Snow Cover and Avalanches in the High Alpine Zone of Western United States

Arthur JUDSON

Rocky Mountain Forest and Range Experiment Station
*Fort Collins, Colorado, U.S.A.**

Abstract

For the past 17 years, alpine snow and avalanches have been studied at a high mountain pass in the Colorado Rockies. The site has a continental climate representative of conditions in the High Alpine Zone of the Western United States.

A brief analysis of the characteristics of 80 avalanche tracks in Colorado, and the frequency and type of avalanches, shows that slab avalanches account for more than 80% of all occurrences, and soft slabs are most frequent.

Snow cover data, taken bimonthly from pits in a level test field in the timber, includes distribution of and changes in: grain shape, grain size, snow temperatures, temperature gradients, density, and hardness in each layer of the snow cover throughout the winter months. Means and extremes of these parameters are discussed, and a comparison of the test field pits with profiles taken at five adjacent avalanche sites are analyzed. The depth, grain shape, and strength of the snow in the lowest layer at the test field was similar to that found in the nearby avalanche starting zones. The greatest difference was found in the strength and thickness of the middle layers of the pack, and is attributed to increased wind action at the avalanche sites.

Avalanche hazard forecasting with reference to the use of snowpits and weather data in the High Alpine Zone is discussed; and a method of using precipitation data to determine when to start avalanche control action during major storms is outlined.

I. Introduction

There are at least three avalanche zones, each designated by different climatic characteristics, in the Western United States. From West to East they include the Coastal Alpine Zone of the Sierra-Cascade Crest along the West Coast, the Middle Alpine Zone of the Wasatch and Sawtooth Ranges in Utah and Idaho, and the High Alpine Zone of the Continental Divide areas in the Rocky Mountain chain.

Lower temperatures, less snowfall, and higher winds are encountered in the interior ranges. The High Alpine Zone is dominated by a continental climate. It includes the northern Colorado Rockies and small portions of Utah, Wyoming, and Montana. The hazard from avalanches in this zone is greatest in Colorado, where numerous all-weather mountain highways traverse avalanche areas. The first comprehensive studies of snow and avalanches in the High Alpine Zone were initiated at Berthoud Pass, Colorado, in October 1949 by W. M. Borland, hydrologist with the U.S. Bureau of Reclamation. The U.S. Forest Service took over the Station in 1950 and continued the snow studies

* Forest Service, U.S. Department of Agriculture, with central headquarters maintained at Fort Collins in cooperation with Colorado State University.

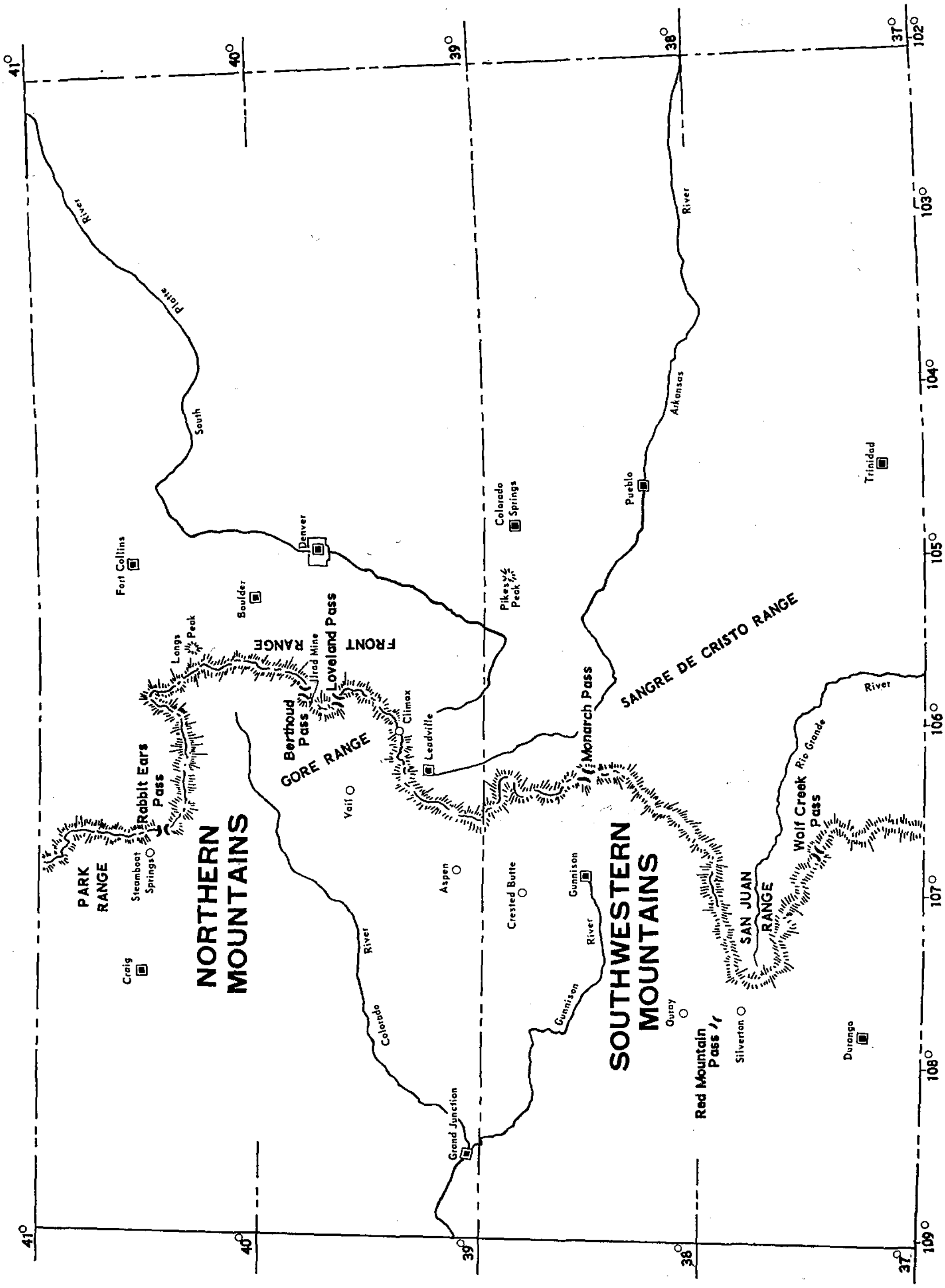


Fig. 1. State of Colorado. The 39th parallel was arbitrarily chosen to separate the northern and southwestern mountains. Most of the high mountain passes cross the Continental Divide, shown meandering north-south across the State

as part of its avalanche hazard forecasting program. There are now 17 consecutive winters of data on snow, weather, and avalanches from this Station. It is located 45 miles west of Denver on an east-west section of the Continental Divide (latitude 39°48′ N, longitude 105°47′ W), at an elevation of 3 450 m.

II. Snow Avalanches in Colorado

Most avalanches affecting life and property in Colorado occur along four high mountain passes (Frutiger, 1964), at hydroelectric and water diversion projects, in the ski areas, and at some of the mining operations. Nearly all of these snowslides are controlled by explosives during the winter months (November-April).

