STRUCTURAL ANALYSIS OF TURTLE MOUNTAIN (ALBERTA) USING DIGITAL ELEVATION MODEL (DEM)

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ABSTRACT
In 1903, the eastern slope of Turtle Mountain (Alberta) was affected by Frank slide (30 M m^3). Assuming that the main discontinuity sets, including bedding, are shaping part of the slope morphology, the structural features of Turtle Mountain are investigated using Digital Elevation Model (DEM). The results are in agreement with discontinuity sets identified by field observations. The DEM analysis confirms and refines the previous geology model of Frank slide by Cruden and Krahn (1973). The rockslide initiated along the bedding and a fault at the base of the slope and propagated up slope by a regressive process following a surface composed of preexisting discontinuities. The method is demonstrated efficiently and is suggested as a preliminary analysis prior to field investigations.

RÉSUMÉ
En 1903 le versant est de la Turtle Mountain (Alberta) fut le siège du glissement de Frank. Partant de l'hypothèse que les principales familles de discontinuités, y compris la stratification, façonnent en partie la morphologie des versants, la structure de la Turtle Mountain est étudiée à l'aide d'un modèle numérique d'altitude (MNA). Les résultas obtenus sont en accord avec les données de terrain. L'analyse du MNA confirme et affine le modèle géologique précédent établi par Cruden et Krahn (1973). Le glissement rocheux s'est développé d'abord au pied du versant le long des bancs et d'une faille, puis s'est propagé vers le haut dans un processus régressif empruntant une surface composée des discontinuités préexistantes. L'efficacité de la méthode est soulignée et elle est proposée comme une analyse préliminaire aux investigations de terrain.

1. INTRODUCTION

Large rockslides are often the result of unfavourable pre-existing discontinuities (Cruden 1976; Sartori et al. 2003). These structures can shape the morphology of the relief. As a consequence, analysing the relief appears to be an efficient tool to detect structures and the volumes that are prone to destabilisation. The back analysis of ancient rockslides is an appropriate way to test methods.

This paper proposes to use Digital Elevation Models (DEM) and the software COLTOP-3D to create a coloured shaded relief map revealing the topography orientation. It makes it possible to identify structural features (main joint sets, fault scarps or landslide scarps) that are involved in rock instabilities (Jaboyedoff et al. 2004a). DEM can also be used to define rock volumes that have moved in a slope by analysing the slope geomorphology. This is achieved by using the concept of Sloping Local Base Level (SLBL), which represents a surface above which rock masses are potentially unstable (Jaboyedoff et al. 2004b).

Taking the opportunity of the recent acquisition of a new DEM by the Geological Survey of Canada, these two new methods were applied to Turtle Mountain (Alberta). The eastern slope of Turtle Mountain fell down, on April 29th, 1903, in a 30 M m^3 rock avalanche killing 70 people of the mining town of Frank (southern Alberta). Frank Slide is Canada's most disastrous landslide.

Several publications are dedicated to Frank slide (Cruden and Krahn 1973, 1978; Cruden and Hungr 1986; Jones 1993; Benko and Stead 1998; Couture 1998). Frank slide is considered as a rock avalanche that slid mainly on the bedding (Cruden and Krahn 1973; Cruden 1976). As a consequence, this area is an interesting site to test the potentialities of methods that use DEM. The aim of this paper is to discuss the relevance of the methods, to show the features that can be extracted from a DEM and not to develop a new theory on the failure mechanism of Turtle Mountain. The results of this study confirm the structural analysis by Cruden and Krahn (1973).

2. FRANK SLIDE SETTINGS

Turtle Mountain cut a thrusted asymmetric anticline toward the east affecting a Palaeozoic series thrusting a Mesozoic series (Figure 1). The rockslide took place on the east slope of the anticline. Cruden and Krahn (1973) assumed that the slide occurred mainly along the bedding and a basal fault. They also reported two well-developed orthogonal joint sets that cut the rock mass. They are both perpendicular to the bedding. One is parallel to its dip direction and the other parallel to its strike.

Jones (1993) demonstrated the importance of the geometry induced by the thrust folding in the Foothills of Alberta. Such a structure can promote rockslides similar to Frank slide. The two perpendicular joint sets are also recognized as a typical structural feature of the thrust fold in the Foothills of the Canadian Rockies (Cooper 1992).

