An integrated management tool for rockfall evaluation along transportation corridors: description and objectives of the Para*Chute* research project

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Des défis du Nord au Sud

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ABSTRACT
Natural and man-made rock slopes are frequent along the railroad linking Port-Cartier to Fermont. The aim of the Para*Chute* research project is to integrate various technologies into a workflow for rockfall characterization along linear infrastructures (including roads) and to test its application along a portion of 260 km of this railroad. Our work will focus around different objectives: (1) to optimize the use of terrestrial, mobile and airborne laser scanners data into terrain analysis, structural geology analysis and rock fall susceptibility rating, (2) to further develop the use of unmanned aerial vehicles for photogrammetry applied to rock cliff characterization, (3) to integrate rockfall simulation studies into a rock slope classification system similar to the Rockfall Hazard Rating System and (4) to consider climate change impact on mass movements. With this paper we want to share our approach and preliminary results.

RÉSUMÉ
Les parois rocheuses naturelles et anthropiques sont fréquentes en bordure de la voie ferrée reliant Port-Cartier à Fermont. Le but du projet de recherche Para*Chute* est d'intégrer diverses technologies de caractérisation des chutes de pierres et de tester l'application de cette approche sur une distance de 260 km du chemin de fer. Notre travail se concentre autour des objectifs suivants : (1) optimiser l'utilisation des scans lasers terrestres, mobiles et aéroportés pour l'analyse de terrain, l'analyse structurale des parois rocheuses et pour la caractérisation de la susceptibilité aux chutes de pierres, (2) continuer de développer l'utilisation d'aéronefs sans pilote pour la photogrammétrie appliquée à la caractérisation de parois rocheuses, (3) intégrer les outils de simulations des chutes de pierres dans un système de classification inspiré du Rockfall Hazard Rating System et (4) évaluer l'impact des changements climatiques sur les mouvements de terrain. Cet article vise à présenter l'approche préconisée ainsi que des résultats préliminaires.

1 INTRODUCTION

To help reduce losses associated with rockfalls, a common and damaging natural hazard (Volkwein et al. 2011), researchers from Université Laval collaborate, through the Para*Chute* project, with the Ministère des transport du Québec and ArcelorMittal-Infrastructures Canada. The name of the project is derived from the french words “Parade” and “Chute” which means a protection against fall.

Knowing where problematic rockfalls originate, and why they do, not only helps, but is crucial to properly manage and mitigate the risk associated with rockfalls (Corominas et al. 2014, Turner and Jayaprakash 2012). The *Rockfall Hazard Rating System* (RHRS, Pierson 2012) was developed in the early 90's to help manage rock slopes mitigation programs. This system offers a way to systematically rate road cuts to compare them and recognize the most problematic ones. Subsequently, many organizations adapted the system to their needs (Pierson and Turner 2012).

The Para*Chute* project aims at integrating various existing but recent tools to develop a customize RHRS methodology. It will be updated to incorporate remote sensing data and rockfall simulations, in order to improve the characterization of rockfall sources and causes.

This 3-year project will extend until the spring of 2017, so in this paper we want to share our approach and some preliminary results. The methodology will be developed using the ArcelorMittal's railroad linking Port-Cartier,

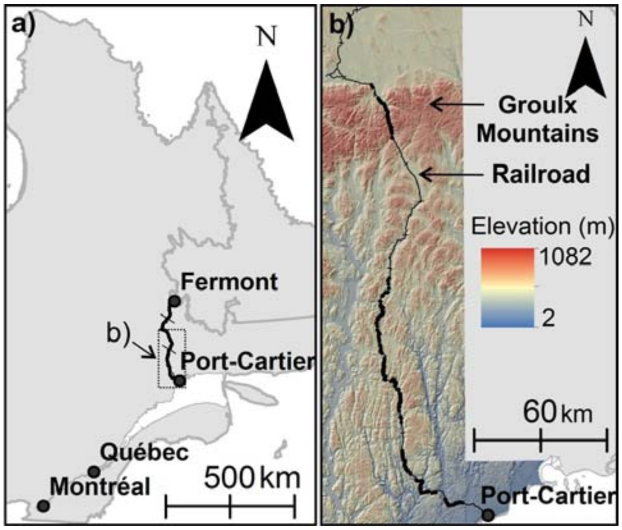

Figure 1 a) Location of the railroad in the Province of Québec b) Zoom of the studied area

