland in Canada. The morphology of the modern margin reflects the results of processes that began when North America and Africa began rifting apart more than 200 million years (Klitgord et al., 1988). Four major basins were formed during that time: the Blake Plateau Basin, the Carolina Trough, the Baltimore Canyon Trough, and the Georges Bank Basin (Klitgord and Behrendt, 1979). These basins coincide with four zones, which from south to north, are influenced by carbonate, salt, fluvial, and glacial processes and exhibit large along-margin variability in sediment supply. From Florida to South Carolina, carbonate production has dominated and modern terrestrial sediment input is low (Dillon et al., 1985), particularly off Florida. This region is centered on the Blake Plateau Basin. Offshore North Carolina, the margin contains salt diapirs sourced from deeply buried Mesozoic rift sediments (Dillon et al., 1982). This region is centered on the Carolina Trough. Between Cape Hatteras and New England, the margin has been dominated by fluvial siliciclastic sediment deposition since the Early Miocene that has buried a deeper and once extensive carbonate reef system (Poag, 1991). Eocene chalk is exposed along stretches of the slope (Poag, 1992). This region is centered on the Baltimore Canyon Trough. Offshore New England, the modern margin reflects glaciogenic processes, which provided abundant sediment from large terrestrial rivers (e.g., Hudson River) that drained extensive glacial landscapes. At the time of the Last Glacial Maximum (LGM), the Wisconsin ice sheet reached part way across the continental shelf of New England and to the shelf edge along the Scotian margin of Canada (Schlee, 1973) (Fig. 1). Mesozoic–Neogene age carbonate and siliciclastic rocks are exposed in some New England canyons (Ryan et al., 1978)(Fig. 1). This region is centered on the Georges Bank Basin.

Examination of the Georges Bank–Southern New England–Hudson Apron margin (Fig. 1) reveals more subtle morphological variations, which are likely governed by the earlier sedimentary history of the margin (Brothers et al., 2013a). The steep Mesozoic reef bank beneath Georges Bank margin appears to have had a profound influence on the evolution and modern-day steepness of the slope, whereas Early Cenozoic stratigraphic packages along the upper and middle slope of Southern New England and the Hudson Apron had gentle, sigmoidal forms that are nearly maintained today (Brothers et al., 2013a).

From Cape Hatteras northward, the shelf slopes gently (<0.5°) to water depths of 100 to 200 m where a significant change in gradient marks the shelf/slope break (inset in Fig. 1). The continental slope, an area affected primarily by downslope and less frequently by along slope transport and deposition, can be separated into an upper slope and lower slope with the transition between them occurring at a major change in gradient which generally occurs between 1800 and 2000 m. The lower slope has been labeled in many publications as “upper rise” based solely on the morphology. This lower slope region, however, contains landslides and large channels more typical of slope processes (sediment transport), albeit on lower gradient surfaces (e.g., Danforth and Schwab, 1990). The transition from the lower slope to the continental rise (where deposition is dominant) occurs between 4000 and 4500 m.

The carbonate zone has a significantly different across-margin character than the other zones (inset in Fig. 1). South of Cape Hatteras, the continental shelf edge occurs at shallower depths of approximately 80–100 m and steps down via a short steep ramp to the Blake Plateau at ~800 to 1200 m. The Blake Escarpment and Blake Outer Ridge are the primary morphologic features of the margin. North of the Blake Outer Ridge, the upper/lower slope transition occurs between 2800 and 3000 m, and the transition to primarily depositional processes occurs at approximately 5000 m. South of the Blake Outer Ridge, the Blake Escarpment descends to abyssal depths abruptly at ~5000 m (Inset in Fig. 1).

2.1.2. Local landslide sources

Submarine landslides along the U.S. Atlantic margin have been described and analyzed in a number of local (e.g., Embley, 1982; Cashman and Popenoe, 1985; O'Leary, 1986; Prior et al., 1986; Locat et al., 2010, 2013; Chaytor et al., 2012a; Mulder et al., 2012) and regional (Booth and O'Leary, 1991; Booth et al., 1993; Twichell et al., 2009) studies. Past compilations of landslides along the U.S. Atlantic margin utilized a variety of geophysical imaging techniques, beginning with single-channel airgun and sparker seismic reflection profiles (Embley and Jacobi, 1977), to GLORIA sidescan backscatter and early low-resolution swath bathymetry (Booth et al., 1993), and higher-resolution but incomplete swath bathymetry coverage of the margin (Chaytor et al., 2007; Twichell et al., 2009). Based on the recent compilation of high-resolution mapping data (Andrews et al., 2013 and references/sources within), landslides and related features along the margin fall into 3 types: Type 1: a landslide ‘complex’ with a clearly-coupled source/evacuation and deposit areas, Type 2: a landslide ‘zone’, where a deposition zone either does not exist next to the source/evacuation zone, or if one is present, it cannot be related to a specific source, and Type 3: mass transport deposits (MTD) with no associated source/evacuation zone.

There are only five well-defined landslide complexes of Type 1 along the U.S. Atlantic margin: the Munson–Nygren–Retriever, Veatch Canyon, Currituck (Albemarle), Cape Lookout, and Cape Fear landslides (marked 1 to 5 in Fig. 1). These previously known landslide complexes are well mapped from early studies (e.g., Embley, 1982; Cashman and Popenoe, 1985; O'Leary, 1986; Prior et al., 1986; Chaytor et al., 2012a), and occur within the various geologic zones with the exception of the carbonate zone. The combined source and deposit areas of these landslide complexes each exceed 3000 km^2, and except for the Veatch Canyon landslide, the volume of material evacuated from each is greater than 100 km^3. Given their size, these landslide complexes are considered the primary benchmarks for the analysis of submarine-landslide-generated tsunamis initiated along the U.S. Atlantic margin (e.g., Geist et al., 2009a).

We identified, or redefined, previously identified landslide zones of Type 2 (Chaytor et al., 2009, 2012a; ten Brink et al., 2012) using new multibeam bathymetry (Andrews et al., 2013) and high-resolution seismic data along the margin north of Cape Fear slide (Figs. 2, 3). Headwalls and multiple failure scars, which may overlap or be morphologically connected, are pervasive along the southern New England, Hudson Apron–New Jersey slope, and Baltimore Canyon parts of the margin, but no associated depositional lobes or mass transport deposits (MTD) have been identified (e.g., Fig. 2). The bulk of these landslide zones are confined to the upper slope and along canyon walls, but they are also found along the lower slope where they lie adjacent to mass transport deposits (MTD) emplaced by multiple landslide events. Most of the Type 1 and Type 2 landslides occur in unlithified sediments. The exceptions are landslides identified in lithified Eocene rock exposed along the upper slope off New Jersey (Figs. 1 and 3) and Eocene and