Monitoring Turtle Mountain using ground-based synthetic aperture radar (GB-InSAR)

John F. Dehls
Alberta Geological Survey, Edmonton, Alberta, Canada
Davide Giudici, Francesco Mariotti
Aresys SRL, Milano, Italy
Paolo Farina
IDS Ingegneria dei Sistemi SpA, Pisa, Italy
Derek Martin
Dept. Civil & Environmental Engineering, University of Alberta, Edmonton, Alberta, Canada
Corey Froese
Alberta Geological Survey, Edmonton, Alberta, Canada

ABSTRACT
As early as the 1930s, a portion of Turtle Mountain known as South Peak was identified as a hazard, threatening the town of Frank, Alberta, with 5 million cubic metres of rock. Since 2005, the Alberta Geological Survey has operated a program dedicated to the long-term monitoring of the mountain.

In 2009, a ground-based synthetic aperture radar (GB-InSAR) system was installed to map displacements on the slope. The GB-InSAR system is an important supplement to existing monitoring systems on Turtle Mountain. Atmospheric effects have been successfully modelled and removed from the interferograms, allowing displacements on the order of 1 mm/year to be measured. The system does not provide useful information when the slope is covered with snow; therefore, it cannot be used as a year-round monitoring system.

RÉSUMÉ
Dès le début des années 1930, la pointe sud « South Peak » de la Montagne Turtle fut reconnue comme un danger naturel, menaçant la ville de Frank, Alberta, avec 5 millions de mètre cube de roche. Depuis 2005, la Commission Géologique de l'Alberta a démarré un programme dédié à la surveillance de la montagne à long terme.

En 2009, un système comprenant un radar terrestre à ouverture synthétique (GB-InSAR) a été installé pour cartographier les mouvements sur la pente. Le GB-InSAR est un supplément important aux systèmes de surveillance déjà en place sur la Montagne Turtle. Les effets atmosphériques ont été modélisés avec succès et ont été soustraits des interférogrammes, ainsi permettant de mesurer des déplacements de l'ordre de 1 mm/an. Le système de surveillance ne peut toutefois être utilisé à longueur d'année puisqu'il ne fournit pas d'information utile lorsque la pente est recouverte de neige.

1 INTRODUCTION

1.1 Frank Slide

In 1903, the east face of Turtle Mountain collapsed, sending an estimated 30 million cubic metres of rock into the valley below, burying a portion of the town of Frank, Alberta, (Figure 1) and killing more than 70 people. As early as the 1930s, a portion of the mountain known as South Peak was identified as a hazard (Allan, 1931), threatening the town with a further 5 million cubic metres of rock. Limited monitoring was carried out for the next 70 years (Allan, 1933; Anderson and Stoliker, 1983; Cruden, 1986; Fraser, 1983; Fraser and Greunig, 1985; Kostak and Cruden, 1990). Since 2005, the Alberta Geological Survey (AGS) has operated a program dedicated to the long-term monitoring of the mountain.

1.2 Instrumentation

More than 40 sensors are installed on the mountain, including crack meters, tilt meters, wire extensometers, and permanent GPS antennas (Moreno and Froese, 2006, 2008a, 2008b, 2009). In addition, a network of reflectors is measured every hour using a computer-controlled, laser-ranging theodolite (Moreno and Froese, 2009). Each year, numerous sensors are lost due to lightning and other factors. In the case of future rapid deformation of the mountainside, a number of these sensor systems will exceed their working range and cease to provide useful information. For this reason, we continue to investigate new monitoring techniques that are robust under all conditions.

Figure 1. Turtle Mountain is in the Crowsnest Pass in southwestern Alberta. It was the site of the 1903 Frank Slide.

1.3 Ground-based InSAR

Ground-based interferometric synthetic aperture radar (GB-InSAR) is a technique that uses radar waves to map ground movement over an area of interest. The technique is fundamentally identical to satellite-base InSAR, but the images are acquired by a radar moving on a rail within a couple kilometres of the area of interest (Antonello et al., 2004; Bozzano et al., 2008). Images can be acquired as often as every five minutes, day and night and regardless of weather. This allows for continuous monitoring of movements ranging from millimetres per year to metres per hour in velocity.