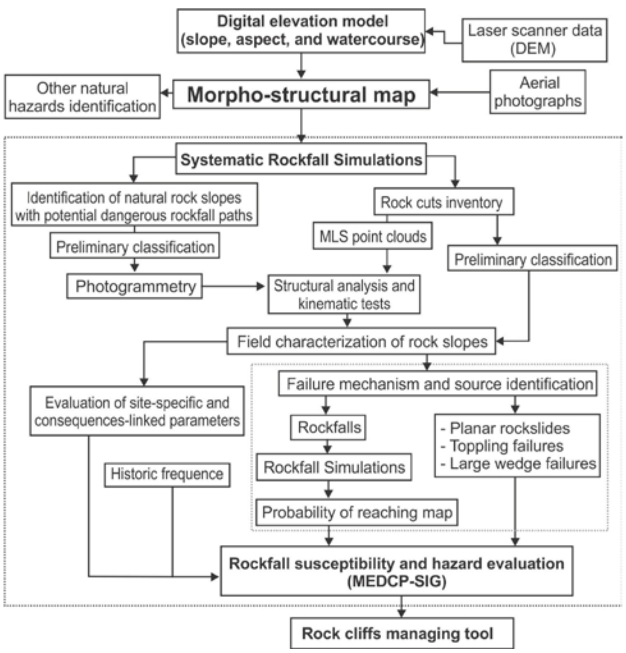

Figure 2. General approach proposed for the development of a rockfall hazard rating system optimizing the use of remote sensing tools. Natural rock cliffs are integrated in the rock slope inventory. The approach focusses on the recognition of failure mechanisms and the identification of rockfall sources.

located on Québec's North Shore, to mining installations near the northern town of Fermont (Fig. 1a).

The needs of ArcelorMittal and Ministère des transports du Québec are not different from the one of any other organization dealing with transportation corridors: increase safety and efficiency. They recognized rockfall as a problematic natural hazard and to reduce its impact they need a better understanding of the causes, characterization of the potential sources and archiving of rockfall activity. So, we believe that the systematic application of a modified RHRS system will help to manage the rock slopes and diminish the losses related to rockfalls.

The integrated approach, which was initially developed in the Charlevoix area in the Province of Québec (Locat et al. 2013) involves two major parts: the development of a morpho-structural map into which all types of mass movements can be considered and the characterization of rockslide hazards along a railroad. One of the major challenges is the size and the large number of, not only, rock cuts but also natural rock cliffs that are located near the railroad. The large number of rock cliffs associated with the high traffic density limits the amount of time available to access the slopes. To limit field work and decrease uncertainty on different parameters, we propose to optimize the use of GIS and digital elevation models (DEM) by integrating and adapting various tools and existing technologies.

2 WHAT DO WE PROPOSE?

The tools we will use (laser scanners, photogrammetry, rockfall simulations, etc.) have been used in different studies (*e.g.* Lan et al. 2010, Lato et al. 2012, Bemis et al. 2014, Wolter et al. 2014). We propose their systematic application to a regional study and their integration into a rock slope classification system. The approach is presented in Figure 2 and the objectives described hereunder.

- To realize a rock cut inventory at the office using remote sensing data.
- To inventory all natural cliffs that can potentially be sources of rockfalls.
- To optimize the use and integration of terrestrial, mobile and airborne laser scanners data into terrain analysis and structural geology analysis.
- To further develop the use of unmanned aerial vehicles (UAV) for photogrammetry applied to rock cliff characterization to obtain structural information on far-cliffs. A digital elevation model (DEM) derived from airborne laser scans do not have sufficient point density on vertical surfaces to characterize the structural geology.
- To consider climate change impact on mass movements.
- To integrate the results of rock fall simulation studies into a rock slope classification system implemented into a GIS software.

