ERCB/AGS Open File Report 2009-15

Turtle Mountain Field Laboratory, Alberta (NTS 82G): 2008 Data and Activity Summary

Energy Resources Conservation Board

Alberta Geological Survey

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September 2009

ISBN 978-0-7785-6983-1

If you use information from this publication in other publications or presentations, please give due acknowledgment to ERCB/AGS. We recommend the following reference format:

Moreno, F. and Froese, C.R. (2009): Turtle Mountain field laboratory, Alberta (NTS 82G): 2008 data and activity summary; Energy Resources Conservation Board, ERCB/AGS Open File Report 2009-15, 22 p.

Published September 2009 by
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Acknowledgments

The authors acknowledge the following colleagues and collaborators who contributed either to the operation and maintenance of the Turtle Mountain monitoring system or to studies on the mountain during 2008:

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Abstract

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), has taken ownership of this system and responsibility for the 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 better understand 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 better define the kinematically feasible 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 2008. 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 discusses 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, in the order of less than a millimetre per year.

Section 4 focuses on results from the most recent studies, including 1) a revised debris-runout analysis for the 12 unstable volumes identified, and 2) an update on the displacement trends revealed by a series of eighteen points as part of a periodic GPS monitoring system. Forward modelling of the potential runout from 12 smaller zones on the eastern face provides alternate scenarios for the potential runout from the eastern face of Turtle Mountain should the mountain continue to ‘break apart’ in a piecemeal manner. Although this piecemeal mode of erosion of the eastern face of Turtle Mountain is more likely than a single large failure event, there is still no conclusive evidence that a large, deep-seated failure of South Peak cannot occur. From a risk-management perspective, the ERCB, provincial and municipal emergency-response officials still consider a single large failure event to be the basis for planning of evacuations and road closures. Sensor networks installed by AGS and contractors during the past two years should be better able to distinguish between the zones of the movement, to provide better definition of the piecemeal versus single-failure scenarios in the future.

1 Introduction

Since 2005, Alberta Geological Survey has been responsible for operating and managing the near–real-time data stream from a network of sensors on the South Peak of Turtle Mountain, and for co-ordinating numerous complementary studies to better understand the state of stability of the mountain's eastern slopes (Figure 1). Since these studies and the interpretation of data coming from the mountain sensor system are ongoing, this report provides the 2008 annual summary of results and interpretations for the benefit of the geotechnical community and stakeholders in the Crowsnest Pass. This report will be brief, with the more detailed scientific results presented in the peer-reviewed journals and conference publications referenced throughout the report.

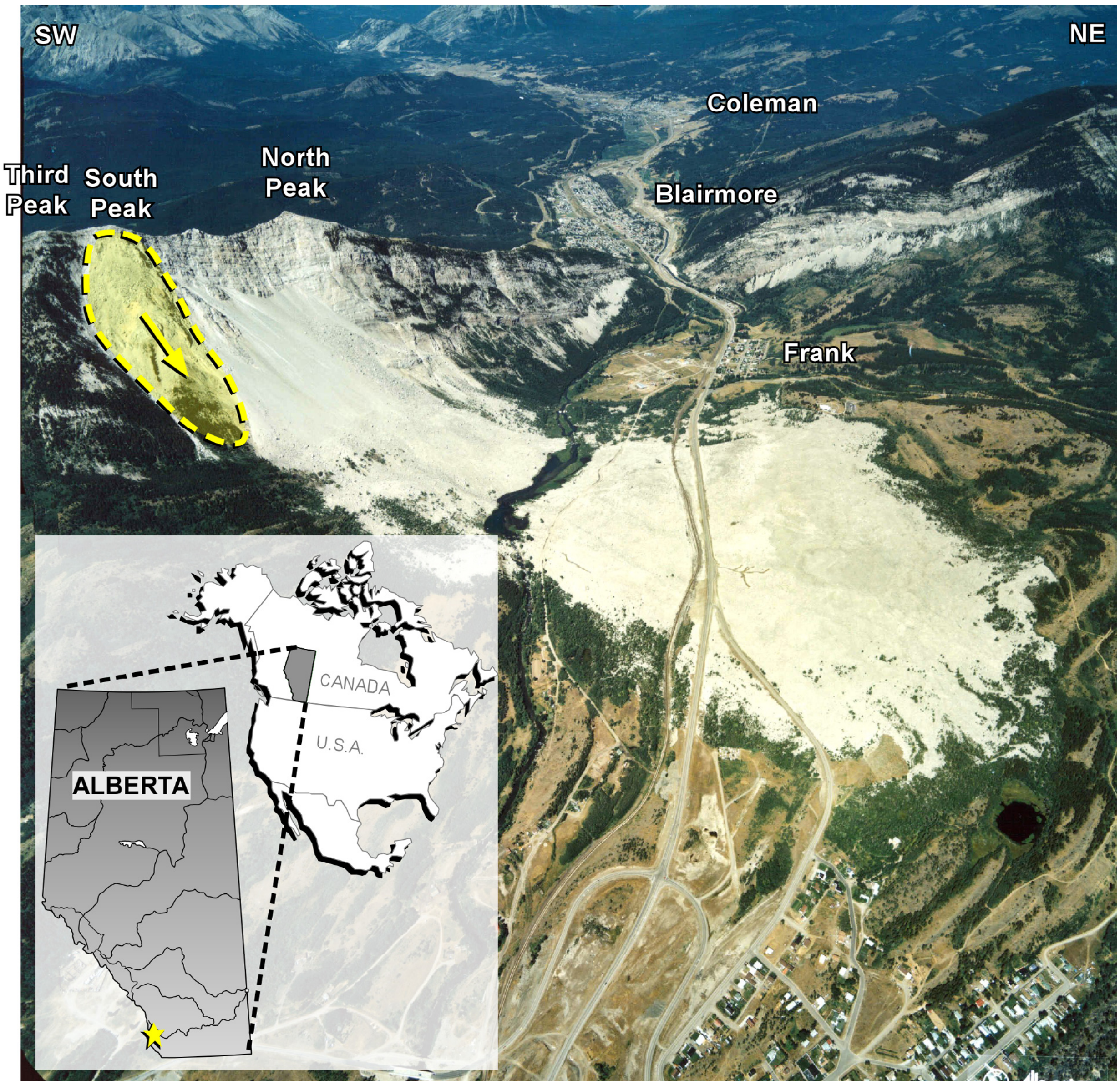

Figure 1. Location of Turtle Mountain in Alberta and full-extent aerial view of the Frank Slide. The dashed line below South Peak outlines the area identified by Allan (1931, Figure 2) as being most unstable. Photo reproduced with permission from Alberta Sustainable Resource Development, Air Photo Distribution.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

2 Sensor Network Activity

This section provides an overview of the major changes to the physical sensor network of the monitoring system during 2008. Documentation of the hardware that forms 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 2008 include

1) replacement of damaged tiltmeter TM-5 and surge arrestor on TM-8;
2) repair of the web camera at the top of South Peak;
3) replacement of two crackmeters and maintenance of the protective housing on five sets of crackmeters;
4) replacement of one extensometer and addition of surge arrestors at the sensor end on all extensometers; and
5) installation of five new differential Global Positioning System (dGPS) stations.

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 2008.

2.1 New Installations

2.1.1 Differential Global Positioning System Network

In addition to the existing dGPS monitoring system, McElhanney Consulting Services Ltd. installed four single-frequency dGPS stations and one base unit near South Peak. Two of these stations are approximately 10 m below and west of South Peak, and two are at the former seismic stations Ridge and Pit, on the middle to lower part of the eastern slope below South Peak. The base station, at Third Peak, is stable relative to those on South Peak and has a short baseline that is acceptable for use as a base station. The Third Peak base station provides a ‘relative’ stable reference for the stations on the mountain. The position of the Third Peak base station is compared regularly to the base station at the Bellevue pump station, in the bottom of the valley, to confirm whether it is indeed stable.

The locations of these stations were chosen for two reasons:

- The two stations on South Peak were installed on the large wedge feature identified by Moreno and Froese (2008b) and discussed in detail by Froese et al. (2009). This area is the largest of the movement zones on South Peak and there had been no instruments on this mass prior to the 2008 field season.
- The Ridge and Pit stations were installed at locations that had previously been occupied by passive seismic stations (Moreno and Froese, 2006). These stations use the existing power and radio connections from the seismic stations to target movements of the lower slopes below South Peak. The Ridge station is intentionally installed downslope of a large fracture that borders a rock mass in the lower Third Peak area.

Each station comprises a reinforced concrete pillar mounted with a dual–metal-plate assembly and a fixed GPS antenna. Staff from McElhanney and AGS installed each of the concrete pillars on top of the mountain using materials transported to the site by helicopter (Figure 3). The GPS antenna is connected to a GPS data recorder and a wireless server inside a waterproof plastic enclosure, allowing true real-time communication. The enclosure, radio antenna and solar panel are attached to a guyed mast that is bolted to the rock outcrop. Deep-cycle marine batteries inside an insulated battery box (Figure 3) power each station.

