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Alberta Energy Regulator

Turtle Mountain Field Laboratory, Alberta (NTS 82G): 2011 Data and Activity Summary

AGS ALBERTA GEOLOGICAL SURVEY

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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, 2011.

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

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

This report comprises three main divisions. Section 2 contains information about the major changes to the TMMS's physical sensor network during the summer of 2011. 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, approximately less than a millimetre per year.

Section 4 focuses on results from the most recent studies, including

- an update on the displacement trends revealed by a series of eighteen points as part of a periodic GPS monitoring system,
- field studies and LiDAR analysis by the University of Lausanne, and
- an update on continuing Ground-Based InSAR monitoring.

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). The first priority for monitoring and studying Turtle Mountain is to provide an early warning to residents of the Crowsnest Pass in the event of a second catastrophic rock avalanche originating from South Peak. The second 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 slow-moving rock masses, hence the working name 'Turtle Mountain Field Laboratory' (TMFL). The AGS will make available to the research community all data from the TMFL, which will enable researchers to test and develop new monitoring technologies for the mountain. This ongoing research will aid in understanding the movements of the entire South Peak mass, including the lower slope and more recently North Peak, thereby providing a better model for prediction of future movements.

This annual report provides the public and researchers with a synthesized update on data trends and research on the mountain as a stimulus for further study. This report is a brief overview and also includes summaries of papers and articles produced by external project partners (Section 4).

2 Sensor Network Activity

This section provides an overview of the major upgrades, repair and maintenance activities, and performance of the sensor network during 2011. 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; however, new or replacement installations are mentioned.

The main activities undertaken during 2011 included

- removal of all the snow that was obstructing the solar panels of the differential Global Positioning System on Third Peak (3rd Peak dGPS)
- installation of uniform radio equipment (including installation of power manager) for the existing Turtle Mountain monitoring network,
- replacement and upgrade of dGPS stations,
- installation of a secondary weather station at the GPS radio site,
- upgrade of the power-supply system at the existing weather station, and
- replacement of damaged multiplexor and datalogger at the borehole station due to a lightning event in May 2011.

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 2011.

2.1 New Installations/Repair

2.1.1 3rd Peak dGPS Base Station Snow Removal

On March 28th, 2011, the solar charging systems for both of the base stations on Turtle Mountain (3rd Peak A and B) were disabled by an unknown event. During the following days, the battery levels gradually decreased until the units automatically turned off to prevent damage to the batteries. 3rd Peak A was disabled on April 19th and 3rd Peak B was disabled on April 22nd.

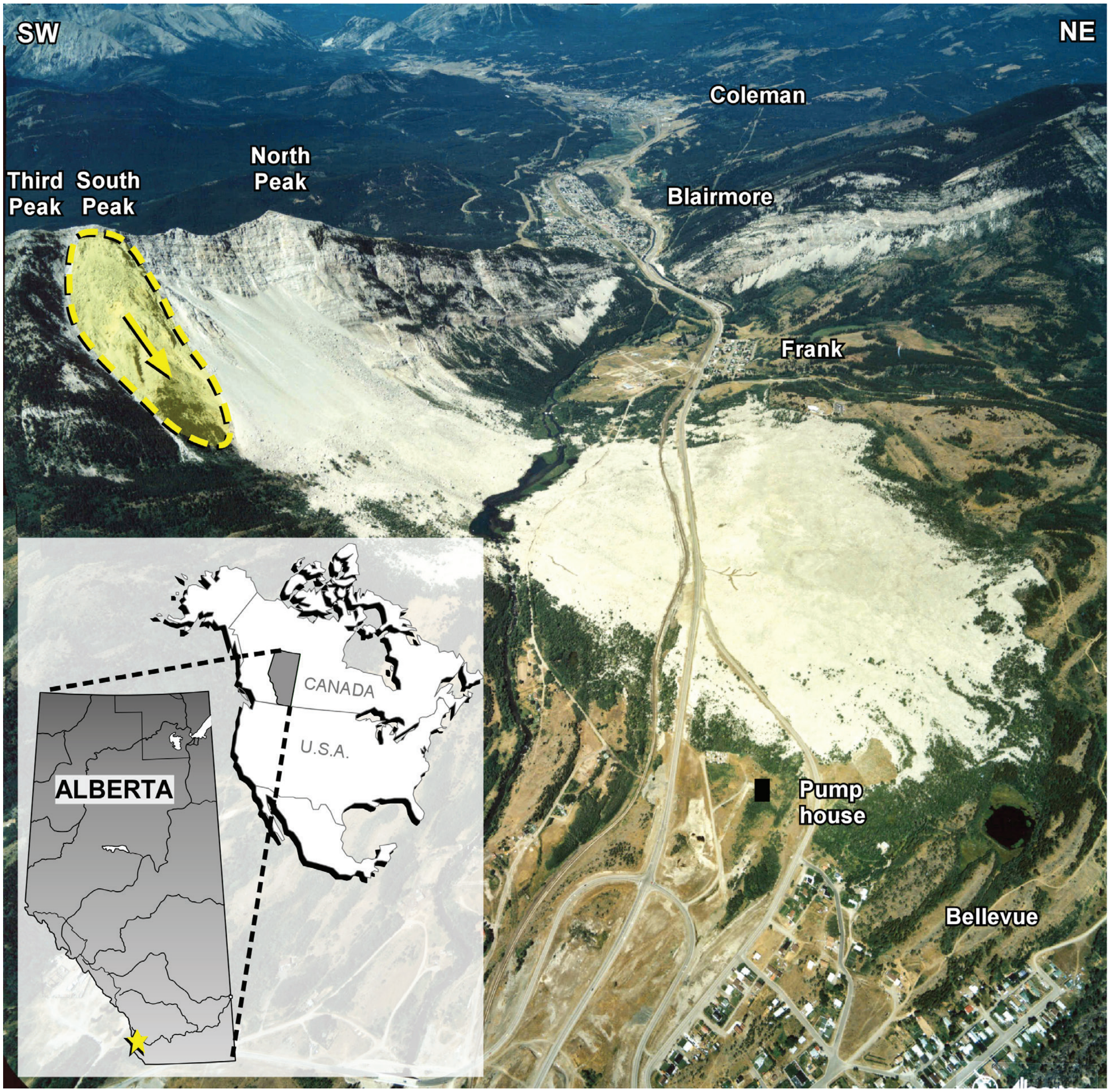


Figure 1. Location of Turtle Mountain in southwestern Alberta and full-extent aerial view of the Frank Slide. The dashed line below South Peak outlines the area identified by Allan (1931, Figure 2) as being most unstable.

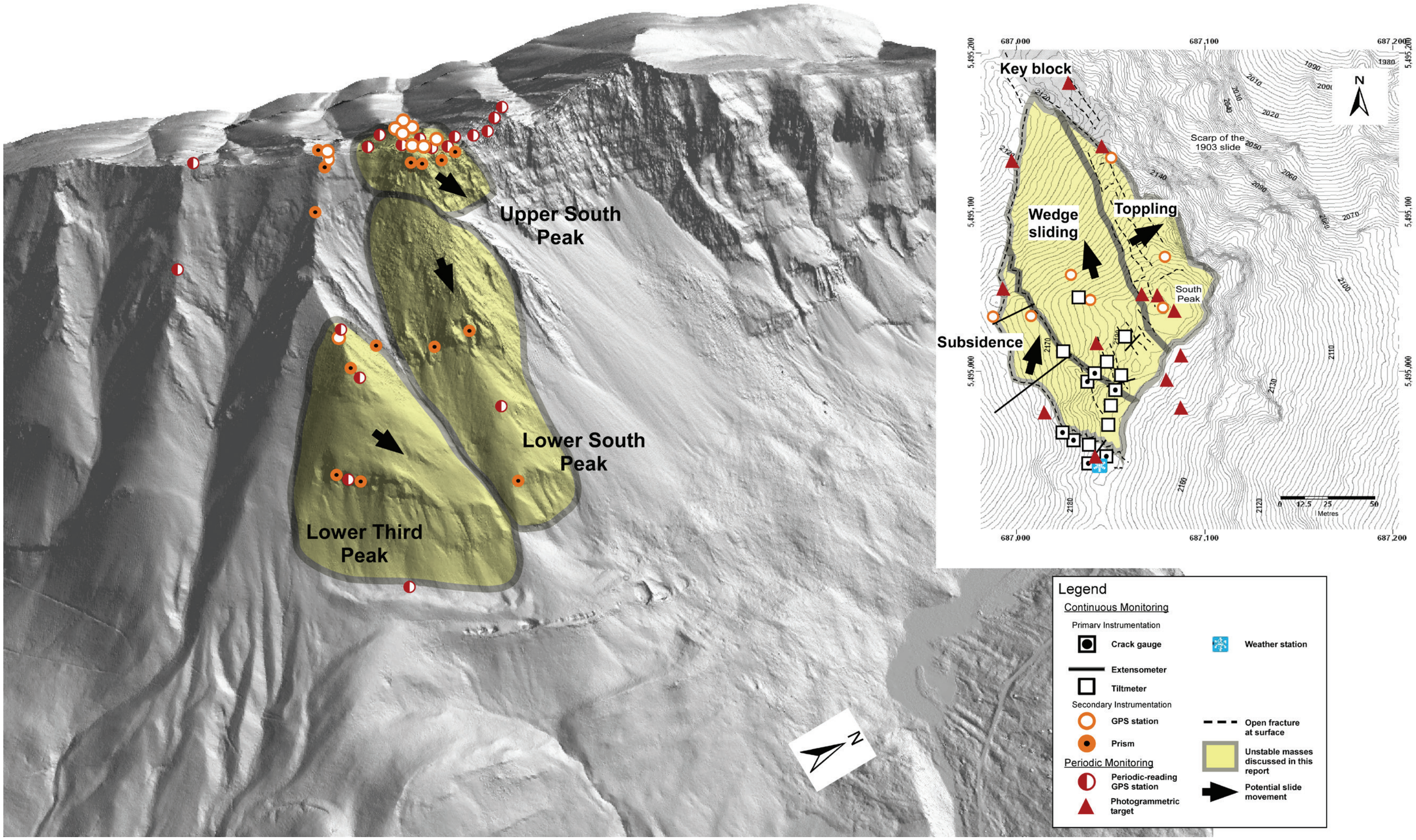


Figure 2. Overview, as of December 2011, of the monitoring network on Turtle Mountain as a whole and South Peak of Turtle Mountain in particular (inset), southwestern Alberta. For readability, primary monitoring instrumentation is shown only on the inset.

