

Turtle Mountain Field Laboratory, Alberta (NTS 82G): 2009 Data and Activity Summary

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Abstract

Since 2005, Turtle Mountain has been the site of ongoing monitoring and research focused on understanding the structure and kinematics of movements of the unstable eastern slopes. As this site provides a rich dataset and optimal conditions for the application of new and evolving warning and characterization technologies, the site has been termed the ‘Turtle Mountain Field Laboratory’ (TMFL). This report provides a summary of both the results and the lessons learned from the Turtle Mountain Monitoring System (TMMS) and from studies undertaken by the Alberta Geological Survey (AGS) and collaborators between January 1 and December 31, 2009.

The Turtle Mountain Monitoring System (TMMS) is a near–real-time monitoring system that provides data from a network of more than 80 geotechnical sensors on the South Peak of Turtle Mountain (site of the 1903 Frank Slide) in the Crowsnest Pass. As of April 1, 2005, the Energy Resources Conservation Board (ERCB), through Alberta Geological Survey (AGS), took ownership of this system and the responsibility for long-term monitoring, interpretation of data and notification of the Alberta Emergency Management Agency (AEMA) should significant movements occur.

As part of this responsibility, AGS performs an annual detailed review of the data stream. To help in this interpretation, AGS initiated specific studies to understand better the structure of the mountain and its relationship with the style and rate of movement seen in recent and historical deformations of South Peak. These studies also define better the unstable volumes from the South Peak and Third Peak areas.

This report comprises three main sections:

Section 2 contains information about the major changes to the physical sensor network of the monitoring system during the summer of 2009. This includes a review of the main repair and maintenance activities, a summary of new installations and a summary of system performance and reliability.

Section 3 provides interpretations of slope conditions and displacement behaviour from instrumentation results. Since climatic factors have affected some of the sensors, this discussion focuses only on the sensors that have provided reliable annual data. Meteorological data receive special attention because they have been essential in explaining general displacement trends observed in the surface instrumentation. In general, near–real-time data continue to show trends related both to seasonal thermal cycles and to slow, long-term creep of the South Peak mass. The observed trends highlight very slow movement along the deep fractures on the west side of South Peak, on the order of less than a millimetre/year.

Section 4 focuses on results from the most recent studies, including 1) preliminary results of the ground-based interferometric synthetic aperture radar (GB-InSAR) monitoring system installed to map displacements on Turtle Mountain, 2) an update on the displacement trends revealed by a series of eighteen points as part of a periodic GPS monitoring system, and 3) an update on continuing detailed geological and structural mapping on South Peak and in nearby areas.

From a risk-management perspective, the ERCB and provincial and municipal emergency-response officials still consider that a single large failure event is the basis for planning of evacuations and road closures. Sensor networks installed by AGS and contractors during the past three years continue to be used to distinguish between the zones of movement and to define incremental-failure scenarios versus single-failure scenarios.

1 Introduction

In 2005, 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). 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 available to the research community all data from the TMFL, which will 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, thereby 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 http://www.ags.gov.ab.ca/geohazards/turtle_mountain/turtle_mountain.html.

This yearly report provides 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 the 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 provides an overview of various supporting studies undertaken in 2009 and new findings relevant to the understanding of the movements on South Peak.

2 Sensor Network Activity

This section provides an overview of the major upgrades, and repair and maintenance activities on the sensor network of the monitoring system during 2009. Documentation of the hardware that makes up the various components of the communication stations was provided in Moreno and Froese (2006, 2008a) and is therefore not included in this summary.

The main activities undertaken with respect to the sensor network during 2009 included

- replacement of damaged sensors due to the lightning events of May, July and September 2009;
- upgrade of the power-supply system at the borehole station; and
- installation of a back-up access link at the South Peak site for the existing differential Global Positioning System (dGPS) monitoring network.

The following sections provide a brief overview and photographs of these activities. Figure 2 provides an overview of the sensor-network layout as of December 2009.

2.1 New Installations

2.1.1 *Secondary Access for Continuous-Reading dGPS Monitoring Network*

Most of the sensors installed on the mountain (crackmeters, tiltmeters and extensometers) have high resolution but a limited working range; thus, they can only be used as the primary tools for characterizing areas of known movement. On the other hand, the dGPS units have the ability to measure large displacements; hence, they can also be considered a critical element in providing warnings. This will be especially true at the final stages of the slope failure, when large movements can be expected.

At present, the main connection between the continuous-reading dGPS monitoring network and the Turtle Mountain network is via a 5 GHz point-to-point link between the radio tower on the west side of South Peak and the Provincial Building in Blairmore. Data collected by the dGPS units on the mountain are streamed in real time, via this link, to a processing server in Kelowna (NavStar Ltd. office).

This link has worked very well since installation in 2007 (Moreno and Froese, 2008b). Nevertheless, since it is a critical tool in providing warnings, it was desirable to have a back-up link to ensure a continuous data stream in all weather conditions. Therefore, in the summer of 2009, a new back-up link was established through South Peak. This link uses the existing power and radio connections set up for the South Peak web camera. Figure 3 is a schematic diagram of the data flow for the dGPS system.

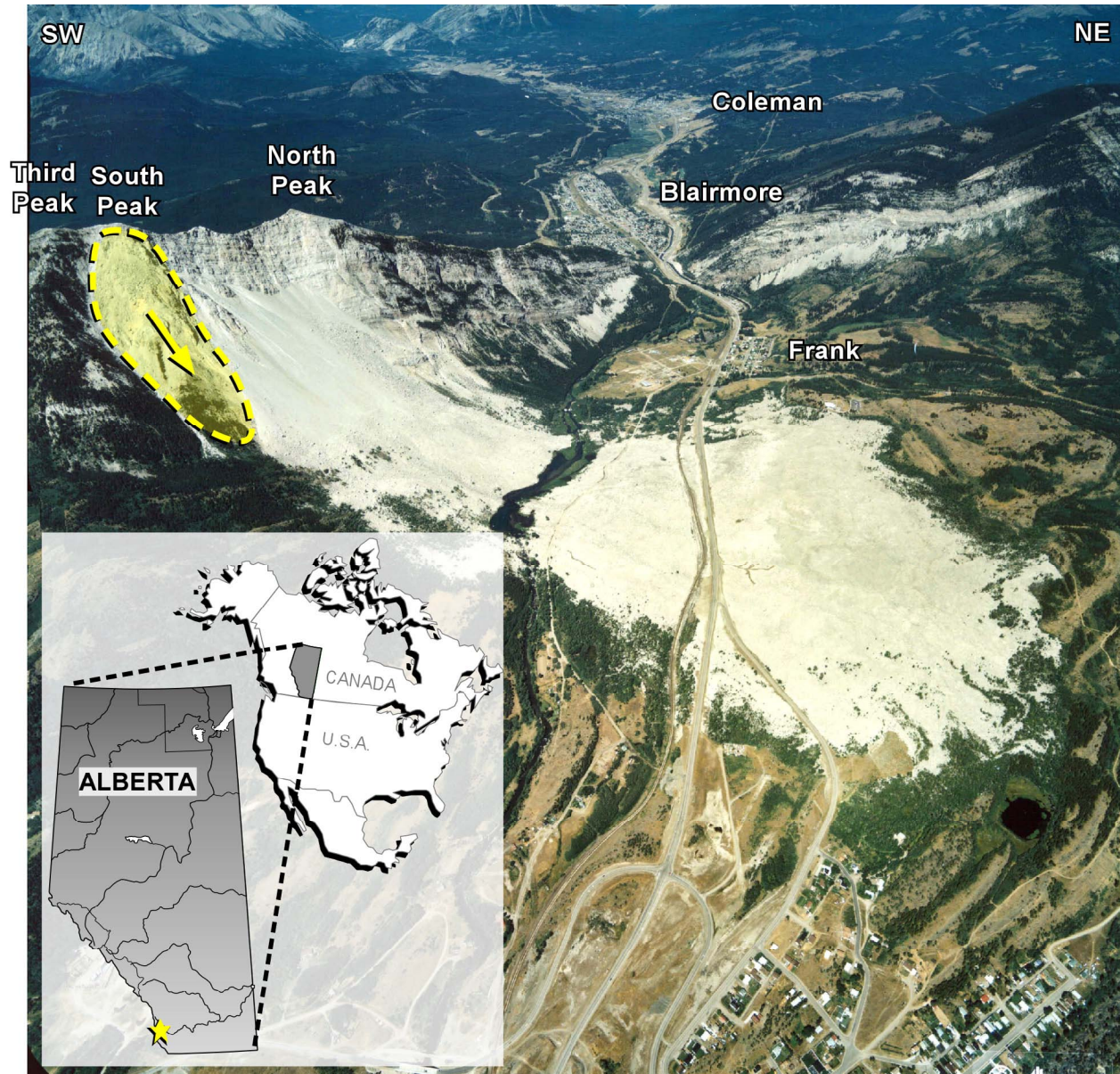


Figure 1. Location of Turtle Mountain in southwestern Alberta and full-extent aerial view of the Frank Slide. The dashed line below South Peak outlines the area identified by Allan (1931, Figure 2) as being most unstable. Photo reproduced with permission from Alberta Sustainable Resource Development, Air Photo Distribution. Image owned by the Government of Alberta and protected under the Copyright Act of Canada.

