



Turtle Mountain Field Laboratory: 2007 Data and Activity Summary

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Abstract

Since 2005, the Alberta Geological Survey (AGS) has undertaken detailed review of the near-real-time data stream from a sensor network installed on the South Peak of Turtle Mountain, and has initiated numerous supporting studies to understand better the style and rate of movement of the slowly moving rock mass. The South Peak site has been called the Turtle Mountain Field Laboratory (TMFL), as the data from the sensor network at the site will be used by the international geotechnical research community to develop a better understanding of 1) the mechanics of slowly moving rock masses, 2) instrumentation for measuring these movements, and 3) the application of new technologies.

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. In general, the observed trends highlighted very slow movement along the deep fractures to the west side of South Peak, in the order of less than a millimetre per year. Preliminary results from detailed mapping of Third and South peaks, including lower slopes, has helped to define potential zones of movement and led to interpretations of the mechanisms for movement and potential volumes involved in these areas.

During 2007, a network of periodically read global positioning system (GPS) monuments was installed on the more active portions of the peak, which had been identified by photogrammetry studies. In addition, installation of the differential global positioning system (dGPS) and electronic distance measurement (EDM) was completed. This included the addition of a number of new prisms on the eastern face of South Peak and lower down the mountain, which will provide a more complete picture of the pattern of movement in potentially unstable areas.

Reliability and continuity of the monitoring system have been reasonable and are expected to improve. Current level of reliability allows the instrumentation installed at Turtle Mountain to provide an indication of increased movements on South Peak. Periodic visual inspections have proven to be a necessary and important element of the monitoring system. Considerable maintenance and repair have been required to increase the reliability of the sensor network. Similar efforts, although possibly diminishing, will likely be necessary in the years to come. Necessary ongoing work will include maintenance of the roof system for the crackmeters, continued protection of the tiltmeters against humidity, and replacement of faulty instruments.

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 coordinating 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 2007 annual summary of results and interpretations for the benefit of the geotechnical community and stakeholders in the Crowsnest Pass. The report is meant to be brief, with the more detailed scientific results being presented in peer-reviewed journals and conference publications.

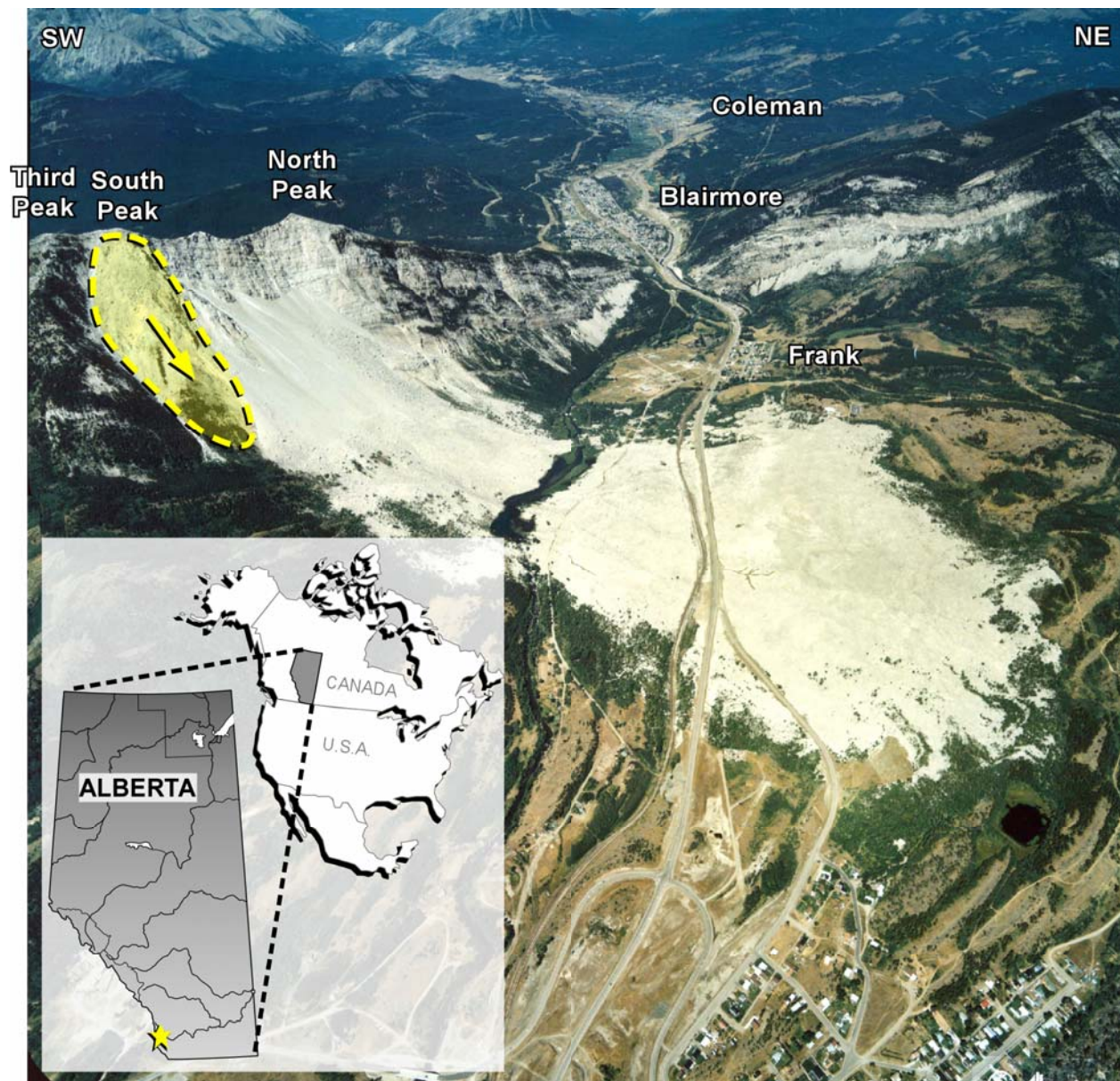


Figure 1. Location of Turtle Mountain in Alberta and full-extent aerial view of the Frank Slide. The dashed line below South Peak outlines the area identified by Allan (1931, Figure 2) as being most unstable. Photo reproduced with permission from Alberta Sustainable Resource Development, Air Photo Distribution. 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 the period between January and December 2007. Documentation of the hardware that forms the various components of the communication stations was provided in Moreno and Froese (2006) and is therefore not included in this summary.

The main activities undertaken with respect to the sensor network during 2007 include

- 1) completion of the design and installation of six global positioning system (GPS) stations on South Peak;
- 2) installation of the electronic distance measurement (EDM) 'total station' and twenty prisms on the east face of the mountain;
- 3) installation of two web cameras (one at the top of the mountain looking down, and one at the bottom of the mountain looking up); and
- 4) replacement of two crackmeters and upgrade of the protective housing on five sets of crackmeter triplets.

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 2007.

2.1 New Installations

2.1.1 *Electronic Distance Measurement (EDM) Network*

An automated laser-ranging survey system was installed during the summer of 2007 by McElhanney Engineering Services of Vancouver (McElhanney Consulting Services Ltd., 2007; Combined GPS and EDM monitoring on Turtle Mountain, Alberta, (Bjorgan and Froese, work in progress, 2008). This system consists of twenty prisms installed on the mountain and a Leica robotic total station in the valley bottom to sight the prisms. Of the 20 prisms, four were co-located with the GPS stations at the Third Peak, South Peak, Upper Saddle and Lower Saddle (Figure 3). The other sixteen prisms were mounted on the east face of Turtle Mountain by Vertical Systems International Inc., using ropes and climbing gear (Figure 4). This work included the addition of a number of prisms on the eastern face of Third Peak and lower down the mountain to obtain a more complete picture of the movement patterns in potential unstable zones highlighted by recent light detection and ranging (LiDAR) studies (Moreno and Froese, 2007). The locations of the prisms are shown in Figure 3.

The total station is located at the municipal pumphouse in Bellevue on a reinforced concrete pillar that was built for the project. A viewing port was constructed through the brick wall of the building and a protective wooden structure built and insulated to keep outside air from affecting any of the equipment in the pumphouse (Figure 5). The total station can measure distance with an accuracy of about ± 3 mm between the pumphouse and the prisms (an absolute distance of almost 3 km). However, given the large change in elevation between the pumphouse and the summit of Turtle Mountain, atmospheric refraction can introduce large errors in measuring absolute distance. To fully correct for refraction effects, distance measurements from the total station to the four ridge prisms are constantly taken by their co-located GPS. These readings are used to calibrate the distance between the ridge and the total station, and these calibrated distances are then used to correct the distances to the other prisms. Since each prism must be visible to the instrument in order to gather readings, readings cannot be obtained when the prisms are obscured (fog, snow, ice on the prisms). The prisms are covered by snow and ice during much of the winter, so the reliability of readings, if obtained, is low.

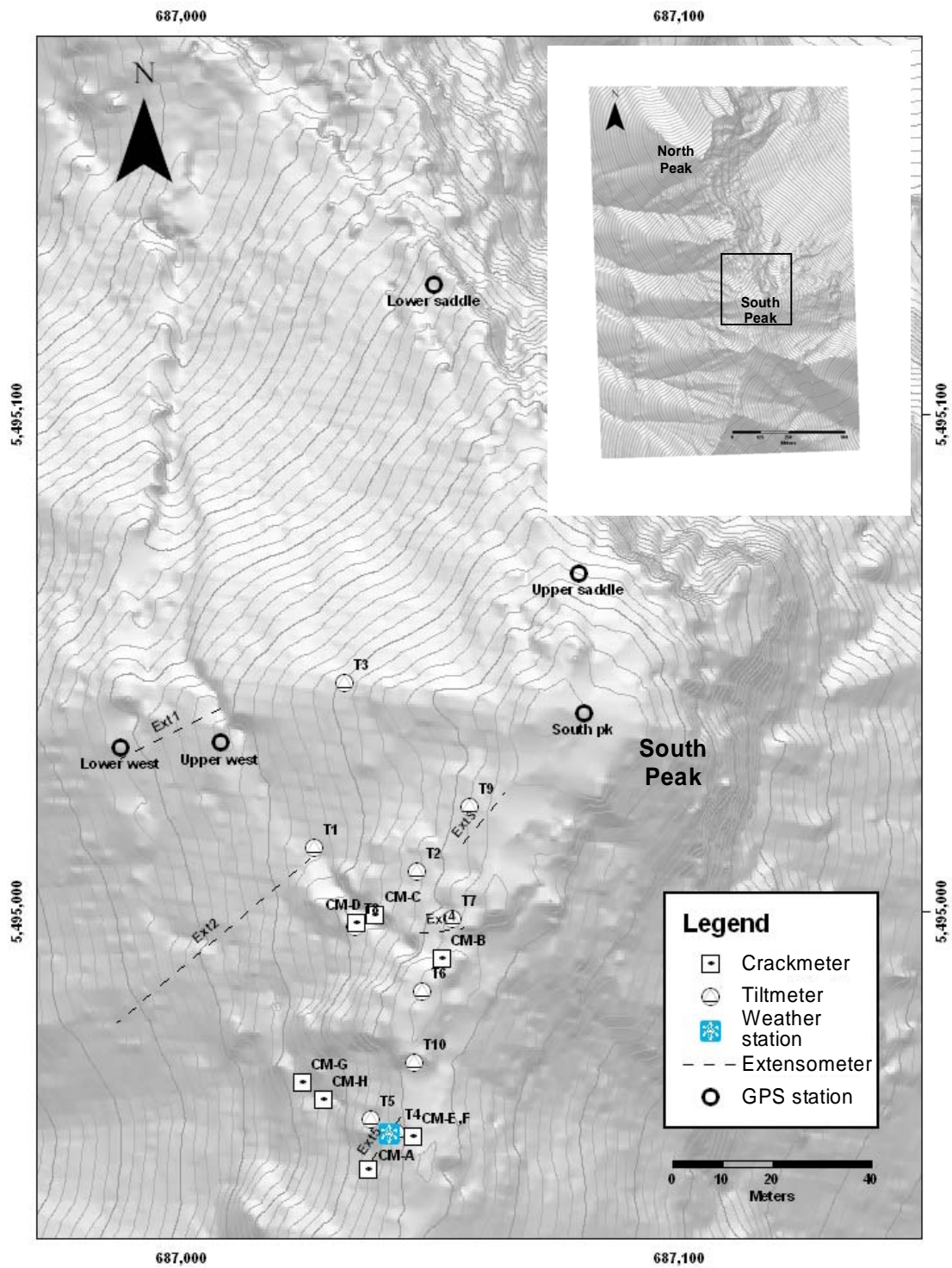


Figure 2. Overview of the sensor network on Turtle Mountain as of December 2007.

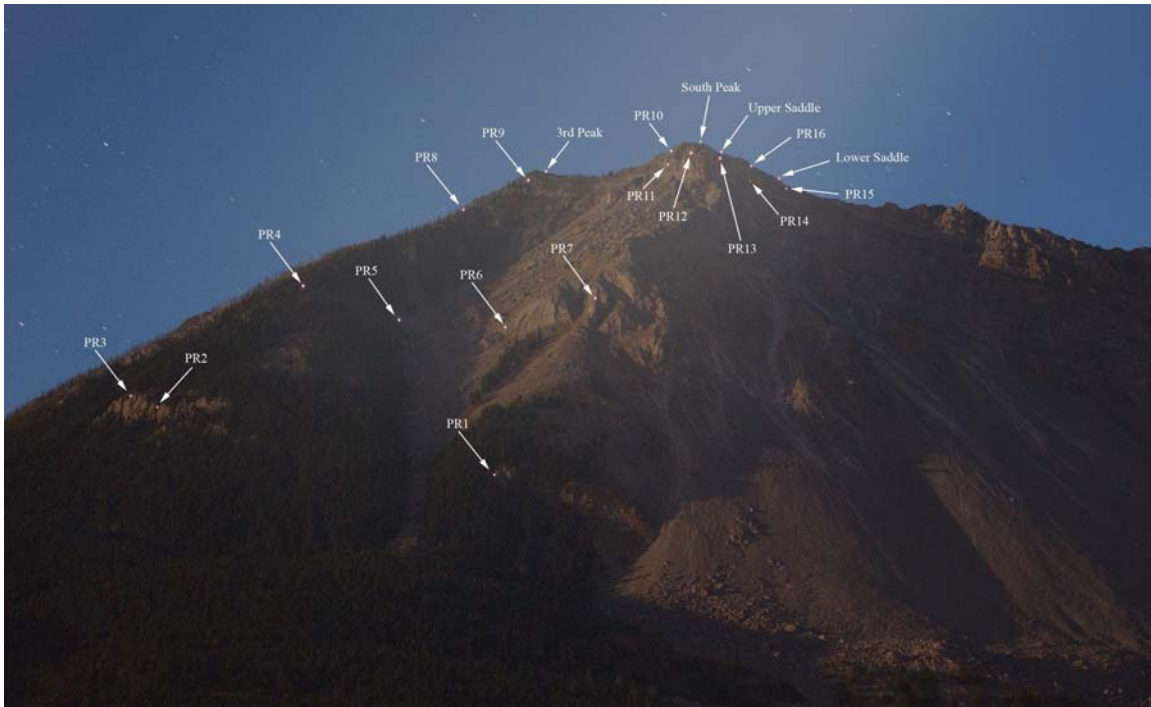


Figure 3. Location of the prisms on Turtle Mountain, as viewed from the pumphouse. Prisms PR1–PR16 were installed in 2007, while the remaining prisms (Third Peak, South Peak, and Upper and Lower Saddle) were installed in conjunction with GPS pillars in 2005. This photo was taken at night on July 28, 2007 using a large spotlight to illuminate the prism locations. Photo: G. Bjorgan, McElhanney Consulting Services Ltd.



Figure 4. Installation of one of the sixteen prisms on the eastern face of Turtle Mountain during July 2007.



Figure 5. The Leica ‘total station’ installation in the municipal pumphouse at Bellevue, near the base of Turtle Mountain. The total station is in an insulated box and located approximately 3 km from the prisms on the eastern face of Turtle Mountain. Photo: G. Bjorgan, McElhanney Consulting Services Ltd.).

In May 2006, Pinnacle Technologies (formerly Alto Instruments Ltd.) managed the installation of a new radio tower on the west side of the pumphouse. This tower establishes a 5 GHz link between the EDM system on the mountain and the Frank Slide Interpretive Centre (FSIC). At present, data collected by the total station are streamed in real time to McElhanney’s processing server in Vancouver via the 5 GHz link between the Bellevue municipal pumphouse and the provincial building in Blairmore. However, it is expected that these data will be transmitted to the FSIC computer server by the end of 2008. This data-streaming modification will be completed in the summer of 2008, with the performance and resulting data being included in the 2008 annual summary report. The advantages of this configuration are that the EDM data can be combined with the data from the other deformation and climate sensors on the mountain and incorporated directly into the emergency warning application.

2.1.2 Differential Global Positioning System (dGPS) Network

In addition to the automated laser-ranging survey system, six single-frequency dGPS stations and one base unit were installed by McElhanney Consulting Services Ltd. (2007; Combined GPS and EDM monitoring on Turtle Mountain, Alberta, Bjorgan and Froese, work in progress, 2008), in the vicinity of South Peak and at the Bellevue pumphouse, respectively. Three of these stations are positioned along the ridge just north of South Peak; two are located on the west face of the mountain, immediately downslope from the South Peak borehole (one on each side of Crack 1); and one is located at Third Peak. The Third Peak GPS station is considered stable relative to those on South Peak and has a short baseline that is acceptable for use as a base station. This project began in September 2005 and was completed in November 2007. The locations of these installations are shown in Figure 2.