On April 23rd, a field visit was carried out to investigate. It was discovered that a significant amount of snow had accumulated. This snow was obstructing the dGPS base station solar panels, thus stopping the panels from delivering enough power to the dGPS equipment.

On April 27th, 2011, NavStar staff visited Turtle Mountain's Third Peak and cleared the snow from the helipad and dGPS base station solar panels. The dGPS base stations came back online after a day of charging.

2.1.2 Radio Installation

Performance of the SmartBridges WiFi radios used for the various communication links in the dGPS monitoring network was poor. These radios would stop working for no apparent reason and would remain offline for several hours, with the majority of such incidents occurring during the winter. Therefore, in 2010, testing of a different brand of radio (Tranzeo) began. New radios were installed on the PROV-GPS radio link (connecting the provincial building in the town of Blairmore to the dGPS radio station on the mountain), and performance was closely monitored. The new radios were extremely easy to configure and operated without problems during the testing phase.

Based on testing results, the old radios were replaced. The new radios have proven to be very reliable since the communication links of the TMMS have been active without interruption since their installation in the summer. The following advantages were noticed during the installation:

- A 48 V power converter is no longer required with the new radios, thus greatly simplifying installation and maintenance.
- The wide input voltage range is well suited to a solar panel / battery-based power system.
- Power consumption is lower compared with the previous radios.
- Configuration and installation was quick and easy.
- The radios are compatible with existing antennae and connectors.

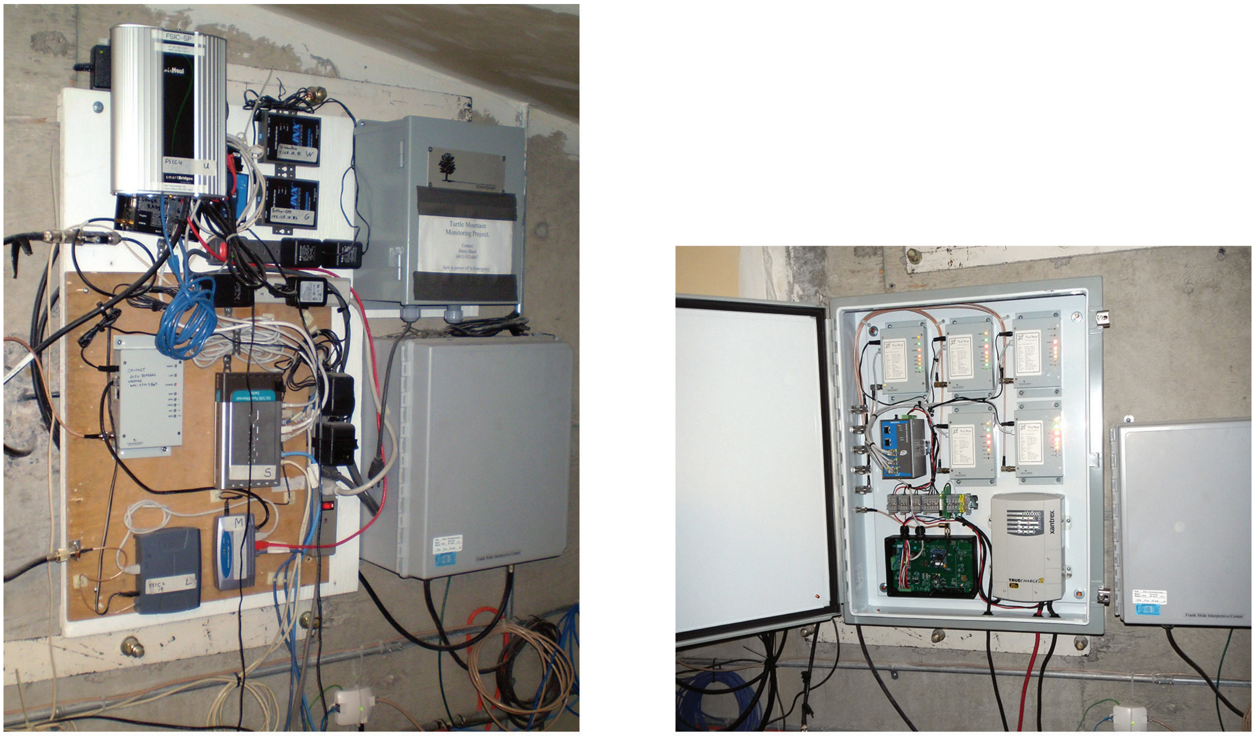
The updated radio network was designed to use as many common radios as possible. Tranzeo TR500 and TR600 radios operate at 5.8 GHz and 2.4 GHz, respectively. In addition, a Tranzeo TR6-SL5 was installed at the pumphouse radio tower because the radio has an integrated antenna. The configuration and setup of this radio is identical to the TR500 radios; only the physical enclosure is different.

As part of the radio standardization, the communication equipment located in the Frank Slide Interpretive Center (FSIC) attic was reconfigured (Figure 3). This included moving all the equipment into a new enclosure for added protection against dust and installing a 270 Ah battery for backup power supply. In the event of a power outage, the battery backup is capable of keeping the radios running for 5–6 days at present power consumption rates.

2.1.3 Radio Power Manager Installation

Intelligent power management devices (WMA100 units) were installed at the FSIC, dGPS, and South Peak radio sites. These power management devices are capable of

- monitoring data communication routes (switching to an alternate communication link if the primary link fails) and
- monitoring power consumption and power system performance.



a) b)

Figure 3. TMMS communication equipment located in the FSIC attic a) before and b) after reconfiguration.

Having the communication intelligently managed by the power manager allows for a truly redundant dGPS communication infrastructure. Without these devices, there was a possibility of data loss if one data communication link failed.

The WMA100s also provide tracking of battery charging, power consumption, and battery voltage for the FSIC, GPS radio, and South Peak radio sites. This information will be very helpful for identifying any future power-related issues at these sites.

2.1.4 Legacy Continuous-Reading dGPS Mast Upgrade

There were five dGPS mast stands remaining from the original Turtle Mountain project. These stands were not very robust and had begun to fail. They were replaced with a new, more robust design that includes a stronger mast bracket, upgraded mast, 3/16″ gauge galvanized aircraft cable for outrigger support, and crimped collars and thimbles to better protect the aircraft cable from friction and weather.

Some of the masts were relocated to more accessible mounting points to improve worker safety during future maintenance visits, as the old locations exposed workers to steep slopes.

In addition to the mast upgrades, all of the old plastic GPS enclosures were replaced with steel National Electrical Manufacturers Association enclosures. Previous experience has shown that metal enclosures significantly improve the resilience of the system to lightning strikes. To date, no lightning damage has been reported on equipment installed within these enclosures.

2.1.5 Continuous-Reading dGPS Stations Upgrade

Six new GMS301 dGPS units were installed on the mountain to optimize power consumption and improve accuracy for the 3rd Peak A, South Peak, Upper Saddle, Lower Saddle, Upper West, and Lower Wedge dGPS stations (as shown in Figure 2). These new units require less than half the power of the previous design, provide significantly more accurate data, and add additional environmental and lightning protection compared with the previous GMS200 units.

Figure 4 shows the noise level of 3-D displacement measurements at the South Peak dGPS station for the previous design (up to the vertical black line) and the noise level with the new units. The improved accuracy will be very helpful for detecting small movements on the mountain.

