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Seismic monitoring of rockfall, Helmet Mountain, British Columbia

J.R. Moore
University of California, Berkeley, Department of Civil and Environmental Engineering, Berkeley, CA, USA

J.W. Sanders & K.M. Cuffey
University of California, Berkeley, Department of Earth and Planetary Science, Berkeley, CA, USA

J.R. Haught
Lawrence Berkeley National Laboratory, Earth Sciences Division, Berkeley, CA, USA

S.D. Glaser
University of California, Berkeley, Department of Civil and Environmental Engineering, Berkeley, CA, USA

ABSTRACT: Seismicity generated by rockfall was monitored intermittently over a 5 week period at the Helmet Mountain cirque in British Columbia, Canada. To understand the timing and frequency of rockfall, we installed a seismic monitoring system consisting of two single-component geophones emplaced on the headwall. Two types of rockfall events were observed: single block fall and surficial talus slide. The seismic response during single block fall is characterized by multiple bursts of high-frequency energy as the rock strikes the wall periodically during the fall. A talus slide, on the other hand, has an emergent response and a constant release of seismic energy as the slide progresses. The timing of seismicity indicated that rockfall activity peaks from 10:00 h to 18:00 h when melting ice destabilizes loose blocks. The rockfall frequency mimics diurnal air temperature fluctuations, although the direct cause of rockfall is related to warming of the cliff.

1 INTRODUCTION

Rockfall originating high on a mountain cliff generates a seismic disturbance as it strikes the wall or other debris en route to the base of the slope. A few researchers have described the seismic signature of rockfall, generally in the context of seismic monitoring of active volcanoes. Tilling et al. (1975) provided a comprehensive overview of rockfall seismicity from their observations during a period of intense rockfall at the Kilauea volcano in Hawaii. They observed that the seismic response during a large rockfall event is emergent, meaning that the arrival of seismic energy is gradual, and that high-frequency components attenuated rapidly with distance. Other researchers have observed large rockfall events on regional seismic networks and were able to triangulate the epicentral location, finding good agreement with local ground observations (e.g. Norris & Lester 1996).

Whereas most previous research focused on seismicity created by large rockfall, our study focuses on smaller, localized events. In this work we will distinguish between two types of rockfall: single block fall and surficial talus slide. A single block falling from high on a cliff strikes the rockwall a number of times as it descends, releasing seismic energy with each strike but leaving intermittent periods of inactivity between strikes. Conversely, a talus slide is a cascade of rock and debris that releases seismic energy continuously.

One of the goals of this investigation was to discover diurnal trends in the timing of rockfall events to reduce the risk of physical injury to researchers working throughout the summer at the base of Helmet Mountain. This work also looks at one aspect of the larger rock cycle, investigating the role of transport mechanisms in bedrock erosion, in an attempt to understand the processes sculpting the cirque basins that are ubiquitous in alpine terrain.

2 EQUIPMENT AND SITE DESCRIPTION

Rockfall seismicity was monitored over a five week period at the Helmet Mountain cirque in eastern British Columbia (Fig. 1). This alpine amphitheater is home to the small West Washmawapta glacier which is actively undercutting the adjacent cliffs, making rockfall from

We emplaced the geophones on the rockwall just above the lip of the glacier, about 50 m apart (Figure 1). Each was epoxied to a flat surface and covered with small rocks to protect it from falling debris.

The system ran intermittently over a 5 week period from 5-Aug-2006 to 7-Sep-2006. The irregular operation was caused by overheating failure of a solar controller. The system recorded a total of 210 hours of seismic data.

3 RESULTS

3.1 *Calibration Data*

Several times during the study period we were able to spend a few hours near the seismic system observing and annotating rockfall activity in the vicinity of the geophones. These observations and simultaneous seismic data allowed us to determine the seismic signature of known events and provided crucial calibration for future observations. From this calibration data we were then able to create detection criteria to identify rockfall events in other data sets.

