Snowpack characteristics associated with avalanche accidents

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Reports of 93 fatal avalanche accidents in Canada between 1972 and 1991 indicate that most of them involved dry snow slabs and were triggered by people. Slab thicknesses averaged 0.86 m and over half the slabs included snow deposited prior to the most recent storm. Two persistent microstructures of snow, namely surface hoar and faceted grains, were commonly reported in the weak layers believed to have released the overlying slabs. The people that had difficulty recognizing or evaluating instabilities involving surface hoar and faceted grains include amateur recreationists as well as professional forecasters and guides. This suggests that present field tests and forecasting techniques may be unsatisfactory for assessing the stability of slabs which overlie layers of surface hoar or faceted grains.

Key words: avalanche accident, avalanche forecasting, critical weak layer, slab avalanche, snowpack microstructure, avalanche trigger.

Des rapports de 93 avalanches ayant causé des accidents meurtriers au Canada entre 1972 et 1991 indiquent que la plupart d'entre elles impliquaient une plaque de neige sèche et étaient déclenchées par des personnes. Les épaisseurs des plaques étaient en moyenne de 0,86 m et plus de la moitié des plaques incluaient de la neige tombée antérieurement à la tempête la plus récente. L'on a rapporté couramment que dans les couches faibles, réputées être le siège du glissement des plaques sus-jacentes, deux microstructures de neige étaient trouvées de façon systématique, soit le givre de surface et les grains à facettes. Les personnes qui avaient de la difficulté à identifier et évaluer les instabilités impliquant du givre de surface et des grains à facettes comprennent les amateurs de récréation en nature de même que les professionnels des prévisions et les guides. Ceci suggère que les essais actuels de terrain et les techniques prévisionnelles peuvent être insatisfaisantes pour évaluer la stabilité des plaques qui recouvrent des couches de givre de surface ou de grains à facettes.

Mots clés : accident d'avalanche, prévision d'avalanche, couche faible critique, avalanche en plaque, microstructure de massif de neige, déclenchement d'avalanche.

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Introduction

The purpose of this study was to determine snowpack characteristics under which forecasting with existing techniques is difficult, so that these conditions can be used to assess new field tests of snow stability and avalanche forecasting techniques. To determine the conditions under which existing techniques have limited effectiveness, we examined the snowpack characteristics common to avalanche accidents, including those involving trained professionals.

We examined the reports (Canadian Avalanche Centre files, Stethem and Schaerer 1979, 1980; Schaerer 1987) of 93 fatal avalanche accidents in Canada that occurred between 1972 and 1991. These accidents resulted in 155 fatalities. The study was limited to fatal accidents in Canada because reports of nonfatal accidents often lack detail and because only about half the nonfatal accidents are reported (Schaerer 1987). Fatal accidents prior to 1972 were not considered because the reports of these accidents frequently lacked the snowpack details relevant to this study and because these earlier accidents might be less representative of the limitations of present field tests and forecasting techniques.

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Decision maker

Some avalanche accidents involved people lacking experience in winter mountain travel who entered avalanche terrain when the avalanche hazard was high or extreme and to whom such hazard information was readily available. Such accidents clearly do not reflect on present forecasting techniques. However, experienced mountaineers and ski tourers, some of whom work as forecasters or guides, have been caught and occasionally injured or killed in avalanches. Also, in 18 relatively well-documented accidents, professionals made decisions regarding the snow stability and (or) terrain that proved fatal to themselves or others. We believe snowpack characteristics common to accidents with professional "decision makers" represent conditions under which existing forecasting techniques may be unsatisfactory.