Each station comprises a reinforced concrete pillar mounted with a dual-metal-plate assembly and a fixed GPS antenna. 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. Each station is powered by deep-cycle marine batteries located inside an insulated battery box. Figure 6 shows a typical installation. The GPS base unit installed at Bellevue pumphouse differs only in that it uses utility power, rather than solar, and a different brand of wireless server. The pumphouse GPS station is more than 3 km from the South Peak GPS array and is therefore used only periodically as a stable base to confirm that the Third Peak GPS station is not moving.

The connection to the Turtle Mountain network is handled by 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 Vancouver (McElhanney Consulting Services Ltd. office). After being accepted by custom software on the processing server, the raw data are archived and then passed on to the Novatel RTKNav processing engine. The GPS data are processed in two different ways:

- 1) A real-time solution is provided from instantaneous readings, which has an accuracy of 1–2 cm.
- 2) An average solution is obtained from one-hour blocks of readings, which is accurate to approximately 3–5 mm.

Both types of processed solutions are then filtered and archived on the processing computer. Raw data processing, filtering and archiving will be migrated to the computer server located at the FSIC in the summer of 2008; the results of this will be reported in the 2008 annual summary. A schematic diagram of the data flow for the GPS and EDM systems is shown in Figure 7.



Figure 6. Typical 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.

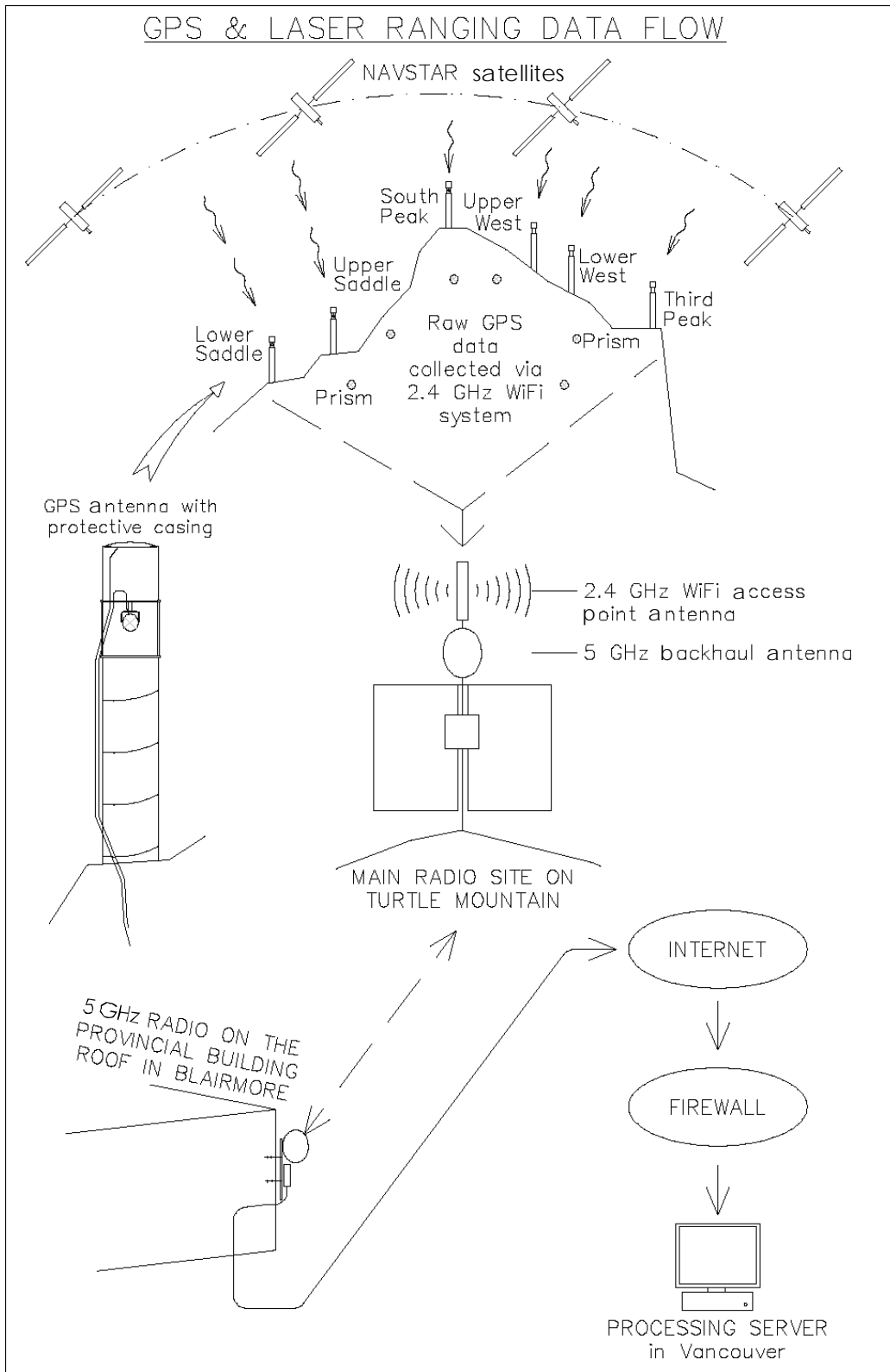


Figure 7. Schematic diagram of data flow for the combined dGPS-EDM system on Turtle Mountain (from McElhanney Consulting Services Ltd., 2007; Combined GPS and EDM monitoring on Turtle Mountain, Alberta, Bjorgan and Froese, work in progress, 2008).

2.1.3 Turtle Mountain web cameras

Two web cameras were installed at Turtle Mountain by H. Bland of Pinnacle Technologies (formerly Alto Instruments Ltd.) to provide visual confirmation and help with interpretation of any displacement detected by the primary monitoring system. One was located at the top of the mountain (South Peak), looking down to the northeast across the head of the 1903 slide, and the other at the bottom of the mountain (Bellevue pumphouse), looking up at the eastern face of Turtle Mountain. The South Peak camera was installed at a former seismic monitoring station at South Peak. Seismic monitoring at this station ceased in 2006 after severe lightning destroyed the monitoring equipment and data radio. During installation, the damaged radio was replaced, a mast extension added to accommodate the camera mount and additional guy wires installed to prevent the mast from twisting under severe winds. Installation also included the re-use of existing equipment enclosures, solar panels, solar controllers and associated batteries (Figure 8). The camera is attached to the mast extension and connected through a single cable to the network radio, which transmits the image data to the computer server at the Frank Slide Interpretive Centre (Figure 9).

The Bellevue pumphouse web camera was established as a secondary visual inspection point. This site is connected to the FSIC via a 5GHz wireless data link. Power for the Bellevue camera is supplied from a power-over-Ethernet injector with an integrated 48V DC supply. The injector and network connection are housed in the electronics enclosure inside the pumphouse building. The camera's data/power cable runs from the enclosure through the conduit to the west. The line passes through the wall via a service cap above the roofline and then to the antenna in the radio tower next to the pumphouse. The two cameras are identical except for a slightly greater zoom on the pumphouse lens.



Figure 8. Web camera installation on the South Peak of Turtle Mountain, showing radio antenna, battery boxes and solar panels (left), and close-up of camera, pole mount and mast extension (right). Photo: H. Bland, Pinnacle Technologies (formerly Alto Instruments Ltd.).

The view captured by the Bellevue pumphouse camera includes the eastern face of South and Third peaks, the Frank Slide scar, North Peak and lower portions of the mountain (Figure 10).

The two cameras have been configured to archive images to the computer server at the FSIC every 5 minutes. In addition, they transmit an image to the server every 10 minutes for use on a web page. This frequency can be adjusted remotely to a few seconds, should conditions warrant more frequent image acquisition. The cameras deposit their image files (in JPEG format) into a time-ordered hierarchy of directories (YYYY/MM/DD). A scheduled task runs on the computer server to build daily movie files based on the collection of JPG images. Both the images and the movie files are available via the web-server software (Apache) running on the Turtle Mountain server (http://www.ags.gov.ab.ca/geohazards/turtle_mountain/turtlecam/turtle_webcam.html).



Figure 9. Image from the web camera on the South Peak of Turtle Mountain. Photo: H. Bland, Pinnacle Technologies (Alto Instruments Ltd.).

2.2 Performance

Overall, the primary deformation-monitoring system (crackmeters, extensometers and tiltmeters) performed reliably during the reporting period. These systems were inspected and modified in July 2007. The following summary statements can be made, based on the inspection and modifications performed:

- Tiltmeter reliability was improved considerably with the addition of desiccant packs inside the enclosures. Despite this, a number of tiltmeters continue to show the effects of high humidity inside the instrument, but with levels of noise that will not impede the ability to provide warnings of worsening rockslide conditions.



Figure 10. Image from the web camera at the Bellevue pumphouse, near the base of Turtle Mountain.

- Several of the 22 crackmeters continue to show evidence of snow or ice loading. However, the data obtained from some of the crackmeters with improved roofs (Set C) show that effective protection against snow can be achieved. It is expected that refurbishment of additional roofs, undertaken in early July 2007, will increase the reliability of this system.
- The five extensometers performed consistently well, providing high-quality data throughout most of the reporting period, although their reliability was somewhat affected by lightning activity. Two extensometers were lost during a thunderstorm event during early September.
- The six GPS stations performed reliably during the reporting period, although some of these stations have been continuously affected by lightning. Several trips were made during the reporting period to repair/replace damaged equipment. Damage due to moisture accumulation in the enclosure has been documented in one case.
- 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 are currently under review and should be implemented in late 2008.

3 Data Analysis

This section discusses interpretations of slope conditions and displacement behaviour from instrumentation results. As some of the sensors have been impacted by climatic factors, discussion will

focus on the sensors that have provided reliable annual performance. Meteorological data have been essential in explaining general displacement trends observed in the surface instrumentation.

3.1 Deformation Monitoring Data

3.1.1 Crackmeters

Crackmeters were installed to monitor continuously the direction and magnitude of surface-fracture opening. Details of installation have been described by Moreno and Froese (2006). Although displacements were observed on many of the crackmeter sets, the most indicative record of slope displacement has been obtained from the cluster of three crackmeters in Set B. These instruments provide the time series of crack opening and temperature over a period of three years (Figure 11). Monitoring results show an annual displacement cycle, which correlates with temperature cycles, that are 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. Magnitudes of displacement rate of 0.4 mm/year have been recorded. Likewise, the measured data show displacement fluctuations, related to daily air-temperature cycles, with crack-width changes on the order of 0.02 mm.

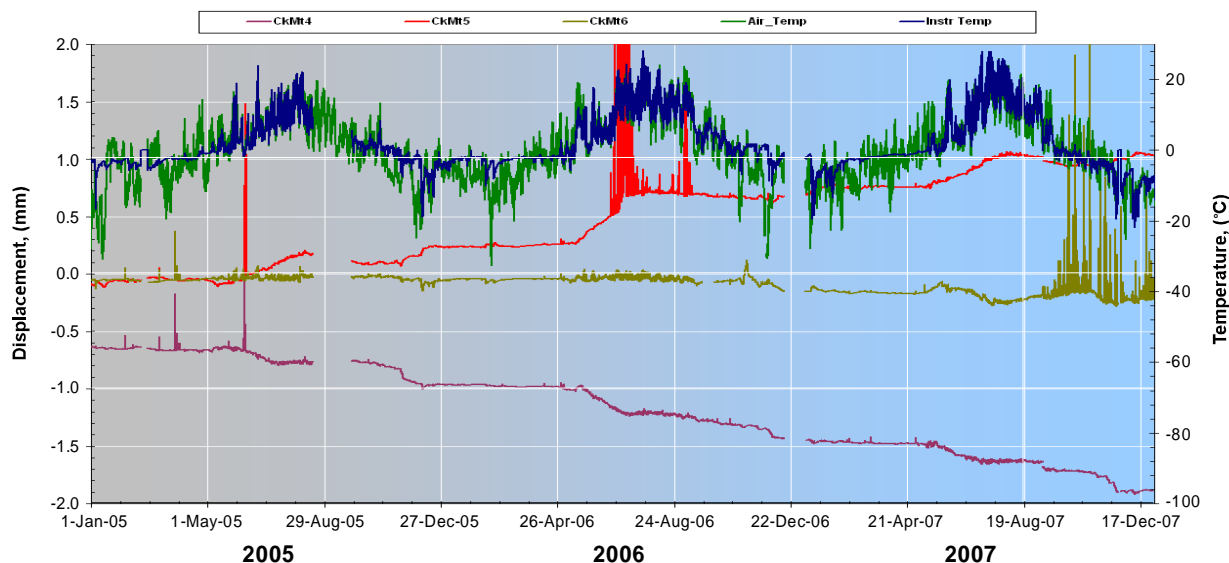


Figure 11. Plot of displacement versus time for crackmeter Set B, South Peak, Turtle Mountain.

3.1.2 Tiltmeters

Results from the tiltmeter network reveal a variety of trends, ranging from sensor fluctuations that mirror the thermal cycles to trends that might indicate cumulative, permanent creep (observed at two of the sensors).

In general, all sensors display an increase in tilt at the start of the summer period and a return to the previous state at the end of it (Figure 12). A similar cyclic variation in tilt associated with diurnal temperature fluctuations is also present, but at a smaller scale ($\sim 0.01^\circ$). Noisy responses due to moisture in the sensors continue to affect the quality of tiltmeter data (T-1, T-8 and T-10), although the addition of desiccant packs during summer 2006 has remarkably improved data quality (T-2 and T-3).

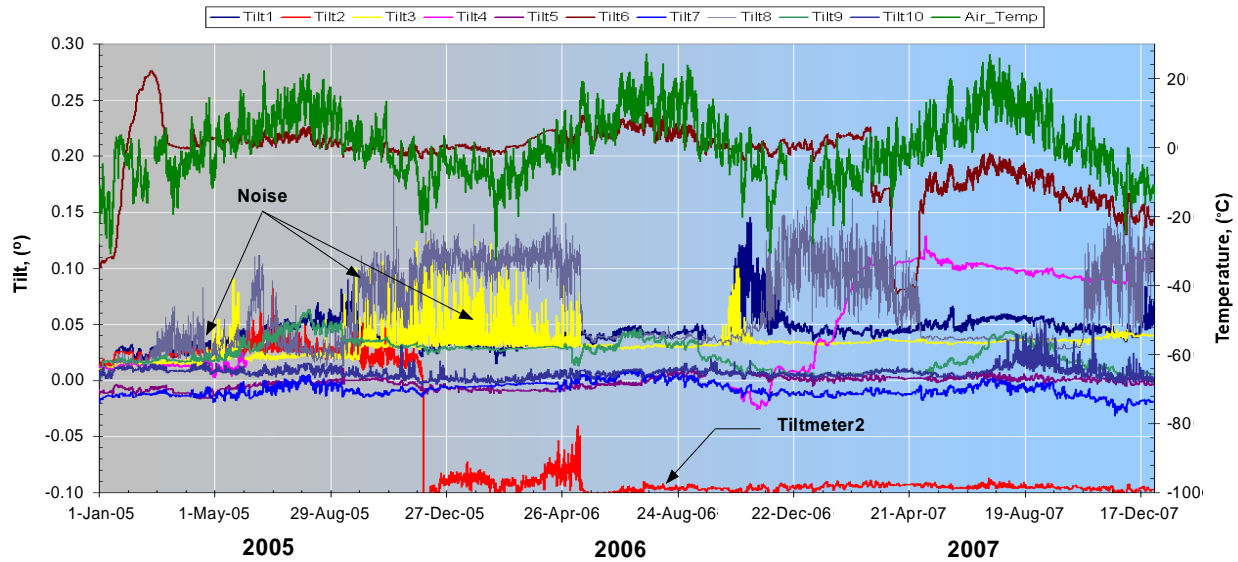


Figure 12. Plot of tilt versus time for tiltmeters, South Peak, Turtle Mountain.

Examination of the records shows a number of short-term displacement events on sensors T-2 and T-6. A sudden offset in tilt occurs and is followed by a flattening in the curve as the rate drops to zero. However, this behaviour is not seen in any of the neighbouring sensors. Thus, it is believed that this signal does not represent an episode of rock-mass rotation but rather local freeze-and-thaw effects, as these occurred with the onset of snowmelt followed by freezing. A recent field trip revealed that these instruments are located on corner blocks with vertical and horizontal free rock faces that favour greater penetration of water into the rock mass and subsequent freezing. Tiltmeter T-1 appears to show trends associated with slow creep, but the overall deformations and the noise in the data do not permit conclusive interpretation. Additional years of data are needed to get a better understanding of the displacement style.

3.1.3 Extensometers

Each of the five extensometers shows very stable responses during the reporting period: no daily or seasonal changes can be seen in the displacement data (Figure 13). Extensometers EX-2 and EX-3 continue to be extended at 19 and 6.17 mm, respectively. These displacements were recorded during two periods of heavy precipitation in early June and early September of 2005. The specifics of these events are discussed in Moreno and Froese (2006, 2007). A gradual displacement of 1.3 mm occurred at extensometer EX-4 in November 2006. This movement is believed to have occurred as the result of a dramatic drop of air temperature between October 29 and 30.

3.2 Other Monitoring Data

3.2.1 Climatic and Thermistor Data

Average temperatures at the top of the South Peak of Turtle Mountain in 2007 were warmer than those recorded in previous years, ranging from -10.4°C in January to $+15.6^{\circ}\text{C}$ in July. In addition, lower extreme maximum ($+26.8^{\circ}\text{C}$) and minimum (-27.1°C) temperatures were registered (Figure 14) than in previous years. Significant daily temperature variations were also common. Rock temperature showed the same general trend as air temperature but was more subdued (lower maximum and minimum readings), with a time lag of about 12 hours relative to significant changes in air temperature. Seasonal temperature fluctuations penetrate only about 15 m into the slope (Th-2) and are negligible below that depth, with significant temperature variations measured 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 14).

