

SPONTANEOUS FRACTURE INITIATION IN MOUNTAIN SNOW - PACKS

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ABSTRACT. Over the past few years an investigation has been conducted to determine the extent of seismic signals associated with avalanching snow slopes. A number of the signals recorded have been examined and classified according to their origin. One of these signals, however, is not clearly defined in terms of an observable source mechanism. To obtain information regarding the origin of this signal we have compared the results from several investigations conducted to study the seismic activity associated with glaciers. A comparative analysis of the snow and glacier signals indicates that the high-frequency signals observed in snow fields are due to internal fracture within the snow.

RÉSUMÉ. *Production spontanée de ruptures dans le manteau neigeux en montagne.* Au cours des années récentes on a conduit des investigations pour déterminer l'ampleur des signaux sismiques associés aux pentes de neige en avalanche. En examinant bien des signaux on les a classés selon leurs origines. Un signal, cependant, reste difficile à classer en ce qui concerne le mécanisme apparent de sa source. Afin d'obtenir des renseignements sur l'origine de ce signal, nous avons comparé les résultats de plusieurs enquêtes menées sur l'activité sismique associée aux glaciers. Une analyse comparative des signaux provenant de la neige d'un côté, et des glaciers de l'autre, nous a permis de conclure que les signaux de haute fréquence observés dans les champs de neige sont émis par des fractures internes.

ZUSAMMENFASSUNG. *Plötzliche Bruchbildung in Gebirgsschneedecken.* Während der letzten Jahre wurde eine Untersuchung vorgenommen, um das Ausmass seismischer Signale, die von abgehenden Lawinen herrühren, zu bestimmen. Ein Teil der aufgezeichneten Signale wurde geprüft und nach ihrer Entstehung klassifiziert. Eines dieser Signale jedoch lässt sich nicht klar einem beobachtbaren Auslösemechanismus zuordnen. Um Anhaltspunkte über den Ursprung dieses Signals zu erhalten, wurden die Ergebnisse mehrerer Untersuchungen zur seismischen Aktivität an Gletschern herangezogen. Eine vergleichende Analyse der Schneee- und Gletschersignale lässt vermuten, dass die in Schneedecken beobachteten hochfrequenten Signale durch Brüche innerhalb des Schnees ausgelöst werden.

INTRODUCTION

Over the past few years a field research program has been conducted by Montana State University to investigate the acoustic phenomena associated with the development of instability in snow slopes. This program is designed to monitor acoustic signals emitted over a wide range of frequencies in both the seismic and ultrasonic region of the frequency spectrum. The purpose of this program is to determine whether a correlation can be established between avalanche instability and the pattern of acoustic signals recorded. Results from our two-year investigation indicate that utilization of acoustic methods may provide a prediction technique for certain types of avalanches.

To date, field monitoring has been carried out in frequency bands from 30 kHz to 200 kHz and from 4 Hz to 100 Hz. Emissions from snow in these two frequency ranges are significant in terms of the mechanical processes taking place within the snow cover. Emissions in the ultrasonic range indicate changes taking place at the granular level within the snow-pack. Generally, this type of emission signifies a change in the state of stress in the snow field but is not necessarily associated with failure of the snow-pack. Emissions from snow in the seismic region of the frequency spectrum, however, are generally indicative of a major displacement of the snow-pack. The type of displacement indicated may be either the catastrophic fracture of the pack which results in an avalanche, or the internal fracture of the snow.

Although a great deal of information can be gained by monitoring both the ultrasonic and seismic bands, this paper will be concerned only with seismic signals. The use of seismic methods will probably lead most directly to a quantitative method for assessing snow slope stability in terms of the delayed-action avalanche.

FIELD INSTALLATION

During the first year of our study (winter 1974–75) a single-channel monitoring system was installed at our field site. This consisted of a geophone mounted vertically on bedrock in the starting zone of an avalanche path. This geophone was connected by a coaxial cable to a portable microearthquake recorder placed in a small instrument shelter located away from the starting zone. This system worked well during our first winter of operation, but we did have some difficulties with system maintenance and data interpretation.

Problems arose with the field recorder, since the recorder had to be maintained every other day. This meant that an excessive amount of time was devoted to instrument maintenance. Also, with the recorder in this location the data was not available for analysis on a real-time basis.

