Frequency-magnitude of rockfall events for hazard analysis; a comparison of data from LiDAR scanning with traditional methods of reporting

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ABSTRACT
Railways in Western Canada are exposed to rockfall hazards that can be understood and managed through the use of a rockfall event database, which includes information on rockfall magnitude and frequency. Traditional rockfall inventories collected by railway personnel are often incomplete or lacking in volume information. In this study, LiDAR change detection is used to understand variations in rockfall magnitude, mechanism, and source zone by rock type and rock mass quality for an area of track along the Thompson River valley near Lytton, BC. Results are compared to traditional inventories to understand how each may contribute to establishing a complete rockfall inventory and characterization for this section of rockfall vulnerable railway track.

RÉSUMÉ
Les chemins de fer de l'ouest du Canada sont exposés aux chutes de pierres. Ces évènements peuvent être mieux compris et mieux gérés grâce à l'utilisation d'une base de données incluant l'ampleur et la fréquence de ces chutes de pierres. Les inventaires traditionnels de chutes de pierres recueillis par le personnel des compagnies de chemins de fer sont souvent incomplets ou manquent d'information sur le volume de pierres. Dans cette étude, la détection des changements par LiDAR est utilisée pour comprendre la grosseur, les mécanismes et les zones sources des effondrements le long du chemin de fer de la vallée de la rivière Thompson près de Lytton, BC. Les résultats obtenus sont comparés aux inventaires traditionnels pour comprendre comment chaque chute de pierres peut contribuer à l'instauration d'un inventaire complet pour cette section de chemin de fer vulnérable.

1 INTRODUCTION

Canadian railway corridors that are built along natural slopes are exposed to frequent rockfall hazards, which may cause disruption to service and damage to infrastructure. Rockfalls are a significant problem, as often, not much warning is given prior to large failure events (Keegan et al., 2000). A thorough understanding of the characteristics of these hazards is an important component of risk assessment, which can assist with the management of railway tracks in these settings. The frequency-magnitude relationship of rockfall events is an important input to risk assessment, which can be evaluated from a rockfall event database. In addition to the volume of failed blocks, effective hazard management systems also require an assessment of the shape of these blocks as block shape is a factor affecting the vulnerability of trains to rockfall events (Lato et. al, 2012b).

Traditionally, rockfall inventories have been collected by railway personnel, and while they may contain estimates of event volumes, event dates, track mileage, and possible source zones or triggering mechanisms, these inventories are often incomplete. Field measurements can be subject to personal bias, and rockfall source zones can be difficult to identify in the field, especially on large complex slopes. One drawback of using traditional rockfall inventories for frequency-magnitude analysis is the incomplete sampling of small rockfall events (Hungr et al., 1999). Events can also be recorded using slide detector fences; however these reports only contain information on the time and general track location of the event, and are lacking volume estimates and information about source zone locations and characteristics.

More recently, LiDAR (Light Detection and Ranging) has been used to characterize rockfall processes on hazardous slopes. LiDAR provides the advantage of spatially complete data coverage, creating a permanent record of the slope at the time, and does not require exposure of personnel to hazardous slopes (Lato et al., 2012b). Analysis of change from sequential LiDAR scans can provide detailed data that can't be obtained from traditional databases, including the magnitude, spatial and temporal distribution of rockfall events, and useful information regarding rockfall source zones and rock structural controls. Collection of high resolution LiDAR data from optimized scan locations has allowed for changes as small as 10 cm to be detected on rock slopes such that very small rockfall events can be identified.

1.1 Study Site

This study focuses on a section of vulnerable railway track located 5km East of Lytton, along the Thompson River valley, in British Columbia. This area, shown in Figure 1, features a large steep slope, the active portion of which is up to 500 m above the railway track, known as the 'White Canyon', spanning Mile 93.1 to 94.6 of the CN Ashcroft Subdivision. The canyon is separated into two bowl shaped sections by a ridge of more competent rock containing a short railway tunnel, denoted herein as the West and East sections. The rock slope is comprised mainly of amphibolite and quartzofeldspathic schists with mafic igneous intrusions, with the westernmost section made up of a weathered chert pebble conglomerate (Brown, 1981). The frequency of rockfall reaching the railway in this area can be significant as the proximity of this section of track to the Thompson River limits the potential for ditch retention of rockfalls. In addition, the cost of delays should an event occur that is large enough to slow or suspend rail service can be substantial. A more precise understanding of the spatial and temporal components of these rockfalls can provide information regarding greater processes that are operating on the slope as a whole (Gauthier et al., 2012).