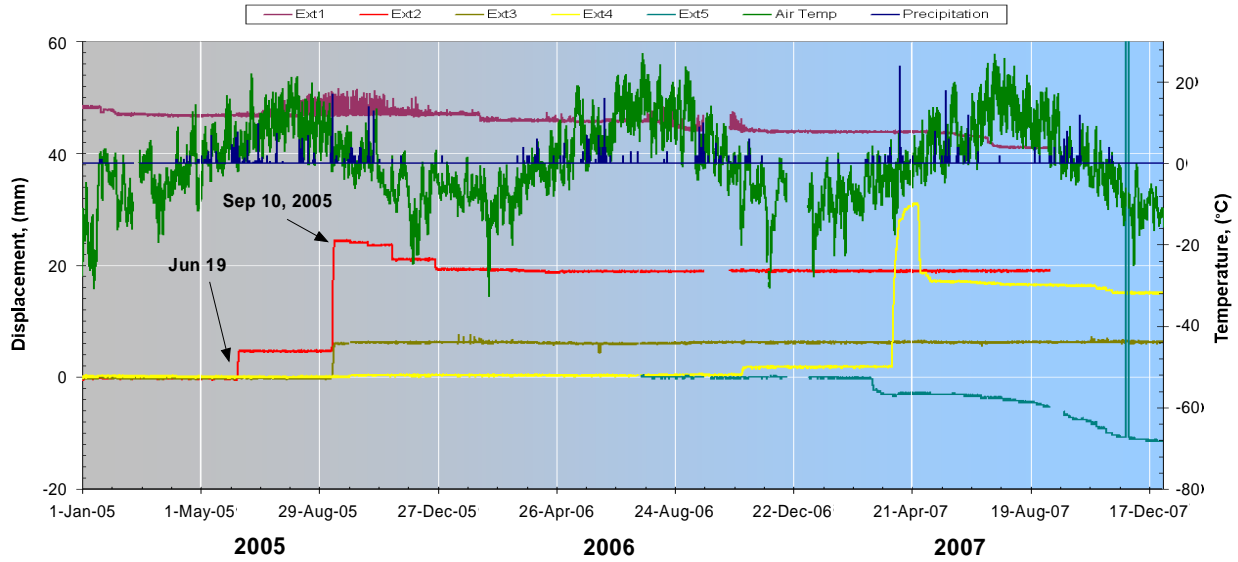


Figure 13. Plot of displacement versus time for extensometers, South Peak, Turtle Mountain.

Total precipitation of 393 mm was measured during the reporting period on South Peak of Turtle Mountain, slightly below of the average precipitation of 397 mm measured at the nearby Coleman weather station of Environment Canada. Climate averages for this station are based on at least 15 years of data between 1971 and 2000. Below-normal winter precipitation was measured (Figure 15) and above-normal precipitation was recorded during the spring, with two major precipitation events recorded in early April and late May. Preliminary data indicate that the total volume measured during this event was among the second to tenth highest in the 3 years for which records exist. The summer of 2007 was a dry season, but precipitation increased to above-normal levels during fall, except for November.

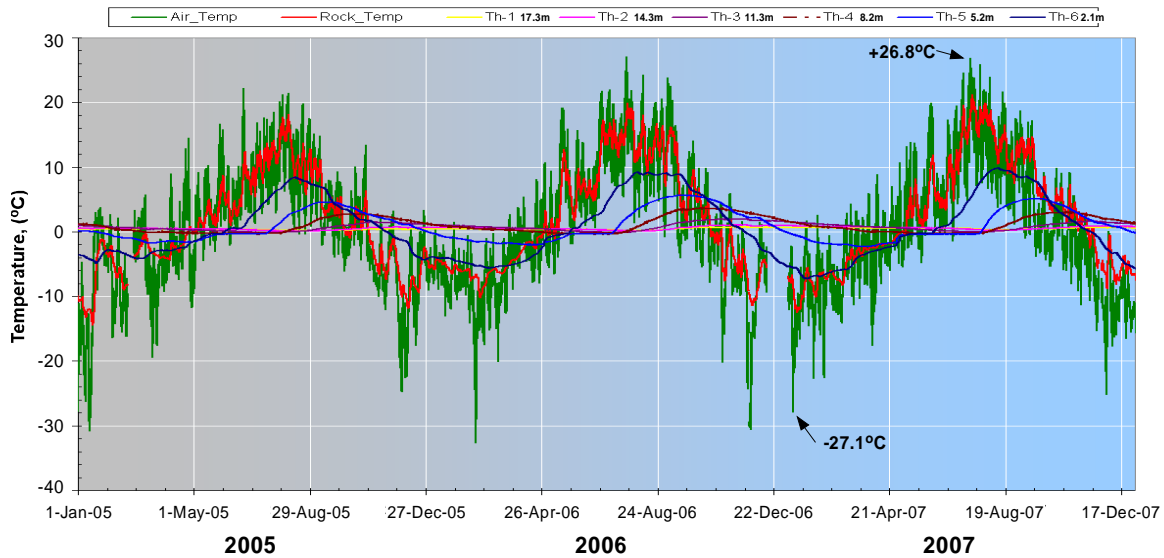


Figure 14. Air temperature and variation of rock temperature with depth in the borehole at the top of South Peak, Turtle Mountain, 2005-2007.

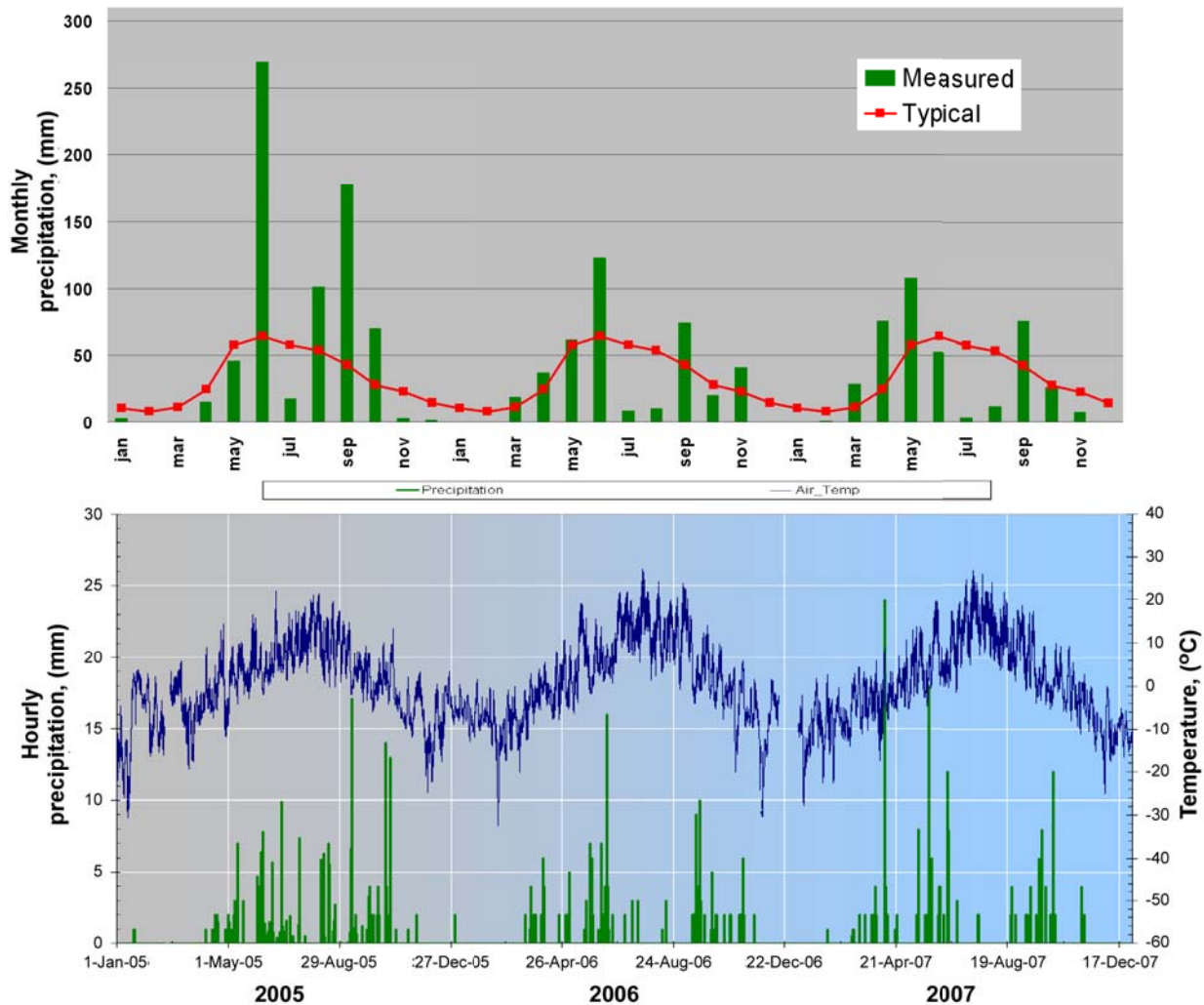


Figure 15. Measured and typical average monthly distribution of rainfall in the vicinity of Turtle Mountain, 2005–2007.

3.2.2 Differential Global Positioning System (dGPS)

As discussed in Section 2.1.2, six dGPS stations were installed during the summer and fall of 2006. These stations are located in two clusters: along the ridge just north of South Peak and on the west face of the mountain immediately downslope from the South Peak borehole (one on each side of Crack 1). Spatial coverage is therefore limited, with only one station situated within the stable part of the rock mass (Third Peak station). The results of monitoring between the summers of 2006 and 2007 are shown in Figure 16. The magnitudes of the displacement-rate vectors vary from 0.7 to 1.8 mm/year. Absolute displacement vectors are directed to the southeast for stations located at upper saddle, South Peak and upper and lower west, and to the southwest for the station located at the lower saddle, and are more or less congruent with the displacement directions observed at the photogrammetric targets (Moreno and Froese, 2007). However, the uncertainty in direction is large because their magnitude is small relative to the instrument resolution. Additional years of data are needed to confirm these results.

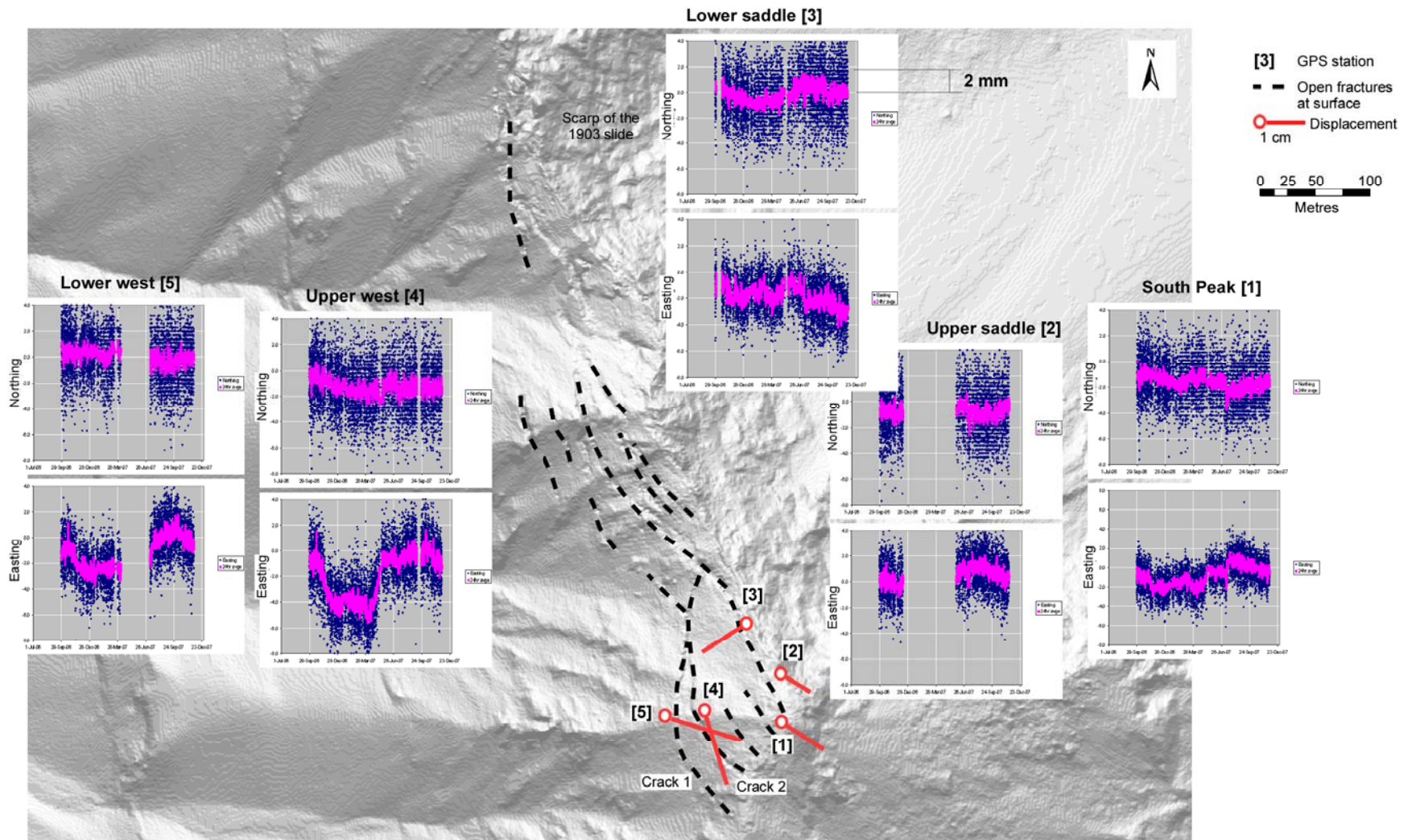


Figure 16. Surface displacements derived from dGPS stations during the period 2006–2007: horizontal component of the surface-displacement vectors plotted on a map of the South Peak of Turtle Mountain (red lines). The displacement vectors of the dGPS stations are absolute, since they are referenced to an external coordinate system.

3.2.3 Electronic Distance Measurement (EDM) System Network

As discussed in Section 2.1.1, twenty prisms were installed during the summer of 2007. The initial three months of data were used for system testing and not analyzed in detail, and are therefore not discussed in this report. It is expected that a more thorough review of the fifteen months of available data will be completed for the 2008 summary report.

3.3 Discussion of Monitoring Data

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

Despite the extreme precipitation event of early April, no associated displacement was recorded by the sensors on South Peak. The South Peak rock mass is heavily fractured and jointed, and relatively well drained, thus allowing water to be shed from the mountain rather than building up pressure in open fractures. A detailed analysis of the seasonal displacement pattern observed, however, indicates a strong correlation with annual temperature variation (Figure 11). Careful scrutiny of crackmeter Set B records indicates distinctive variations in displacement rate during the warming and cooling seasons. An increase in displacement can be seen during periods of prolonged warm air temperatures, typically during summer to autumn. This is followed by cessation of the displacements during the winter period. Comparison of the crackmeter displacements with those inferred from the other instruments indicates that the annual displacement cycle is real rather than an artifact of any temperature sensitivity of the sensor.

Studies undertaken on the Checkerboard Creek rock slope in British Columbia (Watson et al., 2004), using subsurface monitoring and computer modelling, show that deformation can extend well beyond the depth of seasonal frost penetration and that seasonal changes in rock temperature are a significant factor in controlling the slope stability. This model may also apply to Turtle Mountain, although there is currently insufficient information to draw any conclusions.

In light of the above, the authors suggest that the annual fluctuation is cyclical and of primarily thermoelastic origin, and that the long-term trend of fracture opening reflects deeper processes related to rock-mass instability.

4 Supporting Studies and Research

As the main focus of the ongoing work on Turtle Mountain is to understand the landslide hazard, numerous studies have been undertaken to better define, quantify and predict movements of South Peak and other parts of the mountain. These studies have been carried out both by AGS staff and by research partners/collaborators in Canada and Europe.

Studies include not only the enhanced definition and understanding of the South Peak landslide hazard but also an attempt to better understand the landslide potential of other areas of the eastern side of Turtle Mountain where there is significant infrastructure and development. These studies have ranged from detailed reviews of the modern and historical monitoring information to the application of new remote-sensing technologies. The following sections provide details on these studies. Figure 17 provides an overview of the various locations that are discussed.

