# TURTLE MOUNTAIN FIELD LABORATORY (TMFL): PART II - REVIEW OF TRENDS - 2005 TO 2006

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**Abstract:** Very slow movements of rock may occur for long periods prior of catastrophic landslides. A classic example of such event is the 1903 rockslide at Turtle Mountain in southwest Alberta, Canada, where some 30 million $m^3$ covered an area of 3 $km^2$, burying the south end of the town of Frank. The slide left two prominent peaks on Turtle Mountain, denoted as the North Peak and South Peak, and a saddle in between. Many studies over the past century have concluded the South Peak of the Turtle Mountain still poses danger to the surrounding community. In order to prevent the risk associated with a second rock avalanche, the Government of Alberta initiated a two-year multi-disciplinary monitoring project. The Turtle Mountain Monitoring Project involved the implementation of a predictive monitoring system comprising microseismic, displacement, pore pressure, temperature, and other monitoring instruments operating in near-real time. In this paper, we present the result of 2 years of observations of the rock mass and a discussion of the slope displacement behaviour to date. Instrumentation located across major cracks on the west side of South Peak have recorded movements less than 1 mm/year. These movements appears to be driven by the annual thermal cycle experienced by the rock slope, with most of the displacements occurring from September to early May, when air temperature is generally cooler. Conversely, periods of prolonged warm air temperatures, typically during late May to July, can be associated with cessation of displacements. The observed displacement behaviour provides some insight as to the style and rate of movements of South Peak and indicate that South Peak has had a long history of very slow deformation. These movements are of interest but below levels of concern for the stability of the slope, considering the large extensions that have obviously occurred during crack formation.

## INTRODUCTION

Due to renewed interest on the hazard associated with a possible second rock avalanche on the South Peak of Turtle Mountain, a series of over 40 sensors were installed between 2003 and 2005. The types of sensors and layout are described in detail by Read et al (2005) The goal of the project is to remotely monitor in near real-time the short term ground deformations. A secondary focus is on developing an understanding of the slow rock mass movements. The Part I of this paper (Froese and Moreno, 2007) provides a more thorough overview of the history behind the monitoring program. We describe here the results from the monitoring and analysis of the data collected that were carried out by the Alberta Geological Survey (AGS/EUB) during 2005 to 2006.

## TURTLE MOUNTAIN MONITORING NETWORK

The primary area of monitoring at Turtle Mountain lies on top of the South Peak, where several types of sensors were installed. Based on their suitability for providing early warning, the sensors can be grouped into three categories.

Primary sensors provide absolute deformations with submillimetre to millimetre resolution, operate reliably in all weather conditions, and are located in high-hazard areas that may quickly become too dangerous to revisit during a crisis. They include ten tiltmeters, five surface wire extensometers and twenty-two crackmeters (Figure 1).

