ERCB/AGS Open File Report 2008-01

Turtle Mountain Field Laboratory: 2006 Data and Activity Summary

Energy Resources Conservation Board

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Alberta Geological Survey

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- Henry Bland (Alto Instruments);
- Bill Teskey (University of Calgary, Geomatics Engineering);
- Alan Jones (Durham Geo Slope Indicator);
- Doug Bingham (Elegant Computing Solutions);
- Glen Bjorgan (McElhanney Engineering);
- Matthieu Sturzenegger (Simon Fraser University);
- Doug Stead (Simon Fraser University);
- Michel Jaboyedoff (University of Lausanne, Switzerland); and
- The Ǻknes/Tafjord Project Team (Norway).

Abstract

Since 2005, the Alberta Geological Survey has undertaken detailed review of the near real-time data stream from a sensor network installed on the South Peak of Turtle Mountain and initiated numerous supporting studies to better understand the style and rate of movement of the slowly moving rock mass. The South Peak site has been termed the ‘Turtle Mountain Field Laboratory,’ as the intention is to use the data from the sensor network at the site so that the international geotechnical research community will gain increased understanding of the mechanics of slowly moving rock masses, the instrumentation for measuring these movements and the application of new technologies.

Studies of the near real-time data stream have highlighted trends corresponding with both seasonal, thermal cycles and with slow, long-term creep of the South Peak mass. In most cases, the instrumentation performed well during 2006, with some performance issues and maintenance concerns associated with meteorological conditions. In general, the trends observed highlighted very slow movement, less than a millimetre per year, along the deep fractures to the west side of South Peak, During 2006, the more active portions of the peak had not yet been instrumented, but results from previous photogrammetric analyses indicated movements of many millimetres per year on the eastern and northern portions of South Peak.

Supporting studies have relied on the application of new remote sensing techniques to gather information regarding the structure and instability on Turtle Mountain in its entirety. Newly acquired light detection and ranging (LiDAR) data have enabled the generation of a high-resolution, bare-ground model of the mountain, which has lead to new observations of potential historical and ongoing movements at other portions of Turtle Mountain. New insights from the model allow for a more refined delineation of the structures that control instability on South Peak.

1 Introduction

In 2005, the Alberta Geological Survey (AGS) assumed responsibility for the long-term monitoring and studying of a large, slowly moving rock slide at Turtle Mountain, the site of the 1903 Frank Slide (Figure 1). A detailed overview of the system setup, components and initial year of studies was previously documented by Moreno and Froese (2006) and is not discussed in any detail in the current annual summary.

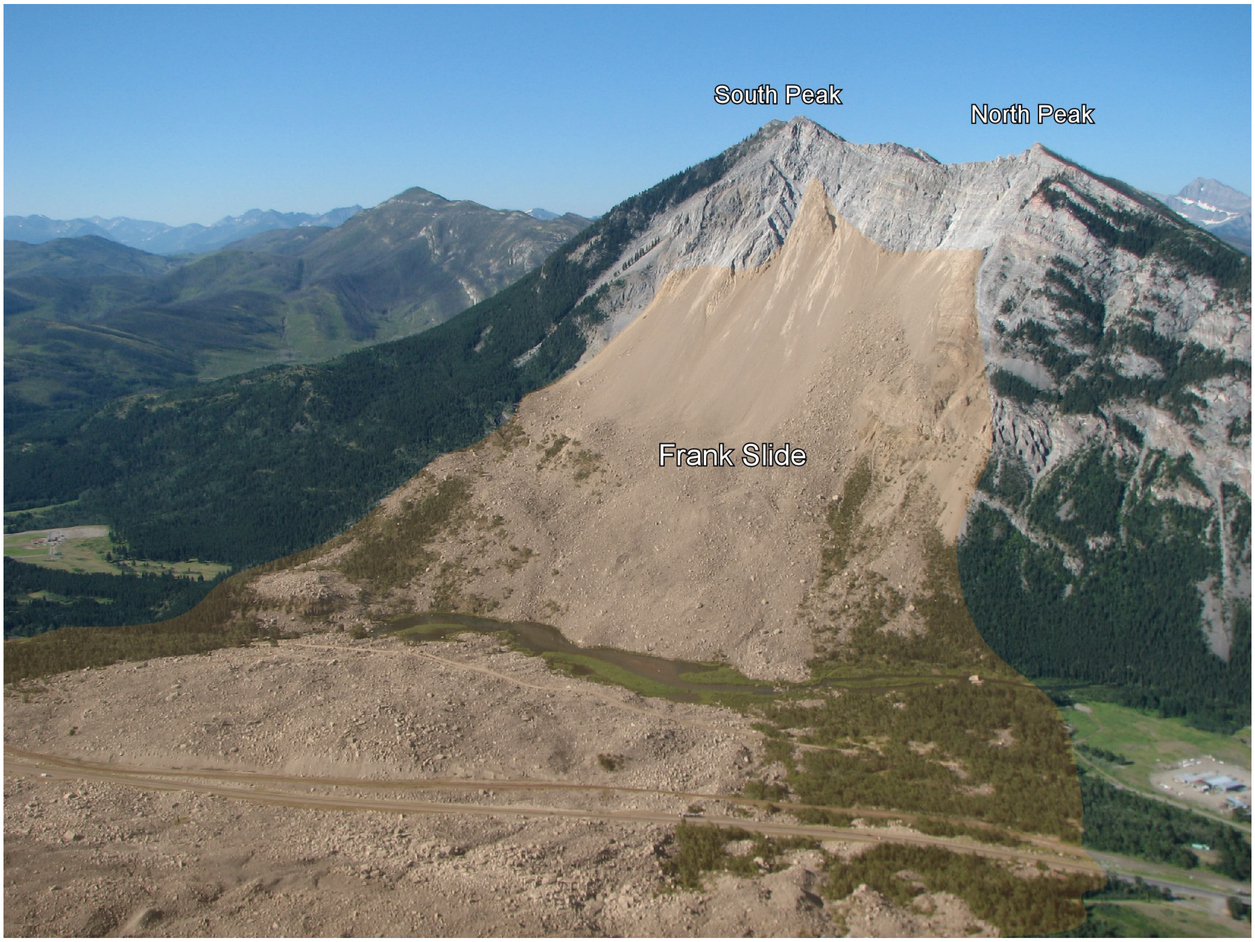

Figure 1. Southwest view of Turtle Mountain showing the prominent peaks in relation to the Frank Slide.

The first priority for monitoring and studying Turtle Mountain is to provide an early warning to residents in the event of a second catastrophic rock avalanche originating from South Peak. The secondary priority is to provide an opportunity for the research community to test and develop instrumentation and monitoring technologies and to better understand the mechanics of slowly moving rock masses; hence, the working name ‘Turtle Mountain Field Laboratory’ (TMFL). The ERCB/AGS will make all data from the TMFL available to the research community and enable researchers to test and develop new monitoring technologies on the mountain. This ongoing research will aid in understanding the movements of the entire South Peak mass, including the lower slope, providing a better model for prediction of future movements. For information on recent developments with the TMFL, please visit the Alberta Geological Survey website at www.ags.gov.ab.ca.

This yearly report will provide the public and researchers with a synthesized update on data trends and research on the mountain as a stimulus for further research. This report is a brief overview and, in many cases, refers to other papers/articles that provide additional detail regarding the information discussed.

The first part of this report provides an overview of any significant changes to the monitoring system documented in the 2005 report (Moreno and Froese, 2006), in addition to highlighting performance and trends of the sensor network. The second part of the report provides an overview of various supporting studies undertaken in 2006 and new findings in relation to the overall understanding of the movements on South Peak.

2 Sensor Network Activity

This section provides an overview of the major changes to the physical sensor network and data management of the monitoring system during the period between January and December 2006. It also provides an overview of any maintenance and repair activities undertaken during that time. Documentation of the hardware that form the various components of the communication stations is provided in Moreno and Froese (2006).

With respect to the sensor network, the main activities in 2006 included maintenance and upgrading of crackmeters and tiltmeters adversely affected by snow and moisture, repair of a number of installations damaged by lightning, and addition of six new differential GPS stations and a surface wire extensometer. The following sections provide both a brief overview and photographs of these activities.

2.1 New Installations

2.1.1 Differential Global Positioning System Network

A new mountaintop global positioning system (GPS) was installed in two phases during the summer and fall of 2006. In July, McElhanney Engineering of Vancouver installed six test systems, consisting of Novatel SuperStarII GPS units connected to Lantronix wireless servers, allowing true real-time communications. The systems were built upon existing infrastructure (concrete pillars, power supplies) and data were transmitted to the base of the valley through an existing 801.11b wireless network (McElhanney, 2006).

In September 2006, McElhanney installed the final components of the mountaintop portion of the system, and installed a new radio tower on the west side of South Peak. This tower establishes a 5 Ghz link between the GPS system on the mountain and the Provincial Building in Blairmore. In September, additions were also made to other systems, such as insulated battery boxes and protective conduit for cables and antenna shrouds (the locations of these installations are shown on Figure 2). Figure 3 provides an example of a typical installation.

Additions to the base station in the valley bottom were not completed; therefore, the measurements from the mountaintop stations were only relative deformations based on data from the already installed single frequency antennas. These installations were completed during the summer of 2007. An inclusion of the performance and data will be included in the 2007 annual summary report.

2.1.2 Extensometer Five

During the July field campaign, a fifth surface-wire extensometer was installed near the weather station. This installation is similar to those outlined for the existing extensometers (Moreno and Froese, 2006),