Characteristics of the avalanche tracks. Of some 80 avalanches affecting major highway routes (Frutiger, 1964), more than half start at or above timberline, which varies from 3 300 to 3 600 m. Most of the tracks have an average gradient between 27° and 35°, and are between 300 and 900 m long. The word track as used here refers to that part of the avalanche which lies below the starting zone and above the runout-damage zone. The longest track is 1 850 m. The avalanche tracks have vertical drops varying from 60 to 1 000 m, with an average of 450 m.

Frequency of occurrence. Avalanche snow from 40% of the highway slide paths crosses the road one or more times during the average winter. Avalanches affecting Colorado highways most frequently are the Seven Sisters on Loveland Pass, and the Brooklyns and Blue Point on Red Mountain Pass. These snowslides cover the road many times each winter, and generally react to every storm of significance. Avalanches at the Urad Mine and the Berthoud Pass ski area have the highest recorded frequency of any area in the State as the result of intensive avalanche control programs.

The number of avalanche tracks and the frequency of avalanches for six areas (Fig. 1) in Colorado, 1950–1965, are as follows:

Location and highway number	Number of avalanche tracks	Average number of avalanches per year
Berthoud Pass ski area U.S. 40	9	50
Urad Mine* 1 mile west of U.S. 40	21	60
Berthoud Pass U.S. 40	12	6
Loveland Pass U.S. 6	13	24
Wolf Creek Pass U.S. 160	12	17
Red Mountain Pass, Molas Divide, Coal Bank Hill U.S. 550	43	40
Total	110	197

* 1964–1966 only.

More than three-fourths of the recorded avalanches in Colorado occur from December through March (Fig. 2). Snowslides have covered the highway as early as September 27 on Berthoud Pass and as late as May 7 on Loveland Pass. The difference in the occurrence pattern shown for the Berthoud Pass-Loveland Pass area, and that for Red Mountain Pass in the southwestern part of the State, is probably related to the deeper and more stable snow cover in the latter area. It may also reflect a difference in the intensity of avalanche control measures in the two areas.

Type of avalanche. Records from the Berthoud Pass ski area show that soft slab avalanches account for 62% of all occurrences (Fig. 3). They almost always fall during

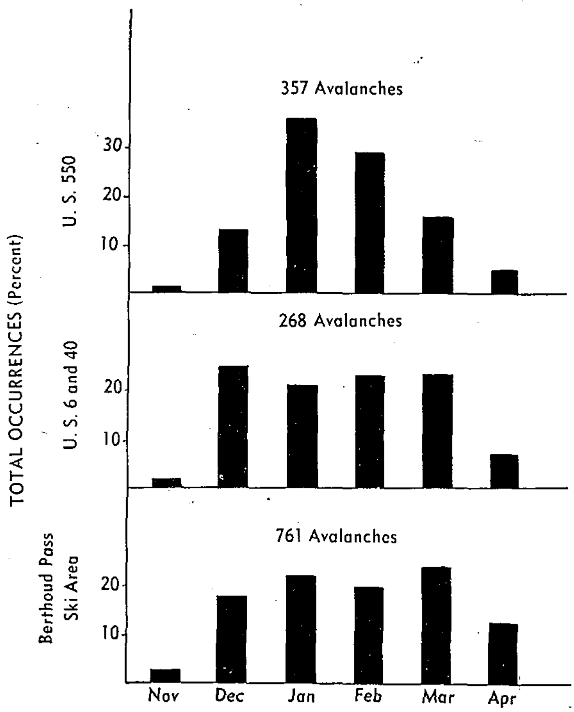


Fig. 2. Avalanche occurrence by months at Berthoud Pass ski area, Loveland and Berthoud Pass (U. S. 6 and 40), and Red Mountain, Molas Divide, Coal Bank Hill (U. S. 550) 1950–1965

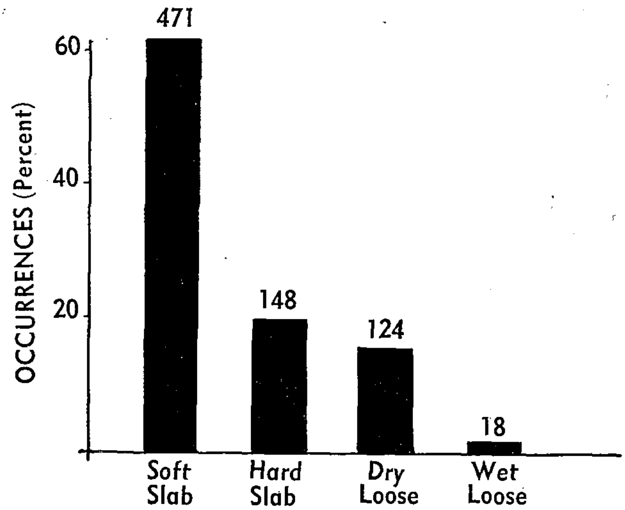


Fig. 3. Avalanche types recorded at Berthoud Pass ski area 1950–1965 (761 occurrences)

or immediately following a storm, and are therefore easily anticipated. Experience gained in the Berthoud Pass area indicates that the soft slab is most frequently formed during periods of heavy snow accompanied by moderate winds and temperatures above −12°C. Nineteen percent of all avalanches at this ski area were classified as hard slab. A hard slab is often formed during periods of high winds accompanied by little or no new snow, with temperatures generally less than −12°C.

Large avalanches involving dry, loose snow are infrequent in this zone because deep snowfalls are almost always accompanied by high winds, which create slabs. Wet, loose snow avalanches account for only 2% of the total.

Records from the Colorado Department of Highways show that 80% of the natural avalanches affecting highways occur during storms. The same percentage has been given for the Alta ski area (Middle Alpine Zone) in the Wasatch mountains of Utah (U. S. Forest Serv., 1953). This frequency emphasizes the importance of weather factors in the development of direct-action avalanches. A recent study (Judson, 1964) showed wind to be the most important factor contributing to direct-action avalanches in the High Alpine Zone. Only 10% of the avalanches in this zone are released when temperatures are above 0°C. Two reasons account for this low percentage of damp or wet slides. Temperatures at the mid and upper track levels are seldom above freezing during the winter months; when they are, it is only for short periods of time. Also, the constant control of avalanches by explosives keeps snow depths in the tracks to minimum levels so that wet slides of major proportions are very rare.

Loss of life. Available records on the number of lives lost in avalanches in Colorado date back to 1884, although figures prior to 1948 are incomplete. The

