TERRESTRIAL LIDAR INVESTIGATION OF THE 2004 ROCKSLIDE ALONG PETIT CHAMPLAIN STREET, QUÉBEC CITY (QUEBEC, CANADA)

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RÉSUMÉ
Au cours des 240 dernières années, 53 mouvements de versant se sont produits le long du promontoire de Québec, causant la mort de 88 personnes principalement lors de chutes de blocs. En octobre 2004, un petit éboulement a atteint la route dans une zone proche de l'éboulement de 1889 qui a tué 35 personnes et blessé 30 autres. Une image 3D a été créée par l'utilisation d'un scanner Lidar terrestre (SLT). Les sept familles de joints identifiées sont en accord avec les mesures effectuées dans de précédentes études. L'imagerie SLT a aussi permit d'estimer les volumes des instabilités passées et d'en analyser le mécanisme: un glissement rocheux qui affecte des blocs débités en parallélépipèdes par d'autres familles de joints. De plus la zone étudiée montre qu'elle est favorable aux chutes de blocs.

ABSTRACT
In nearly 240 years 53 landslides have occurred along the Quebec City Promontory, causing 88 fatalities mainly by rockfalls. In October 2004 a rockfall reached the road close to the 1889 rockfall event which killed 35 people and injured 30 others. Using a terrestrial Lidar scanner (TLS) a 3D image was created. Seven joint sets were accurately determined in agreement with previous research. The TLS imagery permit the estimation of the volumes involved in the past instabilities and analysis of the mechanisms: a rockslide with several joint sets cutting the rock mass into parallelepiped shaped blocks. Furthermore it shows that this location is prone to future rockfall.

1. INTRODUCTION

For some years terrestrial Lidar scanner (TLS) has been used as an efficient tool to analyse rock face structures and for monitoring movements (Lim *et al.*, 2005; Voyat, 2005; Janeras *et al.*, 2004; Oppikofer *et al.*, 2007; Sturzenegger *et al.*, 2007; see Eberhardt *et al.*, 2007). This is especially useful for sites that are not easily accessible and represent areas of potential risks. From this perspective the Quebec City Promontory is a good example where the economic impacts are important and include road closure or propriety destructions.

Since 1775, 53 landslides were indexed along the Quebec City Promontory, causing 88 fatalities and injuring 70 people (Figure 1). Most were related to rock instabilities, including the 1889 rockfall (35 deaths and 30 injured) that was promoted by pre-existing structures (mainly bedding and joint sets) and water seepage with an anthropogenic origin (Baillairgé, 1893; Drolet *et al.*, 1990; Evans, 1997).

During recent years several rock masses of a few cubic meters have fallen down onto the highway Boulevard Champlain. Many sections of the cliff are difficult to access, which does not allow a detailed mapping of the critical structures that can lead to rockfalls.

Since 1893, when Baillairgé (1893) published a very useful and informative study about the 1889 rockfall, some works have been published and others are confidential reports. Drolet *et al.* (1990) and Baillifard *et al.* (2004a; 2004b) analysed the main structural features of the Promontory cliffs as well as undertaking a preliminary hazard assessment. Detailed studies of some sectors are ongoing work at Université Laval. This paper presents preliminary work showing the potential of the Lidar imagery used for cliffs located in urban areas and specifically for the Quebec Promontory.

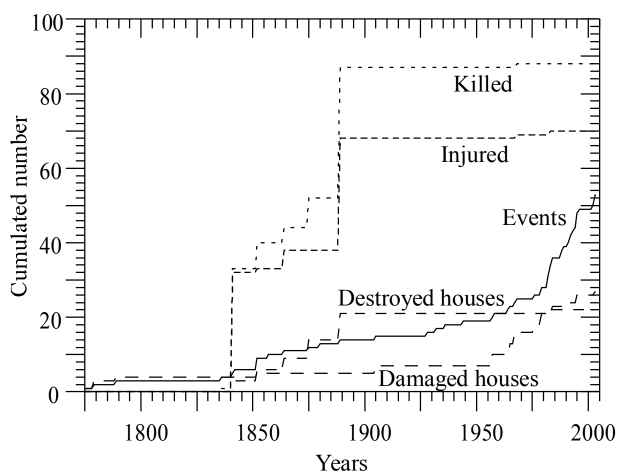

Figure 1. Evolution with time of the cumulative distribution of the events and related damages along the promontory cliff (After Baillifard *et al.*, 2004a).