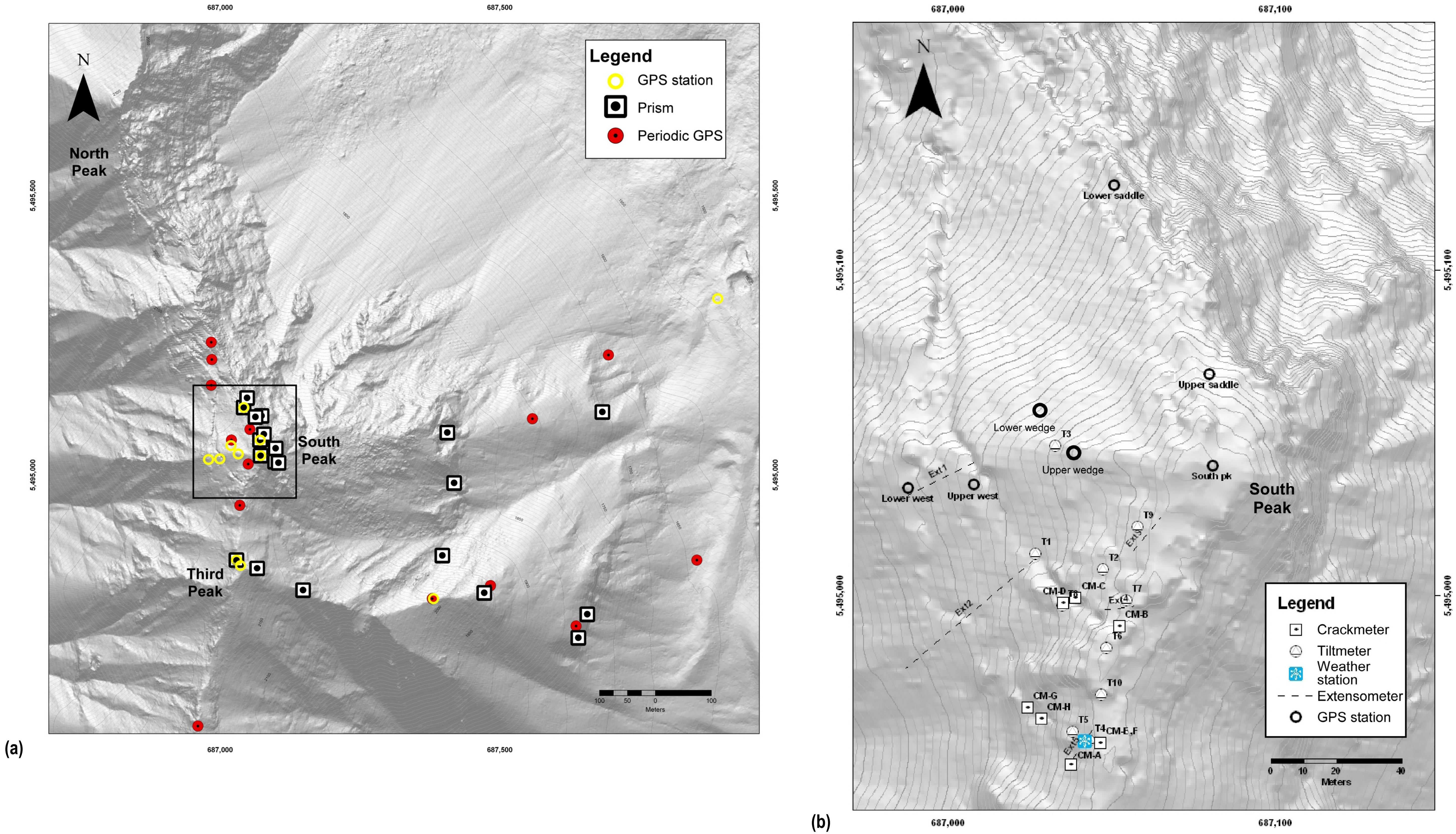

Figure 2. Overview, as of December 2008, of the monitoring network on a) Turtle Mountain, and b) South Peak of Turtle Mountain.

a)

b)

Figure 3. a) Construction of GPS pillar at Third Peak station. b) Typical finished differential GPS installation on Turtle Mountain, showing concrete pillar with Novatel antenna (right), battery box (centre) and solar panel (left). Enclosure hidden behind solar panel. Photo: G. Bjorgan, McElhanney Consulting Services Ltd.

The connection to the Turtle Mountain network is via a 5 GHz link between the new radio tower on the west side of South Peak and the Provincial Building in Blairmore, where data collected by the six units on the mountain are streamed in real time to a processing server in the office of McElhanney Consulting Services Ltd. in Vancouver, British Columbia. The GPS stations installed at the seismic locations connect to the existing radio system, which relays the data collected by these units in real time to Vancouver, British Columbia.

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 in June 2008, we can make the following summary statements:

- Addition of desiccant packs inside the tiltmeter enclosures considerably improved instrument reliability.
- 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, the data obtained from some of the crackmeters with improved roofs (Set C) show that effective protection against snow is possible.
- The five extensometers performed consistently well, providing high-quality data throughout most of the reporting period. Surge arrestors were added on the sensor end as an additional protection against lightning. Although the extensometers continue to be somewhat affected by lightning activity, damage is now limited to the surge arrestors. We can easily replace the arrestors, thus considerably reducing downtime on these instruments.
- The six GPS stations performed reliably during the reporting period. The design and installation of new, more compact units reduced instrument sensitivity to lightning activity. We now believe the old stations had a design flaw that made them susceptible to lightning. No damage due to moisture accumulation in the enclosure was documented during the reporting period.
- Operation of the two web cameras has yielded mixed results. Although the Bellevue camera performed very well during the reporting period, the South Peak camera suffered from frequent damage associated with lightning. Maximum lightning protection options were implemented in late 2008, but their effects have yet to be evaluated.

3 Data Analysis

This section discusses interpretations of slope conditions and displacement behaviour based on instrument results. Since climatic factors have affected some of the sensors, discussion will focus on those sensors that have provided reliable annual performance. Meteorological data have been essential in explaining general displacement trends observed on the surface instruments.

3.1 Deformation Monitoring Data

3.1.1 Crackmeters

Crackmeters continuously monitor the direction and magnitude of surface-fracture opening. Moreno and Froese (2006) have provided details of the installation. Although many of the crackmeter sets measured displacements, the cluster of three crackmeters in set B yielded the most indicative record of slope displacement. These instruments provide the time series of crack opening and temperature over a period of three years (Figure 4). Monitoring results show an annual displacement cycle, correlating with temperature cycles, that is dominated by an active phase, with displacements occurring in early autumn to late winter, and a relatively inactive phase, with limited to no displacements in spring to late summer.

Instruments have recorded displacement rates of 0.4 mm/year and crack-width changes, related to daily air-temperature cycles, of approximately 0.02 mm.

With the improvement of data quality from crackmeter set C, the very slow movement trend of the South Peak mass, seen in set B, is slowly becoming apparent on these sensors (Figure 5). A displacement rate of <0.5 mm/year measured at this site is constant most of the time.

3.1.2 Tiltmeters

In general, all sensors display an increase in tilt at the start of the summer period and a return to the previous state at the end of summer (Figure 6). A similar cyclic variation in tilt associated with diurnal temperature fluctuations is also present but at a smaller scale (~0.01°). Noisy responses due to moisture in

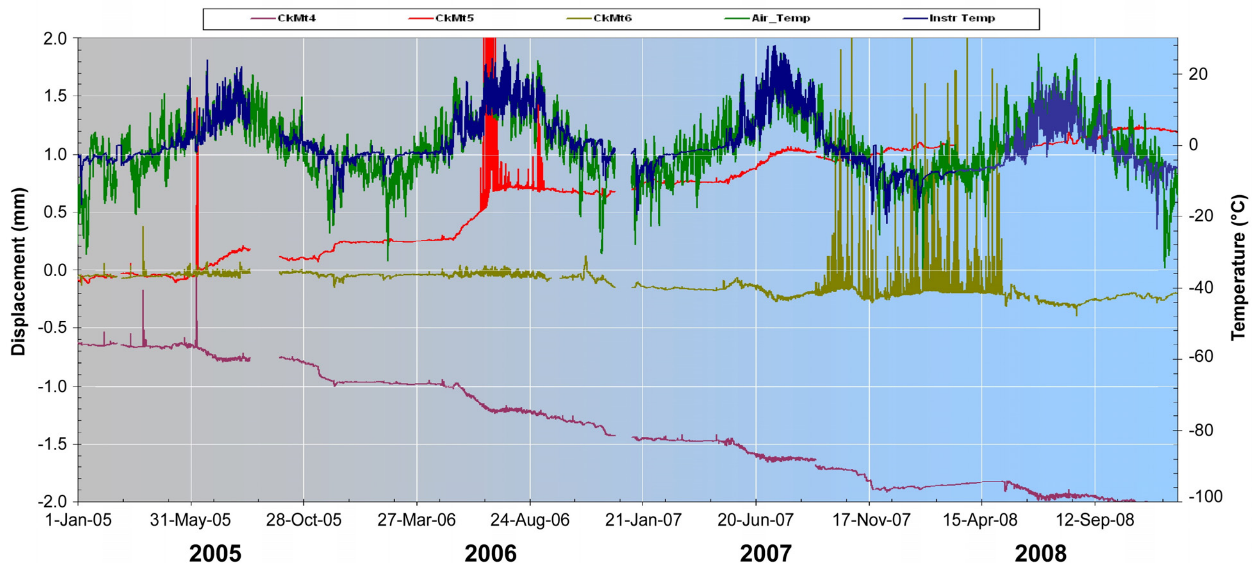

Figure 4. Plot of displacement versus time for crackmeter set B, South Peak, Turtle Mountain.