The crown of the scarp contains cracks parallel to the strike of the beds, which define rock masses that have moved down. Cruden and Krahn (1973) reported that between 1933 and 1972 no movements occurred along these cracks. The 1903 rockslide has left a very fractured head scarp at the summit of Turtle Mountain. The scarp suffered numerous small rockfalls since the main failure event. Movements at Turtle Mountain are now scrutinized through an important monitoring program. InSAR (Interferometric Synthetic Aperture Radar) method has demonstrated movement linked to block falls (Singhroy et al. 2003).

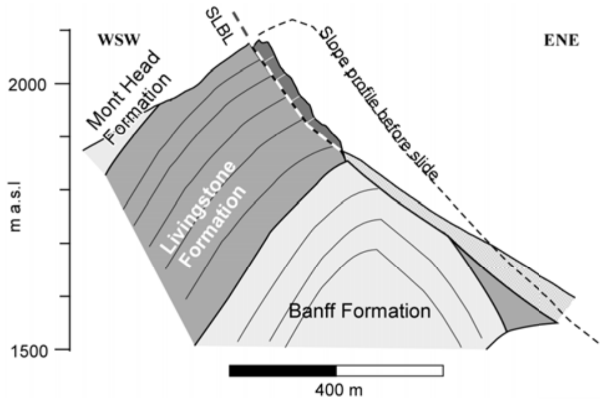

Figure 1. Synthetic cross-section through Turtle Mountain (Modified from figures 6 and 7 of Cruden and Krahn, 1973).

Friedman et al. (2003) have underlined the effect of the concordance of the sliding direction with the slope below and the occurrence of highly fractured rock on the run-out distance for the Frank rock avalanche.

3. DATA

The DEM used has been created by merging a 20 cm resolution colour orthophoto and a 2 m digital elevation model both acquired in fall 2002. . The mesh size of the grid is 0.5 m. The discontinuities measurements were acquired in the field through various field campaigns and from published data (e.g., Cruden and Krahn 1973; Couture 1998).

4. METHODS

4.1 Topography analysis

The program COLTOP-3D computes the orientation of each cell of the DEM (Jaboyedoff and Couture 2003). The result is a coloured shaded relief map combining both terrain slope angle and slope aspect (direction of slope) in a unique document. The slope orientation is coded following the Hue-Saturation-Intensity (HSI) system. Each colour is defined by unique dip direction and dip of the slope (Figure 2). The continuous features such as fault trace are highlighted by such representation. The advantage compared to single shaded relief is that it is not necessary to find the correct sunlight direction. All the directions have their own code.

By clicking on the coloured map it is possible to display the direction of dip and the dip of the topography. Simultaneously a stereonet of points is displayed and the data can be exported. Selecting an area of the DEM a stereonet of the entire zone can be performed. A grid of selected orientation using code can be exported in file format such as Surfer grid or ArcView. In addition, traces of faults can be drawn on the relief.

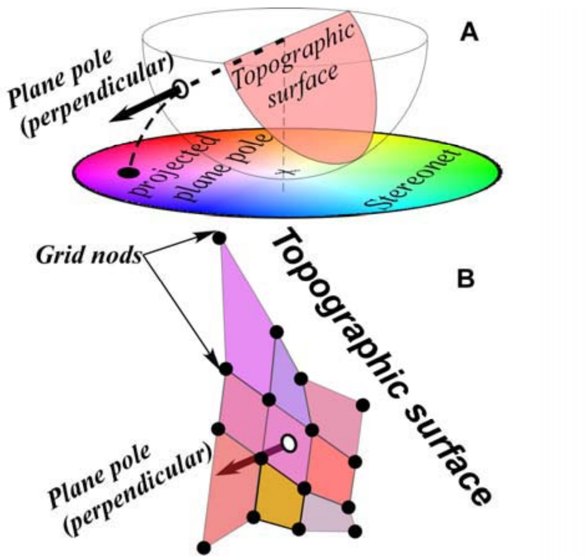

Figure 2. (A) Principle of the colour coding of the pole of a plane is represented in a lower Schmidt-Lambert stereonet. (B) Illustration of the colours of a DEM grid.