In 2009, the Department of Civil & Environmental Engineering at the University of Alberta purchased an IBIS-L GB-InSAR (www.idscompany.it). The radar works in the Ku band (17.1-17.3 GHz) and has a working range up to four kilometres. In mid-September 2009, the system was installed at Turtle Mountain (Figure 2). The radar is controlled locally by a laptop computer, which is connected to the Internet. Images are stored locally. The laptop can be remotely accessed from the AGS office in Edmonton. Images are copied to an AGS server several times each day.

Data were collected from mid-September to late-November 2009. The system was then put into storage for the winter and reinstalled in early April 2010. In this paper the preliminary monitoring results from the IBIS-L system are reviewed and compared to existing traditional monitoring for Turtle Mountain. We plan to continue monitoring throughout 2010.

Figure 2. The IBIS-L GB-InSAR system is installed on a rooftop, facing unstable slopes on Turtle Mountain. The farthest point on the mountain crest is approximately 3200 metres away.

2 DATA PROCESSING

The data are processed using the Ground Radar Analysis by Persistent Scatters (GRAPeS) software package (www.areysys.it). The first step is to convert the raw acquisitions into focused (or single look complex) images that are defined in range (distance) and in aperture angle domain. Signal strength and phase stability statistics are then calculated and used to identify persistent scatterers; pixels that can be used to derive motion estimates. The final step is to determine the actual movement of each pixel over time. This involves the separation of real deformation from atmospheric artifacts.

Changes in atmospheric pressure, temperature and humidity all produce changes in the refractive index of the atmosphere. These changes affect the travel time of the radar signal, thus producing artifacts in the interferograms. These artifacts, if not corrected for, result in apparent ground movement of up to several centimetres. For a large stack of images acquired quite frequently, we can assume that the phase change due to deformation is rather smooth over time compared with changes due to the atmosphere. In the spatial domain, however, neighbouring pixels should have a very similar contribution from the atmosphere, whereas deformation is not necessarily so constrained. We can use these assumptions to model the atmospheric artifacts and produce deformation vs. time curves for each stable pixel, as well as a map showing average deformation over the whole time period.

3 RESULTS

3.1 2009 Campaign

Data were collected continuously from September 18^{th} to November 29^{th}. Images were acquired every 12 minutes, 24 hours per day. During the 2009 monitoring period, the first snow fall occurred on October 3rd. The mountain remained snow-covered until October 18th. The mountain remained snow-free for one week, after which it was at least partially snow-covered for the rest of the monitoring period. We did not expect any significant deformation during this time. The goal was to determine the quality of the data under various weather conditions.

Figure 3 shows the results from September 19th to October 19th. The upper figure shows a map of the total displacement. The total displacement during the first month appears to be ±20 mm, which is unrealistic. The lower figure shows displacement curves for selected pixels. It is clear that after the first snow fall, all apparent displacements are due to changes in the refractive index. To better understand the data, we processed each snow-free or snow-covered period separately.