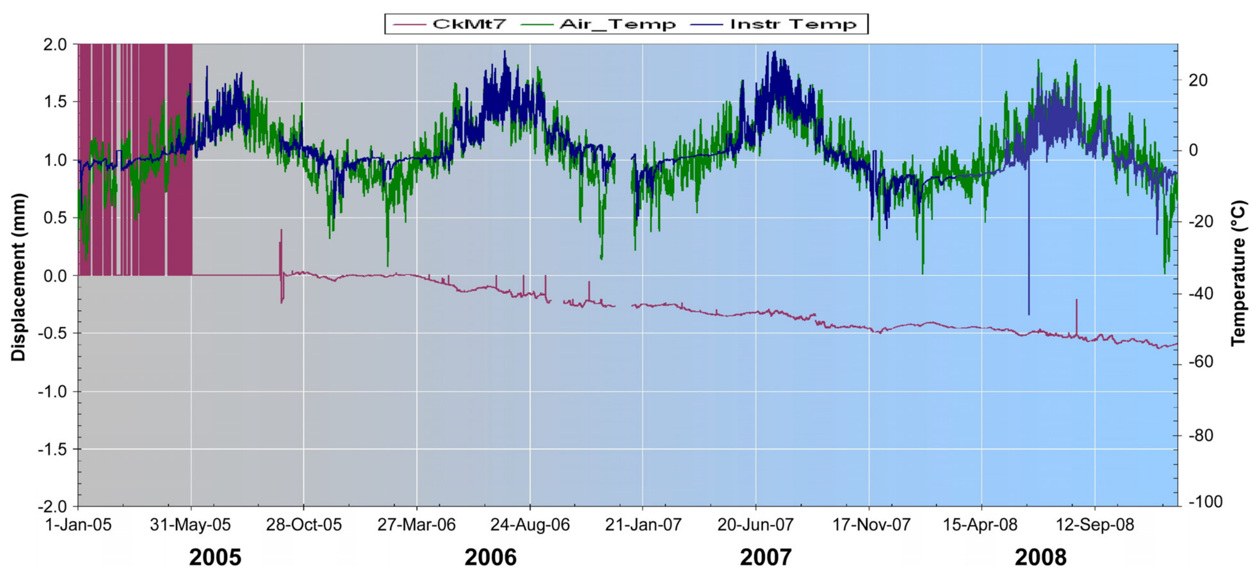

Figure 5. Plot of displacement versus time for crackmeter CM-7 of set C, South Peak, Turtle Mountain.

the sensors continue to affect the quality of tiltmeter data (T-8 and T-10), although the addition of desiccant packs during summer 2006 has remarkably improved data quality (T-1, T-2 and T-3).Tiltmeter T-1 continues to show trends associated with slow creep; however, in spite of noise removal, the corrected data do not permit a conclusive interpretation. A better understanding of the displacement style will depend on several additional years of data.

3.1.3 Extensometers

Each of the five extensometers showed very stable responses during the reporting period: no daily or seasonal changes are apparent in the displacement data (Figure 7). Extensometers EX-2 and EX-3 continue to be extended at 19 and 6.17 mm, respectively. These displacements were recorded during two

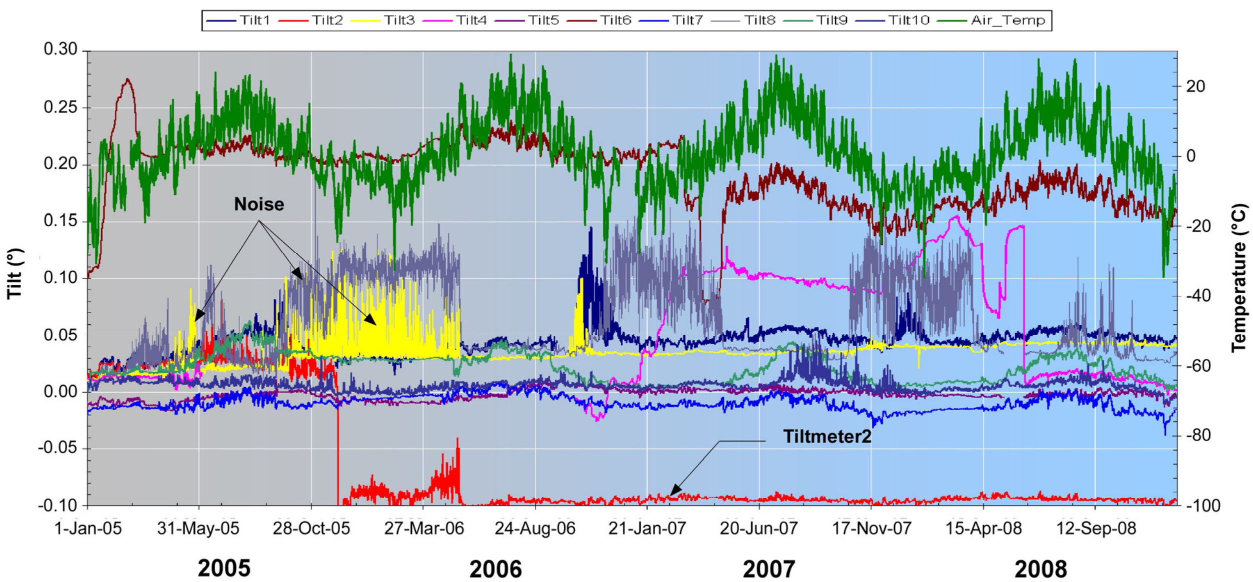

Figure 6. Plot of tilt versus time for tiltmeters, South Peak, Turtle Mountain.

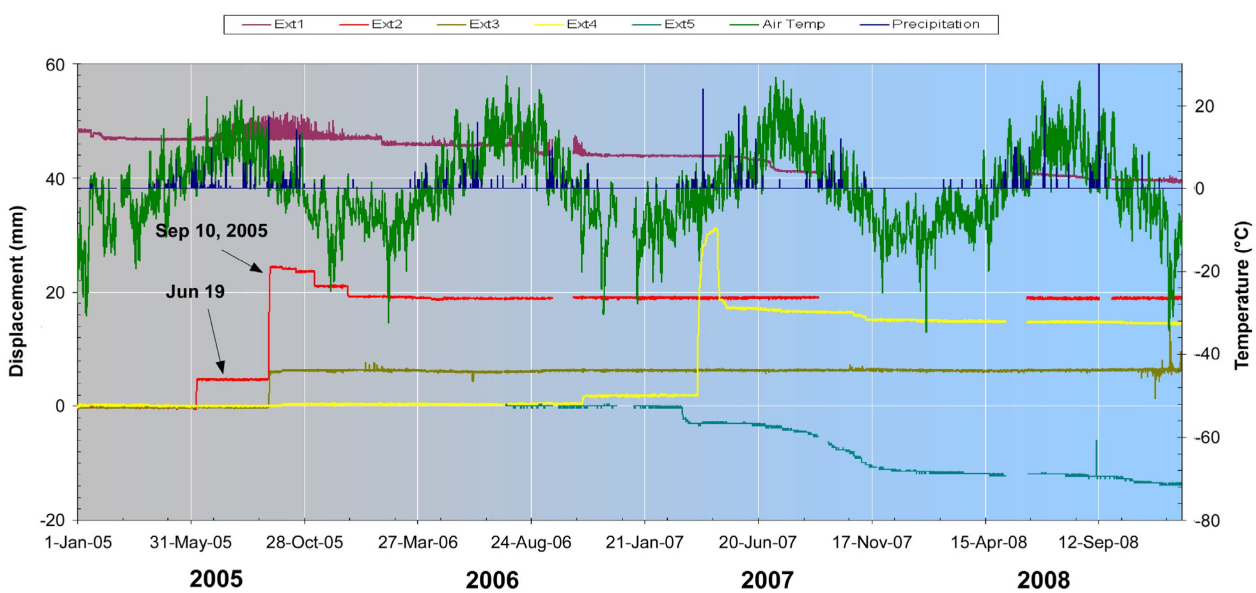

Figure 7. Plot of displacement versus time for extensometers, South Peak, Turtle Mountain.

periods of heavy precipitation in early June and early September of 2005. Moreno and Froese (2006) have discussed the details of these events. We believe the offset in the graph of EX-5 resulted from aspects of the instrument design, since no measurements from nearby sensors verified this movement. Differential Global Positioning System (dGPS)

Figure 8 shows the results from the dGPS monitoring system between 2006 and 2008. The magnitudes of the displacement-rate vectors vary from 1.0 to 1.2 mm/year. Absolute displacement vectors are directed to the south for the station located at South Peak, and to the southwest for the stations located at the Lower Saddle, Upper West and Lower West. However, the uncertainty in direction is large because their magnitude is small relative to the instrument resolution. We need several additional years of data to confirm these results.

Initial data from the four recently installed dGPS stations (Section 2.1.1) were used for system testing and not analyzed in detail, and are therefore not discussed in this report.

3.1.4 Electronic Distance Measurement (EDM) System

As discussed in Moreno and Froese (2008b), 20 prisms were installed during the summer of 2007. Figure 9 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 to resolve any trends.

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

3.2 Other Monitoring Data

3.2.1 Climatic and Thermistor Data

Lower maximum (+25.8°C) but higher minimum (–34.5°C) temperatures than in previous years (Figure 10) 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 10).