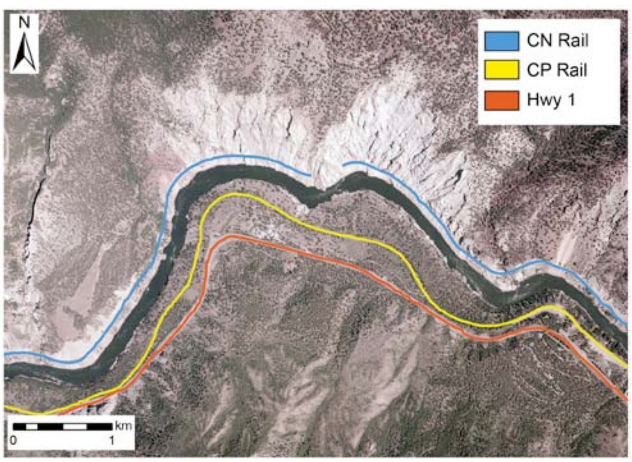

Figure 1. The White Canyon area, located near Lytton, British Columbia

1.2 Available Data

Three years of high resolution LiDAR data has been collected along this section of railway track from survey sites located on the opposite bank of the Thompson River. High-resolution gigapixel photographs were collected simultaneously with the LiDAR data and provide visual confirmation of the failure events. This study focuses on comparison of LiDAR and photo data collected in November 2014 and in February 2015. Slide detection fence activation data for the corresponding time period (November 1st 2014 to February 16th 2015) was provided by CN.

2 METHODS

2.1 Data Collection and Processing

Terrestrial LiDAR data was collected using an Optech ILRIS-3D scanner with Enhanced Range capabilities. Data for the West and East sections of the canyon were collected and processed separately. Scans were collected on November 1st 2014 and February 16th 2015 for the West section and on November 3rd 2014 and February 20th 2015 for the East section. The point cloud data was processed using Optech Parser followed by Polyworks software (Innovmetric, 2015). For each section, scans were taken from several locations and were aligned using an iterative closest point (ICP) algorithm (as outlined further by Besl & McKay, 1992) and then merged together. Colour maps of change detection were created using a shortest distance measurement between the two datasets for each location.

Photographs were collected at the same time using a Nikon D800 DSLR camera with a 135mm lens, mounted on a GigaPan EPIC Pro robotic system. At each scan location, a fan of images was collected (ranging in number from 90 to 200 photos), as described in Lato et. al (2012a). Each image fan was stitched together into a high-resolution panoramic image using the GigaPan Stitch software such that the images could be used as a qualitative, visual comparison to the LiDAR data.

2.2 Data Analysis

Both the LiDAR and gigapixel data were used to analyze individual rockfall events. Rockfalls were identified from the LiDAR change detection and their volumes were calculated using the Data to Data volume measurement tool in the same software. The photographs provided visual confirmation of rockfall events as well as additional qualitative information.

A database was created to record rockfall events and their associated characteristics. In addition to data on the frequency-magnitude aspects of the rockfall events, additional information was recorded including the location of the events, the source zone lithology, rock quality estimate (GSI), and the expected or observed structure and failure mechanism. This data was recorded in order to gain an understanding of the spatial and temporal distribution of rockfall events and their mechanisms, and for potential use in risk management and rockfall modeling.

3 RESULTS

387 rockfalls, ranging in magnitude from 0.01 to 20.5 m^3, were identified from the LiDAR data between November 2014 and February 2015. The distribution of the number of rockfall events based on magnitude is shown in Figure 2. Classification of events based on the magnitude ranges currently used by CN in the field (as outlined by Pritchard, et al., 2005) shows that the majority of rockfall events are grouped into the lowest category (less than 1 m^3). Although the relative number of large events is small, the number of events greater than $1m^3$ is still significant (38 events). Grouping the number of rockfall events into a greater

number of bins based on order of magnitude, as outlined in Figure 2b, allows a further distinction in the distribution of rockfall source volumes to be visualized by highlighting the number of events greater than 10 m^3 and less than 0.1 m^3**.** Many studies have shown a power law relationship between the magnitude and frequency of rockfall events (as outlined by Hungr et al., 1999; Malamud et al., 2004; Santana et al., 2012, and others), which suggests that the number of very small rockfalls identified by this study is an underestimate. However, it is very likely that many smaller events occurred during the study period, which were beyond the range of detection or detection with acceptable accuracy for this data. Additionally, the location of all events (including height) was determined easily using the LiDAR data.

