Ground-based and airborne LiDAR for structural mapping of a large landslide: the Frank Slide

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ABSTRACT: Turtle Mountain, the site of the 1903 the Frank Slide, has been widely studied. A large database of structural measurements allows the comparison and testing of recently developed techniques. This paper commences with a review of recent mapping of Turtle Mountain. A report on a recent investigation of the mountain using a combination of airborne and terrestrial laser scanning techniques is then presented. The advantages and limitations of both methods are highlighted. This study reveals that a combination of methods is required in order to adequately characterize the structure of such a large landslide. Emphasis is given to the different observation scales and the information that they can provide. Recommendations for future mapping strategies of similar high mountain slopes are made based on the results of the Turtle Mountain structural mapping program.

1 INTRODUCTION

Turtle Mountain, the site of the 1903 Frank Slide, provides an ideal site to test a variety of techniques related to landslide characterization and monitoring and has been subject to numerous recent studies, as outlined by Froese & Moreno (2006). In terms of structural mapping, conventional field-based techniques as well as modern intrusive and non-intrusive mapping technologies have been applied (Cruden & Krahn 1973; Fossey 1986; Couture 1998; Jaboyedoff et al. 2006; Spratt & Lamb 2005; Theune et al. in press). Structural mapping is an important step in understanding the potential kinematics of failure and provide necessary input for stability analysis (Krahn & Morgenstern 1976; Cruden & Krahn 1978; Benko & Stead 1998).

This paper reports some recent field investigations performed using ground-based and airborne LiDAR (Light Detection and Ranging) to map the scar of the Frank Slide. The results obtained with these techniques will be presented and critically reviewed with regards to other techniques.

These comments provide the basis for a discussion on the applicability of ground-based and airborne LiDAR for the characterization of large landslides. A review of previous structural geological investigations on the Frank Slide will first be presented.

2 STRUCTURAL MAPPING OF TURTLE MOUNTAIN

The structure of Turtle Mountain and the the Frank Slide has been described by Cruden & Krahn (1973). They showed that the mountain is formed by the Turtle Mountain Anticline, which is underlain by the Turtle Mountain thrust fault. Above this fault, they noticed the presence of a minor thrust fault (Figure 1). The failure surface of the Frank Slide predominantly follows bedding planes located to the east of the anticlinal hinge. At the toe of the slide, the failure surface follows the minor thrust fault and at the top, it is controlled by two joint sets perpendicular to bedding. Bedding joints are persistent, while cross joints are non-persistent.

Fossey (1986) further mapped the area at the southern end of the slide, known as South Peak, where he undertook a more detailed joint survey using conventional field techniques. He subdivided the South Peak area into six domains, based varying attitudes of the bedding. Scanline surveys were also published by Couture (1998) and Spratt & Lamb (2005). A selection of these surveys, performed in different structural domains, is showed in Figures 2a and 2b. Langenberg et al. (2006) observed normal faults on the eastern slope that promote toppling failure of small volumes of rock. He also noted the large cracks on the South Peak that potentially could form the rear release of a future rock slide from the South Peak.

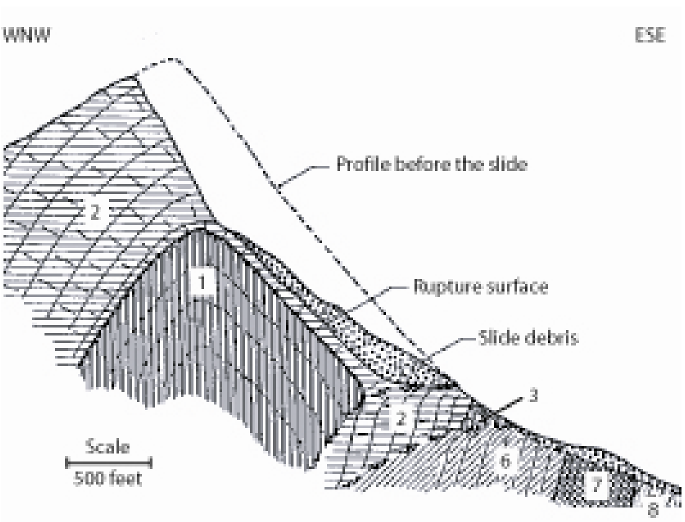

Figure 1. Cross section through the Frank Slide, Turtle Mountain (after Cruden and Krahn 1973). 1: Banff Formation, 2: Livingstone Formation, 3: Mount Head Formation, 6: Fernie Group, 7: Kootenay Formation, 8: Blairmore Group. The Turtle Mountain thrust fault and the minor thrust fault are shown as dashed lines.