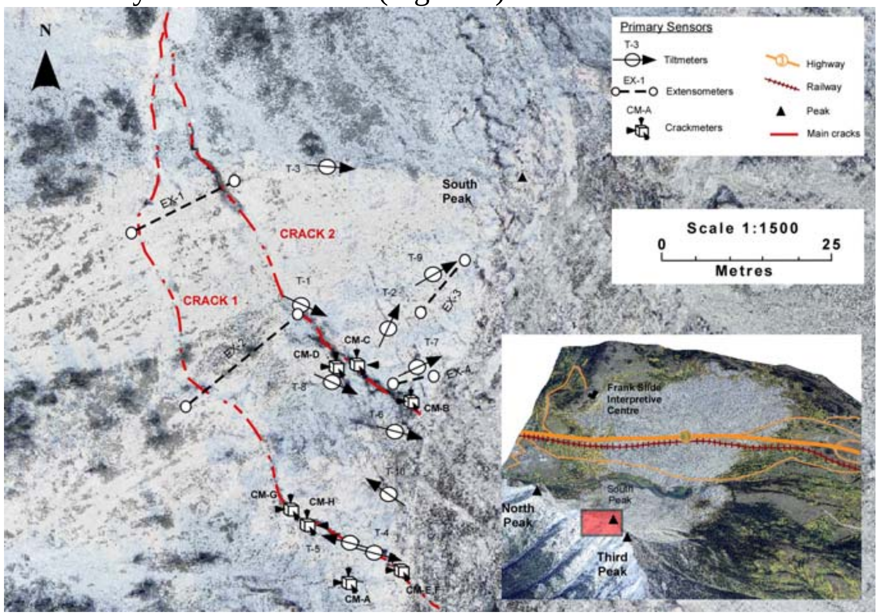


**Figure 1**. Plan view of Turtle Mountain slope, showing the layout of the primary sensor network.

Secondary sensors provide displacements with the level of precision of a few millimetres but currently do not provide reliable readings on a year round basis. The secondary sensor network consists of ten prisms with distance measurement shot from a robotic total station in the base of the valley, and six single frequency GPS receivers (dGPS).

Finally, a tertiary sensor system provides background data that is useful in the interpretation of results from the primary and secondary sensors. The tertiary sensor network consists of a meteorological station (rain, wind, air temperature, barometric pressure and solar radiation); an outflow weir located at the base of the mountain; and six surface passive microseismic sensors and two subsurface microseismic stations. Pore pressure and temperature are being measured using one vibrating-wire piezometer and a string of thermistors installed in a borehole drilled to emplace the subsurface microseismic sensors.

## MONITORING DATA

### Crackmeters

Two quantities are transmitted from the crackmeters: displacement, and temperature. Temperature measurements allow for thermal corrections to the data. Crackmeters were installed in triplets to determine a relative displacement vector. The most accurate record of slope displacement has been obtained from a cluster of three crackmeters (set B). These instruments provide a nearly continuous two year record of slope displacement (Figure 2). Generally speaking, monitoring shows a persistent annual displacement cycle, beginning in spring, and continuing through the summer, as sensors contract going into summer, followed by a period with limited to no extension displacements during fall to early spring. Incremental displacements of the order of approximately 0.4 mm have been measured during each displacement cycle (the total crack widths range between 1.0 and 1.5 m at the crackmeter locations). Crack width changes of 0.02 mm are also seen with daily temperature fluctuations (Figure 3). Small transient displacement spikes can be seen on the crackmeters but they quickly return to the previous trend. This is believed to be related with an electronic effect in which lightning affected the equipment.

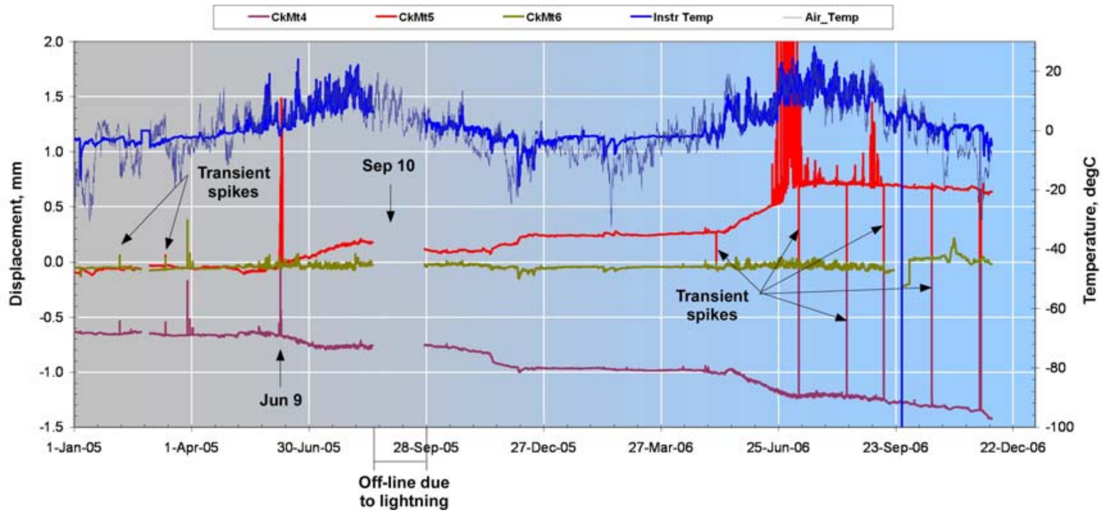


**Figure 2**. Displacement vs time for crackmeter set B. Rainstorm on June 9, 2005 is indicated. September 10, 2005 event not recorded as instruments were off-line.

