# Mapping fractures with GPR at Turtle Mountain

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**Abstract**

The rock avalanche at Turtle Mountain, Canada, in 1903 destroyed the town of Frank causing the death of approximately 70 people. The geological unstable mountain still poses danger for the surrounding villages. In order to prevent future causalities, the Government of Alberta initiated a detailed geotechnical hazard assessment of Turtle Mountain. In this paper, we report on ground penetrating radar (GPR) measurements, which have been conducted on the mountain's summit to determine the depth and dip of potential fractures and fissures. The migrated data sets clearly show many coherent features to a maximum depth below surface of 40 m that reflect the layer bedding at Turtle Mountain as well as steep fractures cutting through the rock. These measurements demonstrate that ground penetrating radar is a useful survey technique to image the near-surface structure for fracture determination.

## Introduction

Turtle Mountain in south-western Alberta, the location of the well-known Frank Slide rock avalanche, may still pose danger to the surrounding settlements. A network of deep sub-vertical fissures still presents a potential cause for future rock slides. When analysing the stability of the South Peak between 1931 and 1933, *Allan* (1933) estimated that approximately 5 million cubic meters form a "danger zone" for a potential future hazard. Therefore, the government of Alberta initiated an extensive monitoring and geotechnical hazard assessment program (e.g., *Read et al*., 2000).

Knowledge of the fracture shapes and trends at depth relative to the mountain slope is important in order to further estimate the amount of rock mass likely to collapse. To assist in the hazard assessment project, we carried out several geophysical measurements using a ground penetrating radar system on Turtle Mountain. GPR is a frequently employed geophysical technique in near surface studies. While it is often used in environmental studies, it has also been utilised in fracture detection (e.g., *Grasmueck*, 1996 and *Willenberg et al*., 2004). The intent of our surveys was to map out the near surface structure of Turtle Mountain's summit at several locations, where large fractures are cutting deep into to the mountain. We carried out four surveys on top of Turtle Mountain using three different antenna frequency systems between 50 and 200 MHz, respectively. However, it seems that the highly fractured summit does not allow a high frequency signal to penetrate substantially deep into the underground, as we were not able to record significant reflections with the 200 MHz antennas. In this paper, we describe measurements conducted with 50 MHz antenna system along an approximately 100 m long profile at the West Slope of Turtle Mountain.

## Data processing

The data were acquired using a Malå–Ramac II GPR system on a former rock avalanche area with the surface layer mainly covered with loose limestone scree. The data were recorded in 0.2 m intervals resulting in 495 traces for the entire survey. The profile crossed several major cracks cutting through Turtle Mountain, which can be used as reference reflectors in the interpretation of the data later on.

To process the data we used the following steps. First, the traces were shifted in time to correct for topographic effects when necessary, followed by amplitude gain (AGC) to correct spherical dispersion and frequency filtering. Afterwards, we apply a Kirchhoff migration algorithm. The processed raw data are shown in the top panel of Figure 1. After processing, linear events dipping downwards with progressing profile length are readily observable. These strong and coherent reflectors are most likely related to bedding planes. However, there are also numerous other reflectors present, thus complicating the interpretation of the data substantially.

As we do not know the actual GPR wave speed of the fractured rock, we are facing an additional difficulty when we want to migrate the data set. We therefore use a wide range of migration velocities distributed around the typical velocity for limestone of v=0.12 m/ns (e.g., *Davis and Annan*, 1989). From the migrated data we choose those for further analysis that do look most

