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Tsunamigenic landslides in Québec

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ABSTRACT
This paper will present some of the known cases histories in Québec where a tsunami wave was or could have been generated by a landslide, either subaerial or subaqueous: the 1908 Notre-Dame-de-la-Salette slide, which is the one that caused the greatest number of casualties (34), the La Grande (1987) slide and the Cap Trinité rockslide (Saguenay Fjord). This analysis will provide an opportunity to illustrate the destructive power of these events. The analysis of those in quick clays will show that the actual tsunami mechanics is very much influenced by the fact that the rupture surface is nearly horizontal. It will be shown that the presence of an ice cover can be a significant aggravating factor associated with the generation of a tsunami wave. Finally, some discussion will be made regarding the approach which could be followed to take this hazard into account as part of a landslide hazard assessment procedure in Québec.

RÉSUMÉ
Cet article a pour but de présenter des cas historiques connus, où un tsunami a été ou a probablement été généré par un glissement de terrain, subaquatique ou subaérien, dans la province du Québec : le cas de Notre-Dame-de-la-Salette de 1908, causant le plus grand nombre de décès (34) ainsi que le cas de celui du glissement de La Grande en 1987 et de la chute de l'éboulis rocheux du Cap Trinité (fjord du Saguenay). Cette analyse permet d'illustrer la puissance destructrice de ces événements. L'analyse des cas survenus dans les argiles sensibles va démontrer que la mécanique entourant les tsunamis est grandement influencée par le fait que la surface de rupture est presque horizontale. Il sera démontré que, dans deux cas particuliers, la présence d'un couvert de glace peut devenir un facteur aggravant significatif associé à la génération de tsunami. Finalement, une discussion sera faite concernant l'approche qui pourrait être suivie afin de considérer la formation de tsunami dans l'évaluation des zones susceptibles aux glissements de terrain au Québec.

1 INTRODUCTION

Tsunamis are often associated with earthquakes but can also result from landslides either submarine or subaerial (Nadim and Locat 2005). Tsunamis have been observed not only along the ocean coastline but also in lakes (L'Heureux et al. 2012) and fjords (Kulikov and Rabionovich 1996). In Canada, Clague et al. (2003) present a synthesis of tsunamis occurences without mentions about those occurring along rivers, as it will be describe below. The first analysis of a tsunami generated by a landslides in Québec has been done by Murty and Durvasula (1977) considering some landslides caused by the 1663 earthquake, very likely the St-Joseph de la Rive slide. Later, El-Sabh et al. (1988) looked at the propagation of tsunami waves along the St. Lawrence River that were considered to be caused by earthquakes. Mapping of large submarine slides along the St. Lawrence north shore between Tadoussac and Baie St-Paul, and also near Matane have also raised the interest in the potential for the generation of some tsunamis. Among them, the St. Siméon and Matane slide was modeled by Poncet et al. (2009). The St. Siméon slide (Fig. 1), with a volume of about 20 hm^3, was likely triggered either by the 1663 or the 1925 Charlevoix earthquakes (Locat et al 2012). The maximum wave height estimated by this modeling was about 4 m (Poncet et al. 2009). Otherwise for the first two cases reported below, slides have generated waves with disastrous consequences but were not reported as a tsunami event. As we will see below, in some cases, the presence of an ice cover has been a major aggravating factor.

But what do we mean by a tsunami? The word tsunami is a Japanese word meaning 'harbour wave' in relation with the inundation of a coastal zone resulting from the propagation of a tsunami wave. Landslide generated tsunami have a very different signature than those generated by the rapid displacement of the sea floor resulting from a strong earthquake (Fig. 2). The landslide typically acts as a point source while an earthquake source is more comparable to a linear source. At the local scale, the tsunami wave originating from a slide will rapidly radiate from its source (Ward 2001). For most of the cases presented below, the initial wave generated by the slide will propagate over short distances, i.e. less than 10 km and typically less than 1 km.