The decision maker was classified as an amateur in 64 of the 93 accidents, as a professional in 18 accidents, and as unknown in 11 accidents based on the following criteria. Professional decision makers were avalanche forecasters or guides trained and employed to evaluate avalanche hazards who selected or "opened" the terrain where the victim was caught. The decision maker was classified as an amateur when the report does not indicate that a guide selected or

TABLE 1. Slab thickness by mountain region

	No. of cases	Thickness, m (average ± SD)
Coast Mountains		
Class 2 and larger slab avalanches (from Duffey Lake area 1980–1992)	259	0.71 ± 0.56
Fatal slab avalanche accidents	8	0.83 ± 0.32
Interior Ranges		
Class 2 and larger slab avalanches (from Cariboos and Monashees 1990–1992)	181	0.53 ± 0.35
Fatal slab avalanche accidents	23	0.78 ± 0.43
Rocky Mountains		
Fatal slab avalanche accidents	27	0.93 ± 0.54
Canada		
Fatal avalanche accidents	58	0.86 ± 0.47

a forecaster opened the specific terrain to the victims. Most of the accidents involving amateur decision makers took place in parks or backcountry areas not used by commercial recreational operations which, in Canada, are rarely closed to the public because of avalanche hazards. In the remaining 11 accidents, the decision maker could not be classified as an amateur or professional since the report either: (*i*) leaves doubt as to the compliance of the victim with the guide's or forecaster's directions, (*ii*) does not indicate a professional decision maker in a situation in which one was likely, or (*iii*) creates doubt as to the training or the employment status of the decision maker.

Release mechanism

The type of avalanche release depends on the cohesion of the unstable snow. Point release avalanches begin in relatively cohesionless snow when a volume of snow, typically the size of a snowball, slips and sets additional snow in motion forming an inverted "V" below the initial failure point. Cohesive snow releases as a slab avalanche (Fig. 1) and such releases begin as a shear failure in a weak snow layer below the relatively cohesive layer(s) of the slab (e.g., McClung 1987).

Of the 93 fatal avalanches in the present study, 67 were reported as slab avalanches, 1 was a point release, and the type of release was unspecified for the remaining 25 avalanches. Although point release avalanches are very common, many point release avalanches, particularly dry ones, are small. The majority of fatal accidents result from slab avalanches because they are often larger than point releases and are frequently triggered from a point below the top of the avalanche. Further, we believe that, compared with point releases, slab avalanches are more likely to occur without a marked increase in air temperature or more than 24 h after loading by precipitation or wind-transported snow. Also, the complex release mechanism that involves stress and strain concentrations around flaws in the weak layer (McClung 1987; Bader and Salm 1990) may contribute to forecasting difficulty.

Geographic distribution of accidents

The mountains of western Canada can be conveniently divided into the Interior Ranges of British Columbia flanked by the Coast Mountains on the west and the Rocky Mountains on the east. The 93 fatal accidents are not evenly distributed. Only 14 occurred in the Coast Mountains whereas 30 occurred in the Interior Ranges and 42 occurred in the Rocky Mountains. Four accidents occurred in the mountains of Quebec. From the accident reports we were unable to determine the mountain range for the three remaining accidents.

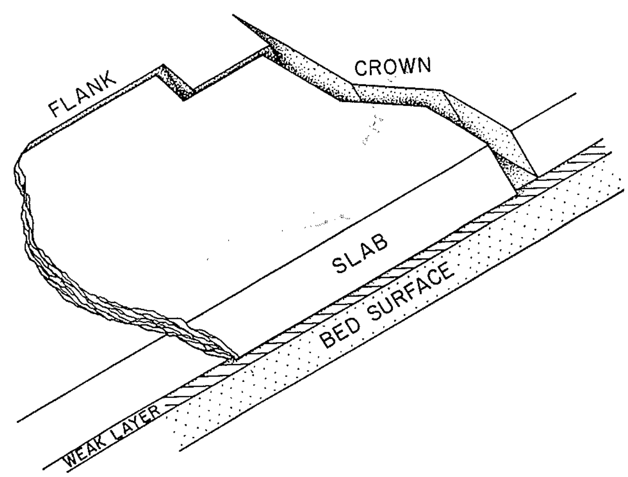

FIG. 1. Slab avalanche nomenclature.