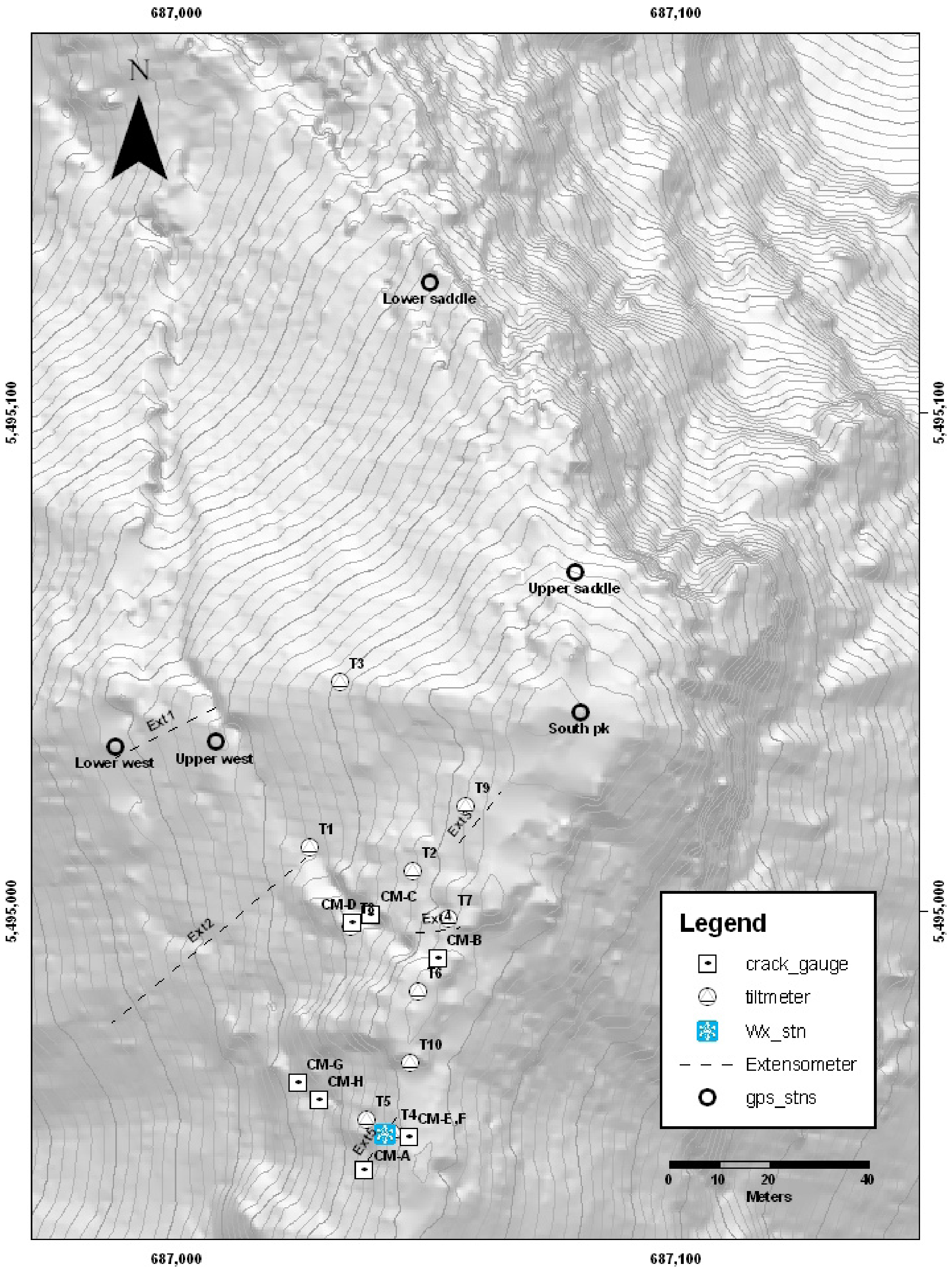

Figure 2. Overview of the sensor network (as of December 2006).

Figure 3. Typical dGPS installation showing concrete pillar with Novatel antenna (right), battery box (centre) and solar panel (left) (Photo: Glen Bjorgan, McElhanney).

except that the data collection occurs at the weather station data logger rather than at the borehole enclosure. The location of Extensometer 5 is provided in Figure 2.

2.2 Performance

Overall, the primary deformation monitoring system (crackmeters, extensometers and tiltmeters) performed reliably during the reporting period. These systems were inspected and modified in July. The following summary statements can be made based on the inspection and modifications performed

- Tiltmeter reliability improved considerably with the addition of desiccant packs inside their enclosures. However, approximately 1/3 of the tiltmeter instruments continue to show the effects of high humidity inside the instrument. Nevertheless, the level of noise on the tiltmeters occurs over a small increment of tilt, relative to what would be considered serious rotation (tilt), and will not impede the ability to provide warnings of worsening rockslide conditions.
- Several of the 22 crackmeters continue to show evidence of snow or ice loading. However, the data obtained from some of the crackmeters with improved roofs (Set C) show that effective protection against snow can be achieved. Expectation is that additional refurbished roofs undertaken in early July 2007 will increase the reliability of this system.

Figure 4. Head assembly for extensometer EX-5.

- The five extensometers performed reliably, providing high-quality data throughout the reporting period. However, their ability to measure small displacement (submillimetre) limits their capacity to assist in the characterization of the very slow slope movement.
- The six GPS stations performed reliably during the reporting period (October to December).

None of the instruments was vandalized during the reporting period; this can be attributed to both instrument signage and datalogging enclosures.

2.3 Maintenance

The primary systems that monitor rock deformation (crackmeters, extensometers and tiltmeters) were all operational during the reporting period. Several maintenance trips were made during the period; one during the third week of July included maintenance and upgrade work previously identified as a priority. The following summarizes the work performed

- upgrades to the protective roof of individual crackmeters (sets A, B, C, D and G);
- replacement of damaged crackmeters CM-10 and CM-17;
- addition of surge protectors to crackmeters CM-16 and CM-17 (Set G);
- placement of desiccant inside every tiltmeter enclosure in an attempt to prevent noisy data values due to high moisture (Styrofoam housing was also built and installed in all tiltmeters in an attempt to shield these instruments from direct sunlight).

On September 21, 2006 at 15:00, several displacement alarms were sent by the automated monitoring system (ARGUS). After a thorough review of the data and local climatic conditions, the conclusion was that instrument damage by lightning that day caused the alarms to sound. On September 27, 2006, AGS and contractor staff evaluated the extent of the damage on the instrumentation system and made some emergency repairs at the site. Table 1 summarizes the final assessment of the instrumentation as a result of the field inspection.

Table 1. Inventory of instrument damage on Turtle Mountain due to lightning on September 21, 2006.

Instrument	Sensor	Surge Arrestor (instrument end)	Surge Arrestor (enclosure end)
TM-1	OK	N/A	Damaged
TM-4	Damaged	N/A	OK
TM-5	Damaged	N/A	Damaged
EX-1	Damaged	N/A	OK
EX-2	Damaged	N/A	Damaged
EX-5	OK	N/A	Damaged
CM-1	Damaged	Damaged	OK
CM-2	OK	Damaged	OK
CM-3	Damaged	Damaged	OK
CM-6	Damaged	OK	OK
CM-7	Damaged	OK	OK
CM-17	Damaged	Damaged	OK
Lower Saddle GPS	OK	Damaged	OK

A third field trip was made between October 17 and 20, during which time a number of contractors completed the repair work identified as a priority during the late September trip.

2.4 Other Monitoring Systems

The outflow monitoring system at the entrance to Frank mine consistently becomes inoperative in late winter a result of a battery charge drop well below normal operating levels, due to the reduced sunlight at the station's shaded location. This issue was addressed in late September 2005 by upgrading the power system to dual 100W panels with eight 100A-hour batteries. This upgraded power supply has reduced, but not eliminated, the time the system is off-line. As the outflow weir does not provide support data for the primary monitoring system, increasing the seasonal reliability of this system is not a priority.

The instrumentation at the South Peak weather station performed reliably during the reporting period; however, the precipitation gauge and wind sensor components from the weather station became inoperable below 0ºC. In addition, snowfall cannot be measured with the current precipitation gauge. The thermistors in the South Peak borehole, and the two piezometers in the fissures near the South Peak weather station, also performed well, with the thermistor string continuing to be the most robust instrument to date. The thermistors have provided a continuous two-year record of rock temperature within the upper 20 m of the surface at the borehole location.

2.5 Data Capture and Management

2.5.1 South Peak Data Stream

The largest modification to the mountaintop data capture and management system was the addition of six GPS stations and a new radio tower at South Peak. The radio tower establishes a 5 GHz link between the GPS system and the Provincial Building in Blairmore (McElhanney, 2006). Each GPS station emits the following types of data: satellite-based time and positional data, battery voltage, enclosure temperature, and humidity (transmitted hourly). The initial three months of data from this system were collected and recorded between October and December 2006 and archived by McElhanney for future review. There are plans to integrate the data from the six GPS stations in 2007 into a common database of information from the other sensors in the network.

A schematic showing the updated wireless arrays coming from the South Peak are shown in Figure 5.

2.5.2 Provincial Building Data Stream

The primary work at the Provincial Building in Blairmore was relocating some of the existing equipment to a more easily accessible location. Prior to the September 25 relocation, most of the equipment was housed above a false ceiling on the second floor. As a result, any troubleshooting would require access to third-party office space, interferring with the normal business operation. The new configuration will, theoretically, create easier access for maintenance and troubleshooting, centralize communication equipment, and ease integration with future connection to Alberta Supernet (planned for 2007/2008). In addition, power and data communication equipment for the new GPS link was also installed. This equipment provides wireless connection from the Provincial Building to the newly installed radio tower located on the South Peak of Turtle Mountain.

2.5.3 Frank Slide Interpretive Centre (FSIC)

The monitoring system at the Frank Slide Interpretive Centre was upgraded on March 28, 2006. As part of this upgrade, the primary database server was replaced and relocated into the electrical room, allowing easier access and providing a cleaner and more secure environment than the previous storage room. In addition, two other computers (that were performing data collection and marshalling for the seismic

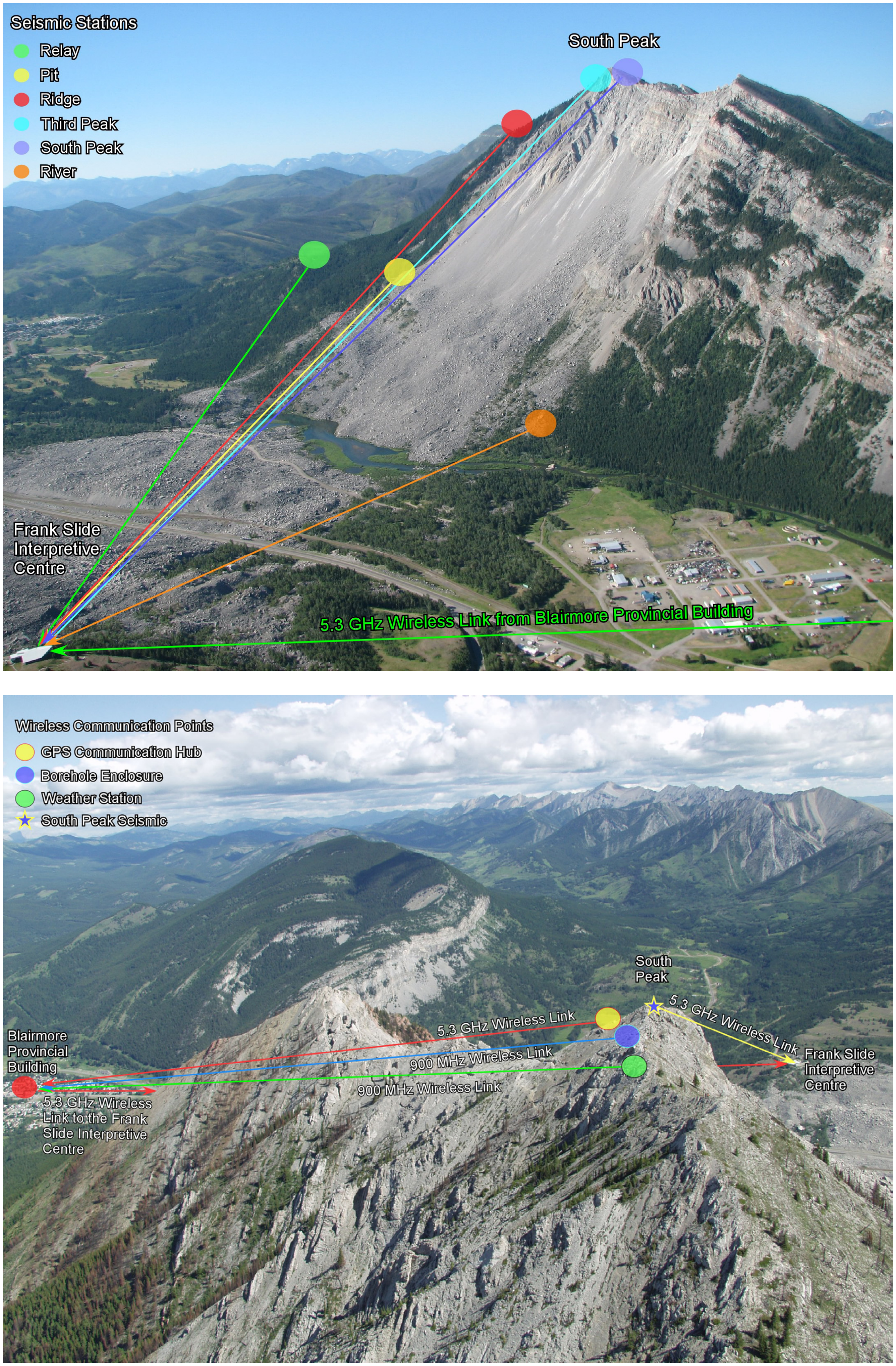

Figure 5. Overview of the wireless data connections on the a) east side, and b) west side of South Peak.