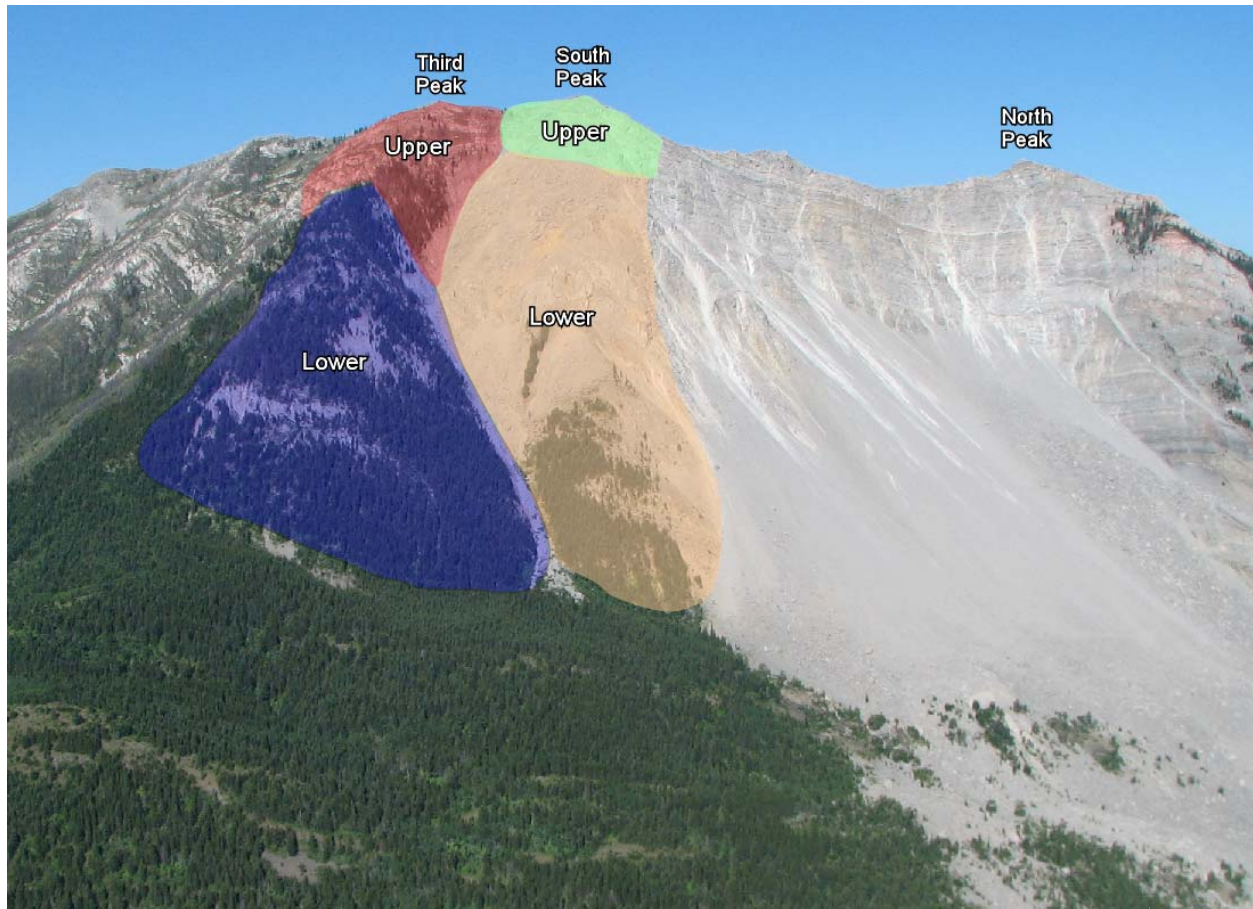


Figure 17. Eastern face of Turtle Mountain, showing the upper and lower zones of Third and South peaks. These areas were the focus of detailed structural mapping and kinematic analysis.

4.1 South Peak Structural Mapping

4.1.1 Previous Studies

The structure of Turtle Mountain was initially described as a monocline of Paleozoic limestone dipping to the west at about 50° (McConnell and Brock, 1904; Daly et al., 1912). The limestone (Livingstone Formation) was initially thought to have been thrust eastwards over subvertical Mesozoic sandstone, shale and coal on the Turtle Mountain Thrust, located near the base of the mountain. Based on this interpretation, the Frank Slide was believed to have occurred across bedding along east-dipping joints. Daly et al. (1912) considered the geological structure of Turtle Mountain to be similar from south of the slide to a point well past North Peak and recommended the relocation of the Town of Frank from its original location to its current location north of Highway 3.

The geological model of Turtle Mountain has evolved considerably since these early investigations. The Turtle Mountain anticline was first recognized by Leach (1904), and was reported by MacKenzie (1913). The axis of the anticline runs approximately north-south; its trace lies on the east face of Turtle Mountain. Subsequent models by Allan (1933), MacKay (1933) and Norris (1955) each incorporated the anticlinal structure of the mountain, and the Turtle Mountain Thrust.

The first studies that focused on the structure of the South Peak were completed by Allan (1933). Allan's three reports (1931, 1932, 1933) mapped the fractures on the peak; estimated the potential volume of a

second large rock avalanche, assuming the same mechanism for the Frank Slide that was generally accepted at that time; and estimated the travel paths of two different volumes of displaced material. His studies clearly mapped the pattern of large fractures on the peak but assumed that deformations would be initiated to the east, on the eastern limb of the Turtle Mountain anticline.

Cruden and Krahn (1973) developed the first kinematic model of the Frank Slide in which a major portion of the rupture surface of the slide followed bedding on the eastern flank of the anticline, and incorporated the subhorizontal thrust and a minor splay at the toe of the slide. The upper part of the slope opened along joints, leaving a subvertical scarp and the prominent North and South peaks (Figure 1).

In 1986, as part of the 1980s monitoring program, Fossey (1986) undertook detailed structural mapping of the South Peak area and identified three kinematically feasible mechanisms for slope movements at South Peak: planar sliding along the east limb of the anticline, and both toppling and wedge failure along the western limb of the anticline. Although Fossey (1986) identified the potential for wedge and toppling failure, he did not complete a detailed zoning of the South Peak area and identify potential volumes associated with each mode of deformation.

4.1.2 Upper South Peak

4.1.2.1 Kinematic Analyses

Since 2003, the acquisition of new digital-elevation-model (DEM) data has allowed the application of emerging computing tools to aid in structural mapping on Turtle Mountain. As part of work undertaken in 2003 for the centennial of the Frank Slide, the Geological Survey of Canada provided a photogrammetric DEM, (for which the raw data density was approximately 1 point per 2 m²). Using this DEM, Jaboyedoff et al. (in press) employed custom-developed software (COLTOP) to assign structural orientations to each grid and plotted these data on an equal-area stereonet to depict the fabric that controlled the morphology of the mountain. Jaboyedoff et al. (in press) highlighted six fabric elements, including three joint sets (J1, J2 and J3) that appeared to control the toppling of large wedges of rock in the headwall of the 1903 slide. Jaboyedoff et al. (in press) also indicated that these structures would likely also exist in the area of South Peak and could control the mechanism for deformation in this area.

In July 2005, an airborne light detection and ranging (LiDAR) survey was undertaken by Airborne Imaging Inc. of Calgary. The AGS purchased the license for an area covering Turtle Mountain and the Frank Slide. Raw point data were acquired at a density of approximately 1 point per m². The new LiDAR digital elevation model (DEM) has the advantage of sufficient data points that the first returns from vegetation can be distinguished from ground returns and therefore allow only ground points to be used to interpolate a model for the ground surface.

In order to create a digital elevation model (DEM) or bare earth model, a surface was interpolated from the triangulated irregular network (TIN) provided by the LiDAR three-dimensional point cloud. The mesh size of the grid is 0.5 m, based on a raw point collection density of 1 point per m². A natural neighbour interpolation technique was used to handle the large number of input points (more than 80 000).

A simplified 3-D discrete model of the pattern of discontinuities was constructed for the South Peak of Turtle Mountain by incorporating the major fracture sets observed. Construction of this model required the extrapolation of the mapped fractures from the surface to depth and from the borehole wall into the rock mass. This 3-D model assumes fully discontinuous polyhedral geometries for the rock blocks. This assumption is an approximation; the slope has been relatively stable for the last hundred years, indicating that rock bridges may be present on discontinuities used as boundary surfaces. As with the photogrammetric DEM, COLTOP was used to analyze the fabric. Based on the analysis of the coloured, shaded relief map, six discontinuity sets were identified (Figure 18). The dip and dip direction of each set mapped are given in Table 1.

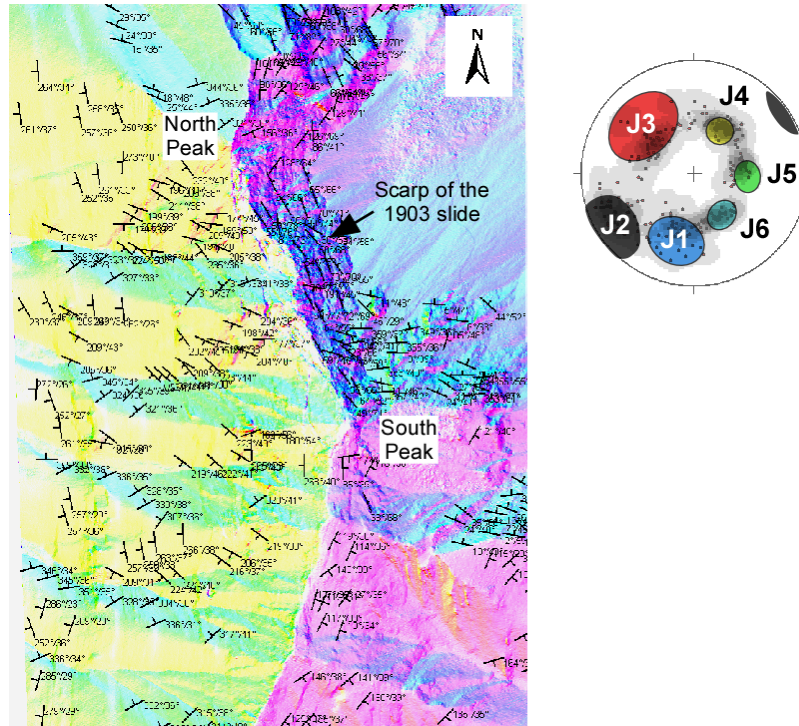


Figure 18. Main discontinuity sets identified using COLTOP software and based on an interpretation of the relief at Turtle Mountain derived from an airborne LiDAR survey. The stereonet on the right (equal-area projection, lower hemisphere) indicates the selected discontinuity orientations J1 to J6.

These results agree well with the structural interpretation based on the photogrammetric DEM in Jaboyedoff et al. (in press). Figure 19 provides a representation of the three main joint sets (J1, J2, J3) and the bedding on the western limb of the anticline and their projection into the peak, to better visualize the intersections and controls on slope deformations. As can be seen, a large wedge is bounded by J2, J3 and bedding, while J2 also delineates potential toppling near parallel to the slope face. A schematic of the interaction between the main mechanisms that control movement on upper South Peak is shown in Figure 19.

When comparing the structural measurements from the DEM with recent oblique aerial photography, the main wedge and toppling zones can be observed on the South Peak area (Figure 20). On this photo, three distinct zones of deformation can be observed on the South Peak wedge: toppling to the east, wedge sliding to the northeast, and formation of a graben to the south and west of the wedge. The features

Table 1. Main structural sets at Turtle Mountain.

Joint set	Dip direction/dip angle (°)
J1	013/50
J2	060/70
J3	136/54
J4	210/39
J5	270/40
J6	325/45
S0	323/36

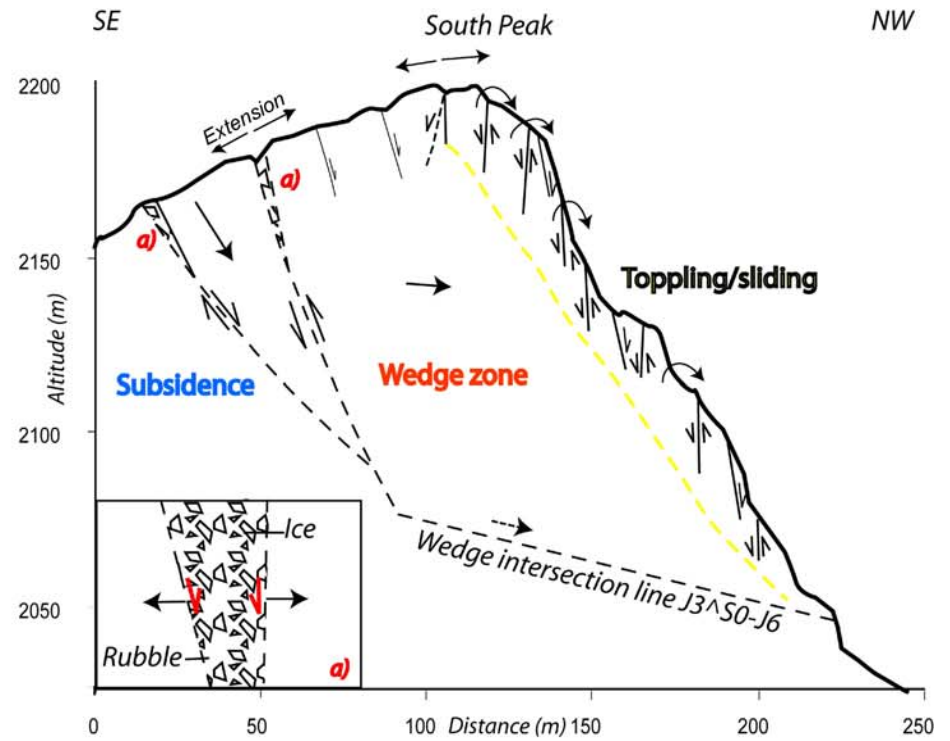
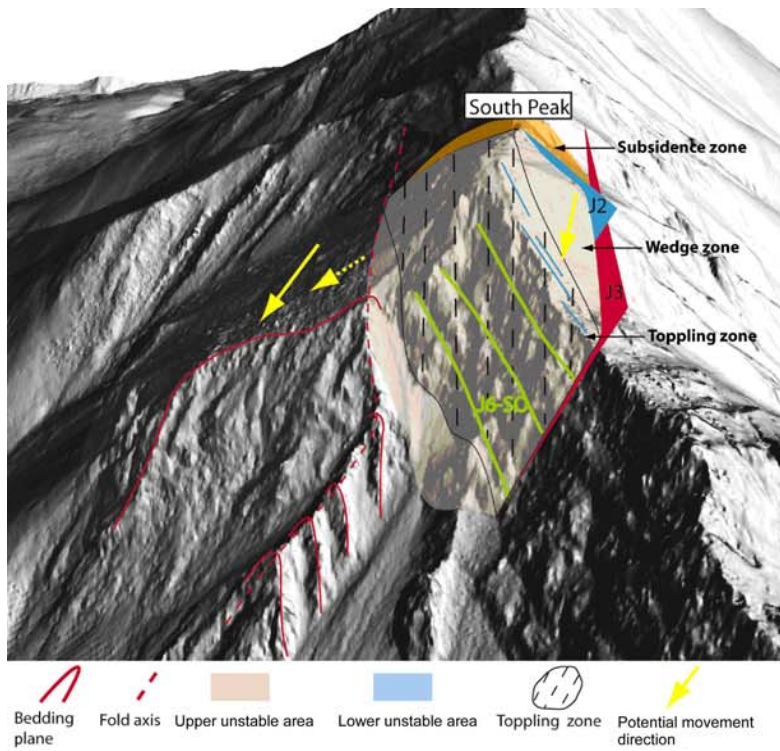


Figure 19. (Left) 3-D model of the South Peak of Turtle Mountain with the three main potential sliding joint sets (J2, J3, J6). (Right) Simplified schematic diagram of the postulated kinematic modes of failure on upper South Peak, Turtle Mountain.

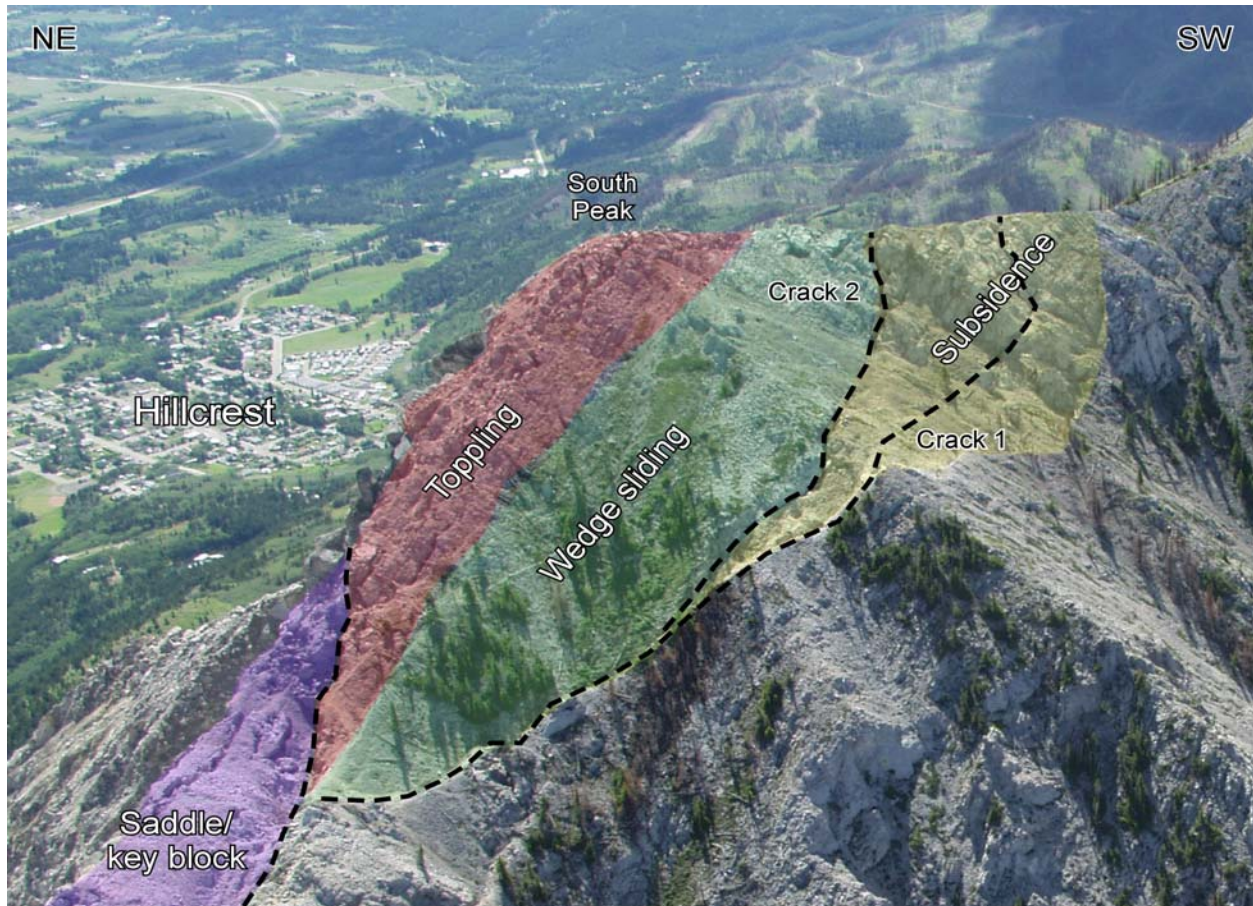


Figure 20. Oblique view toward the south of the South Peak of Turtle Mountain, showing the three main zones of deformation observed.

observed on the peak appear consistent with features described by others (Gutierrez-Santolalla et al., 2005; Kinakin and Stead, 2005; Ambrosi and Crosta, 2006; Hyppolte et al., 2006) on high mountain ridges as a result of lateral unloading. In the case of South Peak, the lateral unloading most likely resulted from the removal of support by the 1903 Frank Slide.