3 GAINING KNOWLEDGE OF THE TERRAIN

3.1 Remote-sensing data and site-specific knowledge acquisition

The first step of the project was to increase our knowledge on the sector. To do so, in the fall 2014, aerial photographs (10 cm pixels) as well as aerial and mobile laser scans were acquired. The first type of data allows for the creation of a mosaic of orthophotos and the second a DEM with 1 m pixels, from which information on the topography and landform are derived.

Rock cliffs are present from Port-Cartier until the north side of the Groulx Mountains (Fig. 1b), limiting our study site to the southernmost 260 km of the railroad.

General information about the study area, such as geology and Quaternary history was gathered and incorporated into the GIS database. The study site is located in the Precambrian Grenville geological Province (Hock et al. 1994). The rock is highly metamorphosed and is composed of different gneiss and migmatite with granite intrusions.

The last glaciation covered all of the Province of Quebec and most deposits dates from the deglaciation, which started around 9,4 ka BP in the studied region (King, 1985). The total extend of the study site was probably free of ice before 7 ka BP. More information on the terrain is acquired by creating a morpho-structural map (next section), which is presented as the first step of the methodology in Fig. 2.

The town of Port-Cartier (Fig. 1a) is located in the Lower-St-Lawrence seismic zone, where 50 to 100 earthquakes are detected annually (Lamontagne et al. 2003). An event of magnitude of 5.1 has been recorded in 1999 (Lamontagne et al. 2004).

3.2 Terrain-analysis and morpho-structural map

The GIS-based morpho-structural map divides the terrain into units of homogeneous geomorphology. The methodology we employed is an adaptation of Cruden and Thompson (1985) terrain classification system that incorporates the use of DEM obtained from airborne laser scans in the analysis (Locat et al. 2013).

The morpho-structural units are based on the landform, the drainage patterns (type and density) and the texture of the DEM, and to lesser extents the vegetation, landuse, and material. Part of the morpho-structual map is shown in Fig. 3. All the parameters used to identify a given morpho-structural unit are entered as attributes in the GIS-based map.

The terrain analysis is done not only from the DEM but also at looking at the orthophotos and visualizing the aerial pictures in 3D. We used Summit Evolution (DA/TEM Systems Intl. 2015) for 3D visualization of aerial pictures synchronised with ArcGIS (Esri Inc, 2010), so the user can easily switch from one set of data to another. Moreover, the user also has access to other useful data, such as geological and Quaternary maps and products derived from the DEM. Indeed, landform features (slope, aspect, drainage) are extracted from the DEM.

This map can then be interrogated to highlight sectors with specific characteristics, *e.g.* steep slopes with a thin till deposit. The most common genetic materials encountered along the railroad are in order: moraines (till), bedrock, fluvio-glacial, fluvial, organic, anthropogenic, and colluvial sediments.

When mass movements are present, they are identified as such. For the case of potential rockfall sources, they can be already identified from the map or extracted from the specific attributes making up the morpho-structural units.