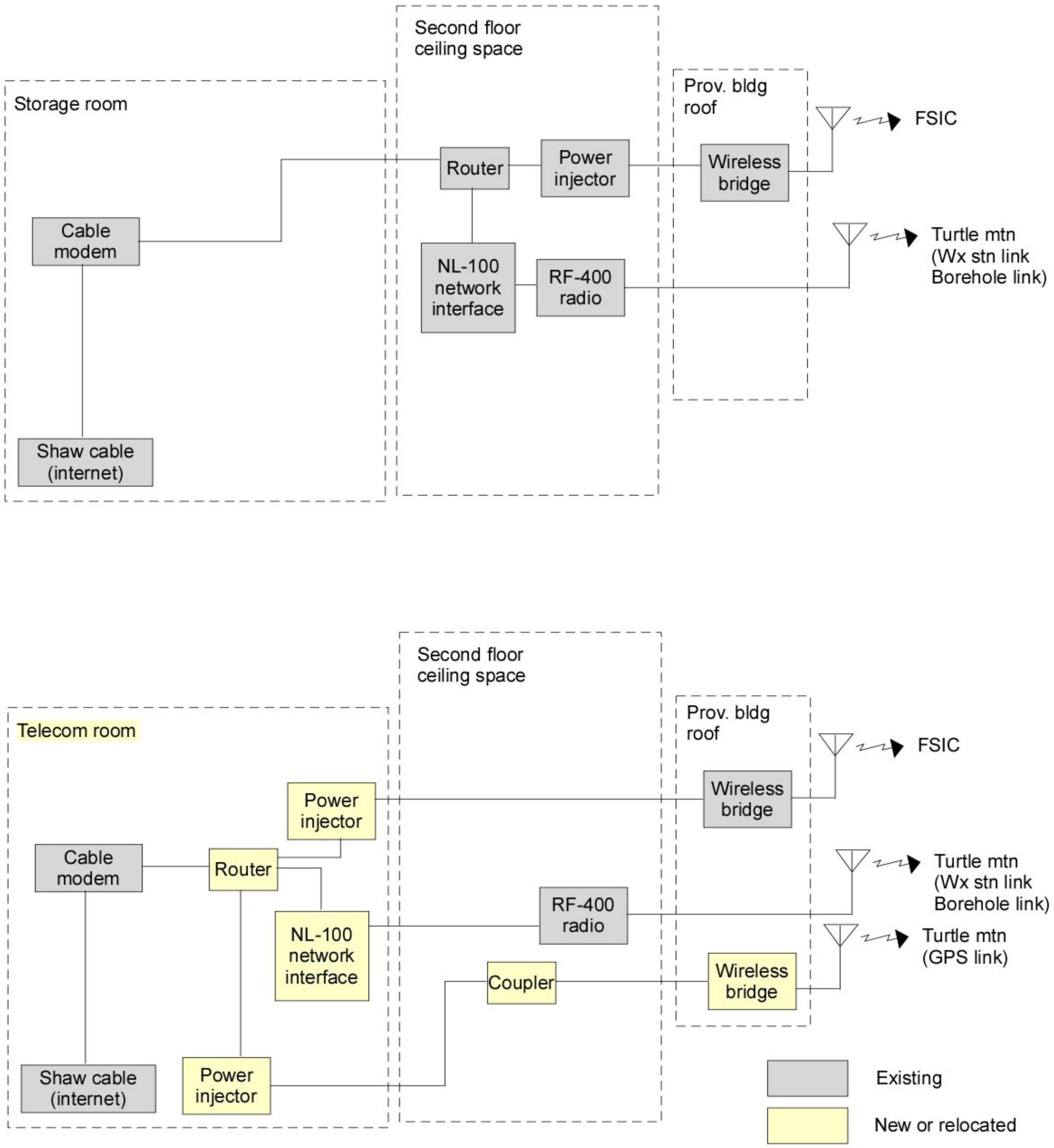

Figure 6. Schematic of wireless data network equipment installed at the Crowsnest Pass Provincial Building; a) before relocation, and b) after relocation.

system) were removed and their operations migrated to the new server with hardware consistent with other ERCB hardware, allowing for easier maintenance and upgrading.

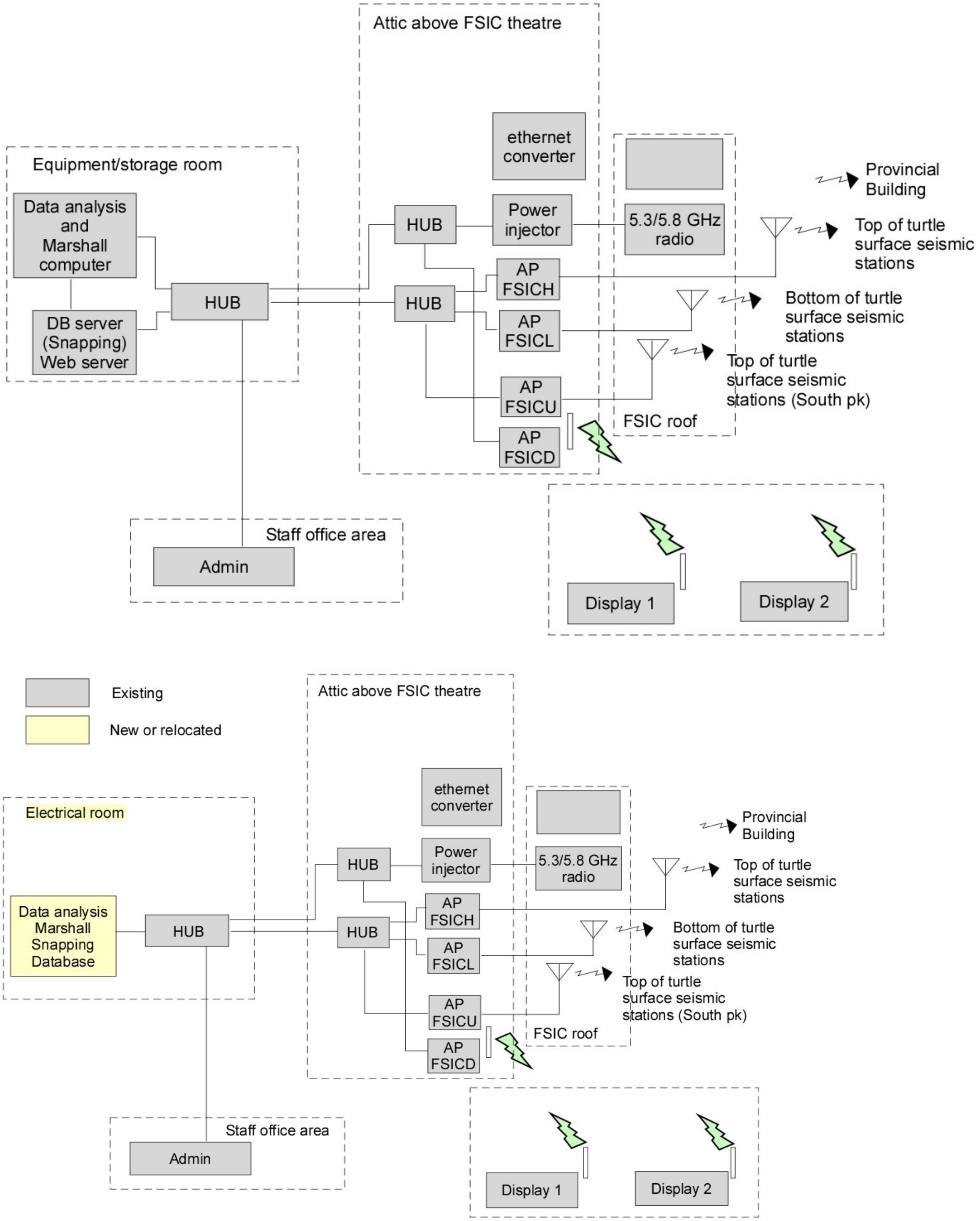

Figure 7. Frank Slide Interpretive Centre wireless data network schematic; a) before March 28, 2006, and b) after March 28, 2006.

3 Data Analysis

The following section discusses interpretations of slope conditions and displacement behaviour from instrumentation results. As some of the sensors have been affected by climatic factors, discussion will focus on the sensors that provided reliable annual performance. Meteorological data have been instrumental in explaining general displacement trends observed in the surface instrumentation.

3.1 Deformation Monitoring Data

3.1.1 Crackmeters

While displacements were observed on many of the crackmeter sets, the most indicative record of slope displacement was obtained from a cluster of three crackmeters at Set B. These instruments provide a nearly continuous two-year record of slope displacement with minimal interruptions or effects from snow loading. Monitoring results from crackmeters Set B reveal a persistent annual displacement cycle, dominated by an active phase with displacements occurring in early autumn to late winter, and a relatively inactive phase with limited to no displacements during the spring to late summer period (Figure 8). Incremental displacements of approximately 0.4 mm have been measured during each displacement cycle (the total width of the cracks range between 1.0 to 1.5 m at the crackmeter locations). Crack-width changes correlated to daily temperature fluctuations can also be observed (~ 0.02 mm); however, no permanent displacement has been recorded after every cycle. Electrical noise, believed to be induced by lightning strikes, has caused apparent changes up to 1.5 mm (as illustrated in Figure 8).

3.1.2 Tiltmeters

There are varieties of trends observed on the tiltmeter network. These range from sensor fluctuations mirroring the thermal cycles to trends that might indicate cumulative, permanent creep (observed at two of the sensors).

In general, all sensors display an increase in tilt when entering the summer period and return to the previous state when exiting. A similar cyclic variation in tilt associated with diurnal temperature fluctuations is also present, only on a smaller scale (~ 0.01 deg). Noisy responses due to moisture in the sensors continue to affect the quality of tiltmeter data (T-1, T-8 and T-10); however, the addition of desiccant packs during summer 2006 has remarkably improved data quality (T-2 and T-3).

Individual tiltmeters display their own characteristics. For example, tiltmeter T-6 shows a larger deviation in tilt angle than the other instruments. A recent field trip revealed this instrument is located on a small, fractured rock knob highly susceptible to freeze and thaw effects. Tiltmeters T-1 and T-2 appear to show trends associated with slow creep, but the overall deformations and noise in the data do not allow for conclusive interpretation of the trends for these sensors. Additional years of data are needed to get a better understanding of the displacement style.

3.1.3 Extensometers

Each of the five extensometers shows very stable responses during the reporting period. No daily or seasonal changes can be seen in the displacement data. Extensometer EX-2 and EX-3 continue to be extended at 19 mm and 6.17 mm, respectively. These displacements were recorded during two periods of heavy precipitation in early June and early September 2005 and are discussed in greater detail in Moreno and Froese (2006, 2007). A gradual displacement of 1.3 mm occurred at extensometer EX-4 in November 2006, believed to be a result of a dramatic drop of air temperature between October 29 and 30.