In general, there were two types of rockfall events: single block fall and surficial talus slide. Single block falls originated high on the rockwall and struck the cliff a number of times during their descent to the glacier. Block size averaged about 0.3 m, and a typical fall lasted from 30 - 120 seconds with about 5 - 10 audible impacts before landing on the soft snow of the upper glacier. The seismic signature of a single block fall was characterized by a long disturbance made up of multiple high-frequency spikes (Figure 2). Our 60 Hz system probably under-sampled this high-frequency signal. Single block fall disturbances attenuated rapidly with distance along the rockwall; commonly a small block falling near geophone #1 was not detected ~50 m away by geophone #2.

The talus slides observed at our field site usually originated near geophone #2, where a talus slope is underlain by stagnant glacial ice. As this ice melted throughout the day, the talus above it shifted and reorganized. Typically, a talus slide encompassed an area of about 1 m^2. These types of events were frequent and generally the length of each slide was only a few meters. The seismic response of a talus slide was characterized by a more continuous release of energy compared to the episodic trace of block falls. The signal was emergent, then decayed over a typical slide time of ~10 seconds (Figure 3).

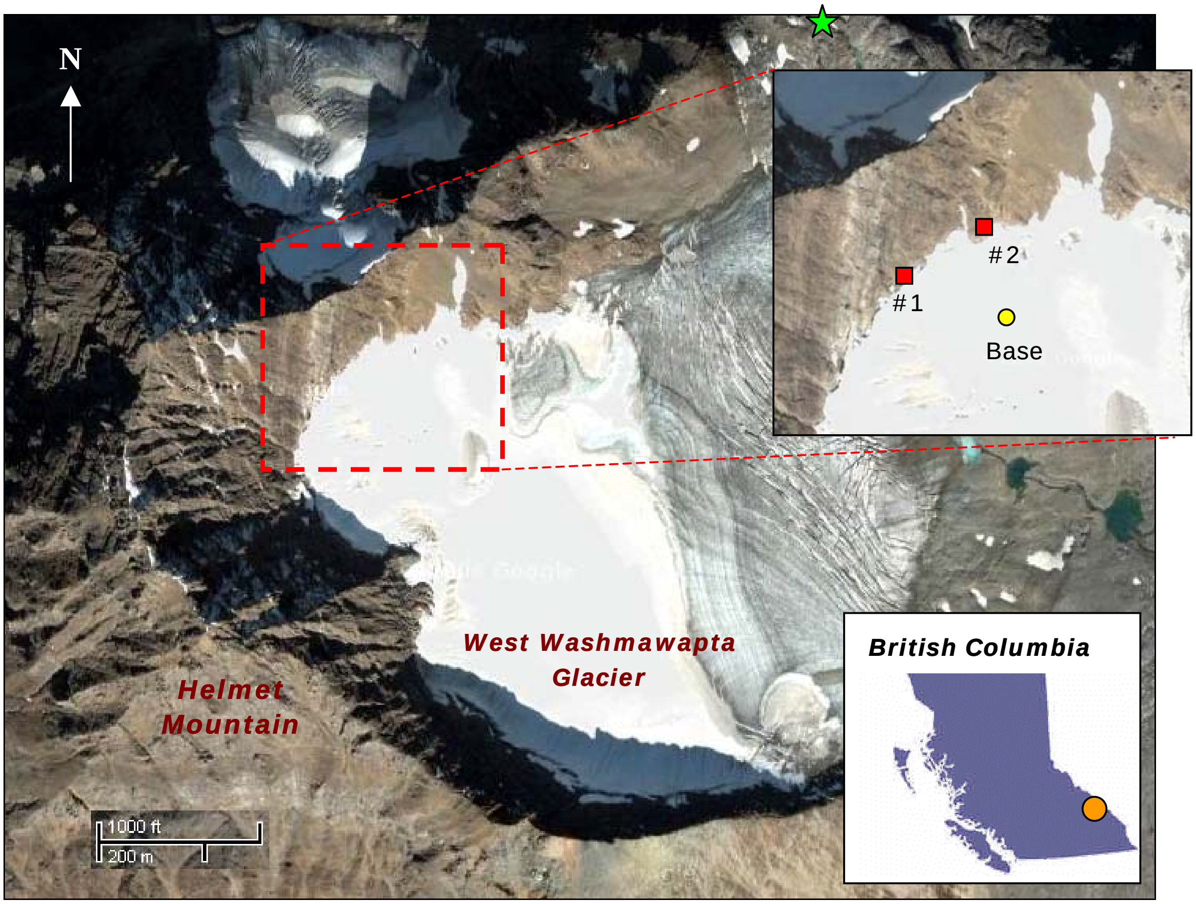

Figure 1. Overview of the study area at Helmet Mountain, British Columbia. The West Washmawapta glacier (seen draining northeast) undercuts the large headwall of Helmet Mountain where heavily jointed meta-sedimentary rocks are prone to degradation by rockfall. Two geophones were emplaced on the rockwall, separated by about 50 m, as shown in the inset figure. The star at the toe of the glacier shows the location of the weather station. (Image: DigitalGlobe)

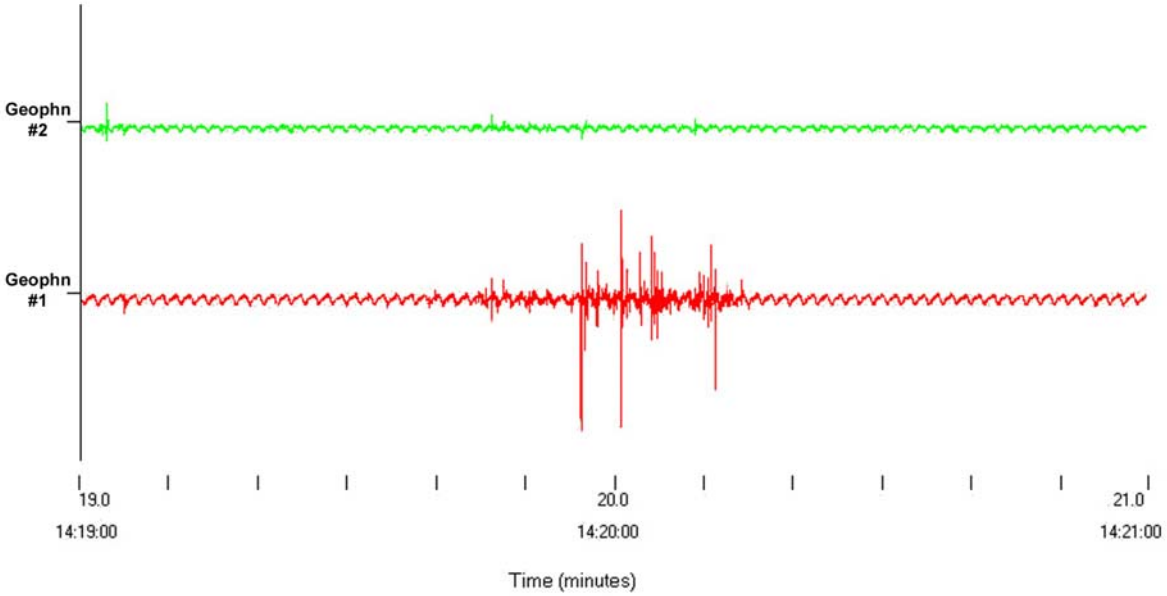

Figure 2. Characteristic high-frequency seismic response during a single block fall (geophone #1). In this particular event a block with an intermediate axis of ~0.3 m tumbled down the cliff face some 300 m, striking the wall a number of times en route. These data, as in Figure 3, are unfiltered.