Only very few landslide generated waves were reported in Québec, as illustrated in Figure 1, and consist of the Notre-Dame-de-la-Salette (1908) slide, the La Grande River 1987 slide (Lefebvre et al. 1991), the Nicolet slide (2006, Fanz et al. 2015, this volume) and the Lac-des-Seize-Îles slide (2014, Leblanc et al. 2015, this volume). It is believed that many more may have taken place as shown by the large submarine mass movements mapped along the St. Lawrence River (Locat et al. 2012) including the Betsiamites-Colombier slide (Cauchon-Voyer et al. 2008, 2010) and the St. Simeon and Matane slides studied by Poncet et al. (2009). The Saguenay fjord may have also experienced tsunami resulting from the very large submarine slides that have taken place there in 1663 (Levesque et al. 2006, Urgeles et al. 2002) and a possible large rockslide (100m in length) from the cliff of Cap Trinité likely caused by the 1870 earthquake (Murty and Durvasula 1977, Lamontagne et al. 2007).

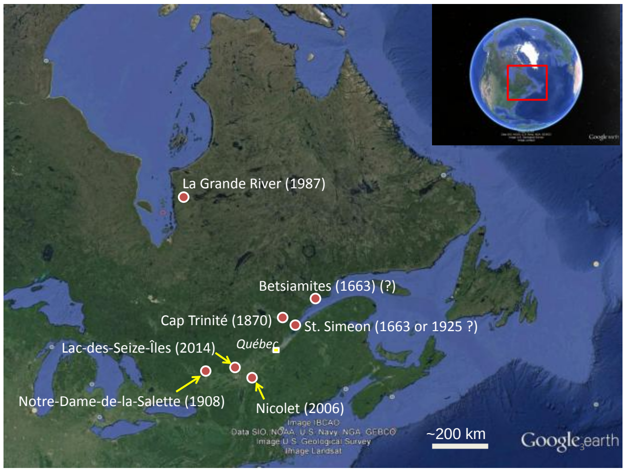

Figure 1 : Location of confirmed and possible tsunami sites in Québec.

As part of this paper, we will review the cases of the La Grande River slide, the Notre-Dame-de-la-Salette (NDS) slide and the Cap Trinity rockslide. The NDS slide will be used to illustrate the role of ice as an aggravating factor, as it has been the case for the Lac-des-Seize-Îles slide (Leblanc et al. 2015, this volume). We will first look at the generation of the first wave and the propagation mechanics. Then we will elaborate on the tsunami mechanics adapted to slide in quick clays. At this stage, we do not have completed the tsunami back analysis of these slides and this will come in upcoming research. Still, some discussion will be made regarding the approach which could be followed to take this hazard into account as part of a landslide hazard assessment procedure in Québec.

2 TSUNAMI SOURCES

Tsunami can be generated by various phenomena. It always involved a rapid displacement of a water body (Figure 2). The most common one result from sea floor displacement caused by earthquakes (Figure 2a). In some occasions, an earthquake will not directly generate a tsunami, but rather a submarine mass movement which may result in a tsunami (e.g. Storegga slide and tsunami, Kvalstad et al. 2005, Figure 2b and 2e). Earthquakes, long term slope creep, erosion or pore pressure variations can generate a coastal or a subaerial slide which, under certain conditions, can also generate a tsunami (Figure 2c and 2d). These later conditions are more typical of what is taking place in the cases presented herein, i.e. along a river or a fjord.