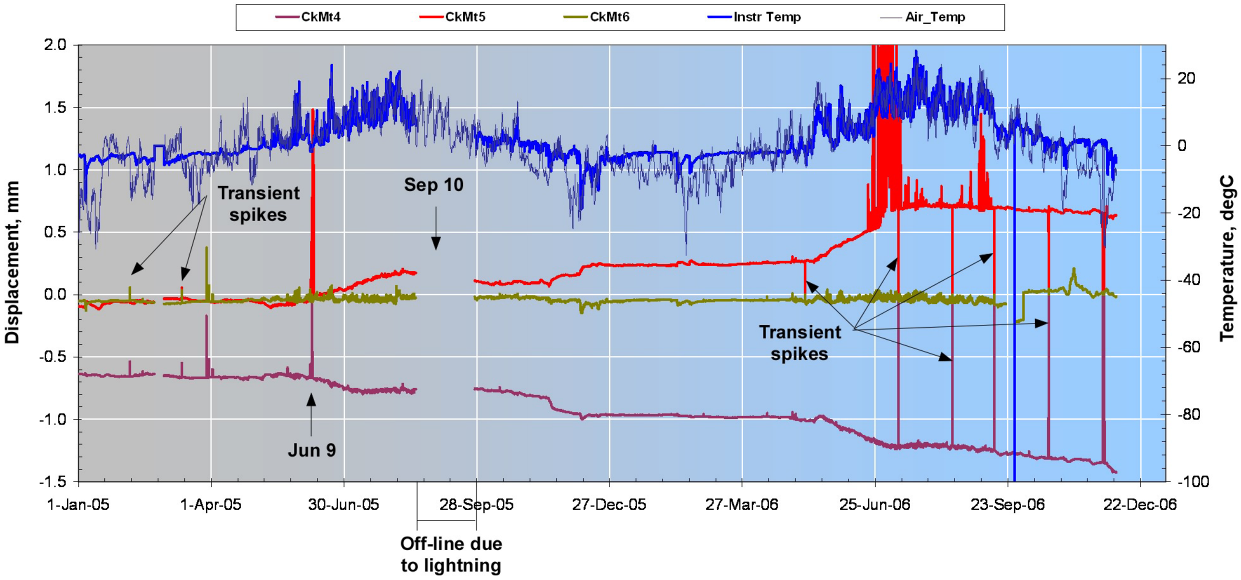

Figure 8. Plot of displacement versus time for crackmeter Set B, South Peak, Turtle Mountain.

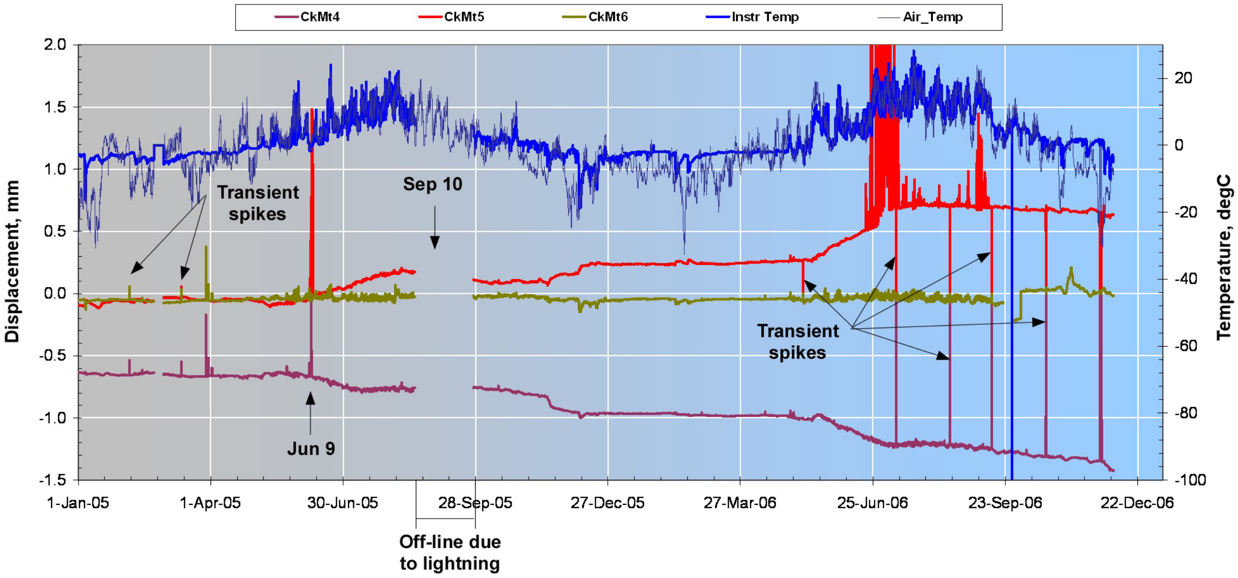

Figure 9. Plot of tilt versus time for tiltmeters, South Peak, Turtle Mountain.

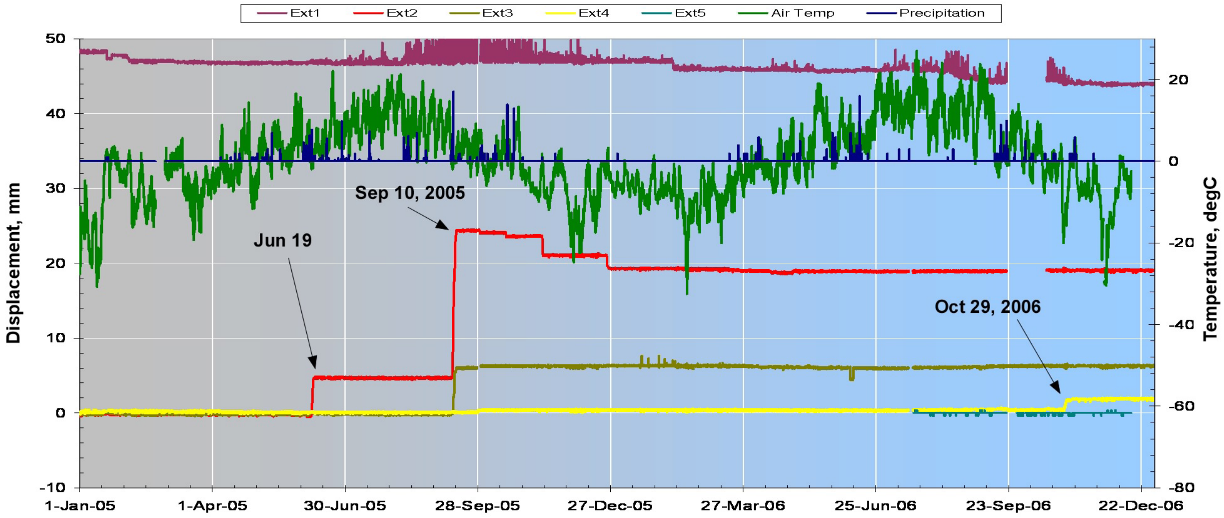

Figure 10. Plot of displacement versus time for extensometers.

3.2 Combined Seismic Monitoring Data

Most of the seismicity observed on Turtle Mountain is minor; however, an obvious correlation exists between increased seismicity and when rock temperatures pass through the 0°C point. A significant, localized seismic event was detected at the South Peak seismic station on February 16, 2006. This event was highly distinctive, but the magnitude was not sufficient to register at any other station. Based on the arrivals, it is believed to have originated in the northeast quadrant relative to South Peak, most likely within a few hundred metres. Figure 11 shows the channels recorded at the northeast (red), southwest (green) and northwest (blue) geophones relative to the mast at South Peak. This event is believed to be related to the fracturing of the rock during a significant recorded temperature drop from -12˚C to -32˚C in less than a day.

3.3 Other Monitoring Data

3.3.1 Climatic and Thermistor Data

Average temperatures at the top of South Peak in 2006 were warmer than in 2005. Records ranged from 6.4°C in January (-10°C in 2005) to +13.9°C in July (+10°C in 2005), with significant variations throughout the year. An extreme maximum of +27°C and an extreme minimum of -32.5°C were recorded on July 22 and February 16, 2006, respectively (Figure 12). Freezing conditions typically prevail from early November through March; although, where blanketed by snow, the ground surface usually remained above freezing throughout the winter. Significant daily temperature variations were also common. Three examples of variations can be seen on the temperature records of January 16, October 30 and November 28. Rock temperature shows the same general trend as air temperature, but is more subdued (lower maximum and minimum readings), with a time lag of about 12 hours relative to significant changes in air temperature. Seasonal temperature fluctuations penetrate only about 15 m into the slope (Th-2) and are negligible below that depth, with significant temperature variations measured to a depth of 8.2 m (Th-4). On the other hand, daily temperature variations are measurable only about 4 m into the slope (Figure 12).

Normal precipitation levels were measured at the weather station on South Peak of Turtle Mountain during 2006 (397 mm). The average annual rainfall data were obtained from a nearby weather station managed by Environment Canada (Coleman station). Climate averages offered by this station are based

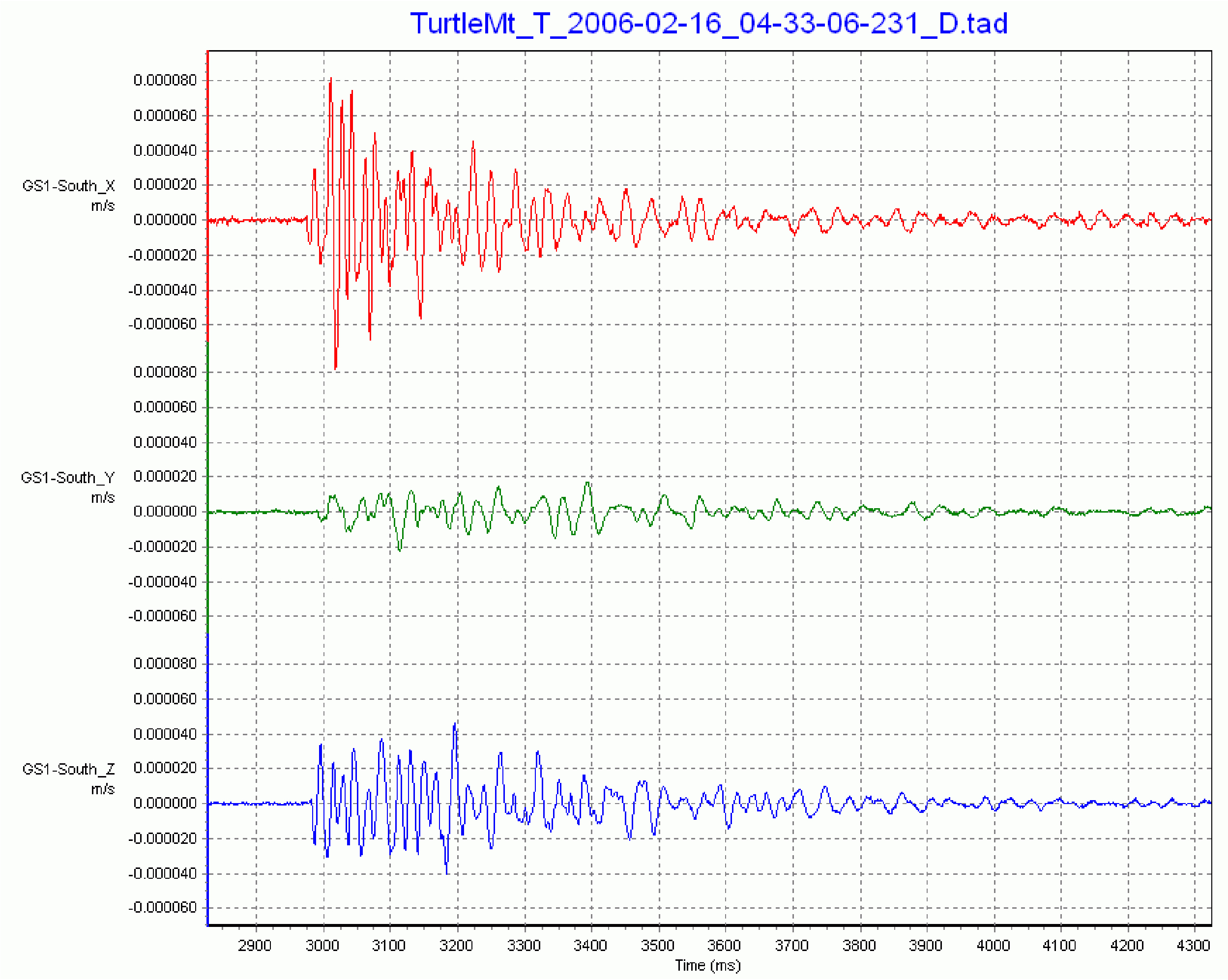

Figure 11. Amplitude traces for a seismic event near South Peak station (seismic data reviewed and interpreted by Henry Bland, Alto Instruments).

on at least 15 years of data between 1971 and 2000. Below-normal winter precipitation was measured in the same area (Figure 13). Normal precipitation was recorded during early spring, but three major precipitation events during June 2006 dramatically increased the total spring precipitation. Summer 2006 was a dry season, with the exception of a couple of storms that moved through the region in late September; whereas, with the exception of December, precipitation increased to normal levels during the fall.

