Microseismic activity and location at Turtle Mountain, Alberta

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Abstract

A six-station microseismic monitoring array at Turtle Mountain in southern Alberta detected numerous microseisms during the observation period from 1986 to 1996. In this paper, we select a subset of the recorded events, those with clear P and S arrivals and detected by more than three stations for hypocenter-location analysis. Hypocenters are located using a computer program named HYPOMH, which employs a Bayesian algorithm. The error distribution of the hypocenters is also determined by the program. Results of the analysis indicate a concentration of hypocenters at the summit and eastern slope of the mountain. Furthermore, several swarms of events are located with foci ranging from 1 to 1.5 km below the surface of the Frank Slide debris. Few microseisms coincide with the distribution of the remaining (un-collapsed) mine works.

Introduction

Passive microseismic monitoring is an emergent technology that has been used to reveal the characteristics of oil reservoirs. We use the microseismic data collected at Turtle Mountain to observe the relationship of microseismic activity to possible tectonic weaknesses and examine the accuracy of hypocenter location by using a well-known hypocenter location program HYPOMH (Hirata & Matsu'ura, 1987). The hypocenter distribution of microseisms can provide evidence for the movement of fractures or faults and thus may help distinguish causes of the landslides. Early microseismic monitoring in the Turtle Mountain area was carried out from June to September of 1981 by Earth Sciences Division of Alberta Environment using a single monitoring station (Weichert and Horner, 1981). During this time, three local swarms of microseisms of small magnitude were detected but could not be located. A more comprehensive observation was carried out by using a six-station monitoring array on the eastern flank of Turtle Mountain and recorded data from November of 1986 until June 1996 (Bingham, 1996). In this paper, we will describe the processes of hypocenter location by using the seismic data recorded by the six-station array and compare the seismicity with other geological data.

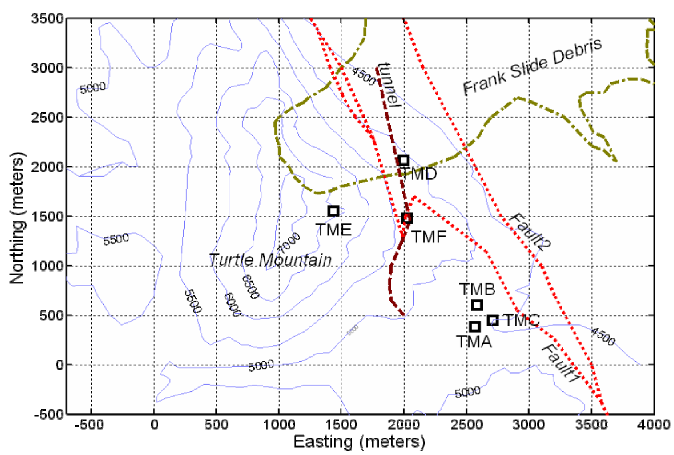


Figure 1. A topographic map shows the study area with seismic stations (squares), local thrust faults (dotted lines), the remaining mine tunnel (dashed line) and the boundary of the Frank Slide debris (dash-dotted lines). Elevation contours are labeled in feet. Sub-arrays named FRANK (stations TMD, TME and TMF) and FARM (stations TMA, TMB and TMC) make-up the six-station array.

Seismic array and phase picking

The six-station microseismic monitoring array consists of two smaller three-station arrays called the FARM and FRANK sub arrays (Figure 1). The FARM sub array was deployed 1.5 km southeast of the Turtle Mountain summit and includes stations denoted TMA, TMB and TMC. The FRANK sub array was located on the east slope of Turtle Mountain and includes stations TMD, TME and TMF.

The precision of first arrival times of P phases from the digital seismograms is limited by the sampling interval (5 ms) and picking errors due to the presence of background noise and multipathing. In general, one can typically pick a P-wave arrival time within one or two samples. The first S- wave arrival is often obscured by the coda of the P- wave arrival. To pick the S- wave arrival, we look for the S-wave's characteristic low-frequency content, high-amplitude and corresponding close abrupt phase changes in different stations (Figure 2). There is much more uncertainty with the S-wave pick-time than with the P-wave pick-time. We estimate errors in the order of 50 ms.