Geographic distribution of snowpack characteristics

Snowpack characteristics including thickness vary between these three mountain regions and are relevant to subsequent discussions of the depth of critical weak layers. In much of the Rocky Mountains of western Canada, the mid-winter snowpack often approximates 1 m in thickness. During early and mid-winter, such a thin snowpack favours the growth of faceted grains including the advanced form known as depth hoar. The relatively thin snowpack of the Rocky Mountains is in contrast with the Coast Range and the Interior Ranges of British Columbia where the mid-winter snowpack often exceeds 2–3 m. As a result of this thicker snowpack, faceted grains including depth hoar are less common in the Interior Ranges and Coast Mountains.

Surface hoar forms when water vapour from the air sublimates as ice crystals on the snowpack surface. Once

TABLE 2. Slab avalanche layering by mountain region

	No. of cases	% slab avalanches that include old snow
Coast Mountains		
Class 2 and larger slab avalanches (from Duffey Lake area 1980–1992)	259	56
Fatal slab avalanche accidents	6	33
Interior Ranges		
Class 2 and larger slab avalanches (from Cariboos and Monashees 1990–1992)	201	30
Fatal slab avalanche accidents	21	86
Rocky Mountains		
Fatal slab avalanche accidents	24	88
Canada		
Fatal avalanche accidents	51	82

TABLE 3. Microstructure of critical weak layers for fatal slab avalanche accidents

	Decision maker		
Weak layer microstructure	Amateur	Professional	Unknown
Unspecified new snow	4 (9%)	0 (0%)	0
Faceted grains	8 (18%)	5 (29%)	0
Depth hoar	8 (18%)	1 (6%)	1
Surface hoar	9 (20%)	8 (47%)	2
Unspecified old snow	5 (11%)	2 (12%)	2
Unknown	11 (24%)	1 (6%)	0
Total	45	17	5

buried by subsequent snowfall, surface hoar usually persists as a thin weak layer (rarely thicker than 25 mm). Persistent surface hoar layers are more common in the Interior Ranges and the Rocky Mountains than in the Coast Mountains.

Slab thickness

Average slab thickness (measured vertically) is reported for 58 of the 67 slab avalanche accidents, specifically 27 of 33 in the Rocky Mountains, 23 of 25 in the Interior Ranges, and all 8 of the slab avalanche accidents in the Coast Mountains (Table 1).

In the Rocky Mountains, slab thicknesses for the fatal slab avalanches averaged 0.93 m (Table 1) and 88% of them included "old" snow, that is, layers deposited prior to the most recent storm (Table 2). In view of the relatively thin snowpack commonly found in the region, this suggests that the weak layers that release many of the fatal slab avalanches are located near the base of the snowpack. These fatal avalanches appear to be typical of the slab avalanches large enough to kill a person (class 2 and larger according to NRCC–CAA 1989) since approximately 80–90% of the class 2 and larger avalanches in the Rocky Mountains include layers of old snow (G. Israelson, personal communication).

We obtained accident reports from a 5000 km^2 area of the Cariboos and Monashees centred around Blue River B.C., an area that we regard as representative of the Interior Ranges. Based on over 180 reports of class 2 and larger slab avalanches that occurred between January 1990 and April 1992, slab thicknesses averaged 0.53 m (Table 1) and 30% of these slab avalanches included layers of old snow (Table 2). This is in contrast with the reports of fatal slab avalanche accidents from the Interior Ranges, for which slab thicknesses averaged 0.78 m and 86% of the slabs included old snow. The increased frequency of old snow layers in the fatal slabs and the greater slab thicknesses suggests that it is more difficult to assess snow stability when the weak layers capable of releasing slab avalanches are deeply buried and underlie layers of old snow.