Based on observations from the DEM structural study and the photographs, the authors hypothesize that three main structural zones exist on South Peak: a smaller volume of rock toppling and sliding controlled by J2; a large sliding wedge controlled by joint sets J2, J3 and bedding on the western limb of the anticline; and a zone of broken rock that is subsiding into the space created behind the sliding wedge. In addition to the three zones on South Peak, a fourth zone of large toppling wedges at the head of the 1903 slide can be identified in Figure 21, which provides an overview of the four main zones and corresponding kinematic analyses.

4.1.2.2 Displacement Model

A critical review of the deformations from the monitoring points installed during the 1980s was undertaken based on the revised interpretation of the mechanisms controlling instability and the revised kinematic model for South Peak. Froese et al. (2008) provided a detailed review of the monitoring points installed in the 1980s and reread and interpreted during the past 2 years. The main monitoring points considered in the discussion below are the array of 24 photogrammetric targets and the two TM-71 crack

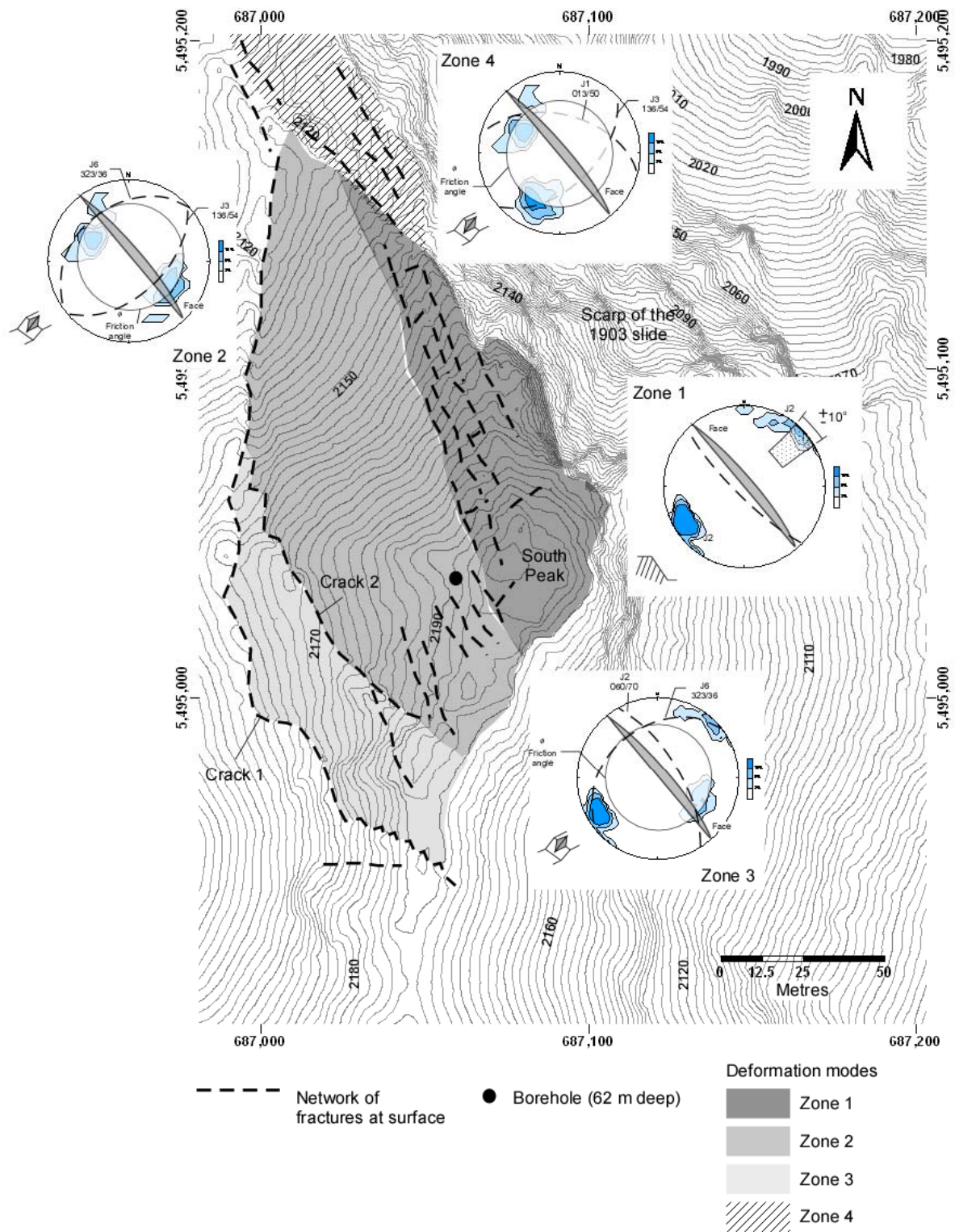


Figure 21. Plan view of three main deformation modes on the South Peak of Turtle Mountain. Zone 4 represents the unstable saddle area at the head of the 1903 Frank Slide.

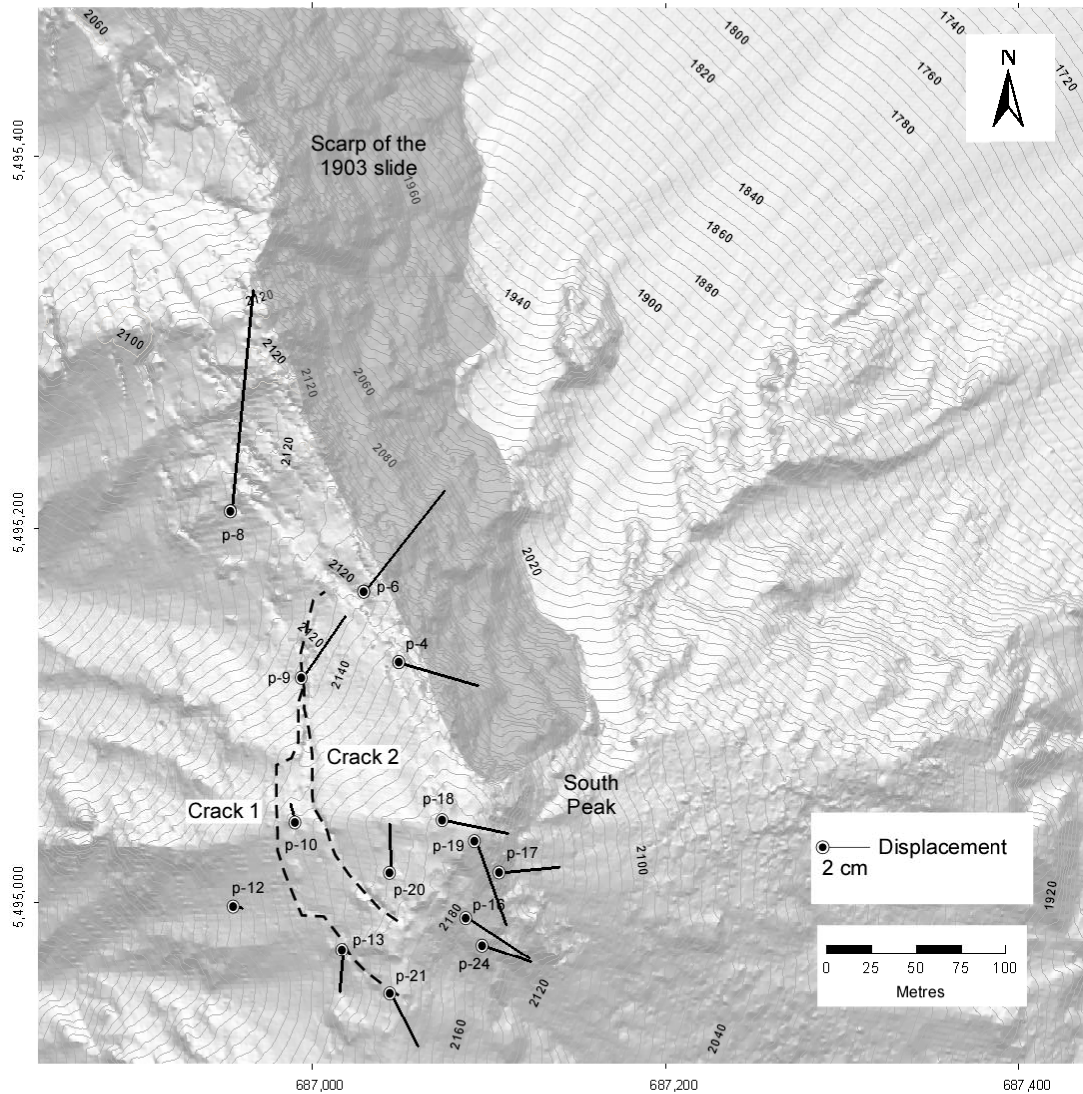


Figure 22. Photogrammetric target layout on the South Peak of Turtle Mountain. The vector plots represent total displacement of the targets between 1982 and 2005 (displacement of Target 20 is from 1984 to 2005).

gauges. Figure 22 is a summary of the displacements observed on the photogrammetric targets on South Peak between 1982 and 2005. Displacement results for the photogrammetric targets and the TM-71 gauges are provided in Tables 2 and 3, respectively.

The following sections discuss the deformations in the four main deformation zones shown in Figures 20 and 21.

Zone 1: Toppling/Block Sliding

The eastern portion of South Peak is characterized by linear fractures and troughs that trend approximately parallel to the trend of the slope face. The authors hypothesize that the mechanism acting on this area is a combination of toppling of blocks and planar sliding along stress-relief-related joints in

the bedrock. Five of the photogrammetric targets were located in this zone, and the results of the displacements observed over the 23-year time period are shown in Figure 23.

Table 2. Photogrammetric target displacements between 1982 and 2005, Turtle Mountain.

Zone	Target	Horizontal (mm)	Vertical (mm)	Magnitude (mm)	Rate (mm/year)	Displacement trend/plunge (°)
1	6	47	74	88	3.8	040/58
1	4	30	24	38	1.7	105/39
1	18	25	20	32	1.4	102/39
1	19	32	20	38	1.7	159/32
1	24	19	37	42	1.8	109/63
2	20	17	1	17	0.81	357/03
3	10	7	8	11	0.48	346/48
3	13	15	11	19	0.83	184/36
3	21	21	8	23	1.0	152/20
4	6	47	74	88	3.8	040/58
4	8	79	18	81	3.5	006/13

Table 3. TM-71 gauge displacements between 1981 and 1994 for Zone 3 area, Turtle Mountain.

Gauge	Horizontal (mm)	Vertical (mm)	Magnitude (mm)	Rate (mm/year)	Displacement trend/plunge (°)
Eastern	3.17	0.94	3.2	0.24	188/16
Western	4.58	0.96	4.6	0.33	218/12

As shown on Figure 23, displacements of the photogrammetric targets appear to be controlled by the exposure of the rock face on which each target is located. Overall displacements ranging between 32 and 88 mm over a 23-year period correspond to average displacements of 1.4–3.8 mm/year (Table 2). With most of these targets, the horizontal and vertical components of the deformation are reasonably similar, indicating that a combination of toppling and planar sliding of these blocks is taking place.

Zone 2: Wedge Failure

For Zone 2, the displacements are structurally controlled by joint sets J2 and J3, and either joint set J6 or the bedding (S0) along the western limb of the Turtle Mountain anticline, as shown in Figure 24. The only target from the 1980's monitoring program located in this zone is P20. The overall displacement of target P-20 between 1982 and 2005 is 17 mm toward 357°. As shown in Table 2, the vertical component of this target's deformation is negligible, indicating that the deformation is predominantly translational, most likely on a bedding-controlled rupture surface. Joint set J2 and joint set J6–bedding S0 (J2/S0-J6) intersect at 344°/33°, reasonably close to the results obtained for the displacement of photogrammetric target P20. Therefore, these likely represent the structural controls on the rupture surfaces, with joint set J3 helping to delineate the volume of the wedge mass. With this orientation for the potential rupture surface, the dip angle of 33° is likely too shallow for the wedge to start sliding as the result of its own weight, so an external force would have to be applied. This could be provided by seasonal ice damming and water accumulation in the cracks behind the mass or the force exerted by the heavily broken, subsiding mass in Zone 3 (*see below*).

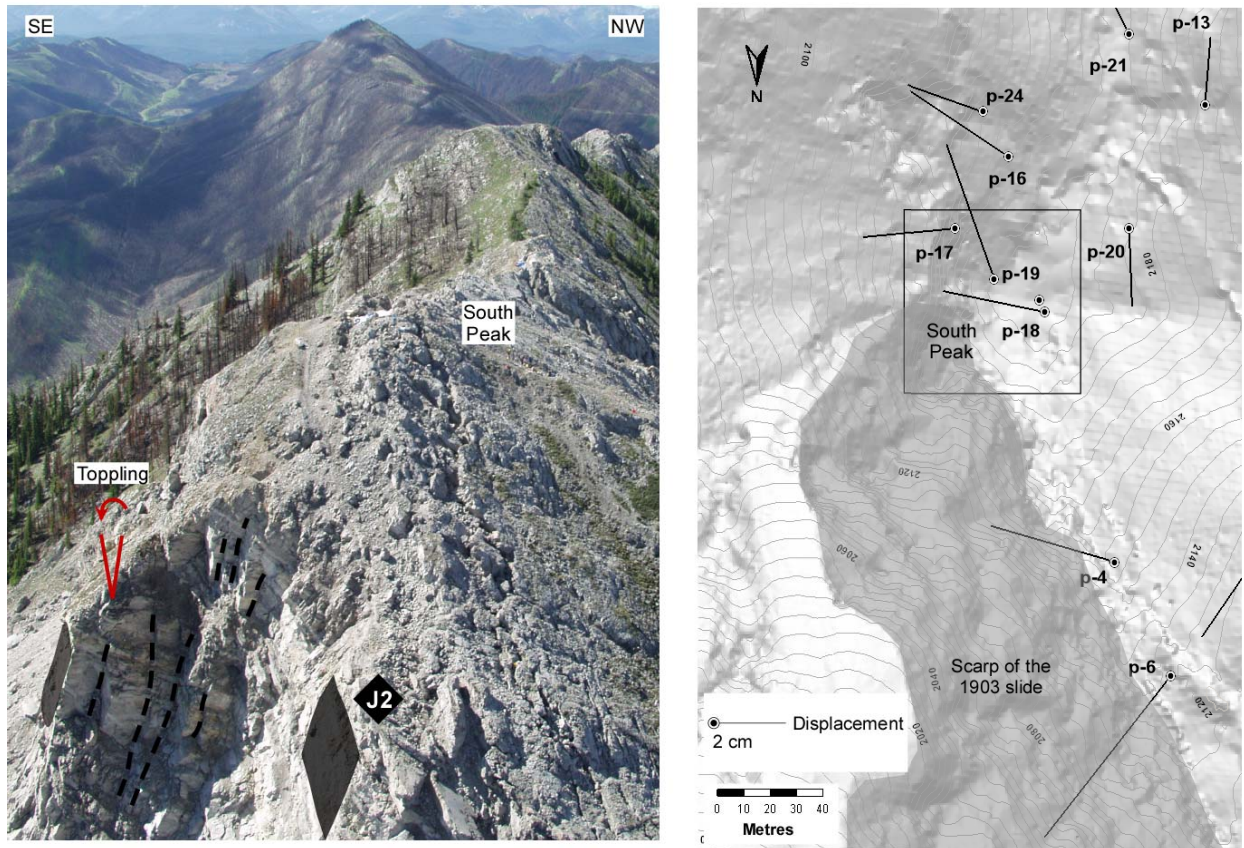


Figure 23. (Left) Close-up of zone of toppling (Zone 1) with photogrammetric displacements. (Right) Deformation vectors for the photogrammetric targets in this zone. Local topography and slope aspect control the movement directions for the blocks on which the targets are situated. Note the influence of discontinuity J2 on slope morphology (black colour). Square denotes area covered by the close-up on the left.

Zone 3: Subsidence

Zone 3 is a heavily fractured zone that appears to have subsided as the result of spreading of the top of South Peak due to the removal of lateral support to the east. The available monitoring points in this zone are three photogrammetric targets (P10, P13, P21), the two Moiré crack motion detection gauges (TM-71 East and West in Figure 25), three EDM prisms (a, b, and c; Teskey, 2006) and the complete network of trilateral signs (Figure 25). The results from the trilateral signs all indicate significant closure of Crack 1, by a few millimetres. As measurement errors are of the same order, the readings are not included in this discussion. Table 2 provides an overview of the displacements observed for the photogrammetric targets, while Table 3 presents displacement data for the Moiré crack gauges.