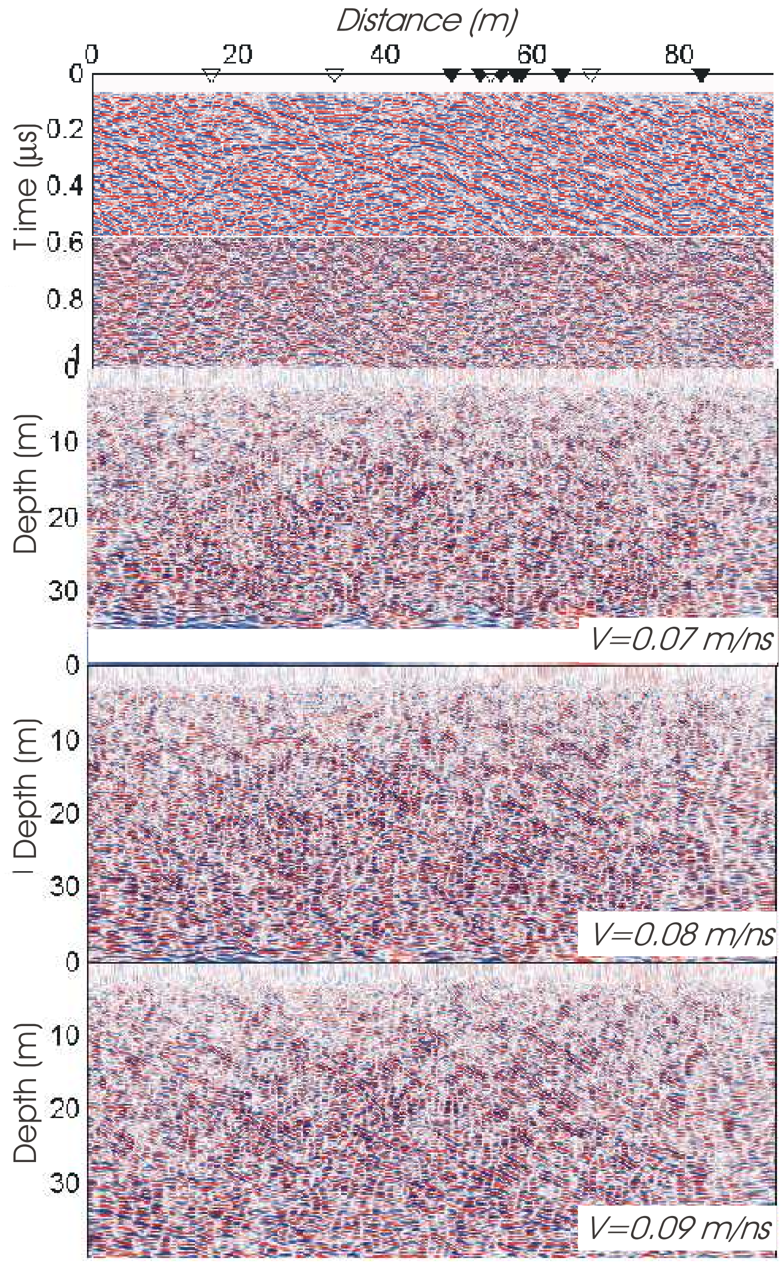


Figure 1Top panel: the processed GPR data acquired at Turtle Mountain. Filled triangles indicate locations along the profile where fractures were visible at the surface, open triangles point to suspected fractures. The second panel shows the data after Kirchhoff migration using $v_{mig}$=0.07 m/ns; $v_{mig}$=0.08 m/ns for the third panel and for the data in the bottom panel, $v_{mig}$=0.09 m/ns has been assumed.

reasonable. This approach mimics that employed when migration trials are used to refine velocity structure in reflection seismology. In our migration trials, we used velocities in the range between 0.06 m/ns and 0.16 m/ns and find that the results using velocities between 0.07 m/ns and 0.09 m/ns give the best results. Three migration results using different velocities are shown in Figure 1.

