SUBMARINE MASS MOVEMENTS IN CANADA: GEOHAZARDS WITH FAR-REACHING IMPLICATIONS

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RÉSUMÉ

Le Canada possède les plus longues zones côtières et marges continentales du monde. Donc, il est significativement exposé aux géorisques marins, comme les glissements de terrain sous-marins (GTSM) comportent également des risques de tsunamis. Les glissements côtiers représentent un risque significatif vu la proximité d'infrastructures et leur capacité de produire des tsunamis. Ils se produisent sans avertissement et peu de délai existe entre leur déclenchement et l'impact possible d'un tsunami. Les GTSM en marge continentale sont communs dans l'histoire géologique mais rare à l'échelle de l'histoire humaine. Quelques anciens dépôts glissés sont de dimensions importantes, mais les nouvelles évidences suggèrent que même les petits glissements sur les marges continentales peuvent générer des tsunamis. L'impact des tsunamis peut être ressenti à des centaines de km de la source. L'identification des régions à potentiel élevé pour l'instabilité des pentes combinées à la compréhension des processus de formation de GTSM et de tsunami, et à des modèles sophistiqués de propagation, sont nécessaires pour identifier les secteurs hautement à risque d'impact.

ABSTRACT

Canada has the longest coastline and largest continental margin of any other nation in the World. As a result it is vulnerable to marine geohazards, such as submarine landslides and consequent tsunamis. Coastal landslides represent a specific threat because of their possible proximity to societal infrastructure and high tsunami potential. They occur without warning and with little time lag between failure and possible tsunami impact. Continental margin landslides are common in the geologic record but rare on human timescales. Some ancient submarine landslides are massive but more recent events indicate that even relatively small slides on continental margins can generate devastating tsunamis. Tsunami impact can be 100's of km away from the source event. Identification of high potential submarine landslide regions, combined with an understanding of landslide and tsunami processes and sophisticated tsunami propagation models are required to identify areas of high risk of impact.

1. INTRODUCTION

Subaerial landslides have been the subject of tremendous volumes of research over the past half century because of their imminent threat to the public and societal infrastructure (*e.g.* Evans and DeGraff, 2002). The US Geological Survey Landslide Hazard program reports that damage in the United States due to landslides is worth \$3.5 billion/year (2005 dollars) with 25 to 50 fatalities per annum (http://landslides.usgs.gov). In Canada, 570 deaths over a 160 year period (1840-1999) have been attributed to disastrous landslides (Evans, 2001). Death tolls in less developed, populated regions are higher (*e.g.* Ancash, Peru, 1970, 18,000 deaths; Layte, Phillipines, 2006, 1,800 fatalities).

Submarine landslides, by comparison, have been much less well researched because of their inaccessibility and general lack of direct societal consequence. With increasing awareness of the potential of tsunami generation and increasing development of offshore regions, however, there is a need for better understanding of offshore landslide processes and landslide potential (Locat and Lee, 2002). For example, a submarine landslide off Papua, New Guinea in 1998 caused a tsunami resulting in 2200 deaths (Tappin *et al.*, 2001). In 2006, a submarine landslide off Taiwan, in the Luzon Strait, caused failure of seven out of nine undersea cables (LaPierre, 2007). These failures halted the entire internet network between Taiwan, Hong Kong, and China and affected communications with Thailand, Malaysia, Vietnam, South Korea and Singapore for 12 hours. The combined GDP of Taiwan, Hong Kong and China approximates \$7.56 billion dollars per day. The complete cable inventory was not operational until January 30th, with 18 cable repairs. It is not known what actual business losses were accrued as a result. Cable breaks in this area are common, as a result of submarine seafloor displacements (Soh *et al.*, 2004).

The elevated awareness of the need for better understanding of underwater landsliding is coupled with great advances in underwater mapping technologies over the past decade and a half. Multibeam sonar, 3D seismic reflection, and remote and autonomous underwater vehicle technologies, for example, provide hitherto unparalleled imagery of the geology beneath the oceans, permitting

In : J. Locat, D. Perret, D. Turmel, D. Demers et S. Leroueil, (2008).
Comptes rendus de la 4e Conférence canadienne sur les géorisques: des causes à la gestion.
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investigation of landslide deposits that exceed onshore capabilities in some cases. This paper reviews known examples of underwater landslides in Canada, separating the discussion into coastal and continental margin events. Some of these landslides are known to have caused tsunamis. It will show the prevalence of such deposits in the geologic record which has implications concerning the frequency of events and therefore the hazard they represent.