Other researchers have also used borehole and seismic methods to obtain fracture measurements on the South Peak. Spratt & Lamb (2005) measured the orientation of discontinuities along a 40.5 meters deep borehole drilled on the western side of the South Peak. They recorded 16 major fractures (aperture greater than 1 cm) and 151 minor fractures (aperture smaller than 1 cm). Theune et al. (in press) undertook fracture mapping with GPR. This technique mainly highlighted a system of fracture representing the bedding and a second minor system.

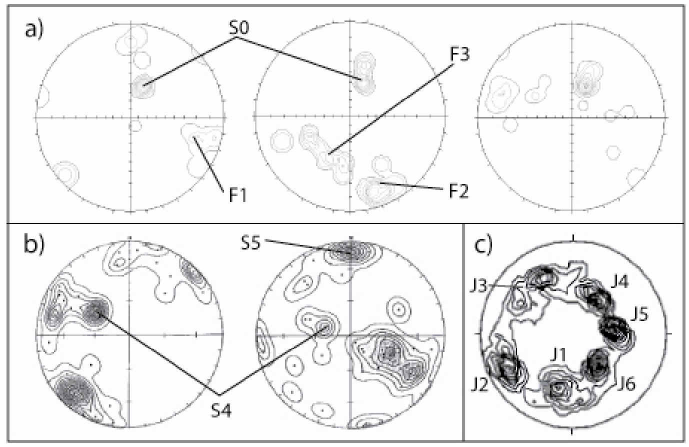

Figure 2. a) And b) orientation measurements performed during scanline surveys in different structural domains at Turtle Mountain by Couture (1998) and Spratt & Lamb (2005), respectively. c) Orientation data obtained from DEM analysis by Jaboyedoff et al. (2006). (Lower hemisphere, equal area projections).

3 LIDAR TECHNIQUES

3.1 *Ground-based laser scanner*

Significant work has been undertaken in the field of rock mass characterization using terrestrial laser scanning. Kemeny & Donovan (2005), Monte (2004) and Slob et al. (2005) present a method, which uses laser scanner point clouds for automated discontinuity analysis of rock slope. Feng & Roeshoff (2004) used a similar approach to create a 3D solid model of fracture planes. These authors showed that the geometric characteristics of discontinuities, such as orientation, spacing, persistence and roughness can be obtained using laser scanning techniques.

The ILRIS-3D laser scanner (Optech Inc.) is a compact, fully portable and highly integrated instrument with digital image capture. It measures the distance and direction between the instrument and an object. A point cloud with coordinate data and reflectance data (intensity) is produced and allows easier recognition of the object. The point cloud, through re-construction software provides a 3D model of a scene, useful for geotechnical investigation.

The ILRIS-3Dlaser scanner has a range of 1500 meters, depending on the orientation and reflectivity of the target. However, 800 meters is usually the practical limit for scanning of rock faces. Scans are performed at a rate of 2000 points per second with range and positional accuracies at 100 m of 7 mm, and 8 mm respectively (Optech Inc.).

Ground-based laser scanning can be expected to provide a high resolution DEM of selected parts of Turtle Mountain. Data point resolution (spacing) for derivation of the Turtle Mountain DEM used by Jaboyedoff et al. (2006) was 2.0 meters. In comparison the average resolution that can be obtained with a ground-based laser scanning at a distance of 500 meters is in the order of 10 cm (Sturzenegger et al. 2007; Lichti 2004). Ground-based laser scanning allows measurements of inaccessible steep slopes like the scar of the Frank Slide. Air-based and field measurements are limited in this type of environment.

3.2 *Airborne laser scanning*

The use of airborne LiDAR sensors is becoming an increasingly common and cost-effective tool. It is essential for many projects requiring characterization of relatively large areas and has been applied successfully to landslide hazard assessment (Ruiz et al. 2003).

Airborne LiDAR systems consist of a laser mounted beneath an airplane or helicopter that follows a predefined path. The ground is then scanned by means of tens of thousands of pulses per second emitted from the laser. In order to obtain measurements for the horizontal coordinates (x, y) and elevation (z) of the objects scanned, the position of the aircraft is determined using accurate differential GPS measurements and the distance from the aircraft to the ground calculated (Zang et al. 2002).

These measurements generate a 3-dimensional point cloud with an irregular spacing. Left unfiltered, the model includes treetops, buildings and vehicles. Many of these non-ground features can be removed to produce a bare earth DEM. Several algorithms to eliminate non-ground objects have been proposed (Kraus & Pfeifer 1997; Pfeifer et al. 2001; Vosselman 2000). However, erroneous elevation data can be obtained by removing non-ground points from LiDAR data sets. A detailed description of the sources of error when classifying LiDAR data by any filtering method can be found in Zang et al. (2002).