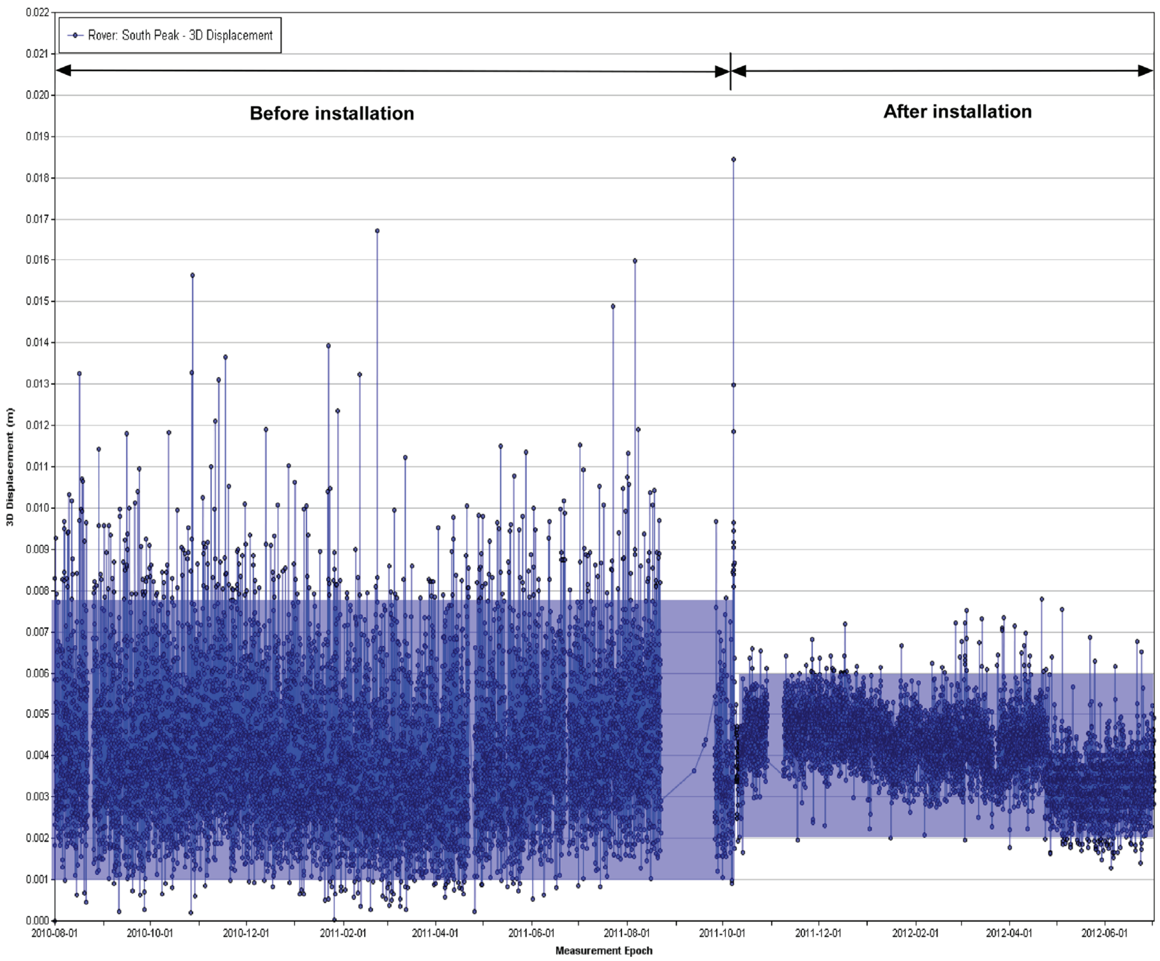


Figure 4. Typical plot of 3-D displacement versus time for South Peak dGPS station, Turtle Mountain. Noise reduction can be clearly seen after installation of the new unit in August 2011.

2.1.6 Weather Station Power Supply Upgrade

The weather station on the mountain had been using one 90 Ah 8G27 gel-cell battery as the storage medium for solar energy. This battery had reached the end of its useful life and was starting to exhibit power problems. To resolve these issues, the old gel-cell battery was replaced with a new 90 Ah absorbed-glass-mat (AGM) battery. This new battery has several advantages over gel-cell batteries, including longer expected life (4–6 years) and the expectation that they will perform much better in the harsh environment on Turtle Mountain.

As part of power supply upgrades, a cleanup of the area near the weather station was also conducted. This included removal of the old battery as well as the old metal box used as a battery enclosure.

2.2 Sensor Performance

Continuous slope monitoring is very difficult in the harsh and highly variable weather conditions on 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 can range from introducing large reading errors to making instrument reading impossible. However, the effects of these adverse conditions on the normal operation of the monitoring system have been minimized with a series of preventive measures. These include frequent sensor inspection, replacement of aging equipment, and system modifications aimed at improving sensor reliability. This section provides detailed information on sensor performance in 2011.

2.2.1 Primary Sensors

The TMMS has been operating for more than seven years. This has enabled us to understand not only the challenges of maintaining a reliable and essentially continuously running system but also to identify the factors that affect the normal operation of the monitoring network. For the primary sensor network (crackmeters, tiltmeters, extensometers), we find that factors such as high humidity in tiltmeters, snow loading on crackmeters, and lightning strikes can severely affect instruments. To mitigate these effects, desiccant packs have been put inside tiltmeter enclosures, protective roofs have been installed over each crackmeter array, and lightning protection has been added to all sensors. These measures have yielded mixed results. While desiccant packs have helped improve tiltmeter reliability considerably, the protective roof has been able to protect the crackmeters against snow loading only in a few cases. None of the different measures taken to protect the primary sensor network against electrical surges has worked well, thus making lightning strikes the main cause of sensor damage.

2.2.2 Secondary Sensors

The secondary sensor network consists of the electronic distance measurement (EDM) system and the continuous-reading dGPS system. Operation of these two systems has yielded mixed results. Although the dGPS system performed relatively well during the reporting period, the EDM system has been affected by environmental factors such as rain and snow, which have introduced large errors into the data or have made prism reading impossible. Given the nature of the site, prisms for the EDM system are also susceptible to damage from falling rocks, which has happened to some stations.

Over the past couple of years, modifications have been introduced to all continuous-reading dGPS stations to increase their reliability. This includes changes to improve

- power supply (new AGM batteries) and consumption (lower-consumption dGPS units),
- communication (new radios),
- data quality (lower-noise dGPS units), and
- protection from environmental factors (new metal enclosures and dGPS units with a greater resistance to lightning strikes).

3 Data Analysis

This section provides interpretations of 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 open surface fractures located on the backside of the mountain, or the slope opposite to the main slide backscarp, dilate at constant rates or if fracture dilation occurs rapidly in one event. However, as already stated in Section 2.2, these sensors are prone to snow or ice loading, which can introduce large errors in the readings. Therefore, discussion of displacements is limited to only those arrays that are known to have operated normally.

These instruments have been providing time series data of fracture-opening and temperature measurements since the beginning of 2005 (Figure 5 and Figure 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. Crackmeters 4, 5, and 6 have recorded displacement rates of up to 0.4 mm/year and crack-width changes related to daily air-temperature cycles of < 0.1 mm/year.

The fracture-opening measurements from crackmeter 7 (Figure 6) also show the very slow long-term trend seen in crackmeters 4, 5 and 6 (Figure 5). Examination of the records shows a mean annual displacement rate of < 0.4 mm/year, which, as is the case with crackmeters 4, 5, and 6, most likely reflects fracture opening due to seasonal changes in air temperature.

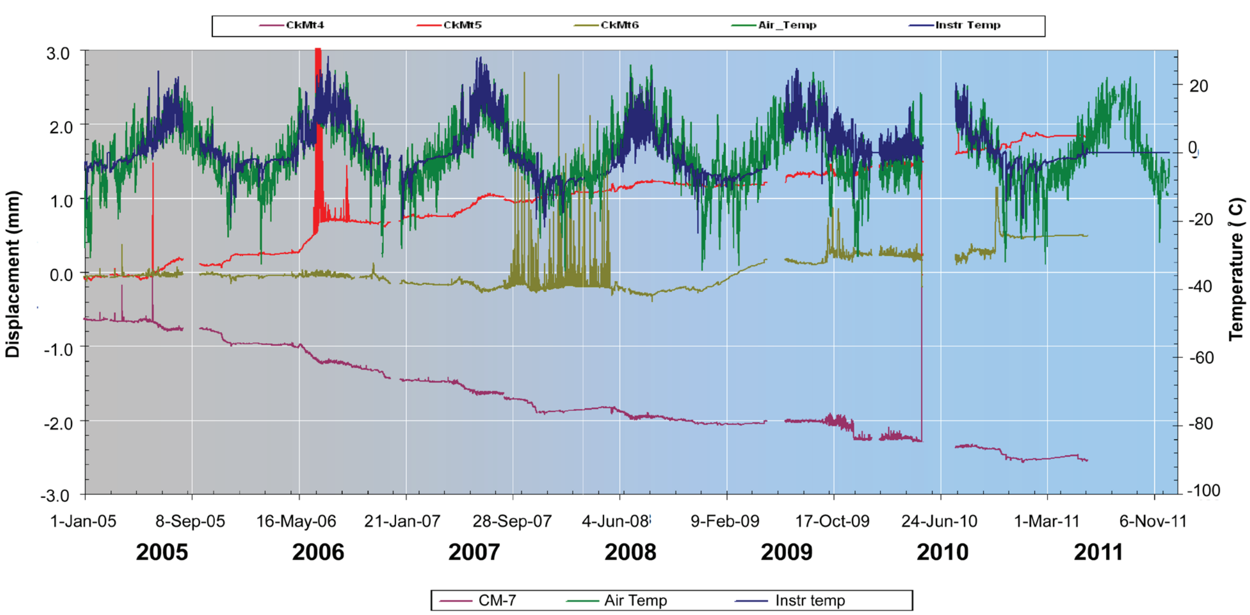


Figure 5. Plot of displacement versus time for crackmeters 4, 5 and 6, South Peak, Turtle Mountain.

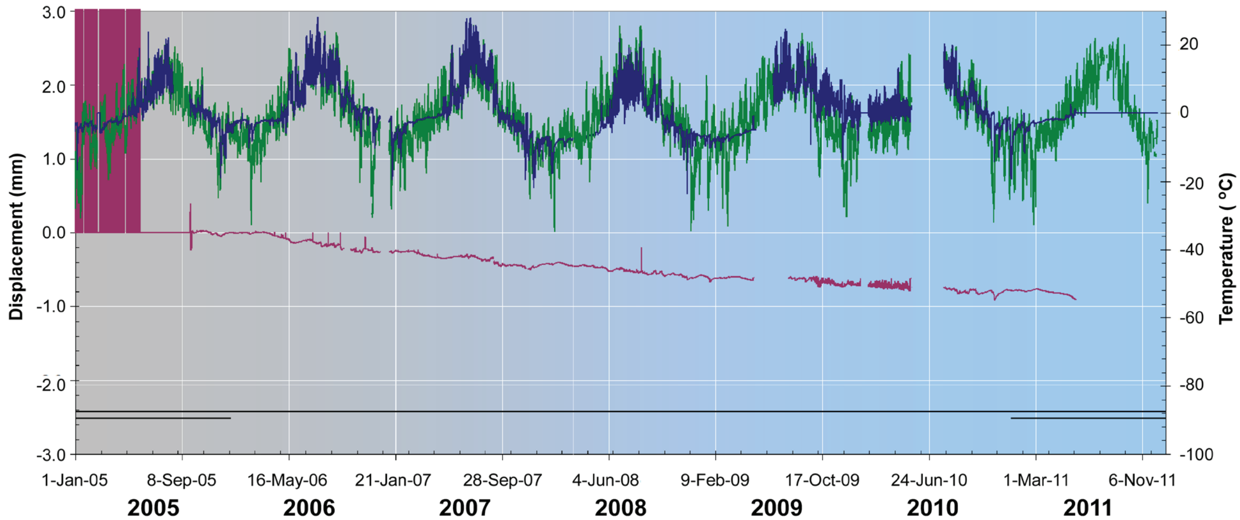


Figure 6. Plot of displacement versus time for crackmeter CM-7, South Peak, Turtle Mountain.