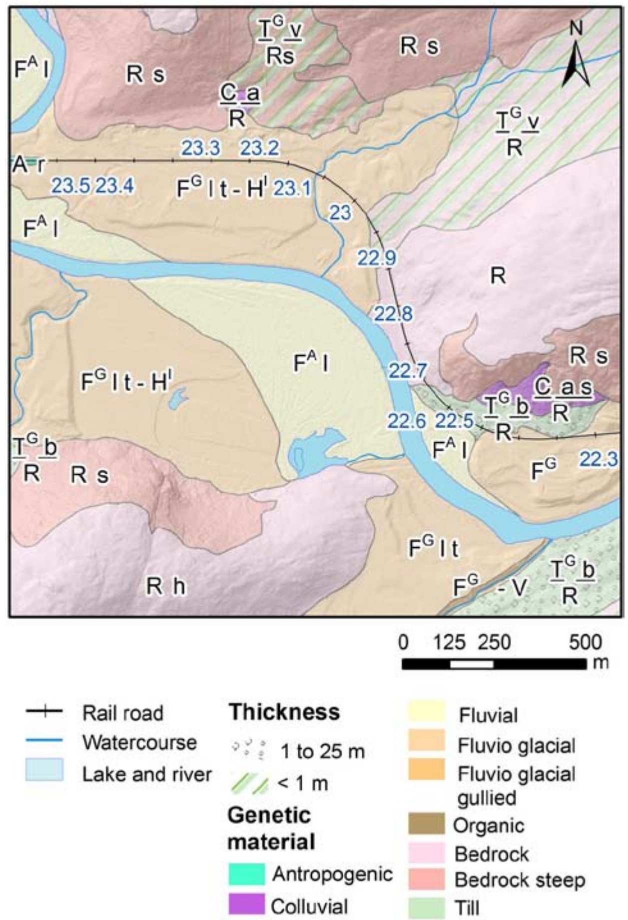

Figure 3. Part of the morpho-structural map along ArcelorMittal's railroad. The lettering on the map is a code that describes the units (Cruden and Thomson 1985). For example, the code $F^{A}l$ is a unit where active fluvial deposit is occurring on a leveled topography and Rs is steep bedrock.

4 ROCK SLOPE CHARACTERIZATION

4.1 Rock slope inventory and preliminary classification

The morpho-structural map can be interrogated to highlight the natural and anthropic rock slopes, in order to conduct an inventory of the rock slopes.

The rock cut inventory was carried out by systematically looking at the MLS point clouds in conjunction with the slope map computed from the DEM. It resulted in an inventory of 273 rock cuts. Slope turned out to be the best parameter to identify rock slopes. This new inventory recognized more slopes than the one previously done looking at orthophotos.

Natural rock cliffs that are further than 20 m away from the railroad were inventoried differently because they were not captured in MLS point clouds (Fig. 4). The technique for the identification of far-cliffs is discussed in section 4.2.

Rock cut features were compiled in the inventory and added to the GIS database: maximum height, length, side of the railroad, distance from the railroad, mileage position and inspection scores when available.

Once the inventory of rock cuts was completed, we proceeded to a preliminary classification, such as is suggested into the original RHRS methodology (Pierson 2012). To do so, we adapted the criteria to the available data: DEM (pixel of 1m²), orthophotos, 5 scores of previous inspections (1973 to 2009), and some rockfall events. An example of data available in the GIS project for the preliminary classification is shown in Fig. 5.

Each rock cut is evaluated according to the following three criteria and classified into high, moderate or low susceptibility categories:

1) Historic rockfall activity: our database of past activities is still very incomplete and efforts will be made to increase it.
2) Past inspections: based on the highest score attributed during past inspections.
3) Potential for rockfalls to reach the railroad: use the slope height and results of rockfall simulations (see section 4.2 and Noël et al. this conference). In general, slope higher than 15 m are rated high while slope lower than 5 m are rated low.

The maximum score obtained in one of the three categories is used as the preliminary classification score. 88, 121 and 73 road cuts were rated A (high), B (moderate), and C (low) respectively.

4.2 Far-cliffs identification by rockfall simulations

Rockfall simulations were run over the whole study domain using conservative values. The objective was to recognize the cliffs further than 20 m away from the railroad that can potentially generate rockfalls reaching the railroad, such as the rock slope in Fig. 4. This part of the Para*Chute* Project is the subject of another paper presented at GeoQuébec (Noël *et al.* this conference).

The modelling procedure had to be optimized to be used on large territories. The first step is to recognize all the cliffs and use them as sources to rockfall simulations, then run the simulations and afterward identify those with paths reaching the railroad (Fig. 5).

Few of these cliffs were inspected previously. So, our rock slope inventory is more complete and the application of our approach allows a better recognition of rockfall danger.

4.3 Structural analysis

The time available to characterize rock cuts along the railroad is extremely limited due to the high traffic density, so, we focussed on gathering as much information as possible before going on site. The points clouds acquired by MLS along the railroad are used in the software Coltop 3D (Jaboyedoff et al. 2009, Terr@num 2011) to conduct a structural analysis. Then, possible failure mechanisms are investigated with stereoscopic kinematic tests. Doing the structural analysis prior to field work will greatly reduce the number of compass measurements required for the characterization. The results of the structural analysis conducted from point clouds will be validated and completed during field work.