The Duffey Lake area north of Garibaldi Park has a snowpack that we regard as typical of the Coast Mountains. Based on 259 class 2 and larger slab avalanches reported during the winters of 1980–1992, slab thicknesses averaged 0.71 m (Table 1) and 56% of such slabs included layers of old snow (Table 2). However, we cannot compare these figures with those for fatal slab avalanche accidents because there are only 14 reports of fatal accidents for Coast Mountains and only 8 of these specify slab thickness and only 6 specify whether the slab included old snow.

As shown in Table 2, more than 85% of the fatal slab avalanche accidents in the Rocky Mountains and the Interior Ranges involve snow layers deposited prior to the most recent storm. One reason why such snow layers are

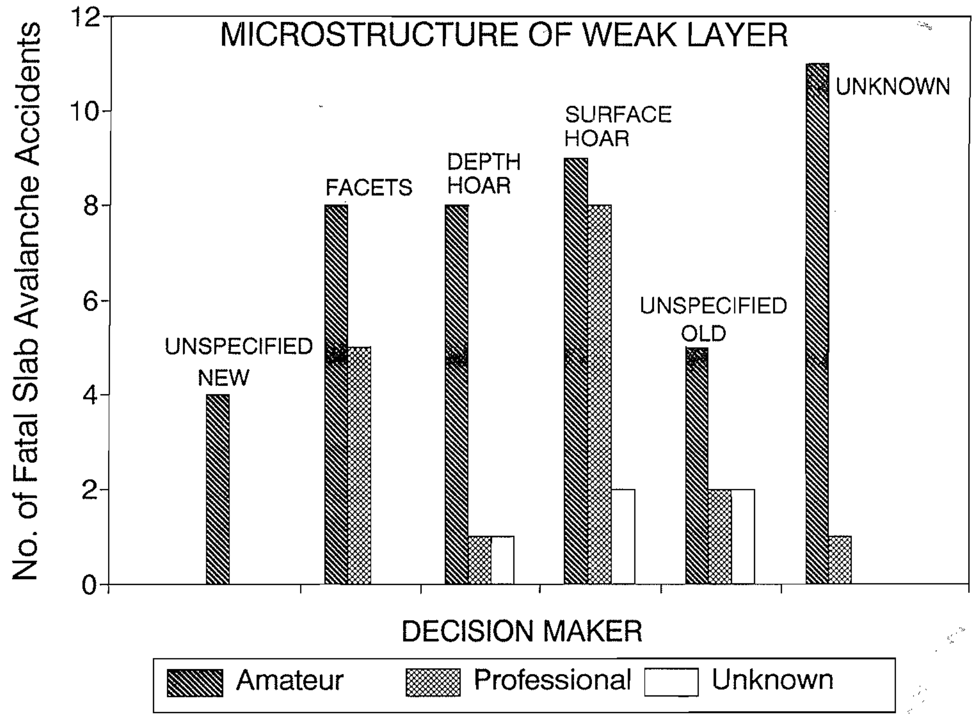

FIG. 2. Critical weak layers and decision makers for fatal slab avalanche accidents in Canada 1972–1991.

associated with a high proportion of fatal accidents may be that "new" snow layers (from the recent storm) are typically not as deeply buried as old snow layers, so slab avalanches involving only layers of new snow are smaller and hence less likely to cause fatalities than those including layers of old snow.

A second reason why slabs that include layers of old snow should cause a majority of the fatal accidents involves forecasting techniques. During storms, forecasting is often facilitated by observations of natural avalanches (triggered by loading) on slopes within the forecast area, if a particular slope releases naturally then nearby slopes with similar aspect and elevation are likely unstable. Furthermore, most forms of newly precipitated snow metamorphose and gain strength (stabilizing the overlying slab) within several days of deposition. Forecasting instabilities, involving older and deeper weak layers, many days after storms, without the observations of naturally triggered avalanches, is more difficult with present techniques. This is supported by the fact that 14 of the 17 fatal accidents with professional decision makers involved slab avalanches that included layers of old snow. In fact, there is no confirmation of any accidents with professional decision makers for slabs that included only snow from the recent storm since the remaining three accidents did not report if the slab included old snow.

