ERCB/AGS Information Series Report 139

Frank Slide and Turtle Mountain Early-Warning System Technical Tour Guidebook (NTS 82G)

Energy Resources Conservation Board

Alberta Geological Survey

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Frank Slide and Turtle Mountain Early-Warning System Technical Tour Guidebook (NTS 82G)

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Contents

Introduction

This guidebook is divided into four parts. The first section provides a brief overview of the Okotoks erratic, the largest and best known glacial erratic in Alberta. The next three sections contain information on the other sites that were visited during the field trip.

This guidebook contains detailed materials compiled by the authors, as well as information from other guidebooks, specifically Paulen (2003), Couture (2001) and Couture and Jamieson (2003).

References to relevant sources are indicated in the text.

Okotoks Erratic

The Big Rock, a house-sized quartzite block, is the largest and best known glacial erratic in Alberta; even an Alberta brewery is named after it (Big Rock Beer). This is the largest in a group of rocks carried by valley glaciers of the Cordilleran Ice Sheet, which then coalesced with the Laurentide Ice Sheet in the Late Wisconsin (Jackson et al., 1997) and flowed southeastward, perpendicular to regional glacial trends for almost 800 km, creating the Foothills erratics train (Stalker, 1956; Jackson, 1980). The erratics lie in a narrow band extending from Jasper National Park to northern Montana. The Foothills erratics train is narrow, ranging in width from 22 km to less than 1 km.

The name of the erratic was derived from the Blackfoot word for rock, 'okatok.' The Okotoks erratic is 9 m high, 41 m long and 18 m wide, and weighs 15 000 tonnes. The rock has been eroded into pieces but is still a large landmark on the flat prairie. If you look closely at the rock, you can see something vaguely familiar: a piece of quartzite that can be seen in outcrops in the Jasper area. It is a piece of the thick-bedded, micaceous, feldspathic quartzite of the Lower Cambrian Gog Group (Price et al., 1972). About 18 000 years ago, a rockslide caused a section of the Gog Group to crash onto the surface of a valley glacier in the present-day Athabasca River valley. The flowing glacier slowly carried this debris eastward to the plains, where the continental ice sheet deflected it southward.

The Foothills erratics train is a group of rocks carried from the Rocky Mountain by glacial ice. This ice flowed southeastward along the edge of the Laurentide Ice Sheet and deposited the rocks in a narrow belt.

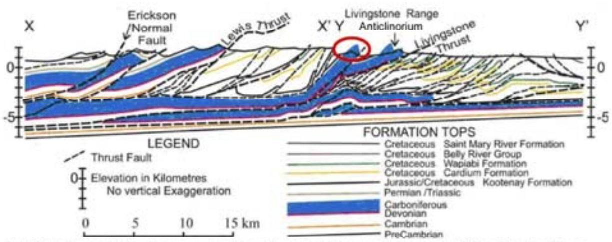
The Big Rock (Okotoks erratic).

In the 1970s, the Big Rock was the first 'natural feature' to be designated as an official provincial historical site. The Big Rock was located on private land until 1987, when the province purchased the land on which it sits.

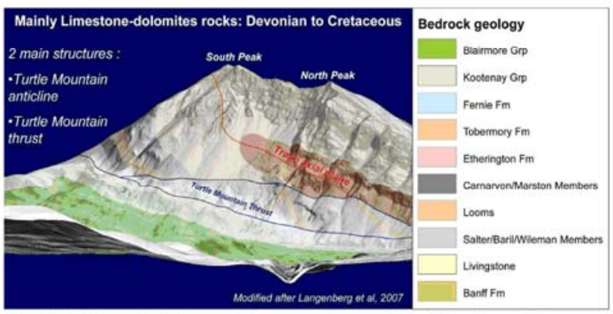
Quartzite is slippery to climb and, although it is hard, pieces can break off in climbers' hands. Please do not climb the rock, as tempting as it looks. Also, there are aboriginal pictographs on the rock, and these could easily be damaged by climbers. Enjoy the beautiful colours, textures and feel of the rock, but stay on the ground.

General Geological Setting of Turtle Mountain

The Turtle Mountain anticline is part of the Livingstone Thrust Sheet of the Alberta Foothills (Langenberg et al., 2007), which forms the easternmost part of the Rocky Mountains. The Rocky Mountains form the eastern margin of the Rocky Mountain Fold-and-Thrust Belt, which is the easternmost part of the Canadian Cordillera.



Regional, geological cross-section through the eastern part of the Rocky Mountains (from Cooley, 2007). Cross-section X–X' was modified by Cooley (2007) after Price (unpublished data, 1972), and Y–Y' after MacKay (unpublished data, 1932). The Turtle Mountain anticline is within the red circle.



Simplified 3-D geological map looking southwest, adapted from Langenberg et al. (2007).

In this region, the rocks range in age from Devonian to Cretaceous and consist mainly of Paleozoic carbonates and Mesozoic clastic rocks.

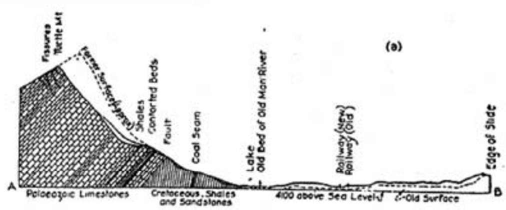
The dominant geological structures in the Turtle Mountain area are the Turtle Mountain anticline and the Turtle Mountain thrust. The fold defines a non-cylindrical, asymmetric and inclined anticline, plunging to the west, that can be outlined as a fault-propagation fold according to Langenberg et al. (2007).

The anticline shows different geometries along the fold axis. In the field, its axis is difficult to follow due to the intense fracturing of the hinge area. Moreover, the Turtle Mountain anticline is affected by the Turtle Mountain thrust. North of the North Peak area, the Turtle Mountain fold is cut by the thrust and only the western limb of the anticline remains.

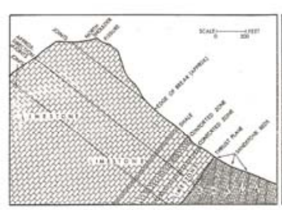
Evolution of the Understanding of Turtle Mountain

Structure and Geology

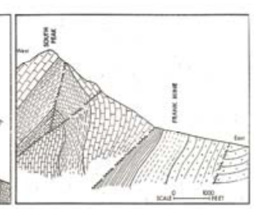
In 1904, McConnell and Brock first studied the cause of the 1903 slide and attributed it to the mountain structure, which was described as a monocline of Paleozoic limestone dipping 50°W (McConnell and Brock, 1904). Daly et al. (1912) reached the same conclusions but highlighted the presence of the coal mine at the base of the mountain as a contributing factor. In 1932, MacKay (1932) then proposed an anticline with two major hinges to describe the geometry of Turtle Mountain. With this new understanding, Allan (1933) focused their studies on the structure of South Peak and realized the influence of the anticline structure on the stability of Turtle Mountain. Then, in 1955, Norris helped to better define the Turtle Mountain anticline. Cruden and Krahn (1973, 1978) suggested that the folding mechanism can be classified as flexural-slip folding. This mechanism was later revisited by Langenberg et al. (2007) and reclassified as a modified fault-propagation fold that can be described as a break-thrust fold.



