TURTLE MOUNTAIN FIELD LABORATORY (TMFL): PART 1 –OVERVIEW AND ACTIVITIES

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Abstract: Studies on the South Peak of Turtle Mountain, site of 1903 Frank Slide, conducted over the past century have identified a rock volume of approximately 5 million m^3 as the possible source of a future rock avalanche. Since 2003, significant effort has gone into installing and monitoring instrumentation on the South Peak and undertaking various supporting studies. The combination of the instrumentation and recently undertaken remote sensing studies have lead to new insights as to the extent and rate of movements on the mountain. Specifically both spaceborne InSAR and airborne LiDAR have been utilized to understand the movement patterns and identify surface morphology that may lead to re-interpretations of the extent of instability on the mountain. The InSAR data has provided a plot of deformation rates for a large portion of the mountain where no other monitoring equipment exists. The bare earth model from the LiDAR data has allowed for observation large scale surface features that had not previously been appreciated and have lead to an expanded area of concern for potential future instability. The combination of the two techniques has also allowed for observation of the extent and rate of subsidence over abandoned coal mine workings at the base of the mountain.

INTRODUCTION

Following the catastrophic rock avalanche that buried a portion of the Town of Frank (Figure 1) in 1903, numerous studies have been undertaken to understand the landslide mechanism and causative factors and determine whether there is the potential for a second catastrophic rock avalanche to develop. John Allan (1933) documented the hazard associated with a possible failure of 5 million m^3 of rock in the area known as South Peak. Following that study, several investigations were undertaken to better understand the rate of movement of the peak (Anderson and Stoliker (1983), Fraser and Gruendig (1985), Kostak and Cruden (1990) but their results were inconclusive. Between 2003 and 2005 a large multidisciplinary project to monitor and characterize the movements at South Peak was undertaken by groups from government, private industry and academia. An overview of this program is described by Read et al (2005). In 2005, a dedicated program and budget were allocated to the long-term monitoring and continued characterization of the structure and instability at Turtle Mountain by the Alberta Geological Survey (AGS). A network of over 40 state-of-the-art sensors installed on the

Figure 1. Location Plan

mountain is primarily utilized as an early warning system for residents and infrastructure companies with interests in the identified hazard zone. The continuous data stream from this network provides valuable insights into the mechanics of the slowly moving rock mass and climatic effects on a variety of different sensor types. This sensor network, coupled with ongoing studies to characterize the structure of the mountain and movement patterns, provides the research community with a valuable data set. It is the intention of the AGS to make the historical data stream available for characterization studies. The aim of this paper is to provide an overview of the current understanding of the hazard, the sensor network, and the results of recent studies utilizing emerging characterization tools used to better understand the hazard.

RE-EVALUATION OF THE 1903 LANDSLIDE MECHANISM

\Since the identification and mapping of the potential South Peak failure by Allan (1933), efforts have been focused on the mapping and monitoring of a series of deep cracks encompassing the South Peak of Turtle Mountain. The cracks are located upslope and to the west of the hinge of an anticlinal fold (Figure 2). Accounts of surveys before and after the 1903 Frank Slide indicate that the series of cracks opened up in response to the catastrophic slide, and that a mass immediately to the south likely continues to move and may eventually fail catastrophically. Until recently, the postulated mechanism has been assumed to be a through going rupture surface originating from above a thrust fault, located at the toe of the mountain and progressing upslope, through the hinge of the anticline and intersected by the prominent fracture network on the west side of anticline hinge (Figure 2).

This mechanism is similar to that postulated and modelled over the past 30 years for the 1903 Frank Slide (Cruden and Krahn, 1973, Benko and Stead, 1998).