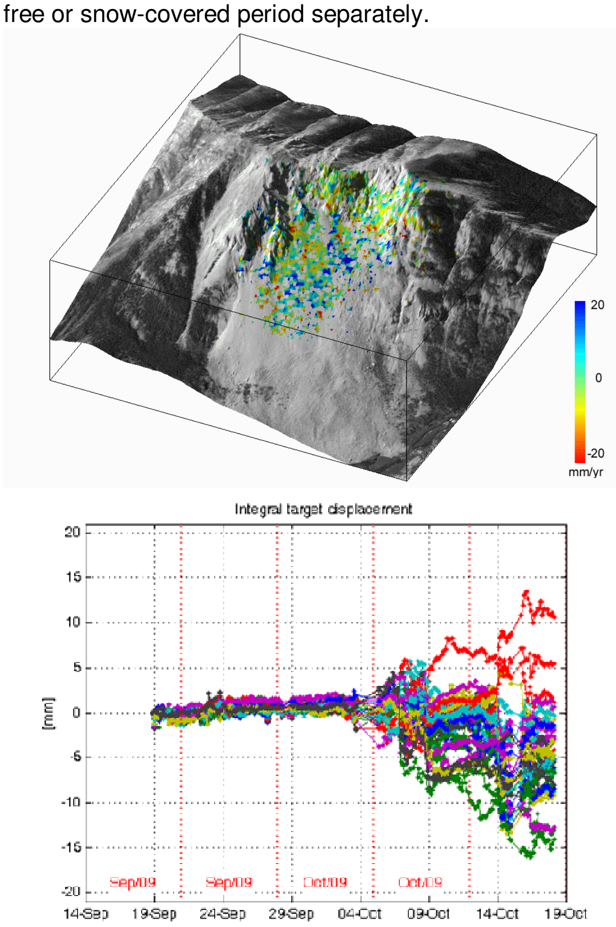


Figure 3. Displacement between Sept. 19th and Oct. 19th. Positive displacements are away from the sensor. Apparent large movements beginning Oct. 3rd are due to snow fall.

Between September 19th and October 3rd there was no snow on the mountain. The displacement map (Figure 4, top) shows a maximum displacement of about 2 mm. This is also shown in the frequency histogram for the total displacement (Figure 4, middle). The very best pixels have a noise level of approximately ±1 mm (Figure 4, bottom).

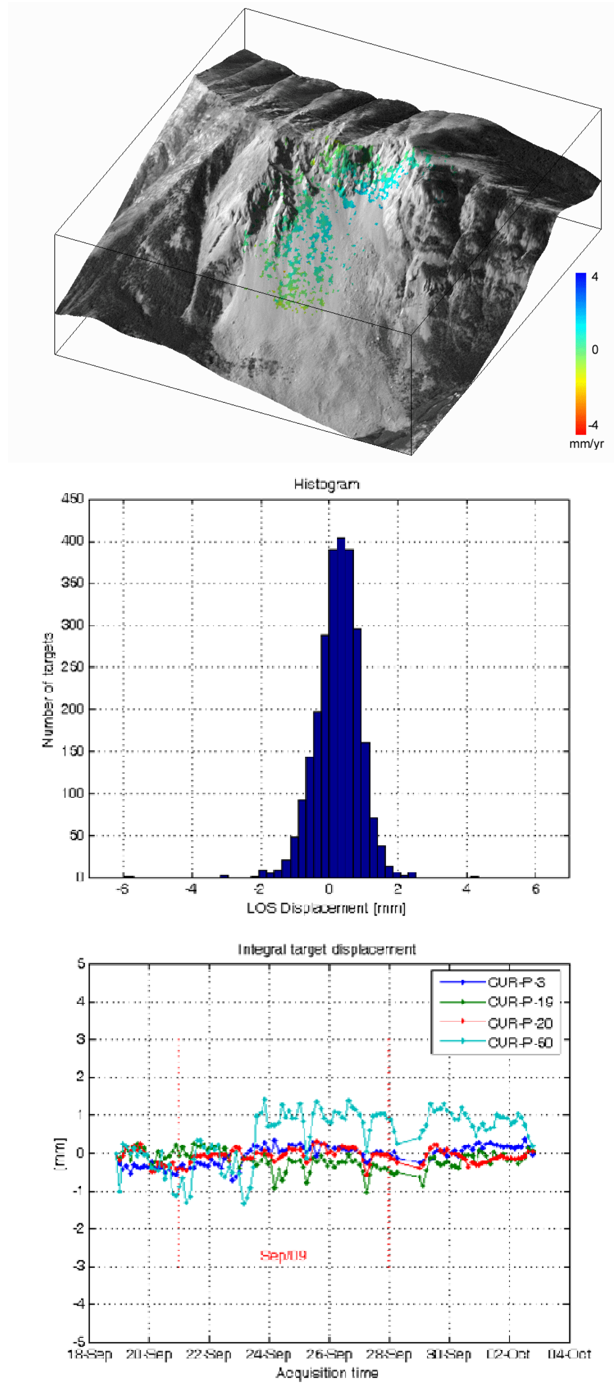


Figure 4. Displacement between Sept. 19th and Oct. 3rd. Positive displacements are away from the sensor. Top: map of displacements. Middle: frequency histogram of displacements. Bottom: displacement vs. time for selected pixels.

