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Avalanche Handbook

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Acknowledgments

Preface

This book is for ski patrolers, snow rangers, mountaineers, rescue teams, and others who encounter avalanches in work or recreation. It is suitable also for persons generally interested in mountain weather, snow, avalanches, and avalanche control. Although avalanches are treated mainly as a problem of physical science, this is not an engineering text. Those interested in engineering design will find references to more technical material in the "Further Reading" lists at the end of each chapter and in the "Literature Cited" section at the end of the book.

In the few places where equations or numerical values are given, the international system of metric units is used, in view of the trend toward the metric system. Moreover, quantities such as snow density, atmospheric pressure, snowpack stress, and avalanche impact pressures are easily expressed in metric units. Tables and arithmetic methods for converting to English units are in Appendix A.

For brevity, *avalanche* is used to mean a mass of snow that sometimes contains rocks, soil, and ice moving rapidly downslope.

This book is meant to supplement, not substitute for, field experience. Hopefully, the reader will gather his field experience painlessly under competent leadership.

Abbreviated units of measure

The commonly accepted abbreviations for units of measure used in this book are listed below, along with the words for which they stand. Appendix A discusses the metric system at some length and gives methods and tables of equivalents for converting from metric to English units and vice versa.

b	bar
°C	degree Celsius
cm	eentimeter
cm²	square centimeter
cm³	cubic centimeter
cm/h	centimeters per hour
ft	foot
g	gram
g/cm³	grams per cubic centimeter
h	hour
Hz	hertz (cycles per second)
in	inch
kg	kilogram
kg/m³	kilograms per cubic meter
km	kilometer
m	meter
m²	square meter
m³	cubic meter
m/s	meters per second
mb	millibar
mi	mile
mi/h	miles per hour
mm	millimeter
mm²	square millimeter
mm³	eubic millimeter
inm/h	millimeters per hour
s	second
t	metric ton
t/m²	metric tons per square meter

Contents

ABOVE IS ALTA 1885

Effects of avalanches

Avalanches are common on steep, snow-covered mountains everywhere. Although most are remote from man and his improvements and damage little except timber, some do considerable damage to man and his works. This chapter describes briefly a few of the most devastating North and South American avalanches of recent times.

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MISPRINT!

Figure 1.—Bingham Canyon, Utah, February 17, 1926: searching for victims amidst wreckage and avalanche debris (death toll 40).

Figure 2.—Recovering victims at Ophir, Utah, February 26, 1939.

Figure 3.—The mining town of Alta, Utah, was nearly destroyed by an avalanche on February 13, 1885. Photo July 3, 1885.

MISPRINT : ABOVE PHOTO IS BINGHAM DISASTER 1926
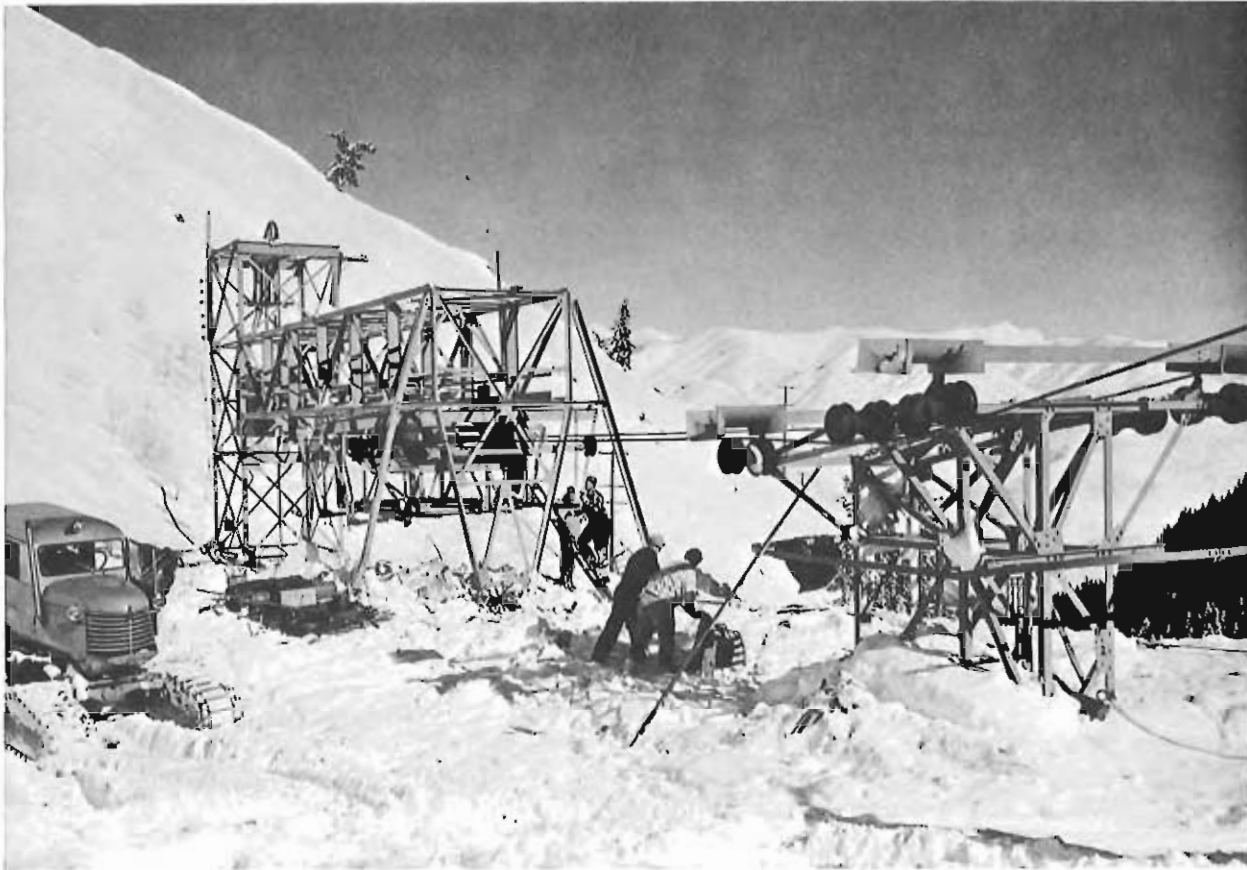
Figure 4.—Avalanche damage to a ski lift terminal at Sun Valley, Idaho, February 11, 1959.

EFFECTS OF AVALANCHES

Disasters of the past

Snow avalanches are powerful forces of nature. A large one may transport not only ice and snow but also rock, soil, and vegetation. Avalanches thus play a significant role in carving and weathering the world's most spectacular peaks. Most of this action occurs in places remote from civilization, but when man and avalanche interact the results can be terrifying, as this description by Benjamin Morales (1966) makes clear:

> In the Santa Valley, Peru, on January 10th, 1962, a great ice avalanche occurred, the first one known in the country, which fell from one of its highest and most beautiful peaks. The avalanche was caused by the breaking off of the west front of the hanging glacier on the summit of North Huascaran at the approximate altitude of 6,300 m. The quantity of ice involved is estimated at 2.5 to 3 million m³, dragging along a great volume of granodiorite blocks from the cliff.
>
> This avalanche traveled 16 km, descended 4,000 m in elevation, and destroyed and demolished everything in its path. The average speed of the avalanche was 60 km/h. More than 4,000 human lives were lost and 9 small towns were destroyed. Cultivated fields were devastated, thousands of animals were killed, and great destruction was caused in an area which had been famous for its fertility and beauty.

The 1962 avalanche spared the nearby city of Yungay, which was protected by a small hill. But on May 31, 1970, a large earthquake shook Peru and released another monstrous avalanche from Mt. Huascaran. This time, the avalanche spilled over the hill, buried Yungay, and took 20,000 lives.

Worldwide, the settlements most vulnerable to very large avalanches are those located where earthquakes, landslides, and avalanches could combine effects, as happened in Peru. Avalanche destruction on this scale, however, is not likely in North America because the higher, steeper mountains (for example, McKinley and Logan) are remote from civilization. On the North American Continent, most avalanches occur on land set aside for recreation, logging, grazing, and watersheds, rather than on areas of dense residential use. Even small avalanche disasters that affect only tens or hundreds of people are bound to be rare in North America because the degree of snow slope instability (except when triggered by earthquakes) can be evaluated with moderate precision

Figure 5.—Bent steel beams on bridge near Teton Pass, Wyo., testify to avalanche force, February 27, 1970. (Photo by Martinelli)

and controlled by modern technology. Other natural disasters such as earthquakes, floods, volcanic eruptions, and tornadoes are much harder to anticipate and often impossible to control.

Small, isolated avalanche disasters have occurred since the early settlement of the West. Reports of avalanche deaths before the Civil War appear in Mormon church records at Salt Lake City. Vivid accounts of later avalanche disasters in the nearby mining communities are described in the *Salt Lake Daily Tribune:*

> Alta, Dec. 26, 1872, 8:30 pm (telegraph) Number killed not ascertained, seven sleighs found, four more missing. Three teamsters got out alive. Eight teamsters and some passengers reported lost. Occurred one mile below. Storm unabated. Alta, Dec. 30, 1872 . . . 200 men probing with 12 foot rods of iron, one sleigh carried across canyon and 200 feet up mountain.

On March 7, 1884, at least 12 people were killed in Alta, and on February 13, 1885, the town was nearly destroyed by an avalanche that claimed 16 lives. The survivors took shelter in mine shafts.

On February 12, 1899, two avalanches ran simultaneously near the town of Silver Plume, Colo., killing ten people and injuring three others. On February 28, 1902, near Telluride, Colo., an avalanche hit the shaft house of the Liberty Bell Mine and killed seven miners; a rescue party was summoned, and two of its members perished in a second avalanche. Three other avalanches on the same day killed ten others.

Figure 6.—Avalanche damage to a ski lift, Alyeska, Alaska, April 14, 1973. (Photo by O'Leary)

Although avalanche accidents were rather frequent in the mining camps, the scattered arrangement of the mines and homes usually limited the number of people involved in any one accident.

The worst avalanche disaster in the United States occurred on March 1, 1910, in Washington State; 96 people died when two snowbound passenger trains near the town of Wellington were swept off the track and into a steep-walled canyon. The ordeal is described in the book *Northwest Disaster* by Ruby El Hult (1960). By coincidence, Canada suffered her worst avalanche disaster in the same month and year, when 62 workmen perished at Rogers Pass, British Columbia, while attempting to rescue a train stalled by an earlier avalanche (Anderson 1968).

On March 22, 1915, in another tragedy in British Columbia, 57 men, women, and children were killed by a rock and snow slide at the "Jane Camp" of the Brittania Mine.

On February 17, 1926, 40 men, women, and children were killed by an avalanche in the mining community of Bingham Canyon, Utah. Twenty-five families were left without homes, and 200 people were seriously affected by the disaster. As human nature often dictates, the community resettled in the same

Figure 7.—Damage to the reinforced concrete base of a lift tower, Alyeska, Alaska, April 14, 1973. (Photo by O'Leary)

EFFECTS OF AVALANCHES

place, only to suffer another disaster on February 8, 1939 (four killed and four injured).

More recently, avalanche disaster has struck the mountain community of Twin Lakes, Colo. (January 21, 1962—7 dead); the Grand Duc Mine, British Columbia (February 18, 1965—26 dead); and a small community near Terrace, British Columbia (January 22, 1974—7 dead). Gallagher (1967) and Williams (1975) give detailed accounts of avalanche accidents in the United States since 1910. European avalanche accidents are reported annually in winter reports of the Swiss Federal Institute for Snow and Avalanche Research at Davos.

Avalanches in the United States are reported to the U.S. Forest Service's Rocky Mountain Forest and Range Experiment Station (240 W. Prospect Street, Fort Collins, Colo.) by a network of observing stations in the western United States. Statistics from this network for the 5 years preceding the winter of 1973–74 show about 10,000 avalanches per year. About 1 percent of these harm man or his property. These account, however, for an average of seven lives lost and $300,000 in property damage each winter.

Although mountain communities will continue to suffer occasional avalanche disasters, the greatest potential for loss of life is in ski areas. On a typical day at the height of the season, several thousand skiers are dispersed on and around avalanche paths in North American ski areas. In some areas, more than 100 skiers may be under major avalanche paths at one time. It is a tribute to avalanche technology that only a few lives are lost to avalanches each season. This fine record is due to the conscientious efforts of those responsible for recognizing and controlling the avalanche hazard.

Further reading

Atwater, Montgomery M.
  1968. The avalanche hunters. 235 p. Philadelphia: MacRae Smith. *One man's account of avalanche control, research, and rescue work in the western U.S. and South America.*

Fraser, Colin.
  1966. The avalanche enigma. 301 p. London: John Murray. *Good account of avalanches, avalanche research and control techniques, and rescue operations, mostly in Switzerland.*

Wechsberg, Joseph.
  1958. Avalanche. 254 p. New York: Alfred A. Knopf. *The true report on the people and events associated with a devastating avalanche that hit the high alpine village of Blons, Austria, on January 11, 1954.*

Figure 8.—A reminder of mining days: an avalanche slams into the ski town of Alta, Utah, January 1, 1974 (3 lodges damaged, 2 people injured, 35 cars damaged or destroyed).

Avalanche
meteorology

Changes in the weather provide the best clues to when and where avalanches are likely to release. With today's technology it is not possible to observe directly subtle changes in the snowpack that signal the onset of its failure and release from the mountainside. However, it is possible to relate changes in weather to changing tendencies of the snowpack toward either failure or increased stability.

This chapter begins with a brief discussion of large-scale meteorology. Avalanche workers are not expected to be weather forecasters, but they must be able to communicate with meteorologists at the well-equipped centers of the National Weather Service. Avalanche workers are supplied with a forecast and in return supply the meteorologists with data in order to improve forecasts. This exchange works most smoothly when avalanche workers and meteorologists are familiar with one another's problems.

Figure 9.—About 90 percent of the wind-transported snow travels in the 50 cm just above the snow surface. (Photo by Kelner)

500-MILLIBAR HEIGHT CONTOURS
(At 7:00 A.M., E.S.T., 1 February, 1972)
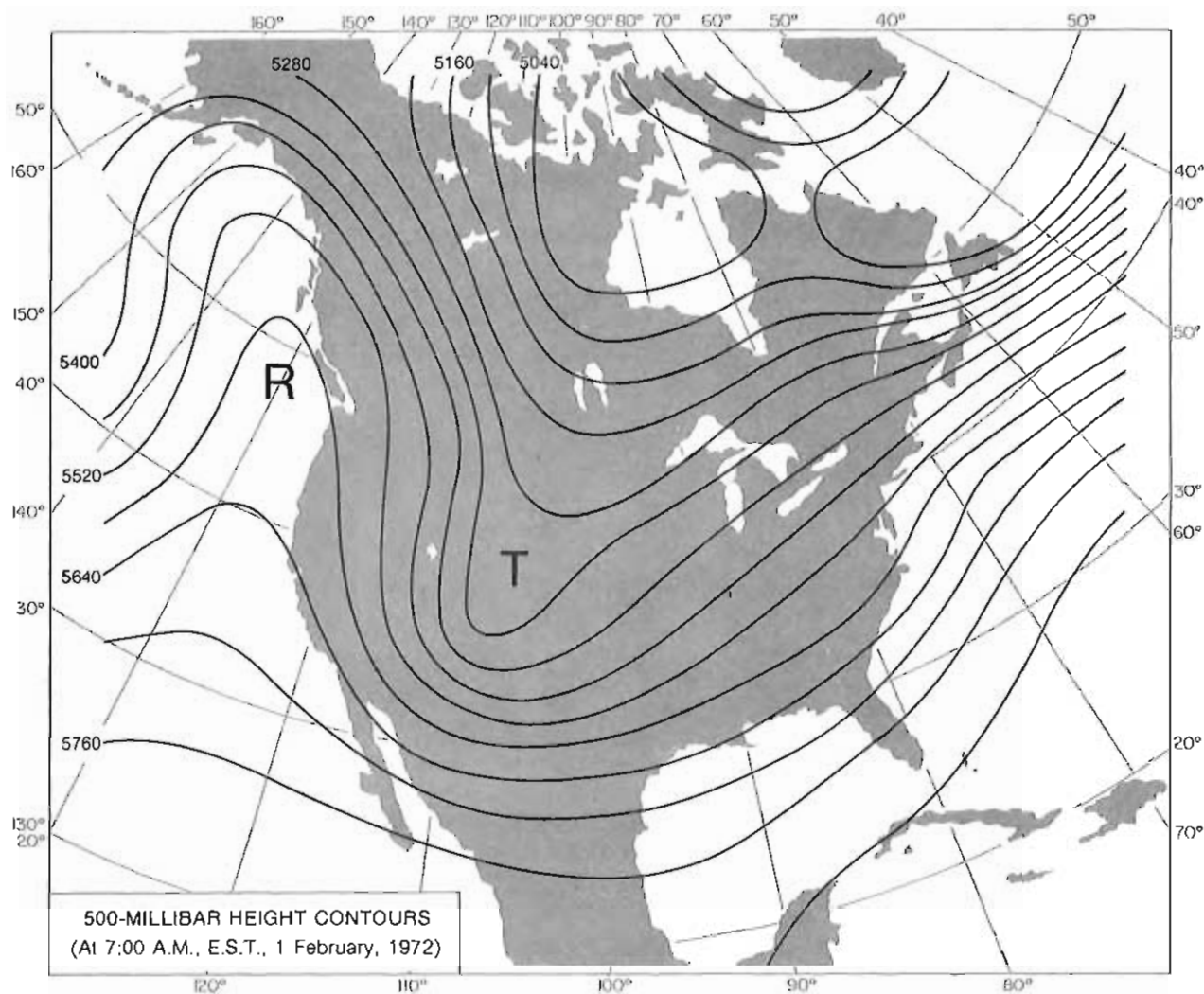
Figure 10.—Map of 500-mb height contours over North America. Contours represent the height in meters of the 500-mb level. Note the wavelike regularity; a ridge (R) alternates with a trough (T). Broadly speaking, winter weather at high mountain stations is determined by the upper-air conditions. A pressure ridge over a mountain area signifies fair weather, and a trough signifies storm conditions.
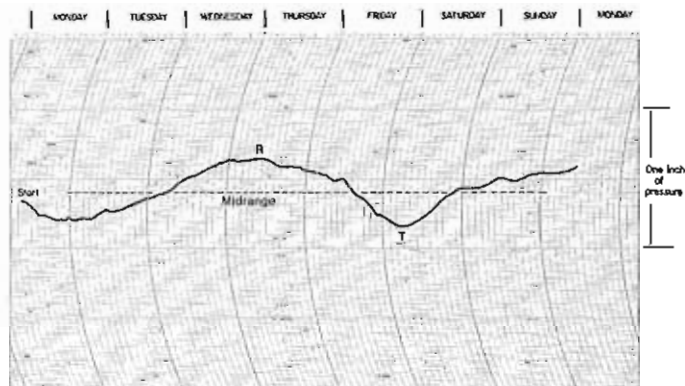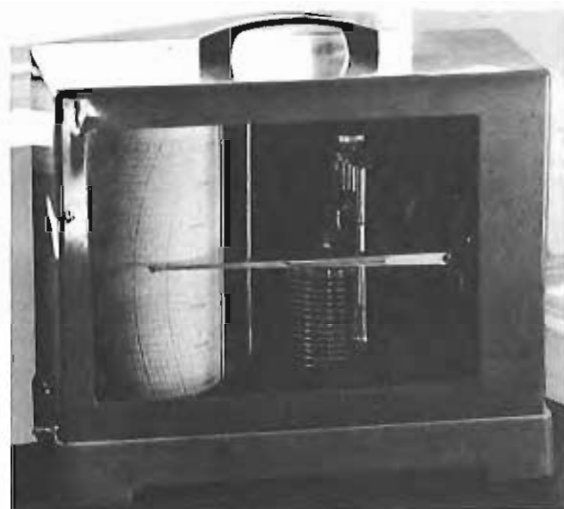
Figure 11.—Left, microbarograph and right, microbarograph chart from Berthoud Pass, Colo., for the week beginning December 13, 1973. Midrange position and trough and ridge periods are identified on the chart.

Flow of large airmasses

Most destructive avalanche cycles are caused by sustained heavy snowfall; other meteorological factors are secondary. Heavy and sustained snowfall in a mountain range occurs when the large-scale flow of the atmosphere assumes certain patterns with respect to the mountain range. To understand these patterns, it is helpful to understand a few basic ideas about an important feature of the atmosphere—barometric pressure and its variation.

Barometric pressure decreases generally with increase in elevation. In metric units, the barometric pressure at sea level is about 1 bar (b), or 1,000 millibars (mb). Pressure decreases with elevation at the rate of about 0.1 mb per meter or, in metric shorthand, 0.1 mb/m.

Meteorologists find it convenient to talk about pressure levels in the atmosphere. The 1,000-mb level is about sea level; the 700-mb level is about 3,000 m above sea level; and the 500-mb level is about 5,500 m above sea level. However, the exact elevation of any pressure level fluctuates with the movement of large airmasses.

A large number of weather stations around the world simultaneously send up balloons to gather data on pressure, wind, temperature, and humidity. From these upper-air data and from surface observations, weather maps are prepared for the earth's surface and for selected pressure levels, usually for the 850-mb, 700-mb, and 500-mb levels and for several higher (lower pressure) levels.

Except over the higher mountain ranges, airflow at the 500-mb level is not much influenced by terrain. Typically, the 500-mb pressure patterns have a smooth, wavelike appearance, with alternate ridges
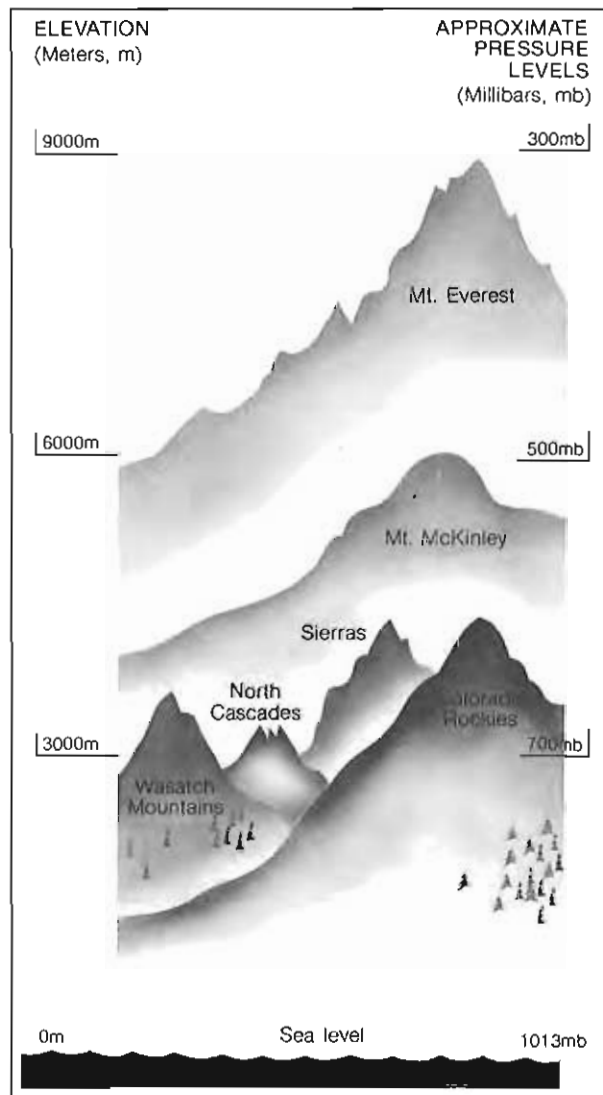
Figure 12.—Atmospheric pressure is measured in millibars (mb). The mean pressure at sea level is 1,013 mb. Pressure decreases with increase in elevation.
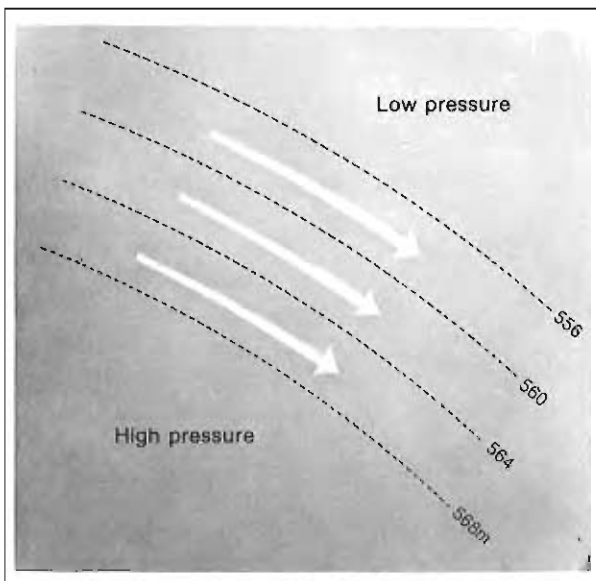
500mb SURFACE
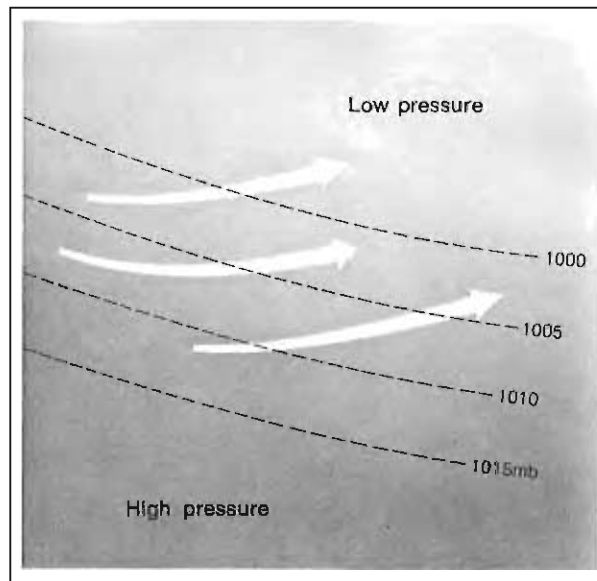
AT EARTH'S SURFACE

Figure 13.—At the 500-mb level (left), wind flows nearly parallel to the height contours. At the surface (right), wind tends to flow across contours from high-pressure to low-pressure areas.
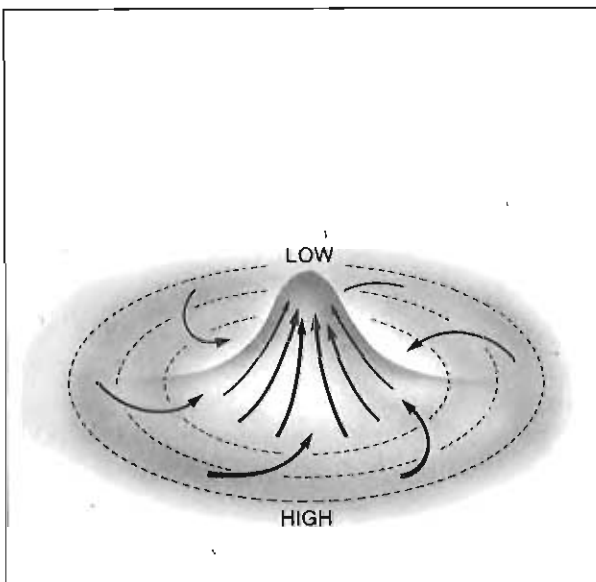
CYCLONIC LIFTING
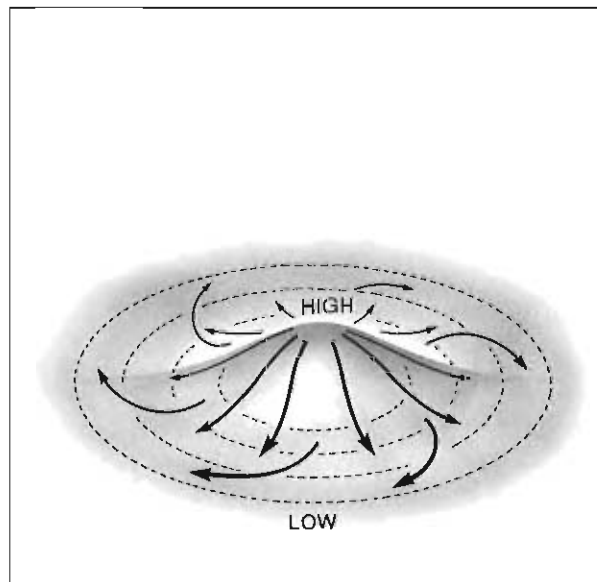
ANTICYCLONIC SINKING

Figure 14.—Cyclonic lifting, or convergence (left), and anticyclonic sinking, or divergence (right). The diameter of the circular flow is between 100 and 1,000 km.

and troughs. These pressure waves are widespread; in fact, four or five waves may link to encircle the globe. The waves tend to move eastward across north temperate regions, but occasionally they retrogress toward the west.

The waves decay and build up while moving, so that pressure patterns change constantly. Superimposed on

the large waves are smaller, faster moving waves. The large waves (long waves) determine the general weather over sustained periods of several days to a week; the smaller waves (short waves) are responsible for hourly or daily changes. Prediction of these combined changes in pressure is done by the National Weather Service on high-speed computers.

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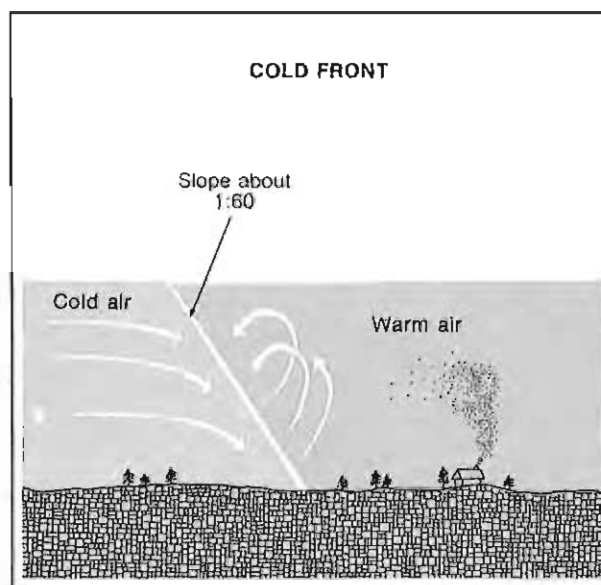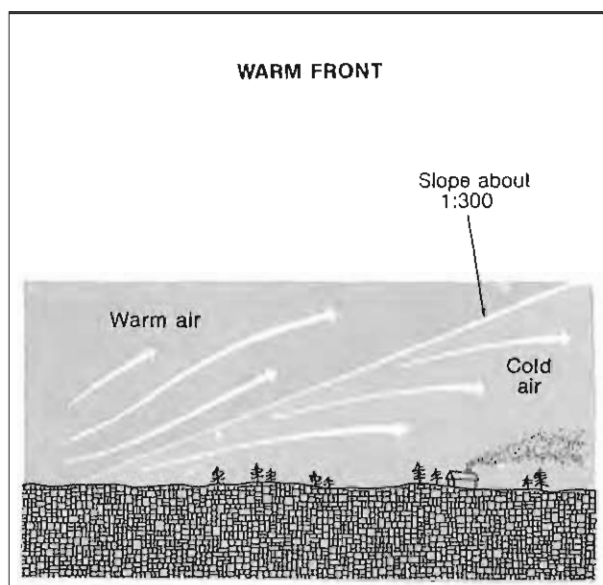
Figure 15.—Lifting of airmasses during the passage of fronts. Warm fronts (top left) on the average advance at about 5 to 10 m/s; cold fronts (top right) advance at about twice the speed of warm fronts. Mountain ranges intensify the lifting effect of warm fronts (bottom right).

The wavelike regularity of pressure patterns, apparent at the 500-mb level, is obscured at the surface, where frictional effects of terrain cause the pressure patterns to assume more complex shapes. The 700-mb level is a transitional level between 500 mb and the surface. The 700-mb pressure patterns have the general regularity of the 500-mb patterns, but they also are influenced by the surface. Since most hazardous avalanche paths are in the pressure band between 1,000 mb and 500 mb, 700-mb balloon measurements of wind, temperature, and humidity are especially useful for evaluating avalanche conditions.

Barometric pressure is easily and accurately measured; it is probably the easiest meteorological variable to monitor unambiguously. Many instruments are available; the microbarograph has proven satisfactory at avalanche stations. With rare exceptions a barometer falling steadily below midrange is an omen of bad weather at high-altitude stations. The barometer rising steadily above midrange usually heralds a clearing trend.

Large airmasses flow from regions of high pressure into regions of low pressure. As shown in figure 13, at the 500-mb level in the free atmosphere, the pressure and the rotational force of the earth are approximately balanced, and the resultant force alines the wind direction parallel to the pressure contours. Between sea level and 1,000 m above, the friction of the surface upsets the balance between pressure and rotational force, causing the wind to deflect across the contours toward lower pressure areas. These deflections may be as great as 45° over very rough surfaces.
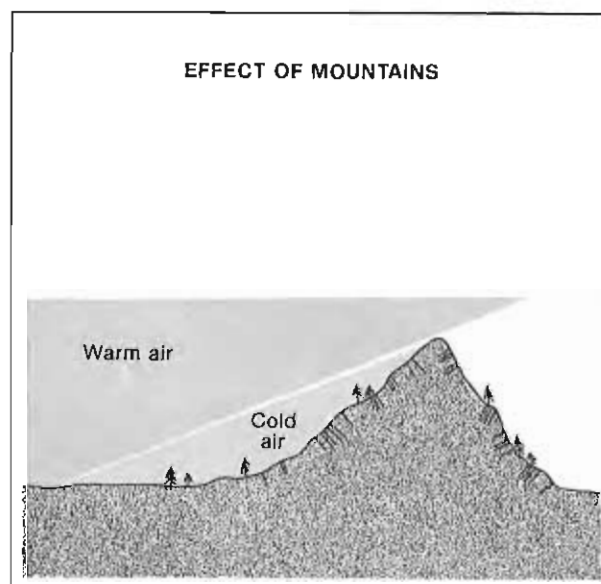
This two-dimensional picture is modified by the rising and sinking of airmasses. Vertical speeds are much lower than horizontal windspeeds, but are important in forming and dissipating clouds and precipitation.

Frontal lifting is the result of either warm air flowing up over a cold airmass or a cold airmass wedging beneath a warm mass. Airmasses do not readily mix,
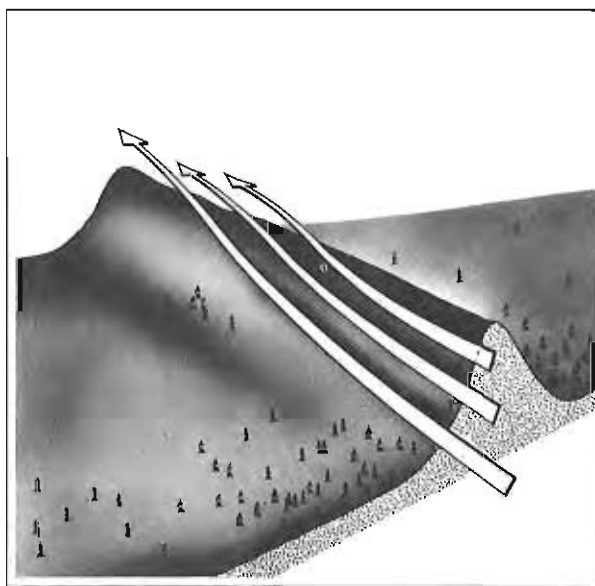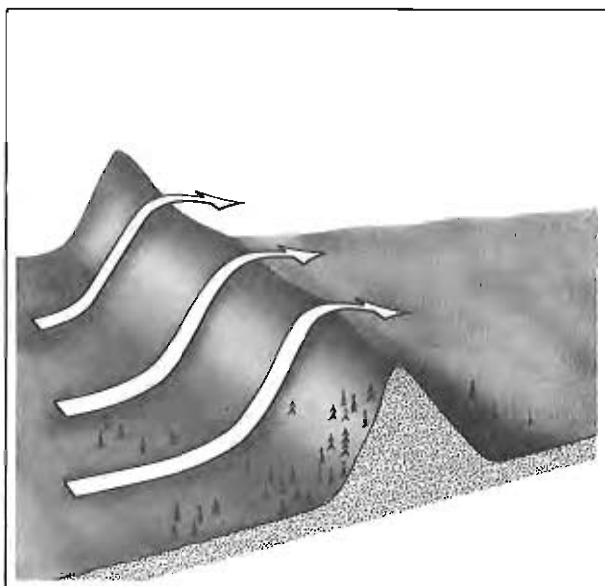
Figure 16.—Maximum orographic lifting occurs when the wind is perpendicular to the mountain barrier (left). Orographic lifting is reduced when the wind strikes the barrier at angles other than perpendicular (right).

and the boundary between two colliding airmasses is a *front*. Vertical air velocities induced depend on the slope of the front; the steeper the slope, the greater the lifting power. A warm front advances as a gently sloped wedge of warm air with relatively low vertical speeds at the frontal surface. A cold front advances as a steep wedge with rapid lifting of the warm air-mass. Mountain ranges trap cold airmasses on their windward sides and intensify the lifting effect of warm fronts.

Orographic lifting, or the forcing of air up and over terrain barriers, is by far the most powerful lifting mechanism. It induces vertical speeds on the order of 1/10 of the horizontal windspeed (compared to 1/100 for cyclonic and frontal effects). Orographic vertical speeds depend on windspeed, the angle at which the wind strikes the mountain barrier, and the slope of the barrier. For example, if the wind strikes perpendicular to a mountain with a slope of 10°, the vertical speed is about 17 percent of the horizontal windspeed. Vertical speeds are reduced if the wind strikes the mountain barrier at an angle other than perpendicular and, in principle, are reduced to zero when the wind is parallel to the barrier. Considering the whole earth, orographic effects are small in comparison to convective, frontal, and cyclonic lifting. However, in mountain regions they are clearly the most important mechanism for lifting airmasses.

Under certain conditions, airmasses sink rapidly on the lee sides of mountain ranges. Very strong, warm and dry winds, called *chinooks* or *foehns*, are

caused by airmasses sinking into low-pressure areas to the lee of ranges. These winds are a consequence of the airmass losing moisture while rising on the windward side of the range and then being heated by compression on the descent down the lee side. Chinooks rapidly warm and evaporate snow cover.

Vertical motions in the atmosphere depend on the vertical distribution of temperature, pressure, and water vapor. If a parcel of air is lifted, it expands and cools because of lower pressure at the higher elevation. If it moves downward, it contracts and gets warmer because of the higher pressure. This decrease of temperature with elevation is the *lapse rate*. For dry air the lapse rate is about 1° C/100 m. For saturated air it is less (0.6° C/100 m is a useful approximation). When a lifted parcel is colder and heavier than the surrounding air, it tends to sink back to its former elevation. However, when a lifted parcel is warmer and lighter than the surrounding air, it tends to keep rising. Once it reaches a temperature called the *dew point*, the water vapor condenses into droplets and clouds form. Further lifting, cooling, and condensation result in precipitation.

During warm seasons, local heating of the ground produces significant lifting. If enough moisture is available, convective clouds may form and showers are possible. In winter, convection plays a small role in vertical motion compared to three other important effects: *cyclonic circulation, frontal lifting,* and *orographic lifting*.

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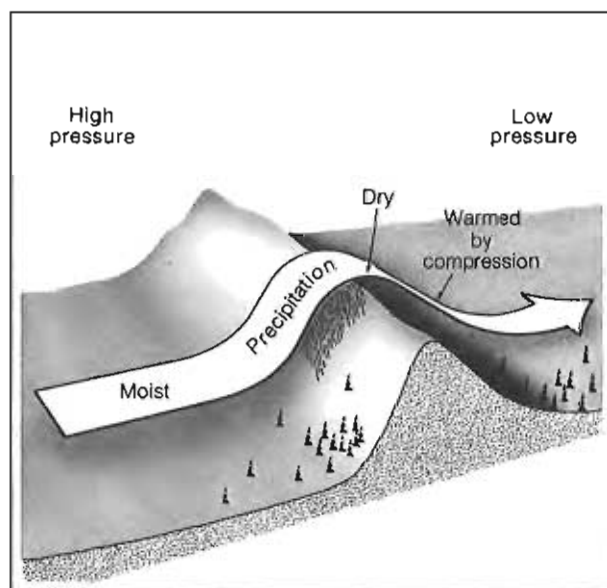
Figure 17.—Mechanism of chinook winds. Although precipitation is not required, it greatly accentuates the chinook effect.

Figure 18.—Centimeters of new snow, December through March, at Mt. Rainier, Wash., Squaw Valley, Calif., Alta, Utah, and Berthoud Pass, Colo.

In cyclonic circulation, airflow is counterclockwise around a low-pressure area and is directed toward the low-pressure center of the cyclone. Hence, at the center, air must rise up from the surface to upper levels. This is called *convergence*. In anticyclonic circulation, the situation is reversed; air sinks downward and out from the high-pressure center of an anticyclone. This is called *divergence*.

Precipitation

The amount of water vapor an air parcel can hold depends on the parcel's temperature; the warmer the air, the greater its holding capacity. Rising air parcels expand as they encounter the lower pressures of higher elevations. The expansion results in cooling and, therefore, a loss of capacity to support water vapor. Droplets or ice crystals form and enlarge in moist rising parcels, eventually dropping out as precipitation. Thus, the two essential elements for precipitation are moist airmasses and vertical lifting.

As discussed in the preceding section, vertical motions are produced by convective, cyclonic, frontal, and orographic mechanisms. Since orographic lifting produces the highest sustained vertical speeds, mountain regions usually receive far heavier snowfalls than flatlands. When the wind is parallel to a mountain range, orographic lifting is minimized, and adjacent mountain and flatland areas receive comparable amounts of precipitation. Orographic lifting is reinforced by cyclonic and frontal lifting and nullified by the sinking motions of anticyclonic flows; large amounts of precipitation rarely occur in the mountains when the airflow is anticyclonic.

Distribution of precipitation in the major mountain ranges of the United States clearly shows the roles of orographic lifting and available moisture. The primary moisture supply for the western United States is the Pacific Ocean. The greatest snowfall is in the Cascade Range of Washington and Oregon, where moisture-laden air carried from the Gulf of Alaska by the Pacific cyclone belt is lifted by a north-south chain of mountains. Substantial precipitation also falls in the Sierras, but there the moisture supply depends on storms that stray south of the main cyclone belt.

Farther inland, precipitation in the mountains falls off rapidly. The north-south running Teton and Wasatch Ranges are precipitation anomalies in an otherwise dry intermountain region. Both ranges are steep
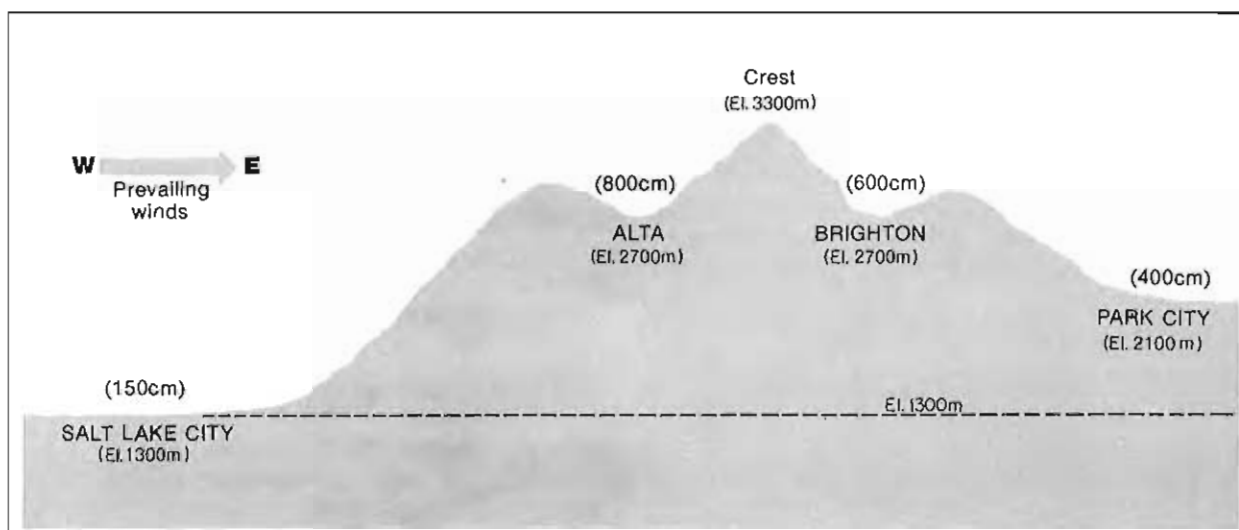
Figure 19.—Seasonal snowfall in the Wasatch Range of Utah.

orographic barriers that rise 2,000 m above relatively flat terrain. Abundant precipitation occurs in the San Juan Range, Colorado's first major barrier to storms tracking from the west and southwest. Storms from the northwest usually deliver heavy snows to the Park Range near Steamboat Springs. Because the mountains of western Colorado pull down much of the precipitation, the Front Range just west of Denver receives less snowfall from Pacific storms. Occasionally, moist air is carried into Colorado from the Gulf of Mexico by storms from the southeast, in which case large amounts of snow fall on the eastern side of the Front Range.

Precipitation increases with elevation on the windward side of mountain ranges, usually reaching a maximum slightly windward of the crest; the lee side of the range is generally the drier side. Figure 19 illustrates this distribution for the Wasatch Range. It must be emphasized that high precipitation on the windward side and scarcity on the lee side is a large-scale characteristic pertaining to entire mountain ranges. The actual distribution for small-scale terrain features,
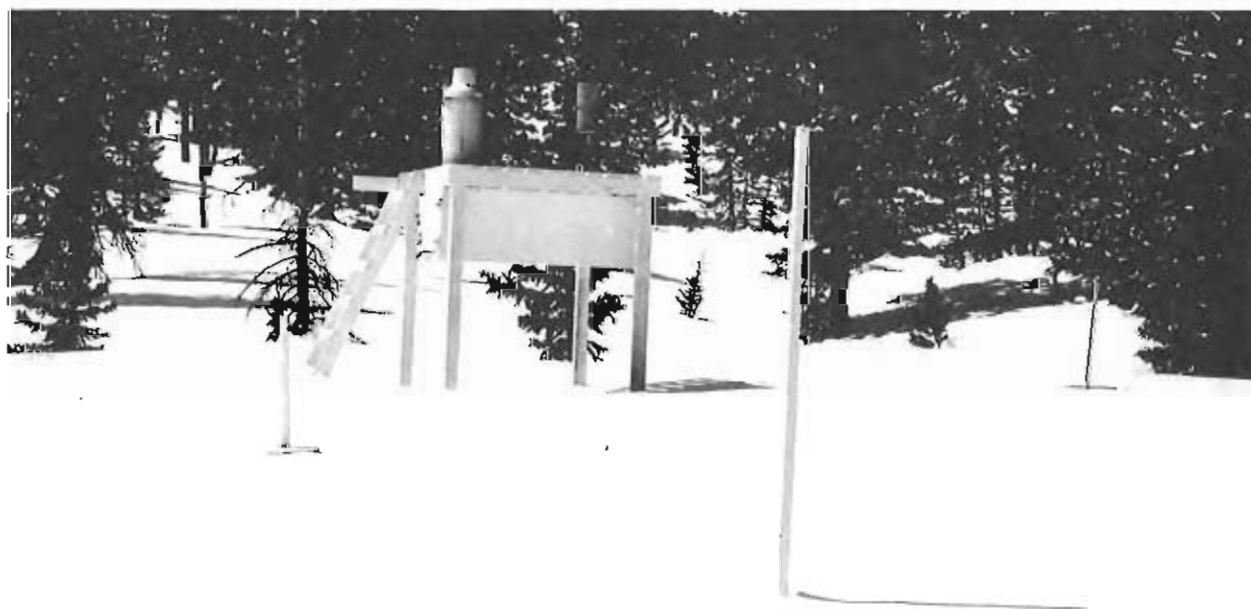
Figure 20.—Recording and nonrecording precipitation gages mounted on a tower. A low railing around the platform is recommended for the observer's safety.

such as ridges and gullies subject to wind transport and deposition of snow, follows the exact opposite rule: erosion of snow on the windward side and accumulation on the lee side.

Precipitation measurements are conveniently given in centimeters (cm) of snowfall or in millimeters (mm) of water equivalent. Some typical measurements of precipitation are:

- Snowfall—typical value, 10 cm
- Water equivalent—typical value, 10 mm
- Snowfall rate—typical value, 1 cm/h
- Precipitation intensity (water equivalent rate)— typical value, 1 mm/h.

The latter measurement represents the rate at which load is added to the snowpack.

Snow density is the fundamental property relating snow and its water equivalent. Density is mass per unit volume; in scientific units, kilograms per cubic meter (kg/m^3). The density of water, 1,000 kg/m^3, should be remembered as a convenient reference. Alpine snow commonly has a density between 30 kg/m^3 for light, newly fallen snow and 500 kg/m^3 for old, highly compressed layers. When measured in areas sheltered from the wind, newly fallen snow is found to have a density that averages between 70 and 120 kg/m^3, depending on the temperature. In areas exposed to the wind, the average densities are about 250 kg/m^3. As a general rule, high densities correlate with warm air or high winds, and low densities correlate with cold air or low winds.

Precipitation is measured either manually from stakes or snowboards or by gages. When windspeeds are low, a gage captures a representative sample of the precipitation. However, high winds cause substantial amounts of precipitation to miss the gage. Recording gages offer one big advantage: they operate around the clock, telling at least when precipitation fell, if not the precise quantities.

Manual measurements are the most accurate way of sampling the quantity of newly fallen snow, but it is impractical to make them hourly around the clock. Recording and manual measurements should be used together so that recorded data tell *when* the precipitation fell, and manual measurements tell *how much*. For avalanche stability evaluation, manual measurements should include:

- Total depth of the snowpack
- 24-hour new snow and water equivalent

Figure 21.—Total snowstake (left), fixed to the ground, and portable snowboard (right) for measuring 24-hour, storm, or interval amounts of precipitation. Various designs are possible, but it is important that the board be made of light, nonmetallic material and that the vertical scale be sturdy.

- Total snow and water equivalent of storm
- Snow and water equivalent for short intervals during the storm.

The total depth of the snowpack is read from a master stake, fixed rigidly to the ground. Three portable, lightweight snowboards, each with a vertical scale, are used to measure the 24-hour, storm, and interval snowfalls (see fig. 21). The 24-hour snowboard is reset daily, the storm snowboard is reset at
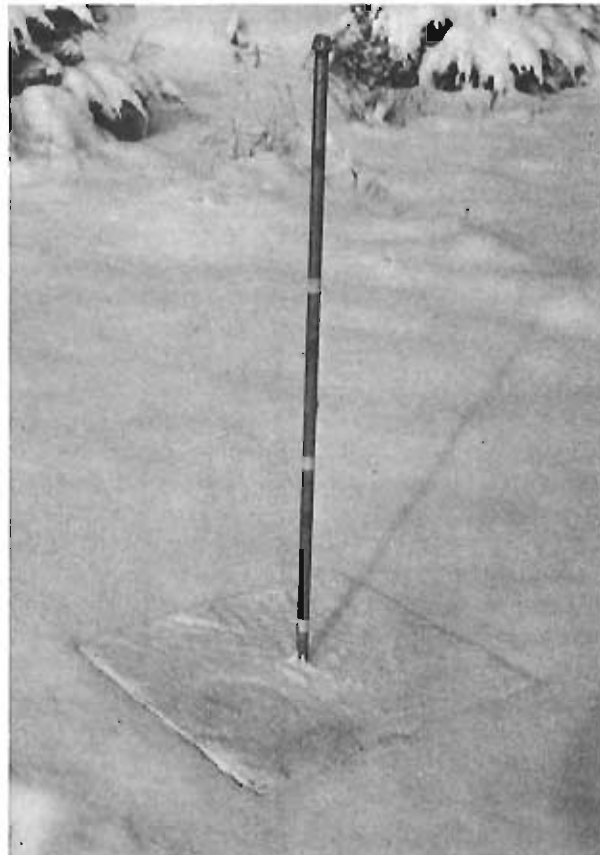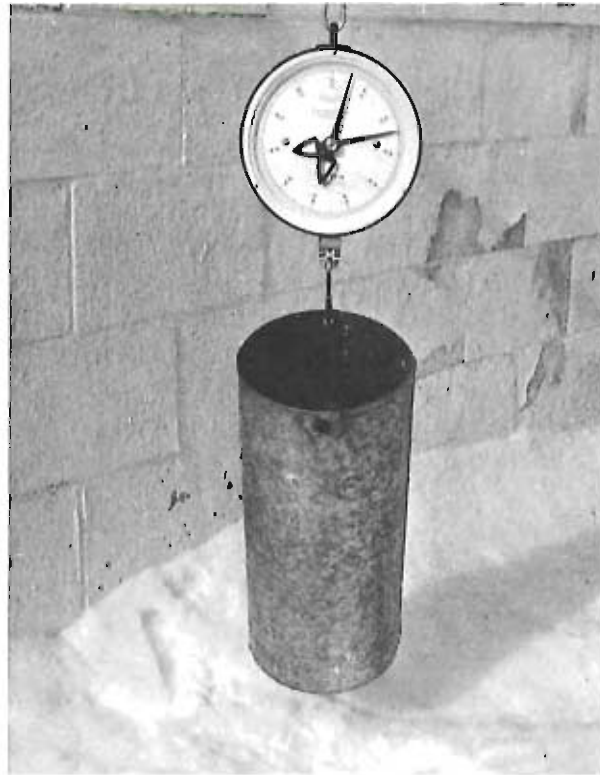
Figure 22.—Gathering and weighing a core sample of precipitation from a portable snowboard.
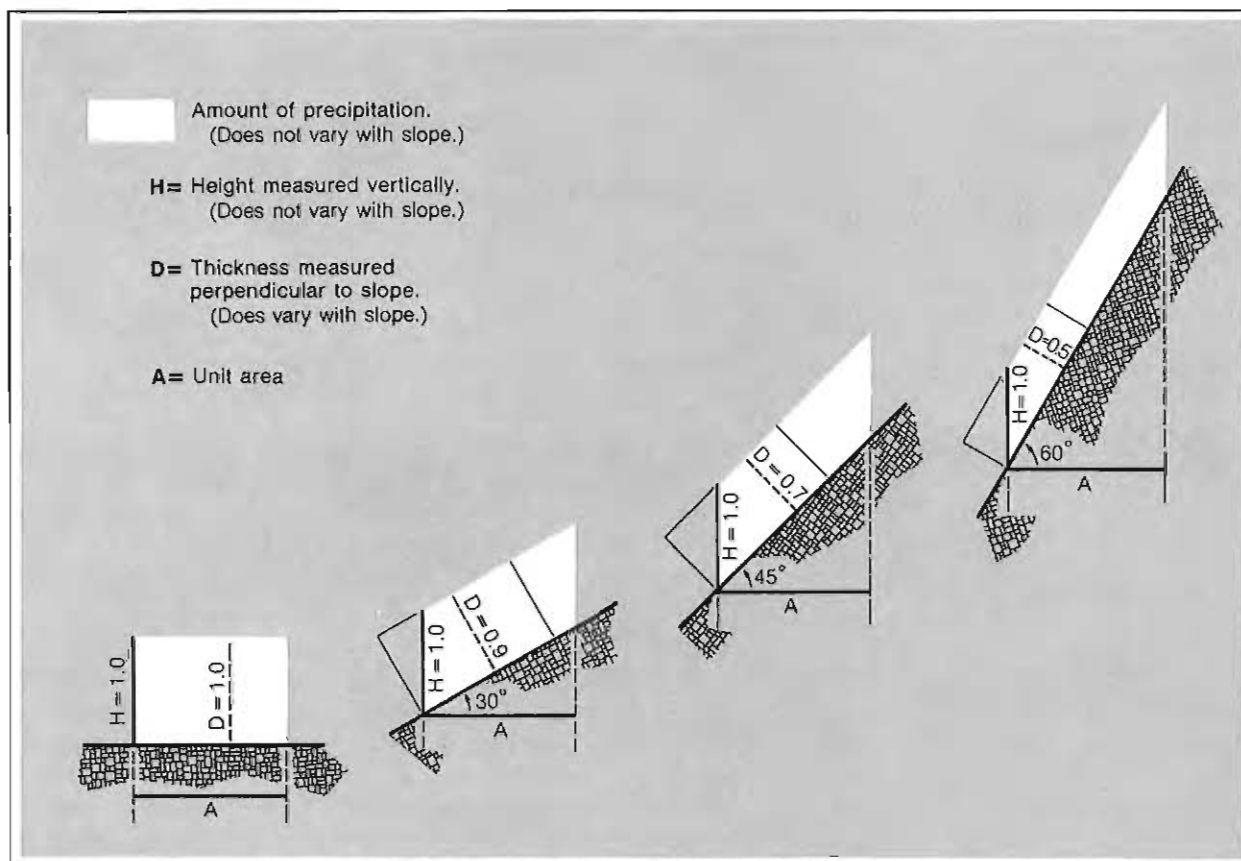
Figure 23.—In the absence of wind, snow height (H), measured vertically, is independent of slope angle. Snow thickness (D), measured perpendicular to the slope, varies as the cosine of the slope angle.

the end of the storm, and the interval snowboard is read and reset periodically throughout the storm. Depending on manpower, the interval snowboard may be read every hour, every 3 hours, or every 6 hours during the storm. A large aluminum can is used to obtain a core sample from the snowboards, and the sample is weighed in a sheltered enclosure (fig. 22).

When precipitation occurs without wind, a rare case in mountain storms, precipitation amounts and vertically measured snow heights are the same for all slopes. Snow-cover thickness (measured prependicular to the slope) varies as the cosine of the slope angle, as shown in figure 23. Under the influence of wind, snow is transported and deposited in uneven layers that do not follow the simple cosine rule. Accumulations in adjacent areas of similar slope may then vary by a factor of more than 10.

Since it is feasible neither to install a host of recording gages nor habitually to take manual measurements in a large number of areas, the most practical scheme is to measure precipitation at one study plot, in a sheltered area where deposition does not depend greatly on windspeed and direction. The study plot should be level and located in a sheltered clearing, the diameter of which is about one tree height. If this condition can be met, recording and manual measurements will be in fair agreement. The plot should be easily and safely accessible during storm periods and avalanche cycles.

Interpreting study-plot data to show what is actually being deposited on wind-exposed slopes is a central problem in avalanche technology. At best, observers synthesize study-plot data and wind information and make rough estimates of deposition on the slopes in question. Maintaining a high-altitude study plot not far below the avalanche slopes is a considerable advantage, but the final choice of location will no doubt be a compromise between accessibility, shelter efficiency, and ability to provide meaningful data for avalanche slopes.

Precipitation
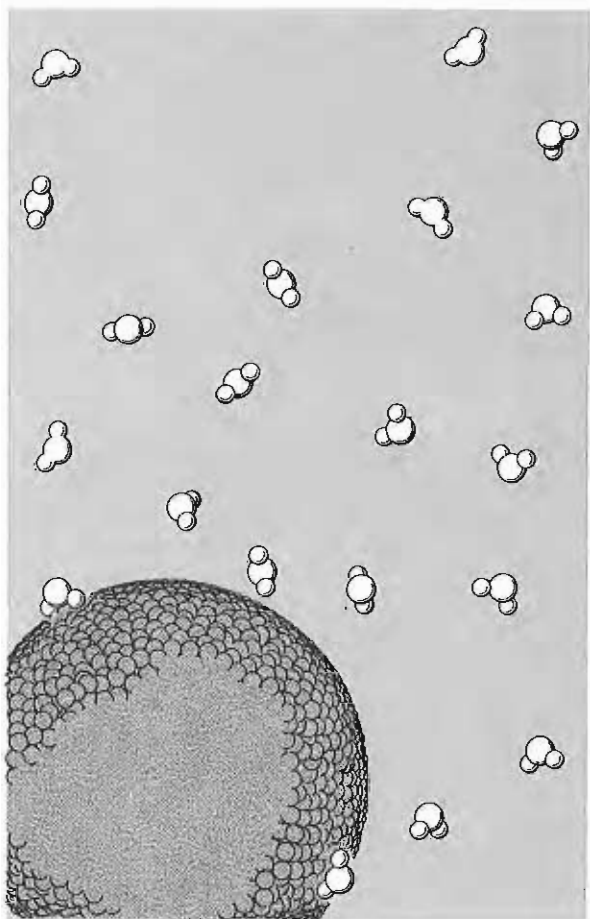
Figure 24.—When the number of water molecules condensing onto a droplet equals the number leaving the droplet, the air is said to be saturated with respect to the droplet. If the air and water-droplet temperatures are lowered, there will be a net flow of water molecules toward the droplet until a new balance is reached.

Snow crystals

To understand how snow crystals form and change shape, it is necessary to discuss briefly certain molecular processes. First, imagine a drop of water suspended in the atmosphere. Water molecules are exchanged constantly at the surface of the drop. The air is said to be saturated with respect to the drop's surface when the number of molecules leaving the drop is equal to the number falling onto the drop. Now suppose the air temperature is lowered. The result is an increase in the number of molecules condensing onto the drop because, as pointed out in the preceding section, the water vapor capacity of air decreases with decreasing temperature. The transfer of molecules continues until a new balance is reached; that is, until

saturation is reached for the new air temperature. The amount of water vapor that the air can support over the drop is called the saturation vapor pressure with respect to the surface of the drop.

Next, consider a rising, moist air pareel that is cooled to saturation with respect to water. In this state, water molecules tend to condense onto water droplets, *if droplets exist.* But where do the droplets come from to begin with? Although droplet formation is complex and not fully understood, it is known that initial condensation occurs on microscopic dust, salt, or soil particles that are lifted from the earth by wind. These so-called *condensation nuclei* have dimensions on the order of 10^{-6} m, or 1 μm. Each cubic centimeter of air contains 10 to 10,000 such nuclei.

Even if the air temperature is well below 0° C, a droplet will not automatically freeze unless it contains another type of impurity called a *freezing nucleus.* These are much rarer than condensation nuclei; a cubic centimeter of the atmosphere may contain only 10 freezing nuclei that are active at —10° C and above. However, the colder the air, the greater the probability of finding active freezing nuclei and hence frozen droplets. At —10° C, only about one in a million droplets freeze; at —30° C, one in a thousand; and at —40° C, all droplets freeze spontaneously. A rising parcel brought to saturation at air temperatures between 0° and —40° C, therefore, consists of a mixture of ice crystals and supercooled water droplets.

Finally, consider an ice particle suspended in the atmosphere. Again, the transfer of molecules between the ice surface and the air is controlled by temperature; the warmer the temperature, the higher the saturation vapor pressure over the ice surface. A fundamental law of snow physics is that for a given temperature below freezing less vapor can be retained over an ice surface than over water. In other words, the saturation vapor pressure is less with respect to ice than with respect to liquid water.

Ice crystals grow at the expense of the water droplets in two ways. First, water vapor deposits directly onto the crystal. As already noted, the vapor pressure over an ice crystal is less than over a water droplet; hence, there is a net transfer of water molecules from droplets to the air and thence to the ice crystals. By this vapor process, ice crystals grow into a variety of hexagonal forms. In the second mode of growth, ice crystals collide with the supercooled droplets, and the droplets freeze onto the crystals. The crystals become coated with a layer of frozen droplets, called *rime.* Vapor deposition and riming may occur simultaneously, although one process usually dominates in

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ICE CRYSTAL

Water droplet

Water droplet

Water droplet

VAPOR

Droplet

Droplet

Droplet
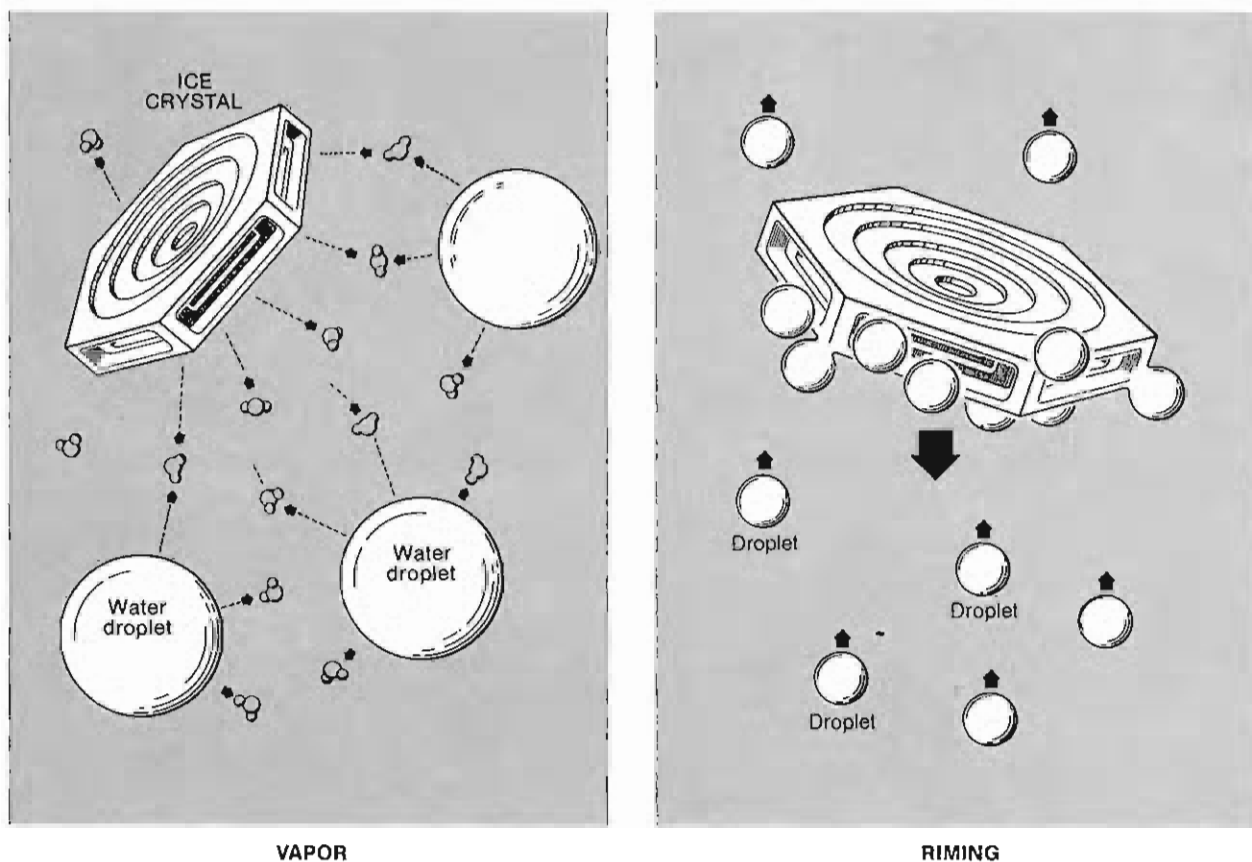
Droplet

RIMING

Figure 25.—Two modes of growth of ice crystals at the expense of water droplets. In the vapor deposition mode (left), there is a net transfer of water molecules from the droplet to the air and then from the air to the crystal. In riming (right), water droplets collide with and freeze to the crystal.

each atmospheric layer. In general, riming tends to obscure the hexagonal form of the parent crystal.

The wide variety of solid precipitation forms observed in nature does not lend itself to a simple classification scheme. However, a system proposed in 1949 by the International Commission on Snow and Ice uses a letter-number code to describe the basic forms, their major modifications, and their average sizes. In "The International Classification of Solid Precipitation" (Mason 1957, UNESCO/IASH/WMO 1970), 10 basic forms are distinguished and coded F1, F2, . . ., F0 (fig. 26). Four modifications or additional characteristics of the basic forms are shown by the following letters: broken (p), rimed (r), cluster or flake (f), and wet (w). Average size is designated D and is best given in millimeters and fractions, but if size categories are preferred, symbols are given for five categories as follows:

Symbol		Size
Da	Very small	0–0.49 mm
Db	Small	0.50–0.99 mm
Dc	Medium	1.00–1.99 mm
Dd	Large	2.00–3.99 mm
De	Very large	4.00 mm and larger

A natural snowfall should be described on the basis of the most frequent basic form, not the relatively few most easily recognized forms. Size refers to the greatest extension of a particle or the average of the greatest extensions when many particles are considered. For a cluster of crystals, it refers to the average size of the crystals composing the cluster. In coded form F1wD0.3 means wet plates 0.3 mm in diameter, and F2frDc means clusters of rimed stellar crystals between 1 and 2 mm in diameter.

In avalanche technology, it is felt that modifications are of equal or greater importance than the basic forms. Broken crystals are usually the result of deposition in a strong wind. The crystals collide with one another, are dragged along the ground, or bounce off terrain obstacles. Delicate ones, especially form F2, cannot remain intact under such treatment. The important modification, rime (r), described above as growth by accretion of supercooled droplets on the

Snow crystals

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			F1 Plates	⬡
			F2 Stellar crystals	✳
			F3 Columns	▭
			F4 Needles	↔
			F5 Spatial dendrites	⊕
			F6 Capped columns	⊟
			F7 Irregular particles	⌒
			F8 Graupel	⬙
			F9 Sleet	⧌
			F0 Hail	▲
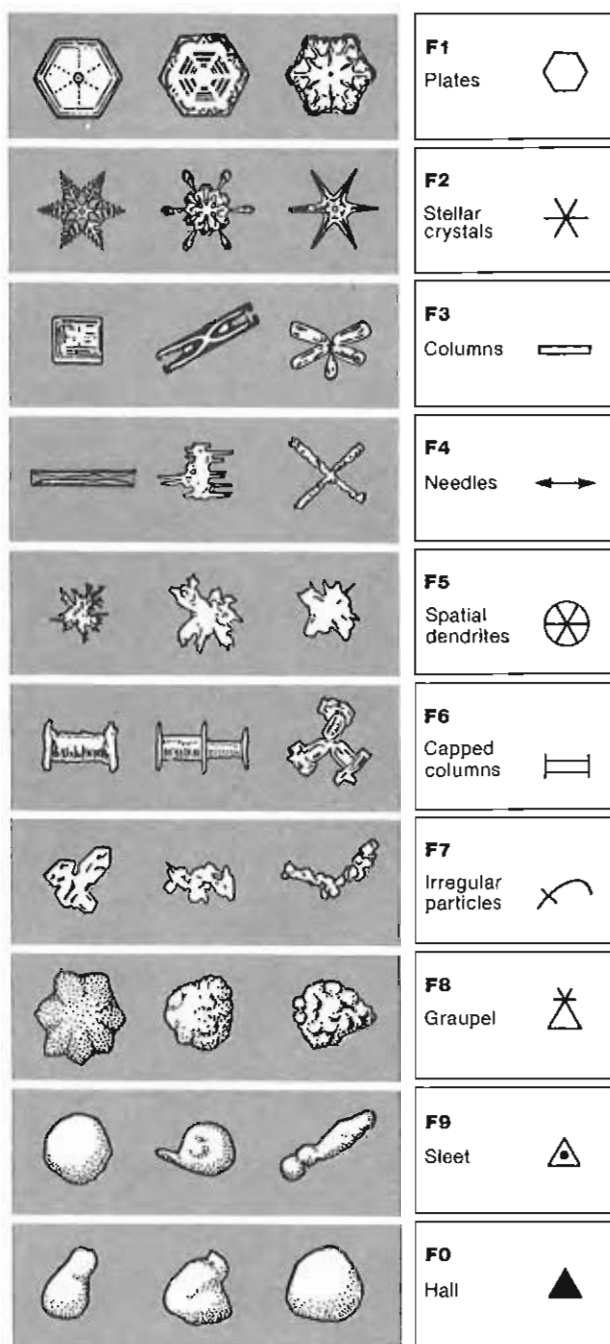
Figure 26.—The international classification of the basic forms of solid precipitation.

Figure 27.—Modifications of basic forms—above, rimed crystals and below, broken, partly metamorphosed, and clustered crystals. (Photos by LaChapelle)

parent crystal, is most common when snow crystals are transferred turbulently through moist atmospheric layers. Some riming is almost always present, especially in orographic storms. The heaviest riming occurs during the passage of a cold front, when turbulent transfer is strongest. Deposition of the solidly rimed form F8, graupel, usually signals cold-front passage. The term *snowflake* technically means a coagulation of several snow crystals. Whereas large crystals have dimensions up to 0.5 cm, snowflakes may have a spread of 5 cm or larger. Large snowflakes are predominantly composed of interlocked stellar crystals, form F2.

The international classification scheme may suffice for most avalanche work, but its apparent simplicity leads to much misclassification. Because many particles do not fit into its relatively few categories, there is a tendency to classify samples on the basis of the few that do fit or to overuse the "irregular particle" category. The more detailed system of Magono and Lee (1966) offers a much better chance of proper classification. Its 80 categories, based on extensive field and laboratory work, may appear overwhelming, but with good optical equipment and a field guide, it is easy to use.

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N1a Elementary needle	**P1b** Crystal with sectorlike branches	**P6c** Stellar crystal with spatial plates	**R2a** Densely rimed plate or sector
N1b Bundle of elementary needles	**P1c** Crystal with broad branches	**P6d** Stellar crystal with spatial dendrites	**R2b** Densely rimed stellar crystal
N1c Elementary sheath	**P1d** Stellar crystal	**P7a** Radiating assemblage of plates	**R2c** Stellar crystal with rimed spatial branches
N1d Bundle of elementary sheaths	**P1e** Ordinary dendritic crystal	**P7b** Radiating assemblage of dendrites	**R3a** Graupel-like snow of hexagonal type
N1e Long, solid column	**P1f** Fernlike crystal	**CP1a** Column with plates	**R3b** Graupel-like snow of lump type
N2a Combination of needles	**P2a** Stellar crystal with plates at ends	**CP1b** Column with dendrites	**R3c** Graupel-like snow with nonrimed extensions
N2b Combination of sheaths	**P2b** Stellar crystal with sectorlike ends	**CP1c** Multiple capped column	**R4a** Hexagonal graupel
N2c Combination of long, solid columns	**P2c** Dendritic crystal with plates at ends	**CP2a** Bullet with plates	**R4b** Lump graupel
C1a Pyramid	**P2d** Dendritic crystal with sectorlike ends	**CP2b** Bullet with dendrites	**R4c** Conelike graupel
C1b Cup	**P2e** Plate with simple extensions	**CP3a** Stellar crystal with needles	**I1** Ice particle
C1c Solid bullet	**P2f** Plate with sectorlike extensions	**CP3b** Stellar crystal with columns	**I2** Rimed particle
C1d Hollow bullet	**P2g** Plate with dendritic extensions	**CP3c** Stellar crystal with scrolls at ends	**I3a** Broken branch
C1e Solid column	**P3a** Two-branched crystal	**CP3d** Plate with scrolls at ends	**I3b** Rimed broken branch
C1f Hollow column	**P3b** Three-branched crystal	**S1** Side planes	**I4** Miscellaneous
C1g Solid thick plate	**P3c** Four-branched crystal	**S2** Scalelike side planes	**G1** Minute column
C1h Thick plate of skeleton form	**P4a** Broad branch crystal with 12 branches	**S3** Combination of side planes, bullets, columns	**G2** Germ of skeletal form
C1l Scroll	**P4b** Dendritic crystal with 12 branches	**R1a** Rimed needle crystal	**G3** Minute hexagonal plate
C2a Combination of bullets	**P5** Malformed crystal	**R1b** Rimed columnar crystal	**G4** Minute stellar crystal
C2b Combination of columns	**P6a** Plate with spatial plates	**R1c** Rimed plate or sector	**G5** Minute assemblage of plates
P1a Hexagonal plate	**P6b** Plate with spatial dendrites	**R1d** Rimed stellar crystal	**G6** Irregular germ

Figure 28.—The classification of snow crystals according to Magono and Lee (1966).
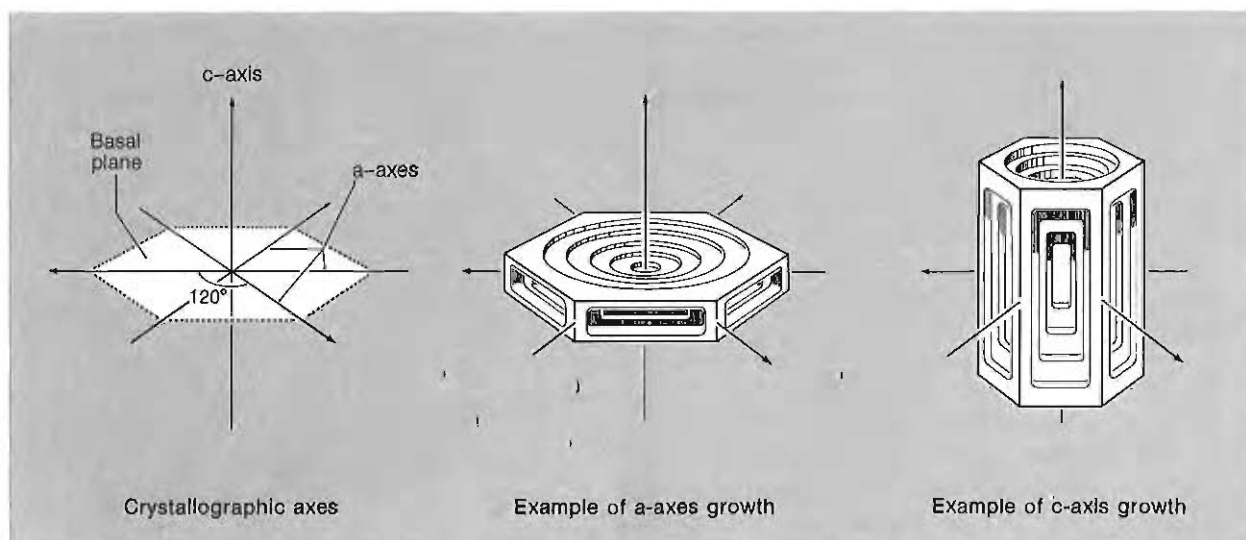
Figure 29.—Crystallographic axes of snow and ice crystals. If the growth rate along the *a*-axes exceeds that along the *c*-axis, the crystals tend toward a platelike structure. If *c*-axis growth dominates, the crystals assume a columnlike appearance. The mechanisms that cause differences in growth rates are not fully understood; air temperature plays an important role.
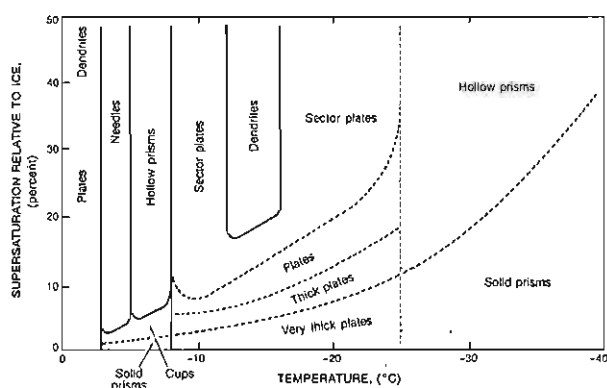
Figure 30.—Snow crystal type as a function of temperature and supersaturation, based on the laboratory observations of Mason (1957) and others. Note that as the temperature changes from 0° C to —25° C, the crystal shape of mid-supersaturation changes from plates (*a*-axis growth) to needles (*c*-axis) to hollow prisms (*c*-axis) to sector plates (*a*-axes) to dendrites (*a*-axes), and finally to hollow prisms (*c*-axis). At —15° C, as the supersaturation increases from 0 to 15 percent, the crystal structure increases in complexity from very thick plates, to thick plates, to sector plates, and finally, to dendrites. Dashed lines indicate uncertainty due to insufficient data.

The crystal structure of snow is described by four intrinsic axes, three *a*-axes and a *c*-axis. The *a*-axes lie in the basal plane of the crystal; the *c*-axis is perpendicular to the basal plane.

Depending on meteorological conditions, crystal growth occurs either in the basal plane or perpendicular to the basal plane. Growth in the basal plane results in flat, platelike crystals like forms F1 and F2, while growth along the *c*-axis results in columnlike structures like forms F3, F4, and F6. Many field and laboratory observations have demonstrated that relative growth along the *a*- and *c*-axes is controlled mostly by air temperature and somewhat by the abundance of water vapor in excess of saturation. The latter condition is called supersaturation; it is thought to control the complexity of the crystal. High supersaturations favor the development of intricate arms and branches, or dendritic growth, as in forms F2 and F5. The most peculiar feature of snow crystal formation is the extreme dependence of crystal form on small changes in temperature within a narrow range. As air temperature changes from 0° C to —25° C, the patterns change from *a*-axis growth to *c*-axis growth and back to *a*-axis growth.