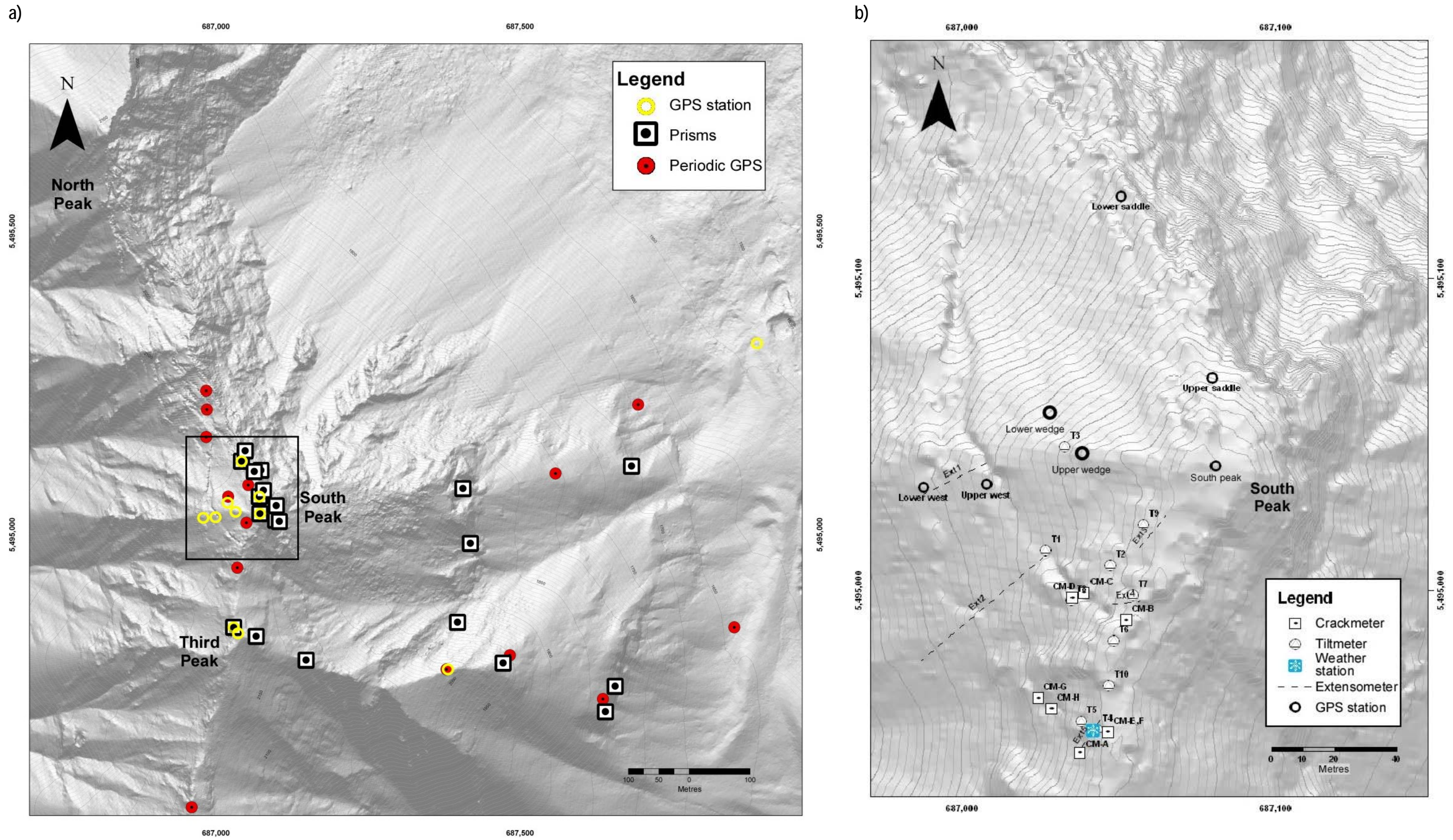


Figure 2. Overview, as of December 2009, of the monitoring network on a) Turtle Mountain as a whole, and b) South Peak of Turtle Mountain in particular, southwestern Alberta.

2.2 Performance

The primary deformation-monitoring system (crackmeters, extensometers and tiltmeters) performed reliably during the reporting period. Based on inspection and modification of these systems during the summer of 2009, we can make the following summary statements:

- After several years of operation under the particularly harsh and highly variable climatic conditions on Turtle Mountain, the power-supply systems in 75% of the monitoring and data-recording stations have started to show signs of deterioration. Most of the batteries are more than four years old and have likely reached the end of their useful life. In one case (borehole station), the situation was so critical that the system had difficulties generating enough power to operate the communication equipment. This station operated intermittently throughout the winter and finally shut down in May 2009. The power system at the borehole station was therefore upgraded in the summer of 2009. This included removing the old batteries and solar panel, and replacing them with new ones. All other aging power-generating equipment will be replaced during the summer of 2010.
- In spite of major refurbishment of the crackmeter roofs in June 2008, snow or ice loading continues to affect several of the 22 crackmeters. However, most of the crackmeters installed are located within the subsidence zone on the west side of South Peak. The majority of this blocky mass is moving downward into the void created by the toppling zone and the moving wedge (Figure 4). As such, we expect these blocks to shift very slowly; therefore, any movements within this zone will be difficult to record. As a result, we decided to stop any maintenance work on the protective roofs installed over most of the crackmeter arrays. Maintenance work will continue only on those sets that have provided the most indicative record of displacement (sets B and C).
- Lightning activity continues to be the main cause of sensor damage. During 2009, a higher-than-average number of lightning events was recorded. This included three damaging lightning strikes during May (8, 9 and 14), one on July 11 and one on September 20. In total, these events damaged more than 20 sensors. In spite of this, the system continued to provide continuous high-quality data. This can be attributed to the large number of monitoring points available on Turtle Mountain, which provide redundant measurements.

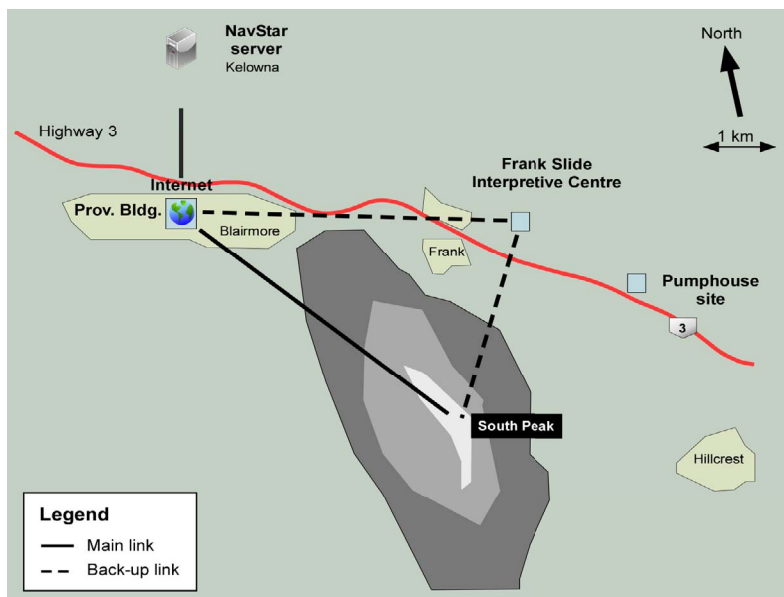


Figure 3. Generalized data-flow model for the continuous-reading dGPS monitoring network on Turtle Mountain, southwestern Alberta.