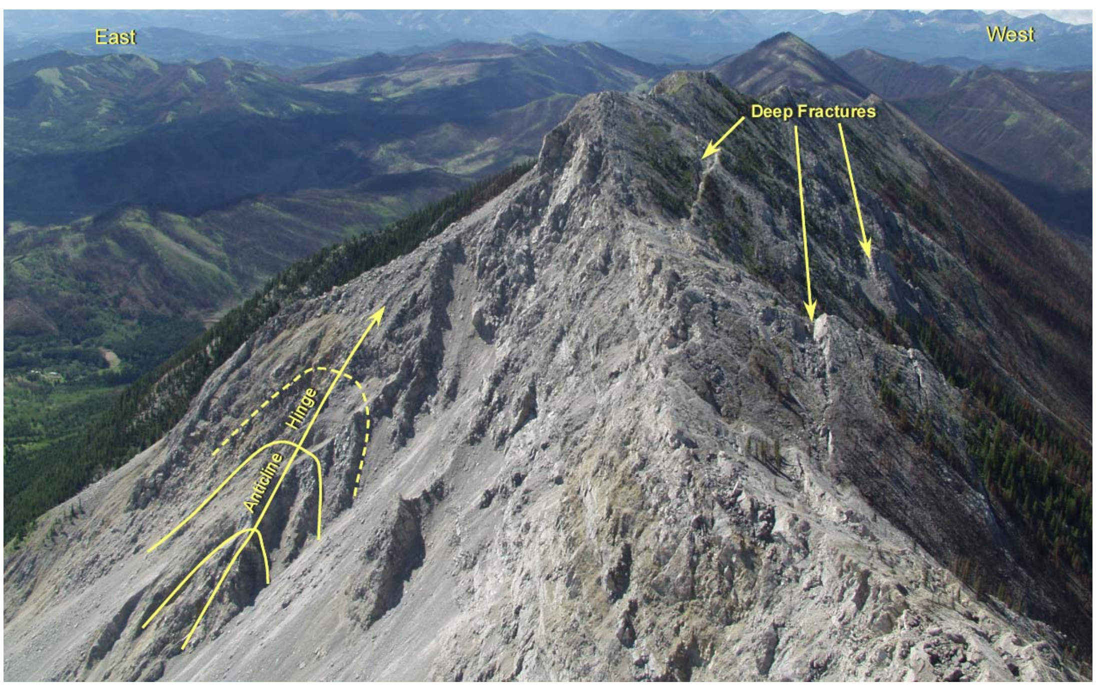

Figure 2. View towards the South Peak showing series of large fractures to the west and the orientation of the anticline hinge downslope, to the east.

More recently, studies undertaken by Jaboyedoff et al (2006) have postulated that the 1903 slide was a composite failure that consisted of sliding along bedding on the east limb of the Turtle Mountain anticline, which then undermined a large mass which toppled in response to the removal of support by the sliding mass. At this time, the actual contributions of sliding, rotation and toppling are not clear for the South Peak area, but surface expressions of all three styles of movement are observed. As there remains uncertainty as to the style and rate of current movement, various deformation monitoring and characterization techniques have been and are being utilized. The following sections provide an overview of these techniques and the findings to date.

SENSOR NETWORK

Based on the recommendations made, by BGC Engineering (2000), as part of their geotechnical hazard assessment the monitoring system on Turtle Mountain was designed to include a number of different types of instruments that communicate in near-real time to a data acquisition/processing centre located at the Frank Slide Interpretative Centre. The conceptual design framework for the system is outlined by Read (2003) with details of the installations provided by Moreno and Froese (2006b).

In order to provide warning of movement and to better understand the mechanism for movement at South Peak, the following attributes are being monitored:

Deformation: Because the mechanism for deformation is not well established on South Peak, an arrangement of sensors that measure displacements and tilt was installed between 2003 and 2005. These sensors consist of a series of 22 crack metres, 10 tiltmeters, 4 surface wire extensometers, 10 reflective prisms and 6 differential GPS (dGPS) receivers. All of these deformation types of sensors were installed in a wide array around South Peak (Moreno and Froese, 2007) in order to provide as much spatial coverage as practical, considering power and telemetry requirements. By comparing these groups of sensors with other remote sensing techniques, as discussed in Section 3, a better understanding of the style and rate of movement should become available. The installation of a borehole sensor (inclinometer or TDR cable) had originally been planned but the highly fractured bedrock made such an installation impractical.