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Comptes rendus de la 4e Conférence canadienne sur les géorisques: des causes à la gestion.
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Figure 2. The 2004 failure surface (Locat and Kirkwood, 2004).

This study presents the structural analysis of the Lidar images of the rock cliff located at the site of the 1875 snow avalanche which killed 5 people and injured 7 others. The snow avalanche probably took place over an older rupture surface which must have provided an excellent slip surface for the snow failure. Lidar images reveal some of the structures leading to the pre 1875 failure which have been likely re-activated in October 2004.

2. STUDY SITE

2.1 Geological setting and structures

The city of Quebec is built on a promontory, located on the north shore of the St. Lawrence River oriented south-eastwards. River bank erosion has up to the time of settlement actively eroded the bottom of the promontory cliff (Baillifard *et al.*, 2004b). The cliff height ranges between 60 and 100 m directly overlooking in many places the Champlain Boulevard, houses and the historical neighbourhood of Quebec City.

The investigated rockfalls (Figures 2 to 4) are located in the north-eastern part of the cliff which belongs to the Quebec Promontory nappe (St-Julien, 1995). The lithologies outcropping comprise of an alternating clayed limestone, calcarenites and black shales with beds thicknesses not exceeding 1 m. Faults, oriented towards the St. Lawrence River, are cutting the Promontory.

Table 1: Discontinuity sets from field survey (from Baillifard *et al.*, 2004a)

Set	Dip direction/dip
S_0	120/75
J1:	020/50
J2:	250/50
J3:	040/80
J4:	120/40
J5:	195/40

Baillifard *et al.* (2004a) identified 6 joint sets including bedding along the cliff (Table 1). Along the cliff the bedding is folded inducing changes in the rock fall mechanisms (Baillifard *et al.*, 2004a, 2004b). The main mechanisms recognized along the Boulevard Champlain are sliding on J4 or S_0 (Baillifard *et al.*, 2004b), and also toppling using S_0. In the studied area, the bedding (S_0) is steep and dipping to the southeast.

