GÉORISQUES IV GEOHAZARDS

APPLICATION OF DIGITAL CARTOGRAPHIC TECHNIQUES IN THE CHARACTERISATION AND ANALYSIS OF CATASTROPHIC LANDSLIDES; THE 1997 MOUNT MUNDAY ROCK AVALANCHE, BRITISH COLUMBIA

K.B. Delaney
Department of Earth and Environmental Sciences, University of Waterloo. Waterloo, Ontario, Canada, kbdelane@uwaterloo.ca
S.G. Evans
Department of Earth and Environmental Sciences, University of Waterloo. Waterloo, Ontario, Canada

RÉSUMÉ
Une étude de l'avalanche rocheuse du Mont Munday, survenue en 1997 dans une région isolée de la Chaîne côtière de la Colombie-Britannique près du mont Waddington, illustre l'application des techniques de cartographies digitales. Premièrement, en utilisant des images SPOT et LANDSAT successives, on a pu déterminer l'occurrence de l'événement à l'intérieur d'une fenêtre de 19 jours entre le 18 juillet et le 6 août 1997. Deuxièmement, des photographies aériennes à grande échelle, prises le 30 août 1997, ont fourni la base pour la confection d'un modèle de terrain à haute résolution. Une comparaison avec la topographie d'avant le glissement nous a permis de déterminer les changements tant à la source que dans la zone de déposition rendant ainsi possible une mesure précise des volumes de départ et de déposition. Troisièmement, les photographies aériennes à grande échelle ont aussi permis la réalisation d'une analyse d'image des débris afin de définir les caractéristiques de fragmentation. Le nombre total, les axes mineur et majeur ainsi que le volume de chacun des rochers a été compilé. Finalement, les mouvements post-déposition des débris de l'avalanche rocheuse reposant sur le glacier et la vitesse du transport de sédiment ont été suivis à l'aide des images satellites. L'avalanche rocheuse a un volume de $3.2x10^6$ m^3, couvrant une surface totale de $2.5x10^6$ m^2. Elle a couvert une distance de 4.5km sur la surface du glacier Valley avec une vitesse moyenne d'environ 10 m/s et une épaisseur moyenne de 1.5 m, consommant ainsi une énergie d'environ $4.33x10^{12}$ J.

ABSTRACT
An investigation of the 1997 Mount Munday rock avalanche that occurred near Mount Waddington in a remote part of the Coast Mountains of British Columbia illustrates four applications of digital cartographic techniques. First, using successive SPOT and LANDSAT satellite imagery we established that the landslide occurred in a 19 day window between July 18 and August 6, 1997. Second, large scale aerial photographs were taken on August 30, 1997 providing the basis for a high-resolution digital elevation model of the landslide. A comparison to pre-slide topography enabled us to determine changes in the source and depositional area of the rock avalanche, resulting in accurate estimates of source and deposit volumes. Thirdly, the large-scale aerial photographs also enabled us to conduct image analysis of the debris with the objective of defining its fragmentation characteristics. Total number, major/minor axis (m) and volume (m^3) of each boulder are tabulated. Lastly, the post-depositional movement of the rock avalanche debris on the glacier surface and velocity of surface sediment transport has been tracked using satellite imagery. The rock avalanche involved a total volume of $3.2x10^6$ m^3 covering a total area of $2.5x10^6$ m^2. It traveled over 4.5 km on the surface of Ice Valley Glacier with a mean velocity of about 10 m/s and mean thickness of 1.5 m, expending a total energy of $4.33x10^{12}$ J.

1. INTRODUCTION

The availability of digital cartographic techniques has revolutionized the extent that catastrophic landslides may be characterised for description and analysis (e.g. Evans et al., 2007). Such techniques include the interpretation of optical satellite imagery, the generation and analysis of high-resolution digital elevation models, and the use of image analysis software. These techniques are especially useful when the event takes place in a remote location where extensive field operations are not feasible due to weather, safety, and/or financial considerations.

Rock avalanches onto glaciers are a common occurrence in the mountains of northwest North America (Shreve, 1966; Post, 1967; Maragunic and Bull, 1968; Evans and Clague, 1988; 1999; O'Connor and Costa, 1993; McSaveney, 1978; Jibson, et al. 2006). They are of interest since in most cases they afford an excellent opportunity to examine rock avalanche emplacement mechanisms without either substantial topographic interference in runout mechanics or other earth materials being entrained in the debris. Rock avalanches onto glacier surfaces thus allow us to trace the movement and disintegration of a rock mass from initial failure to deposition without the contamination of materials entrained along its path.