3.3.2 Differential Global Positioning System (dGPS)

As discussed in Section 2.1.1, six GPS stations were installed during the summer/fall of 2006, but the initial three months of data were used for system testing and not analyzed in detail; therefore, they are not discussed in this report. A more thorough review of the 15 months of available data is expected to be completed for the 2007 summary report.

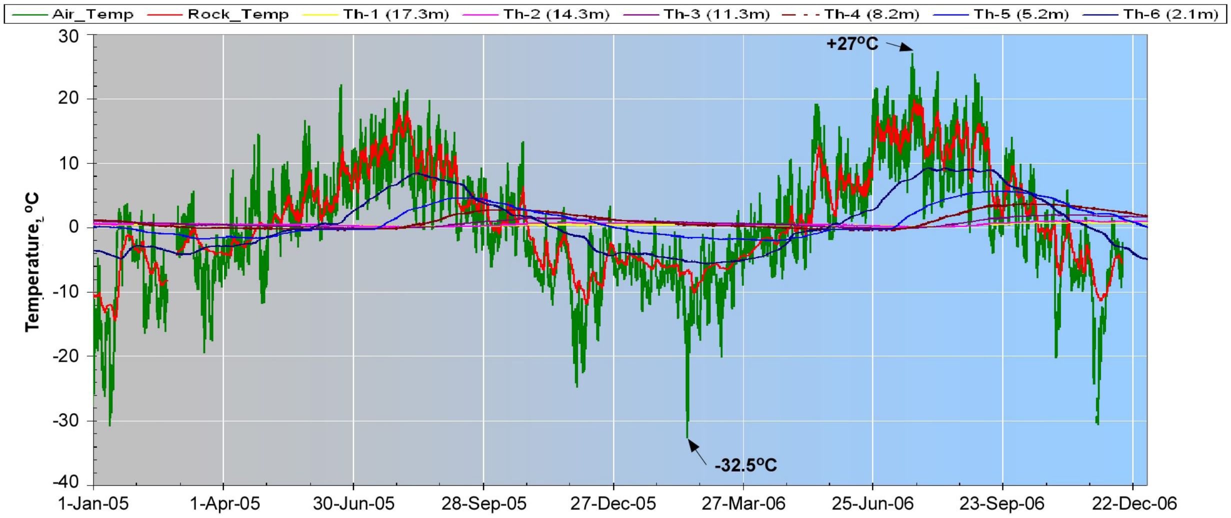

Figure 12. Air temperature and rock temperature variations with depth at the borehole for 2006.

3.4 Discussion of Monitoring Data Results

The slow movements of the last two years recorded by the sensors on the South Peak of Turtle Mountain is consistent with observations from surface monitoring points installed during the 1980s (Moreno and Froese, 2006). Generally speaking, the annual rate of movement is on average less than 1 mm/year. The largest rate of displacements, up to 3.9 mm/year, has been measured at the highly fractured region to the north and east of South Peak (based on results of aerial photogrammetry reported in the 2005 summary report (Moreno and Froese, 2006)). In the southwestern portion of the peak, movements are typically less than 0.5 mm/year.

Measured displacements appear to correspond to two distinct types of mechanisms:

1) downslope movement originating from the seasonal change of air temperature; and

2) slope erosion by physical breaking of rock caused by rapid drop of air temperature.

In the absence of deeper, subsurface information on deformations and pore pressures, much of the current interpretations are speculative, based on observations and findings from similar studies found in the geotechnical literature. The following provides an overview of both mechanisms.

A seasonal pattern can be observed on measured surface displacements and strongly correlates to annual temperature variations (Figure 8). Careful scrutiny of crackmeter Set B records indicates distinctive variations in the displacement rate during the warming and cooling seasons. An increase in displacement can be seen during periods of prolonged warm air temperatures, typically during summer to autumn. This is followed by cessation of the displacements during the winter phase. During the winter phase, there can be two acting mechanisms: 1) thermal contraction due to rock cooling, and 2) apermanent slip on discontinuities, created from stress introduced by thermal contraction of the rock mass. These displacements are in opposite directions, resulting in an overall displacement having insignificant values (almost zero). Unfortunately, due to reliability and accuracy issues, these displacement patterns cannot be confirmed by any of the other primary surface instruments.

Although borehole thermistors indicate that seasonal temperature fluctuations penetrate only about 15 m into the slope, studies undertaken on the Checkerboard Creek rock slope in British Columbia (Watson

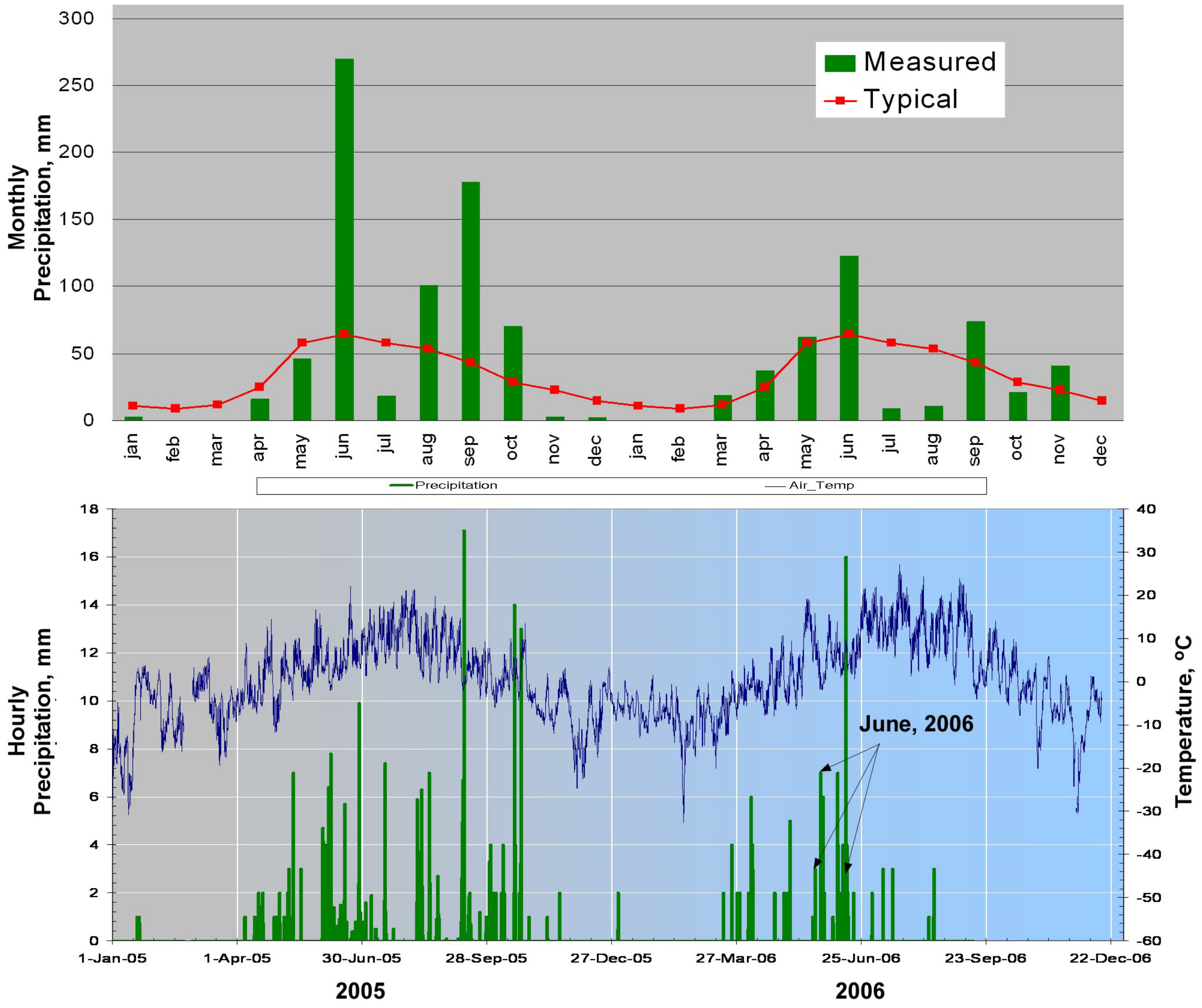

Figure 13. Measured and typical average monthly distribution of rainfall in the region of Turtle Mountain (2005–2006).

et al., 2004) using subsurface monitoring and computer modelling show that deformation extends well beyond the depth of seasonal frost penetration, and that seasonal changes in rock temperature are a significant factor in controlling the slope stability. This model may also apply to Turtle Mountain, although there is currently insufficient information to reach this conclusion.

Slope erosion is defined here as the breakage of the rock structure caused by rapid temperature drop to levels well below freezing. Contrary to seasonal air temperature changes, this mechanism results (in most cases) on very localized damage limited to the uppermost few metres and with the extent controlled by slope geometry and aspect. Evidence of the second displacement mechanism can be seen on Extensometer EX-4 records (Figure 10). Seismic station records also support this slope erosion model (Figure 11). In both cases, breaking activity was concurrent with a rapid drop of air temperature.

With respect to the effects of water infiltration into the fractures, displacement data suggest there is no direct correlation with increased piezometric levels associated with summer precipitation and spring snowmelt. Due to very warm weather, rapid snowmelt in mid-May resulted in high run-off volumes in the area, but no displacement was observed associated with this event. In addition, conspicuous slope features observed include a fairly steep slope and numerous open cracks. In general, these observations indicate that surface and groundwater drain quickly. The conclusion is that pore water pressure and frost action are unlikely to play a major role in the stability of South Peak.

4 Supporting Studies and Research

In 2006, specific studies were done to increase understanding of both the mountain's structure and its recent and historical deformations. Airborne and spaceborne remote-sensing technologies have been applied to Turtle Mountain to provide a broader picture of the movement of South Peak and the mountain in its entirety, as compared to the network of point-source readings being collected by recently installed sensors. Remote-sensing studies involved the use of a digital elevation model (DEM) derived from remote sensing data (LiDAR) to gather information on the structure of the mountain, and satellite-based interferometry to map subcentimetre deformations of the entire mountain surface. In addition, a ground-based survey took new sets of readings for survey prisms installed on South Peak in the 1980s. The following sections provide a brief overview of the progress on these studies.