A rapid extension followed by a recovery was recorded on both June 9, 2005 and September 10, 2005 (not recorded in set B due to lightning damage) and correlates with heavy rainstorms registered on the same dates. A more detailed plot of the data recorded during the precipitation event of September 10 is shown in Figure 3. The gradual displacement trend during the precipitation event of September 10 continued until about 3 pm local time and then it began to accelerate, coincident with intensifying precipitation. Over the next 4 hours more than 2 mm of displacement was measured. Finally, during the last hours of the rainstorm, slower than normal rates were recorded until the displacement rates returned to their background levels. A permanent displacement ranging from 0.05 to 0.15 mm was recorded in the crackmeter sensors.

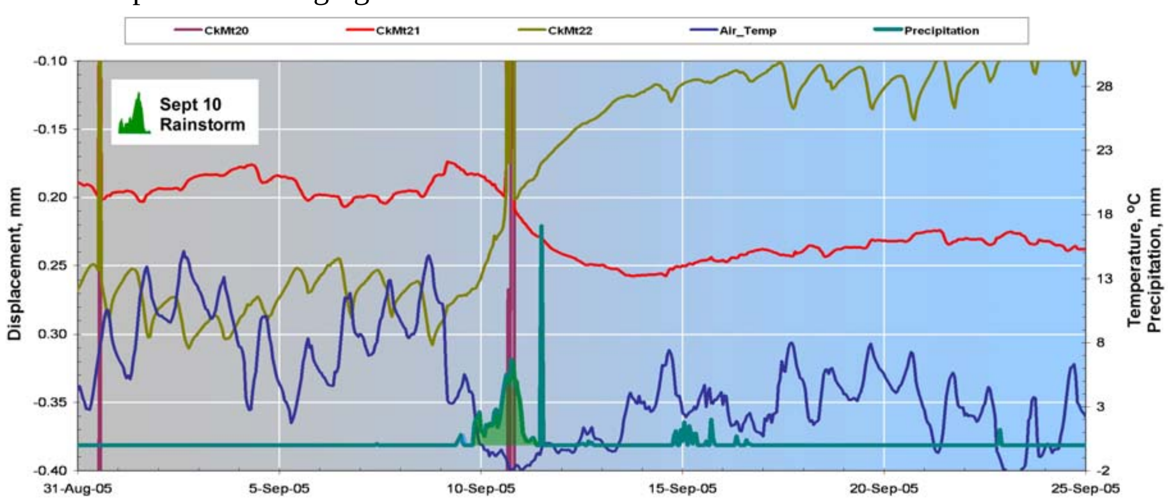


**Figure 3**. Displacement vs time for crackmeter set H. September 10 precipitation event.

**Tiltmeters**

Tiltmeters measure angular deformation (or tilt). Installation locations were selected to be as close as possible to a vertical plane striking in the same direction as the expected tilt direction. Tiltmeters T5 and T10 were installed with the faceplate facing south; therefore the positive tilt from a vertical up orientation is westerly. All of the other tiltmeters were installed with their faceplates facing north, and therefore measure positive tilt to the east relative to a vertical up orientation (Figure 1).

