Seismic measurement of the propagation speed of a fracture through a weak snowpack layer

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ABSTRACT

Weak layers in the snowpack can fail, often resulting in a snow fracture and possibly resulting in an avalanche. Occasionally, these weak layer fractures are triggered on horizontal terrain and propagate into steep terrain to release an avalanche. Avalanches released in this type of manner are considered remotely triggered avalanches. A new field technique has been developed using geophones to measure the speed of a propagating fracture through horizontal terrain. We used six geophones placed approximately 5 m apart and artificially triggered a fracture in a weaker layer. During the winter of 1999/2000, a fracture was measured propagating at 19.9 m/s.

INTRODUCTION

Weak layer fractures on horizontal terrain are widely observed by professionals who work in snow related industries and by winter recreationists. Typically, a person on foot, snowshoes, skis or oversnow machine initiates a fracture in a weak snowpack layer, usually with a thickness of 10 to 100 mm. Downward displacement of the snow surface is often noticeable. This fracture propagates outwards from the trigger point, producing a distinctive "whumpf" sound. Although the terms *firn quake* and *settlement* have been used for the phenomenon, we prefer the onomatopoeic term *whumpf*. The term *firn quake* is not well suited to seasonal snow and *settlement* is best restricted to the gradual compaction of snow layers due to gravity and granular metamorphism.

Often, a vertical perimeter crack extends from the edge of the weak layer fracture through the overlying slab and can be observed on the surface of the snow (Figure 1). In this case, collapse of the failed weak layer is obvious, with a displacement of the snow surface. There have been several observations of these events (DenHartog, 1982; Truman, 1973; Bohren and Beschta, 1974; and Benson, 1962) but no measurements. Bohren and Beschta observed a wave-like pattern on the surface of the snow. They estimated a speed of 6 m/s and concluded that it was not a compression or shear wave. They also noted a downward displacement of approximately 2.5 cm after the wave had passed a point. Benson reported the collapse of a softer snow layer that propagated outwards from the initial location of collapse, but made no estimate of speed or extent of propagation. DenHartog reported a firn quake where a collapse of a weaker snowpack layer propagated from the source. The propagation traveled at least 5 km, with the fracture traveling slightly slower then the speed of sound in air.

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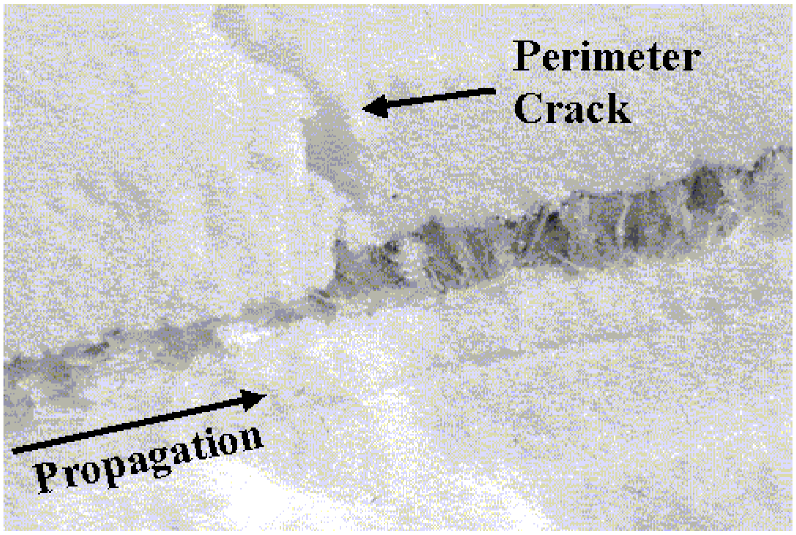

Figure 1. Photograph of a weak layer after a whumpf has occurred. This whumpf was triggered approximately 8 m to the left of the area photographed. The left side of the photo shows the fractured weak layer that has collapsed. The weak layer on the right side has not fractured. A crack extends vertically between the fractured and unfractured portions of the weak layer. This crack can be seen on the surface, marking the perimeter of the failed weak layer region.

Reports of weaker snowpack layers fracturing and collapsing downward during a whumpf has lead to the development of an experiment, using standard geophysical equipment, to measure the actual speed of these propagation fractures. Information about the characteristics of both the weak layer in the snowpack and the slab overlying this weak layer were gathered concurrently.

OBSERVATIONS AND RESULTS

On 19 February 2000, the authors, along with several staff from the University of Calgary Applied Snow and Avalanche Research Group, successfully triggered and measured the speed of a propagating fracture in a buried weak snowpack layer (Figure 2). The experiment took place in Banff National Park, Alberta, Canada. Several days prior to the experiment, whumpfs were occurring on a widespread basis in this area. Upon arriving, this was confirmed by triggering several whumpfs while walking on snowshoes through several open meadows. This experiment was carried out for several days with eight attempts made before the equipment setup coincided with the artificial triggering of a whumpf. The extent of propagation can often be detected by observing downward displacement of the snow surface, locating perimeter cracks, and/or the movements of trees and bushes that protrude through the snow surface.