Climatic Factors: In order to better understand how climatic effects influence the rock mass movements, a weather station was installed on South Peak. Sensors on the weather station include a tipping bucket rain gauge, barometer, thermometer, wind gauge and devices to measure solar radiation. When deformations occur, the weather data is key to the interpretation of climatic factors that may have contributed to the movement.

Seismicity: A six station passive seismic network was installed by Gennix Technology (2004) in order to detect seismic event generated by slope movements, rock falls, collapse of nearby abandoned mine workings or natural seismicity in the region. These stations were spread out between the South Peak and the toe of the mountain in order to provide a wide spatial coverage that would theoretically be able to source locate seismic events within this array.

Observations on the performance of these various sensor arrays is discussed in more detail by Moreno and Froese (2006a,b).

As noted previously it is now believed likely that the lower east flank of the slide is moving at a faster rate than that of the peak. Because the existing instrumentation is focussed on the top and west side of the South Peak mass there are currently no monitoring points that characterize deformations on the lower east flank. Therefore, the focus of future monitoring (including both surface and subsurface sensors) will be on the lower east flank. As of September 2006, a series of ten reflective prisms are planned on the lower east flank, with plans to also drill and instrument up to two test holes within this area in either 2007 or 2008.

REMOTE SENSING STUDIES

The emergence of new airborne, spaceborne and ground-based remote sensing techniques have allowed for a better understanding of the structure and instability of South Peak and Turtle Mountain as a whole. A recent study by Chapman (2006) analyzed deformations of a network of 24 photogrammetric targets for the time period between 1982 and 2005 in order to better understand deformation rates and patterns for the top and west side of South Peak. This study documented movements ranging between 0.8 and 3.8 mm/year. These results have been previously reported in Froese and Moreno (2006). More recently, studies utilizing airborne photogrammetry, LIDAR and spaceborne InSAR are providing valuable insights into the style and rate of deformations of the entire mountain, with specific valuable information for the lower east flank and lower adjoining areas. The initial results of these studies are provided below.

LIDAR (Light Detection and Ranging)

In July 2005, an airborne LIDAR survey with an average data spacing of one point per metre was flown over an area encompassing Turtle Mountain. The raw data was then processed using the Nearest Neighbour interpolation to produce a 0.5 metre grid, and bare earth and three dimensional models were created using ERSI Arcscene. The ability to rotate this model and apply various sunshade angles to the bare earth model allows for evaluation of subtle features on the ground surface previously not visible on available digital elevation models (DEM) or air photos. The initial viewing of the bare earth DEM has allowed for the following preliminary observations of the mountain.

Mine Subsidence: The influence of the mining of a coal seam in the lower portion of the mountain on the timing of the 1903 slide continues to be debated in the geotechnical community (Benko and Stead (1998), Cruden and Martin (2004)). The question concerns whether there was sufficient yielding of the mine openings to allow for displacement along bedding upslope and whether or not continued movement of the mine workings below South Peak are contributing to current movement. Figure 3 provides a sunshade model of the east side of Turtle Mountain, with a focus on the area encompassing South Peak, Third Peak and the Frank Slide. As shown, a line of south-trending subsidence pits exist along the trend of the mine coal seam below South Peak. In addition, subtle subsidence features are also observed within the 1903 slide mass, suggesting continued collapse of the mine workings. These features are not obvious from the previous photogrammetric DEM nor on available aerial photography.

