Are submarine landslides an underestimated hazard on the western North Atlantic passive margin?

Alexandre Normandeau, D. Calvin Campbell, David J.W. Piper, and Kimberley A. Jenner

Geological Survey of Canada (Atlantic), Natural Resources Canada, 1 Challenger Drive, Dartmouth, Nova Scotia B2Y 4A2, Canada.

ABSTRACT

The western North Atlantic passive margin is considered relatively stable, with few slope instabilities recognized during the Holocene. However, new multibeam bathymetry mapping and sediment core acquisition off eastern Canada indicate that previously unidentified, large, submarine landslide events occurred during the Late Holocene, between 4 and 1.5 ka. The recognition of these new gravitational events, in addition to the well-known C.E. 1929 Grand Banks earthquake-induced landslide, indicates that approximately one large landslide event per 1000 years has occurred offshore eastern Canada within the past 4000 years, a much shorter recurrence interval than hitherto reported. This Late Holocene recurrence rate is also similar to active margins around the world and is likely due to the under-consolidation and resultant instability of Scotian Slope sediments attributable to high glacial sedimentation rates. The discovery of these new Late Holocene landslides was made possible through detailed examination of cores recovered from the lower slope. These results demonstrate that submarine landslide hazard has been underestimated on the western North Atlantic margin—home to significant submarine infrastructure and proximal to a large coastal population.

INTRODUCTION

Submarine landslides are ubiquitous on the North Atlantic seafloor, and have potential societal impacts on public safety, the environment and the economy. Most large submarine landslides preserved on the North Atlantic seabed, defined here as having reached distal locations on the lower slope or rise (Clare et al., 2014), were triggered during the Pleistocene or immediately following deglaciation (Maslin et al., 2004; Brothers et al., 2013). On a global scale, Urlaub et al. (2013) observed significantly fewer landslides in the Late Holocene compared to the Late Pleistocene and Early Holocene, thus suggesting a decreased risk for coastal populations and submarine infrastructure (Chaytor et al., 2009; ten Brink et al., 2014).

In the western North Atlantic, the largest known Holocene submarine landslide was triggered by the C.E. 1929 Grand Banks M7.2 earthquake (Kuenen, 1952). This earthquake, and subsequent submarine landslide, generated a tsunami that killed 28 people (Ruffman and Hann, 2001). Additionally, 17 submarine cable breaks were reported (Doxsee, 1948), costing millions of dollars in telecommunications damage. The widespread 1929 event is considered a rare event in the Holocene, since other documented Holocene landslides are smaller and confined to regions of the Scotian margin cut by steep-walled canyons (Piper, 2005; Jenner et al., 2007).

An understanding of the precise age of landslide recurrence, and stability of the seafloor over time, is crucial to correctly assessing geohazards, especially proximal to large coastal populations and submarine infrastructure, such as in the western North Atlantic (ten Brink et al., 2014). In this study, we analyzed sediment cores collected on the lower Scotian Slope in water depths of 4000–5000 m for evidence of landslides that have affected a large area. Our study reveals that large landslide events are more frequent during the past 4000 yr than previously reported, potentially representing a significantly underestimated hazard along the western North Atlantic.

REGIONAL SETTING

The study area encompasses the eastern Scotian Slope, where the seafloor morphology comprises deeply incised submarine canyons—The Gully and Shortland canyons being the most prominent—and relatively flat intercanyon areas that formed during Pleistocene proglacial sedimentation (Mosher et al., 2004). The dominant morphological feature along this part of the margin is the Laurentian Fan (Fig. 1). Recent seafloor mapping along the lower slope of the eastern Canadian margin revealed a variety of submarine landslide deposits (Mosher et al., 2017) and the identification of a previously unmapped submarine landslide complex (>14 000 km² area) on the western levee of the Laurentian Fan (Normandeau et al., 2019: Fig. 1) that is among the largest on the western Atlantic margin (within the 10% largest in the world compared to a compilation by Moscardelli and Wood [2016]).