The second and more serious problem which arose from this arrangement was that it was extremely difficult to distinguish between signals of snow origin and those which originated from extraneous sources. In monitoring events at very low frequencies, a large number of extraneous events are recorded. Snow events represent only a small percentage of all events recorded.

To remedy these problems during the second field season (winter 1975–76) a two-channel telemetered system was installed with a radio link between the field site and a central data collection center. This alleviated the servicing problem and also made the data available on a real-time basis.

This two-channel capability allowed us to instrument two slide paths 1.2 km from one another. In this way we were able to distinguish more easily between snow events which originated locally and extraneous events of a more global origin. Local events were detected on only one channel, or were of high amplitude on one channel and of reduced amplitude on the second channel, whereas extraneous events were recorded with equal amplitude on both recording systems.

The geophones used in this second investigation were mounted by cementing them into bedrock outcrops in the slide paths prior to the winter snows. It was found that, when the geophone was mounted in the snow of the slide path, a rotation occurred which altered the calibration of the geophone.

INSTRUMENTATION SYSTEM

The transducers used in this investigation are miniature refraction geophones with a natural frequency of 4.5 Hz. These geophones are operated at 62% of critical damping which produces a generally flat velocity response as a function of frequency. This geophone was chosen for its low-frequency characteristics and also for its low cost.

The geophone is coupled to a specially designed low-noise preamplifier with a gain of 20 dB and a noise level of 0.1 μ V. The signal from the preamplifier is amplified by 84 dB and then modulated onto a carrier signal. The carrier signals from the two geophones are then mixed and transmitted 11 km to the data collection center where they are demodulated.

Since our field site is in a relatively remote location, the preamplifier and amplifiers were designed to operate at a very low power of 2.6 mW. Since the amplifiers exhibited some variation in gain with temperature, they were placed at the snow–ground interface so that they might operate at a constant temperature. This also meant that the mercury batteries operated efficiently when the air temperature was well below 0°C.

The radio transmitter used has a power consumption of 9.6 W with an output of 4 W. The radio and ancillary electronic equipment is powered by a 40 W thermoelectric generator. Modifications to our radio transmitter have now reduced its power consumption to 0.36 W with an output power of 40 mW.

After the signals are demodulated at the data collection center they are displayed on a two-channel helical drum recorder. The recorder is capable of displaying two channels of analogue data collected over a 24 h period. This type of recorder has the advantage of allowing one to observe the seismic signals as they occur and to make visual comparisons between data recorded on the two channels. It has, however, the severe disadvantage that it limits the amount of quantitative data that can be obtained from the record. With this recorder we can obtain information that an event has occurred and also obtain some idea of the signal envelope. Ideally this type of recorder should be interfaced to a digital or magnetic tape recorder capable of recording accurately the frequency and amplitude of the incoming signals. A magnetic tape recorder has been obtained for this purpose and will be operated during the coming field season.

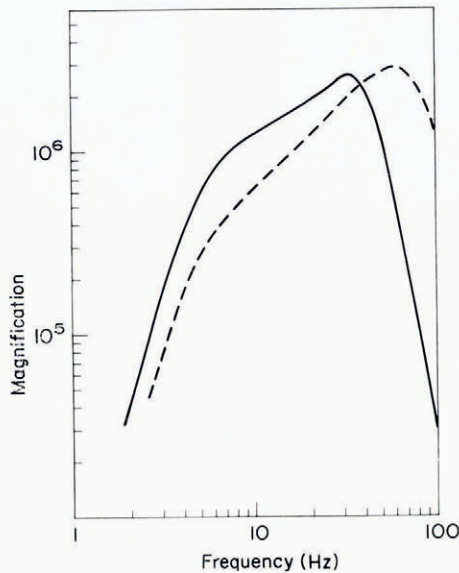


Fig. 1. System response characteristics, log magnification versus log frequency. Solid line, remote-sensing system; broken line, microearthquake recorder.

Figure 1 shows curves of magnification versus frequency for the systems used. The solid curve in this figure shows data for the remote-sensing system. The broken curve shows the response of the portable microearthquake recorder. The calibration for both these systems is given since the data discussed is drawn from both.

The data recorded during the 1974–75 winter season was collected exclusively on the microearthquake recorder. The data obtained during the 1975–76 season was recorded primarily on the remote-sensing system.