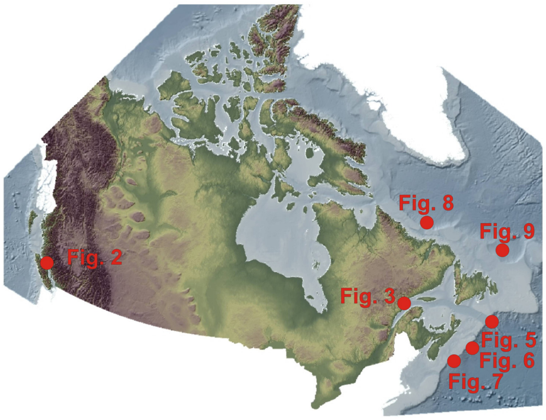

Figure 1. Canada's on- and offshore territory, with locations of figures indicated.

2. COASTAL LANDSLIDES

Canada's coastline is >243,000 km long; the longest in the World (Fig. 1). Coastal landslides present a particular hazard because of their high potential for tsunami generation and their possible proximity to societal infrastructure. Many coastal regions exhibit a variety of factors that establish conditions for sediment mass-failure. Because of wave, long-shore current and glacial erosion, coastal regions commonly have steep slopes. Quaternary glaciations deposited coastal sediments of mixed lithologies that in many cases lack cohesive strength. Most coastal regions have endured episodes of sea level rise and fall, thus sediments are of marine and lacustrine origin. This history results in sediments of variable adjacent geotechnical states. Finally, pore pressure conditions have a great potential to vary significantly spatially and temporally because of adjacent subaerial and submarine conditions, possible aquifers, meteoric waters, and tidal and wave fluctuations.

Because of these conditions and high seismicity potential, the coast of British Columbia is the region in Canada most prone to landslides and consequent tsunamis (Bornhold *et al.*, 2001). Many examples of coastal landslides were caused by anthropogenic activity: the Kitimat Arm failure of 1975 in British Columbia, (Prior *et al.*, 1982), and Skagway, Alaska in 1994 (Rabinovich *et al.*, 1999) were a result of coastal construction. Both generated waves within inhabited coastal embayments that caused significant infrastructure damage.

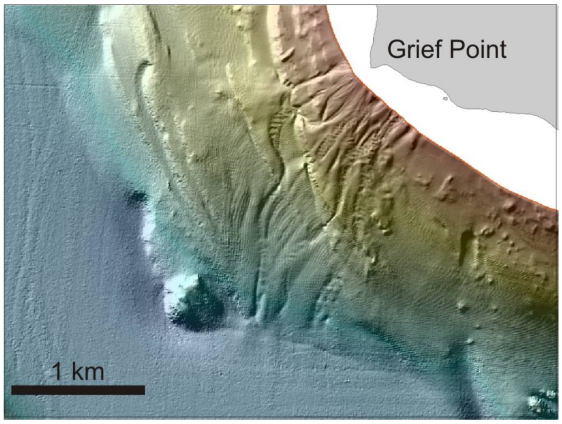

Figure 2. Multibeam image of coastal landslide off Grief Pt, British Columbia, resulting from the 1946 Vancouver Island Earthquake. (Image compliments J.V. Barrie, GSC-Pacific)

Coastal failures may be triggered by natural causes as well. The 1946 Vancouver Island M7.2 earthquake caused underwater landslides within the Strait of Georgia; for example, Deep Bay, Goose Spit, and Grief Point (Mosher *et al.*, 2004c). The failure in Deep Bay is known to have caused a water wave that is reported to have overturned a vessel. The Grief Point failure (Fig. 2) severed an underwater telephone cable running between Texada Island and the mainland.

After British Columbia, the second highest earthquake prone area in Canada is the Laurentian Valley of Quebec (Mazzotti *et al.*, 2005). Along the banks and submarine slope of the St. Lawrence estuary and the Saguenay Fjord are numerous examples of mass failure (*e.g.* Fig. 3; Cauchon-Voyer *et al.*, 2007; Levesque *et al.*, 2006; Urgeles *et al.*, 2001). Most are pre-historic but a few are recent events, *e.g.* 1663 and circa 1860 (Cauchon-Voyer *et al.*, 2007). Depending upon conditions of failure and location, a modern instability event in these areas could readily cause damage to underwater structures and generate waves that will damage coastal infrastructure.