Sometime in late-July early-August 1997, a large rock avalanche occurred on the southern flank of Mount Munday (3367 m.a.s.l.; 51º 19.9' N / 125º 12.8' W) in the Waddington Range of British Columbia's Coast Mountains, 280 km northwest of Vancouver (Fig. 1). The rock avalanche took place 6.5 km southeast of Mount Waddington (4019 m), British Columbia's highest peak, and involved the highly resistant gneissic rocks of the Coast Plutonic Complex (Roddick, 1985) which form a number of jagged peaks in the Waddington Range. The debris flowed across and down Ice

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Valley Glacier, forming a spectacular tongue-shaped deposit on the glacier surface (Fig. 1).

2. MOUNT MUNDAY ROCK AVALANCHE

2.1 Date of Occurrence

Due to the remote location, the rock avalanche was not witnessed. However, we have been able to establish the date of the event to within a 19 day window by an examination of satellite images collected during July and August 1997. The rock avalanche is first visible beneath a thin cloud cover on a SPOT image obtained on August 6, 1997. A SPOT image obtained on July 18, 1997 does not show the rock avalanche. This refines and revises the estimated time of occurrence initially reported by Evans and Clague (1998; 1999).

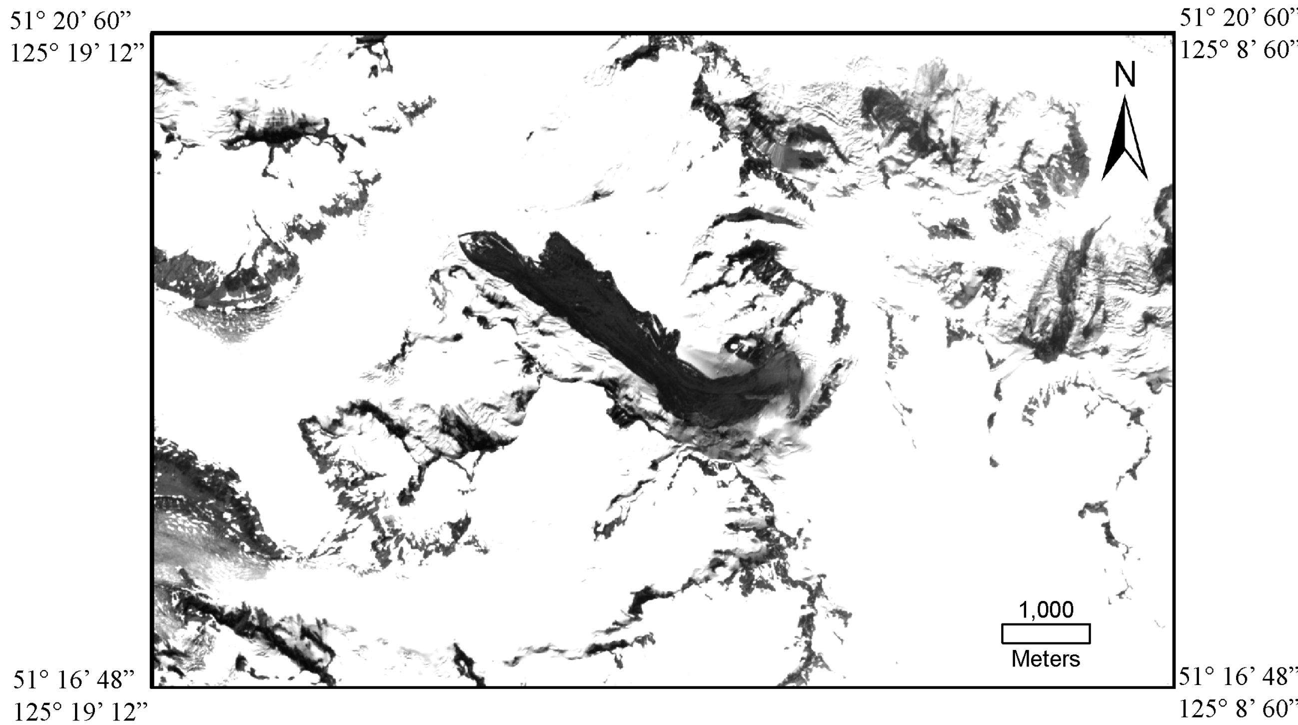

Figure 1: SPOT satellite image of Mount Munday rock avalanche collected on August 11, 1997. Note the absence of snow cover on the debris and dust still visible on the snow surface adjacent to the rock avalanche. The rock avalanche is first evident on satellite imagery obtained on August 6, 1997.