In the field, large crystals such as graupel and stellars are easily identified by the naked eye. Identification of medium and smaller specimens and their modifications requires 10- to 25-power magnification. Pocket magnifiers with good depth of field are most useful in day-to-day work.

In making observations, one should beware of classifying newly fallen snow solely on the basis of one or two very prominent symmetrical specimens. The life history of a snow crystal is complicated by a journey through different temperature, supersaturation, and wind layers, and the final product is rarely in the form of the textbook illustrations.

22

Windflow over mountain terrain

Windspeed and direction are quite variable over a mountainside from ridgecrest to canyon floor. About 10 m above the ridgecrest, windspeed and direction are approximately that of the free air as measured by balloon at a nearby upstream station. For example, over a 3,000-m isolated ridgecrest, the windspeed and direction have approximately the 700-mb values. The wind below the ridgecrest depends on the orientation of the terrain. At a canyon floor, winds usually are deflected to aline with the canyon's direction. The amount of deflection depends on the steepness and length of the canyon. Often, flow at the canyon floor is deflected 90° or more from the free airflow over the ridgecrests.

Terrain obstacles exert drag forces that disturb the typically smooth flow of free air. Hence, flow over mountain terrain is relatively irregular. As the terrain exerts drag on the wind, the wind in return exerts a shear stress on the terrain. This shear stress loosens the snow from the terrain. The eroded snow is carried by the wind and redeposited.

Since deposition of snow is controlled by wind, it is important to understand how air flows over and around terrain obstacles. Picture, first, the flow over a wedge-shaped ridge, as shown in figure 32. The flow lines represent the trajectories of air parcels. At levels high above the ridge (region B), the flow lines show almost none of the ridge's influence. However, a parcel that flows close to the ridge is accelerated in region A, the windward side of the ridge, reaches a maximum velocity above the crest (region C), and decelerates in region D, the lee side of the ridge. It is easy to see that the acceleration and deceleration effect will depend strongly on the "sharpness" of the ridge, as measured by apex angle θ. Accelerations and decelerations oc-
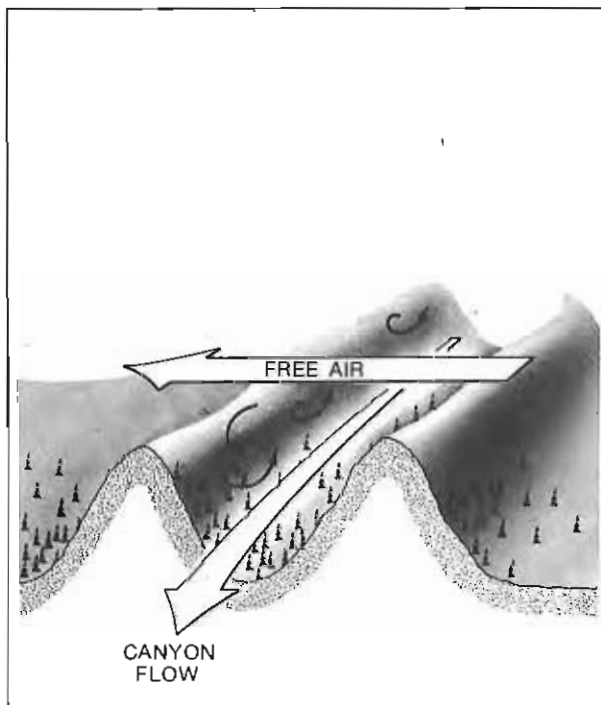
Figure 31.—Flow above the ridgecrests is approximated by the free airflow. Canyons tend to deflect the wind to aline with the canyon direction. Flow over the mountainside is generally irregular and unsteady.

Figure 32 (*right*).—Airflow over a wedge-shaped ridge.
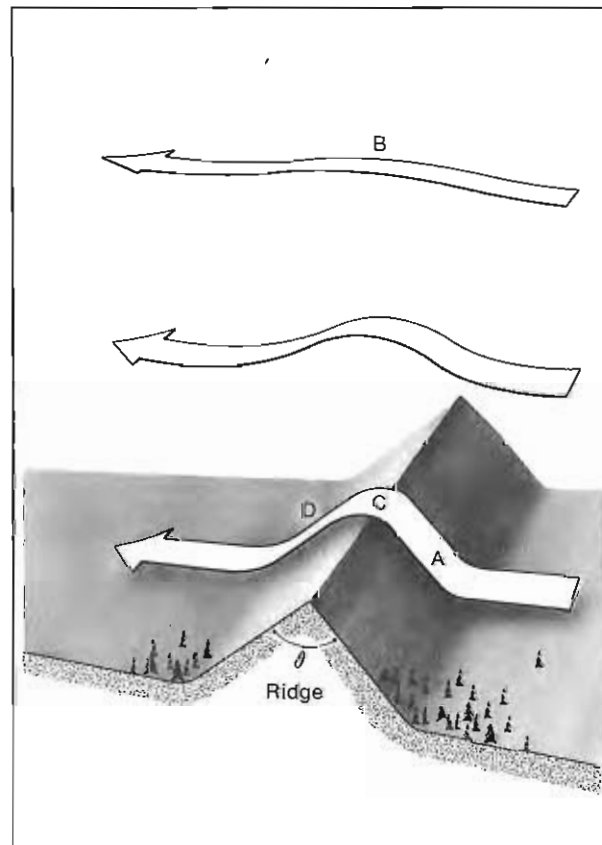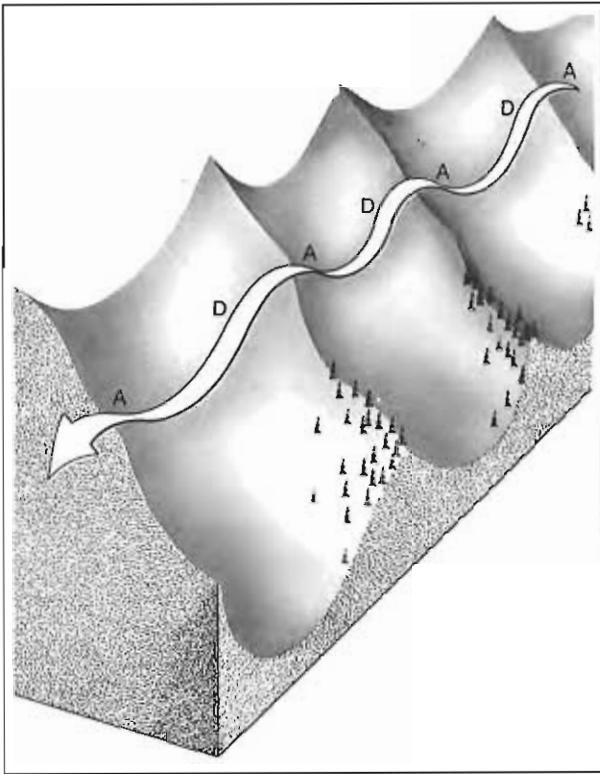
Figure 33.—Flow across a slope. Acceleration regions are designated A, deceleration regions, D.
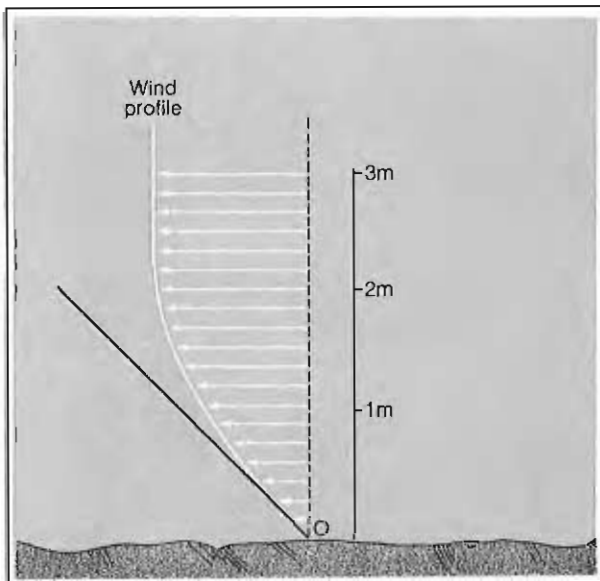
Figure 34.—Windflow over a surface. The shearing force of the wind depends on the gradient of the windspeed at the surface. The gradient at the surface is represented by the slope of line OL.

cur over a variety of terrain geometries. Of particular importance is flow across a slope where accelerations and decelerations are caused by shoulders and gullies.
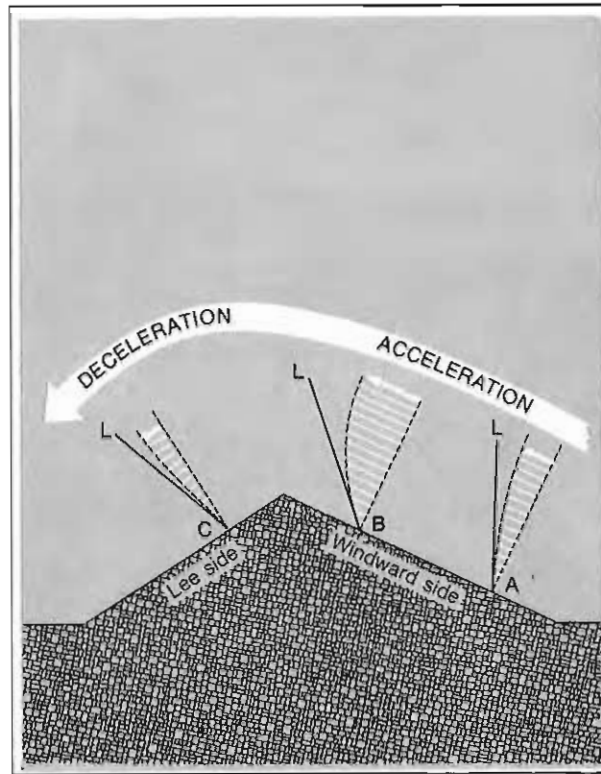
Figure 35.—Flow over a blunt ridge. The windspeed gradient at B (BL) exceeds the gradient at A (AL). Hence, the shear at B is greater than the shear at A. Gradients reduce on the decelerating or lee side of the ridge.

Next, imagine the thin windflow layer just above the surface of a terrain obstruction. The wind velocity is zero at the surface and varies with height above the surface. This variation is the *windspeed gradient*. As already noted, the wind exerts a shear stress against the surface. The amount of stress depends on the gradient of the windspeed at the surface.

Terrain obstacles cause variations in gradients and thus variations in shear stress. Consider flow over a blunt ridge, as shown in figure 35. In the accelerating region, the gradient increases with increasing proximity to the ridgecrest. Since the gradient is larger at B than at A, there is a greater shear stress at B than at A. In the decelerating region, the gradient decreases, and therefore shear stress decreases. The amount of shear stress at some point in the decelerating region, say point C, depends on the terrain, particularly the sharpness of the ridge and the steepness of the lee slope.

The decelerating effect intensifies as the lee side steepens or the ridge becomes sharper. Over steep lee slopes or sharp ridges, the wind profile may have the
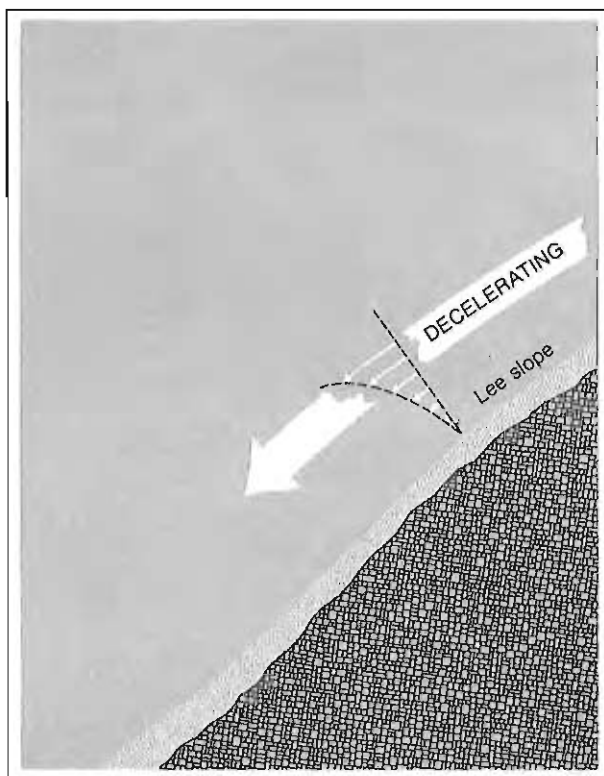
Figure 36.—Over part of a steep lee slope, the windspeed gradient at the surface may vanish. In this case, the shear at the surface also reduces to zero.

Figure 37.—Reverse flow and shear on steep lee slopes. The reverse flow joins the main flow in a circular pattern called a vortex.

shape shown in figure 36. The shear stress vanishes on a surface beneath such a profile. On even steeper lee slopes, typical of many avalanche paths, the deceleration is sometimes strong enough to reverse airflow and so reverse shear, as shown in figure 37. The reverse flows join the main stream to form circular swirls called vortexes or eddies. Each terrain feature induces a unique vortex pattern strongly dependent on the speed and direction of the main flow. Vortexes are generated in all sizes, from large "rolls," with dimensions on the order of the ridge height, to pea-sized eddies. In general, vortexes are stationary in neither position nor size, but are shed by the terrain and carried downstream by the main flow. Vortexes build up and decay continuously, and new ones take the places of dissipated ones. The passage of a vortex is observed as a gust or a sudden change in wind direction and by "snow devils."

The foregoing discussion is an idealized picture of flow over terrain obstacles. Actual small-scale flow is much more complicated. Each small protrusion of terrain has an effect, producing accelerations, decelerations, and vortexes on its own scale.

Wind redistribution of snow

In the absence of wind, snow crystals fall at rates that vary between about 0.3 m/s for flat, platelike crystals and 2 m/s for graupel. Very light winds deflect the snow crystals in the horizontal direction, plastering snow against the windward sides of obstacles, especially when the snow is wet. However, when windspeed exceeds a few meters per second, as it usually does during mountain storms, the shearing forces exerted by airflow against the snow surface erode the snow from regions of high wind stress. Eroded snow is redeposited in regions of low wind stress. Looked at in terms of windspeed, the snow is picked up where windspeed is increasing and deposited where windspeed is decreasing. When snow is transferred, it tends to accumulate in localized zones instead of spreading out evenly. These zones are usually terrain indentations bounded by rock outcroppings, gully walls, tree groups, or other irregularities. The deepest accumulations are in gullies and bowls, where the snow may be several meters deep, but large accumulations can also form on flat or even convex slopes.
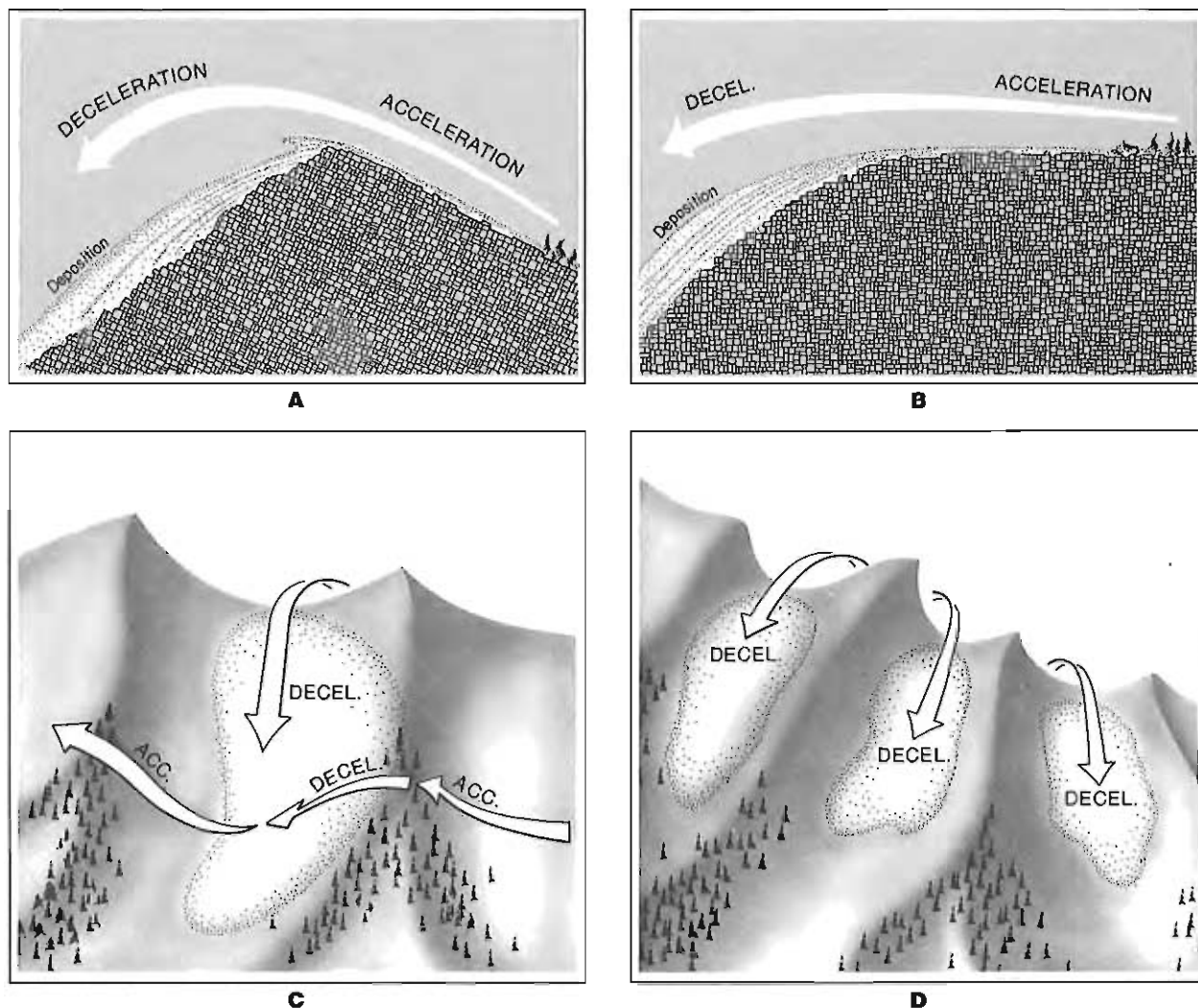
Figure 38.—Snow is eroded from acceleration regions and redeposited in deceleration regions. Four examples of transport are shown: *A*, transport from the windward to the lee side of a ridge; *B*, transport to a region of increasing slope steepness; *C*, transport into gullies from side and top; and *D*, transport through notches in a ridgecrest.

Figure 39.—Examples of natural accumulation zones in a mountain basin. The accumulation zones, shown by arrows, depend on the prevailing wind direction.

The amount of snow eroded by high winds depends on the "looseness" of the surface. The largest amounts are transferred during or immediately after storm periods, since newly fallen snow is especially susceptible to erosion. Wet snow is not as easily sheared loose. However, some snow can always be moved during winter if the wind is strong.

It is difficult to give threshold values of windspeed that shear loose all types of snow from all types of terrain, but it is observed that the amounts transported depend strongly on the windspeed. According to some studies, the volume of snow transported depends on the third power of the speed; that is, doubling the windspeed increases the horizontal transport by a factor of eight.

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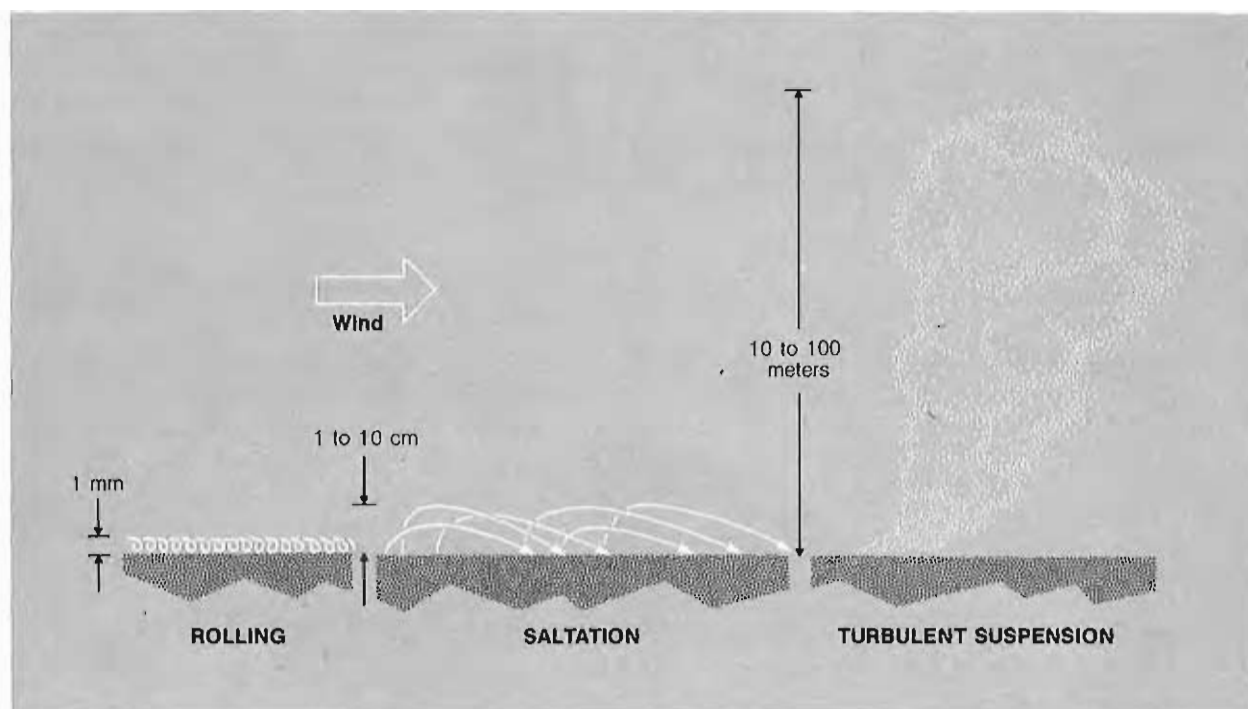
Snow is transported in three ways: *rolling, saltation,* and *turbulent suspension.* Rolling is limited to a thin layer, no higher than 5 mm thick, on the surface of the pack. This is not thought to be important in loading avalanche slopes. Saltation involves bouncing particles. Each particle is supposedly kicked up into the airstream by the impact of another particle. Although saltation may lift particles as high as 100 cm, it is most effective in the first few centimeters above the surface. Turbulent suspension refers to particles suspended in the wind by aerodynamic forces. Heavy particles are suspended near the surface, light particles as high as 100 m above; however, the greatest mass transport by this process occurs in the first 2 m above the surface, and it is thought that 90 percent of the transfer is limited to the first 50 cm above the surface.

There is some disagreement as to whether saltation or turbulent suspension is the dominant mode for loading avalanche slopes, but working together the two modes rapidly transfer snow to regions of low wind stress. In a test at Berthoud Pass, Colo., snow was deposited in a lee-exposed gully at a rate of 45 cm/h.

Due to pulverization, the average size of the blowing snow particles may be only $\frac{1}{10}$ the size of those that fall undisturbed. Because of small particle size, wind-deposited snow is two to four times denser than snow that falls in a sheltered study plot. Also, due to
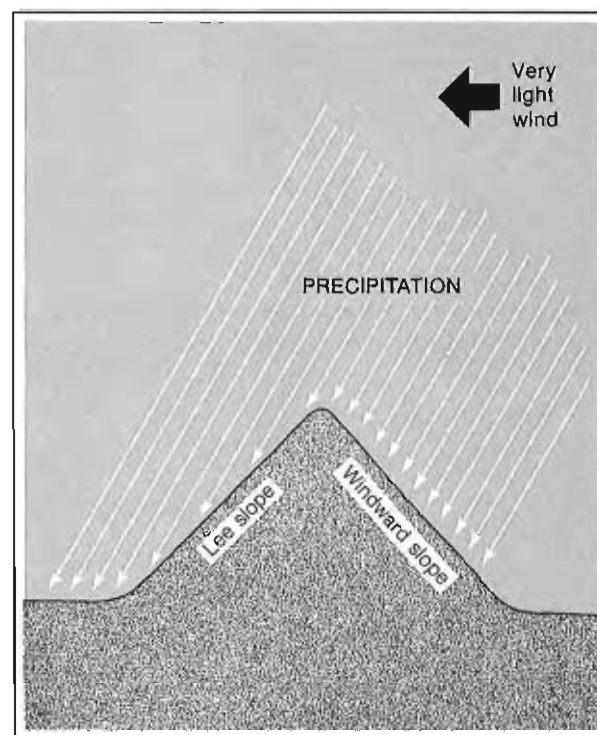
Figure 41.—Snow deposition, especially with wet snow, is heavier on the windward side of a terrain obstacle during very light winds of only a few meters per second.

Wind redistribution of snow
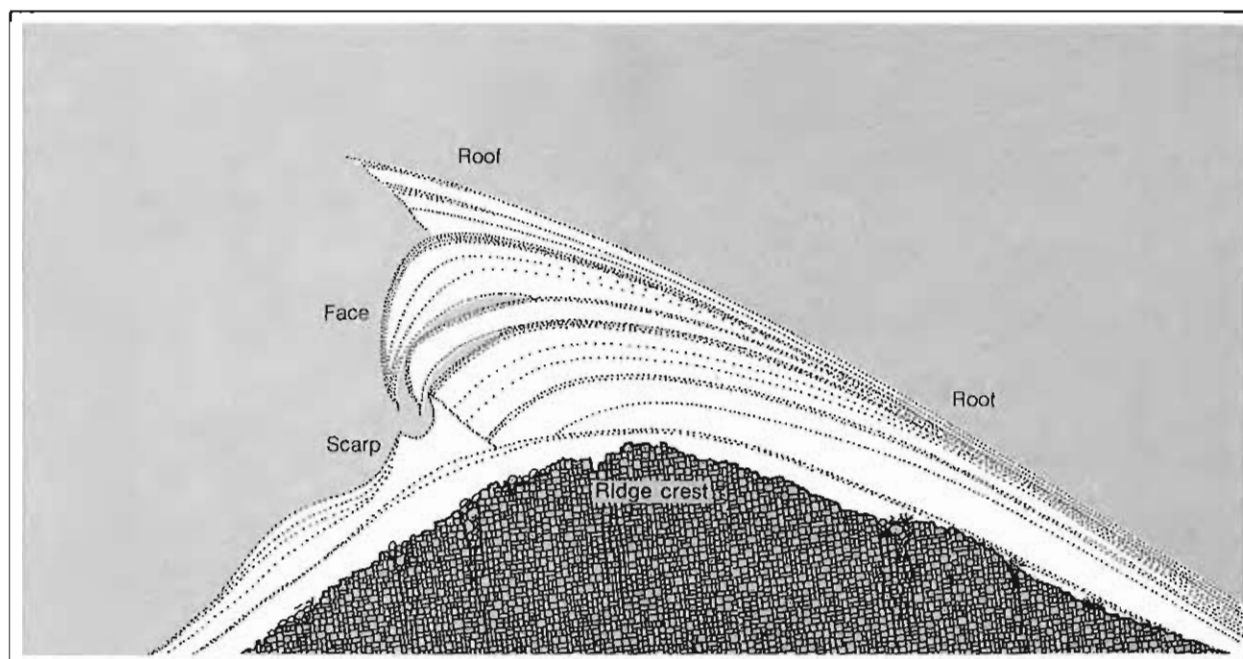
Figure 42.—Basic structure of a snow cornice.

Figure 43.—A large cornice at Rottalsattel, near Jungfraujoch, Switzerland. (Photo by Roch)

the small particle size and many particle contacts, wind-transported snow quickly takes on a firm, slab-like structure.

Large amounts of snow accumulate in the form of cornices at sharp terrain bends. The most common cornice locations are at ridgecrests, sides of gullies, and other local steepenings. The basic structure of a cornice consists of a root, roof, face, and scarp.

Cornices grow as successive layers that are added during each period of snow transport. In the Bridger Range of Montana, cornices were observed forming with winds as light as 7 m/s, whereas winds of 27 m/s scoured the cornice surface and abruptly reduced its height (Montagne et al. 1968). As each layer accretes onto the roof, it tends to extend out over the cornice face, supported as a cantilever sheet. The mechanisms that favor this growth are not fully understood. After attachment to the roof, the layers are deformed slowly by gravity and bend toward the cornice face as a curved tongue that often encloses an airspace.

The far end of the top layer with its poor attachment to the old cornice surface and the cavities caused by the deformed layers are major sources of structural weakness. Also, throughout its life, the entire cornice deforms steadily outward over the slope, usually reaching a position of precarious balance. Overhanging cornices can be extremely massive. Cornices often extend as much as 15 m upward and outward from

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the ridgecrest, with size and shape a function of ridge shape and lee-slope steepness. The density of cornice snow can exceed 400 kg/m³. Cornices are usually more stable over slopes of less than 50° than over steeper slopes where support is lacking.

Wind analysis

Through a combination of human observations and wind instrumentation, it is possible to judge qualitatively the effects of wind on the snowpack. In evaluating the avalanche hazard, there is no substitute for an experienced observer being at the area in question and seeing where snow is being deposited. The observer first watches the visual evidence of transport (snow plumes over ridgecrests, vortexes, etc.). Based on these clues, he makes as thorough a field inspection as possible to verify his suspicions about where snow is being deposited. This approach is generally limited by lack of manpower, severe weather, and the size or inaccessibility of important accumulation zones. It is therefore necessary to rely heavily on wind instruments.

Many types of wind systems are available, featuring simple and complex, inexpensive and expensive components. It has not been demonstrated that any one system solves all the problems of measuring mountain winds. The most popular sensors from an eco-

Figure 44.—Rotating-cup anemometer and wind vane. These instruments should be located on a high, isolated ridgecrest and set on a tower at least 3 m above the ridge.

nomic and operational standpoint are the rotating-cup anemometer for measuring windspeed and the wind vane for measuring wind direction. The sensors can be wired to recorders, or, in the more deluxe systems, the signals can be transmitted to receivers that are wired to reeorders.
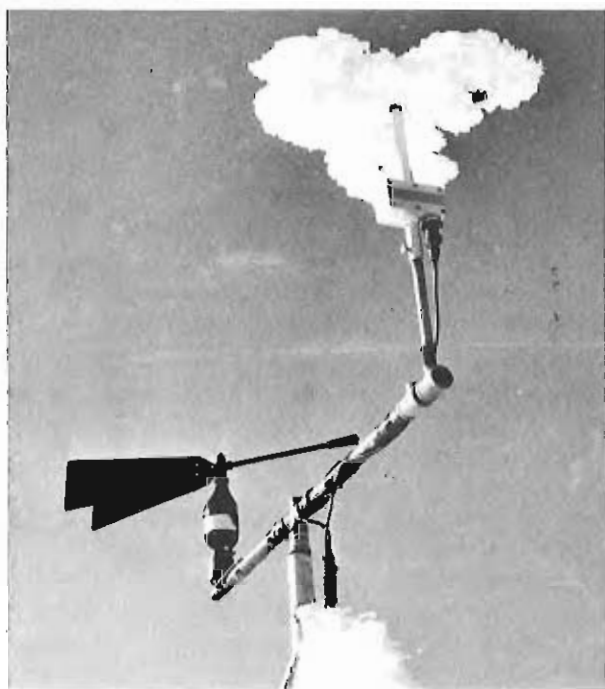
Figure 45.—The formation of rime on wind sensors (left). One solution is to heat the sensors with infrared lamps (right). (Photos by Judson)
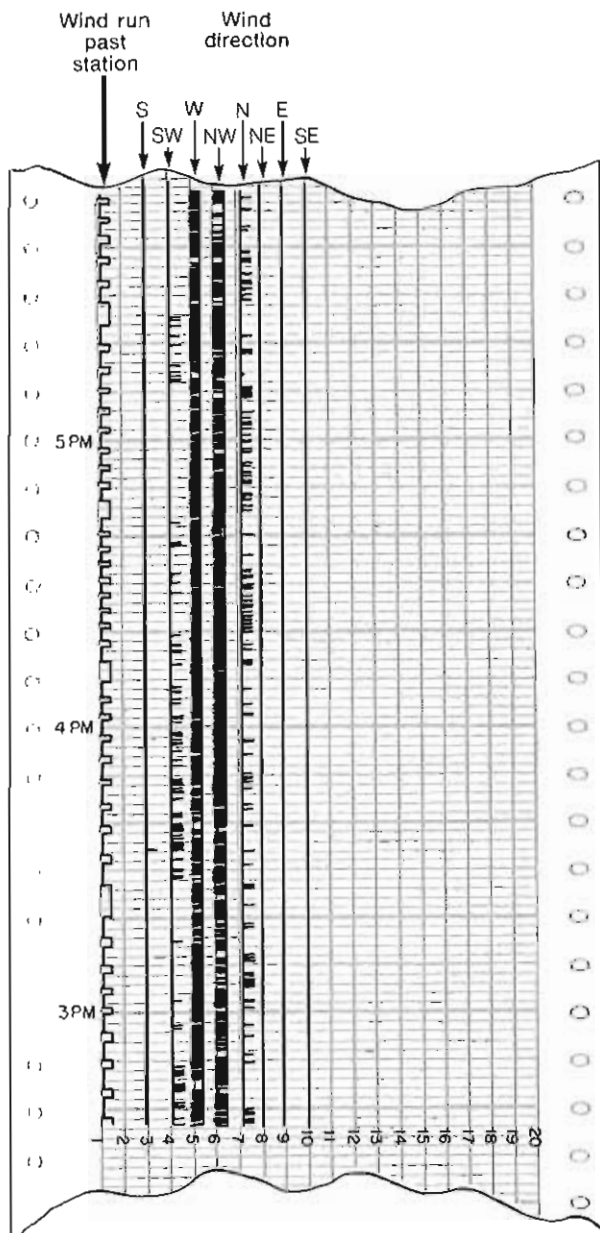
Figure 46.—Digital wind-direction and speed record. Each small notch in the left trace indicates 1 mile of wind travel. Each of the large notches indicates 10 miles of travel. Wind direction is determined from the other traces, by the relative number of marks from each direction. For example, at 4 p.m. the wind was from the west-northwest.

Since it is generally not practical to install a large number of sensors, one good location must be chosen. The sensors should be placed where they can monitor the windflow that feeds the greatest number of the most important lee slopes. A high, isolated ridgecrest is a natural choice if it is reasonably accessible in winter. Long experience teaches that even the most reli-

able wind system needs periodic attention to help it stand up to the rigors of winter at high elevations. The sensors should be erected on a tower so as to always clear the snow surface by at least 3 m. The windspeed at the 3-m level is roughly 90 percent of the speed at the 10-m level.

Wind sensors on high ridgecrests are exposed to rime and lightning. Rime can completely cover the wind sensors, locking them and often causing damage. One solution is to heat the sensors with infrared lamps. Lightning also presents a serious problem. The instruments must be removed from the tower when threatened by lightning. Circuitry should be connected through lightning arrestors. When not in use, circuitry should be removed from the tower and electrically grounded.

Wind measurements can be based on either digital or analog signals. In the simplest digital system, an impulse is recorded after a predetermined amount of wind passes the sensor. From the digital data, it is simple to compute the average windspeed, perhaps on an hourly basis.

Analog systems give a continuous reading of windspeed and direction. This enables one to judge the gustiness of the wind, or the difference between the average windspeed and the peak values. Since the amount of transported snow depends on some exponential power of the windspeed (perhaps the third power), large amounts of snow are transported by gusts. Gust information can be obtained in digital form, but this requires expensive and complex equipment.

Many gusts originate as vortexes shed by terrain obstacles; therefore, gustiness, as measured at a sensor, depends somewhat on the position of the sensor with respect to upstream terrain features that shed the gusts. For a given wind direction, the flow may be gusty over one ridge but smooth over a neighboring ridge that has a slightly different orientation. If the wind shifts, the situation could be just the opposite. Hence, for broad answers about wind transport over a wide variety of terrain, the average windspeed is probably sufficient.

Because wind direction fluctuates considerably, it is often difficult to compute average wind direction from digital charts, unless again one wants to resort to complex and expensive components. Comparing the wind-direction data in figures 46 and 47 shows that average wind direction is more easily computed from analog traces than from digital traces.

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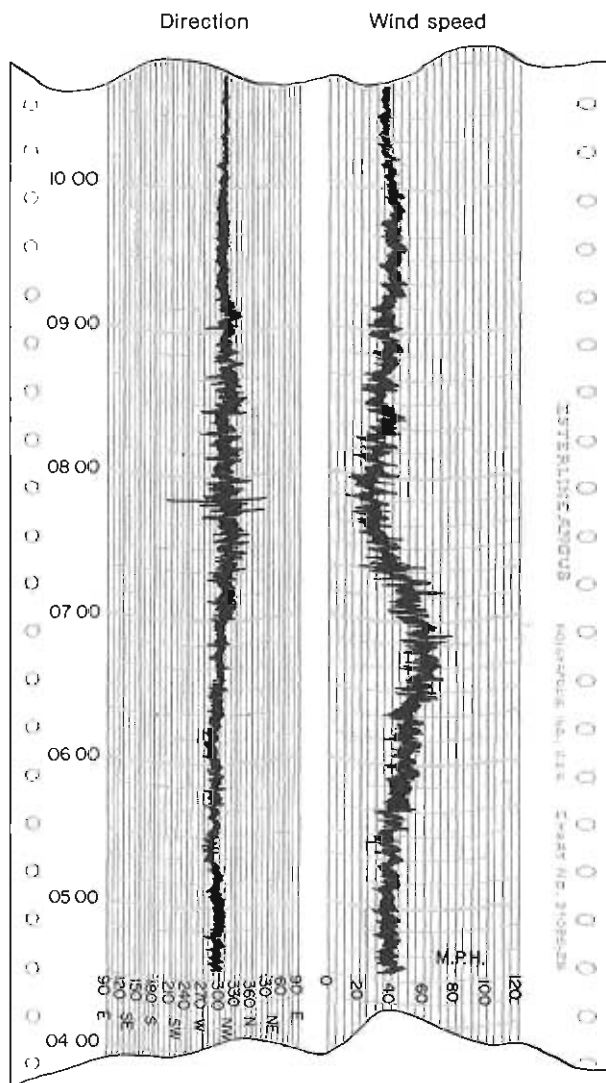
Figure 47.—Analog windspeed and direction record. Between 0800 and 0900, the average windspeed is about 35 mi/h (16 m/s). Peaks are in the range of 45 to 48 mi/h (20–21 m/s). One advantage of the analog system is the clarity with which the information is displayed.

Figure 48.—National Weather Service upper-air network in the western United States. Instrumented balloons released from these stations twice a day send back information on windspeed, wind direction, temperature, humidity, and pressure. Additional upper-air soundings are sometimes taken at local airports and by agencies involved in cloud seeding and related projects.

When local wind sensors are not operating, avalanche workers may contact the National Weather Service for information on windspeed and direction at ridgecrest level. Weather Service information is based on balloon soundings of the upper air. The usefulness of this information depends, first, on how far downstream the avalanche area is from the nearest balloon-release station; second, on how dense the network of balloon-release points that surrounds the area is; and third, on the complexity of the terrain. Many avalanche-threatened areas in the United States are well located to use Weather Service wind data.

Heat exchange at the snow surface

Heat energy is exchanged constantly between the snowpack and the atmosphere. Generally speaking, heat energy can enter and leave the snowpack by molecular or radiative processes. Both processes occur simultaneously, and together they determine how the snowpack heats up and cools down near the surface.

The basic law for molecular transfer of heat energy between the snow and atmosphere is simple. If the snow is warmer than the air, the snow loses heat to the atmosphere; conversely, if the atmosphere is

Distance above snow surface	Air temperature		Distance above snow surface	Air temperature
60cm	—4°	Heat transfer	60cm	—18°	Heat transfer
40cm	—5°		40cm	—17°
20cm	—8°		20cm	—15°
0cm	—10° Snow surface		0cm	—10° Snow surface

A   **B**
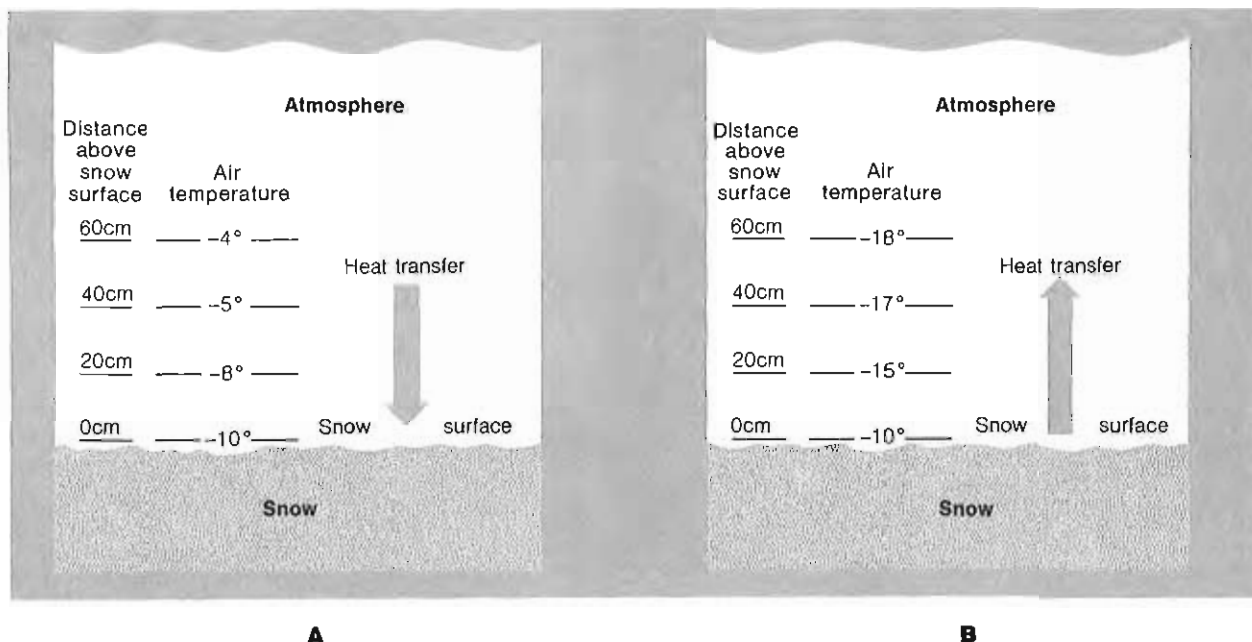
Figure 49.—Examples of air-temperature gradients above the snow surface in calm air. For temperature profile A, the transfer of heat is into the snowpack; for profile B, the heat transfer is out of the snowpack.

Figure 50.—Standard instrument shelter for housing thermometers and other meteorological instruments. The metal frame and pulley allow the shelter to be raised or lowered to keep it the proper height above the snow.

warmer than the snow surface, heat flows from the atmosphere to the snow surface. In the absence of wind, molecular transfer is comparatively slow. With increasing wind, there is increasing opportunity for molecular contact due to mixing, and the energy exchange occurs as much as 10,000 times faster. Like the snow-transport mechanism discussed in the previous sections, the rate of removal or addition of heat depends on wind shear against the snow surface. The greater the shear, the greater the exchange of heat.

The rate of molecular heat exchange also depends on how much water vapor is being transferred between atmosphere and snowpack. If the air layer above the snow is oversaturated with respect to the snow surface, energy transfer into the snowpack is increased by vapor deposition of molecules onto the snow surface. Conversely, if warm, dry air is blown over the snow surface, water vapor molecules may sublimate from the snow surface and thus return some heat energy back to the atmosphere. As snow grains fall on the snowpack, they either bring heat energy into the pack or absorb heat, depending on the relative temperatures of the precipitation particles and the snowpack. Rain can only add heat.

In the above discussion, the concept of air temperature is used rather imprecisely. Air temperature

SOLAR COMPONENTS **TERRESTRIAL COMPONENTS**

Incoming solar radiation

Atmospheric radiation into space

Radiation of clouds into space

Reflected solar radiation

Arbitrary atmospheric layer

Terrestrial radiation into atmosphere

Back radiation of atmosphere

Back radiation from clouds

Terrestrial radiation into clouds

SNOW

Absorbed solar radiation

SNOW

[handwritten: THIS BLOCK BELONGS]

Figure 51.—Some of the important components of the radiation balance: incoming solar radiation, absorbed solar radiation, reflected solar radiation, terrestrial radiation into the atmosphere, radiation of atmosphere toward space, back-radiation of atmosphere toward earth, terrestrial radiation into cloud, back-radiation of cloud toward earth, and radiation of cloud toward space.

[handwritten: PRINTERS ACCIDENTALLY FLIPPED FIGURE WHICH WAS IN THREE LAYERS]

varies with height above the snow surface; this variation is called the air-temperature gradient. Heat energy flows so as to minimize the air-temperature gradient above the snow.

Because temperature varies with height, it is standard practice to measure air temperature about 1.2 m above the surface. At this level the gradient is reduced. Air temperature should be measured in a well-ventilated shelter, facing north and constructed according to National Weather Service specifications (fig. 50).

Determining the temperature gradient just above the snow requires knowledge of the snow surface temperature, which is not easily measured. The main difficulty in determining the surface temperature is due to radiation—the other important process by which heat is exchanged at the surface. Radiation is emitted from the sun (solar radiation) and reradiated from the earth (terrestrial radiation).

The intensity of the solar radiation that arrives at the surface depends on the time of day, calendar date, cloud cover, and aspect of the slope. Much of this radiation is reflected back into space. Some is absorbed by the snow, adding heat energy. New, dry snow reflects more than 90 percent of the solar radiation, making less than 10 percent available as heat

energy. (This is still a considerable amount of energy, especially at midday in spring.) Wet snow can absorb almost 50 percent of the incoming solar radiation. Absorption takes place almost exclusively in the top meter of the pack and mostly in the top 20 cm. The ratio of the amount of solar radiation reflected by a surface to the amount incident upon it is called the *albedo* of that surface. It is usually expressed as a percentage.

The entire surface of the earth reradiates energy into space. This so-called terrestrial or longwave radiation is not as penetrating as solar radiation, and it is absorbed by the atmosphere, which in turn radiates energy back toward the earth as well as into space. Thus, the net flow of terrestrial radiation is extremely complex, depending critically on such factors as snow surface temperature, cloud temperatures, and the humidity and temperature structure of the atmosphere. If the atmosphere is clear and dry, relatively large amounts of terrestrial radiation can escape from the snow surface into space. On the other hand, if a warm cloud passes over, the back-radiation from the cloud can counteract the surface emission.

Considering this complex state of affairs, it is possible to make only broad generalizations about the combined effects of solar and terrestrial radiation:

Heat exchange at the snow surface

• During the middle of the day in winter, December through March, there is a small gain of radiant energy on south-facing slopes due to the excess of incoming solar radiation over outgoing terrestrial radiation. On steep, north-facing slopes, there is a continued loss of terrestrial radiation only partly offset by small amounts of incoming solar radiation.

• During the middle of the day in spring, there is a large gain of radiation on south-facing slopes and a small gain on north-facing slopes.

• During evenings, all slopes radiate terrestrial energy into space. The amount that escapes depends mostly on humidity and cloud cover.

Using the air temperature and some qualitative information about radiation, it is possible to guess the trends in the energy balance at the snow surface and be right more times than wrong. For example, one may assume the following:

(1) If the air temperature is rising, the snow temperature near the surface is also rising, at least up to 0° C. If the snow is wet and the air temperature rises above 0° C, then the snow will get wetter. This correspondence between snow- and air-temperature change is especially true when there is wind.

(2) Similarly, falling air temperatures imply falling snow surface temperatures.

(3) The important exception to *(1)* and *(2)* occurs in the evening, under clear skies, when terrestrial radiation loss from the surface is so strong that snow temperatures fall regardless of air-temperature trends. The terrestrial loss is even strong enough to compete with warm winds.

(4) During the daylight hours of winter, there may be some exceptions to *(1)* and *(2)*, especially when winds are light. The air temperature may be observed to rise, but the snow could lose terrestrial radiation through clear skies, in which case, the snow temperature would be maintained at fairly constant levels. This exception is more likely on north-facing slopes.

Some interesting examples can be given to illustrate the combined effects of exchange of energy at a snow surface. Consider a canyon bounded by two ridges. The terrain is snow covered. On clear eve-
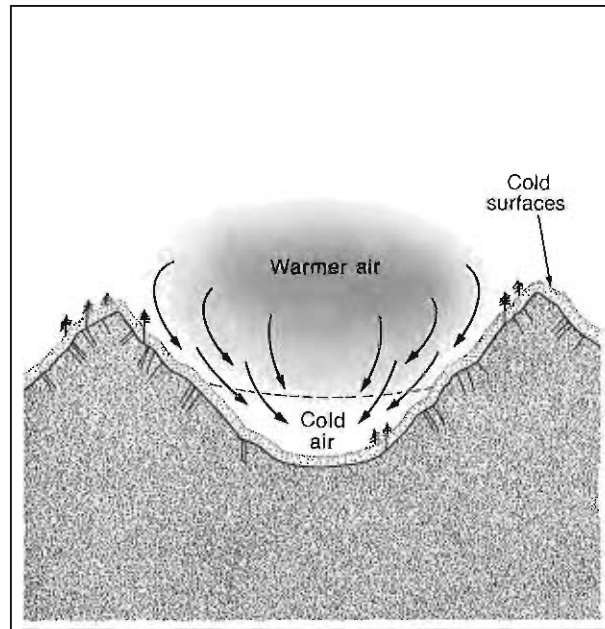
Figure 52.—Temperature inversion in a mountain canyon. Inversions are the result of nocturnal cooling of the snow surface by radiation loss.

nings, when the temperature of the snow surface drops due to terrestrial radiation loss, cold layers of air form over the snow surface. These cold layers, being denser and heavier than the warm air, drain down to the canyon floor. The warmer air that still retains some of its daytime heat energy is suspended in the canyon. On the upper slopes, the warm air mixes in with the cold surface layers, tending to produce warmer air and snow surface temperatures. This stratification of warm air over cold air is referred to as an *inversion*. During early morning hours, when the inversion is fully developed, air temperatures at the canyon floor may be 15° C colder than at midslope.

The growth of surface hoar affords another interesting example of surface energy exchanges. During the day, the relatively warm air layer above the snow may contain an appreciable amount of water vapor. Although the air is unsaturated at the daytime temperature, it may become saturated with respect to the snow surface at the colder evening temperature. Thus, at night the vapor condenses on the surface of the pack in the form of surface hoar, the solid equivalent of dew. Surface hoar layers are a few millimeters to several centimeters thick. They are extremely weak and cohesionless. Once buried in the snowpack, they represent serious structural weakness.

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Figure 53.—Surface hoar crystals. (Photo by LaChapelle)

Figure 54.—Analysis of storm data provides clues as to which avalanche paths are being loaded, the amount of loading, and the rate of loading. Further application of storm analysis to stability evaluation is explained in chapter 5.

Storm analysis

It is an observed fact that the vast majority of avalanches release during or shortly after storm periods. In this text, the term *storm period* is used in the broadest sense to include periods of snowfall, snow transport, or both. Each storm is a unique combination of meteorological variables; the combinations are almost infinite. As already pointed out, meteorological data cannot be gathered at every avalanche path of interest. For practical reasons, wind, precipitation, temperature, etc., are measured at one or two locations. Thus, storm analysis consists of interpreting available data in terms of what is happening on the slopes of interest.

Storm data can be recorded and analyzed in many ways. Each avalanche worker sooner or later develops a system that best fits his own day-by-day operation. As a minimum, some analysis must be made of wind and precipitation measurements. More refined systems also include measurements of temperature, radiation, snow-crystal type, etc. To visualize the interaction of storm variables, it is helpful to plot the data in graph form. This is called a *storm plot* (see fig. 54).

From a storm plot, one tries to deduce which slopes are being loaded with new deposition, the amount of loading, and the rate of loading. The analysis is weighted heavily by the observer's experience and feel for the terrain. Beyond this, only the following general indications can be mentioned:

Indications of which slopes are being loaded. Windspeed and direction determine which slopes are being loaded:

- In the absence of ridgecrest winds, or for very light winds, windward and lee slopes have an equal probability of being loaded.

- For moderate ridgecrest winds, the loading is almost all on lee slopes or the lee sides of gullies.

- For very strong winds, loading is on the lee side, but snow tends to accumulate in relatively isolated, deep pockets rather than being spread over the entire lee slope. In general, the higher the wind, the more difficult it is to locate these pockets. A field inspection is essential.

- Glaze, an ice layer resulting from freezing of supercooled water, tends to be deposited on windward exposures.

- Rain affects all slopes.

Indications of the amount of loading. The amount of loading is inferred from ridgecrest winds and precipitation observed at a study plot.

• Heavy loading generally correlates with high precipitation intensity, as observed at a study plot.

• Regardless of the study-plot precipitation values, heavy loading correlates with sustained winds if the snow surface is dry and loose.

Indications of the rate of loading. The rate of loading is inferred from the precipitation intensity and ridgecrest wind data.

As an illustration, consider the storm plot in figure 54. Based on precipitation, this storm consists of three phases: an initial period from 0700 to 1600, January 24, during which precipitation intensity (represented by the slope of the curve of water equivalent) is comparatively low; an intermediate period, from 1600, January 24, to 0400, January 25, characterized by relatively high precipitation intensity; and a final tapering-off period, from 0400 to 1300, January 25, with a relatively low precipitation intensity. The precipitation data can be summarized as:

		Water equivalent	*Precipitation intensity*
Phase I	(9 h)	10 mm	1.1 mm/h (moderate)
Phase II	(12 h)	30 mm	2.5 mm/h (intense)
Phase III	(9 h)	5 mm	0.6 mm/h (light)
	Total	45 mm	

During phase I, the wind is light to moderate and has a definite southerly component. The windspeeds are probably high enough to transport snow from windward to lee slopes; hence, loading is presumably on north-facing slopes. From the precipitation and wind data, it is reasonable to conclude that moderate loads are developing, and at moderate rates.

During phase II, the wind direction changes from south-southwest to northwest. Since windspeeds are clearly high enough to transport snow, accumulations are most likely forming on east-facing slopes. Precipitation data suggest that total loads and loading rates are significantly large.

During phase III, wind and precipitation data indicate that only small loads are developing on south-facing slopes. Also, the north winds of phase III do not appear strong enough to significantly erode the accumulations from phase I. At the conclusion of this storm, large depositions should be expected on east-facing avalanche paths and moderate depositions on north-facing paths.

Storms also may be analyzed on the basis of temperature trends. There are two broad categories: standard trends and inverted trends. In the standard trend, initial storm temperatures are relatively high, and the temperature falls as the storm progresses. In the inverted trend, the initial temperatures are relatively cold, and temperatures rise as the storm progresses. The storm plot shown in figure 54 is an example of the standard trend. For the mountain ranges of the western United States, the standard trend usually begins with southwesterly airflows that carry in warm, moist airmasses. Eventually, the winds shift to the west and finally to the northwest. In the inverted trend, the initial surge of moisture is carried in on a northwesterly airflow. This is followed by a wind shift to the southwest and consequently warmer and usually more intense precipitation.

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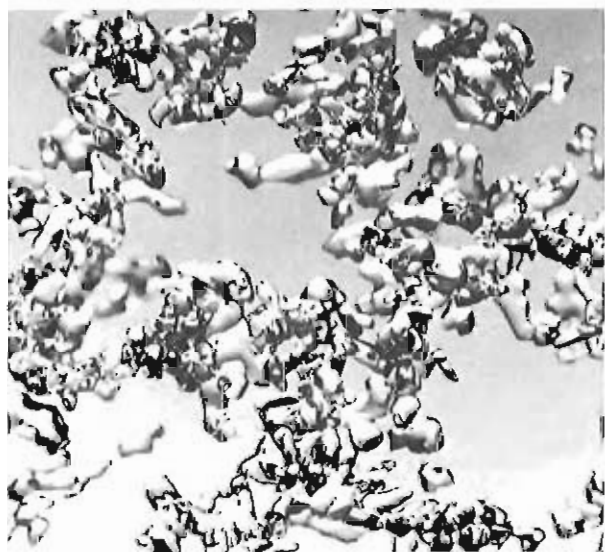
The mountain snowpack

*As soon as a snow crystal falls onto the snowpack
it fastens to its neighbors and becomes part of
an interconnected skeleton of ice grains. The ice
grains are quite free to move into available voids
or pores; therefore, the ice skeleton constantly
deforms in response to its own weight. In addition,
the shape of each ice grain changes continually
until eventually the grain loses all resemblance to
the original snow crystal. This chapter discusses
these processes and how they influence the
snowpack. The emphasis is on broad characteristics
that are fundamental to stability evaluation and
control of avalanche slopes.*

The intricate changes that take place within the snowpack,
depicted by the three snow crystal photos, are often not obvious at the
snow surface. (Photos by LaChapelle and Kelner)
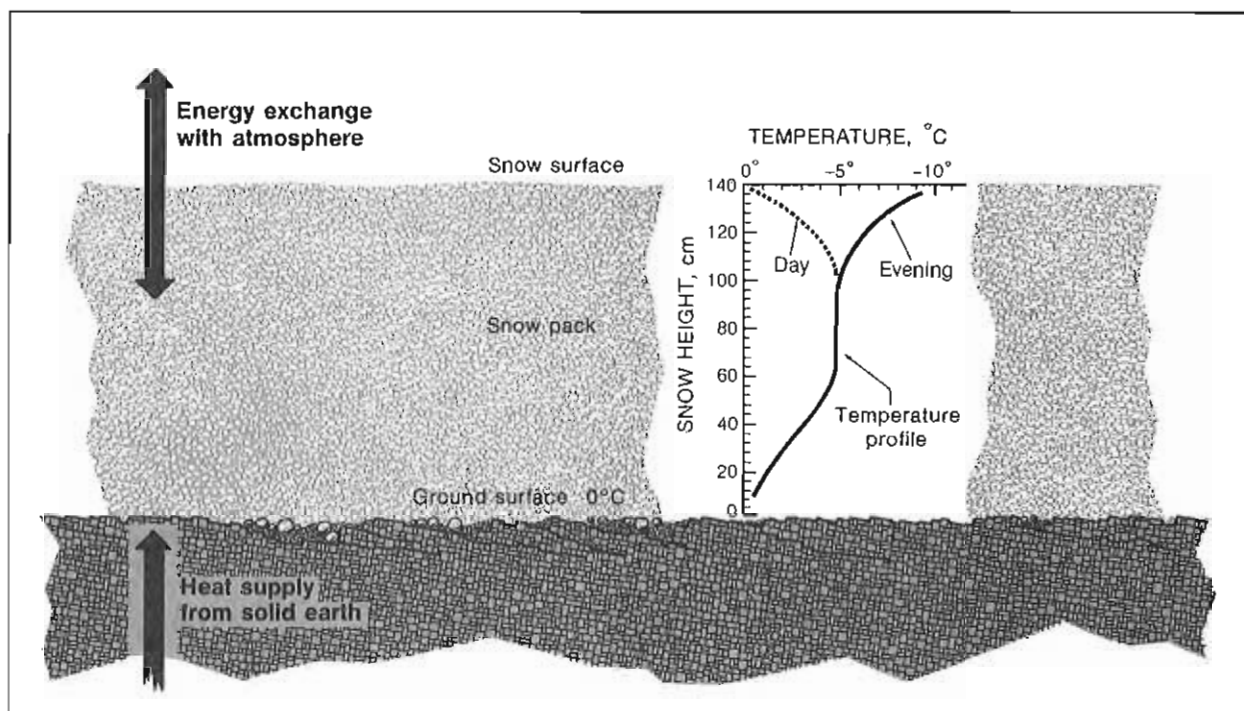
Figure 55.—Example of the temperature variation in a mountain snowpack. The topmost layer is characterized by temperatures that change throughout the day in response to the energy exchange at the snow surface. During most of the winter, temperature gradients exist throughout the snowpack. A typical strong temperature gradient is 0.2° C/cm to 0.3° C/cm.

Structure of the snowpack

The snowpack is bounded on top by the atmosphere and underneath by the ground. The top boundary is called simply the *snow surface;* the bottom boundary, the *ground surface.* The snow surface is a moving boundary, fluctuating up and down in response to deposition, settlement, and loss of mass due to melting, evaporation, erosion, and sublimation. As explained in chapter 2, the heat exchange across the snow surface may be directed into or out of the pack, depending on conditions. At the ground surface, heat generally flows in one direction—into the snowpack from the ground. The heat is supplied mostly from the energy stored in the surface soil layers during summer. In temperate zones, the ground surface is maintained throughout the winter very close to the melting point, 0° C. In northern zones and at high alpine locations, the ground surface may be colder than 0° C. Heat can also be supplied to the snowpack from tree trunks, rocks, and other objects extending up through the snow.

Every snowpack, therefore, contains some temperature variation. The variation in temperature with distance, measured up or down, is the *snow-temperature gradient.* Assuming the ground temperature to be fixed at 0° C, the average temperature gradient through the snowpack is determined by the thickness of the pack and the mean snow surface temperature. If the snowpack is thin and the snow surface temperature is well below 0° C, then the temperature gradient is relatively large. Such conditions could exist, for example, early in winter on shaded slopes. In the spring, when the snowpack finally warms up to the meltpoint, temperature gradients vanish, and the snowpack is *isothermal* (the same temperature throughout).

A snowpack consists of many separate layers, some relatively thick, others microscopically thin. The difference between layers can range from well defined to practically indistinguishable. Thick layers are deposited by steady and consistent snowfalls, by wind drift, or by prolonged periods of similar weather that wipe out the original differences in layers near the surface. Typically, thin layers consist of snow crystals deposited during special storm conditions, such as a thin graupel layer laid down during the passage of a front. Distinct thin layers also form at the snow sur-

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face between storms; for example, ice crusts formed by melting and refreezing, surface hoar, and wind crusts.

The structural details of a snow layer are rather difficult to examine in the field. However, it is possible to prepare thin sections of snow layers in a laboratory and to examine them under a microscope. When this is done, it is found that the texture of the layer consists of a complex, randomly arranged skeleton of ice and much vacant space. The vacant space is called *pore space*.

Pores contain a mixture of air and water vapor. If the snow layer is warmed, liquid water may also be present. The water vapor in the pore space is maintained very close to the saturation vapor pressure over a flat ice surface. In most seasonal snow layers, the pore spaces are interconnected and are described as *communicating* with one another. For densities typical of glacier ice (800 kg/m^3 and higher), the pore spaces are isolated, or *noncommunicating*. In communicating pore spaces the mixture of air and vapor is free to circulate and hence to readily transfer water molecules from one part of the ice skeleton to another.

Figure 57 shows details of snow texture in a medium-aged layer. The bulkier units of the ice skeleton are called *grains*.[1] Grains are interconnected by relatively narrow links called *necks*. The thicker the necks, the stronger the ice skeleton, all other properties being the same. The ice skeleton consists of convexities (regions of positive curvature) and concavities (regions of negative curvature). It will be seen that these differences in curvature determine, in part, the future evolution of the snow layer.

Density is one of the most fundamental and easily measured properties of a snow layer. Some thin layers, such as ice crusts, may have relatively high densities (above 500 kg/m^3), but most of the thicker layers in a seasonal pack have average densities in the range of 100 to 500 kg/m^3, depending on the age of the layer and its depth below the surface.

Compared to other natural and artificial solids, snow layers have the unique ability to sustain large, irreversible density changes. A layer deposited with an original density of 100 kg/m^3 may densify to 400 kg/m^3 in the course of the winter. Higher densities are the result of metamorphism and the weight of the over-

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[1]When referring to particles of the snowpack, the term *grain* is used in preference to the term *crystal*, which has a more specific meaning relating to the arrangement of atoms and molecules of the material. As used here, the term *grain* refers to the general appearance of the ice particle when observed with the naked eye or with a simple hand lens.
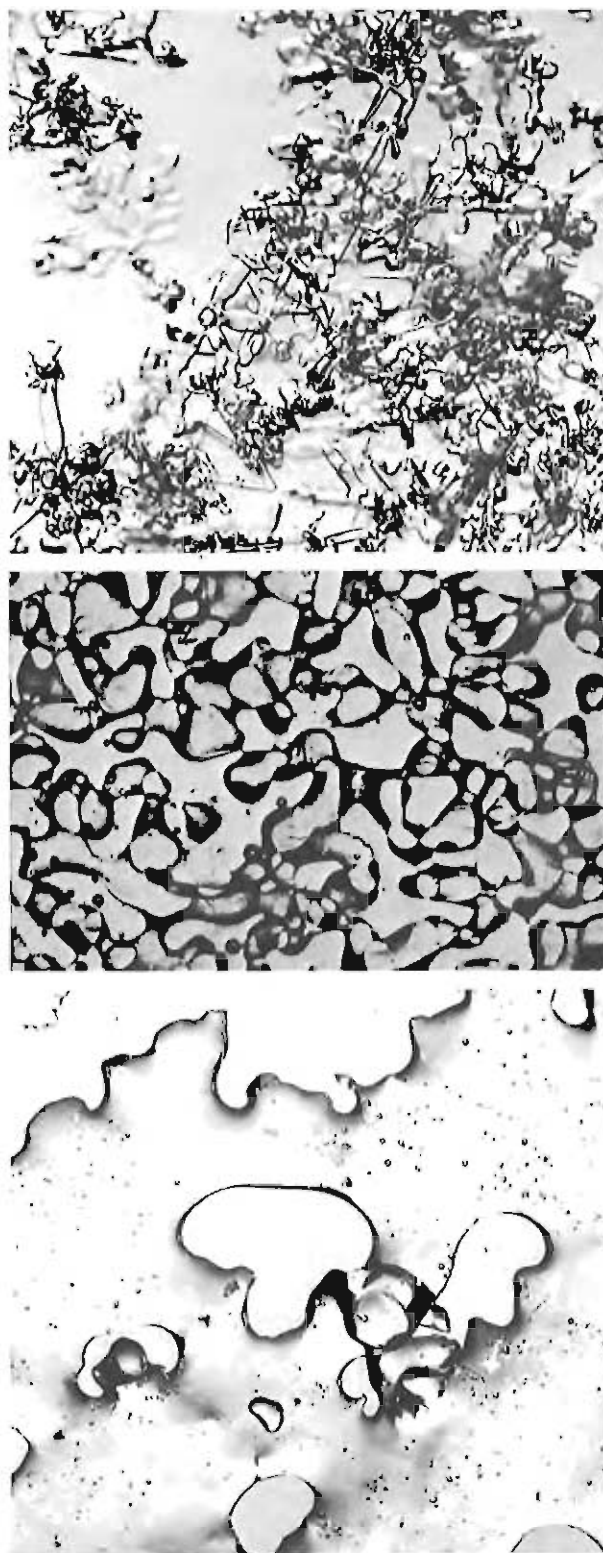
Figure 56.—Microscopic photographs of thin sections of snow and ice layers: Top, newly fallen snow a few hours old; middle, old, dense snow; and bottom, thin ice crust. Note the random arrangement of the ice skeleton and the general decrease in pore space with age.
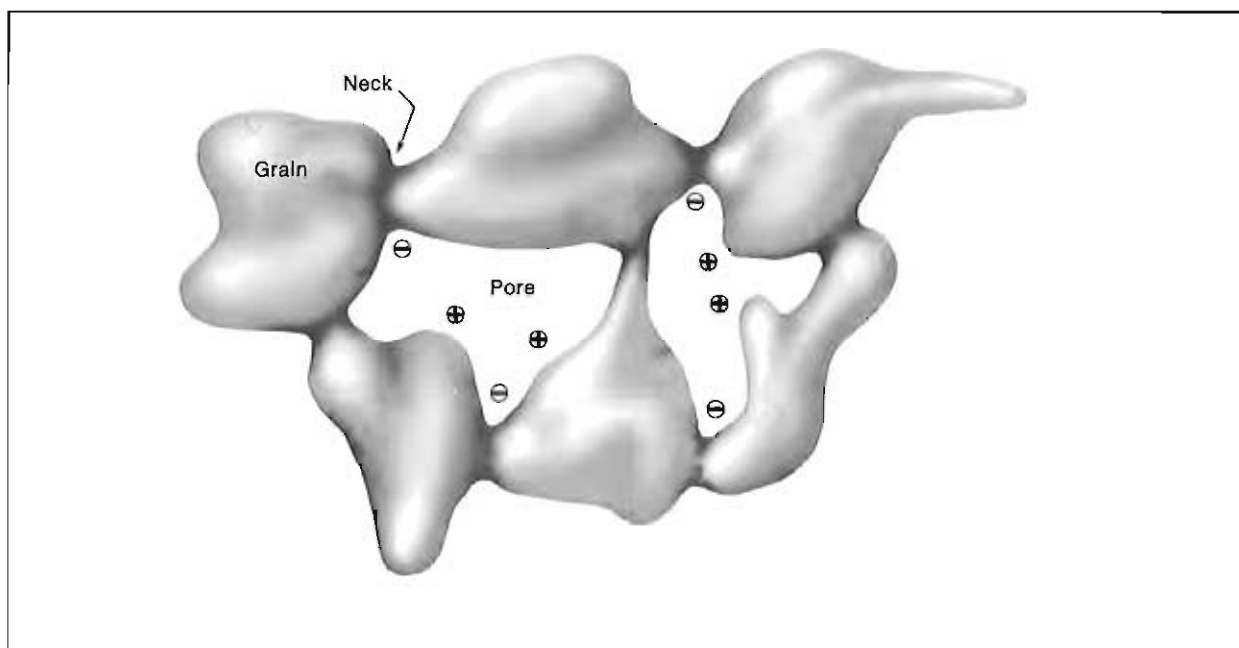
Figure 57.—Illustration of the microscopic detail of the ice skeleton-pore structure. Typical regions of positive curvature, or convexities, are designated +; regions of negative curvature, or concavities, are shown as —.

lying snowpack. Large density changes can occur in a relatively small time; a 100-kg/m^3 layer may be compressed to 150 kg/m^3 in a day by the weight of that day's snowfall. However, as the density of the layer increases, so does its resistance to further densification.

Evidence of densification is observed in a gradual settling of the snow surface. Settlement occurs at rates on the order of 1 cm/day and depends on snow cover depth and crystal types. Higher rates are observed during or immediately after heavy snowfalls. It is not uncommon for settlement to be on the order of 10 cm/day when new snow is being deposited at the rate of about 30 cm/day. Then, most of the settlement takes place in the top layers. During light snowfalls, the settlement rate of the older snow may exceed the new snowfall rate, in which case the total depth of the pack decreases, in spite of the incoming snow.

The high compressibility of low-density snow is largely due to the flexibility of the ice skeleton. When load is applied, relatively high forces concentrate at the necks and other narrow regions of the skeleton. The necks are easily distorted by the concentrated forces, and the grains are free to move into new positions, filling up vacant pore space. The necks then re-form. This type of deformation is irreversible; once the ice skeleton has been rearranged with new necks, it cannot spring back to its original shape.

Types of metamorphism

Unlike most materials encountered in nature, snow exists quite close to its melting point. When any solid is near its melting point, its molecules have a great amount of mobility and it changes quickly in response to changes in external conditions. Newly fallen snow is one of the most unstable natural substances on earth.

The instability of snow is revealed by the drastic changes or metamorphism of crystal form that begin as soon as the snow is deposited. *Metamorphism* is a term borrowed from the geological sciences. In snow hydrology it refers to changes in snow texture caused by pressure and temperature conditions. The temperature of the layer determines the rate of metamorphism, and the temperature gradient across the layer largely determines the type of metamorphism. Within a short time after deposition, a few days at the most, it is normally impossible to identify the original form of the deposition. Within about 2 weeks a deposited crystal may shrink to a small ice grain of only one-fourth its original size or, under a different set of conditions, grow to a grain of four times the original size.

In a dry, seasonal snowpack, it is convenient to distinguish two types of metamorphism. If the metamorphism is in response to a strong temperature gra-
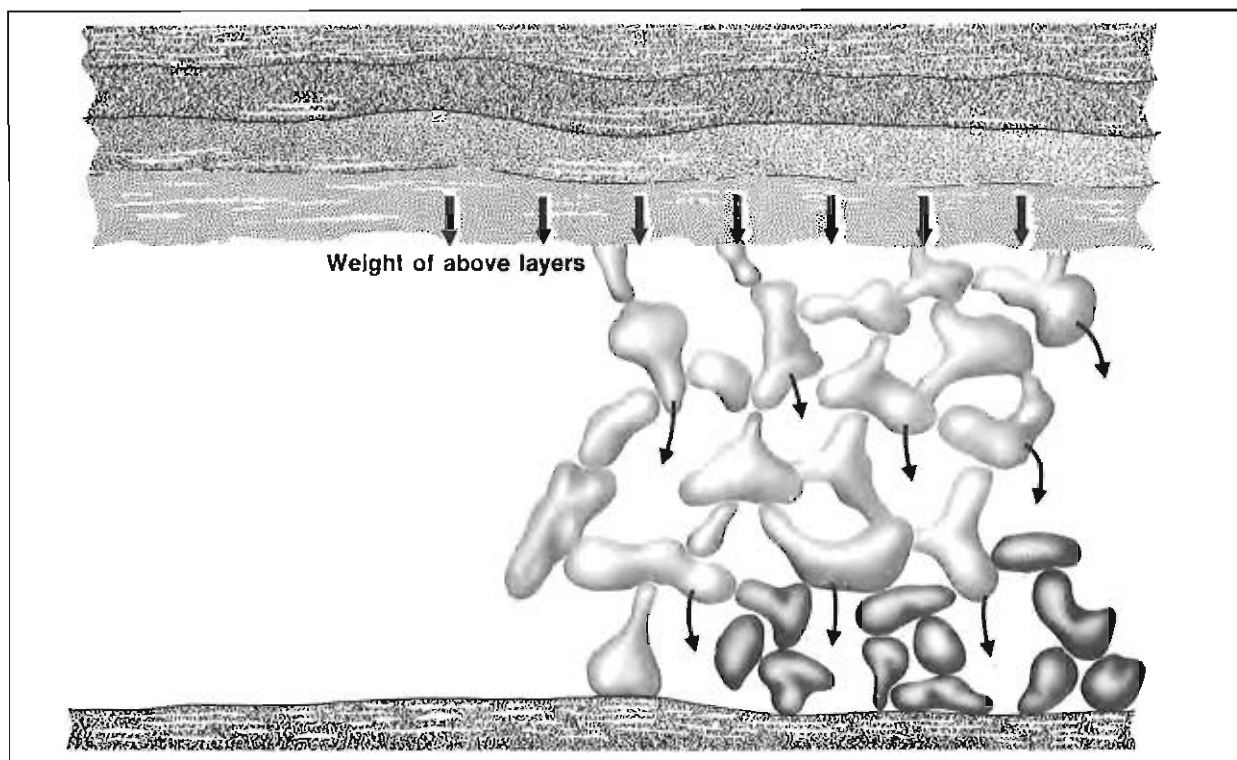
Figure 58.—Because of the mobility of the grains, snow layers can undergo large compressive deformations. The driving force for deformation is the weight of overlying layers.

dient, the process is called *TG metamorphism* (*temperature-gradient metamorphism*). If the process is not driven by the temperature gradient, but instead results from the tendency of the snow to "simplify" its form and knit into a tighter, stronger texture, the process is called *ET metamorphism* (*equitemperature metamorphism*).

A third type of metamorphism takes place when snowpack temperatures reach 0° C and surface snow layers undergo frequent melt-freeze cycles. Under these conditions, the smaller ice grains in the surface layers melt during the day, and melt water refreezes at night. Repeated freeze-thaw cycles produce large, rounded clusters of ice grains by a process called *MF metamorphism* (*melt-freeze metamorphism*).

Equitemperature metamorphism

To understand ET metamorphism, consider again saturation vapor pressure over an ice grain. When this subject was introduced in chapter 2 under "Snow Crystals," the effects of surface curvature were not explained. The curvature of the ice surface influences
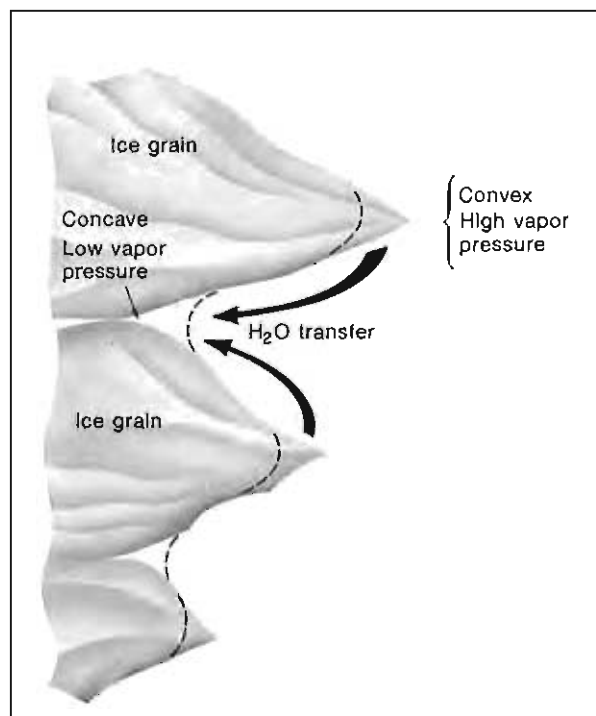
Figure 59.—Vapor pressure is higher over a convex ice surface than over a concave ice surface. Hence, water molecules tend to be transferred from convexities to concavities. This mechanism has the effect of removing sharp curvatures in the ice skeleton and causes individual grains to assume simpler, more rounded configurations.

Figure 60.—Examples of grains in succeeding states of ET metamorphism. Grains are evolving toward rounded forms. (Photos by LaChapelle)
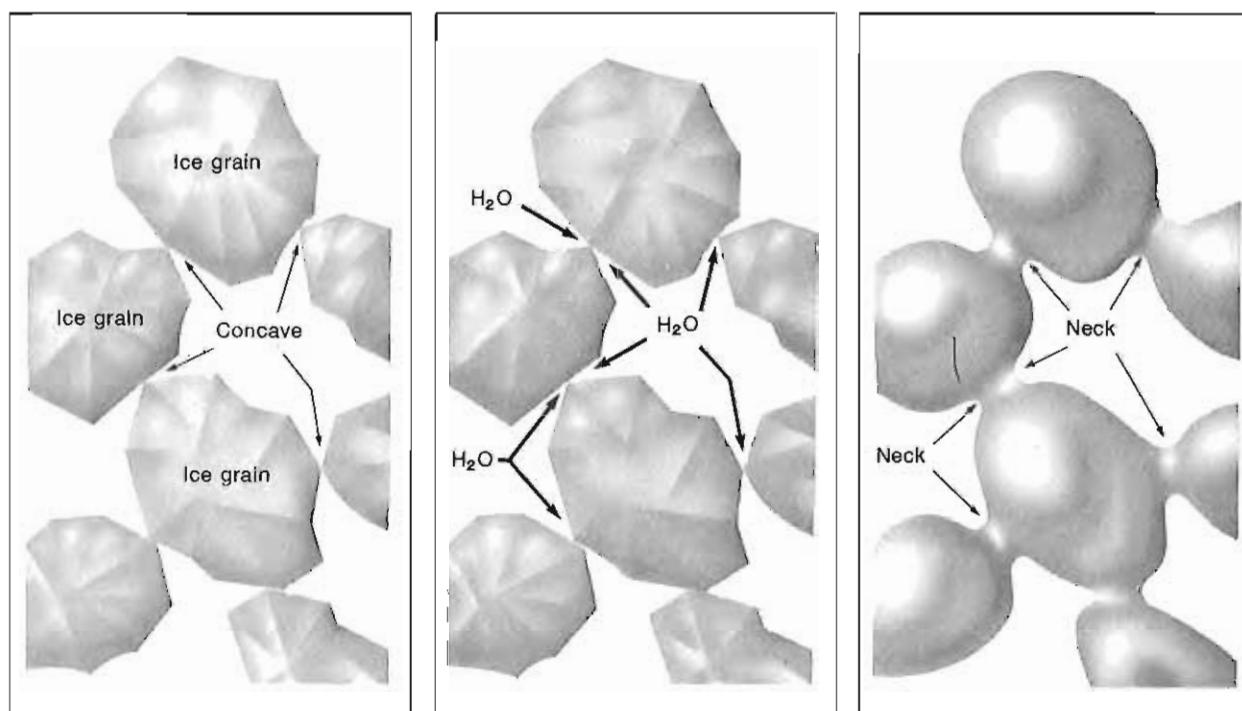
Figure 61.—The weight of the snowpack presses grains into contact. Sharp concave regions are thus formed between grains. Water molecules migrate into these concavities from convex regions. This process, which joins individual grains together in an ice skeleton, is called sintering.

the amount of water vapor that can be supported in the air above the surface. More vapor can be supported over a convex surface than over a flat surface, and more can be supported over a flat surface than over a concave one. Thus, there is a vapor-pressure difference between convex and concave surfaces and consequently a net transfer of water molecules from convexities, such as crystal corners and dendritic branches, to concavities.