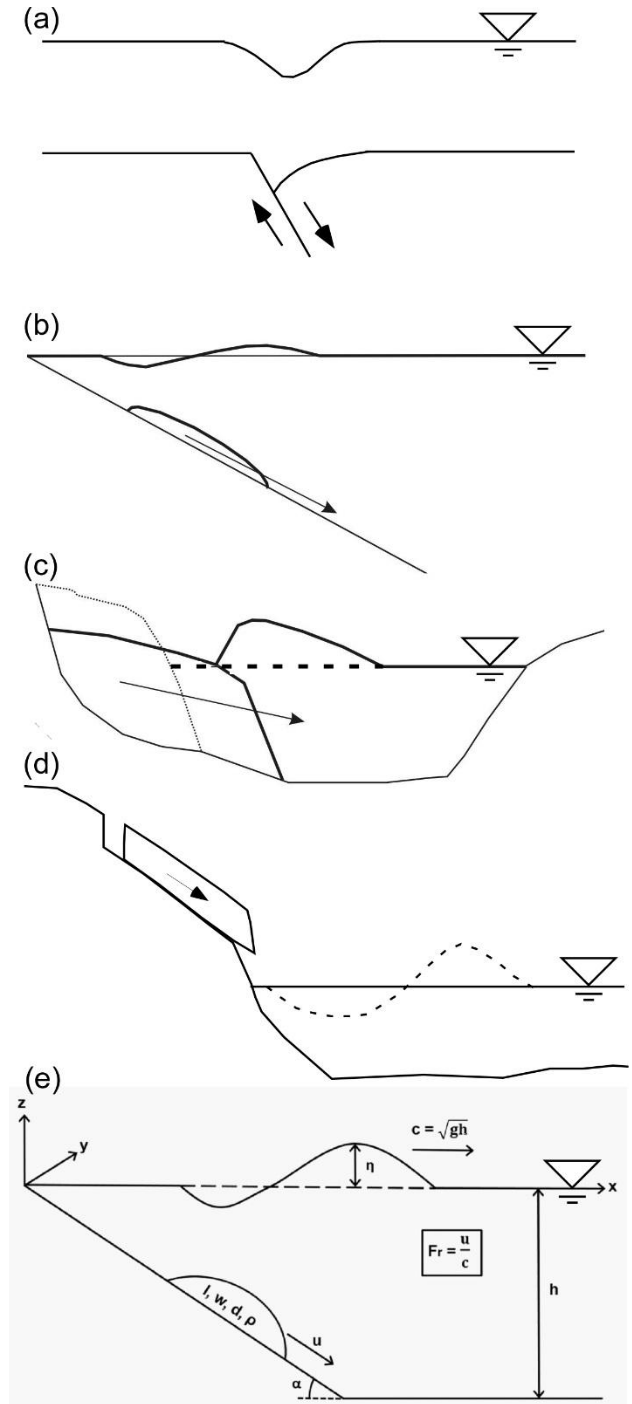

Figure 2: Schematic view of possible tsunami sources. (a): earthquake displacement of the sea floor; (b): submarine mass movement; (c) coastal slide in shallow water; (d): a mass movement falling into a water body, (e) some physical considerations of a tsunami generated by an underwater slide (see text for symbols).

Subaerial or submarine landslides can generate tsunami waves by an energy transfer from the landslide mass to the water body during the impact and the underwater runout (Mohammed and Fritz, 2012). Usually, the extent of the landslide, defined by the length *l*, the width *w* and the thickness *d*, and the dynamics, defined as the velocity and the acceleration of the slide *u* and *a* as well as the wave celerity *c*, are used to characterize the tsunami generation (Lovholt et al., 2015). Beside these parameters, water depth *h*, slide density *ρ*, slide position relative to the initial water level elevation and the slope angle *α* over which the mass is sliding are also of importance (Fig. 2e).

The critical parameter determining the energy transfer efficiency is the Froude number Fr, defined as the ratio between the slide and the wave velocity. The rate of energy transfer is particularly high near resonance, when Fr = 1.0. Numerical modeling from Fine et al. (2003) shows that a generated wave from a resonant regime will have a crest of high amplitude *η* with a steep frontal side and a trough located in the rear of the slide. If $u > c$ (Fr > 1.0), there is only one generated crest moving with the slide. Finally, if $u < c$ (Fr < 1.0), the first generated crest will be faster than the slide and will propagate away while the generated trough will move with the slide and decrease slowly with time. Subaerial landslides are much more efficient tsunami generators than submarine slides because the subaerial component brings an additional volume causing displacements of the water surface and because there is always a point in time where Fr =1.0, maximizing the rate of energy transfer from the sliding mass to the water body (Fine et al., 2003). An increase in the extent of the landslide, the slide density or the slope angle will always increase the generated wave amplitude. However, an increase in water depth will decrease the tsunami generation. The slide position effect on wave generation depends on the type of the slide. The higher the initial rigid-body slide is above initial water level the higher the impact velocity and the higher are going to be the resulting waves. Fine et al. (2003) observed a different behavior with viscous slides. It seems that there is an optimal slide position in the slope located closer to the shore which generates higher tsunami waves. The generation efficiency is affected by the deformation and the spread of the viscous slide, which increase with higher initial slide position.