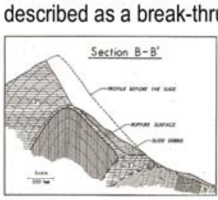
(McConnell and Brock, 1904)



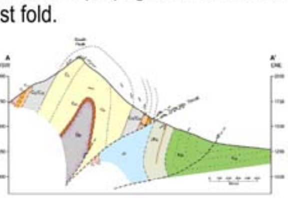
(Daly et al., 1912)



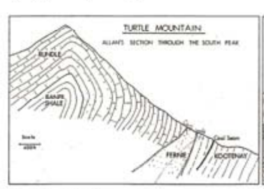
(MacKay, 1932)



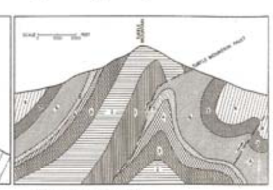
(Cruden and Krahn, 1973)



(Langenberg et al., 2007)



(Allan, 1933)



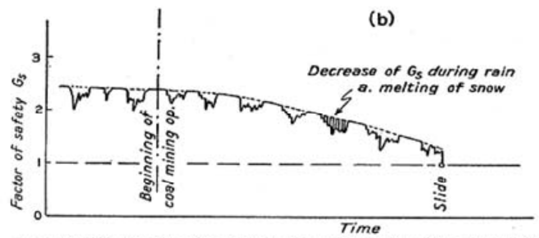
(Norris, 1955)

Failure Mechanism

Early interpretation by Daly et al. (1912) indicated planar sliding along steep joints orthogonal to the bedding planes in the western fold limb. Then, using Daly's interpretation, Terzaghi (1950) applied the concept of progressive failure to assess the decrease in the safety factor prior to the slide.

During the last 40 years, the accepted opinion, introduced by Cruden and Krahn (1973, 1978), is that the failure followed the bedding planes on the eastern limb of the Turtle Mountain anticline, with the rear release provided by a series of two steep joint sets. Following this assumption, several geomechanical models have been carried out to describe the failure and to define the main triggering factor leading to the failure.

The first geomechanical models, developed by Cruden and Krahn (1973, 1978), used limiting-equilibrium-stability analysis to show that the slope was in a state of marginal stability. Benko and Stead (1998), and subsequently Cruden and Martin (2007), applied finite-difference and finite-element modelling to better define the influence of the different triggering and predisposing factors.



Conceptual illustration of changes in the safety factor of the slope prior to the slide (from Therzagi, 1950).

Summary of factors influencing the stability of Turtle Mountain.

Main predisposing or triggering factor	*Main reference*
Creep of limestone units	Terzaghi 1950
Adverse jointing and faulting in the rock mass	Cruden and Krahn (1978), Jaboyedoff et al., (2009)
Underground coal mining at the foot of Turtle Mountain	Benko and Stead (1998)
Ice wedging in the discontinuities	Cruden and Krahn (1978)
Excessive rainfall over the 4 years preceding the slide	Cruden and Krahn (1978)
Water table fluctuations	Jaboyedoff et al., (2009)
Seismic loading	Cruden and Krahn (1978)
Intense fracturing of the hinge zone	Pedrazzini et al., (in press)
Undercut by Crowsnest river erosion	Cruden and Martin (2007)
Karst formation and limestone dissolution	Cruden and Martin (2007) Pedrazzini et al., (in press)

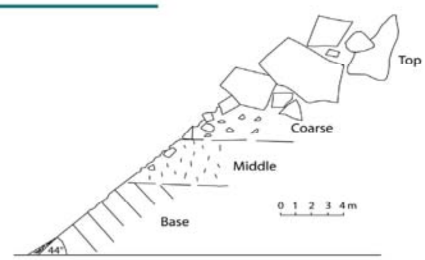
Results of the two studies differ, especially concerning the influence of the mine at the base of the slope. Recently, Jaboyedoff et al. (2009) combined DEM-based techniques and field observations to propose an evolution of the failure mechanism for the 1903 event. Theirs is essentially a composite mechanism involving progressive toppling of a large flat wedge formed by persistent discontinuity sets that are clearly visible in the upper part of the scar. One of the weakening factors was related to water-table fluctuation.

Evolution in the Understanding of the Run-Out Event

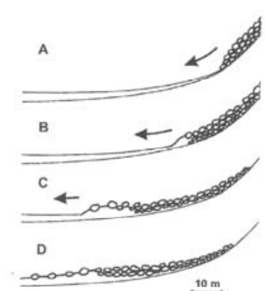
Frank Slide Deposit

A study of the vertical structure of the deposit showed the debris deposit to be inversely graded (Cruden and Hungr, 1986), with two types of slide margins. In areas where the slide climbed the steep slopes of the opposite side of the valley, the edge is clearly defined and consists of boulders. Elsewhere, the margins are composed of fine material. They called this zone the 'splash area.'

Block diameter varies between 0.25 and 11 m (Drapeau, 1997; Couture et al., 1998), with a diminution in block size from the proximal zone of the deposit to the distal zone (diameter-distance correlation, $R = 0.78$).



Cross-section of the deposit, showing inverse grading (modified from Cruden and Hungr, 1986).



Hypothetical mechanism for transfer of momentum between a moving rock mass and liquefiable substrate at full scale (i.e., not in the laboratory): A) rock mass approaching the substrate layer; B) impact liquefaction, partial displacement and overriding of the substrate; C) mud wave projected forward; and D) rock mass and mud deposit (after Hungr and Evans, 2004).

Run-Out Mechanism

Kent (1966) and Shreve (1968) proposed fluidization by air trapped under the mass during the first stage of the fall as the only plausible mechanism to explain the high mobility of Frank Slide. However, this theory would require permeabilities that are "implausibly low" (Melosh, 1987) and a normally graded deposit, which was not observed in the case of the Frank Slide (Cruden and Hungr, 1986).