2.2 Trigger

Data from the Geological Survey of Canada indicates that no significant earthquakes occurred in the region during the time window that could have triggered the rock avalanche (Natural Resources Canada, 2007). Climate data from Tatlyoko Lake (el. 868 m.a.s.l.), approximately 60 km to the east shows no exceptional climatic conditions that could have been a trigger except for a possible freeze-thaw cycle on July 22-24, 2007 (Environment Canada, 2007).

2.3 Source Area

The source area is located on a shoulder that forms the lower southwest part of Mount Munday and rises steeply (46°) from the surface of Ice Valley Glacier. The rocks in the source area are hornblende-rich dioritic granitoid gneiss of the Central Gneiss Complex of the Coast Mountains pluton (Roddick, 1985). These rocks are coarsely foliated, with foliation dipping steeply (70º-82º) to the SW – SSW (Roddick, 1985).

The highest elevation of the source area is 3180 m.a.s.l. The base of the detachment runs from an elevation of 2600 to 2650 m.a.s.l., and daylights at the surface of Ice Valley glacier. Failure involved a rock slope roughly 500 m in height that had an average slope of 46º, an orientation of 220º SSW. The average depth of rock removed from the source area is estimated to be 55 m. Comparison of digital elevation models (DEMs) obtained from pre-slide (1987) and post-slide (1997) photography indicates that the volume of rock that detached from Mount Munday is 3.2 M m^3 (Fig. 2).

The initial movement direction of the main mass was SSW before turning to the NW to flow down Ice Valley Glacier (Fig. 1 & 3).

2.4 Emplacement Mechanism

Aerial photographs of the rock avalanche debris taken on August 20 1997, a maximum of 33 days after the landslide took place affords a unique opportunity to examine primary directional features and structures on the surface of the debris resulting from emplacement (Fig. 3). The features are assumed not to have been modified by glacier motion in the short interval between emplacement and photography.

The mechanics of initial sliding are complex but appear to have been controlled by a steeply dipping planar fault surface that has a more southerly strike than the foliation and cuts across it at a lower dip angle. This discontinuity geometry gives rise to multiple wedges some of which detached completely, whilst others slid only a limited distance. In the centre of the source area, for example, a substantial volume of disturbed rock remains on the failed slope; although this mass slid a short distance, it did not completely detach from the mountain side.

An examination of flow streamlines and their cross cutting relationships indicate two distinct zones in the debris down-glacier of the sharp turn (Fig. 3); suggestive of two streams in the debris, reflecting to some extent the micro-topography of the glacier surface (*A* and *B* in Fig. 3). A more northerly spreading stream traveled a much shorter distance than the furthest distal NW tip of the debris.

The initial movement of debris from the source area travelled less than half the distance down slope before topographic factors directed it to the north, back up-slope, stopping the flow (*A* in Fig. 3). The second and larger flow overcame this topographic anomaly and continued down-glacier, traveling several more kilometres (*B* in Fig. 3). The flow lines in Figure 3 illustrate the main flow paths of the debris.

A topographic depression near the toe of the debris, allowed part of the mass to travel about 930 m further down slope and seems to have taken advantage of an elongated area of the glacier surface which acted like a shallow channel for the debris (*B* in Fig. 3). Because of this, the streamlines in the debris are almost unidirectional in the direction of the distal tip.