4.2 Unstable volume characterisation

The concept of SLBL is a generalisation of the base level defined in geomorphology (Mills 2003), applied to landslides. It permits to define a surface above which rocks are assumed erodible.

The SLBL can be determined either manually, or by using an iterative routine. Considering a spur along an infinite slope in a 2D-approach, the SLBL corresponds to a line joining the top and the bottom of the spur. Assuming equidistant z_i altitude raw data, the SLBL is found by an iterative procedure (Figure 3). All points located above the mean of their two neighbours are replaced by their mean value or by there mean value $\pm$ a tolerance Δ (Jaboyedoff et al., 2004b). In 3D, the procedure is similar. The test is simply made by using the highest and the lowest value among the four direct neighbours. This method can be applied either to rock slopes or to soil slopes.

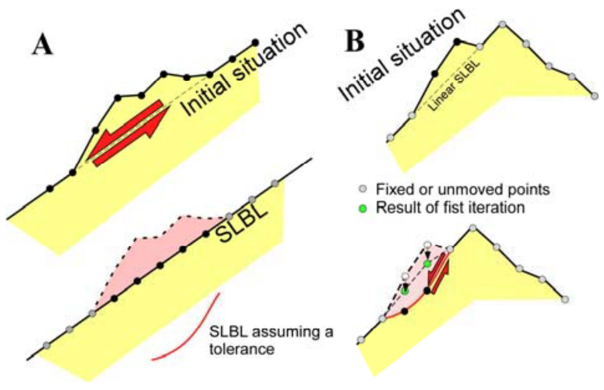

Figure 3. (A) Illustration of the linear SLBL for a spur. (B) Curved SLBL assuming a tolerance leading to rotational-like surface.

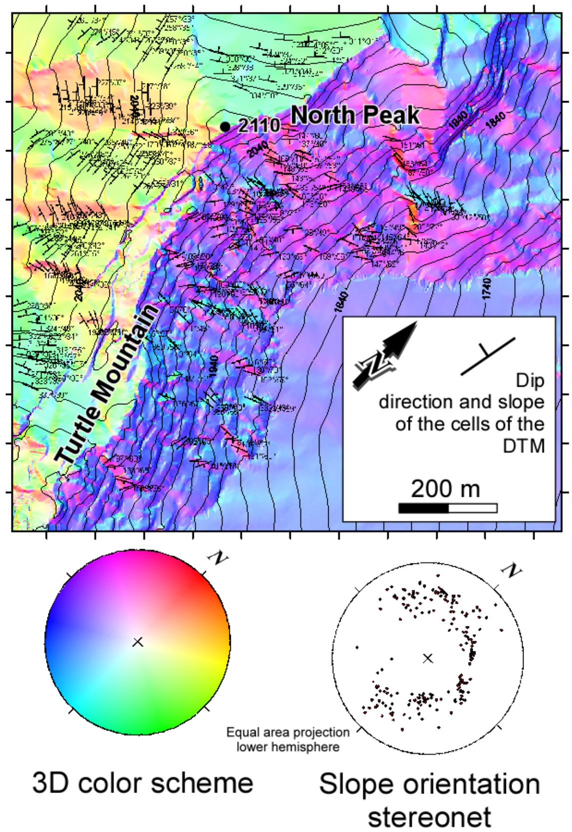

Figure 4. Interpretation of the relief of Turtle Mountain using COLTOP-3D using the pole orientation of surface relief.

For computation, some points of the SLBL must be fixed; otherwise the result is a flat topography. The SLBL can be computed by defining the limits within which the SLBL must be estimated, i.e. an unstable rock mass or a landslide. The limits are defined using geomorphic features. The base of the zone is either the bottom of the valley or a slope angle break. The top is estimated using the cracks or any trace of fault. The lateral limits are defined by the extent of the top geomorphic feature.

5. RESULTS

5.1 Structure

Based on the analysis of the colorized relief, six main discontinuity sets are identified using 0.5-meter DEM without any knowledge of the field data (Figure 5; Table 1). The direction of each set was mapped using ranges of angles from 10° to 25° around the mean directions depending on the sets (Figures 6 and 7). This representation allows the visualization of geomorphic features. These six joint set orientations represent around 45% of the surface of Turtle Mountain. On the equal area stereonet, the six joint sets represent 29% of the surface which is steeper than 30° and 25% for all orientations. This indicates that the relief is partly controlled by discontinuities.