ET metamorphism, the result of this preferential transfer of water molecules, causes two important changes in snow texture: (1) a general rounding out of grains, and (2) strengthening of the ice skeleton by the formation of necks between grains. The rate of these changes increases with increasing temperature, being very rapid near 0° C and almost nonexistent at —40° C.

Consider first the general rounding out of grains. In the beginning stages of ET metamorphism, each original grain loses its fine details. The basic shape of the grain can still be recognized, but sharp corners and fine branches disappear. The apparent size of the grain begins to decrease. Beginning stages require from a few hours at warm temperatures to a few days at cold temperatures. In the intermediate stage of ET metamorphism, the original shape can no longer be identified. The grains continue to become more rounded, and large grains tend to grow at the expense of smaller grains. In the final stages of ET metamorphism, there is a strong tendency toward uniform, rounded, well-bonded grains. Almost all crystal types are strongly affected by ET metamorphism. An exception is graupel. This snow grain type, which is rounded to begin with, resists metamorphism so much that its original shape is easily identified several weeks after deposition.

The second important texture change caused by ET metamorphism is strengthening of the ice skeleton. When two grains make contact, a highly concave region is formed between the grains. There is a strong tendency for water molecules to migrate to this region. The influx of mass fills up the concavity, forming a neck between the grains. This joining by forming necks is *sintering*. Since the neck material migrates from convex regions, sintering and rounding of grains occur together.

It is thought that the migration of molecules to the contact point and their later deposition in these concavities is mostly by sublimation. This is a process whereby a substance goes from the solid state (ice) to the vapor state (water vapor), or vice versa, without going through the liquid state (water). Some additional migration occurs within the ice skeleton and on the surface of the ice skeleton by poorly understood processes. In any case, ET metamorphism takes place in the absence of an appreciable temperature gradient.

Temperature-gradient metamorphism

It was mentioned in chapter 2 that the vapor pressure over an ice surface depends on the temperature; the higher the temperature, the higher the vapor pressure. This principle, which explains snow crystal growth in the atmosphere, also explains how ice grains grow in the snowpack. The fact that vapor pressure depends on temperature means that more vapor can be supported in a warm pore space than in a cold
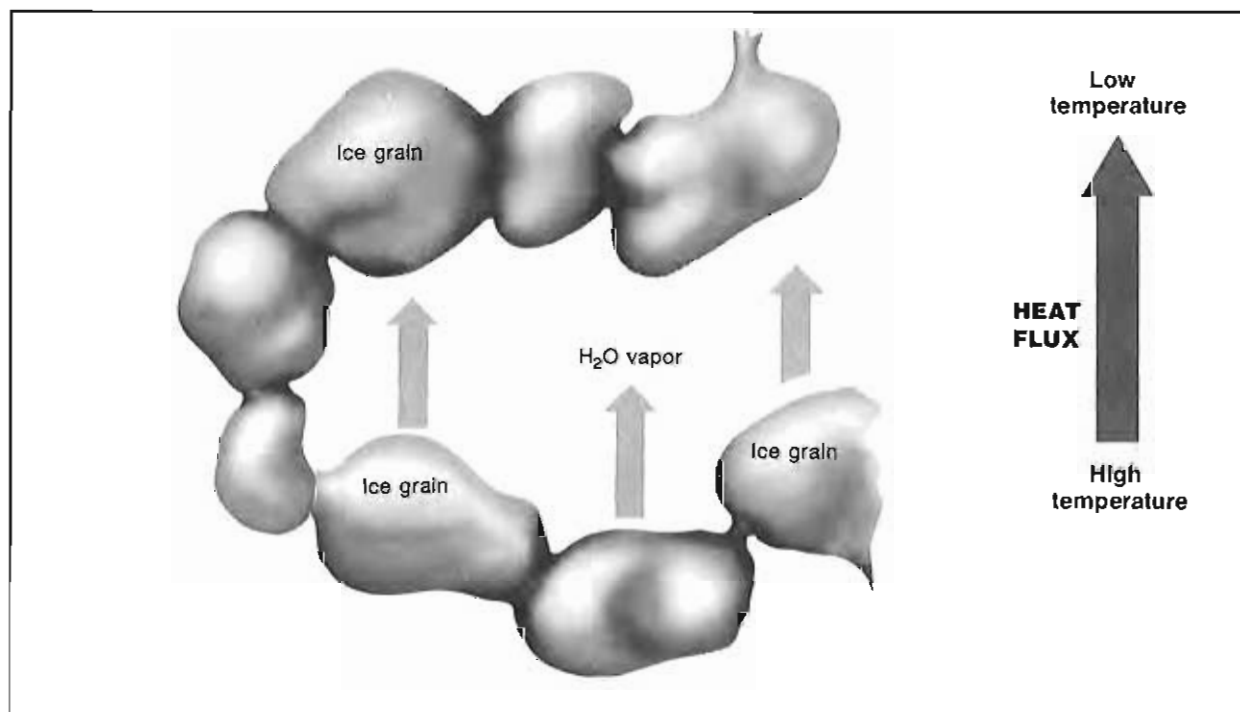
Figure 62.—Water vapor flows in the ice skeleton from regions of high temperature to regions of low temperature.

pore space. This implies that if there is a temperature gradient in the snowpack, vapor flows from high- to low-temperature regions of the snowpack. As the vapor circulates it carries heat energy from warm pores to colder pores.

Vapor flow is not fully understood. It is thought that vapor diffuses from the warmer grains across the pore spaces to neighboring colder grains. Another idea is that "channels" of vapor flow are established. Once these channels are primed, flow proceeds rapidly. Only small quantities of vapor are required to transport heat in this manner because of the high energy of sublimation and vapor deposition (about 600 calories are released for every gram of water vapor that is converted to ice). In any case, because the vapor flow is driven by the temperature gradient, the resulting change in the ice skeleton is called TG metamorphism.

For heat energy to be transferred efficiently, vapor is deposited on the grains instead of on the necks between grains. Hence, in TG metamorphism the individual grains enlarge while the neck thickness remains essentially constant. This is in direct contrast with ET metamorphism, in which neck regions grow at the expense of grain convexities.

The enlarged grains that result from TG metamorphism are called TG grains. They are characterized by flat, sometimes steplike or striated faces. The faces intersect, forming sharp, angular corners that give the grains a coarse texture as compared with the rounded, smooth grains of ET metamorphism. In the advanced stages of TG metamorphism, TG grains enlarge to about 8 mm in diameter and have very distinct faces and corners. These large TG grains are called *depth hoar*.

The larger TG grains are easily identified with the naked eye. However, it is instructive to view these grains with 10- to 25-power magnification and note how much they differ from ET grains. Under magnification, depth hoar grains appear as assorted prisms, cups, and pyramids.

TG metamorphism and ET metamorphism occur in all snow layers, but one process usually dominates at a given time in a given layer. Because grains of newly fallen snow contain sharply curved convex and concave regions, there is an initial tendency to simplify the shape of the newly fallen snow by mass transfer from convexity to concavity. At first, therefore, metamorphism of a layer is ET-controlled. After the sharp
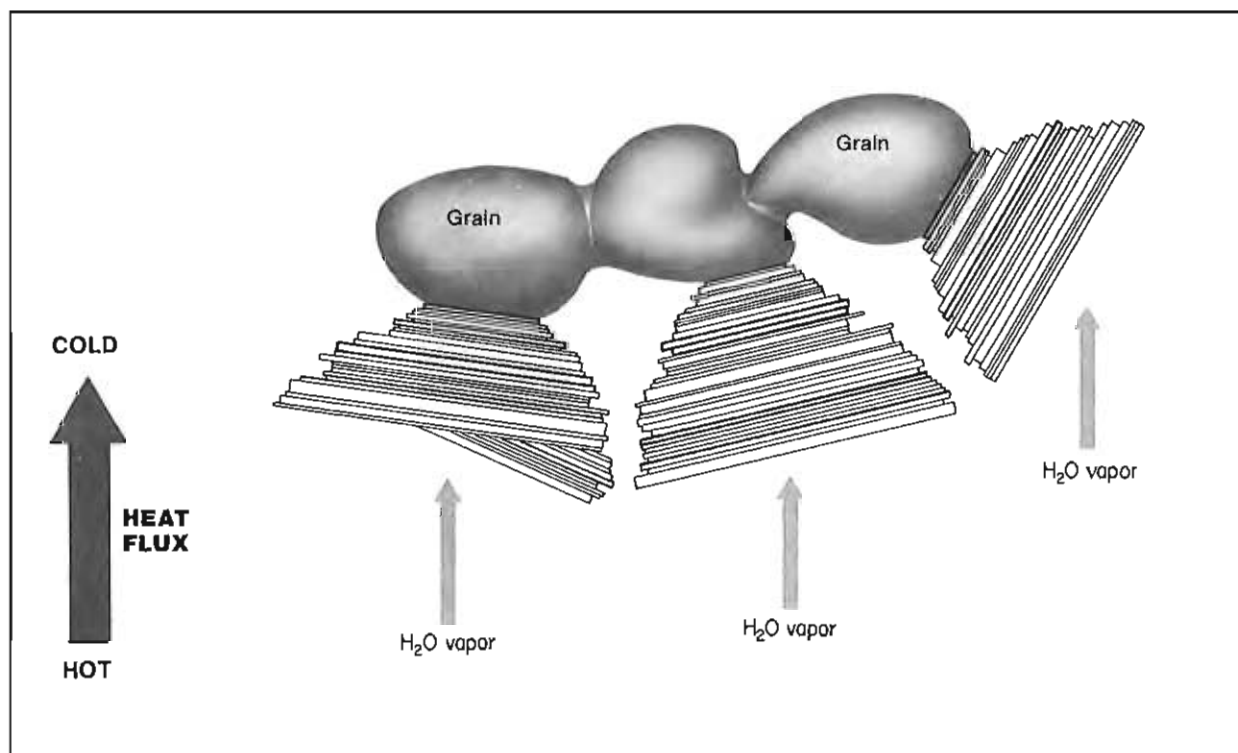
Figure 63.—In temperature gradient (TG) metamorphism water vapor deposits on the grains instead of on the neck between the grains. This leads to an increase in grain size and an overall decrease in the strength of the ice skeleton.
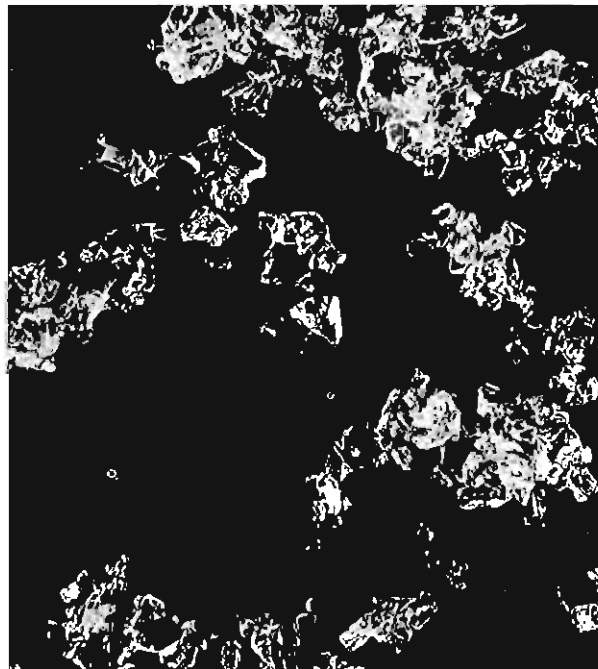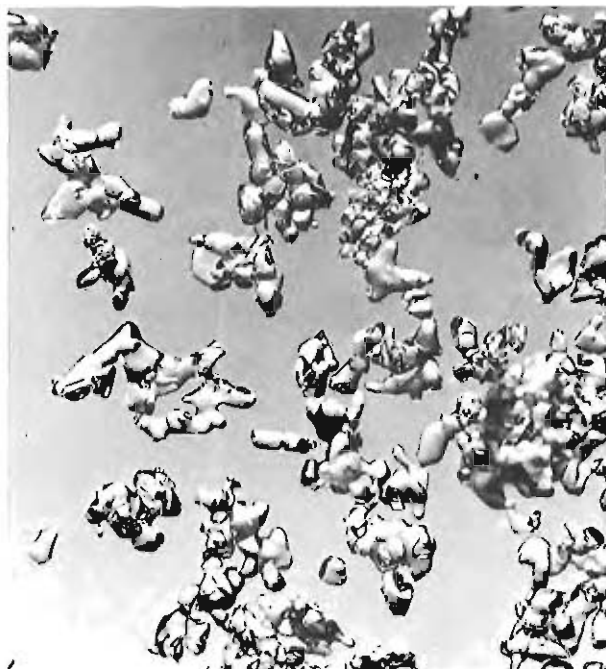
Figure 64.—Top left, ET grains, top right, intermediate stage of TG grains, and bottom right, advanced stage of TG grains.

branches and corners have been removed by ET metamorphism and the crystal has turned into a smaller and more rounded grain, ET and TG processes compete for control. If the temperature gradient across the layer is strong enough, the TG process dominates. As winter progresses and the snowpack becomes thicker, temperature gradients become minimal, and again ET processes tend to dominate. At the end of the season, when the snowpack becomes isothermal and temperature gradients vanish completely, TG metamorphism is no longer possible, and ET metamorphism competes with melt-freeze processes for control.

Clearly, the properties of a snow layer depend strongly on whether the ice skeleton has ET or TG texture. If the ice skeleton is predominantly ET-metamorphosed, the grains are relatively small and well joined; if TG metamorphism dominates, the grains are large and not well joined and have many fewer bonds. It is easy to see that the ET structure is stronger than the TG structure if other variables (such as density and temperature) are equivalent. The strength of snow and its relation to metamorphism are discussed more fully later in this chapter under "Fracture Mechanics of Snow."

The temperature difference across the layer is fundamental to determining whether ET or TG meta-

morphism dominates. However, another important factor is snow density. In low-density snow, vapor flow is much easier, and for the same temperature conditions and time the TG process can go faster and produce larger grains. As density increases, the process slows.

Depending on the duration and intensity of the temperature gradient, the advanced types of TG grains

Temperature-gradient metamorphism

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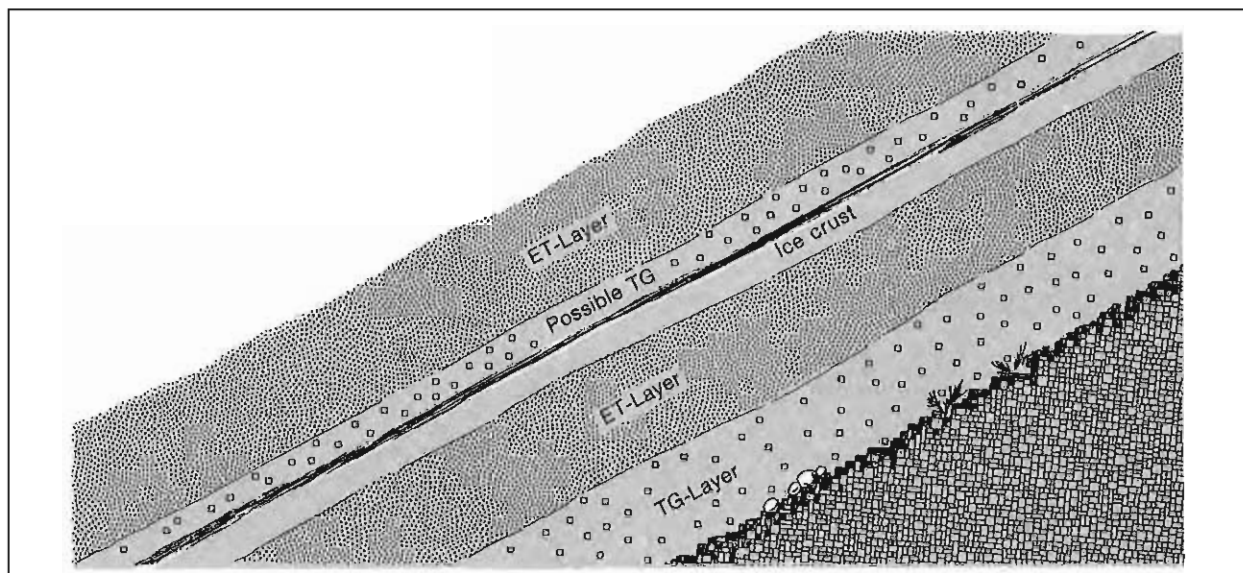
Figure 65.—TG layers are most commonly found just above the ground surface. Occasionally, thin TG layers form above, or less commonly below, ice crusts. TG grains also are likely to be found near terrain irregularities, such as rocks and vegetation.

appear about a week to a month after the TG process begins. Depth hoar normally requires at least 2 weeks to form from newly fallen crystals or ET grains, but there are reports of depth hoar layers that formed within a week.

The strongest, most sustained temperature gradients are on north-facing slopes and in deep, shaded gullies. In such places, the snow surface is kept at relatively low temperatures by continuous radiation loss. TG layers occasionally form in areas that are not protected from solar radiation, and sometimes even on south-facing slopes, but the more protected the slope from the sun's rays, the greater the chance of finding a TG layer.

The probability of forming a TG layer is highest early in the winter when the snowpack is thin and unconsolidated. The climatological combination that normally leads to TG layers is an early storm, say in October or November, followed by a month or so of cold, clear weather. Such conditions occur frequently in the inland mountain ranges of the United States, such as the Rockies and the Wasatch and Teton Ranges, but less frequently in the Pacific Coastal Range, which usually has an almost continuous storm cycle once winter begins. Advanced TG metamorphism is rare in maritime climates.

In continental climates, TG layers generally are found in the first 30 cm above the ground, but layers more than 1 m thick have been observed in the Colorado Rockies. Advanced TG metamorphism often occurs next to trees and between rocks, presumably because surface irregularities support the snow, preventing densification and providing sites for vapor circulation. Thin TG layers sometimes form in the upper and middle layers of the pack. These layers are often difficult to locate, but they often form immediately above or below ice or sun crusts, especially when such layers are at 0° C.

TG layers are more prevalent at higher elevations for many reasons. First, the snow surface is colder at higher elevations; hence temperature gradients are stronger. Second, strong winds at high elevations tend to erode the snow and thin out the snowpack in exposed places. Finally, avalanches remove snow from high elevations, and temperature gradients can arise in the remaining snow. Considering these complications, one cannot be assured of conditions in the higher elevation snowpack if observations are made only at a low-elevation study plot. A field inspection of the high elevations is essential. The necessary techniques for such field inspections are discussed later in this chapter under "Snowpack Analysis" and in chapter 5.

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Melt-freeze metamorphism

Liquid water present in a snow layer is called *free water*. Free water is usually measured in percent by mass. Very wet snow may contain 15 percent or more free water; for example, 150 g of water in 1 kg of snow.

At present, devices that measure free water are relatively complex and are not used routinely in avalanche control and forecasting. It generally suffices for avalanche observers to note qualitatively the "wetness" of the snow according to the nomenclature of the International Association of Scientific Hydrology: dry, moist, wet, very wet, and slush (see table 1).

The two sources of free water are rainfall and melting. If the temperature of the top layer of the pack is below 0° C, then light rainfall is likely to freeze onto the snow surface as a thin ice layer. If the top layer is raised to 0° C by sustained heavy rain or by warm weather, rainfall is absorbed by the pack as free water. It should be emphasized that rain is important as a source of free water, but not as a melting agent. In winter, rain is rarely warm enough to cause significant melting, since 1g of water contains 1 calorie for each degree above 0° C, and it takes 80 calories to melt 1 g of snow at 0° C.

The main cause of melting is heat input at the snow surface. The convective and radiative components of the heat exchange both contribute to melting, evaporation, and sublimation, but radiation is usually the most important cause of melting and free-water production.

Radiation produces free water at an accelerating pace. When snow is dry and clean, it absorbs little solar radiation. When wet, it absorbs much more radiation, and melting quickens. The process accelerates to a peak by midafternoon, usually about 1300 to 1600 hours. The largest amounts of free water are

TABLE 1.—*Free water content*

Term	Remarks
Dry	Usually T is below 0° C, but dry snow can occur at any temperature up to and including 0° C. When its texture is broken down by crushing and the loose grains are lightly pressed together as in making a snowball, the grains have little tendency to cling to each other.
Moist	T = 0° C. The water is not visible even with the aid of a magnifying glass. When lightly crushed, the snow has a distinct tendency to stick together.
Wet	T = 0° C. The water can be recognized by its meniscus between adjacent snow grains, but water cannot be pressed out by moderately squeezing the snow in the hands.
Very wet	T = 0° C. The water can be pressed out by moderately squeezing the snow in the hands, but there still is an appreciable amount of air confined in the snow.
Slush	T = 0° C. Snow flooded with water; contains a relatively small amount of air.
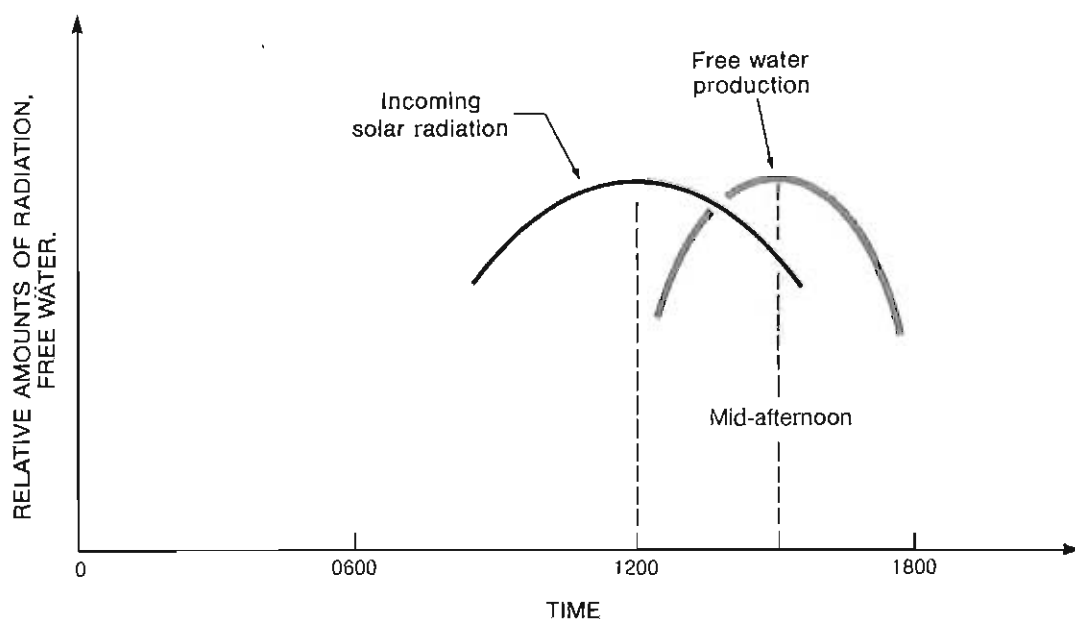
Figure 66.—Comparison of typical daily variation of solar radiation and free water production. The largest amount of free water is produced between noon and late afternoon.
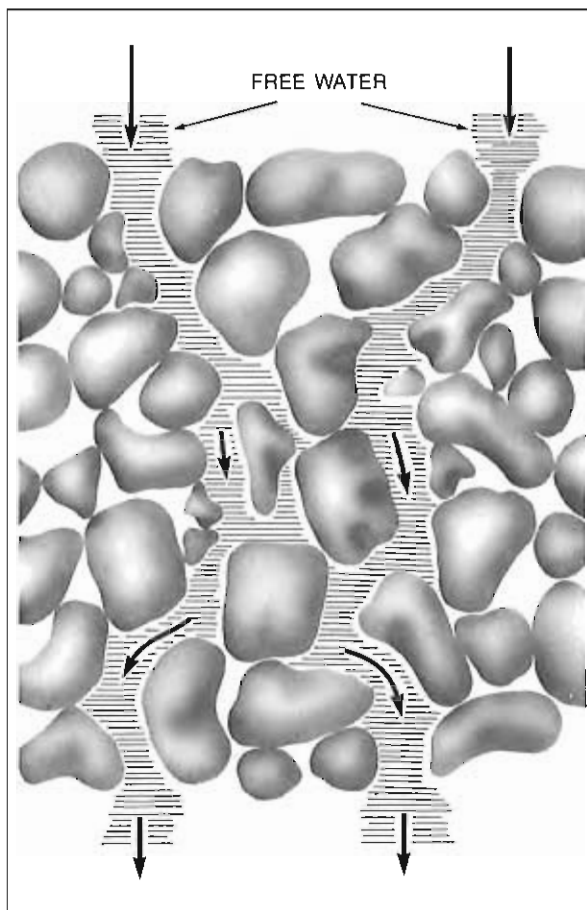
Figure 67.—In one mode of flow, free water percolates through the pore space, under the influence of capillarity and gravity.

Figure 68.—Comparison of ET grains (top) and MF grains (bottom). Note that the MF grains are large clusters of smaller, angular grains.

produced next to rocks and other terrain features that absorb radiation efficiently and can transfer heat to the snow. Large amounts of free water concentrate in gullies and form streams under the snowpack.

Because of surface tension, small amounts of free water cling to melting grains. As melting accelerates, free water begins to flow into the pack. The rate of flow depends on the texture of the snow, the temperature of the ice skeleton, and the amount of water available. Although some water flows by capillary motion through the pore space, it is thought that a large amount flows in special channels melted by heat stored in the free water. In any case, free water flows down until it either freezes on contact with a cold layer or is blocked by a hard layer. The water tends to spread out over a hard layer until a channel is eroded or melted. Free water flows very slowly, and the flow is referred to as percolation. When free water percolates into a

Figure 69.—Free water penetrating the snowpack tends to spread out on top of hard layers and melts or erodes the attachment between the hard layer and the layer above. This effect is known as "lubrication."

cold region of the pack, the water often freezes to form an ice lens.

In spring, the entire snowpack achieves a temperature very close to 0° C. The snow temperature at the surface may vary widely between day and night extremes, however. These fluctuations originate at the surface, but penetrate deeper into the pack as a wave-like disturbance of the average temperature. Where temperature fluctuations cause melting and refreezing, a special type of metamorphism occurs. This *melt-freeze (MF) metamorphism* builds clusters of large grains in the following way. During melting of the ice skeleton, the smaller bonds and grains have a very slightly lower melting temperature than the larger bonds and grains. The difference in melting temperature is exceedingly minute, perhaps on the order of 10^{-5} ° C. Nevertheless, this tiny difference causes small grains to melt first, before larger grains *begin* to melt. Some melt water is retained between neighboring grains; it tends to bond the remaining grains together by surface tension. When the temperature fluctuates back to freezing, the bond freezes and locks the surviving large grains into polygranular units. It appears that there is also vapor transport from the smaller grains to the larger grains, similar to TG metamorphism in dry snow; this produces many large grains.

After several melt-freeze cycles, it is possible for each polygranular unit to consist of 50 or more large, coarse grains. Depending on the number of cycles, the time of day, the depth of the layer, etc., the polygranular units may form into any of a variety of well-known forms of spring snow, such as "corn snow" or "rotten snow." The large polygranular forms that result from repeated melt-freeze cycles (MF metamorphism) are called MF grains.

The strength of a layer of MF grains varies widely, depending on whether the layer is in the melt or the freeze part of the cycle. In the melt part, the grains are essentially separate and are held together only by surface tension. The structure is then extremely weak and ductile. When the layer refreezes, it can assume enormous strength. A case of interest occurs when a cold snow layer of early winter is drenched by rain and then freezes. In such a layer, enlargement of grains by MF metamorphism is at a minimum, and the layer freezes into a very strong structure.

The great changes in strength that result from melting and freezing have important implications in avalanche stability evaluation (see chapter 5). A prime cause of spring avalanches is *lubrication* of the sliding surface. This is the result of free water percolating

Melt-freeze metamorphism   51
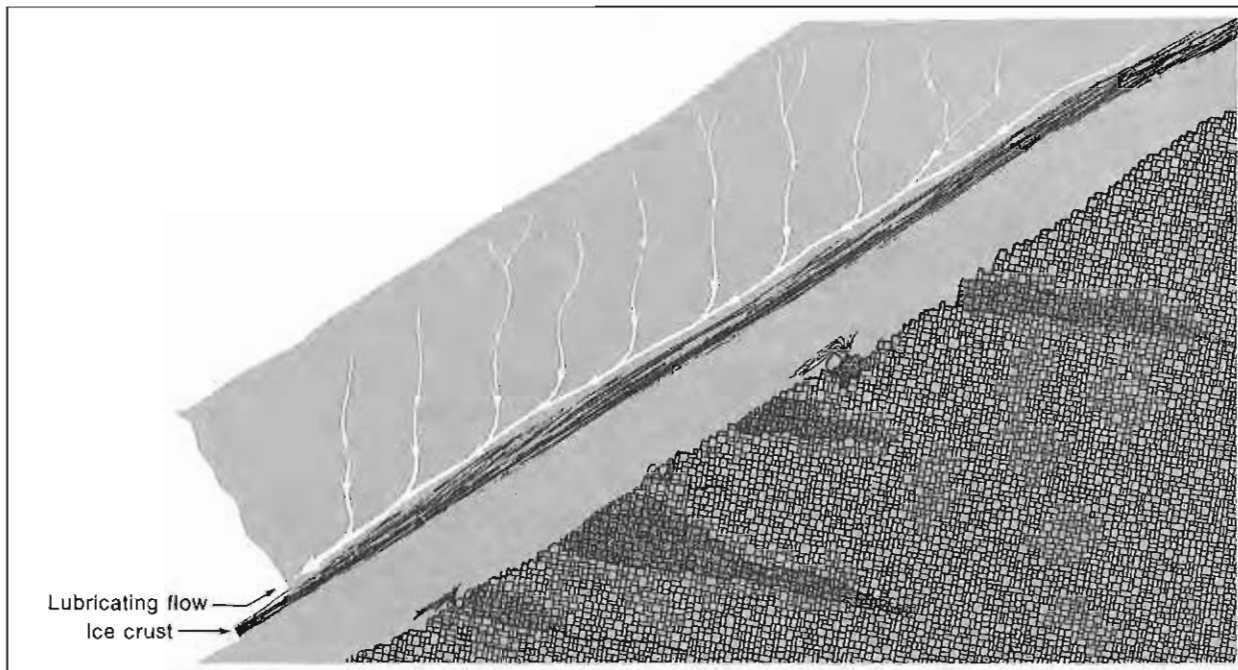
Figure 70.—Intensive lubrication of an ice layer in an inclined snowpack. Lubrication is also commonly observed above the ground surface.

down to a hard surface such as an ice layer or the ground. If the water cannot penetrate the surface, it tends to spread out and melt or erode the bond between this surface and the snow above.

Fracture mechanics of snow

The properties of steel, wood, ceramics, and other common materials have been worked out in the laboratory and in theory to an accuracy that permits confident engineering design. Snow has also been studied as a material. As would be expected, the higher its density, the more it behaves like other materials. In fact, many studies have been made of the suitability of high-density snow (more than 400 kg/m³) as a construction material in polar regions.

Some studies have also been made of the lower density snow typical of alpine, seasonal snowpacks. It is fair to conclude from these tests that low-density snow is a complex and unique material. Unfortunately, its properties are so complex that it is hardly possible to predict confidently how it will behave on the mountainside. On the other hand, although many properties of low-density snow cannot be identified accurately, laboratory tests provide at least a broad picture of its behavior.

In the laboratory, when a compressive force is applied to a snow sample, the sample deforms considerably. The amount of deformation depends on the intensity of the force and the rate at which the force is applied. When the force is removed suddenly, the sample springs back slightly, but a large amount of permanent deformation remains in the sample. The important point is that in the deformation of snow under load there are both a springy or elastic component and a permanent deformation component. The elastic component represents energy that is stored and recovered, and the permanent deformation component represents energy that is unrecoverable or has been dissipated.

The recoverable component of the deformation is a consequence of the springiness or elastic nature of the grains and necks in the ice skeleton. The unrecoverable energy is lost in the sliding of grains and necks. Some energy is also lost through viscouslike flow of the skeleton. Many other substances, which are classified as *viscoelastic*, have recoverable and unrecoverable components. Almost all solids have a viscoelastic response when deformed at temperatures near their melting point.

As mentioned earlier, the ice skeleton is highly compressible and can sustain large amounts of per-

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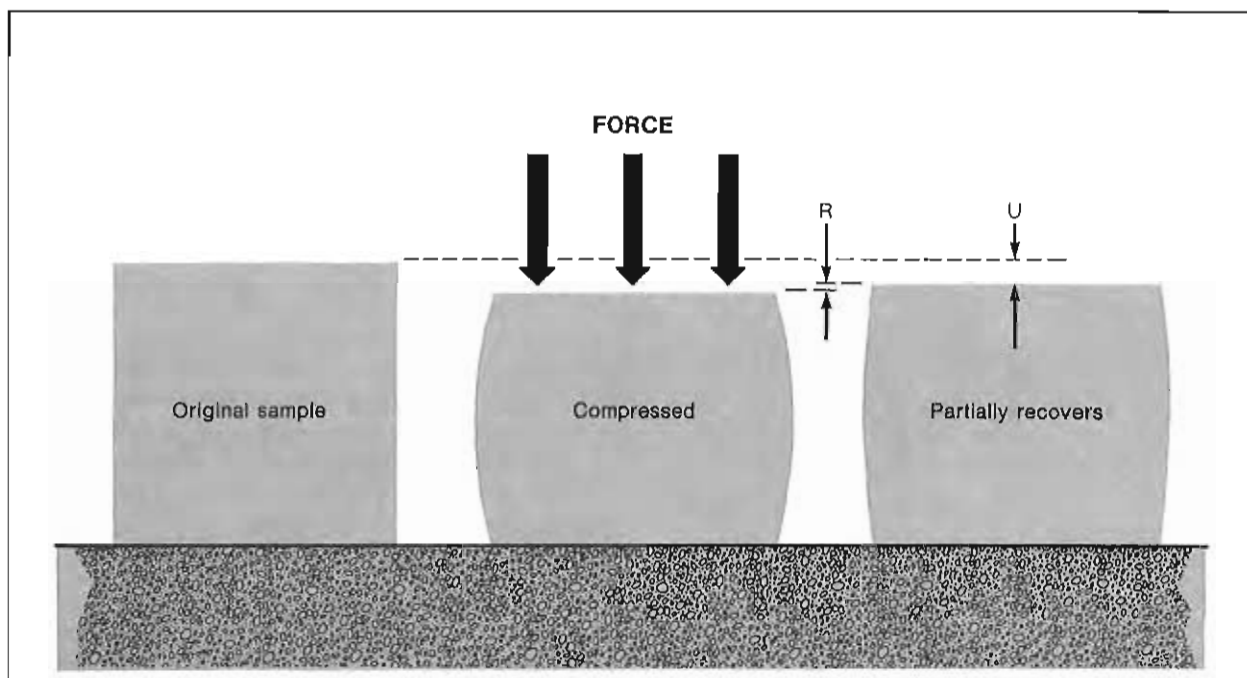
Figure 71.—A snow sample is compressed. When the force is suddenly removed, most of the deformation appears to be permanent or unrecoverable (U). However, there is a slight tendency for the sample to spring back or recover (R). This indicates that elastic energy is stored in the sample and available to propagate fractures.

TENSION   **COMPRESSION**   **SHEAR**
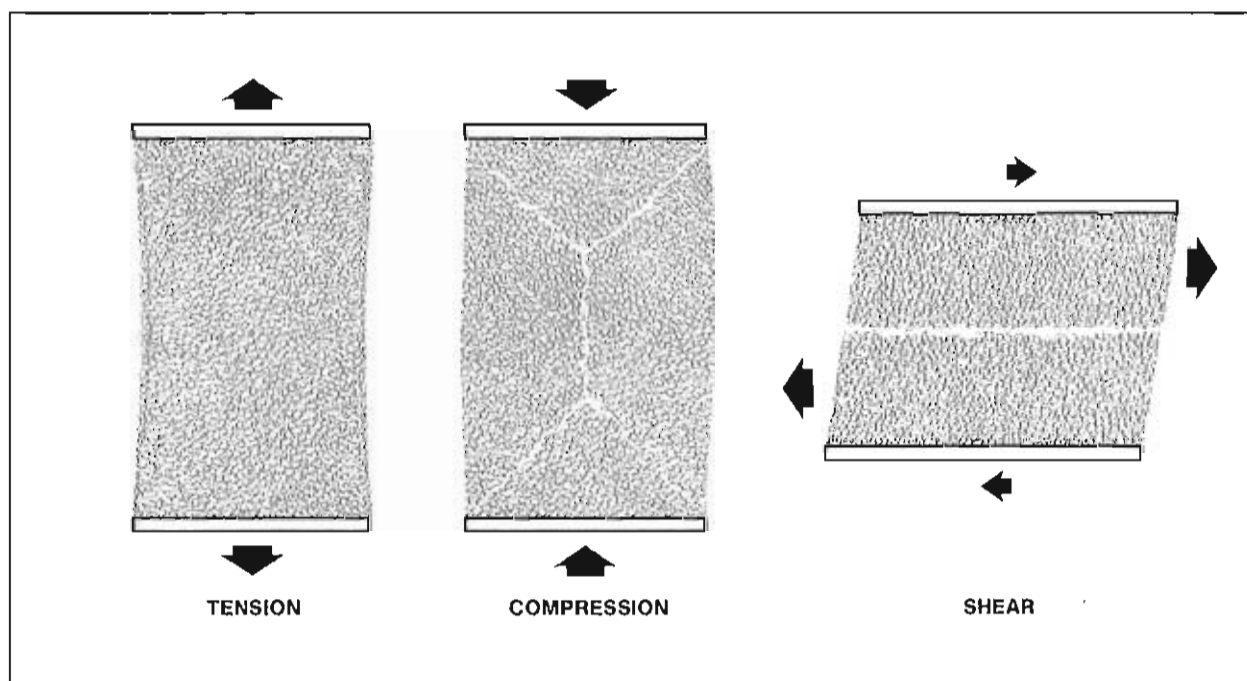
Figure 72.—Snow in three modes of brittle failure.

manent deformation. If the load is applied slowly enough that deformation is slow, then, in principle, the sample can be compressed to a mass of solid ice. If the applied force is strong enough and pushes fast enough on the sample, then the snow cannot respond by gradual collapse, and brittle fracture occurs.

Fracture mechanics of snow
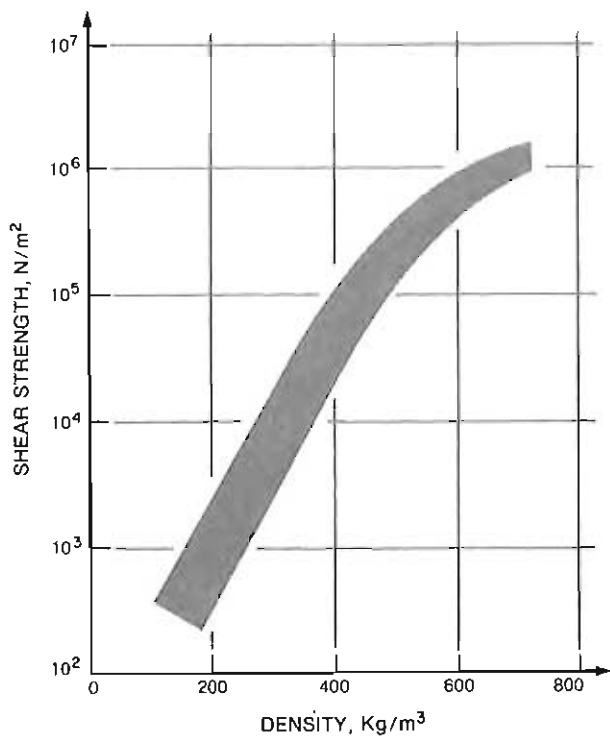
Figure 73.—Shear strength envelopes of small snow samples as a function of snow density (Mellor 1974).

What causes brittle fracture in snow? The answer, which is of deep significance in avalanche stability evaluation, is that any snowmass, depending on its temperature and texture, has two limitations: (1) it can store only a limited amount of elastic strain energy, and (2) it can dissipate the extra energy at a limited rate.

During brittle fracture propagation, the energy of the system is quickly redistributed into fracture surfaces, kinetic motion, and heat. Fractures initiate at flaws or localized regions of stress concentration. Because of the random nature of the ice skeleton, any snowmass is bound to have a weakest site where fractures are most likely to originate. In the mountain snowpack, trees, rocks, ski tracks, etc. are regions of stress concentrations and likely spots for fracture initiation.

The ability of a material to withstand catastrophic failure is called its *fracture toughness*. This is difficult to measure and not necessarily related to the apparent strength or hardness of snow. Hard, strong snow
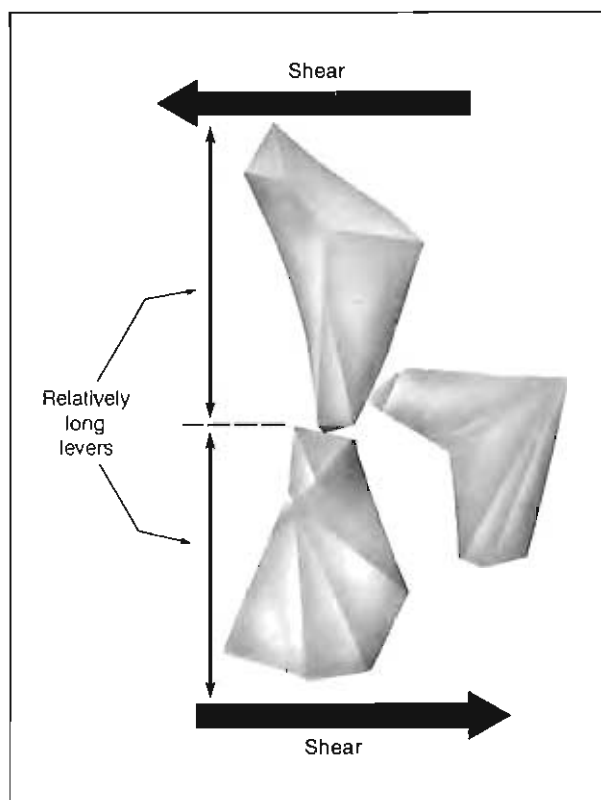
TG
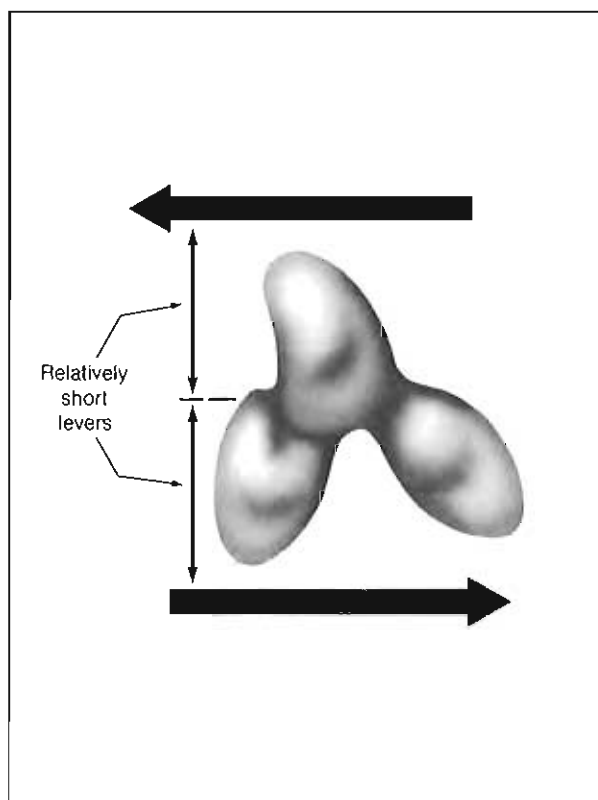
ET

Figure 74.—Due to lever action, applied force is redistributed as high stress concentration at the neck between grains. The larger the grains compared to the neck cross section, the greater this effect.

layers are as apt to propagate fractures as weak, soft snow.

From laboratory and field tests, some qualitative information has been assembled concerning the fracture of snow. Like all materials, snow can fracture when loaded in tension, compression, or shear. Furthermore, like most materials, snow has substantial resistance to fracture in compression but is easily fractured in tension. The usual explanation for the different behavior in compression and tension is that in compression, the potential fracture surfaces are pushed together so that the material gains strength from friction. Also, in the case of snow, forcing the grains together by compression allows the material to gain strength by sintering.

The fracture toughness of snow is a strong function of density; polar snow with a density of 800 kg/m³ may be more than 1,000 times as strong as alpine snow with density of 200 kg/m³ (see figure 73). At the lower densities typical of the mountain snowpack, snow strength varies greatly depending on grain texture. For example, fine-grained ET layers may have 10 times the shear strength of large-grained TG layers of the same density. As a general rule, the larger the

grains, the weaker the snow, all other factors remaining the same. One explanation for this dependence on grain size is shown in figure 74.

How does temperature affect the fracture toughness of snow? Intuitively, one suspects that the colder the snow, the more brittle its behavior. On the other hand, laboratory tests indicate that snow gains strength as its temperature decreases. At present, the overall effects of temperature on the fracture toughness of snow are largely unknown. Certainly, snow exhibits brittle fractures at all temperatures up to 0° C, and sometimes even when an appreciable amount of free water is present.

The inclined snowpack

To understand failure of inclined snowpacks, it is helpful to study first the simpler case of horizontal snowpacks. Consider the idealized case of a long, horizontal snowpack, as shown in figure 75. For this simple case, it is evident that the deformation of the snowpack is downward and that each element of the snowpack is subject to a compressive stress component in the vertical direction, caused by the weight of
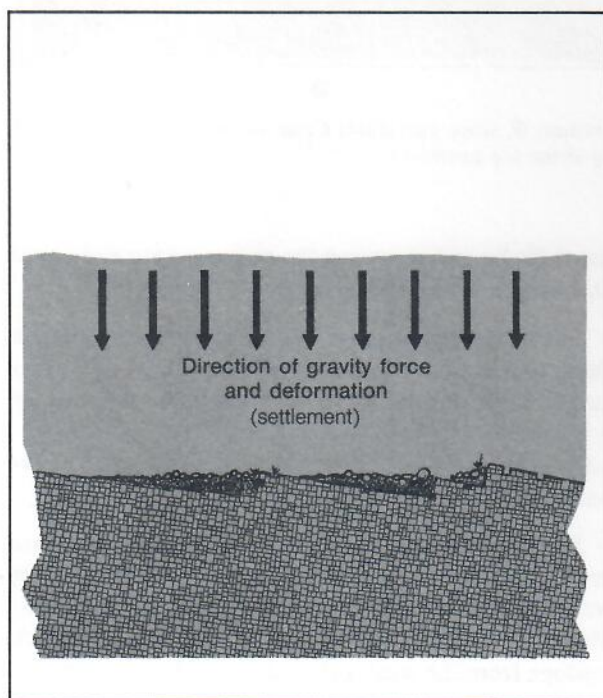
Horizontal snowpack
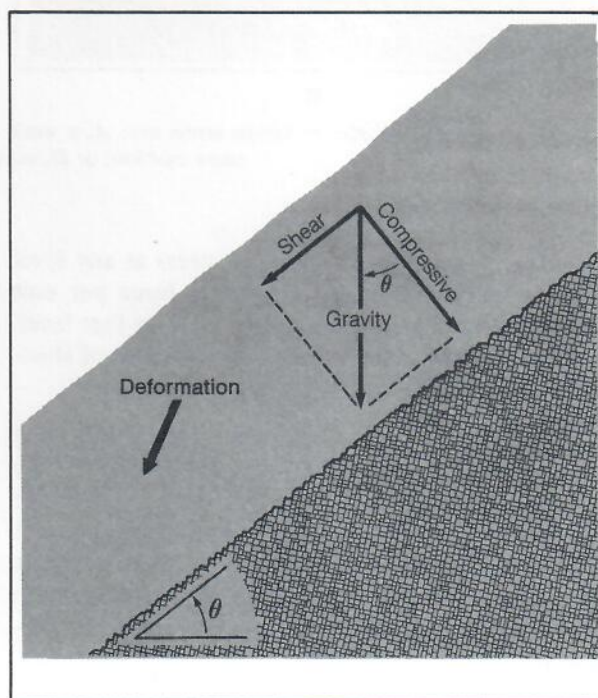
Inclined snowpack

Figure 75.—Left, in a horizontal snowpack, the gravity force and deformation (settlement) are both directed perpendicular to the ground. Right, in an inclined snowpack, the shear component of the gravity force produces a downslope component of deformation.
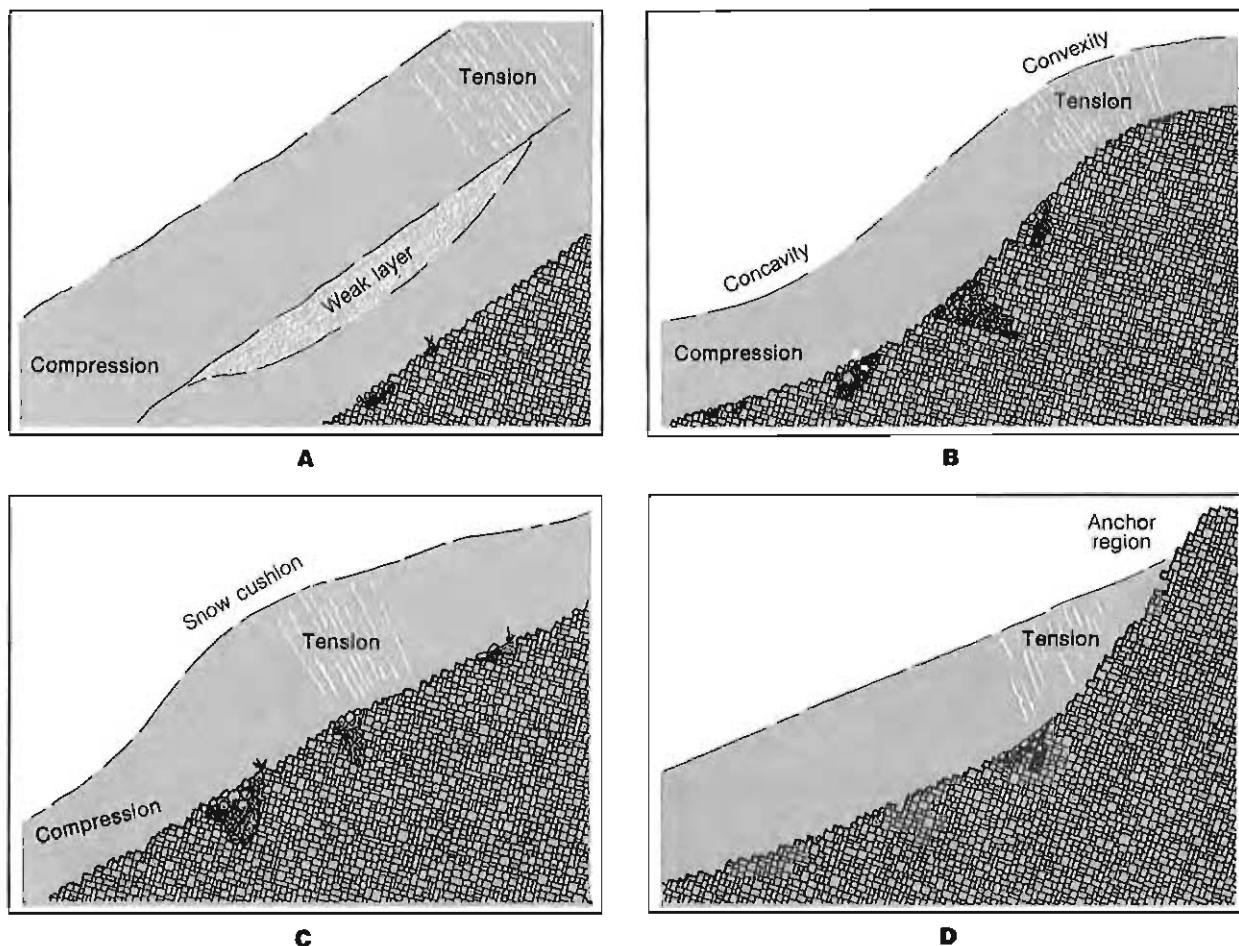
Figure 76.—Possible sources of tensile stress are: A, a weak substratum; B, slope curvature; C, an inhomogeneity, such as a snow cushion; or D, anchoring at the top boundary.

the snow above. The compressive stress at any level is easily calculated as the weight or force per unit area exerted by the column of snow above that level. It is also evident that there is no component of shear stress acting in the horizontal snowpack.

What happens when the horizontal pack is tilted at angles typical of avalanche paths (30° to 50°)? To analyze this situation, it is convenient to resolve the gravity force into compressive and shear components as shown in figure 75. It is then possible to compute the approximate compressive and shear stresses (in N/m^2) along any surface parallel to the snow surface as: .

$$\text{Compressive stress} = \rho\, D\, g \cos\theta$$
$$\text{Shear stress} = \rho\, D\, g \sin\theta$$

where θ is the slope angle, D is the depth in meters beneath the snow surface (measured perpendicular to the snow surface), ρ is the average density of the

snow (in kg/m^3) between the snow surface and depth D, and g is the acceleration due to gravity.[2]

In the simplest model, failure occurs because the shear stress exceeds the shear strength at a certain depth. However, another important factor to consider is tensile stress. Mathematical analysis shows that significant tensile stress can develop in an inclined snowpack through:

Substratum weakness. If an inclined snowpack rests on a locally weak substratum that cannot support its weight, then, in order for the snowpack to be in equilibrium, a tensile stress must develop in the snowpack upslope from the weak substratum, and a compressive stress must develop downslope. The redistribution of stress due to the weak substratum is shown in part A

[2]Taking g as 9.8 m/s^2, stresses are in newtons per square meter (N/m^2).

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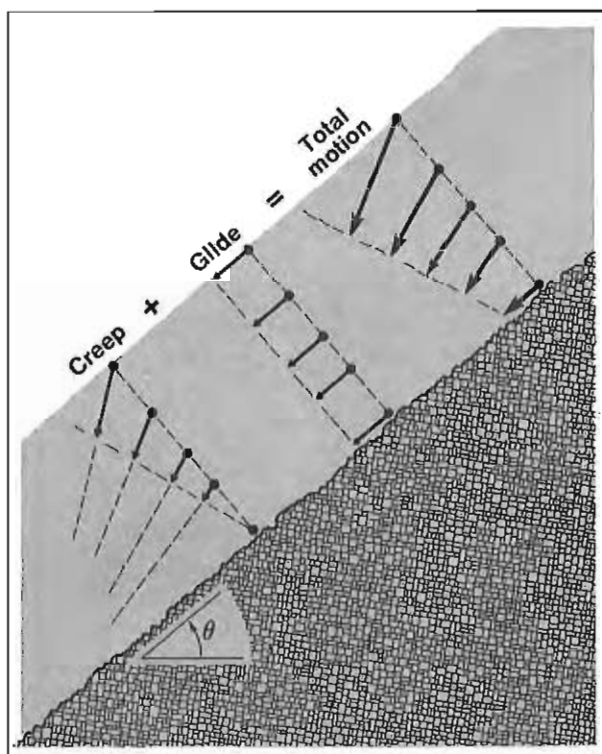
Figure 77.—The complex motion of an inclined snowpack is the total of creep and glide components. Glide is the slip of the snowpack with respect to the ground. Creep is the internal deformation of the snowpaek.

Figure 78.—Dramatic evidence of glide on a grass-covered mountain slope. (Photo by Frutiger)

of figure 76. The weak substratum may be a layer of TG grains, graupel, surface hoar, or any weak, cohesionless snow.

Localized curvature. Regions of tension and compression can develop wherever the inclined snowpack is curved. Tension regions develop over convex terrain features, and compression regions develop over concave terrain features (fig. 76, part *B*).

Snow cushions. Another source of localized curvature is the nonuniform thickness of a snowpack deposited by strong winds. The pack may be shaped like a pillow or cushion, and hence is called a snow cushion. As shown in part *C* of figure 76, a snow cushion has several regions of comparatively high stress.

Anchoring or clamping effects. The ends of snowpacks are often wedge shaped, as shown in part *D* of figure 76. The top of the wedge tends to be anchored to the terrain. The snowpack pulls on the anchoring point, and a region of tension develops below the anchor. Trees, rocks, and other protrusions may also function as anchoring points and induce high local stresses.

The deformation of an inclined snowpack is rather complicated. In response to compressive stress, the inclined layer settles and densifies, and hence strengthens with time. The rate of settlement depends on the amount of compressive stress and on the snow temperature; the higher the temperature, the faster the settlement. In response to the shear stress, the snowpack glides and creeps downslope as shown in figure 77. *Glide* is slippage of the snow layer with respect to the ground. *Creep* is often defined as the internal deformation of the snowpack (determined by subtracting glide from total motion). The creep and glide pressures of the snow must be taken into account in designing ski lift towers and other structures on slopes.

Snowpack analysis

The previous sections of chapter 3 have explained some of the fundamental qualities of mountain snowpacks. Definite guidelines for stress and failure analysis could not be given. The question, therefore, arises: What field observations are useful in evaluating slope stability, in spite of the complexities of the snowpack? It is generally agreed that some measure or index of strength is of primary importance. Other helpful observations are snow depth, density, relative hardness or strength of individual layers, snow temperature, grain type, and degree of bonding within as well as between layers. This section emphasizes only those very basic techniques of snowpack analysis that are generally agreed to be important. Interpreting observations in order to make stability evaluations of avalanche slopes is discussed in chapter 5.
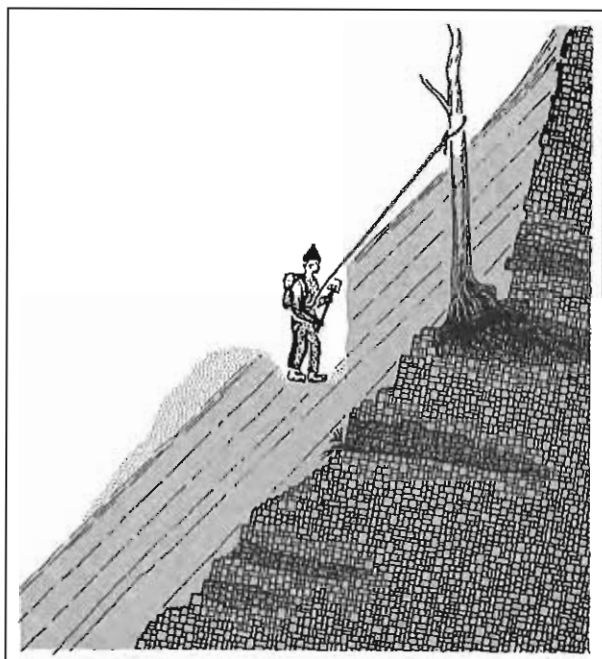
Figure 79.—Cross section of a snowpit on a steep slope. Snowpits should be excavated as close as possible to the avalanche starting zones. Special safety precautions, including rope belays, may need to be taken.

H = Weight of hammer

f

T = Weight of tube

$$R = T + H + \frac{nfH}{p}$$

Figure 81.—The ram number for a snow layer is computed from the amount of ram penetration p for a hammer fall height f; n is the number of hammer blows.

Figure 80.—The ram penetrometer is a convenient tool for snowpack observations from the surface. Using the ram, an observer can quickly determine the location of weak layers. Snowpits are required to confirm ram results.

Snowpack observations are made essentially by digging snowpits as close as possible to avalanche release points. Snowpits are relatively easy to dig on steep slopes because disposing of the snow is not hard. A pit much deeper than 2 m is usually not worthwhile because of the large variation in the thickness of the mountain snowpack and the small return of information for the labor involved.

Thus, after a representative slope has been chosen for analysis and all safety precautions have been taken for travel and work on the slope, the first step is to determine the depth of the pack. If the pack is deeper than a ski-pole length, the depth can be determined conveniently with a collapsible probe. The type of probe used in avalanche rescue work (see chapter 8) is perfectly suitable. Although it is common practice to measure the amount of snow on the ground by probing and to refer to it as snow depth, snow profiles (appendix B) are plotted in terms of height above the ground, because the constantly changing snow surface is a poor reference plane.

After depth has been established by probing, there is some advantage to taking a second, more refined

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sounding with a special instrument called a *ram penetrometer*. This instrument is driven slowly into the snowpack by blows from a hammer that is dropped down a guiderod from known heights. After one or more blows, the penetration of the ram is noted. The amount of penetration per blow increases substantially when the ram passes through a weak layer such as a layer of TG grains. The ram gives the observer quick and convenient information about the relative strength of the snowpack in many locations without the work of excavating a pit in each place.

From ram penetration data, it is possible to compute a relative strength index called the *ram number*. The most popular formula for computing the ram number is:

$$R = T + H + \frac{nfH}{p}$$

where

   R is the ram number
   T is the mass of the tube (usually 1 kg per section)
   H is the mass of the hammer (usually 1 kg)
   n is the number of blows of the hammer
   f is the fall height of the hammer
   p is the penetration after n blows.

This formula is based on the assumption that all the energy of the hammer blow is transferred to the tip of the ram. Although this is not strictly correct, there is no harm in using the formula for computing a relative strength index. T and H are measured in kilograms, and f and p are measured in centimeters. The ram number usually ranges between 1, for newly fallen snow, and 1,000, for ice crusts. The ram number 1 represents the lowest resolution of the ram, that is, the penetration due to the weight of the ram tube. A plot of the variation of ram number with depth is shown in figure 82.

Besides the ram number, several quantitative tests for snow strength have been devised. Most of these are time consuming, and none has been demonstrated to give more insight into stability than qualitative observation.

Preliminary probing and the more refined ram-penetrometer test give the observer a feel for the snowpack depth and structure. After several probes and ram tests, the observer should excavate a pit. Except in the very deep snowpacks of maritime climates, the pit should be large enough to permit unobstructed observation of the bottom layer, which in many cases,
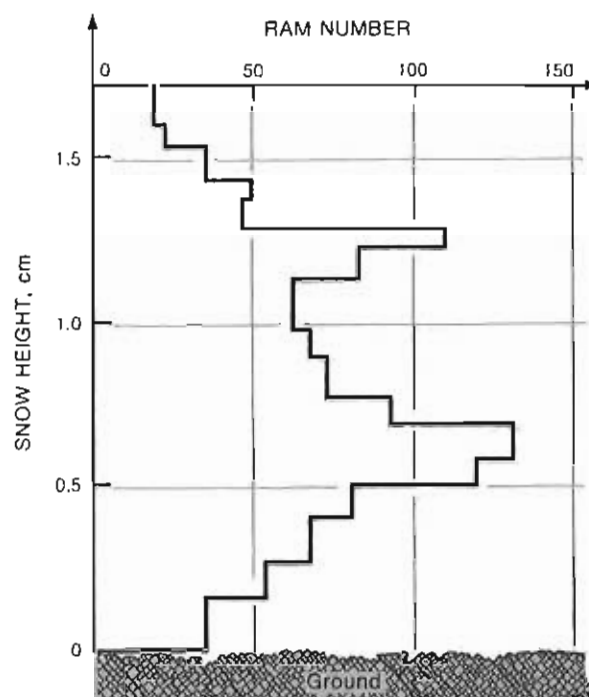
Figure 82.—Variation of ram number with depth. Flagstaff avalanche path, Alta, Utah. Feb. 8, 1970, 1345 h.

especially in continental climates, contains the only obvious weakness in the snowpack.

Several tests can be performed on the walls of the snowpit. However, if time is limited, the observer should concentrate on a qualitative investigation of the texture of the pitwall. The pitwall should be smoothed with the tip of the shovel, and then gently brushed with horizontal strokes of a soft brush, to bring out variations in hardness of the layers.

The first thing to look for is major weak layers. In the deep snowpacks of maritime climates, these may be buried layers of cold, dry snow or thick layers of hard ice that may later be lubricated by melt water and act as avalanche bed surfaces. In more continental climates they are most likely layers of TG grains, usually just above the ground surface. The stage of TG metamorphism should be noted: beginning, intermediate, or advanced (depth hoar). The strength of the TG layer should be noted qualitatively as weak, medium, or strong. No guidelines can be stated for these strength categories, except that the observer learns quickly the great difference in strength between firm, well-sintered ET layers at one extreme and weak, cohesionless layers of depth hoar at the other.

Having searched for major weak layers, the observer should look next for more subtle weaknesses.

Figure 83.—Snowpit stratigraphy observation. Top left, smoothing wall with shovel; top right, brushing wall to accentuate stratigraphy; bottom left, running straightedge down wall; and bottom right, hand lens observation of snow texture.

The existence of any of the following may be worth noting: thin TG layers; weak layers above or below ice crusts; graupel layers; buried layers of surface hoar; or wet, cohesionless grains.

To help locate crusts and thin layers, the tip of a small straightedge can be run down the pitwall. It is also instructive to view the pitwall texture through a hand lens.

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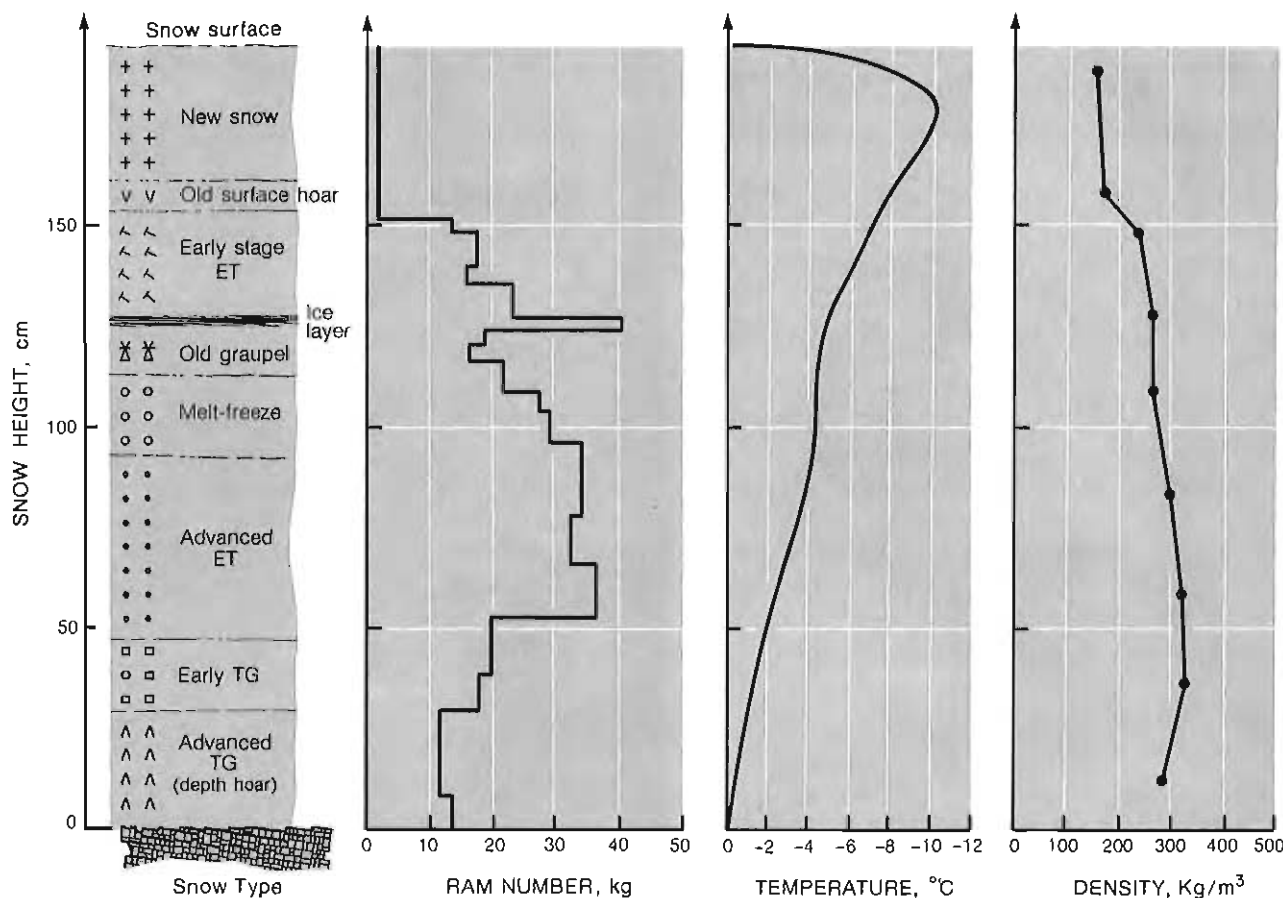
Figure 84.—Typical plot of snowpit data, showing symbols for various types of deposited snow.

Occasionally it is worthwhile to note the temperature variation in the snowpack. Temperature data give the observer a feel for whether TG metamorphism can be expected to intensify in the near future. They also can indicate how close the snowpack is to thaw (0° C throughout). The temperatures of the weak layers can indicate how rapidly they will gain strength through ET metamorphism and sintering. Temperature measurements should be taken in a north-facing pitwall as soon as the pit is excavated. This is especially critical in spring, when pitwalls are likely to heat up rapidly. Because of their ruggedness, dial-stem thermometers are more suitable for pit work than breakable glass thermometers. (However, the 0° C point of each dial-stem thermometer should be checked by putting the stem in a well-stirred slush of clean snow and water.) The procedure for measuring pitwall temperature is first to set the thermometer stem into the layer and allow a few minutes for the

stem to come into equilibrium with the snow, then shift the stem horizontally to a fresh spot for the final reading. Working with several thermometers simultaneously saves time.

There is, of course, no limit to the amount of data that can be measured in a snowpit; each avalanche worker forms his own opinions on what data are most useful for daily operations. The wise observer strikes a compromise between thorough examination of one snowpit and hasty examination of several snowpits on many different exposures. A snowpit examination plot that includes temperature, density, ram number, and grain texture is shown in figure 84. A complete set of field notes and the resulting snow profile are given in appendix B.

A suitable kit for carrying on skis might consist of the following items:
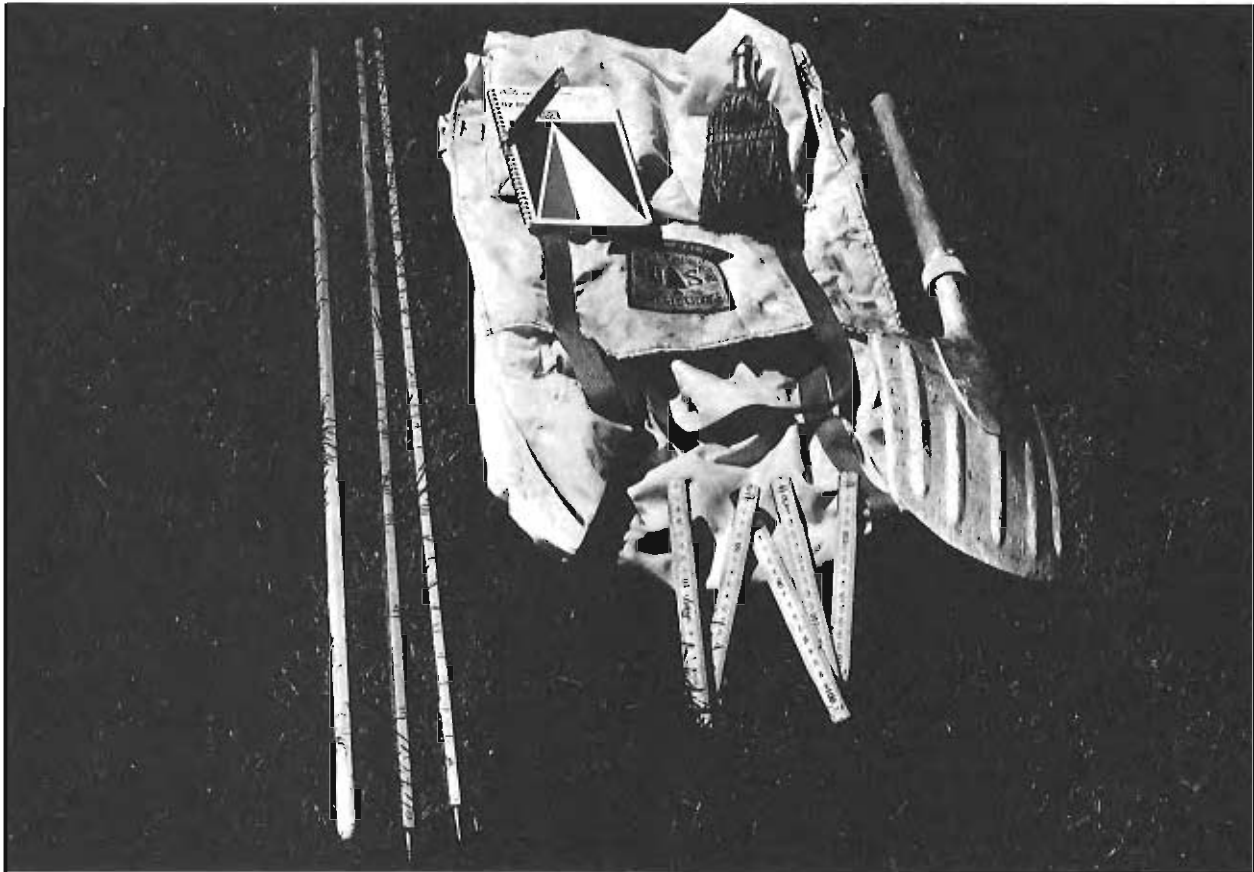
Figure 85.—Above, required and, below, optional equipment for snowpack observations. The shovel pictured here may be too light for some snow conditions.

Required

Collapsible probe 3 m long and marked
    in centimeters
Aluminum shovel (coal and street
    cleaners model or grain scoop)
Brush
Folding rule (3 m)
Notebook and pencils
Rucksack

Optional

Ram penetrometer
Hand lens (and millimeter grid)
Two thermometers (dial-stem preferred)
Portable density kit
Any of a variety of strength-measuring devices,
    such as a shear frame or Canadian hardness
    gage.

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Avalanche phenomena

The first half of this chapter explains some current ideas about avalanche release mechanisms. The intent is to supply the reader with the foundations needed for stability evaluation and avalanche control, practical subjects treated in later chapters of this text. It will be seen that slope failure occurs in many different ways, depending on meteorological conditions, snowpack structure, and the way the slope is "triggered."

The second half of the chapter deals with avalanche paths and avalanche motion. Once a snow slope fails, the energy and impact forces of the avalanche are a function of path length, shape, vegetation, and other path variables. Approximate methods are given for estimating impact forces.

Figure 86.—Slab avalanche triggered by skier. (Photos by Ludwig)
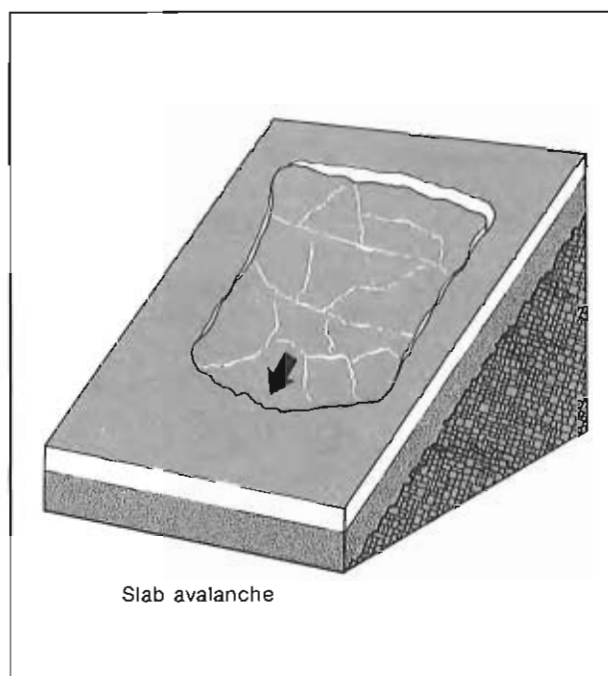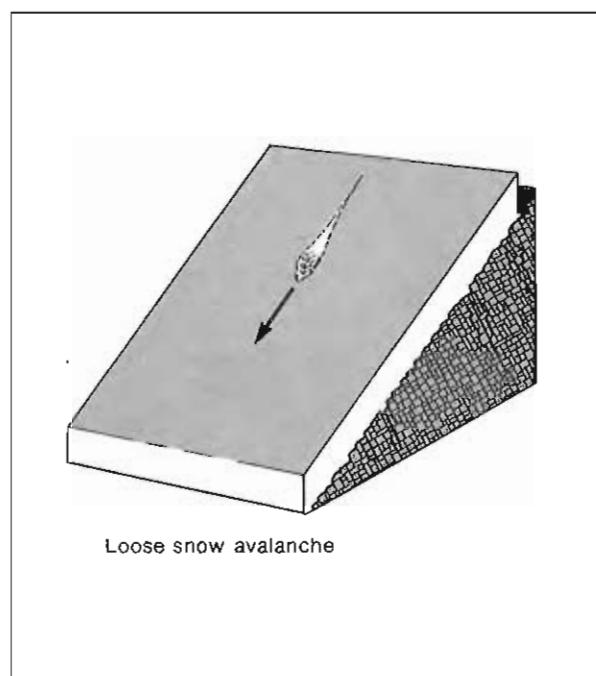
Figure 87.—Two modes of snow slope failure: (left), loose-snow avalanche and (right), slab avalanche; slab avalanches are usually more dangerous.

Figure 88.—Damp, new snow has a comparatively high angle of repose, as evidenced by snow clinging to steep slopes and trees; Denny Mountain, Wash. (Photo by Emetaz)

Failure of snow slopes

Avalanche failure may occur by either of two distinct processes. In one process, failure begins near the snow surface. A small amount of cohesionless snow, usually less than 1 m³, slips out of place and starts down the slope. The initial mass may set an increasing amount of snow into motion if the snow in its path is also fairly cohesionless. When this process is observed from a distance, the avalanche seems to start at a point, and the sliding snow spreads down from the point, leaving an inverted V-shaped scar. Avalanches that form this way are called *loose-snow avalanches*.

The other failure process begins with brittle, catastrophic fracturing of cohesive snow that frees a slab-like region of the slope. The slab quickly breaks into smaller cohesive blocks, whose size varies with their cohesiveness and the roughness of the avalanche track. Avalanches that begin in this manner are called *slab avalanches*. The initial slab may vary from about 100 to 10,000 m² in area and from about 0.1 to 10 m in thickness. Clearly, movement of the larger slabs releases enormous amounts of energy. In contrast to loose-snow avalanches, slab avalanches depend on the propagation of fractures by stored energy in the relatively cohesive layers.

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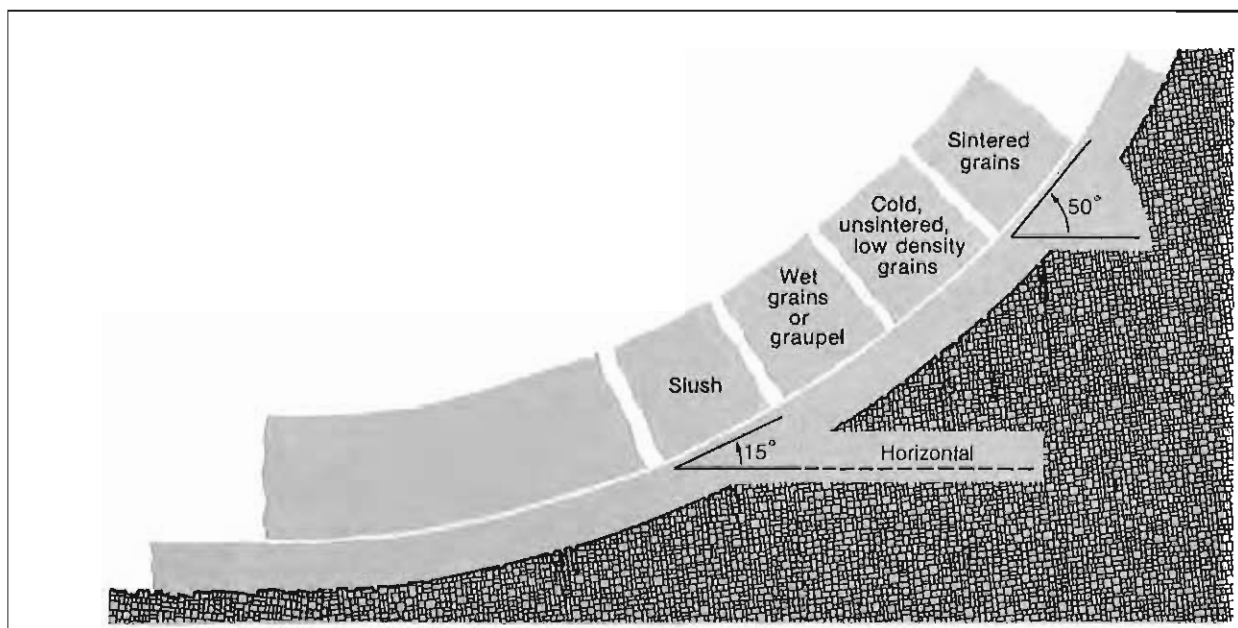
Figure 89.—Depending on its temperature, wetness, and texture, each snow type has a critical angle of repose, above which it will not cling to the snowpack. Loose-snow avalanches result when this critical angle is exceeded.