4 RESULTS

4.1 *Ground-based laser scanning*

15 scans have been performed at 5 different locations on the South Peak, the North Peak and on the north crest of Turtle Mountain (Table 1 and Figure 3). The surveyed area covers most of the upper part of the failure surface (scar) and part of the back scar, where the tension cracks are located (Figure 3). Each scan has been analyzed with Split FX (Split Engineering 2005). This software automatically recognizes surfaces that represent discontinuities. The analysis provided orientation and size measurements of several hundreds of surfaces. Facility for manual checking and editing of derived joint surfaces exist.

Figures 4a and 4b show the orientation measurements for surfaces obtained from scan NCA2. The results show that most of the poles are concentrated on one side of the stereonet. This probably results from orientation bias and occlusion, caused by the position of the laser scanner relatively to the rock slope (figure 5) (Sturzenegger et al. 2007). This problem occurred on each data set, which suggests that an additional approach should be used to complement measurement of discontinuity characteristics. Further analysis will focus on the individual characterization of large structures that can be observed from the point clouds.

Figures 4c and 4d show the size measurements (persistence) of the surfaces obtained from scan NCA2. These values represent the measured apparent persistence and not the true persistence. They may be subject to both truncation and censoring errors (Sturzenegger et al. 2007). The latter bias occurs where surfaces are not completely sampled. Truncation results from the selected resolution of the scans wherein surfaces smaller than a certain size will not be measured (Sturzenegger et al. 2007). In this case the resolution of the terrestrial laser scanner was in the order of 10 cm and hence the surfaces that were measured are composite surfaces and not necessarily discrete joint surfaces. This will be discussed in more detail in section 5.

Figures 6 and 7 show scans of the North Peak and of details of the tension cracks situated along the crest, north of the North Peak. Figure 7 illustrates the detailed morphology of the cracks.

Table 1. Scan locations and resolutions

Scanner location	Scan name	Resolution (spot spacing in cm)
North Crest A	NCA1	7.1
	NCA2	8.7
	NCA3	26.6
North Crest B	NCB1	15.2
	NCB2	9
	NCB3	90
North Peak	NP1	12.3
	NP2	3.7
	NP3	5.8
South Peak A	SPA1	3.8
	SPA2	3.5
	SPA3	4.5
South Peak B	SPB1	10.7
	SPB2	5.5
	SPB3	4.3

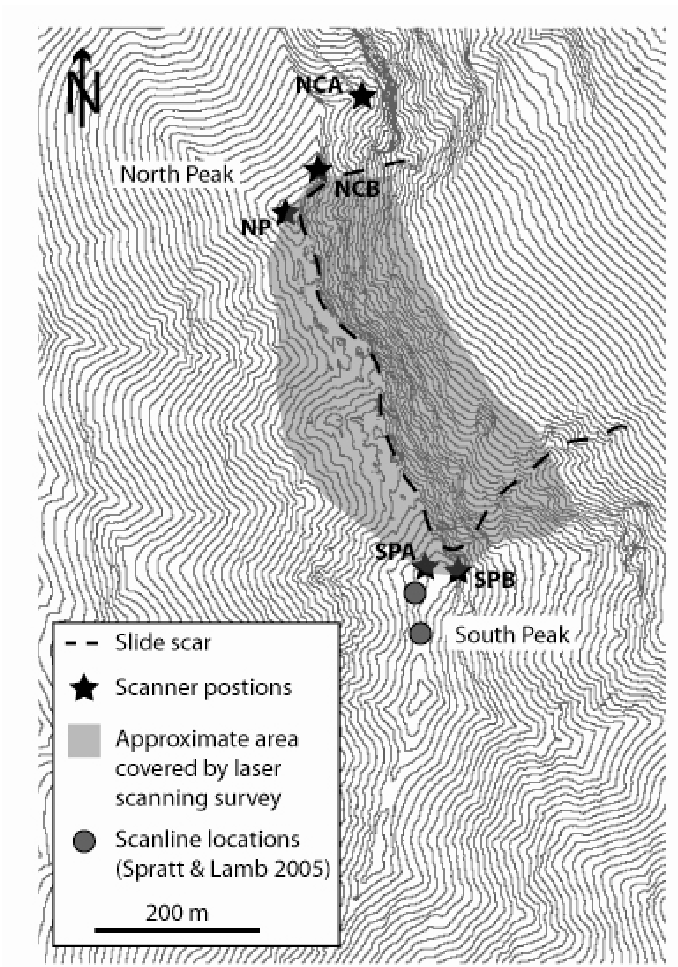

Figure 3. Digital elevation model of Turtle Mountain, indicating the ground-based laser scanner positions and the area covered by ground-baser laser scanning survey.