In some cases, mass failure occurs with no readily apparent trigger. Spontaneous failure in river mouth deltas, for example, may be caused by rapid sediment loading (Terzaghi, 1956). For example, a well documented failure at the mouth of the Fraser River involved 10^6 m^3 of sediment and retrogression of the head of the principal sea valley to within 100 m of the Sand Heads lighthouse (McKenna and Luternauer, 1987; Atkins and Luternauer, 1991, Christian *et al.*, 1998). Similarly, failure of coastal regions have been observed, perhaps related purely to pore pressure responses to tidal change or storm activity (*e.g.* Fig. 3; Christian *et al.*, 1997, 1998; Mosher *et al.*, 2004b).

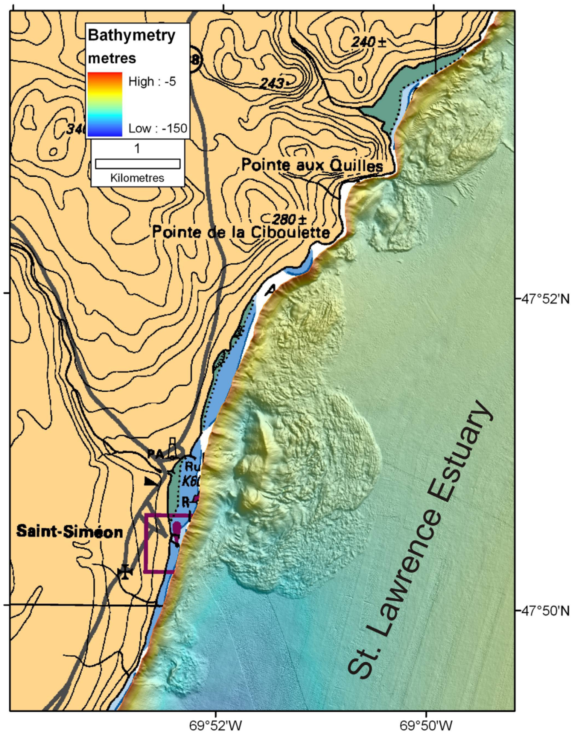

Figure 3. Example of a coastal landslide on the flank of the St. Lawrence Estuary. Saint-Siméon host a port facility with a public ferry terminal. (Image compliments D.C. Campbell, GSC-Atlantic).

3. CONTINENTAL MARGIN LANDSLIDES

Canada's underwater landmass below the 200 m (approximate depth of the shelf break) and above the 3000 m isobath represents an area of 2,960,000 km^2; the largest of any country in the world. Seabed slope angles within this zone typically range between <1° and 4°, although canyon and channel wall or subduction thrust ridge slope angles can exceed 45° (*e.g.* Mosher *et al.*, 2004a). The continental slope typically supports a stable thick unconsolidated sediment overburden (Mosher *et al.*, 1994). Aside from these conditions, other factors that establish slope instability potential include interstitial biogenic or hydrocarbon free gas, gas hydrate, salt mobility, high sedimentation rates (*e.g.* deglacial periods), high pore pressures and vertical lithologic (porosity/permeability) variability (Mosher *et al.*, 2004b). In most continental margin settings; however, it is inferred that seismicity, or ground shaking due to earthquakes, is required to initiate instability (Lykousis *et al.*, 2007).

Figure 4. Headwall from collapse of Mapleguard Spit in 1999. Results from a similar event were observed in 1998 as well.(photo compliments P. Monahan)

On Canada's West Coast, seismicity along the continental slope is common because of active convergent and transform margins (Hyndman, 1995). Sediment mass transport processes are a common phenomenon along convergent subduction margins because of frequent and strong seismicity combined with steep slope angles and potential for elevated pore-pressures (*e.g.* Tappin *et al.*, 2001; 2007; Goldfinger *et al.*, 2003). The complex geology of accretionary margins results in a variable situation for landslide generation. It also makes identification of landslides difficult. Few investigations along the Canadian portion of the Cascadia subduction margin have been conducted specific to recognition of landslides. Along the adjacent Oregon margin, however, Goldfinger *et al.* (2000) and MacAdoo *et al.* (2004) recognized large landslide deposits and assessed their tsunami-generating potential. MacAdoo *et al.* (2004) argue that the Cascadia margin of northern Oregon, closest to Canadian territory, is unlikely to produce landslides during modern earthquake events. They suggest that ground accelerations on the slope would not be sufficient to initiate sediment failure.