Figure 3 : (a)The 1987 La Grande slide, (b) insert showing details of the scarp (photos from C. Locat 1987).

Wave or tsunami formation due to a landslide in a river is likely to be different from the ones formed by underwater landslides such as in lakes or in the ocean. An underwater landslide will cause a tsunami with a dipolar character (e.g. Okal and Synolakis, 2003), the slide creates a bulge (and hence a positive hump) at the surface, and at its toe, it leaves a masse deficiency (and hence a trough) (Figure 2b). For underwater landslides, tsunamis have amplitude proportional to their vertical center of mass displacement (Murty, 1979; Watts, 1998 and 2000). In a river or in a shallow lake, we believe that the wave formation will be different (Figure 2c). In this situation, the water depth is most of the time less than the height of the landslide, and the landslide will not move underwater and thus creating a dipolar wave, but will push the water as a piston would do (see also, e.g. Franz et al. 2015, this volume). We do believe that this mode of formation of the wave, as well as the very short distance of propagation of the wave, will lead in a directional wave that will inundate the opposite shore, without a large lateral spreading of the tsunami.

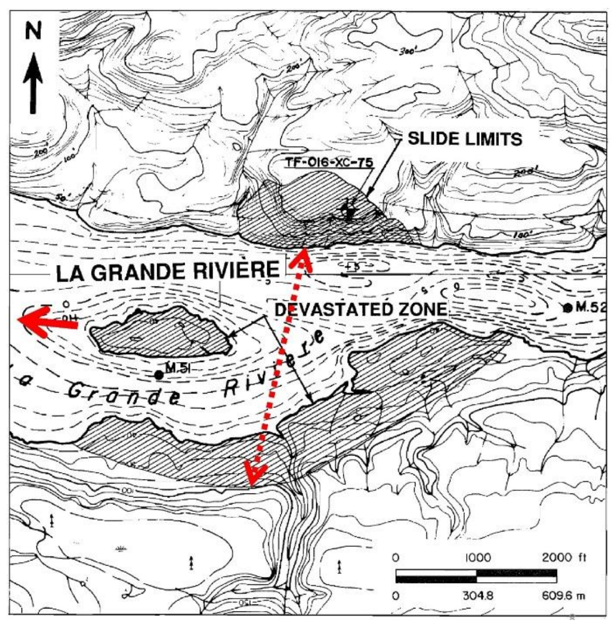

Figure 4 : The extent of the disturbed area and tsunami wave inundation of the 1987 La Grande slide (modified after Lefebvre et al. 1991).

3 THE 1987 LA GRANDE RIVER SLIDE

The La Grande river slide-tsunami was first reported by Lefebvre et al. (1991) and took place on September 5th 1987 (Figs. 1, 3 and 4). The slide took place on a 60 m high slope with a cliff sloping at 35° and its rupture surface located about 10 to 15 m above the river level but reaching about 6-13 m at the river's edge (Figure 3b). It has a length of 550 m and retrogressed 290 m from the river for a total volume of 3.5 hm^3 (Lefebvre et al 1991). According to the description, little sediments were left over the failure surface inclined at about 6° toward the river and the sliding surface would corresponds to a level of lower resistance (Lefebvre et al. 1991). From their analysis, Lefebvre et al (1991) concluded that the sediment involved in the slide consist of 10% of clay, 40% of silt and 50% of sand. The main consequences of this slide was on the water source of the village of Chisasibi which became mucky and was not usable for a few days.

As a result of the slide, Lefebvre et al. (1991, p.264) indicate that: "*a large portion of the opposite bank was devastated to an elevation of 14 m above the river level by the slide-related waves. In front of the landslide, the river is some 350 m wide at its eastern limit and widens rapidly to about 700 m at its western limit (Figure 4*[1]*). In the devastated area, all trees, some 20 cm in diameter, were broken or pulled out. No trace of slide debris was found on the south bank or on the rocky island slightly downstream, and it is believed that the devastation on the opposite bank was related only to the waves created by the landslide. There was no sign that the river was temporarily blocked or diverted by debris from the slide*." So the slide did generate a tsunami and the material had largely liquefied as part of the post-failure process. Figure 4 illustrates the actual extent of the devastation made by the slide in the river and on the opposite side. It is interesting to note here that using the extent of the devastated area (Figure 4), the wave directivity is strong with an angle of planar propagation of about 90°.