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 ten 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 on upper South Peak (Figure 2). Spatial coverage is therefore limited, and no sensors are located within the most active part of the rock mass at the northeastern part of South Peak. The monitoring results between 2005 and 2011 are shown in Figure 7.

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 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.

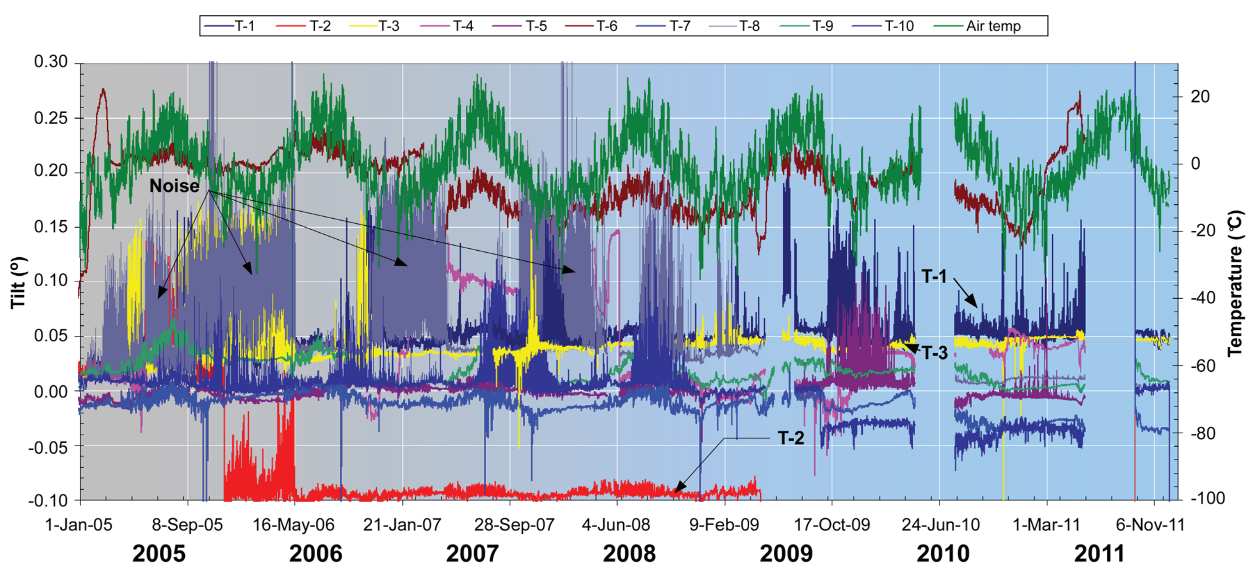


Figure 7. Plot of tilt versus time for tiltmeters, South Peak, Turtle Mountain.

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 monitoring period from 2005 through 2011. 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.

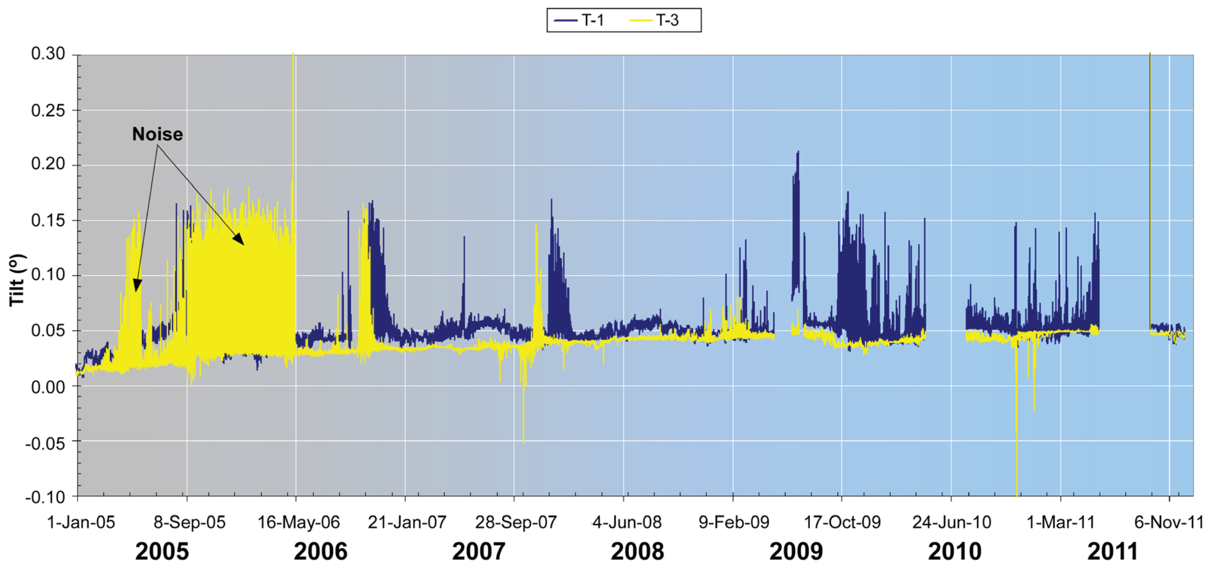


Figure 8. Plot of displacement versus time for tiltmeters T-1 and T-3, South Peak, Turtle Mountain.

3.1.3 Extensometers

Displacement versus time plots for 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 sensor types, with the extensometers observing measurements two orders of magnitude lower than that of the crackmeters. Extensometers EX-2 and EX-3 continue to be extended at 19 and 6 mm, respectively. These displacements were recorded during two periods of heavy precipitation in early June and early September of 2005; Moreno and Froese (2006) discussed the

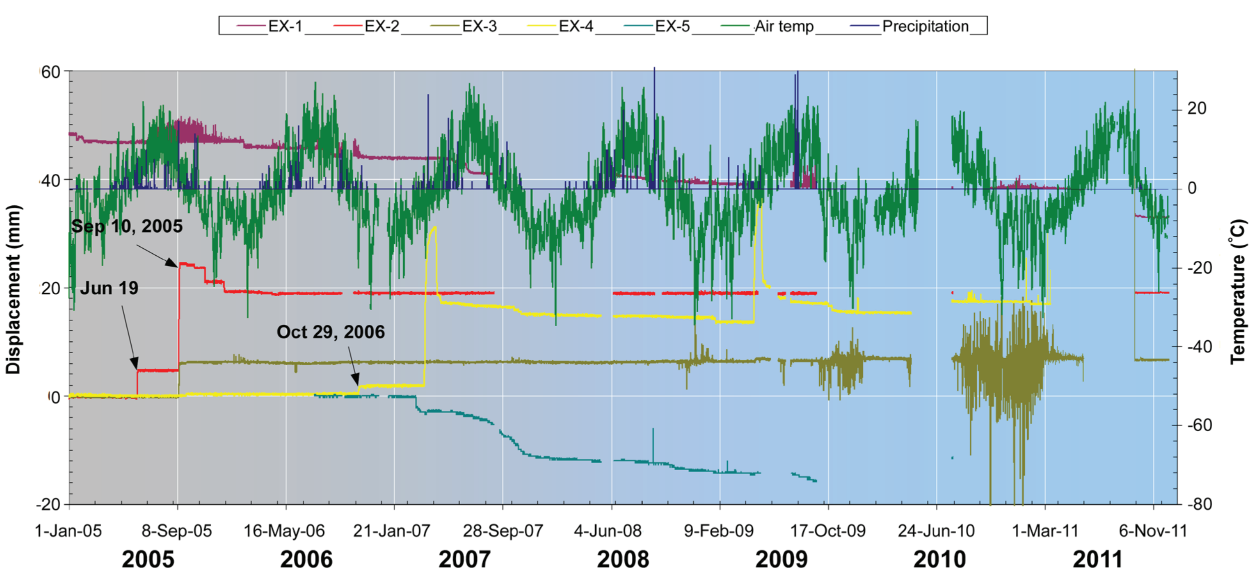


Figure 9. Plot of displacement versus time for extensometers, South Peak, Turtle Mountain.

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 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 millimetre resolution in the horizontal direction and centimetre resolution in the vertical direction. Later in 2008, this network was complemented with four dGPS stations: two on South Peak (areas with the largest movements) and two on the middle to lower part of the eastern slope below South Peak (areas of suspected movement; Figure 2).

Figure 10 depicts the monitoring results from the dGPS stations. Measurable displacement rates can be seen only at the Lower and Upper Saddle and Upper West stations. The annual displacement rates at the Lower and Upper Saddle stations range mainly between 0.5 and 2 mm/year, which is consistent with previous photogrammetric monitoring (Moreno and Froese, 2006). In contrast to these measurements, the Upper West station indicates a displacement of more than 6 mm. This result is considered suspect and is likely related to a poorly constructed concrete pillar. A detailed on-site inspection of the pillar revealed signs of deterioration; also, the pillar is located on heavily broken rock, which can be very susceptible to freeze-thaw events and result in large local displacements.

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 four years of available data. In general, all records show evidence of the annual displacement fluctuation clearly seen with the crackmeters. However, with the exception of prism PR15, 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. As mentioned in Section 2, this system is affected by several environmental factors that introduce large errors into the data.