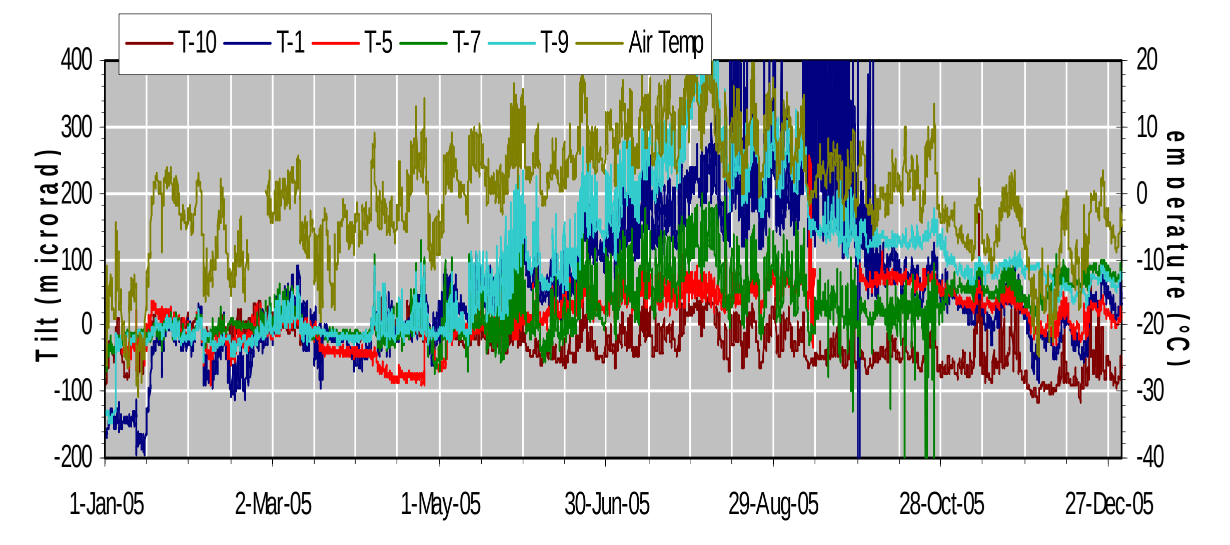


**Figure 4**. Tilting with time at several points with time on the South Peak of Turtle Mountain.

Tiltmeters are very sensitive to air temperature that results in apparent daily fluctuations in tilt angle. Seasonal changes are also seen and, in general, all sensors display an increase in tilt when going into summer and a decrease when coming out of summer. Some trends in angular deformation are evident in the tiltmeter data. Tiltmeter T-9 detected about 90 to 110 microradians of cumulative tilt between late 2004 and early 2006. Tiltmeters T-1 and T-7 also show an increase in tilt but of lesser magnitude. A negative permanent tilt can be seen in tiltmeter T-10. However, in this case, the positive tilt axis of this instrument is parallel to the rotating axis of the other instruments but of opposite direction. No evident permanent tilt can be seen on tiltmeter T-5 (Figure 4). No measurable tilt was recorded on these instruments during the precipitation events of June 9 and September 10, 2005. High fluctuations of tilt, due to instrument noise, impeded the capacity to detect subtle movements.

**Extensometers**

Extensometers consist of a head assembly anchored into bedrock on one side of the surface of a crack and an anchor end that is situated on the opposite side of the crack. The head assembly contains a weight that is connected to the anchor end by a steel cable and is suspended over a rotary potentiometer. Deformations of the rock mass cause a change in position of the suspended weight, which is converted to an electrical signal through a potentiometer. Extensometer locations were selected such that the head assembly (upslope end) and anchor (downslope end) were installed in exposed bedrock, with the extensometer cable roughly parallel to the expected direction of movement.

Starting almost immediately after installation, the extensometer records were reasonably stable. No diurnal or seasonal changes are seen in the displacement data. These steady trends were interrupted on June 9 and September 10, 2005 when heavy rainstorms came through the area, and caused significant displacement. Extensometer EX-2 was extended from 0 to 4.5 mm and from 4.5 mm to 24.6 mm during the periods of heavy precipitation recorded in early June and from September 9 to 11 respectively. A displacement of 5.9 mm was recorded on EX-3 during the precipitation event in September (Figure 5). No significant displacement occurred at extensometers EX-1 and EX-4. Abrupt displacement occurred on September 28, 2005 and July 18, 2006 and resulted from deflection of the cable during upgrading work of the extensometer network. Small stepped displacement recoveries can be seen on extensometer EX-2 on October 18, November 10 and December 24, 2005. Similar recovery events were observed on extensometer EX-1 on February, 2006. It is believed that this is related with specifics of the instrument design. During a field inspection, it was noted that the rotary mechanism of the instrument does not fully return to its original position after intentionally deflecting and releasing the steel cable of the instrument.