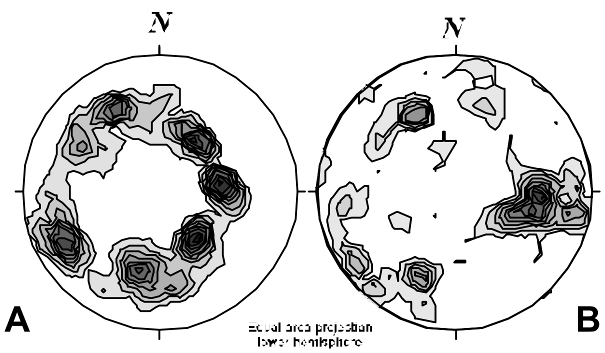

Figure 5. Pole density stereonet (A) Density stereonet of the COLTOP-3D interpretation for the point of figure 4. (B) Idem for the field data.

Table 1. Dip direction and dip of the two field data analyses from COLTOP 3D. The range of values used to interpret data is indicated.

Name	Interpretation1	Interpretation2	COLTOP 3D
J1	003°/68°	023°/60°	013°/50° (±20°)
J2	076°/69°	076°/70°	060°/70° (±20°)
J3	134°/69°	151°/57°	136°/54° (±25°)
J4		201°/56°	210°/39° (±10°)
J5	289°/47°		270°/40° (±10°)
J6			323°/36° (±10°)

Three sets are shaping the west side of Turtle Mountain and three are involved in the failure surface of the 1903 rockslide. The morphology of both sides of the scar is clearly affected by two joint sets J1 and J3. They define a wedge in the direction 072°/32°. The central part is mainly shaped by J2 forming the steeper zones of the scar. These three sets are clearly identified by the density stereo plot as well as the two field data interpretations (Figure 5). The field observations lead to slightly steeper discontinuity orientations. The remaining of the scar area has an intermediate position between these three sets.

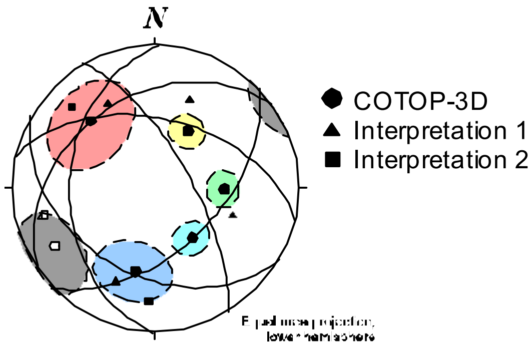

Figure 6. Interpretation of the pole plane data extracted from DEM. The results of the average field data interpretation are also plotted.

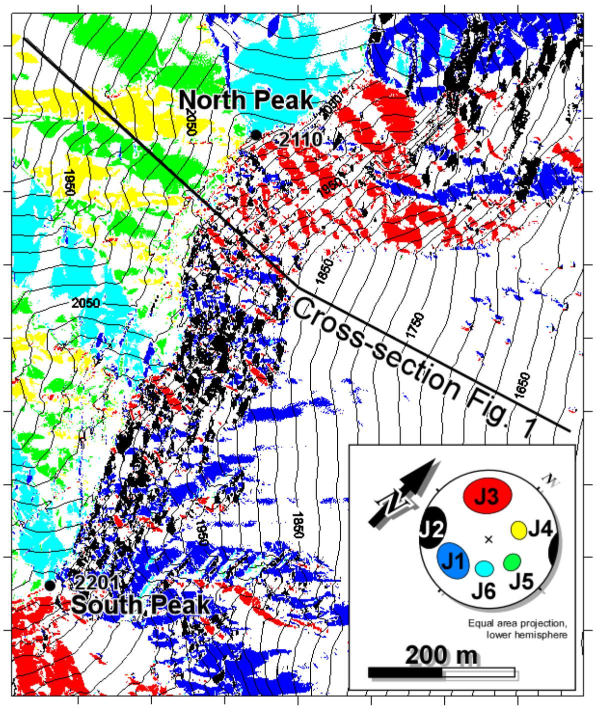

Figure 7. Representation of the selected orientation J1-J6. The cross-section of figure 1 is indicated.