4 THE NOTRE-DAME-DE-LA-SALETTE SLIDE

The Notre-Dame-de-la Salette slide (NDS, Ells 1908) took place on April 6^{th} 1908, killing 33 people, the largest in Québec for landslides in clays (Figure 5). It is located along the Lièvre River and is located in the Ottawa-Gatineau area (Figure 1). The slide length is 450 m and the width is 150 m with a thickness of 18 m for an estimated volume of 1,2 hm^3 (Figures 5 and 6). As part of his report, Ells mentioned that "*the ice in the river was apparently unbroken at the time, and was lifted and carried forward over the east bank on which Salette village is located, at an elevation not more than twelve to fifteen feet above the present level of the river, and which was some feet above the ordinary summer level. The rush of ice came with such force against the village as to completely demolish the greater portion of the village. In fact, everything within its course was destroyed: including twelve houses and some twenty five outbuildings, which were entirely destroyed to their foundation; while on the margin of the ice movement several buildings were more or less damaged*." (p. 6). According to Ells (1908), the tsunami wave flooded up to an elevation of 15 m above the water level of the river at the time. The ice thickness is estimated to be about 0.5 m (Ells 1908). The damages caused by the ice are illustrated in Figure 5b where pieces of ice still remain but with no evidences of sediments from the slide itself clearly indicating that the ice was a significant aggravating factor here.

[1] In Lefebvre et al. 1991.

From the records of the casualties and the list repairs (Lapointe, 2008), and also using the terrain model with a flood level at 15 m, we have been able to constrain the extent of the tsunami wave as shown in Figure 6. It is interesting to note that the radial propagation of the tsunami is quite limited and resemble that of the tsunami wave generated for the La Grande River slide. The destruction was limited to the sector of the village build on the lower fluvial terrace which is only about 4 to 5 m above the river level.

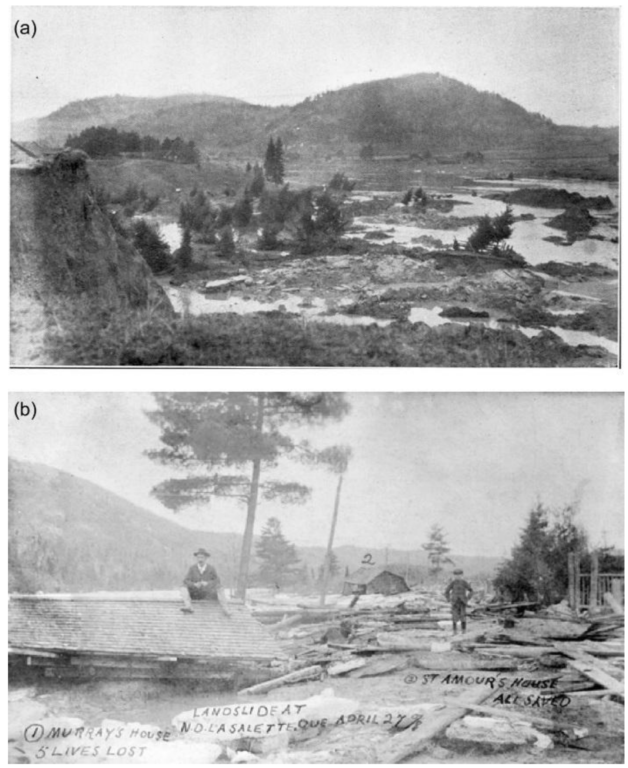

Figure 5 : (a) The 1908 Notre-Dame-de-la-Salette slide, and (b) some damages showing the presence of ice remnants with no sediment (photo source: Ells (1908).

