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TOWARDS A NATIONAL TSUNAMI HAZARD MAP FOR CANADA: TSUNAMI SOURCES

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ABSTRACT

We present a summary of geological tsunami sources with the potential to threaten the coasts of Canada. The study is part of a Geological Survey of Canada project to quantify tsunami hazard with the aim of producing a national tsunami hazard map. The Pacific coast is most at risk. Large tsunamis resulting from M~9 Cascadia megathrust earthquakes have impacted the British Columbia coast on average every 500 years throughout the Holocene, most recently in A.D. 1700. Tsunami potential along the Explorer-North America margin and southern Queen Charlotte fault is not well understood. Far-field earthquake-generated tsunamis are also a significant hazard to the outer coast and inlets; the 1964 Alaska tsunami caused considerable damage in Port Alberni and other western Vancouver Island communities. Landslides can generate locally destructive tsunamis, especially in coastal fjords. A submarine slide in Kitimat Arm in 1975 produced a tsunami with amplitudes up to 8.2 m that caused extensive local damage. The Strait of Georgia (including lower elevations in greater Vancouver) may be at risk from submarine landslide tsunamis, e.g., from the unstable foreslope of the Fraser River Delta. Offshore Vancouver Island, continental slope failures have been mapped along the Cascadia subduction zone deformation front. Future landslides could generate locally destructive tsunamis, or may increase amplitudes of megathrust tsunamis. Canada's Atlantic coast is far from active plate boundaries, yet was the site of Canada's most tragic historical earthquake/tsunami. In 1929, an M_s 7.2 earthquake triggered the Grand Banks submarine slide, resulting in 3-8 m tsunami waves that killed 28 people in southern Newfoundland. Locally destructive tsunamis may result from other submarine landslides on the continental shelf edge and in the St. Lawrence Estuary. Far-field sources may include plate-boundary earthquakes in the Caribbean and offshore Gibraltar, and Canary Island volcanic flank failures. Little is known about the tsunami history of the Arctic coastline. Potential sources include submarine slope failures and large thrust earthquakes on the Mackenzie Delta front. Tsunami hazard in the Arctic is reduced by the extensive sea ice.

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Introduction

The Geological Survey of Canada (GSC) is undertaking a National Tsunami Hazard Assessment (within the Public Safety Geoscience Program) in order to produce a first-order national tsunami hazard map for Canada, and to identify key areas for future research. As a first step in this process, we have compiled an annotated bibliography of tsunami references with relevance to tsunami hazard in Canada (Leonard et al. 2010). In this paper, we summarize the geological sources of tsunamis that may pose a threat to the coasts of Canada.

Canada has the longest coastline of any country in the world, and it is susceptible to tsunamis generated in three different oceans – the Pacific, Atlantic and Arctic (Fig. 1). Of primary concern are tsunamis generated tectonically by earthquakes in both near- and far-field regions; such tsunamis have the potential for widespread destruction (e.g., Clague et al. 2003). However, landslide-generated tsunamis, which may be seismically triggered, also present a significant hazard over more localized coastal areas of Canada (e.g., Mosher 2009). Inland, landslides also present a tsunami hazard along steep-sided rivers and lakes with active submarine fan-deltas and/or unstable surrounding slopes; past events in B.C. and Quebec have caused fatalities (Evans 2001), but we deal only with marine/coastal phenomena here. Meteorological tsunamis are now also recognized as a potentially destructive and likely common regional hazard (e.g., Montserrat et al. 2006; Stephenson and Rabinovich 2009). As these are atmospheric rather than geological phenomena, and are likely ubiquitous rather than having a distinct source area, we do not discuss meteorological tsunamis further. Also possible, but much less probable, are tsunamis generated by volcanic eruptions and asteroid impacts.

Tsunami Sources for the Pacific Coast of Canada

The Pacific coast is considered to have the largest tsunami hazard in Canada, from both near- and far-field sources. A recent compilation (Stephenson et al. 2007; 2010) updates the catalogue of tsunamis documented on the Pacific coast of Canada since A.D. 1700, building on the work of Soloviev and Go (1975) and Wigen (1983). The greatest tsunami hazard comes from local megathrust earthquake-generated tsunamis similar to the devastating 2004 Indian Ocean tsunami, but also significant are tsunamis from local crustal earthquakes and far-field subduction earthquakes, as well as local landslide-generated tsunamis.