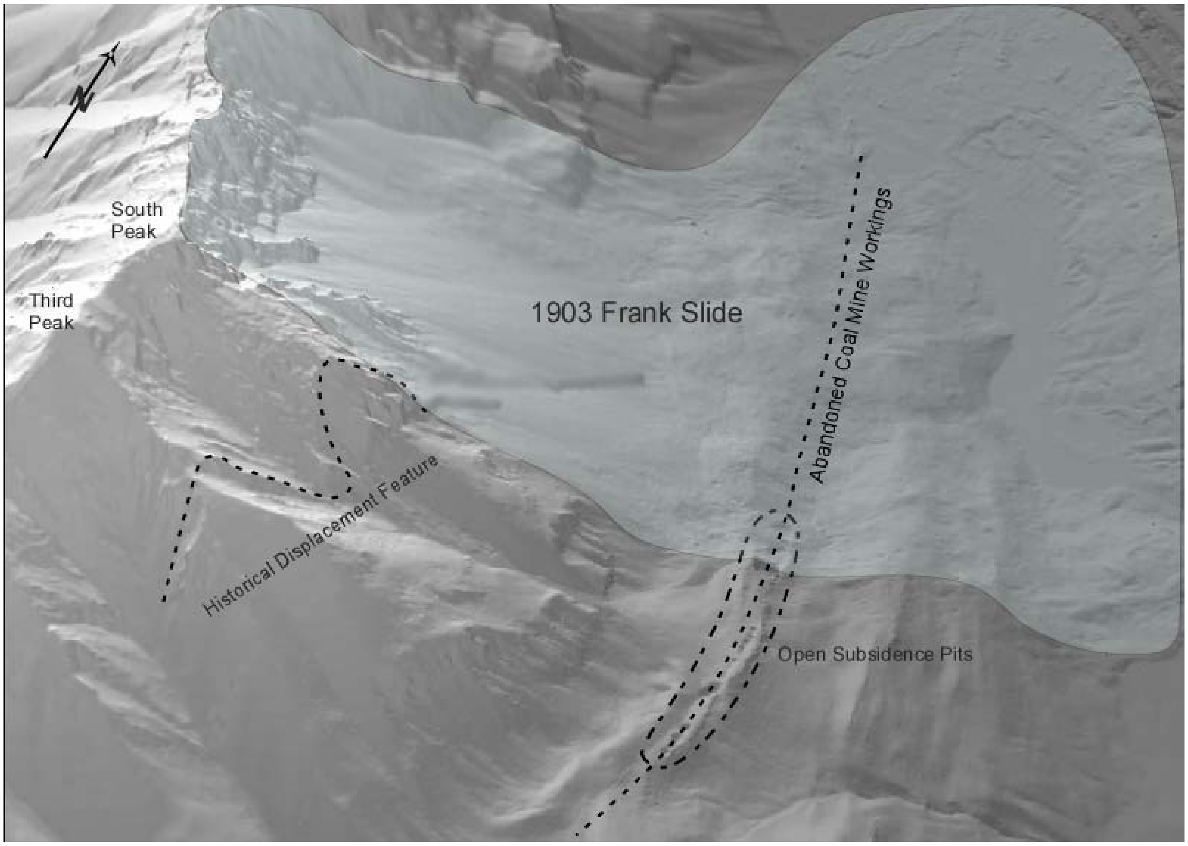

Figure 2. Portion of LIDAR DEM looking north across the South Peak area showing coal mine subsidence features and possible historic displacement features.

Possible Larger Instability: In addition to the obvious signs of mine subsidence, a prominent cliff feature is observed extending below both South and Third Peaks. The lack of a geological contact at this location and the occurrence of cracking upslope (and signs of distressed vegetation on the lower slope below this point) strongly suggest that this may be a historical displacement feature. This feature is shown on Figure 2. To this point, the assumption has been that the South Peak failure was the extent of the hazard but this new piece of data highlights the potential for a larger displacement feature. Based on these findings, field activities for the summer of 2007, are planned to include more detailed mapping and documentation of surface distress in this area and the establishment of a surface GPS monitoring network to characterize possible movements.