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

3.2 Other Monitoring Data

3.2.1 Climatic and Thermistor Data

A maximum air temperature of (+22.3°C) and a minimum of (−32.6°C) were recorded at the top of South Peak of Turtle Mountain during the 2011 monitoring period (Figure 12). Significant daily temperature variations were also common. Rock temperature, measured by a series of thermistors installed in a borehole located at the top of Third Peak, 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 13 on page 14).

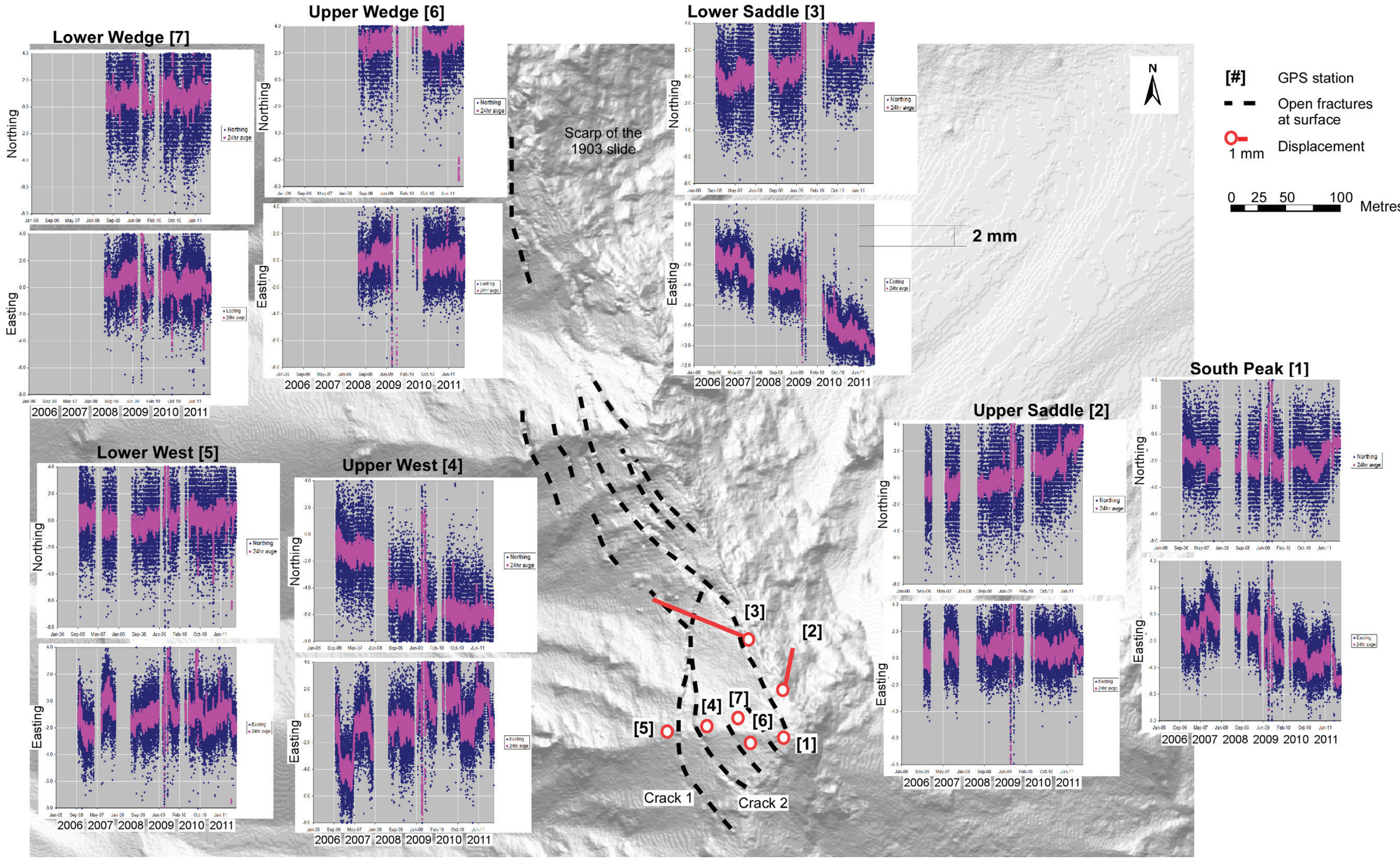


Figure 10. Surface displacements derived from dGPS stations during the period 2006–2011. Horizontal component of the surface-displacement vectors (red lines) plotted on a map of South Peak of Turtle Mountain. The displacement vectors of the dGPS stations are absolute since they are referenced to an external co-ordinate system.

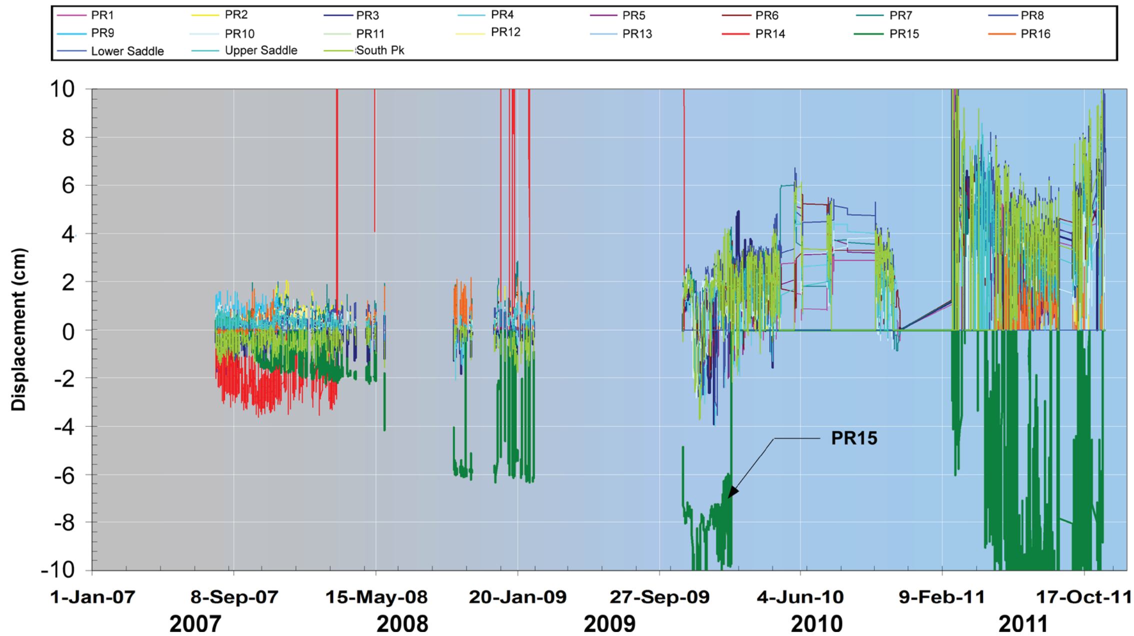


Figure 11. Plot of displacement versus time for prisms at Turtle Mountain.

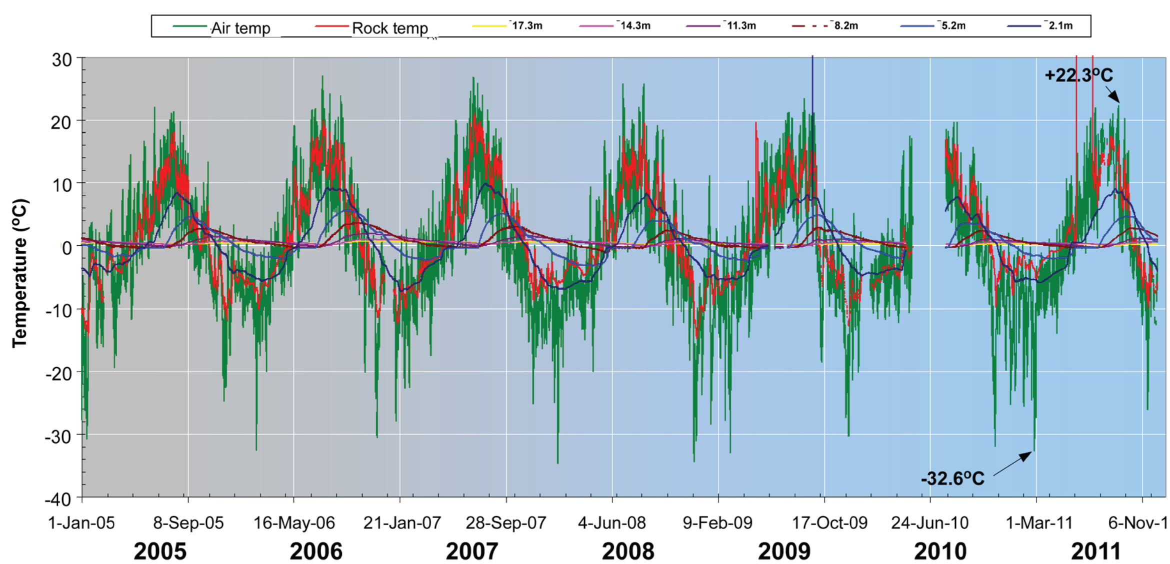


Figure 12. Air temperature and variation of rock temperature with depth in the borehole at the top of South Peak, Turtle Mountain, 2005–2011.