J1 is a well-defined set developing clear geomorphic prints. In the northern part of the scar, one J1 discontinuity clearly cuts the base of the cliff. Some J1 discontinuities are also developed outside of the scar (Figure 8). J3 seems to be less planar; as a consequence the chosen angle range around its mean value is ±25°. Nevertheless, looking at pictures of the scar those surfaces are clearly cutting Turtle Mountain. On the northern part of the map (Figure 7) the black areas underlining J2 give the shape of a succession of sub-vertical faults.

The western slope of Turtle Mountain shows clearly 3 orientations that are very constant, J4, J5 and J6. More than 50% of the surface belongs to these orientations with ranges of ±10° around the mean values. These consistencies indicate that J4, J5 and J6 are probably regional faults and that one of them is probably dependent on a slope regressive process controlled by the others. In the northern part of the map, J6 orientation represents the bedding orientation but not in other parts of the map.

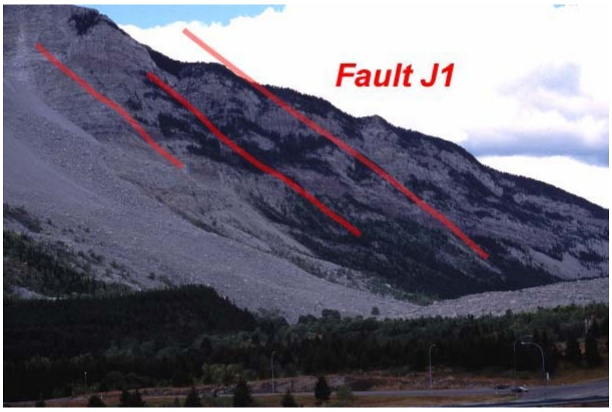

Figure 8. Illustration of the J1 effect on the geomorphology of the northern part of the eastern slope of Turtle Mountain.

5.2 Cracks direction

Open cracks (Cruden and Krahn, 1973) can be observed over a large range of the western flank of Turtle Mountain (Figures 7 and 9). The cross-section of figure 1, based on the DEM shows that movements along the cracks down to the valley can reach approximately 10 m. The mean orientations of the cracks surfaces extracted from their scarps indicated by the DEM is approximately 085°/55° with an angle range of ±25° around this value.

The comparison of the crack orientations with scar orientations indicates that the surface of failure of Frank slide has essentially the same mean orientation as the cracks (Figure 9). This orientation includes partly J2 and J3. Thus, the breakage of rock bridges along J1, J2, and J3 generates a composite surface of failure. This crack orientation is similar to the bedding orientation at the bottom of the slope before the rockslide.

5.3 Volume definition

As an example of volume estimation using the SLBL, the cracks close to the scar were used as upper limits of the potential unstable volume. The bottom of the cliff is assumed as the base. The lateral extension is chosen in accordance with discontinuity sets (Figure 9).

The SLBL was calculated using a 2.5 m grid DEM, with a tolerance of -0.01 m. The rock mass volume defined is of 3.2 M m^3. The result gives a curved surface close to the rock slope angle below the scar at its bottom (Figure 1), revealing retrogressive erosion processes. This represents the first rock slice of several slices that have probably moved just after the Frank slide as suggested by Cruden and Krahn (1973).