Historic Instability: Since the 1903 slide, studies have focussed on the areas immediately adjacent to the 1903 slide mass. The availability of the new bare earth LIDAR data provides a view of a large portion of the eastern side of Turtle Mountain as is shown in Figure 3. Initial review of the LIDAR data shows slope morphology indicative of a previous large rock avalanche to the south of the 1903 slide. This feature is distinguished by the disruption of prominent bedding features on the slope, the jagged peak (as opposed to typical rounded peaks in the region) and the appearance of a run out fan on the lower slope. This data was only recently obtained, and studies for late 2006 and 2007 aim to better understand the origin and implications of this feature on the instability on the mountain.

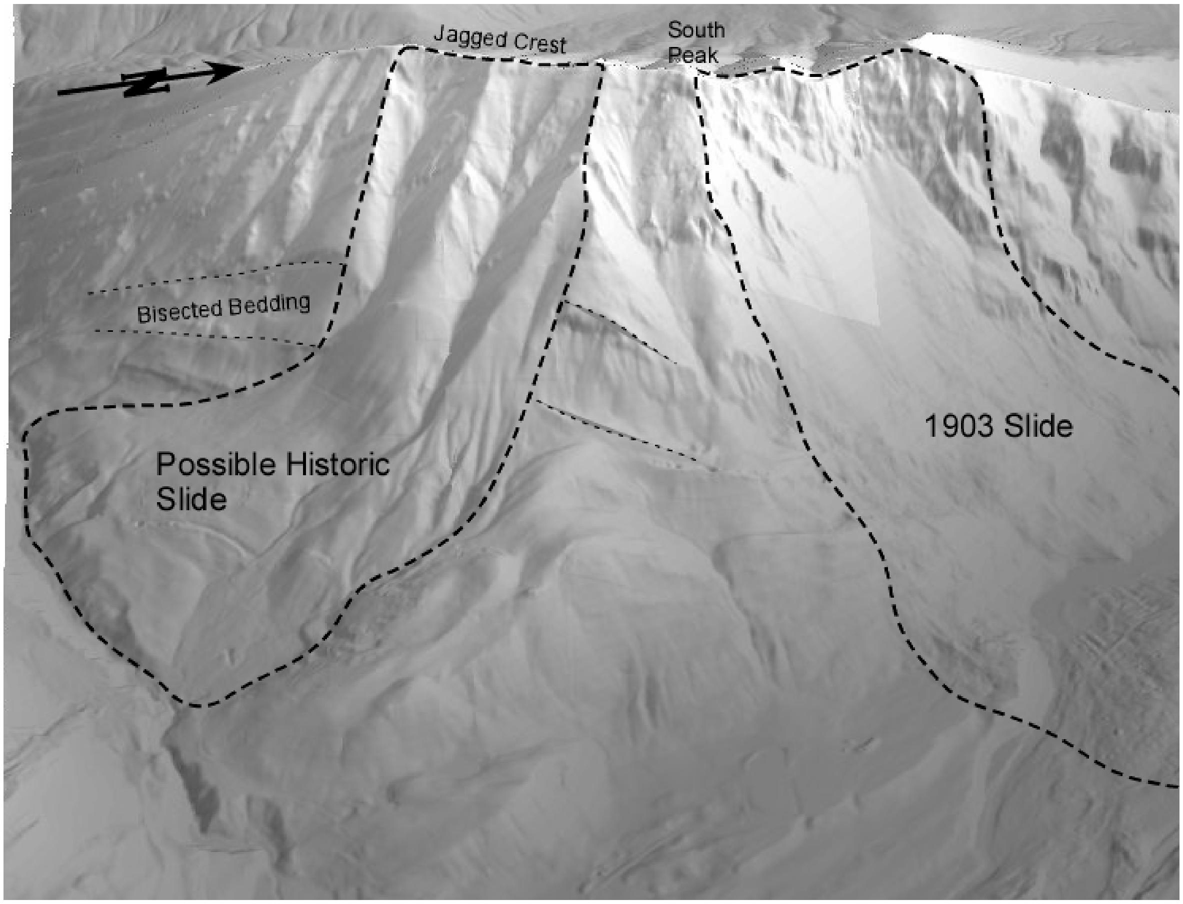

Figure 3. Bare earth LIDAR model showing a postulated historical rock avalanche to the south of the 1903 slide.