Above-normal precipitation during the reporting period was recorded on the South Peak of Turtle Mountain. Total precipitation in 2008 was 553 mm, 39% greater than the annual average of 397 mm, which is based on at least 15 years of data measured between 1971 and 2000 at the nearby Coleman weather station of Environment Canada. Winter precipitation was below normal (Figure 11), whereas above-normal precipitation was recorded during the spring, with most of it occurring during May. Precipitation for much of the summer was normal to below normal, varying during the fall months from considerably above normal (September) to below normal (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 Moreno and Froese (2008b) and discussed in detail in 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

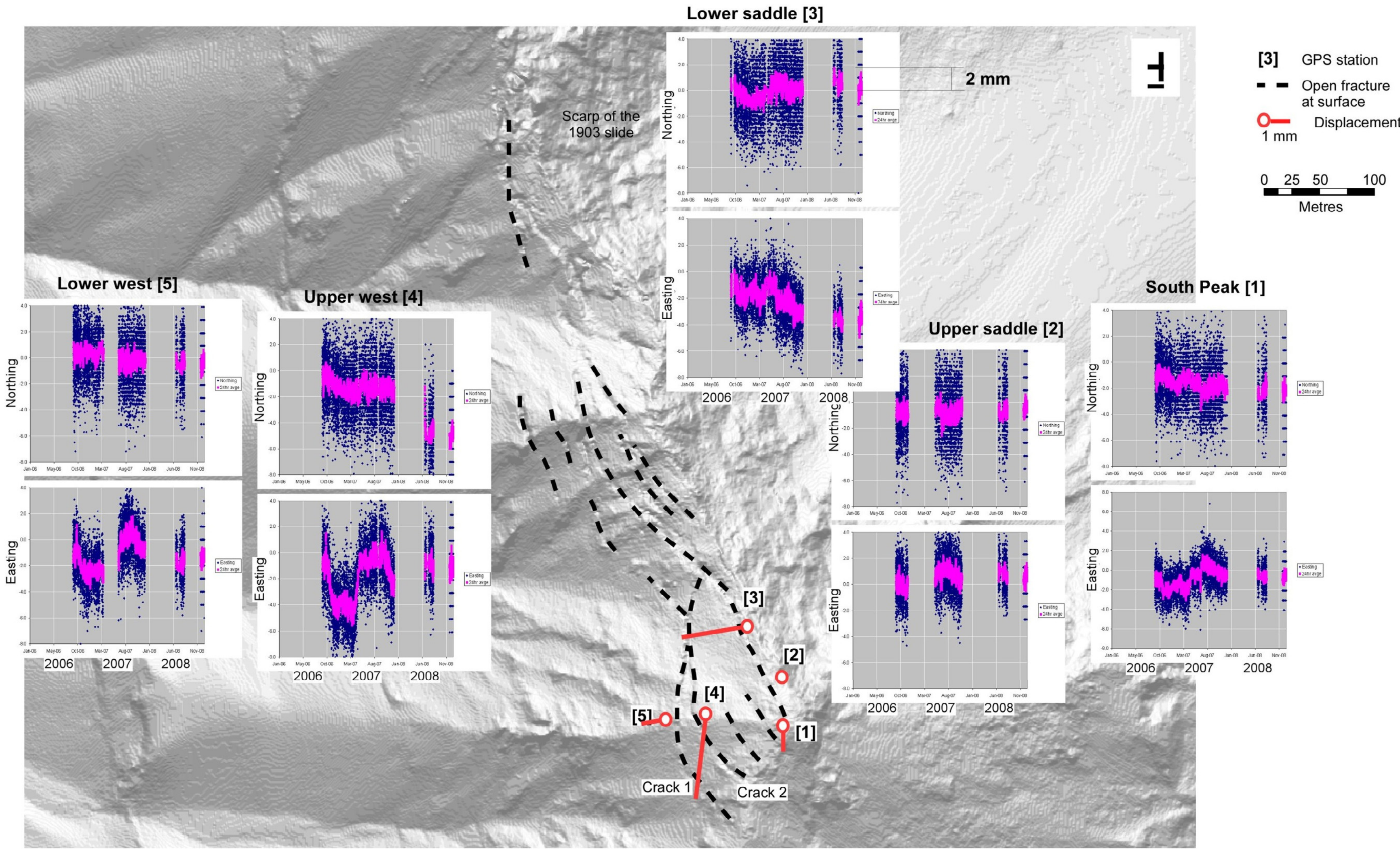

Figure 8. Surface displacements derived from dGPS stations during the period 2006–2008: horizontal component of the surface-displacement vectors plotted on a map of the South Peak of Turtle Mountain (red lines). The displacement vectors of the dGPS stations are absolute, since they reference an external co-ordinate system. dGPS stations: [1], South Peak; [2], Upper saddle; [3], Lower saddle;[4], Upper west; [5], Lower west.

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 most 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 on the sensors. This section discusses the specific sensor trends in relation to the expected deformations.

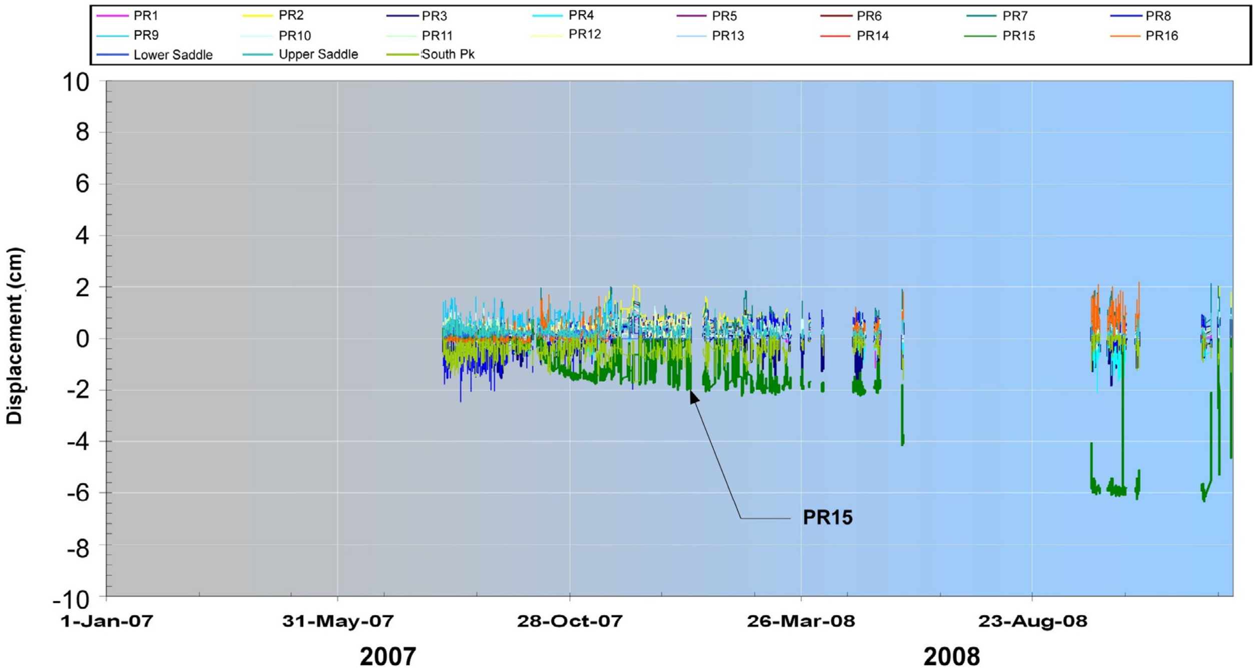

Figure 9. Plot of displacement versus time for prisms at Turtle Mountain.

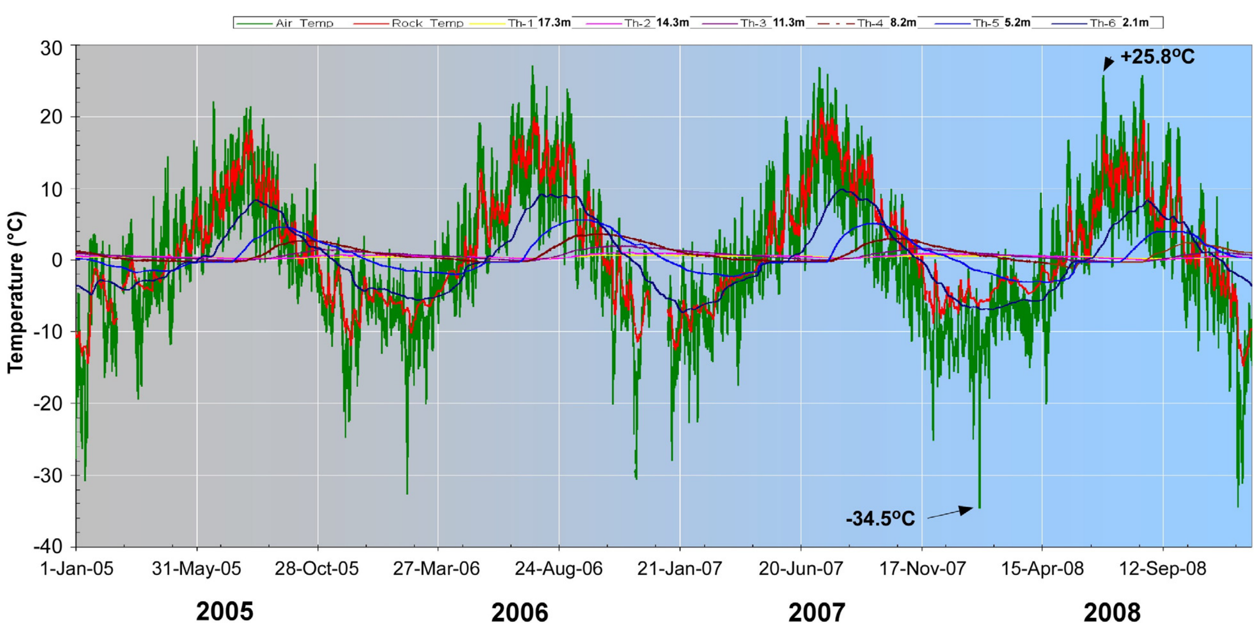

Figure 10. Air temperature and variation of rock temperature with depth in the borehole at the top of South Peak, Turtle Mountain, 2005–2008.