Much of this chapter is devoted to studying the slab avalanche, which is by far the more dangerous type. Loose-snow avalanches occur mostly because the steepness of the slope exceeds the angle of repose of certain types of weak snow. The exact critical angle of repose depends on the temperature, wetness, and shape of the snow grains. For example, wet, slushy snow has very little strength for its weight and can avalanche off slopes as gradual as 15°. Newly fallen snow has relatively low cohesion but generally has enough strength to cling to 40° to 50° slopes. However, if the new snowfall is cold enough, avalanches of cold, dry snow may occur on slopes of 30° to 40° because sintering cannot proceed fast enough at the cold temperatures to anchor the snow. Rounded graupel crystals generally will not cling to slopes steeper than 40° and often roll down steep slopes like ball bearings. In the Andes, conditions exist that permit thick slabs to cling to inclinations as steep as 50° or 60°.

The sequence of failure in a loose-snow layer that is resting at a steeper-than-critical angle of repose is as follows (fig. 90):

(1) The layer is disturbed by any of several natural or artificial processes: overloading, from the added weight of newly fallen snow or a skier; vibration, from
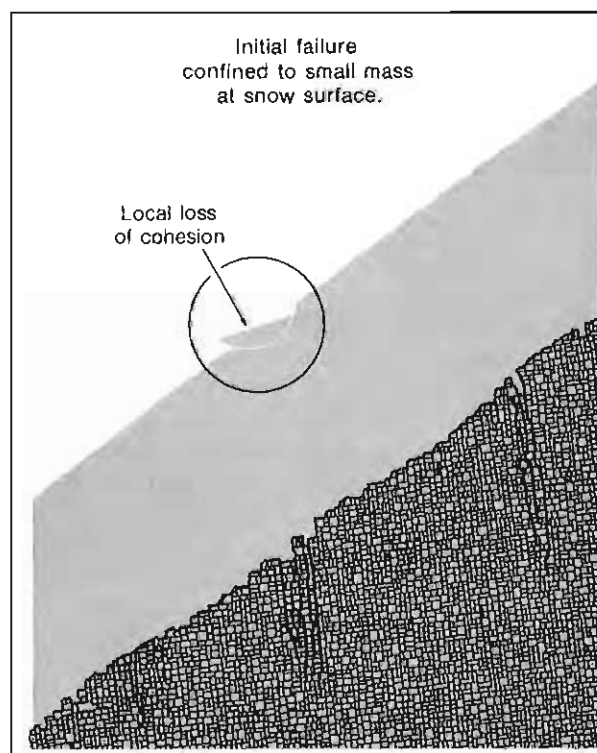
Figure 90.—Start of a loose-snow avalanche. Initial failure is confined to a small mass at the snow surface.

an earth tremor or explosive force; or, most important, internal changes such as the warming of the layer to a state of drastic loss of cohesion.

Failure of snow slopes

Figure 91.—Examples of dry loose-snow avalanches. Most loose-snow avalanches are small, harmless releases called sluffs, although occasionally they reach hazardous sizes. (Photos by Roch and O'Leary)

(2) A small piece of the layer slips out; the piece can be as small as a single grain but is typically the size of a large snowball.

(3) The loose piece either comes to rest at a new angle of repose or imparts enough energy to the snow in its track to cause an avalanche.

Loose-snow avalanches occur frequently throughout the snow season, from early fall to late spring. It is customary to distinguish between dry and wet loose-snow avalanches, although there is no sharp dividing line between these categories, since avalanches may have any of the wetness values outlined in table 1.

Loose-snow avalanches occur in a variety of sizes. Most fall as small, innocuous masses called *sluffs*. Dangerous wet loose-snow avalanches are sometimes observed, especially in the Pacific Coastal ranges, where they have destroyed life and property. The hazard from large, dry loose-snow avalanches is not well documented. Many observers feel that dry loose-snow avalanches pose a threat only when they trigger slab avalanches. In any case, the effects of loose-snow avalanches depend on the amount of snow set in mo-

tion. It is worthwhile to summarize the more important effects:

Hazard to mountaineers and skiers. Loose-snow avalanches are generally small, but they are large enough to knock a mountaineer or skier from a safe stance. Small loose-snow avalanches have sent skiers on leg-breaking rides and have taken mountaineers over cliffs and into crevasses.

Hazard to facilities. Occasionally, loose-snow avalanches are large enough to threaten moving or parked cars, fixed facilities, etc. Most of the notorious cases occurred either in spring or after continuous rain, when the snowpack became soaked and cohesionless to depths of a meter or more.

Stabilization of high-angle slopes. Loose-snow avalanches remove snow from steep slopes. During storms, sluffing occurs almost continuously where the slope angle is steeper than about 50°. Because of sluffing, dangerously thick layers rarely build on such steep slopes. The exceptions to the 50° rule occur where snow is plastered against perpetual icefields and snowfields, in narrow couloirs, or where snow conditions result in unusually steep angles of repose.

Stabilization of lower slopes. In terrain where high-angle slopes empty down onto lower slopes, sluffing from the higher slopes may force the lower slopes gradually to shed small avalanches and become stable.

Loading of lower slopes. Sluffing may transfer snow to the lower slopes, building up large deposits that later may release as slab avalanches.

Triggering of slab avalanches. Loose-snow avalanches that would be harmless by themselves may spill onto lower slopes and trigger dangerous slab avalanches.

Before discussing slab avalanches in further detail, the customary distinction between natural and artificial avalanches (loose-snow and slab types) should be made. *Natural avalanches* are not triggered directly by man or his equipment. A falling cornice, sluffing snow, stress change due to metamorphism, stress change due to weight of new snow, earth tremors, snow falling from trees, etc., can all trigger avalanches. *Artificial avalanches* are triggered by man or his equipment. A ski pass, a mountaineer's weight, an explosive blast, a sonic boom, etc., commonly precipitate artificial avalanches. There seems to be no difference in appearance between natural and artificial avalanches. *The important fact is that artificial triggering leads to a far greater frequency of avalanches on a given path than if the path were left to avalanche naturally.*

Slab analysis

Slab avalanches begin with the fracturing of snow slopes. Cracks usually propagate quickly and follow unique and complex paths that depend on slope geometry and slab anchorage. Obviously, for a slab to detach completely from the slope, fractures must proceed around the entire slab boundary. The following nomenclature (see fig. 92) is used to describe the boundary fracture surfaces:
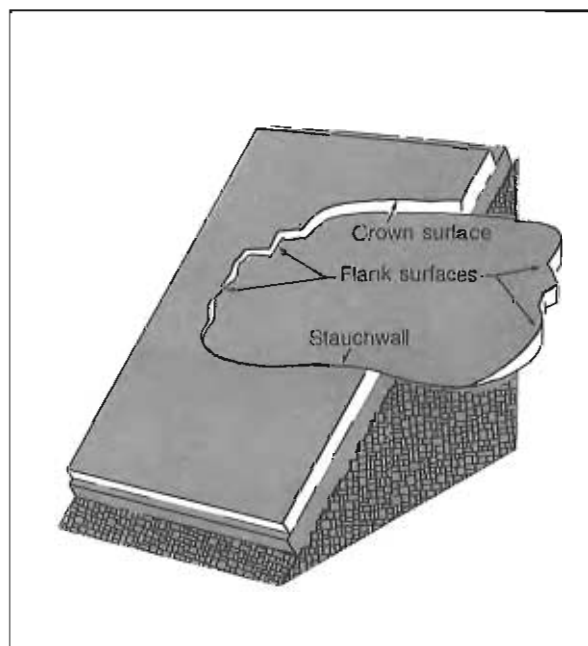
Figure 92.—Top, nomenclature for the fracture surfaces of a snow slab. Bottom, a classic example of a soft slab avalanche.

Crown surface. The top fracture surface of the slab, usually a smooth, clean cut, generally perpendicular to the slope. The snow that remains on the slope above the crown surface is called the crown.

Flank surface. The side boundary of the slab, often sawtoothed.

Figure 93.—Cross section of a typical snow slab.

Bed surface. The main sliding surface of the slab, generally smoothed and compacted by the sliding blocks.

Stauchwall. The downslope fracture surface of the slab, often difficult to identify since it is usually overridden and obliterated by the sliding blocks.

Viewing the fracture pattern in ideal cross section, the bed surface and the crown surface typically intersect at approximately 90°; the slab has a wedgelike shape at the stauchwall (see fig. 93).

Because the bed surface is hidden entirely during the fracture process, the sequence of fracturing is not known. Although the first observed fractures are usually spectacular crown fractures, the crown may in fact be the last link to break.

Crown fractures may extend considerable distances, jumping gullies and bowls and linking together several smaller slabs. Crown lengths of more than a kilometer have been recorded. A characteristic feature of the fracture boundary is that crown length usually exceeds flank length. In some cases, the crown surface blends directly into the stauchwall, forming an oval, flankless slab.

Regardless of their geometric peculiarities, slabs often contain large masses of snow and great amounts of potential energy. It is not uncommon for a slab to have an area the size of a football field and an average

Figure 94.—Crown fractures may propagate over long distances, connecting a series of smaller slabs. (Photo by Wilson)

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thickness of 1 m. Moreover, when a slab breaks loose and slides down the mountainside, it may bring down 100 times the initially released amount of snow.

Slab avalanches originate on a wide variety of terrain. The main requirement is steepness. One hundred observations of bed-surface inclinations for dangerous-sized slabs are summarized in figure 95. Dangerous slabs are most likely to start on slopes in the 30°-to-45° range. Fortunately, good recreational skiing, even under deep powder conditions, can be enjoyed on slopes that are not this steep. Explanations for the distribution shown in figure 95 are:

• For slopes of less than about 30°, shear stress on the bed surface is not large enough to cause shear failure. It is interesting that collapse and fracturing are often observed on slopes with inclinations of less than 30°, and even on horizontal surfaces, but in those cases vertical collapse is not followed by avalanching.

• The upper limit of about 45° probably indicates the tendency of snow to sluff gradually off steep slopes (45° to 60°).

It must be emphasized that many isolated examples of slab avalanches are outside the 30° to 45° range. Certainly, mountaineers should not venture confidently onto 50° snow slopes. In cases where snow accumulates on steep terrain (45° to 60°), slab avalanches are a definite possibility. Also, slab fracture can propagate from high-angle slopes to slopes of less than 30°.

As shown in figure 76, slope curvature can influence the stress distribution in a slab. However, the bed surfaces of almost all slabs are quite planar. Moreover, crown fractures usually form just below a terrain bend rather than directly on the bend. Thus, it appears that bends do not play the fundamental role of increasing stress, but instead contribute to avalanching by influencing the way snow is deposited and anchored.

A few studies have been made of the properties of slab avalanches. These studies provide the following limited information:

Crown thickness. This dimension can vary widely, from a few centimeters in the case of sluffs to several meters. Typically, slab avalanches become hazardous to skiers when the crown thickness exceeds 15 cm, the minimum thickness for extensive fracture propagation.

Slab density. Normally slab avalanches consist of snow with densities between 100 and 400 kg/m³. In almost all slabs, there is substantial variation in density between snow surface and bed surface. The density just above the bed surface is usually about twice the density at the snow surface. In the vast majority of larger slabs (crown thickness more than 1 m), average snow density lies within the narrow range of 200 to 300 kg/m³. This range is typical of wind-deposited new snow or sintered snow.

Slab hardness. It is customary to distinguish two hardness categories, hard slab and soft slab. This distinction is based on subjective observations. For example, extreme hard slab snow cannot be penetrated by ski tracks; ski edges leave only a faint line. In contrast, excellent powder skiing is often possible through soft slab snow. Another subjective basis for distinction is that on slopes of similar roughness, hard slab blocks can survive lengthy trips down the slope without disaggregating, while soft slab blocks break up very quickly into smaller lumps. There is, of course, no fundamental distinction between hard and soft slab; slabs come in a wide range of hardnesses. From a practical viewpoint, the harder slabs pose special control problems in ski areas. Generally, hard slabs consist of high-density snow (300 kg/m³ or higher), either de-
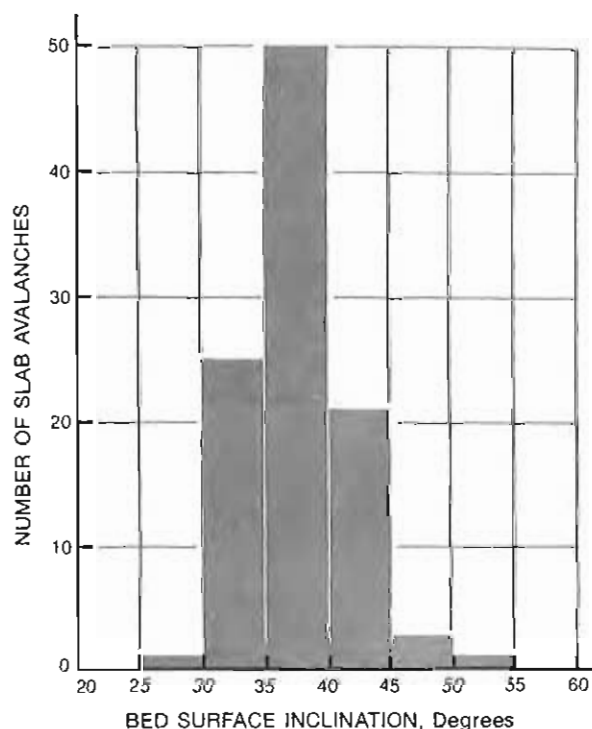
Figure 95.—Bed-surface inclinations of 100 large slabs observed in the United States, Switzerland, and Japan. (Average slab thickness is about 1 m.)

Figure 96.—Examples of slab avalanche fracture patterns. (Photos by Gabriel, Judson, Kelner, and Roch)
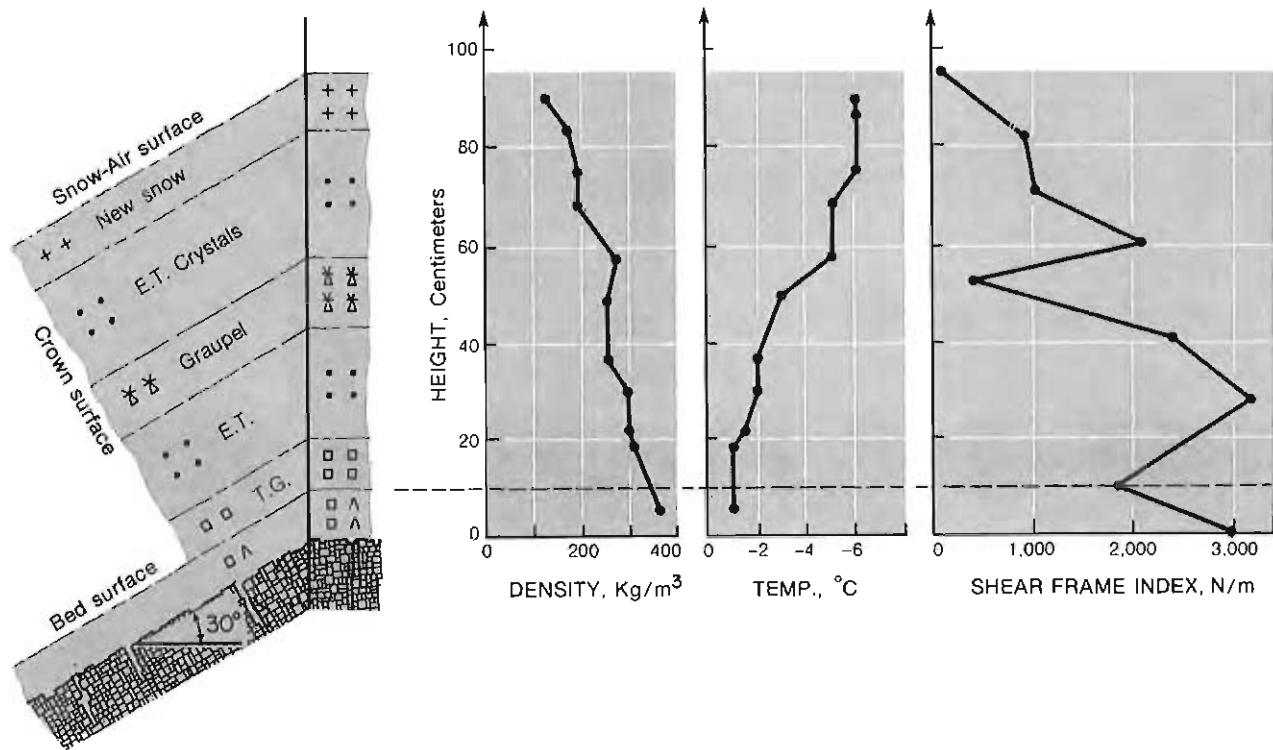
Figure 97.—Snow stratigraphy of a 1-m-thick slab that released at Alta, Utah. As indicated by the shear-frame measure of strength, either the graupel or the TG layer was a possible bed surface; in fact, a nearby slide ran on graupel the same day.

posited by high winds or the result of aging and compaction.

Slab temperature and wetness. Slab temperatures reflect the air temperatures of the mountain range. Avalanches have been observed in the cold environments of the Himalayas and on the slopes of Mount McKinley. At the other extreme, slab avalanches have been observed when the snow was thoroughly drenched with free water (see table 1). It is customary to distinguish dry and wet slabs as follows: Dry slab snow when squeezed in a gloved hand will not make a snowball, but liquid water can be squeezed from wet slab snow. This test should be made with snow from near the starting zone, not with avalanche debris.

Slab stratigraphy. The slab layers above the bed surface consist of a wide assortment of snow types. The most frequently observed layers are:

• Newly deposited snow up to a few days old. Most of the basic forms and modifications (see fig. 26) have been identified. Firm, wind-deposited layers are very common.

• Metamorphosed snow. Mostly ET grains and grains in the early stages of TG metamorphism. Quite often thin TG layers, crusts, graupel layers,

and other special layers are sandwiched between thick ET layers.

• Wet layers (table 1).

Bed surface. Because the bed surface is altered by the sliding slab, definite information on its structure is rarely available. A limited number of studies on the extension of the bed surface into the crown reveal the following:

• In some cases it is possible to identify a distinct discontinuity, such as a transition from ET grains to TG grains, a graupel layer, the ground surface, an ice crust, or thin layers of surface hoar.

• In many cases it is not possible to identify any special discontinuity of snow stratigraphy at the bed surface extension, although snow at the bed surface is typically about 50 percent weaker than snow immediately above the bed surface.

Slab substratum. In most cases investigated in continental climates, the slab substratum beneath the bed surface consisted of TG grains. In maritime climates, TG substrata are rare, and the limited data indicate that most of the substrata consist of new snow, partly metamorphosed snow, or wet snow.

Mechanics of slab failure

In one possible sequence leading to slab avalanche release, failure begins when shear stress exceeds shear strength at the bed surface. This may be the result of either an *increase* in the bed surface shear stress or a *decrease* in the bed surface shear strength, or a combination of the two. Such changes may be caused by the following situations:

- High-intensity snowfall or wind redistribution of older snow

- Rapid application of shock load, explosive blast, cornice fall, etc.

- Load of one or more skiers traversing the slab

- Weakening of the bed surface by TG metamorphism

- Weakening of the bed surface due to slow straining

- Weakening of the bed surface by melting.

The initial bed surface failure is always hidden from sight, so it is not obvious how rapidly failure progresses. There may be rather widespread shear fractures, or possibly slow, progressive straining. In any case, after shear failure begins, tensile stress begins to increase in the slab. Finally the slab fractures in tension, and the entire slab releases very rapidly as the shear support along the flanks and the compressive support at the stauehwall are overcome. This sequence could result in crown fractures propagating above a skier, trapping the skier as shown in figure 98.

A second possible and related sequence of slab failure begins with the sudden collapse of a thick, weak layer of TG grains, or low-density snow. The collapse can be due to new snow load, weakening by metamorphism, or sudden shock. As shown in figure 99, the sequence of events would be first, collapse of the substratum; second, high bending stress upslope from the collapsed area; third, tension fracture in the region of high bending stress; and fourth, shear fracture at the bed surface. It is known that substratum collapse is an important mechanism, since it explains the intense instability associated with thick TG layers. However, in many cases slabs have failed on hard substrata, where collapse was not possible.

A third possible mechanism of slab failure begins with tension fracture, which in turn activates fracture at the bed surface (fig. 100). This requires a previous internal failure or straining in the snowpack to build up the necessary tensile stresses. Tension fracture could result from:

Figure 98.—In one possible sequence, initial slab failure occurs in shear along the bed surface. High tensile stress develops upslope, ahead of the propagating shear failure. Finally, the slab layer fractures in tension.

- Sudden ski traverse across crown, explosive blast, etc.

- Decrease in tensile strength due to warming of slab

- Increase in tensile stress due to thermal contraction brought on by protracted cooling

- Increase in tensile stress due to creep or glide.

In all three proposed mechanisms, the necessary condition for failure is that a relatively stiff layer (the slab layer) rests on a relatively weak layer that contains the bed surface. Regardless of the mechanism, tensile stress eventually develops in the slab layer, which stores elastic strain energy. When the slab layer fractures, a sudden jolt is thrown onto the bed surface. This jolt reinforces any bed surface failure that began earlier. Finally, the shear fractures at the bed surface and the tension fractures at the crown reinforce one another, so that the slab rapidly breaks free on all boundaries.

It is not difficult to see that heavy snowfall, rain, thaw, and dynamic loads are important triggers of slab avalanches. However, can abrupt temperature changes cause instability in dry snow deeper in the

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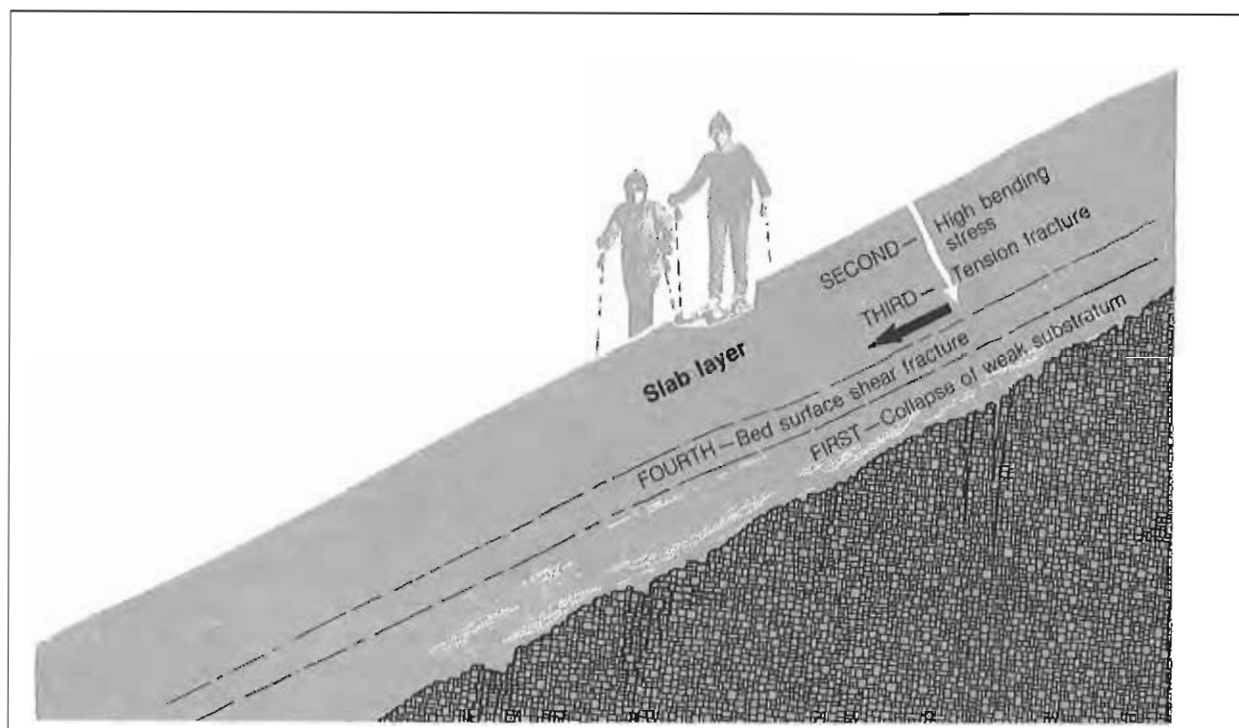
Figure 99.—Initial failure may occur as collapse of a weak substratum. This would induce high bending stress, tension fracture, and finally shear fracture at the bed surface.

snowpack than about 0.5 m? The question comes up because avalanche slopes in ski areas often seem to be stable when tested with explosives in the early morning but release a deep slab in the afternoon. It is sometimes said that such *postcontrol avalanches* are caused by an abrupt rise or fall of snow temperature.

This so-called "temperature-release" mechanism is controversial. Rapid changes in snow temperature are certainly confined to the surface layers. The thermal conductivity of snow is very low—about 1/10,000 that of copper—and it is difficult to see how a dry slab any thicker than about 0.5 m could be affected by rapid fluctuations in the surface energy balance. Moreover, solar radiation is the most important variable in the short-time energy balance, yet most avalanches attributed to temperature release have been on north-facing slopes, where hourly radiation changes are minimal. Finally, in mountain ranges where sudden temperature changes are most extreme (for example in the Canadian Rockies, where the temperature may go up or down 25° or 30° C in a few hours), there are few complaints about temperature release.

Figure 100.—Initial failure may occur as a tension crack. The opening of the tension crack would induce shear fracture at the bed surface.

Mechanics of slab failure

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The avalanche path

Once set in motion, avalanches can move great distances. The larger avalanche paths in North America are about 3,000 m long and have a vertical drop of about 1,800 m. Some avalanche paths in the Alps, the Andes, and the Asiatic mountains are much longer. The average inclination for most avalanche paths that extend for a long distance is between 20° and 35°.

The term *avalanche path* is used to describe terrain boundaries of known avalanches or suspected avalanches. It is customary to divide an avalanche path into three sections: *starting zone, track,* and *runout zone.* The typical dimensions of each section of a given path are best determined by systematic records of field observations. However, the maximum dimensions can only be guessed from historical evidence and assumptions about "what could happen" under unusual conditions. An avalanche may overrun its presumed boundaries so that a former runout zone becomes a track for a new runout zone. The vast majority of avalanches that run on a given path will not be observed to reach their maximum boundaries in a short-time study. There are examples from the Alps of buildings destroyed by avalanches after standing for 100 years or more (Fraser 1966).

The essential characteristics of the starting zone have been described. It must be steeper than about 30° and must receive large amounts of snow. The latter characteristic is satisfied for certain wind directions if the slope is in the lee of a source of blowing snow or if the lee slope is an efficient collector of snow (see chapter 2). Gullies and bowls are especially efficient collectors and make up a large proportion of the most active starting zones. Buttresses and flat, exposed faces are less efficient collectors and therefore less likely to contain active starting zones. However, when large amounts of snow are deposited with little or no wind, normally inactive and exposed starting zones may become quite active. The most active starting zones are gullies bounded at the top by horseshoe ridges or cliffs. Most starting zones are bare of trees, some have sparse timber, and a few contain stands of fairly dense timber. In the last case, slab fracture may spread into the timber from the clearings.

The term *track* refers to the part of the path between the starting zone at the top and the runout zone at the bottom. As a very general rule of thumb, avalanche tracks have an inclination of at least 15°; more

Figure 101.—Three sections of an avalanche path: starting zone, track, and runout zone.

What alternative explanation, then, can be given for latent instability of tested slopes? If a slope is structurally unstable, early-morning explosive tests might jar the slab loose from its substratum. Tensile stress would then begin to build up in the slab as the day progressed. The slab may reach a hair-trigger state later in the day; the fact that the snow temperature is also changing is of secondary importance and most likely a coincidence. It is interesting that most cases of "temperature release" have occurred where noticeably weak substrata could be identified.

To summarize current ideas about temperature releases and postcontrol avalanches:

• Temperature changes at the snow surface may cause failure and sliding in the surface layers. This, in turn, could trigger deeper slab releases.

• Sudden temperature changes at the surface very likely do not cause deep slab instability in dry snowpacks.

• There is growing concern that explosives alone do not give an infallible test of snowpack stability and in some rare cases may weaken the slope.

Figure 102.—Active starting zones are found at the tops of gullies and bowls and in the lee of ridges. Many starting zones are bounded by cliffs or rock outcrops. (Photos by Kelner and Roch)

The avalanche path

Safe?

Figure 103.—The terrain looks safe, but a skier was killed in this avalanche path. Open timber does not guarantee safety. Floral Park Avalanche, Berthoud Pass, Colo.

Figure 104.—An example of main tracks fed by several branches. Cement Creek, near Silverton, Colo.

commonly, 20° to 25°. Avalanche tracks can be subdivided into two categories: channeled and unconfined. Channeled tracks are gullies, couloirs, gulches, etc., with or without summer streams. Unconfined tracks are on plane, open slopes. Most of the longer avalanche tracks in the United States are channeled, because the confining action of the channel tends to concentrate the flow and propel the moving snow efficiently.

An avalanche track may have several branches. A common situation is a main channeled track fed by several small tracks, each beginning at a separate starting zone. It is important to keep in mind that multibranched tracks may run several times in quick succession, as each branch empties into the main track. A number of fatal accidents has occurred when workers clearing the debris of a first avalanche were struck by a second that ran down the same track within hours of the first.

Dry avalanches tend to follow straight lines. Where a gully makes an abrupt turn, the fast-moving "snow dust cloud" of a dry avalanche may jump the gully walls and continue on its straight-line path. Wet avalanches flow more slowly and are more easily channeled to follow curved gullies. An interesting case that illustrates the different paths taken by dry and wet avalanches occurred recently at a popular United States ski area. Based on the recollection of the older

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Figure 105.—Comparison of a channeled track and an unconfined track: Top, N.W. Red Avalanche, near Empire, Colo.; bottom, Ironton Park Avalanche, near Ouray, Colo.
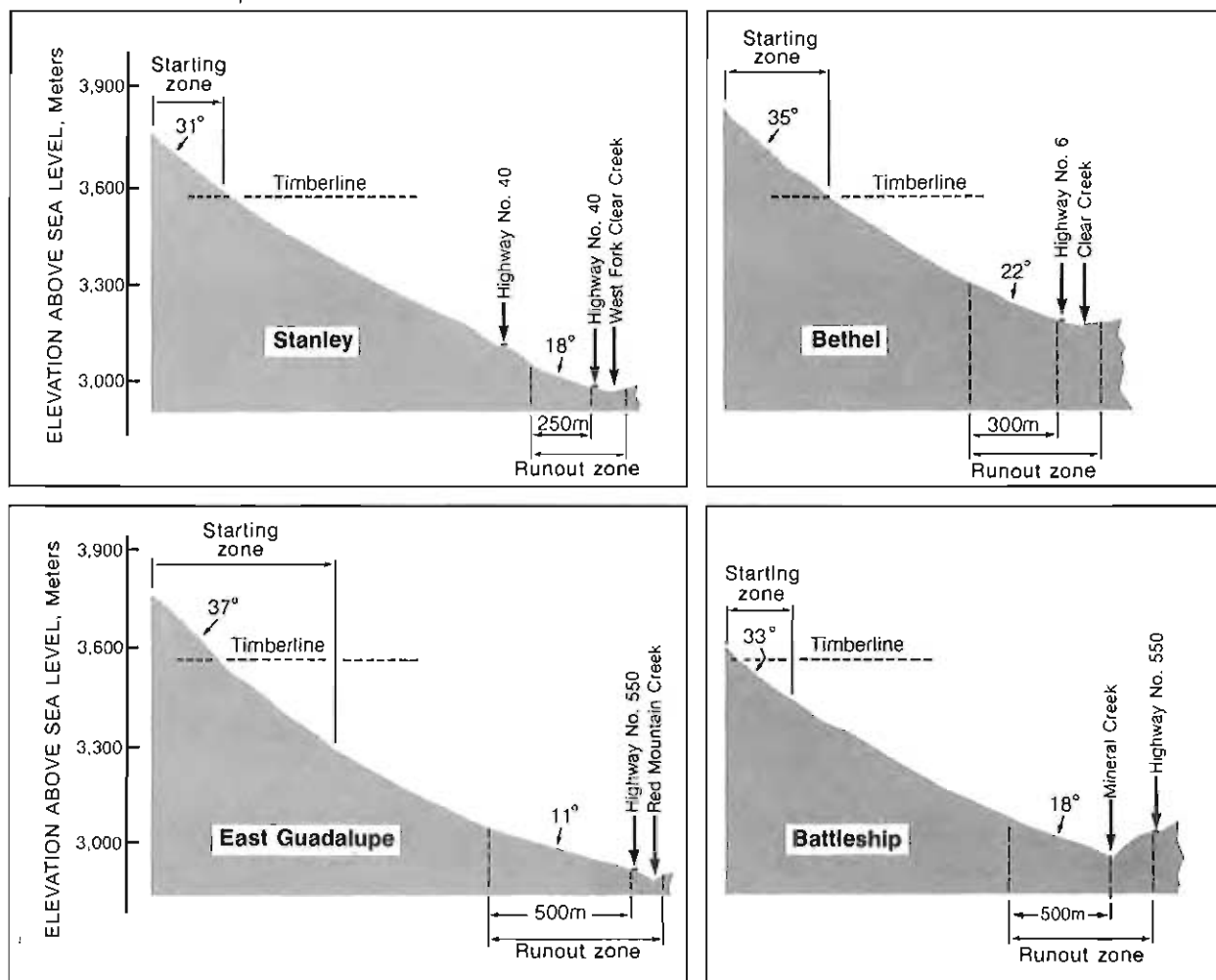
Figure 106.—Longitudinal profiles of four avalanche paths in Colorado.

residents of the area, a building site was planned in a supposedly avalanche-free gully. There was an avalanche above, but everyone remembered that it customarily failed to make an abrupt turn halfway down the gully and jumped the gully walls, finishing on a straight course. Just before construction a wet spring avalanche did not jump the gully and continued into the middle of the proposed site.

Although starting zones must have the required steepness, avalanche tracks may include gentle slopes or even level terrain. The runout zone is usually the valley floor, but it may in extreme cases extend uphill. As an example, an avalanche in the Alps, with a starting zone at elevation 2,500 m, ran down its track to elevation 1,740 m and then continued across the valley and uphill to elevation 1,960 m. In an incident from United States history (1872), a convoy of horse-drawn sleds was struck by an avalanche from Mt. Superior near Alta, Utah. Several bodies were found in debris on the opposite side of the valley, 100 m above the road.

The runout zone is the bottom boundary of the path. For several reasons, it is difficult to be certain of this boundary. One problem, of course, is the great variation in weather from one winter to the next. In a severe winter, starting zones and tracks may be loaded with abnormally large amounts of snow. In those winters, avalanches may overrun historical boundaries. There is also the possibility that two large avalanches down the same path in fairly rapid succession will result in the second avalanche exceeding the known boundaries because it flows down a track and across a runout zone smoothed by the first avalanche. Finally, a series of avalanches may gradually force a

Figure 107.—Avalanche debris across two-lane highway. Little Cottonwood Road, Utah.

path through a forest stand that before stopped the avalanche. Once most of the timber is destroyed, a major avalanche can break through and continue into a formerly protected area. As a general guideline, runout zones on slopes of 5° to 10° can extend 300 to 500 m.

In determining the limits of the runout zone, it is necessary to account for the airblast caused by the moving snow (described later in this chapter under "Avalanche Movement"). It appears that the airblast zone may extend about 100 m beyond the boundaries of a major avalanche path.

The snow deposited in the runout zone is about two or three times denser than the starting-zone snow, and it is much harder. While moving down the track, some of the snow is pulverized into fine particles. When the mass comes to rest, the fine particles and the larger pieces sinter rapidly to form a very firm aggregate. Wet avalanche debris is remarkably hard and icelike, probably due to *regelation*—the refreezing of pressure-induced melt water. To dig into the debris of a large wet snow avalanche requires pickax and shovel (fig. 107).

Identification of avalanche paths

One method of studying avalanche paths is direct observation for as long as possible by a trained, reliable observer. The second method is to rely on a synthesis of indirect evidence: topography, climate, avalanche damage to vegetation, and information from the local population. Since long-term avalanche records are usually unavailable, most planning of facilities in avalanche terrain relies heavily on the second method, with due consideration for any existing observations.

If a ski area, highway, village, etc., is to be built in suspected avalanche country, 3 to 5 years of continual observation are desirable before the area is opened to the public. The observation should be recorded in a systematic way. In 3 to 5 years it should be possible to observe at least the avalanches that run on the average of once each season and to acquire a feel for the potential of inactive paths. The difficulty is, of course, that some avalanches run on the average of once per season, others once every 5 to 15 years, and others less frequently. Another complication is that many avalanche paths are not active every winter but run several times in winters when they are active.

A good way to begin is to gather as much information as possible from the local population or from people who have lived and worked in the area for long periods. Highway crews, electric power companies, telephone companies, sheriffs' crews, etc., may be able to contribute information. The first avalanche maps of the areas can be based on their recollections. Information collected from local people will probably be incomplete, and it probably will include only the most spectacular avalanches of recent years.

Path identification should be conducted throughout the year. In winter the obvious features are fracture lines and avalanche debris. Winter observations should be made immediately after storms. Some fracture lines and debris will be plainly visible, and some will be obscured by new snow and wind drifts. Avalanches that run early in the storm cycle may be obscured and quite difficult to identify. In spring also, avalanche paths are most active after storms, especially those that are followed by warming trends. Major avalanches may occur whenever the snowpack is thawed. Late in spring, and even in summer and fall, avalanche debris may be seen in gullies. This lumpy debris, which is dense and hard and often contains rocks, branches, mud, small animals, etc., persists in gullies long after the snow melts from the neighboring

Figure 108.—At a distance, avalanche paths often appear as treeless strips. Seven Sisters Avalanche Paths, near Loveland Pass, Colo. (Photo by Frutiger)

Figure 109.—Destruction of trees is an indication of avalanche activity. Broken trees are alined in the direction of the moving snow. Trees are disaster, or pioneer, species, which normally do not dominate. Superior Avalanche Path, Alta, Utah.

AVALANCHE PHENOMENA

terrain. In summer, detailed inspection can be made of the vegetation and topography of avalanche paths.

Many avalanche paths are not obvious. This is especially true of small paths that would be hazardous in a ski area. A good way to investigate and map these small avalanches before construction of a proposed ski area is to carefully and thoroughly ski tour the area and record observations on high-quality aerial oblique photographs.

In alpine and subalpine ski areas it can be assumed, as a start, that all treeless slopes, gullies, and bowls steeper than about 30° are possible avalanche paths. There is hardly any lower limit to the size of hazardous paths in ski areas. People have been buried and killed by avalanches on paths 10 m long.

Identification of large avalanche paths presents several problems. For one thing, it is necessary to view the entire path. For very long paths, this may be impossible without using air reconnaissance or ascending the ridge across the valley from the suspected path. A view up from the valley floor often gives a distorted impression and may miss completely the starting zone. In some cases, large starting zones are hidden by cliff bands or other terrain features. A view up from a proposed development site may make the suspected avalanche path seem deceptively short. The view down the path from the starting zone gives the best perspective of potential damage. A proposed site might diminish to a small point, well within the possible boundaries of the path.

Large avalanches have enough power to destroy trees, and landscape scars provide important clues to avalanche activity. From far away, an active avalanche path below timberline normally appears as a treeless strip, often following a gully. Less active paths appear as strips of smaller trees, or strips of trees of a different species from those outside the path. From the air or from an opposing ridge, the runout zone may be outlined clearly by changes in vegetation.

It is often impossible to enter large starting zones in the winter because of risk or inaccessibility. In those cases, the starting zone should be entered in summer to collect information not available from maps. Of particular interest are the slope angle and aspect. It may be necessary to study the ground surface of the starting zone in order to plan defense structures or reforestation.

Close inspection of vegetation in the runout zone is important. Vegetation gives important clues to boundaries. The things to look for are:

Figure 110.—Branch damage on the uphill ..de of a tree may be evidence of avalanche activity. Bethel Avalanche Path, near Silver Plume, Colo.

Obvious destruction of trees and branches. The most convincing evidence of past avalanche activity is a patch of fallen trees, alined in the same direction and sheared at about the same height above the ground. The common shear height can be assumed to be about the height of the snowpack at the time of the avalanche. At the boundary of the runout zone branches of upright trees may be damaged. Some of this damage may be caused by airblast or low-density snow dust. In many cases, branches are removed from the uphill sides of trees.

Change in species. As noted above, another indication of past avalanche activity is a marked change in vegetation in the neighborhood of a suspected runout zone. A typical example might be a patch of slide alder, yellow cedar, or aspen surrounded by a closed forest of spruce and fir or other climax species. The explanation for these patches is that certain species of shrubs and fast-growing, light-tolerant trees invade disturbed sites more readily than climax plants. Trees of the climax species usually become established in the shade of the pioneer species and eventually crowd them out if given enough time without further disturbance.

Figure 111.—Stout limber pine growing in the middle of Flagstaff Avalanche Path, Alta, Utah.

Differences in height of trees. Trees survive avalanches up to a height that varies with the strength and flexibility of the species and the thickness of the pack. Since avalanches ordinarily do not penetrate deeply under the pack in the runout zone, short trees may escape destruction. Thin, flexible trees up to about 3 m high may be bent by the moving snow and then recover. Certain rugged subalpine trees, such as thick limber pines, may be resistant to avalanches, and an occasional high tree is found in the middle of a path. In the great majority of cases, though, trees in the runout zone are shorter than trees outside the zone.

Vegetation can be used for making a rough estimate of avalanche frequency. Table 2 gives some idea of how frequency can be correlated with vegetative clues. Increment cores from selected trees give their relative ages (Chapman and Meyer 1949, and Cuno 1938). It should be kept in mind that there is an inde-

terminate time lag between avalanche activity and establishment of trees. The lag may be 1 to 10 years or more. Thus, detailed age analysis by increment coring is justified only for activity less frequent than once in 25 years. The ages of mature trees that are definitely outside the runout zone provide a reference for increment core analysis. Trees in a suspected runout zone should be older the closer they are to the reference. It helps to summarize information about tree species, age, and height on a vegetation map.

Identified paths should be marked on as detailed a topographical map as is available. To begin with, avalanche areas can be located on standard U.S. Geological Survey maps (for example, 7- to 15-minute quadrangles). However, for zoning purposes (see chapter 7), it is necessary to use maps as detailed as possible, with contour intervals of 5 m or less. Planning defense structures (see chapter 7) may require even more detailed surveys.

TABLE 2.—*Vegetation as a rough indicator of avalanche frequency*

Frequency: at least one avalanche in an interval of—	Vegetation clues
1–2 years	Bare patches, willows and shrubs, no trees higher than about 1 to 2 m. Broken timber.
2–10 years	Few trees higher than 1 to 2 m. Immature trees of disaster or pioneer species. Broken timber.
10–25 years	Predominantly pioneer species, young trees of the local climax species (increment core data).
25–100 years	Mature trees of pioneer species, young trees of the local climax species (increment core data).
Over 100 years	Increment core data.

Avalanche movement[3]

Avalanche motion may be described as *flowing, airborne powder,* or *mixed.* Flowing motion is the turbulent, tumbling action of snow moving mostly along the ground. In airborne-powder (usually called simply powder) motion, most of the snow is swirling through the air. Pure powder motion seldom occurs except when the snow goes over a cliff (fig. 112). Almost all avalanches move with mixed motion; large blocks and particles tumble and bounce along the ground, and smaller particles are airborne.

A slab avalanche usually passes quickly through several types of motion as it attains its maximum velocity. After breaking loose from the starting zone, a snow slab accelerates down the track and very quickly splits into smaller blocks. Within a short distance, the blocks begin tumbling and colliding. If the track is extended and the motion continues, the blocks disaggregate into chunks and particles. The smallest particles are tossed into the air, forming a snow dust cloud. This results in mixed avalanche motion, with part of the snow flowing along the ground and part moving in a snow dust cloud.

It is thought that in large, mixed-motion avalanches the great majority of debris is transported close to the

[3]In this and other sections that deal with engineering aspects of avalanches, pressures are given in the more conventional units of metric tons per square meter (t/m²) rather than newtons per square meter. See appendix A for conversion factors.

Figure 112.—An airborne-powder avalanche shooting over a cliff in central Colorado. (Photos by Standley)
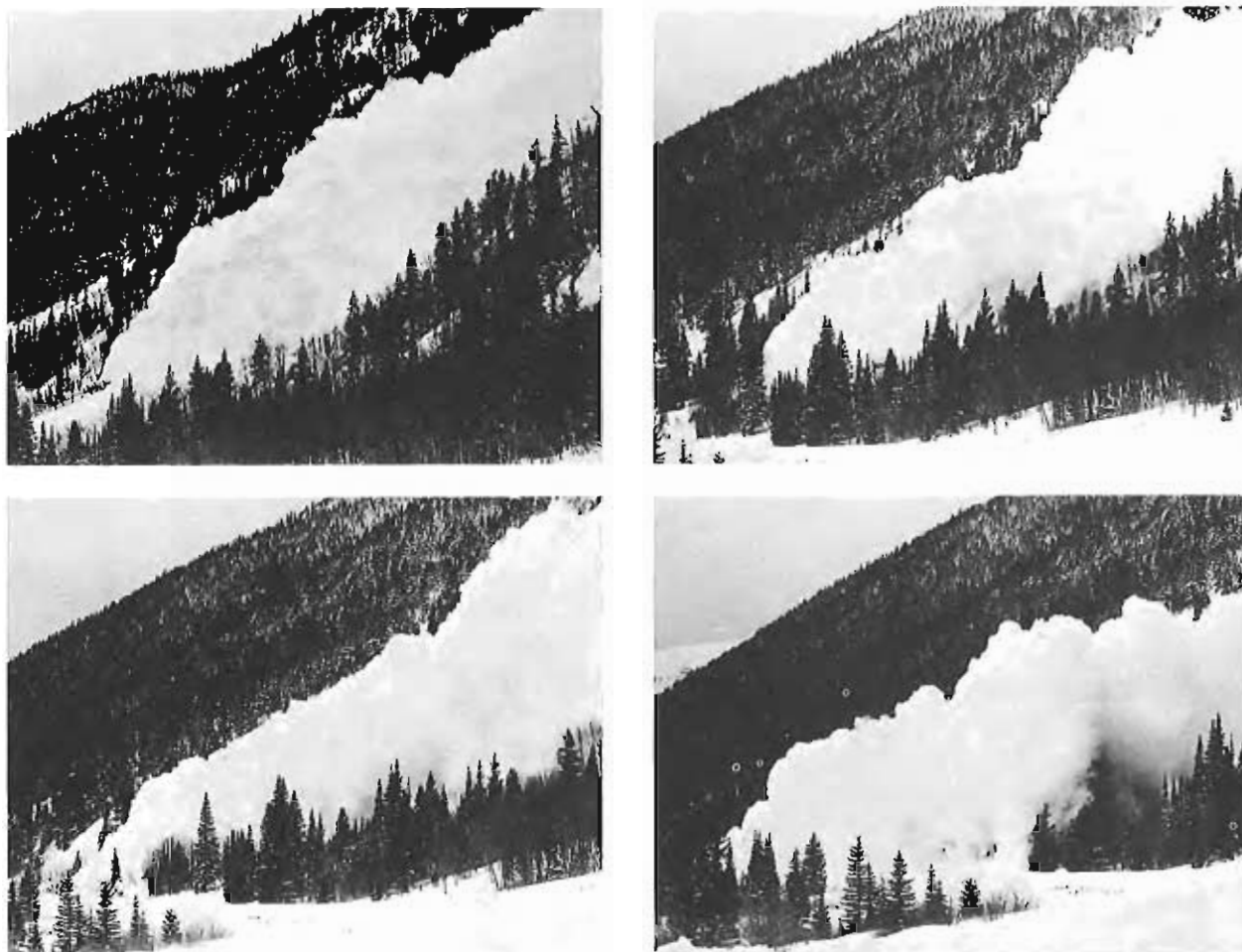
Figure 113.—The mixed type of avalanche motion is characterized by a prominent snow dust cloud. In this sequence, the snow dust cloud is about 40 m high and 150 m wide. One of the Jones Brothers Avalanche Paths, near Empire, Colo. (Photos by Cleveland)

snow surface. Debris drops out continuously. The avalanche continues undiminished as long as the snow in the track feeds the moving mass and replaces the debris that drops out. This condition is fulfilled when the track snow is relatively unconsolidated or of soft slab texture. Thus, in a sense, a moving avalanche is the result of successive failures connected by a common track. Under certain conditions, avalanches can run long distances over level terrain or up adverse grades (figs. 114 and 115). Extremely powerful avalanches like the Huascaran avalanches described in chapter 1 can run long distances even over bare ground. It must be remembered, however, they were largely avalanches of glacial ice, not seasonal snow.

If the snow density and the avalanche velocity are known, it is possible to compute approximate impact pressures, in kilograms per square meter, from the following simple relationships:

$$\text{Maximum impact pressure} = \rho V^2/g$$

$$\text{Mean impact pressure} = \rho V^2/2g$$

where

ρ is the snow density (kg/m^3)
g is the acceleration due to gravity ($9.8\ m/s^2$)
V is the speed of the avalanche (m/s).

It is not known how the density varies in a mature avalanche. One possibility is that close to the snow surface, the density is about that of the undisturbed track snow, perhaps 100 to 200 kg/m^3 or higher. It is thought that density falls off rapidly with height above the snow surface. At the upper boundary of the visible snow dust cloud, the density may be 10 kg/m^3 or less.

AVALANCHE PHENOMENA
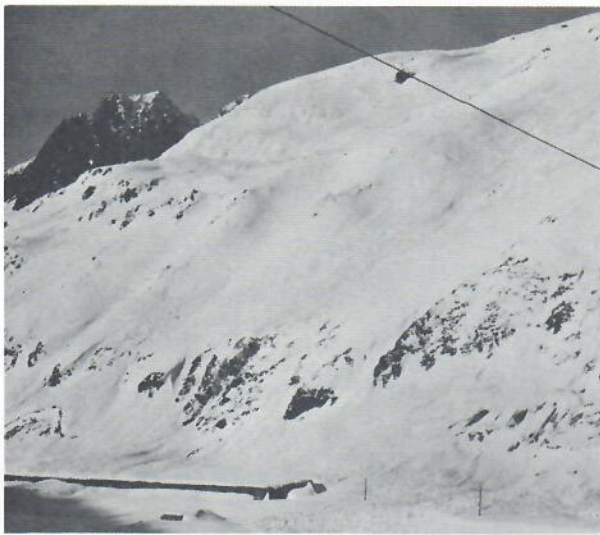
Figure 114.—This mixed-motion avalanche ran down the slope, over the roof of an avalanche shed, across a lake 150 m wide, and up the opposite slope near Oberalp Pass, Switzerland. (Photos by Frutiger)

Figure 115.—Large, wet, midwinter avalanches that ran for 450 m across the level Plains of Abraham on the east side of Mt. St. Helens, Wash. (Photo by Emetaz)

Avalanche velocities are also a matter of speculation; however, many have been clocked, and typical speeds seem to be in the range of 25 to 75 m/s. It is reported that avalanches have reached speeds up to 125 m/s. Observed speeds are higher than would be expected on the basis of a balance between the pull of gravity and frictional drag resistance of the snow surface and the air. It has been suggested that large avalanches adjust their shapes to minimize drag and that friction is minimized by an air-cushion effect. Probably other mechanisms also contribute to the high observed speeds.

Speeds in excess of 30 m/s are observed only for large, dry avalanches with well-developed snow dust clouds. If an avalanche is very wet, it moves along the snow surface as a slurry with little or no snow dust cloud. The speed of wet-snow avalanches is typically in the range of 5 to 30 m/s; the higher limit is approached only by very large, wet avalanches.

Using reasonable values for density and speed, it is possible to make simple calculations that demonstrate the enormous impact pressures of a moderate-sized avalanche. Consider an avalanche moving at

50 m/s with a density distribution that varies from 100 kg/m^3 at the snow surface to 10 kg/m^3 at the top of the snow dust cloud. For this hypothetical avalanche, the maximum impact pressure at the snow surface is about 25 t/m^2; impact pressure at the top of the snow dust cloud is about 2.5 t/m^2. From more detailed theoretical calculations, it appears that maximum impact pressures should be in the range of 5 to 50 t/m^2. These values have been confirmed by measurements on large avalanches and by inspection of damage to homes, railroad cars, concrete foundations, and other property. In one test on a very large and fast-moving avalanche, the maximum impact pressure exceeded 100 t/m^2 (Salm 1965). Table 3 gives a rough correlation between avalanche pressure and potential damage.

From the viewpoint of engineering design, avalanche impact pressures represent an extremely high external load; even concrete structures require substantial reinforcement.

Avalanches cause damage in several ways. First is the direct thrust of the avalanche, with impact pressures as given above. In addition, avalanches may

AVALANCHE PHENOMENA
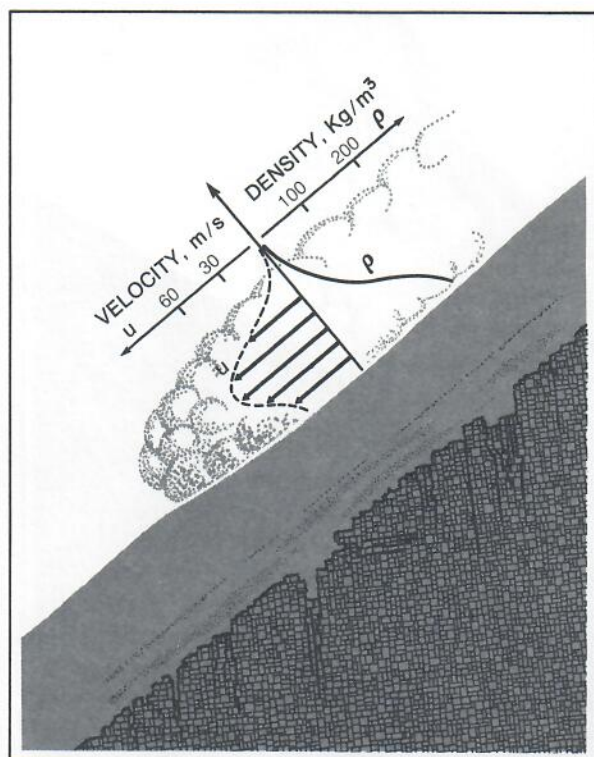
Figure 116.—Possible speed and density variations in the profile of a large mixed-motion avalanche.

TABLE 3.—*Correlation between impact pressure and potential damage*

Impact pressure (t/m^2)	Potential damage
0.1	Break windows
0.5	Push in doors
3	Destroy wood-frame structures
10	Uproot mature spruce
100	Move reinforced-concrete structures

exert upward and downward forces; they have been known to lift up and move large locomotives, road graders, and buildings. From field measurements and observations of damage, it appears that the upward and downward forces are about one-fourth to one-half the direct thrust. Thus, a large avalanche over-riding a structure could exert a vertical pressure of 25 t/m^2. Finally, the airblast of a fast-moving avalanche (speed in excess of 30 m/s) may exert pressures up to about 0.5 t/m^2. Although small compared to the main thrust of the moving snow, such pressures are capable of destroying doors, windows, and poorly designed roofs. There are also reports that the air-
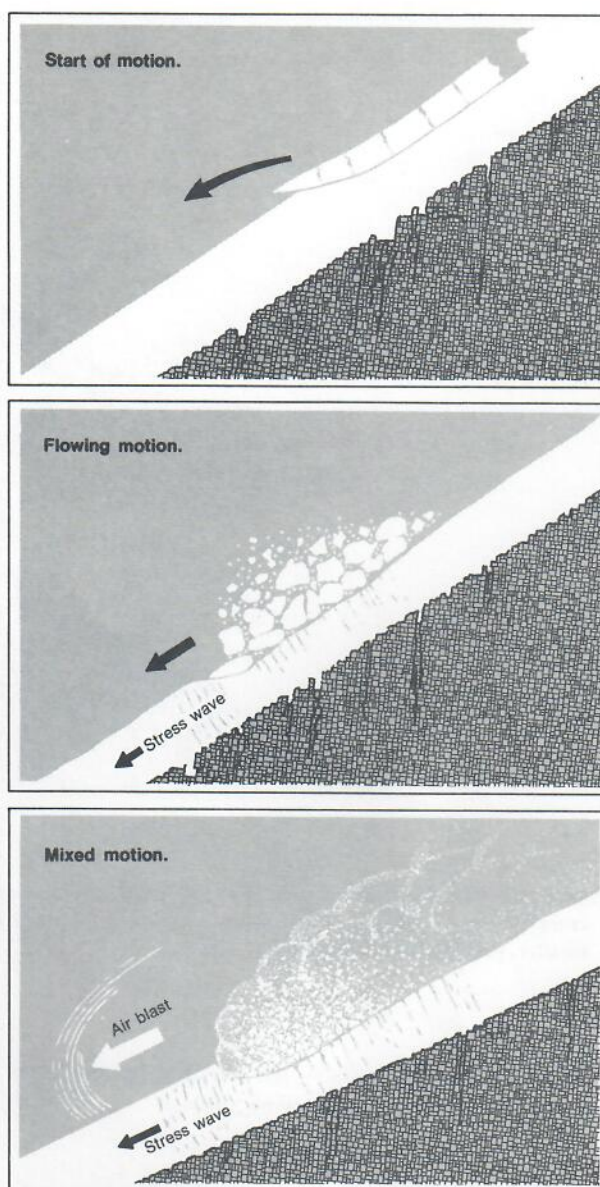
Figure 117.—A possible model for the buildup of a dry snow avalanche. The stress wave of the avalanche advances in the snow slightly ahead of the avalanche front. As the avalanche passes over, new mass is fed into the main body An airblast sometimes precedes the avalanches.

blast has induced lung injuries. The strongest airblast effects are confined to within 100 m of the observed boundary of the snow dust cloud. As a very rough rule, the extension of the airblast is about equal to the height of the snow dust cloud. Slow-moving wet avalanches that cling to the snow surface have no airblast.

Intuitively, it would seem that the impact pressure should be higher in channeled paths than in uncon-fined paths. Some data support this notion. Presum-
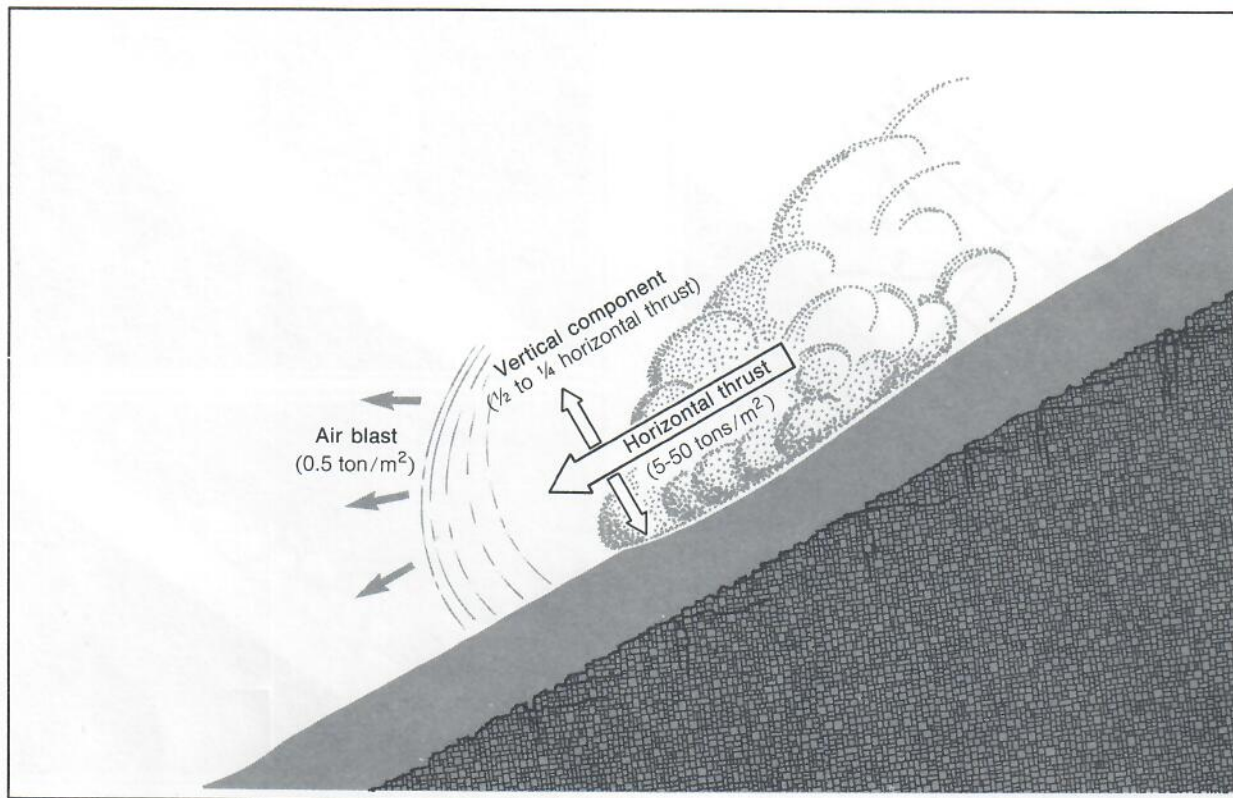
Figure 118.—The horizontal thrust of a large avalanche may cause impact pressures in the range of 5 to 50 t/m². Vertical impact components are typically one-fourth to one-half the magnitude of the horizontal components. Airblast pressures are much smaller, perhaps no higher than 0.5 t/m².

ably, the confining walls of the channel increase the speed and density of the flowing snow.

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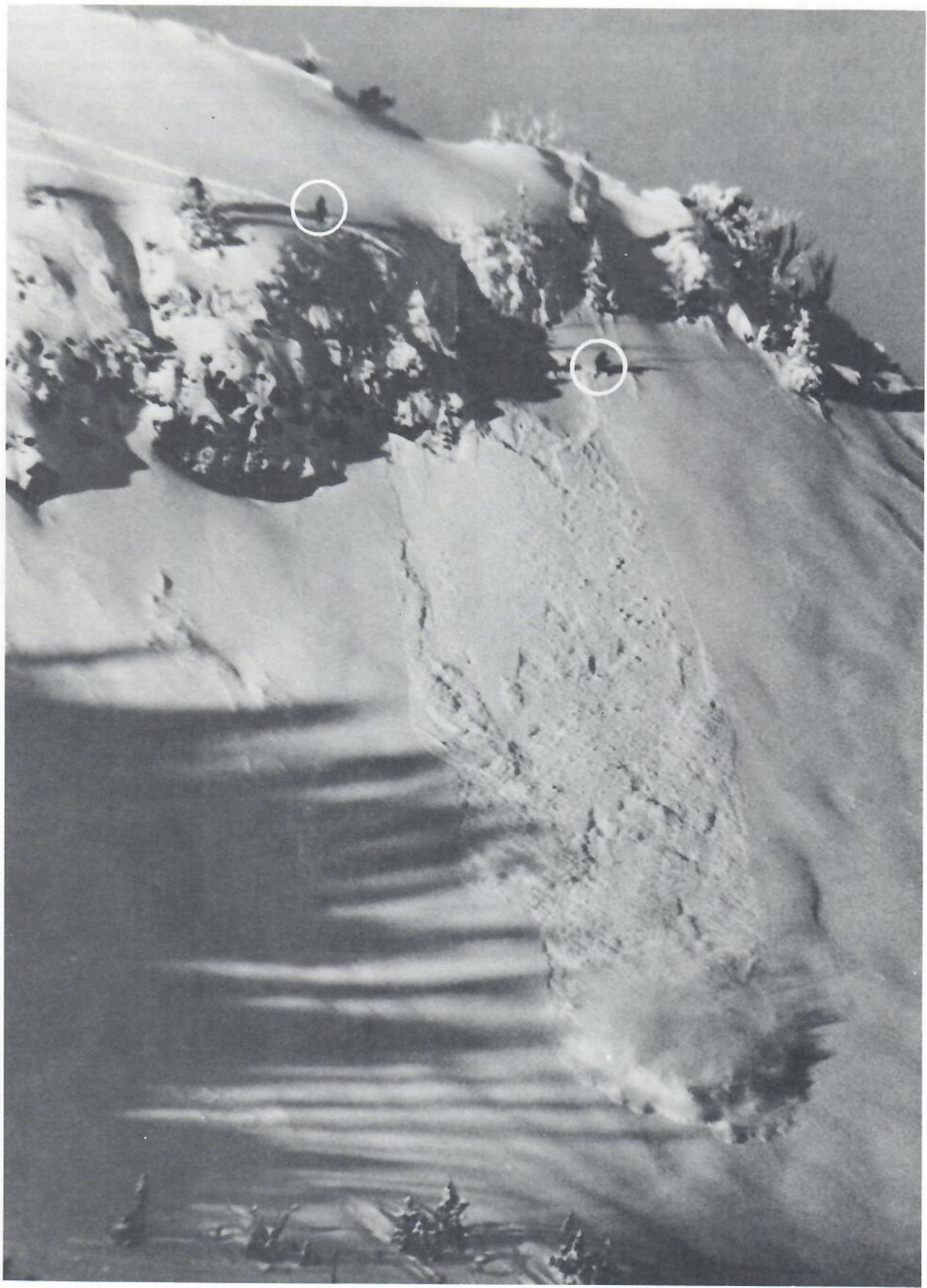
Stability
evaluation

*The previous three chapters concentrated on snow
and avalanche fundamentals. In this chapter, an
important application of fundamentals is discussed
—the forecasting of likely avalanche activity. This
evaluation of slope stability, with no reference to
hazards to humans and their facilities, is strictly a
geophysical problem and therefore is given the
technical name "stability evaluation."*

*Stability evaluations are based on six kinds of
"inputs," or categories of information. These
include quantitative meteorological measurements,
such as study-plot precipitation and ridgecrest
winds, as well as such qualitative observations as
test skiing and visual observations of avalanche
path loading.*

Figure 119.—Test skiing may be performed "belayed" or "free." Free
test skiing should be restricted to miniature or lightly loaded
slopes that involve minimum risks. If this slope had been more heavily
loaded, the skiers would have roped up or used explosives, or both.
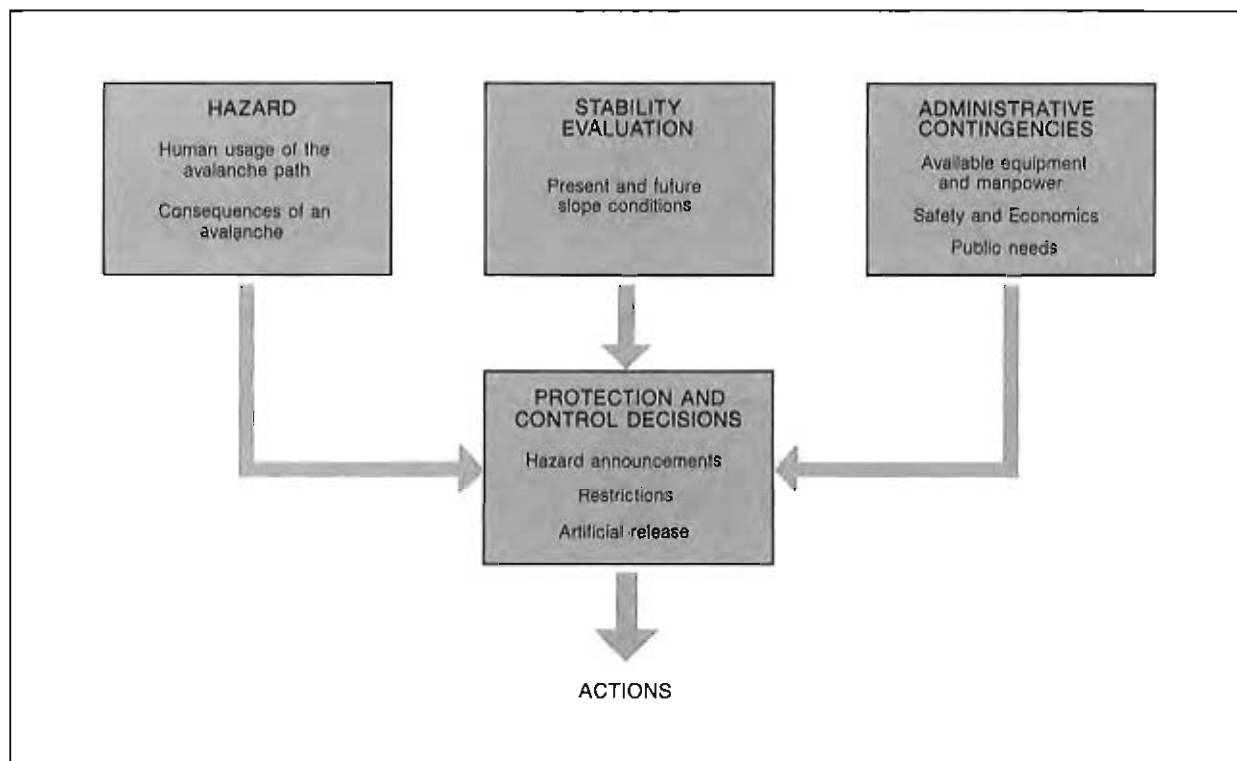
Figure 120.—Day-by-day decisions concerning avalanche protection and control are influenced by many complex factors. Stability evaluations play an important role.

The general problem

An estimate of the likelihood that avalanches will release in a given region and within a given time interval is called a *stability evaluation*. The region may be a single avalanche path or a group of paths. The time interval is measured from the present into the future. Usually, stability evaluations are made for the immediate future; that is, within several hours of the present. Occasionally, evaluations for longer times are required.

Stability evaluations influence decisions on whether or not to control the avalanches in the region and on what type of control or protection is appropriate. They also determine when avalanche warnings should be issued. To understand the role of stability evaluation in decisionmaking, it helps to consider briefly two very different avalanche problems; the first concerns ski areas, and the second has to do with highways.

In developed ski areas, small as well as large paths contribute to the avalanche hazard. Because of the large number of skiers on the slopes, any instability is very likely to be triggered. It is also highly probable that an avalanche triggered by one skier will sweep into another. Finally, there is a high likelihood that the encounter of a skier with even a small avalanche will result in a serious accident.

A simple mathematical notion connects all these probabilities; if an event depends on several independent preliminary actions, then the probability of that event is equal to the products of the probabilities of the preliminary actions. Consider a case in which stability evaluation indicates that there is one chance in 100 (or a probability of 1/100) that a particular slope is unstable enough to be released by a skier. Next suppose that it is certain (or 1/1) that a skier will cross the slope during the day. Moreover, there is one chance in two (or 1/2) that a skier can be found in this potential avalanche path at any time during the day. For this situation the probability of a serious accident is (1/100) × (1/1) × (1/2), or (1/200). Although this is a small probability, it is significant and cannot be ignored. In practice, one does not indulge in probability calculations, but the point is clear: *Any suspected instability in a ski area entails a risk that should motivate some sort of hazard control or protective action.*
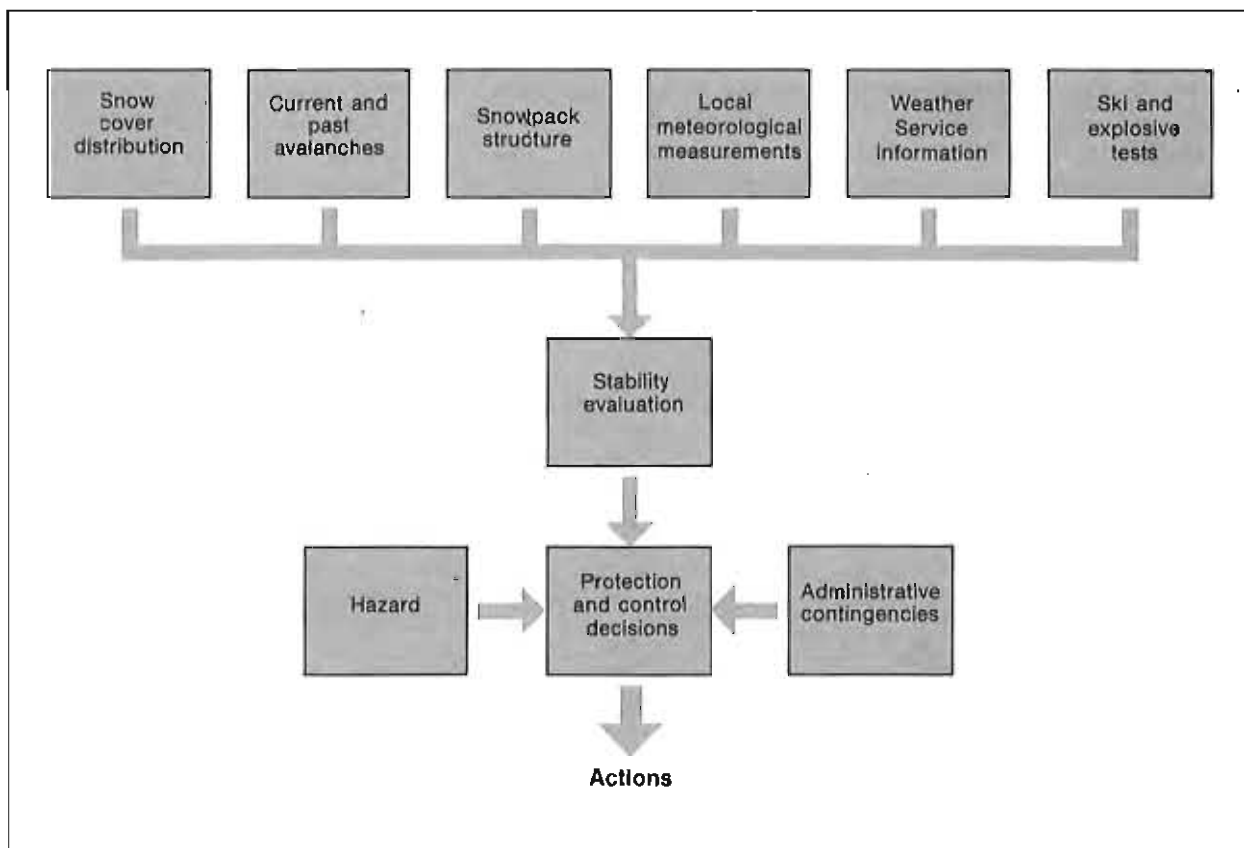
Figure 121.—Stability evaluations are based on six kinds of inputs. Current avalanche events greatly influence the evaluations.

Highway problems may allow a little more leeway in accepting risk. Consider the hypothetical evaluation that gives a 1/100 chance that a given slope will be triggered naturally and avalanche across a highway in the next 8 hours. In that 8 hours, suppose traffic will be under the path in question 1/100 of the time. For this situation, the probability of a serious accident is 1/10,000. Here it may be quite reasonable to chance the accident, leave the highway open to traffic (or at least to supervised convoys), and wait for an opportune time to take action. (Chapters 6 and 7 describe *avalanche control*.)

The above figures are fictitious, but they demonstrate that decisions about protective and control actions must be based on stability evaluation of the slopes plus analysis of human problems. Although the stability evaluation is not the sole determiner of the protective decision, the more precise the stability evaluation, the sounder the decision. This chapter discusses methods for evaluating slope stability. The more complex problem of making protective decisions for ski areas and highways is discussed in later chapters.

Broadly speaking, stability evaluations are based on six kinds of input:

- Snow-cover distribution
- Current and past avalanches
- Snowpack structure
- Local meteorological measurements
- National Weather Service information
- Ski and explosive tests.

Several of these inputs require a close liaison between the control team and the person who makes the evaluation. *The most precise stability evaluation for a slope must be based on knowledge of recent avalanche activity on nearby slopes.* For this reason, the stability evaluation and the control work are generally performed either by the same team or by teams working in close cooperation. Often stability evaluation and control work are so interlinked that the boundary is not clear. This interlinking is a unique feature of avalanche technology, in contrast to the forecasting and control of wildfires, earthquakes, and other natural hazards.

How are the above six kinds of inputs converted into a stability evaluation? Generally, working systems in mountain ranges around the world follow similar lines. A team of experienced workers studies the inputs, issues broad directives about the likelihood of instability, and in most instances supervises control work. These systems rely almost entirely on human judgment, and they obviously depend critically on the competence of the team. Many other decision systems follow impersonal "cookbook" formulas, but replacement of even small parts of the customary subjectivity in stability evaluation remains a research topic. Moreover, teams are structured like trade guilds; a "master" hands down his skills to "apprentices," often chosen more for mountaineering and administrative talents than for formal scientific training.

In the next sections, it will be shown how each input contributes to the overall picture. Although the inputs will be discussed separately, the reader should keep in mind that in practice the separate inputs are not considered separately but instead are integrated and weighted subjectively to form a single judgment.

Snow-cover distribution and avalanche activity

This section concerns the first two inputs; namely, (1) snow-cover distribution and (2) current and past avalanches. For the most part, these are simple, visual observations, but they form the basis of the most reliable stability evaluations.

Snow-cover distribution is determined by *direct visual observation* of whether an avalanche path is filled with snow and primed for release. To begin

with, significant avalanches cannot occur on a path until, first, terrain irregularities such as boulders and brush are covered with snow, and then additional snow is deposited on this smoothed foundation. For most paths, this requires about 1 m of snow in the starting zone and track. The exceptions are paths on permanent snowfields, smooth rock, dirt, grass, etc., where avalanches may run with perhaps 15 cm of coverage in the starting zone.

Normally, the beginning of the avalanche season on a particular slope can be anticipated from visual observations of snow-cover amount and distribution and conditions in the starting zone and track. If visual observations cannot be made, it may be helpful to correlate statistically the earliest significant avalanche on a given path with snow depth at an accessible study plot. An example of such a correlation is given in table 4. Many years of historical data are required for the correlation, which still must be used with a large safety factor.

After the beginning of the avalanche season, direct observation continues to provide the most reliable information on snow buildup in the starting zones. For ski areas, direct observations include watching the wind-deposition patterns and field checking the starting zones. During operating hours, it is essential to keep track of new snow buildup in or near the avalanche paths in the area. Generally, 15 to 30 cm of new snow in the starting zone can be considered significant and worthy of further investigation. Observation of snow loading in large avalanche paths above highways or villages may not be possible during critical periods. Here, direct observation may be limited to occasional inspections from a distance during temporary clearing of the weather.

TABLE 4.—*Study-plot snow depth (cm) at time of earliest avalanche onto Little Cottonwood Road, Utah*

Season	Depth	Season	Depth
1950–51	244	1960–61	198
1951–52	158	1961–62	183
1952–53	145	1962–63	203
1953–54	132	1963–64	208
1954–55	256	1964–65	206
1955–56	216	1965–66	191
1956–57	259	1966–67	132
1957–58	256	1967–68	132
1958–59	137	1968–69	218
1959–60	226	1969–70	165

Note: There has never been an avalanche to the road with less than 132 cm of snow in the study plot.

Figure 122.—Avalanche release on slopes of common aspect. All areas between avalanches are suspect.

After avalanches empty out a starting zone, direct observations provide information on when the zone is reprimed with new snow. The old crown surface is an excellent natural snow stake.

In ski areas, where some avalanche paths may also be ski runs, the amount of ski compaction on the path in question is important. Lightly skied slopes are far more unstable than heavily skied slopes. Moguled slopes are virtually immune to avalanches, except during very wet or slushy conditions, and rarely as a dry slab on depth hoar.

The second input, "observations of current and past avalanches," includes the following:

Observation of slopes with common aspect. Because loading is sensitive to wind direction, avalanches tend to occur on slopes that have a common aspect. For example, after a storm, it may be noticed that avalanche activity was most intense on southeast-facing slopes. All southeast-facing slopes that did not avalanche during the storm should then be suspected of instability.

Observation of slopes with common elevation. Similarly, in an area that has a wide range of starting-zone elevations, it may be observed that avalanche activity is confined to particular elevation zones. For example, the higher zones may be relatively inactive, but serious instability may exist at lower elevations. This phenomenon is usually caused by wind or temperature patterns.