There is good agreement between the displacements of photogrammetric targets P13 and P21 and those measured by the two Moiré crack gauges (TM71 East and West). Both sets of instruments indicate deformations that are both down and into the slope (south-southeast) and are consistent with visual observations that this highly broken zone is subsiding into the void created by the sliding wedge that constitutes Zone 2. In addition, the results from the readings of the EDM prisms between 1982 and 2006 indicate a decrease in crack width between targets a and c, rather than the opening that was expected when these targets were originally installed.

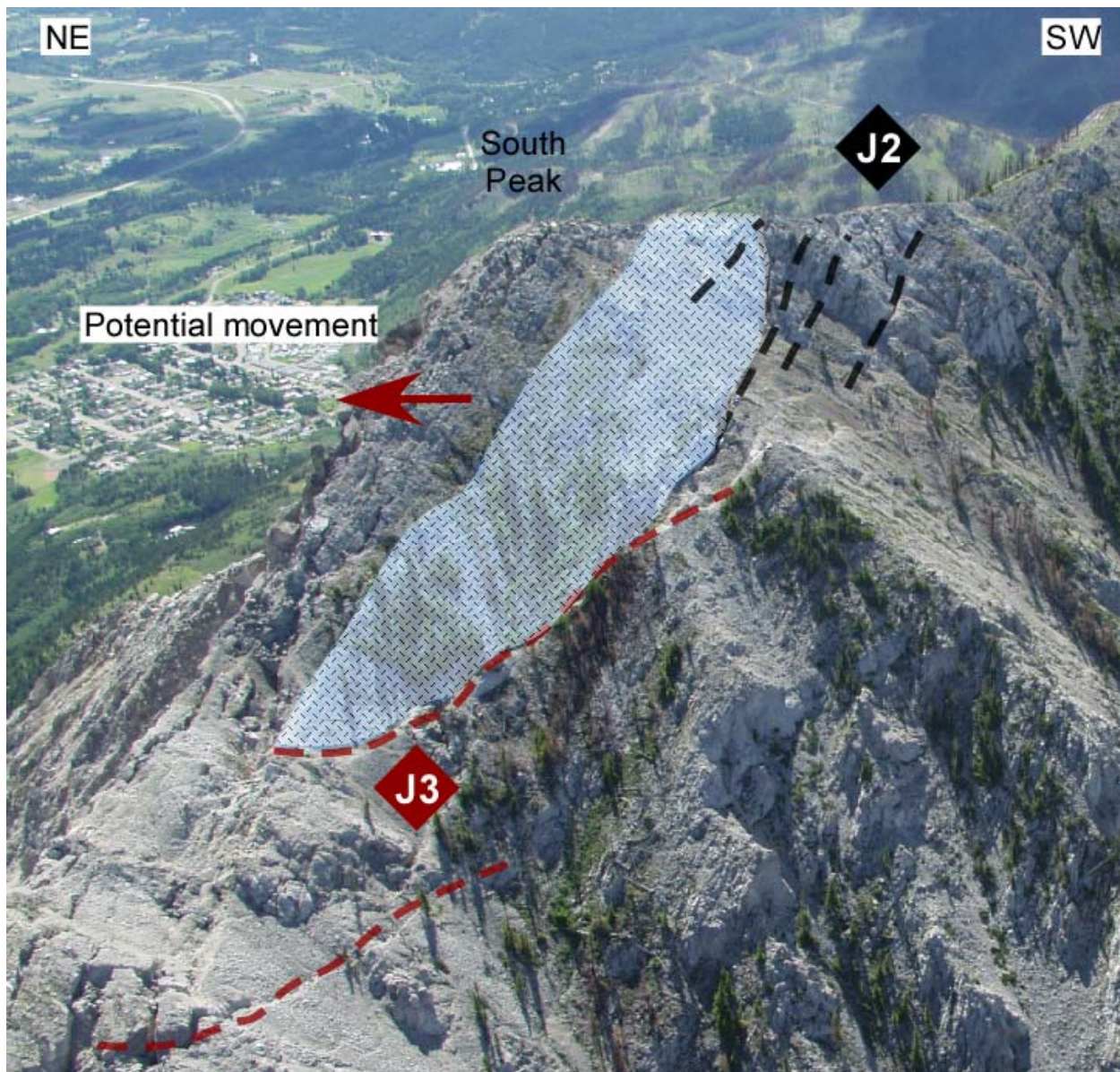


Figure 24. Lateral view of the postulated wedge failure zone (Zone 2). This zone is bounded by joint sets J2 (black) and J3 (red) and, at its base, by the bedding on the western limb of the Turtle Mountain anticline.

Zone 4: Saddle/Key Block

Looking at the wedge failure mechanism for Zone 2, it is apparent that the toe of this feature is at least partially buttressed by the zone of highly fractured material at the head of the 1903 Frank Slide in a zone that has been referred to as the saddle between North and South peaks (Allan, 1931, Figure 2). This is the zone that was the focus of the discussion by Jaboyedoff et al. (in press), where active rock topples and rock falls are structurally controlled by joint sets J1, J2 and J3. Three photogrammetric targets (P6, P8, P9) are located in this zone (Figures 21, 22). The displacements of these targets between 1983 and 2005 are provided in Table 2.

As shown in Table 2, displacements in Zone 4 have higher velocities than those observed in the other three zones, with the vertical component increasing with proximity to the eastern face of the mountain.

Displacements of 81–88 mm (3.5–3.8 mm/year) were observed for these targets between 1982 and 2005. Target P8, located approximately 60 m from the eastern face, is moving mainly by translation and P6, within 12 m of the exposed eastern face, has a significant downward component to the movement. In this zone, large blocks fall annually, leaving fresh debris tracks on the upper portion of the Frank Slide debris slope.

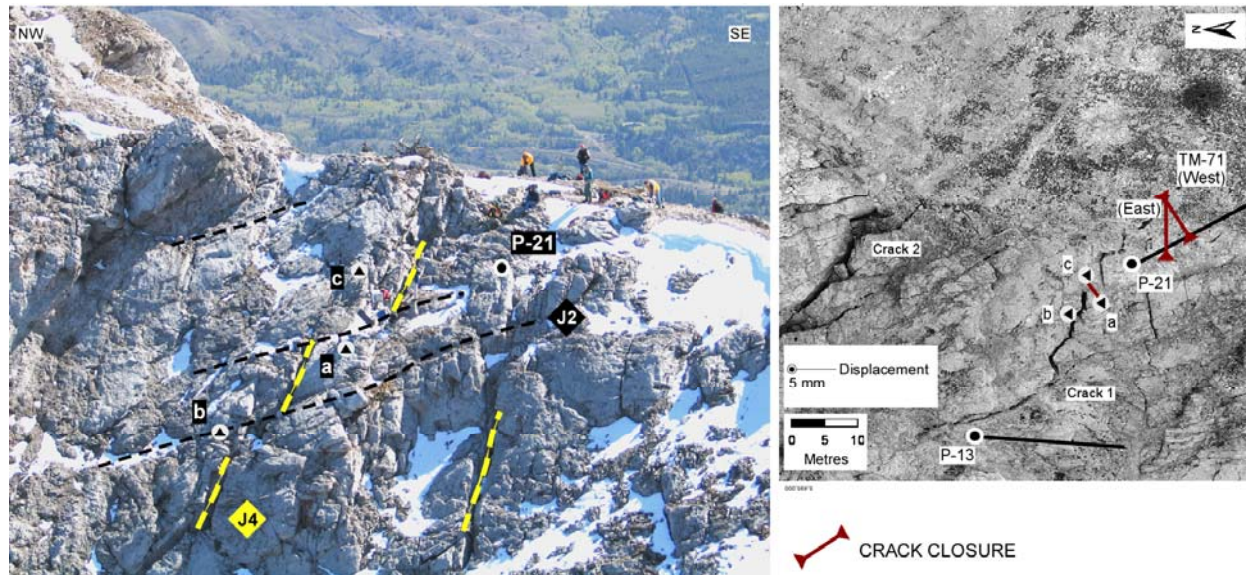


Figure 25. (Left) Close-up of subsidence zone (Zone 3), with locations of the three prism points (a, b, c) and photogrammetric target P-21. (Right) Vertical airphoto showing the relative locations of the photogrammetric targets (P-13, P-21), the EDM prisms (a, b, c) and the Moiré crack gauges (TM71 East and West), and the deformation vectors for each installation.

4.1.3 Lower South Peak

The lower portion of the lower slope below South Peak is heavily fractured and obscured by rock-fall debris. This fracturing is most likely related to the presence of the anticline hinge zone. Many cracks in the area are oriented toward the northwest, generally following the J2 joint set. The crack opening width is variable but generally increases toward the northeast, based on manual measurements. The J1 joint set is very persistent and its influence is clearly visible through the morphology of the slope (Figure 26).

4.1.3.1 Kinematic Analysis

A kinematic analysis was undertaken by Pedrazzini and Jaboyedoff (2008) to provide a more representative analysis of possible failure mechanisms for the lower South Peak area. Two slope attitudes were chosen: one in a northeasterly direction, toward the Frank Slide deposit ($030^{\circ}/50^{\circ}$), and the second subparallel to the bedding planes that form the slope ($090^{\circ}/55^{\circ}$). The friction angle was set to 35° for the analyses (Table 4).

The kinematic results and the field mapping show that the main potential mechanisms in the area are directed toward the north-northeast, following planar sliding on J1 or a wedge sliding on $J1^{\wedge}S0$.¹ Mechanisms in the main slope direction, particularly the wedge $J2^{\wedge}J3$, are only locally developed and involve small unstable volumes.

¹ The \wedge symbol stands for 'and'.

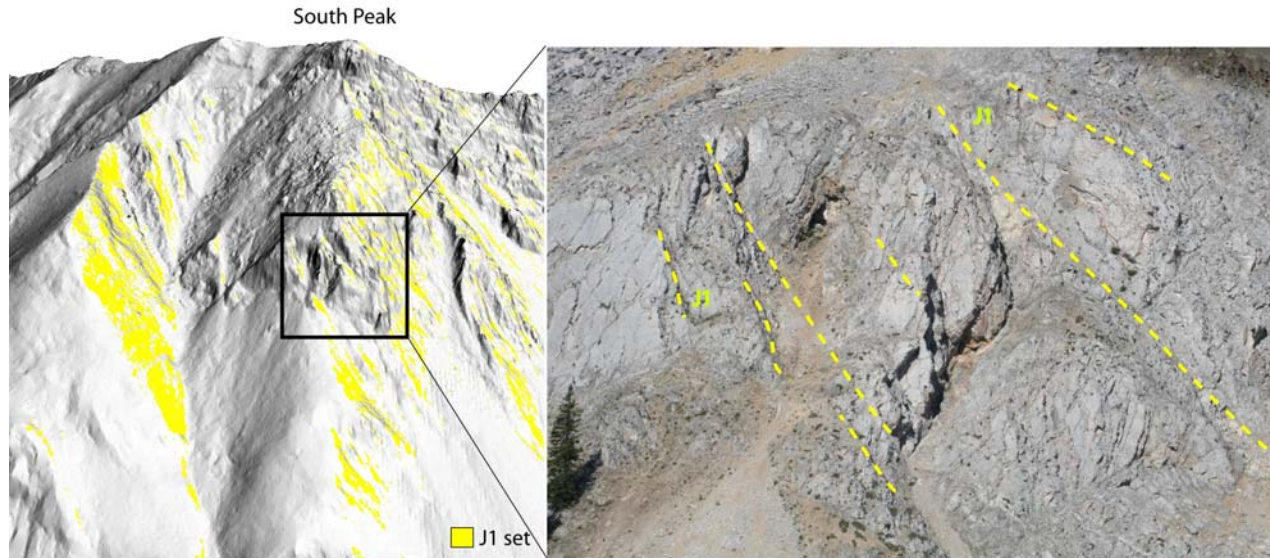


Figure 26. Influence on morphology of the joint set J1: (Left) 3-D DEM view showing extraction of joint set J1 from the COLTOP 3-D analysis. (Right) Close-up of outcrop conditions in the lower South Peak area; rock fracturing along J1 joint set indicates possible activity.

4.1.3.2 Structural Model for the Lower South Peak Area

Until recently, there has been no reliable deformation data available for the lower South Peak area. Based on the results of kinematic analyses, as well as field measurements of crack orientations and the morphology of the slope, the lower South Peak area could be divided into at least six potentially unstable zones. The different areas appear to move towards the northeast, following the J1 joint set. Based on visual observations of crack orientations and openings, movement appears to be more active in the upper portion of the stacked instabilities and, in particular, in the northwestern part of the area. This is suggested by the important rockfall activity in this area and by the fracturing along the J1 joint set.

Movement parallel to the slope direction is possible, following the wedge $J2 \wedge J3$, but the crack orientations observed during the field mapping did not provide evidence of such movement. Large-scale planar sliding on the bedding seems unlikely, as the bedding dips more steeply than the slope angle. However, in the case of large slope movements involving the entire lower South Peak area, a flexural buckling mechanism of the bedding cannot be excluded.

Following the failure model and the crack orientations observed during the field mapping, the lower slope below South Peak has been divided into six zones (Figure 27). The Sloping Local Base Level (SLBL) computation has been applied to each zone (Pedrazzini and Jaboyedoff, 2008). The best fit, according to the geometry of the discontinuity sets, has been used for the estimation of volumes.

Table 4. Results of kinematic test performed in lower South Peak area (from Pedrazzini and Jaboyedoff, 2008).

Potential mechanism	Planar sliding	Wedge sliding	Toppling
Slope orientation (030/50)	J1	Locally $J1 \wedge J2$ ⁽¹⁾	-
Slope orientation (95/55)	Locally S0, J3	Locally $J2 \wedge J3$ and $J1 \wedge S0$	-

⁽¹⁾ The ^ symbol stands for 'and'.

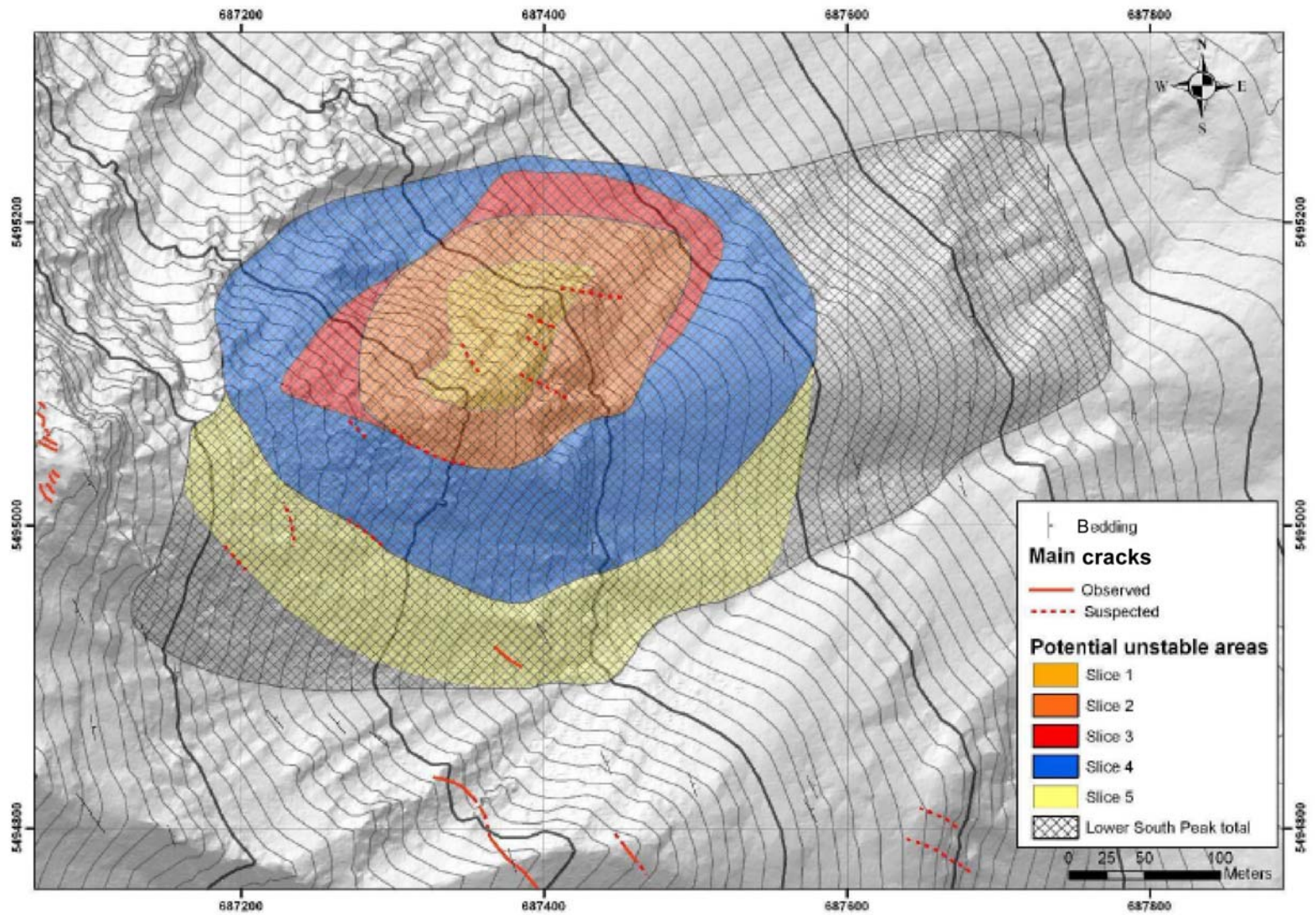


Figure 27. Six main instability zones on the lower South Peak, identified in the detailed structural mapping and kinematic analysis (from Pedrazzini and Jaboyedoff, 2008).