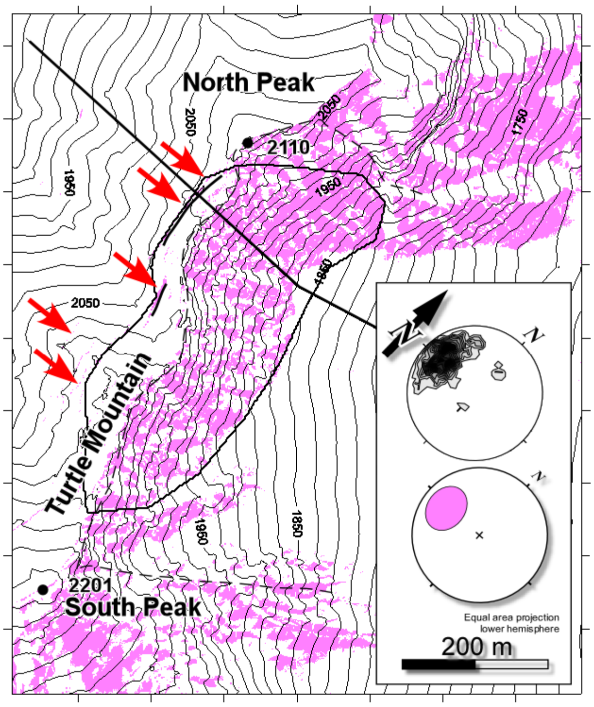

Figure 9. Representation of the directions deduced from the cracks located on the western slope of Turtle Mountain. The average direction is slightly shifted in order to display the cracks better (085°/55° ±25°). The arrows indicate the cracks that affect a large volume of the western flank. The dashed line corresponds to the scar limit. The polygon indicates the limit used for the SLBL computation

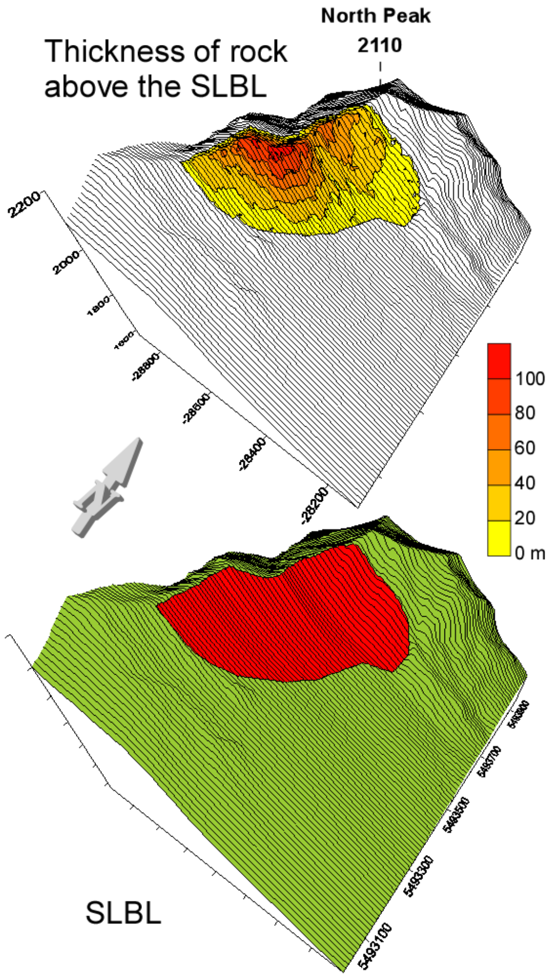

Figure 10. Top: the present topography with the thickness of rock above the SLBL. Bottom: the topography (red) including the SLBL.

6. DISCUSSION

The efficiency of the use of DEM for structure characterisations and rockslide analysis is demonstrated by the agreement existing between field data and DEM data. The discrepancies are within the range of variation of data (Figure 6). Nevertheless the discontinuity orientations obtained using COLTOP-3D are less steep than the observed ones. Three factors can induce differences between field data and DEM data:

1. The slope angles deduced from a DEM are usually smaller than the relief because of the mesh size of the DEM. In the present case the 0.5 m does not represent the precision of the data acquisition, the artefact in the slope changes demonstrate this problem.
2. The erosion tends to affect more highly the angular relief (high second derivative value) often resulting from discontinuities. As a consequence surfaces are smoothed compared to the true discontinuity or bedding.
3. DEM analysis takes into account the entire relief contrasting with the local observations made by the geologists, because of the steep topography.

In the present case, factors 1 and 2 seem relevant. However, factor 3 has also an impact; the two sets perpendicular to the bedding (Cruden and Krahn 1973; Cooper 1992) are probably detectable only at a small scale, i.e. from field investigations, which are confirmed by a picture of the hinge zone (Figure 11). The present method can be improved by using high precision Laser-DEM which can obtain results even at small scales (Abellán et al., 2004).

The use of the SLBL to define potential unstable volumes allows the analysis of failure mechanisms. The results fit well with the presently observed scar.

The consistency and planarity of the structure lead us to believe that the six detected discontinuity sets are caused by regional tectonic features.