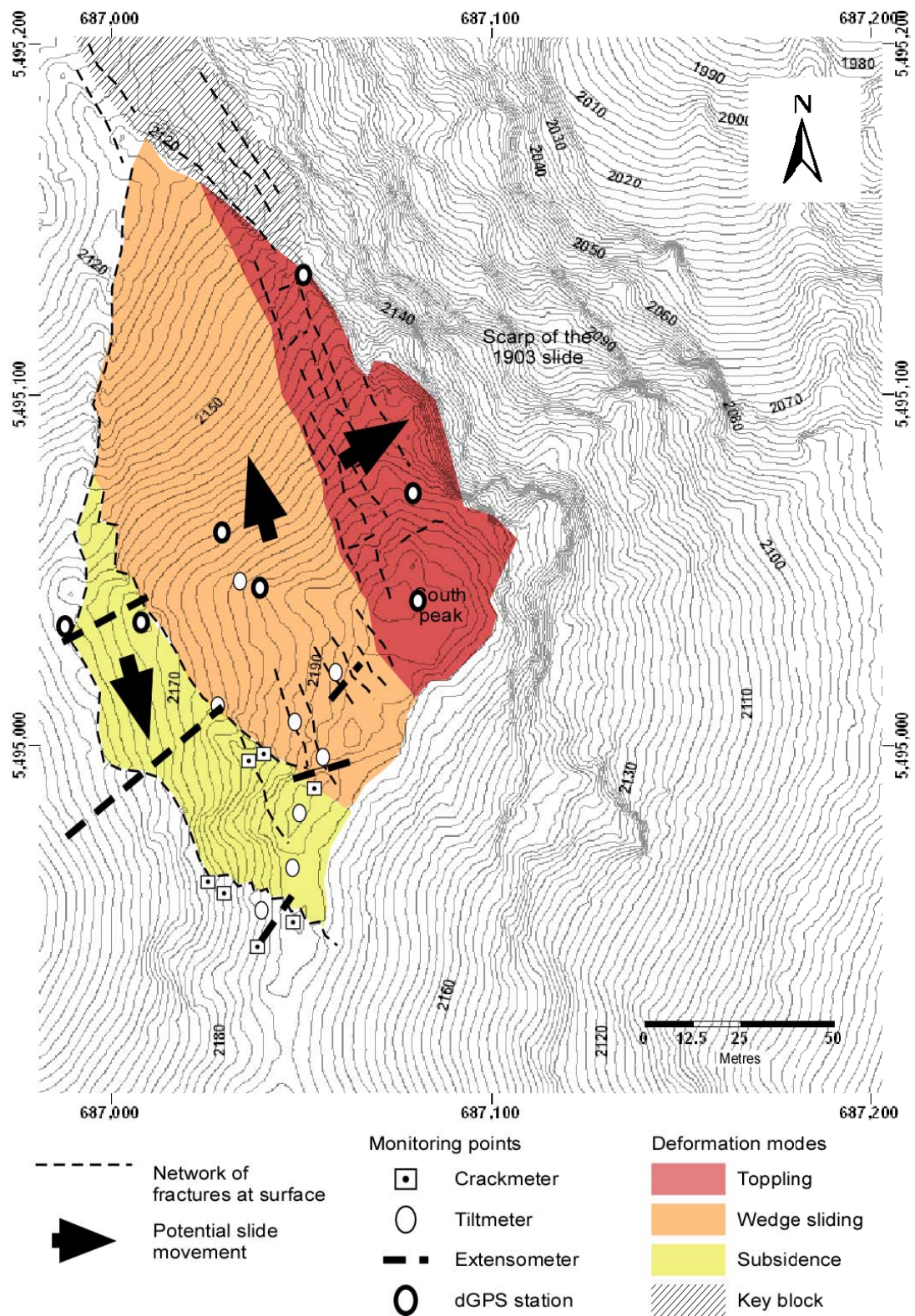


Figure 4. Location of monitoring points relative to the main zones of deformation observed on the South Peak of Turtle Mountain, southwestern Alberta.

- Expertise recently developed in house has also contributed to the increased reliability of the system. These skills were acquired through training and are focused primarily on sensor troubleshooting and installation. This has allowed us to do our own repairs, thus considerably reducing downtime on damaged sensors. In the past, all repairs had to be done through contractors, and many times this help was not readily available.
- Lightning-protection options implemented at the South Peak camera have worked well. Despite numerous lightning strikes throughout 2009, the equipment suffered only minor damage. The Bellevue camera also performed well during the reporting period, although this camera is at the bottom of the mountain, a location that has proven less susceptible to lightning strikes.

3 Data Analysis

Continuous slope monitoring is very difficult in the particularly harsh and highly variable climate conditions at Turtle Mountain. Several factors affect the normal operation of the instruments, including atmospheric events such as rain, snow and lightning. The effect of these factors on the instruments varies widely, and can range from introducing large reading errors to making instrument reading impossible.

This section provides interpretations of slope conditions and displacement behaviour based on instrument results, with a focus on only those sensors that operated normally during the reporting period.

3.1 Deformation Monitoring Data

3.1.1 Crackmeters

The continuously recording crackmeters serve to determine whether the surface fractures open at constant rates or if fracture opening occurs rapidly in one event. However, as already stated in Section 2.2, these sensors are prone to snow or ice loading, which introduces large errors in the readings. Therefore, discussion of displacements is limited to only those arrays that are known to have operated normally (sets B and C).

These instruments provide time series of crack opening and temperature over a period of five years (Figures 5 and 6). Monitoring results show diurnal and annual cycles that correlate with air-temperature cycles. The annual cycles exhibit an active phase, with displacements occurring in early autumn to late winter, and a relatively inactive phase, with limited to no displacement in spring to late summer. Instruments in set B have recorded displacement rates of up to 0.4 mm/year and crack-width changes, related to daily air-temperature cycles, of approximately 0.02 mm.

The fracture-opening measurements from crackmeter set C (Figure 6) also show the very slow long-term trend seen in set B (Figure 5). Examination of the records shows a mean annual displacement rate of <0.4 mm/year, which, as is the case with set B, most likely reflects fracture opening due to air-temperature seasonal changes.

3.1.2 Tiltmeters

The results from the tiltmeter network are important because they allow an understanding of the rotating component of the displacements. This system, consisting of 10 sensors, was installed during 2005 by AMEC Earth and Environmental (2005). The sensors are located in two clusters, one at the sliding wedge and the other at the subsiding zone behind the sliding wedge (Figure 4). Spatial coverage is therefore limited, with no sensors situated within the most active part of the rock mass at the northeastern part of South Peak. Figure 7 shows the monitoring results between 2005 and 2009. About half of the sensors show the effects of high humidity inside the instrument enclosure, making the interpretation of small rotations very difficult. In spite of this, some trends can still be identified. In general, all sensors show

annual fluctuations, but with no long-term cumulative rotations, and diurnal fluctuations associated with daily air-temperature cycles.

Small rotations are found in tiltmeters T-1 and T-3 (Figure 8), with the magnitude and rate of rotation at each station remaining essentially constant for the five-year span of monitoring. This implies that the pattern of deformation of the rock mass has been constant, which is consistent with the trends seen in the crackmeter data.

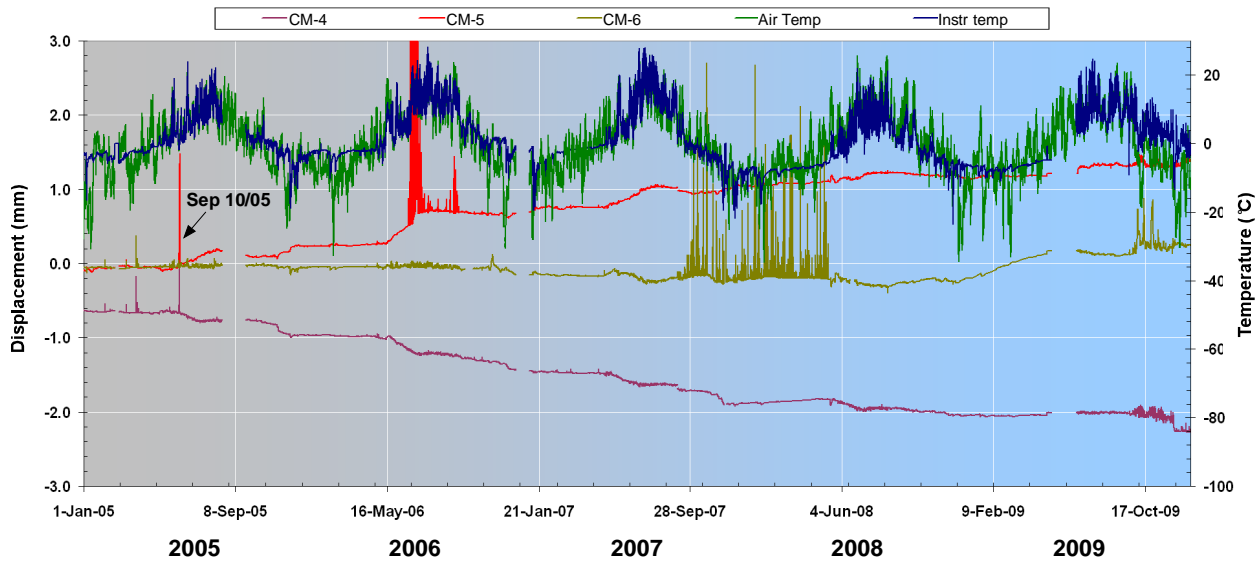


Figure 5. Plot of displacement versus time for crackmeter set B, South Peak, Turtle Mountain.