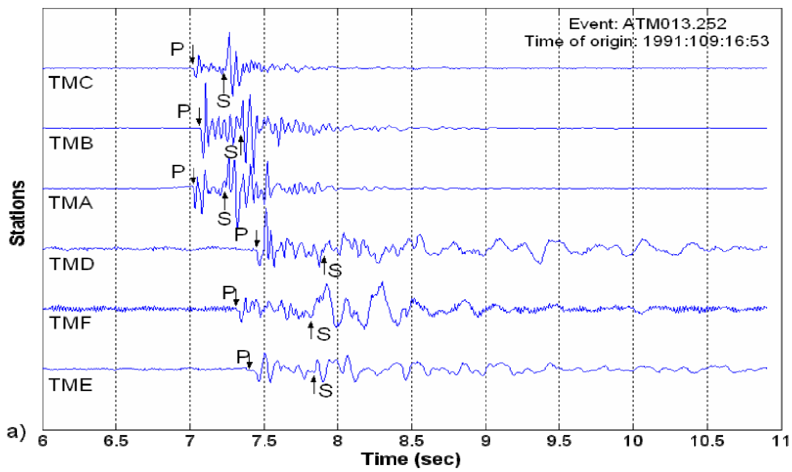


Figure 2. A seismogram recorded on April, 1991 by the FRANK and FARM sub arrays. Stations codes are shown at the beginning of each record. The arrival times of P- and S-waves are indicated by arrows. The FRANK waveforms have been scaled-up to better match the FARM amplitudes.

Hypocenter location algorithm and velocity model

The hypocenter location algorithm used by HYPOMH is based on both observed and prior data from a Bayesian point of view. Marginal probability density function (PDF) is defined to eliminate the origin time from the location problem; the posterior PDF of hypocenter parameters is integrated over the whole range of origin time. The best estimate of the hypocenter location defines a set of spatial coordinates which maximizes the PDF. These coordinate estimates are assumed to have Gaussian error distributions. Estimation errors are evaluated by an asymptotic covariance matrix with an asymptotic posterior PDF (Hirata & Matsu'ura, 1987).

A homogeneous model of the mountain with a P-wave velocity of 4.7 km/s and a V_P/V_S ratio of 1.73 was used to locate hypocenters. These rock parameters were mainly determined using in-situ hammer-seismic measurements and ultrasonic analysis of hand-samples (Bland et al., 2003). The depth reference (Z=0) was selected as the summit of Turtle Mountain and stations are assigned pseudo-depths based on their total vertical distance from the summit. The hypocenter location method requires an initial first-guess (we selected the TME station) a search radius (6.6 km), and a search depth (5.0 km).

Results

Computed hypocenters and the corresponding error estimates are shown in Figure 3 and Figure 4. Vertical hypocenter distributions are graphed along two vertical sections (A-A' and B-B') which are perpendicular to the general strikes of northern and southern segments of Fault 1. Fault 1 and Fault 2 are splays of the Turtle Mountain Thrust with a dip angle of approximate 45° toward west (GSC, 1993).

Twenty five events were recorded and located by both the FRANK and FARM arrays. Seven of the events are located no deeper than 200m in the shallow region beneath the South Peak and eastern slopes of Turtle Mountain. The spatial relationship between the hypocenters, Fault 1, and a mine tunnel is highlighted in profile A-A'. We observe one event which coincides with the mine tunnel. Since this event was computed with a low error, it is likely that this microseism occurred quite close to the mine tunnel. Eleven events are distributed in the region southwest of the southern segment of Fault 1 mostly between 300 and 400 m below the surface. They appear to run parallel to the fault. Some events appear to coincide with the projection of Fault 1 (B-B' profile). This suggests that they are either along the fault plane, or within the hanging wall. Four events (labelled *S1-4* on Figure 3) exhibit similar waveforms and were recorded during a 44-minute swarm. These are located in a depth range of 1450-1950 m below the southeastern boundary of the Frank Slide debris.