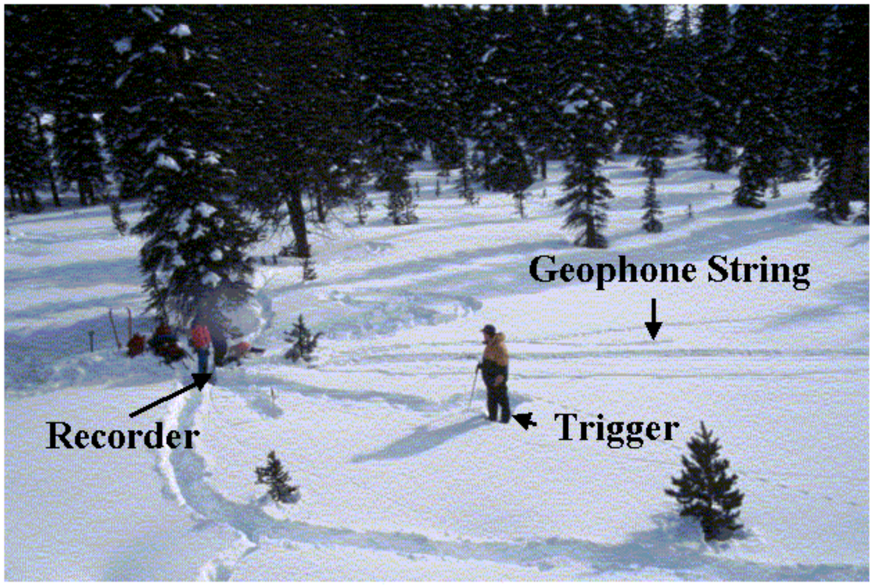

Figure 2. Experiment site showing the location of the geophone string, geophone recorder and spot where a whumpf was successfully triggered.

At an undisturbed site a string of six geophones were laid in a line spaced approximated six metres apart, across the site on the surface of the snow. These were connected to a Bison 9000 Series Digital Seismograph, sampling at 2000 Hertz with 0db gain (Figure 3). Positioning the geophones without disturbing the site required walking around the perimeter of the meadow and then the geophones were pulled across the meadow with a load bearing rope. Using the rope, the geophones were placed as close to vertical as possible. Once setup was complete, the Bison recorder was triggered manually. It was capable of a record length of 20 seconds using six channels at 2000 samples per channel per second. After the recorder was triggered, a person on snowshoes loaded the snowpack near one end of the geophone string by walking in a small area. A whumpf was triggered, and each geophone recorded displacement in the vertical direction as the fracture propagated beneath. Figure 4 shows a schematic of the experiment. The distances from the trigger point to each geophone were measured. The trace (Figure 5) clearly shows when the fracture propagated beneath geophones six, five, and three. The fourth geophone was malfunctioning. The trace also indicates that the propagating fracture did not reach Geophones 1 and 2 (the farthest two from the source). This indicates that the fracture propagated between 12.7 and 17.4 meters. With this information, the speed of the fracture was calculated at 19.9 m/s between the fifth and third geophones. Table 1 shows the distance between the trigger and each geophone, and the arrival time of surface displacement associated with fracture of the weak layer.

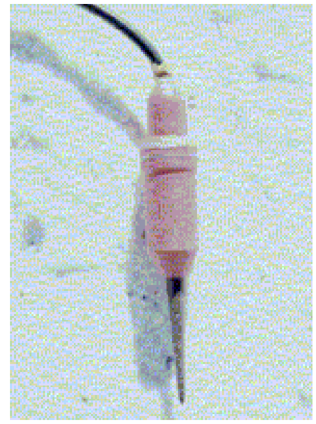

Figure 3. Bison 9000 Series Digital Seismograph and geophones used to measure propagation of fracture through a weak snow layer.