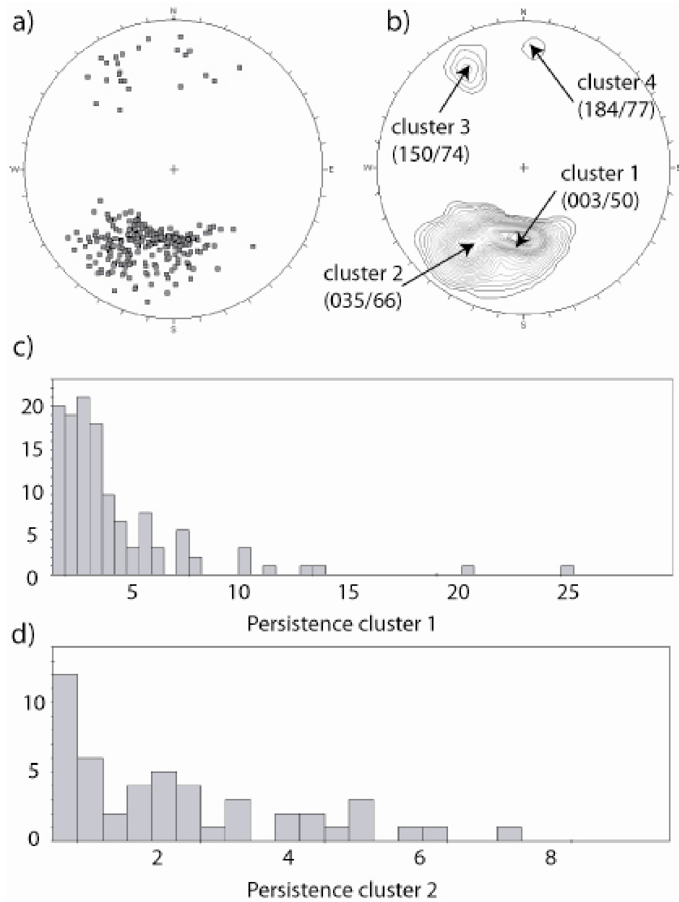

Figure 4. Orientation measurements (281 entries) of surfaces on scan NCA2. a) Pole plot, lower hemisphere, equal area projections, b) contour plot, c) persistence distribution for cluster 1, d) persistence distribution for cluster 2.

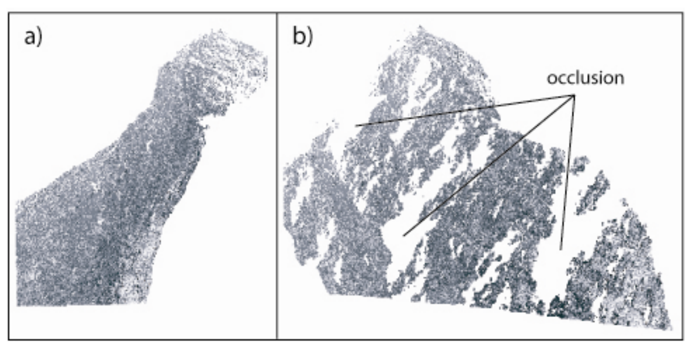

Figure 5. Point cloud (NCA2) of the South Peak scanned from the North Peak crest. a) Point cloud of the rock slope as seen from the laser scanner position, b) point cloud of the same rock slope rotated, showing a number of occlusion zones.

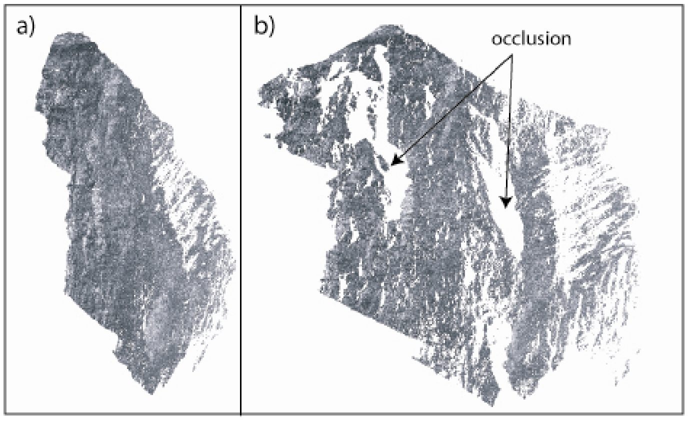

Figure 6. Point cloud (SPB2) of the North Peak scanned from the South Peak. a) Point cloud of the rock slope as seen from the laser scanner position, b) point cloud of the same rock slope rotated, showing a number of occlusion zones.