Canada's eastern and northern continental margins are tectonically passive margins and seismicity is rare (Adams and Halchuk, 2003). Earthquakes up to M7+; however, can be expected (Mazzotti and Adams, 2005), and do occur, such as the 1929 M7.2 event off the southern tail of the Grand Banks (Bent, 1995). In the past, seismicity was probably more common due to deglacial isostatic rebound, or periods when possible ocean basin scale tectonism was active (*e.g.* Weaver, 2003). This paper focuses on Canada's eastern margin where submarine landslide deposits are recognized from available industry and research geophysical data. In addition, this region sustained a landslide generated tsunami in 1929; a consequence of the aforementioned M7.2 earthquake on the Grand Banks.

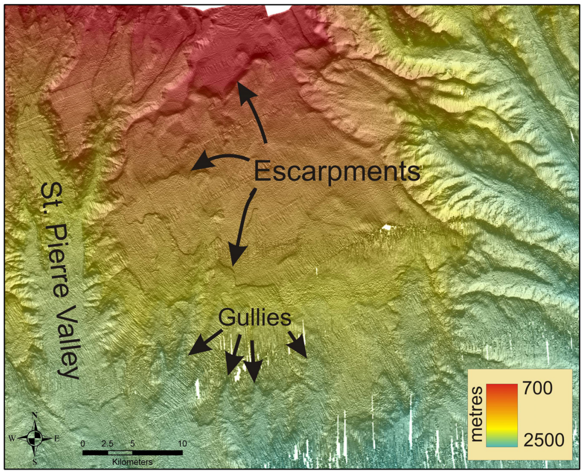

Figure 5. Multibeam image over the St. Pierrre Slope; main source area for the 1929 Grand Banks landslide, showing 80-100 m-high escarpments.

Amongst geoscientists, this 1929 Grand Banks landslide is perhaps the most famous historic submarine mass-transport deposit. It led both to the first formal recognition of naturally occurring turbidity currents (*e.g.* Heezen *et al.*, 1954; Piper *et al.*, 1988), and that seafloor displacements due to mass-failure can cause damaging tsunamis at great distance from their source (*e.g.* Ruffman and Tuttle, 1995; Ruffman, 2001; Fine *et al.*, 2005). It also showed that undersea events can cause damage to engineering structures; 12 trans-Atlantic telegraph cables were sheared by the resulting turbidity current.

Mosher and Piper (2007a&b) recently studied the seafloor of the St. Pierre Slope; the area of the 1929 event, using multibeam sonar data (Fig. 5). These data show numerous fresh escarpments ranging from 5 to 100 m in height but no evidence of a single large headscarp or debris lobe. These results suggest that the landslide was relatively thin (5-100 m thick but average about 20 m) and dispersed over a relatively large area (~7,200 km^2), as suggested by earlier studies (Masson *et al.*, 1985; Piper *et al.*, 1988, 1992, 1999). McCall (2006) estimated the total volume of failed sediment in the area of St Pierre Valley and St Pierre Slope, between the 500 and 2000 m isobaths, was about 93.5 km^3, of which about half was evacuated and half remained.

The shoaling series of escarpments on St. Pierre Slope (Fig. 5) with rotational blocks and debris at their bases (McCall *et al.*, 2005), suggests a retrogressive style of failure. This terrain is similar to the morphology seen everywhere on the Scotian Slope, particularly on broad flat intercanyon regions (*e.g.* Fig. 6; Mosher *et al.*, 2004a). This fact suggests that similar thin-skinned underwater landslides may be relatively common on the eastern Canadian continental margin.