Frequent and infrequent paths. This observation is most applicable to large avalanche paths that threaten highways and villages. Based on historical data, avalanche paths can be classified according to frequency. It is accepted practice to defer evaluation of infrequent paths until the stability conditions of the more frequent paths are known. If frequent paths are moderately unstable, then instability can be expected on the infrequent paths. Conversely, if the frequent paths are stable, it is usually possible to evaluate as stable the infrequent paths.

Thaw warnings. Small, wet avalanches of either the loose-snow or slab type often give ample warning that free water is accumulating in the thawed snowpack. Wet avalanches of increasing size can be expected.

Repeaters. Statistical evidence shows that once an avalanche path is activated, there is a good chance it will be reactivated later in the season. Many avalanche paths that are not active every avalanche season tend to run more than once in seasons when they are active. There is some evidence that the second avalanche on a path is usually larger than the first.

Sluffing. The remarks made on sluffing in chapter 4 under "Failure of Snow Slopes" should be recalled. Visual observation may indicate that conditions were highly unstable during a storm and that small avalanches released to remove the instability. These avalanches may be partly obscured by additional snowfall.

Snow-cover distribution and avalanche activity

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Figure 123.—Sluffing activity covered up by fresh snow. Parts of these slopes self-stabilized during the storm. (Photo by LaChapelle)

Snowpack structure

During storms, observers are occupied with keeping track of storm parameters, conditions of the newly fallen snow, and the increased avalanche activity that comes with heavy precipitation. Between storms it is possible for them to investigate the condition of the deeper snowpack.

Diagnosis of snowpack structure involves searching for weak layers. Some kinds of weak layers that are definitely correlated with instability are those that contain TG grains; loose, cold snow; surface hoar; graupel; radiation-recrystallized grains; or wet snow. Although a hard crust cannot be considered a weakness, there is much evidence that instability is greatly intensified when any of these weak layers is immediately above or beneath a firm crust (fig. 124). Methods of analyzing pits for weak layers are described in chapter 3 under "Snowpack Analysis." It is worth reemphasizing that digging pits near the avalanche release points is the only reliable and efficient way to locate significant weak layers. The farther the pits are from the avalanche release points, the less reliable the pit information.

TG-metamorphosed grains. An explanation of TG metamorphism was given in chapter 3. Weak TG grains are considered the most obvious clue that the snowpack is potentially unstable. Thick TG layers stand out from ET layers in the pitwalls and are easily identified. The importance of TG metamorphism in stability evaluation cannot be overemphasized. Instability is most apt to exist where metamorphism has advanced toward weak, large, depth-hoar grains.

When weak TG layers have been identified, the following should be kept in mind:

• The probability of deep slab instability is many times greater on slopes that have depth hoar than on those that have an ET structure throughout.

• Although instability is most likely to be triggered during or immediately after storms, slopes with weak TG layers remain unstable for long periods between storms. Instability can be triggered at almost any time.

• The first storm that deposits snow on a TG layer may not produce avalanches. This should not give

STABILITY EVALUATION
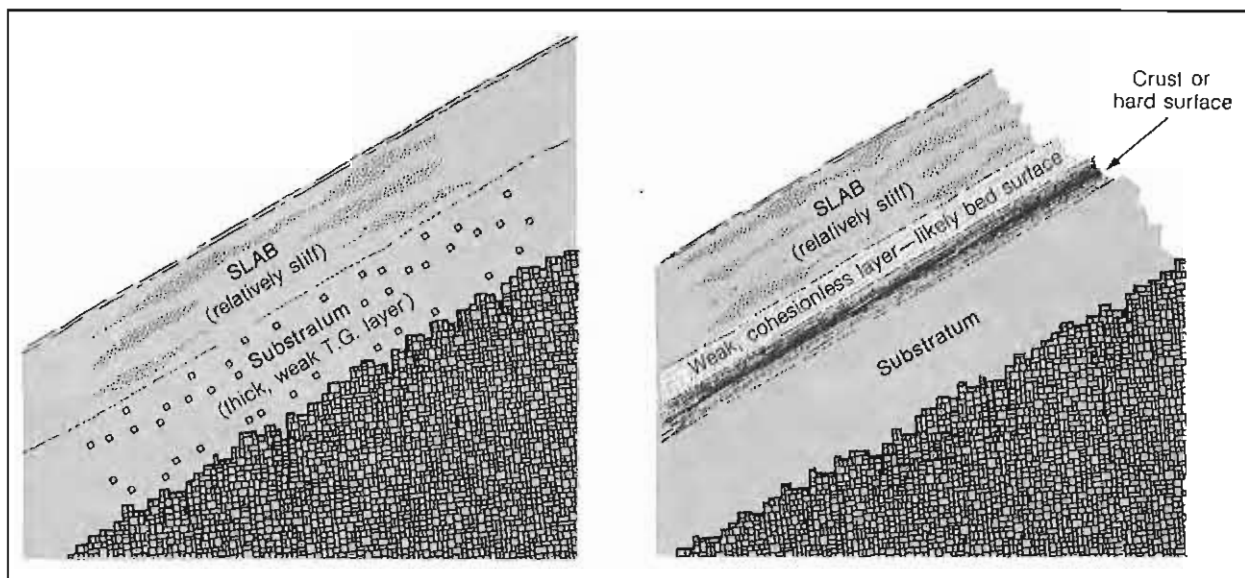
Figure 124.—Investigation of snowpack structure near the starting zones is an important input. Generally, one looks for both thick and thin weak layers. A thick, weak TG layer is the most obvious clue of potential structural instability. A thin, weak layer sandwiched between a stiff slab and a crust is also highly unstable, but this combination is difficult to detect in practice.

observers a false sense of security. Two or more storms may be required to build a slab on the TG substratum.

• Slopes with weak TG layers do not always respond immediately to explosive control (see chapter 6, "Use of Explosives"). Instability is sometimes triggered several hours after avalanche control.

• If a slab is removed down to the TG substratum, TG metamorphism normally continues in the thinned snowpack, and instability reappears and sometimes intensifies.

• Instability remains until the TG grains are sintered under the pressure of a thick snowpack or until MF metamorphism dominates. Normally, TG instability is most acute during December and January and begins to diminish in February. Strengthening of the TG layers usually occurs by early March.

• After TG layers are strengthened, instability may reappear in spring because of melting of the bonds (thaw instability). Full-depth avalanches have run on layers of wet TG grains.

These seven points make it clear that the evaluation must show potential instability when TG layers are prevalent. The situation becomes especially critical in a ski area or along a ski-tour route where localized patches of TG grains produce small but dangerous slab avalanches. Stability varies remarkably from sea-son to season, depending on the weakness and extent of TG layers.

Loose, cold snow. If the snow surface is maintained at a low temperature for a long period after a storm and the surface snow is relatively loose and cohesionless, there is a good chance that any new snow may not bond well to the loose, cold surface. Typically, potential instability is acute after air temperatures have remained below about $-15°$ C for several days and the new storm brings in at least moderate amounts of precipitation before the old snow surface has a chance to warm up significantly. Extreme instability can be expected when the old surface is a cold crust and the first few centimeters of new snow consist of very cold, cohesionless grains.

Surface hoar. Surface hoar growth was described in chapter 2 under "Heat Exchange at the Snow Surface." Uncompressed layers of surface hoar are extremely weak. It is therefore not surprising that widespread coverage of a slope by surface hoar leads to instability. Surface hoar layers must be detected while they are still on the surface, before they are buried and compressed. Once buried, they are almost impossible to identify. It appears that in many cases, surface hoar instability is relatively short lived, lasting for only one or two storms.

Graupel. (See "Snow Crystals" in chapter 2.) Graupel is easily observed in snowpits. This type of

grain is known to cause instability; however, for some unclear reasons, graupel does not cause the intense instability that would be expected on the basis of its weak structure in snowpit walls. Graupel seems mainly to induce slab avalanches of one storm thickness. It appears that few deep slab avalanches have released on graupel bed surfaces.

Radiation-recrystallized grains. These grains are caused by a rather peculiar radiation phenomenon that occurs only rarely during the avalanche season and then only at high altitudes on south-facing slopes in late winter. On clear, dry days, an intense temperature gradient may be established between the snow surface, cooled by terrestrial radiation loss, and the sublayer, warmed by penetrating solar radiation. This produces a weak layer of recrystallized grains resembling depth hoar and, generally, an underlying ice crust.

Wet snow. In practice, wet snow instability is evaluated more from meteorological data than from snowpits. Snowpits are useful in determining when the temperature of a large part of the snowpack reaches 0° C and therefore approximately when the snowpack is susceptible to thaw. Snowpits are also useful in evaluating the amount of free water remaining in the pack after a rainstorm.

Ice crusts are potential glide surfaces. The closer ice crusts are to the snow surface, where free water is produced, the greater the possibility that the free water can dissolve the bonds between ice and slab. Deeply buried ice crusts are usually not a problem.

Figure 125.—A glide crack between two wet snow avalanches. (Photo by Frutiger)

Slowly opening tensile cracks may sometimes be observed when a wet slab is gliding along a wet, lubricated surface. Most glide cracks that open early in the season (November through January) do not develop into dangerous slabs. Glide cracks later in the season are more likely to become unstable, but the process is slow enough to provide ample warning.

Local meteorological data

Field observations of snow buildup on or near avalanche release areas are often not feasible. When conditions are especially critical it is rarely possible to tour to the release zones of high-elevation paths that threaten highways and villages. Even in ski areas, field observations of avalanche paths are limited to daylight hours. It is therefore necessary to rely heavily on meteorological measurements.

As discussed in chapter 2 under "Storm Analysis," indirect evidence of avalanche path loading can be inferred from study-plot precipitation measurements and ridgetop wind measurements. From chapter 3, recall that the requirement for catastrophic snow failure is rapid loading to some critical value. Thus, the basic problem in making stability evaluations from meteorological measurements is to infer from the study-plot and ridgetop data whether the rate of loading and total load are approaching critical values in the avalanche paths in question. The simplest way to use the numerical data furnished by instruments is to identify, for each path or group of paths, the following critical conditions:

(1) Wind directions that load the paths in question (for example, winds from southwest to northwest)

(2) Windspeed required for lee-slope loading (usually above 5 m/s)

(3) Critical precipitation intensity (for example, 2 mm/h)

(4) Critical total water equivalent (for example, 20 mm).

Each storm is then monitored and analyzed. The slopes in question are evaluated as unstable when the four critical conditions just mentioned are satisfied simultaneously. An example of this kind of analysis for the storm plot of figure 54 is shown in the example below. The critical values of the four conditions for each path or group of paths are derived from at least 3 to 5 years of records of meteorological measurements and avalanche conditions. New data are used

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continually to improve the choice of critical conditions. Thus, the success of the above method depends on keeping careful records of meteorological and avalanche observations. For avalanche problems in general the importance of good records cannot be overemphasized.

For example, suppose historical data indicate that a group of east-facing slopes that affect a highway becomes unstable when the following conditions are satisfied simultaneously: wind direction $270° \pm 60°$, windspeed above 5 m/s, precipitation intensity 2 mm/h, and total water equivalent 20 mm.

The storm plotted in figure 54 would then be analyzed as follows in terms of water equivalent of precipitation, wind direction, windspeed, and air temperature:

From 0700 to 1600, January 24. Winds are approximately critical, but the precipitation intensity of 1.1 mm/h is below critical. Instability is only gradually increasing (explosive control may be premature).

From 1600, January 24, to 0400, January 25. Winds are critical, precipitation intensity is above critical at 2.5 mm/h, and the total water equivalent deposited at the critical rate exceeds 20 mm. A high level of instability is reached (explosive control should be effective during the early morning of January 25).

From 0400, January 25, to end of storm. All factors, except accumulated water equivalent, are less than critical. Instability is beginning to decrease.

Critical conditions (*3*) and (*4*) can be modified to account for snowpack structure. If the snowpack is known to have a weak structure, the critical values of precipitation intensity and total water equivalent can be reduced. Similarly, if the snowpack has a relatively strong structure, it is possible to use increased critical values. However, even with these corrections, there will be a great amount of uncertainty in the evaluation, and the analysis must be interpreted cautiously in making control decisions. For ski areas, where a stability evaluation error could be disastrous, a large safety factor is required, and the above analysis may be of less practical use. For highways, where slight error is less dangerous, the above method, or even a more complex one, may be useful. Also, as a general rule, the larger the starting zones of the paths in question, the more applicable a numerical analysis of the simultaneous effects of precipitation and wind. A numerical technique for issuing "extreme hazard" warnings for large areas is given in chapter 7.

For small paths, normally a threat in ski areas and on back-country tour routes, critical loading due to wind transport is always possible regardless of study-plot precipitation measurements. Thus, it is worthwhile to monitor ridgetop windspeed and direction continually. Wind redistribution is greatest for a few days after a new snowfall, but transport may occur as long as the surface snow remains uncrusted.

Meteorological measurements are useful for evaluating wet snow instability. The important variables to monitor, at least qualitatively, are rainfall, radiation, and air temperature. Heavy rain causes wet snow instability by adding weight, decreasing cohesion in the surface layers, and lubricating a potential bed surface. The amount of rain required for instability depends on the temperature of the top layers of the snowpack. If these layers are near 0° C before the rain, then relatively little rain can cause avalanches. Cold snowpacks have a high capacity for absorbing rain.

Wet snow instability is most likely during the first warmup (thaw) after a heavy snowfall. Wet snow instability should be expected after late spring and summer snowstorms. The delay between the end of the storm and the thaw can be estimated from the air temperature. If the air remained cold during the storm and then climbed slowly afterwards, instability may be delayed for several days. Air temperatures at high elevations can be estimated most of the time by subtracting 6° C per 1,000 m of elevation above the elevation at which measurements are taken. Wet snow instability is most intense from midafternoon, shortly after solar radiation reaches its peak. Melting is at first delayed, since the *heat of fusion* (80 calories per gram of ice) must be supplied. Once melting begins, the process accelerates because wet snow absorbs far more solar radiation than dry snow, and the onset of wet snow instability may seem to come rather rapidly. Similarly, wet snow instability may persist into late afternoon, until the melt water releases its heat of fusion (again, 80 calories per gram).

Usually, wet snow instability is confined to the most recently deposited layers, to a depth of about 1 m. Prolonged thawing occasionally triggers deeper or even full-depth slabs. These deep, wet slabs may release almost any time during a prolonged thaw.

Several other meteorological features may influence stability evaluation. Humidity, air-temperature trends during a storm, and the form of the new snow crystals have been proposed.
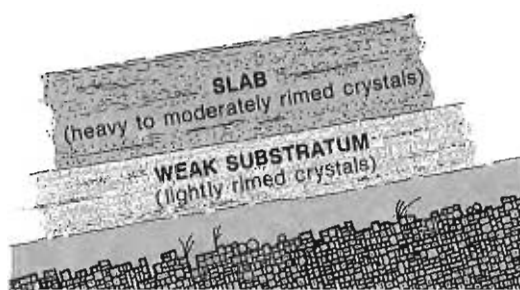
Figure 126.—New snow instability is usually a result of a heavy, stiff layer deposited on a light, weak layer. This pattern may be caused by changes in temperature, snow-crystal form, and wind.

Humidity could be important because of two different effects. First, it controls how far a windblown snow grain can travel before sublimating. When relative humidity is high, wind transport of snow is more effective. When the air is dry, large amounts of blowing snow sublimate and never reach the lee slopes. High humidity is also thought to promote a slablike texture in deposited snow and therefore a more fracture-sensitive structure. This second possibility has not been substantiated.

Air-temperature trends are known to correlate with slab stability. Rising air temperature during a storm is considered an unstable trend, presumably because heavy snow is being deposited on lighter snow. Falling air temperature is considered a stable trend. In the north temperate zone, temperatures normally fall at the end of a storm, but when one storm follows on the tail of another, it is possible that some precipitation could fall at cold temperatures, and then the bulk of the precipitation could follow during the warmer temperatures of the next storm.

Many avalanche workers believe that stability is influenced by the form of the new snow crystals. In particular, it has been suggested that instability increases with riming. Of course, heavily rimed crystals are deposited as layers that have a high water equivalent, so it is not clear how much of the observed instability is due to high water equivalent and how much to snow-crystal form.

It is possible to generalize the effects that humidity, temperature, and crystal form have on the stability of new snow. The unstable pattern seems to be a relatively heavy or strong layer over a relatively light or weak layer. This pattern might be generated by:

- Rising temperatures during a storm

- Lightly rimed or rime-free crystals falling early in the storm, followed by a thick layer of heavily rimed crystals

- Initial deposition during light winds, followed by rising winds toward the end of the storm.

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Finally, it must be emphasized that humidity, temperature, wind, and the form of snow crystals are at best secondary compared to precipitation and its transport. The glaring fact is that 90 percent of all avalanche activity occurs during or shortly after storms. Regardless of secondary influences, the probability of instability on a given path rises rapidly as the path is loaded with snow.

National Weather Service data

The National Weather Service may assist avalanche workers by providing data on winds, temperature, and humidity at upper levels; short-term forecasts to guide immediate control decisions; and extended forecasts for operation planning.

The National Weather Service releases balloons from major weather stations twice a day. These balloons are released simultaneously all over the world at Greenwich Time 0000 Z and 1200 Z. The corresponding Rocky Mountain and Pacific Standard times of release can be found from table 5. About 2 hours after balloon release, weather stations may be contacted for upper-air data. Normally, avalanche workers in the Rockies and Sierras should be interested in data taken between the 700-mb and 500-mb levels (see fig. 10). For the Cascades, the band of interest would be mainly between 850 mb and 700 mb. The balloon data of most use in avalanche work are windspeed, wind direction, temperature, and dewpoint.

Balloon wind data supplement local measurements for estimating the avalanche path loading in a large region. When local wind instruments are rendered inoperative by rime, lightning, or some other cause, balloon wind measurements must be used as backup. Balloon temperature data for the same elevation as the starting zones give a reasonable estimate for air temperatures near the ground in the starting zones.

Some avalanche-threatened areas in the Cascades and Wasatch Mountains are immediately downstream from balloon release points. Balloons occasionally fly directly over these areas and transmit accurate ridge-top information. Where avalanche stations are not favorably located with respect to release points, it may be necessary to interpolate data from surrounding release points. For example, upper winds near Aspen, Colo., can be inferred by interpolating Grand Junction and Denver measurements.

It is a relatively easy task for Weather Service personnel to give the raw balloon data to avalanche workers. However, interpreting the data and issuing forecasts for specific avalanche areas require some effort and time on the part of the Weather Service and a reciprocal effort by avalanche workers.

It is easy to understand that interpretations and forecasts of small-scale or local weather are imprecise. Forecasting mountain weather is especially complex. Nevertheless, with existing physical models, reporting networks, and experience, weather forecasters usually do a creditable job of predicting air temperatures, windspeeds and directions, and the likelihood of precipitation. Forecasters still have trouble, however, determining the amount of precipitation for mountainous areas. Good communications between the field and the forecast center, especially during storm periods, help forecasters to adjust precipitation forecasts and, in the long run, to improve their forecasting skills.

How is this communication established? First, working through appropriate channels, avalanche workers must find out which weather center is in a position to issue special forecasts and to exchange information on a personal basis. A preseason meeting is then set up between avalanche workers and the meteorologist-in-charge of the chosen station. A plan for exchanging information is developed; it will no doubt have to be renewed and improved each year. Routine communication can be by telephone, radio, or teletype. A direct telephone link into the forecast center poses the fewest operational problems. Unlisted telephone numbers, which ensure prompt service, can be obtained if avalanche workers explain to the meteorologist-in-charge the need for this special service. It may help for Weather Service personnel to visit the avalanche workers' area, and avalanche workers may benefit from an inspection of the weather center.

Generally, the communication plan should provide for a morning exchange of routine information and supplementary exchanges during emergencies.

Morning exchange. Each morning, at a set time after balloon data are available, an avalanche worker should phone the Weather Service. He should furnish the Weather Service with local weather informa-

TABLE 5.—*Release times of weather service balloons*

	Greenwich Time 1200 Z	Greenwich Time 0000 Z
Mountain Standard	5 a.m.	5 p.m.
Pacific Standard	4 a.m.	4 p.m.

Note: 0000 Z is 1 day ahead of continental U.S. time. Thus, 0000 Z on December 12 is equivalent to 5 p.m. December 11 Mountain Standard Time.

tion, following a format set up in the preseason meeting. The following kinds of local information may be useful to the forecaster:

- Present state of the weather
- Present precipitation rate
- Cloud cover
- Present temperature
- Dewpoint
- Local windspeed and direction
- Maximum and minimum temperatures during the previous 24 hours
- Precipitation during the past 24 hours
- Observed freezing level
- Evidence of front passage or other special weather phenomena
- Other information that could be communicated by the Weather Service to the public; for example, highway conditions, avalanche warnings, etc.

In return, the Weather Service may supply some or all of the following information to the avalanche worker:

- 1200 Z and 0000 Z upper-air data
- Maximum and minimum forecast temperatures for the next 24 hours
- Expected amount of precipitation in the next 24 hours and expected times of precipitation surges
- Trends in ridgetop windspeeds and directions
- Freezing level
- Cloud cover
- Extended forecast of general weather for the next 2 days, 3 days, and 7 days.

Emergency supplements. Arrangements should be made for additional communication during critical periods. There are times during the day when the Weather Service staff is loaded down preparing and issuing general public bulletins. Requests for supplementary information should be made at other times. The avalanche worker should first give his local measurements. The forecaster can then give a revised forecast. How well the forecaster can pinpoint precipitation surges or lulls may depend on his experience and knowledge of local effects. Weather stations often have personnel with special interests in mountain weather, avalanches, skiing, etc. Avalanche workers should learn who these people are and work with them during critical periods.

Ski and explosive tests

The stability of new snow layers is most conveniently determined by test skiing relatively steep slopes and simply observing the behavior of the snow under and around the skis. Test skiing is conceptually simple and plays a very important role in stability evaluation. Skis have two advantages over other mechanical testing gadgets. First, skis test a large sample of snow quickly and efficiently; this is important since the snowpack varies greatly from point to point. Second, they submit the snow to a realistic test of fracture toughness. However, certain limitations of ski tests must be noted:

- Ski tests involve some risk and require strict safety precautions. They cannot be used where the skier may be exposed to the severe forces of large moving slabs.
- Although ski tests are the most reliable way to measure the stability of surface layers, they do not give a reliable measure of hard-slab conditions nor of deep instability.
- Ski tests (or, for that matter, and mechanical test) cannot be used on remote slopes.

Performing and interpreting tests are skills that are developed by experience; there are no quantitative guidelines. Ski tests can be made "belayed" or "free." In belayed skiing, the tester is tied to a rope that is anchored to a secure point, such as a tree or lift tower. In free test skiing, the tester moves across the slope without the protection of a rope. The following safety precautions apply:

(1) All test skiing on avalanche paths should be observed by a second person.

(2) Test skiing parties should carry electronic transceivers and collapsible probes (see chapter 8 for an explanation of rescue devices).

(3) Free test skiing should be strictly limited to those slopes where an avalanche ride could not have serious consequences.

(4) Test skiers should never enter a dangerous slope unbelayed on the assumption that they can ski across the slope fast enough to avoid being trapped.

(5) Before entering the slope, the tester should have his transceiver in the transmit position. It is recommended that the transceiver be turned on when the tester gathers his equipment in the morning and left on all day.

(6) For belayed test skiing, 11-mm mountaineering rope should be used. The tester should be tied in
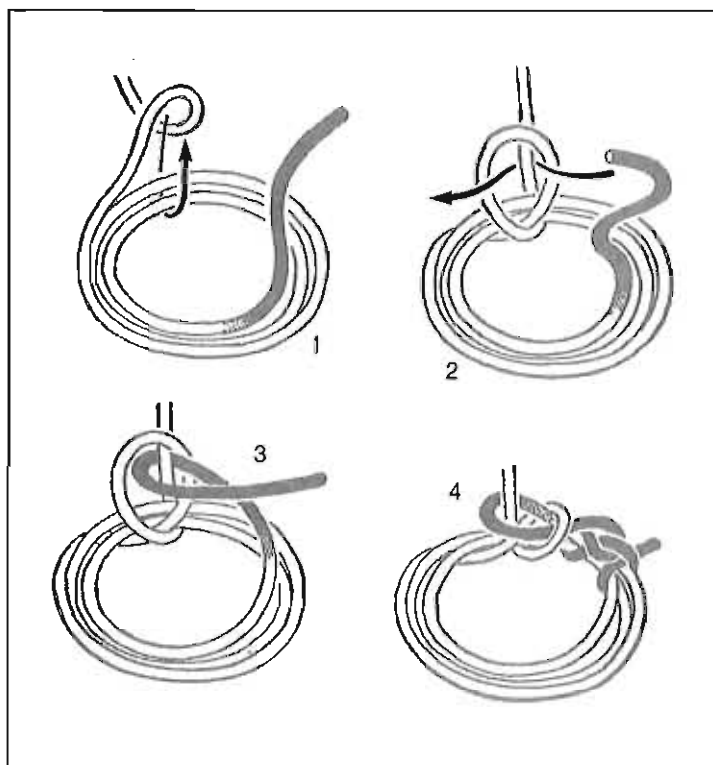
Figure 127.—In belayed skiing, one end of an 11-mm rope is tied securely to the tester by a bowline on the coil, and the other end is anchored to a secure point, such as a tree or life tower (Manning 1960). (Photos by Martinelli and Kelner)
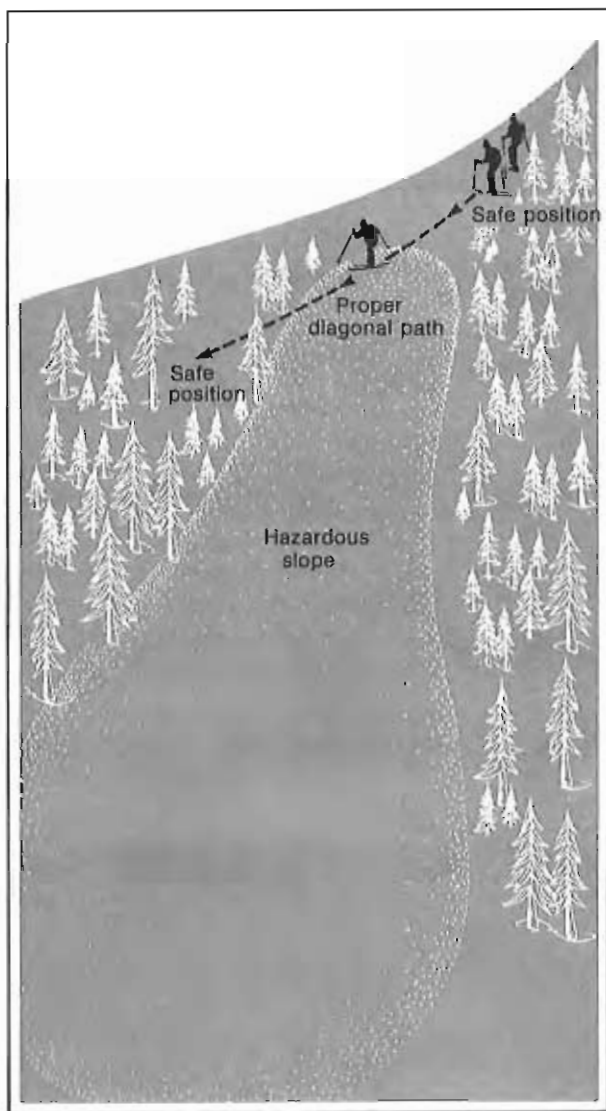
Figure 128.—The test skier should move diagonally across the crown from one safe position to the next. His progress should be observed by a companion. Test skiers should never rest in the middle of the slope.

around the waist with two or more loops (or a harness) knotted by a "bowline on the coil"; the rope must be anchored to a strong fixed point, such as a tree or lift tower. There should be as little slack as possible in the rope.

(7) Standard belays that are acceptable in rock climbing may not hold against the steady forces of snow pounding on a body. In any case, test skiing should not be performed where there is danger of such large forces against the tester's body.

(8) Test skiers should move as quickly as possible between safe points, and they should never stop in the middle of the slope.

(9) Test skiing should not be performed if there is any possible hazard to people in the track or runout zone.

Test skiing may be practiced on miniature avalanche slopes and on the major avalanche paths of a ski area if the above safety precautions are taken. The larger slopes are test skied as a check on meteorological observations that indicate small amounts of new precipitation have been added to the slopes in question. Regardless of precipitation amounts, test skiing should not be performed on large paths that have not been thoroughly ski packed (see chapter 6, "Control by Compaction") before the new snow loading. If the tester finds larger amounts of new snow than indicated by meteorological observations, he must perform belayed skiing or resort to explosive tests (or retreat if he is unprepared to do the job safely).

If the slope can be free tested, the standard procedure is for the tester to enter at one corner, under the watchful supervision of a second tester. The first tester skis diagonally down and across the crown region, bounding and thrusting his skis to add extra stress to the slope. The line of travel begins in a safe spot outside the starting zone, crosses the starting zone, and ends in a safe place. After the first tester arrives at the end of the diagonal, roles switch, and the first tester watches as the second tester comes across. The second tester traverses a slightly lower line. Testing may then continue diagonally down and back across the slope. A slope should not be judged absolutely stable on the basis of one or two ski traverses.

A good habit to develop in skiing all avalanche paths, regardless of their apparent stability, is to end ski runs at the side of the path. Stopping to rest in the middle of the path should be avoided. In many cases skiers have been trapped because the crown fractured above them while they stood resting in the middle of the slope.

During test skiing, one looks for the following signs of structural instability in the new snow:

Propagation of fractures. This is the most direct evidence of new snow instability. The deeper and more extensive the fracturing, the more unstable the new snow. Fracture propagation on the order of one ski length or more generally indicates structural instability.

Collapse noise. In some cases, although sudden collapsing sounds in the snowcover are clearly audible,

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Figure 129.—Fracture propagation is direct evidence of instability. Fractures may propagate from the tester's skis or, in cases of extreme instability, around the periphery of the slab. (Photo by LaChapelle)

fracture may not be observed. This effect can be observed on horizontal as well as inclined slopes. It is an indication of a weak structure and extreme instability. The exception is collapse noises from the fracture of very thin surface crusts in the spring. These are usually harmless.

Hard surfaces. It is necessary to distinguish between wind-scoured slopes and deep, hard deposits in lee pockets. Wind-scoured surfaces are identified by erosional features and are generally not an avalanche problem. However, hard deposits in lee pockets may be quite unstable. When skis cannot penetrate a lee deposition, the tester should suspect *hard slab instability,* and should further investigate the structure by digging a pit to search for the combination of a *hard slab* over a weak substratum or by placing an explosive charge.

Very unstable thin slabs. Occasionally, test skiing shows that the new snow is extremely unstable but that the instability is confined to a thin surface slab

less than 15 cm thick. These thin slabs are comparatively harmless. However, avalanche activity can be expected when new deposits build on this weakness.

Obviously, test skiing is an efficient and reliable tool when the test slopes are located very near to the problem slopes or, better yet, when the test slopes are the problem slopes. A slightly different application of the technique is to test miniature slopes that behave similarly to more remote and larger problem slopes. This approach is normally used to evaluate stability on paths that threaten highways and villages. Reliability decreases with increasing separation and elevation difference between test and problem slopes.

The limitations of test skiing can be resummarized: hazard to testers on large slopes, unreliability for evaluating deep slab instability, and unreliability for evaluating conditions on remote slopes. The alternative and more expensive test is to bomb the slopes with hand-placed or artillery-launched explosives. This tests the stability of the slopes and at the same

Figure 130.—Effects of wind. Left, erosional features, such as the sastrugi here, indicate that the slope is wind scoured and probably not an avalanche problem; right, note that the tester's skis are not penetrating the smooth, hard surface of the lee-exposed pocket. This indicates potential hard slab instability. (Photos by Kelner)

time accomplishes control objectives (see chapter 6 under "Control by Explosives"). In some areas, avalanche workers are criticized for using unnecessary and uneconomical explosive testing instead of a more "analytical" stability evaluation. It should be understood that explosive testing is the avalanche worker's main tool. Improved analysis can replace some of the current explosive testing, but it cannot be expected to replace very much. Many ski areas are operable only because of exact and thorough use of explosives.

Here are a few guidelines for explosive testing:

• In general, extensive explosive testing is justified for stability evaluation in ski areas or in any situation where uncertainties cannot be tolerated. Extensive explosive *testing* is seldom required over highways and villages.

• Explosive testing should be used in connection with other inputs. For example, after precipitation driven by sustained south winds, north-facing slopes should be tested thoroughly and south-facing slopes less thoroughly.

• Testing should be concentrated on those elevations and aspects that respond positively to explosive tests.

• Testers should look for patterns in the way slopes respond to tests. Which elevations and aspects seem to be unstable? If all but one of neighboring slopes of similar aspect and elevation test unstable, retest the anomaly, perhaps in a slightly different target area.

The use of explosives for control, as well as testing, is described in more detail in the next chapter.

STABILITY EVALUATION

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Protection
of ski areas

Avalanche control in ski areas uses several methods, including barring the public from hazardous runs, stabilizing slopes by compaction, and artificially releasing avalanches by explosives or artillery. This chapter explores these methods in detail. Judging by the excellent safety record of avalanche workers in today's ski areas, it is fair to say that avalanche control is a successful technology. However, avalanche control cannot work miracles if a ski area is poorly planned to begin with. Though the need for planning is universally recognized by the ski industry, sometimes avalanche planning is dismissed quickly with the thought, "the problems will somehow be controlled." The result is future wrestling with an avalanche hazard and sacrificing much of the operating budget. In this chapter, planning is discussed last, but it should be stressed that avalanche control properly begins in the planning stages, when a ski area is first conceived.

Figure 131.—Recoilless rifle, 105 mm, fired from a fixed position on a cement block tower. (Photo by Bob and Ira Spring)
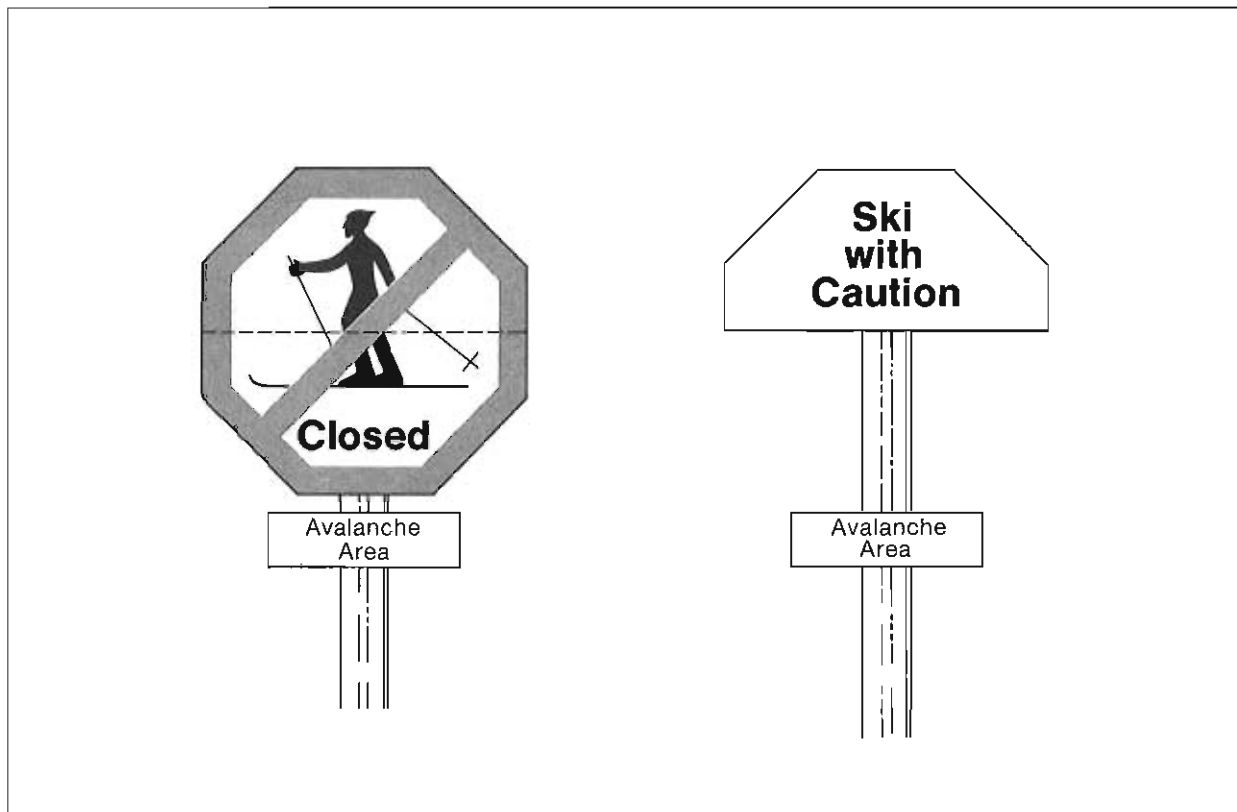
Figure 132.—Ski area avalanche control sign in two positions. In its normal position, this center-hinged sign closes the slope. When folded upward and latched at the top, it opens the slope but reads "Ski with Caution." This emphasizes that the best control is not completely effective and that the skier shoulders some responsibility for his own safety.
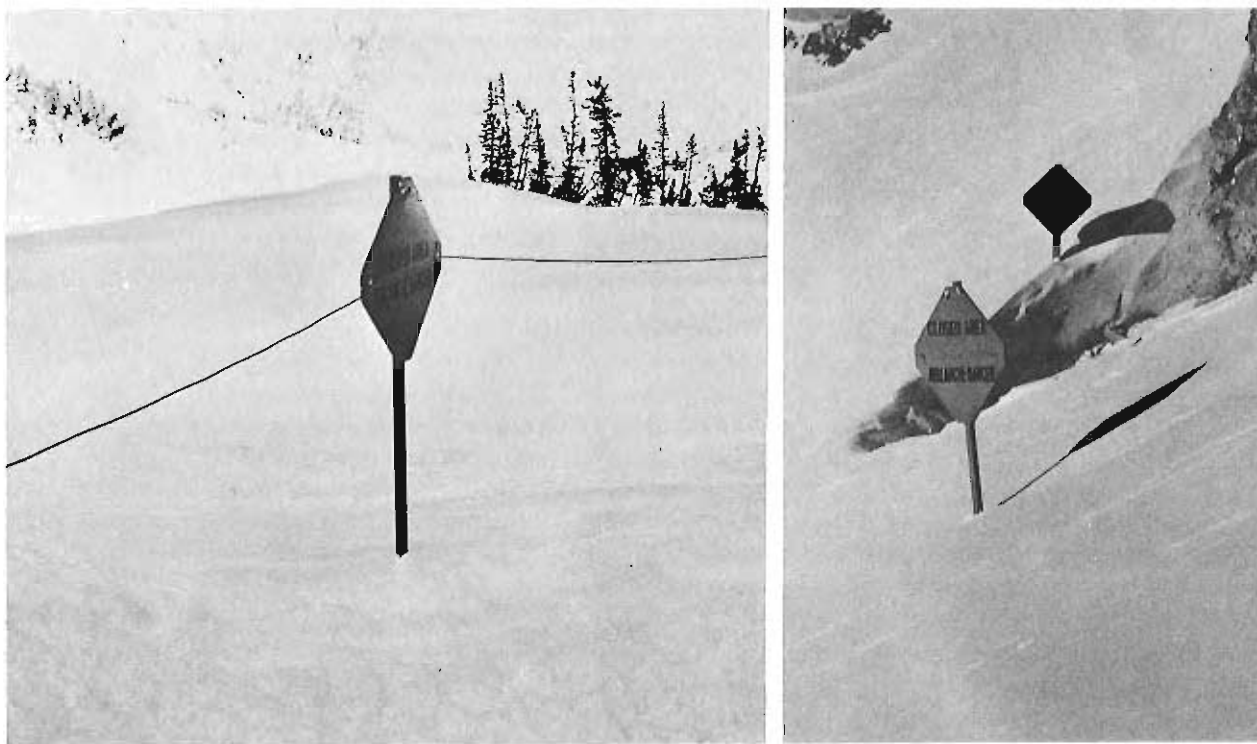
Figure 133.—Avalanche sign lines, used to close off large areas.

Figure 134.—Lift-terminal displays that give backup information on avalanche and other warning signs in the area.

Control by restrictions

It is essential that ski area operators develop effective ways to restrict public access to avalanche areas. An effective system includes:

• Making the skiing public aware of what parts of the area are hazardous and therefore closed to skiing, either permanently or from time to time as conditions warrant

• Closing ski runs only as long as the avalanche hazard exists

• Enforcing restrictions consistently and fairly.

If a ski area is lax on any of the above points, the public will lose respect for the area's avalanche-control program.

Well-placed signs help make the public aware of hazardous areas. Avalanche signs should be about 75 by 75 cm and should be painted international orange with clear black letters. For simplicity, signs may be made square or rectangular, but the international octagonal shape is preferred. A hinged avalanche closure sign is shown in figure 132.

Ultimately, avalanche safety is best achieved by "educating" the public. It is, therefore, in the public's

Figure 135.—Permanent closures should be used to keep skiers out of terrain traps such as gullies fed by large starting zones. A skier was trapped in this gully and buried under 5 m of snow.

interest that the sign actually say "AVALANCHE," so that the public is informed of the reason for the closure. Similarly, when part of a ski area is closed because of ice, rocks, insufficient snow, etc., signs should not give the impression that closure is due to the avalanche hazard. One excellent system is to use the international sign for all closures, but to attach removable plaques that identify the main hazard. This achieves safety and educational goals and at the same time is consistent with international practice.

In placing avalanche signs, every advantage should be taken of natural terrain features. It is good to place avalanche signs at fixed locations so that at least the "return customers" know where to look. Standard traverse paths are natural choices. Occasionally, it is necessary to set several signs in a neat line to convincingly block off an extensive avalanche area. Whenever possible, the signs in such a line should be connected with colored or flagged rope.

It is good practice to supplement closure signs with master bulletin boards or chalkboards that tell which areas are closed. This avoids temptations that arise when a skier goes out a long way to the closure sign and asks himself, "Did they really intend to close this area?" It is also good practice to post at lift ter-

minals additional displays asking the public to be on guard for the various warnings in the area. Much confusion is eliminated if all posted signs are in agreement as to whether an area is open or closed. This is critically important. To keep signs in agreement requires good communications and organization. In the long run, such efforts are rewarded by the skiers' respect for warnings.

Closures are most effective when used as temporary measures. It is best to remove the closure as soon as the slope is tested and the hazard removed. Permanent closures should be kept to a minimum and strictly enforced. However, permanent closures are justified where the hazard cannot be cleared confidently, especially where the terrain forms deadly traps. As an example, it is good practice to keep skiers permanently out of deep gullies that are fed from above by large catchment basins. Although an area is permanently closed, it still should be monitored and possibly controlled by ski release or explosives. Several skiers have been killed when they accidentally or purposely entered permanently closed areas.

A ski area strongly compromises its stabilization program when it does not lift restrictions shortly after slopes are evaluated as stable. For one thing, the ski-

ing public may begin to question the closure, especially when all neighboring slopes are skied out. More important, continual heavy skiing is by far the best way to solidify and thus stabilize weak substrata. Many slopes that once produced major avalanches are now relatively inactive because of heavy skiing.

Violations of restrictions can be quite serious. They may affect violators as well as innocent skiers below, and they add to public confusion. The normal enforcement procedure is to deny violators lift privileges. While many violators are sincerely naive and victims of unclear sign programs, many other violations are premeditated. For habitual violators, it is worthwhile to have a fairly strong county ordinance that allows prompt arrest and fining.

When a violation could have serious consequences, it is sometimes necessary to post guards temporarily at the closure sign. Such precautions should be used to guarantee that skiers do not enter an area during blasting operations that are conducted during normal lift operating hours.

Control by compaction

Trampling the snow by ski or boot is one effective technique for densifying and strengthening the snow in avalanche starting zones. It is an excellent way to reduce instability due to TG metamorphism. Such compaction does not stop TG metamorphism, but it does remove much of the attendant hollowness and tendency to collapse. Because ski and boot packing takes considerable effort, they are used normally on fairly small starting zones of readily accessible paths and typically on paths with runout zones that cross lifts, base facilities, or areas where people congregate.

Systematic compaction of such areas should begin as soon as possible after an early-season snowstorm. To make the task easier, it helps to start by sidestepping the slope on skis. For maneuverability, "shorty" skis with climbing skins are an asset. After ski compaction, skis can be removed, and compaction can be finished by repeated foot traverses.

It is not necessary to compact the entire starting zone; the job can be cut in half by compacting alternate bands from the top down. This tedious process is best performed by a squad of several packers, but one or two strong avalanche workers can stabilize small starting zones in reasonable time. Systematic ski or boot packing may be repeated several times each season on the more critical starting zones.

Figure 136.—County ordinance in support of avalanche control signs.

Figure 137.—An example of avalanche paths that should be thoroughly compacted beginning with the first snowstorm of the season. These paths threaten base facilities.

Control by compaction

Figure 138.—Compacted and uncompacted slopes, side by side. Despite its steepness, the compacted slope (center and right) is a negligible avalanche problem. The uncompacted slopes (left) avalanche frequently.

Figure 139.—Some avalanche paths remain uncompacted throughout the season. If the paths threaten developed areas they should be stabilized.

　　　　　　　　　　　　　　　　　PROTECTION OF SKI AREAS

Once the recreational season is underway, compaction consists of two phases:

Control or protective skiing. Preliminary compaction of potentially dangerous slopes is done by experienced avalanche workers. During this phase, the slopes are closed to the public.

Public skiing. The slopes are evaluated stable, and they are opened to the public for normal use.

To minimize risk, ski compaction should be preceded by appropriate tests, either test skiing or explosive control or a combination of both.

Test skiing is discussed in chapter 5 in connection with stability evaluation. The precautions used in test skiing also apply during control skiing. Often control skiing is just a followup phase to test skiing, and in most cases there is no fine dividing line between the end of the test phase and the beginning of the control phase.

In control skiing the team skis cautiously, one at a time, down through the starting zone, deliberately making wide and deep turns which chop up as much of the starting zone as possible. The compaction should continue down the track. Wiggling down the fall line is ineffective; it also makes public relations more difficult, since it gives the impression that the control skier is hogging the good powder. Control skiing (and sometimes boot packing) cannot be used on hard slabs. Normally, hard slabs must be broken up by explosives.

The intensity of control skiing is an important variable. The team chooses an intensity that depends on slope conditions. Fairly intense control skiing is needed on slopes that have not had continual public skiing (and thus have comparatively weak substrata) and have received large amounts of new precipitation. Control-skiing intensity can be reduced on slopes that are skied steadily. Intense control skiing involves chopping up the starting zone with ski tracks 1 to 5 m apart. Of course, even such intense control skiing is not a safeguard against deep instabilities caused by failure to maintain compaction from the beginning of the season. Intensity may be reduced to a few passes where small amounts of new snow have been added to a well-compacted substratum. Whenever possible, control skiing should be performed continuously during sustained precipitation periods or periods of drifting snow. This keeps ahead of the problem.

After control skiing and as soon as a ski path is judged stable, it should be opened to the public. It is important that avalanche workers monitor the amount of public skiing on critical paths. If for some reason the public is avoiding a path and stability of the path becomes suspect because of new precipitation, wind drift, etc., avalanche workers should reclose the path and prepare for appropriate test and control at the first opportunity.

There is increasing evidence that even the best planned and executed control programs are not 100 percent effective. Public skiing of avalanche paths involves a small but not negligible risk. The local ski population should be informed of this in the schools, in ski clubs, and through radio and television programs. Instruction can be given to nonlocal skiers at lodges and in warming huts. The important points to get across to the public are the following:

• Because a slope is open, don't assume it cannot avalanche.

• Enter the slope cautiously.

• Don't stop to rest in the middle of the slope. End all turns on the side of the slope, preferably in the shelter of trees.

• Make a practice of skiing avalanche slopes with a companion. Keep watch on each other by skiing one at a time.

• If the snow acts suspiciously (sudden settling or fracturing), turn back and notify ski area personnel.

It must be emphasized that these precautions are for developed ski areas. Many additional precautions must be followed when skiing in the back country on uncompacted paths. These precautions are outlined in chapter 8.

Clearly, the small risk that the public assumes when skiing avalanche paths is more than compensated for by the compaction benefits. However, the risk can increase considerably if the area, for economic reasons, uses the public to perform the control skiing phase. To maintain a proper balance between control and public phases, the ski area must provide a competent, well-trained control team of a size to match the area hazard. The economics of supporting this team must be worked out in the initial planning of the area.

Control by explosives

Explosives are important tools in avalanche work; they are used regularly to test and control slopes in ski areas. As pointed out in chapter 5, often the test and control objectives are inseparable and are achieved simultaneously. In that chapter the test objectives of explosive blasting were explained. In this
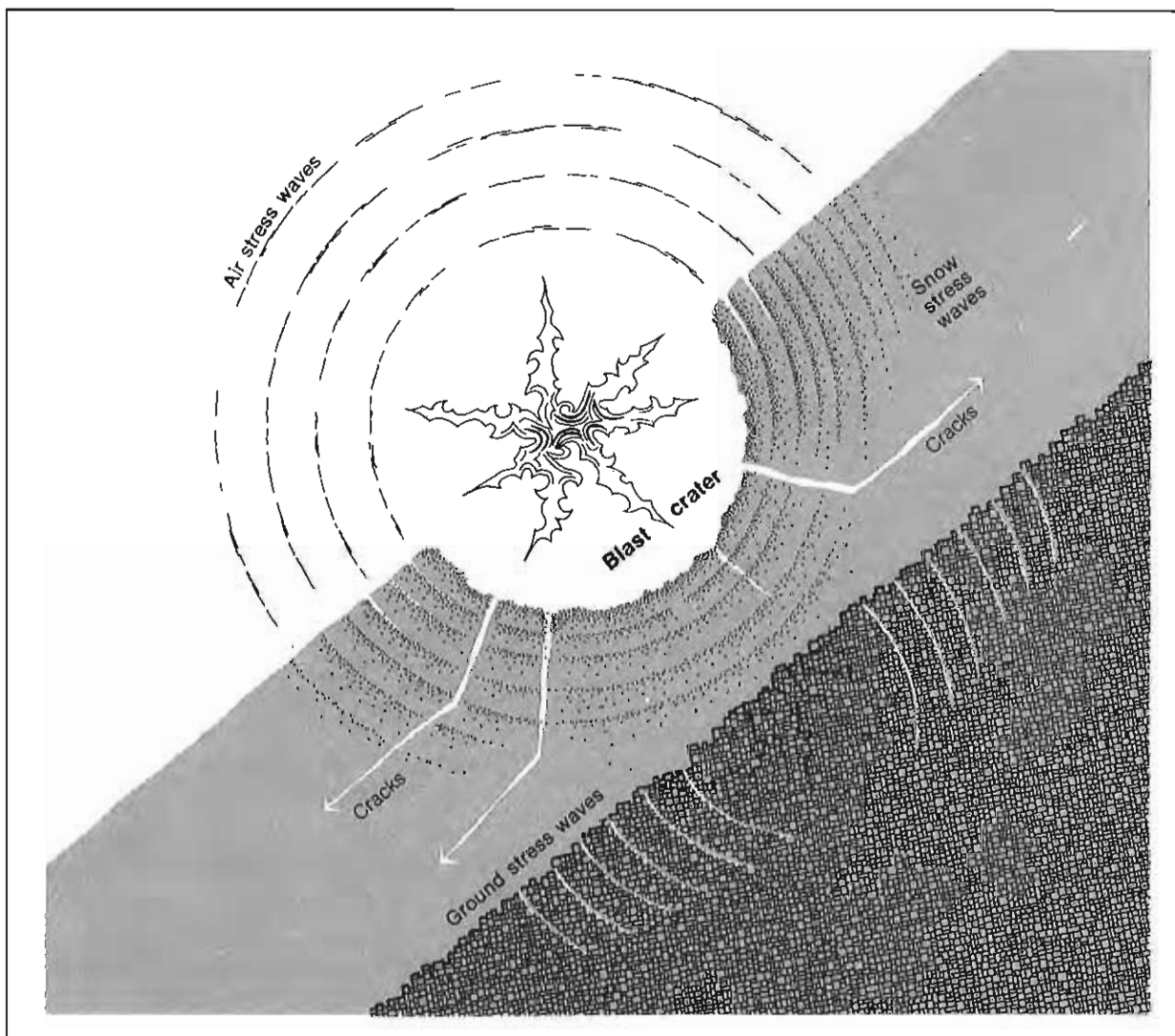
Figure 140.—Explosive blasts cause cracks to shoot out from the crater. Some of the blast energy is converted into stress waves that travel through the air, snow, and ground. These stress waves reinforce fracture propagation.

section emphasis is on the control objectives. Some of the more important control objectives are:

Release of avalanches from uncompacted paths. Many avalanche paths that cross developed areas are not regularly skied and therefore remain uncompacted throughout the avalanche season. These paths must be stabilized. Usually explosive techniques are most effective, although structures sometimes offer a better solution (chapter 7). The more frequent the blasting of unskied paths, the less likely they are to shed large, unexpected avalanches. Although frequent blasting greatly increases the number of avalanches, the average size of the avalanches is greatly reduced.

Release of medium to large avalanches on skiable paths. In many cases, setting up safe belays for test

and control skiing is too time consuming. It is generally more economical to control larger paths initially with explosives. If a path does not avalanche when controlled with explosives, it probably will not avalanche when entered by a ski control team. Because there is not a 100-percent guarantee of safety, the team may still wish to enter on belay and take other precautions as outlined in chapter 5 under "Ski and Explosive Tests."

Release of deep-slab instability. Ski control is normally ineffective against deep-slab instability and hard slabs. Explosive blasting is needed to control deep-slab instability and to break up hard slabs. The observed difficulties in controlling deep-slab instability reemphasize the need for a thorough compaction program.

Explosive blasting may release avalanches in several ways. It is speculated that the following are important:

Mechanical fracturing around the crater. The explosive blast causes cracks to shoot out from the crater. Fractures continue to spread, branching into weak regions and eventually cutting loose the entire slab. This is considered the most important effect of blasting; the observed fact that explosives are not very effective against wet slabs confirms the central role of brittle fracture. Fracturing is reinforced by thrust and three types of stress waves.

Thrust. The explosive blast also thrusts or heaves against the slab. When applying explosives to rocks and related materials, optimum thrust is normally achieved when the detonation speed of the explosive (see the next section) is approximately equal to the speed of sound in the rock. Although convincing experiments are lacking, there is evidence that speed matching to optimize thrust is not important in snow slab blasting. Instead, field preference generally is for explosives with speeds about 10 times as great as the speed of sound in snow. For blasting snow cornices, however, field preference is for reducing the explosive speed and thus gaining thrust effects.

Snow stress waves. Compared to rock, metals, and other solids, snow is a poor carrier of stress waves. Just how poor depends somewhat on the frequency of the waves. It is thought that only a very small amount of the blasting energy is transmitted across the slab via stress waves in the snow, and that any wave disturbance that propagates a long distance from the blast is transmitted via the ground or air. Nevertheless, snow stress waves work locally to generate and extend cracks.

Ground stress waves. The ground is much more effective than snow for transmitting stress waves. The waves of largest amplitude travel at the ground surface and are known as Rayleigh waves. Occasionally a subsurface explosive blast in a slab triggers instability in another slab separated from the first by a continuous rock ridge. This indicates that ground stress waves carry enough energy to induce avalanching. It is also known that artillery shells fired into rock bands often cause avalanches on adjacent slopes. The relative importance of ground waves in comparison to air stress waves is unknown.

Air stress waves. Compared to snow, air is an effective medium for spreading shock waves. Since most avalanche charges are exploded on the surface, air stress waves may play an important role. Several experiments have demonstrated that avalanches can be released by explosive bursts above the snow. As a special case of air shock, sonic booms from jet aircraft sometimes release avalanches on highly unstable slopes.

Choice of explosives

Several types of explosives can be used for avalanche blasting. Each has something to offer in terms of performance, safety, storage, handling, and cost.

Two fundamental properties of an explosive largely determine its performance: *detonation speed* and *density*. Detonation speed is the rate of propagation of the explosive reaction through the explosive material (measured in meters per second). Density is the mass-to-volume ratio of the explosive (measured in grams per cubic centimeter; the density of water is 1 g/cm^3). From detonation speed and density it is possible to compute a performance index known as the *detonation pressure* of the explosive. Detonation pressure varies, approximately, as the square of the detonation speed and directly as the density. Thus, an explosive that is twice as fast as another has roughly four times its detonation pressure. The higher the detonation pressure, the greater the shattering effect of the explosive. Table 6 gives speed, density, and detonation pressure of explosives used in avalanche work.

Avalanche workers generally prefer explosive mixtures with high detonation pressures, the denser and faster explosives. It is claimed that higher detonation pressures are more effective in activating instability, all other factors being equal. There is no obvious explanation for this claim, since low-pressure explosives are known to be quite effective for blasting soft rock (see comments on thrust in previous section). The difference may be that avalanche charges are normally detonated as unconfined surface blasts (external charge), while rock blasting frequently is done in confined boreholes. More studies are needed to confirm and explain the advantage of a high detonation pressure for avalanche blasting.

In choosing an explosive for avalanche work, the following requirements should also be considered:

• The explosive and its detonation system should be safe, simple, and usable under severe winter conditions.

• The explosive should not be adversely affected by moisture, cold, frost, or other elements of the winter environment.

TABLE 6.—*Characteristics of explosives used in avalanche work*

Explosive	Content	Approximate density (g/cm³)	Approximate confined detonation speed (m/s)	Detonation pressure relative to cast TNT	Typical application
Cast TNT	TNT	1.56	6,700	1.0	HE ammunition, primer, booster, demolition
PETN	PETN	1.60	7,600	1.4	Detonating cord, caps (unconfined velocity—6,400 m/s)
Cast pentolite	TNT and PETN	1.65	7,400	1.3	Primer, booster
Military composition A3, B, C3, C4	RDX, TNT, and others	1.65	7,600 (63% RDX)	1.3	Demolition, shaped charges, HEP ammunition
Military tetrytol	Tetrytol	1.60	7,000	1.2	Demolition
Amatol	TNT and ammonium nitrate	1.50	6,200 (60% TNT)	.9	Primer, booster, HE ammunition
Straight" gelatin (80% wt.)	65% nitroglycerin	1.35	6,700	1.0	Hard rock blasting, primer, deep wells
Straight gelatin (60% wt.)	50% nitroglycerin	1.40	6,100	.9	Hard rock blasting, primer, deep wells
Straight gelatin (40% wt.)	32% nitroglycerin	1.50	5,000	.6	Hard rock blasting, primer, deep wells
Straight gelatin (20% wt.)	20% nitroglycerin	1.70	3,400	.3	Softer rock
Two-component explosives	Ammonium nitrate and nitromethane	.95	4,300	.4	Miscellaneous storage advantages

ᵃAmmonia gelatin and semigelatin explosives have somewhat less detonation pressure than straight gelatin for equivalent percent weight ratings. "High-velocity" gelatins are designed to detonate at rated speeds regardless of confinement and are preferred for avalanche work.

• Misfires (or duds) should be infrequent. If a misfire is lost on a slope and exposed to the elements, it should not become shock-sensitive.

• The explosive should be packaged in a non-shrapnel container.

• The explosive should be reasonably nontoxic under normal outdoor handling.

• The explosive should have a high density so that field loads are not bulky.

Many commercial explosives have been tested and found satisfactory for avalanche blasting. The preferred avalanche explosives are known commercially as primers or boosters, a class of explosives used mainly to detonate insensitive blasting agents such as ammonium nitrate. Primers are divided into two categories: cast primers and gelatin primers. Their composition varies according to manufacturer.

Cast primers are usually high-density, pressed or cast cylinders of TNT and other ingredients. TNT is a fast, powerful explosive that is not extremely sensitive to accidental detonation by shock. It was developed by the military to withstand the rigors of the battlefield. Its fumes do not produce headaches, as do those of some other explosives; they are toxic, but this is not a problem in normal outdoor use. TNT has the peculiarity of reacting with atmospheric oxygen. This adds some energy to the blast, especially when the charge is detonated on the surface. One disadvantage of TNT is that it leaves a messy black crater; another disadvantage is high cost. TNT is not reliably detonated by No. 6 or No. 8 blasting caps, so that cast primers of TNT include a more sensitive explosive, such as PETN. The PETN content of cast primers for avalanche work should not exceed 50 percent.

Gelatin primers are cheaper and do not leave a black crater. They are as fast as TNT but slightly more bulky. They have a high percentage of nitroglycerin and share the disadvantages of all nitroglycerin mixtures; they produce headaches, deteriorate, and are more shock-sensitive than primers that consist, for example, of TNT.

Gelatin and cast primers are classified as high explosives and must be stored and handled according to strict codes (see chapter 6 under "Explosive Safety"). Because of regulations dealing with explosives security, storage is expensive. Where there is a limited need for explosives, avalanche workers may wish to avoid the more expensive storage requirements by using a "two-component system." Stored separately, the components are not high explosives. They are classified as high explosives only when mixed. The storage advantage is offset by higher cost of materials, lower detonation speeds, bulkier charges, the inconvenience of mixing the explosive in the field, and the requirement of a mixing time of about ½ hour to bring the mixture to full strength. Mixing should be done at temperatures of 0° C or above, but once mixed, the explosives will detonate at — 50° C or lower.

Use of explosives

Ideally, explosive efficiency could be achieved in several ways: by selecting the minimum amount of explosive, by detonating the charge in the most critical region of the slab, or by properly timing the control action. All these refinements have their limitations, but timing is the most limited. Control work in ski areas generally is performed at set times while the public is off the slopes, and there is little chance to adjust the timing. (The situation is quite different for highway control, where timing can be adjusted.)

It is conventional to blast each target with 1 kg of TNT or its equivalent. The 1-kg-TNT equivalent charge is called the "standard charge." Depending on the circumstances, it may sometimes be necessary to use more than the standard charge. The following guidelines have evolved from field experience:

• A charge of 2 kg often can be used to trigger marginally stable deep slabs.

• Charges larger than 2 kg no doubt "manufacture" instability in some instances when a 2-kg charge is insufficient, but it is highly probable that such avalanches could not be ski-released from the vicinity of the target and would certainly not be released by internal natural triggers.

• For explosives other than TNT, amounts should be scaled to the detonation pressure relative to TNT (table 6). As an example, 2 kg is the standard charge of an explosive with half the detonation pressure of TNT.

• The effectiveness of a surface-placed charge is determined by the detonation pressure. Scaling exclusively to detonation pressure probably over-penalizes low-detonation-pressure explosives, but it does provide an estimate on the safe side. There is no reason to penalize for low detonation pressure if the charge is buried in a borehole. Further comments on buried charges will be made shortly.

To interpret the above guidelines, it is necessary to make some assumptions about the minimum target area tested for instability by a given amount of charge. This area may be thought of as the radius of influence of the charge. Within this radius, an explosive ought to release any avalanche that could be released by a skier. From field experience, it may be assumed as a safe estimate that the radius of influence of the standard 1-kg charge is about 10 m. In many cases the disturbance of the charge propagates over a much larger area, but 10 m is taken as the minimum radius. By this guideline, a series of 1-kg charges should be spaced no closer than 20 m when blasting a wide, continuous slab. Considering the uncertain basis of avalanche blasting theory, it is fortunate that the target areas of most slabs are well defined by terrain barriers such as gully walls, rock outcrops, timber stands, etc., so it is rarely necessary to estimate the number of charges needed to cover a given slab area.

For field purposes, it may be assumed that doubling the amount of surface-placed charge increases the radius of influence by a factor of $\sqrt{2}$, or a little over 40 percent. Thus, for blasting wide slabs, two or more 1-kg charges spread out over the width are likely to be more efficient than fewer 2-kg charges. However, if the slab width (distance between flanks) and slab length (distance between crown and stauchwall) are about equal, a 2-kg charge with its 14-m radius of influence may be more efficient than two 1-kg charges.

It is tempting to blast with larger and larger charges, especially if pit studies indicate that a slope has deep slab instability and the above-recommended amounts fail to activate the instability. A little sober reflection shows that no matter how large the charge, it may only loosen the slab to the brink of failure. When a 1- or 2-kg charge fails to trigger instability and the control team is still uncertain about the slope, there are several alternatives, depending on conditions. For small slopes and shallow snow cover, the workers may enter the slope to perform systematic compaction by boot packing or intense control skiing, provided proper belays and other safety precautions are taken. For larger slopes with deeper snow cover, where boot

Figure 141.—Target areas along control routes at a Utah ski area. Explosives should normally be placed within the slab boundaries about halfway between the slab center and crown. If possible, the radius of influence should sweep into shaded pockets where structural weakness is likely to be most pronounced.

packing would be ineffective, the area may have to be closed for a half or full day and then retested with explosives.

In connection with deep-slab instability, one must keep in mind that avalanches may release, although fortunately infrequently, several minutes to several hours after explosive control failed to trigger instability. There is no reason to believe that these *post-control releases* can be avoided by "forcing instability" with larger and larger charges. "Forcing instability" is questionable in terms of economics and environmental damage, and it may even be questioned in terms of safety objectives.

There is still some dispute as to where explosives should be placed for maximum efficiency. Field opinion is that charges normally should be placed within the boundaries of the slab as determined by the observed crown, stauchwall, and flanks. As discussed at length in the earlier chapters, slab boundaries are determined by terrain and wind-deposition patterns. Hence, boundaries shift with conditions, and specific target points must be adjusted accordingly.

There is some difference of opinion as to how far the explosive should be placed from the slab center. For most conditions, the favored position is about halfway between crown and slab center, but arguments can be given for placing charges at or above the crown, at the slab center, or even at the stauchwall region. The case for keeping the charge high is that tension fractures are easier to activate than shear or compression fractures. Occasionally, charges can be placed in narrow, steep gullies, cliff bands, and other deposition zones above the crown. Here, the idea is to release small slabs or loose-snow avalanches that could trigger the main slab.

As an added refinement, it may be possible to improve efficiency by carefully choosing the target so that the radius of influence sweeps into rock outcrops or trees. This exploits stress-concentration effects and helps generate tensile cracks, which tend to shoot out from rocks and trees. Also, TG metamorphism and other structural weakness are apt to develop in the shade of rock outcrops and trees, and slab failure is most likely to originate in such regions. Pit studies

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can confirm the degree of weakness in a given shaded region. Although blasting next to rocks may produce stress waves in the ground that aid in releasing avalanches, this practice sometimes produces flying pieces of rock that are an added hazard.

Refinements in target location should in no way jeopardize the safety of the control crew. The charges must always be thrown from a safe stance that offers a foolproof escape route from the area of explosive blast. Normally, this entails throwing the charges down from a ridge, perhaps over a cornice or cliff, and there may be little opportunity to refine the target selection.

An important question related to crew safety concerns the feasibility of burying charges. In principle, placing a charge in a well-prepared borehole increases the efficiency of the blast. Also, as discussed earlier, there is reason to suspect that low-cost, low-detonation-pressure explosives such as 40-percent gelatin are quite effective in borehole blasting. However, any advantages of borehole blasting must be balanced against safety precautions imposed on the control team. Borehole blasting must be done on belay, and foolproof escape routes must be worked out. Because of these required precautions, the great majority of explosive control must be done with surface charges. The main exception is cornice blasting.

In conclusion, it should be understood that many of these field practices have not been tested objectively. Research may show that acceptable safety results can be obtained with reduced amounts of low-cost explosives, used in new and more efficient schemes.

Assembly of explosives

This section describes accepted field techniques for preparing and delivering explosives. No attempt is made to treat explosive technology thoroughly; avalanche workers are strongly urged to consult Dick (1968), DuPont de Nemours (1969), Mellor (1965), and U.S. Department of the Army (1959) for more complete discussion of explosive techniques.

Avalanche blasting is based on nonelectric detonating systems for the following reasons:

- Casualties have been caused by the static electricity of snowstorms unexpectedly setting off electric detonation systems.

- The electric-field intensity of the atmosphere in the vicinity of ridgecrests is prohibitively high.
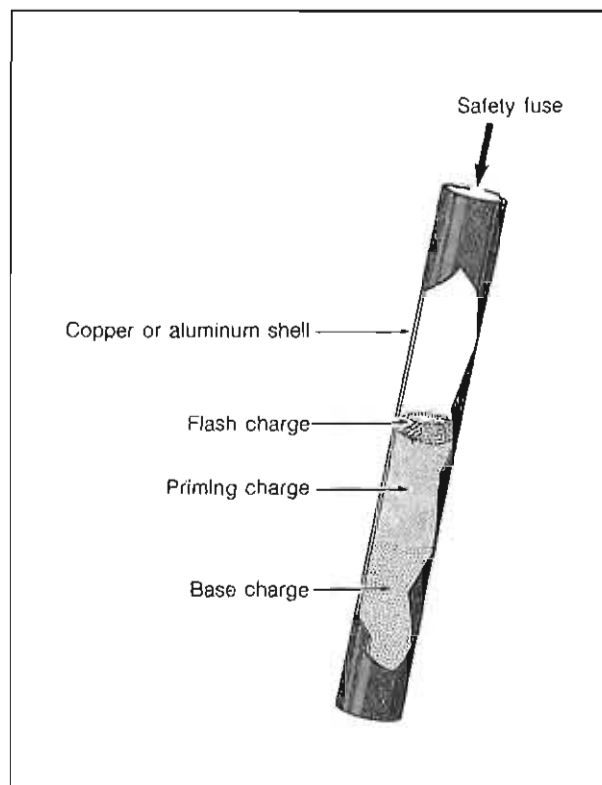

Figure 142.—Typical construction of a blasting cap.

- Electric blasting is not practical under the severe weather and terrain conditions normally encountered in avalanche blasting.

However, even with nonelectric blasting caps, avalanche blasting should not be done when there is evidence of a strong static field (cumulonimbus clouds, electric buzzing). For safety, the nonelectric system must be as simple and foolproof as possible. The recommended system consists of an explosive charge, a blasting cap, a safety fuse, and a safety-fuse igniter. Some general considerations for charge preparation follow:

Blasting cap. The explosive charge is detonated by a nonelectric cap that contains explosives far more heat- and shock-sensitive than the main explosive charge. Typical construction of a cap is shown in figure 142. Most primers or boosters can be detonated by a No. 6 cap; however, under severe winter conditions, some primers with a high ammonium nitrate content require a No. 8 cap. Some compounds (like TNT) may require the equivalent of a No. 10 cap. It is preferable to use primers that can be detonated reliably by a No. 6 cap under all field conditions (providing the charge is made up properly).
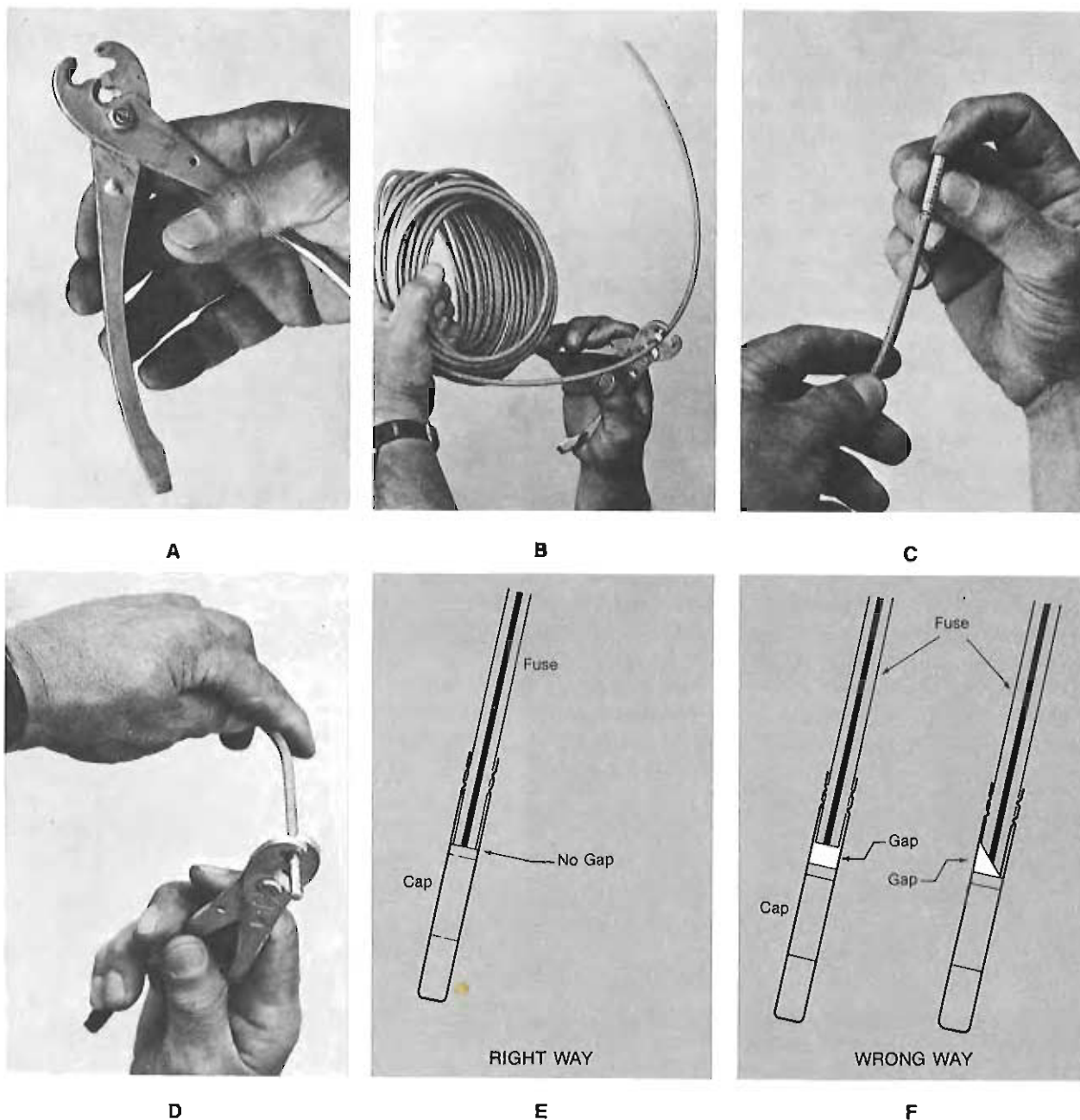
Figure 143.—Assembly of cap and fuse (DuPont de Nemours 1969), *A*, Use only the proper tool, a cap crimper. *B*, Cut a sufficient length of fuse. Square the tip of the fuse. *C*, Select one cap, large enough to detonate the charge reliably under winter conditions. *D*, Gently insert fuse into cap until fuse butts against cap wall. *E*, Crimp cap in two places as shown. *F*, Do not allow any gaps between fuse and cap wall.

Safety fuse. The highest quality safety fuse should be used in avalanche work. It should have excellent water resistance and flexibility. The standard burning rate of fuse marketed in the United States is 0.5 m in 65 seconds (s) (± 10 percent) at sea level. At elevation 2,500 m, standard fuse burns at a rate of about 0.5 m in 70 seconds (± 10 percent). After the fuse is purchased, a test segment should be ignited and the burning rate timed. The minimum length of the safety fuse depends on the time needed for escape from the blasting location. *Under no circumstances should a fuse be cut to a length that allows less than 90 seconds burning time.* The 90-second burning time allows a trained blaster to make two attempts to ignite the fuse. There are several sad cases of casualties caused by short safety fuse. Where the escape route is complex or difficult, it may be necessary to use burning times longer than 90 seconds.
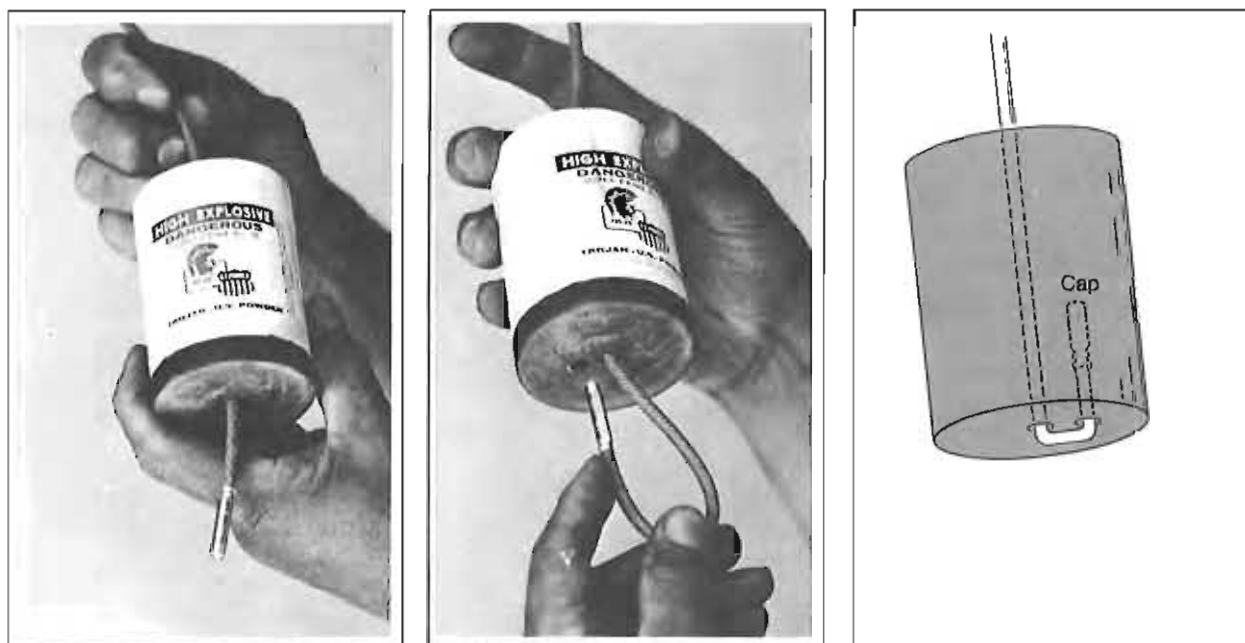
PROTECTION OF SKI AREAS

Figure 144.—Arming cast primer. It is important that the explosive end of the cap be inserted into the off-center hole (the cap-sensitive hole). Misfires will result if the cap is inserted in the wrong hole or is not firmly fitted into the proper hole with snug contact at the firing end.

Safety fuse-cap assembly. Safety fuse should be stored, uncoiled, and assembled to the cap at room temperatures. Working at comfortable temperatures helps ensure correct assembly and minimizes misfires and duds. The procedure for assembling cap and fuse is shown in figure 143. Just before inserting the fuse into the cap, the tip of the fuse must be clipped square. The fuse is then gently inserted into the cap until flush against the inside wall of the cap. There should be no gap between the fuse and cap wall. The cap is then crimped onto the fuse with, and only with, a cap crimper. Scrupulous observance of these details minimizes misfires or duds. On request, several fuse manufacturers supply the fuse and cap already assembled according to procedures recommended by the industry.

Fuse, cap, explosive assembly—general considerations. As soon as the cap is inserted into the explosive, the system is armed. From this instant, the relatively insensitive explosive contains a sensitive cap and is vulnerable to accidental detonation. For this reason, arming should be delayed as long as possible in the field. Sometimes it is possible to arm the explosive just before tossing the charge onto the target. In other cases, wind and temperatures on the control route are quite severe, and overall safety is served if the explosives are armed in a shelter before starting out on the control route.