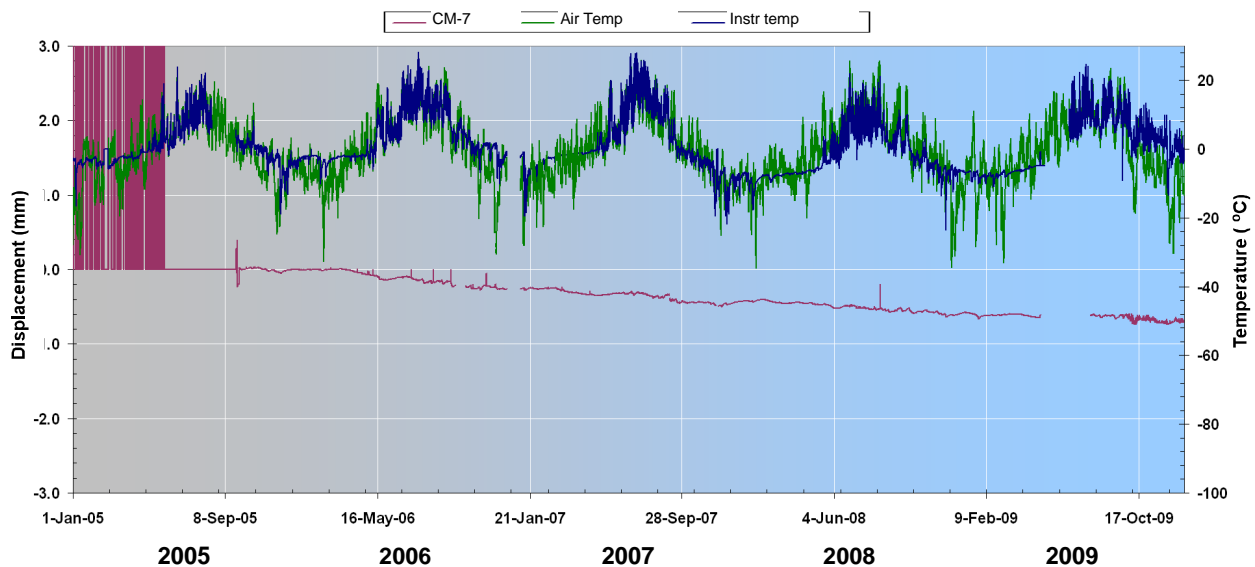


Figure 6. Plot of displacement versus time for crackmeter CM-7 of set C, South Peak, Turtle Mountain.

3.1.3 Extensometers

Displacement versus time plots for all extensometers do not show the cyclical daily and annual fluctuations observed in crackmeter and tiltmeter data (Figure 9). This noticeable difference likely arises from the difference in resolution between the sensor types, with resolution in extensometers being two orders of magnitude lower than that of the crackmeters. Extensometers 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 2005 and early September 2005; Moreno and Froese (2006) discussed the specifics of these events. In addition, the displacement versus time plot in Figure 9 shows a number of transient jumps or steps recorded by sensors EX-4 and EX-5; however, these events are believed to be

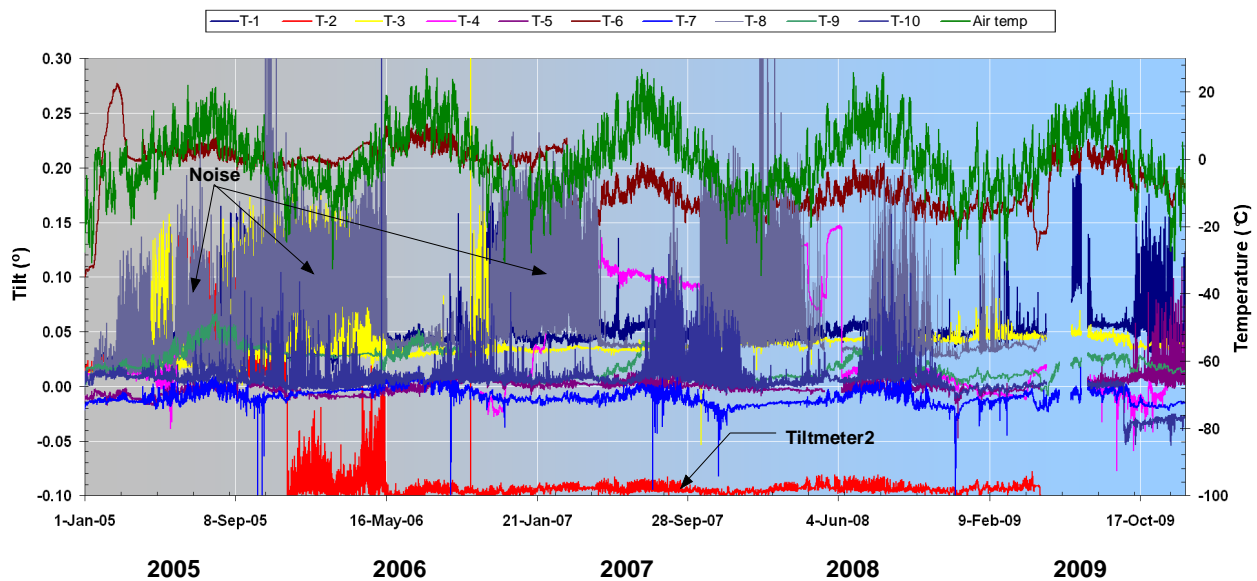


Figure 7. Plot of tilt versus time for tiltmeters, South Peak, Turtle Mountain.

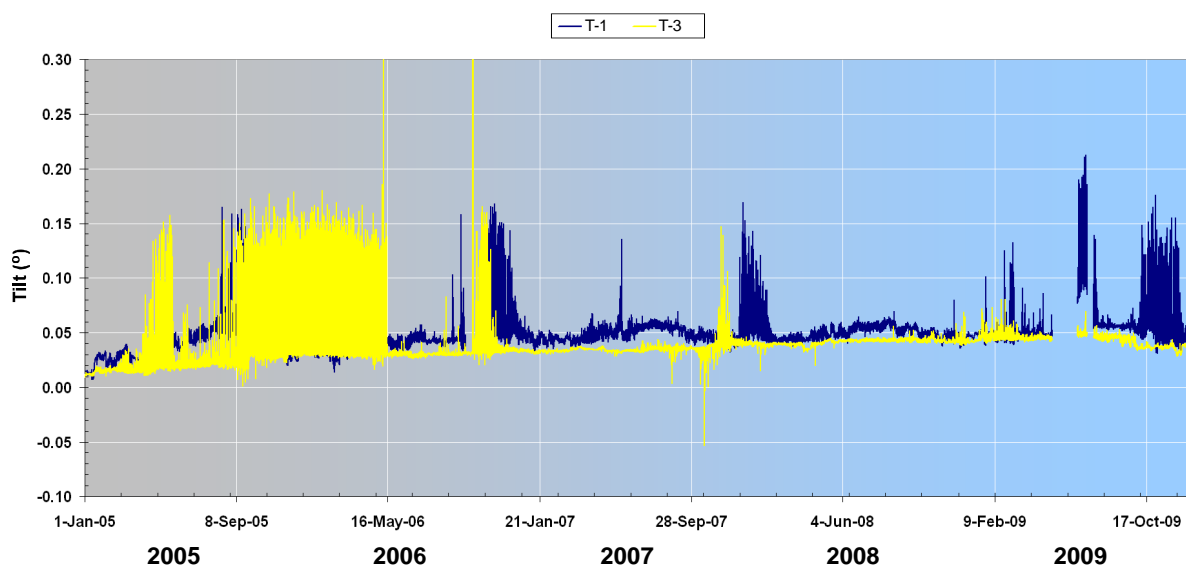


Figure 8. Plot of displacement versus time for tiltmeters T-1 and T-3, South Peak, Turtle Mountain.

associated with sensor drift rather than rock displacement. The exact cause of such deficiency has yet to be determined, but we believe that it will not affect the sensors' ability to measure real deformations.

3.1.4 Continuous-Reading dGPS Monitoring Network

To determine the detailed history of displacements on active fractures, six single-frequency dGPS stations were installed near prominent fractures (Moreno and Froese, 2008a). These Novatel SuperStar II dGPS units have a resolution in the millimetre range in the horizontal direction and in the centimetre range in the vertical direction. Later in 2008, this network was complemented with four dGPS stations, two on South Peak and two on the middle to lower part of the eastern slope below South Peak (Figure 2).

This was done to monitor displacements in areas with the largest movements (South Peak vicinity) or suspected movements (eastern slope) but no previous monitoring (Moreno and Froese, 2009).

The monitoring results from the dGPS stations are shown in Figure 10. Measurable displacement rates can be seen only at the Lower saddle and Upper west stations. Annual displacement rate at the Lower saddle station ranges mainly between 0.5 mm and 2 mm/year, which is consistent with previous photogrammetric monitoring (Moreno and Froese, 2006). However, measured displacement orientation appears to conflict with the postulated deformation direction for this part of the mountain (Figure 4). One must consider that measured movement directions will be controlled by local topography and slope aspects on which the monitoring points are situated. As a result, displacement direction measured at some local points may differ from the overall area displacement direction. On the other hand, the Upper west station indicates a displacement of more than 6 mm. This is almost certainly incorrect and likely related to a poorly constructed concrete pillar. A detailed on-site inspection of the pillar revealed evident signs of deterioration; also, the pillar is on a heavily broken rock. This material can be very susceptible to freeze and thaw events, which can result in large local displacements.