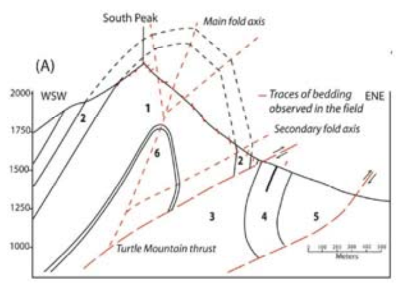
Hungr and Evans (2004) proposed that the high mobility of rock avalanches is linked to the presence of alluvium in the path of the moving mass. The mechanism can be separated intofr several stages: first, the failure occurs; second, the rockslide overrides a pre-existing deposit of saturated alluvium; and, finally, the alluvium is liquefied by the load of the moving mass, thereby reducing the friction coefficient and allowing the slide to travel an unusually long distance. As the rock mass slides on a part of this liquefied soil, the latter is projected forward. However, in the case of Frank Slide, this happened sideways.

New Information from Turtle Mountain

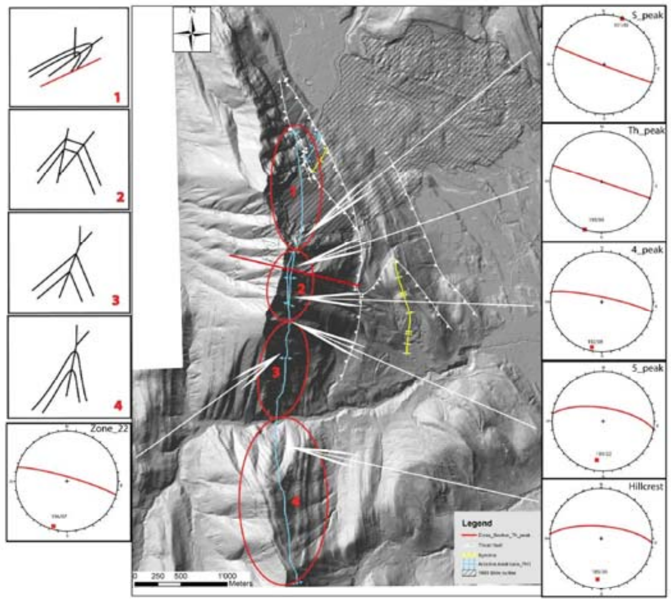
Turtle Mountain Anticline

The Turtle Mountain anticline can be described as an easterly verging, asymmetrical, inclined chevron-box fold with multiple hinges (Humair et al., 2010). The main axial surface is a single hinge at depth that divides upwards into two hinge segments with a V shape.

The fold axis plunges 021°/02° north of Third Peak, 190°±5°/05°–22° between Third Peak and Drum Creek, and 185°/20° on Hillcrest Mountain.



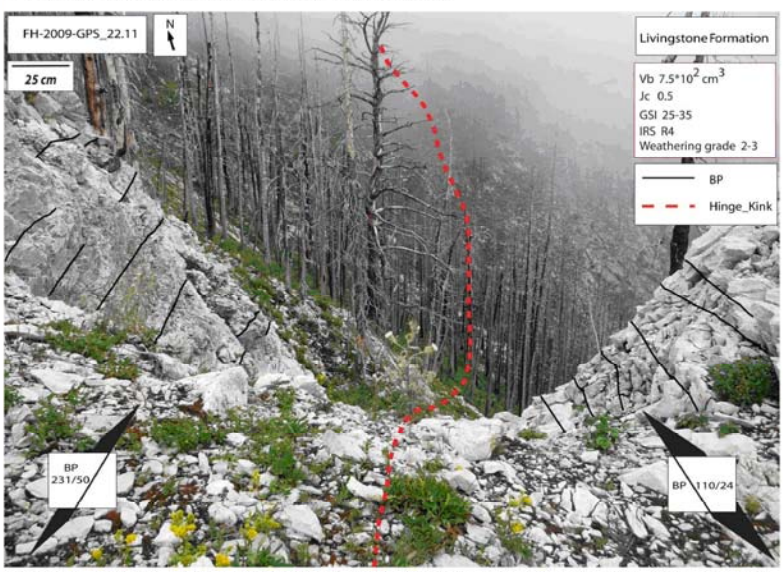
Turtle Mountain anticline cross-section beneath South Peak (from Pedrazzini et al., 2011).



Turtle Mountain structural synthesis on a hillshaded image constructed from a high-resolution digital elevation model, showing the anticline axial trace with the fold axis and anticline geometry highlighted (from F. Humair, M.Sc. thesis in progress, 2011).

Characteristics of the Hinge Area

The Turtle Mountain anticline is characterized by a disturbed hinge zone. In this area, discontinuity persistence is higher and discontinuity spacing lower than elsewhere. The general trend of the hinge could only be defined by distant observations, and it is difficult to follow clearly the bedding planes and the progressive transition from eastern to western limb. In addition, some local limb thrusts are suspected along bedding planes close to the hinge area (Ramsey and Huber, 1987). Close to the hinge zone, a field survey indicated the presence of at least four discontinuity sets with frequently close spacing and a medium to high persistence (International Society of Rock Mechanics, 1978). The fracturing is caused mainly by compressive stress during the folding phase and by the presence of rocks with differing elasticities (e.g., massive limestone versus silty dolomite) in the stratigraphic sequence (Ramsey and Huber, 1987).



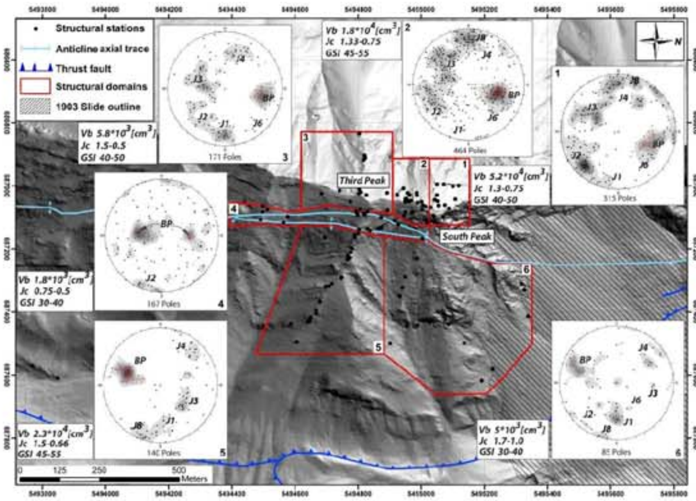
Trend of the anticline axial trace southward from Third Peak (from F. Humair, M.Sc. thesis, in progress).

These differences in the mechanical behaviour also affect the general morphology of the mountain. Silty dolomite layers of the Mount Head Formation are generally more weathered and form significant topographic depressions on both fold limbs. Positive relief is created by competent limestone beds. Rock dissolution is in the coarse-grained limestone (Livingstone and Mount Head formations) of the hinge area in the form of numerous cavities and heavy weathered zones.