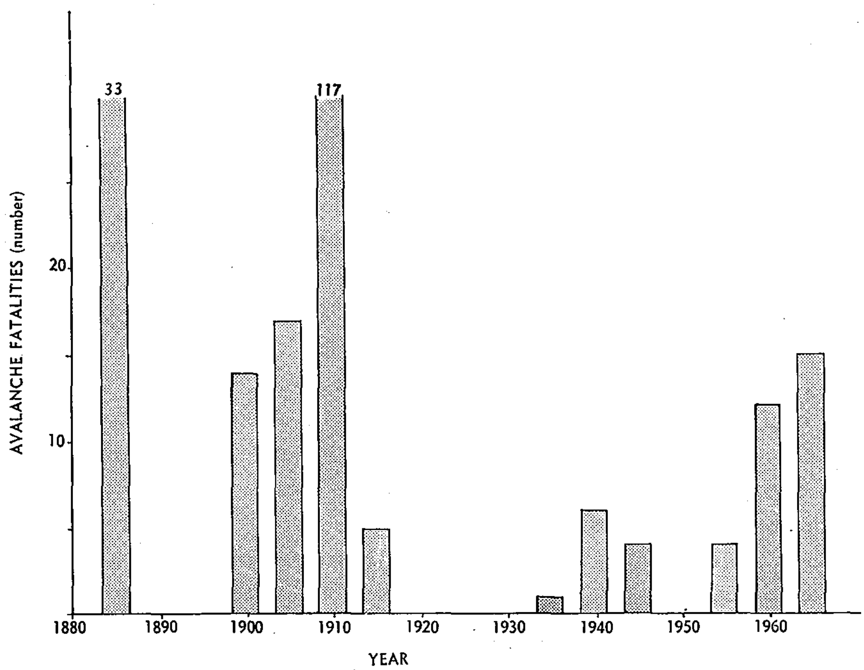


Fig. 4. Avalanche fatalities in Colorado by 5-year periods, 1880–1965

Colorado mountains were heavily populated during the Gold Rush period from 1860 to 1910. From 1884 to 1910, more than 170 people were killed by avalanches in Colorado. Many of these deaths resulted when houses were built directly in the avalanche paths—more than 113 people, most of then in buildings, were killed by avalanches during the 1905–1906 winter. In the years following 1910, a general population decline in the mountain communities reduced the hazard from avalanches greatly. This trend was reversed in the late 1940's with the advent of the winter sports boom. Today winter automobile traffic through the mountains is heavier than ever before, with an average of 4 000 cars per weekday crossing Loveland Pass alone. On weekends it increases to 8 000 vehicles per day on this Pass. The increasing number of avalanche victims in the past decade, shown in Fig. 4, is a reflection of the greater number of people now exposed to avalanche hazard. This is occurring despite stepped-up avalanche control efforts which now feature both structural and explosive control techniques. The greatest potential avalanche hazard today in Colorado is to the highway traveler, and a maximum planning effort is needed, particularly where new highway alignments are contemplated. The introduction of moderately-priced, oversnow vehicles is expected to further increase hazard from snowslides in the more remote regions of the Colorado mountains. A general avalanche warning service is now needed to cope with the increased avalanche hazard.

III. Regional Climate

Average annual precipitation in the alpine regions of northern Colorado ranges from 635 to 1 020 mm, about three-fourths of which falls in the form of snow above 3 000 m. Snowfalls are frequent and light, with measurable amounts occurring on 42% of the November-April days at Berthoud Pass (Judson, 1965). Annual snowfalls average from 917 cm at Berthoud Pass to more than 1 016 cm at Rabbit Ears Pass in northwestern Colorado. A major portion of the winter precipitation on the Continental Divide is from Pacific moisture. Gulf moisture from the Texas coast is responsible for only a small percentage of the winter snows on the Divide, but, in conjunction with Arctic air from Canada, produces the highest snowfall intensities—239 cm fell in one 3-day period at Berthoud Pass.

Mean annual temperatures average below 0°C in all areas above 3 400 m in northern Colorado. Maximums seldom exceed 0°C during the winter months, and minimums below −20°C are common. The coldest temperatures, about −35°C in the alpine areas and −45°C in the mountain valleys, are associated with Arctic outbreaks from Canada.

Winds over the exposed sections of the Continental Divide above 3 700 m are strong, and average 11–13 m/sec from November to April. During zonal flow conditions that favor development of the mountain wave, sustained windspeeds of 25 m/sec are common, with one-hour averages up to 37 m/sec recorded on the Divide east of Berthoud Pass. Peak gusts to 49 m/sec were recorded at this site in December 1964. The combination of strong winds and cold, dry snow leaves portions of the windward side of the Divide free of snow throughout much of the winter, and results in deep deposits on lee slopes. Snow depths in such areas commonly reach 5–8 m during the winter. Windspeeds are sharply reduced below timberline—and average about 4-6 m/sec from November-April.

IV. Snow Cover

The seasonal snow cover at the 3 400 m level usually begins in late October or early November, and is accompanied by constructive metamorphism. The resulting snowpack is structurally weak. Snow depths gradually increase through December while stability decreases. The early season snowpack below timberline will not support the weight of a man on skis except on packed trails. By mid-January the middle layers begin to show a marked gain in strength, presumably due to an increase in intergranular bonding associated with age hardening. The snow depth then increases linearly with time to its average maximum depth of 2.2 m by mid-April. Snowpack temperatures usually become isothermal for the first time in late April, and strength decreases. The intrusion of melt water accompanying higher temperatures further weakens the fragile depth hoar layer, and oversnow travel is usually confined to periods when ambient temperatures are well below freezing. This "rotten snow" is widespread throughout the High Alpine Zone during May and June. Snow depths average near 1.5 m until late May, when they decrease at an average of 5 cm/day. The continuous snow cover usually disappears during the third week in June.

Bimonthly stratigraphic sections, taken routinely since 1950 at the Berthoud Pass test field, have provided a valuable record of deposited snow in the High Alpine Zone. The field, 3 450 m above sea level, is located in a small opening in the spruce-fir forest north of the Pass. It has an average radius of 18 m with an east exposure. The test field, well protected from wind, was artificially leveled in the fall of 1955.

Ten-year average values for layer heights, grain shape and size, density, temperature, and ram resistance for the profiles taken during mid-December, mid-February, and mid-April for the 1956-1965 period, are shown in Fig. 5 to illustrate the evolution of the snow cover during the winter months. For convenience, the layers shown in Fig. 5 are classified on the basis of grain shape, as outlined in the International Classification for Snow (Canada Nat. Res. Counc., 1954). The depth hoar layer, for lack of a better definition, is assumed to be composed of well-developed, coarse-grained, laminated, hemimorphic crystals, with or without cup development.

Depth hoar—grain shape e. Depth hoar crystals are a common feature of the snow cover in the Colorado Rockies where midwinter snow loads and settlement rates are low. The unstable crystals are particularly well developed during years when early season (November-December) snowfalls are light. Diameter growth rates average about 0.03 mm/day from November to January. Average crystal diameters vary from 2.1 mm in December to 3.0 mm in April. Maximum diameters seldom exceed 5 mm; the greatest observed was 10 mm. Density values average 0.27 g/cm^3 in December, and increase to 0.32 g/cm^3 in April. The decrease in specific weight in the lowest layer reported by other investigators is not apparent at Berthoud Pass. Snow temperatures at the soil-snow interface range from 0 to -2°C, with the mode being -1°C. Temperature gradients in this layer average -0.16°C/cm during early winter although gradients