Three examples of explosive assemblies are presented below:

Arming of cast primer. Figure 144 shows the steps in the arming of cast primers. Most east primers are manufactured with two axial holes, a central one and an off-center one. The central hole is designed to be detonated by high-explosive detonating cord. The off-center hole is usually lined with a primer, which is sensitive to No. 6 blasting cap. It is essential to place the cap in the proper hole, or a misfire is likely. In avalanche work, it is convenient to lace the safety fuse tightly through the central hole and then into the off-center hole, snug against the end of the hole. This requires a high-quality safety fuse that can function reliably despite sharp bends. The assembly is then taped securely. Because of its simplicity, this assembly lends itself nicely to "field mass production," in which the control team assembles perhaps 100 or more charges for a morning operation. Because of the insensitivity to shock of the cast primer and the fact that the cap is protected in the middle of the charge from shock and static electricity, this assembly is the safest armed charge that can be carried on a severe mountain ridge.
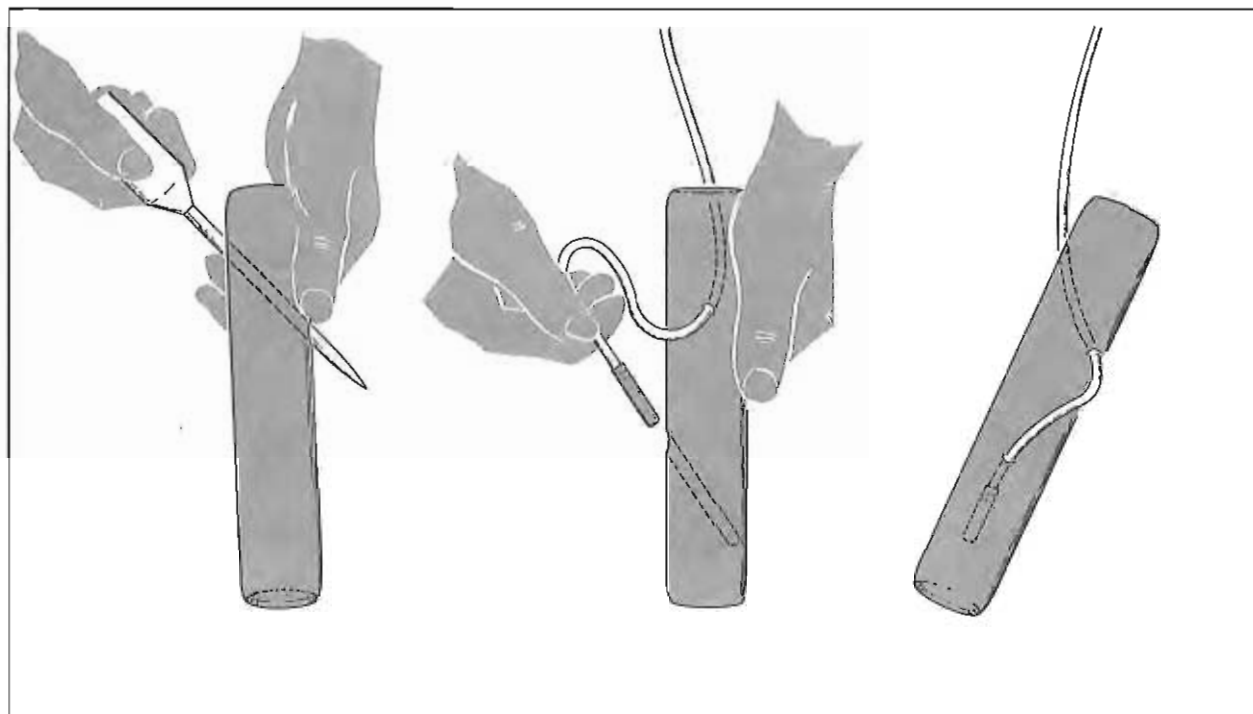
Figure 145.—Arming gelatin-primer by lacing. Two diagonal holes are punched; the upper one goes completely through the cartridge, and the lower one is a little deeper than the length of the cap. The capped fuse is then threaded through the upper hole and the cap inserted into the bottom of the lower hole. The assembly is then taped securely.

Arming of gelatin primer. The arming of a gelatin primer is shown in figure 145. Gelatin primers do not have preeast holes; it is necessary to punch two diagonal holes. First, a diagonal hole is punched through the charge with the puneh end of the erimper. Then the charge is rotated one-fourth turn, and a seeond diagonal hole is punched slightly deeper than the length of the cap. The fused cap is then laced through the first hole, and the cap is inserted into the latter hole. The assembly is taped securely.

Arming of detonating cord. Some explosives (for example, military tetrytol) are detonated by a high-explosive cord known as detonating cord. Such charges are armed by taping the cap to the detonating cord or joining the cap and cord with special connectors. The explosive end of the cap should point along the detonating cord, toward the main charge. Because in both these systems the cap is exposed and vulnerable to accidental shock, the final connection of cap and detonating cord should be made only at the blasting position. Further comments on the use of detonating cord are made in a later section on "Cornice Control."

The prepared charge is carried in the patroller's jacket or pack. Patrollers should not be loaded so heavily that skiing is clumsy. About 15 kg of explosives is a maximum load. Igniters are carried separately from the explosives. The procedure at the blasting position is as follows:

(1) Make sure all possible runout zones are free of people and traffic. For areas not visible from the blasting point, arrange for signals from an observer.

(2) Work with only one charge at a time.

(3) Step into blasting position and make final check of target and escape route.

(4) Clip end of safety fuse and firmly insert the fuse into the igniter. The igniter should be activated immediately. Caution: occasionally the act of inserting the fuse into the igniter may cause ignition (before the igniter is activated).

(5) Make a quick check (1 or 2 seconds at the most) to see that the fuse has ignited, then immediately place charge.

(6) Get to a safe position and await detonation.

If it appears that the igniter has failed to ignite the fuse:

(1) Quickly remove the igniter.
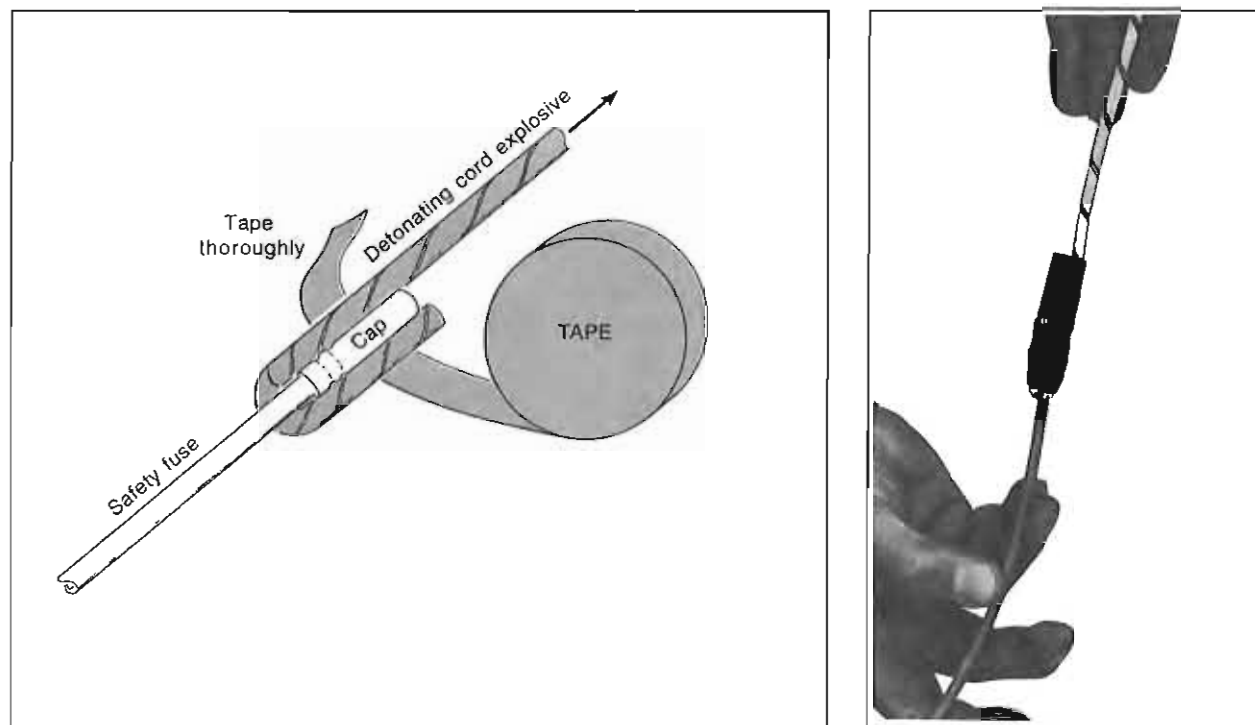
(2) Make a fast visual check of fuse end.

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Figure 146.—Fastening safety fuse to detonating cord.

(3) If there is no sign of ignition, reclip the end, insert a new igniter, ignite, and immediately toss the charge.

Be properly organized, so that the above steps for reignition can be completed within 45 seconds, since there is a very small, but not negligible, chance that the powder was ignited on the first attempt, despite lack of visible signs. In at least one case a blaster could not see a visible sign and was killed while trying a second ignition.

Explosive safety

All avalanche blasting work, including storage, transportation, and handling of explosives, must comply with Federal, State, and local laws. The U.S. Code of Federal Regulations (CFR) treats explosive regulations in detail. In particular, U.S. avalanche workers should be acquainted with the following sections:

Department of Treasury (Alcohol, Tobacco, and Firearms Bureau), sections 181.181 to 181.198. These sections pertain to licensing, record keeping, and the location, construction, and maintenance of explosive storage magazines of various types.

Department of Labor, Title 29 CFR, section 1910.109 and sections 1926.900 to 1926.909. These sections broadly define explosives and explosive terminology and review storage and transportation regulations. They discuss blaster's qualifications, safety procedures for handling and preparing explosive charges, and the use of safety fuse, caps, detonating cord, and primers.

Department of Transportation, Title 49 CFR, sections 173.50 to 173.114 and section 177.848. These sections first define in detail various types of explosives and ammunitions and then give the transportation regulations for each type.

In addition to general Federal, State, and local regulations, employees should be thoroughly familiar with:

Employing agency regulations. For example, U.S. Forest Service Health and Safety Code, sections 6.1 to 6.19 (USDA Forest Service 1972). These pertain to Forest Service employees and may, by terms of the special use permit, pertain to permittee's employees.

Manufacturers' literature. Instructions, warnings, and other literature, published by the manufacturer, that pertain to the chosen explosive.
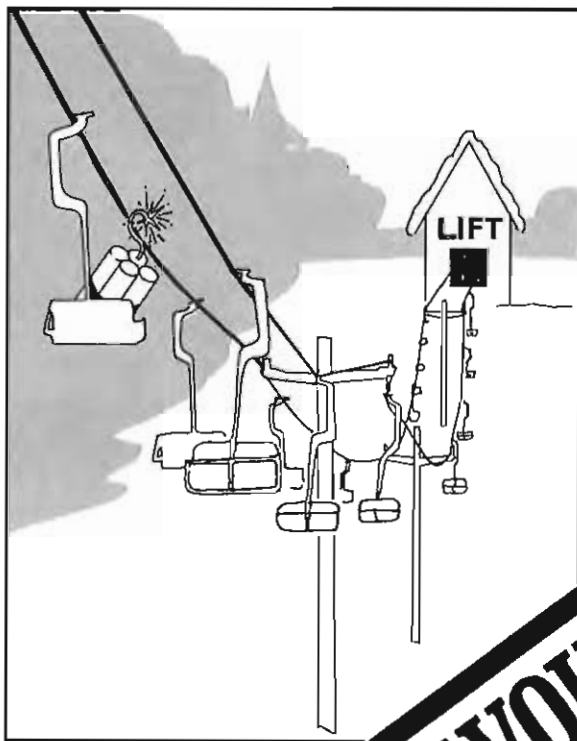
Figure 147.—Tossing charges from ski lifts entails special risks. Take special precautions against entangling charges in any of the lift equipment. All chairs should be vacant except for the blasting team. Charges should be tossed downslope and away from chairs that are moving uphill.

Since avalanche blasting is conducted under severe weather and terrain conditions, it is necessary to supplement the above extensive regulations with additional guidelines for avalanche safety. To a large extent, the following guidelines briefly summarize points made in chapter 6.

General:

(1) An avalanche should not be released artificially until the avalanche path, including the potential runout zone, is cleared of people.

(2) Avalanche guards should be positioned at the entrance to the path if there is any chance that people will enter the path during blasting.

(3) During very unstable conditions, artificial release of one avalanche may trigger sympathetic release over a wide area. Avalanche workers should consider such possibilities and clear the appropriate area.

(4) Explosives should be handled always with utmost care.

(5) In all mountaineering work, safety is achieved by simplicity. Avoid any undue complications.

Personnel:

(1) The blasting party should consist of the blaster-in-charge and at least one assistant.

(2) All members of the blasting party should be in good physical and mental condition and should be competent ski mountaineers.

(3) All members of the blasting party should be properly trained and qualified by the employing agency.

(4) Responsibility for the preparation and placement of the charge should not be divided. The blaster-in-charge is responsible for supervising all phases.

Explosives:

(1) Explosives should have a shelf life in normal storage of at least one operating season.

(2) Explosives should not be packaged in metal containers.

(3) Explosives should have excellent water and frost resistance.

(4) Misfires should not be shock-sensitive.

(5) Recommended explosives are industrial primers (or boosters) that consist mainly of TNT or gelatin.

Detonation systems:

(1) Except for exploding-bridge-wire caps, electrical blasting caps should not be used.

(2) The detonation system should be as simple as possible; the recommended system is: explosive, cap, safety fuse, and fuse igniter.

(3) Blasting caps should not be larger than No. 8 (No. 6 preferred).

(4) Caps should be protected fully from external shock during control maneuvers.

Safety fuse:

(1) Use only the highest quality safety fuse, which has excellent water resistance and excellent flexibility.

(2) Safety fuse should burn no faster than 0.5 m per minute. A section of fuse should be tested after purchase and before use.

(3) Safety fuse lengths should be selected to allow the control crew to escape from the blast area under all reasonable contingencies (falls, release of safety bindings, etc.). Burning time should be at least 90 seconds.

Preparation of detonating systems:

(1) Blasting caps should be crimped onto the safety fuse only with special crimper tools.

(2) To prevent misfires, the fuse-cap assembly should be fastened or taped securely to the explosive charge.

(3) Charges should be armed with caps as late as possible in the blasting operation.

(4) The igniter should not be attached to the safety fuse until the control crew is at the blasting position and ready to release the charge.

Firing of charge:

(1) The blaster should be at the blasting position before attaching the igniter.

(2) Ignite only one fuse at a time. (Double fusing is an unnecessary complication.)

(3) Check quickly that the fuse is ignited, then immediately toss charge.

Tossing charge from control route:

(1) Normally, the charge is tossed down onto the target from a safe position, preferably a ridge.

(2) The control team then escapes to a safe position behind a terrain barrier at least 30 m from the target.

(3) In cases where the charge could slide down on a hard snow surface, it should be belayed with nylon cord.

Tossing charges from ski lifts and trams:

(1) The number of charges tossed from lifts and trams should be kept to an absolute minimum.

(2) The lift operation crew should be informed of the blasting plans.

(3) The lift crew should stand by in full readiness for emergency procedures (transfer of lift to auxiliary power, evacuation, etc.).

(4) The lift crew and the blaster-in-charge should be in radio contact at all times during the blasting operation.

(5) Only the blasting crew and the essential operating personnel should be on the lift or tram.

(6) The lift should be in motion when the charge is tossed, and the blasting crew should be moving upslope. The charge should be tossed downslope and to the side.

(7) Charges should not exceed 2 kg of TNT equivalent.

Figure 148.—Small cornices are routinely kicked off on daily control routes.

(8) The minimum distance from target to closest point of lift should be 20 m.

(9) Fuses should be cut so that blasting crews have moved on the lift at least 100 m from the target by the time of detonation.

(10) All tram and gondola cars should be at least 100 m from the target at time of detonation.

(11) Precautions should be taken to avoid tossing charge into any of the lift equipment, moving chairs, cables, lift towers, etc.

Blasting from aircraft:

In addition to the regulations outlined above, avalanche blasting from aircraft is subject to special permission from the Federal Aviation Administration, in accordance with FAA Regulation Part 103. Each case must be considered individually in context with the alternatives. (Helicopter blasting is treated in more detail in chapter 7.)

Retrieving misfires (duds):

(1) A conscientious effort should be made to retrieve each misfire.

(2) If conditions make it impossible to retrieve the misfire, the slope should be closed and a search begun as soon as possible.

(3) The control team should wait at least 1 hour before approaching any misfire. Any misfire that is aflame or emitting smoke should be left alone.

(4) Secure fixed belays should be set up, and all necessary precautions to guarantee a safe entry to the slope should be taken.

(5) The normal procedure is to retrieve the charge and escape to an avalanche-free location as soon as possible, preferably by retracing steps in the upslope direction.

(6) Deviation from the normal procedure (for example, planting a second charge next to the misfire) depends on the cause of the misfire and the sensitivity of the explosive. These procedures should be worked out in consultation with the manufacturer.

(7) Following recommended procedures for assembling primers, it should be possible to reduce misfire incidence to less than 0.1 percent. Any organization that is not maintaining this standard should thoroughly investigate equipment and procedures.

Cornice control

Cornices are described in chapter 2, under "Wind Redistribution of Snow." Falling cornice blocks may be quite massive and hard; they can survive a long ride without pulverizing and then smash into a skier. They may trigger slab avalanches, sometimes even where explosive charges failed to trigger instability. Because of these hazards, it is necessary to watch closely cornice buildup in ski areas and to take control action before cornices fall naturally.

Whenever possible, cornices should be controlled routinely, especially after periods of snow transport. Small cornices can be kicked or skied off by an unbelayed ski mountaineer who takes standard precautions. Larger cornices are kicked off from sturdy belays; more massive cornices, which consist of several cubic meters of hard, dense snow, should be released only by explosives. A proper belay affords enough protection for work on small to medium cornices, but it offers incomplete protection from the crushing forces of gigantic cornice blocks.

The general safety principles for work on massive cornices are:

- Post guards to restrict the public from entering slopes beneath the cornice. Maintain radio contact as required.
- Never work on a massive cornice without secure belays using 11-mm mountaineering rope.
- Allow only one person to work on the roof of the cornice at a time.
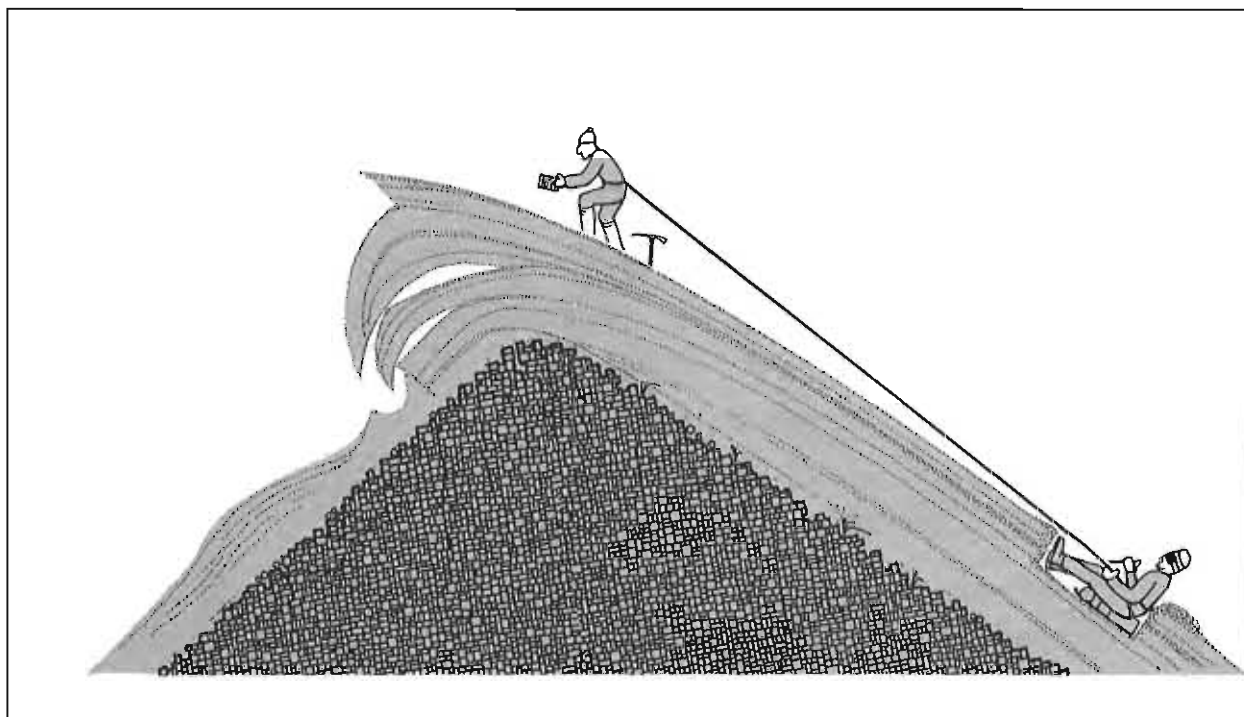- Work on cornices only when weather is favorable.

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Figure 149.—Cornice collapse may place enormous forces on the belay system. The belayer should be in a sitting position and as far down the windward side of the ridge as possible. It is important to keep the belay rope taut.

The belay should be set up as far downslope as possible on the windward side of the ridge. Full use should be made of trees and natural anchors. The belayer should be sitting, and the belay rope should be kept as tight as possible. Full use should be made of standard mountaineering equipment, such as ice axe, snow pickets, slings, carabiners, etc., to help anchor the belay as required. Whenever the belay position is changed, the worker should retreat back from the cornice roof.

Although the belay is essential, it must be regarded as a second line of defense, for backup protection only. Every possible precaution should be taken to remain on the safe side of the cornice roof. Before proceeding out on the cornice roof, establish the closest safe working line to the edge. Here, mountaineering experience and skill are the only guidelines, and such experience teaches that cornices can break a considerable distance back from the edge. Sometimes, an observer stationed at a nearby vantage point can help establish the safe line. It is good practice to flag the working line and strictly obey the flagging.

Cornices should be blasted only after they achieve a mature overhanging structure. Pushing vertical cornice walls over the ridge is a waste of explosives. Knowing when to blast is, again, based on mountaineering judgment.

The simplest and safest procedure for cornice blasting is based on 1-kg surface charges of cast or gelatin primers, or the equivalent. The charges are placed at 2-m intervals along the estimated tension line of the cornice roof, at arm's length from the working line. The charges are linked to a main line of detonating cord. The recommended details are as follows:

(1) Select the number of charges necessary to cover adequately the tension line of the cornice roof. Lace each charge with a 0.5-m length of detonating cord, referred to as branch line.

(2) Set out a main line of detonating cord along the safe working line.

(3) Set the first charge into position along the working line. Tie the branch line of the first charge to the main line with a girth hitch or clove hitch.

(4) In a similar manner, connect the next charge 2 m from the first, and so on down the working line.

(5) After all branch lines are connected to the main, carefully push each charge from the working line to the presumed tension line of the cornice.

(6) Aline each branch line approximately perpendicular to the main line.

(7) After the charge is in place, tape a blasting cap with safety fuse to one free end of the main line. The
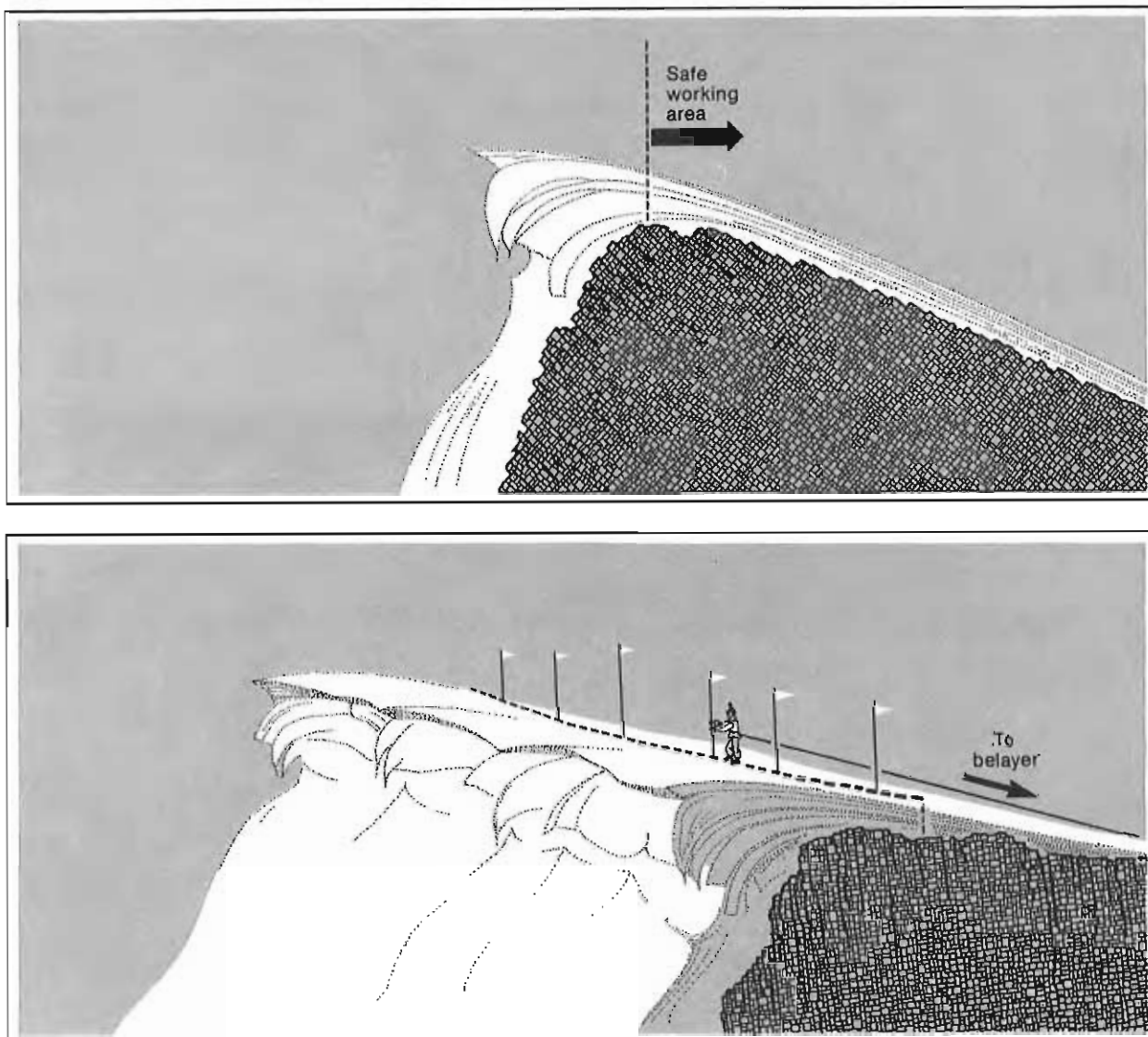
Figure 150.—Before proceeding out toward the cornice roof it is important to flag a safe working line.

explosive end of the cap must point down the main line toward the charges.

(8) In order to allow enough time to escape from the blast area, the safety fuse length should be at least 1 m long. Before igniting, check with the posted guards.

Cast primers can be connected in series without branch lines; the main line of detonating cord is simply run axially through the appropriate hole in the primer. As in the above steps, the system is assembled and pushed into place without stepping over the safe line. This shortcut should not be used to connect buried charges.

A more efficient blasting scheme is to bury the charges in a row of boreholes. In borehole cornice blasting, one may achieve satisfactory results with about half the explosive used in surface blasting. It is also possible to blast effectively with low-cost, low-detonation-pressure explosives. Although borehole blasting of cornices increases efficiency, boring holes along the presumed tensile fracture line exposes the avalanche worker to considerable danger. Safety in borehole blasting depends critically on:

• The ability of the control team to judge correctly the safe working line.

• The feasibility of maintaining a tight, secure belay.

• The ability of the driller to bore holes along the tension line while remaining on the safe side of the working line.
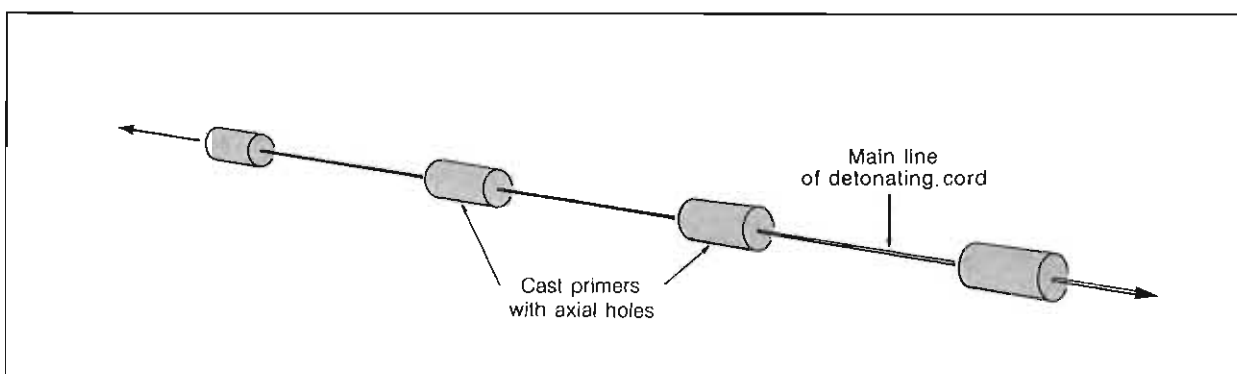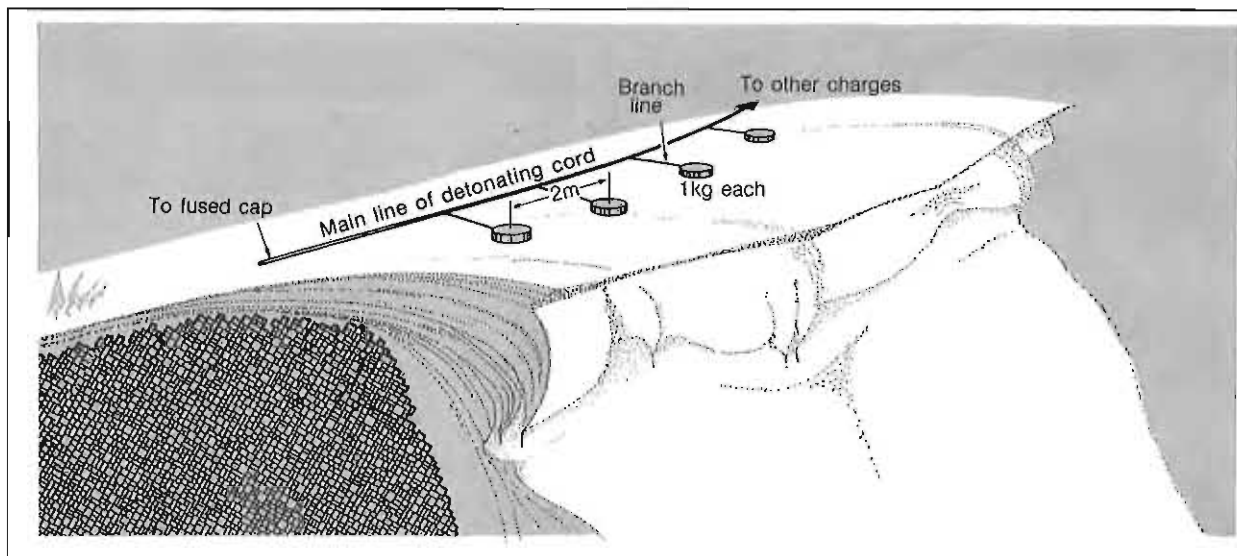
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Figure 151.—Cornices may be blasted with 1-kg surface charges of cast or gelatin primers, or the equivalent. The charges are spaced 2 m apart and connected to a main line of detonating cord by branch lines. For some types of cast primers, it is possible to run the main line directly through the axial hole of the primer, as shown.

The recommended steps in borehole blasting are as follows:

(1) The driller, belayed securely, steps into position on the safe side of the working line and drills a row of holes up to 1 m in depth, but no deeper than half the thickness of the roof. The boreholes should be as close as possible to the potential tensile fracture line of the cornice.

(2) The diameter of the holes should be such that the charges fit as tightly as possible. The holes should be spaced 2 m apart. Since cornice snow is normally quite hard, boring will require a soil auger of diameter appropriate to the charge.

(3) After all holes are bored, the main line of detonating cord is strung out. To prevent loss of explosives in the event of a sudden cornice collapse, a free end of the main line should be secured to an anchor until the system is ready to be detonated.

(4) A charge laced with a 2-m branch line is inserted into the first hole. The branch line is connected to the main line, and the hole is refilled with snow and stemmed (tamped) compactly.

(5) After all boreholes are prepared in a similar manner, a free end of the detonating cord is armed with cap and fuse. Firing takes place after the usual check with the posted guard.

Whereas surface blasting of cornices requires 1-kg charges, buried charges can be limited to about 0.5 kg per hole. All of the recommended explosives for slope control (see table 6) can be buried. Moreover, it is not necessary to penalize explosives for low detonation pressure in comparison to TNT; in fact some
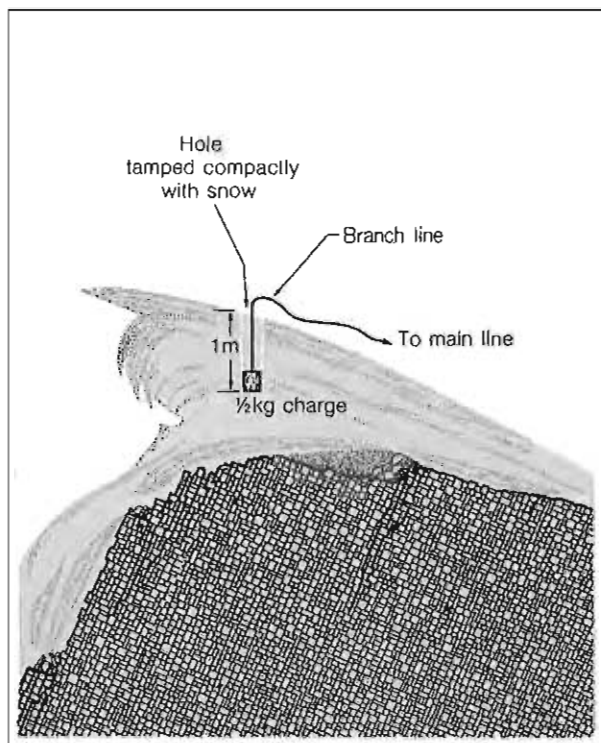
Figure 152.—Borehole blasting requires half the explosive used in surface blasting (0.5 kg of buried charge compared to 1 kg of surface charge). Buried charges should fit snugly in the base of the borehole. The hole is then filled and stemmed (tamped) compactly. The charges should be buried no deeper than about 1 m.

field evidence favors low-detonation-pressure explosive for buried-charge cornice blasting.

Because detonating cord plays an important role in cornice blasting, one should be acquainted with the basic techniques for working with this high explosive. The following points should be kept in mind:

• Use reinforced detonating cord. This gives an extra margin of safety by retaining the explosive system should the cornice fail during preparation.

• Because of knot-tying problems, do not use detonating cord with an outside plastic sheath.

• Kinks and sharp bends are to be avoided.

• Special care should be taken in cold weather to avoid breaking or cracking the cord.

• Detonating cord lines should be laid out as straight as possible but not stretched taut.

• Main lines can be spliced with conventional square knots; the knots should be pulled tight. Leave 10 cm of free end. Splices should be kept to a minimum.

• Branch lines should be connected to the main line with a girth hitch or clove hitch to achieve a 90° tie. Tighten up securely and leave a 10-cm free end.

• Wet detonating cord loses sensitivity. Keep the cord as dry as possible during storage and handling. While blasting wet-snow cornices, take special precautions to keep the free end, where the cap is attached, as dry as possible.

• Any number of branch lines can be connected to the main line; however, connections should not be made at a splice.

It should be clear that blasting massive cornices requires adequate manpower and special equipment. A typical blasting operation should include a minimum of four qualified avalanche workers plus the blaster-in-charge, who distributes and supervises the various jobs. The minimum equipment needed in massive cornice operations is quite impressive. The blaster-in-charge should be certain that the following equipment is taken:

• Adequate clothing for ridgetop conditions (Hypothermia is a serious threat and can dull senses just when alertness is needed.)

• Adequate footwear (generally double mountaineering boots, rather than competition plastic ski boots)

• The required explosives, caps, detonating cord, safety fuse, and igniters

• Flagging to identify the working line

• Auger, if charges are to be buried

• Belay rope (and slings and carabiners as required for anchor)

• Snow pickets, if required for anchors

• Radios

• Collapsible probes and avalanche transceivers (see chapter 8).

Blasting a massive cornice presents many technical problems as well as high costs. Serious thought should be given to the alternative, controlling the cornice with preventive structures installed near the ridgecrest. The general subject of structures for avalanche control is presented in chapter 7.

Figure 153 (on page 135).—A, Sections of main line are spliced with a conventional square knot. B, Branch lines are joined to the main with a girth hitch. C, Technique for connecting branch line to cast primer.

A

Main line

To other charges

90°

Branch line

B

C
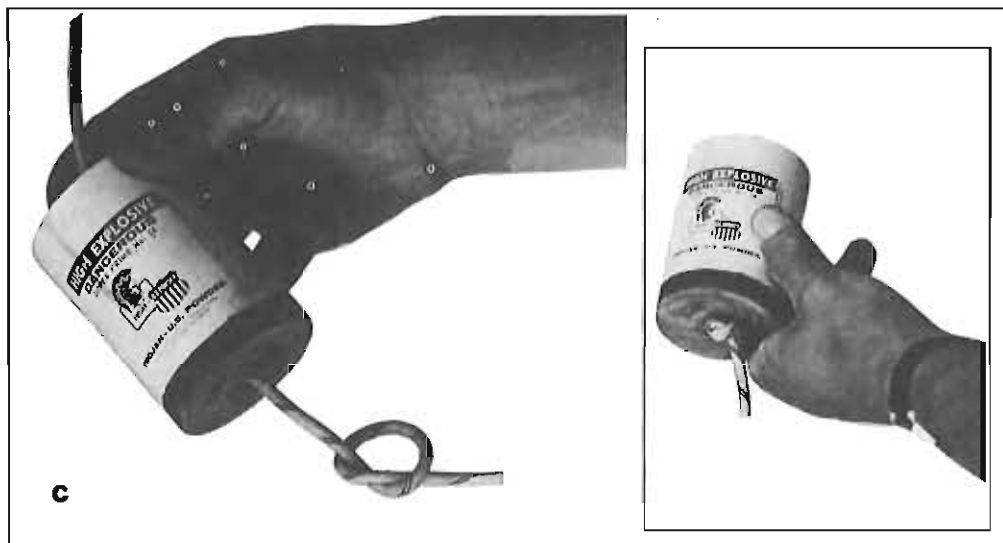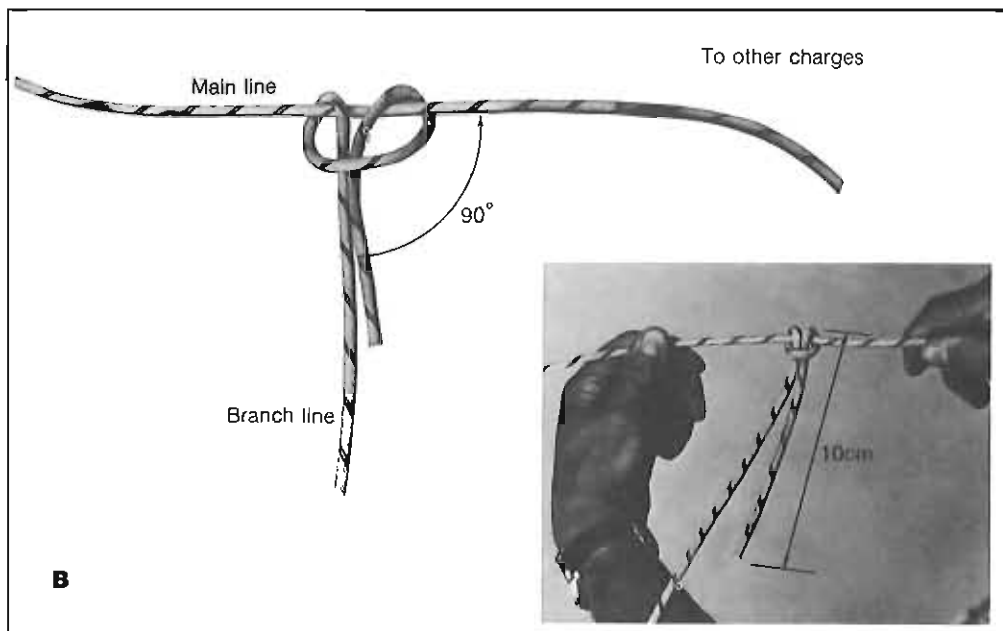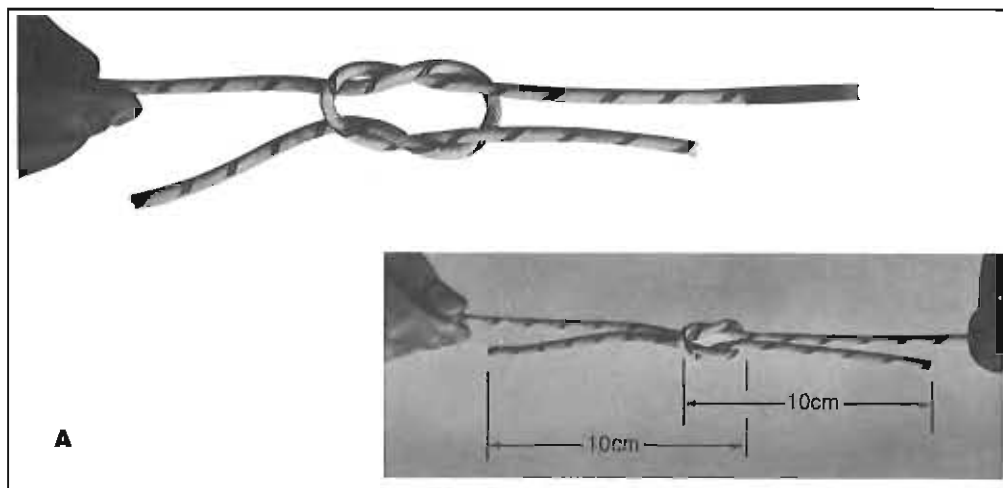
Use of artillery

Military weapons may be used where it is unsafe or impractical to blast with hand-placed explosives. Many remote avalanche paths that endanger highways are routinely blasted with artillery (according to techniques described in chapter 7). Artillery is also used to blast remote avalanche paths that affect ski runs. There are several problems, however, that planners must consider before embarking on an artillery control program in a ski area. For example:

• Obtaining military weapons and ammunition is becoming increasingly more difficult and expensive.

• The military does not remanufacture weapons no longer required for national defense, and it is difficult to obtain artillery pieces, replacement parts, and ammunition for weapon systems no longer in current production.

• Obsolete weapon systems brought into the field after long-term storage suffer some loss in reliability and safety.

• Artillery pieces, replacement parts, and ammunition are relatively expensive.

• Reliability and safety decrease if ammunition is not stored properly in the field. Ammunition storage facilities are expensive.

• Reliability and safety decrease if pieces are not maintained properly. Maintenance involves additional expense and manpower.

• Gun positions must be sturdy, and the artillery pieces should be secure from theft, which means more expense.

• Artillery rounds are designed to detonate against hard objects. Deep snow slabs have a cushioning effect; the result is an intrinsic dud rate in avalanche work of about 1 percent (compared to about 0.1 percent for hand-thrown explosives). Duds are clearly undesirable in any area used by the public.

• Backblast and concussion can shake buildings and break windows up to 500 m away.

• *Shrapnel is a major problem to be considered at all times.* While it is true that most shrapnel is confined to within 100 m of target center, freak pieces of shrapnel travel considerably farther. In at least one case an avalanche worker was struck by a piece of shrapnel that ricocheted 1,000 m from the target. Shrapnel is also a serious hazard in storage and in some situations results in prohibitive costs.

The above problems are serious enough that full consideration must be given to alternatives. In planning new developments, the developer should realize that the difficulty of procuring obsolete weapon systems, irrespective of cost, is increasing. Existing ski areas with operations that depend on military artillery are expected to deplete the present inventory of obsolete ammunition in the near future. Planning for any new ski developments must *demonstrate the feasibility of avalanche control and snow safety without military weaponry.*

Many of the problems associated with military artillery are solved when the pieces are fired and maintained by military units serving winter or mountain-warfare training assignments. Avalanche workers who are familiar with local terrain can function as civilian advisers to military units. This system works quite effectively in Switzerland and Canada (see chapter 7). If civilians are responsible for firing and maintaining weapons, it is essential that they receive training from military units. No attempt will be made in this handbook to cover military guidelines and field-manual material, such as U.S. Department of the Army (1957, 1958a, 1958b, and 1962), which, if followed strictly, result in a high standard of safety and efficiency.[4]

At present, the military artillery used in ski area control are the 75-mm recoilless rifle, the 75-mm howitzer, and the 105-mm recoilless rifle. The 105-mm howitzer is excellent for highway control, but it requires a five-man military crew and is too cumbersome for ski-area work. It is thought that the 57-mm military ammunition has too small a charge to be effective,[5] while the 155-mm howitzer is too large and complex. Unfortunately, existing high-explosive (HE) ammunition for the 90-mm recoilless rifle has insufficient range for avalanche work. The 106-mm recoilless rifle should be satisfactory, but it is in use by the military and has not been released for avalanche work. Considering accuracy, crew safety, dud problems, and simplicity, most mortars, rockets, and related systems are poor second choices to recoilless rifles or howitzers.

Characteristics of the 75-mm recoilless rifle (fig. 154), 75-mm howitzer, 105-mm recoilless rifle (fig.

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[4]D.C. DuLac. Firing Manual, 75-mm and 105-mm Recoilless Rifle. Information on file at U.S. Forest Service, Region 6, Portland, Oreg.

[5]However, a 57-mm projectile designed specifically for avalanche work could carry a standard charge of 1 kg of TNT.

131), and 105-mm howitzer are summarized in table 7. Information on the 106-mm recoilless rifle is also included for possible future reference. Since all the listed weapons deliver a large enough payload to release avalanches, the choice of weapons should be based predominantly on range requirements. As a general rule, slab targets should be within half the rated maximum range of the weapon. At half range, it should be possible to maintain acceptable accuracy despite high winds and other contingencies. Also, at half range it should be possible to fire the weapons accurately with aiming-stake references, as well as with direct visual sight on target. For targets beyond half range, accuracy decreases drastically, and the number of duds becomes unacceptable.

If range is not a problem, the 75-mm recoilless rifle is probably the best military piece available, considering cost and flexibility. It is light enough to be moved routinely by truck, snowcat, toboggan, or lift from a sheltered and secure storage to a temporary or permanent firing position. One class of ammunition for the 75-mm weapons has somewhat less payload than the recommended 1-kg TNT equivalent. However, judging by the excellent safety record for the 75-mm weapons in past years, the payload seems adequate. (In this connection, postcontrol releases have occurred after slopes were hit with 105-mm ammunition; firing larger rounds is no guarantee against postcontrol release.)

Only two types of recoilless-rifle and howitzer ammunition are considered satisfactory for avalanche work; namely, *High Explosive* (HE) and *High Explosive Plastic* (HEP, HEP-T). The *High Explosive Anti-Tank* (HEAT) round is intended for armor piercing and is not suitable for avalanche work. The 90-mm HEXM is also disqualified because of its low range.

HE rounds contain a payload of TNT (or the more powerful composition B) in a relatively thick steel encasement. The rounds are intended to produce shrapnel and blast damage. HE rounds may be detonated by several types of fuses. Avalanche workers are advised to use only the impact type of fuse, specifically the Type M557 Impact Fuse. This fuse does not arm the round until the round has traveled a fairly safe distance from the barrel. Thus, crew safety is improved should the round detonate prematurely because of collision with precipitation particles or some other obstacle. Other types of fuses, known as time fuses and time-impact fuses, are designed to detonate HE rounds in midflight, or at a certain distance from

Figure 154.—Recoilless rifle, 75 mm, fired as a portable weapon from a temporary position. Gunner's ears should be protected from blast noise.

the target. Rounds equipped with these fuses should be handled only by military crews.

The impact fuse on HE rounds is a point-detonating (PD) component in the nose cone of the round. The PD component can be set to detonate either instantaneously on impact (the so-called "super-quick" setting) or with a small time delay of 0.05 second after impact. If the "super-quick" element does not function, the delay component takes over to detonate the round, giving extra assurance against obtaining a dud. HE rounds are normally shipped with the "super-quick" setting. Avalanche workers are advised to use only the "super-quick" setting in order to maintain a low dud rate.

HEP (HEP-T) ammunition carries about 75 percent more payload than HE ammunition. The intended effect of HEP ammunition is to squash against a tilted armor plate, detonate, and produce "scabbing"; that is, turn the back side of the plate into shrapnel. Shrapnel from the round itself is minimal, but still dangerous. Shrapnel weight is replaced by composition A3, which is more powerful and sensitive than TNT. Because the round is designed to "squash" against armor, the explosive is detonated by a fuse located in the base of the round. The base-detonating fuse (Type M91) is actuated by the deceleration of the charge on impact. The round is armed almost immediately after leaving the weapon; however, the

base-detonating fuse is not apt to function prematurely on collision with precipitation particles. After hitting a solid target, the round detonates without delay. There is no setting on the fuse.

The increased payload and reduced shrapnel of the HEP round is, of course, very desirable in avalanche work. Unfortunately, the base-detonating fuse may not be activated by a snow target. A rather high proportion of duds can be expected when HEP rounds are fired against deep slabs. The dud rate is substantially reduced if the HEP round is fired into a shallow region of the slab, perhaps into rock bands immediately above or to the side of the slab. The increased explosive payload of the HEP round appears to generate a large enough shock wave in the ground to compensate for deviation from normal target center.

Because of the sensitivity of composition A3, HEP rounds are more hazardous in storage than HE rounds. Accidental detonation of an HEP round is likely to detonate the entire storage supply.

Up to the mid-1970's, about 100,000 rounds were fired at avalanche slopes with no casualties caused by malfunction of ammunition or artillery piece. The one death attributed to artillery occurred when an experienced avalanche worker inexplicably stepped behind a 75-mm recoilless rifle. The victim had fired the weapon many times and was well acquainted with the backblast force. During this time, about 1,000 duds were destroyed in the field without mishap. Most duds were not armed, but each was handled with great respect (see the next section, "Artillery Techniques").

TABLE 7.—*Military artillery suitable for avalanche control*

Artillery piece and weight	Round	Fuse	Maximum range[a] (m)	Payload[b] (kg)	Weight of complete round (kg)	Length of complete round (cm)	Muzzle velocity (m/s)	Armed distance[c] (m)
75-mm howitzer M1A1 Weight: 230 kg	HE M48 (4 bags)	PD M557	8,800	0.7 TNT	8	60	380	61+
75-mm recoilless rifle. M20 Weight: 80 kg	HE M309A1	PD M557	6,350	0.7 TNT	10	73	300	61+
	HEP-T M349	BD M91A1	6,350	1.2 A3	8	67	430	1.5
105-mm howitzer M2A4, M4A1, M49 Weight: 2,260 kg	HE M1	PD M557	11,300	2.3 TNT	19	79	480	61+
	HEP-T M327	BD M62A1 M91	8,670	3.5 A3	15	74	720	1.5
105-mm recoilless rifle. M27A1 Weight: 320 kg	HE M323	PD M557	8,600	2.0 TNT	19	79	480	61+
	HEP-T M326	BD M62A1 M91	7,550	3.4 A3	19	97	380	1.5
106-mm recoilless rifle.[d] M40A1 Weight: 210 kg	HEP-T M346A1	BD M91A2	6,850	3.5 A3	19	97	500	1.5

[a]For avalanche work, target distance should not exceed half the maximum range.

[b]Composition A3 is a military explosive that has about a 40 percent higher detonation pressure than TNT. It contains 91 percent RDX and 9 percent desensitizing wax. The explosive is more sensitive than TNT and can be detonated with a No. 6 blasting cap.

[c]Distance out from barrel required for fuse to arm round.

[d]106-mm recoilless rifles have not been released for avalanche work.

Artillery techniques

Before firing an artillery piece, avalanche workers should be quite certain that no person or facility will be hit by shrapnel or blast. Except for the gun crew, no one should be allowed to stand exposed within 1,000 m of the target area. Targets should be no closer than 300 m to ski lifts or other vulnerable facilities. Gun-to-target distance should be no less than 500 m for 75-mm ammunition and no less than 700 m for 105-mm ammunition.

Quality control of ammunition is good, but not perfect. Rounds may land short of target by a wide error. To prevent damage caused by short rounds, one should avoid aiming over vulnerable facilities. Also, the line of fire should diverge away from roads and other developed areas.

Under no circumstances should a round be fired when there is chance of overshooting the target and hitting a developed area. If there is any question, the flight trajectory should be plotted on a topographic sheet. Targets near ridges should be hit purposely low, at least 50 m below the ridgecrest for each 1,000 m of target distance. The sight assembly should be mounted correctly and firmly in its housing on the artillery piece; this should be checked routinely, especially before high ridge shots. It is also important periodically to check sight alinement by boresighting the weapon. A sure way to prevent overshooting is to install an overshoot guard as shown in figure 156.

Firing positions are selected on the basis of several considerations: safety, backblast and concussion, target coverage, accessibility, and working conditions. There can be no compromise on crew safety. All firing positions should be free from avalanche danger either originating at the target or as sympathetic releases from nearby slopes. Backblast and concussion effects on fixed facilities should be minimum. Dangerous backblast cones extend about 100 m behind recoilless weapons. Concussion zones can extend much farther, depending on the weapon, terrain, amount of snow on the ground, and atmospheric conditions. Large win-

dows directly behind a 75-mm recoilless rifle and within about 500 m are apt to be broken. The concussion is not as great to the side, but it can still break windows perhaps 250 m directly to the side. Windows may be protected by shutters. Concussion from 75-mm howitzer fire is not as intense.

If crew safety and concussion effects are not problems, the choice of firing positions is made by weighing the benefits of target coverage versus accessibility
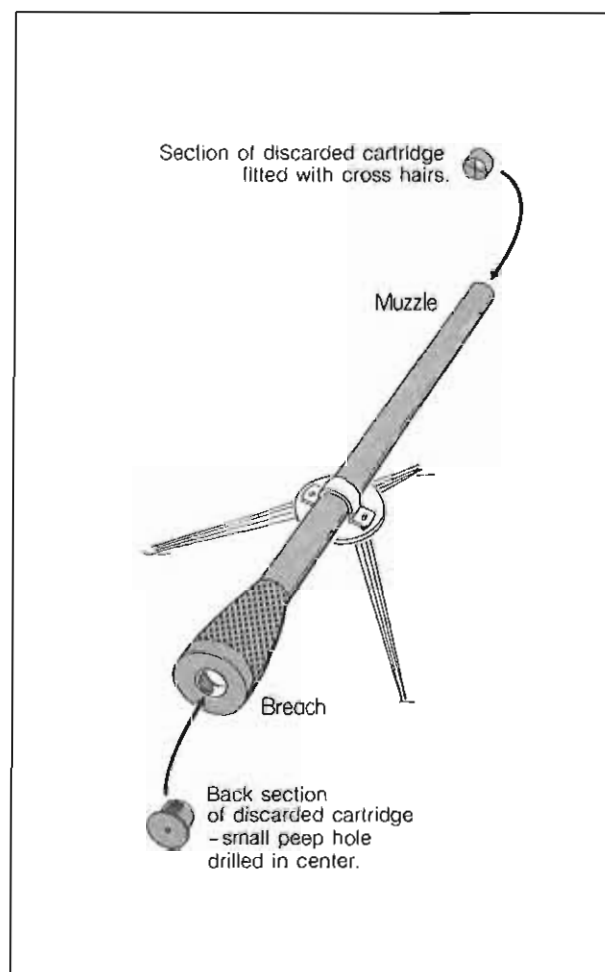

Figure 155.—Sight alinement should be checked occasionally by boresighting on a target about 1,000 m from the weapon. Boresighting equipment can be made from a discarded cartridge sliced into two sections as shown in the figure.

Figure 156.—Overshoot guard at Carson Pass, Calif.

Figure 157.—Reinforced concrete enclosure used to protect a 75-mm howitzer at Snowbird, Utah. The howitzer pivots on a large steel plate.

and working conditions during inclement weather. Before operation, at least 1 year of reconnaissance is needed to select the best sites.

Figure 158 shows two gun towers; one constructed with tubular steel, the other with corrugated pipe. Both types of construction are satisfactory. The tower should be protected from lightning. Figure 157 shows a reinforced concrete enclosure for a 75-mm howitzer. The howitzer pivots on a large steel plate to facilitate rapid and efficient coverage of the target area. When the howitzer is not being used, the enclosure is sealed off by sliding wooden doors. The cost of such a sophisticated facility is prohibitive unless a ski area has very pressing avalanche problems.

There are two methods for sighting artillery. If the starting zones are visible, artillery may be sighted directly with a telescopic sight. This is called direct sighting. The alternative, which is used when the starting zones are not visible, is indirect sighting. Essentially, indirect sighting consists of:

• Putting the artillery piece in a sturdy mount

• Setting the horizontal and vertical adjustments on an indirect sight, which is firmly mounted on the piece

• Elevating and traversing the weapon until the cross hairs of the indirect sight aline with a reference point on an aiming stake about 10 to 30 m from the weapon.

Indirect sight data must be set up carefully and periodically checked by firing indirectly when starting zones are visible. Before firing, it is necessary to

Figure 158.—Examples of gun towers used in avalanche control.

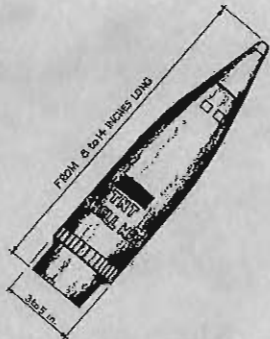Figure 159.—Direct sighting of 75-mm recoilless rifle during clear visibility.

Figure 160.—Indirect firing during poor visibility. Gunner alines sight on reference (right).

DANGER

EXPLOSIVES ON THE MOUNTAIN

unexploded warheads used in avalanche control
may be found lying in target areas

UNEXPLODED WARHEAD
(warhead may be distorted)

IF YOU FIND A WARHEAD DO THE FOLLOWING

1- do not disturb or touch
2- mark location, 10ft. away, with rock, bright cloth, etc.
3- immediately report location to district forest
ranger at 524-5042

Figure 161.—Dud warning sign on the USDA Forest Service garage at Alta, Utah.
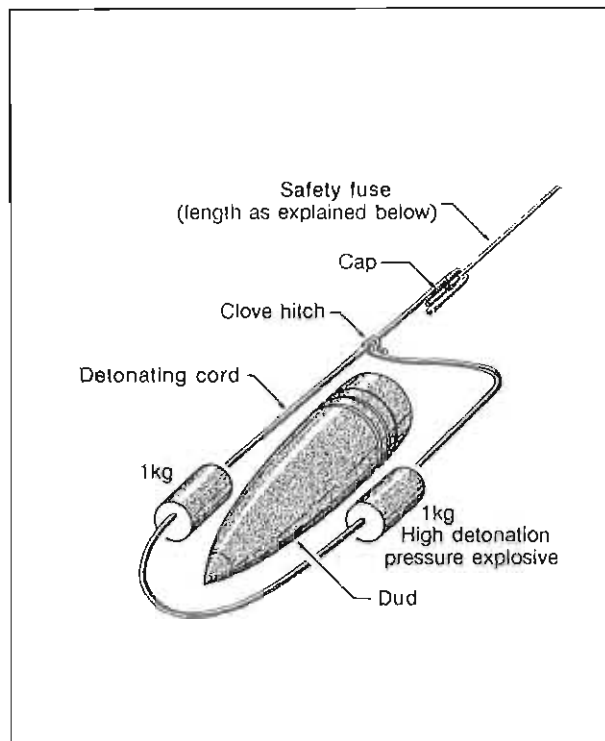
Figure 162.—Duds should be destroyed by a qualified blasting crew. Two blocks of high-detonation-pressure explosive, each at least the equivalent of 1 kg of TNT, are placed along the sides of the dud, close to the dud but not touching. The explosives are detonated simultaneously by detonating cord. Leave enough escape time in the fusing to retreat from the shrapnel zone (1,000 m in the open or behind good cover).

double check the indirect settings as follows: The first gunner calls out the target name and the horizontal and vertical settings; the second gunner sets the indirect sight; and the first gunner checks the settings.

As mentioned earlier, a 1-percent artillery dud rate can be expected in avalanche work. All duds should be considered dangerous and armed; the duds should be disposed of in place, preferably by military demolition crews. The location of each dud should be carefully noted on a photograph of the target area. Duds will penetrate to the ground and cannot be recovered until the snow melts in early summer. It is wise to begin the search as soon as the snow melts, before the summer growth of vegetation. Searching for duds can be tedious if performed by one searcher. It is advisable to flag the area and bring in a rather large crew.

If a military demolition team is not available, duds may be destroyed by qualified blasters. Since the blasting operation is conducted in the summer, precautions

against fire may be necessary. If the duds are not armed, they may be surprisingly difficult to detonate. The recommended procedure is to use two charges of a military or commercial explosive with a high detonation pressure. The amount should be at least the equivalent of 1 kg of TNT per charge. The charges are placed on both sides of the dud, as close as possible without disturbing the dud. The charges are detonated simultaneously by detonating cord, using a fuse long enough to leave time to withdraw from the shrapnel area, at least 5 minutes. Dud terrain should be posted with warning signs that advise the public about procedure to be followed should a dud be encountered.

Planning the control program

Many avalanche problems at ski areas could have been avoided had the developer given more attention at the outset to studying and planning the avalanche control program. At the time a new development or expansion is proposed, the developer should prepare an initial avalanche study. The initial avalanche study should include (1) identification of the hazard and (2) proposed control, including costs.

Hazard identification is based on techniques described in chapter 4 under "Identification of Avalanche Paths." The starting point is a thorough reconnaissance of the area in winter and summer. On the basis of the reconnaissance, it is possible to prepare a map and description of the hazardous paths in the proposed development. At the same time, meteorological and snowpit data should be collected, to indicate avalanche size and frequency. An example of a hazard identification is shown in figure 163 and table 8 (on page 144).

After the hazard is identified, a control plan must be prepared. Among other things, this shows:

• Method of control for each avalanche path (or group of paths)

• Routes for ski-testing and control and for blasting

• Facilities to shelter the control teams

• Storage facilities for explosives

• Stability evaluation instruments and equipment

• Operational procedure for various conditions

• Manpower needs and organization of manpower, including leadership, training, and career ladder

• Costs.

TABLE 8.—Hazard identification and control for Berthoud Pass, Colorado (mean elevation 3,500 m)

Number on photo map[a] (fig. 163)	Name	Approximate number of avalanches per season	Approximate starting zone angle	Aspect	Description	Hazard	Snow weather conditions
1	Timber	6	42	NNE	Several small paths in timber	This group of paths is a hazard to descending skiers and to the base facilities.	Wind loaded by strong prevailing west to northwest winds. Deep instability caused by TG metamorphism is quite common. Slab thickness varies widely; average about 1 m thick.
2	Trough	4	37	ENE	Wide gully		
3	Lift gully	16	42	E	Deep gully beneath cornice		
4	Cliffs	9	40	E	Spills over cliffs		
5	Roll	4	40	ENE	Open slope beneath convex roll		

[a]Avalanche paths 3, 4, and 5 are permanently closed to the public. Avalanche paths 1 and 2 are ski compacted by a professional ski patrol and opened to the public. Handthrown explosives are periodically used on paths 2, 3, and 4. Path 5 is not controlled.

If the expansion or new development is feasible and is approved, the next step is to work up a detailed *avalanche control plan* for the new area. This valuable document, written during the construction of the new area, serves as an operating manual for day-by-day problems. It is an extension of the initial avalanche study. Whenever possible, it should be written by experienced personnel who are intimately acquainted with the terrain and meteorological conditions. The services of experienced avalanche workers should be enlisted from the beginning. The avalanche control plan may be part of a more general snow-safety plan; however, many areas with severe avalanche problems may prefer to work up the avalanche control plan as a separate manual.

Undoubtedly, the control plan will evolve and improve with operating experience. However, a developer is responsible for maintaining safety from the instant the development is opened to the public, and the first edition of the control plan should be well along toward a finished product by the time the area opens. From the first the person responsible for snow safety, such as a mountain manager or ski patrol leader, must be designated clearly and distinctly.

One important function of the control plan is to explain how hazardous areas are checked systematically by control routes. Control routes are normally skied early in the morning before the public arrives. Each control route is skied by at least two avalanche workers who should not have to carry any more than 15 kg of equipment per man, including explosives, a radio, an avalanche transceiver, and other safety equipment. Control routes usually work down the mountain, following ridges and threading from one safe location to another. The routes may crisscross, and the progress of one crew may depend on the results of another crew. On the more complex routes, signs should be posted indicating blasting positions.

If control routes are intricate, it is wise to permanently assign one crew to each route. Permanent assignments define responsibilities. Also, a crew can become quite familiar with snow conditions on its route and can watch for developing instability throughout the day. It is wise, however, to rotate crew members often enough that others can take over a route in case of sickness or accidents to the regular crew members.

Daily control methods depend on the stability evaluation, which, as explained in chapter 5, is adjusted continually depending on control results. Normally, the avalanche control leader briefs the control teams in the morning on stability conditions as they appear before the control routes are skied. He then advises the teams on the amount of explosives to be taken on each route, the slopes to be opened and closed, the slopes to be intensively control skied, etc. Teams often run into conditions not anticipated in the morning stability evaluation. This requires decisions concern-

Figure 163.—Hazard identification for a small ski area at Berthoud Pass, Colo. The existing lift is AB. The proposed (never seriously) expansion by a lift BC is not feasible because of severe weather and avalanche problems. If lift BC were built, the public would need protection from the avalanche hazard in the cross-hatched areas (see table 8).

ing public safety to be made at the control-team level, and the control teams must have experience and competence to match the responsibility. They should also maintain radio contact with other teams and the avalanche control leader so that significant differences from anticipated conditions are quickly passed on.

Many excellent control plans have been prepared. The interested reader is referred to Aspen Skiing Corp. (n.d.), Hastings et al. (1969), and Krisjansons (1971).

To be profitable, few ski areas can rely entirely on closing runs and allowing the snow to stabilize naturally, even though such techniques require the least capital outlay. Most ski areas that suffer from recurring avalanche hazards use artificial stabilization to some extent.

In estimating the cost of reducing hazards, a number of conditions must be considered:

- Frequency of avalanche hazards during the skiing season.

- Amount of available, skiable terrain affected by the hazard.

- Need to protect lifts and other physical improvements such as buildings, access roads, and parking lots from avalanche damage.

Figure 164.—On the more complex routes, it is necessary to mark blasting positions with small signs.
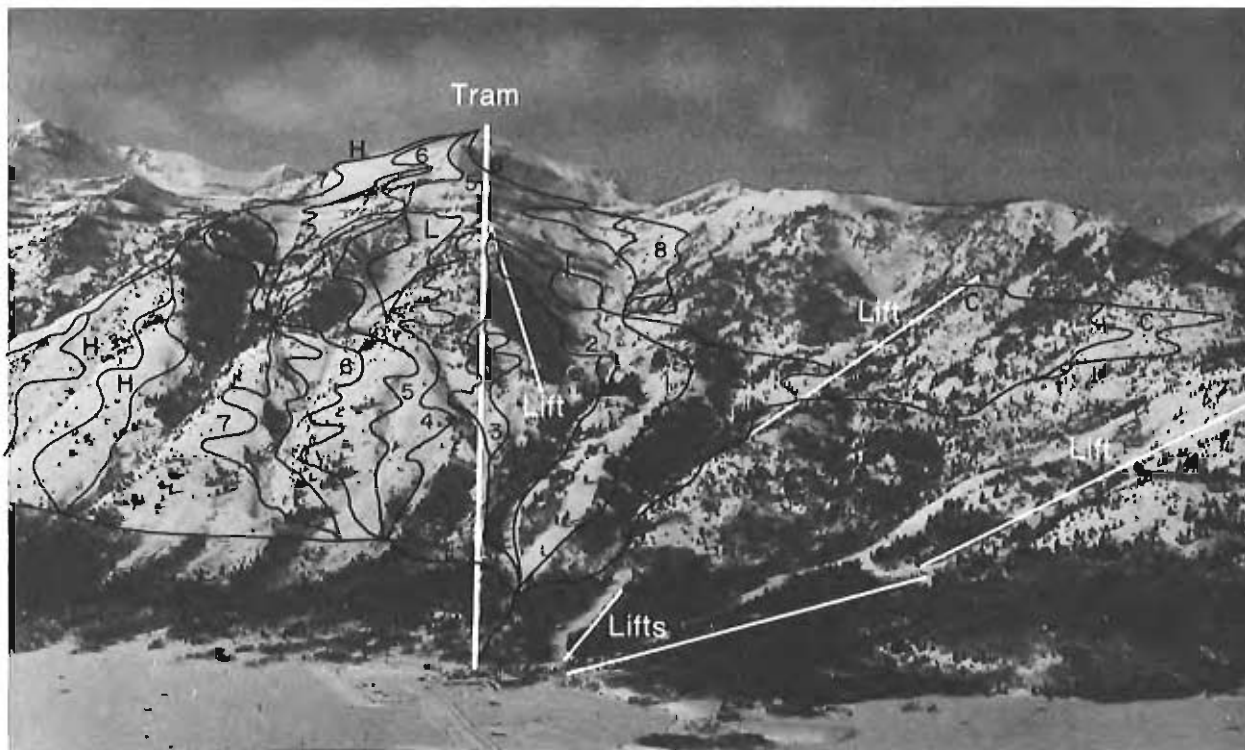
Figure 165.—Intricate system of control routes at the Jackson Hole Ski Area, Wyo.

• Kind of clientele served by the area. If the customers are vacationing skiers who have traveled a considerable distance, they will not be pleased to find the slopes closed. Day skiers who live nearby are more willing to accept avalanche closures and can be more easily informed by radio and television announcements.

• Relative costs and benefits to the area of various intensities of control programs. For example, during times of high avalanche hazard the policy may be to have: (1) all slopes open daily at 9 a.m., (2) some slopes open daily at 9 a.m. and others closed until noon or 1 p.m. to allow for avalanche control during the morning hours, or (3) no slopes opened until the snow stabilizes naturally.

• Relative demand for specific kinds of slopes. Spending large sums to keep certain slopes open may not be economic if they are used by only a few exceptionally skillful skiers. Such a procedure generates little additional revenue.

PROTECTION OF SKI AREAS

Further reading

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Mellor, Malcolm.
1965. Explosives and snow. Cold Reg. Sci. and Eng., Part III-A3a, 34 p. U.S. Army Corps Eng., Cold Reg. Res. and Eng. Lab., Hanover, N.H. *Rather technical coverage of the effects of explosives on snow and of snow on explosives. Mostly related to polar conditions. Use for avalanche control is given very brief mention.*

Mellor, Malcolm.
1968. Avalanches. Cold Reg. Sci. and Eng., Part III-A3d, 215 p. (see especially p. 121–139). U.S. Army Corps Eng., Cold Reg. Res. and Eng. Lab., Hanover, N.H. *State-of-the-art paper covering all phases of avalanches and their control.*

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Protection of highways and villages

This chapter starts with a discussion of structural control of avalanches. Certain kinds of structures can be built in the starting zones to keep avalanches from starting and to influence snow deposition patterns. Other kinds are placed in the track and runout zone to guide avalanches away from objects or to give direct protection. Artillery can be used to protect highways, but it has serious limitations when avalanches threaten towns or dwellings. In the case of highway protection, shooting is intended to release the avalanches before they get large enough to reach the road. This requires a good method of stability evaluation, backed up by an organized artillery team ready to fire at any time and under any weather conditions. The chapter continues with factors to be considered when planning a highway avalanche-control program, using the Trans-Canada Highway as an example. Finally, avalanche zoning and avalanche warnings are discussed as ways of avoiding additional avalanche problems and of informing the public during high-hazard periods.

Figure 166.—A century of avalanche defense at Davos, Switzerland. Ancient masonry walls and terraces, with Arlberg fences added later, are flanked by modern structures. (Photo by Wengi)
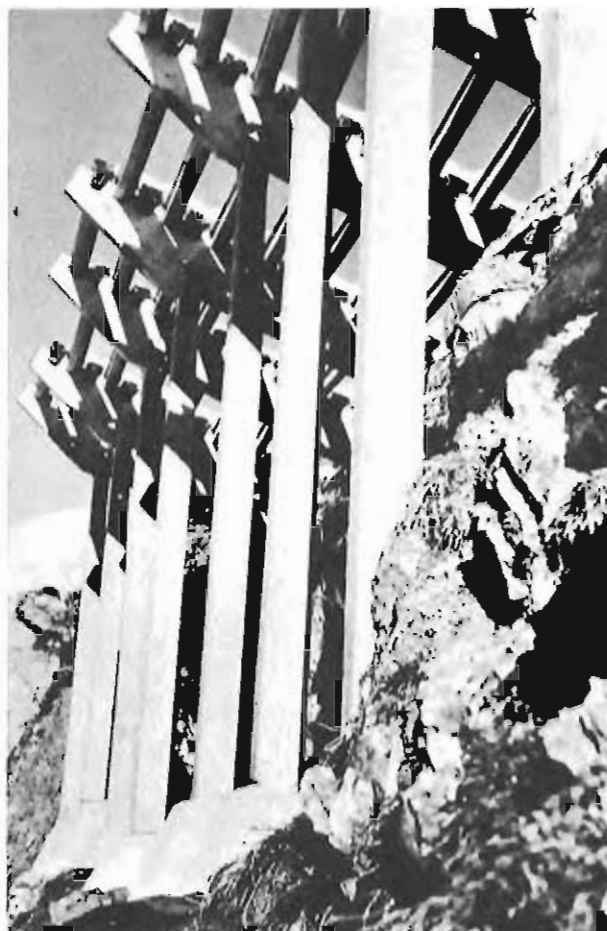
Figure 167.—Rigid supporting structures in the starting zone can be made from a variety of materials: Top left, aluminum frame and braces with wood crossbeams on the grate. Single snow bridges are no longer used; a continuous line of bridges is better. Mattstock Avalanche, near Amden, Switzerland (Wagner and Hopf 1959). Bottom left, aluminum snow bridges. Mattstock Avalanche, near Amden, Switzerland (Wagner and Hopf 1959). Top right, prestressed .concrete snow bridge. Kühnihorn, near St. Antönien-Castels, Switzerland (Frutiger and Martinelli 1966).

Defense structures

Many types of structures are used throughout the world to defend against avalanches. Massive earth, stone, or concrete walls, terraces, and mounds that require little or no detailed design have been used for more than a century in central Europe. Lighter weight, open structures of wood, aluminum, steel, prestressed concrete, or some combination of these materials have evolved in recent years, after enough was learned about snow pressures to permit proper design.

The wide variety of avalanche defense structures can be classified in four groups: (1) Supporting structures in the starting zone, (2) deflecting and retarding structures in the track and runout zone, (3) direct-protection structures in the runout zone, and (4) snowfences and wind baffles.

Supporting structures in the starting zone. This kind of structure is built in the upper part of the avalanche path to prevent avalanches from starting or to catch any that do start before they gain momentum. The earliest supporting structures were massive walls and terraces made of stone and earth. These were intended

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to interrupt the continuity of the snowpack and were moderately successful in some places as long as snow depths were not great and the structures were kept in good repair (fig. 166).

During the 1930's and 1940's scientists working mainly at the Swiss Federal Institute for Snow and Avalanche Research (SFISAR) in eastern Switzerland learned enough about the forces in snow cover lying on steep slopes to permit the design and construction of lightweight structures. At first these were open wood and metal units with the grates almost horizontal. They looked something like bridges and functioned much like terraces.

Modern supporting structures in the starting zone may be rigid, flexible, or a combination. They can be made of wood, steel, aluminum, prestressed concrete, or a combination of these materials (fig. 167). Today the most commonly used material is steel. Some structures have crossbeams that are horizontal, and some have crossbeams that are roughly perpendicular to the slope. The former are called *snow bridges*, the latter *snow rakes*. These structures are tilted about 15° downhill from the perpendicular to the slope to get better support from the back braces without sacrificing too much effective height. The structures are usually arranged in continuous lines or segments of lines. In a few cases, the grates or open supporting structures are vertical; these are called *fences*. Snow bridges, snow rakes, or fences may be combined with earth walls or terraces to gain height in areas of deep snow.

Snow nets are flexible supporting structures (fig. 168). Steel cables are used to form the nets, which are held up by steel poles guyed with cable at the top. Although good foundations are needed for all supporting structures, bedrock anchors are required for nets. Use of this kind of structure is limited to slopes with snow depths not much greater than 2 m and with little rockfall.

Supporting structures are expensive to install and maintain, not only because of the materials involved, but because of the access problem at most sites. Their reliability when properly planned, installed, and maintained makes them desirable where the starting zones of the avalanches are relatively small and the objects to be protected are numerous and valuable, such as the homes and buildings of a town. To be effective, supporting structures must be taller than the snow cover and must be designed to support the snow above themselves and to catch and hold small avalanches that might start in the protected area. Details for plan-

Figure 168.—Snow nets are flexible supporting structures. The triangular-shaped nets of wire rope are hung on tubular steel posts. Kneugrat, Braunwald, Switzerland (Frutiger and Martinelli 1966).

ning and designing avalanche control projects using this type of structure are given in SFISAR (1961) and Frutiger and Martinelli (1966).

Deflecting and retarding structures. These are massive structures usually made of earth, rock, or concrete and located in or near avalanche tracks or runout zones. They are intended to keep the moving snow of an avalanche away from valuable objects.

Structures to deflect moving snow should divert it as little as possible from its normal direction of flow (fig. 169). Deflections no greater than 15° to 20° have been most successful. Walls built at sharp angles to the flowing snow are likely to be overrun by fast-moving masses of dry snow. The contact faces of deflecting walls and dikes should be as smooth and steep as possible.

Retarding structures are usually earth mounds or dams (fig. 170) built on benches or gently sloping parts of paths where avalanches slow or stop naturally. The additional roughness and cross-currents set up in the moving snow by these structures usually
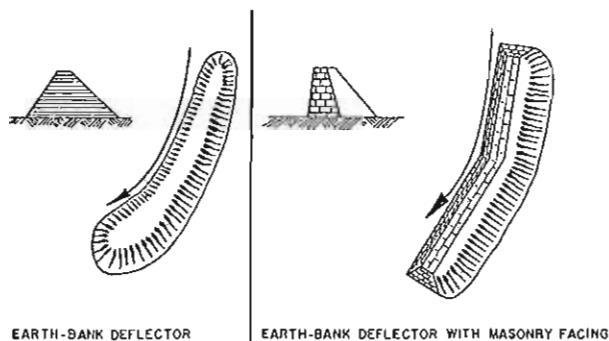
EARTH-BANK DEFLECTOR   EARTH-BANK DEFLECTOR WITH MASONRY FACING

Figure 169.—Deflecting structures: Top, sketches of earth or earth and masonry walls (Mellor 1968); bottom, concrete walls backfilled with earth to keep the avalanche that runs down the stream channel left of the fence from spreading to the right (Beratungsstelle für Stahlverwendung 1962).

stop all but large dry-snow avalanches. Mounds are inexpensive to install and relatively easy to maintain; however, they are ineffective on slopes steeper than 20°. A height of 5 to 8 m generally is sufficient. Where frequent, large, wet-snow avalanches occur, dry masonry or a concrete slab on the uphill face helps reduce erosion. Earth dams or concrete walls are built perpendicular to the flow direction of the avalanche and are intended to stop slow-moving avalanches. The trapping capacity of the dam must be adequate for the size of avalanches expected. A cover of native vegetation softens the visual impact of such structures and helps stablize them.

A snow dam bulldozed up from deposited snow can be used in some places as a substitute for a small earth dam. Benches with snow dams are adequate protection against small spring-thaw avalanches.