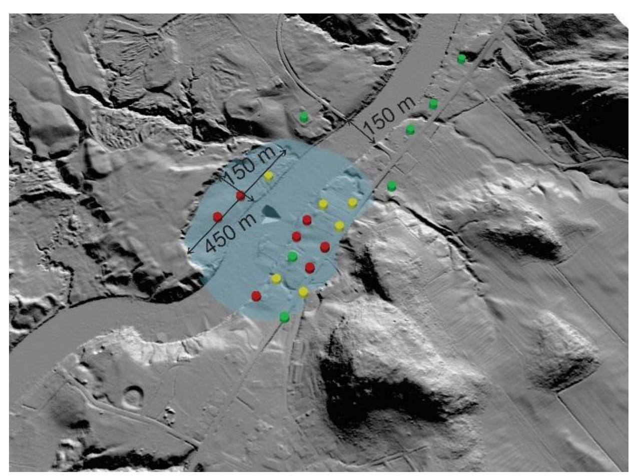

Figure 6: Oblique view of the extent of the tsunami wave based on damages and also on water levels variation as indicated by Ells (1908). Legend for houses, red:

destroyed, yellow: damaged houses, green: no information (North is up). (LiDAR source: Transports Québec).

5 CAP TRINITÉ 1870 ROCKSLIDE EVENT

According to the *Québec Daily Mercury* of October 22nd 1870 (in Lamontagne et al. 2007), "*Near Cape Trinity, a mass of rock of more than four hundred feet in length, has been detached from the lofty banks and precipitated into the river Saguenay*". Recent rock falls from a cliff can easily be located by the contrasting colour of the recently exposed surface (brownish). At this time, we do not know how much time it takes for the colour of that surface to come back to the background colour of the fully weathered surface. Assuming that it would take more than 200 years, our recent investigation of the cliffs surrounding the Cap Trinity in 2011 provide some hints as to where it may have taken place as shown in Figure 7. The area shown by the dashed line is the only one that would be close to what has been described above. We estimate that the maximum volume of this rockfall would be about 20 000 m^3. We can see that there are many other scars left of rockfalls of unknown origin. This rockslide must have triggered a tsunami (Murty and Durvasula 1977) in a context illustrated in Figure 2d.

6 DISCUSSION

The following discussion will center on the following points: (1) tsunami hazard and (2) modeling approach for landslide hazard mapping.

6.1 Tsunamis hazard in Québec

From known records, if we do not consider the potential tsunamis that may have been triggered by submarine mass movements in lakes, rivers or fjords, the actual account is rather small. The tsunamis reported here and in the data base of the Québec Ministry of Transport may total about 10 events. Considering a period of about 400 years, it would suggest that the frequency is very low at about 0.025 per year. Considering that there are about some hundreds landslides per year in Québec (Demers et al., 2008), may be 300, it would indicate that the probability that a slide generates a tsunami in a given year is about 0,000083, i.e. very low but an estimate with a large uncertainty. However, as it was the case for the La Grande River slide of 1987, it was not reported as a tsunamigenic slide so that there may be many more cases that were not registered as such. Maybe that with more data, the yearly probability of a slide to generate a tsunami may increase to 1 in 1000. There may be many slides, like the Nicolet slide (Franz et al. 2015, this volume), where some spill took place over the ground in front of the slide. There is clearly a need to go back to the records to ascertain this phenomenon in order to better evaluate the hazard. Still the hazard may remain very low, but the consequences (or the risk), may be high enough, as in the case of the NDS slide, pointing towards the need to develop ways of integrating it into geohazards studies in Québec.

6.2 Modeling tsunami as part of landslide hazard assessment

Our analysis of the Notre-Dame-de-la-Salette and the Lac-des-Seizes-Îles (Leblanc et al. 2015, this volume) slides, although of very different type, underline the potential aggravating factor caused by the presence of ice cover on the water. Since many large landslides do occur during the spring this is something to consider in hazard and risk assessment, particularly for slides in quick clays.

The work of Franz et al (2015, this volume) and the cases reported herein do indicate the need for developing a tsunami model similar to what has be shown in Figure 2c and 2d that may be integrated in landslide hazard assessment in Québec.