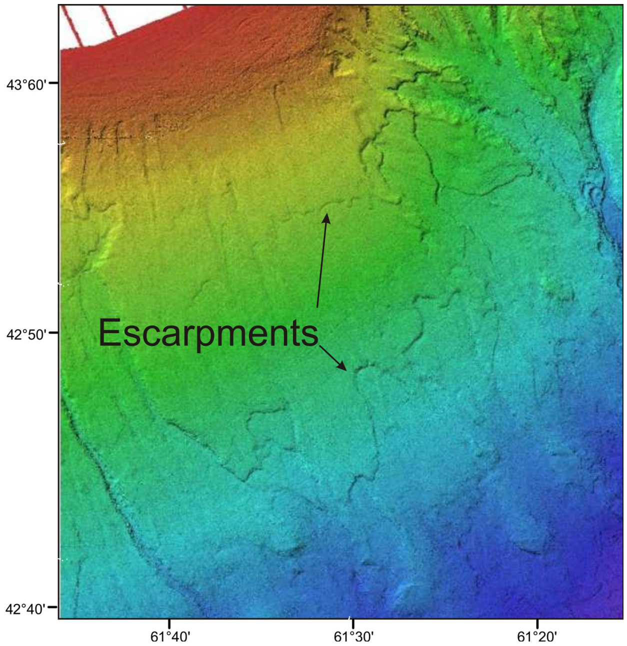

Figure 6. Multibeam image from the central Scotian Slope, showing lateral escarpments 20-80 m high, similar to those seen on the St. Pierre Slope data.

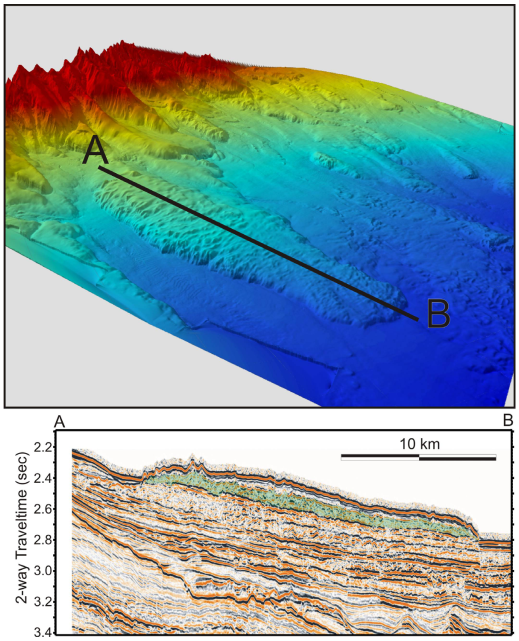

Figure 7. An MTD off the SW margin of Nova Scotia, revealed 3D seismic data. Top is the seafloor rendering and below is a seismic profile through the feature. The highlighted zone in the profile is the MTD.

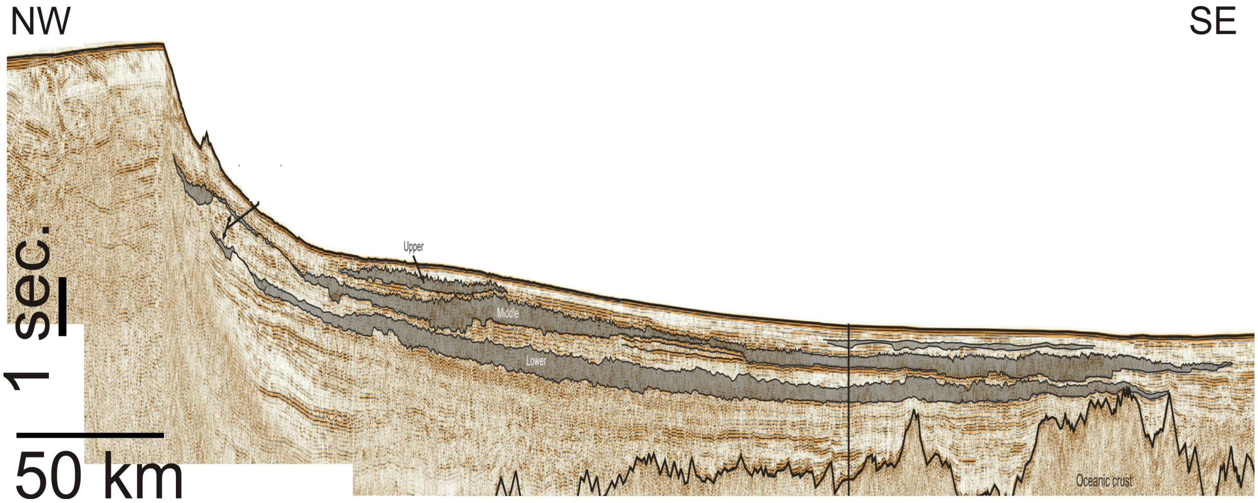

Figure 8. Lithoprobe line 90-1, 2 from the Labrador margin, off Hopedale Saddle. MTDs are highlighted in grey.