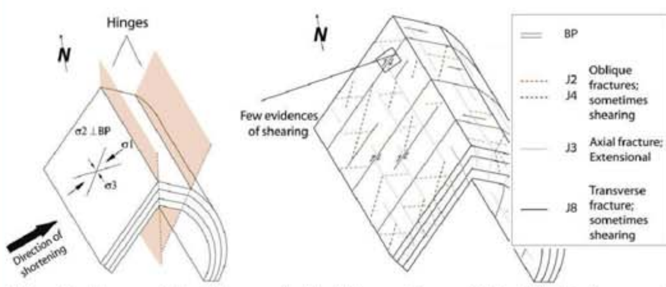
Joint Sets

Eight discontinuity sets can be identified at Turtle Mountain (Pedrazzini et al., 2011; Jaboyedoff et al., 2009; Cruden and Krahn, 1973):

- bedding plane (BP),
- axial fracturing perpendicular to the BP (J3)
- transverse subvertical fracturing (J8)
- oblique fractures (J2 and J4)
- discontinuity set trending 270°/60°±20° (J5)
- discontinuity set trending 015°/50°±20° (J1)
- minor discontinuity set trending 325°/45°±20° (J6)
- evidence of shearing observed on J2, J4 and J8



Structural domains and related geomechanical properties defined between Third Peak and South Peak (from Pedrazzini et al., in press).



Schematic diagram of the fold geometry, including positions of fold-related fractures and directions of major stresses (from Humair et al., 2010).

Other fractures (J1 and J6) certainly have a post-folding origin. The J1 set is present in both limbs of the fold, as well as in the hinge areas, and seems to be linked to the transpressive phase. The origin of J6 is still unclear. More study is necessary to explain its origin.

Origin of Joint Sets

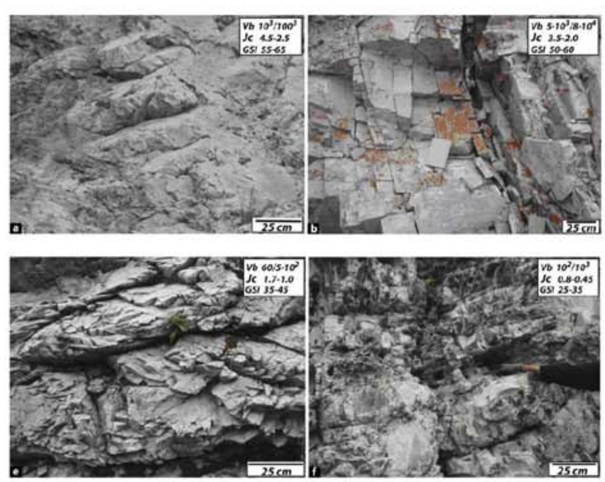
Discontinuity sets (J2, J3, J4 and J8) can be linked with the tectonic phases described by Cooper (1992) and Price and Carmichael (1986). Chronologically, these are:

- Late Jurassic to Early Cretaceous: folding and thrusting phase, mainly east-west
- Late Cretaceous to Paleocene: left-lateral transpressional regime, mainly northeast-southwest
- Early and Middle Miocene: left-lateral extension phase, mainly northwest-southeast
- Early Miocene to present: stress release (unloading)

Rock-Mass Conditions

Rock-mass conditions at Turtle Mountain are very changeable, depending on local conditions and the location of the outcrops related to the anticline geometry. In general, both uniaxial compressive strength (UCS) and intact rock strength (IRS; International Society for Rock Mechanics, 1978) give consistent results: 100–150 MPa but generally slightly lower close to the hinge area.

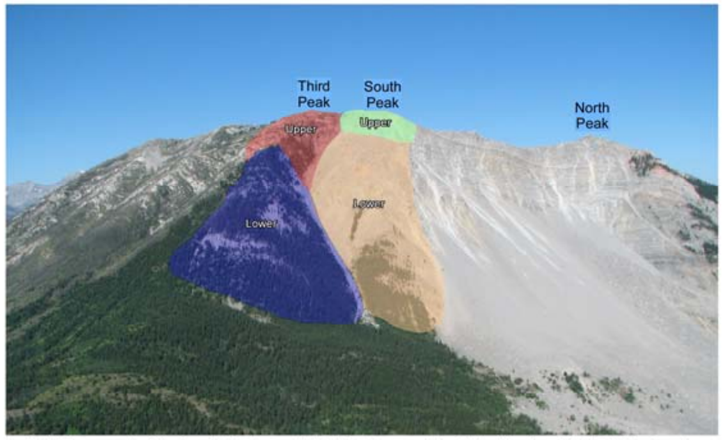
Weathering grade indicates a medium weathering rate for the study area as a whole. The estimates of geological strength index (GSI; Hoek et al., 1992) have a normal distribution, averaging 35–50, but tend to decrease closer to the hinge area. The GSI values in the hinge area show considerable scatter and a mean value clearly lower than in the two fold limbs.



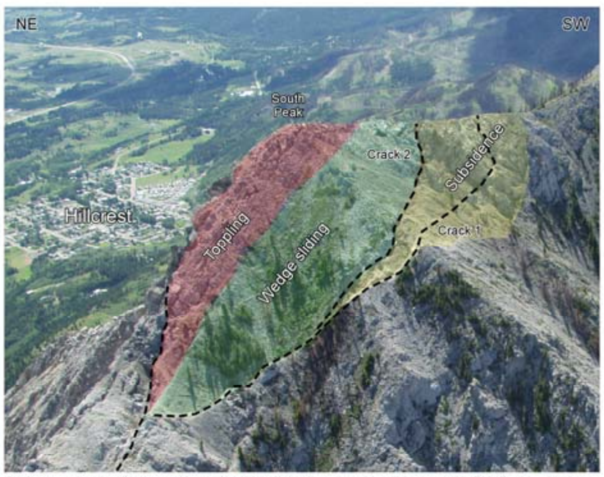
Examples of rock-mass characteristics from various outcrops across Turtle Mountain.

Present-Day Potentially Unstable Zones

The geological model of Turtle Mountain has evolved considerably since the first investigations of the early 1930s and the subsequent studies of 1970s. This was made possible by the acquisition of digital elevation model (DEM) data and the application of emerging computing tools to aid in structural mapping on the mountain. These more recent studies have led to a re-interpretation of the South Peak instability and the highlighting of several different instabilities on the eastern face of the mountain that had not been identified in previous studies (Jaboyedoff et al., 2009).