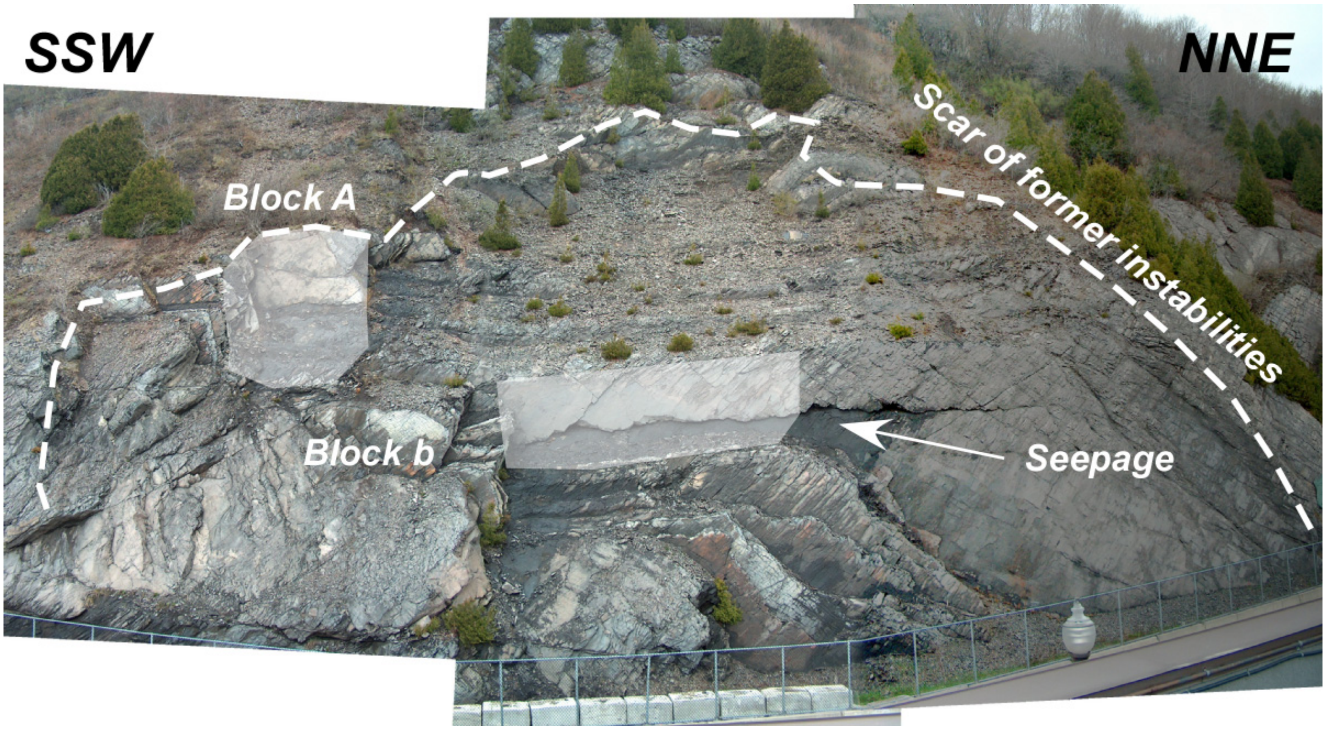

Figure 3. View of recently fallen blocks and former areas of instability including the October 2004 event.

The slope has been undercut by the construction of the Boulevard Champlain road creating cliff toes where stability is controlled by bedding. The upper slope has been cut back to bedding, and the slope is less steep and follows more or less the discontinuities.

3. METHODOLOGY

The TLS system used in this study is an ILRIS-3D laser scanning system from Optech Inc. (Optech, 2007) with a wavelength of 1500 nm. A 40° wide and 40° high window (field of view) can be scanned in a single acquisition at the speed of about 2500 points per second. The XYZ position of each point is known by its distance and direction relative to the scanner. At a distance of 100 m, the instrument accuracy equals approximately 7 mm for the distance and 8 mm for the position. The maximum distance range depends on the target reflectivity. The resolution depends on the distance of the object and the chosen angular spacing between two spots. The manufacturer indicates that the scanning range is from 3 m to 1,500 m (for an 80% reflectivity target), 800 m (20%) or 350 m (4%). This is not easy to estimate in the field because of the terrain humidity condition, which can strongly diminish the reflectivity (Rosser *et al.*, 2007).

A complete 3D model of the cliff was obtained using 3 TLS scans from 3 different viewpoints. Since LIDAR images provide 3D point clouds of the surface, including the terrain and vegetation, the raw scans were treated and vegetation and unwanted objects removed. The registration of the last pulse of the returned signal was used, because it discards some reflections due to the vegetation. The vegetation was removed from the point clouds manually using the software Polyworks™ (InnovMetric, 2007) and our own software under development COLTOP3D (Jaboyedoff *et al.*, 2007).

After removing the vegetation points, individual scans were merged into one data set. The numbers of points per raw scan ranges between 1’200’000 and 1’650’000. The merged data set contained 4'563'237 points which was reduced to 3'478'995 points after cleaning. The average distance of the target was 50 m and average spacing between points was approximately 26 mm. The georeferencing was performed *a posteriori* using the high resolution Google Earth images and knowledge of the area. The result is produced in the coordinate system WGS 1984 UTM Zone 19N.

The orientations of the structures were deduced by fitting planar surfaces on limited, selected areas of the cloud points within a Polyworks™ environment and with COLTOP3D. COLTOP3D computes the spatial orientation of each XYZ point by taking into account its neighbouring points and expresses the slope angle and slope aspect with a unique colour code. Discontinuity sets are easily detected since are represented with the same colour.

The cross-sections were also extracted using the Polyworks™ software. Instability volumes were estimated using the computed spacing between joints and angle between joint sets and the length and width of the concerned area.