4.1 Electronic Distance Measurements (EDM)

In the early 1980s, the University of Calgary, Department of Survey Engineering (now Geomatics Engineering), installed a series of remotely monitored reflective prisms on the west side of South Peak of Turtle Mountain (Fraser, 1983). The three points were each measured remotely using a laser-ranging survey total station from four locations west of Turtle Mountain. The concept behind the approach was that, based upon the object point coordinates established using the initial set of readings (Epoch 1) data, the results obtained from subsequent epochs could be compared in a relative manner using a distance difference mathematical model. This model uses the observed coordinates of the target points to calculate the distance difference between points. A set of equations can be written for each epoch (set) of observations, and in each epoch a solution for each distance difference can be computed. Changes in distances between epochs can then be computed and compared with their associated standard deviations to determine if actual movement occurred.

Several epochs of EDM measurements were made in the 1980s; however, the analysis of this data did not reveal any movement between pairs of target points other than an artificial movement deliberately introduced to test the system. EDM monitoring was abandoned by late 1980s with the last set of readings reported in 1986 (Chapman, 1986).

Figure 14 shows one of the targets, each of which is approximately .07 m in diameter, and the metal canister housing. The layout of the target network is shown in detail in Figure 15, monitoring station C2 is shown in Figure 16.

In August 2006, a new set of EDM measurements was taken by the University of Calgary, Department of Geomatics Engineering (Teskey, 2006). This consisted of distance measurements to target points from each observing station. The targets were wrapped with high visibility tape and painted prior to observations being collected, due to their metal canister housing being corroded (which made gathering its localization from the observing stations very difficult) A total of 12 observations were taken and attempts were made to replicate as closely as possible the parameters of previous epoch observations. The details of the analysis and complete set of EDM distance observations are presented by Teskey (2006).

For the analysis, the target coordinates were compared to the original epoch 1 EDM measurements from 1982. The results of this analysis, with the associated standard deviation given in brackets, are shown in Table 2.

Figure 14. EDM target installed on Turtle Mountain in 1982.

Table 2. Displacement measurements from EDM at Turtle Mountain (from Teskey, 2006).

	change in distance (mm)	standard deviation (mm)
a–b	-3.4	[4.9]
a–c	-15.7	[2.5]
b–c	-5.9	[4.4]

According to this analysis, only the distance a–c had significant movement with a decrease of 15.7 mm. This corresponds to an average displacement rate of 0.65 mm/year over the 24-year period. This 'shortening' or apparent closing of the cracks between a–c may be the result of two proposed mechanisms. One hypothesis is that the portion of south peak on which target C is located is a large wedge that is moving to the northeast. This direction of movement would subparallel the fracture between a–c and target C would be moving laterally in relation to target A. Another possible mechanism is that the highly fractured zone of extension in which the targets are located is subsiding into a graben, and that the fractures are closing as the graben settles into the void created at the backscarp of the large wedge that comprises South Peak. Further work is being undertaken to these hypotheses and is discussed in greater detail by Moreno et al. (in press).

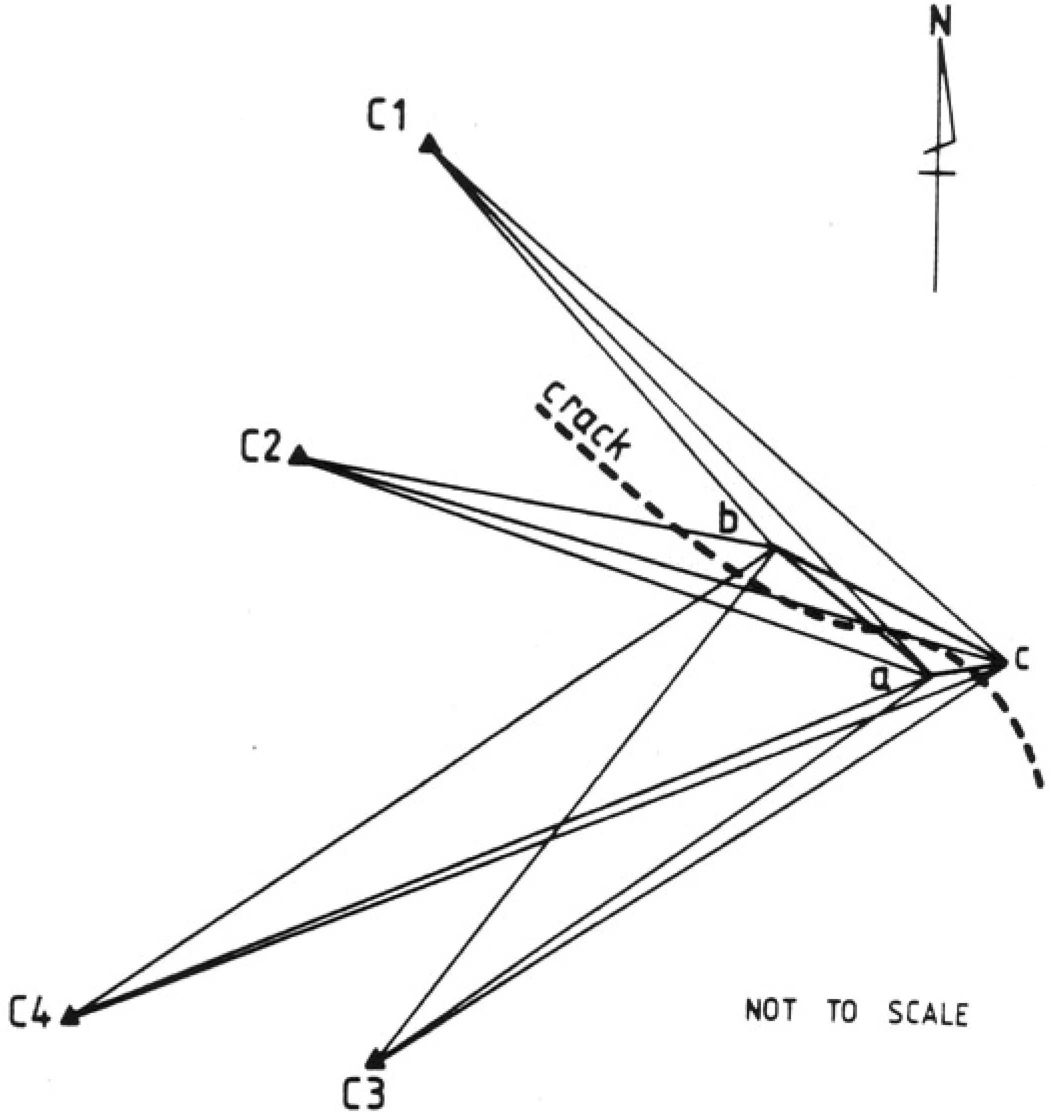

Figure 15. Schematic of remote monitoring stations (C1, C2, C3, C4) and Target Points near South Peak (a, b, c) (from Teskey, 2006).

4.2 Digital Elevation Model Studies

There have been two separate but complementary studies undertaken on Turtle Mountain using digital elevation models (DEM):

1) Jaboyedoff et al. (in press) used a DEM obtained by merging a 20 cm resolution color orthophoto and a 2 m-DEM to complete a structural analysis of Turtle Mountain; and

2) recent studies at AGS used a high-resolution DEM and new relief analysis techniques to revisit the structural interpretation of the Turtle Mountain reached by Jaboyedoff et al. (in press). The following provides an overview of the findings of both studies.

Figure 16. Monitoring Station C2 and target network layout (a, b, and c – box insert).

Jaboyedoff et al. (in press) used a DEM to identify the main structural fault sets and to confirm and refine the exiting geological models for the Frank Slide and the South Peak. The structural analysis was done using the software Coltop-3D (Quanterra™), which allows for classification of the topography of the DEM in terms of dip and dip direction. The slope orientation is coded following the Intensity-Hue-Saturation (IHS) system filling a stereonet. Each colour is defined by a unique dip direction and dip of the slope defined by the normal to the surface—the pole of the DEM cell. The result is a coloured, shaded relief map combining both terrain slope angle and slope aspect (direction of slope) in a unique representation where continuous features as joint sets are then defined by such representation (Figure 17).

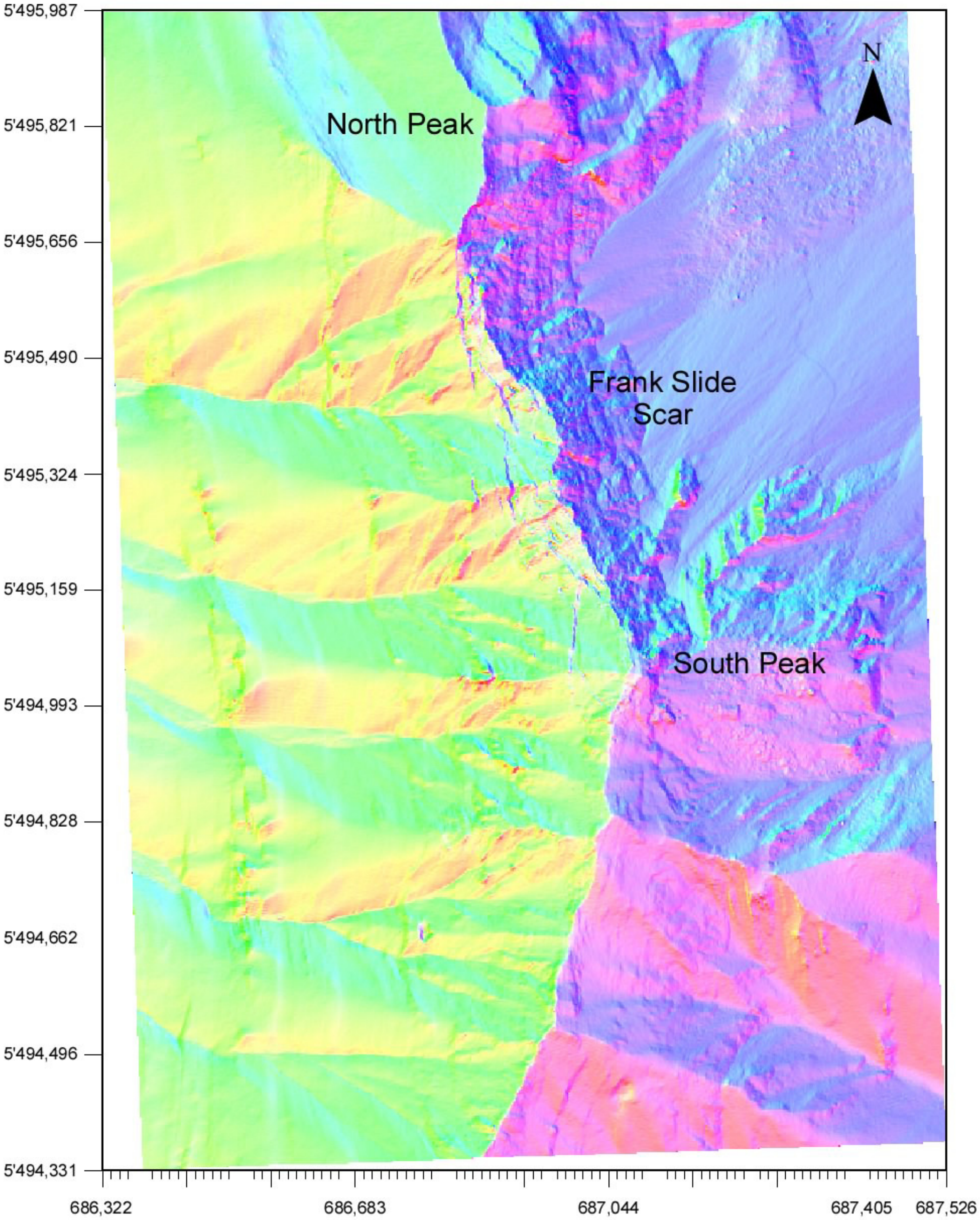

Figure 17. Interpretation of the relief of the rockslide scar at Turtle Mountain from LiDAR data using COLTOP-3D.