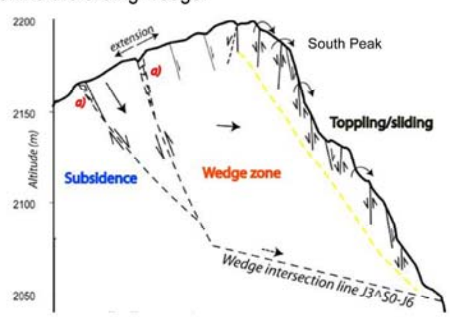
Instability zones in the South Peak and Third Peak areas identified by the detailed structural mapping and kinematic analysis. From Moreno and Froese (2008).



Oblique view to the southeast, showing the three main zones of deformation on upper South Peak (from Froese et al., 2009).

Upper South Peak

Based on the DEM structural study (Froese et al., 2009), three main structural zones can be identified on upper South Peak: a smaller volume of rock toppling and sliding controlled by joint set J2; a large sliding wedge controlled by J2, J3, J6 and bedding on the western limb of the anticline (S0); and a zone of broken rock that is subsiding into the space created behind the sliding wedge.

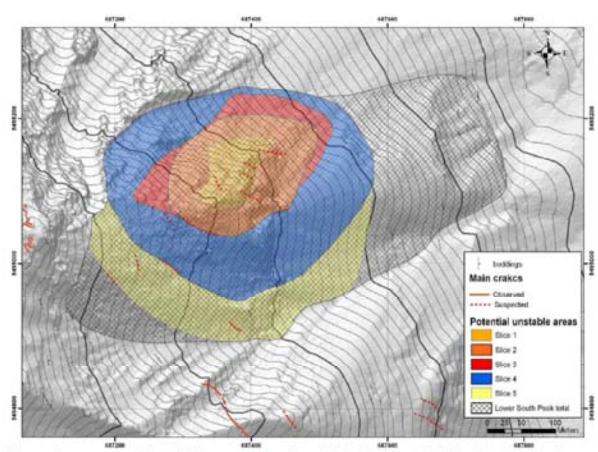


Conceptual model of the unstable area on upper South Peak.

Lower South Peak

The lower portion of South Peak is heavily fractured and obscured by rock fall talus originating from the cliffs above. The fractured nature is likely due to its proximity of the anticline hinge (Pedrazzini et al., 2011). Many open fractures in this zone appear to be related to movement, and show visible indications of previous slope movement, oriented primarily to the northeast, generally following the J2 discontinuity set. The width of crack openings is variable but generally increases towards the northeast.

Based on the results of kinematic analyses, as well as field measurements of crack orientations, the lower South Peak area can be divided in at least six potentially unstable zones. The various zones appear to be moving towards the northeast, following the J1 discontinuity set. Large-scale planar sliding on the bedding seems unlikely due to the very steep dip angle of the bedding compared to the topography.



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

Lower Third Peak

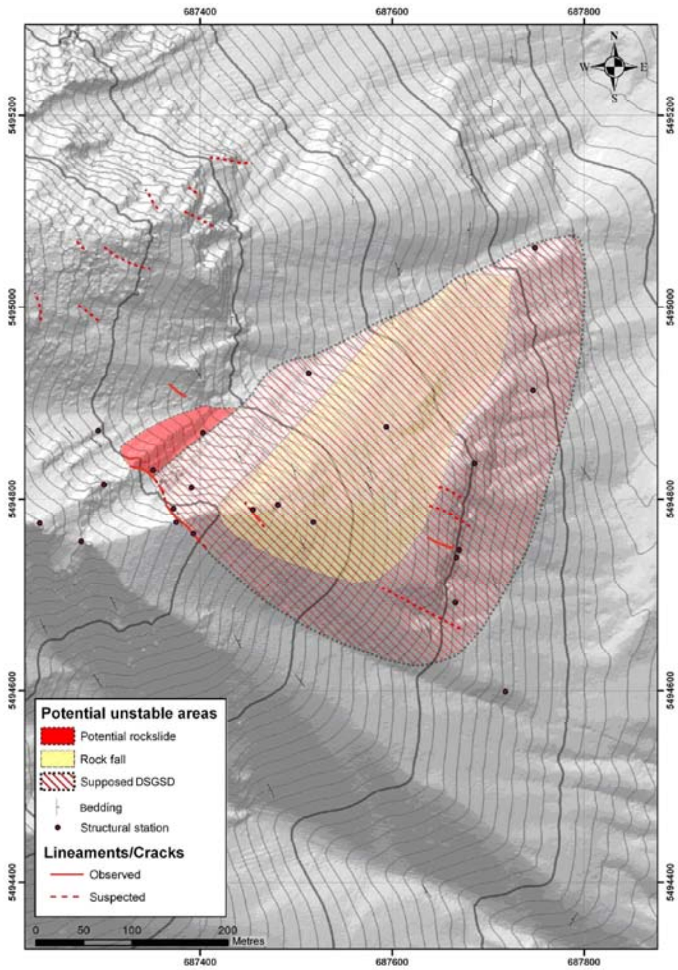
Significant cracks have been detected on the lower slope below Third Peak, demonstrating that pre-failure movements occurred in this area. These cracks can be followed to both the southeast and the northwest from the apex of the ridge below Third Peak.

The rock mass at the surface often shows a low quality. These characteristics, associated with the slope morphology and shallow instability, indicate the possible existence of a deep-seated gravitational slope deformation (DSGSD) affecting the lower Third Peak area.

Displacement vectors measured along cracks, as well as kinematic analyses, indicate that the most likely mechanism is step-like planar failure along discontinuity J1, with bedding planes as the lateral release surface and J2 playing the role of back-crack.

Upper Third Peak

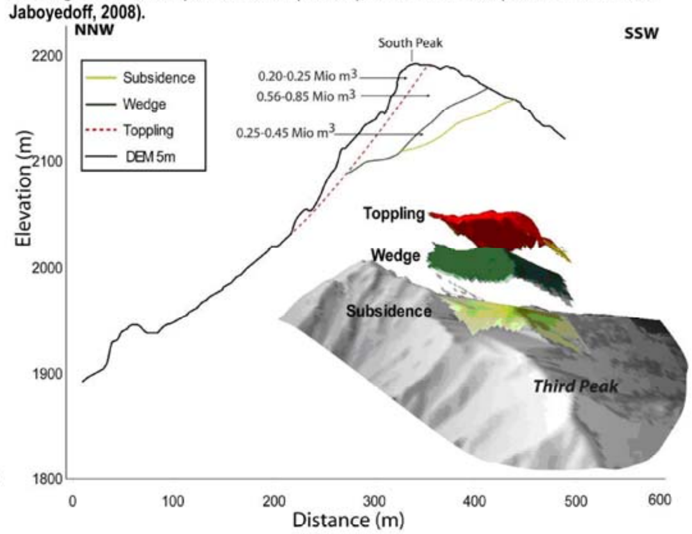
No significant failure volumes can be identified on the upper portion of Third Peak (Pedrazzini and Jaboyedoff, 2008). Due to the proximity to the fold hinge, kinematically feasible failure mechanisms are limited to shallow sliding and toppling, involving only small volumes of rock.