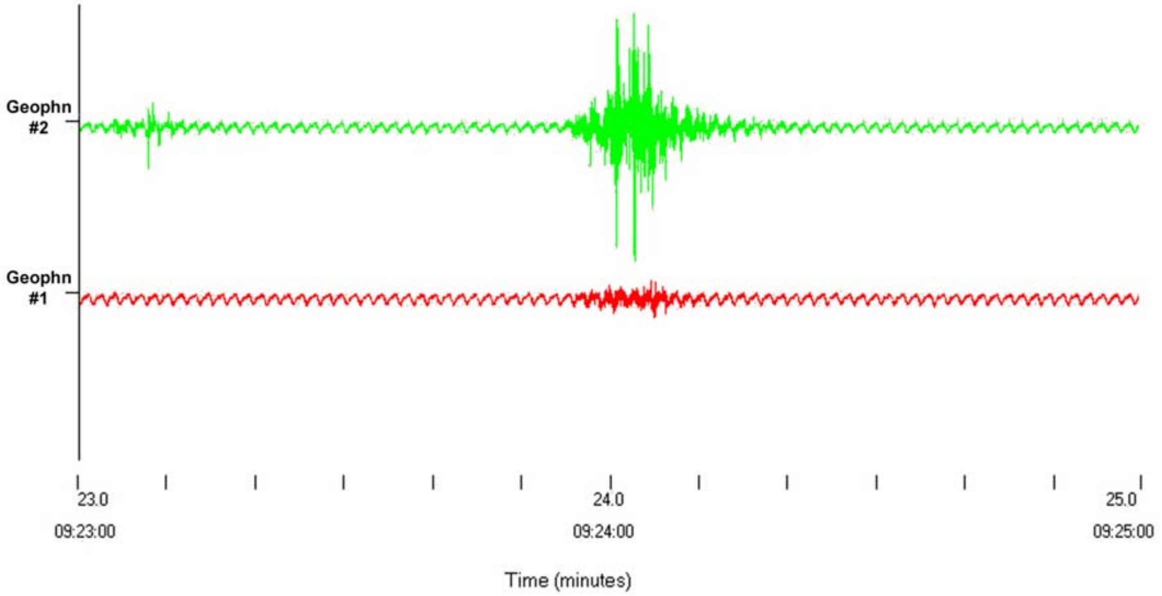

Figure 3. A typical emergent seismic response during a small talus slide (geophone #2). Events like these were common in an area near geophone #2 where talus overlays stagnant glacial ice. As the ice melts throughout the day, the talus above shifts and reorganizes. Typical slide lengths were on the order of 1 m. The vertical scale is the same as in Figure 2.

Rockfall events were monitored by an observer over a few hours on several days, notably six hours on 27-Aug-2006. In general there was a good match between personal and seismic observations of rockfall and talus reorganization. Nevertheless, there were a few events in the seismic record that were not identified by the field observer. These may be caused by more distant rockfall on the opposite side of the slope, or possibly ice calving at the toe of the glacier (which happened frequently).

From the calibration data we were able to create event detection criteria to identify rockfall in the longer records of August 5-9 and September 1-7. The criteria are based on the amplitude, duration, and shape of the seismic disturbance. The amplitude must clearly exceed the background noise level, which was variable. The disturbance must persist for several seconds, to distinguish real data from intermittent electronic noise. The form of the response must match the appearance of known types of rockfall events, as illustrated in Figures 2 and 3.

3.2 *Record of Rockfall*

In this work we analyze the seismic record from 1-Sep-2006 at 12:00h to 7-Sep-2006 at 06:00h, a span of 138 hours. This data set is fairly continuous with a few notable exceptions: the system was not operational on 5-Sep-2006 or on the morning of 4-Sep-2006, while in the early morning hours of 6-Sep-2006 and 7-Sep-2006 the seismic records were too noisy to interpret.