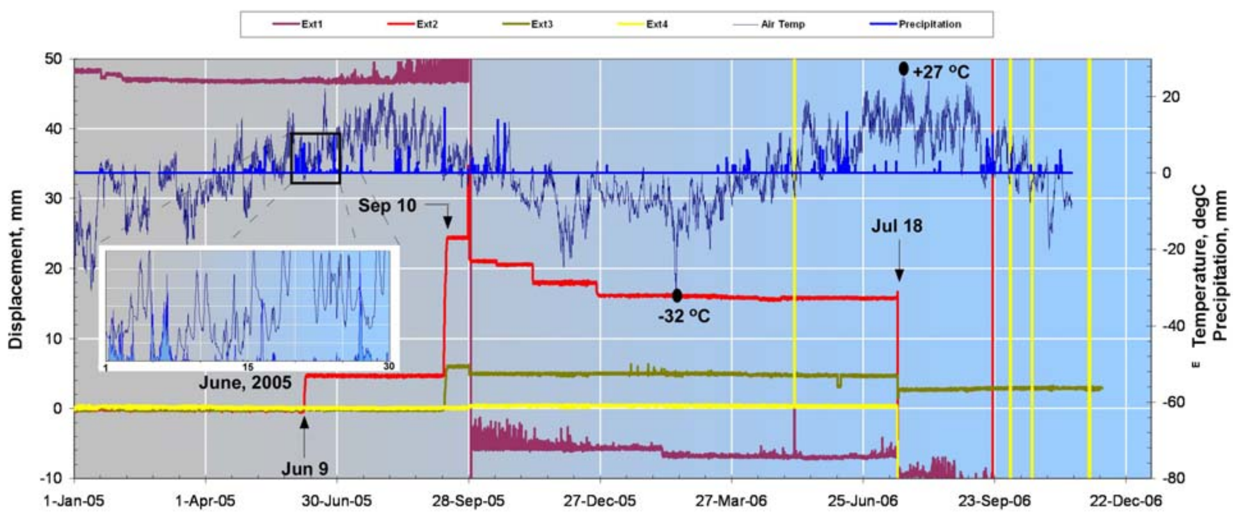


**Figure 5.** Displacement measured from extensometers.

**Meteorological Data**

Temperatures have typically ranged between -10°C in January to +10°C in July with significant variations throughout the year. An extreme maximum of +27.0°C and an extreme minimum of -32.5°C were recorded on July 22, 2006 and February 16, 2006 respectively. Temperatures were significantly above zero during the first week of September, 2005 but dropped notably after that (Figure 5). Sudden temperature drops can be seen throughout the year with sudden fluctuations of as high as 29°C/day being recorded.

The summer months produced the highest daily temperature variations with minor temperature fluctuations recorded in January, November and December. Rock temperature shows the same general trend as air temperature, but is more subdued (lower maximum and higher minimum readings) with a time lag of about 12 hours relative to significant changes in air temperature (Figure 6). 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 7).