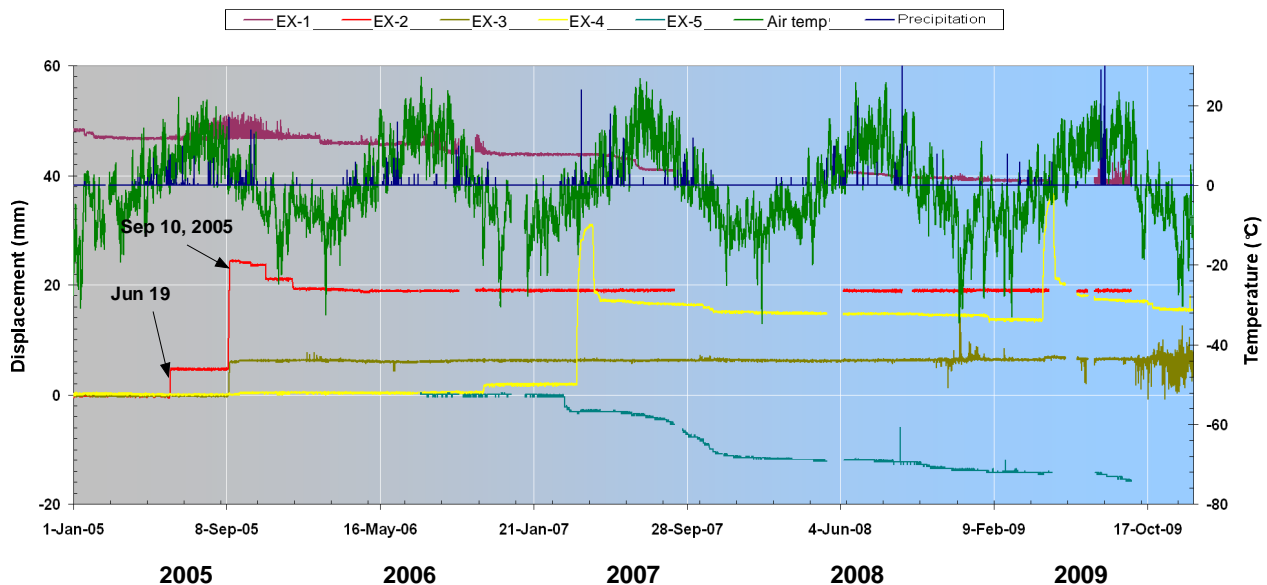


Figure 9. Plot of displacement versus time for extensometers, South Peak, Turtle Mountain.

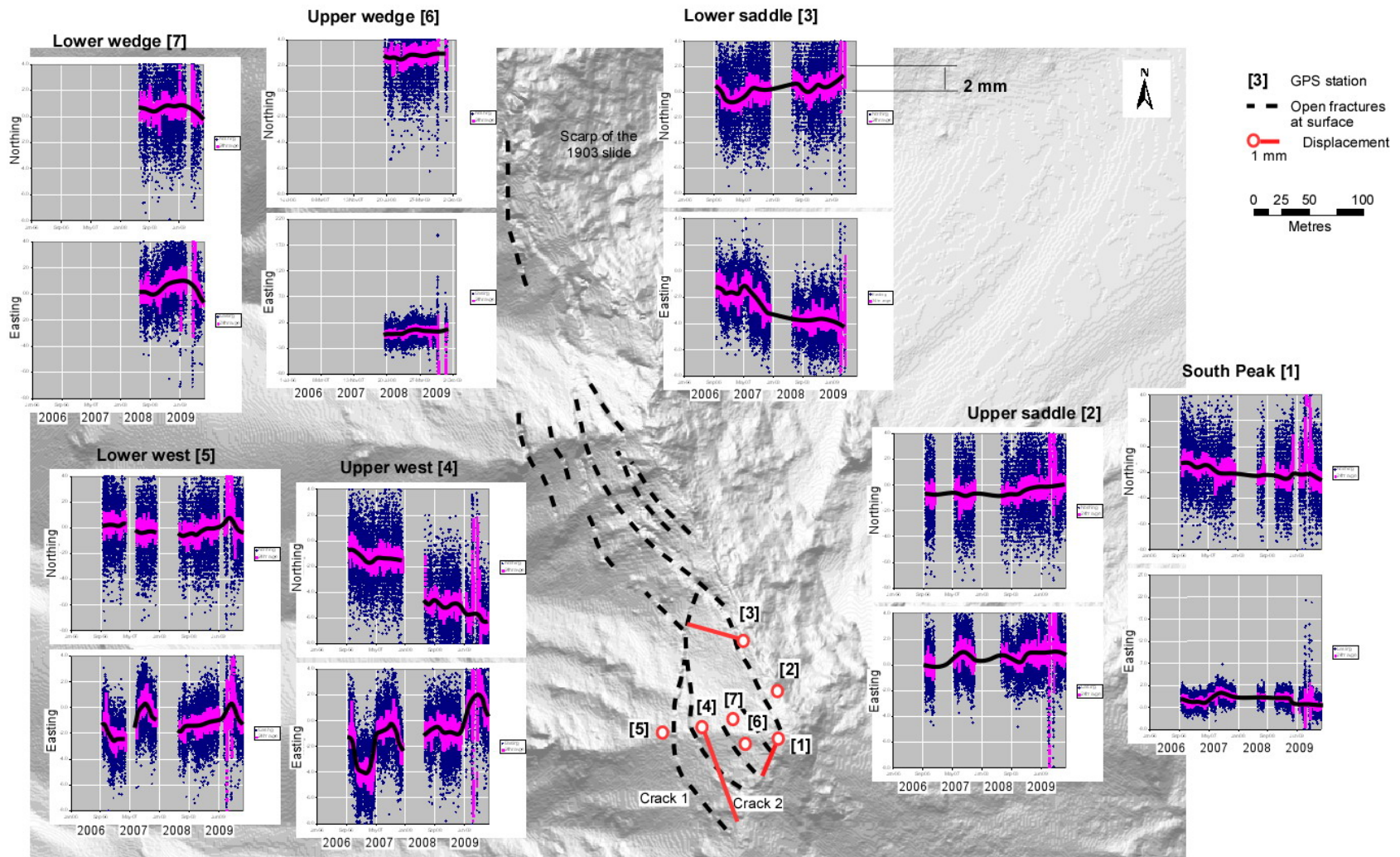


Figure 10. Surface displacements derived from dGPS stations during the period 2006–2008: horizontal component of the surface-displacement vectors (red lines) plotted on a map of the South Peak of Turtle Mountain. The displacement vectors of the dGPS stations are absolute, since they are referenced to an external co-ordinate system. dGPS stations: [1] South Peak; [2] Upper saddle; [3] Lower saddle; [4] Upper west; [5] Lower west; [6] Upper wedge; [7] Lower wedge.

3.1.5 Electronic Distance Measurement (EDM) System

As discussed in Moreno and Froese (2008b), twenty prisms were installed during the summer of 2007. Figure 11 shows the results of the fifteen months of available data. In general, all records show evidence of the annual displacement fluctuation seen most clearly with the crackmeters. However, with the exception of prism PR-15, it is not possible to give a definite magnitude and direction of displacement at this time due to the small scale of the displacements measured. We need data over a longer period of time to resolve any trends.

From May 2008 until October 2008 and from May until November 2009, the system underwent major software upgrades. During this period, data were used only for testing and therefore not written to the main database.

3.2 Other Monitoring Data

3.2.1 Climatic and Thermistor Data

Lower maximum (+23.5°C) but higher minimum (-32.8°C) temperatures than in previous years (Figure 12) were recorded at the top of the South Peak of Turtle Mountain. Significant daily temperature variations were also common. Rock temperature showed the same general trend as air temperature but was more subdued (lower maximum and higher 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 down 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).

Above-normal precipitation during the reporting period was recorded on the South Peak of Turtle Mountain. Total precipitation in 2009 was 432 mm, 9% greater than the average annual precipitation of 397 mm, which is based on data measured between 1971 and 2000 at the nearby Coleman weather station of Environment Canada. Winter precipitation was below normal (Figure 13), whereas above-normal precipitation was recorded during early spring. Precipitation activity well below normal was seen during

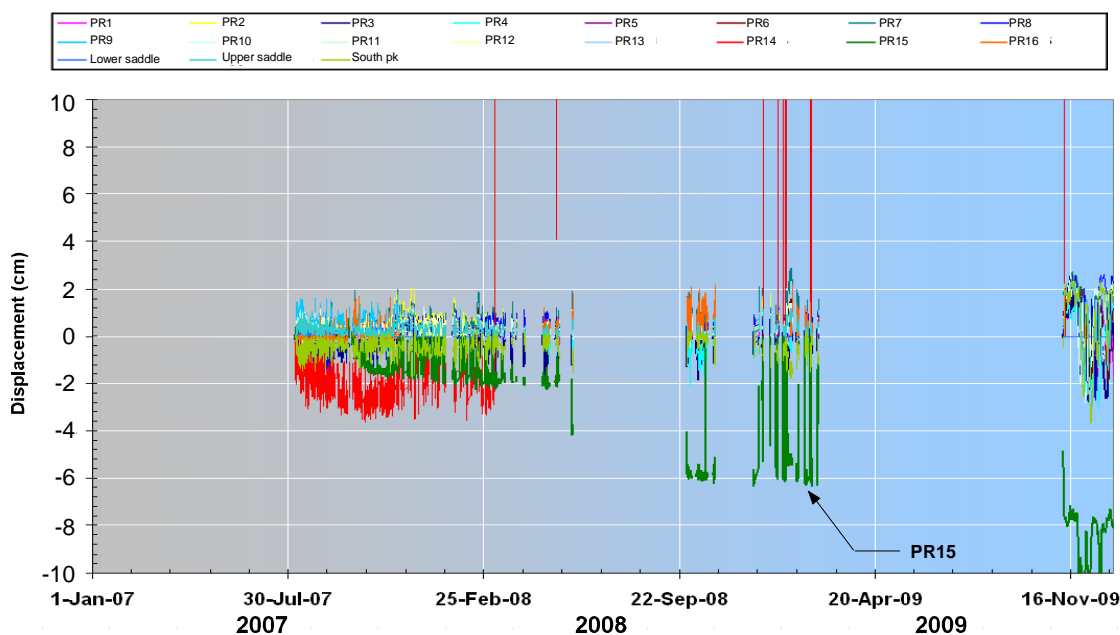


Figure 11. Plot of displacement versus time for prisms at Turtle Mountain.