METHODS

Sediment cores (collected during RV Atlantis cruise AT22, and CCGS Hudson Expedition 2016-011 Phase 1) (01, 02, 03, and 08; Fig. 1) were analyzed using X-ray systems to image internal structures. The cores were then photographed and put through a multi-sensor core logger (MSCL) for bulk density (ρ_b), magnetic susceptibility, and color reflectance measurements. In addition, discrete shear-strength measurements using a miniature vane shear (following ASTM D4648/D4648M-16 [Standard Test Methods for Laboratory Miniature Vane Shear Test for Saturated Fine-Grained Clayey Soil]) were made at 10 cm intervals and thin sections were prepared on selected intervals. Undrained shear strength (S_u) was used to estimate the two-dimensional (2-D) static factor of safety (FOS) for infinite slope approximation by

$$\text{FOS} = \frac{S_u}{\gamma' H \cos \beta \sin \beta}$$

(1)

where γ' is submerged unit weight (using measured bulk density and 1.024 g cm⁻³ for seawater density), H is depth in meters below the seafloor (mbsf), and β is seabed slope angle (calculated from average slope of the levee base). Samples were collected over a 2–3 cm interval for age dating of planktonic foraminifera
RESULTS

Core 01, consisting of laminated red-brown mud and sand, was collected on the western levee above the landslide scarp at 4220 mbsf (Figs. 1 and 2; Fig. DR1B). Undrained shear strength is low (<10 kPa) and the sediments are under-consolidated below 4 mbsf ($S_v/\sigma' < 0.25$, where $\sigma'$ is the vertical effective stress; Ladd and Foott, 1974) (Fig. 2). The sediments were deposited between 18.2 and 17.7 ka, representing relatively high Late Pleistocene sedimentation rates of 1 cm yr$^{-1}$; sediments younger than 17.7 ka were not recovered in the piston core. This core was used to estimate the FOS of the surficial sediments because it represents unfailed sediment above the landslide scarp. At ~7 mbsf, the FOS is ~7 on a slope of 1° and the critical slope angle is ~7°. These values are considered conservative since some sediments were likely destroyed during the piston coring operation and were not included in this calculation.

Core 02 was collected beyond the distal edge of the landslide in 5000 mbsl (Fig. 1; Fig. DR1C). Late Pleistocene sandy turbidites were deposited between 20 ka and 13 ka, when average sedimentation rates (0.06 cm yr$^{-1}$) were higher than present day (Fig. 3B). At ~300 cm, red-brown mud passes upward into bioturbated lighter red-brown mud with very few sandy turbidites. Accordingly, sedimentation rates diminish to ~0.02 cm yr$^{-1}$. A 25-cm-thick turbidite, at 130 cm, consists of laminated sand with fluidized sand at the top, possibly due to post-depositional dewatering. Above this turbidite, bioturbated light red-brown mud is dated at 3.9 ka (95 cm) and 2.5 ka (60 cm). At 60 cm, bioturbated mud abruptly transitions up-core to laminated red-brown and olive-gray sands and muds (Fig. 3B). These two facies were deposited between 2.5 ka and 1.8 ka, at twice the regional sedimentation rate (0.04 cm yr$^{-1}$). In thin section, this facies is characterized by sand and silt turbidites with sharp contacts and fine sand laminae (Figs. 3D and 3E). From 20 cm to 8 cm, the sediment consists of bioturbated, light red-brown mud; from 8 cm to the core top, a turbidite is interpreted to represent the 1929 event.

Core 08 was collected on the levee of Shortland Canyon, in 3850 m water depth, upslope from the other cores (Fig. 1). It consists mainly of bioturbated olive-gray mud (Fig. 3). At 60 cm, a thin sand layer with overlying red-brown mud is tentatively correlated to the 25-cm-thick sand deposited between 20 ka and 13 ka, when average sedimentation rates (0.06 cm yr$^{-1}$) were higher than present day (Fig. 3B). At ~300 cm, red-brown mud passes upward into bioturbated lighter red-brown mud with very few sandy turbidites. Accordingly, sedimentation rates diminish to ~0.02 cm yr$^{-1}$. A 25-cm-thick turbidite, at 130 cm, consists of laminated sand with fluidized sand at the top, possibly due to post-depositional dewatering. Above this turbidite, bioturbated light red-brown mud is dated at 3.9 ka (95 cm) and 2.5 ka (60 cm). At 60 cm, bioturbated mud abruptly transitions up-core to laminated red-brown and olive-gray sands and muds (Fig. 3B). These two facies were deposited between 2.5 ka and 1.8 ka, at twice the regional sedimentation rate (0.04 cm yr$^{-1}$). In thin section, this facies is characterized by sand and silt turbidites with sharp contacts and fine sand laminae (Figs. 3D and 3E). From 20 cm to 8 cm, the sediment consists of bioturbated, light red-brown mud; from 8 cm to the core top, a turbidite is interpreted to represent the 1929 event.