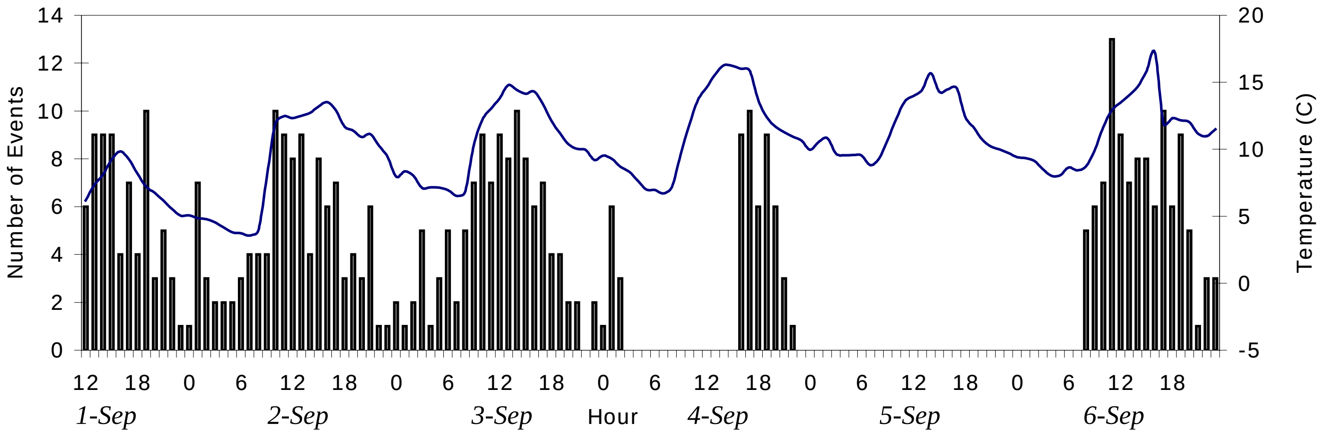

Figure 4. The number of inferred rockfall events per hour for a period of time spanning 1-Sep-2006 at 12:00h to 7-Sep-2006 at 00:00h. The event frequency was determined from the seismic record using the detection criteria created from calibration data. Rockfall activity peaks from 10:00h to 18:00h. Missing data are from times the system was not operating or times when noise overwhelmed the signal. The ambient air temperature record from the weather station at the toe of the glacier is shown by a solid line.

The data were processed manually in ten-minute intervals. Using the detection criteria developed from the calibration data, we identified individual seismic disturbances, and determined the number of inferred rockfall events per hour. Figure 4 shows the number of events per hour over the time period of investigation. Figure 5 is a histogram of the average number of rockfall events per hour. These results demonstrate that rockfall activity peaks daily from 10:00h to 18:00h, while activity decreases at night and early morning.

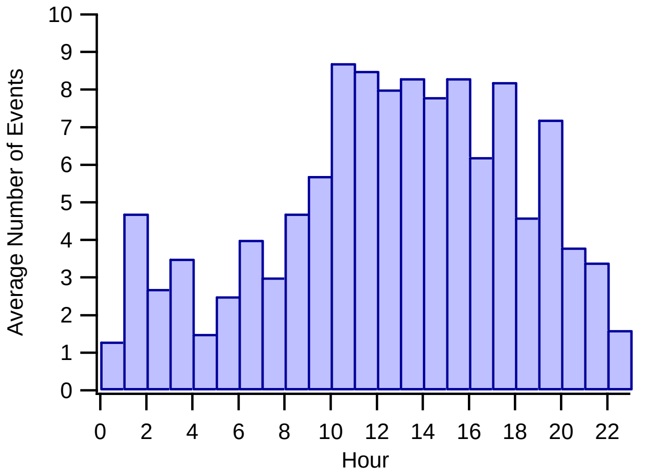

Figure 5. Average number of rockfall events per hour for the time period shown in Figure 4. The histogram demonstrates that rockfall activity increases from about 10:00h to 18:00h, while at night and early morning the frequency of rockfall is low.

The field site is located in a remote area of the Canadian Rockies so there is little cultural seismic background noise. The only sources of noise contamination we are aware of are natural and include wind, telluric activity, and glacial seismicity. Wind could affect the record of geophone #1 because the wire had to span a ~2 m chasm across the bergschrund. As a result, data from this geophone were not useful during windy periods. Significant electrical noise also occurred during times of high telluric activity. We found that this noise most affected the record of geophone #1, whose wire trended west, while geophone #2, which had a wire running north, was relatively unaffected by telluric noise. Temporal variations in telluric activity are monitored by the National Oceanic & Atmospheric Administration. These records correspond well with times of high telluric activity inferred from noise in our seismic system. Sources of glacial seismicity including ice crevassing and sliding; this noise is poorly constrained at this time. Finally, consulting the Canadian National Seismograph Network, we verified that no nearby earthquakes occurred during the monitoring period.