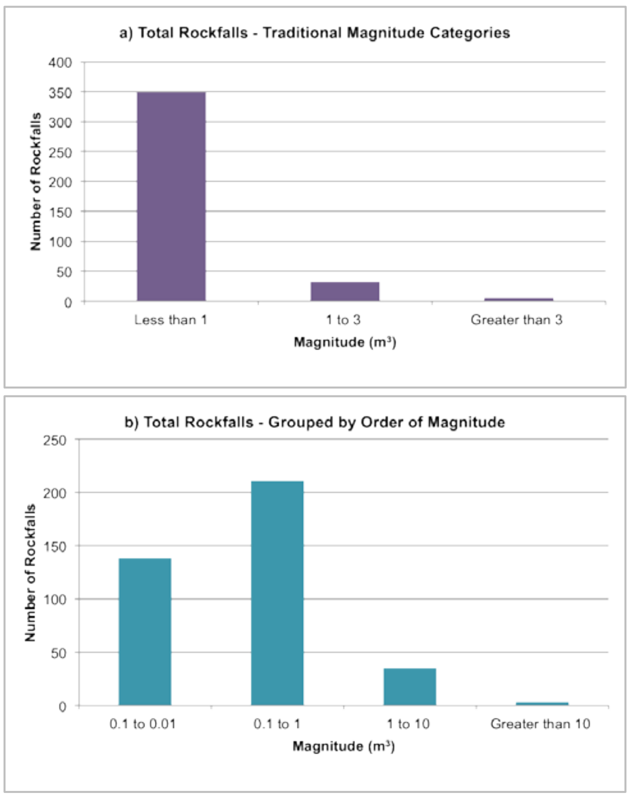

Figure 2. Number of rockfall events by magnitude a) grouped into bins traditionally used in the field and b) grouped into smaller bins (0.01 to 0.1, 0.1 to 1, 1 to 10 and greater than 10 m^3)

For the West section of the canyon, gigapixel photos were used for visual inspection of rockfall events, to gain additional information. An example of this process is outlined in Figure 3. Information was collected on rockfall source zone lithology, rock quality, expected or observed failure mechanism, and the shape of the block that fell. Lithology could be easily determined from photos based on the known location of the rockfall and visual identification of the lithology type. An estimate of rock mass quality, using the GSI system, was determined from photographs by inspecting the presence of joints and the surface characteristics of the rock. The failure mechanism and block shape could be estimated based on absence of specific blocks in later photos, changes in colouring and markings on the slope, slope angle, and the presence and orientations of discontinuities. There were several cases in which a rockfall location could not be corroborated with the photos. The primary reasons for this were poorer resolution of photos in the upper slope region (because of greater distance from the camera), over or underexposure of photos (such that individual blocks could not be distinguished), or that the rockfall area was blocked by other parts of the slope in the images. In these cases, the lithology and rock quality were estimated based on the general location of the rockfall and the failure mechanism and block shape were estimated using the LiDAR data only.

Figure 4 outlines the distribution of rockfall events based on lithology, failure mechanism, and block shape. Based on lithology, the most rockfalls occurred within the metamorphic schists (also the most prevalent rock type) and the fewest in areas of igneous intrusion. Table 1 shows a comparison between the percentages of each lithology (based on total outcrop area) to the percentage of rockfalls that occurred within each of the three categories of lithology on the slope. From this it can be seen that the percentage of rockfalls in the igneous and conglomerate units are higher than the percentage of the slope area that these units occupy, suggesting that the relative frequency of rockfall events in these units is greater than for the metamorphic unit. Sliding was the most dominant failure mechanism observed and smaller rockfalls were generally blockier while larger ones were more likely to be irregular in shape. From the photos, it was observed that many rockfalls may have occurred as a group of smaller blocks falling from the same area at the same time.

Slide detector fence reports showed 46 fence activations for the section of railway track along the canyon, compared to the 387 rockfalls identified from LiDAR change detection data. The fence was activated on 41 out of 108 days and there were 5 days where the fence was activated multiple times, which provides an idea of the frequency of events making it to track level. Often these slide fences become deactivated for long periods of time as they must be repaired once triggered, and the time to repair is dependent on daylight and weather conditions for personnel safety reasons. Based on the time it took to repair the fence after each of the detected events for this time period, the fence was deactivated for 34% of the study period. Although it is possible that multiple blocks fell in the same area at the same time, triggering the slide detection fence only once, and that not all of the events detected from the LiDAR made it to track level, the large number of rockfalls seen from the LiDAR in comparison to the slide fence activation events suggests that the data collected from the slide fence is an undersampling of rockfall events making it to track level.