Earthquake Sources

Large tsunamis resulting from M~9 megathrust earthquakes on the Cascadia subduction zone (Fig. 1) have likely impacted the Pacific coast of North America regularly throughout the Holocene, most recently in A.D. 1700. Although prior to historical time, Native American oral records document a shaking/flooding event between 1690 and 1715 (Ludwin et al. 2005) that correlates with a damaging tsunami recorded in Japan (Satake et al. 1996) and paleoseismic evidence from submerged trees, buried soils, and sand layers in coastal marshes (e.g., Atwater et al. 2005). Coastal marshes and offshore turbidite deposits provide evidence that similar great earthquakes and tsunamis have occurred throughout the Holocene, with a return period that averages ~500 years but ranges from ~200 to ~800 years (e.g., Goldfinger et al. 2010; Leonard et al. 2010). Tsunami modelling of a Cascadia megathrust source shows that the west coast and inlets of Vancouver Island are most at risk. Modelling of a tsunami due to release of 500 years of accumulated strain suggests wave amplitudes of 5-8 m on the southwest coast of Vancouver Island (16 m predicted at one location) and currents up to 17 m/s in narrow channels and near headlands (Cherniawsky et al. 2007). Wave amplitudes in the Strait of Georgia are expected to be only ~20% of the outer coast values (e.g., Ng et al. 1992), but inundation depends strongly on bathymetry; for this model, waves > 4 m are expected in the harbours of Victoria, B.C. (Cherniawsky et al. 2007).

The tsunami potential further north along the Explorer-North America boundary and southern Queen Charlotte fault (Fig. 1) is poorly understood as yet. A M_w 6.6 earthquake 150 km offshore within the Explorer plate in 2004 had a thrust component that generated a small tsunami (~10 cm on the west coast of Vancouver Island), and a M_w 6.1 thrust earthquake that occurred near the southern portion of the Queen Charlotte fault in 2001 caused a tsunami with maximum recorded amplitudes of 23 cm (Rabinovich et al. 2008). Thus, the potential for damaging tsunamis from larger earthquakes on these and nearby sources cannot be discounted.

Crustal earthquakes within the North America plate can generate tsunamis if they cause vertical seafloor displacement and/or trigger mass movements that disturb the water column. Vertical offsets are observed on active faults in the Strait of Georgia and eastern Juan de Fuca Strait, including the transpressional Devil's Mountain–Leech River fault system (e.g., Johnson et al. 2001). The 1946 M_s 7.3 central Vancouver Island earthquake (Fig. 1) triggered landslides and submarine slides, some of which generated tsunami waves, drowning a man whose boat tipped over, and causing some damage and flooding (Hodgson 1946; Rogers and Hasegawa 1978).

Far-field tsunamis generated by earthquakes elsewhere in the Pacific (Fig. 2) represent a significant hazard to parts of the B.C. coast, particularly where resonance amplification occurs in coastal inlets, notably the Alberni Inlet (Fig. 1) (e.g., Henry and Murty 1995). The tsunami from the M_w 9.2 1964 Alaska earthquake caused considerable damage (~$10 million in 1964 dollars) to Port Alberni and other communities on western Vancouver Island (White 1966; Thomson 1981). The trans-Pacific tsunami generated by the M_w 9.5 1960 Chile earthquake also caused some damage on the west coasts of Vancouver Island and the Queen Charlotte Islands, but maximum wave amplitudes were significantly smaller (1.3 m at Tofino, west coast Vancouver Island, compared with 2.4 m in 1964, Wigen 1960) due to the longer distance from the source and the more oblique propagation direction. Small tsunamis from other far-field locations around the Pacific Ocean are detected regularly on the B.C. coast, e.g., 11 out of 16 tsunamis recorded between 1994 and 2007 were far-field events, originating in Japan, the Kuril Islands, Chile, Mexico, Peru, Indonesia, and the Tonga Islands (Stephenson and Rabinovich 2009). Additional far-field sources include Kamchatka and the Aleutian Islands; some modelling suggests that a tsunami generated in a large subduction earthquake on the Aleutian trench could be even more damaging to the B.C. coast than the 1964 Alaska event (Dunbar et al. 1989).

Landslide Sources

Subaerial and submarine landslides are a potential source of locally destructive tsunamis on the Pacific coast. Fjords along the mainland coast (Fig. 1) are particularly at risk. For example, the 1975 submarine slide in Kitimat Arm produced a tsunami with amplitudes up to 8.2 m, resulting in substantial local damage (e.g., Murty 1979; Skvortsov and Bornhold 2007). In Knight Inlet a rock avalanche generated a tsunami that destroyed the First Nations village of Kwalate, probably in the 16th century (Bornhold et al. 2007).