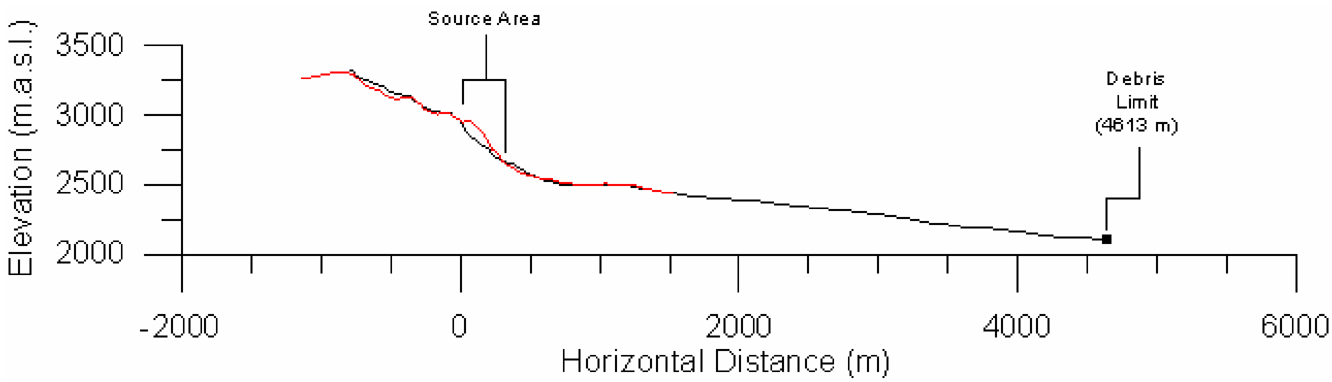

Figure 2: Topographic profile of the pre-event surface (bulge in red) and post-event surface (in black) of the 1997 Mount Munday rock avalanche.

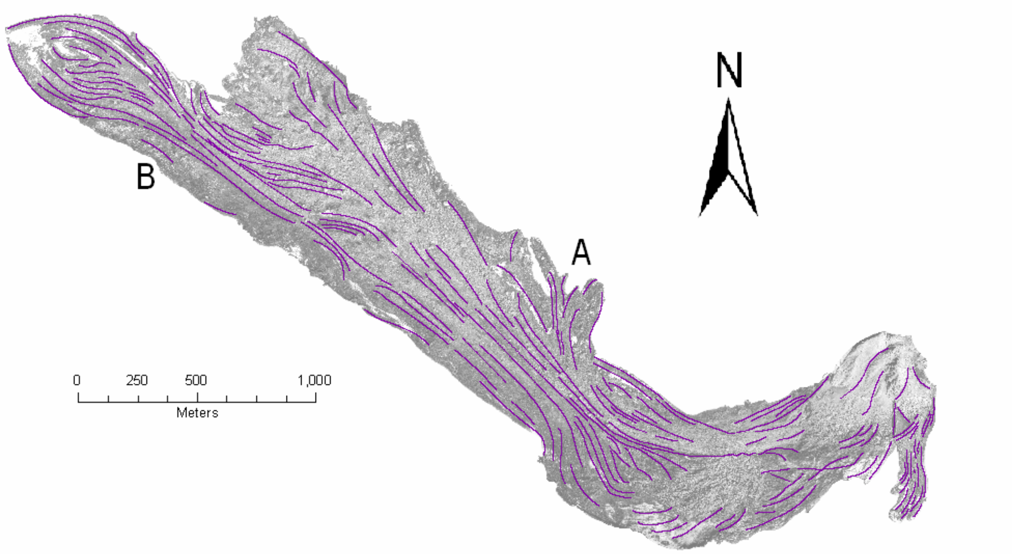

Figure 3: The main flow streamlines in the debris of the Mount Munday rock avalanche, interpreted from large scale aerial photographs, flown August 20 1997.

2.5 Geometry and Volume

The highest point of failed rock in the source area is approximately 3180 m.a.s.l and the distal tip of the debris is at 2100 m.a.s.l. (H = 1080 m). The total distance of travel (L) is 4.6 km; thus the fahrböschung is 13º.

Comparison of digital elevation models (DEMs) obtained from pre-slide (1987) and post-slide (1997) photography, and topographic maps carried out in the ESRI ArcGIS™ 9.2 software suite indicates that the volume of rock that detached from Mount Munday is 3.2 M m^3. The debris covers a total area of 2.5 km^2.

If we assume that bulking of the rock mass during fragmentation and transport is 20%, as in the case of the Sherman Glacier rock avalanche (Marangunic and Bull, 1968; McSaveney, 1978), then the debris volume of the rock avalanche is 3.8 M m^3 with an average thickness of debris of only 1.5 m over the same area. In comparison, the average thickness of the 1964 Sherman Glacier rock avalanche debris was 1.65 m (McSaveney, 1978).