4.1.4 Results

Three discrete masses of rock on the lower South Peak, identified using the SLBL method, are susceptible to planar sliding to the northeast along the J1 joint set. Their volumes have been estimated to range between 0.065 and 0.5 million m³. According to field observations, they exhibit signs of previous and ongoing movement. Three other, deeper, potentially unstable masses (slice 4, lower instability and total South Peak area), ranging between 1.2 and 5.5 million m³, have a more southerly direction of movement. These volumes are in agreement with previous estimations (Allan, 1933; Jaboyedoff et al., in press).

In the case of the largest of the volumes identified for the lower South Peak area (5.5 million m³), large-scale planar sliding seems unlikely. Thus, identification of the instability limits and the relevant volume could not be directly determined from discontinuity orientations but was based mainly on morphological indications (i.e., shallow activity extension and irregularities in the topography).

4.2 Third Peak Structural and Kinematic Analyses

As highlighted in the 2006 annual summary (Moreno and Froese, 2008), analysis of the airborne LiDAR bare earth model highlighted features associated with instability observed below Third Peak. In order to better understand the possible kinematic modes of failure and the associated volumes, a detailed study was undertaken by the University of Lausanne, Switzerland (Pedrazzini and Jaboyedoff, 2008; Pedrazzini et al., 2008). This study consisted of detailed field mapping by staff from the University of Lausanne and the AGS, followed by detailed analysis of the LiDAR DEM to assess both the feasible kinematic mechanisms and the associated volumes for potentially unstable areas below South and Third peaks. The results of the analyses on South Peak were discussed in the previous section; this section discusses the findings for the upper and lower portions of the Third Peak area of Turtle Mountain.

4.2.1 Upper Third Peak

Pedrazzini and Jaboyedoff (2008) did not highlight any significant failure volumes on the upper portion of Third Peak. Due to the proximity to the fold hinge, kinematically feasible failure mechanisms were limited to shallow sliding and toppling, involving only small volumes of rock. Figure 28 illustrates the instability mechanisms in the upper Third Peak area.

4.2.2 Lower Third Peak

Detailed review of the surface morphology for the lower Third Peak area on the airborne LiDAR data highlighted the surface indications of a large, deep-seated, rock slope movement. This, coupled with the occurrence of at least one known large crack near the ridge seismic station justified further investigation in the area. The field and office studies of the area by Pedrazzini and Jaboyedoff (2008) have mapped in detail the condition, spacing and orientation of fractures and rock structure in the lower Third Peak area, and have highlighted a number of kinematically feasible movement mechanisms and associated volumes.

Although Pedrazzini and Jaboyedoff (2008) highlighted several small zones of rock-fall potential, there were two large areas where rock slides are considered to be kinematically feasible: a 0.85 million m³ volume and a 2.2 million m³ volume. These zones are delineated in the head region by two large cracks, and movement is likely controlled by bedding on the western limb of the anticline. The estimated areal extent and section view of these two zones are shown in Figures 29 and 30.

There is currently no information on the rates of deformation of these masses, as the instrumentation was installed in this area during the summer of 2007 (*see* Section 3.2.3). At least one new continuous dGPS station will be added to this area in the summer of 2008.

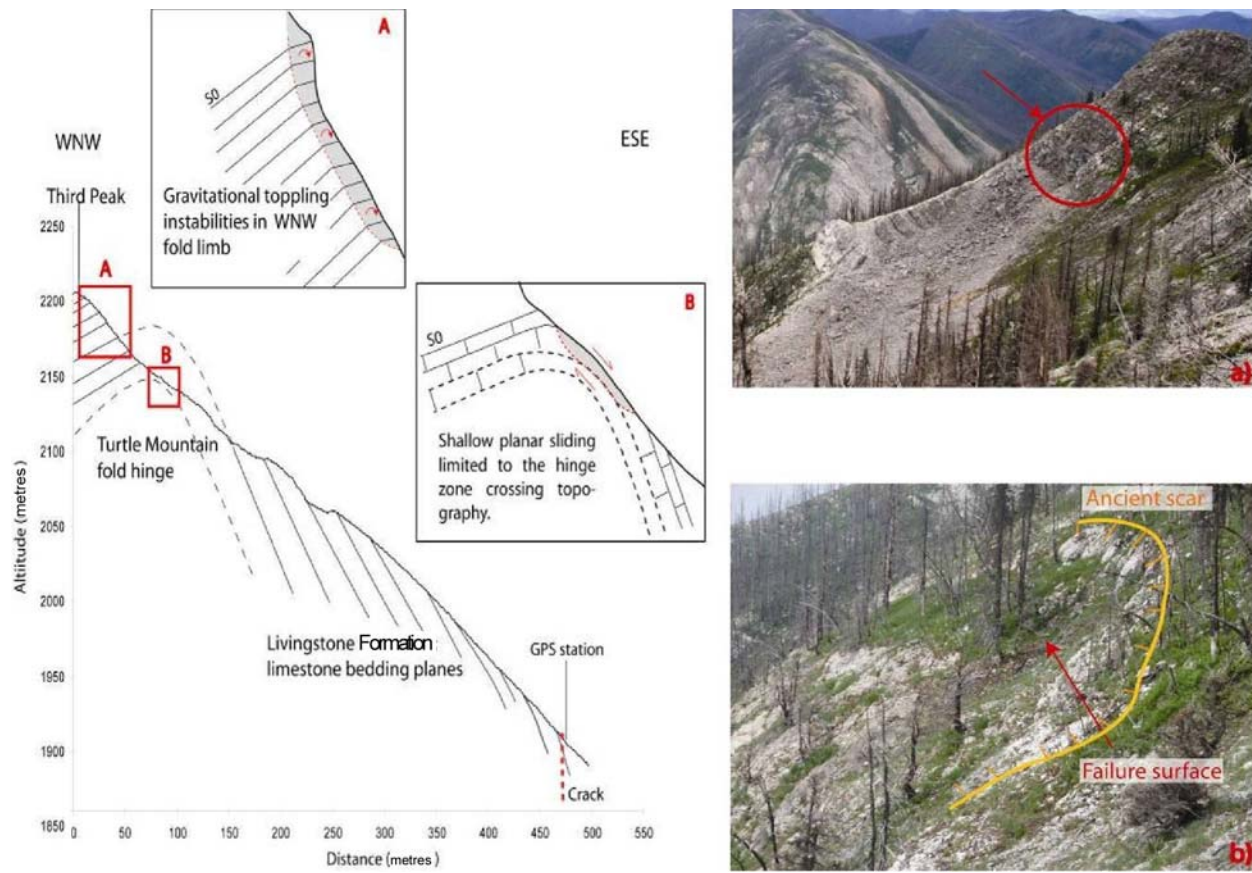


Figure 28. Schematic diagram and photos of the shallow instability mechanism identified from the field and office structural studies of the upper Third Peak area, Turtle Mountain (from Pedrazzini and Jaboyedoff, 2008).

4.3 Run-Out Studies

The identification and detailed mapping of the South Peak hazard in the 1930s by Allan (1931, 1932, 1933) represented the initial attempt to understand the extent of the area at risk from a rock avalanche from South Peak (Figure 31). This zoning was based on an assumed volume for the South Peak movement and empirical relationships (fall height and travel distance) that were likely derived from the behaviour of the Frank Slide. Based on Allan's zoning, a Notice of Danger was issued by the Government of Alberta and provided to all residents in the danger zone.

In 2000, a report by BGC Engineering (2000) revisited Allan's assumed failure mechanism and volume calculation, used more recent empirical relations for rock-fall height, volume and travel distance formulated by Hutchinson (1988), and came up with a set of revised danger zones (Figure 32). All of the current early-warning and emergency-response planning and protocols (Froese et al., 2005; 'Turtle Mountain warning system: ERCB roles and responsibilities manual', Moreno and Froese, work in progress, 2008) have utilized the zone defined by the BGC empirical upper limit.

With the refined definition of the volume for a South Peak failure, the availability of a higher resolution DEM and improved 3-D analytical techniques (McDougall and Hungr, 2004), new predictions for the run-out of a South Peak failure have been undertaken by O. Hungr Geotechnical Research (2007). The modelling package DAN3D was used for the updated analyses. Two existing computer run-out models were used to predict the run-out distance. The models were first calibrated by back-analysis of the 36 million m³ 1903 Frank Slide and two smaller rock avalanches in the Rocky Mountains. Forward analyses

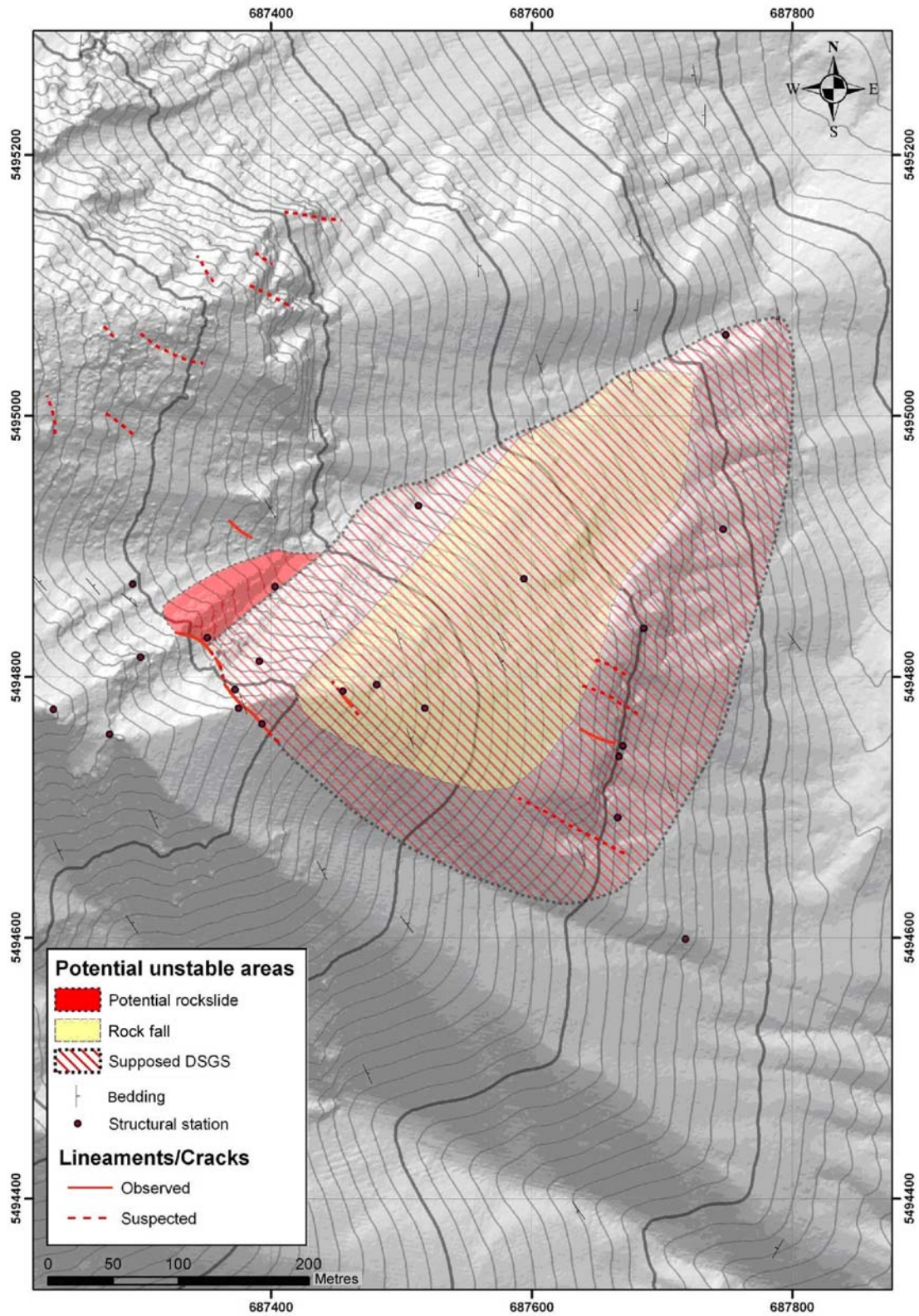


Figure 29. Plan view of mapped structural features and postulated unstable volumes, including a deep-seated gravitational surface (DSGS, lower Third Peak, Turtle Mountain *from* Pedrazzini and Jaboyedoff, 2008).

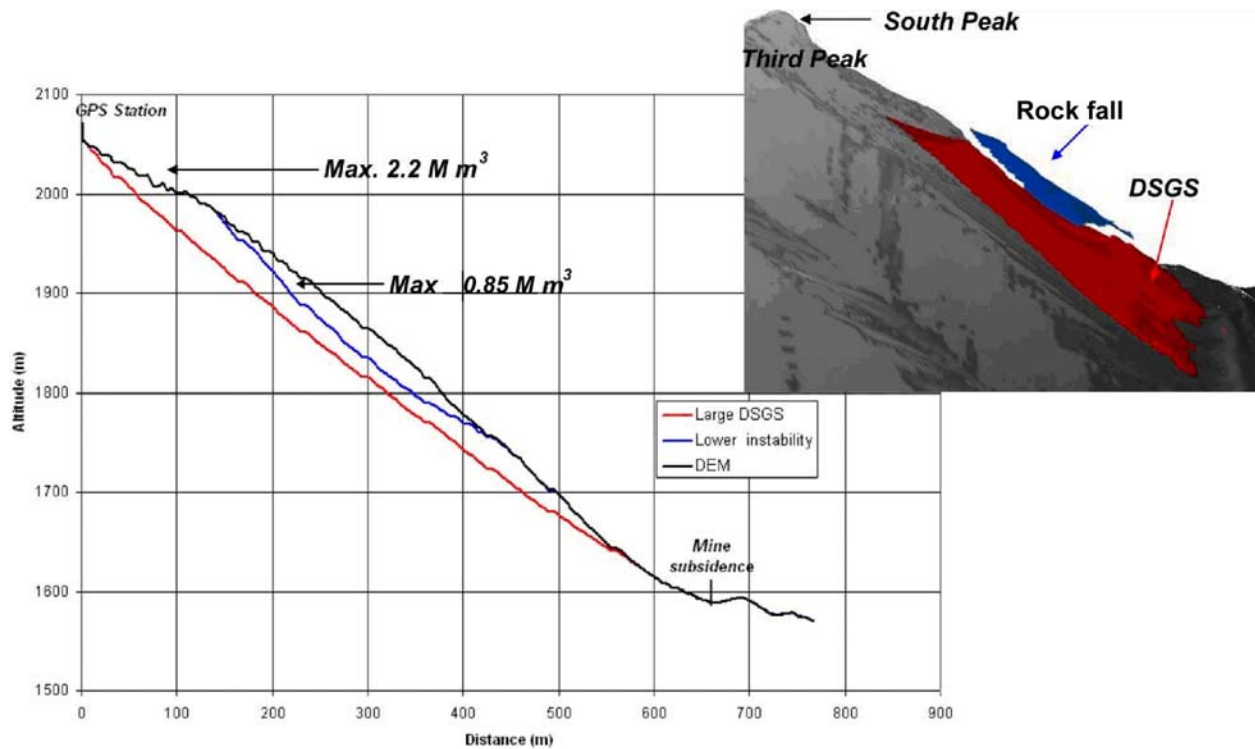


Figure 30. Cross-section of the two main unstable volumes identified on the lower Third Peak (from Pedrazzini and Jaboyedoff, 2008). Abbreviations: DEM, digital elevation model; DSGS, deep-seated gravitational surface; M, million.

were then completed for a potential rock slide from South Peak, a planar slide with a volume of 6.7 million m^3 .

Based on the updated sensitivity analysis for a volume of rock of up to 6 million m^3 , a number of different scenarios for the bounds of potential run-out were identified and are shown on Figure 33. When compared to the previous studies by Allan (1933) and BGC Engineering (2000), the run-out limits are similar and do not justify revision of emergency-response planning boundaries.

As future work is done to refine the movement mechanisms and volumes on the areas below South Peak and Third Peak, any resulting revision of the run-out estimates will be reported.

4.4 New Monitoring Studies

As discussed in Section 4, field and office studies have highlighted other potentially unstable areas on the eastern face of Turtle Mountain. In order to characterize the potential zones of movement, an overlapping array of complementary monitoring techniques was proposed that used different principles to monitor movement and provide redundancy. The set of EDM prisms (Section 3.2.3) was integrated into the sensor network in the summer of 2007 and monitoring was initiated by the Precise Engineering and Deformation Surveys (PEDS) Group in the Department of Geomatics Engineering at the University of Calgary, as both a complementary monitoring technique and a Ph.D. research project.