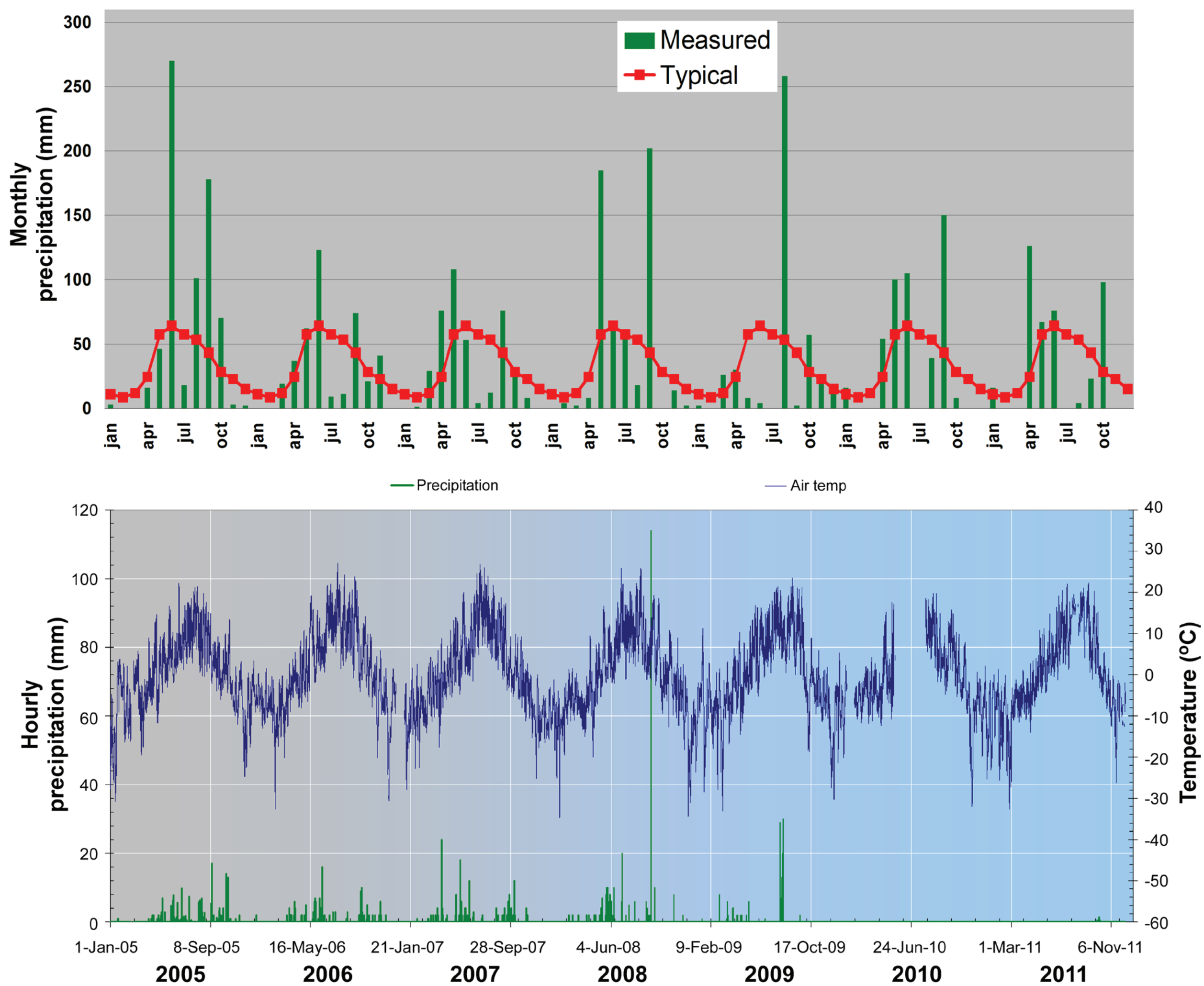


Figure 13. Measured and average monthly precipitation (top), and temperature and hourly precipitation (bottom) near Turtle Mountain, 2005–2011.

Above-normal precipitation was recorded on South Peak during the reporting period. Total precipitation in 2011 was 410 mm (Figure 13), 3% greater than the average annual precipitation of 397 mm measured between 1971 and 2000 at Environment Canada's nearby Coleman weather station. Winter precipitation was below normal, whereas above-normal precipitation was recorded during early spring. Normal precipitation was seen during late spring, and precipitation was below normal for much of the summer. Above-normal precipitation was recorded during the fall months (September, October, and November).

3.3 Discussion and Interpretation of Monitoring Data

Since the installation of most of the sensors in 2005 and 2006, 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 (Figure 2). 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 degree of resolution as do the crackmeters and tiltmeters, so they are sensitive only to large displacement (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 displacement only during very large movements.

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.

3.3.4 Continuous-Reading dGPS Monitoring Network

In contrast to the previous three sensor types, the most 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 discussed in Section 3.1.5, we do not expect to be able to detect any trends due to many factors that affect the data quality of the EDM system. The trend shown by PR-15 is a reflection of the very unstable block on which the prism was located, on the head of the 1903 Frank 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 North Peak Instability

Studies by the University of Lausanne (Humair, 2011; Humair et al, 2012) using a high-resolution digital elevation model (DEM) allowed us to update the interpretation of the potential failure mechanism for South Peak. They also led to identifying new instabilities below the South and Third peaks. In an effort to understand the landslide hazard on these areas, numerous studies were undertaken. These studies consisted of detailed field mapping by staff from the University of Lausanne followed by detailed analysis of the LiDAR DEM.

Field surveys were carried out every summer from 2007 through 2010 (Humair, 2011). Features associated with instability but missed by the high-resolution DEM studies were observed near North Peak during initial field surveys. As a result, field mapping was extended to cover this area (field campaigns of 2009 and 2010; Figure 14).

The results of the field studies by the University of Lausanne and structural analyses (Humair, 2011; Humair et al., 2012; Humair et al., 2013; Froese et al., 2012) highlighted an unstable volume of rock between 100 000 and 250 000 m^3. More details on rates of movement and monitoring are discussed in subsequent sections.

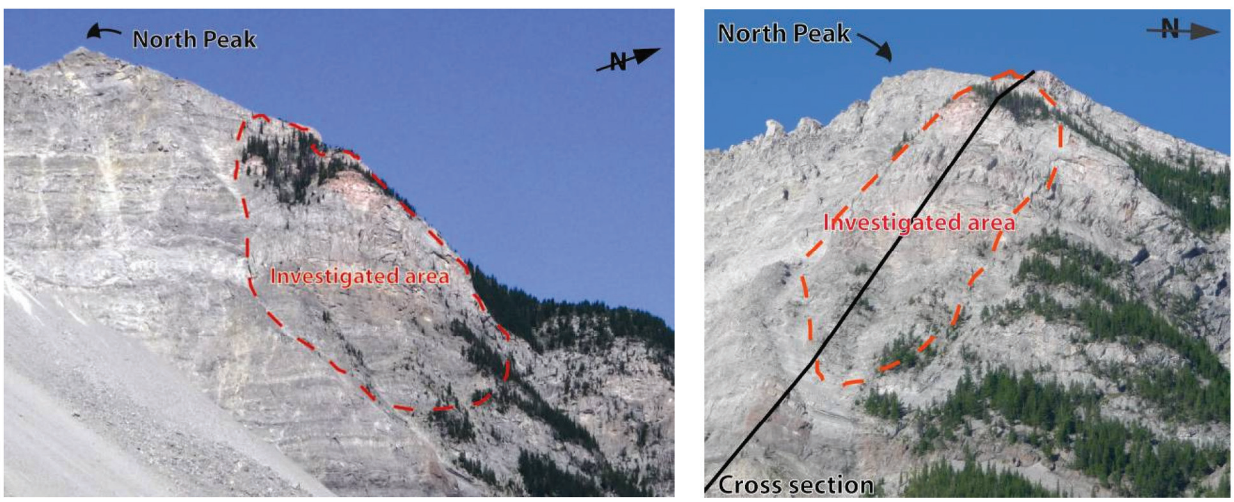


Figure 14. Views of investigated zone below North Peak of Turtle Mountain (Humair, 2011).

4.2 Ground-Based InSAR

In April 2011 we installed a ground-based interferometric synthetic radar (GB-InSAR, also called IBIS) device for monitoring small displacements on the east face of the mountain. Since the instruments at the top of the mountain are vulnerable to lightning strikes and require frequent maintenance or replacement, a ground-based radar system provides a continual means of observing the mountain face remotely. It is much less likely than the mountain-top instruments to be struck by lightning, and maintenance can be performed without climbing the mountain. We installed the system on the roof of a pumphouse located just under 3 km east of the base of the mountain (see Figure 15).

IBIS is built by Ingegneria Dei Systemi (IDS) in Italy and can measure small displacements at each point on the mountain face with accuracies of up to 0.1 mm. The radar head is mounted on a 2 m horizontal rail and it slides slowly across the rail (each sweep lasts about 2 minutes), then returns and begins a new

Figure 15. The IBIS system installed in front of Turtle Mountain. The maximum distance from the radar head to the furthest point on the mountain face is about 2.9 km.

pass at time intervals specified by the user (we chose intervals of 10 minutes). IBIS is an active sensor: as it moves along the rail it emits a stepped frequency continuous wave (i.e., a continuous EM wave with step-wise increases in frequency throughout the sweep). The emitted radiation is scattered back by the mountain face, and the return signal is recorded by a receiver antenna on the radar head. IBIS emits at frequencies in the Ku radar band, with frequencies from 17.05–17.35 GHz (which corresponds to wavelengths of approximately 1.7 cm). Because the instrument emits its own radiation, it does not rely on illumination from the sun; and unlike visible light, radar waves can be transmitted through clouds, so IBIS can be used day and night and in all weather conditions.

During each pass along the rail, the receiver records the return time, amplitude, and phase of the return signal. The receiver calculates the return time and phase of the backscattered signal to measure the distance from the instrument to each point on the mountain face as well as the brightness of the reflecting surface. By the end of each pass, the instrument has produced a synthetic aperture radar (SAR) image—a map of the amplitude and phase of the radiation backscattered from each point on the mountain face. The instrument then returns to the beginning of the rail to make another pass and creates another SAR image.