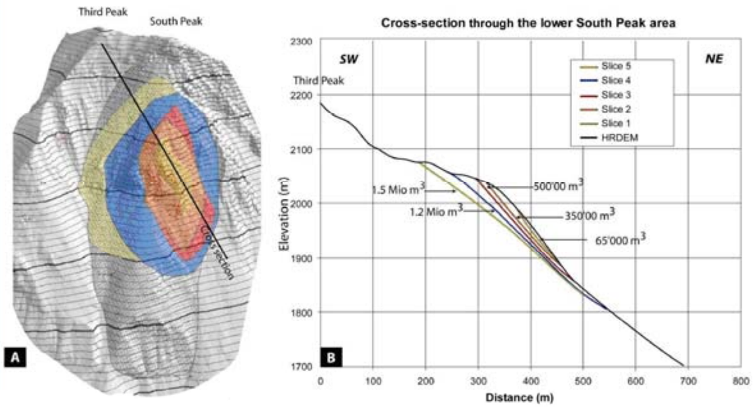
Plan view of mapped structural features and postulated unstable volumes, including a deep-seated gravitational slope defirmation (DSGSD), lower Third Peak (from Pedrazzini and Jaboyedoff, 2008).

Volume Calculation

The volume estimation is performed using the sloping local base level (SLBL) method (Jaboyedoff and Derron, 2005; Jaboyedoff et al., 2009). The SLBL method applied to a 3-D surface (DEM) consists of replacing the altitude z_{ij} of a DEM node with the mean value of the highest and the lowest node altitude among the four direct neighbours, if the altitude z_{ij} is greater than the mean value (Jaboyedoff and Tacher, 2006). Structural and failure-mechanism information has been taken into account to better constrain the model (Pedrazzini et al., in press).

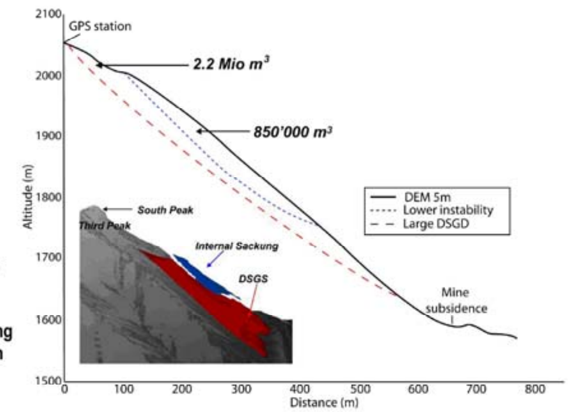


Three-dimensional representation of the SLBL results obtained for the upper South Peak instability, showing the calculated volumes for the three potentially unstable areas (from Pedrazzini et al., in press).



A) Representation of the unstable zones detected in the lower South Peak area, and

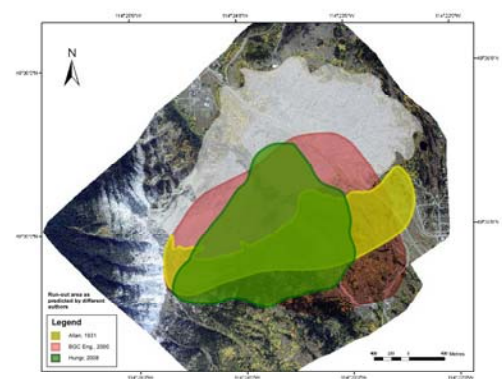
B) their calculated volume (cross-sections oriented in direction of expected movements (from Pedrazzini et al., in press).



Cross-section of the Third Peak instability oriented in the potential movement direction and showing the limits of potential unstable masses, calculated using the SLBL method (from Pedrazzini et al., in press).

Run-Out Analysis of Unstable Zones

For emergency-response and land-use planning, it is necessary to know the run-out distance of a potential rockslide from South Peak. Allan (1931) attempted to understand the extent of the area at risk. This zoning was based on an assumed volume for the South Peak movement and empirical relationships (fall height and travel distance), likely derived from the behaviour of the Frank Slide. In 2000, BGC Engineering revisited Allan's calculated run-out distance. Using recent empirical relations for rock-fall height, volume and travel distance, they revised the danger zones. All current early warning and emergency-response planning and protocols use the zone defined by BGC's empirical upper limit.



Updated piecewise run out scenario envelopes as compared to the previous estimates for a single large event from the South Peak (from Pedrazzini et al., in press).

With a refined definition of the volume for a South Peak failure, higher resolution DEM and improved 3-D analytical techniques, Hungr (2008) predicted a new run-out distance. A computer model was first calibrated by back-analysis of the 36 million m^3 1903 Frank Slide and two smaller rock avalanches in the Rocky Mountains. Forward analyses were then completed for two potential rockslides from South Peak, a planar slide with a volume of 6.7 million m^3 and a deeper rockslide with a volume of 13.8 million m^3. When compared to studies by Allan (1931) and BGC Engineering (2000), the run-out limits are similar and do not justify revision of emergency-response planning boundaries.

Dynamic analyses of the 12 potential instabilities on South and Third peaks, defined by Jaboyedoff et al. (2009), were carried out (Pedrazzini et al., in press). All potential landslides are smaller than the two major South Peak detachments analyzed by Hungr in 2008, with volumes ranging from 40 000 to 6 million m^3. In general, the hazard areas corresponding to the 12 landslide events analyzed do not exceed the hazard limits established previously for possible full-scale failures from the South Peak, as shown by Hungr (2008).

Monitoring System

Since fall of 2003, a network of more than 80 sensors has been installed around Turtle Mountain, the majority concentrated on South Peak. This network can be considered to span the full spectrum of monitoring, as outlined by Laroque (1977). There are sensors and monitoring points installed at various points on the mountain that detect whether movements exist (Level 1), aim to characterize areas of known movement (Level 2) and provide near–real-time warning (Level 3).

Sensors used to provide warning are considered primary sensors, whereas those that characterize movements (Level 2) are categorized as secondary sensors. It should be noted that the instrumentation system falls short of that envisaged in the framework report by RSRead Consulting Inc. (2002), in that no subsurface (borehole) instrumentation was installed because drilling is cost prohibitive.