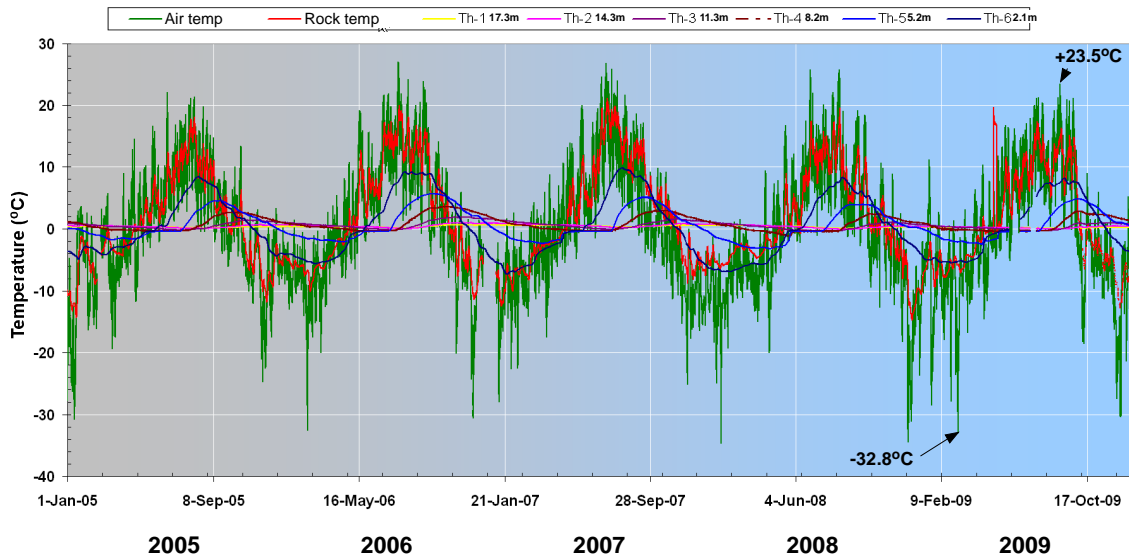


Figure 12. Air temperature and variation of rock temperature with depth in the borehole at the top of South Peak, Turtle Mountain, 2005–2009.

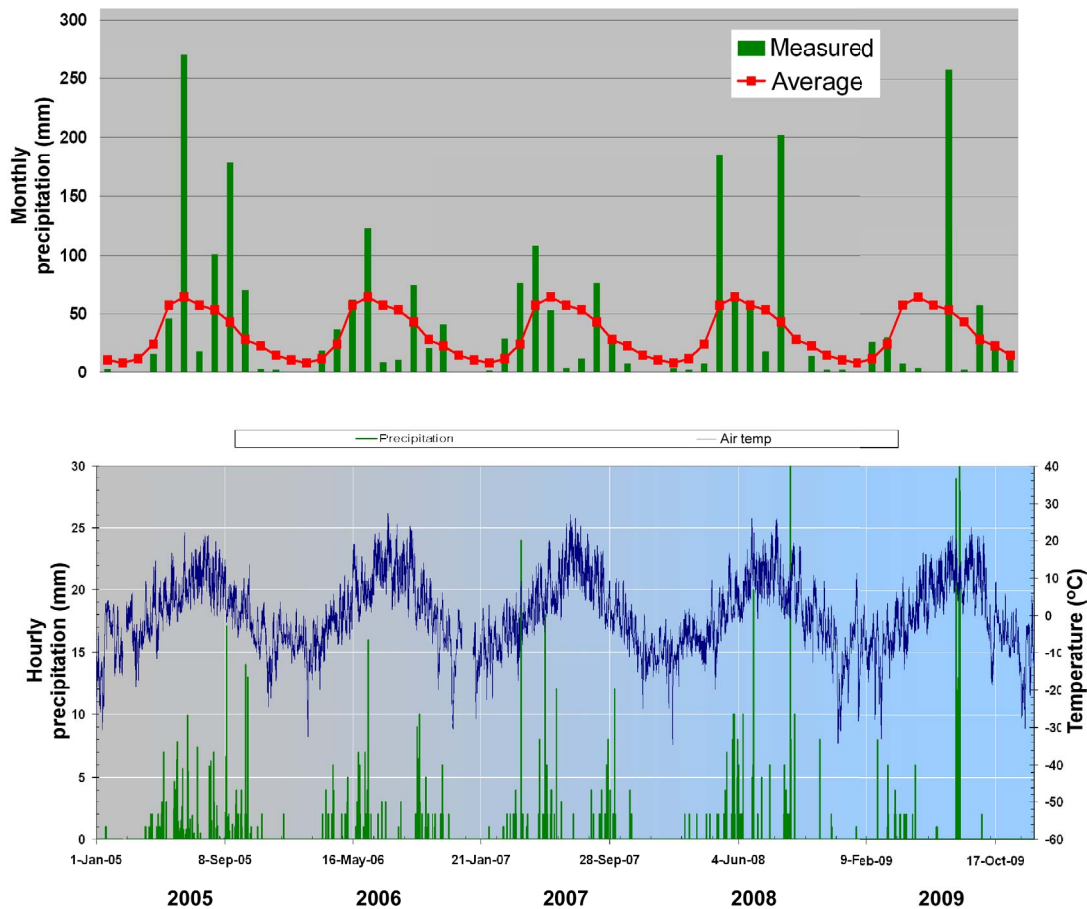


Figure 13. Measured and average monthly precipitation (top), and temperature and hourly precipitation (bottom) near Turtle Mountain, 2005–2009.

late spring, which brought the overall precipitation during this season to below-normal values. Precipitation was normal to below normal for much of the summer but increased significantly after August 1. Above-normal precipitation was recorded during the fall months (September, October and November).

3.3 Discussion and Interpretation of Monitoring Data

During the five to six years since the installation of most of the sensors, new studies have updated our understanding of the complex slope deformations on South Peak. The model proposed by Froese et al. (2009) indicates that South Peak is moving as three different masses: a toppling zone, with blocks moving to the east; a wedge zone that is sliding to the northeast; and a subsidence zone that is moving predominantly downward and to the west. The subsidence zone comprises the heavily fractured area on the west side of South Peak, where the majority of the sensors have been located. The new understanding of the kinematics of these three separate masses has enabled a more critical evaluation of the movement trends measured by the sensors. This section is a discussion of the specific sensor trends in relation to the expected deformations.

3.3.1 Crackmeters

The time-series data of crack opening and temperature for the crackmeters deployed at Turtle Mountain have been described in Section 3.1.1. The displacement measurements exhibit diurnal and annual cycles, which correlate with temperature cycles and are probably of thermoelastic origin.

3.3.2 Tiltmeters

As with the crackmeters, most of the tiltmeters are in the subsidence zone. Therefore, we expect these sensors to register small displacements over time. Unfortunately, most of the tiltmeters display different degrees of noise in their readings (Figure 7), which makes the small displacements almost impossible to detect.

3.3.3 Extensometers

The five extensometers do not have the same fine level of resolution as do the crackmeters and tiltmeters, so they are sensitive only to large movements (many millimetres to centimetres). In addition, the installation of these sensors in the summer of 2004 preceded the updated understanding of deformation kinematics on South Peak. These sensors measure only the component of displacement in the line of the sensor, but the movement in some cases is expected to be at oblique angles to the orientation of the extensometer. Therefore, we expect these sensors to identify movements only during very large movements.

Figure 4 shows the hypothesized direction of movement for the various zones on South Peak in relation to the orientations of the five extensometers. It suggests that the displacement events related to rainfall/freezing in 2005 and 2006 (Moreno and Froese, 2006, 2008a) may have been larger than originally reported. Of the five extensometers, EX-1 likely provides the most promise for mapping deformations across the various zones identified on South Peak by Froese et al. (2009), as it is anchored on the 'stable' portion of the mountain, with the head assembly on the large wedge. Although the sensor is oriented at an oblique angle to the expected direction of movement, it should provide an indication of deformations of the wedge, along with the other sensors.

3.3.4 Continuous-Reading dGPS Monitoring Network

In contrast to the previous three sensor types, many of the more recent dGPS stations have been installed based on the updated understanding of the deformation mechanisms on South Peak and on other portions of the eastern face of Turtle Mountain. In most reported applications of GPS monitoring to landslides, the

relative displacements accrued were in the centimetre range. At South Peak, however, the annual displacements across fractures are only a couple of millimetres, so most of the measurements observed on the dGPS stations are within measurement error. We expect that deformations will continue to be sufficiently small that additional years of data will be required to identify clear trends.