3. FRAGMENTATION

The Mount Munday rock avalanche resulted in a high degree of fragmentation of the source rock mass. The debris contained a wide range of grain sizes from blocks as large as 30 m in diameter to very fine dust. The lack of complete fragmentation at Mount Munday relates to the total potential energy available (4.33×10^{12} J) in the rock avalanche, and the impact the moving mass had with the glacier surface.

Assuming an average density of 2600 kg/m^3 (Locat et al., 2007), the total mass of the source rock is 8.32×10^9 kg. Therefore, the rock avalanche expended a total of 5.2×10^5 Joules/tonne. This compares to a range of 1.0-6.5 Joules/tonne for nine rock avalanches reported by Locat et al. (2006).

The difference in slope angle between the source area (45°) and the glacier surface (6°) plays an important role in the fragmentation process. In other settings, where rock avalanches occur, the source rock mass often falls onto a much steeper lower slope, or transport surface, with only a slight difference in angles. The source rock mass on Mount Munday immediately impacted the almost flat glacier surface, effectively eliminating much of its kinetic energy and forward momentum, shortly after failure.

Compared to the fall heights of other larger rock avalanches onto glaciers in northwest North America, such as Mount Steele (> 2 km) (Lipovsky et al., this volume) or the Sherman Glacier (~ 700 m) (McSaveney, 1978) events, Mount Munday had a small fall height of 500 m. This short fall limits the total energy available for fragmentation and transportation of the source rock.

The combination of the fall height and the difference in angles between the source and deposit areas is the main control on fragmentation. Once the rock mass impacted the glacier surface below the source, it imparted a large portion of energy to its initial break-up and heat loss. This quick reduction of kinetic energy allowed the debris to ‘slide’ the remainder of the distance down-glacier, with very little rolling, limiting the energy transfer for any additional fragmentation during the down-glacier transport.

Using Image Tool™ software, a grain size analysis of the debris was completed. This software allows the user to preferentially select and analyse boulders from a single, or series of images. The smallest boulders which can be imaged will be a result of the resolution of the imagery and objectives of the study. To obtain the fragmentation data, aerial photographs are loaded into Image Tool where they are reduced to black and white polarisation for easier image analysis. Once the images are calibrated, the software counts and measures any blocks found within the image, applying an imported real-world scale.

The image software is calibrated to detect boulders of at least 3 pixels in size, with a pixel resolution of 0.86 m^2 (Fig. 4). This size was chosen as the lower limit to avoid confusion of the image analysis with background noise in the imagery.

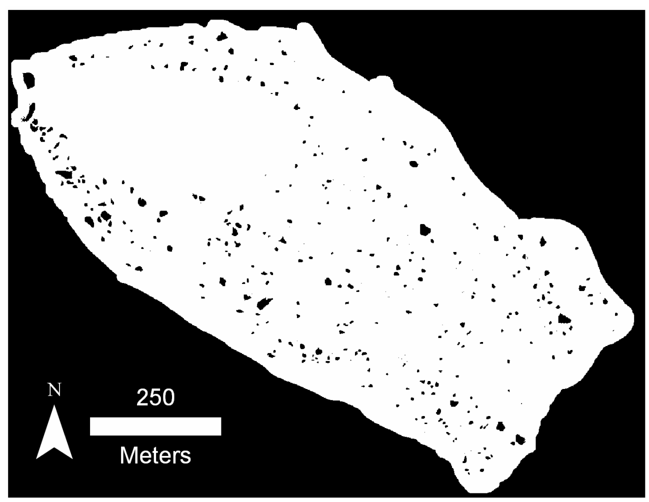

Figure 4: Image analysis of fragmentation in the distal tip of the rock avalanche.

Using this detection limit, the smallest boulders which could be imaged and counted have a surface area of 2.3 m^2 and volume of 4.6 m^3. The software detected and counted 3053 blocks above the detection limit. The imaged boulders constituted about 3.5% (87,766 m^2) of the total area and 24.5% (1,165,498 m^3) of the total volume. Therefore, a majority of the source rock was fragmented to a size smaller than 2.3 m^2.

The average length of all the counted blocks is 6.33 m for the major axis and 3.75 m for the minor axis.