3.3.1 Crackmeters

All 22 crackmeters installed in 2003 and 2004 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 12). As such, we expect that these blocks are slowly settling and that movements within the zone and between blocks are highly irregular. Of the eight sets of crackmeters, sets B and C are at the transition between the wedge and subsidence zones, and have exhibited long-term creep and seasonal accelerations, likely associated with the wedge pulling away (to the northwest) from the subsidence zone. The remaining six sets of (sets A, D, E, F, G, H) do not show any consistent trends that are indicative of movement.

3.3.2 Tiltmeters

As with the crackmeters, most of the tiltmeters are in the subsidence zone. It is very difficult to distinguish any clear deformation trends on the tiltmeters; we attribute any trends observed to this point to local movements on blocks or on the walls of the large fractures. The level of noise inherent in the tiltmeters is sufficient to largely mask these movements.

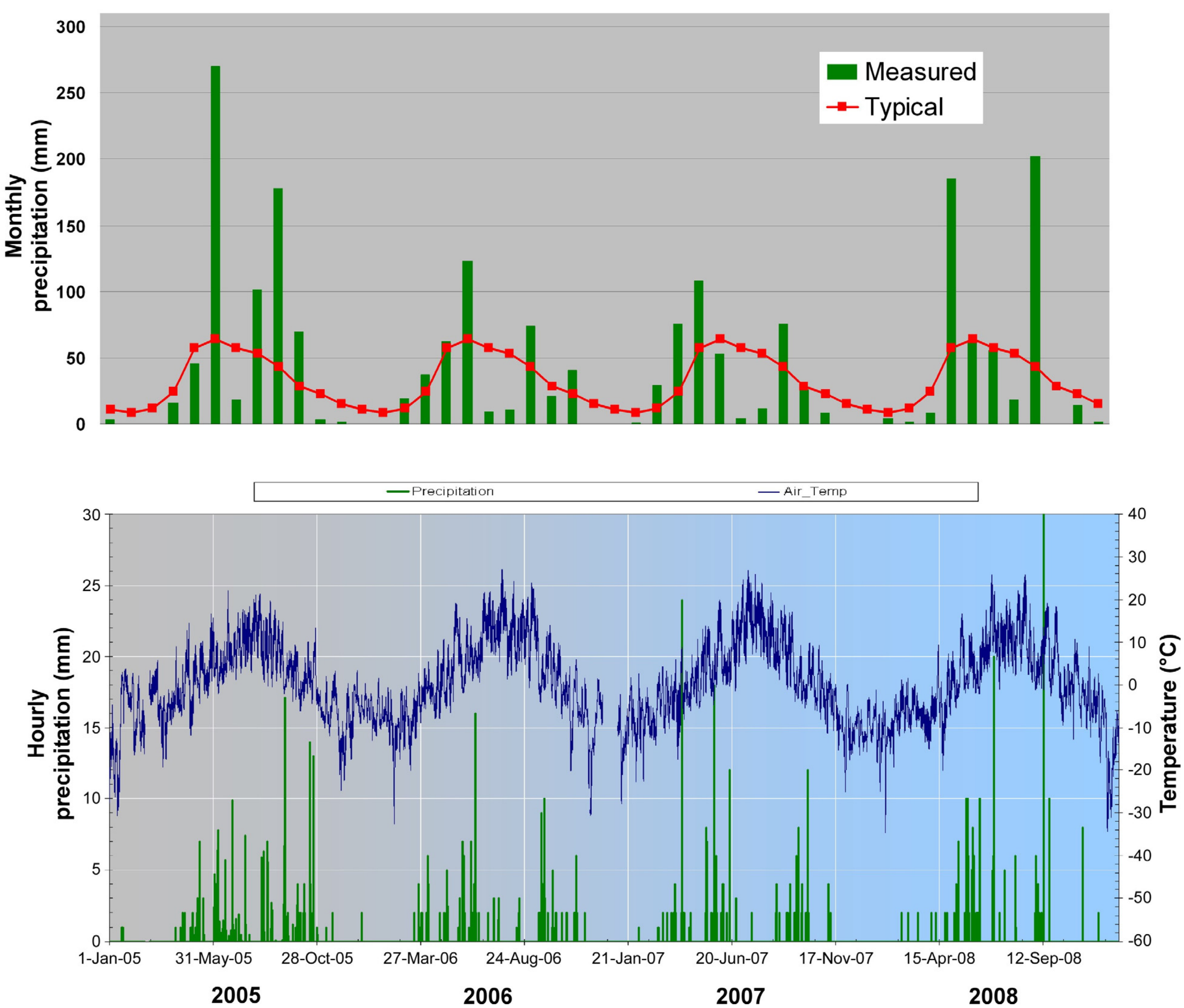

Figure 11. Measured and typical average monthly precipitation (top), and temperature and hourly precipitation (bottom) near Turtle Mountain, 2005–2008.

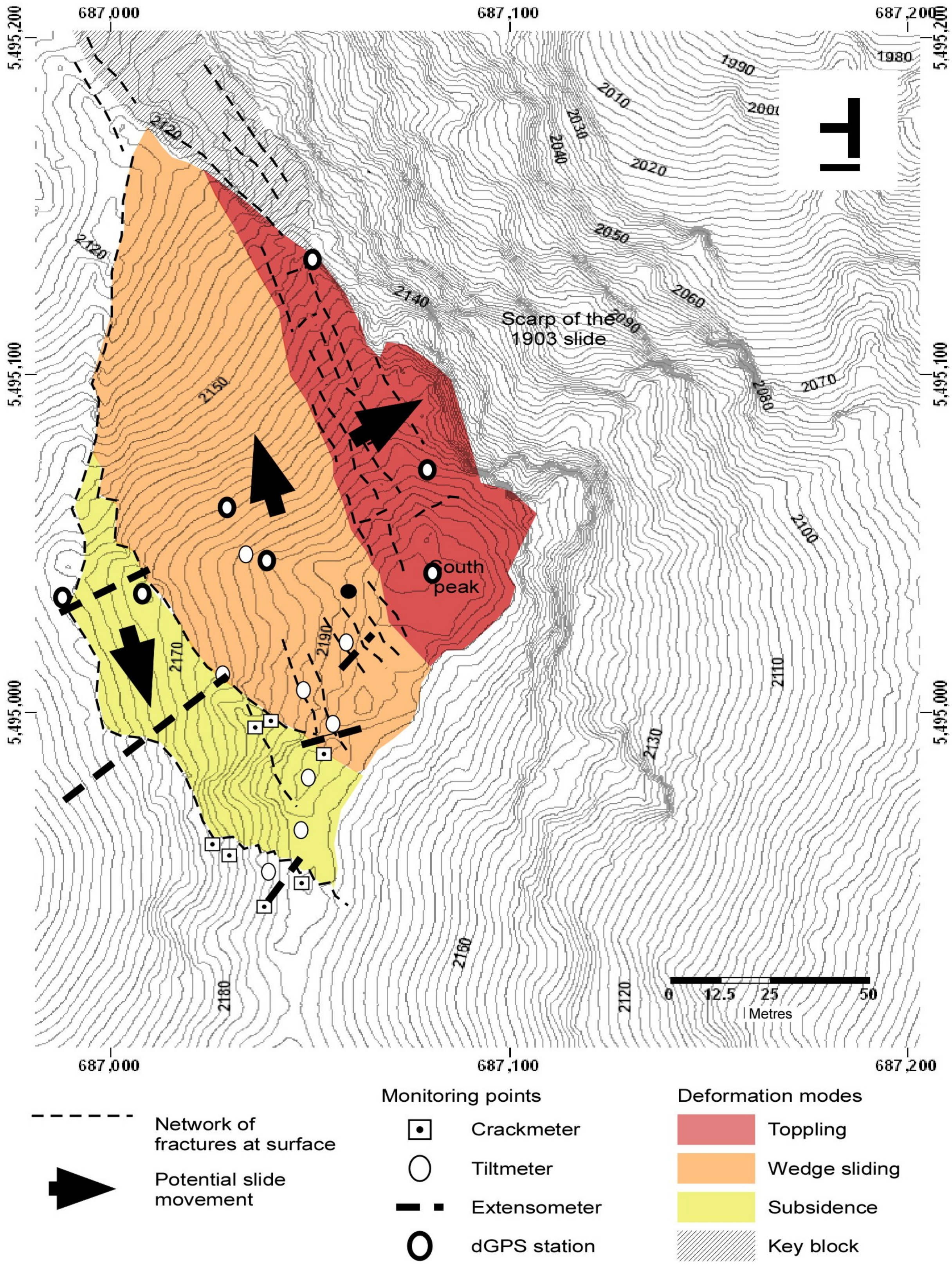

Figure 12. Location of monitoring points relative to the four main zones of deformation observed on the South Peak of Turtle Mountain.

3.3.3 Extensometers

The five extensometers do not have the same fine level of resolution as the crackmeters and tiltmeters, and are therefore sensitive only to large movements (many millimetres to centimetres). In addition, the summer 2004 installation of these sensors preceded the updated understanding of deformation kinematics on South Peak. Figure 12 shows the hypothesized direction of movement for the various zones on South Peak in relation to the orientations of the five extensometers. We expect the movements in some cases to be at oblique angles to the optimal orientation for the extensometers, so that only very large movements would be readily distinguishable on the instruments. This suggests that the rainfall/freezing-related displacement events in 2005 and 2006 (Moreno and Froese, 2006, 2008a, b) 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 data from other sensors, in the future.