The migrated data in three panels of Figure 1 show several linear coherent events. The data show basically two patterns with different dips. A dominant system of reflectors appears to dip approximately 54° to 59°. However, this is also approximately the dip of the layer bedding at this part of Turtle Mountain (C.W. Langenberg, personal communication). Therefore, these events are probably not related to fractures. On the other hand, these reflections are discontinuous and often intersected by reflectors that dip

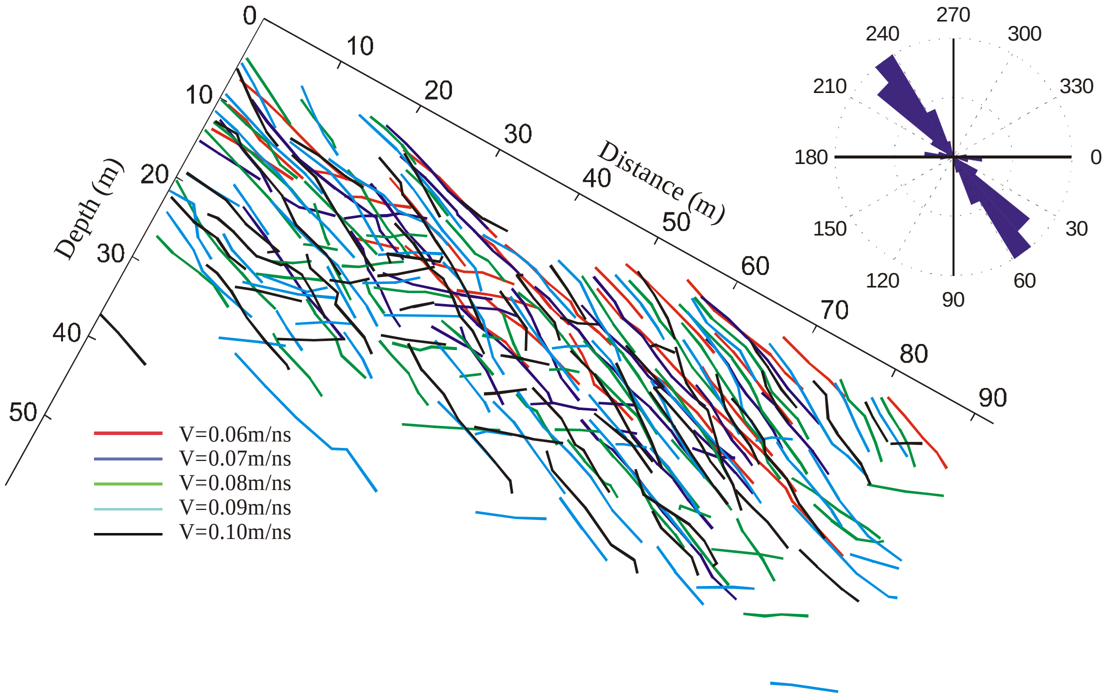


Figure 2 This figure combines the interpretation results of the GPR data migrated with five different velocities. The axis systemhas been rotated by 29° to accomodate for the mountain's slope at the measurement site. The histogram plot shows the combined distribution of fractures in all five migrated data sets.

approximately 179°, indicating that the bedding planes are possibly fractured. As a last step in the analysis procedure we attempt to determine the maximum depth and dip of these events. Unfortunately, the images of these two important parameters in constructing geomechanical models depend on the migration velocity (see, for example, the three panels in Figure 1, which have been migrated with different velocities). This non-uniqueness adds a significant uncertainty to the interpretation results. To address this uncertainty, we first determine these parameters for coherent linear events in each data set migrated with different velocities separately. In a second step, we combine all the inferred dips and analyse them statistically. It is generally difficult to follow a reflector in the migrated data, as the rock mass seems to be highly fractured. Many reflectors are discontinuous and often intersected by other reflections. Often, the position of a point on a reflection must be assumed. Therefore, a significant uncertainty in the inferred events from the migrated data must be taken into account. The interpretation results are summarised in Figure 2, in which the axis system has been rotated by 29° to accommodate for the mountain's slope, as measured by differential GPS surveying. The dominant pattern with dips of approximately 58° measured from the horizontal becomes readily apparent. In particular, numerous events with nearly horizontal dips may be seen at depths from 10 to 30 m at profile length positions between 20 and 40 m. The rosette in Figure 2 displays the relative number of dips for all reflectors. The length of each segment represents the relative number of dipping reflectors per 10° interval. This diagram also shows that probably the layer bedding dominates the reflections in the GPR survey at the West slope but that there is also a quite significant pattern with nearly horizontal dip.