A comparison of the discontinuity sets obtained on the photogrammetric DEM with field measurement shows that the DEM interpretation provides a good assessment of the main structures present in the area (Figure 18).

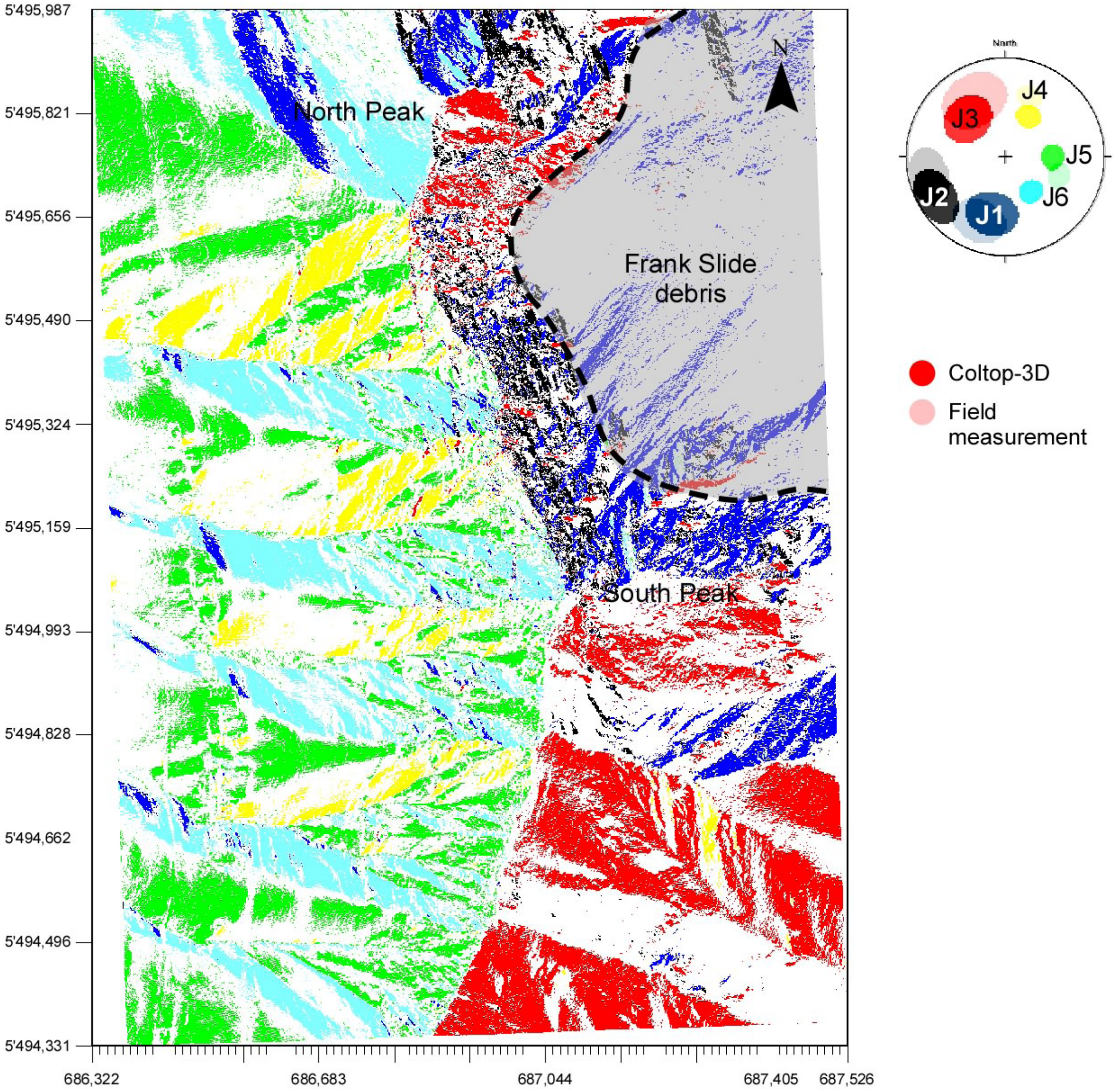

Figure 18. Representation of the selected discontinuity orientations J1 to J6 based on the selected directions of stereonet from Figure 14 and field data interpretation.

Based on his study, Jaboyedoff proposed a reinterpretation of the failure mechanism for the 1903 Frank Slide: specifically a lower slope failure along bedding that then permitted the progressive failure of a second rock mass, to the west of the anticline hinge, as a series of gently dipping wedges. For South Peak, Jaboyedoff et al. (in press) considered that failure mechanisms similar to the one responsible for the 1903 slide exist today, but that the angle of the structural discontinuities are less steep and, therefore, the potential failure surface is unclear. Jaboyedoff et al. (in press) utilized the COLTOP-3D™ analysis, the

DEM and the concept of Slope Local Base Level (SLBL; Jaboyedoff et al., in press) to develop volume estimates and configurations for a failure of South Peak that range from 5.5 to 10 million m^3.

In 2005, AGS purchased a LiDAR data license for an area covering Turtle Mountain and the Frank Slide, an area of approx. 33 sq. km. The airborne LiDAR survey was conducted using a flight line spacing designed to provide an overlap of 50% between flight lines. One mission was required to cover the project area, and was flown on July 24, 2005. The details of the data acquisition and processing are presented by Airborne Imaging (2006).

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. 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 while the distance from the aircraft to the ground is calculated. These measurements generate a 3-D point cloud with an irregular spacing.

A digital terrain model (DTM), was created from the triangulated irregular network (TIN) provided by the LiDAR 3-D point cloud. The mesh size of the grid is 0.5 m, based on a raw point collection distribution of approx. 1 point per metre (Figure 19). This high-resolution DEM was analysed by using new relief analysis techniques (Sturzenegger et al., 2007). These results have confirmed the structural analysis performed with the photogrammetric DEM (Jaboyedoff et al., in press).

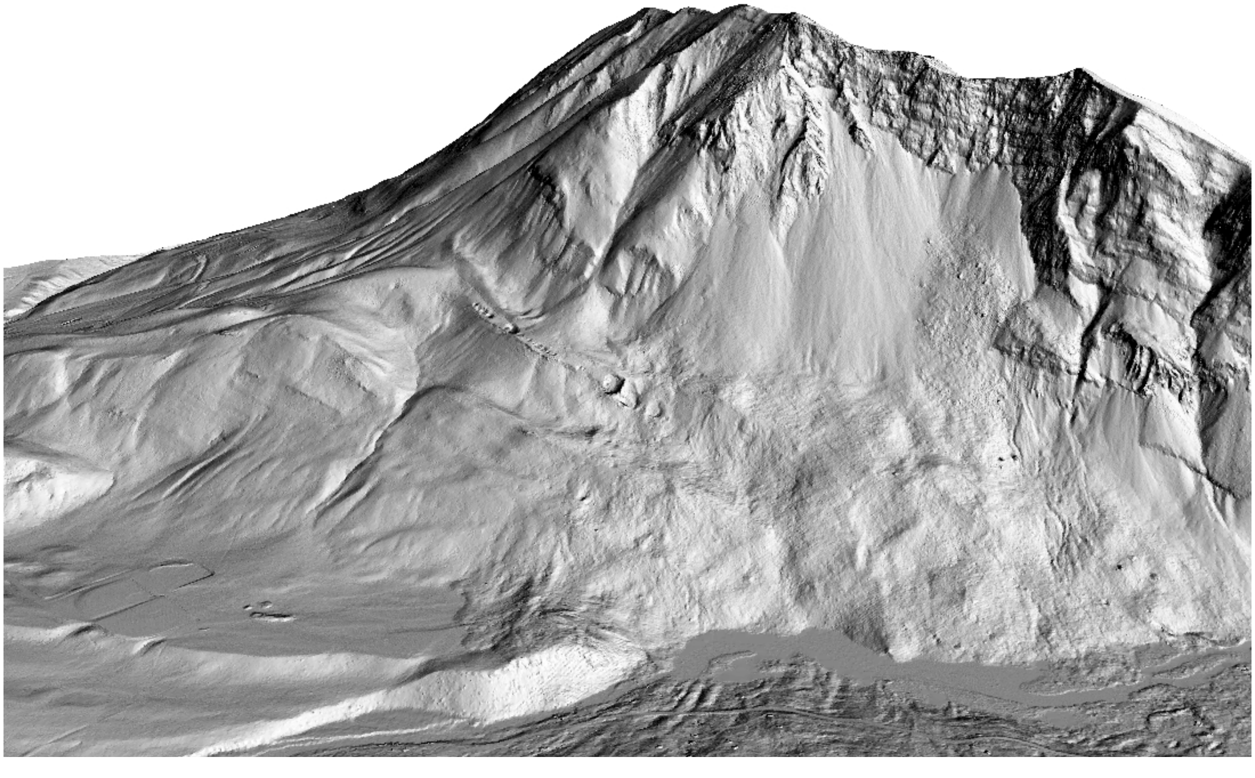

Figure 19. High resolution 3-D digital terrain model (DTM) of Turtle Mountain.

A separate, but complementary, work undertaken on Turtle Mountain using the recently acquired LiDAR proposes an updated interpretation of the failure mechanism for the South Peak of Turtle Mountain (Moreno et al., in press.). The revised interpretation divides the South Peak into three main modes of failure: 1) toppling off the east side of South Peak, 2) wedge failure below along the western limb of the Turtle Mountain anticline, incorporating South Peak, and 3) subsidence of heavily fractured rock into the graben at the back of the wedge (Figure 20). The significance of these studies is a reassessing of the interpretation of the historical monitoring results from the 1930s to present. As these studies have been focussed on the peak itself, they provide deformation data for the toppling and wedge failure mechanisms, but do not provide data for the larger lower slope planar failure. Initial estimates indicate that the volume of the toppling and wedge failures are likely in the order of 0.5 million m^3 and that the lower slope planar failure has a likely volume in the order of 5.5 million m^3 and is controlled by two major fracture sets dipping NE (J2) and ESE (J3), with sliding along bedding planes along the east limb of the Turtle Mountain Anticline. As this work was initiated in late 2006, an update will be provided in the 2007 summary and published in Moreno et al. (in press).

Figure 20. Southeast facing oblique view of South Peak showing simplified zoning of postulated deformation zones.

The recently acquired DEM by airborne LiDAR have also shown that the areas below both South Peak and Third Peaks have probably suffered several past rock avalanches or major landslides. It shows also some instabilities that have been confirmed by aerial photo interpretations (Froese and Moreno, 2007). Since these new instabilities have been individualized in the vicinity of the Third and South Peak summits, field work surveys providing increased understanding of the subsurface structure of the mountain will be done in these areas during summer 2007. In addition to the DEM data obtained from aerial platforms, studies by Simon Fraser University (Sturzenegger et al., 2007) utilized terrestrial LiDAR to generate high-resolution models of the mountain to map the structural fabric. Preliminary results of these studies were reported by Sturzenegger et al. (2007).

4.3 Satellite-Based InSAR

As reported in the 2005 Summary Report (Moreno and Froese, 2006), an initial setup phase of deformation monitoring at Turtle Mountain using Spaceborne Interferometric synthetic aperture radar (InSAR) was completed by Vexcel (now MDA Geospatial) (2005). In the initial phase, 21 scenes of Radarsat-1 for the ascending F4F and F1 beam mode were tasked, of which nine F4F were used for the permanent scatter InSAR (PS-INSAR) technique, generating deformation plots for the time period between spring and fall 2004.