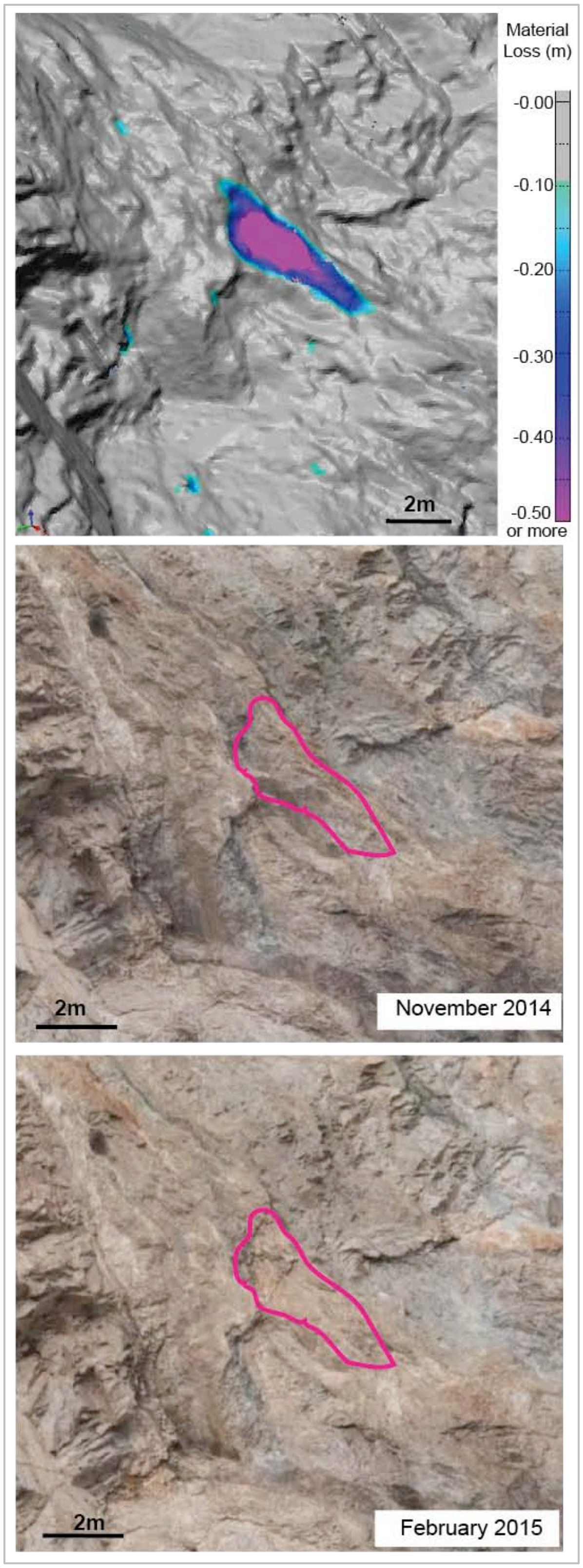

Figure 3. Visual inspection of 3.9 m^3 rockfall using gigapixel images

Table 1. Comparison of total areal extent of lithologies to the percentage of rockfalls occurring within each lithology on the slope. Percentage of total outcrop area for each lithology calculated based on data from Jolivet et al. (2015).

Lithology	% of Total Outcrop Area	% of Rockfalls
Metamorphic Schists	78	66
Igneous Dykes/Intrusions	9	14
Weathered Conglomerate	13	20