CHARACTERISTIC SIGNALS

In an earlier paper, St. Lawrence and Williams (1976) discussed a number of seismic signals associated with snow slopes and avalanche phenomena. An examination of the signal envelopes showed that these signals could be catalogued in terms of their signal origins. The signals can be identified broadly in terms of four signal types: (1) signals emitted from slab avalanches, (2) signals emitted from point-source avalanches, (3) signals from surface events such as cornice fall or snow rolling down a slope, and (4) signals emitted from internal

snow events. Generally, the first three types of signals are of interest for recording the occurrence of an avalanche or for obtaining information relating to overall stability. The last type of signal was somewhat enigmatic since it was not associated with any observable displacement of the snow. In fact its origin can only be traced to snow by the fact that it cannot be detected in the absence of snow cover. In our initial paper we made the hypothesis that these impulsive signals represented small internal fractures within the snow-pack. Figure 2(a) shows a typical group of these signals as recorded on the microearthquake recorder.

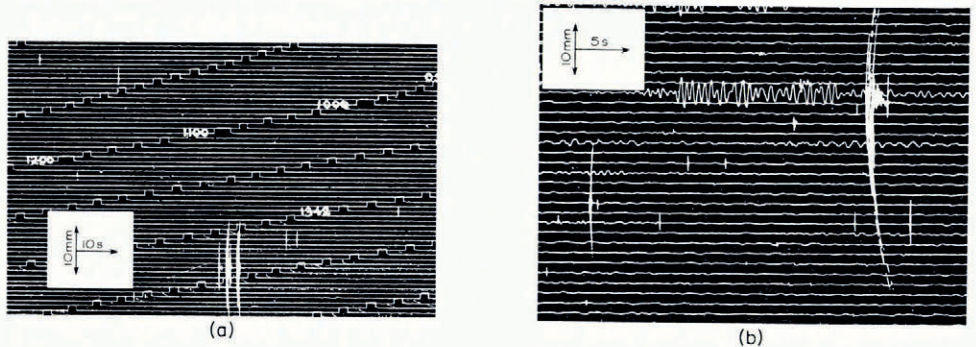


Fig. 2. (a) Record of events recorded in an avalanche path in the Bridger Range. (b) Microearthquake record from the Variegated Glacier showing a number of Type I events and a single Type II event. Note that the recording in (a) is magnified $32\times$ relative to (b).

INTERNAL FRACTURE OF THE SNOW-PACK

As was discussed earlier, the systems used during the two field seasons did not differ significantly in terms of the quality of data collected. However, by relating information from similar studies in other fields we can infer the origin of this puzzling signal.

Two types of seismic signals have been identified as being of glacial origin in structural glaciology.* These events have been classified as Type I and Type II events by Dewart (1968). The Type II event is a low-frequency signal which is almost monochromatic. This type of signal occurs in Figure 2(b). The Type I event is a high-frequency, short duration signal differing markedly from the Type II event. A number of these Type I events appear in Figure 2(b). The record shown in Figure 2(b) was made with a microearthquake recorder on the Variegated Glacier, Alaska in 1974.

For comparison with this, Figure 2(a) is a recording made during a period of instability in an avalanche path at our field research site. Qualitatively, the Type I glacier signals and those recorded in the avalanche path show a great deal of similarity. Given this similarity in signals, and the fact that they are not recorded with similar monitoring equipment if snow cover is absent, leads us to the supposition that the origin of these signals is similar.

We can refer to the work of Neave and Savage (1970) in order to obtain information on the origin of these signals. A consideration of the monitoring system used in their investigation of icequakes on the Athabasca Glacier in Canada shows that it is reasonable to assume that the icequakes recorded were similar to the Type I signals recorded on the Variegated Glacier. Neave and Savage used an extensive seismic array and were able to identify the origin of this type of signal as extensional faulting at or near the glacier surface. They were also able to make a rough estimate of the length of the fault (10 m) and the amount of wall separation (on the order of $1\ \mu$).

* Paper in preparation by A. Qamar (University of Montana, Missoula, Montana, U.S.A.) and R. Bindshadler (University of Washington, Seattle, Washington, U.S.A.).

Given the similarity of the signals observed on essentially identical recording systems, we feel that it is reasonable to assume that the origin of the signals recorded in snow fields and on glaciers is essentially the same. Due to a lack of quantitative data, however, we cannot identify the source mechanism as originating from tension fracture. It is possible that these fractures originate from shear fracture or compressional failures within the snow-pack.