As data have become more widely available, it has become recognized that mass-transport deposits are prevalent on the surface and in the subsurface on passive margins. Figure 7 shows a large mass transport deposit (MTD) on the SW Scotian Slope, about 12.5 km^3 in volume, buried by about 30 m of unconsolidated late-Pleistocene sedimentary drape. Four additional MTD's are distinguished below the surficial feature.

MTDs, often characterised in seismic profile as incoherent reflections with typically irregular surfaces and possible erosional bases, are widely recognized throughout the eastern Canadian margin. For example, Campbell *et al.*, 2004 identified a massive buried MTD on the Scotian Slope with a run-out distance >100 km and a volume in excess of 350 km^3. Deptuck *et al.* , 2007 mapped several MTD's on the Labrador margin that extend over 300 km into the Labrador basin, covering an area of at least 28,000 km^2 (Fig. 8). Tripsanas and Piper (In Press) observed MTD's in Orphan Basin, off Newfoundland, that comprise 100% of the sediment section to a depth of at least 1km below seafloor (Fig. 9). Mass-transport processes, therefore, are common phenomena along the eastern Canadian passive continental margin, and comprise a significant proportion of the sediment column.

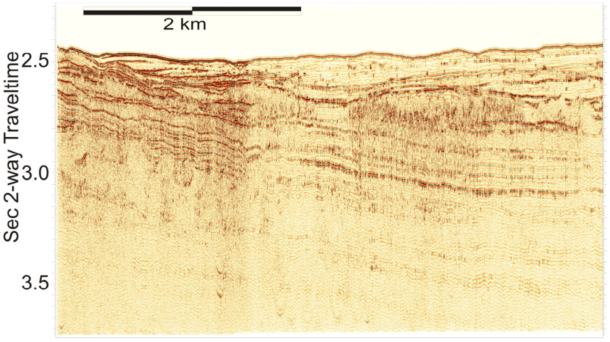

Figure 9. Seismic profile (2005033-018) in Orphan Basin, showing a thick ac-cumulation of stacked MTDs.

4. TSUNAMIS HAZARD

Common submarine landslides in coastal and continental margin settings in Canada infer the potential for future submarine landslides in these environments. Coastal landslides can directly damage local infrastructure but can also create local tsunamis with significant wave heights. In 1908, a landslide on the Liève River in western Québec produced a wave that killed 27 people in the village of Notre-Dame-de-la Salette (Evans, 2001). The 1975 Kittimat slide produced a series of waves, the largest of which was an estimated 8.2 m high (Prior *et al.*, 1982). A subaerial rockfall, splashed into Gilbert Inlet, Alaska in 1958 producing a tsunami in Lituya Bay that denuded the landscape at elevations up to an incredible 524 m above sea level (Miller, 1960).

Causes of coastal landslides in Canada are varied, but in all cases there is no opportunity for warning and very little delay time between landslide displacement, and tsunami generation and impact. To mitigate against these hazards, coastal zones with high potential for landsliding must be identified and sufficient precautionary measures, such as building regulations, enacted in order to avoid disaster.

Better quality and greater amounts of geoscience data show that MTDs are geologically common, even on passive margins. These data also show that MTDs are potentially immense in scale, with significant potential to generate tsunamis. The 1929 Grand Banks and 1998 Papua, New Guinea (Tappin *et al.*, 2001) events showed that even relatively small underwater landslides can generate tsunamis that cause significant loss of life and infrastructure damage. This knowledge raises the issue as to scale and frequency of events. If small-scale mass-transport events can generate tsunamis, then the tsunami-hazard potential of the Canadian East Coast margin is larger than previously thought.