Figure 4. Example of a 150 m high far-cliff along ArcelorMittal's railroad.

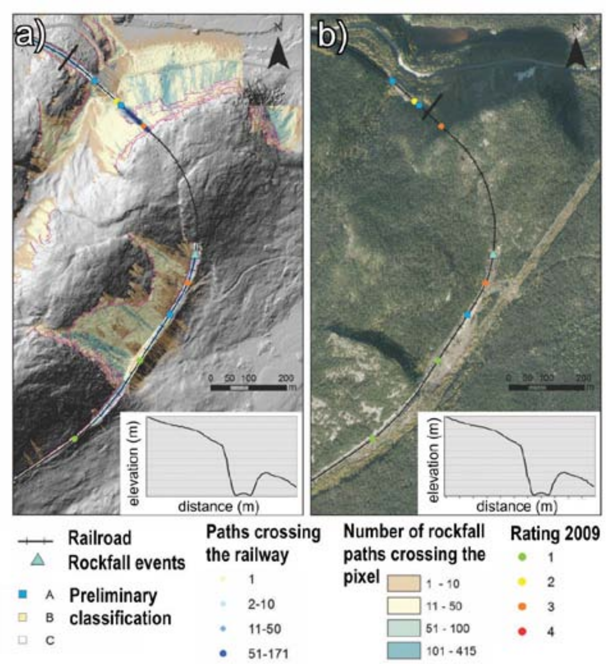

Figure 5. Two scenes in the GIS project used for the preliminary classification of rock slopes. a) Rockfall simulations over the shaded relief image of the topography. b) Same sector as in a), but showing the orthophotos.

The rock cuts' geological structure will then be integrated to generate structural domains over which the rock structure is mostly homogeneous. This will be used to run kinematic tests for each pixels of the DEM identified as rock slopes. This technique improves the sensibility to slope orientation because it does not use a mean value as the stereoscopic technique does.

Far cliffs will need a different type of inspections as they are not visible from the railroad and difficult to reach. For this reason, evaluation of their characteristics will be based essentially on remotely acquired data: the DEM and orthophotos already available, but also by applying photogrammetric method with pictures taken from helicopters and UAV. The same also applies to high slopes that are near the railroad, because the upper part is not visible from the railroad. Terrestrial laser scanner (TLS) will be used where feasible; however, the land configuration will limit the application of TLS to a few cases. Photogrammetry by UAV will be developed to overcome TLS limitations.

5 ADAPTATION OF THE RHRS

The systematic application of a rockfall hazard rating system along a linear infrastructure has great advantages (Pierson and Turner 2012), such as:

- the creation of a rockfall inventory;
- providing a set of consistent and comparable information;
- providing a relative ranking of potential hazardous slopes that is used to prioritize works;
- and lowering the risk related to rockfalls if mitigation is applied pro-actively;

and must

- be easy to use and implement;
- be carried by trained geotechnical engineers;
- give reproducible results.

The methodology that we propose will not replace the periodic inspections carried out along the railroad nor invalidate them. We want to increase their reliability by increasing the amount of information available. For example, discontinuity orientations and failure mechanism are permanent characteristics of a rock slope (Fig. 2), so their definition will be useful to geotechnical engineers doing future inspections. These inspections should concentrate on evolving slope conditions, such as fracture opening, weathering, water, infilling and mitigation reliability (Fig. 2). Moreover, a rockfall inventory system will be implemented, so the long term effectiveness of rock slope mitigations can be evaluated.

The consequence-linked parameters of the original RHRS are not relevant for a single railroad. For example the roadway width and the average number of vehicle per day are continuous parameters along the railroad length. So, some of the RHRS parameters must be customized to local conditions.