**Figure 6.** Rock temperature variation with depth at the South Peak of Turtle Mountain for the years 2005 - 2006.

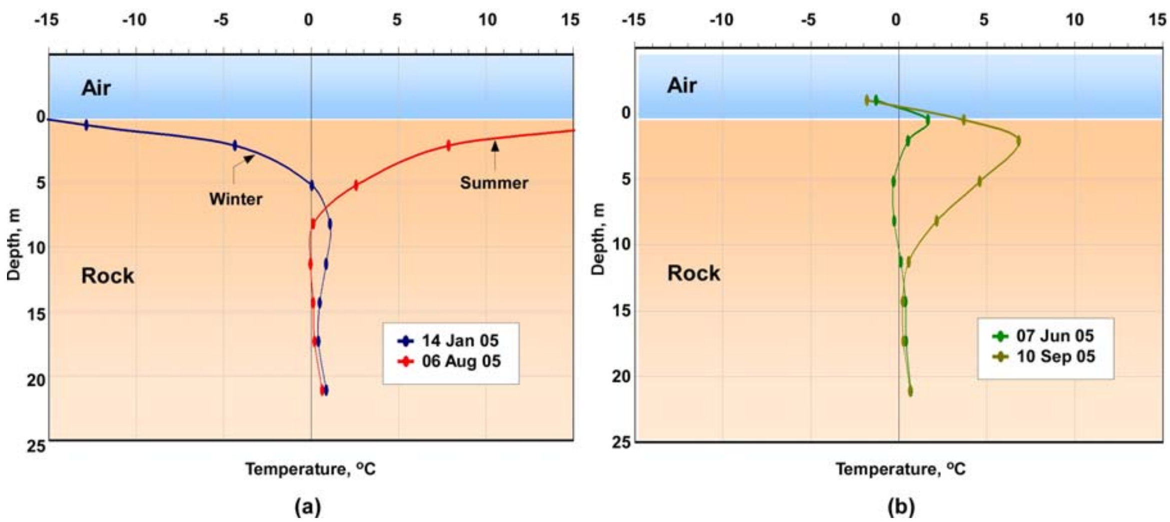


**Figure 7.** Typical rock temperature variation with depth at the South Peak of Turtle Mountain a) during winter and summer, and b) at two extreme air temperature drop.

The total rainfall amount measured at the weather station located on South Peak of Turtle Mountain during 2005 was 707 mm. This total rainfall volume was significantly above the average value for the region (397 mm). The average annual rainfall data was obtained from a nearby weather station managed by Environment Canada (Coleman station). Climate averages offered by this station are based on at least 15 years of data between 1971 and 2000. Precipitation levels significantly below normal were recorded throughout spring season, however, above normal precipitation levels were recorded later during summer 2005. Three major precipitation events during June, 2005 dramatically increased the total precipitation during this month to four times normal in the area of Turtle Mountain (Figure 5 and Figure 8). Rainfall totals for the fall period of 2005 (September through October) were above normal. One major precipitation event was recorded on September 9 to 11 (Figure 5). Precipitation totals for the year 2006 were slightly below normal. Normal precipitation levels were recorded during spring

2006, on the other hand, summer 2006 was a dry season with the exception of one storm event which moved through the region in mid-June. From early September through October, 2006 precipitation was above normal.

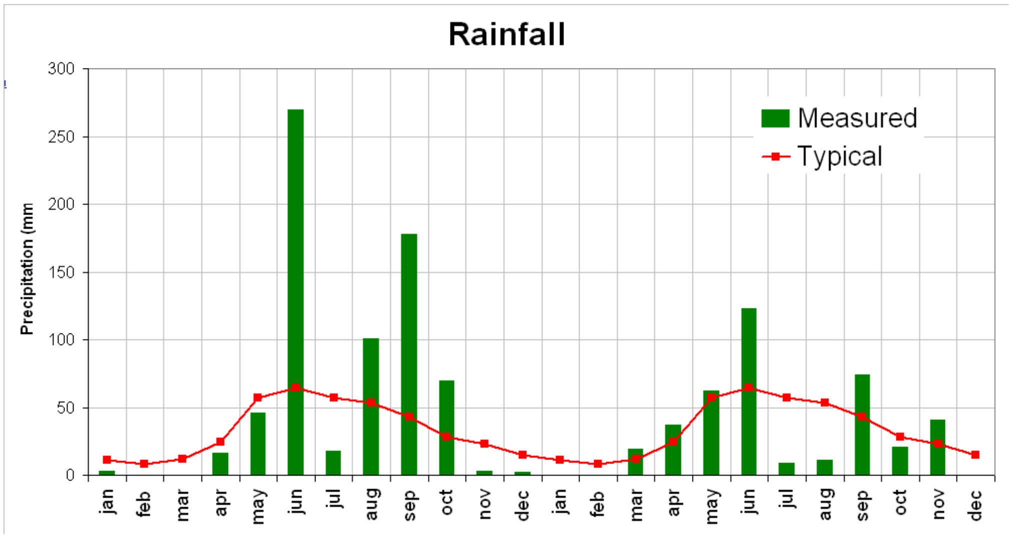


**Figure 8**. Measured and typical average monthly distribution of rainfall in the region of Turtle Mountain (2005 - 2006).

Snow pillow readings were taken from a station close to the study area and managed by Alberta Environment (Gardiner Creek station, elevation 1970m). For these two locations snow depth ranged from 96 to 117% of average. Snowmelt occurred a few weeks earlier than usual in 2006 due to very warm weather in mid May (Figure 9), and resulted in above average runoff volumes in the area.