4 DISCUSSION

The seismic signatures of two types of rockfall events were determined by field measurement and simultaneous direct observation. The seismic response of a single block fall was characterized by multiple high-frequency spikes, as demonstrated in Figure 2. This signal attenuated rapidly with distance along the cliff face. Tilling et al. (1975) reported similar findings, noting that the seismic disturbance is transmitted primarily by surface waves which are prone to attenuation as they travel through the broken weathered surface of a rock face.

For talus slides, or surficial rock avalanches, we found that the seismic response was emergent then decayed over a typical slide time of a few seconds (Figure 3). This type of response is similar to that observed by previous researchers for larger rock slides (Tilling et al. 1975, Norris 1995). The slide initiates as one or more blocks are destabilized and progressively loosen adjacent debris, cascading into a rock avalanche. As the slide comes to rest, blocks jostle and reorganize for some time.

The timing and frequency of rockfall events was determined for a time period spanning 138 hours in early September, 2006. Analysis of the seismic record (Figures 4 and 5) reveals that rockfall activity peaks from about 10:00h to 18:00h and decreases at night and in the early morning hours. This diurnal pattern is similar to direct observations in the nearby Mt. Rae area by Gardner (1983).

Much of the rockfall activity in our area can be attributed to melting of ice-filled discontinuities and consequent destabilization of rock blocks. Conceptually, the stability of a *broken* rock slope is maintained by both friction at the interface of blocks and the cohesion offered by ice-filled discontinuities (Bjerrum and Jorsbad 1968, Davies et al. 2001). When binding ice melts, certain blocks are made free to fall (Matsuoka and Sakai 1999, Gruber et al. 2004). Similarly, in the area of the slope near geophone #2, loose talus overlays stagnant glacial ice. As this ice melts, individual blocks are freed and can initiate a small avalanche of debris.

A nearby weather station located at the toe of the glacier (Figure 1) recorded ambient air temperature every 15 minutes. The daily pattern of sun exposure at this station was similar to that on the instrumented area of the rockwall. Air temperature and the number of rockfall events per hour is shown in Figure 4, demonstrating that the frequency of rockfall mimics the diurnal fluctuations in air temperature. Rockfall activity increases when the temperature of the *slope* is warm enough to melt the ice binding loose blocks. Our data show that this temperature condition is met simultaneously with the rise in ambient air temperature each morning around 10:00h. To fully understand the cause of the daily pattern of rockfall activity, the temperature of the rock slope should be monitored. These data are currently unavailable.

Another weather station was located nearby on the glacier surface. The air temperature at this station was modulated by the temperature of the snow, which decreased the amplitude of the daily fluctuations. We believe that the air temperature record from the station at the toe of the glacier more accurately reflects the conditions on the rockwall, so chose to include these data in Figure 4.

Rockfall from this portion of the Helmet Mountain headwall is relatively frequent, with up to 13 events observed in one hour. From the diurnal pattern of seismicity we can identify portions of the day when it is relatively safe for researchers to work at the base of this slope. To minimize the risk of injury by rockfall, we suggest that personnel work in this area only in the early morning, vacating the base of the rockwall by 10:00h.

Finally, we caution that the conclusions drawn from this study are based solely on climatic conditions during the study period, and should not be extrapolated to predict rockfall frequencies during any other season.

5 CONCLUSION

Rockfall seismicity was monitored intermittently over a five week period at an alpine cirque in British Columbia, Canada. Unique seismic signatures were discovered for different types of rockfall events including single block fall and surficial talus slide. The seismic record revealed a strong diurnal pattern in the frequency of rockfall. Activity peaks around mid-day to afternoon and decreases significantly at night and in the early morning hours. We propose that rockfall in our area was mostly caused by melting of ice-filled discontinuities and destabilization of loose rock blocks. The variation in the frequency of rockfall mimics the daily air temperature fluctuations, where air temperature is a proxy for temperature of the cliff. This work is a step towards better understanding the mechanisms that sculpt alpine landscapes, and will help elucidate the relative importance of glacial and periglacial processes in the formation of cirque basins.

ACKNOWLEDGEMENTS

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