The Strait of Georgia, including low-lying parts of greater Vancouver, is potentially at risk from submarine landslide tsunamis (Fig. 1). In particular, the foreslope of the Fraser River Delta has been identified as unstable (e.g., Mosher et al. 1997). Modelling of tsunamis from hypothetical underwater landslides from the delta foreslope suggests that waves up to several metres high could strike the nearby mainland coast, with waves up to 18 m in amplitude reaching the Gulf Islands of Mayne and Galiano across the Strait (Rabinovich et al. 2003).

Continental slope failures have been mapped along the deformation front of the Cascadia subduction zone offshore Vancouver Island (Fig. 1), as well as further south along the margin (e.g., Goldfinger et al. 2000; McAdoo and Watts 2004). Future landslides could result in locally destructive tsunamis, or, if synchronous with megathrust rupture, could contribute to locally-increased amplitudes of tsunamis generated by megathrust seafloor displacement.

Landslides off the shores of the Hawaiian Islands (Fig. 2) have likely resulted in very large local tsunamis in the past (e.g., Moore et al. 1994); some suggest that a large flank collapse could generate a tsunami with significant far-field effects (e.g., Ward 2001), but the waves would likely attenuate significantly before reaching the west coast of North America (Pararas-Carayannis 2002). Modelling of potential large submarine mass flows off the Aleutian Islands (Fig. 2) by Waythomas et al. (2009) suggests possible generation of transoceanic tsunamis with waves several metres in amplitude reaching the west coast of North America.

Tsunami Sources for the Atlantic Coast of Canada

Tsunami hazard along the Atlantic coast of Canada is significantly lower than for the Pacific. Few tsunamis have been documented in historical time (e.g., Ruffman and Peterson 1988). There are no active plate boundaries nearby to generate tsunamis by tectonic displacement of the seafloor, but submarine landslides triggered by earthquakes can produce locally devastating tsunamis, as demonstrated by Canada’s most tragic historical earthquake/tsunami in 1929. In the historical record, the number of tsunamis generated in the Atlantic Ocean is about one fifth of those generated in the Pacific (Gusiakov 2009).

Earthquake Sources

Potential earthquake sources of a far-field tsunami impacting Canada’s east coast include the source of the 1755 Lisbon earthquake/tsunami, and interplate faults in the Caribbean (Fig. 2). The M~8.7 Lisbon earthquake (Johnston 1996) involved thrusting along a complex part of the African-Eurasian plate boundary off Gibraltar, although the source fault(s) are still under debate (e.g., Gutscher et al. 2006). The resultant tsunami caused much damage along eastern Atlantic coasts from the British Isles to Morocco; it was also observed in Brazil and the Caribbean. In Bonavista, Newfoundland, Canada, an unusual rise and fall was noted in the harbour, along with flooding of low-lying areas (Ruffman 2006; Roger et al. 2010). Simulations of this tsunami result in wave heights over 1.5 m at several coastal locations in Newfoundland, and up to 2.5 m or more on parts of the Bonavista peninsula (Barkan et al. 2009; Roger et al. 2010).

In the northeastern Caribbean (Fig. 2), locally catastrophic tsunamis have resulted from interplate thrust earthquakes along the Hispaniola trench, but along the Puerto Rico trench earthquake slip tends to be more oblique with a relatively small thrust component (ten Brink and Lin 2004). Simulations by Knight (2006) and the Atlantic and Gulf of Mexico Tsunami Hazard Assessment Group (2008) show that a M~9 thrust earthquake on the Puerto Rico trench (bigger than observed in the 500-year history, e.g., O'Loughlin and Lander 2003) could produce damaging waves along the U.S. Atlantic coast (~0.5-1.5 m at the shelf edge with significantly higher runup expected). Similar values could reasonably be expected to result in Atlantic Canada where the shelf edge is almost orthogonal to the main expected tsunami propagation direction.

Landslide Sources

In 1929, an M_s 7.2 earthquake at the edge of the Grand Banks south of Newfoundland (Fig. 1) triggered a large submarine landslide-turbidity current that broke 12 seafloor telegraph cables (e.g., Heezen and Ewing 1952). The landslide triggered a tsunami that struck the Burin Peninsula in southern Newfoundland with 3-8 m waves and runup of up to 13 m; 28 people were killed, and property and cable damage was estimated at $400,000 in 1929 dollars (e.g., Ruffman, 2001; Fine et al. 2005). Future locally destructive tsunamis may result from other submarine landslides along the continental shelf edge, where mass failures much larger than the Grand Banks deposit have been mapped (e.g., Piper and Ingram 2003). Such failures would likely also be triggered by earthquakes; recurrence intervals for a 1929-size event are estimated at between a few hundred and 1000 years (e.g., Clague et al. 2003), but not all earthquakes of this size will necessarily trigger a tsunamigenic landslide.