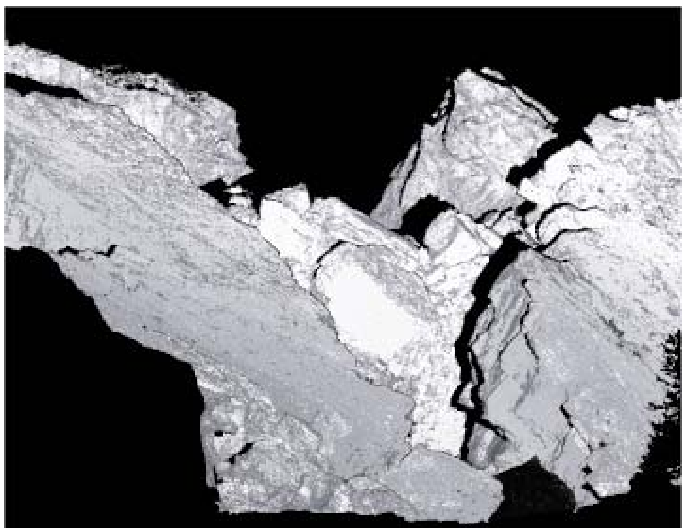
Figure 7. Point cloud (NP2) of area to the north of North Peak showing details of tension crack morphology.

4.2 *Airborne laser scanning*

Airborne Imaging Inc. acquired LiDAR data near the town of Frank, Alberta, Canada in the summer of 2005. The Alberta Geological Survey purchased the license for an area covering Turtle Mountain and the Frank Slide. The project covers an area of 33 sq. km. (Figure 8).

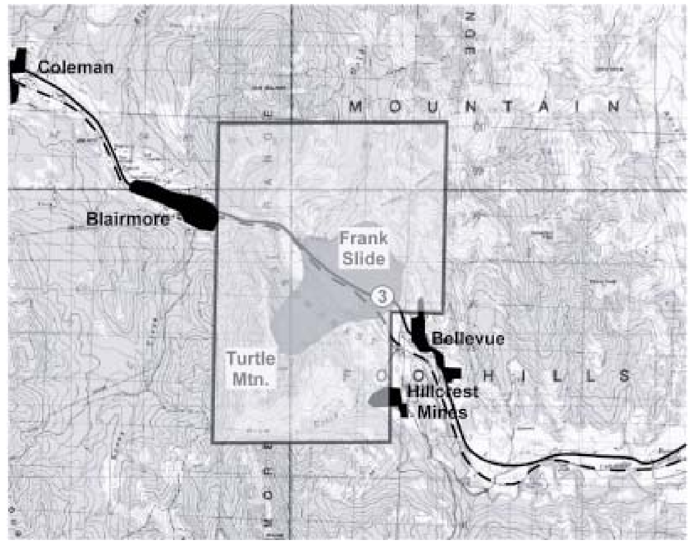

Figure 8. Location map with project area outlined in black.

An extensive geodetic network was established in the area including existing government control and newly established points. The network was held fixed in three dimensions to Geodetic Survey station 55A105 on the Nad83 CSRS datum. The aircraft positions were derived from a base station WAT4 located at the Pincher Creek airport.

The Airborne LiDAR survey was conducted using an OPTECH 3100 system. Flight line spacing was designed to provide an overlap of 50% between flight lines. These strips had a full scan angle of 50° (Table 2). The lines were flown in a North-South direction, with adjacent lines typically flown in opposing directions. One mission was required to cover the project area, and was flown on July 24, 2005.

Table 2. Flight parameter settings

Velocity (knots)	150
Full scan angle (degrees)	50
Height above ground (m)	1400
Scan frequency (Hz)	27
Laser pulse repetition (Hz)	50,000
Strip overlap (%)	50

The raw airborne kinematic data measurements were blended with the post-processed aircraft trajectory to compute an optimally accurate, best estimate navigation solution (position and attitude). The aircraft position, attitude, mirror angles and ranges were combined to produce X, Y, Z coordinates with intensity values. As a means to virtually remove the vegetation above the ground, a series of algorithms were run to classify LiDAR points into ground (second return) and non-ground points (first return).

In order to create a digital terrain model (DTM), a surface was interpolated from the triangulated irregular network (TIN) provided by the LiDAR three-dimensional point cloud. The mesh size of the grid is 0.5 meters based on a raw point collection distribution of approximately 1 point per meter. A natural neighbor interpolation technique was used due to its efficiency to handle large number of input points and as other interpolators may have difficulty with large point datasets.