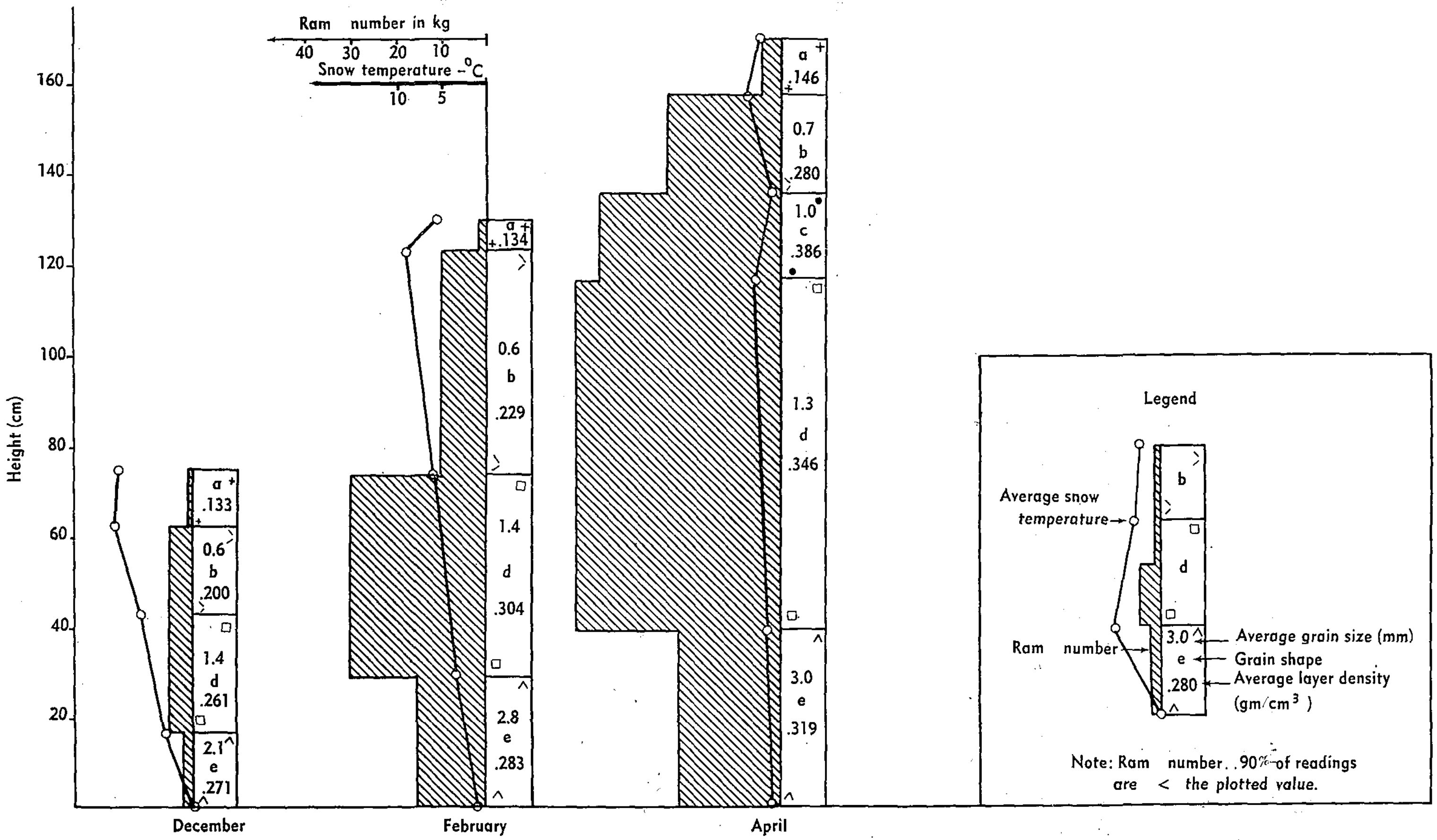


Fig. 5. Stratigraphic sections based on 10-year average values for pits dug in mid-December, mid-February, and mid-April 1956–1965, Berthoud Pass, Colorado

as high as $-0.60°C/cm$ have been recorded. Ram numbers are usually <5 kg, and frequently cannot be measured by the standard Haefeli rammsonde. Resistance to penetration increases slightly in April, but values are still low.

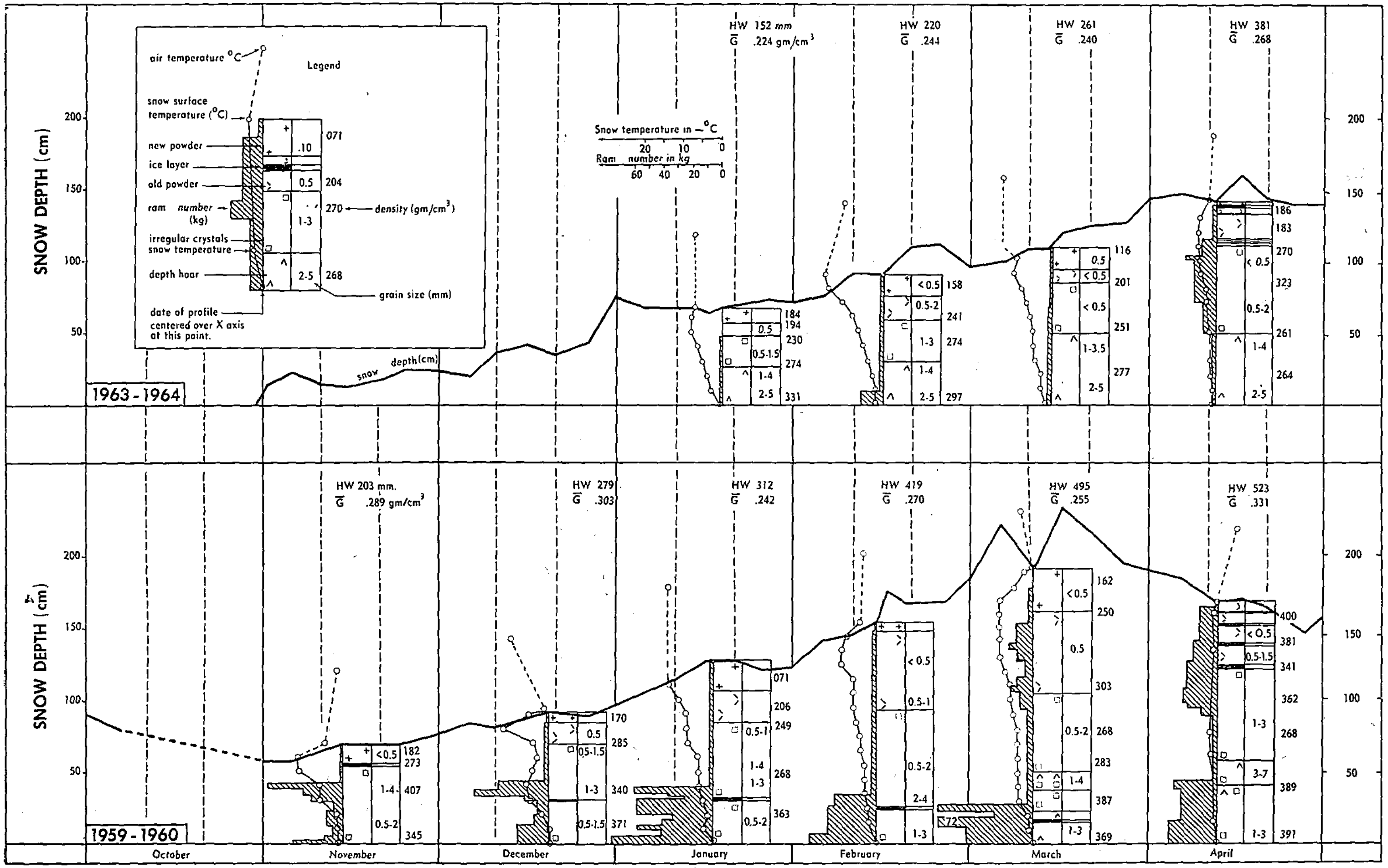
Stable old snow—grain shape d. Sintering of the medium-sized irregular grains composing this layer gives it greater strength than any other part of the snow cover at this altitude in Colorado. Grain diameters vary from 0.5 to 2.0 mm, and average about 1.4 mm throughout the winter. The average grain size in this layer remains nearly constant from December to April, as shown in Fig. 5. Densities average from 0.26 g/cm^3 in December to 0.35 g/cm^3 in April, when values as high as 0.40 have been recorded. Temperatures in the layer usually range from -3 to $-7°C$, and occasionally drop to $-12°C$. The steepest average negative temperature gradient ($-0.22°C/cm$) in the pack is found in the lower part of this stratum. Gradients average from $-0.13°C/cm$ in December to $-0.07°C/cm$ in April. Ram resistance varies from 4 to 50 kg, occasionally reaching 60 kg.