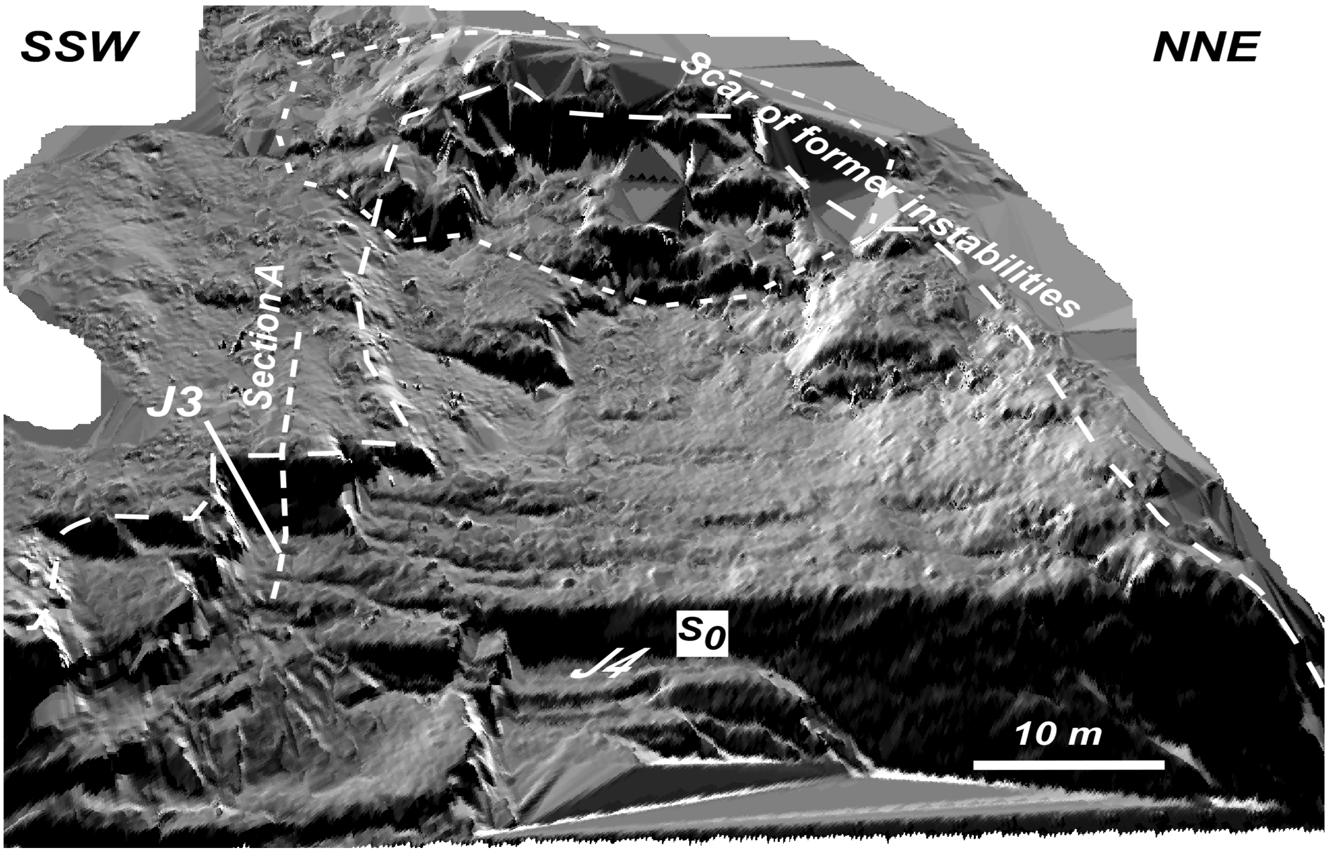

Figure 4. Shaded 3D view of the topography using a 10 cm grid DEM obtained from the cleaned point clouds. Several structures can be observed. The long dashed line indicates the scar limits and the short dashed line shows the potential unstable mass at the top of the slope.

4. RESULTS

The morphology displayed by the Lidar Imagery shows clearly that the event of 2004 occurred within a zone that suffered several slides (Figures 3 to 7). The scar morphology has limits that are clearly controlled by the joint sets. An important potential unstable mass can be observed at the top of the top of the slope, where some J4 joints probably daylight (Figure 4).

Table 2: Characteristics of the main discontinuity sets derived from the TLS model.

Set	N° poles	Mean orientation (±1σ)	
S_0	20	124/74	±7°
J1	12	043/37	±14°
J2	18	242/54	±10°
J3	18	060/71	±10°
J4	18	123/40	±8°
J6	15	212/70	±7°
J7	19	300/78	±14°

Analyses of the point clouds allow the detection of 7 joint sets including the bedding (Figures 5 and 6; Table 2). They agree closely with field investigations from Baillifard *et al.* (2004a) (Tables 1 and 2). The sliding occurs clearly on J4. S_0 and J7 act as rear release surfaces and back cracks. J6, J2 and J3 form lateral release surfaces (Figures 5 and 7). These sets delimit parallelepiped shaped blocks and permit a planar sliding mechanism. Joint set J5 described by Baillifard *et al.* (2004a) is not detected, but TLS analysis allows the detection of 2 new discontinuity sets.