The region of the St. Lawrence Estuary, Quebec (Fig. 1), is characterized by Quaternary sediments, moderate seismicity concentrated in the Charlevoix seismic zone underlying the estuary, and at least a million people at risk from tsunamis (e.g., Poncet et al. 2009). Tsunamis could be triggered by seismic displacements or landslides; of numerous mass failures along the banks and submarine slopes, many have been linked to an M~7 earthquake in 1663 (e.g., Locat et al. 2003). Modelling of earthquake and landslide sources suggests that 1-2 m waves are likely (El-Sabh et al. 1988; Chassé et al. 1993), with local amplitudes up to ~5 m (Poncet et al. 2010).

Large volcanic flank collapses off the Canary Islands offshore northern Africa (Fig. 2) have been proposed as a source of far-field tsunamis with potentially catastrophic consequences for the Atlantic coast of North America (up to 10-25 m waves; Ward and Day 2001). However, turbidite evidence suggests that smaller landslides are more likely (Wynn and Masson 2003). More recent modelling of such a collapse implies that very large, short-period local waves would strongly dissipate with distance, leading to less catastrophic but still potentially damaging waves up to 3 m in amplitude striking the east coast of North America (Mader 2001; Gisler et al. 2006).

Tsunami Sources for the Arctic Coast of Canada

Very little is known about the tsunami history and hazard of the sparsely-populated Arctic region of Canada. There is only a very recent written history and very limited and recent tide gauge monitoring. Hazard is likely much lower than both the Pacific and Atlantic coasts, particularly as the presence of extensive sea ice is expected to attenuate tsunami waves. Concentrated seismicity occurs beneath the Beaufort Sea (likely deep extensional faulting due to sediment loading; Hasegawa et al. 1979) and in the Baffin Bay area (postglacial extensional faulting on eastern Baffin Island and mainly strike-slip faulting in Baffin Bay; Bent 2002) (Fig. 1). Tectonically-generated tsunamis are unlikely from either of these sources, but Hyndman et al. (2005) suggest the potential for large thrust earthquakes beneath the Mackenzie Delta that could act as a trigger. Locally-damaging landslide tsunamis may be generated by earthquakes or other processes. Landslide tsunamis have been documented in the Disko Island region off western Greenland (Ruffman and Murty 2006), and several failures noted in the fjords of eastern Baffin Island (Syvitski et al. 1987, and references therein). A large mass failure has also been mapped along the Mackenzie Delta front (e.g., Mosher 2009), and significant mass transport deposits imaged within shallow sediments of the deep Canada Basin (e.g., Mosher et al. 2010).