Snow transformed by melting and freezing—grain shape c. Only present in mid- or late April, this stratum is composed of rounded grains caused by repeated thawing and refreezing. Strength properties are highly variable, depending on snow temperature. Grain diameters vary between 0.5 and 3.0 mm, and average 0.7 mm. Density is greater than in any other section of the pack—it averages 0.39 g/cm^3 and may exceed 0.54 g/cm^3 on occasions. Temperatures are frequently isothermal at 0°C, and the sign of the gradient may change several times during any 24-hour period. The average gradient in this stratum is $+0.11°C/cm$. Ram numbers are extremely variable—they range from 0–80 kg.

Old powder—grain shape b. Irregular and crystalline forms characterize this low-strength layer. Average grain diameters remain near 0.6 mm throughout the winter. Average densities range from 0.20 g/cm^3 in December to 0.28 g/cm^3 in April. Temperatures vary between -4 and $-12°C$, but the average gradients are similar to those found in the d layer. They range from $-0.14°C/cm$ in December to $-0.01°C/cm$ in April. Resistance to penetration varies from 3 to 30 kg.

New snow—grain shape a. Irregular, stellar, and spatial dendrites each make up about 25% of all new snow crystal types falling at Berthoud Pass. Initial densities average 0.07 g/cm^3 and reach 0.20 g/cm^3 in less than 20 days. Listed values from 0.13 to 0.15 g/cm^3 shown in Fig. 5 are higher than expected due to wind action and lack of samples in the upper 5 cm. Grain diameters were not recorded in this stratum due to measurement problems encountered with surface samples. A wide range of temperatures is common in the new snow layer, with recorded values ranging from -1 to $-30°C$. Average gradients vary from $+0.02°C/cm$ in December to a maximum of $+0.35°C/cm$ in February. The sign commonly reverses at night, and under cold ambient conditions the gradient may attain $-1.0°C/cm$ near the surface. Resistance to penetration is too low to be measured by the Haefeli rammsonde.

Snow cover development in different types of winters. As in most geographical regions, there is considerable variation in the strength properties of the snow cover in the High Alpine Zone from winter to winter. These variations, particularly in the basal layers, have a direct influence on the behavior of snow avalanches (that is, whether


Legend
air temperature °C
snow surface temperature (°C)
new powder
ice layer
old powder
ram number (kg)
irregular crystals
snow temperature
depth hoar
date of profile centered over X axis at this point.
density (gm/cm³)
grain size (mm)
Snow temperature in −°C
20 10 0
Ram number in kg
60 40 20 0
snow depth(cm)
SNOW DEPTH (cm)
1963 - 1964
1959 - 1960
HW 152 mm
G .224 gm/cm³
HW 220
G .244
HW 261
G .240
HW 381
G .268
HW 203 mm.
G .289 gm/cm³
HW 279
G .303
HW 312
G .242
HW 419
G .270
HW 495
G .255
HW 523
G .331
October
November
December
January
February
March
April

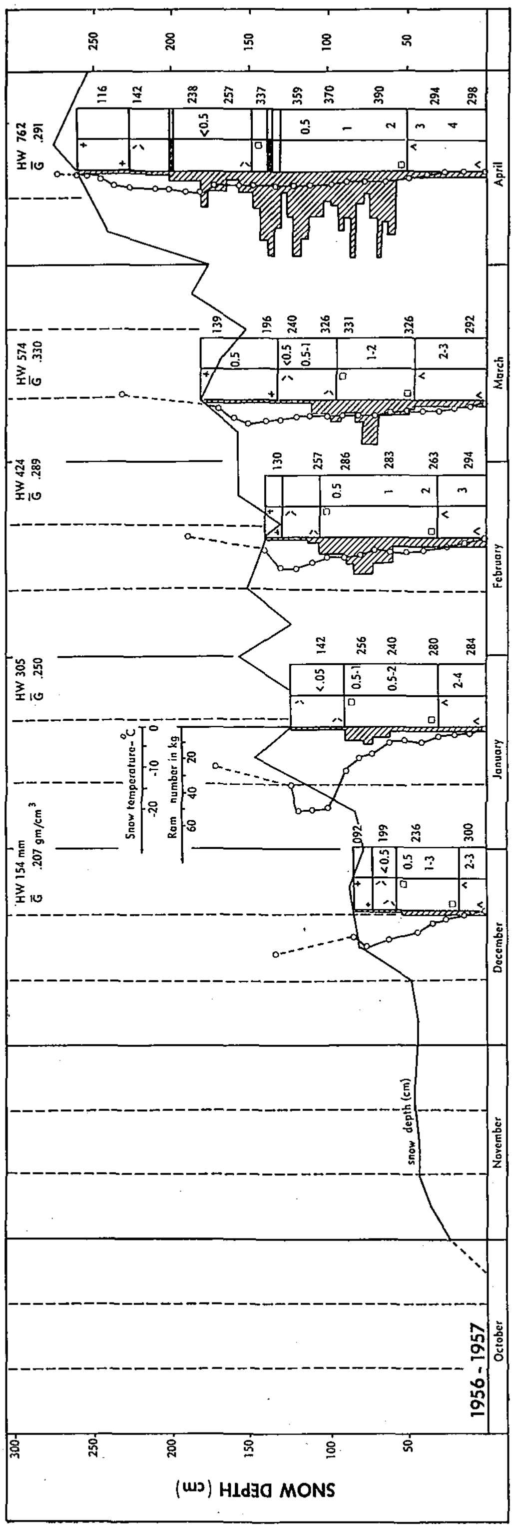


Fig. 6. Progressive snow profiles for three winters showing snow cover anomalies in years with different snowfall regimes at Berthoud Pass, Colorado. Q-12 Park test field. Elevation 3 450 m

they will be full-depth or surface slides). Three winters were chosen to show the differences in strength properties and snow depth (Fig. 6) that have occurred at Berthoud Pass.

Depth hoar development was above average and strength properties were low during the 1963–1964 winter. Snowfall was very light; only 38 cm of snow covered the ground in mid-December. Low temperatures enhanced depth hoar development, and 32 cm of the unstable crystals were present by mid-January. Grain sizes averaged about 3 mm, and densities ranged from 0.25 to 0.33 g/cm^3 in the depth hoar layer. Resistance to penetration remained less than 5 kg through late March. Numerous full-depth avalanches occurred throughout the winter.