## Results and Discussion

The experimental results of the GPR data acquired at Turtle Mountain are promising for mapping fractures at the mountain's summit. A significant depth penetration normal to the surface was achieved, especially with lower frequency antennas, allowing mapping out the fracture system to a depth of approximately 40 meters. Many fractures were readily apparent in the raw data, and more features become clearly visible after basic processing, mainly consisting of amplitude recovery and frequency filtering (Figure 1, top panel). However, due to the highly fractured nature of the rock material these images contain many details besides the main reflectors.

The migrated GPR data are the important interface to further use of the data. For example, fracture shapes determined from such GPR images may be used in geomechanical modelling. As such, the migration must be performed carefully with a proper choice of the input parameters, most importantly is the migration velocity. For our work it was not possible to provide a measured value; instead, we used several migration velocities. From the different migrated data we chose those for further analysis that appeared to be visually reasonable. Of course, more credibility in the migrated data is achieved when a proper, experimentally determined value is used.

After migrating the data acquired at the West Slope, a pattern of two consistent events was detected which we interpret as a network of two fracture systems. A system with an average fracture dip of 54±8° dominates in number of fractures and fracture length. The second fracture system, less in number of fractures, is nearly horizontal and oriented approximately 120° to the main fractures. In the migrated sections it seems that the events are not continuous but often terminate at another fracture. Sometimes, a reflector continues deeper but with an offset to its original locus. Even if the major reflections are caused by bedding planes, such information are important, since sliding along bedding planes occurs at Turtle Mountain (C. W. Langenberg, personal communication); the failure planes of the 1903 disaster have been presumed to lie along the bedding planes of the same rock but dipping to the east on the other side of the anticline forming parts of Turtle Mountian.

From our observation it appears that migration velocities lower than those typical for limestone result in more reasonable GPR images. For such fractured material the presence of water could reduce the effective velocity substantially due to the high dielectric constant of water, as simple effective medium theories (Voigt or Reuss averages, e.g., *Mavko et al.*, 1998) suggest. Indeed, from measurements in deep cracks it seems to be possible that water is present but not saturating the cracks (N. Iverson, personal communication). On the other hand, for dry cracks and fractures one would expect higher velocities.

Finally, we note that we have attempted to increase the accuracy of the fracture interpretation through the means of wavefield decomposition techniques. This is still work in progress, and some initial results are described in *Theune et al.* (2005).


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#### References


Allan, J.A., Report on stability of Turtle Mountain, Alberta, and survey of fissures between North Peak and South Peak, Dept. of Public Works, Edmonton, 1933.

Davis, J.L., and A.P. Annan, Ground-penetrating radar for high-resolution mapping of soil and rock stratigraphy, *Geophysical Prospecting*, Vol.*37*, 531-551, 1989.

Grasmueck, M., 3-D ground-penetrating radar applied to fracture imaging in gneiss, *Geophysics*, Vol.*61*, 1050-1064, 1996.

Mavko, G., T. Mukerji, and J. Dvorkin, *The rock physics handbook*, 1998.

Read, R.S., K.W. Savigny, F. Oboni, D.M. Cruden, and C.W. Langenberg, Geotechnical hazard assessment of the south flank of Frank Slide, Hillcrest, Alberta, in *CSEG annual convention*, Calgary, 2000.

Theune, U., M.D. Sacchi, and D.R. Schmitt, Generalized Deconvolution for GPR image enhancement, in *CSEG annual convention*, CSEG, Calgary, 2005.

Willenberg, H., K.F. Evans, E. Eberhardt, S. Loew, T. Spillmann, and H.R. Maurer, Geological, geophysical and geotechnical investigations into the internal structure and kinematics of an unstable, complex sliding mass in crystalline rock, in *International Symposium on Landslides*, pp. 489-494, Rio de Janeiro, 2004.