An important point to note is that the signals in Figure 2(a) (snow signals) were recorded at a magnification 32 times larger than those in Figure 2(b) (glacier signals). This indicates that the energy release from a typical snow event is considerably less than from corresponding glacier events.

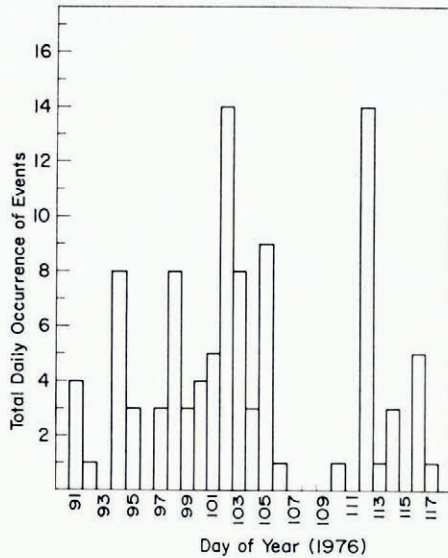


Fig. 3. Record of the occurrence of high-frequency signals recorded daily over a 27 d period during March and April 1976.

OCCURRENCE OF SIGNALS

The signals discussed have exhibited no identifiable patterns which can be correlated with either diurnal cycles or storm periods. Generally the number of these events detected on a daily basis is very small. Figure 3 is a graph of the number of these events recorded daily over a 27 d period in March and April 1976. This period was one of stability with two periods of moderate to light avalanche activity occurring on 11 and 21 April. On these dates the number of events recorded shows a slight rise. It should be noted from the data that no avalanches occurred in the two paths being monitored, although paths in the near vicinity did avalanche at this time.

In the previous year (winter 1974-75), avalanches did occur on two instances in the path being monitored. The number of events recorded in the 24 h period preceding these avalanches showed a slight increase. On several occasions, when the number of events observed showed a noticeable increase no avalanche activity was associated with this rise.

In counting the number of events, we have chosen only those which produced a ground motion in excess of 1.6×10^{-9} m at the transducer. This somewhat arbitrary number produces a signal on our recorder which is roughly twice the noise level of our system and makes the signals easily identifiable above the system noise.

DISCUSSION

In this paper we have attempted to relate the origin of particular seismic signals to the development of small fractures within the snow-pack. We have become interested in this signal because, to date, it is the only signal of snow origin that we cannot clearly associate with its source. Also, we find a slight correlation between an increase in the occurrence of these signals on our records and a decrease in the stability of the snow-pack.

Working on the hypothesis that a material system becomes locally unstable prior to catastrophic failure (Liptai and others, 1971) we have conducted our investigations in an attempt to identify local instabilities. We feel that these signals may indicate such instabilities.

A difficult problem of working with snow (especially in the field) is that we cannot easily determine its fracture properties. These properties vary greatly depending on the type of snow we are considering and the stress or strain history to which the snow has been subjected. It seems probable then that if we can identify periods of spontaneous fracture in the snow we can obtain an index of snow stability.

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DISCUSSION

P. R. KRY: Can you comment on why your recordings before and during avalanches show no indication of the impending avalanche whereas the records reported by Dr Sommerfeld show increasing activity prior to an avalanche?

W. ST. LAWRENCE: I think there are some fundamental differences between our instrumentation systems and our signal analysis techniques. I do not think we can resolve this dilemma until we can evaluate our data on a common base. I also feel that it is possible that Dr Sommerfeld may be measuring signal artefacts rather than snow signals.

R. A. SOMMERFELD: I would like to comment that Dr St. Lawrence showed only about 30 s of record preceding the avalanche while my counts were for 500 s. If I count for shorter periods I obtain very large variability in the results. Also, my counts are from a heavily filtered and highly amplified signal as already discussed after my paper. Our results, therefore, are not strictly comparable.

E. R. LACHAPPELLE: During tests with our airbag system I had occasion to observe closely the development of strain in a heavy layer of high-density snow. The strain became obvious when a trickle of individual snow crystals began to flow from the vertical face of the strained snow section. Does this phenomenon relate to your observational experience, and do you identify your recorded sounds with individual crystal-bond failures or with cascades of failures?

ST. LAWRENCE: I believe that what we are observing in our impulsive-type signals is a rapidly propagating crack. In this instance I do not feel that the signals are the result of events between individual ice grains. It is possible that the flow of snow grains you observe is the after-effect of such a fracture.