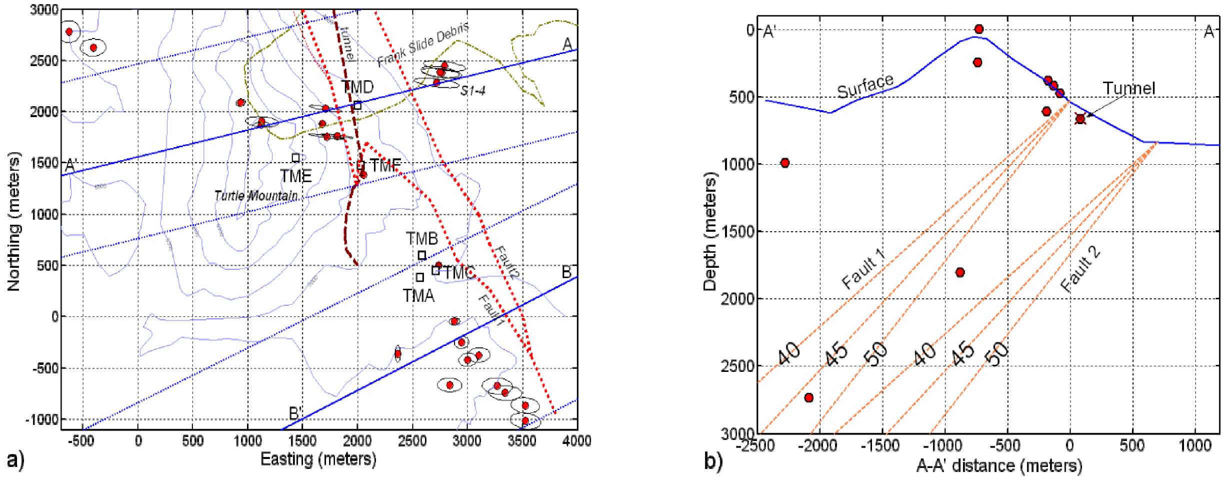
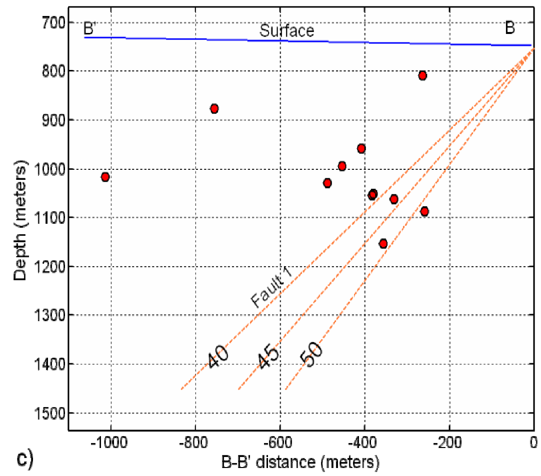


Figure 3a) A plain-view map shows the location of computed hypocenters (red dots) and estimated one-standard-deviation error ellipses. 3b) Hypocenters in A-A' profile. The width of the profile is marked by the two adjacent dotted parallel lines; faults with possible dip angles (40°, 45°, and 50°) are plotted with dashed lines; The mine tunnel is marked by a cross. Indicated depths are relative to the summit. 3c) Hypocenters in B-B' profile. Annotation is same as 3b.



Thirty eight microseisms were recorded and located by the FRANK sub array only (not the FARM sub-array). These were processed separately and yield lateral positioning errors of less than 150 meters. The distribution of microseisms is generally similar to the previous combined sub-array results with the most intensive area of shallow events (<1 km in depth) located adjacent to the TME station. Only one event was located near the mine workings. Few microseisms are observed on the gentler lower portions of the further northern and further southern slopes of Turtle Mountain.