The term "rockfall" is often used in a broad sense to encompass most rock slopes movements (Bourrier et al. 2013). We wish to differentiate slopes that are prone to single rockfall defined as: "the detachment of rock from a steep slope along a surface on which little or no shear displacement takes place" (Cruden and Varnes 1996) and "whose trajectory is dominated by free fall" (Higgins and Andrew 2012) from those prone to larger failures, such as toppling failures, and address their characterization differently.

Finally, we want a system that can be easily updated and helpful to evaluate the causes and sources in case of a rockfall event.

5.1 Field work

Every rock cuts will be visited and characterized. We propose to first evaluate how detailed must be the characterization depending on the confidence we have in some parameters. For example, a rock cut that is clearly unstable and has many features unfavorable to stability will remain with a high priority even if we extend the characterization. However, for rock cuts with limited or ambiguous data, for example in case of a complex geological structure, a more detailed analysis in the field should help to refine the score and gain confidence in the resulting classification. So, the big point here is that the preliminary classification will not be used directly as our way of determining the amount of effort put in field investigation.

The methodology will be refined throughout the field work and subsequent office work will permit to develop a robust classification method.

Our work will focus on characterizing the rock cliffs in term of failure mechanisms and other parameters which are permanent characteristics of a cliff. The weathering, opening of cracks, ditch cleanness and other signs of instability are evolving through time and thus should be observed frequently by railroad employees trained to observe these signs and also evaluated during periodic inspections done by geotechnical engineers.

5.2 Susceptibility mapping

The final product will gather all the pertinent results presented in a graphical form along the railroad and incorporated into a GIS database. The reason why a particular slope scores high or low should be easily traceable for the end-user.

6 CONCLUDING REMARKS

The Para*Chute* research project aims at integrating various tools into a rock fall hazard rating system. The use of DEM, rockfall simulations and photogrammetry are optimized into a common approach. The Para*Chute* project started in the fall 2014 and will end in 2017, so, in this paper we presented a general description of the proposed methodology.

The systematic application of rockfall simulations provides an efficient way for adding natural cliffs as potential rockfall sources in the rock slope inventory.

One of the project's objectives is to decrease the required time for rock slope field characterization. To do so, mobile laser scanners point clouds of every rock cuts were acquired and analyzed for the recognition of discontinuity sets and to investigate potential failure mechanisms.

To make sure the tools are readily accessible and used by the end-users, training on the system is part of the research program. The implementation of tools to keep records of rockfall events is also an objective, because a good historic knowledge is the basis of a reliable and meaningful susceptibility map (Corominas et al. 2014).

Rockfall is just one of the various natural hazards affecting the railroad. We wish that the morpho-structural map helps to address other types of hazards, such as debris-flow.

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REFERENCES

Bemis, S., Micklethwaite, S., Turner, D., James, M.R., Akciz, S., Thiele, S., and Bangash, H.A. 2014. Ground-based and UAV-based photogrammetry: A multi-scale, high-resolution mapping tool for structural geology and paleoseismology, *Journal of Structural Geology,* 69(A):163-178.

Bourrier, F., Dorren, L., and Hungr, O. 2013. The use of ballistic trajectory and granular flow models in predicting rockfall propagation. *Earth Surface Processes and Landforms*, 38:435–440.

Corominas, J., Van Westen, C., Frattini, P., Cascini, L., Malet, J-P., Fotopoulou, S., Catani, F. et al. 2014. Recommendations for the quantitative analysis of landslide risk, *Bulletin of Engineering Geology and the Environment* 73(2): 209-263.

Cruden, D.M. and Thomson, S. 1985. *Exercises in Terrain Analysis*, The Pica Pica Press, textbook division of the University of Alberta Press, Alberta, Canada.

DA/TEM Systems International, 2015. Summit Evolution, Photogrammetric workstation, Alaska, USA www.datem.com

Esri Canada Inc, 2010 ArcGIS 10.1, software for georeferencing, mapping and analysing geographic information. Toronto, Canada. http://www.esri.ca/en/content/arcgis

Hock, M., Verpaelst, P., Chartrand, F., Clark, T., Lamothe, D., Brisebois, D., Brun, J., and Martineau, G., 1994. *Géologie du Québec*, Ed.: C., Dubé., Bibliothèque nationale du Québec, Gouvernement du Québec.