Sensor Types

Primary Sensors

These sensors have high resolution but a limited working range, so they will provide warning only during early stages of the slide. They include 10 tiltmeters, 5 surface wire extensometers and 22 crackmeters.

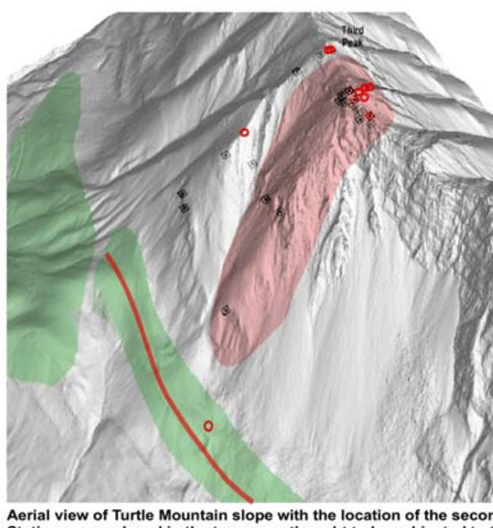
Typical head assembly of a wire extensometer, in which a weighted wire runs over a rotary potentiometer, calibrated to measure millimetres of displacement.

Ten narrow-angle uniaxial tiltmeters are distributed on near-vertical surfaces within the large fractures to measure slow angular deformations.

Typical configuration of crackmeters, with aluminum roof mounted to provide protection from snow overburden and falling rocks. Crackmeters were installed in sets of three in order to determine deformation vectors.

Secondary Sensors

These are sensors with low resolution but a great ability to measure large displacements. They will take on the role of providing continuous data during the final stages of the slide, once the working range of the primary sensors has been exceeded by the slope displacements. They consist of 20 prisms with distance measurements shot from a robotic total station located in the bottom of the valley, and 12 single-frequency GPS receivers.



Weather station. showing the various instruments.

Aerial view of Turtle Mountain slope with the location of the secondary-sensor network. Stations were placed in the two areas thought to be subjected to the greatest deformation (South Peak summit and coal-mine workings).

Tertiary Sensors

These provide background data useful in the interpretation of the results from the primary and secondary sensors. The tertiary-sensor network consists of meteorological stations (rain, wind, temperature, barometric pressure) and web cameras at both the top and the base of the mountain.

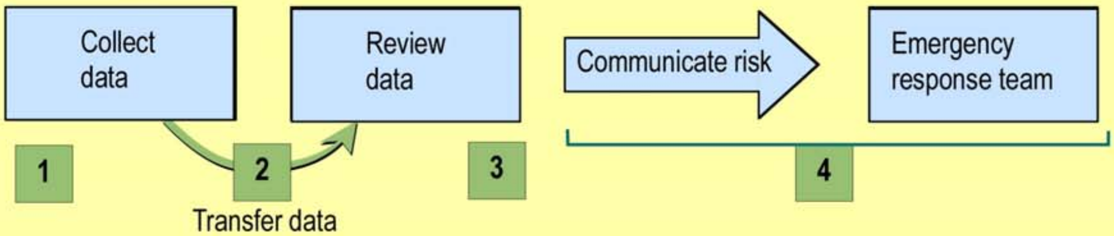
These sensors were augmented with six surface, passive microseismic stations to provide the source location of the potential sliding surface. However, seismic monitoring was later abandoned due to difficulties in the interpretation and accurate location of events. Some of the stations were later converted to GPS stations.

Early-Warning System

For most geo-engineering professionals involved with the characterization and monitoring of hazards, the main considerations focus on the sensor types, data interpretation and alarm-threshold development. However, other important factors must be considered to ensure that the data can be obtained and that the population at risk receives timely notification to avoid the hazard.

The schematic below illustrates the structure required to provide warning of and response to a rock slide, which should serve as a guide for developing other warning systems for natural hazards.

Ideal warning system



Collect Data

To provide an effective early-warning system, it must function as designed on a near-continuous basis. To achieve this, there must be an equipment inventory and a review process for the system, including troubleshooting and contingency plans.

Sensor Network

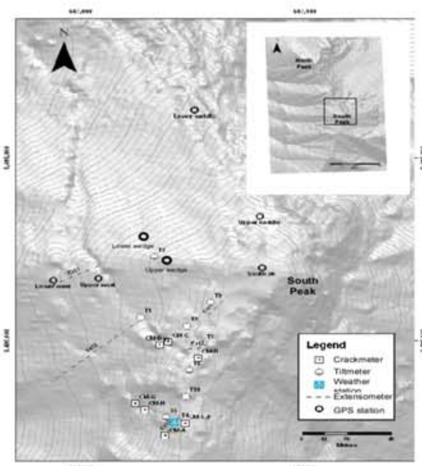
The network comprises complementary instrument types with varying degrees of sensitivity to movement and climate. The built-in redundancies provide a reliable, continuous data stream.

Daily Checks

Daily checks of the system's status ensure proper data collection and transmission.

Annual Inspection and Repair

Alberta Geological Survey staff annually inspect all installations to confirm conditions and assess the need for maintenance and repairs.

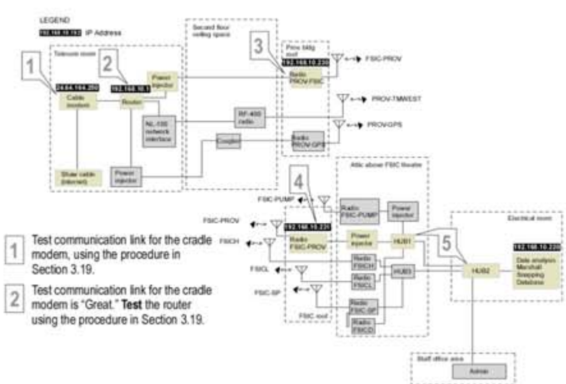


Sensor locations (Moreno and Froese, 2009c).

System Manual

The system manual provides step-by-step instructions for troubleshooting and repairing each component.

Alberta Geological Survey staff inspecting equipment.



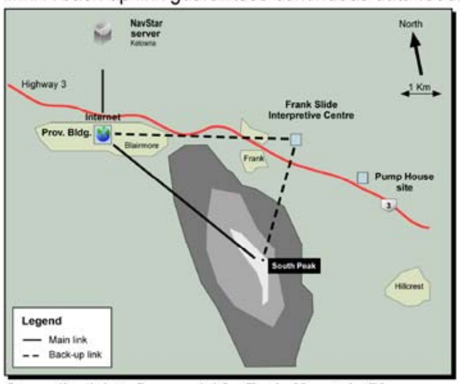
Typical troubleshooting protocol (Moreno and Froese, 2009b).