From October 3rd to October 18th, the slope was snow-covered. The snow causes a general loss of coherence, which manifests itself as a false displacement with a random pattern (Figure 5, top). The displacement curves show movements of ±10 mm during the 15-day period (Figure 5, bottom).

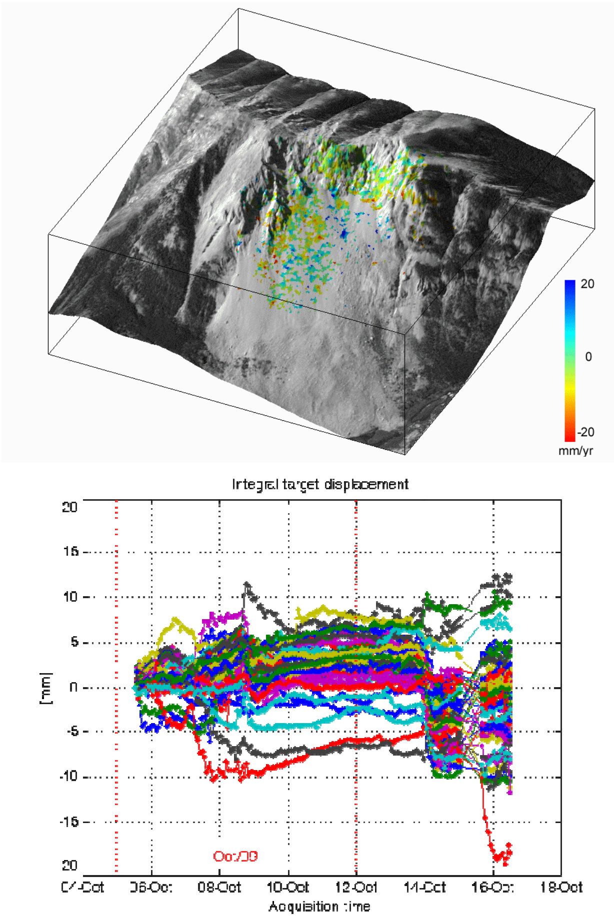


Figure 5. Displacement between Oct. 3rd and Oct. 18th. Positive displacements are away from the sensor. Top: map of displacements. Bottom: displacement vs. time for selected pixels.