Core 03, collected from the western levee landslide deposit at 4500 mbsl (Figs. 1 and 3A) sampled a landslide deposit, which is consistent with the seismic facies at the core site (Fig. DR1D). The base of the core comprises large intact blocks (clasts) within the landslide. Up core, the sediment consists of highly disturbed polymictic olive-gray, brown, red-brown and tan mud clasts. Planktonic foraminifera samples collected from olive-gray mud clasts are dated at 3.6 ka (335 cm) and 3.9 ka (240 cm), which places a maximum age for the top-most part of the landslide at 3.6 ka. Two planktonic foraminifera samples collected above the landslide deposit were dated at 1.5 ka (55 cm) and 0.6 ka (30 cm). The sedimentation rate between these two ages (0.02 cm yr$^{-1}$) is consistent with reported Holocene sedimentation rates in the region (Skene and Piper, 2003). A graded sand at the top of the core likely corresponds to the 1929 event (Fig. 3).

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turbidite in core 02. The red-brown turbidite is overlain by bioturbated olive-gray mud to the top of the core, where a sand bed is interpreted to record the 1929 earthquake.

**LATE HOLOCENE LANDSLIDE RECURRENCE**

We interpret Holocene turbidites on the lower Scotian Slope as generated by landslides for the following reasons: (1) unlike shore-connected canyons (e.g., Sweet and Blum, 2016), the Scotian margin is located far from the coast (>200 km); (2) river-mouth related flows are impossible in the Holocene due to the absence of nearby rivers; and (3) large storm-induced turbidity currents are unlikely because the submarine canyon heads are deeper than 60 mbsl. Therefore, large landslides are the most plausible explanation for the rare occurrence of Late Holocene distal turbidites on the lower Scotian Slope.

The 25-cm-thick distal turbidite in core 02 dated ca. 4 ka is interpreted to represent a significant landslide event (Fig. 3B). The tentative correlation of this turbidite to the turbidite in core 08 suggests a landslide source triggered in the Shortland Canyon region more than 100 km away. Alternatively, the two turbidites could represent two distinct events triggered at (approximately) the same time. In this scenario, the distal turbidite may represent the first stage of the western levee landslide, because it is the...
thickest turbidite in the core and is located near the western levee landslide (Fig. 4). The current dataset cannot confirm this hypothesis because core 03 only records the last stage of the landslide event. Nonetheless, a significant landslide occurred at ca. 4 ka.

Core 02 has a thin red-brown turbidite at a core depth of ~60 cm, deposited at ca. 2.5 ka, interbedded with laminated olive-gray Holocene sediment. Red-brown sediment on the Scotian Margin is only found in Pleistocene and older deposits (Piper et al. 2007). In order to deposit the red-brown turbidite, a process is required that erodes the surficial (generally 2 m) olive-gray sediment in order to reach and mobilize the underlying Pleistocene red-brown mud. A landslide is the most likely process to achieve this. This event potentially represents the reactivation of the western levee landslide, since no age-equivalent turbidite is recorded in core 08 from Shortland Canyon.