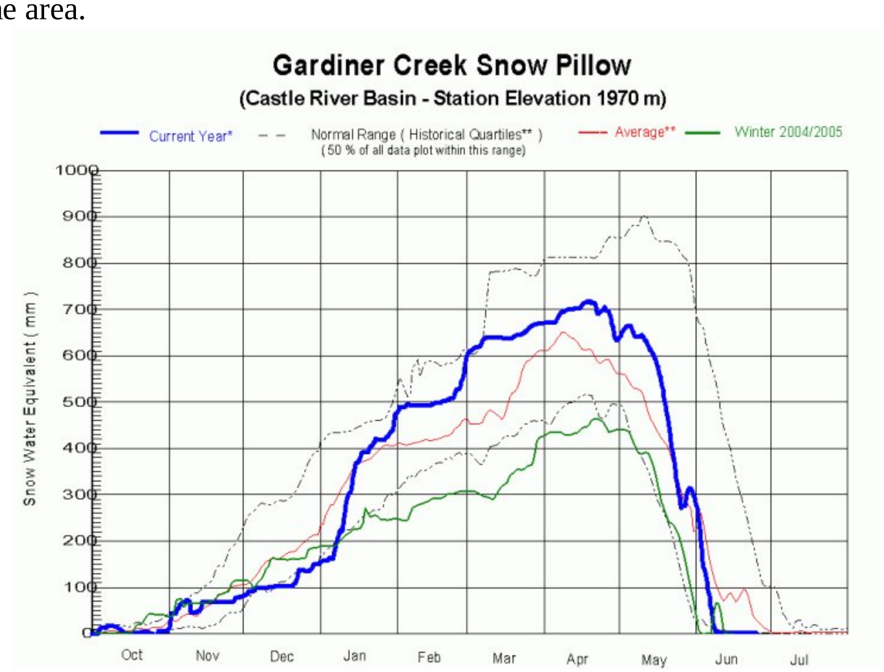


**Figure 9**. Gardiner Creek snow pillow for winter 2005/2006 (from Alberta Environment).

## DISCUSSION OF MONITORING DATA

Discussion of slope displacement behaviour focuses on the response of the rock mass to seasonal temperature variations, and to the two extreme precipitation events of June 9 and September 10, 2005.

Generally speaking, slope monitoring since early 2005 indicate that very slow displacements have occurred, with displacement rates of less than 1 mm/year. A seasonal pattern can be observed on displacements and appears to be correlated with seasonal temperature variations. This can be supported by the amplitude of the change and the seasonal nature of the displacement. Detailed scrutiny of the tiltmeter T-9 records indicates distinctive variations in tilt rate, during the warming and cooling seasons (Figure 4). Periods of small tilt change with temperature, seen during fall and winter, correlate with continuous record of low temperature. Conversely, higher tilt response to temperature variation are triggered during the warmer months. A similar behaviour can be noted on tiltmeters T-1, T-7 and T-10. No evident change of tilt response to temperature is seen on T-5.

Two hypotheses can be offered to explain this behaviour. The first is that a deficient coupling exists between the tiltmeter base and bedrock. Quality control performed for the tilt data on a recent monitoring study for volcanic risk mitigation at Cape Verde (Fonseca et al., 2003), revealed that defective coupling can lead to polarity reversal and erroneous readings. Increased levels of solar radiation during the warmer months might also add to the deficient coupling effects. The second hypothesis proposes that permanent tilt (displacement) might come from slip on discontinuities. This slip might occur in response to the stresses induced during cooling of the near surface bedrock. Stability analysis run on Checkerboard Creek rock slope showed that thermal contraction during cooling of the near surface bedrock introduces enough stress change into the slope to cause slip on discontinuities (Watson et al., 2004). This process results in a permanent downward and outward displacement (tilt) of the slope. This permanent displacement during the cooling season will reduce the amount of tilt recovery measured after every annual cycle.

Crackmeter set B also seems to support the relationship between displacement cycles and seasonal temperature variations. Unfortunately, due to reliability and accuracy issues, these observations can not be confirmed by any of the other primary surface instruments. Several years of observation of this very slow movement are needed to confirm small long-term trends and the possible acting mechanisms.