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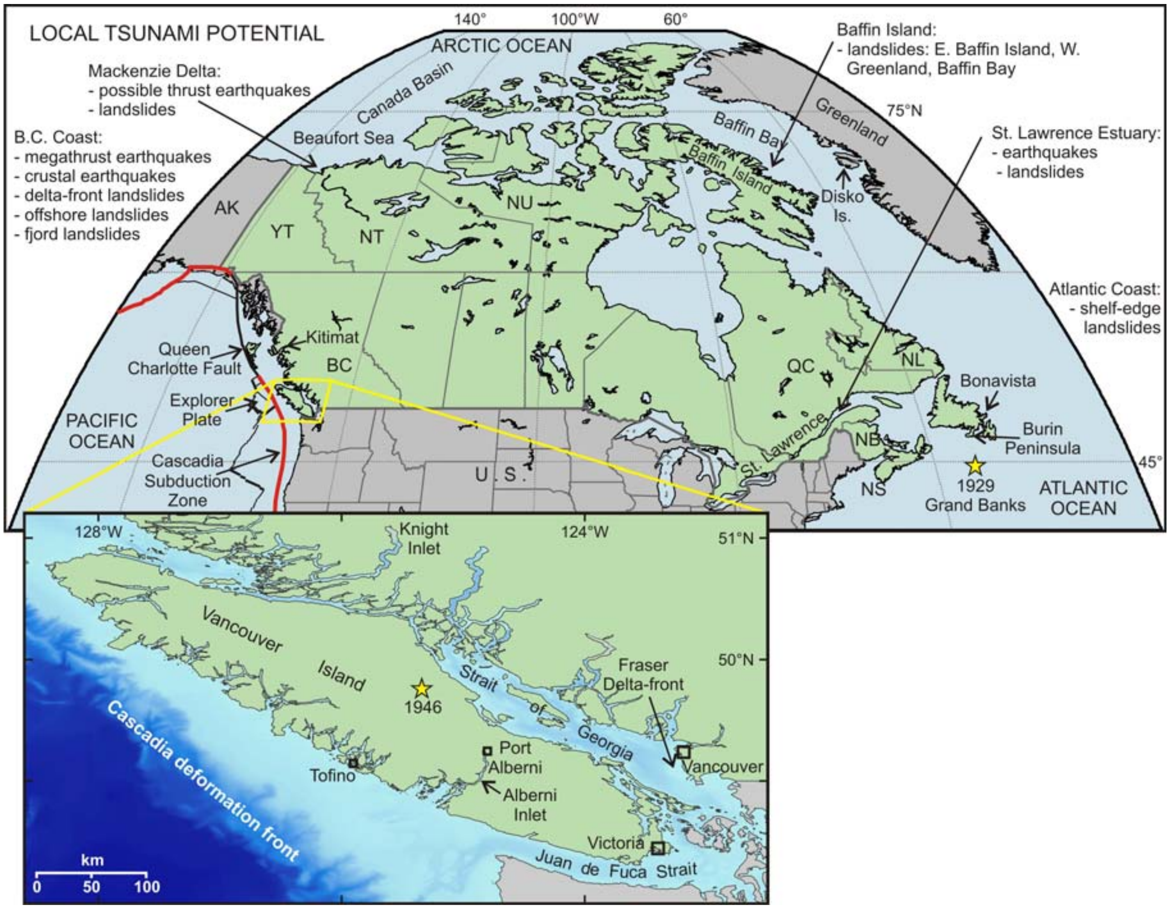

Figure 1. Potential sources of local tsunamis on the Pacific, Arctic, and Atlantic coasts of Canada. Megathrust plate boundaries are shown in red (other boundaries in black).

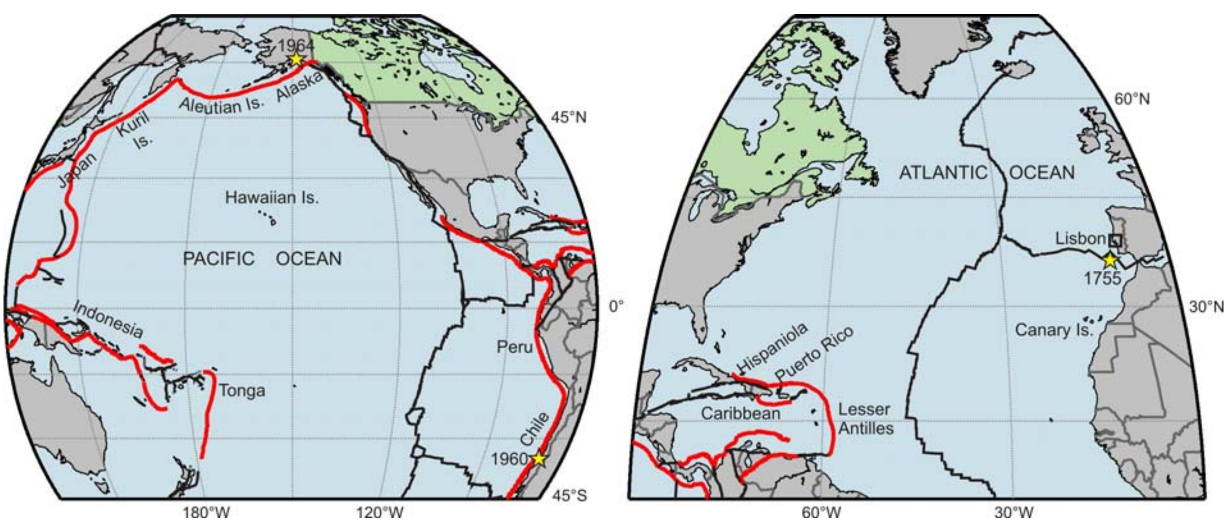

Figure 2. Potential sources of far-field tsunamis for the Pacific (left) and Atlantic (right) coasts of Canada. Plate boundaries as in Fig. 1.