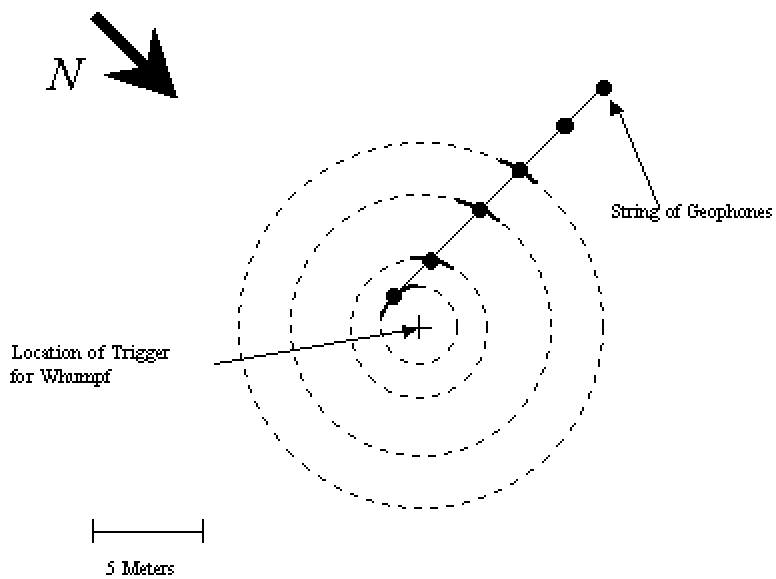

Figure 4. Schematic of propagation experiment. This shows the relative positions of the whumpf trigger point, the recorder and the six geophones. The concentric circles represent the propagating fracture of the weak layer. The dashed lines show assumed propagation.

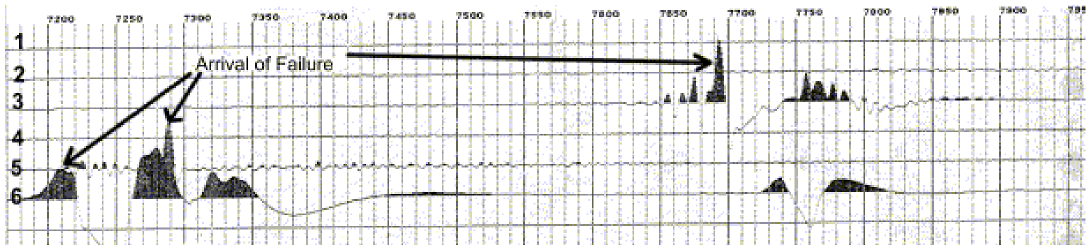

Figure 5. Signal traces produced by the Bison recorder clearly indicating the time of arrival for fracture in the weak layer.

Table 1. Distance from the whumpf trigger point to each geophone and arrival time of the surface displacement.

Geophone Number	Distance From Trigger Point to Geophone(m)	Arrival Time (milliseconds after triggering recorder)
One	21.30	No arrival
Two	17.40	No arrival
Three	12.70	7690
Four	9.00	Defective
Five	4.75	7290
Six	2.65	7200

The weak layer that failed was 0.4 m below the surface and approximately 10 mm thick. It was composed of surface hoar crystals that had formed during a cold clear period approximately fifty days prior. The overlying slab had an average density of 189 kg/m^3 with lower density layers near the surface and higher density layers (240 kg/m^3) closer to the weak layer. At other whumpfs in the vicinity, vertical displacement of the surface was measured at 2 mm downward.

DISCUSSION

This experiment brings more insight to a poorly explained phenomenon. Bohren and Beschta (1974) state that the low velocity of propagation for these waves seem to rule out elastic shear or compressional waves. Much higher velocities have been estimated in Antarctica and Greenland, the slabs overlying the weak layers were several meters deep and very dense, e.g. 500 kg m^{-3}.

Lackinger (1989) proposed one mechanism of avalanche initiation and propagation. A weak layer fails in compression, and that an area of bending in the overlying slab widens outward from the initial failure. Fracture mechanics texts (Broeck) indicate that a component of shear is necessary for fracture propagation in through a weak layer. We hypothesize that propagating fractures on level terrain also require a compressive component. This mixed mode fracture of a weak layer should be associated with whumpfs and remotely triggered avalanches, most of which involve propagation on low-angled terrain.

Meyers (1994) report that the five most common types of elastic waves in solids are: longitudinal waves, distortional waves, surface waves (Rayleigh), interfacial waves and flexural waves (in bars and plates). The slab overlying a weak layer is considered a plate that can propagate flexural waves. The fracture and collapse of the weak layer creates a flexural wave in the overlying slab. This flexural wave is couple to the fracture and collapse of the weak layer, and controls the propagation speed of the fracture. Flexural waves are dispersive, that is, velocity changes with wavelength. This could help to explain the large difference between estimated speeds by observers in different locations. Wilson (1955) states that any disturbance of a floating sheet of ice generates flexural waves in the sheet of ice, and that as the stiffness of the ice sheet increases so to does the flexural wave velocity. A flexural wave would travel much slower in a thinner seasonal snowpack than in thicker firn layers located in Antarctica and Greenland.

This experiment was the first to make this important snowpack measurement. Future work should focus on using more geophones in a two dimensional array. Motion should also be recorded in two directions so that the wave traveling through the overlying slab can better be characterized.

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