It is very well known that in general the magnitude of a tsunami is function of volume, velocity of the sliding mass as it enters the water body and the water depth. At this time we have not made any estimate of the velocity of the slides reported herein, but the analysis of the Rissa slide (L'Heureux et al. 2013) indicates that even flow slides are able to generate a tsunami wave of a few meters.

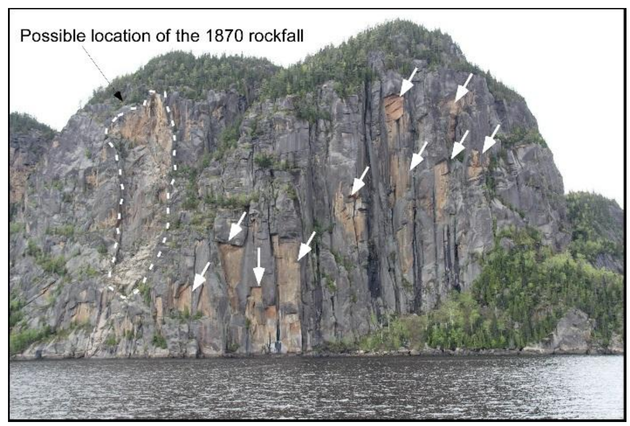

Figure 7: The possible location of the 1870 rockslide at Cap Trinité (Saguenay fjord). Other white arrows indicate the location of rockfalls of unknown origin. The width of the view is about 500m.

6.3 Future developments

The first element to consider in the analysis of the tsunami potential at a given site is the terrain morphology. As for the NDS case, infrastructures or buildings lying on low terraces located across a river with a higher terrace actively cut into sensitive clay may represent more hazardous morphological conditions. Although we have access to excellent terrain model mostly produced by LiDAR survey, our knowledge of the river bathymetry is rather lacking. Recently developed techniques involving interferometric sonar or multibeam instruments can now be used effectively for this purpose in lakes and rivers.

Another element to consider is the initial slide mechanics and how it influences the acceleration and the velocity versus time. Here also, the evolution of the slope profile under erosion, undercutting in particular, may be aggravating factors in terms of slide initiation. As pointed out before (L'Heureux et al. 2012), flow slides can also generate significant tsunamis and understanding its mechanics and developing our modeling capacity is another need for proper risk assessment related to both the flow itself and its tsunamigenic potential under certain conditions.

The role of ice is discussed in accompanying paper (Leblanc et al. 20015, this volume). We need to improve our knowledge of how the characteristics of the ice evolves during the winter and early spring since this may affect its response to wave propagation. A changing climate may also change the timing of occurrence of some landslide and ice thickness and strength may be an aggravating factor which will need to be considered.

The tsunami hazard along lakes and fjord from subaqueous mass movement is not easy to determine. However, event mapping in the Saguenay fjord (Levesque et al. 2006), in lakes (e.g. Lajeunesse et al. 2008, Locat et al. 2015) and along the St. Lawrence river (e.g Poncet et al. 2009, Campbell et al 2008, Locat et al 2012) have shown many landslide scars showing a nearly complete evacuation of the sediment in the departure zone thus indicating that the slide movement was rather rapid. Poncet et al. (2009) have shown that there are some tsunami hazard related to these environments. It is likely that not all these sites do present a significant tsunami hazard, bu further studies should be done in order to define sites and conditions under which tsunamigenic landslide would require a hazard assessment.

7 CONCLUDING REMARKS

This paper is a first attempt to consider tsunami hazard in Québec. It is by far not complete and the topic will require much more considerations both in terms of its relevance and the physics to be considered. The number of cases that have been modeled is very limited (e.g. Poncet et al. 2009). Current work at Université Laval will go back to model few more cases like the Lac-des-Seizes-îles, the Notre-Dame-de-la-Salette and the La Grande slides. This will provide an opportunity to develop a modeling approach which is adapted to the quick clay tsunamigenic slides.

The acquisition of better terrain model, a better understanding of quick slides (flow slides and spreads) and post-failure modeling tools including flow/debris slides and tsunami models, will provide a unique opportunity to better assess the overall risk associated with landslides in Québec.

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