Spaceborne InSAR (Interferometric Synthetic Aperture Radar)

Spaceborne Interferometric Synthetic Aperture Radar (InSAR) is a technique that utilizes repeat pass data from polar orbit satellites with SAR sensors to map subcentimetre ground movements over relatively large areas. Specific details on the application of InSAR to detect slope movements due to landsliding are provided by Froese et al (2004) and Singhroy et al (2005).

Previous preliminary studies for Turtle Mountain have been reported by both Singhroy et al (2005) and Froese and Moreno (2006b). Recent work by the AGS and the Canadian Centre for Remote Sensing (CCRS) has utilized the Coherent Target Monitoring (CTM) (www.vexcel.com) approach to review trends in Radarsat-1 F4F Fine Beam SAR data from 2001 to May 2006. In this recent work a series of eighteen scenes were utilized to generate a time-displacement plot between December 12, 2000 and May 7, 2006. At the time of the preparation of this paper, the preliminary results were providing valuable data as to the deformations associated with the movement of lower east flank of South Peak and the subsidence associated with the coal mine workings on the lower slope. Figure 4a shows a series of targets (coloured dots) that have been chosen as coherent targets for the monitoring time frame.

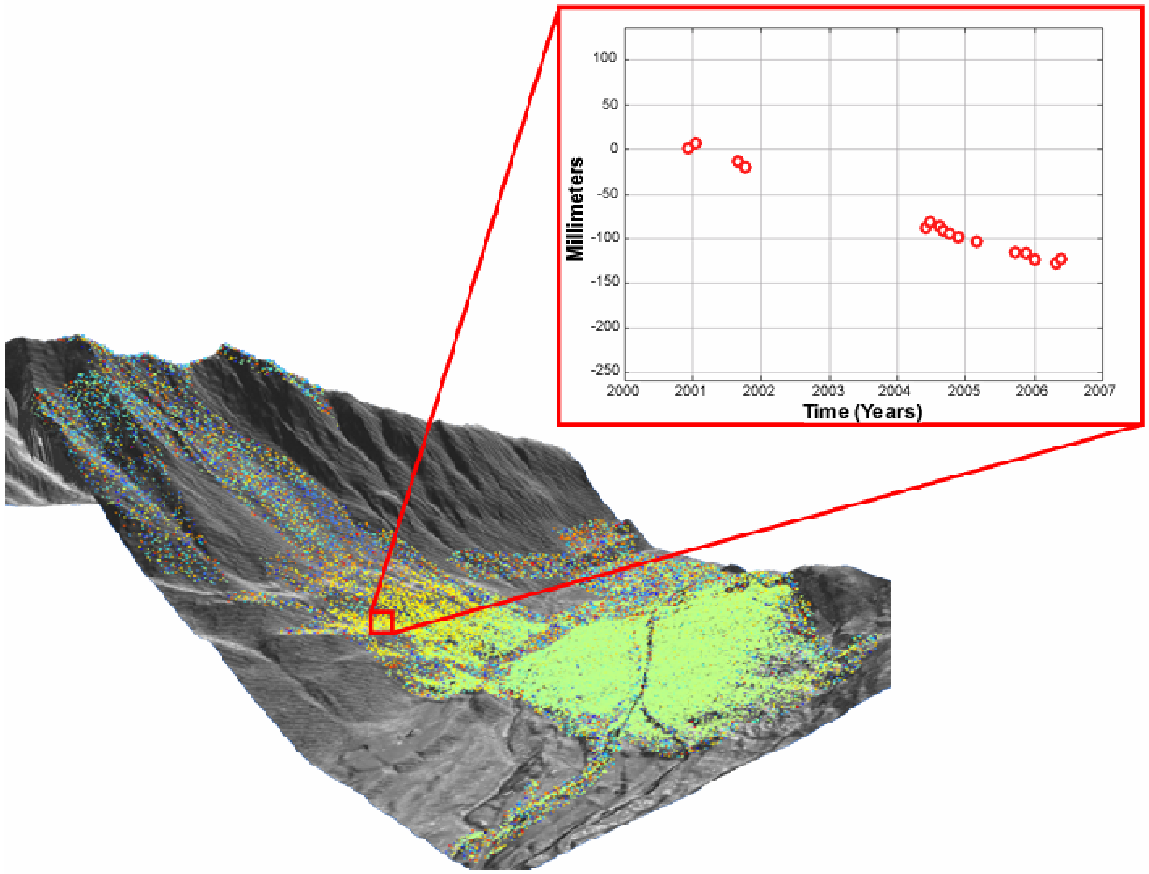

Figure 4. a) Coherent deformation points (coloured dots) superimposed on the radar backscatter image with b) example of deformation observed over the abandoned coal mine workings.

Figure 4b is a plot of displacement in the line of site of the satellite on the lower slope for a subsidence feature that overlies a line of abandoned underground coal workings. Estimated displacement of this target over the evaluation period shows a consistent linear displacement trend of up to 140 mm, corresponding to a rate of deformation of 25 mm/year. As discussed previously, there are currently no sensors on the lower east flank of South Peak. The InSAR data thus provides the first deformation data in this area. In fall 2007, survey prisms will be installed in this area so that additional data can be collected to provide validation of the preliminary CTM results.

OTHER STUDIES

In addition to the studies that are being undertaken to better understand the patterns and trends of movement, other studies that will aid in the understanding of the structural geology and the potential impacted areas are also underway.

Since the initial discovery of the hazard at South Peak in 1931, the structure of the mountain has been identified as the main factor leading to the instability at South Peak (and for the Frank Slide). Conventional mapping studies have been undertaken in order to better understand the structure through mapping of surface exposures, and new technologies are being utilized to understand the structure at the surface and in the subsurface.