During the 1959–1960 winter, depth hoar development was inhibited and strength properties in the lower portion of the pack were much greater than average. Snowfall was moderate and started early. Heavy snows in late September developed a 50 cm cover by October 1. Warm temperatures through October accelerated destructive metamorphism to produce a stable snow cover, which in November exhibited many features of a late-season snowpack. Fine-grained, irregular crystals of above-average densities (0.27–0.37 g/cm^3) were present throughout November and December. Ram resistance in the lower layers of the pack varied between 25 and 40 kg. Depth hoar was conspicuously absent through February, even though temperature gradients were favorable for constructive metamorphism.

Avalanche activity consisted of soft-slab surface slides until depth hoar developed in March.

The 1956–1957 profiles show snow cover conditions during a heavy snowfall winter. About 76 cm of snow covered the ground by mid-December 1956. Depth hoar development was somewhat less than average. By mid-January, snow depths increased to 142 cm, and densities varied from 0.24 to 0.28 g/cm^3 in the irregular crystals and depth hoar composing the lower layers of the pack. Snow depths increased steadily through mid-April, when more than 254 cm covered the ground. Depth hoar crystals averaging 4 mm in diameter were found from the soil to a height of 48 cm; density values ranged between 0.28 g/cm^3 in the depth hoar layer to 0.39 g/cm^3 in the c layer. Large, full-depth avalanches were common from January through April. The sudden decrease in ram resistance shown in the late March and mid-April profiles marks the upper boundary of the depth hoar layer.

Snow cover in avalanche starting zones. For reasons involving time, safety, and manpower, snow cover tests are almost always taken in accessible areas that are not affected by avalanches. The supposition is that the character of snow in the test field is basically similar to snow in nearby avalanche starting zones. At Berthoud Pass, there were only seven occasions when snowpits were made in both the starting zones of the avalanches (Fig. 7) and in the test field at Q–12 Park on the same days. For ease of comparison, the pits are grouped sequentially by months (Fig. 8).

The pits on December 22, 1956, show a remarkable similarity of grain shape, size, and arrangement. Ram numbers in the two areas (A–2 and T–1) are nearly identical. On December 24, 1965, the arrangement, size, and density of the lower layers of the pack again show basic similarities. The new powder shown in the test plot (T–1) does not appear on the A–4 profile because it was removed by wind during the previous night. The much lower temperatures shown near this avalanche fracture line are due, in part, to aspect (northeast) and steepness of slope, which keep the area in the shade during the entire afternoon, whereas the test field is exposed to sun during most of the daylight hours. Ram numbers are similar at both sites with the exception of the surface layer, where a hard wind crust is apparent on the A–4 site.

On January 13 and 14, 1956, the profiles (A–1 and T–1) show their greatest similarity in the e, d, and a layers. Again, the distribution of grain shapes is similar in the lowest layers. Densities are somewhat higher in the test plot than in the starting zone in the lower section of the profile, probably because of differences in aspect and slope. This trend is reversed for the upper sections because of greater exposure to wind at the fracture line profile. Ram profiles show low strength properties at both areas. Temperatures are also similar, but the gradient is less at the avalanche site.

The January 15–16, 1955, pits (A–5 and T–2) illustrate the extreme variations in snow depths encountered in the Colorado alpine region. Even so, the depth hoar layers at the two sites show a striking similarity in grain shape, density, and temperature. The catchment basin of the A–5 site receives more snow than any other slide path in the Berthoud Pass ski area because of heavy wind deposition. The density values shown in this profile are characteristic of the hard-slab layers that form on this slope each winter.

The T-2 test site is comparable to T-1 in elevation, aspect, and slope, but the opening in the spruce-fir forest is smaller at T-2. Snow depth on January 16, 1955, was 80 cm at T-2 and 91 cm at T-1.

On March 23 and 25, 1956, the profiles (A-1 and T-1) again show basic similarities in the e and d layers. Measurements were not taken in the shallow old powder layer in the test field. The greater depth of this layer at the avalanche site is due to wind deposition. Warm ambient temperatures make the thin, isothermal c layer comparable at both sites. In general, the ram numbers from these profiles have a similar range.

Grain sizes are about the same in all layers of the April 2, 1955, profiles (A-3

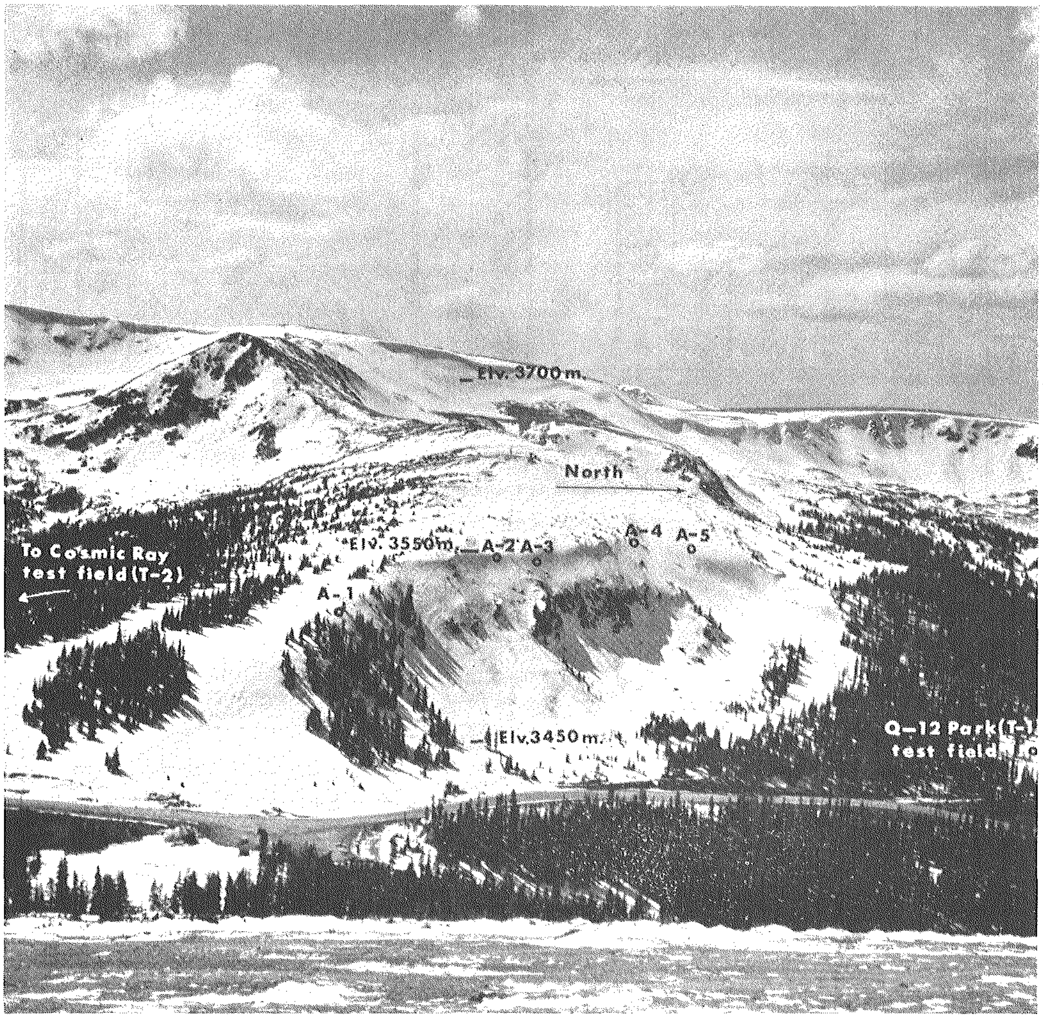


Fig. 7. Berthoud Pass study area on the west side of the Pass. Avalanche sites, numbered A-1 through A-5, show locations where snowpits were taken periodically from 1950-1966. The level test field called Q-12 Park (T-1), is site where bimonthly snowpits are taken each winter. Pits were dug at the T-2 site during winter 1954-1955