Transfer Data

The success of any warning system relies not only on the adequate planning, design and implementation of a series of instruments, but also on a proper data-management strategy.

Transmission

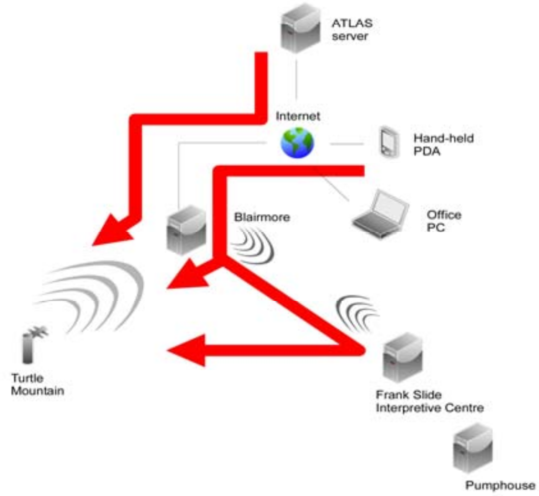
Data are transmitted to a permanent repository via a wireless link. A back-up link guarantees continuous data feed.



Generalized data-flow model for Turtle Mountain (Moreno and Froese, 2009a).

Accessibility

Numerous options exist for accessing data at the server or at the dataloggers on the mountain.



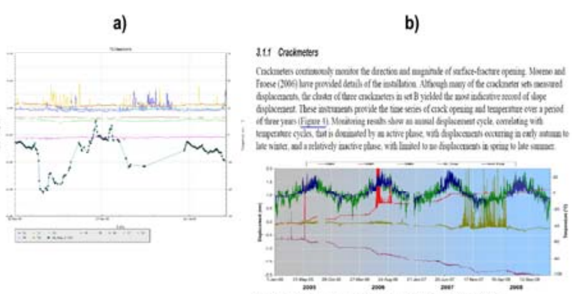
Main data-access protocols (Moreno and Froese, 2009a).

Review Data

It is important to determine who reviews data and how often, how data are evaluated and how threshold exceedance is determined. Also, an understanding of the deformation mechanism is needed to interpret the data.

Review Procedure

A protocol ensures data are reviewed on a specified frequency and in a repeatable manner. The levels of review range from daily checks of the completeness of the data to annual reviews and interpretation of the data trends.



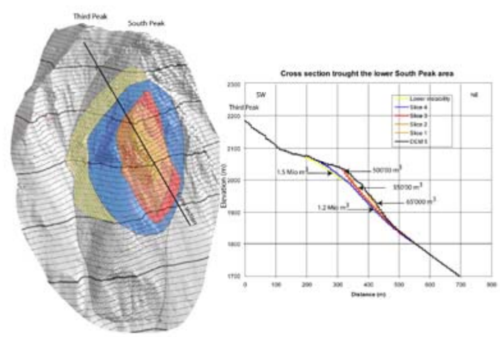
Typical data reports: a) automatically generated on a weekly basis in the form of preconfigured graphs, and b) yearly data review with a complete interpretation of movement trends

Determine Thresholds

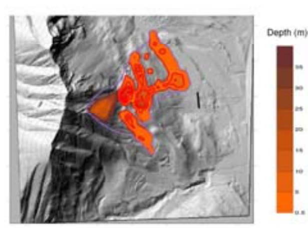
This component determines the thresholds against which the sensor results are evaluated. Continued revision of these thresholds is required as more data are obtained and data trends are better understood.

Deformation Mechanism

With developing knowledge of the hazards and sufficient long-term data trends available, studies were undertaken to better understand the stability of the mountain as a whole. Based on the revised interpretation, the focus shifted to monitoring a wider area on the eastern face of the mountain.



Areas of instability detected in the lower South Peak area (Pedrazzini and Jaboyedoff, 2008).



Results of Third Peak run-out analysis.

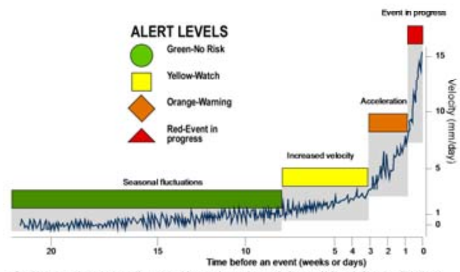
Any changes to the interpretation of the potential failure mechanism should prompt a review of the hazard areas that could be impacted in the event of a slide.

Communicate Risk

A warning and emergency response plan outlines responsibilities and communication protocols during an emergency, as well as operational responses and procedures to ensure the system remains operational.

Alert Conditions

Based on a review of the sensor configurations and expected behaviour of the mountain prior to a collapse, four alert levels were developed. Each level has an associated action.

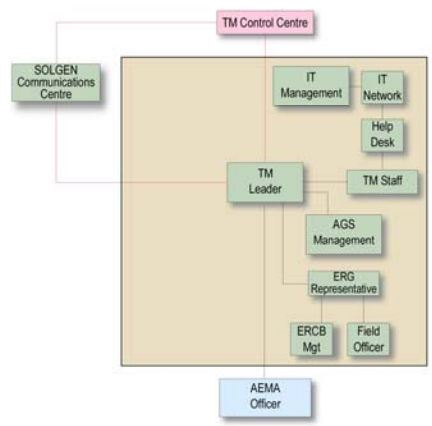


Schematic velocity and/or alert level (modified from Blikra, 2008).

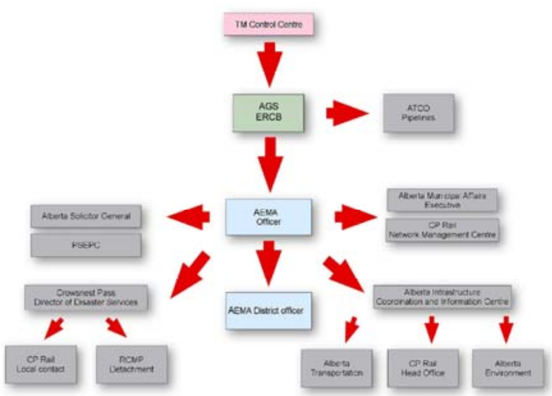
Training and Exercises

An annual emergency exercise validates the response plan and trains staff. There are two main type of exercises: discussion based and operation based. Discussion-based exercises are primarily used to familiarize staff with existing plans. Operation-based exercises are more involved and are used for the purpose of testing emergency plans and includes drills, functional exercises and full-scale exercises.

Operation-based exercise conducted in October, 2009



Internal communication flow (Moreno and Froese, 2009a).



External communication flow (Moreno and Froese, 2009a).

Communications

A communication protocol co-ordinates response from Alberta Geological Survey to external organizations.

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