3.3.5 *Electronic Distance Measurement (EDM) System*

As with the dGPS and discussed in the previous section, we do not expect any trends to be apparent at this time due to the relatively low resolution of the EDM system and the slow rate of movement of those parts of the mountain on which the prisms are located. The trend shown by prism 15 is a reflection of the very unstable block on which the prism was located, on the head of the 1903 slide. We expect that this trend will continue until the block breaks away and falls into the Frank Slide debris below.

4 Supporting Studies and Research

4.1 Ground-Based InSAR

Each year, numerous sensors are lost due to lightning strikes and other factors. In addition, a number of the sensors have a limited working range, which could be easily exceeded in the event of large deformations prior to a slide. This can lead to a monitoring system that can no longer provide useful information. For this reason, AGS continues to test new monitoring techniques that can offer a reliable system under all conditions.

One of the new techniques being evaluated is ground-based interferometric synthetic aperture radar (GB-InSAR). This is a system that uses radar to map ground movement. It is fundamentally identical to satellite-based InSAR (Mei et al., 2008) but, instead of acquiring the images from several hundred kilometres away, the images are acquired by a radar unit moving along a rail set up within a few kilometres of the area being monitored. The satellite-based system collects images every few weeks, whereas the ground-based system can acquire images as often as every five minutes. This allows continuous monitoring of movement ranging in velocity from millimetres/year to metres/hour. The working range is up to 4 km along line of sight.

On September 16, 2009 an IBIS-L GB-InSAR system (IDS SpA), owned by the Geotechnical Engineering Department at the University of Alberta, was installed at the Bellevue pumphouse (Figure 14). The system acquired images every 12 minutes, nearly continuously until November 29, when the system was put into storage for the winter. The system was reinstalled in April 2010 to continue measurements.

Figure 15 presents some of the preliminary monitoring results. The figure shows the results from September 19 to October 19. The upper part of the figure shows a map of the total displacement, and the lower figure shows displacement curves for selected pixels. The total displacement during the first month appears to be ± 20 mm, but the lower part of the figure reveals that most of the apparent large movements were recorded after the first snowfall occurred (October 3, 2009). It is clear that snow will cause a general loss of coherence, which will manifest itself as a false displacement with a random pattern (Figure 15, bottom).



Figure 14. The IBIS-L GB-InSAR system is installed on a rooftop, facing unstable slopes on Turtle Mountain. The farthest point on the mountain crest is approximately 3200 m away.

4.2 Periodic Reading dGPS Monitoring Network

As outlined in Moreno and Froese (2008b), a series of 14 monitoring points was installed by the University of Calgary Geomatics Engineering Department (Teskey and Ebeling, 2008) in May 2007. This network was later augmented with the addition of four target points in 2008. These monitoring points are located in potentially unstable zones highlighted by recent light detection and ranging (LiDAR) studies (Moreno and Froese, 2008b), including portions of the eastern face, below South and Third peaks, and the visibly unstable saddle area between North and South peaks (Figure 2a). The researchers expect this layout will provide the coverage required to obtain a more complete picture of the movement patterns in these potentially unstable areas.

In general, two sets of observations are made every year at all 18 target points, one during early summer and a second in late fall. These readings are taken using two types of device: a high-precision total station (HPTS) and a differential Global Positioning System (dGPS) instrument. An initial set of readings was taken during June 2007, and then repeated in 2008 and 2009. To fully correct for sensor effects, measurements at selected points are taken during every observation campaign. These points are considered stable relative to those on South Peak and are therefore chosen for use as base stations. These readings are used to calculate correction factors, and these factors are then used to correct the measurements on the target points.

Table 1 summarizes the 2007–2009 readings and the number of base stations used.

To determine movements, a multiparameter-transformation (MPT) mathematical model was applied (Teskey and Ebeling, 2009). This model, which relates initial and subsequent readings connecting base

stations and target points, was applied to independently analyze both dGPS and HPTS measurements. The results show that apparent movements calculated at all target points are less than the potential dGPS measurement error, so they cannot be considered as statistically significant (i.e., no movement detected). On the other hand, analysis of HPTS measurements confirms the existence of movements in the saddle area between North Peak and South Peak. These movements are consistent with a slumping and sliding

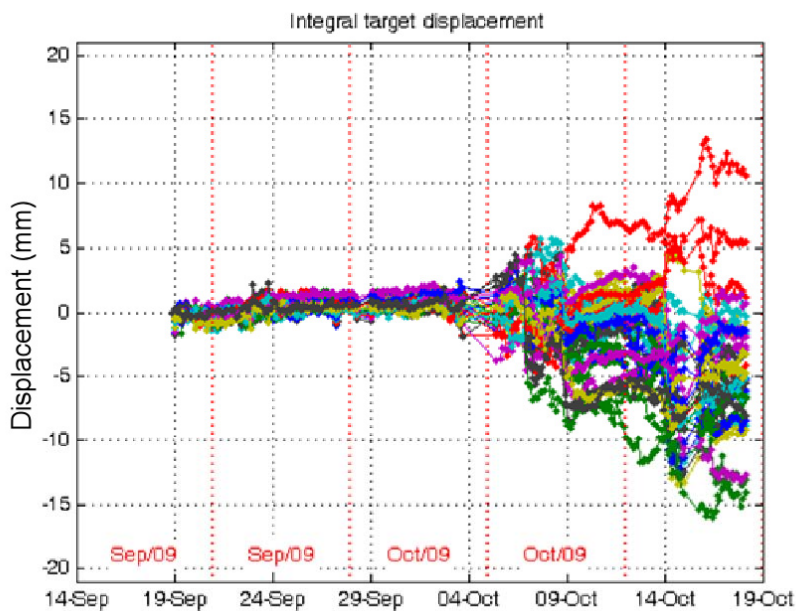
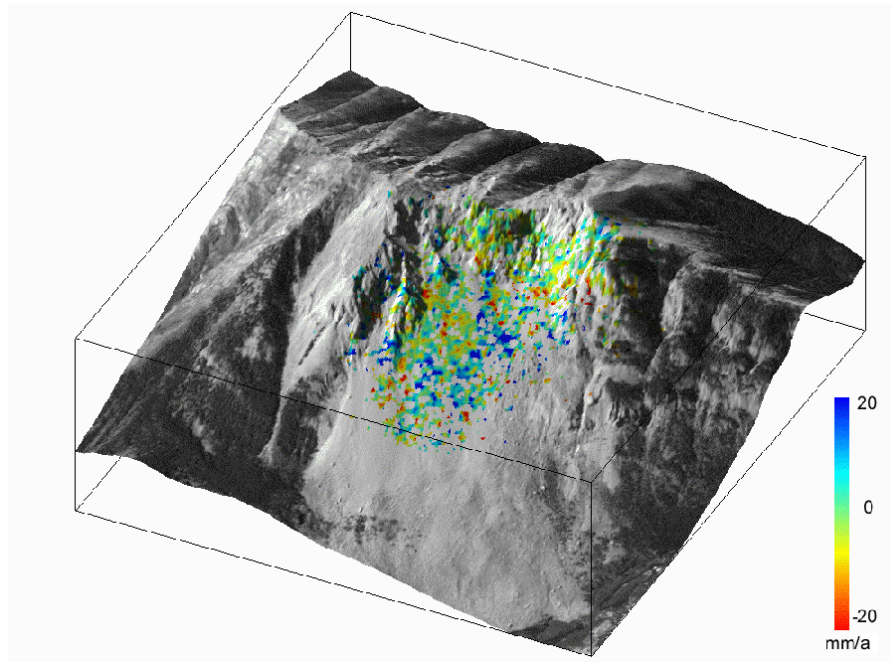


Figure 15. Displacement between September 19 and October 19, 2009. Positive displacements are away from the sensor. Apparent large movements beginning October 3 are due to snowfall.

Table 1. Target point readings during 2007–2009.

Differential Global Positioning System (dGPS)			
Year	Number of Reading Campaigns	Number of Targets Read	Number of Base Stations
2007	2	14	1
2008	2	18 (5) ^(a)	1
2009	1	18	3

High-Precision Total Station (HPTS)			
Year	Number of Reading Campaigns	Number of Targets Read	Number of Base Stations
2007	2	14	2
2008	2	7 ^(b)	1
2009	18	7 ^(b)	3

^(a) Subset of dGPS observations made in September 2008 at target points located in the saddle between North and South peaks

^(b) HPTS observations made only at target points located in the saddle between North and South peaks

movement, and agree quite well with independent tilt measurements taken on target points in the saddle area by Teskey and Ebeling (2009).

Deformation monitoring will continue through 2010 and is expected to go on for years to come. We expect that this continued monitoring will be able to detect movements in future field seasons.