In 2006, AGS, in collaboration with the Canadian Centre for Remote Sensing (CCRS), acquired the Radarsat-1 data utilized in the initial Vexcel study, plus the data available for 2006, to complete deformation mapping for the time period spanning from April 2004 to October 2006. For this study, 23 scenes of Radarsat-1 F4F data were utilized to complete permanent scatter interferometry (PSI) analysis utilizing Vexcel (now MDA Geospatial) EV-InSAR CTM module. The results of the study, along with the theory and processing background, are documented by Mei et al. (2007).

Following are some results regarding the success of the application of spaceborne InSAR to map ground deformation over the Frank Slide area, using Radarsat-1 data acquired with Fine beam 4 of the ascending pass from April 2004 to October 2006:

On the upper portion of the mountain, foreshortening distortions associated with the incidence angle of the satellite beam and the steep topography do not allow for reliable mapping of ground deformation. Although there were a small number of point targets extracted to map deformation on the west side of South Peak and the Upper Frank Slide, these points are not representative of the deeper-seated deformations of the rock slope, but rather of isolated and discrete blocks or boulders. To obtain more reliable deformation data for the peak, consideration may also be given for including the descending pass Radarsat-1 data, although foreshortening distortions may persist with the descending pass as well. The greatest potential to map deformation for the peak area will likely be the future ability of Radarsat-2 view flexible in both a left- and right-looking modes. This will possibly allow for suitable satellite look geometry to overcome foreshortening distortion and obtain a better picture of the patterns and rates of deformation for larger areas of the peak than currently being monitored and studied.

The lower slope of the Frank Slide and the valley bottom are very well suited for the application of PS-InSAR for mapping ground deformations. Due to the bare and dry nature of the landscape and the slow systematic nature of the deformations, both slow creep of talus slopes and subsidence of the surface above abandoned underground coal mine workings were observed and quantified. On the talus-covered lower slopes of Turtle Mountain, the PS-InSAR was able to differentiate between recently deposited, more active talus, and older, more stable debris. In addition, the ground surface above the Frank Mine was found to subside in some areas underlain by abandoned coalmines at an average annual rate of about 3.15 mm per year, relative to the reference area which is located in the middle part of Frank slide, during the period from April 2004 to October 2006. Some isolated targets, associated with pit holes caused by collapsing of the Frank Mine, were found to subside at an annual rate of more than 20 mm per year in the line of sight of radar during this period. Upslope the Frank Mine, a subsidence rate of more than 10 mm per year, relative to the reference area, was detected for a group of targets located in the lower slope of the Frank Slide. For more than 100 years since the 1903 Frank Slide, there has been speculation that the subsidence induced by the underground coalmines at the foot of Turtle Mountain might have eventually triggered the slide. PSI results in this study provide the quantitative evidence for subsidence induced by the underground coalmines.

In addition to providing quantification for an area where visual observations of subsidence had been made (the Frank Mine), average regional deformations of up to 3.2 mm/year, relative to the reference area, were observed overlying the footprint of the abandoned Bellevue underground mine to the east. At the time of the preparation of this report, there was no published information on the subsidence of the ground surface in this area so the findings of this study may be important as a tool for the municipality to better understand the potential hazards associated with the mine on the existing and planned development on the ground surface. Discussions with personnel from the municipality have verified that there have been frequent collapses above the Bellevue Mine below roads and fields over the past few years and there is interest in the potential application of the technology to aid the municipality in mapping the onset of collapse and proactively planning mitigation.

As all of the ground deformation monitoring undertaken until this time has focused on the western side of South Peak, the PSI results discussed in this report provide new deformation for other portions of Turtle Mountain that had previously not been monitored and, as such lack ground data to verify the results presented herein. The results of the present study provide valuable data that can then be used to plan future monitoring programs. This may include the installation of prisms or differential GPS stations on the slopes above the coal mine workings or on the talus-covered slope below South Peak. Additional consideration is currently being given for the installation of a number of artificial corner reflectors below Third or South Peaks to both acquire new data and improve image co-registration for future PSI processing on Turtle Mountain. At this time the AGS has tasked continued Radarsat-1 F4F acquisitions for Turtle Mountain and intends to continue adding to the model on an annual basis in order to continue an enhanced understanding of the complexities of movements on Turtle Mountain. Consideration is also being given to the processing of an alternative beam mode that would allow for deformation mapping in the peak area of Turtle Mountain. This could either involve using a descending Radarsat-1 beam mode or utilizing the left- and righ-looking capabilities of Radarsat-2 once it is in orbit and operational. Turtle Mountain would likely be an ideal case study for this enhanced feature and the high resolution fine beam (3 m pixel size).

In addition to the processing steps available in CTM analysis, this study has demonstrated a post-processing step that applies statistical and geostatistical analysis to discriminate the reliable targets from false alarm targets, and differentiate between isolated point target movement and regional ground deformation. This also renders the present report a useful reference manual for millimetre-scale ground deformation mapping using EV-C1-InSAR.

5 Summary and Conclusions

With the sensor network and the supporting studies, initial findings regarding the style and rate of movements of South Peak are slowly coming available. While the sensors are enabling a detailed understanding of the patterns of the very slow movement, the remote-sensing studies are now allowing for a new appreciation of the movement trends of the South Peak rock mass as a whole.

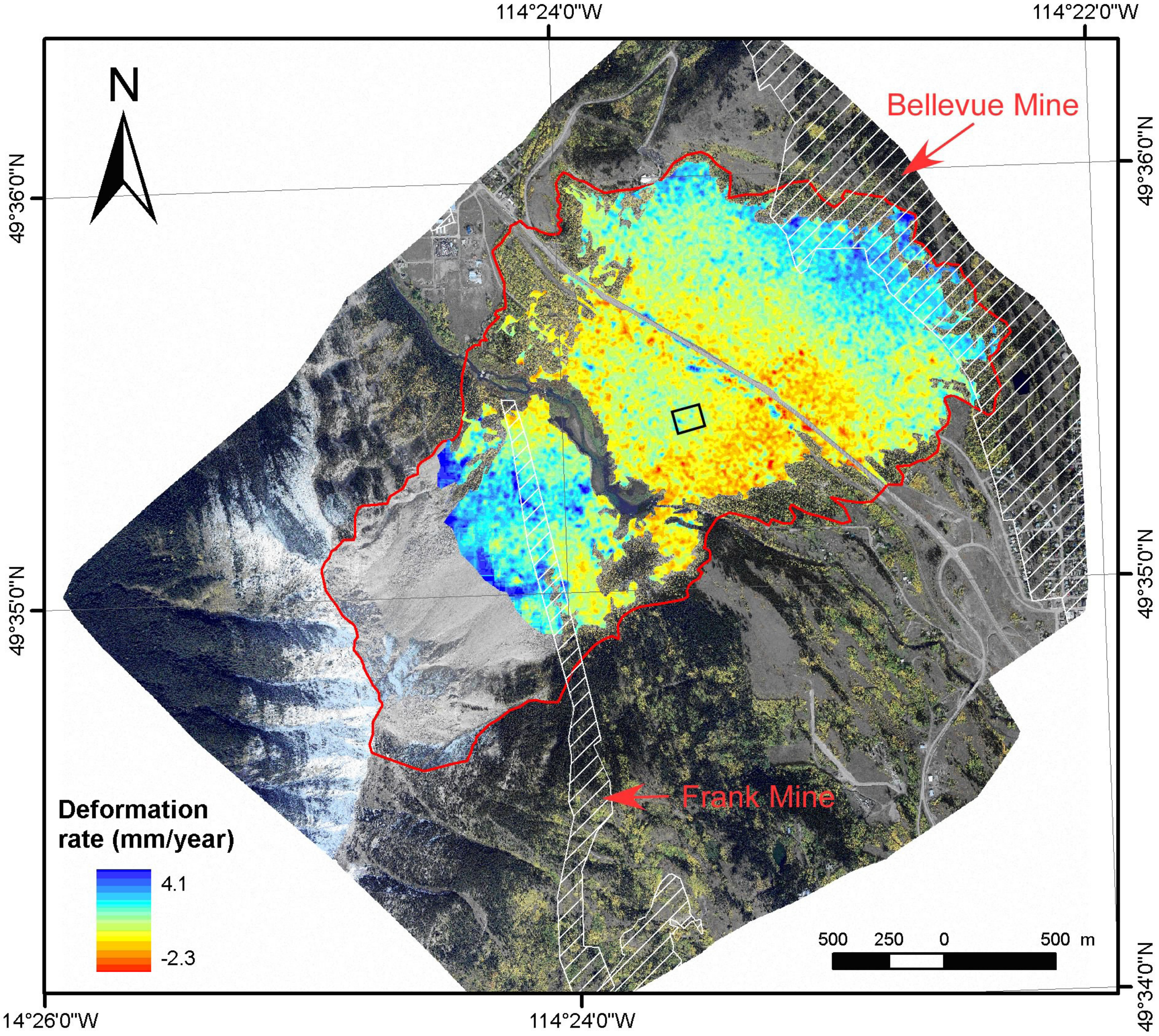

Figure 21. Deformation pattern of the lower part of Frank Slide. The area marked by white strips indicates the location of underground coal mines. The red line outlines the Frank Slide boundary and the black rectangle denotes the reference area (from Mei et al., 2007).

From the sensor network, cumulative movements of up to 0.4 mm were reliably observed in 2006 on the crackmeters as a result of a combination of both sudden and seasonal thermal fluctuations. When combined with results from historic monitoring points, as reported by Moreno and Froese (2006), these results are consistent with long-term deformations along the network of deep fissures along the west side of South Peak. Historical monitoring has highlighted movements up to many millimetres to the west and north of the peak.

Perhaps some of the most exciting findings from 2006 are from the use of digital elevation models, derived from both photogrammetry and LiDAR, as means to derive structural measurements and visual observations. In particular, the initial review of the LiDAR data has lead to revised interpretations of the mechanisms for movement on South Peak, which has then lead to a re-interpretation of the monitoring results. In addition, new directions for studies in 2007 are formulated based on these new findings.

Additional data from 2006 demonstrate that the InSAR is most effective when used to map deformations on the lower slopes and valley bottom but is severely limited in the upper portions of the mountain. Deformations associated with subsidence of the ground over abandoned coal mines with a magnitude of up to 4 mm/year were observed for a time period between April 2004 and October 2006.

To continue increased understanding of the style of movements on South Peak and the extent of the landslide hazard on Turtle Mountain, the following activities have been planned and studies initiated for 2007:

1. detailed geological mapping of Third and South Peaks, including the lower slopes, in order to define potential zones of movement in areas highlighted by the LiDAR studies (this work will be done by AGS and the University of Lausanne, Switzerland)
2. completion of the continous dGPS and EDM network installations during the summer of 2007 and initiating data review by the end of 2007 (this work will be completed by McElhanney Engineering of Vancouver, B.C.)
3. installation of a network of periodically read dGPS monuments and support for a graduate student in Geomatics Engineering at the University of Calgary review and interpret trends
4. completion of additional structural studies with the airborne LiDAR data to better understand the structural controls on instability on Turtle Mountain
5. the obtainment of updated studies as to potential rock avalanche run-out for a failure of South Peak based on updated models developed Oldrich Hungr of the University of British Columbia
6. continued work with the Municipality of Crowsnest Pass and other levels of government on emergency response planning and risk communication

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