Core 03 constrains the minimum and maximum ages of the last stage of the western levee landslide to 1.5 ka and 3.6 ka, respectively. Radiocarbon data show that the 20-cm-thick laminated olive-gray mud and silt in core 02 (1.8 ka) is concomitant with the last stage of the >25-m-thick landslide deposit observed in seismic reflection data and cored in core 03. This suggests that the top of the olive-gray laminated mud facies represents the distal deposit of the large western levee landslide (Fig. 3). These results indicate that the western levee landslide did not produce a widespread turbidite during its last stage of retrogression. The graded olive-gray mud deposited between 2.5 and 1.5 ka likely represents thin mud turbidites originating from sediment in suspension during multi-staged landslide retrogression. Therefore, the last stage of landslide retrogression likely represents a series of smaller events deposited sequentially within 1000 yr, from 2.5 to 1.5 ky B.P. These new ages show that the western levee landslide is among the largest Holocene submarine landslides in the western North Atlantic.

Finally, the well-known C.E. 1929 landslide turbidite is preserved in three of the cores, probably reaching the western levee area by overtopping the crest of the western levee (Fig. 1).

**MODERN SLOPE STABILITY**

In a review of submarine landslides worldwide, Urlaub et al. (2013) showed that significantly fewer landslides occurred during the past 6 k.y. than since the Late Glacial Maximum (LGM). Only four large failures (>1 km²) were recognized, with the highest frequency on the Iberian margin (1 every 1000 yr) (Gracia et al., 2010). Recently, Li et al. (2017) also recognized a Late Holocene landslide (2 ka) event in the eastern Atlantic. Our study shows that at least four landslide events, likely originating from the western levee of the Laurentian Fan, occurred during the past 4000 yr on a small area of the Scotian margin. The total volume of the multi-staged landslide on the western levee was estimated at ~300–400 km³ (Normandeau et al., 2019). These results indicate that the recurrence and distribution of medium to large submarine landslides might be underestimated in the Holocene due to the absence of appropriate mapping and dating.

The discovery of these Late Holocene landslide events also raises questions surrounding the stability of the modern slope, especially the Laurentian Fan levee. FOS analysis indicates a minimum critical slope of 7° (Fig. 2), a gradient commonly found where escarpments are present. Evidence for instability along escarpments is shown by the presence of crown cracks in the upper reaches of the levee (see imagery in Normandeau et al. [2019]). These slopes could thus fail without an external trigger, and may currently be under slow lateral spreading.

Away from escarpments, the slope is statically stable over much of the study area, suggesting an external mechanism is required to trigger slope failure. Seismic activity is a strong candidate for triggering the landslides in the Laurentian Fan region, especially because there is an active seismic zone on the Laurentian Slope (Hasegawa and Kanamori, 1987). In addition, fluid overpressure due to high Pleistocene sedimentation rates have led to the under-consolidation and low shear strength of the sediments, making them more susceptible to failure (e.g., Sawyer et al., 2017). Taken together, these factors likely make the area more prone to large submarine landslides but cone penetrometer testing and piezometers would be needed to confirm this hypothesis.

**CONCLUSIONS AND SOCIETAL IMPLICATIONS**

Our study shows that four large landslide events occurred offshore eastern Canada since 4 ka, sourced from a giant channel levee on the lower slope and from the upper slope. This ~1000 yr, Late Holocene recurrence rate of large submarine landslides is more frequent than previously reported, potentially indicating a higher probability of a submarine landslide occurring in the future in the study area. Two of the world’s largest Late Holocene failures (C.E. 1929 and 1.5 ka on the Laurentian Fan levee) occurred in the Laurentian Fan region, one of which (1929) had dramatic consequences on offshore infrastructure and loss of life; the other (1.5 ka) is potentially unstable to this day.

Although these landslide events occurred far from the coast, there are considerations for impacts to seabed infrastructure. Three submarine cables cross the Laurentian Fan region, all located on the large Laurentian Fan levee landslide described here. Additionally, the Canadian Atlantic margin is an area of active oil and gas exploration, with recent exploration wells drilled in water depths >2000 m and a potential for deepwater oil production. The tsunamiogenic potential of these newly identified landslides is unknown, but the potential threat to coastal communities of eastern North America should not be discounted. A reevaluation of submarine-landslide risk across the western North Atlantic margin is recommended, and would require more systematic seafloor mapping, analysis of the distal record of large events, targeted slope stability analysis, and numerical modeling of landslide tsunamiogenic potential.

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