4.3 Hazard Mapping

The structural and geological settings in the South Peak and nearby areas continue to be studied in detail (Humair et al., 2010). The 2009 campaign focused on determining the possible origin of the main discontinuity sets identified in previous field studies (Pedrazzini and Jaboyedoff, 2008; Pedrazzini et al., 2008; Froese et al., 2009). Proper classification of fracture origin is important because these pre-existing features can play different roles in the instability development. Of particular interest is the identification of fold-related fractures, as they are a key factor not only for local-scale instabilities but also for the development of large rock-slope failures. Both of these are generally attributed to fold-induced reduction of rock mass strength caused by damage. The damage is physically represented by weakness zones in the rock mass, consisting of microcracks, mylonitic layers or void areas (Brideau et al., 2009).

Most of the 2009 field survey was carried out on the southern part of Turtle Mountain (Third Peak–South Peak area), where several structural assessments were completed. Supplementary structural assessments were conducted in the Drum Creek area to minimize the potential influence of the Frank Slide movements on identification of the initial fracture development. At each site, the characteristics of the joint sets were measured and the condition of the rock mass described following the methodology suggested by the International Society for Rock Mechanics (1978). The Geological Strength Index (GSI) has been estimated to quantify the rock-mass quality in the different portions of the Turtle Mountain anticline. The GSI results show increasing damage to the rock mass approaching the fold-hinge area due to higher fracture persistence and more intense weathering (Figure 16). However, these are only preliminary results and remain under investigation.

5 Summary and Conclusions

5.1 Sensor Network

Analysis of the data from the near-real-time monitoring system and other studies of Turtle Mountain are ongoing. The monitoring system continues to be optimized to focus on sensors and technologies that provide the most reliable and accurate record of movements on the mountain. Recent advances in our understanding of the movement mechanisms on South Peak and other portions of the mountain by Pedrazzini and Jaboyedoff (2008) and Froese et al. (2009) mean that our understanding of the value of the data from the various instruments is also changing. For example, when we installed sensors during the period 2003–2005 (Moreno and Froese, 2006), we assumed that the large fissures on the top and west side of South Peak were the head of the large (approximately 5 million m³) mass that was moving to the east. As demonstrated by Froese et al. (2009), the upper part of South Peak is more likely moving as three masses. This means that much of the instrumentation was installed in a rubbly zone of subsidence, making many of the crackmeters and tiltmeters of little use for prediction and warning because they reflect the subsidence and/or are oriented incorrectly to detect and quantify direction of movement.

Based on these findings, the focus shifted to monitoring of a wider area on the eastern face of Turtle Mountain, as described by Moreno and Froese (2008b). This focus shift involved incorporation of dGPS

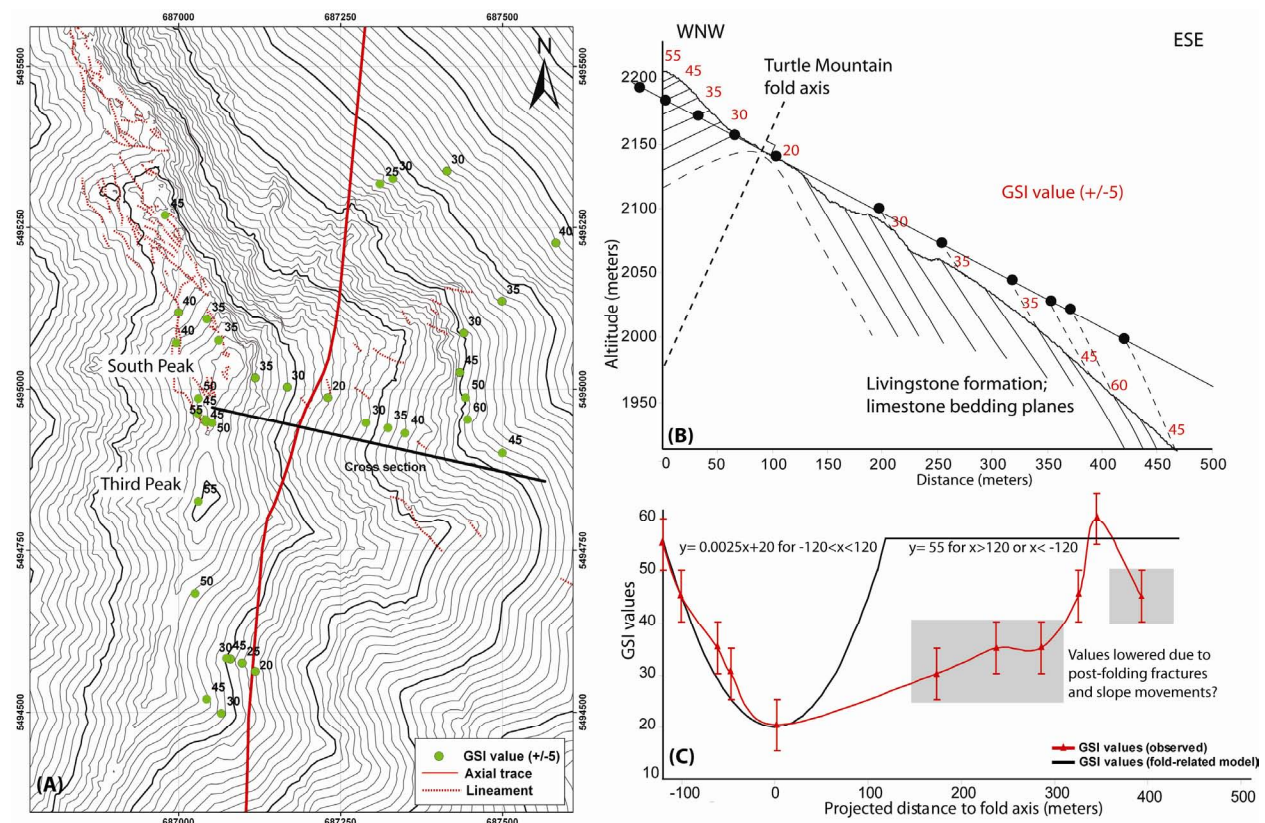


Figure 16. Rock-mass characterization using GSI estimates: a) location of the structural stations where GSI values were estimated; b) schematic cross-section of the area between South Peak and Third Peak, showing the variation of GSI values along the anticline; c) comparison of GSI values calculated in the field and those of a theoretical model that takes into account the presence of the hinge zone as a disturbance factor. Note the good fit on the western fold limb and the differences in the eastern fold limb due to the important influences of post-folding movements (Pedrazzini et al., in press).

and laser-ranging technologies to monitor movements of the various blocks. We consider the dGPS technology more promising because displacements are measured relative to a geographic reference system rather than the installation orientation of the device.

Continuous slope monitoring is very difficult given the harsh and highly variable climatic conditions on Turtle Mountain, as evidenced by the number of times the system's normal operation has been affected by environmental factors, particularly lightning damage. In addition, we recognize that the current monitoring network is not well suited to the range of deformation expected on the mountain, so future deformation of the mountain will cause the system to stop providing useful information. For this reason, we continue to investigate new monitoring techniques that are more robust and will provide measurements over the entire range of expected deformations.

Remote-monitoring techniques have become an increasingly common and cost-effective tool for projects covering areas that are relatively large and/or difficult to access. Typical techniques include dGPS stations (continuous-reading monitoring network), EDM prisms and GB-InSAR. Given the potential of such techniques to provide reliable monitoring alternatives at Turtle Mountain, AGS decided to test them. Preliminary results show that

- The GB-InSAR system is an important supplement to existing monitoring systems on the mountain. This system returns valid data from tens of thousands of locations, thus allowing identification of deformation domains within the area of interest (Dehls et al., 2010). However, the system does not provide useful information when the slope is covered with snow, although limited data can still be obtained from near-vertical slopes on the headwall of the 1903 slide.
- The dGPS system is not affected by snow coverage, but it is limited by sparse data coverage. The dGPS stations monitor only a limited number of points, the locations of which were chosen according to our understanding of the deformation mechanisms.
- The EDM system is considered the least reliable of the three remote-monitoring techniques tested at Turtle Mountain. It suffers from the same limitations identified for GB-InSAR (atmospheric effects) and dGPS (low spatial coverage of monitoring points), so it does not provide useful information on a year-round basis.

5.2 Risk Management

With the establishment of new zones that are potentially susceptible to runout (Moreno and Froese, 2009), management and communication of the hazard and risk are currently underway.

These new, potentially unstable structures have only been identified at this point, so there is currently no monitoring information available on the spatial and temporal characteristics of the deformations. However, we have installed a monitoring system on the lower Third Peak and lower South Peak areas to characterize the movements. This system consists of an array of overlapping differential Global Positioning System (dGPS) monitoring points (monitored both continuously and periodically) and a series of 20 mirror prisms that is monitored via the robotic total station from across the valley. Because we expect that deformation rates are in the millimetre to sub-millimetre range, many years of continuous monitoring will likely be required to gain confidence in identification of the displacement trends.

Communication of the risk associated with these hazards to the affected population is also ongoing. We publish the most recent results annually (Moreno and Froese, 2008b) and present them in public meetings with the municipal officials and residents in the affected zones. Updates are also available on the Turtle Mountain Monitoring Project & Field Laboratory web page on the Alberta Geological Survey website (http://www.ags.gov.ab.ca/geohazards/turtle_mountain/turtle_mountain.html).

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