3.3.4 Differential Global Positioning System (dGPS)

As opposed to the previous three sensor types, many of the more recent dGPS stations were installed based on the updated understanding of the deformation mechanisms on South Peak and on other portions of the eastern face of Turtle Mountain. As discussed in Section 3.1.4, the deformations observed on the dGPS stations are so far sufficiently small that they could be within the range of error for the instruments or based on installation conditions. 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 Section 3.1.5, we do not expected that any trends would be apparent at this time due to the 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 on 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 Hazard Mapping and Runout Analysis

Moreno and Froese (2008b) presented results to support identification of kinematically feasible unstable volumes from the South Peak and Third Peak areas using remotely sensing data (Pedrazzini and Jaboyedoff, 2008; Pedrazzini et al., 2008; Froese et al., 2009). It also presented runout analyses for a large-volume failure of South Peak, based on previously hypothesized failure mechanisms (Hungr Geotechnical Research, 2007). In 2008, AGS and the University of Lausanne undertook additional field studies to field-truth the LiDAR structural analysis (Pedrazzini and Jaboyedoff, 2008; Pedrazzini et al., 2008).

4.1.1 Unstable Volume Estimation

As outlined in Moreno and Froese (2008b), studies by Pedrazzini and Jaboyedoff (2008) provided detailed mapping of potentially unstable volumes of rock in the South Peak and Third Peak areas (Figure 13). This work identified 12 zones where kinematically feasible movement mechanisms exist and, in some cases, signs of instability observed during field mapping. Figure 13 provides a plan-view summary of the unstable areas identified.

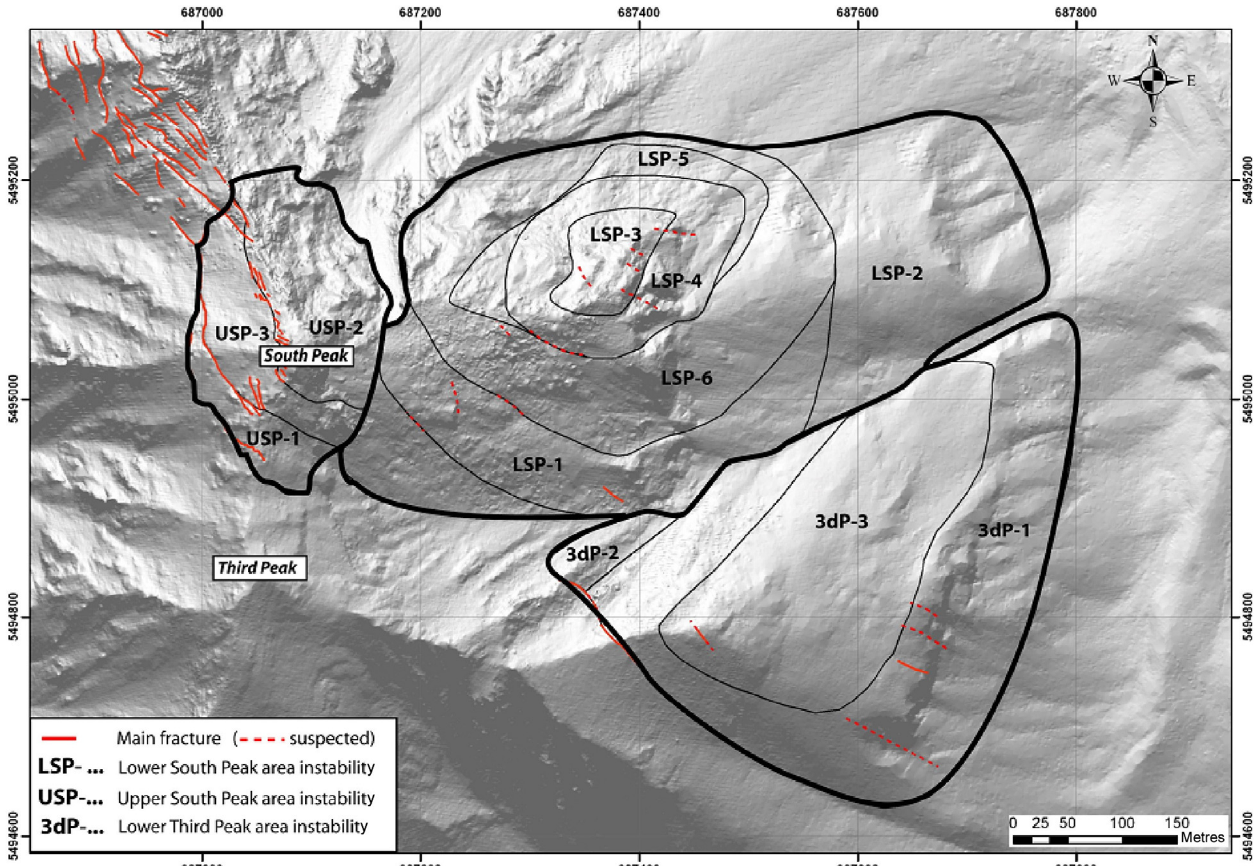

Figure 13. Instability zones in the South Peak and Third Peak areas identified by the detailed structural mapping and kinematic analysis (*from* Pedrazzini and Jaboyedoff, 2008)

4.1.2 Runout Analysis

Previous forward modelling (Allan, 1933; Read, 2002, Hungr Geotechnical Research, 2007) for a failure from the eastern face of Turtle Mountain had always addressed the case of a mass of approximately 5 million m^3 failing as a single mass. These simulations all used the model adopted (Cruden and Krahn, 1973) for the failure of the Frank Slide in 1903. Moreno and Froese (2008b) have provided visual depictions of the Allan (1933), BGC Engineering Inc. (2000) and Hungr Geotechnical Research (2007) studies.

Using the revised interpretations of the failure mechanisms for South Peak (Froese et al., 2009) and a more detailed breakdown of potentially unstable zones (Pedrazzini and Jaboyedoff, 2008), the dynamic runout models for the single South Peak failure (Hungr Geotechnical Research, 2007) have been applied to predict runout for the 12 unstable volumes identified by Pedrazzini and Jaboyedoff (2008). This work, undertaken by Hungr Geotechnical Research (2008), is summarized in this section.

4.1.2.1 Model Calibration

Given the relatively small volume of the potential rock avalanches and the characteristics of the upper slope of Turtle Mountain, the motion of these landslides is most likely to remain frictional (Hungr et al., 2005). To develop a predictive model for the 12 unstable volumes identified using the digital-elevation-model analysis tools COLTOP and SLBL, Hungr Geotechnical Research (2008) carried out calibration back-analyses for nine rock avalanche cases. They selected the cases to represent rock avalanches that traversed relatively dry slopes, free of deep, saturated soil deposits. Four of these avalanches originated in limestone rock and five in strong igneous or metamorphic rock. All the cases ran out over steep mountain slopes, but only those larger than 10 million m^3 reached the valley bottom. Table 1 gives the (bulked) volumes of the rock avalanches and the value of bulk friction angle (Hungr, 1995) required to produce the observed runout in each case.

Table 1 Rock avalanche cases selected for calibration (from Hungr Geotechnical Research, 2008).

Location	Volume (million m^3)	Bulk Friction Angle (°)	Reference
Afternoon Ck	0.7	35	Strouth et al. (2006)
Thurwieser	1.9	26	Sosio et al. (2008)
Jonas North	2.4	25	Bruce (1978)
Jonas South	3.7	26	Bruce (1978)
Madison	33	15	Hungr and Evans (1996)
Frank, 1903	36	14	Cruden and Krahn (1973)
ValPola	59	18	Hungr and Evans (1996)
Hope1965	64	22	Hungr and Evans (1996)
Diablerets	73	17	Hungr and Evans (1996)

The back-analysis (Hungr, 2008) clearly indicates an inverse relationship between volume and friction angle, as shown in Figure 14. The reasons for such a trend, observed in previous analyses, are not presently clear but may include

- increased likelihood for the larger slides to encounter unconsolidated saturated material on lower slopes,
- greater intensity of possible undrained loading of material over-run by a larger slide, and
- more intensive grain crushing and destruction of rock asperities in the larger events.

Figure 14 shows a semilogarithmic lower-limit envelope, drawn to the calibration data. This envelope was used to select bulk friction angles for the forward analysis, given the volume of each detachment. As a result, the larger rock avalanches are more mobile.

Analyses were completed by Hungr Geotechnical Research (2008) using both a three-dimensional model (DAN3D) and a pseudo–three-dimensional model (DAN-W). Hungr and McDougall (2008) provided descriptions of both models. Usually, both models give comparable results when applied to the same travel paths with the same resistance parameters. In this case, however, the DAN-W analyses examined potential mobility of the rock avalanches in the event that less lateral spreading takes place than is implied by the DAN3D model.

4.1.2.2 Results of Analyses

The final distribution of debris for each of the 12 rock avalanches was predicted by DAN3D analysis (Hungr Geotechnical Research, 2008), as shown by the example in Figure 15. All of the rock avalanches are essentially complete in less than 1.5 minutes, similar to the 1903 Frank Slide. The maximum velocities are in excess of 50 m/s (180 km/h). The deposit thickness, shown in Figure 15 in 5 m contour intervals, is typically up to 10 m but ranges up to 20 m.