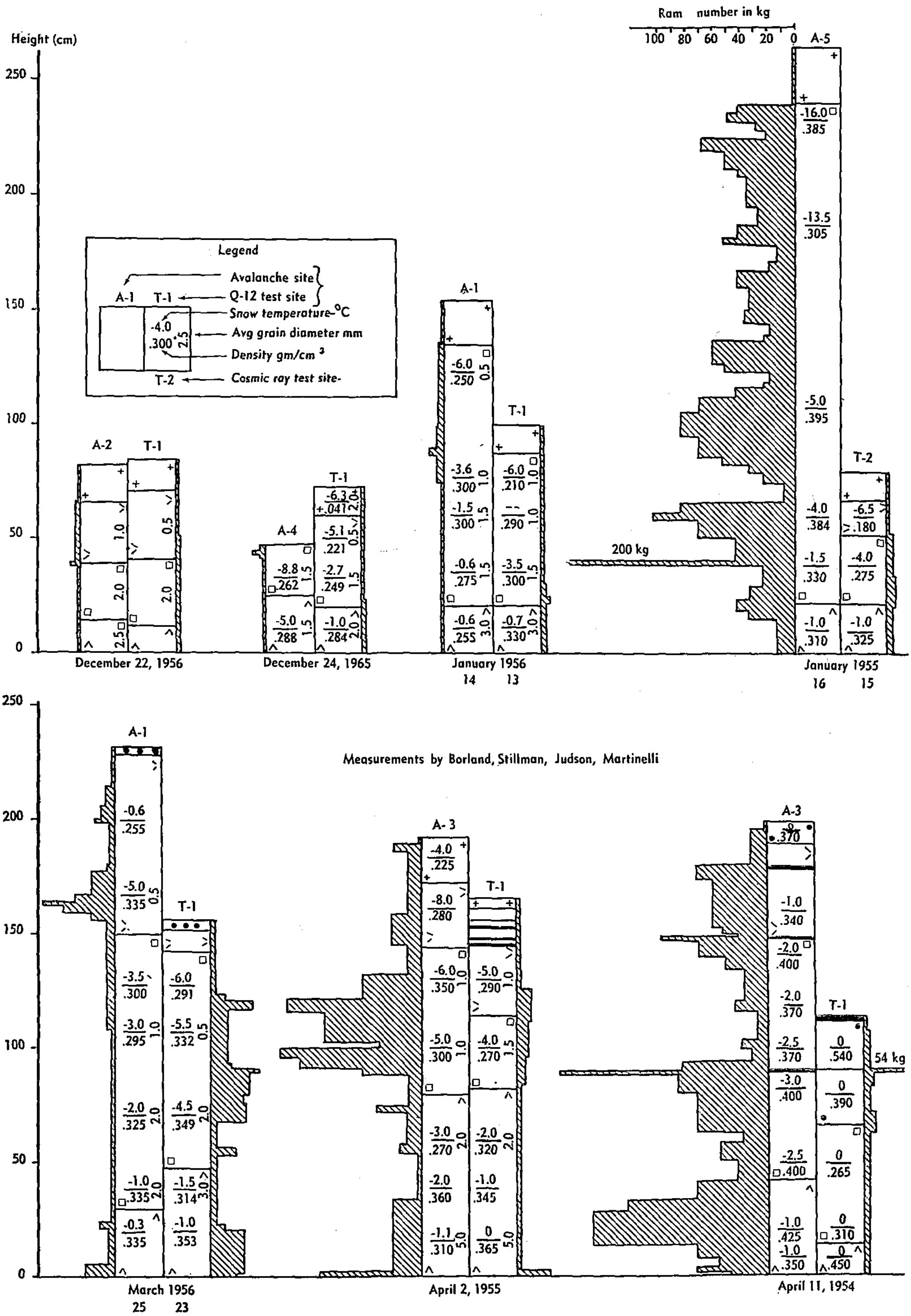


Fig. 8. Comparative stratigraphic sections at five avalanche sites (A-1 through A-5) with sections taken at two level test fields (T-1 and T-2) Berthoud Pass, Colorado

and T–1), as are temperatures and temperature gradients. Density differences in the e layer are probably due to the isothermal temperature in the lower section at the test field. Densities in the d layers are greater in the A–3 profile as a result of wind action. They are similar in the b layer. Variations in resistance to penetration are probably related to increased sintering caused by excessive wind at the avalanche site.

The April 11, 1954, pits (A–3 and T–1) are difficult to evaluate because the snow in the test field is isothermal, while most of the snow in the A–3 profile is still cold due to differences in elevation, exposure, and depth. Grain shapes in the e and c layers are similar. The b layer is missing in the test field due to warm temperatures. Differences in resistance to penetration in the two areas are also related to the differences in temperature. The ice lens present at 180 cm at the avalanche site is present at the 90 cm level in the test field pit.

Based on the information shown in Fig. 8 and on experience in the Berthoud Pass area, the following conclusions can be drawn in regard to projecting snow profile information from the test field to nearby avalanche paths:

1. The depth, grain shape, and strength of the snow in the lowest layer at the Berthoud Pass test field is a good indicator of these parameters in the same layer in adjacent avalanche starting zones.
2. The test field profiles indicate the character of the snowpack in adjacent avalanche tracks prior to the first avalanche on each track.
3. The d and b layers of snow in the starting zones above timberline show a slightly higher density and much greater strength than the same layers at the test field. These differences are related to greater windspeeds in the starting zones.
4. Snow temperatures in the starting zone are lower and their gradients are less than those in the test field. Lower snow temperatures are due to the greater altitude and changes in aspect and slope, while temperature gradients are less because of the greater snow depth in the starting zone.

V. Avalanche Hazard Forecasting in Colorado

Forecasting technique has been based on combined information obtained from snowpits, test skiing (to observe the relative amount of tensile stress present in the snow cover near the starting zones) and weather data. Subjective integration of the data by a trained observer provided valuable information on the relative stability of the snow cover, and served as a guide to decisions involving avalanche and traffic control at local ski areas.

Use of snowpits. From the standpoint of an operational avalanche control program in the High Alpine Zone, it appears that information gained from periodic examinations of the snow cover in areas very close to the avalanche starting zones, as well as occasional snow tests at the midtrack level, would be more useful than the routine pit data taken from a flat, sheltered, test field. In areas where the snow depth exceeds 2 m, a surface pit about 1 m in depth combined with a full-depth ram penetrometer test would give valuable information about the stability of the surface snow slabs.