Jaboyedoff et al. (2006) completed a structural analysis of Turtle Mountain using the digital terrain model (DEM) and the software Coltop-3D, which allows for classification of the topography of the DEM in terms of dip and dip direction. Discontinuity sets are then defined through observation of structural features on the DEM (Figure 2c). A comparison of the discontinuity sets obtained on this photogrammetric DEM with field measurement shows that the DEM interpretation provides a good assessment of the main structures present in the area.

Discontinuities that are defined by large areas (i.e. bedding) can be accurately sampled using the airborne DEM observation, despite the relatively low resolution (figure 9). In contrast when the discontinuities are impersistent and steeply inclined, Jaboyedoff et al. (2006) note that the discontinuity orientations obtained from the DEM are less steep than the actual ones. One possible explanation is that slope angles deduced with this technique are usually smaller than the relief due to the mesh size of the DEM. In addition, vertical to near vertical structural features may not be observable when utilizing an air based platform for DEM generation.

In addition to structural measurement, shaded relief images of the DEM with different sun directions and heights can be used to delineate subtle geomorphic features such as faults, cracks and lineaments of uncertain origin. With high resolution DEMs, geologists are not restricted to sun positions on a given day and can look at an infinite number of lightning combinations on the computer. Figure 10 illustrates the LiDAR model on a lightened version of a shaded relief map. On this map, low sun angle shaded relief image have the potential to highlight features like cracks located at the scarp of the slide. Crack orientation and density can then be used to study possible mechanisms of failure.

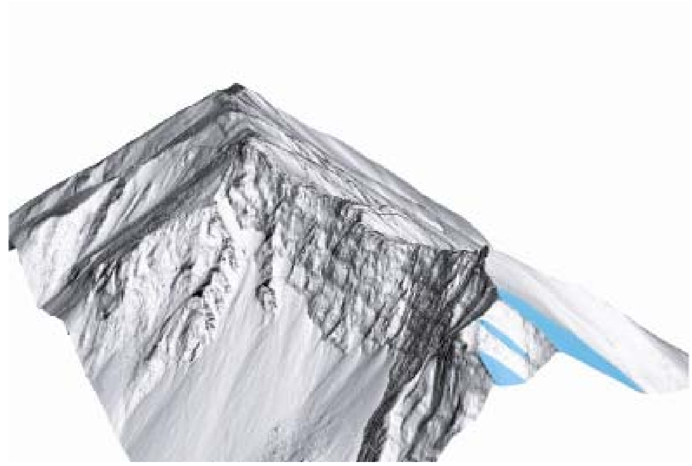

Figure 9. Bedding identified on Turtle Mountain using COLTOP-3D and overlaid on the DEM.

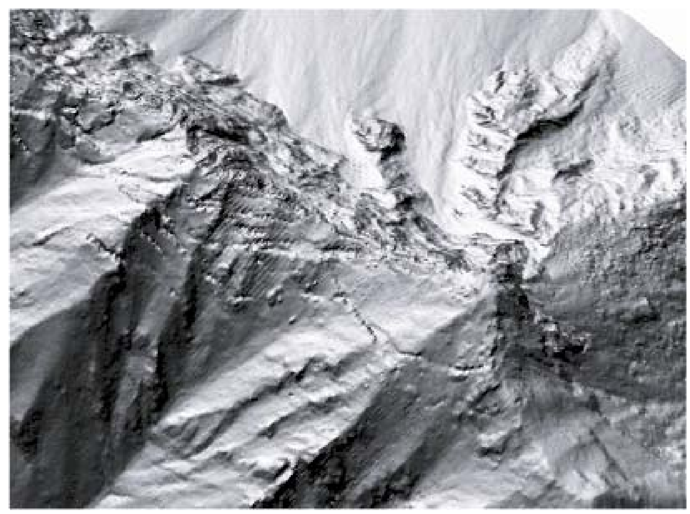

Figure 10. Scar cracks on Turtle Mountain using lightning combination on the computer.

5 DISCUSSION

One remarkable feature about airborne LiDAR, is the capability to remove non-ground objects, that otherwise would make geomorphic interpretation difficult. Figure 11 shows the unfiltered and filtered LiDAR shaded relief maps for an area covering the old mine workings at the toe of the mountain. In this case, LiDAR presents a valuable tool to recognize features that would otherwise remain obscured by vegetation. In addition, shaded relief images provide a very useful tool to pick out subtle geomorphic features such as faults, cracks and lineaments of uncertain origin.