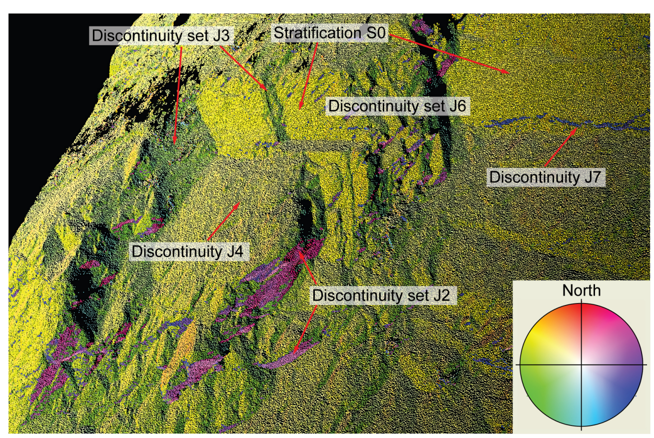

Figure 5. COLTOP3D colour representation of TLS point cloud and the corresponding stereonet (lower hemisphere). The mean orientation and variability of major discontinuity sets can be easily determined by their colour (Figure in colour on CD-ROM).

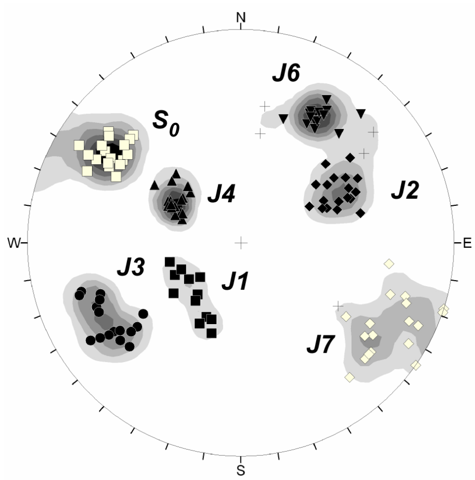

Figure 6. Lower hemisphere stereonet showing the main discontinuity sets in the study area derived from Lidar. Some non-attributed data are represented by crosses.

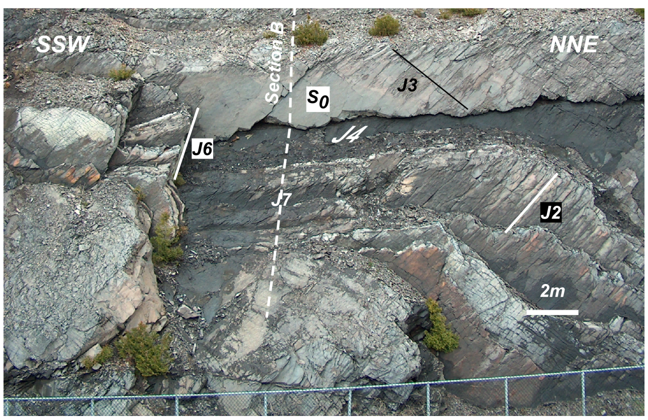

Figure 7. Photograph of the October 2004 rockfall. Most of the joint sets derived from laser scanning can be identified.

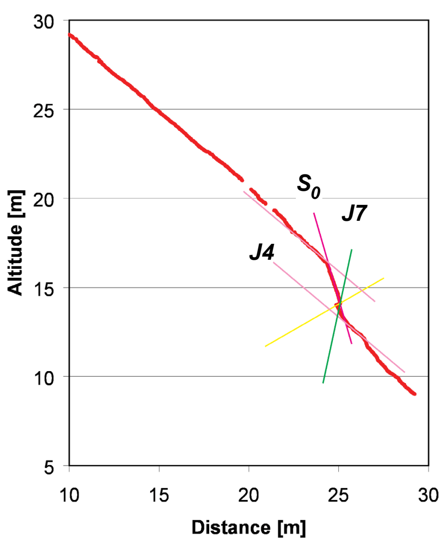

Figure 8. Section B from the Figure 7, showing the different joint sets controlling the slope profile.