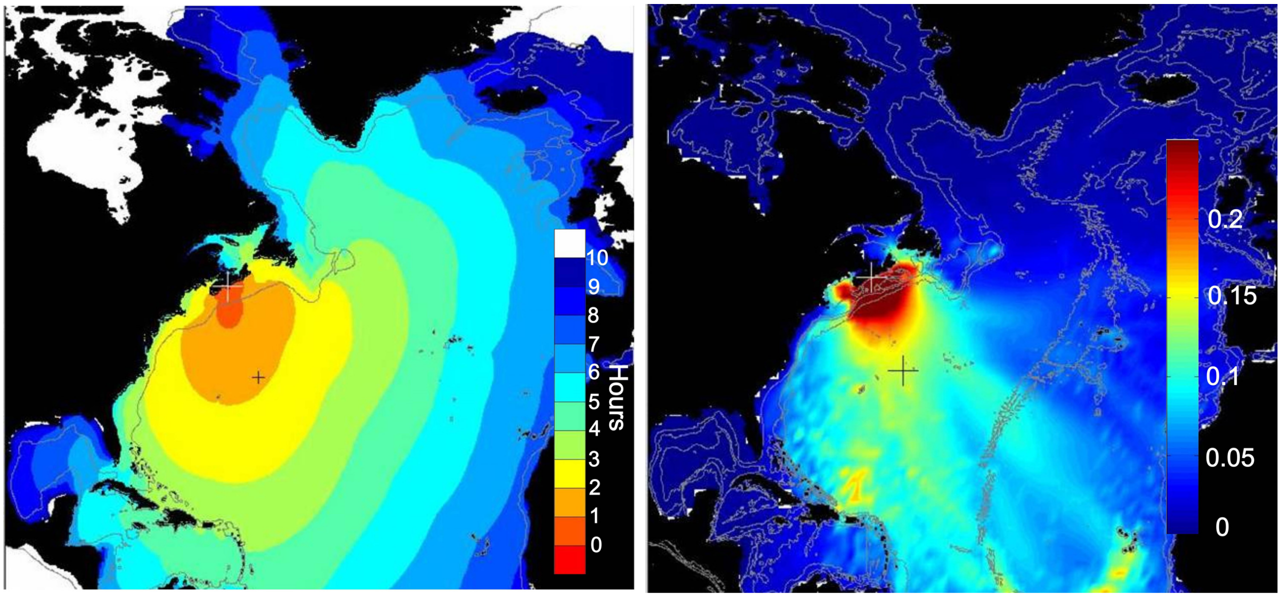

Figure 10. Tsunami arrival maps of Xu (2006) for Halifax from a source anywhere in the North Atlantic. Left is the arrival time and right is a relative gain chart (unity at Halifax). Nearly 8000 Green's functions were pre-calculated for Halifax; therefore the response at Halifax can be quickly calculated for any tsunami triggered anywhere in North Atlantic Ocean in real time.

During the Grand Banks tsunami of 1929, there was a delay of nearly 2 hours from the source earthquake to tsunami impact. Warnings can be issued in that time with appropriate infrastructure. For this infrastructure to be implemented and maintained, it requires recognition of the tsunami-generating potential of underwater landslides and of the regions where landslide potential exists. Models are being improved upon to both better simulate landslide–tsunami coupling and tsunami propagation properties such as speed and amplitude, which ultimately will provide prediction capability (*e.g.*, Fine *et al.*, 2005).

A good example of a numerical model development comes from Xu (2007). He developed a real-time web-based technique based on properties of the all source Green's function (ASGF). Instead of guessing a future epicentre to predict tsunami arrival, the focus is on a point of interest; Halifax in the example shown in Figure 10. The ASGF is pre-calculated for points of interest (*e.g.* Halifax) to describe exactly how the water level at Halifax will respond to a unit forcing in any part of the model domain. The response to a real-time global forcing will then be a linear combination of the pre-calculated ASGFs, allowing rapid generation of results. Simulation at any points of interest proceeds alone without the simulations elsewhere because decoupling has been handled by the ASGF; parallel computations are thus ready for multiple local domains. Based on the ASGF, an interactive tool was developed on a PC and web server. On specifying a real-time tsunami source, the software provides instantaneously the tsunami arrive time series including the first arrival time and the relative maximum amplitude (gain).

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