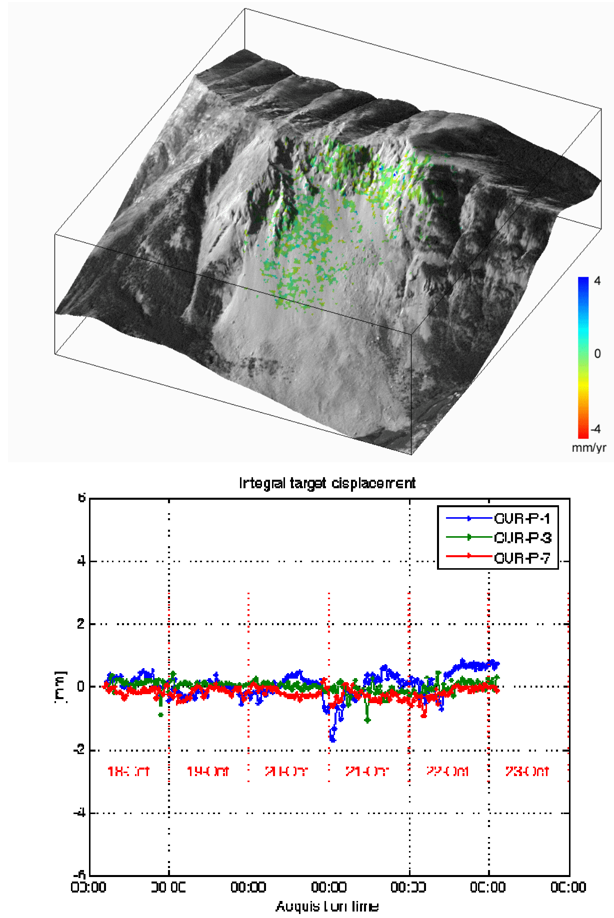


Figure 6. Displacement between Oct. 18th and Oct. 23rd. Positive displacements are away from the sensor. Top: map of displacements. Bottom: displacement vs. time for selected pixels.

By October 18th, the snow had melted and the slope remained snow-free until October 23rd. During this week there was no apparent deformation (Figure 6, top), and once again, the noise level was about ±1-2 mm (Figure 6, bottom. The slope remained snow covered until the system was removed in early December.

3.2 2010 Campaign

The IBIS-L system was reinstalled at Turtle Mountain on April 14th, 2010. Since most of the mounting hardware was left in place during removal in December, it was possible to reinstall the system in the identical position. In this way, it was possible to acquire images that could be compared with the previous images without any geometrical correction. Images were collected every 6 minutes, 24 hours per day. When the system was reinstalled, the mountain was still snow-covered.

By April 20th, almost all of the snow had melted, and the mountain remained mostly snow free until April 28th.

To determine the total deformation between the fall of 2009 and the spring of 2010, the average phase was calculated for 50 images from September and compared with the average phase of 50 images from April. Short-term atmospheric effects for each of these periods are removed during the averaging. The remaining long-term atmospheric change between the two sets of acquisitions was modelled as a second-order surface in both azimuth and range directions. All velocities are in mm/yr and reflect the line-of-sight component of the total movement. The result is shown in Figure 7. Negative values (in yellow and red) are moving toward the sensor.

The upper portion of the talus slope ('A' in Figure 7.) is moving up to 2.5 mm/yr along the line-of-sight. This is consistent with the fact that this is a zone of talus accumulation. Movement is triggered by rocks falling on the area and enhanced by oversteepening. The lower portion of South Peak ('B' in Figure 7.) is also moving up to 2.0 mm/yr along the line-of-sight. This area of the slope is highly fractured and previous field mapping has identified signs of active movement along pre-existing joints and bedding planes.

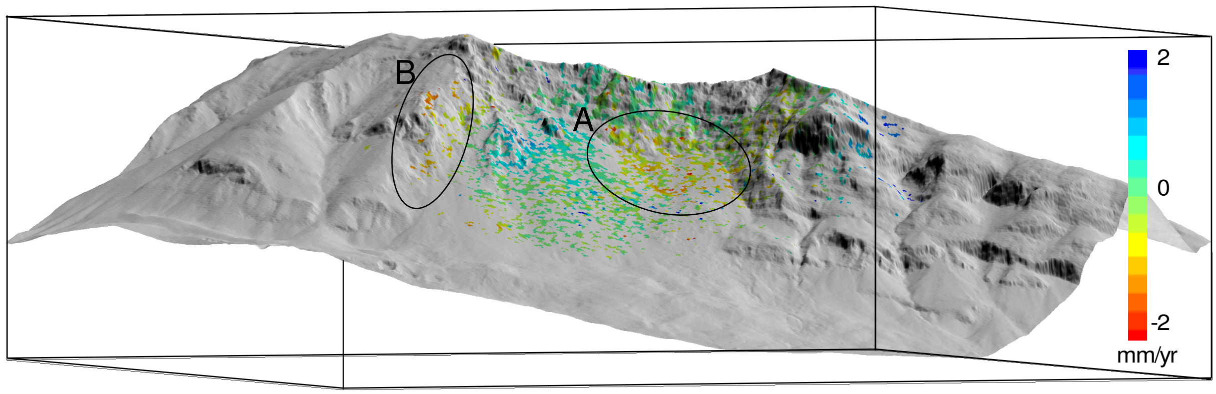
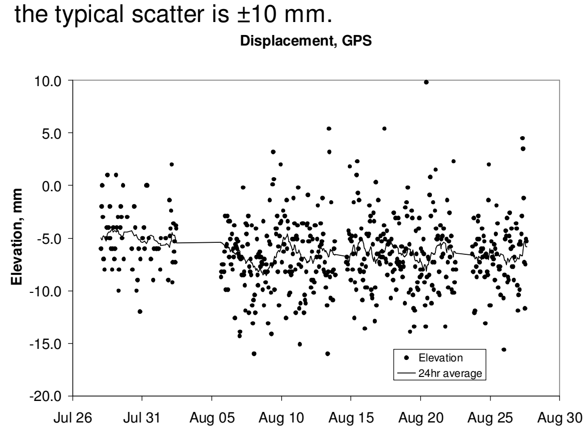