Microstructure of critical weak layers

The microstructure of snowpack layers can be classified (NRCC–CAA 1989; Colbeck *et al.* 1990). The number of fatal accidents for particular microstructures of weak layers and types of decision makers is shown in Table 3 and Fig. 2. Various forms of "new snow" (precipitation forms recognizable under low magnification) only account for four accidents, all of which involve amateur decision makers. Note that 25 (56%) of the slab avalanche accidents with amateur decision makers and 14 of the 17 (76%) accidents with professional decision makers involve weak layers of surface hoar, faceted grains or depth hoar, all of which are slow to metamorphose to the stronger, more rounded microstructure described in Colbeck *et al.* (1990). Such layers may persist for weeks as potential failure planes within the snowpack.

Either surface hoar or faceted grains may form a snowpack layer as thin as 1–2 mm, which is difficult to observe in a profile of snow layers. Some field tests such as the rutschblock (Föhn 1987*a*) are, within limitations, useful for finding thin critically weak layers.

Triggers

Of the 70 fatal avalanches for which the trigger was reported, 42 were triggered by skiers, 15 were triggered by persons on foot or in a few cases on toboggan, 8 were triggered by snowmobiles, and 5 were triggered naturally. In short, people triggered 93% of the 70 fatal avalanches for which the trigger was reported. The high incidence of human triggers in recreational activities is consistent with Schaerer (1988) who reports that, between 1969 and 1987, approximately 85% of avalanche victims were engaged in recreation at the time of the accident and with Daffern (1983, p. 3) who notes that the majority of avalanche victims triggered the avalanche themselves.

The additional shear stress within the snowpack caused by skiers and people on foot decreases with depth. Approximate values based on static loading have been calculated by (Föhn 1987*b*). For depths less than 0.5 m, the additional shear stress caused by human load may be many times the stress caused by the overlying snowpack layers. At greater depths the incremental shear stress decreases gradually from approximately 60% of the shear stress caused by the overburden at 0.5 m to approximately 15% at 1 m. Although snow is a highly rate-sensitive material (Narita 1980), and the loading caused by skiers and people on foot involves dynamic loading which Föhn did not consider, his estimates clarify the effectiveness of people for triggering slab avalanches.

Free water content of snow

Of the 63 fatal avalanches for which the free water content was reported, 55 were dry (90%), 2 were moist, and 6 were wet. Fourteen of the 63 accidents involved a professional decision maker and all 14 of these were reported as dry snow avalanches. However, this does not necessarily imply that the stability of dry snow is more difficult to evaluate, since most recreationists, such as skiers, prefer dry snow and would likely expose themselves to avalanche hazards in moist and wet snow much less frequently. Consequently, most accidents probably involved dry snow simply because recreationists (potential victims and potential triggers) seek out dry snow conditions.

Conclusions

Reports of 93 fatal avalanche accidents in Canada between 1972 and 1991 show that at least 59% of the fatal avalanches were dry, 70% were triggered by people, 72% were slab avalanches, 61% of the 67 fatal slabs included layers of snow deposited prior to the most recent storm, and 63% of all fatal slab accidents and 82% of the fatal slab accidents involving decisions made by professional guides or forecasters involved weak layers of surface hoar, faceted grains or depth hoar.

However, these minimum percentages make no assumption about the information missing from some accident reports. By assuming that such missing information does not differ substantially from the more complete information from other accidents, we estimate that: 87% of the fatal avalanches were dry, 93% were triggered by people, 99% were slab avalanches, 82% of fatal slabs included layers of snow deposited prior to the most recent storm, and 91% of all fatal slab avalanche accidents and almost all slab accidents involving decisions made by professional guides or forecasters involved weak layers of surface hoar, faceted grains or depth hoar.

Research into forecasting techniques should focus on dry slab avalanches involving layers of old snow. Also, more effective forecasting techniques and field tests are needed for recognizing and evaluating weak layers involving surface hoar, faceted grains or depth hoar.

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