4.4.1 Periodic GPS system

The aim of this project was to set up a series of monitoring points that would be used to collect differential global positioning system (dGPS) readings at least biannually, in order to detect and characterize displacements at these monitoring points. Although the initial focus of the monitoring was on

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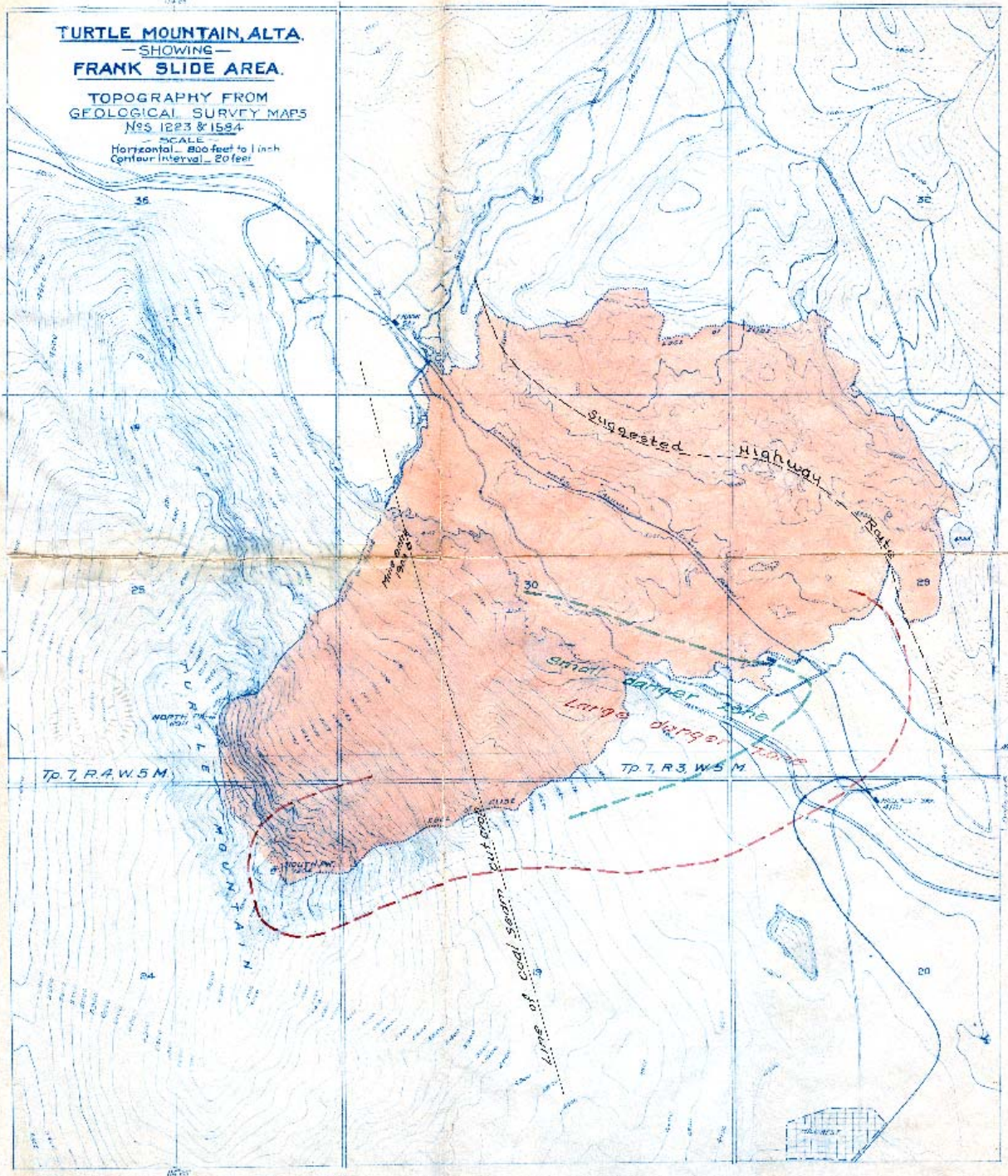


Figure 31. Original map prepared by Allan (1931) outlining to two estimates of run-out boundaries for a 5 million m³ rock avalanche originating from South Peak, Turtle Mountain.

the eastern face of the mountain (below Third and South peaks), monitoring points also covered areas to the south that are assumed to be stable and very unstable, active areas on the Saddle zone, between South and North peaks. Figure 34 provides the locations of the monitoring points.

Fifteen structural steel target points were designed, fabricated and installed on Turtle Mountain in May 2007 by PEDS. Each of the points was first observed in June 2007 to provide the baseline set of readings, and a second set of readings was taken in late September and early October 2007. A typical 10 cm x 10 cm (4 inch x 4 inch) structural steel target point is shown in Figure 35. Points were observed using both reflectorless total station (RTS) and differential GPS (dGPS) from a base station located in the valley bottom northeast of Turtle Mountain.

As expected, no significant movements were observed during the June to October 2007 time frame. Possible movements were observed on targets 6 and 13, but further readings in the summer and fall of 2008 will be required to confirm these trends. It is expected that, for most of the movements on the east face, many years of observation will be required to gain confidence in movement rates and patterns. It is expected that trends will become clear in a shorter time frame in the Saddle zone, due the high relative activity in this area.

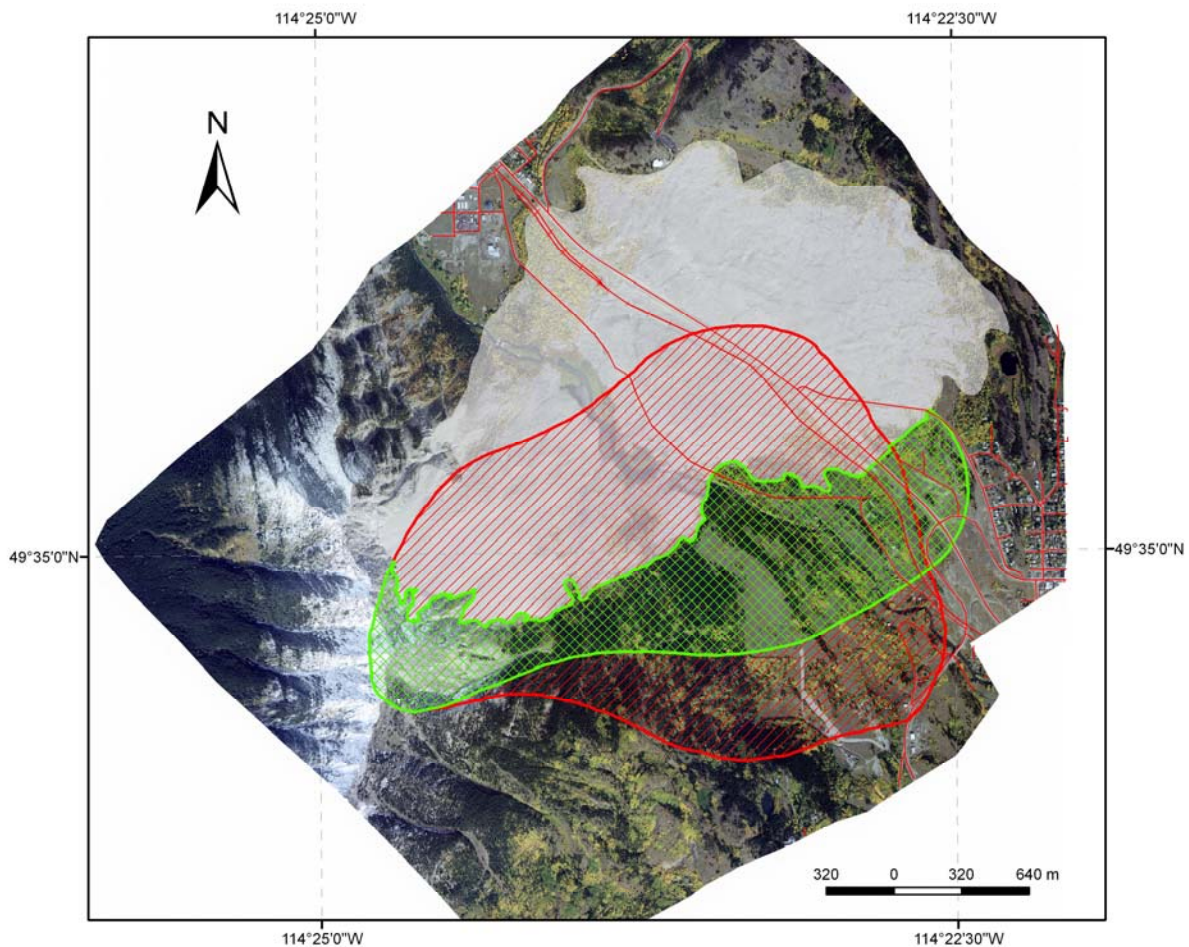


Figure 32. BGC Engineering (2000) empirical upper limit boundary (RED) in relation to the large danger zone (GREEN) identified by Allan (1931) for a rock avalanche originating from South Peak, Turtle Mountain.

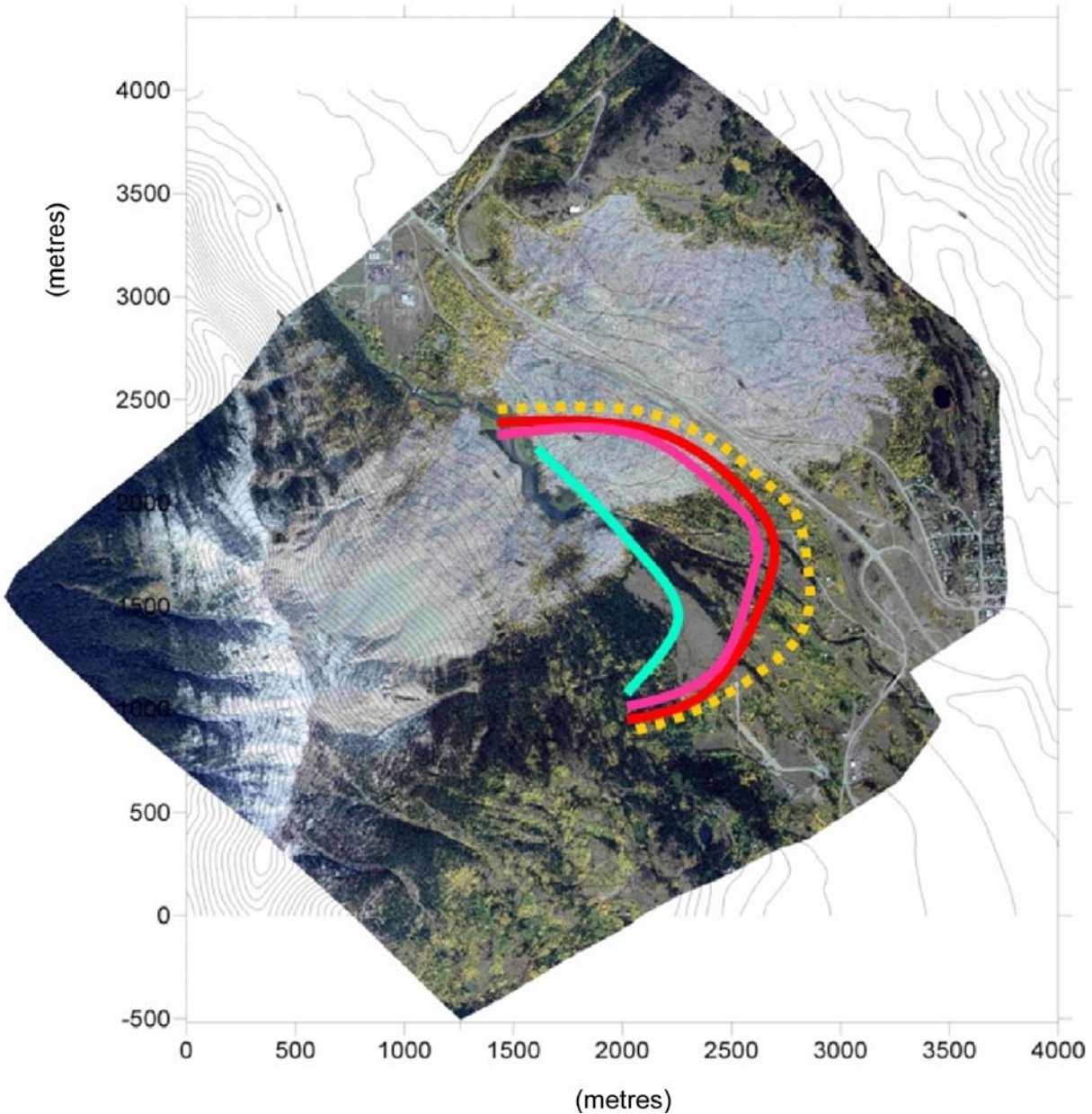


Figure 33. Results of the sensitivity analysis undertaken by O. Hungr Geotechnical Research (2007), showing various scenarios for run-out boundaries for a 6 million m³ rock avalanche originating from South Peak, Turtle Mountain. Results were obtained using a dynamic analysis software application called DAN3D (O. Hungr Geotechnical Research, 2007) Legend: red, most likely prediction; purple, alternative prediction; yellow, extreme run-out prediction; turquoise, piecemeal detachment prediction.

5 Summary and Conclusions

A clearer picture of deformations on the South Peak of Turtle Mountain is now possible by combining observations from newly available remote-sensing data and digital air photos with an updated set of readings from monitoring points installed in the 1980s. Rather than simply deformation of the entire wedge of South Peak to the east, it is now known that there are at least three kinematic modes of

deformation — toppling, wedge sliding and subsidence — acting on South Peak at rates ranging from 0.24 to 3.8 mm/year.

These observations have significant impact on the modern monitoring and risk management of South Peak. Firstly, this study provides a baseline for understanding the near-real-time data that have been collected since 2003 from more than forty sensors installed on the peak. Secondly, assumptions regarding the volume of the moving rock and the approach to monitoring and warning now need to be re-evaluated. Previous monitoring had assumed that monitoring the fractures on the western side of South Peak would provide warning of movement of the South Peak mass (~0.5 million m³) and the slope below

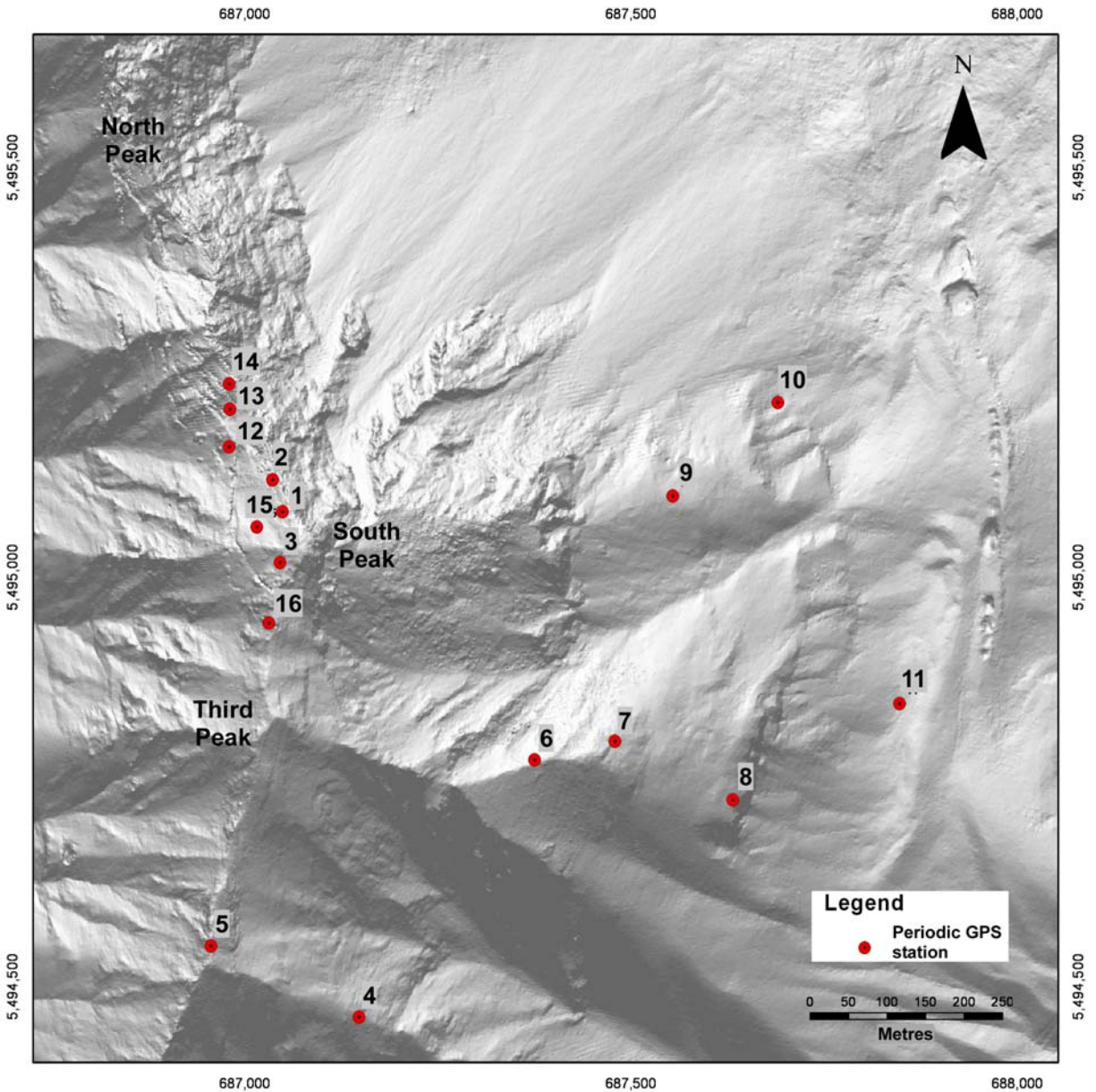


Figure 34. Locations of the 15 periodic dGPS monitoring points installed in the summer of 2007 by the University of Calgary Geomatics Engineering Group.

(~4.5 million m³). The findings summarized above indicate that historical monitoring would not provide a warning for the larger lower slope movement. Expanded monitoring and characterization of the lower slope is therefore required to provide a more realistic indication of the risk to the developments and infrastructure below this portion of Turtle Mountain.



Figure 35. Typical periodic GPS point installation on Turtle Mountain.

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