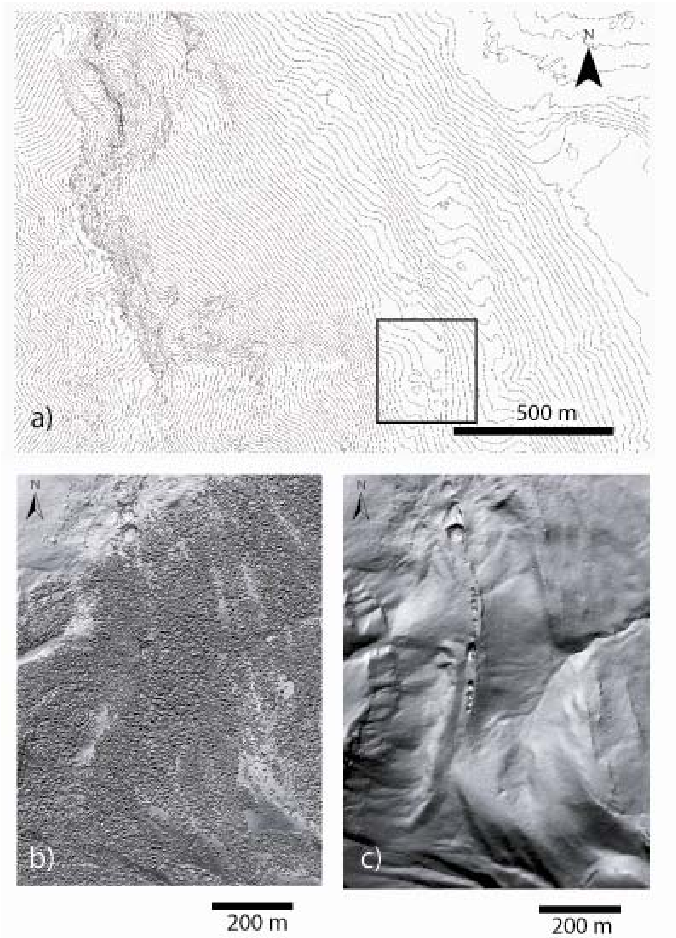

Figure 11. a) Details of the digital elevation model of Turtle Mountain. b) And c) shaded relief maps for two grids generated from unfiltered and filtered data, respectively. Mine workings subsidence can be easily identified on the filtered map.

It has been shown that the airborne DEM can also be used to perform structural analysis and preliminary hazard assessment. The advantage of such a method is to allow an interpretation at the scale of the slope, which is not possible while carrying out fieldwork at the outcrop scale.

The expectation of the ground-based laser scanner field investigation was to be able to obtain a high resolution DEM of the scar of the Frank Slide. Indeed, the scar area is inaccessible for scanline surveys and the resolution of the DEM that can be obtained from airborne techniques is limited by the angle of the slope.

Indeed, airborne LiDAR has a high precision in height on flat areas and large surfaces, but this precision decreases with slope due to the decreasing precision of angular measurements and footprint size (Figure 12). Consequently, the surface model is not appropriate for the representation of overhanging areas, where a single (x, y) point can have three corresponding elevation values, and small vertical walls. In such cases, ground-based LiDAR can be used. A high accuracy should be expected because the laser ray direction could be close to the surface normal. Combination of aerial and terrestrial LiDAR should be implemented to obtain a product of better quality than possible using only one of these techniques.