Figure 7. Digital elevation model of Turtle Mountain, as viewed from the instrument location. The colours represent the average velocity along line-of-sight from Sept. 2009 to Apr. 2010. Negative velocities represent movement toward the sensor. Area ‘A’, in the upper portion of the talus slope, shows increased movement due to oversteepening and continued accumulation from above. Movement in area ‘B’, on the lower portion of South Peak, is consistent with field mapping in this heavily fractured area.

4 DISCUSSION

Of the current sensor systems on Turtle Mountain, the most relevant for comparison are the permanent differential global positioning system (dGPS) stations and the electronic distance measurement (EDM) system. There are 11 permanent GPS stations on the south face and eastern slope of the mountain. These stations provide full 3-dimensional displacement information, although the vertical accuracy is less than the horizontal. A computer-controlled, laser-ranging theodolite, installed in the same location as the IBIS-L, measures the distance to an array of 20 prisms installed on the slope.

Figure 8 shows the displacement data for a typical one-month period, in north-south and vertical directions for one of the dGPS stations. The typical scatter in the horizontal displacements is ±5 mm, whereas the 24-hour average is better than ±1 mm. In the vertical direction, the typical scatter is ±10 mm.



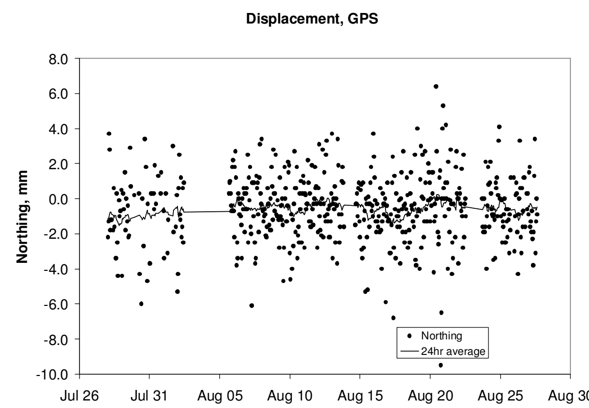


Figure 8. Typical displacement data from one of the dGPS stations on Turtle Mountain.

Figure 9 shows the displacement data for a typical one-month period for one of the prisms, mounted on the upper saddle area of Turtle Mountain. The laser distance measurement is also affected by atmospheric changes. The typical scatter is ±10 mm.

Both GPS and EDM systems are affected by atmospheric changes. Unlike the GB-InSAR system, there is little we can do to correct for the resulting errors. However, since both systems are measuring absolute distance or location, we can temporally filter the data to obtain smoother deformation curves. The main limitation of these systems, compared to the GB-InSAR, is the sparseness of the data coverage. The GB-InSAR system returns valid data from tens of thousands of locations. The dGPS stations and EDM prisms are installed in locations chosen according to our current understanding of the deformation, whereas the high spatial coverage of the GB-InSAR data allows the identification of deformation domains within the area of interest.