The phase maps for each SAR image appear as random speckles, with each pixel represented by a return wave phase (between 0 and 2π); however, if two successive SAR images are subtracted, the phase difference map (interferogram) can be converted to a measure of displacement that has occurred (towards or away from the instrument) for each point on the mountain in the time between the two SAR acquisitions, and a coherent displacement map emerges.

The instrument was installed in April 2011 and taken down in November 2011 for the winter. (The instrument does not have a cover to protect it from snow damage.) Data was not gathered continuously throughout the summer due to some technical difficulties with the instrument (e.g., loose cables and problems with Internet connectivity). However, we have continuous data spanning April 22, 2011, to July 25, 2011, which show displacements towards the instrument of up to 10 mm accumulating at various points on the mountain face. While the rest of the monitoring system focuses on South Peak instability, IBIS reveals that significant motion is occurring at North Peak. The instability observed at North Peak is similar in size and shape to the instability previously identified by Humair (2011).

Figure 16 shows total displacement from April 20 to July 25, 2011. The displacement map is draped over a LiDAR DEM. Red indicates motion towards the radar instrument and blue indicates motion away. Total displacements range from 10 mm (away from sensor) to −10.5 mm (towards the sensor). The data is noisy in the vegetated areas on the flanks and in the areas of debris flow. However, there is a strong, consistent signal of motion towards the radar instrument on some parts of the mountain face, particularly in an area below North Peak, named here North Peak unstable area (labelled NP on Figure 16). This appears to be consistent with the shallow failure instability zone identified by Humair (2011).

Average displacement as a function of time for the North Peak unstable area is plotted in Figure 17. Most of the displacement appears to be occurring over short discrete intervals with long periods of stability in between. Although the velocities appear large in those intervals, a plot of velocity as a function of time (Figure 18 shows that the maximum velocity reached over the entire four-month interval is about 0.04 mm/hour, or about 1 mm/day.

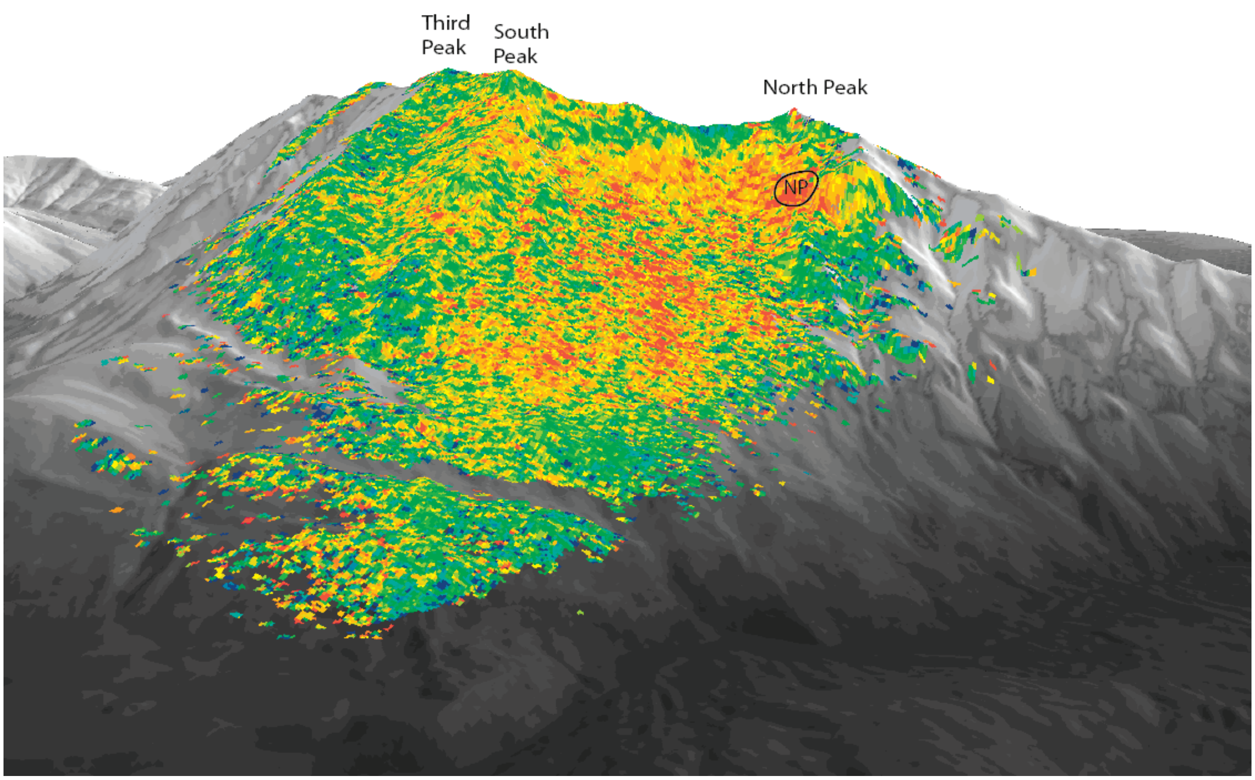


Figure 16. DEM of Turtle Mountain, viewed from the IBIS instrument location, with GB-InSAR displacement map superimposed. Colours represent total displacement along the instrument line-of-sight between April 20, 2011, and July 25, 2011. Red indicates motion towards the instrument, blue indicates motion away, and green areas are zero displacement. Bright red areas indicate motion greater than 10 mm towards the instrument. The North Peak unstable area is labelled as NP.

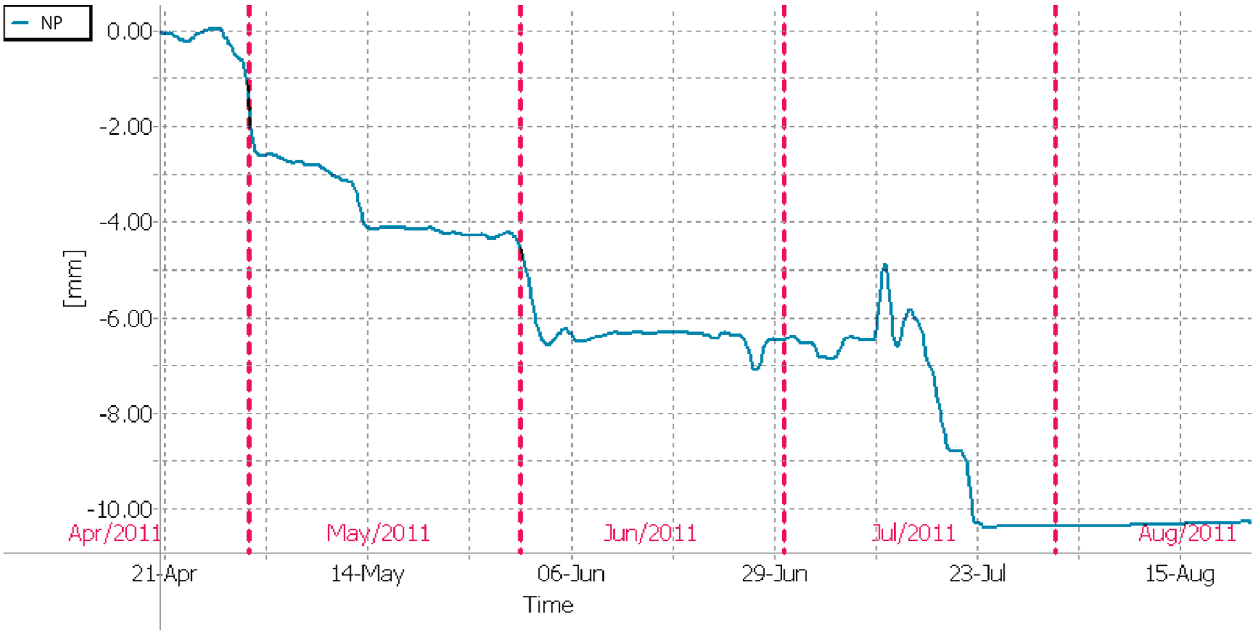


Figure 17. Time history of displacement averaged over the North Peak unstable area (NP) in the previous figure. Note that data collection was interrupted due to technical difficulties with the IBIS instrument, so displacement was not measured after July 25, 2011. Displacements are in millimetres, with negative displacements indicating motion towards the instrument.