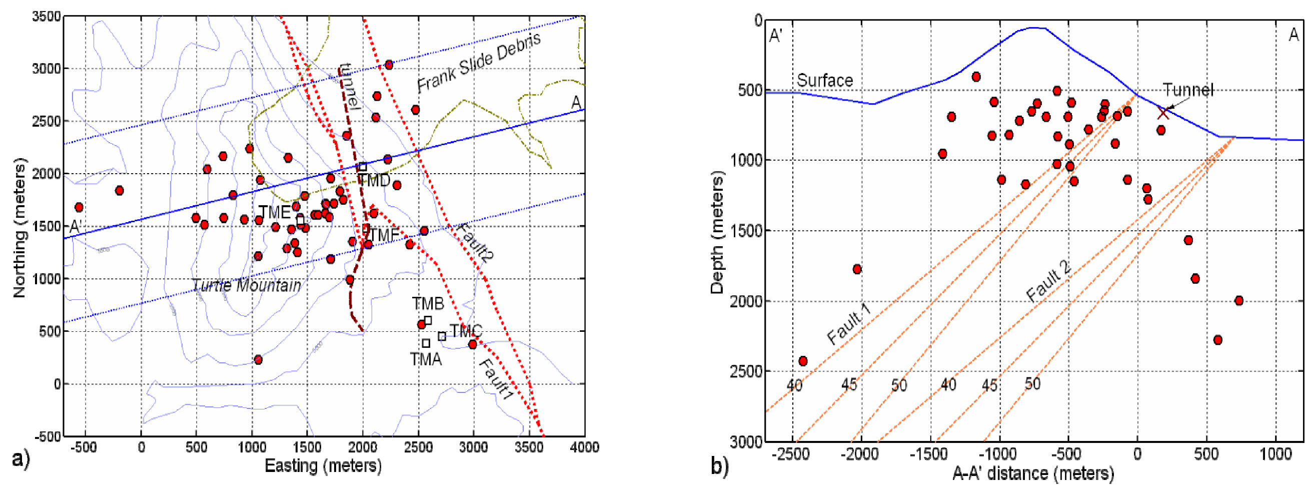


Figure 4a) Lateral distribution of hypocenters (red dots) and corresponding one-standard-deviation error ellipses of relatively well-resolved earthquakes located by FRANK sub array. All three error ellipses have radii less than 150 m. Annotation is as in Figure 3a. 4b) Hypocenters in the A-A' profile. The width of the profile is marked by the two adjacent dotted parallel lines; faults with possible dip angles (40°, 45°, and 50°) are plotted with dashed lines; The location of the mine tunnel is marked by a cross.

Discussion

Coal mining at the base of Turtle Mountain has been suggested as a possible cause of the 1903 Frank Slide. Prior to the Slide, coal was removed from the vertical coal seam running parallel to the mountain's unstable anticline. There are reports that mine workers underground noticed strange movements of the mountain as much as seven months prior to the 1903 slide. Large timbers were reported to have cracked, and coal, under pressure, had "mined itself" at night. It is additionally reported that the mine pitched as if rocked by an ocean wave. These reports suggest that considerable seismic activity would have taken place prior to the 1903 collapse.

A portion of the original mine tunnel still runs parallel to what remains of the mountain's crest (South Peak). If seismicity was previously generated by the application of a load to a mined-out coal seam, then we might expect seismicity in the remaining portion of the mine tunnel. Analysis of the dataset does not show very much activity between the mine tunnel and hypocenter locations. Only two hypocenters were located near the mine tunnel. Either the conditions for gradual mine collapse were not present during the 1986-1996 observation period or the seismicity observed prior to the 1903 collapse was caused by a different mechanism. One novel theory is that the local thrust faults were reactivated in 1903 and eastward movement of the hanging wall weakened support of the overlying loads thereby causing the slide. The clustering of events along near known faults appears to support this theory.

Conclusions

To summarize we have drawn the following conclusions:

1) There is significant seismic activity within and adjacent to Turtle Mountain.

2) Microseisms related to surface fractures are also observed. These events are mainly distributed along the surface of the eastern slope and summit of Turtle Mountain.

3) Only two events spatially coincide with the remaining mine tunnel. Most shallow activity originates near the TME station (located 600 meters west of the remaining mine tunnel). On the gentle lower portions of the northern and southern slopes of Turtle Mountain, microseismic activity is not observed.

4) Microseismic swarms occurred frequently below the eastern and southeastern boundaries of the Frank Slide. The estimated depth of these swarms is between 1 and 1.5 km below the surface.

5) The microseismic activity may be assiciated with the faults or fractures.

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