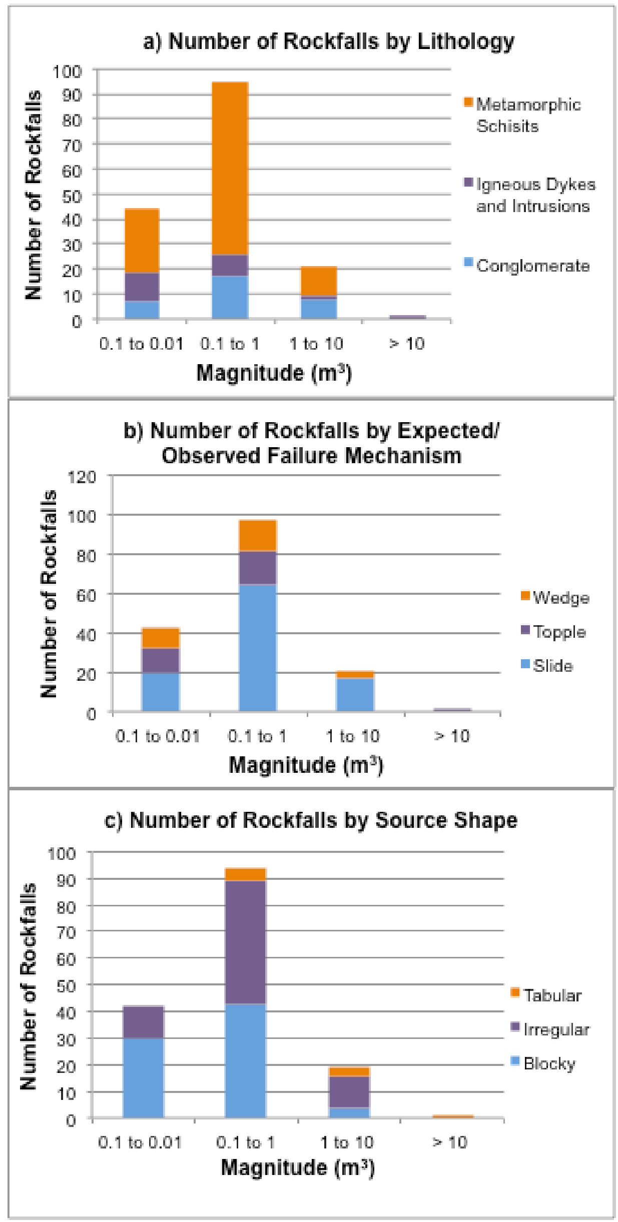

Figure 4. Rockfall events for White Canyon West section separated by a) lithology, b) failure mechanism and c) structure

4 DISCUSSION

While traditional rockfall inventories are often lacking information, the results of this study demonstrate that useful information can be obtained from LiDAR change detection that can be used in understanding rockfall magnitude-frequency relationships as well as other statistics that may be useful in characterizing these hazards. Using this data, the volume of rockfall events can be accurately determined, providing a detailed overview of the spectrum of hazardous and nonhazardous blocks that may make it to track level. As outlined by Pritchard et al. (2005), the use of the High Energy Impact factor (probability of rockfalls damaging or destroying rails) in traditional rockfall hazard ratings has been discontinued as it was determined that more information on the size, rock mass strength, and potential energy of blocks hitting the track must be known to make this factor more accurate. Information obtained from LiDAR and photo data could provide a better estimate of this potential based on the combined knowledge of magnitude, height, and rock quality for each rockfall. In comparison to the rockfall inventory, the number of slide detection fence activations suggests an underestimate of the number of rockfall events. While it is likely that not all of the events detected using LiDAR made it to the fence, the fence was also deactivated for a significant portion of time rendering the slide fence activation inventory incomplete.

Previous studies of rockfall magnitude-frequency relationships along both highways and railways in this area (Hungr et al., 1999) identified an incomplete sampling of small rockfalls, which an inventory based on LiDAR change detection may be able to provide. These studies show a power law relationship between rockfall magnitude-frequency for volumes greater than 1 m^3 in all of of southwest BC. As LiDAR data has only been collected for several years, the data obtained in this study may not span larger, infrequent events to investigate this relationship. Other limitations of the process used for this study include the large amount of time required to identify and visually review each rockfall event due to the high amount of activity on this slope. In areas with less annual rockfall activity, this would likely not be as onerous. In the future, attempts could be made to further automate this process.

5 CONCLUSIONS

Many traditional rockfall inventories are incomplete making it difficult to perform a reliable assessment of rockfall hazards. LiDAR change detection, with the aid of high-resolution gigapixel photography, can be used to determine information on the location and magnitude of rockfall events as small as 0.01 m^3 and can provide additional information on rockfall source zones, block characteristics, and failure mechanisms that can be used in hazard and risk assessment. In the White Canyon area, 387 rockfalls were identified between the period between November 2014 and February 2015. Moving forward, this technique can be applied to additional datasets to create a more complete inventory spanning several years. Once sufficient information is collected, the frequency-magnitude data will be evaluated for use in risk management analyses.

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