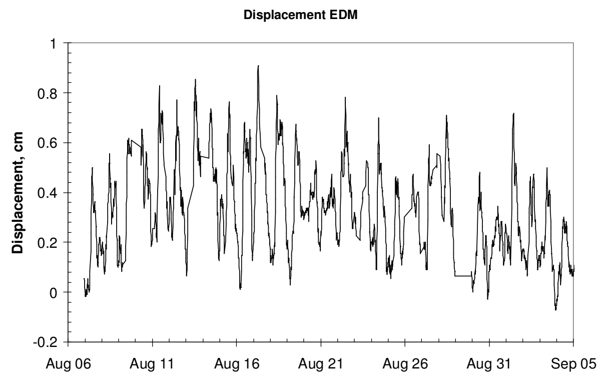


Figure 9. Typical displacement data from one prism being monitored by the EDM system.

5 CONCLUSIONS

The GB-InSAR system provides an important supplement to existing monitoring systems on Turtle Mountain. Atmospheric effects were successfully modelled and removed from the interferograms, allowing displacements on the order of 1 mm/year to be measured.

The system does not provide useful information when the slope is covered with snow; therefore, it cannot be used as a year-round monitoring system.

ACKNOWLEDGEMENTS

The authors thank Renato Macciotta, Jamie Warren, Paul Mathieson and Glen Bjorgan for their assistance in installing the IBIS-L system. The Municipality of Crowsnest Pass also provided technical assistance. The IBIS-L system was purchased with funds provided by the Natural Sciences and Engineering Research Council of Canada.

REFERENCES

Allan, J.A. 1931. *Report on the stability of Turtle Mountain, Crowsnest District, Alberta*. Alberta Department of Public Works. Alberta Provincial Archives. 14 p.

Allan, J.A., 1933. *Report on stability of Turtle Mountain, Alberta and survey of fissures between North Peak and South Peak*. Alberta Department of Public Works, Alberta Provincial Archives. 28 p.

Anderson, E.G., and Stoliker, P.C. 1983. *Remote EDM monitoring of fractures on Turtle Mountain, Phase 1*. Research Management Division, Alberta Environment, 24 p.

Antonello, G., Casagli, N., Farina, P., Leva, D., Nico, G., Sieber, A.J. and Tarchi, D. 2004. Ground-based SAR interferometry for monitoring mass movements. *Landslides*, 1(1): 21-28.

Bozzano, F., Mazzanti, P. and Prestininzi, A. 2008. A radar platform for continuous monitoring of a landslide interacting with an under-construction infrastructure, *Italian Journal of Engineering Geology and Environment*, 2: 35-50.

Cruden, D.M. 1986. *Monitoring the South Peak of Turtle Mountain, 1980 to 1985*. Research Management Division and Earth Sciences Division RMD Report 86/37. Alberta Environment, Edmonton.

Fraser, C.S. 1983. Photogrammetric monitoring of Turtle Mountain: A feasibility study. *Photogrammmetric Engineering and Remote Sensing*, 49: 1551-1559.

Fraser, C.S. and Greunig, L. 1985. The analysis of photogrammetric deformation measurements on Turtle Mountain. *Photogrammetric Engineering and Remote Sensing*, 51: 207-216.

Kostak, B. and Cruden, D.M. 1990. The Moire crack gauges on the crown of the Frank Slide. *Canadian Geotechnical Journal*, 27:835-840.

Moreno, F. and Froese, C.R. 2006. *Turtle Mountain Field Laboratory Monitoring and Research Summary Report*. Energy and Utilities Board, EUB/AGS Earth Sciences Report 2006-07.

Moreno, F. and Froese, C.R. 2008a. *Turtle Mountain Field Laboratory: 2006 Data and activity summary*. Energy Resources Conservation Board, ERCB/AGS Open File Report 2008-01.

Moreno, F. and Froese, C.R. 2008b. Turtle *Mountain Field Laboratory: 2007 Data and activity summary*. Energy Resources Conservation Board, ERCB/AGS Open File Report 2008-07.

Moreno, F. and Froese, C.R. 2009. *Turtle Mountain Field Laboratory: 2008 Data and activity summary*. Energy Resources Conservation Board, ERCB/AGS Open File Report 2009-15.