Recent field studies to characterize the fracture patterns at the surface have been carried out by Langenberg et al (2006). This field mapping has also been supplemented by reviews of structural trends derived from the available digital elevation model (DEM) by Langenberg et al (2005) and Jaboyedoff et al (2006).

Langenberg et al (2005) utilized two sets of DEM data points (DEM data and break-line data) and two separate orthophotos (10 cm pixel black and white and 15 cm pixel colour) to identify lineaments near the crest of Turtle Mountain. Using the modelled DEM and a sharpened orthophoto, Langenberg et al (2005) were able to detect 1159 lineaments, including fissures and joints, which were used to generate rose diagrams indicating the dominant structural trends on the peaks.

A more recent study by Jaboyedoff et al (2006) used the DEM and a computer program called COLTOP-3D to identify the main structural fault sets and to confirm and refine the existing geological models. This study also proposed a failure mechanism for the 1903 Frank Slide that incorporates the progressive failure of the rock mass as a series of gently dipping wedges. For the South Peak, Jaboyedoff et al (2006) consider that similar failure mechanisms, as those that lead to the 1903 slide, exist but the angle of the structural discontinuities are less steep and therefore the potential failure surface is unclear. Although this is true, Jaboyedoff et al (2006) have utilized the COLTOP-3D analysis and the DEM and the concept of Slope Local Base Level (SLBL) (Jaboyedoff et al, 2004) to develop volume estimates and configurations for a potential failure of South Peak ranging from 5.5 million m^3 to 10 million m^3.

Future work is expected to utilize the new LIDAR DEM, and recent ground based laser scanning completed by Simon Fraser University in June 2006, to undertake more detailed analysis that will build on the work detailed above.

CONCLUSION

With the existence of a continuous stream of displacement and supporting data, and a focus on the application of emerging monitoring technologies, the Turtle Mountain Field Laboratory provides the international geo-engineering and geoscience communities a unique opportunity to better understand both the deformations at Turtle Mountain and potential applications of these techniques to similar sites around the world. Data and findings from the TMFL will continue to be reported for the research community and updated status reports provided.

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