Direct-protection structures. This type of structure is built immediately adjacent to the object to be protected; in a few cases it is part of the object itself. The aim is to render complete protection regardless of avalanche size, type, or frequency of occurrence. The avalanche gallery or avalanche shed is a good example (fig. 171). *Avalanche sheds* are merely roofs over roads or railroads that allow avalanches to cross without interrupting traffic. They are more economical for railroads or narrow roads than for the multilaned superhighways now being built in some mountainous areas, but they offer the most positive protection against avalanches. Design criteria are given in Schaerer (1966) and Sommerhalder (1972). The

Figure 170.—Retarding structures used in avalanche paths: Left, mounds near Innsbruck, Austria. Right, mounds in the runout zone of Mt. Tupper Avalanche, Rogers Pass, B.C. (Photos by LaChapelle)

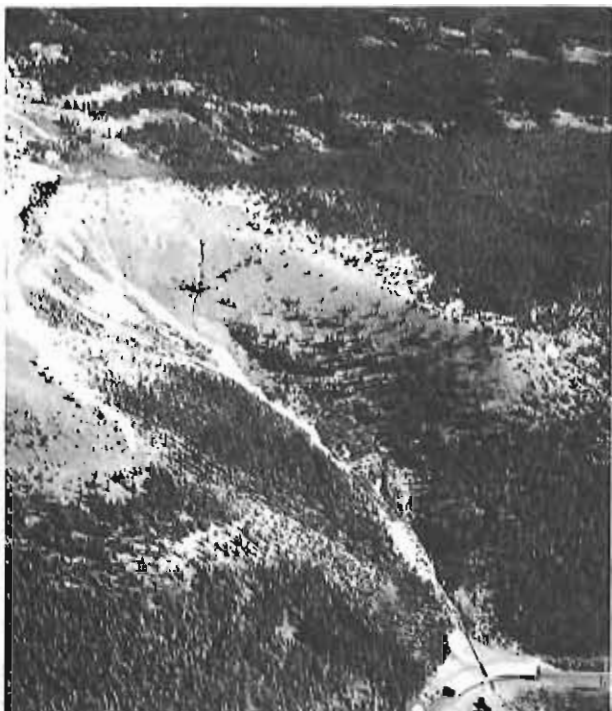   PROTECTION OF HIGHWAYS AND VILLAGES

Figure 171.—Direct-protection structure: Avalanche shed over U.S. Highway 160, near Wolf Creek Pass, Colo. Two avalanche paths cross the three-lane highway at this point. (Photo by Martinelli)
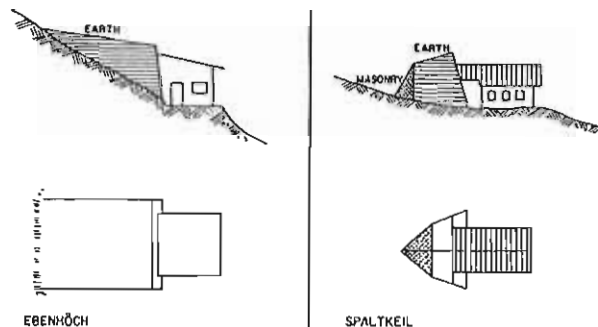

EBENHÖCH   SPALTKEIL

Figure 172.—Direct-protection structures: Top, earth ramps and wedges to protect buildings (Mellor 1968). Bottom, every house of the alpine settlement of St. Antönien has a mound of earth on the uphill side to protect it from avalanches. Gädmen-Matten-Meierhof, St. Antönien, Switzerland. (Photo by Frutiger)
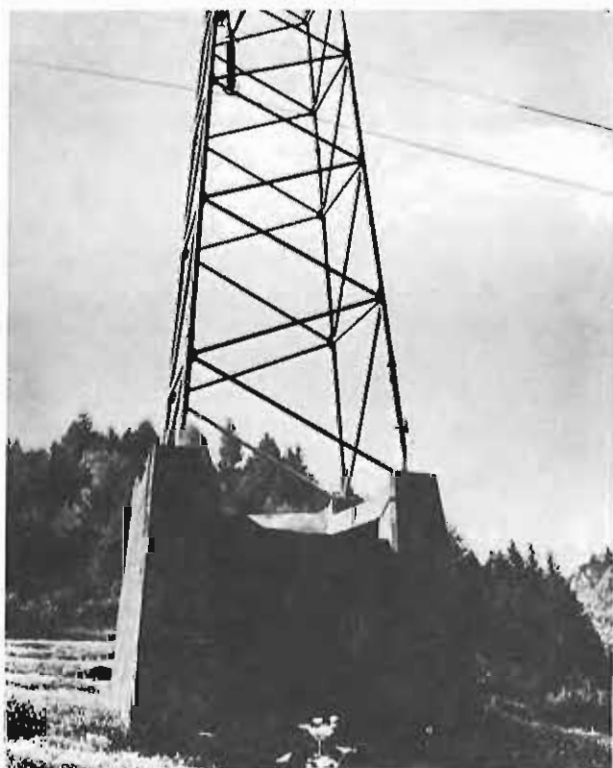
Figure 173.—Direct-protection structures: Left, a wedge-shaped concrete base for a high-voltage transmission tower located in an avalanche path (Beratungsstelle für Stahlverwendung 1962). Right, solid concrete blocks uphill from high-voltage towers. (Photo by Frutiger)

Defense structures

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Figure 174.—Direct-protection structure: Special construction of the church at Davos-Frauenkirch, Switzerland, to withstand the impact of moving snow. (Photo by LaChapelle)

Figure 176.—Direct-protection structure: A sketch of a concrete wedge protecting a high-voltage transmission tower. (Mellor 1968)

Figure 175.—Snowfences on a flat ridge to catch drifting snow before it goes over the steep rim where it might become an avalanche. Clünas, Ftan, Switzerland. (Photo by Frutiger)

choice between sheds and supporting structures in the starting zone is discussed in Frutiger and Martinelli (1966). Sheds are not without problems; there is evidence that some sheds cause more accidents because of restricted visibility and ice on the road than would result from avalanche encounters.

Where isolated buildings must be protected from avalanches, special precautions are needed. Earth ramps or wedges on the uphill side often deflect most of the snow away from the structure (fig. 172). Special roof design and construction allow any snow that gets past the earth wall to slide over the roof and down the valley. This type of direct protection is used for the homes and schools of several mountain communities in Switzerland, even though in at least one of the cases there are also many supporting structures in the avalanche starting zones. A building in the path of slow-moving, small avalanches may be built with a wall that is perpendicular to the avalanche and strong enough to resist its impact.

When an object such as a high-voltage transmission tower or a ski lift tower must be built directly in an avalanche path, it can be built on top of a massive concrete base designed to take the impact of an avalanche. At other times, it is better to build a wedge-shaped wall or mound uphill from the structure to divert the snow.

PROTECTION OF HIGHWAYS AND VILLAGES

The splitter-wedge principle has also been built directly into some buildings located, for one reason or another, in avalanche paths. A striking example is the old church at Davos-Frauenkirch, Switzerland (fig. 174). The uphill wall of this church is a massive wedge that has split several avalanches in the past century.

Snowfences and wind baffles. The snow cover in most avalanche starting zones is influenced by the winds common to mountain summits and ridgecrests. In areas where the snow distribution pattern leads to avalanches, it is reasonable to assume that a change in this pattern will lead to a change in the size and frequency of the avalanches. Snowfences and several types of wind baffles have been used in many areas to reduce the number and size of avalanches and to prevent the formation of cornices.

Traditional snowfences are effective where snow can be trapped on relatively flat ridges and gentle slopes before it gets to steeper terrain (fig. 175). The volume of snow caught by a series of such fences can appreciably reduce the size of cornices or the amount of snow in avalanche starting zones. The number, size, and location of fences depends upon the amount of precipitation, wind direction during drifting, length of the upwind contributing area, fence density, and several terrain features.

Three types of wind baffles have been used to prevent or reduce cornices. One type designed to create severe wind turbulence is a vertical wooden wall. These "eddy panels" (called *Kolk tafeln* in Austria and Switzerland) are built at the terrain break where a cornice might form (fig. 177). They are seldom more than 4 m long or 3 m tall and are usually solid, although densities as low as 75 percent have been used successfully. A bottom gap of 1 to 1.5 m is often advantageous.
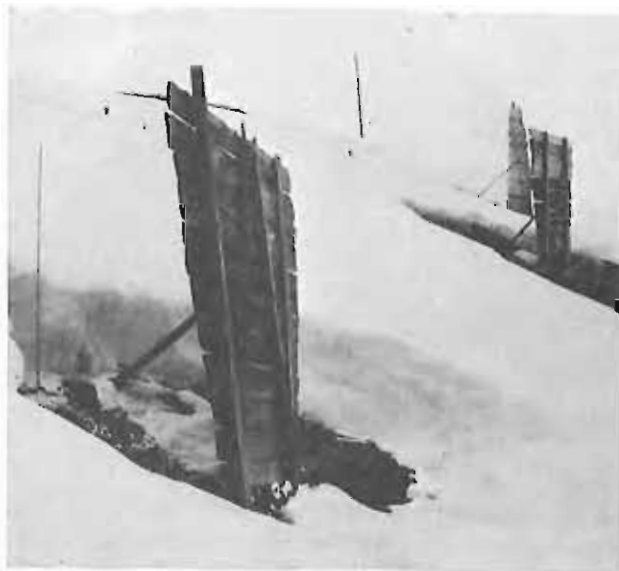

Figure 177.—Wooden eddy panels *(Kolktafeln)* on a slope (above) and a ridgecrest (below) above supporting structures. Note the disruption in the snow deposition caused by winds eddying around the baffles. (Photos by Frutiger)
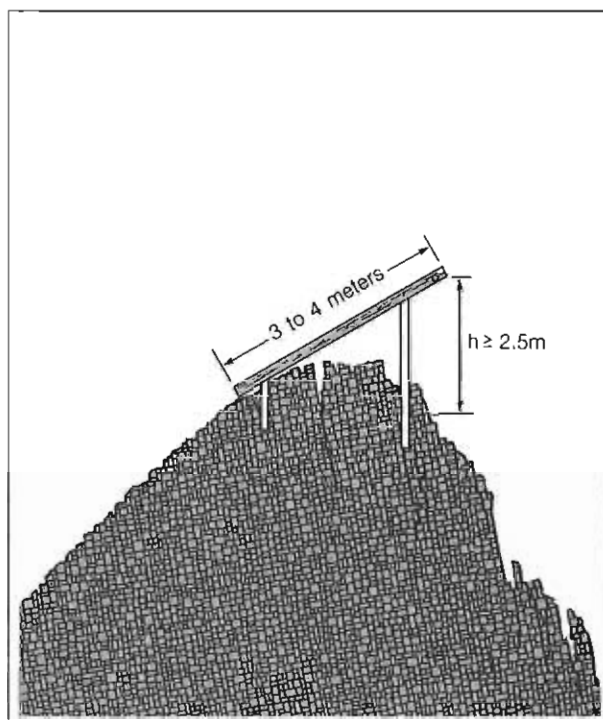
Defense structures

Figure 178.—Two types of sloping wind baffles used to prevent cornices: Left, pulpit used to carry wind and snow beyond the usual accumulation area. Right, jet roof that deflects wind down the lee slope so a cornice cannot form. (Photo by Frutiger)

The other two types of wind baffles used for cornice prevention are sloping. One (fig. 178), called a "pulpit" is shaped to carry wind and snow upward at the cornice-prone ridgecrest so the snow will be distributed more uniformly and farther down the lee slope. Pulpits seem to be most successful on narrow ridges with steep lee slopes.

The second type of sloping wind baffle (fig. 178), called a "jet roof," is designed to trap wind blowing over the crest and deflect it down the lee slope, to prevent snow accumulation in the shelter normally offered by the ridge. For best results, the roof should have about the same inclination as the lee slope, and the gap on the lee side should be 1 to 1.5 m. The height on the windward edge is governed by the slope and width of the roof, which is seldom more than 4 m wide. Air jetting under the roof keeps the upper 10 to 15 m of the lee slope snow-free or nearly so, but creates a snow deposit farther down the slope.

Role of defense structures. The various types of structures have been discussed here one at a time as a matter of convenience. In practice, it is common to use many types of structures on a single path. For example, to protect a village and roads from large avalanches, supporting structures, wind baffles, and snowfences may be used in or near starting zones to stabilize the upper parts of avalanche paths. Mounds, walls, and dams may be used farther down the mountain to catch any avalanches that start below the supporting structures. Ramps, wedges, and other direct-protection structures may be needed to protect isolated objects such as electric power poles, ski-lift towers, mines, or buildings. In addition, most European avalanche defense systems include reforestation (see the next section) up to the natural treeline.

Obviously, the most desirable and effective protection against avalanches is to locate buildings, roads, and other objects away from avalanches. With plenty of room and a population wise to the ways of the mountains, this is not hard to do. However, as the population grows and less desirable sites must be used, advanced planning and often enforced zoning appear the best solutions. In some cases, even these are not able to afford complete freedom from avalanches, and certain risks must be assumed, especially in the case of roads, powerlines, and railroads. These risks can be reduced, however, if appropriate structural controls are used.

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Figure 179.—The results of reforesting an avalanche path about 2.5 km south of Bergün on the Albula route of the Rhätische Bahn Grison, Switzerland. Left picture was taken in 1907; middle in 1938; right in 1957. A gallery 117 m long was built over the railroad at the foot of the right avalanche path. More than 10 km of retaining walls were built above timberline and over much of the rest of the mountain, then trees were planted. (Photos from Swiss Snow and Avalanche Research Institute with the permission of the Rhätische Bahn)

Reforestation

Since large, destructive avalanches seldom start on densely forested slopes, there is a strong incentive to try reforesting existing avalanche paths. In some mountainous countries, the need for additional forest land is another incentive for reforesting avalanche paths. There are many examples from central Europe of avalanche paths that have been successfully planted (fig. 179). The task, however, is neither easy nor cheap and should be undertaken only after a careful check of growing conditions and a firm conviction that reforestation is the proper action for the site.

Most avalanche paths that have adequate soil can be reforested, provided the time and money are available. On some paths, thin, droughty soils and large areas of bare rock offer few places for trees to grow. Reforestation is not feasible on such sites.

Avalanche paths that start above timberline or those that start on steep, rocky slopes or in rocky gullies are also poor prospects for reforestation unless supporting structures are used to stabilize the snow in the starting zone. Paths that are completely within the forest and have deep soils and good moisture conditions offer the best chances for reforestation.

An avalanche path, even under the best conditions, must be considered a harsh planting site that requires

special care, not only in such site-preparation necessities as terraces, fertilizers, and supplemental water, but also in the selection of species and handling of planting stock. High-quality planting stock of the fastest growing native species is preferred. Seedlings should be from locally collected seeds that are germinated and grown at a nursery in biodegradable pots. This potted stock suffers considerably less setback when it is moved from the nursery to the planting site than the more traditional bare-rooted stock. Light-sensitive species, such as Engelmann spruce, should be planted in the shade of rocks, stumps, logs, or other objects.

On some sites, it may be better to plant one of the successional species rather than the climax species. For example, in the central Rocky Mountains, consideration should be given to lodgepole pine on sites where there is insufficient shade for planting spruce. The pine is fast growing, has a good survival rate, prefers sunlight to shade, and provides a good microclimate for the natural establishment and growth of spruce, the climax species.

Because of the harsh environment, heavy losses must be expected the first year, and several replantings are usually needed for complete coverage. In some European areas, avalanche paths are planted at the rate of 2,000 seedlings to the acre in an attempt to get

Figure 180.—Young trees on an avalanche slope in Switzerland with creep- and glide-control structures. (Photo by Frutiger)

at least 1,800 trees to the acre. It is not known that even this density of stocking eliminates all avalanches.

Once planted, the young trees must be protected from avalanches and from snow creep and glide for many years (fig. 180). This usually means that supporting structures must be installed and maintained for at least 25 to 50 years. Where spruce or other slow-growing species are planted, longer protection is needed, since they often take 75 to 100 years to reach diameters of 10 to 15 cm, 1 m above the ground.

Snow distribution may have to be modified on some sites before planting. Windy locations with shallow soils are very droughty and hard to reforest. On the other hand, areas of late-lying snow may have a growing season 30 to 60 days shorter than nearby places. Trees growing in areas of deep, persistent snow are subject to damage and possibly death from snowmold fungi. Snowfences are one way to modify snow distribution before planting.

Reforested areas also must be protected from domestic grazing animals and fire.

Control by explosives

The strategy of artificially releasing avalanches above highways is intended to produce small avalanches that clear out the track and either stop short of the road or deposit only small loads on it. Ideally, the avalanches should stop just before crossing the highway. Experience demonstrates that it is much more efficient to plow out many small deposits than one very large deposit. Also, the release of many small avalanches in the winter prevents large avalanches from running in the spring thaw.

Thus, highway control strategy differs from control strategy in ski areas. For the latter, an important objective is to use explosives to test and prepare the way for ski compaction, which can proceed cautiously even if explosives do not cause slab release. By contrast, for almost all highway paths, as well as inaccessible avalanche paths in ski areas, the release of small avalanches in response to explosives is the desired effect. The notion that explosives always stabilize a slab, regardless of whether or not the avalanche releases, is disputable. In some cases, explosives may

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release tensions, but such relief is only temporary. Of course, if the slab is saturated with explosive holes, stability may be reached by force. However, the environmental damage of saturation blasting is rarely justified.

What is the strategy for explosive control of paths that have the potential to run into residential areas or other developments? The primary objective is to safeguard the lives of people that need to move in and around the threatened facilities; protection of facilities is secondary. It should be understood that buildings in a developed area protected solely by explosive release are on borrowed time. Sooner or later, a sequence of climatological events will cause avalanches that cannot be completely controlled by explosives. Developers must account for this economic risk, and they have full responsibility to explain to their clients the vulnerability of the facilities. In addition, developers must either work out a satisfactory procedure for evacuation during critical periods or provide adequate avalanche shelters. Moreover, threatened lodges, buildings, condominiums, etc., should be equipped with complete rescue caches including probes, shovels, and medical supplies.

From limited experience with the few developments that are gambling on artificial release for protection, it appears that the strategy of releasing small avalanches is helping to extend the life of the development over what would be expected if the avalanches were left uncontrolled. Just as in highway control, the release of many small avalanches has a strategic advantage over waiting for one large avalanche. Nevertheless, avalanche workers called upon to blast in such a risky situation must be released from liability before control is begun. This may require a civil ordinance that delegates authority to perform control on specific slopes for the "general public welfare," in full understanding of risks and uncertainty of results.

Inaccessible avalanche paths over highways, villages, and ski areas are routinely controlled by artillery or helicopters. Of these two principal techniques, artillery control is apt to be the more expensive, since artillery ammunition plus purchase and maintenance of weapons cost many times more than handthrown charges plus helicopter time. On the other hand, helicopters are limited to favorable weather. Since visibility constraints should not be imposed if control is to be most effective, helicopters are best used in combination with artillery rather than as the sole technique.

Artillery methods were discussed in detail in chapter 6. Because range is a problem, most highway con-

Figure 181.—75-mm recoilless rifle tower on Washington State highway. Winches are used to lift gun onto tower.

trol is performed with military weapons. At present, the alternatives to military weapons do not have adequate range and accuracy for most highway control. Whenever possible, military units stationed at the area should fire the weapons and maintain the weapons and ammunition. The weapons should be fired from fixed mounts that permit accurate indirect aiming during poor visibility. Firing positions should be chosen to minimize avalanche hazard to firing crews. Recoilless rifles and howitzers (75 mm to 105 mm) are suitable; the howitzer should be used where steep gun elevations might bounce recoilless-rifle backblast into the gunner.

After firing, it is important to note which paths failed to release; on the next shoot such stubborn paths can be hit twice. When large snow accumulations have built up, it may be possible to decrease the avalanche runout by firing a special target sequence; for example, firing on a low target before hitting the

high target. In other cases, there is a gain of efficiency in first hitting the high target and allowing the slide to clean out the lower slopes. This procedure, however, usually results in a large avalanche.

During firing and hazardous periods, roads should be closed by strong blockades or by a patrol car with red lights, or by both. Road closures should be on wide, level stretches that allow traffic to turn around (Gardner and Judson 1970). The "waiting-out" area should be avalanche-free and not exposed to recoilless rifle backblast. Enough space should be maintained between parked vehicles to avoid exhaust gas poisoning. Whenever possible, a public telephone and shelter should be provided.

When weather is favorable, helicopter control is a valuable supplement to artillery. Helicopters may be used either to transport control teams to ridgetops or for direct bombing from the air. This may save time and money, make possible the control of paths not accessible to artillery, and add safety to the overall control program. This last advantage must be qualified immediately, since helicopter flying over mountainous terrain is not without risk. Just how much safety a helicopter can add or subtract from the program depends on the ability of the pilot and the capability of the helicopter, as well as on the blasting crew and their equipment and procedures.

Pilot requirements for avalanche blasting are not yet standardized nationally; however, blasting from aircraft requires special permission from the Federal Aviation Administration (FAA), and permission is granted only to the most experienced and responsible pilots who have had considerable mountain flying experience. Excellent knowledge of local terrain is essential, and the pilot should be acquainted with avalanches and mountaineering in general. The FAA waiver also is based on using a helicopter with suitable power, range, and cabin capacity. In addition, the FAA must review the blasting procedures and emergency plan, all of which may be specified in the waiver. Operating on Government land may require other approvals and regulations. All crew members must be experienced in basic helicopter procedures. Dummy charges can be used for simulated drills on transportation, charge preparation, and jettison of explosives during emergencies.

Charge preparation should follow the techniques outlined in chapter 6. The cap-fuse assembly can be prepared before flight. It is the pilot's responsibility to determine the point in the operation when the charges are armed. In flight, cap-fuse assemblies and explo-

sives should be carried in containers that are securely fastened to the helicopter floor. Cast-primer explosives consisting mainly of TNT are preferred; however, the castings should be quite solid and properly encased to resist impact shattering. Explosive loads should be kept to a minimum; 1-kg units are the normal charge, but charges in excess of 1 kg can be used at the blaster's discretion, since it is sometimes difficult to achieve target accuracy when blasting from a helicopter. Charge preparation is the responsibility of one crew member. At the pilot's discretion, a second crew member can be added for assistance and training.

It is possible to control remote paths by preplanting explosives in the starting zone before the avalanche season. Preplanted charges are detonated by transmitting a VHF-coded signal. Because a preplanted unit, complete with signaling equipment, is much more expensive than an artillery round, the technique is justified only for remote paths that cannot be reached by artillery, yet must be occasionally controlled during bad visibility when helicopter flight is restricted. Preplanted charges should be anchored securely to the terrain. Using a shock-insensitive explosive, it is possible to anchor a large number of units in the same starting zone (at about 5-m spacings) and detonate each unit separately. At present, preplanted-charge technology is still in the development stages. Although preliminary results are promising, this method is expensive.

Planning the protection of highways

Avalanche planning begins when a highway is first conceived. The basic location of the road is determined by many constraints that have little to do with avalanches; for example, grades, soil, curves, climate, etc. Nevertheless, avalanche problems could affect some of the fine points in the road layout.

If the avalanche hazard is serious enough, closing the road during the avalanche season should be considered. Economics and politics will determine whether this simple solution is possible. If politics indicate that the road should be kept open year-round, an experienced consultant should estimate the approximate costs of protecting the maintenance staff and the general public. Assuming the estimate does not disqualify the road for winter operation, a more detailed study can be made. Avalanche paths that threaten the highway should be inventoried and mapped according to techniques discussed in chapter

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4. Important data to collect are avalanche frequency, expected amounts of snow deposition on the highway, extent of the runout zone, type of slides (dry winter or wet spring), and weather conditions for activity. Normally, it takes 3 or more years to collect such information.

After the paths have been inventoried, control methods can be established for each path. The choice is usually from among several methods that can be used in various combinations: *Do nothing; Temporarily close the road; Artificially release avalanches; Build sheds; Use miscellaneous defense structures; Relocate the road;* and *Control traffic.*

Do nothing. It is usually uneconomical to control avalanches that release naturally and cross the road less than once in 10 years. Explosive control of such infrequent avalanches could offset tree growth, increase the frequency of activity on the path, and build a significant hazard where one did not exist before.

Temporarily close the road. The public can be protected from infrequent avalanches by temporary closure during and immediately after severe storms or thaws. Closure can be relaxed to allow passage of supervised convoys of groups who are familiar with the risk, have well-equipped vehicles, and have urgent business on the other side of the path. Maintenance crews and the general public should not be allowed to cross the closure. This procedure is impractical on heavily traveled routes.

Artificially release avalanches. Temporary closures can be shortened by controlling avalanches with explosives. The normal technique is to close the road and release the avalanche by using explosives. Artificial release increases the avalanche frequency significantly. Decisions about road closure and explosive control are made by experienced avalanche workers who understand both the stability-evaluation techniques described in chapter 5 and the administrative problems of highway operations. Provision for a competent decisionmaking team is an important part of overall planning.

Build sheds. This costly technique may be justified if traffic flow must be maintained and protected from paths that release large avalanches one or more times each season. The construction of a shed costs more in the long run than a combined artillery and plowing program. In addition, sheds are hazardous because of limited visibility, icing, and obstacles close to the roadway.

Use miscellaneous defense structures. Mounds, dams, bridges over avalanche paths, and supporting structures in the starting zone can be justified where traffic flow is critical and where paths have a configuration that permits economical use of such structures. Earth structures such as mounds and dams de-
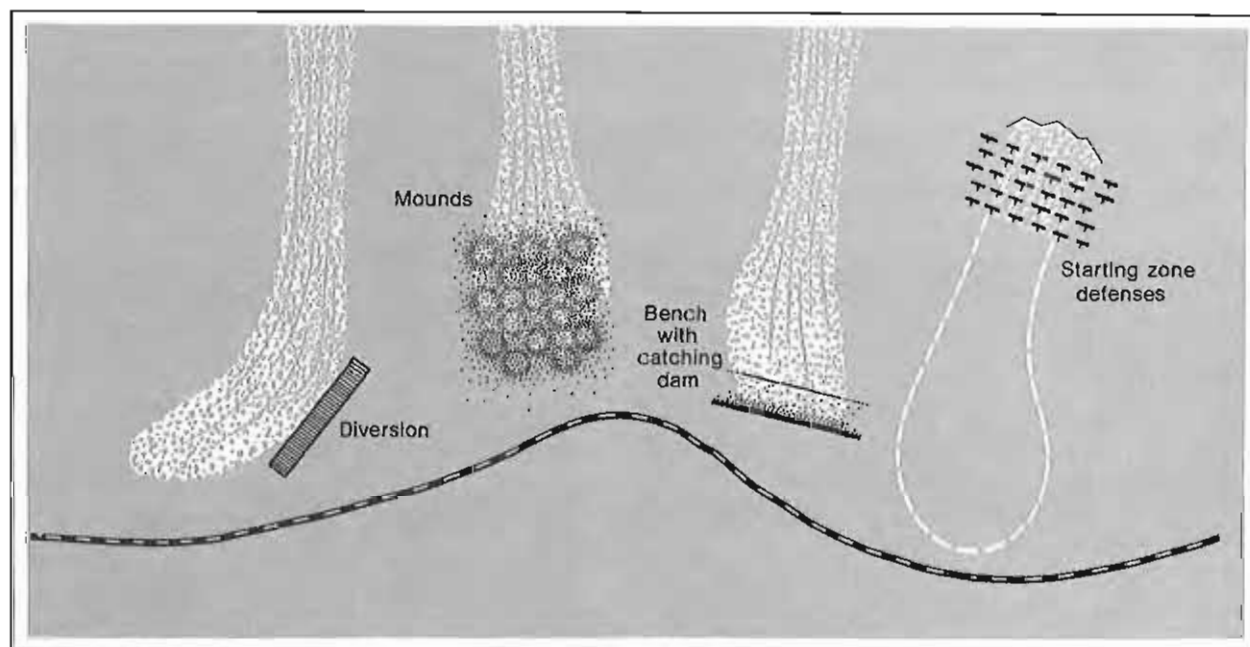
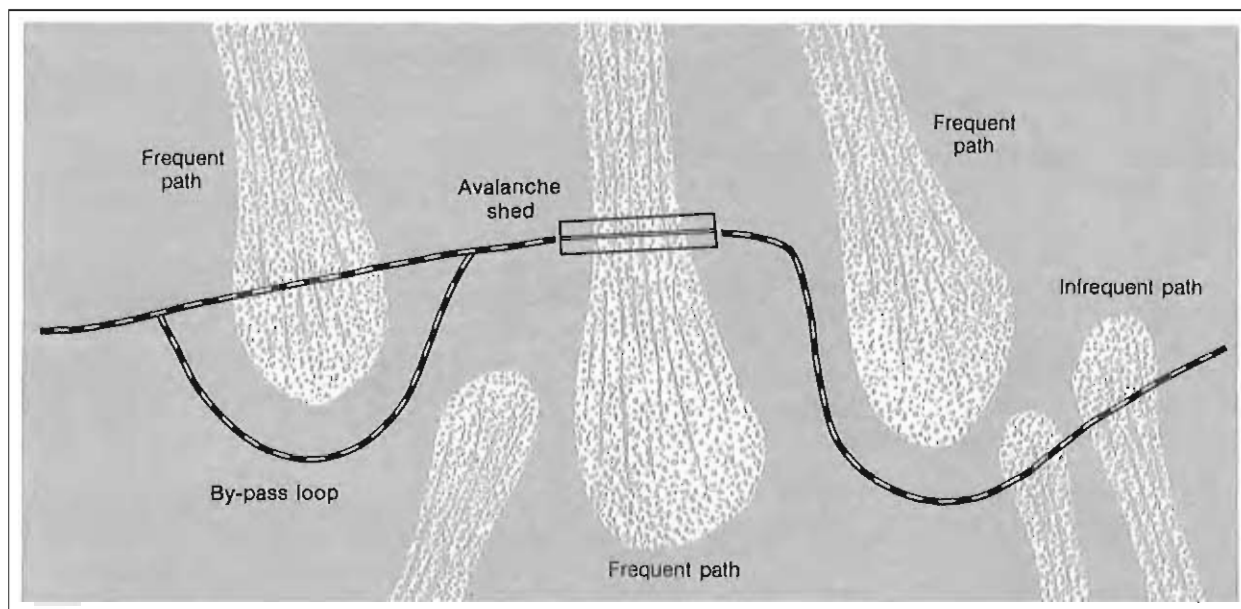Figure 182.—Miscellaneous defense structures for protection of mountain highways.

Figure 183.—Major relocation can rarely be used to avoid a hazard, although in some cases it may be possible to introduce bypass loops, angle the road to minimize shed length, or curve the road around the runout zone.

fend best against slow-moving wet avalanches. They are effective on paths that usually have no more than two avalanches per year. It is sometimes possible to bridge the road over a deeply channeled avalanche, but this must be done cautiously, since it is difficult to estimate the boundaries of the flowing avalanche. Supporting structures in the starting zone may be economical protection on small, steep slopes that do not dump large volumes of snow on the road but still pose a threat to fast-moving traffic (fig. 182). There may be opportunity to combine the defense structures with reforestation.

Relocate the road. As mentioned above, highway construction is based on many constraints, and relocation can seldom be counted on to avoid hazard. However, on low-traffic, low-priority roads, it may be possible to construct small bypass loops that can be used as temporary detours in the winter during periods of high hazard. Minor relocations may help minimize the length of protective sheds. For example, it may be possible to angle across the narrowest section of the path. Also, it may be economical to extend the road by curving it around runout zones or causing it to cross back and forth along a canyon bottom so as to intersect the runout zones of paths that have smaller and fewer avalanches (fig. 183). The ecological damage of adding detours must be weighed; the avalanche hazard is no excuse for scarring the landscape. Except

for road segments protected by sheds, it is best to facilitate snow removal by locating avalanche-threatened segments on fills rather than cuts.

Control traffic. Temporary closures, artificial release, mounds, and dams are not perfect control methods. Unexpected avalanches sometimes reach roads even where defense measures have been taken.

Most avalanche accidents on roads occur when traffic has stopped in front of avalanche paths, usually because an earlier avalanche blocked the road or because cars have stalled due to slippery conditions or people are resting, sightseeing, or putting chains on their vehicles. Exposing stationary vehicles to avalanches can be prevented by:

- Placing signs ("Avalanche Area, Do Not Stop" and "End Avalanche Area") at either side of avalanche paths

- Directing vehicles to safe areas as soon as avalanches have covered the road

- Requiring chains or adequate snow tires during slippery conditions.

Road-maintenance personnel should be trained in safety measures and search-and-rescue procedures. Rescue equipment should be kept in areas that have frequent avalanches.

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Protection of the Trans-Canada Highway

The Trans-Canada Highway crosses nearly 100 avalanche paths in the 145 km (91 mi) between Golden and Revelstoke, B.C. Some of the starting zones that affect the highway are 1,600 m above the road. The hazard is most intense in the vicinity of Rogers Pass, where, according to traffic surveys, it is probable that at least one motor vehicle is under a major avalanche path at any given time. The combination of the number of avalanche paths, the frequency of avalanches, and the volume of traffic makes this the most hazardous highway in North America with respect to avalanches. Despite the hazard and the constant pressure to keep the road open, the safety record over the past 10 years of operation has been commendable. This is a credit to years of planning before the highway was opened (fig. 184).

Snow and avalanche observations were formally begun in 1953, when the route was proposed. In 1956, the route was approved for construction. Avalanche observations were then extended to provide detailed information for design of highway defenses, including an artillery program. Based on these early studies, planners decided to install and improve the defense system in three phases (Schaerer 1962a), the general features of which are:

First phase. Initial defenses were to be in service when the highway was first opened to the public. With the completion of the first phase, the highway was expected to be closed about 280 hours in an average winter. The duration of any one closure would vary from 4 hours to 6 days, including time for snow removal.

Second phase. These defenses would be added later, based on experience with the first phase. The highway was expected to be closed about 120 hours each winter.

Third phase. The final goal would be to extend defenses so that the highway would be closed only for periods of about 2 hours. Once in 10 years, closure could extend up to 2 days.

After establishing these general goals, the next step was to select a specific defense for each path. This required a rather complex engineering-cost study (Schaerer 1962a, 1962b, 1962c). With the second phase in effect, highway closure has averaged 100 hours each season. For example, in the winter 1968–69, there were 88 closures of 76.5 total hours for artillery shooting, one closure for 8.5 hours because

of visibility and road conditions, and one closure of 11.5 hours to clear a major avalanche that released naturally.

The success of the program is based on the cooperative efforts of five teams:

Snow Research Group. This team consists of two analysts, two observers, and four assistant observers. They are responsible for:

- Collecting and recording weather, snow-cover, and avalanche data

- Analyzing all technical data and preparing forecasts of avalanche hazards

- Ordering closures of the highway

- Determining when and where to use artillery

- Conducting research for improving forecasts.

Army Detachment. This group consists of one detachment commander, seven gunners, and one gun mechanic; it is equipped with two 105-mm howitzers.

Maintenance Group. This group consists of about 28 men with the equipment needed for snow removal, ice control, and all other maintenance required to keep the highway open and safe for the traveling public.

Warden Service. This team consists of five men trained in avalanche rescue; it is responsible for traffic control, public information, and general safety.

Equipment Maintenance Team. This group consists of five men responsible for maintaining and repairing all equipment.

The operation center is at the summit of Rogers Pass (elevation 1,320 m), which is headquarters for all five teams and includes maintenance sheds, warden headquarters, dormitories, military facilities, avalanche-forecasting instruments, and a snow study plot. In addition, the Snow Research Group makes snow and weather observations at a higher station (1,900 m) on Mt. Fidelity and measures wind at two ridgetop sites. A weekly tour is made to a remote high-elevation study plot (2,100 m) on Mt. Abbott to read charts and make snowpit tests.

The method of stability evaluation used by the Snow Research Group is of particular interest. Essentially, evaluations are based on all six inputs discussed in chapter 5, but they are biased strongly toward *new snow instability* rather than *deep slab* or *wet snow* instability. The main idea is to determine when the new snow is unstable and then use artillery to bring out small slabs that clean out the track. Little snow
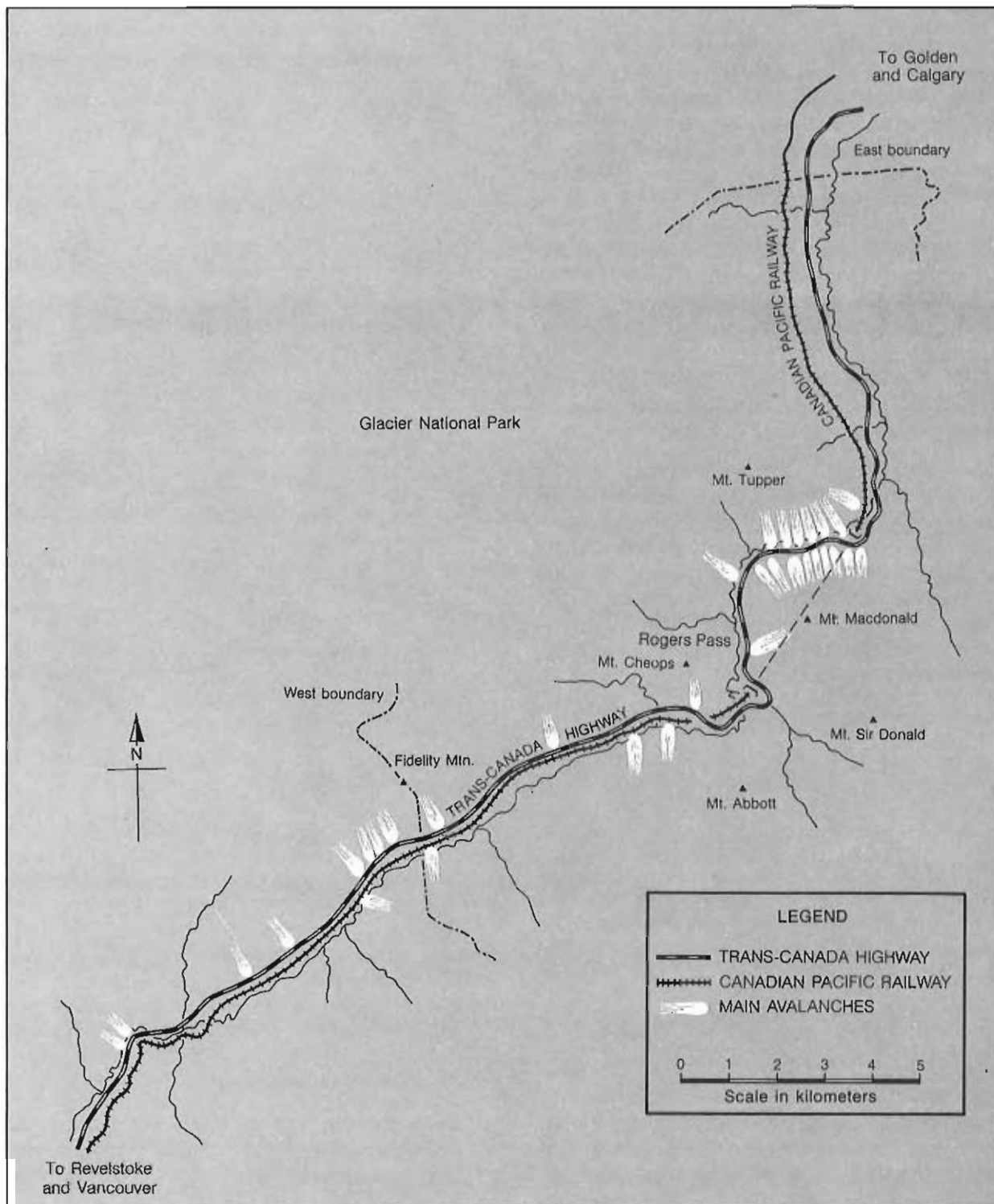
Figure 184.—Main avalanche paths near Rogers Pass, B.C.

PROTECTION OF HIGHWAYS AND VILLAGES

is left in the starting zones, and the spring thaw hazard is minimized. Deep slab instability due to TG metamorphism is not usually a serious problem at Rogers Pass, since long periods of clear, cold weather between storms are uncommon. (Deep slab instability is a more serious problem in the Canadian Rockies near the Banff–Jasper Highway, which is influenced by a continental climate.) This is not meant to imply that deep slab and wet snow instability are ignored; snowpit measurements of density, temperature, grain structure, and hardness are taken routinely.

To distinguish between stable and unstable layers of newly fallen snow, the Snow Research Group uses meteorological data and the following test procedure (Schleiss and Schleiss 1970):

Penetration test. This test is performed at study plots that represent conditions at midtrack and in the lower part of the track for most of the avalanche paths in question. The first section of the ram penetrometer is allowed to sink into the newly fallen snow. Depth of penetration is monitored. Normally, about 40 cm of penetration indicates that enough snow can be entrained in a moving avalanche to cause hazard to the highway.

Inclined-table test. The next step is to determine by a rather delicate procedure if a critical shear plane exists in the newly fallen snow. First, a 40-cm cubical block is cut out of the topmost layer. The block is set gently on a table, which is tilted, then given a jarring blow. If the snow is unstable, a shear fracture propagates, and the block separates as shown in figure 185.

Shear-frame test. The final step is to determine the stability index of the critical shear plane with a special snow instrument called a *shear frame*. The load on the critical shear plane is computed from the density and thickness of the snow above the critical shear plane. If the ratio of the *shear strength* to the *load* is less than 1.5, the critical plane is considered unstable.