Higgins, J.D. and Andrews, R.D. 2012. *Chapter 2: Rockfall Types and Causes in Rockfall: Characterization and Control*, A.K. Turner and R.L. Schuster (Eds.), Transportation Research Board, Washington D.C., USA, 21-55.

Jaboyedoff M, Couture R, and Locat P. 2009. Structural analysis of Turtle Mountain (Alberta) using digital elevation model: toward a progressive failure, *Geomorphology*, 103:5‑16.

King, G.A., 1985. A Standard Method for Evaluating Radiocarbon Dates of Local Deglaciation : Application to the Deglaciation History of Southern Labrador and Adjacent Québec, *Géographie physique et Quaternaire,* 39(2):163-182.

Lamontagne, M., Bent, A.L., Woodgold, C.R.D., Ma, S., and Peci, V., 2004. The 16 March 1999 m_n 5,1 Côte-Nord Earthquake: The Largest Earthquake Ever Recorded in the Lower St. Lawrence Seismic Zone, Canada., *Seismological Research Letters*, 75(2): 299-316.

Lamontagne, M., Keating, P., and Perrault, S., 2003. Seismotectonic characteristics of the Lower St. Lawrence Seismic Zone, Quebec: insights from geology, magnetics, gravity, and seismics. *Canandian Journal of Earth Sciences,* 40: 317-336.

Lan, H., Martin, C.D., Zhou, C., and Lim, C.H. 2010. Rockfall hazard analysis using LiDAR and spatial modeling, *Geomorphology*, 118(1): 213-223.

Lato, M.J., Diederichs, M.S., Hutchinson, D.J., and Harrap, R. 2012. Evaluating roadside rockmasses for rockfall hazards using LiDAR data: optimizing data collection and processing protocols. *Natural Hazards*, 60(3) : 831-864.

Locat, J., Fontaine, A., Turmel, D., Noël, F., Lajeunesse, P., Joyal, G., and Bernatchez, P. 2013. Carte morpho-structurale et mouvements de terrain le long de la façade maritime de Charlevoix : intégration des levés LiDAR, interferométriques et multifaisceaux, dans les compte-rendus de la *66e Conférence annuelle de la société canadienne de géotechnique et la 11e conférence conjointe SCG/AIH-SNC sur les eaux souterraines,* 7p.

Noël, F., Cloutier, C., Turmel, D., Locat, J. 2015. L'aléa chutes de pierres : la modélisation préliminaire 3D des trajectoires le long d'une infrastructure linéaire, in GéoQuébec 2015, Québec, Qc, Canada.

Pierson, L.A. 2012. *Rockfall Hazard Rating Systems*, in *Rockfall: Characterization and Control,* A. K. Turner and R.L. Schuster (Eds.), Transportation Research of the National Academies Board, Washington D.C., 56-71.

Pierson L.A. and Turner A.K. 2012. *Chapter 4 Implementation of Rock Slope Management Systems in Rockfall: Characterization and Control*, A.K. Turner and R.L. Schuster (Eds.), Transportation Research Board, Washington D.C., USA, 72-110.

Terr@num, 2011. Coltop 3D v1.8.9, software for interactive structural analysis on Lidar data, Lausanne, Switzerland, http://www.terranum.ch/

Turner, A.K. and Jayaprakash, G.P. 2012. *Chapter 1 in Rockfall: Characterization and Control*, A.K. Turner and R.L. Schuster (Eds.), Transportation Research Board, Washington D.C., USA, 1-19.

Volkwein, A., Schellenberg, K., Labiouse, V., Agliardi, F., Berger, F., Bourrier, F., Dorren, L.K.A., Gerber W., and Jaboyedoff, M. 2011. Rockfall characterisation and structural protection-a review, *Natural Hazards and Earth System Sciences*, 11: 2617-2651.

Wolter, A., Stead, D., and Clague, J. 2014. A morphologic characterisation of the 1963 Vajont Slide, Italy, using long-range terrestrial photogrammetry. *Geomorphology*, 206: 147-164.