Image analysis also highlighted that a majority of the blocks were concentrated in the lower-middle sections of the rock avalanche, just upslope of the extended distal tip. We also found that, on average, the block size increased down slope from the source area. The new centre of gravity of the rock avalanche debris is located at an elevation of 2316 m.a.s.l., 521 m lower than the pre-event location.

The image and fragmentation analysis was possible due in part to the shallow depth of the rock avalanche. The average depth of the debris is only 1.5 m, therefore, we can assume that most blocks, at or above the detection limit, were in fact counted.

4. POST-DEPOSITIONAL DEBRIS TRANSPORT ON GLACIAL SURFACE

The post-depositional transport of the rock avalanche debris on the surface of Ice Valley Glacier below Mount Munday can be tracked on successive satellite images between August 11 1997 and October 10 2001 (Fig. 5). Since the majority of the debris was deposited above the equilibrium line altitude (ELA) of Ice Valley Glacier, most of the debris is not visible on the newer images as it is covered by seasonal snowfall. However, approximately 500 m of the distal toe is below the ELA and therefore is visible on successive satellite images (Fig. 5).

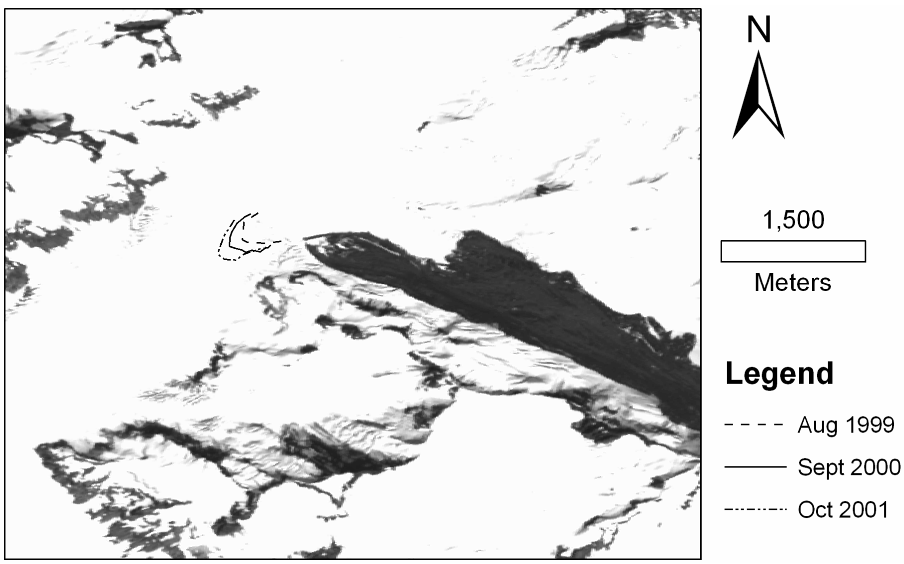

Figure 5: 1997 SPOT image with distal tip(s) superimposed from successive satellite images, illustrating the post-depositional movement of the debris from 1997 to 2001.

Four satellite images of the Mount Munday region were obtained from the LANDSAT and SPOT image archives. These images were geo-referenced and imported into ArcGIS 9.2. By overlaying the various imagery files, the down-slope movement of the debris on the glacial surface can be resolved (Fig. 5).

Table 1 outlines the results from the GIS-based velocity analysis of the upper Ice Valley Glacier:

Table 1: Velocities of the upper Ice Valley Glacier 1997 - 2001

Image Dates	Displacement (m)	Velocity (m / day)
Aug 1997 – Aug 1999	389.5	0.539
Aug 1999 – Sept 2000	98.7	0.237
Sept 2000 – Oct 2001	128.5	0.325

The results show that on average, the Ice Valley glacier is travelling down-slope at an average velocity of slightly less than 0.4 m/day.

5. CONCLUSIONS

The ability to quickly research, quantify, and analyze events in remote regions using GIS and remote sensing techniques has revolutionized the geo-hazard and rock avalanche fields. These methods have enabled scientists to study events currently inaccessible, without sacrificing accuracy of data.

The use of image analysis software has allowed for the general analysis and characterisation of debris generated by a rock avalanche. This creates the unique opportunity to study the relationships between energy, fragmentation, and deposition of a rock avalanche event.

6. ACKNOWLEDGEMENTS

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