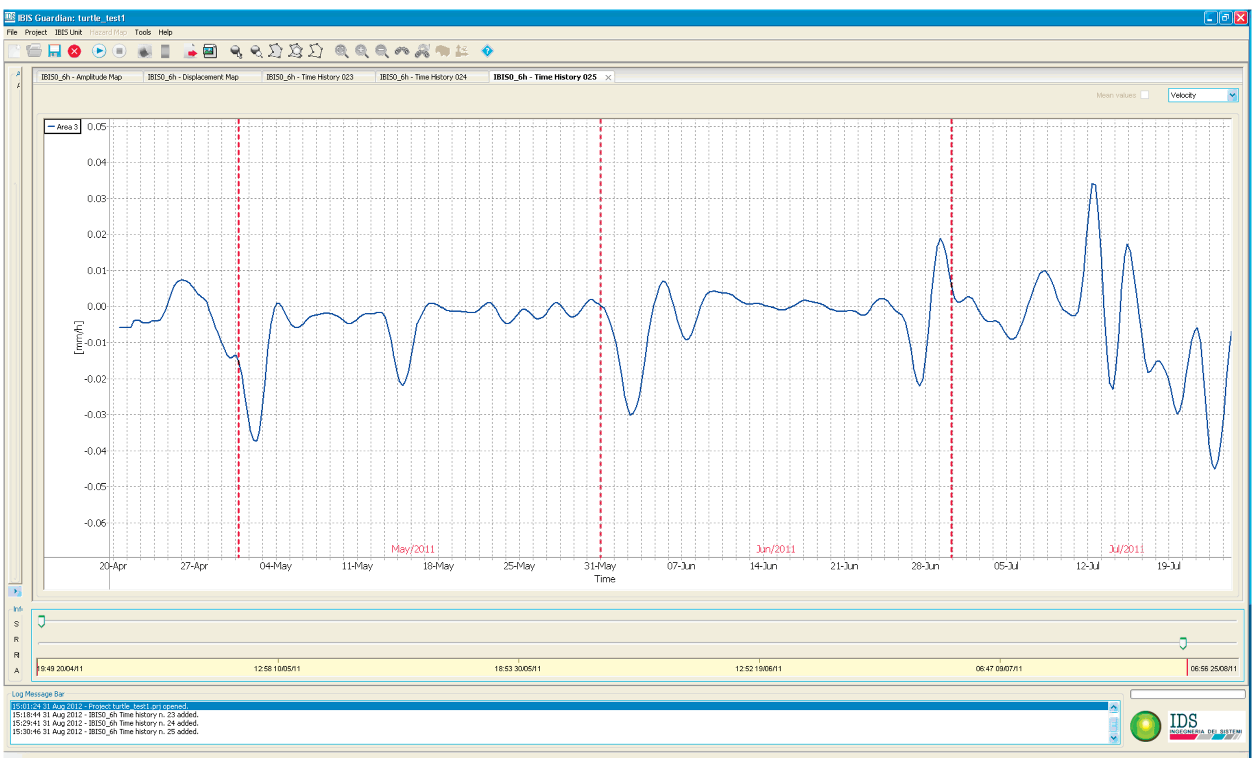


Figure 18. Line-of-sight velocity as a function of time for the North Peak unstable area (NP). Long intervals of slow motion are interspersed with relatively rapid motions occurring over intervals of 1–2 days at a time. However, the most rapid velocity observed over the summer of 2011 was about 1 mm/day.

4.3 Periodic-Reading dGPS Monitoring Network

In May 2007, the University of Calgary Geomatics Engineering Department, in collaboration with the AGS, started the monitoring of two areas on the mountain that were highlighted by field mapping as potentially unstable zones (Moreno and Froese, 2008b). The first area is within the active parts of the Saddle zone, between South and North peaks; the second is the eastern face of the mountain (below Third and South peaks). The monitoring network initially consisted of 14 steel targets but was expanded to 18 targets during the summer of 2008 (Figure 2).

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 observations are taken using two types of device: a high-precision total station (HPTS) and a dGPS instrument. Initial dGPS and HPTS readings were taken during June 2007 and subsequent readings repeated annually (Table 1). To fully correct for sensor effects, measurements at selected points that are considered stable relative to those on South Peak are taken during every observation campaign. These readings are used to calculate correction factors, and these factors are then used to correct the measurements of the other target points.

Table 1. Target point readings during the period 2007–2011.

Differential Global Positioning System (dGPS)			
Year	**No. of Reading Campaigns**	**No. of Targets Read**	**No. of Base Stations**
2007	2	14	1
2008	2	18 (5)[a]	1
2009	1	18	3
2010	1	18[b]	3
2011	1	18[b]	3

High-Precision Total Station (HPTS)			
Year	**No. of Reading Campaigns**	**No. of Targets Read**	**No. of Base Stations**
2007	2	14	2
2008	2	7[c]	1
2009	1	7[c]	1
2010	1	7[c]	1
2011	1	7[c]	1

a subset of dGPS observations made in September 2008 at target points in the saddle between North and South peaks
b dGPS observations made for a 24-hour period
c HPTS observations made only at target points in the saddle between North and South peaks

To determine movements, a multi-parameter transformation (MPT) mathematical model was applied (Teskey and Ebeling, 2011). 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 of dGPS readings show that two types of movement occurred at 7 of the 18 target points (Figure 19):

- backwards or sideways tilting with little or no downhill translation (points 1, 3, 15 and 16) and
- downhill translation or forward tilting (points 12, 17, and 19).

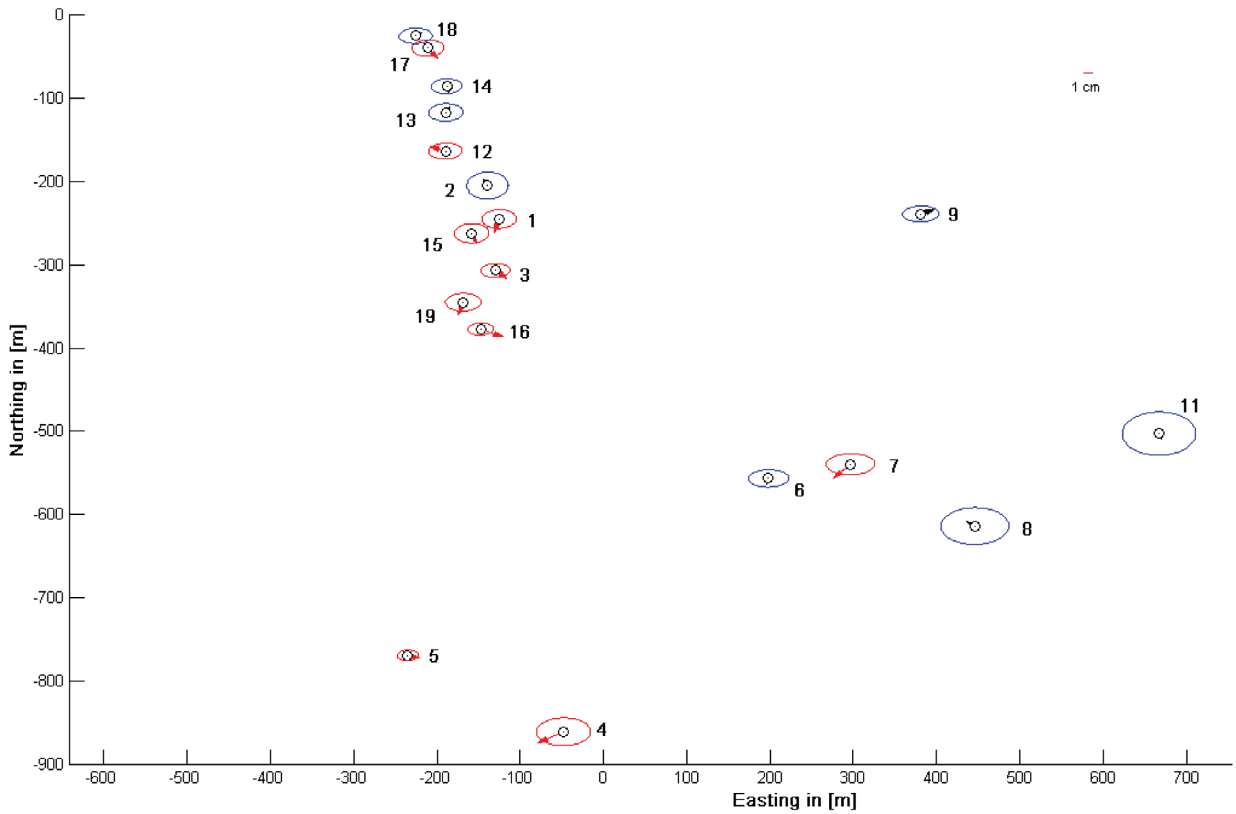


Figure 19. Horizontal movements of Turtle Mountain dGPS target points between 2010 and 2011 (Teskey and Ebeling, 2011).

Analysis of HPTS measurements also confirms the existence of slumping and sliding movements in the Saddle area between North Peak and South Peak and agrees quite well with dGPS readings.

Given that the movement pattern in the Saddle area is now well established by using both the dGPS and HTPS devices, observations will be made every second year. The next observation campaign is planned for 2013.

5 Conclusions

Recent application of modern characterization, monitoring, and modelling technologies has greatly increased our understanding of the 1903 Frank Slide and of the existing rock-slope hazard at Turtle Mountain. Based on these findings, monitoring focus was shifted to a wider area on the eastern face of Turtle Mountain below Third Peak and South Peak). Analysis of the data from the near-real-time, on-mountain monitoring system in these areas and remote monitoring indicates that movements are typically in the range of sub-millimetre per year to nonexistent for large rock masses and up to 10 millimetres per year for isolated smaller volumes (<10 000 m^3) on the face of the mountain. Over seven years of monitoring on the larger blocks on South Peak, displacement trends in this area have been identified that consist of diurnal and annual cycles that correlate with air-temperature cycles. The annual cycles exhibit an active phase, with displacements in the order of millimetres per year occurring in early autumn to late winter, and a relatively inactive phase with limited to no displacement in spring to late summer. The rate of displacement is well below any level of concern and has remained essentially constant for the seven-year span of monitoring.

Features associated with instability were observed near North Peak on Turtle Mountain during field surveys conducted by the University of Lausanne (Humair, 2011). Predicted volume for a shallow failure scenario ranges between 180 000 and 250 000 m^3.

Keeping the primary sensor network continuously running has proven to be very difficult and expensive. As discussed in Section 2, several factors affect the normal operation of the primary network, particularly lightning. An average of two lightning events capable of causing sensor damage are recorded each year. Each event can leave up to 50% of the primary system disabled, and the associated cost of repairing this equipment is relatively high. In addition, it is recognized that the primary monitoring network is not well suited to the range of deformation expected on the mountain. Thus, the information provided by the system will become less useful as deformation continues. Therefore, we continue to investigate new monitoring techniques that are more robust and will provide measurements over the entire range of expected deformations. Typical techniques include dGPS stations (continuous-reading monitoring network) and GB-InSAR. Over the past couple of years, the dGPS monitoring system has proven to be reliable, and it is expected to slowly replace the primary system as the main early warning monitoring system. The GB-InSAR system has the potential to supplement the existing dGPS monitoring system. However, more testing is needed before it can be used as a reliable monitoring alternative.

In 2012, data will continue to be collected from the primary sensors, the dGPS network, and the GB-InSAR unit.

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