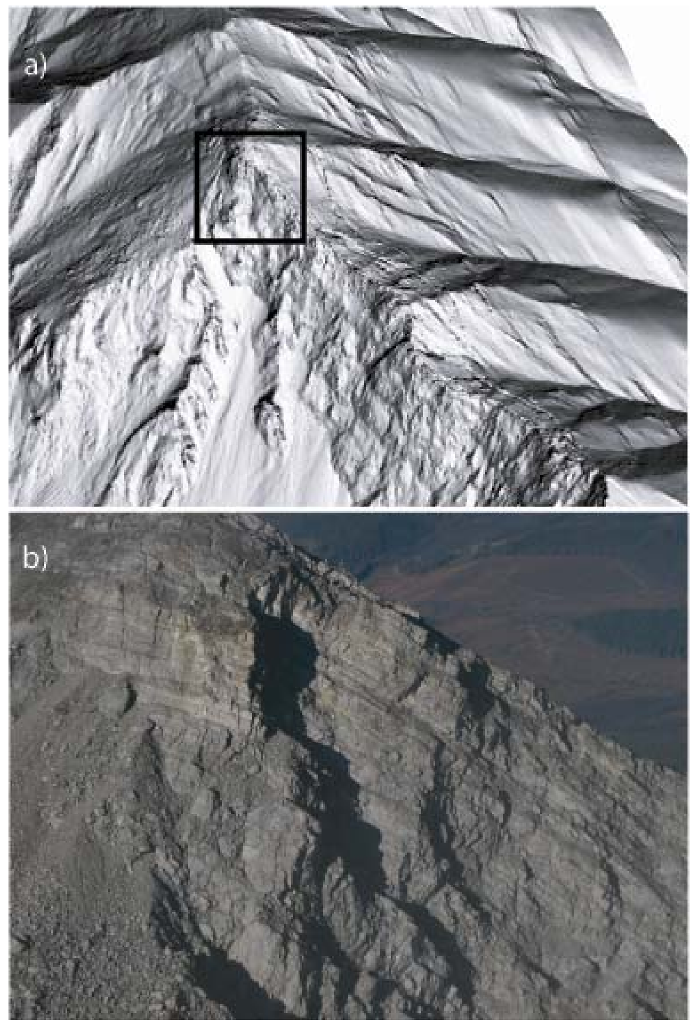

Figure 12. Perspective view of the 3D surface model. a) Detail of the South Peak and b) photograph of the area outlined in black.

A comparison between the ground-based laser data in figure 4 and the scanline data in figures 2a and 2b is not a trivial process. The first problem in comparing techniques is the variation in measurement scale. Consequently, there is a possibility that the clusters shown on figure 4 represent composite surfaces instead of actual discontinuities. This emphasizes the need to use automated surface delineation algorithms with care. Discrete discontinuity surfaces must be delineated using manual intervention and checking of automatically derived orientation data using geological principles. Figure 3 illustrates the different scales that have been applied to Turtle Mountain: the grey dots represent the area covered by a scanline survey, the shaded area represents the ground-based LiDAR survey and the entire map is the area covered by airborne LiDAR or DEM survey.

Secondly, as mentioned previously the scans are subject to occlusion and orientation bias. As a result, some orientations are inevitably omitted. Finally, the scan shown in figure 4 represents a large area, which might be subdivided into several structural domains. Consequently, comparing these results with the localized scanline measurements shown in figure 2 may be inappropriate.

Currently, a major problem in the application of ground-based LiDAR in the investigation of large landslides is the limitation of laser scanning range. Terrestrial LiDAR survey with an ILRIS-3D scanner was not possible from the toe of the slope necessitating location of the laser scanner on the crest of Turtle Mountain itself. Such a location however entails very oblique lines of sight with respect to the slide scar and leads to significant occlusion bias. Improvements of terrestrial LiDAR technology in term of range will no doubt solve this problem.

The second issue is the resolution of ground-based LiDAR survey. This study suggests that the discontinuities that can be measured using the laser scanner may often represent composite surfaces. This type of structures is important, because failure surfaces of large landslides are often created by such composite surfaces. Further analysis of the Turtle Mountain point cloud data sets will focus on the characterization of individual structures that can be observed in the point cloud.

With the current state of laser scanning technology, the authors recommend that ground-based laser scanning be used predominantly to characterize selected outcrops on large landslides thereby complementing conventional scanline measurements. Careful use of automatic surface delineation algorithms is required. Current research is focusing on varying size sample windows allowing for structural domains so that scanner bias can be minimized and control ensured.

6 CONCLUSION

A field investigation on Turtle Mountain has been performed using a combination of airborne and terrestrial laser scanning. The objective was to characterize the structure and morphology of the mountain. It is shown that airborne LiDAR is extremely useful to observe feature at the scale of the entire area. It is also proposed that preliminary hazard assessment can be performed.

Airborne LiDAR is limited in the characterization of steep slopes, like the scar of the Frank Slide. Consequently, terrestrial LiDAR surveys were undertaken to complement airborne methods. Preliminary analyses show that although ground based laser scanning can sample detailed morphological features in the failure scar, its use is limited for accurate discontinuity characterization by both distance and oblique lines of sight, (due to resolution and bias issues). Digital terrestrial photogrammetry is being used by the authors to complement laser scanning technologies in order to minimize these problems.

Longer range and higher resolution scanners are also under development and will circumvent many of the current limitations to some degree. These digital imaging techniques have significant potential in the characterization of composite failure surfaces, which are often of particular interest in large landslides.

The present study shows that it is important to combine various imaging techniques, both airborne and terrestrial. This allows rock mass characterization at different scales and the limitations of one method to be compensated by the advantages of another one.

Indeed, the airborne LiDAR and ground-based maps each have relative strengths and weaknesses. Pebbly texture covering parts of the airborne LiDAR image can be a result of dense brush that does not allow laser penetration and, unlike trees, cannot be removed using automated data processing techniques. In other situations, erosion processes can change the slope of the main discontinuities, making a difficult task to investigate these structures. Therefore, it is imperative to supplement LiDAR image interpretation with fieldwork, terrestrial LiDAR or aerial photograph interpretation.

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