Using the point cloud data it is possible to estimate the volume of the recent rockfall. The volumes are clearly limited by the joint sets; as a consequence the volume can be based on the estimation of their spacing (Figure 9). If (h) is the spacing between two joints J4, (t) the thickness of the bedding, (l) the length of the failure surface along the basal surface J4, (w) the width of the block and α the angle between J4 and S_0, the volume is given by (Eq. 1):

$$V = h \times l \times w = h \times t/\sin\alpha \times w \qquad [1]$$

The volume of the block A (Figure 3 and section A in Figures 9) equals (Eq. 2):

$$V_A = 2.5\ \text{m} \times 2.4\ \text{m} / \sin(34°) \times 5.1\ \text{m} = 55\ \text{m}^3 \qquad [2]$$

A second fresh scar has been identified close to the first one. The volume of block B (Figures 3, 7 and 8) is approximately 20.5 m^3 (Eq. 3)

$$V_B = 1.8\ \text{m} \times 0.5\ \text{m} / \sin(34°) \times 11.5\ \text{m} = 20.5\ \text{m}^3 \qquad [3]$$

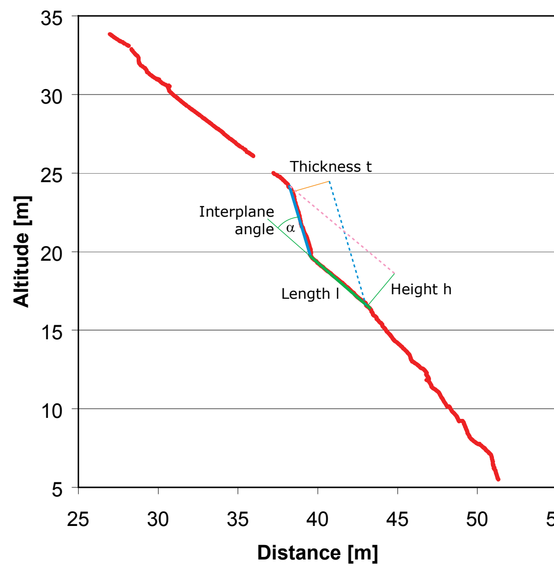

Figure 9. Section A from Figure 4, showing volume computation.

5. DISCUSSION

Figure 6 shows that TLS methods lead to homogeneous discontinuity data sets. These data must be reinterpreted because sets like J1 and J3 are certainly the same fabric and probably represent the refraction of a foliation. Such phenomenon is inferred from outcrop inspection in Figure 7. Nevertheless, such a TLS study allows easy identification and characterization of the failure mechanism.
As shown by Baillairgé (1893) for the 1889 event, water is suspected to play an important role in the destabilisation of

the slope. Observing the seepage along the joints J4, acting as sliding surface, it seems clear that during the freezing period the water induces stress and fatigue of the rocks. In spring and autumn the freeze and thaw cycles can provoke overpressure by plugging joints with ice. Such mechanism can produce instability of several tens of cubic meters.

In the interpretation of Baillairgé (1893) toppling appears as the main mechanism, while Drolet *et al.* (1990) consider also limited sliding. The present site is only 300 m from the 1889 site and it appears here that sliding has also played an important role suggesting the rapid change in the structural condition for failure along the escarpment.

Figure 4 shows clearly that the studied slope posses a long story of small rockfall events. The irregular morphology and the relatively small spacing between joints have created several small rock fall events in the past. The surface of the zone that suffered past rockfall is about 680 m^2. Based on the Lidar data it appears that the material was removed over a thickness of 5 m. This leads to a total volume of 3400 m^3. We have obtained previously volumes of 20.5 m^3 and 55 m^3, which correspond on average to 38 m^3.

Probably one large event occurred before the period considered as we can expected by the power law distribution of rockfalls (Hungr *et al.*, 1998). Nevertheless the apparent freshness of the scar indicates clearly that the activity is frequent or the unstable block are cleaned by the Transportation department over the years, which means that a more detailed assessment must be performed in order to determine if the present situation is above or below the threshold of acceptable risk.

6. CONCLUSION

It is clear from the analysis of Lidar data that an active mechanism of destabilisation is present at the studied site. It seems also that several rockfall events have occurred in the past. The presented results, which can be obtained within a few days, do not represent a full hazard assessment. The presented data indicate that geomechanical investigations and further field investigations must be performed. This is necessary because we can expect new rockfalls in the near future because of freezing and thaw cycles that have been identified as important for the rockfall activity (Baillifard *et al.*, 2004b). The upper part of the scar that contains significant spur needs a careful examination.

This study shows also that Lidar imagery allows a quick and accurate analysis of cliffs that are difficult to access. It also however shows also some limitations of the TLS, where vegetation often hides too much of the rock faces. Nevertheless this technique is promising, and will certainly be an important tool for performing a complete hazard assessment of the Boulevard Champlain in the future.

7. ACKNOWLEDGEMENTS

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