J1 and J6 are dipping to the North and NW. J1 is an outstanding feature of the eastern slope in the northern part of the North Peak. It appears to be an extension fault.

J6 and J5 can also be extension faults. J4 cannot be interpreted in such a way, but the picture of figure 10 in Cruden and Krahn (1978) shows that the Turtle Mountain anticline is cut by large regional structures that are certainly J1 and J4. The tectonic history of the Foothills (Price 1994) permitted a local N-S to NW-SE extensional regime in this area during Palaeogene time. The combination of the couple J1, J6 and J4 and J5 strongly influence the local geomorphology. Some strike-slip movements can be also considered.

J2 and J3 appear as regional features, but no argument can be given for their origin. J4 morphology indicates probably a sub-vertical extensional fault system and J3 through cuts Turtle Mountain clearly.

An interesting fact is that the bedding has apparently a strong influence on the slope failure even where it does not correspond to the failure surface. As proposed by Cruden and Krahn (1973) the bedding is probably the main structural feature of the Frank slide including the basal fault (which is not yet visible). In the upper part the bedding is crossed, but it follows approximately the same orientation as the bedding at the bottom of the slope. The development of a failure surface following the bedding at the base of the slope may indicate a regressive failure propagating upward in the slope following the bedding orientation of the base. Such an argument is also valid in the western flank because even if J6 corresponds to the bedding, some joints are also probably linked to the same regressive erosion.

The volume defined by the cracks using the SLBL underlines the retrogressive movements, which have occurred during Frank slide. All the western slopes of Turtle Mountain have moved at that time, but now no movement affects all those retrogressive surfaces.

The failure surface of the Frank scar appears as composite. Frank slide was initiated by the bottom eastern rock face of Turtle Mountain which moved down along the bedding and the faults. This buttress removed, the upper part may have moved down by sliding on J1 and J3 and by the toppling of the wedged J1-J3 using j2 as a rear limit, while breaking a rock bridge along the direction controlled by the bedding at the bottom. The fracturing linked to the hinge fold (Cruden and Krahn 1973; Copper 1992) contributed to the fragmentation of the rock mass (Couture 1998; Locat et al. 2003). The toppling direction close to the slope direction has certainly increased the mobility of the rock avalanche (Friedman et al. 2003).

7. CONCLUSION

Results show that analysis based on DEM allows identification of large-scale structures, volume estimation and surface of failure as well as regional tectonic features. The main structural features that contributed to rock slope instabilities can be proposed.

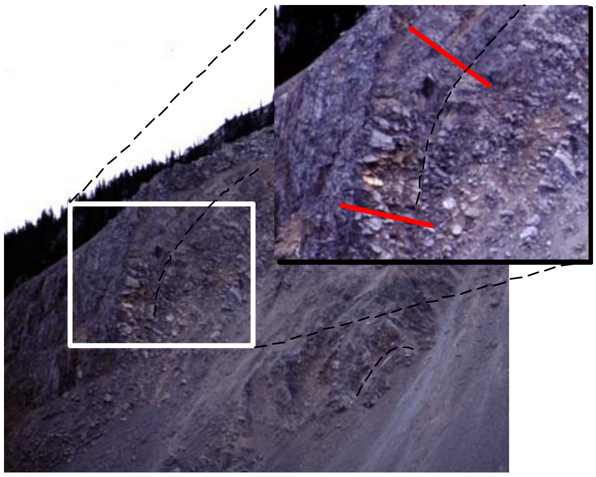

Figure 11. Hinge zone of the fold of Turtle Mountain displaying the fracturing in a fan (in red), that is not possible to detect from the DEM used. A local scan Laser can characterize such small scale fracturing.

The above analysis shows how the use of a DEM with a few pictures can help to obtain a first interpretation of instability, which is consistent with field data. In the present case, the results are pushed voluntarily to their limits, in order to show what can be done. The present approach asks more questions than it gives answers, but it appears as a powerful tool. It allows for a preliminary assessment of geomorphic and structural features. This approach should be considered as a preliminary technique to be undertaken before carrying out field investigations.

The increasing availability of DEM and their increasing precision will soon make it possible to apply such a method anywhere in the world, for a low cost.

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