The many ram penetrometer tests made in the vicinity of Berthoud Pass during the past 17 years show that this instrument gives a reliable indication of the depth and extent of the fragile depth hoar layer, and thus eliminates the need for a deep snowpit.

Use of weather data. A continuous record of wind, temperature, and precipitation is essential to the evaluation of avalanche hazard. When these parameters are combined with information from snowpits, a reasonable estimate of the general avalanche hazard can be made. The following rules-of-thumb have been developed from the studies at Berthoud Pass:

a. Avalanches may be expected to release as surface slabs following 12 hours or more of wind averaging 8 m/sec or more when the temperature is <-3°C and 10 cm or more new snow accompanies or precedes the wind.
b. Large natural avalanches may be expected to fall regardless of the temperature trend after 25 mm water equivalent falls in a continuous storm.
c. An abundance of graupel falling during a storm enhances the formation of soft slabs.
d. The occurrence of rime on the snowpack late in a storm, followed by a drop in temperature, lessens the likelihood of avalanches.
e. Most avalanches are released while the temperature is falling unless these falling temperatures are preceded by rime.
f. Three consecutive sunny days, accompanied by temperatures near or above freezing, alleviate much of the general avalanche hazard on south and west exposures.
g. Seven consecutive sunny days with temperatures between -18 and -7°C are required before most of the hazard is alleviated on south and west exposures.
h. Windspeeds >11 m/sec for 24 hours or more produce a localized hazard from slabs, even when there is no precipitation.
i. The depth of snow deposited in the starting zones averages about three times the depth of new snow measured in a sheltered clearing.

Avalanche control timing. An important aspect of any avalanche control job is the determination of when explosive control should begin. Various empirical techniques have been developed (Atwater, 1952; U.S. Forest Serv., 1953) for following the buildup of avalanche hazard during storms, but only one is known to the author that was specifically designed to determine the onset of control action. The technique was designed by N. C. Gardner* and using the same basic approach taken by Atwater has been successfully used on the Rogers Pass section of the Trans-Canada Highway since 1962. A detailed account of this method will soon be available from the Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colorado. Part of Gardner's procedure has been modified for the Loveland Pass-Berthoud Pass area in Colorado. It is presented here in simplified form to illustrate how precipitation and avalanche occurrence data can be used to determine when to start avalanche control with artillery or other delivery systems.

The basic technique involves construction of a control curve of new snow weight

* Gardner, N. C. Avalanche hazard forecasting and artillery control of avalanches on trans-mountain highways (in review for publication).

plotted against time. The object is twofold: to determine, through past storm and natural avalanche records, the weight of new snow which can be tolerated without causing avalanches; and the time to release avalanches so they will run the full length of their track in small volume. The method is only applicable in areas where intense avalanche control programs are carried out on a daily basis.

Based on 10 years of data for Berthoud and Loveland Passes in Colorado, the allowable new snow weight is 2.2 g/cm^2 in 18 hours for high-intensity storms, and 2.7 g/cm^2 in 48 hours for low-intensity storms (Fig. 9). The first natural avalanches occurred 4 to 6 hours after these weight levels were exceeded—provided the storm continued that long. Avalanche control action should be initiated when these weight levels are reached during a storm if the temperature in the starting zones is $\leq$0°C and the wind is $\geq$7 m/sec.

Constructing the control curve. Five or more years of winter precipitation and avalanche occurrence records are needed before a reliable control curve can be constructed. The precipitation amounts should be available at 6- or 12-hour intervals, and avalanche occurrence records should give the time of release to the nearest hour. Charts from a recording rain and snow gage will satisfy the precipitation requirement, although snow core weights from a snowboard are preferred.

The first step is to select each storm which produced avalanches that blocked the highway. Plot new snow weight against storm duration. Mark an arrow on the snow weight curve opposite the time of release for each avalanche affecting the highway. You soon have a family of snow weight curves with arrows indicating each avalanche occurrence. It may be necessary to group curves by storm types as was done for the Berthoud-Loveland Pass areas (Fig. 9). In this case, two predominant storm types appeared: one for long-duration, low-intensity storms, and the other for short-duration, high-intensity storms. All storms in each type can be plotted as a scatter diagram, and a mean curve (the control) can then be fitted. An arrow, which precedes the first avalanche by 4 to 6 hours, should be marked on each control curve. These arrows

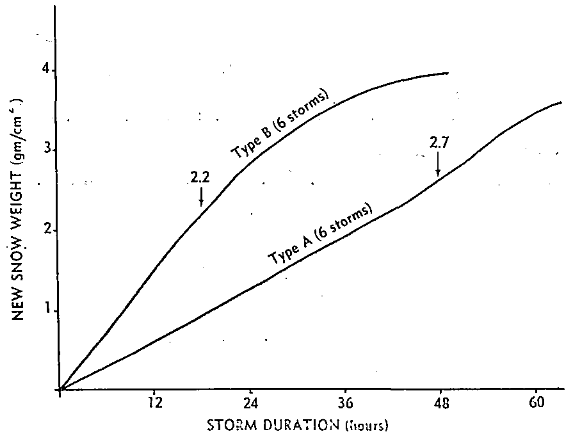


Fig. 9. Control curves for determining the onset of avalanche control by artillery for two different storm types. Data for Loveland and Berthoud Pass in Colorado's Front Range. Arrows indicate empirically determined critical weight levels of the new snow

indicate the time when control action should begin. The 4 to 6 hours lead time provides a safety margin for the stabilization program, based on the expected precipitation intensity shown by the control curve.

Using the control curve. The empirically derived control curve should be etched on a piece of stiff, transparent plastic for use as an overlay on current storm plots. As soon as the new snow weight in any given storm exceeds 1 g/cm², the control curve can be used as a guide to avalanche hazard buildup. The decision to start avalanche control is based on the rate at which the current snow weight curve approaches the predetermined critical weight (Fig. 10). The control curve thus gives the expected precipitation intensity based on past storm records. Special attention is given to the rate at which the new snow weight approaches the control curve, for this will determine when the artificial stabilization program must begin. If precipitation intensity for a current storm exceeds that of the control curve after the 1.5 g/cm² level is reached, then the time until avalanche control should begin is reduced. Control action is delayed when precipitation intensity remains below the control curve. The final decision is based on the experience of the forecaster involved. With the addition of more complete snow weight and avalanche occurrence data, it is possible to establish two or more critical weight levels for each control curve. This was done by Gardner at Rogers Pass, on the basis of avalanche frequency groups. Judicious use of the control curves insures greater highway safety and lessens the probability of unexpected traffic delays due to avalanches.

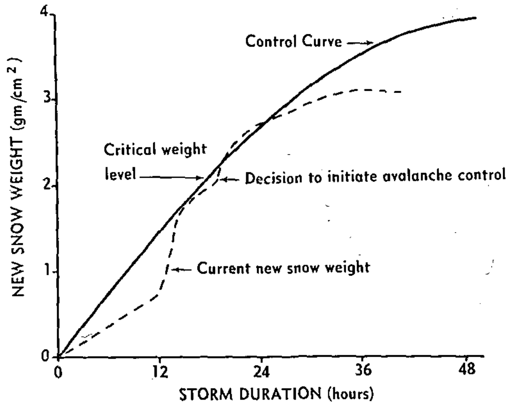


Fig. 10. An example of how the control curve may be used to decide when to initiate avalanche control with explosives

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