Figure 16 shows envelopes of maximum runout resulting from all 12 potential rock avalanches, as analyzed in 2-D and 3-D. The 2-D maximum runout distances are typically somewhat longer than the 3-D results. The reason for this is that the 2-D analyses were conservatively forced to travel on relatively narrow paths and their energy is therefore more confined. Such a situation could actually arise in reality, as the rock slide mass may remain somewhat coherent in the initial stages of its movement, in contrast to the 3-D model that assumes instant, fluid-like lateral spreading. The direction of movement of the 3-D slide and the assumed 2-D profile did not often agree.

The largest runout is associated with LSP-2, the total failure of lower South Peak, with a volume of 6.6 million m^3.

Figure 17 is an updated plan showing the maximum extents of the piecemeal failure analyses (Hungr Geotechnical Research, 2008) versus the previous single-mass failure estimates (Allan, 1933; BGC Engineering Inc., 2000).

4.2 Periodic GPS

As outlined in Moreno and Froese (2008b), a series of 18 monitoring points was installed by the University of Calgary Geomatics Engineering Department (Teskey and Ebeling, 2008), with readings taken using differential Global Positioning System (dGPS) instruments. These monitoring points are

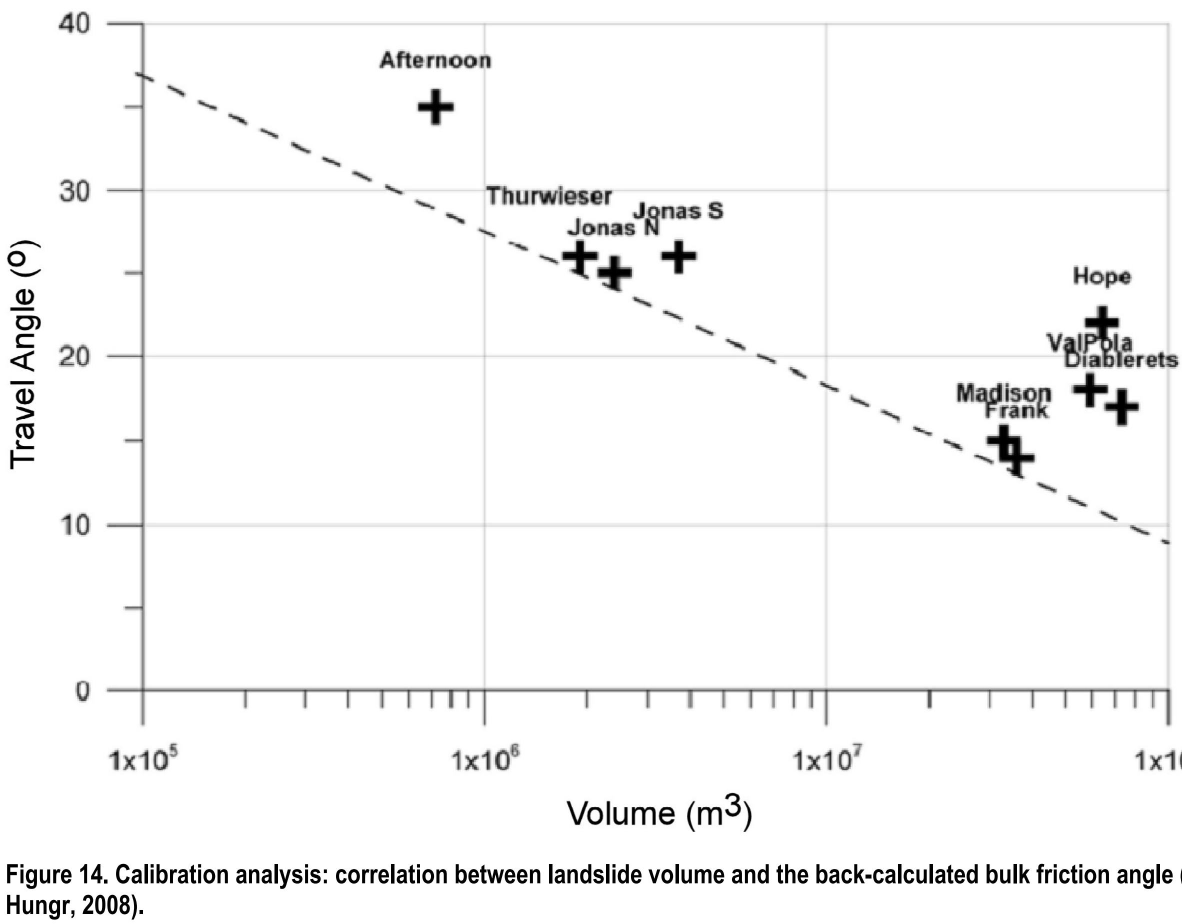

Figure 14. Calibration analysis: correlation between landslide volume and the back-calculated bulk friction angle (*from* Hungr, 2008).

along portions of the eastern face, below South and Third peaks and on the visibly unstable saddle area between North and South peaks. The annual summary report of the Geomatics Engineering Department (Teskey and Ebeling, 2008) indicated that, given the 10 mm expected resolution of the measurements, the displacements of the monitoring points are thus far sufficiently small to be less than the potential

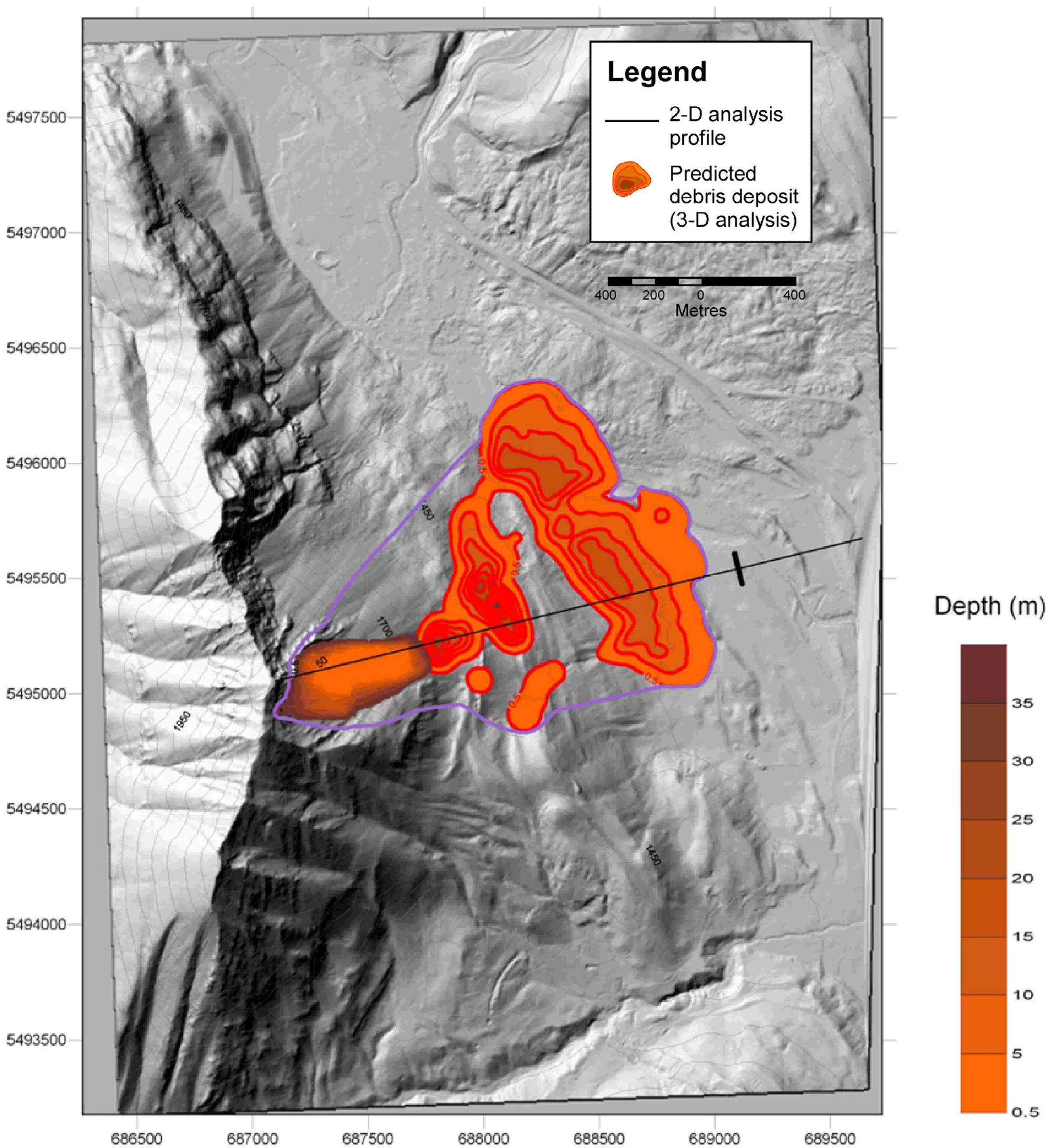

Figure 15. DAN3D three-dimensional forward prediction of the 6.6 million m^3 slide from the lower portion of South Peak (*from* Hungr Geotechnical Research, 2008).