Clear evidence of the role of thermal stresses on rock degradation is also found on the seismic data recorded by the surface passive microseismic sensors. An increase in seismicity correlated with the time when rock temperature passes through the 0 °C point has been noted. A significant, localized seismic event was detected at the South Peak seismic station on February 16, 2006. This event was very sharp but it was not big enough to register at any other of the surface stations located on the mountain. Based on the arrivals, it is believed the event originated in the northeast quadrant relative to South Peak - probably within a few hundred metres. This event is thought to be related with fracturing of the rock during a cold snap recorded that day, where temperature dropped from -12 ˚C to -32 ˚C in less than a day.

Accelerated displacements have been also recorded during periods of high precipitation; however the correlation with precipitation level is not consistent. Absence of displacement at the same levels of precipitation during warm temperatures has been seen. A cause for this inconsistency is the air temperature. Displacement is strongly correlated with not only precipitation but with freezing temperatures. As can be seen in Figure 3 and Figure 5, three major precipitation events were recorded in June, 2005 and one from September 9 to 11, 2005. Only in the cases were heavy precipitation occurred simultaneously with below zero temperatures, displacement was recorded (June 9 and September 10, 2005). These displacements are believed to be associated with a rapid cooling of the rock mass as cool water travels through the cracks and heat from the rock mass is transferred to the water flowing. During this process a greater volume of rock is involved than during the progression of cooling due to air temperature decrease. As a result, a greater deformation occurs. With the end of precipitation any cooling effects cease and the rock gradually returns to its background temperature levels. Precipitation intensity will play a key role in determining the magnitude of crack width change, as the cooling capacity of the water is a function of the area, and flow rate. The short lived nature of displacements after heavy freezing rainstorms have also been observed at the Checkerboard Creek rock slope (Watson et al., 2004) and during tunnel dewatering (Moore pers. communication).

## CONCLUSIONS

Initial findings as to the style and rate of movements of South Peak are slowly coming available and indicate that South Peak has had a long history of very slow deformation. These movements are of interest but fall below levels of concern for the stability of the slope, considering the large extensions that have obviously occurred during crack formation. Thermal stresses are believed to play a significant role on slope stability. Continuous cooling and warming cycles give origin to temperature gradients, causing slight readjustments in the rock blocks forming the slope (Watson et al. 2004). Measurement of displacement in the crackmeters and extensometers across Crack 1 and Crack 2 was confined to the two heavy rainstorm events of June 9 and September 10, 2005. The total displacements shown on Extensometers EX-2 and EX-3 are considered to be indicative of the sudden movement across the cracks that they span associated with precipitation and cold weather. Seasonal displacement patterns were also observed on the tiltmeters and one set of crackmeters.

McConnell and Brock (1904) suggested that rapid snow melting due to an unseasonably warm spring, created a large water inflow into the mountain’s fracture network, which followed by a sudden temperature drop during the night of April 28, caused the water to freeze and eventually trigger the collapse of the mountain. They also suggested that heavy precipitation in the months preceding the slide may have also contributed to trigger the Frank Slide. However, the recent data challenges this argument. Above average runoff for the March through May, 2006 period were reported as a result of early snowmelt (Figure 9); however, no displacements were recorded during the same period. Several major precipitation events were recorded during June and September, 2005 and June, 2006, but displacements were only measured when simultaneous freezing temperatures were recorded.

When the recently recorded data (crackmeters, extensometers and tiltmeters) is compared to the results of other historical (painted measurement points and Moire Crack gauges) and recently flown photogrammetric targets, the overall rates of movement seem to agree and provide the best picture to date of the overall patterns of movement of the South Peak area. The results from the photogrammetric study (as reported by Froese and Moreno, 2007) indicate that deformations over the past 23 years range from 19 mm to 88 mm, corresponding to average movement rates over that time period of 0.8 mm/year to 3.8 mm/year. The lack of a geological and hydrogeological model of South Peak remains a serious handicap to the interpretation of data and prediction of probability of any future slide. Additional monitoring points on the east face of the South Peak are required to verify the postulated sliding surface in the BGC Engineering report (2000) and to find, if any, the relationship between crack movement and movement on the extensive sliding surface.

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