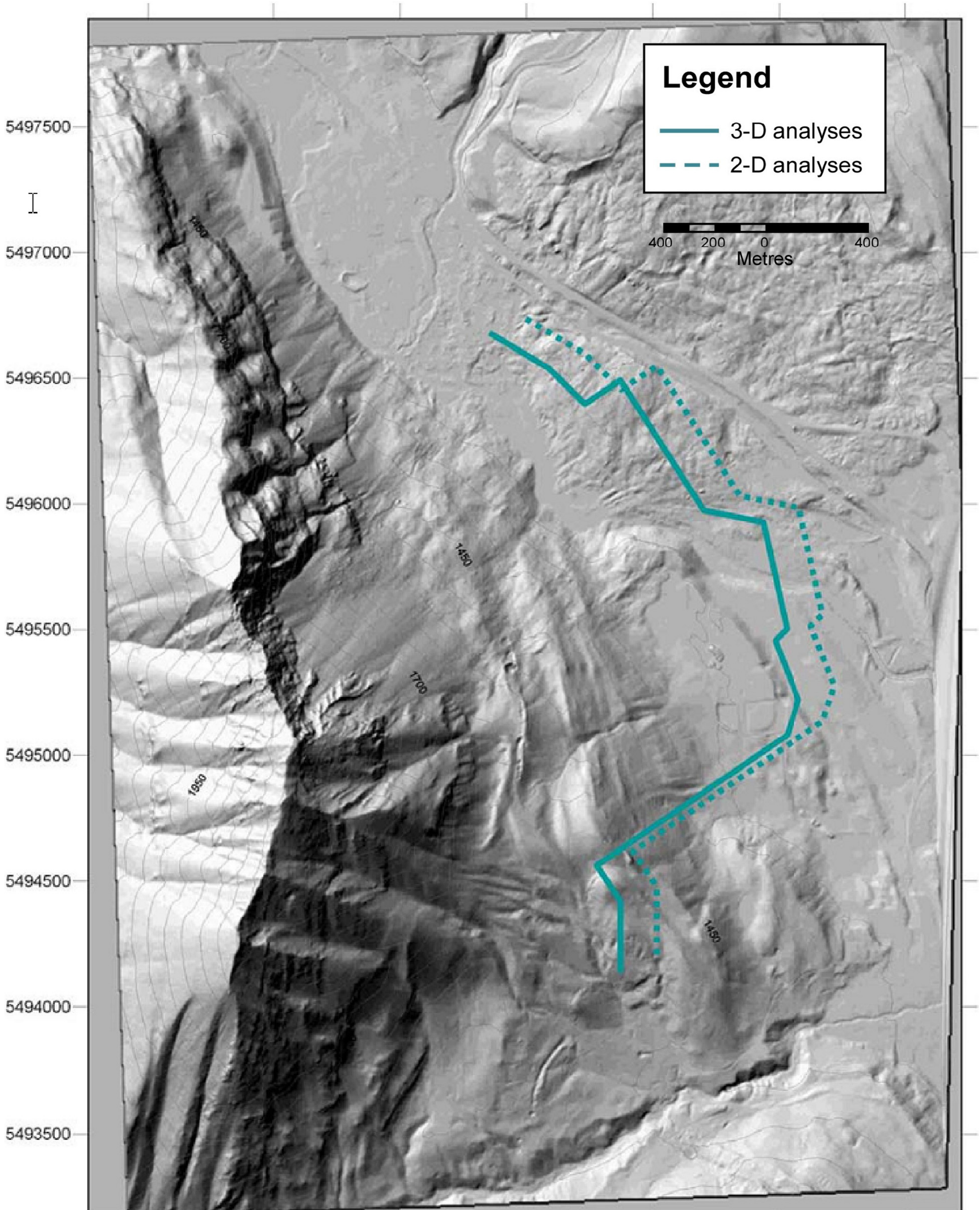

Figure 16. Envelope of hazard areas for 12 potential rock avalanches from the South Peak and Third Peak areas of Turtle Mountain (*from* Hungr Geotechnical Research, 2008).

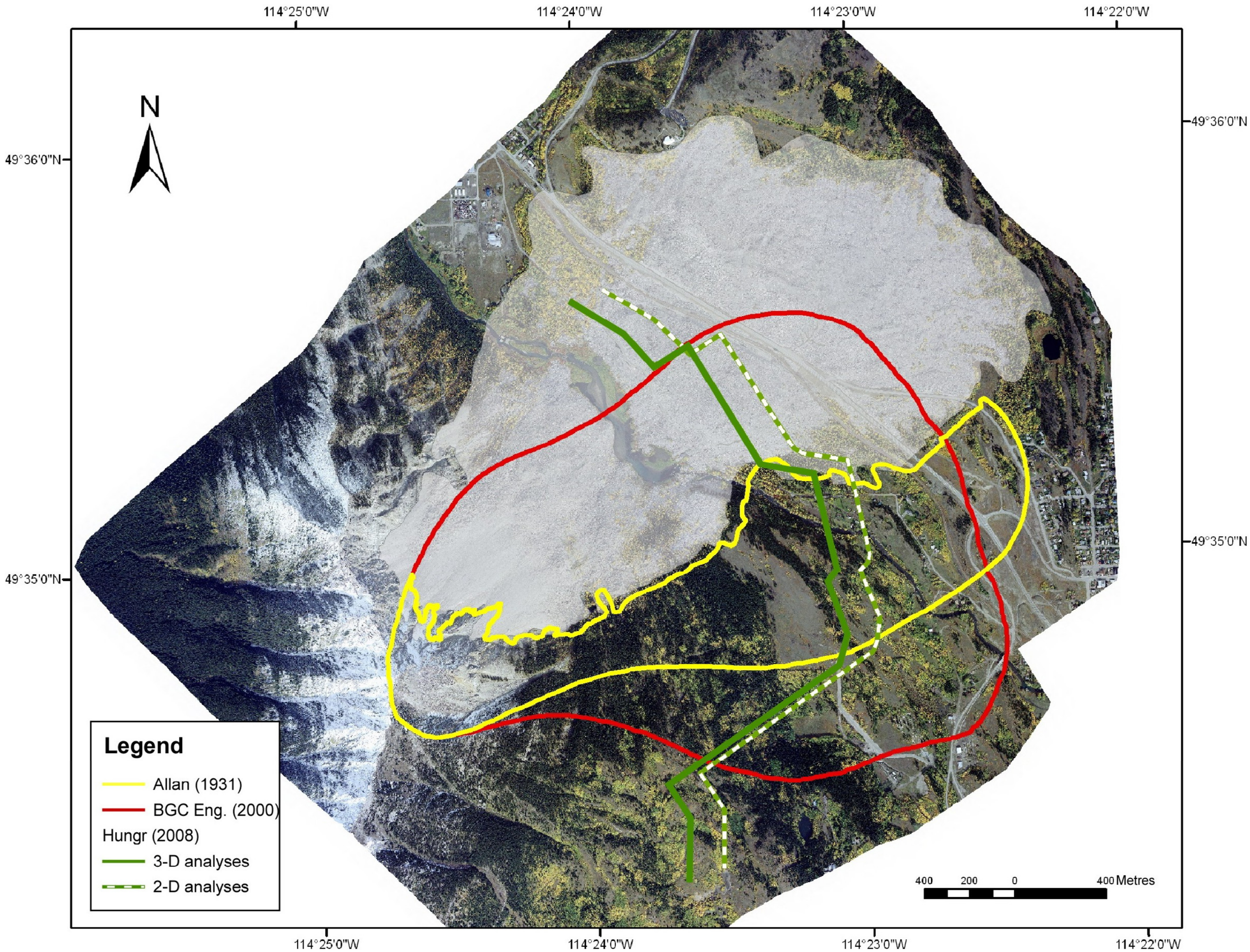

Figure 17. Summary of maximum run-out extent results from piecemeal failure analysis by Hungr Geotechnical Research in 2008, in relation to previous single-mass failure estimates (Allan, 1931; BGC Engineering, 2000).

measurement error. However, given the previously measured displacements of the large unstable blocks in the saddle area, we expect that displacement trends will become clear in the third year of readings (2009).Summary and Conclusions

4.3 Sensor Network

Analysis of the data from the near–real-time monitoring system and study 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 view of movements on the mountain. Recent changes in the understanding of the movement mechanisms on South Peak and other portions of the mountain by Froese et al. (2009) and Pedrazzini and Jaboyedoff (2008) mean that our understanding of the value of the data from the various instruments continues to change as well. For example, when the system was installed during the period 2003–2005 (Moreno and Froese, 2006), we assumed that the large fissures present on the top and west side of South Peak were the head of the large (~5 million m^3) mass that was moving to the east. As demonstrated by Froese et al. (2009), the upper South Peak is more likely moving as three masses. This means that much of the instrumentation was installed in a rubbly zone of subsidence, rendering a large number of the crackmeters and tiltmeters of little use from a prediction and warning perspective because many of these sensors reflect the subsidence and/or are oriented for the wrong 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 and laser-ranging technologies to monitor movements of the various blocks. Specifically, the dGPS technology is considered the most promising because displacements are measured relative to a geographic reference system rather than the installation orientation of the device.

Future monitoring on Turtle Mountain will focus more on directionally independent and remote monitoring technologies to minimize expenditure on monitoring technologies that have questionable reliability or are not well suited to the deformations expected on the mountain.

4.4 Hazard Management

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

Because the potentially unstable structures have only been identified at this point and there is no information on the spatial and temporal characteristics of the deformations, 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 (both continuously monitored and periodically monitored) and a series of 20 mirror prisms that are monitored via 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. On an annual basis, we not only publish the most recent results (Moreno and Froese, 2008b) but also present them in public meetings to the municipal officials and residents in the affected zones. Frequent updates are also available on the Alberta Geological Survey website (http://www.ags.gov.ab.ca/geohazards/turtle_mountain/turtle_mountain.html).

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