These tests are performed routinely at 7:30 a.m. and 4:30 p.m. and on a concentrated schedule during intense storms. Results are reported to the analyst at the Rogers Pass headquarters who considers all six inputs discussed in chapter 5 and arrives at a stability evaluation, on the basis of which he issues written directives. These may call for an "alert" to a developing hazard, or for "action," to close the highway and begin artillery firing. Examples of typical written directives:
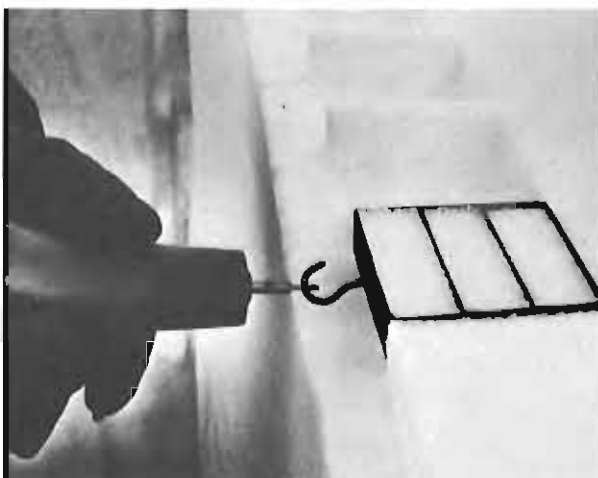
Figure 185.—Rogers Pass test procedure for evaluating new snow instability.

```
┌─────────────────────────────────────┐   ┌─────────────────────────────────────┐
│               ALERT                 │   │              ACTION                 │
│                                     │   │                                     │
│  Date:     January 10    1967       │   │  Date:     January 10    1967       │
│                                     │   │                                     │
│  Hour of issue:    2200             │   │  Hour of issue:    2200             │
│                                     │   │                                     │
│ 1. Avalanche warning: High winds    │   │ 1. Avalanche warning: High winds    │
│    and heavy snowfall will cause    │   │    and heavy snowfall are causing   │
│    avalanche activity which may     │   │    avalanche hazard to the          │
│    affect the Trans-Canada Highway  │   │    Trans-Canada Highway.            │
│    in form of dry dust action.      │   │                                     │
│    Extra attention is advised.      │   │    Expect periodic closures not     │
│                                     │   │    exceeding 2 hours.               │
│ 2. Stabilizing gunfire may be       │   │                                     │
│    recommended between:             │   │    Expected action time: 2300 to    │
│                                     │   │    0400, January 10, 1967.          │
│    2300   hours and   2400  hours   │   │                                     │
│                                     │   │ 2. Gunfire should commence at:      │
│ 3. Gun positions likely to be       │   │    2300   hours.                    │
│    occupied are those between:      │   │                                     │
│                                     │   │ 3. Sequence of gun positions:       │
│    Summit East   to   Connaught     │   │                                     │
│                                     │   │    Summit East   to   Connaught     │
│    Mortar        to   Fidelity      │   │                                     │
│                                     │   │    Mortar        to   Fidelity      │
│ 4. Guns likely required:            │   │                                     │
│                                     │   │                  to                 │
│    105mm Howitzer      x            │   │                                     │
│                                     │   │ 4. Guns and estimated ammunition    │
│    75mm Pack Howitzer  ___          │   │    required:                        │
│                                     │   │                                     │
│ 5. C.P.R. representation may be     │   │    105mm Howitzer  x  and  40       │
│    required at                      │   │    rounds.                          │
│                                     │   │                                     │
│    approximately:   2400  hours for │   │    75mm Pack Howitzer ___ and ___   │
│                                     │   │    rounds.                          │
│    Observatory to Fidelity  gun     │   │ 5. C.P.R. representative required:  │
│    positions.                       │   │    between 0030                     │
│                                     │   │                                     │
│         Analyst:  John Doe,         │   │    hours and    0200    hours at    │
│                   Forecaster        │   │                                     │
│                                     │   │    Observatory to Fidelity  gun     │
│ Received by:  Maintenance, Warden   │   │    positions.                       │
│    i.C., Gateways, C.P.R., Army.    │   │                                     │
│                                     │   │ Residents of fan house and station  │
│ for Park Superintendent             │   │    areas to be warned for           │
│                                     │   │    0300    hours.                   │
│ Issued by:  Joe Doe  of Snow        │   │                                     │
│             Research Section        │   │         Analyst:  John Doe,         │
│                                     │   │                   Forecaster        │
└─────────────────────────────────────┘   │                                     │
                                           │ Received by:  Maintenance, Warden   │
                                           │    i.C., Gateways C.P.R., Army.     │
                                           │                                     │
                                           │ for Park Superintendent             │
                                           │                                     │
                                           │ Issued by:  Joe Doe  of Snow        │
                                           │             Research Section        │
                                           └─────────────────────────────────────┘
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Artillery firing is done by the Canadian Army detachment on assignment for winter training. Firing may be performed at any hour of the day and under any conditions, and it is therefore based strictly on indirect techniques using fixed aiming stakes. The 105-mm howitzer appears to be the best weapon because of its range and ability to fire at a high barrel elevation. The weapon is fixed on special concrete pads (fig. 186). There are about 144 targets. Most are at the very tops of the starting zones, often in steep cliff bands. The idea is to release small sluffs that trigger the bulk of the starting zone. The amount of ammunition fired varies considerably from year to year (423 rounds minimum to 1,850 maximum). In the severe winter of 1971–72, 129 avalanches crossed the road, and about 480,000 m^3 of snow were removed by plows, loaders, and graders.

Special emphasis is given to personal safety. All members of the Rogers Pass operation are instructed in basic avalanche safety and rescue. The research

Figure 186.—Firing of 105-mm howitzer from concrete pad, Rogers Pass, B.C. A marker on the highway shed is used as reference for indirect firing.

Figure 187.—Avalanche warning sign on the Trans-Canada Highway. Signs are essential for the protection of maintenance staff as well as the general public.

group is given additional training in safe travel over avalanche terrain. Everyone carries a manual that includes avalanche charts with reference mileage, radio communication instructions, and a list of avalanche safety rules.

Motorists who enter the threatened highway section receive a pamphlet, "Winter Guide to Rogers Pass Section," which explains the avalanche problem, tells how avalanches are controlled, and gives general advice. The safety program is backed up by a large number of warning signs (fig. 187).

Land-use regulation

Federal, State, and local governments may regulate or prevent construction in avalanche paths. Since most avalanche paths are on Federal land, agencies such as the USDA Forest Service and the USDI Bureau of Land Management and National Park Service play a central role. Their main tool is to withhold approval of Federal land-use or concession permits until satisfied with the avalanche protection proposed by the applicant. The Federal Government may also purchase land with the object of reducing the avalanche hazard. The Federal Government does not have authority to regulate the use of non-Federal land.

Regulation of non-Federal land in the interest of general public welfare is delegated by the Constitution to the State governments. The use of individual property may be controlled if a State government can demonstrate that the owner's intentions conflict with general public welfare. This, of course, leads to disputes between individuals and the government. On the principle that such disputes are best handled at the local level, the States have passed enabling acts that delegate their constitutional authority to home rule municipalities, statutory municipalities, and counties. However, the trend is beginning to reverse, as more and more State governments realize that land-use planning is crucial enough to require State intervention. As an example, the Oregon State Legislature passed a bill making zoning mandatory in all cities and

counties and further required that local government begin work on comprehensive plans. Should the local government not comply, the State would intervene and do the job for them. Although the law was tough sounding, it was supported by the voters when it was challenged a year later at the polls.

On the basis of delegated authority, local government can regulate land use with combinations of the following tools:

Zoning ordinances. This important tool will be discussed in more detail in the next section. The fundamental idea is for the local government to prepare maps that divide the land under their jurisdiction into several zones, delineated on the basis of the avalanche hazard. Appropriate restrictions on construction and habitation are matched to the degree of hazard. The zoning statute of the Swiss canton of Nidwaldon is a good example:

STATUTE
CONCERNING THE AVALANCHE ZONING PLANS
OF 26 APRIL 1964

Amendment No. 470

Art. 1 The avalanche zoning plans define areas in which the erection of buildings is forbidden or placed under restrictions.

Art. 2 For districts in which ground suitable for construction lies in zones endangered by snow slips or avalanches, the Agriculture and Forestry Commissions, in cooperation with the district government, are required to prepare avalanche zoning plans.

In districts for which an avalanche zoning plan still does not exist, construction may be forbidden or placed under certain restrictions, for a period not to exceed one year, by the Agriculture and Forestry Commissions prior to publication of the avalanche zoning plan.

Art. 3 Before being placed in force, the avalanche zoning plans shall be open to public inspection at the district government offices for a period of 30 days, during which objections may be lodged.

The Agriculture and Forestry Commissions shall decide on the merit of any objections.

Art. 4 The avalanche zoning plans prepared by the Agriculture and Forestry Commissions are public documents.

Special property restrictions involving public rights introduced by these avalanche zoning plans shall be entered in the land registry.

Art. 5 Decrees of the Agriculture and Forestry Commissions may be appealed within 20 days to the cantonal court, whose decision shall be final.

Art. 6 The provisions of Art. 3 shall apply to later alterations or additions to the avalanche zoning plans.

Art. 7 Violations of this Statute shall be punished according to the penalty provisions of the Cantonal Construction Law of 30 April 1961.

Art. 8 The stipulation concerning the registering of property restrictions (Art. 4, Par. 2) is subject to ratification by the Federal Legislature (Art. 962 ZGB).

Art. 9 This Statute takes effect upon enactment by the Landsgemeinde, except the paragraph requiring ratification by the Federal Legislature.

So concluded before the Landsgemeinde

Wil an der Aa   26 April 1964

Art. 4, Par. 2, ratified by the Federal Legislature on 15 May 1964.

(Translated by LaChapelle)

Subdivision regulations. This shifts some of the burden of mapmaking to the subdivider, who must submit a map of his parcels, showing avalanche paths and other hazardous areas. A local government board (with the help of consultants) reviews the map and requires modification according to its technical analysis of the problem. Subdivision regulations should supplement, not replace, zoning ordinances.

Building, housing, and miscellaneous codes. These important supplements to the basic zoning ordinances allow local governments to examine construction and maintenance details of proposed and existing developments. In particular, structures weakened by avalanches can be made to conform to the most recent standards for new structures. Protection can be required for sanitary and water facilities.

Taxation. The justification for taxation is that improper use of avalanche land burdens the community with special problems; the property owner must contribute accordingly. Likewise, lower taxes can be assessed for avalanche land not developed by the landowner.

Comprehensive plan. In some instances, the local government (and State and Federal governments) can develop roads, parks, ski lifts, and water and sanitation facilities in a way that discourages the development of hazardous private land.

Public acquisition. This includes land purchase, easement purchase, and land exchange. The State can assist by providing funds and land-exchange possibilities when it can be shown that the State will save money in the long run.

Despite all these options, the local government is not in an enviable position. In practice, land-use planning can be limited by a barrage of legal and social pressures. Legally, each case tends to be unique and is handled individually through the tiring process of hearings and appeals. Socially, local government often faces traditional public sympathy for property

Figure 188.—An example of the false sense of security that may be offered by a small band of timber at the foot of an avalanche path. The housing development in the scattered timber at the foot of the mountain was invaded by avalanches, which destroyed two cabins and killed several people. (Photo by Emetaz)

rights and the right of individuals to take risks. To make matters more complicated, delegated authority implies responsibility, and the local government is obligated to protect those who place themselves in danger, knowingly or not. Caught in the middle, local governments face court action if they block development, but they may face damage suits if they fail to block development and an avalanche strikes.

To withstand legal and social attack, local governments must carry out a three-pronged attack. First, technically sound data, maps, and recommendations must be compiled. This invariably means hiring independent avalanche experts; the courts typically respond to a thorough, professional job. Second, local governments must comply strictly with procedure and regulations. Third, and perhaps most important, local governments must carry out active public-educaton campaigns to encourage public acceptance.

By contrast, insurance companies and banks can exert direct influence without the legal and social complications facing government agencies. Since avalanche insurance is not generally available, banks and loan corporations can refuse financial support for avalanche-threatened property. Insurance companies can raise their fees for liability protection. At best, financial organizations cooperate closely with local government. Unfortunately, in some cases banks may support a development that seems lucrative despite the avalanche potential. Thus, the government cannot always depend on cooperation from financial institutions.

Figure 189a.—Aerial photograph, Alta, Utah.

PROTECTION OF HIGHWAYS AND VILLAGES

Avalanche zoning

Techniques for identifying and mapping avalanche paths are presented in chapter 4. In summary, mapping is based on qualitative analysis of topography, climate, vegetation, and past records. For some cases, the numerical methods of Voellmy (1955) can be used to estimate boundaries of runout zones. Because of uncertainties in the analysis, avalanche maps are never finished; they constantly evolve as new information becomes available.

The Swiss have given much thought to avalanche maps and avalanche zoning plans (Frutiger 1970). After long study and debate at both scientific and government levels, they are using a "three-zone" system of mapping (sometimes referred to as a "three-color" map). The three zones are: "high hazard" (red), "potential hazard" (blue), "no hazard" (white). The criteria for each zone are the estimated avalanche force and an estimate of the average time between avalanches. The latter is called the *return interval* of the avalanche. The three zones are defined as follows:

High-hazard (red) zone. This zone includes terrain exposed to frequent and powerful avalanches that satisfy either of the following:

- Any avalanche with return interval of 30 years or less.
- Avalanches with impact pressures of 3 t/m^2 or more and with a return interval up to 300 years.

Buildings and winter parking lots generally are not permitted in high-hazard zones. Special bunkers may be installed for equipment.

Potential-hazard (blue) zone. This is the transition zone betwen high hazard and no hazard, and includes avalanches that are either small or infrequent:

- Avalanches with impact pressures less than 3 t/m^2 and a return interval from 30 to 300 years.

Private homes may be erected in potential-hazard zones if care is taken to design for the above forces. Schools, hospitals, lodges, and other buildings that encourage gatherings of people should not be erected. The local government is responsible for closure, evacuation, and rescue during periods of hazard.
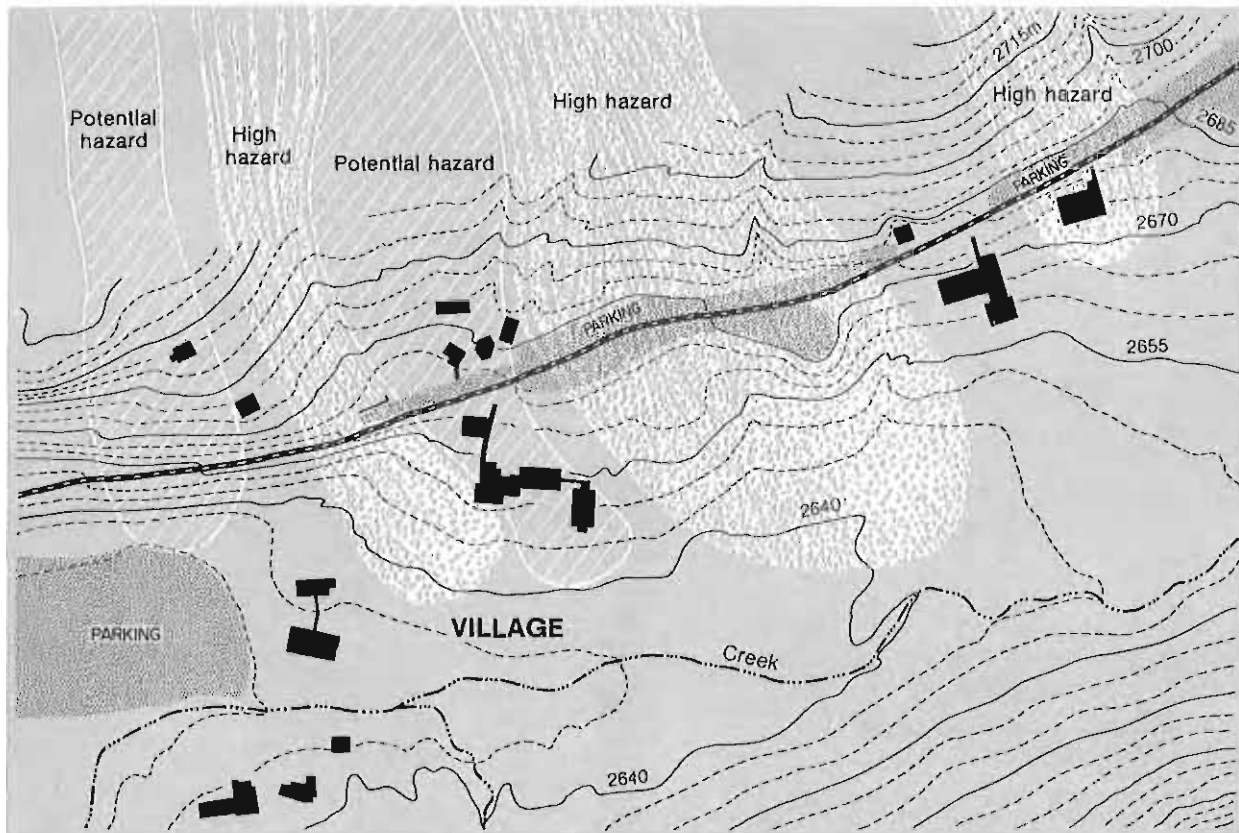
Figure 189b.—Detailed avalanche map for the lodge area, Alta, Utah.
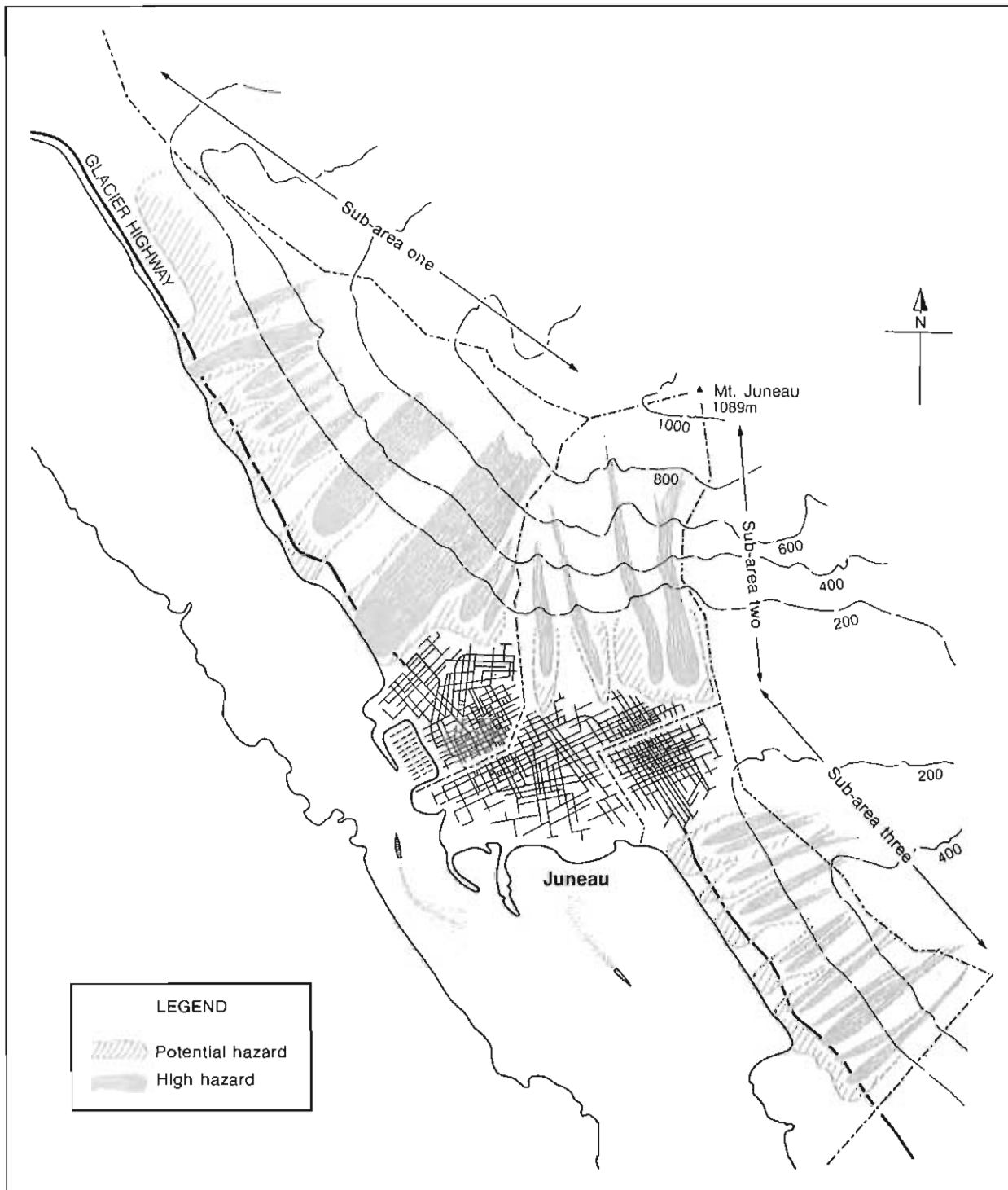
Figure 190.—Initial zoning map for Juneau, Alaska (Daniel et al. 1972).

No-hazard (white) zone. Occasionally, the terrain may be affected by small airblast pressures, up to 0.1 t/m². There are no building restrictions with respect to the avalanche hazard.[6]

Avalanche zones can be plotted first on standard topographic maps, but if decisions are needed for individual building sites, it is necessary eventually to generate special maps at a scale no coarser than 1:5,000, with contour intervals of 5 m or less. Figures 189b and 190 show, respectively, a detailed and an initial avalanche zoning map.

Enforcing restrictions for a high-hazard zone is usually not an administrative problem, since in most cases the hazard is obvious. On the other hand, it may be hard to agree on appropriate restrictions for some potential-hazard zones. Assuming that human life is not gambled, the question often boils down to economic risk (in some benefit-cost studies, a money value is even assigned to human lives). Economic risk is determined from the probability that a facility will be hit by an avalanche within the estimated life of the facility; this probability, which is called the *encounter probability,* is a function of the *return interval* of the avalanche and the *design life* of the facility. The latter depends mainly on construction methods and materials. Table 9 shows approximate encounter probabilities in percent as a function of design life and return interval.

TABLE 9.—*Encounter probabilities based on design life of structures*

Design life of structure (years)	Encounter probability (in percent) based on an avalanche return interval of:					
	5 years	*10 years*	*20 years*	*30 years*	*50 years*	*100 years*
1	20	10	5	3	2	1
5	67	41	23	16	10	5
10	89	65	40	29	18	10
25	>99	93	72	57	40	22
50	>99	96	92	82	64	40

Source: LaChapelle (1966).

It is common for a site to be affected by several geological hazards in addition to avalanches. Many avalanche gullies are in fact mud and rock slide gullies in the spring and summer. In some regions, such as part of Alaska, it is necessary to consider the combined effects of avalanches and earthquakes, since ground vibration can trigger very large avalanches.

[6] A four-zone system which takes into account airblast and highly infrequent avalanches is under study in Switzerland.

Figure 191.—An example of a system for assigning a dual-hazard index.

It is possible to compute encounter probabilities for multiple hazards. Suppose, for example, a site has an avalanche encounter probability of P_A and a landslide encounter probability of P_L. The combined encounter probability for either a landslide or an avalanche is $P_A + P_L - P_A P_L$.

Local planners can use various schemes to classify land exposed to multiple hazards. For example, a dual-hazard index for landslides and avalanches is shown in figure 191. Such schemes lend support to regulations against developing sites with multiple hazards.

For a model study of zoning for multiple hazards, including administrative and legal procedures, the reader may refer to the planning work of the City of Juneau, Alaska (Daniel et al. 1972).

Public information and warnings

An important part of avalanche hazard control is public education—convincing people that the zoning ordinance, ski-run closure, or highway restriction is in their best interest. The avalanche worker has much on his side. Avalanches are spectacular and can be portrayed in exciting and convincing presentations via television, radio, newspapers, ski magazines, films, lectures, and pamphlets. Besides the general public,

some groups that may benefit from avalanche information and education include:

    Ski clubs
    Ski patrols
    Public utility crews
    State highway crews
    Ski area operators
    Snowmobile clubs
    Rescue organizations
    Sheriff departments
    National Guard units
    State and Federal Agencies
    Ski schools
    Mountaineering clubs
    Scout groups
    Local planning commissions
    Mining corporations.

The information program should underscore the "common sense" of avalanche safety.

An effective way to develop awareness of the avalanche hazard is to release periodically a report of avalanche conditions in the neighboring mountains. The report can be made daily, on weekends, or intermittently during periods of high and extreme hazard.

Daily report. An estimate of current avalanche conditions can be included in the early morning snow and ski report. To minimize distortion by the media, it is advisable either to prerecord a radio tape or to prepare a formal written statement that gives exactly the message that should reach the public. Before the avalanche season, proper contact should be established with the media to ensure that reports are treated as routine bulletins rather than sensational news scoops. Reports may include a variety of information on ski and highway conditions; for avalanche purposes, they should include:

• 24-hour snowfall

• Present weather, including temperature and winds

• Forecast weather, including amount of snow, temperature, and wind

• Recent avalanche activity (natural and artificial)

• Expected avalanche activity in the next 24 hours

• Back-country travel recommendations.

Preparing and releasing the report depends on the combined efforts of field observers in the mountains,

a coordinator who may or may not be stationed in the mountains, and interest on the part of the media. In a system that works well in the Salt Lake City, Utah area, observers at various ski resorts in the Wasatch Mountains take 5:30 a.m. weather observations that are phoned to a coordinator in Salt Lake City, along with avalanche observations and recommendations for back-country travel. The coordinator prepares a tape summarizing the observations. The tape is played on public radio at about 8:00 a.m. each morning.

Weekend report. For small population centers, it may not be economically feasible to issue daily reports of snow and avalanche conditions. As a compromise, a report of anticipated weekend conditions can be issued Friday afternoon, Friday evening, or early Saturday morning. For large metropolitan areas, a special weekend report that emphasizes touring problems may supplement the daily report.

Intermittent warning. Intermittent warnings are released via the National Weather Service Network when conditions are especially critical. Although intended for a more general audience, intermittent warnings may serve to supplement any daily or weekend report. Used properly, intermittent warnings are avalanche workers' most powerful method of establishing public awareness. The rest of this section will describe this important tool.

In contrast to daily and weekend reports, intermittent warnings are released exclusively through the National Weather Service, as part of its program of warning against natural hazards. Intermittent warnings are not released informally to the press, since they may be misrepresented as a sensational curiosity or, just as likely, set aside if a better curiosity comes across the editor's desk. When received at the local branch of the National Weather Service, the warning is officially relayed on teletype loops to television, radio, and newspapers. At the same time, the warning is broadcast on VHF radio with a coverage of about 100 km (60 mi). The warning may also be fed into the national teletype circuit for the benefit of meteorologists in neighboring States.

The warning message must be simple and concise and should assume the listener has no prior knowledge of the phenomenon. The message should define the exact area affected and include a termination time. A statement about protective measures is equally important. As an example, a warning for the mountains west of Denver, Colorado, was issued:

AVALANCHE WARNING BULLETIN NO. 1
IMMEDIATE BROADCAST REQUESTED
U.S. FOREST SERVICE FORT COLLINS, COLORADO
ISSUED 11AM MST FRIDAY, DECEMBER 14, 1973

NORTHERN COLORADO MOUNTAINS

AN AVALANCHE WARNING IS IN EFFECT FOR
THE MOUNTAINS OF COLORADO NORTH OF A
LINE FROM COLORADO SPRINGS TO GRAND
JUNCTION. THIS WARNING IS VALID THROUGH
MONDAY, 17 DECEMBER 1973. HEAVY SNOW AND
HIGH WINDS HAVE CREATED DANGEROUS
AVALANCHE CONDITIONS.

BACK-COUNTRY TRAVELERS SHOULD AVOID
KNOWN AVALANCHE PATHS, STEEP SLOPES, AND
GULLIES.

THE NEXT AVALANCHE WARNING BULLETIN
WILL BE ISSUED SATURDAY AT 8 AM OR EAR-
LIER IF CONDITIONS WARRANT.

JUDSON . . . . U.S.F.S. FORT COLLINS, COLORADO.

Intermittent warnings can be based on two hazard levels:

• Moderate hazard. Avalanche hazard will most likely result from artificial release of starting zones in the high elevations.

• High hazard. Avalanche hazard is due to larger avalanches reaching developed areas and roads. The warning is usually made to include the lower elevations. Wording may be equivalent to: "Moun-tain travelers should avoid steep slopes, gullies, and narrow valleys," or as follows:

AVALANCHE WARNING BULLETIN NO. 2
IMMEDIATE BROADCAST REQUESTED
U.S. FOREST SERVICE FORT COLLINS, COLORADO
ISSUED 8 AM MST SATURDAY, DECEMBER 15,
1973.

HEAVY SNOW HAS INTENSIFIED AVALANCHE
DANGER AT ALL AREAS ABOVE 9000 FEET FROM
LEADVILLE NORTH ALONG CONTINENTAL DIV-
IDE TO CAMERON PASS. LARGE AVALANCHES
ARE EXPECTED THROUGH 19 DECEMBER. MOUN-
TAIN TRAVELERS ARE ADVISED TO EXERCISE
EXTREME CAUTION.

For continuity of record, at the end of the instability period, the analyst should issue a termination bulletin. The termination bulletin may mention that "isolated pockets of instability remain in the higher elevations" or some such statement of the type and degree of hazard remaining. For example:

AVALANCHE WARNING TERMINATION . . . BUL-
LETIN NO. 3

IMMEDIATE BROADCAST REQUESTED
U.S. FOREST SERVICE FORT COLLINS, COLORADO
ISSUED 9AM MST THURSDAY, DECEMBER 20, 1973

NORTHERN COLORADO MOUNTAINS

AVALANCHE WARNINGS FOR THE NORTHERN
COLORADO MOUNTAINS ARE NO LONGER IN
EFFECT. ISOLATED POCKETS OF INSTABILITY
REMAIN IN THE HIGH ELEVATIONS.

The criteria for deciding when to issue a warning were covered in chapter 5. The analyst must rely heavily on his observer's subjective analysis of weather and avalanche conditions. The main objective criterion for issuing an avalanche warning is the water equiva-lent of the new snow accumulated over a 3- to 5-day period. To provide for systematic improvement in the warning program, it is possible to use a numerical technique for totalling water equivalent. One scheme is to use an index I of the form

$$I = W_0 + a_1 W_1 + a_2 W_2 + a_3 W_3 + \cdots$$

where $W_0, W_1, W_2, \ldots$ are the respective water equiva-lents of the snowfall on the present day, 1 day in the past, 2 days in the past, etc. The $a_1, a_2, a_3, \ldots$ are de-cay coefficients that represent the fading "memory" of the snowpack for past amounts of precipitation. The decay coefficients have values less than one, such that a_1 is greater than a_2, which is greater than a_3, etc. For example:

$$I = W_0 + 0.6 W_1 + 0.3 W_2 + 0.1 W_3.$$

A warning may be issued when I exceeds some critical value. The critical I and the optimum values of the decay coefficients are found from computer analysis of several years of avalanche and precipita-tion data for a given area.

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    Switzerland. An up-to-date treatment of the subject.*

Safety
and rescue

This chapter discusses route finding and decision making for back-country travel, based on terrain, snow, and weather conditions. The careful selection of a route or the wise decision to turn back are the best ways to avoid accidents. Once a person is buried, outside help is usually needed for rescue. A buried victim must be recovered as soon as possible, because the chances of survival decrease sharply with increasing time. For back-country areas, this means members of the party must carry out the rescue, since there is seldom time to go for help. For ski areas, it emphasizes the need to have rescue manpower and equipment at the top of the mountain. This chapter emphasizes in considerable detail rescue techniques with and without special aids such as avalanche dogs or electronic transceivers. It also outlines revival and evacuation procedures, with special attention to resuscitation techniques, since most avalanche deaths are from suffocation.

Figure 192.—Members of a touring party hurry to the aid of a comrade caught in a small avalanche. The accident occurred when a skier crossed in midtrack above the victim. (Photo by Roch)

Avalanche accidents

Although avalanches kill people in many ways, the great majority of fatalities are due to suffocation. In a typical avalanche burial, rather little air is trapped in the space around the victim, and it is only a matter of time until the victim loses consciousness and dies. The weight of snow bears down on the victim's throat and chest and further accelerates respiratory failure. The snow usually packs so tightly that the victim is immobilized and must helplessly await his fate.

Some victims are killed outright or severely injured by the moving avalanche. The victim may be dashed into a tree or building or hit by flying debris. Head injuries, abdominal injuries, and broken necks, backs, and legs are common. There are also reports of lung injuries caused by avalanche pressure forces. Some victims die of hypothermia, exhaustion, or shock. Less than 20 percent of the victims buried with no trace showing are recovered alive.

Statistics compiled in Switzerland and in the United States (Vanni Eigenmann International Foundation 1963, Williams 1975) show that the victim's chance of survival diminishes rapidly with burial time (fig. 193) and depth of burial. Statistically, after half an hour of burial, the victim's chance of surviving is about 50 percent. A victim often cannot survive a 15-minute burial in an unfavorable position (snow packed tightly around mouth and nose). This is understandable, since after stoppage of breath, a person loses consciousness in about 45 to 120 seconds. The first permanent brain damage occurs in about 4 minutes, and after 8 minutes, survival is unlikely even if it were possible to restore breathing and circulation. On the other hand, if the victim is buried in a favorable position, without snow packed tightly around mouth and nose, he may survive for many hours.

Table 10 summarizes data from 61 organized rescues conducted in the United States. A great contrast appears between rescues conducted in the back country and those conducted in developed areas such as ski areas, villages, and highways. *The victim has almost 10 times the chance of being found alive if the burial occurs in the immediate vicinity of organized rescue groups.*

Almost 50 percent of the fatal accidents resulted from slides that ran less than 100 m. This supports the mountaineer's guideline that small slides can kill as easily as large slides. The danger is determined not only by the length of the path but also by the terrain;
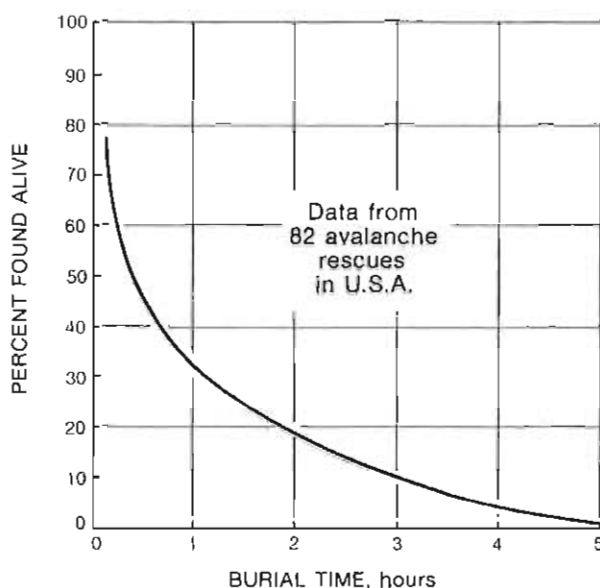
Figure 193.—The victim's chances diminish rapidly with burial time. Based on 82 cases in the United States (taken from Williams 1975), 50 percent of the buried victims perish in the first half hour.

a relatively small avalanche can produce a deep burial in gully terrain.

Avalanche accidents in North America fall into the following categories:

Back-country accidents. At present, this category accounts for the largest number of fatalities in North America. The victims are usually ski tourers, helicopter skiers, or mountaineers. In almost all cases, the victims triggered their own avalanche while crossing the starting zone. In a few rare cases, the avalanche was triggered naturally and swept into the touring party lower down in the track or runout zone. In a few cases, the avalanche overran a camp area and buried victims in their tents. The back-country category of

TABLE 10.—*Average delay in organized rescues of buried victims*

Hours after accident before:

Location	Sounding of alarm	Arrival of rescuers at accident	Discovery of victims[a]
Developed areas	0.75	1.25	2.5
Back country	5.25	10	38
All rescues	3.5	6.25	20.5

[a]In six cases, the rescue was abandoned and the victim was not found until summer. These cases have been deleted from this column.

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Figure 194.—Rescuers uncover mountaineering victim on Mt. Washington, N.H. (April 6, 1964). Back-country accidents account for the largest number of fatalities. (Photos by Warren)

accidents can be traced to a combination of inexperience and taking a calculated risk (and losing). Rescue depends on the actions of the unburied survivors. Organized rescue from afar usually turns into a body-recovery operation rather than a live rescue.

Ski-area accidents. The victims include ski patrollers as well as the general public. Ski-patrol accidents usually result from carelessness or errors. Typically, the patroller should have used explosives but decided to ski the slope instead. In other cases, the explosive test was negative, but the avalanche released during skiing (postcontrol release). Generally, too much reliance was placed on the explosive test, and the ski entrance was not carried out cautiously. For example, in several accidents, the patroller skied down the fall line (and in a few cases, stopped to rest in the middle of the path). Ski patrollers and others who carry electronic transceivers (described later in this chapter) can be more readily rescued.

Figure 195.—Make camp well away from the runout zone, since distances in the mountains can sometimes be deceptive. This campsite on the American Dhaulagiri Expedition is properly set back from the threatening wall in the background. (Photo by American Dhaulagiri Expedition)

Accidents involving the general public usually occur on uncompacted slopes (postcontrol releases have also taken their toll on the general public). Several accidents have been due to skiers who willingly or unknowingly skied into restricted areas. Rescue depends on fast and efficient mobilization of organized probe teams.

Highway accidents. In this category, the largest number of fatalities are suffered by highway maintenance crews. Several fatalities have resulted when the victim was plowing out debris from one avalanche and the avalanche path ran a second time. In one fatal accident, a plow operator stopped for lunch under a path. Another accident occurred while a plow operator was giving assistance to a motorist caught in avalanche debris. Some avalanches have enough force to toss around the largest highway-maintenance machines. The operator usually has a better chance to survive if he remains in the vehicle, although snow can be expected to crash through windows and pack tightly around the victim. Prevention requires a thor-

ough set of avalanche signs, safety education, and a good avalanche-control program.

Buildings hit by avalanches. Mining camps were the traditional targets, but an increasing number of lodges and condominiums are being constructed in avalanche paths as good building sites become scarce (see chapter 7 for "Avalanche Zoning"). Rescue in demolished buildings is very tedious and time consuming, since the snow and building debris pack together in an almost inseparable mass. However, building debris may provide breathing space that prolongs the victim's chances of survival. In one case the avalanche started a fire, and the victims burned to death while trapped in the debris.

Railroad accidents. The largest single avalanche disaster in North America occurred in 1910 near Wellington, Wash. (El Hult 1960). This case provides a testament to the enormous forces of avalanches. Two railway cars of people and several locomotives were swept off their tracks. In all, 96 people perished. The avalanche was not unusually large; its vertical drop

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was slightly more than 500 m. Rescue required the tedious disentangling of train wreckage and avalanche debris. There were 22 survivors.

Miscellaneous. Tragic accidents have struck snowmobilers, utility servicemen, hunters, and dam construction workers. Families have been buried while playing in the runout zones of avalanche paths. Two children were buried fatally while playing in a ravine in the middle of a major eastern city. For such isolated cases rescue invariably comes too late; the best hope is prevention by public education.

Decisionmaking and route selection

Back-country safety is first of all a matter of controlling enthusiasm and exercising sound judgment. In the spirit of adventure, even the most experienced ski-mountaineer may cause an accident by taking what he thinks is a small risk to reach his objective. This enthusiasm is reinforced by the feeling of group security that comes when several people push forward together; no member of the group likes to admit concern and turn the party around prematurely.

Another important cause of accidents is the physical strain imposed by severe weather and terrain. Working under this strain, one may exhibit a carelessness that one would condemn while sipping tea in front of the fireplace.

It may be unrealistic to expect the weekend enthusiast to have a flawless record when he escapes to the mountains. On the other hand, professional mountain guides must set the highest safety standards and cannot habitually lead unknowing clients into areas of extreme avalanche danger. In a famous case, the courts in Switzerland did in fact accuse a guide of negligence when he led 14 people into an avalanche path that took the lives of Olympic skiers Bud Werner and Barbara Henneberger (Schild 1965).
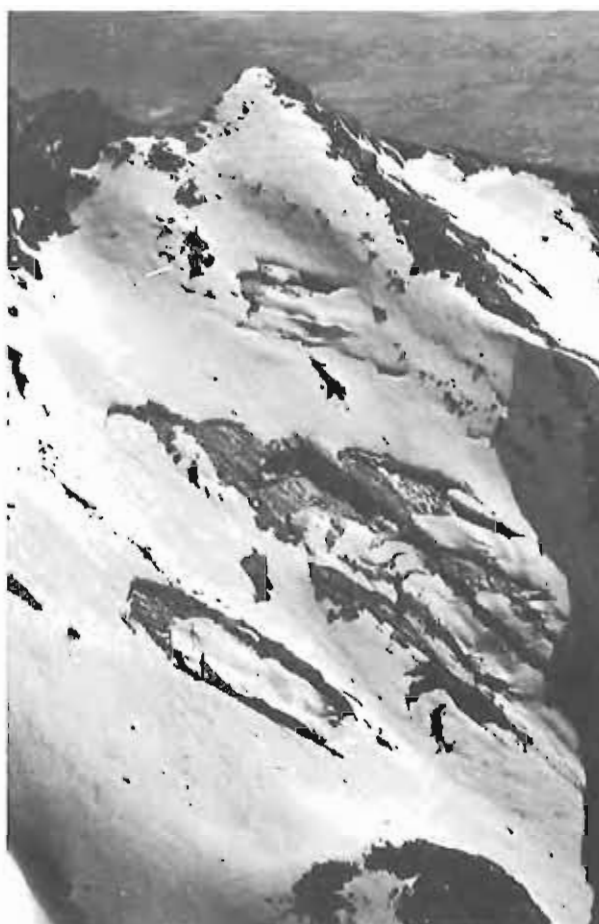
Figure 196.—Glide cracks on a wet, steeply dipping rock face in the Wasatch Mountains of Utah. Left photo taken in late February 1975; right photo, early May 1975. Such highly unstable slopes are no place for touring. (Photos from *Wasatch Tours* by Kelner and Hanscom)

Figure 197.—The best time to tour is in spring, when avalanche activity is most predictable. (Photo by Kelner)

Figure 199.—The most efficient route is often the safest. Here winter mountaineers thread their way on the windward side of the ridgecrest. (Photo by Kelner)

Figure 198.—A good example of bad route selection and poor technique. Skiers are in an obvious avalanche path. They have made at least three traverses and are still a long way from a safe spot. The slope is one that is loaded by the wind, as evidenced by the large cornices. Fresh snow has recently been deposited on the slope. The party is small and much too close together.

Decisionmaking depends mainly on snowpack stability evaluation. The basic principles of stability evaluation are set forth in chapter 5, which explains the six inputs needed for routine operations, namely: *snow-cover distribution, current and past avalanches, snowpack structure, local meteorological measurements, Weather Service information, and ski and explosive tests.* It is unlikely that a tour leader will have personal access to all of these inputs, but he can call on nearby avalanche specialists for help and opinions. For example, in Switzerland, touring parties may dial on the telephone prerecorded tapes that summarize most of the pertinent weather and avalanche conditions. In North America, it is usually necessary to make contact with the nearest ski patrol, Forest Service office, park warden office, etc., on an individual basis. If the touring club is large, it is preferable to assign one club member the task of establishing and maintaining contact with mountain-based observers throughout the season. In this way, continuity will be provided and duplication minimized.

Stability evaluations are adjusted according to the lateness of the season:

Early season. This usually includes the period from November to February. The main problem is that the snowpack is unconsolidated. Touring is most hazard-

SAFETY AND RESCUE

Figure 200.—Tourer enjoying alpine skiing on slopes of 20° to 30°; steeper slopes should be avoided until spring. (Photo by Kelner)

ous during and immediately after storms, but instability persists between storms. In general, the most dangerous slopes are north-facing or shaded. Such slopes are most likely to have significant TG layers during the early part of the season. If enough time is allowed for new snow to stabilize, it may be possible to tour on south-facing slopes.

Mid-season. This is the transition period, usually from February through April. The snowpack is consolidating, and deep slab instability tends to relax a few days after a storm. Touring must still be conducted with caution.

Late season. From April through summer, the mountain snowpack compacts and becomes isothermal. This is the best time for alpine touring. With rare exception, slab avalanches are restricted to the first few days of thaw after a new snowfall. Deep slab instability is rare; the thickness of the slab will be confined to the layer of new snow. After a few days of warm temperatures, the slab hazard will be essentially stabilized, and the main threat to tourers will be loose, wet avalanches that run "on schedule" in the after-

noon. These avalanches can be completely avoided by making an early morning start across the frozen pack and completing the tour as the snow surface turns to "corn" (when the skiing happens to be best). This usually means getting off all hazardous terrain before noon.

Regardless of the lateness of the season, proper attention should be given to warning signs, most of which are discussed in chapter 5. Sudden collapse of the snow, fractures propagating out from skis, increasing wet snow instability, wind slab, persistent heavy snow, heavy rain, etc., are reasons to turn back or consider a safer route.

It is not possible to give universal rules for route selection. Each tour has peculiarities that overrule idealizations; the route is chosen to optimize efficiency, safety, and pleasure. Fortunately, the most efficient route and the safest route are very often the same. For example, since one can travel much faster on flat, windblown slopes than on steep, snow-filled slopes, route selection generally favors ridges or low-angle windward slopes rather than lee slopes.

Decisionmaking and route selection

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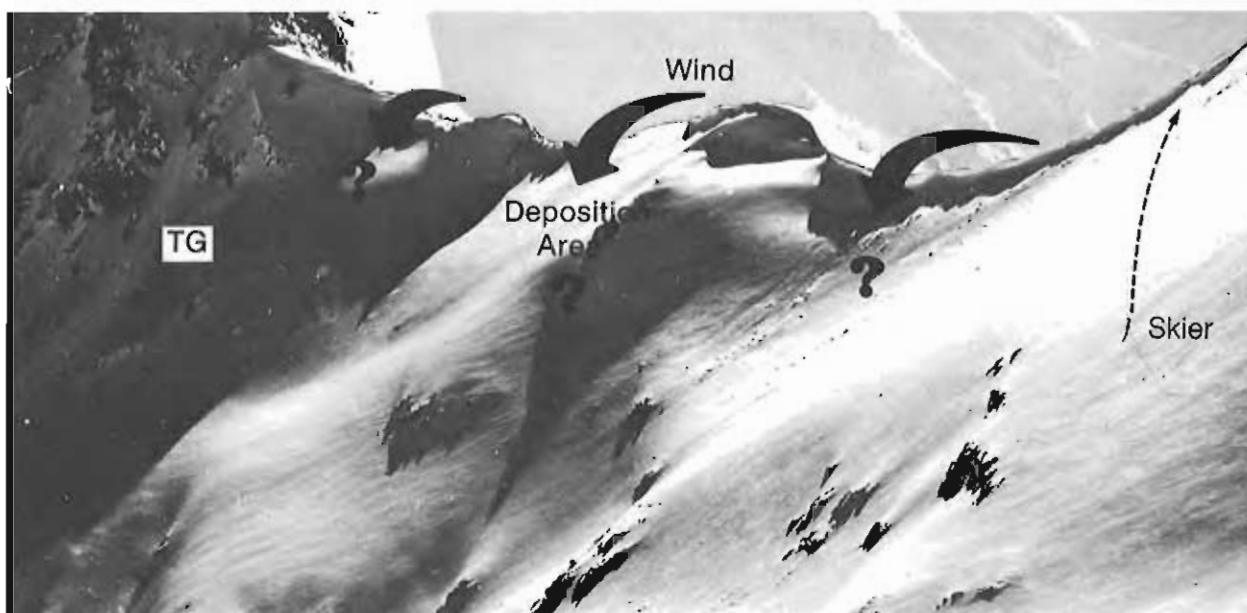
Figure 201.—When approaching a saddle or ridge, cross the starting zone as high as possible. Avoid suspected areas of wind deposition and TG metamorphism. Dotted arrow shows recommended route. (Photo by Kelner)

However, when instability is suspected, it is necessary to avoid avalanche paths completely. This may mean using a roundabout or inefficient route that gains or loses precious elevation, or it may mean traveling over difficult but avalanche-free terrain. For example, one may avoid open slopes and travel instead on forested slopes. As a simple rule, if trees are spaced within a few meters of one another (just close enough to make ski travel annoying), the protection they offer should be adequate.

Generally, one must stay clear of slopes steeper than 30° during periods of potential instability. This is not overly restrictive, since downhill skiing can be enjoyed on slopes in the range from 20° to 30° under most snow conditions, including deep powder. The more spectacular tours on steeper slopes must be saved for spring.

If it is necessary to cross an avalanche path during a period of potential instability, it is better to move quickly across the runout zone rather than across the starting zone or track. This is because most avalanches are triggered by the victims. If an emergency makes it necessary to cross a starting zone, the tourer can improve his chances by the following strategies:

- While climbing to a ridge or saddle, enter the starting zone as high as possible. If the slab frac-

tures, the chance of ending up on the surface is better (fig. 201).

- When climbing or descending in a starting zone, try to keep to the flanks rather than the slab center. If the slab fractures, the flank snow tends to be deposited over snow from the slab center. More important, there is a better chance to escape by traversing out of the slab area.

- If there is a choice, favor starting zones that feed into flat, open runout zones, as opposed to gullies. There is a better chance for shallow burial on flat, open slopes.

- Avoid starting zones that feed into crevasses, cliffs, icefalls, and other terrain hazards.

- When TG instability is a possibility, choose a route that favors sun-exposed sections over shaded sections.

- Avoid suspected areas of wind slab.

- Expect crown fractures to propagate between snowpack anchors such as rocks and trees; try to contour above the suspected fracture path (see fig. 94).

Besides these route-finding principles, many other safety practices to be used when crossing avalanche terrain are discussed in the next section.

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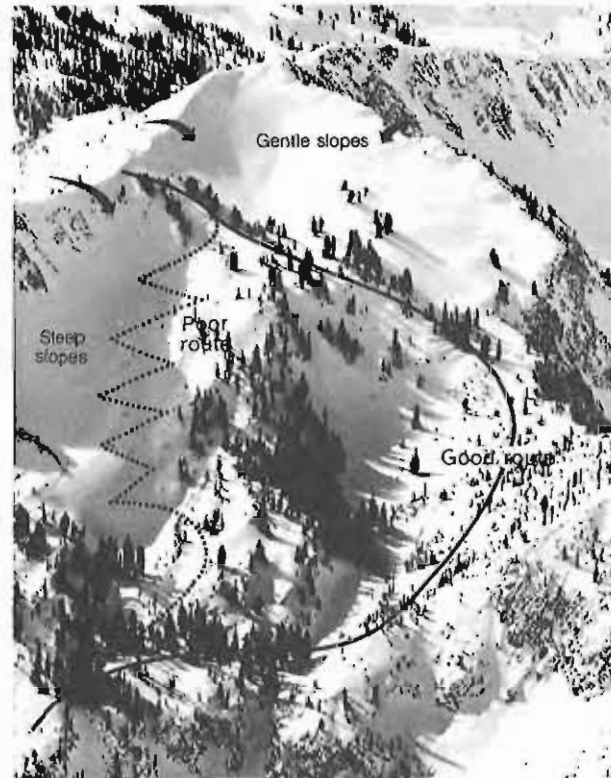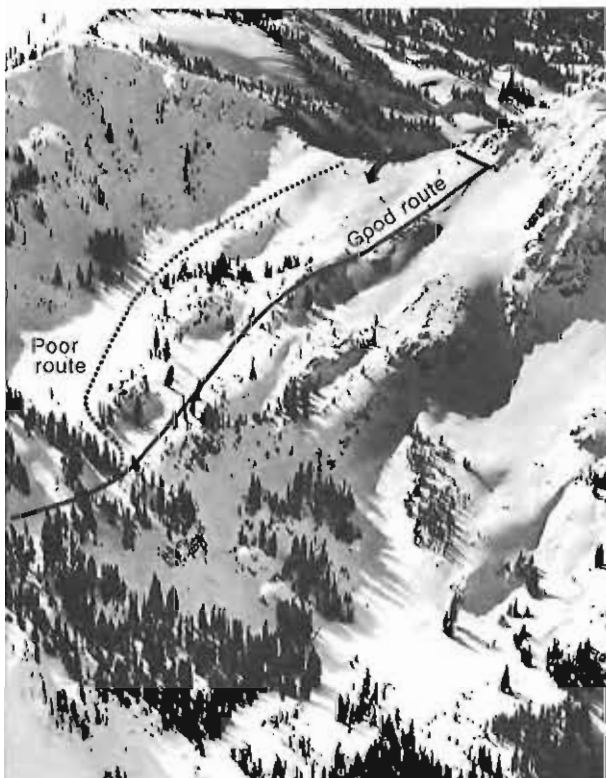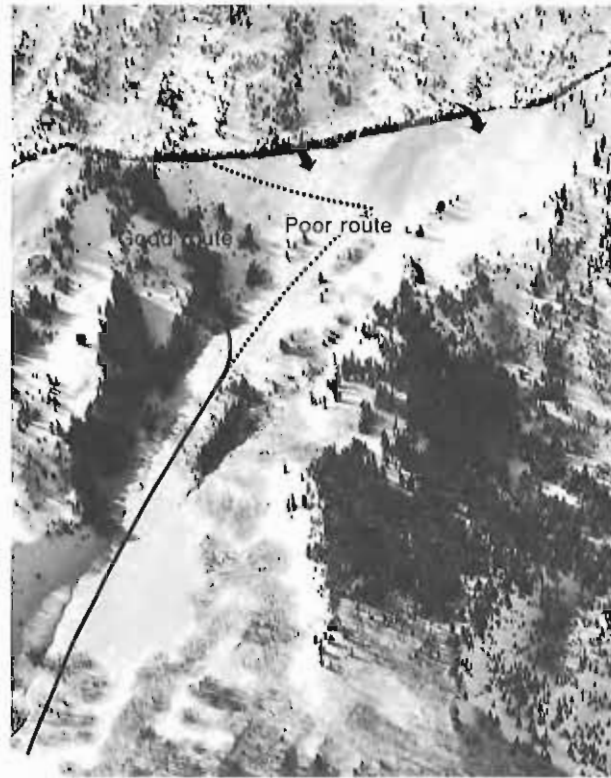
Figure 202.—Four ski-tour areas with the safer routes shown by solid lines and the more dangerous ones by dotted lines.
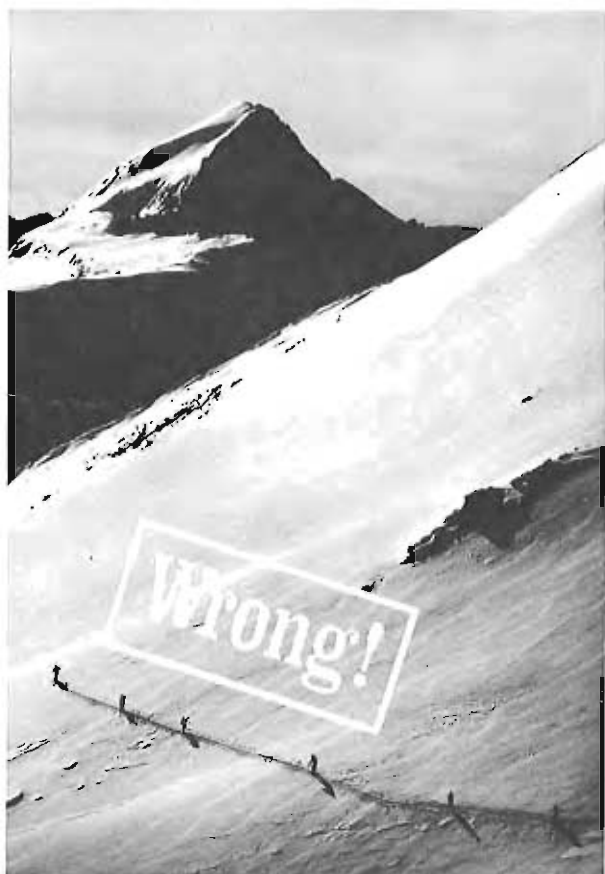
Figure 203.—A good example of the incorrect (left) and the correct (right) procedure. Only one person should cross an avalanche path at a time, while other members of the party watch from safe positions. The selection of a route through such an extensive avalanche path must be questioned. (Photos by Kelner)

Precautions for back-country travel

If a victim is buried completely, according to present data, there is statistically one chance in five he will be found alive. The "one-chance-in-five" statistic is based on a wide variety of accidents; in many cases, the victims neither paid attention to route selection nor took precautions. This section will discuss actions that may improve a victim's chances:

Mountaineering rope. A rope is often essential for crossing starting zones, especially where paths feed into gullies, crevasses, cliffs, etc. Although the rope may give protection against the forces of small powder avalanches, the dynamic forces of moderate to large avalanches far exceed the forces sustained in mountaineering falls. Avalanche forces are also of much longer duration. To sustain these forces, the belay should be tied to a fixed anchor, such as a tree, rock,

or rock pitons, rather than hand held. In an emergency, the belay may be supported by ice pitons, snow picket, or ice axe. A rope is especially useful in descending slopes where avalanches can be kicked off to clear the descent route.

Probes and shovels. Collapsible avalanche probes that fit into rucksacks can be purchased at some mountaineering shops. As an alternative, some special ski poles have removable baskets and can be attached together to make a probe about 3 m long. One or more strong, lightweight shovels should be taken on hazardous tours. Digging only with skis and hands, it takes almost half an hour in typical avalanche debris to dig a hole 1.5 m deep and wide enough to give assistance to a buried victim. The time can be cut to about 10 minutes with a stout mountain shovel. In a 1974 Colorado tragedy, the victim was located immediately by the transceiver technique, but the

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Figure 204.—Rope protection across an avalanche path.

A TREE TOO SMALL BAD EXAMPLE (handwritten annotation)

survivor had no shovel and was unable to dig down to the victim buried under 2 m of soft slab debris. The survivor was forced to go for help, and the victim was dead when recovered.

Picking out escape route. Before starting across a slide path, carefully study it and make a plan for escape should it fracture. When a slab fractures around and above a victim, his best chance is to escape to one side. If on skis, he should try to keep his balance and ski out the nearest flank exit. This means keeping track of the escape route and reacting almost instantly when the slab fractures. The closer the victim gets to the flank, the better his chance for a shallow burial. Very often the crown fracture occurs exactly along the victim's ski tracks, in which case he should attempt to hold his position above the moving slab.

Crossing starting zones one at a time. The correct procedure is for one person to cross at a time; the other members of the party watch from safe positions. When the first skier arrives at a safe location, he signals for the next to cross. Repeat the process until the entire party is at the safe location. Never assume that a slope is stable because one, two, three, or more people have crossed without triggering the slab. The first to cross may disturb the slab and initiate a relatively slow bed surface failure. The last to cross may trigger the final fractures.
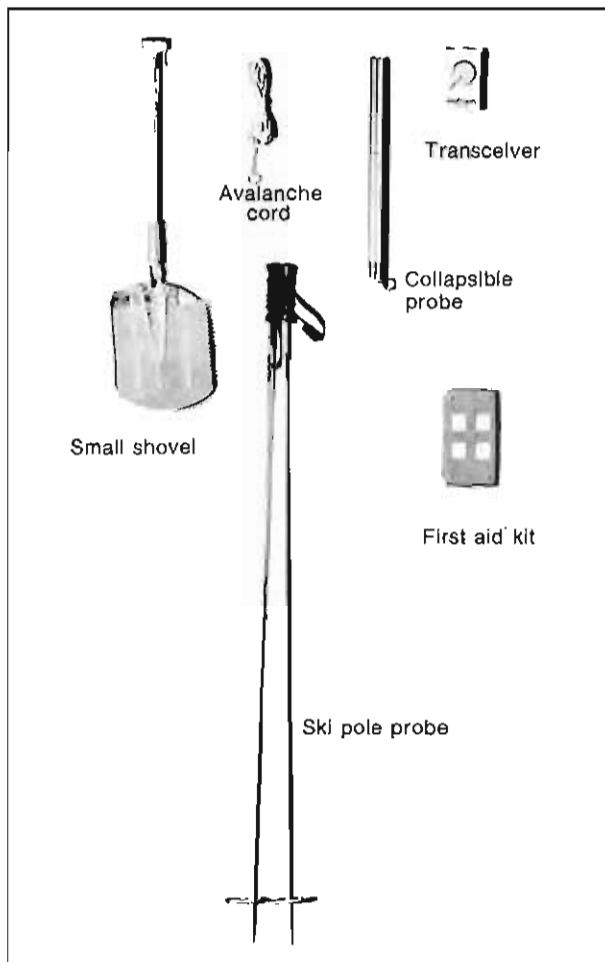
Figure 205.—Safety equipment for back-country travel: avalanche cord, small shovel, collapsible probe or ski pole probe, transceiver, and first aid kit.

Figure 206.—Comrades rush to aid a partially buried victim (arrow). Note that the victim's avalanche cord is on the surface. Such cords are a worthwhile safety device even though there are only a few authenticated cases where the victim was completely buried and his cord stayed on the surface. (Photo from *Wasatch Tours* by Kelner and Hanscom)

Electronic transceiver. A transceiver is a radio that can transmit and receive. It is the most effective safety device, and one should be carried by every avalanche worker and ski mountaineer. Before starting out, all members of the party should switch to *transmit*. If a member of the party is buried, the survivors switch to *receive* and home in on the signal according to procedures described more fully later in this chapter.

Avalanche cord. Trailing out at least 15 m of brightly colored nylon cord known as "avalanche cord," which is commercially available at most mountaineering shops, can be a safeguard. Avalanche cords are only partly reliable. According to tests conducted by the Swiss Avalanche Institute, in only 40 percent of the burials can a completely buried victim expect to have part of his avalanche cord on the surface. In

actual rescues, there is one documented case of an avalanche cord saving the life of a completely buried victim. Using the cord may be worthwhile, however, if it makes the traveler stop and reconsider his route selection and the possible danger. Effectiveness of the avalanche cord is improved by attaching a small helium-filled balloon to the free end.

Removing ski-pole wrist straps. If the victim is carried down, his survival chances are improved if his hands are free. For this reason, the wrist straps are removed before entering an avalanche slope, so that the ski poles can be discarded when balance on skis becomes impossible. Whether or not a victim wants to keep his skis attached will vary from case to case; thus, no general rule can be given for removing ski safety straps before entering a slope. First of all, the victim wants to keep his skis on long enough to get over to the flank. However, if the victim is carried down, his skis will flail against his body, compounding his injuries. There is also a chance that his skis will drag him under to a deeper burial. On the other hand, buried victims have been found because part of a ski was on the surface or because a probe pole hit a buried ski.
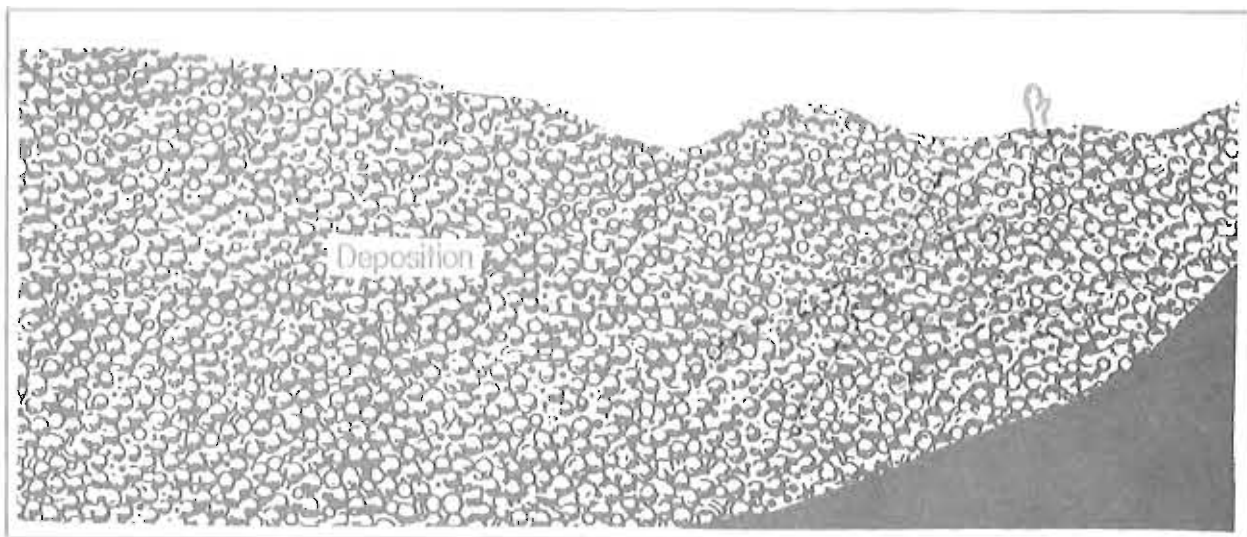
Figure 207.—This survivor of an avalanche at Mission Ridge, Washington, owes his life to thrusting a hand out of the snow. (Photo by Whitmire Photography, Yakima, Wash.)

Swimming. If he is caught in an avalanche and unable to make a flank exit, or if he loses balance, the victim should discard his ski poles and attempt to stay above the snow by swimming. The swimming motion should be as efficient as possible so that the victim is neither winded at the bottom nor choked by snow.

Thrusting a hand up. If snow starts to pile up on the victim after he reaches the bottom, he should attempt to thrust a hand up as high as possible before the snow sets up. A few victims owe their lives to having a hand above the snow. The other arm and hand should be in front of the chest and face to form a breathing space.

Figure 208.—One useful system for ski touring is to carry ski poles that can be assembled into probe-poles.

Conserving oxygen. In order to conserve oxygen, the victim should relax and not fight the sensation of blackout.

Action of the survivors. A buried victim's chance for survival depends on what the surviving members of the party do in the next few minutes. Hopefully, the survivors have followed the first precaution in this section and are standing in a safe place from which they can watch the victim's path. The survivors should search with whatever resources are available. If the victim is not wearing an electronic transceiver, the survivors must probe with skis, poles, collapsible avalanche probes, improvised probes made from tree branches, etc. Only if the touring party is large or if additional manpower is a few minutes away should a messenger be spared and sent for help. The history of avalanche accidents has too many instances of survivors departing the scene in panic to seek help when a few minutes' search would have uncovered the victim.

Probing for the victim

Compared to transceivers or avalanche dogs (see the later section "Avalanche Dogs") probing is a slow and tedious method of search. However, it is the only practical method if the victim is not carrying a transceiver of if a dog is not available. More complex detection systems that rely on the victim's body heat, body odor, sound, electromagnetic properties, gravitational field, etc., are still in the research stages (Vanni Eigenmann International Foundation 1963).

The first problem in making a speedy rescue may be the hazard to rescuers. The fact that an avalanche ran is proof of instability on neighboring slopes. After precautions are taken to safeguard rescue personnel, including a lookout in a safe spot to watch for and warn probers of additional avalanches (see the later section "Special Rescue Problems"), the search moves quickly and efficiently through the following steps:

(1) From witnesses or by examination of clues, establish where each victim was at the time of the avalanche.

(2) Determine the area where each victim disappeared—the "last-seen area."

(3) Using this information, establish probable trajectories for each victim.

(4) Determine the regions of highest priority search (usually a rough estimate).

(5) Make a rapid but systematic search of the avalanche debris surface in the regions of highest priority. Mark the location of all clues. Searching the surface is the first part of the probing operation, and it offers the greatest probability of a live rescue.

Immediately after completing the surface search, rescuers should be organized into probe lines, using whatever probe equipment is available. Ideally, probe poles should consist of rigid steel or aluminum tubing, 3 to 4 m long. Longer poles are difficult to manage; besides, the chance for making a live rescue of a victim buried deeper than 3 m is extremely small. There is an advantage to standardizing probe length, since this may make it more obvious to the probe leader when one probe is stopped short of full probe depth by an obstacle.

Probing is simple and requires very little practice; it is a technique as old as avalanche disasters and is readily learned by well-meaning volunteers. It is easy to feel the difference between striking a body and striking a snow layer; the real problem is discriminat-

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ing between the ground surface and a deeply buried victim. Before starting to probe the avalanche debris, the probers should be briefed on their mission and given directions for evacuating quickly.

Probe lines must be ordered and properly spaced for probing to be effective. About 20 probers per line is satisfactory, and 30 is an upper limit. If extra manpower is available, a person can be placed at each end of the line to hold a string for alining the probers. The string should be marked to help properly space the probers.

The probe line advances steadily upslope. Advancing uphill automatically helps set the proper pace and keeps order. Even so, proper spacing and discipline often become a problem after probing has continued for some time. Downhill probing is more difficult to control, although, if the rescue team approaches from above, the initial surface search can proceed downslope. Probing does not come to a halt when a possible strike is made. The probe line continues to advance, and a small crew falls out and shovels down to investigate the strike.

Coarse probing. As long as there is any hope for a live rescue, probing is conducted at a vigorous pace according to a system known as "coarse probing." The idea behind coarse probing is to sacrifice some thoroughness to improve speed and thus maximize the chance of finding the victim alive. Coarse probing gives about a 70-percent chance of finding the victim; this may be compared with the alternative and more thorough method of probing known as "fine probing," which gives nearly a 100-percent chance of finding the victim. However, fine probing takes four or five times longer than coarse probing, and it is best to make several passes using coarse probing before resigning the operation to slow, thorough fine probing. Coarse probing does sacrifice some thoroughness because of the grid size, and it must be carried out precisely to keep the sacrifice to a minimum. Coarse probing proceeds as follows (see fig. 210):

(1) Probers are spaced along a line, 75 cm (center to center) apart. A distance of 50 cm is straddled, leaving 25 cm between the toes of adjacent probers.

(2) The probe pole is inserted once at the center of the straddled span. (An alternative method, used where terrain is steep or there are only a few probers, is to stand "fingertip-to-fingertip." The prober then probes first on one side of his body, then on the other side. If done carefully, this gives the same probe spacing as the single-insertion system.)
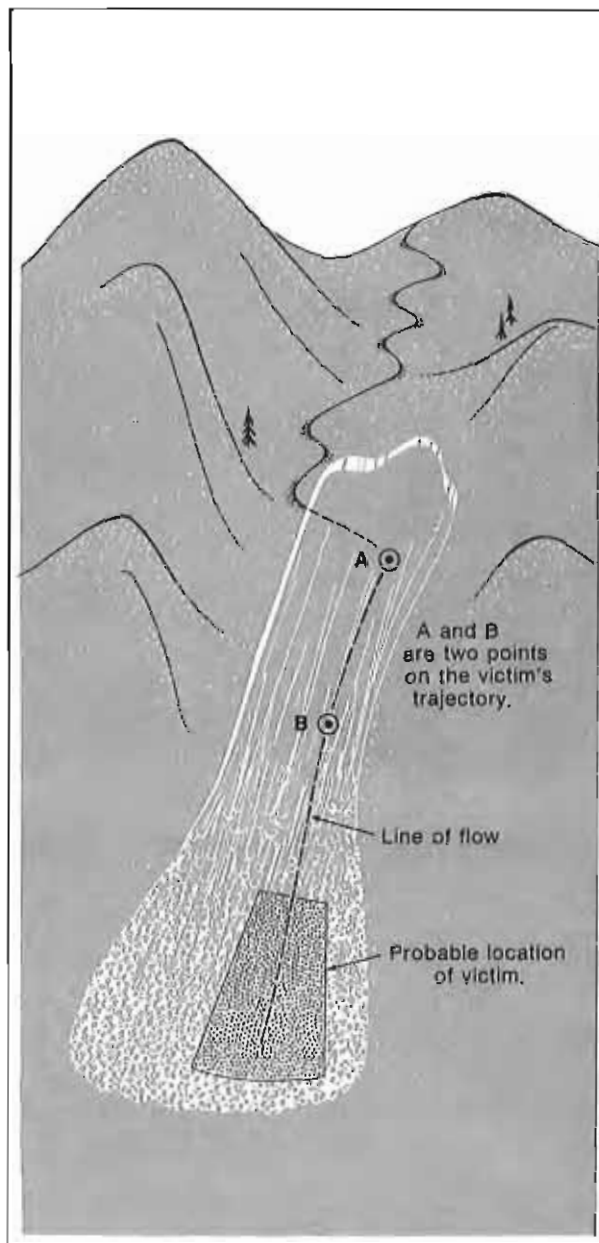
Figure 209.—If two points of the victim's trajectory can be established, a high probability exists that the victim will be near the downhill flow line passing through these two points.

(3) On signal from the probe-line leader, the line advances one step (about 70 cm) and repeats step 2.

Usually one signal suffices for the complete sequence—insertion of probe, retraction of probe, and advancement of line. The signals should be at a rhythm that enforces the maximum reasonable pace. Strict military discipline and firm, clear commands are essential for efficient probing. The probers should work silently. The spacing of the probe holes is 75 by
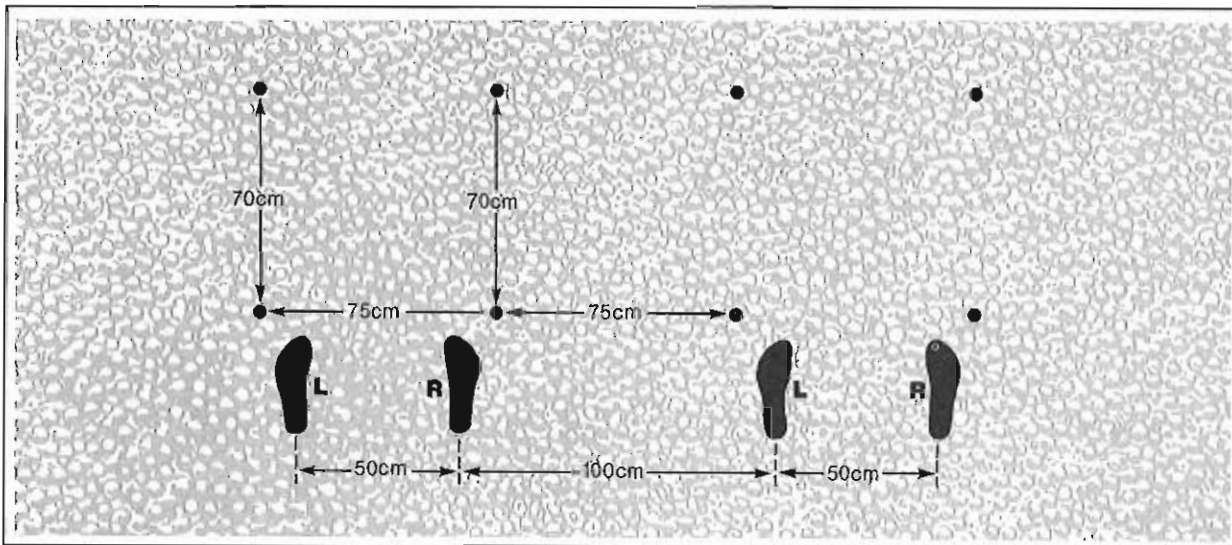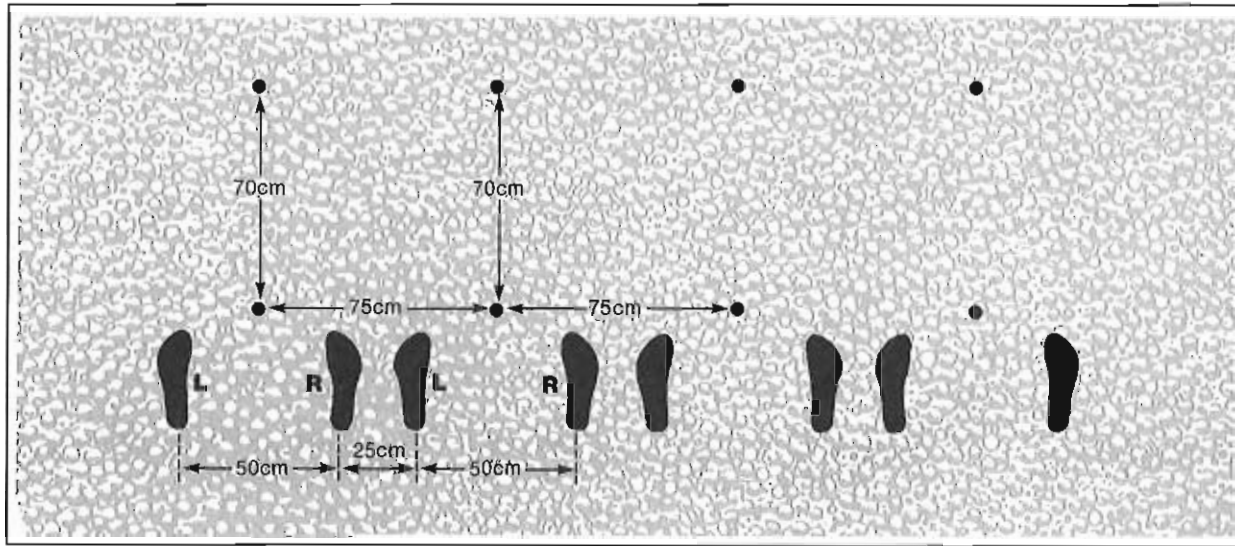
Figure 210.—Execution of coarse probe. The coarse probe is used whenever live rescue is expected. The above spacing can be achieved by dressing the line "elbow-to-elbow" in "hands-on-hips" position. One probe insertion is made, and the line advances one step. An alternative method, useful when the number of probers is limited or terrain is steep, is to have probers stand fingertip-to-fingertip. Probers then probe once to the left of their body and once to the right before the line advances.

70 cm, which is equivalent to 1.9 probes per m². The chances for direct strike of victim are:

Person lying on his stomach or back ... 95%
Person on his side 75%
Person in vertical position 20%
Average position 70%

On the average, 20 men can search an area 100 by 100 m in 4 hours. Depth of probing is adjusted to depth of deposition, but should be no deeper than 3 m.

Fine probing. After repeating the coarse probe several times, it may be obvious that the objective is body recovery rather than live rescue. In order to preserve the strength and morale of the volunteers, the pace and discipline of the operation may relax to the more thorough and less vigorous fine-probe technique, which functions as follows (fig. 212):

(1) Volunteers are arranged the same as for the coarse probe.

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Figure 211.—Ideally, a probe line should consist of about 20 rescuers. A large group tends to get out of alinement, with consequent loss of efficiency.

(2) Each volunteer probes in front of his left foot, then in the center of his straddled position, and finally in front of his right foot.

(3) On signal, the line advances 30 cm and repeats the three probes.

The spacing of the probe holes is 25 by 30 cm, or 13 probes per m². This means that if the victim is in a favorable position, five direct strikes are likely to be made. If he is in an unfavorable position, one direct strike is likely. The overall probability of finding the victim is therefore 100 percent, providing the burial is not deeper than about 3 to 4 m. On the average, 20 men can fine probe an area 100 by 100 m in 16 to 20 hours, depending on the depth of probing.

In most cases the victim is carried by the moving avalanche to the places of greatest snow deposition—usually the toe of the slide. Occasionally he is snared by rocks, trees, or benches in the terrain. If the avalanche follows a wandering gully, all bends with snow deposits are likely burial places; again, the victim is likely to be where the greatest amount of snow is deposited. Finally, the victim may be thrown out of the slide. In a few cases, victims have been found dangling from trees. There is a sad case of a young boy who escaped from an avalanche but died of hypothermia in the woods while his rescuers carefully probed the avalanche debris.

Since there is usually a shortage of manpower during the initial and critical phase of the probing operation, it is necessary to decide which areas have the highest priority for search and in what order these areas will be probed. The decision involves weighing the approximate probability that a victim is in a given area versus the relative time required to search that area. Normally, initial search is made of the main debris area, since this area can be searched most efficiently with the greatest chance of success. However, there may be clues that indicate a high probability that the victim was snared above the main debris or perhaps that the victim has escaped the slide. In such cases, manpower should be allocated to follow up the clues.
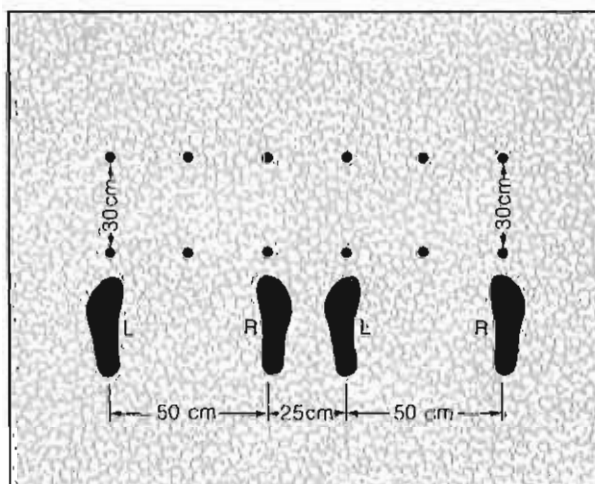
Figure 212.—Execution of fine probe. The fine probe is used when live rescue is not anticipated. The setup is the same as in coarse probing. Three probe insertions are made, and the line advances about a half step.
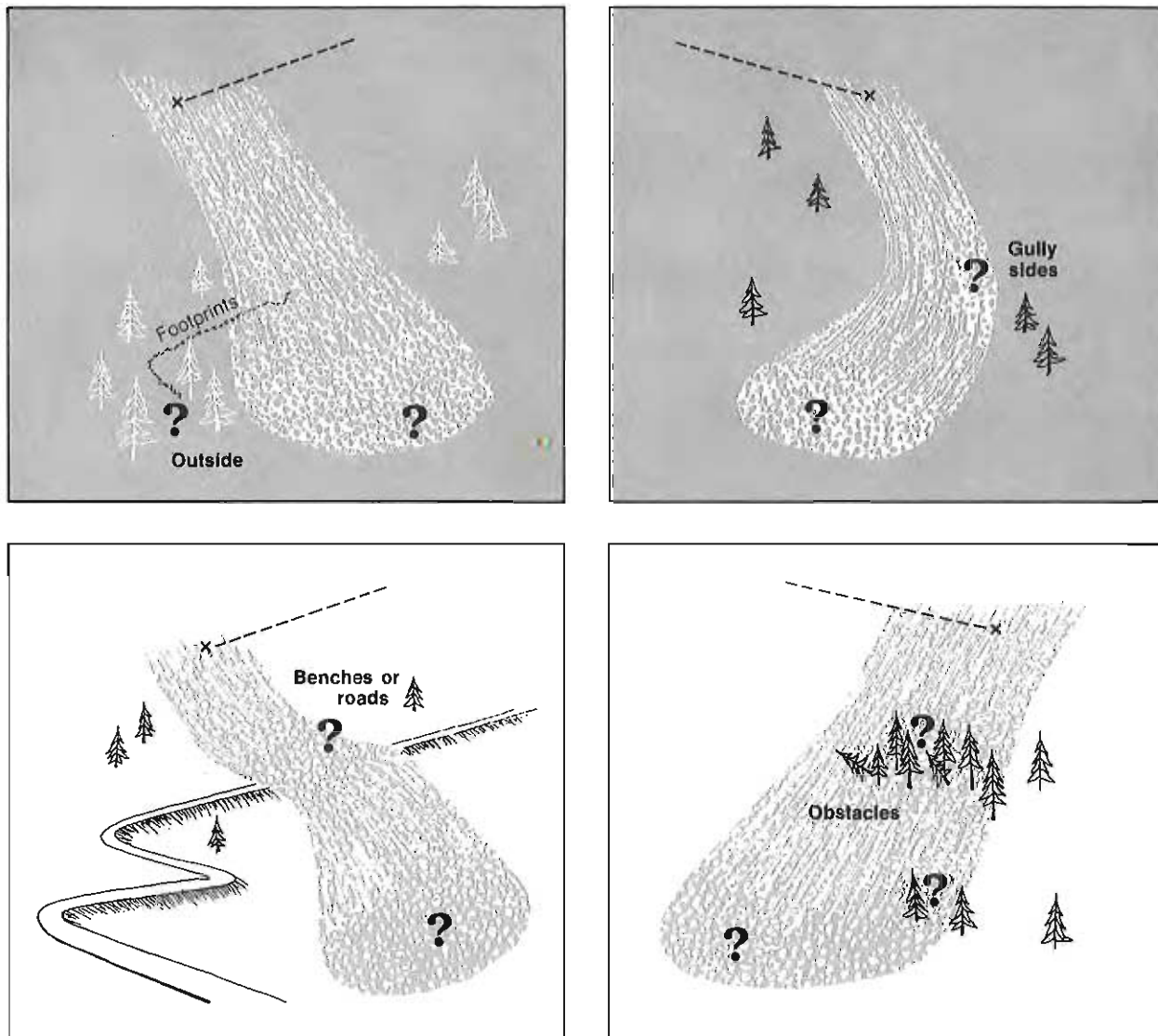
Figure 213.—Most victims are carried to areas of greatest deposition. However, other burial clues may require followup.

Search by electronic transceiver

People who travel regularly in avalanche terrain cannot depend on probe lines for backup protection. They need a device that offers speedy detection regardless of the size of the avalanche. The electronic transceiver mentioned in several earlier sections enables the victim to be found within 10 minutes after his signal is first picked up, providing rescuers know the correct procedure for using their transceivers and participate in practice drills at least once each season.

As an example, the basic procedure for using one of the transceivers[7] is outlined below.

[7]The "Skadi" system developed by Lawtronics, Inc., was the first transceiver to be marketed and proven by saving lives. It is based on a 2275-Hz audio-induction signal. There are two important reasons for choosing this audio frequency as opposed to a higher radio frequency: (a) There is no interference from radio broadcasts; and (b) the electronic circuitry is relatively simple, and there is less chance for a malfunction. Unfortunately, several other systems are being marketed at noncompatible frequencies. In a recent accident involving 20 helicopter skiers who were wearing transceivers,
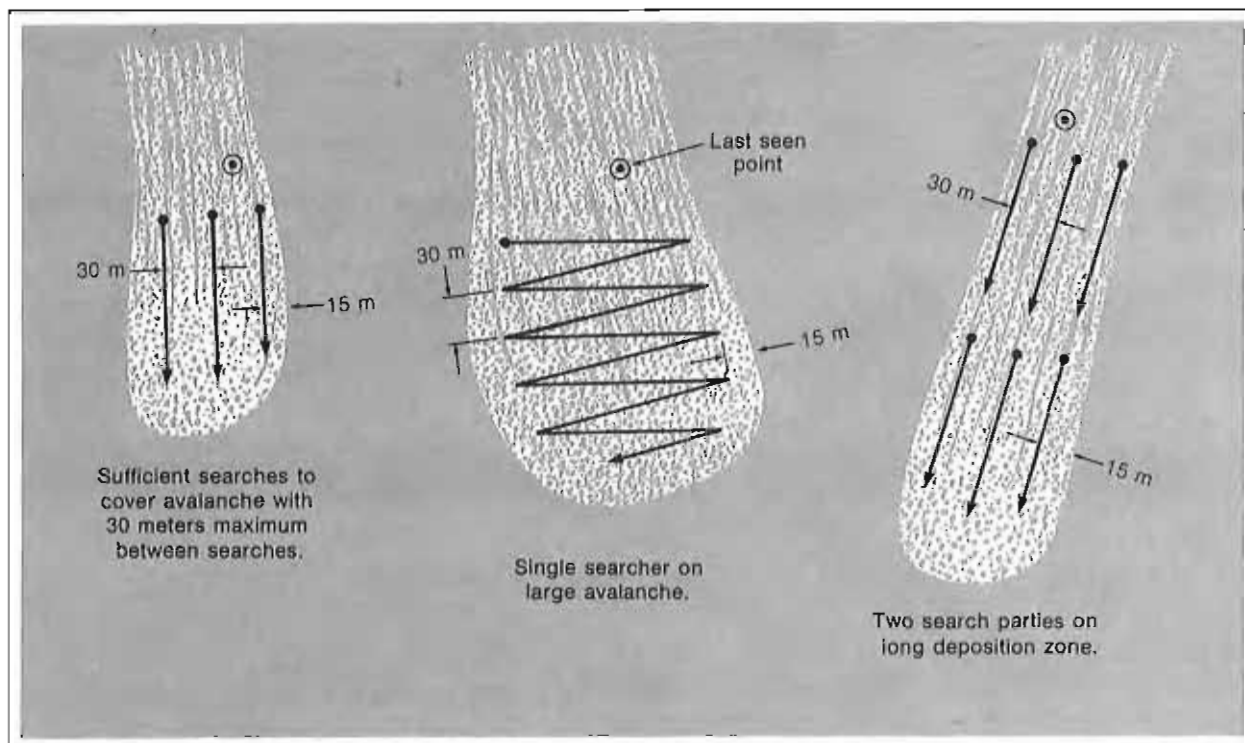
Figure 214.—Initial search procedure using transceivers with effective range of 30 m (Lawton 1969).

Consider the most common situation, in which the victim is swept down by the avalanche, and the rest of the party is above the area where the victim was last seen. Switch the transceiver to *receive,* and proceed as follows (Lawton 1969):

(1) Carefully note and mark the last-seen area. If there is danger of further avalanches, post an avalanche guard and be prepared to switch back to *transmit.*

(2) Be sure all transceivers are switched to *receive.* The leader must check this, since a single searcher with his transceiver left on *transmit* can frustrate the entire search.

(3) Deploy a line of searchers at the level of the last-seen area and search downward. The spacing between searchers should not exceed 30 m (fig. 214).

(4) Keep volume control turned all the way up until a signal is received. You should be able to hear some background noise (static).

(5) Move in unison, keep the line straight, and keep noise and talking to a minimum. All searchers stop every 10 paces and slowly rotate their transceivers left and right, then front and back.

(6) When a signal is heard, everyone should be informed, but the line of searchers should not be broken up. Orient the transceivers for maximum signal strength. Turn the volume down until the signal can just be heard; the ear detects changes in signal strength much more readily at low levels.

(7) Do not change the orientation of the transceiver in space while moving. This is very important because it causes false changes in signal level.

(8) Halt every few paces to refine the orientation for maximum signal strength and reduce the volume. The best orientation will change as you get closer.

(9) When the signal starts to get weaker, the victim has been passed. Scribe a line *A* in the snow to mark this point (fig. 215).

(10) Again orient the transceiver for maximum signal, maintain this orientation, and reduce the volume until the signal can just be heard. Now, back up until the maximum signal point has been passed and the signal fades again. Mark this fade point (line *A'*

there was added confusion when units that were incompatible with those of the victims were brought to the scene. It is recommended that rescue teams purchase only brands that operate at 2275 Hz.
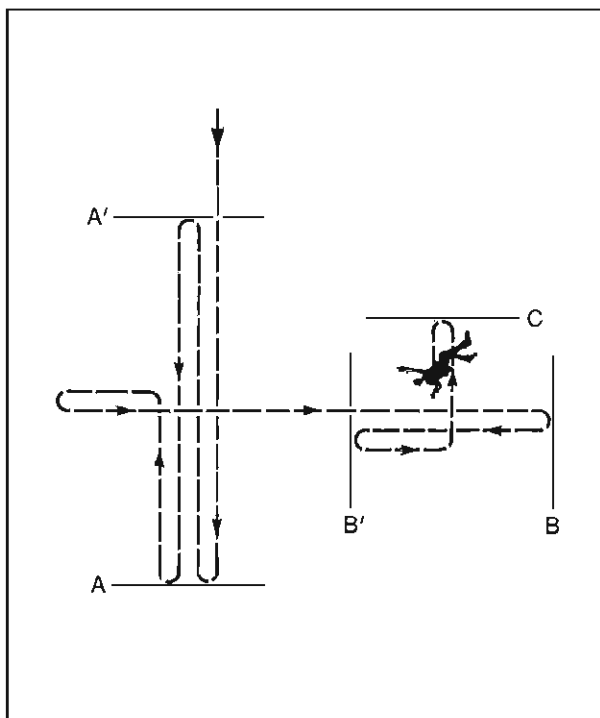
Figure 215.—Terminal phase of search by bracketing (Lawton 1969).

in fig. 215). The two fade points bracket the position of the victim.

(11) Locate yourself halfway between the fade points. Orient the transceiver for maximum signal, then reduce the volume until the signal can just be heard. Search at right angles to the original search direction. Establish bracket *B–B'*. Hundreds of practice sessions have shown the right-angle technique to be the fastest way of finding a victim.

(12) Continue systematically to improve the estimate of the victim's position until it is pinpointed. Three or four crisscrosses are usually sufficient.

(13) It pays to pinpoint the position of the victim. Otherwise, a great deal of snow may have to be moved and a good bit of time lost before the victim is found. Experience has shown that it is possible to refine the fix to about one-fourth of the burial depth.

If more than one person is buried, turn each victim's transceiver off as soon as possible. In most cases, it is not very difficult to separate signals from more than one stationary transmitter; however, the added complication of searching for several transmitters reemphasizes that only one person should cross an avalanche path at a time. It is recommended that groups who purchase transceivers attend practice field clinics arranged by the manufaeturer.

One problem with transceivers is their cost. They are a specialty item that must be manufactured and tested for the highest standards of reliability. Detailed testing of all components takes time and money—costs that the consumer pays if he wants a dependable unit. However, mountaineering shops or ski-touring clubs can purchase several units at reduced prices and rent them to individuals on a temporary basis.

Finally, some victims wearing transceivers have been located quickly but not quickly enough to save their lives. Although the transceiver is an important tool for backup protection, the user should not believe that transceivers (or any rescue system) permit increased risks to be taken on potential avalanche slopes.

Avalanche dogs

Working mostly by scent, a well-trained avalanche dog can make a rough search of an area 100 by 100 m in about half an hour or about eight times as fast as a 20-man team could "coarse probe" the same area. A dog requires about 1 to 2 hours to make a detailed search, whereas a "fine probe" would take 16 to 20 hours.

Avalanche dogs are used extensively in the Alps, where dense settlement makes practical the time-consuming training of dogs to search efficiently for buried victims. According to Swiss statistics, avalanche dogs participated in 305 rescues from 1945 to 1972; 45 victims were found alive, 224 victims were found dead, and in 36 cases the dog failed to find the victims. The large number of dead recoveries is no reflection on the ability of the dogs; it is proof of the slim chance of survival of a buried victim.

All told, there are about 500 certified avalanche dogs in Europe. The system is most highly organized in Switzerland, where a call to a central telephone number brings the nearest avalanche dog to the scene of the accident (by plane or helicopter, if necessary). The famous Parsenndienst rescue patrol at Davos maintains an avalanche-dog kennel near their headquarters at the top of the Weissflujoch ski area. Keeping dogs on call at the top of a ski area is the best system for live rescue.

Because the avalanche hazard in North America is dispersed in space and time, a different approach has evolved—the training of dogs for multipurpose search. In addition to avalanche victims, dogs are trained to find flood victims, people lost in the wilderness, plane-crash victims, earthquake victims, etc. Thus, the dogs

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are used much more often than if they were saved for avalanche work. This approach has been proven in a wide assortment of rescues when dog and leader were quickly airlifted to the disaster scene.

The advantage of housing special avalanche dogs at ski areas to improve the chances for a live rescue is often somewhat outweighed by the fact there are seldom enough avalanche rescues to keep dogs and handlers working at peak efficiency. Special efforts must be made to keep search skills and physical conditioning high. On the other hand, the versatility of multipurpose search dogs means they and their handlers usually have enough missions to stay in training. Unfortunately, it also means the dogs are normally not housed at ski areas and therefore often are not available soon enough for live rescues.

Avalanche dogs work best to retrieve persons still alive or victims who have died within a few hours. They are less successful at finding dead persons buried deeper than about 2 m, although under favorable conditions a dog has made a live rescue of a victim buried under 5 m of snow. Cold temperatures, strong winds, wet snow, and contamination of the search area are other important limiting factors. The exhaust and gasoline fumes from hovering or landing helicopters make it very difficult for dogs to work.

There are several prerequisites for dog and master. The dog must have:

- A well-developed sense of smell

- A strong constitution and the ability to withstand the rigors of winter travel, wading through snow, etc.

- A hair coat resistant to cold

- A temperament suited to training

- A healthy physical and mental structure.

German Shepherds and related breeds are proven and are an excellent choice, but satisfactory results may be obtained with other breeds, such as Labrador retrievers, golden retrievers, border collies, etc. A trainer will be operating at a disadvantage if he chooses breeds that are "game-oriented" or are either too large or too small for vigorous travel.

Besides an understanding of canine psychology and a talent for training dogs, avalanche dog leaders need impressive qualifications:

- Knowledge of mountaineering and avalanche safety

- A strong constitution and reasonable ability to hike and ski

Figure 216.—A trained avalanche dog is a welcome addition to any touring party.

- Training in first aid

- Training in flying and helicopter safety

- Availability during the winter on short notice.

In the Swiss Alps, dogs and masters attend weeklong training clinics, followed by continual local practice. Dogs are rated according to three classes: Class A (beginning), Class B (intermediate), and Class C (operational). A dog is about 3 or 4 years old before he achieves Class C; this leaves about 4 to 6 years of useful service.

In one system of training, explained more fully in Austrian Mountain Rescue Service of Tirol (1962), the dog is given the following four initial exercises:

Exercise 1. A shallow pit large enough for two men to lie in is excavated on a slope, preferably one covered with avalanche debris. Participants are the dog's master (M), a trainer (T), and two helpers (H$_1$ and H$_2$). M delivers his dog to T and then hurries to the pit, calls the dog, and disappears into the pit. With his left hand, T holds the leashed dog by his collar, stimulates the dog's eagerness, and at the moment M disappears into the pit, points impressively with his right hand, commands "search!", and releases the dog. The dog should rush to M and be received with praise. M puts the dog on a leash and returns it to T.

Exercise 2. M quickly returns to the pit and is given a shallow burial (10 to 20 cm) by H$_1$. M has a delicacy ready in hand. H$_1$ quickly returns past the dog, giving the dog a chance to sniff and determine that M has not returned. T performs as above but follows
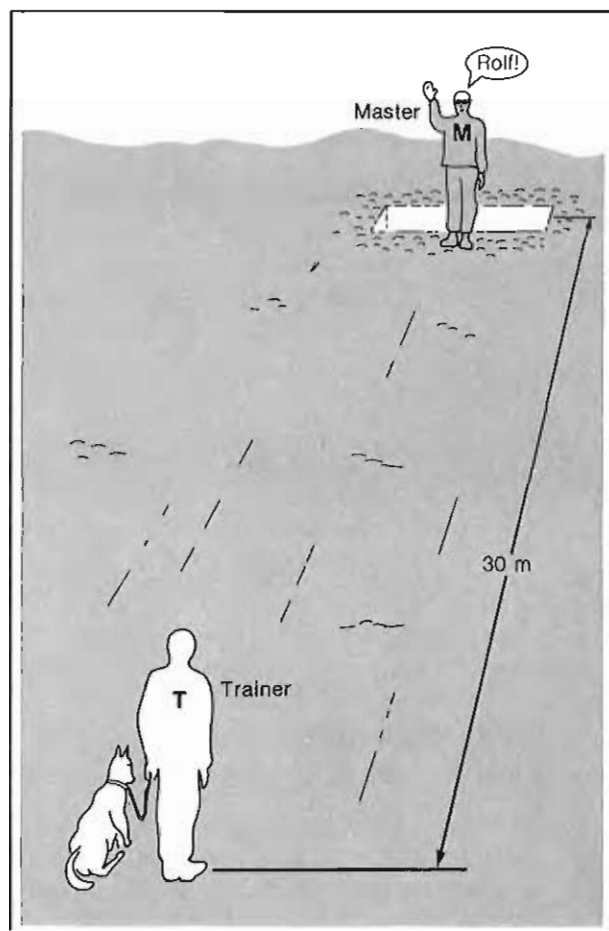
Figure 217.—Training the avalanche dog. Exercise 1.

the dog to the pit. If the dog does not start digging, T points to the pit, commands "search!", and begins digging and scratching on the snow. M helps by groaning. After detection, the dog is rewarded with praise and a delicacy.

Exercise 3. H_2 buries H_1 and M together, as shown in figure 219, and then returns past the dog. The search proceeds as above. Upon detection, H_1 and M both praise the dog, and H_1 hands the dog a delicacy.

Exercise 4. In the last of the initial exercises, M does not hand the dog over to T but enacts T's role. H_1 is buried alone and receives the dog with a delicacy and praise.

These exercises are done quickly in sequence. The dog is then given several hours of rest. When the dog has mastered completely the above sequence, he moves on to more difficult exercises:

- Helper buried in the original pit, out of sight of the dog

- Burial out of sight of the dog, about 10 m beyond the original pit

- Burial out of sight of the dog, shifting the exercise pits to the right or left

- Burial at random anywhere on the exercise slope, out of sight of dog

- Deeper burials (taking adequate precautions to ensure the safety of the helper)

- Enlargement of the search area, adverse conditions, etc.

- Tactical missions, including long approach marches.

In general, these advanced exercises are practiced in order of increasing difficulty; however, the dog is sometimes reinforced with easier problems that he can solve readily. Should the dog fail on an actual rescue, he should be provided with a solvable problem (such as digging up a planted glove) and praised when he succeeds.

SAFETY AND RESCUE
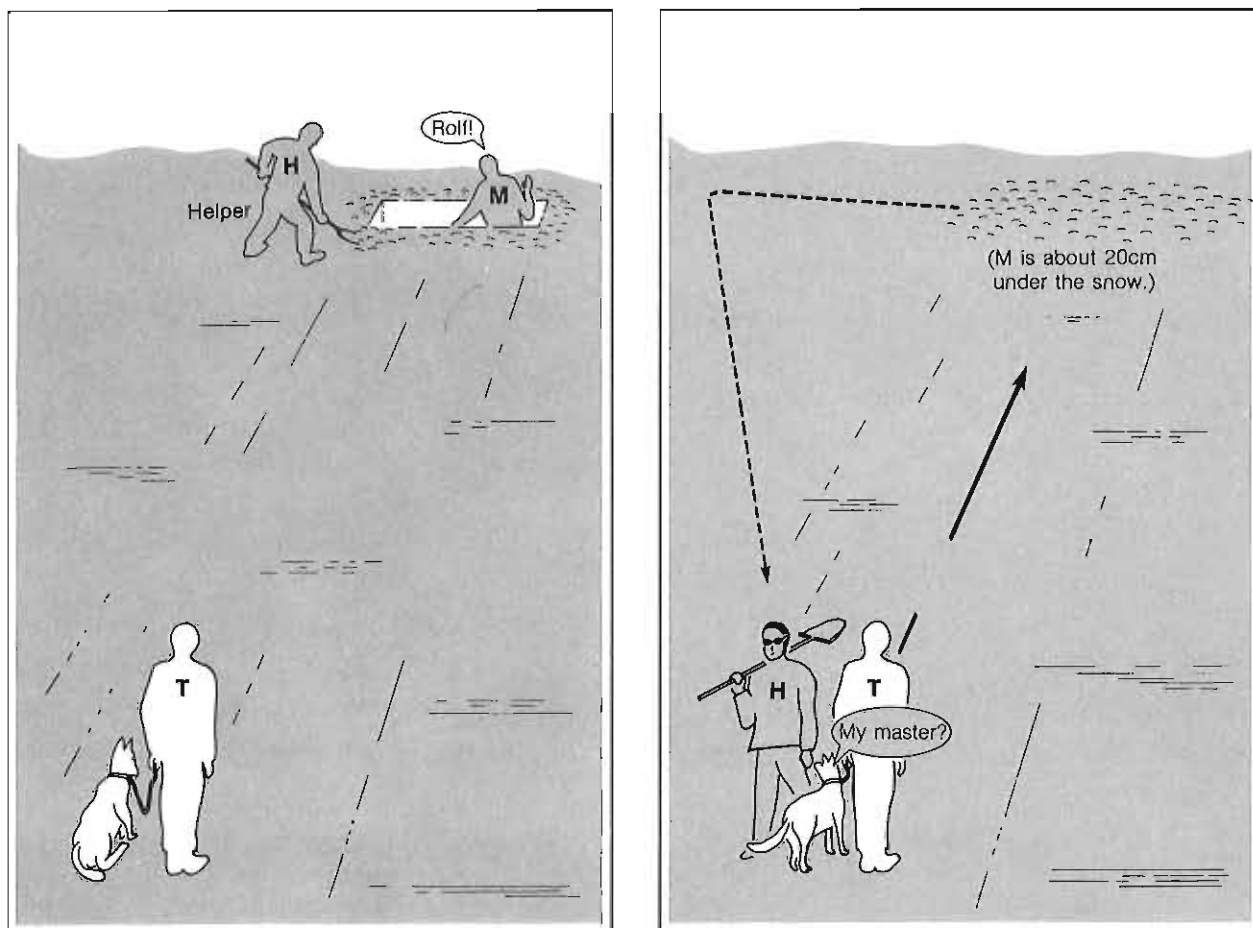
Figure 218.—Training the avalanche dog. Exercise 2.
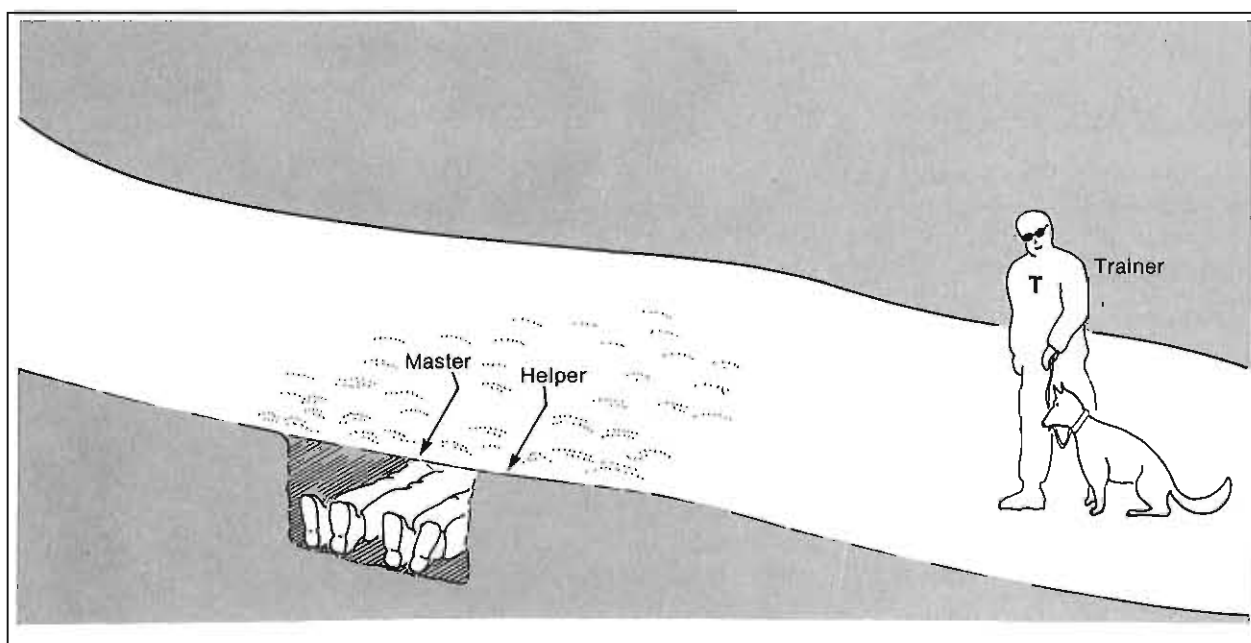
Figure 219.—Training the avalanche dog. Exercise 3.

Figure 220.—Training the avalanche dog. Exercise 4.

Figure 221.—Suction pump for clearing obstruction from breathing passages.

Revival and evacuation of the victim

Suppose a victim has been located and uncovered by an efficient and speedy rescue. Will the victim survive? The answer may be determined by what takes place in the next few minutes.

To all external appearances, the victim may exhibit no signs of life, but unless there are unmistakable signs of death, resuscitation must begin immediately. At a European ski area, a buried victim was uncovered and pronounced dead by two doctors. Against the protests of an avalanche dog leader, resuscitation was halted and the victim was transported to a hospital. On arrival, the victim was revived but died 15 hours later. In another case, a Swiss soldier buried by an avalanche for 8 hours was found at a depth of 1.5 m with minimum life functions and was saved. He had lost consciousness quickly after burial. His

body temperature at time of rescue had dropped to 30° C (86° F); his blood pressure was 80/65; his pulse rate was 44/minute; and his breathing was extremely superficial and slow. Other victims have been resuscitated from similar states of greatly lowered body temperature and metabolism. Although this reduction of body functions to an absolute minimum helps the victim to conserve oxygen and thus prolongs his survival time while buried, it poses a problem to the rescuers, since body heat must be restored to aid revival.

If the victim is breathing normally, it is important to restore the body's heat as soon as possible. It can be assumed that the victim is suffering some degree of hypothermia. Further chilling must be avoided. The victim's reaction to the cold consumes large amounts of energy. Not only must existing heat be conserved, but external heat must be supplied to counteract the body's cooling. A warm sleeping bag is essential. This may be heated by chemical hot pads or hot water bottles, or by preliminary occupation by a healthy person. A large sleeping bag is best, to make it possible for one of the rescuers to get in with the victim. Wet clothing should be removed, his body dried, and dry clothing (blankets, down gear) provided. If adequate shelter from wind and snow is in question, a small, lightweight tent that can be quickly erected and a small portable stove should be brought to the scene.

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Figure 222.—*A*, Breathing-bag apparatus and *B*, portable oxygen unit for administering artificial respiration.

Because of continuing research into the treatment of hypothermia, the most recent publications on the subject should be consulted.

Restoration of heat is secondary if the victim is not breathing; the first urgent treatment is restoration of breathing by artificial respiration. As soon as the victim's head is exposed, his nose and mouth should be cleared of snow, blood, and vomit. After preliminary cleaning, it may be necessary to apply suction. Organized rescue teams will need to carry a foot-operated suction pump. If a suction pump is not available, then one should attempt to suck the liquid from the throat and pharynx with a catheter or with a small rubber tube. Meanwhile, the unconscious victim should be positioned horizontally with the upper body and head lowered; this helps prevent water, blood, and vomit from entering the deeper breathing passages. In some cases, an airway tube or resuscitube will be useful to keep the passage clear, both during resuscitation and after normal breathing is restored. Suction attempts are not always required, although if the airways are clogged, artificial respiration is pointless. In any event, very little time should be lost debating whether or not the airways are clogged, because during the first attempts to inflate the victim's lungs it will be clear whether there is a major obstruction.

If respiration equipment is not available, the preferred technique is mouth-to-mouth resuscitation, which is taught in first-aid clinics. The first puffs of breath are often decisive; the victim should be respirated at least 10 times in quick succession before the more normal rhythm of 10 to 12 breaths per minute is started. If a victim is recovered in a state of cardiac arrest (no pulse or heartbeat, pupils dilated), artificial respiration should be augmented by closed-chest heart massage. This technique is covered in advanced first-aid clinics; it requires training and practice. At high elevations, prolonged application of cardiopulmonary resuscitation, or even mouth-to-mouth resuscitation, is quite demanding, especially if performed by one rescuer. For this reason, rescue teams must bring respiration equipment to the scene of the accident.

Revival and evacuation of the victim

The type of resuscitator that uses a self-inflating bag (AMBU, Hope, etc.) is preferred. The elasticity of the bag forces a proper rhythm so that danger of under- or overrespiration is lessened. The breathing bag and its auxiliary equipment must function properly under severe weather conditions. Atmospheric air is almost always sufficient for revival. If oxygen is available it may be administered as an extra measure, but the resuscitator, not the oxygen bottle, is the important thing to get to the victim first. It is possible to obtain sufficient blood-oxygen saturation with forced breathing of air alone up to an elevation of 5,800 m.

Even if the victim shows signs of life (swallowing, slight movements, weak breathing), supported respiration with the breathing apparatus must continue. When the blue discoloration of the lips, tongue, and fingernails disappears and the normal rosy color returns, it is a sign that respiration and circulation have improved.

Below is a list of resuscitation equipment for medical worker and physician:[8]

Medical worker
Suction pump with suction catheter
Breathing bag with air and oxygen inlet and breathing valve (resuscitator complete with accessories)
"Airway" or "resuscitube" breathing tube
Tent, stoves
Sleeping bag, blankets
Standard first-aid equipment (splints, bandages, back splint)

Physician

Drugs
Demerol solution (50 mg/cm^3)—30 cm^3
Demerol tablets (50 mg)—6
Lidocaine (1% or 2% solution)—50 cm^3
Epinephrine (1:1000 solution)—3 1-cm^3 amps
Sodium bicarbonate solution (3.75 gm—50 cm^3)—3 amps
Atropine (1 mg)—3 or 4 vials
Isuprel (1:5000 solution)—2 or 3 1-cm^3 amps
Aramine (1% solution)—10 cm^3
Levophed (0.2% solution—8 mg)—3 to 4 amps
Dextrose solution (50%)—50 cm^3
Sodium chloride (0.9% solution for injection)—30 cm^3
Sterile water for injection—30 cm^3
Dextrose and water (5% solution)—1,000 cm^3
Sodium chloride (0.9% solution)—1,000 cm^3
Blood plasma—2 250-cm^3 bottles
Tubing, tape, etc., for administering last three items

Hypodermic Needles
#18 x 1½"—3
#20 x 1½"—5
#22 x 1½"—5
#20 x 6" (intracardiac)—2
#20 x 4" (intracardiac)—2
#15 x 2½" (emergency airway)—2
#15 x 1½" (emergency airway)—2

Syringes
2½ cm^3—3
5 cm^3—3
10 cm^3—3
30 cm^3—2
50 cm^3—1

Supervision Equipment
Blood-pressure apparatus
Flat stethoscope
Cardboard tags and pencil

The drugs listed above should be kept in a cool, dry place and they should not be subjected to freezing temperatures. Most of these drugs should have a 2- to 3-year expiration period, and the person purchasing them should try to buy compounds that all expire at about the same time, so that replacements can be made all at one time. The procurement, storage, and packing of these items in a suitable rucksack should be supervised by a physician.

The possibility of mechanical injury is always present. The rescue team should exercise special care to check for the possibility of neck fracture before manipulating the patient to clear the air passages and begin resuscitation. If a neck fracture appears possible, traction is permissible, but flexing of the neck should be minimized. If breathing has stopped, resuscitation must begin in any case.

As long as the victim remains unconscious, full attention has to be paid to keeping the breathing passages open and to the possible need for artificial respiration. The unconscious victim is positioned on sled or stretcher, on his back, with neck slightly extended; the head and upper part of the trunk lie flat or are inclined slightly downward. According to his condition, the rescued person is transported to the hospital or to his home in the company of an attendant who observes him continually. Medical supervision must be continued; in one tragic case, a buried victim was revived and appeared fully recovered, but died of shock the following day.

Avalanche victims under maintenance of artificial respiration can withstand air flight to a valley hospital in the company of emergency clinic personnel. Immediate air transportation to a hospital may, in fact, be the victim's only hope for survival. (See Washington,

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[8]Prepared by Burton Janis, M.D., College of Medicine, University of Utah, Salt Lake City.

State of, 1972, for discussion of helicopter rescue and evacuation.) Throughout Europe, ski tourers and mountaineers can purchase an insurance policy that provides air-rescue service to a hospital. Telephoning a central number alerts the nearest air-rescue team, which is fully prepared with probes, avalanche dogs, artificial-respiration equipment, etc., and medical personnel as required.

The following is an outline of the procedure to follow in caring for avalanche victims:[9]

Determine whether victim is breathing or has an obviously fatal injury.

If the victim is not breathing:
  (1) Examine for fractured cervical spine
  (2) Clear snow away from chest and examine for penetrating injuries
  (3) Treat any penetrating chest injuries
  (4) Determine whether heart is beating by checking for:
      (a) Bleeding from open wounds
      (b) Peripheral pulses
      (c) Audible heartbeat
  (5) Institute artificial respiration
      (a) Clear mouth and throat of all foreign material
      (b) Extend head
      (c) Give mouth-to-mouth artificial respiration
  (6) Institute cardiac resuscitation
      (a) Sharp blows over chest
      (b) Cardiac massage

If the victim is breathing (or after resuscitation attempts have begun):
  (1) Examine for major open wounds
      (a) Control bleeding with *direct pressure*
      (b) Apply temporary bandage
  (2) Examine for and treat fractures
      (a) Fractured spine
      (b) Fractured pelvis
      (c) Fractured arms and legs
      (d) Fractured ribs (flail chest)
  (3) Treat for shock
      (a) Elevate legs and lower body
      (b) Control pain
      (c) Administer plasma or plasma substitutes
  (4) Treat for exposure
      (a) Protect from environment
      (b) Supply warm clothing
      (c) Supply external heat (*vital!*)
      (d) Provide nutrients

[9]Prepared by James A. Wilkerson, M.D., Merced Pathology Laboratory, Merced, Calif.

Evacuation
  If unconscious:
      (a) Keep airway open (*vital!*)
      (b) Keep head level with body or slightly lower
      (c) Continue treatment for shock and exposure

Signs of death
  (1) Livor mortis (black and blue death color)
  (2) Rigor mortis
  (3) Dilated pupils unresponsive to light.

Organized rescue in ski areas

It must be reemphasized that many more lives will be saved by public education, avalanche control, and caution than by rescue of buried victims, regardless of how organized, sophisticated, or well equipped the rescue efforts. Nevertheless, ski areas are responsible for providing the public with fast and efficient rescue service in full accordance with modern standards and equipment.

To give a buried victim a better than 50-percent statistical chance of surviving, he must be uncovered in less than half an hour. This is generally impossible if the rescue team is mobilized in a valley and transported up a major ski lift system. It is generally possible, however, to find the victim within half an hour if a small, well-equipped rescue team is on the alert at a high ski terminal. The Parsenndienst can be cited again as an example of preparedness. This team maintains headquarters at a summit station. In case of burial they act as follows:

(1) The entire crew at the station is called into the patrol room by the alarm siren.

(2) The situation is announced on a loudspeaker; for example, "two persons buried at Meirhofer, one survivor at the accident site."

(3) The acting rescue leader on duty at the station issues necessary instructions.

(4) Rescue teams, including avalanche dog and leader, move out within 4 to 8 minutes after receiving the accident call.

(5) Announcement is made at the lift terminal. Additional volunteers, doctors, mountain guides, ski instructors, and good skiers are asked to contact rescue headquarters. Volunteers are equipped and moved out to the accident scene with qualified leaders.

Since every minute counts, ski developments with serious avalanche hazards need to follow the Parsenn-
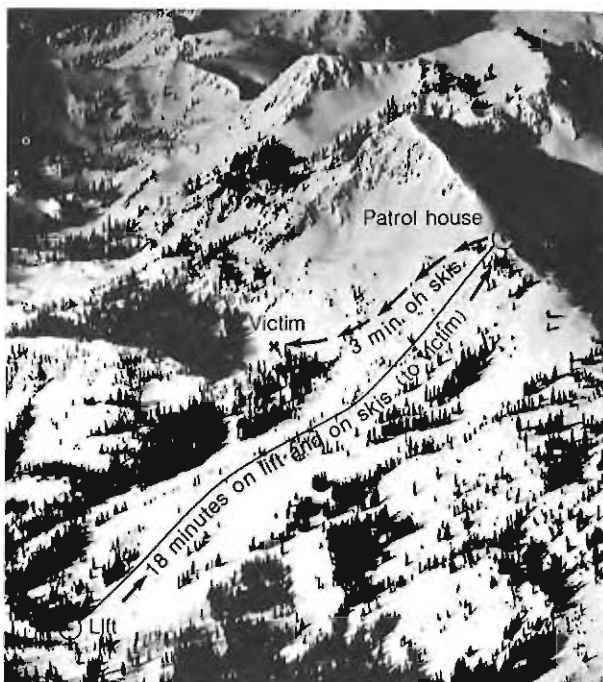
Figure 223.—Speedy rescue of a buried victim on many ski areas requires a professional team to stand alert at an upper terminal station.

Figure 224.—Time schedule for organized rescue in ski area.

dienst's example. A loss of 10 to 15 minutes may be incurred by transporting an initial search party up a lift from a midmountain station. A buried victim cannot be penalized this transportation time. Of course, if the avalanche hazard is spread out over a great range of elevation, supplementary manpower and equipment can be dispatched from a midway terminal; however, an upper station is still essential.

A speedy organized rescue depends crucially on developing a plan of action before the accident. This is called the rescue plan. It is a written plan that is studied by all employees of the area. It is updated before each ski season begins. The plan is precise about how an accident alarm is transmitted and received. It precisely spells out manpower responsibilities and equipment management. Rescue plans drawn up before 1975 should be reevaluated on the basis of new evidence indicating a 50-percent chance of survival after half an hour, rather than 1 hour as previously thought. In general, the plan provides for the following key personnel:

Rescue leader. He is the overall coordinator of the operation. Typically, he would be head or assistant head of the ski patrol or a person with equivalent experience in all facets of avalanche rescue, and he should be thoroughly familiar with the area. There

should be one qualified rescue leader on duty at all times to receive alarms and at least begin dispatching workers. In addition to coordinating the quick dispatch of manpower, the rescue leader is responsible for contacting medical support, air support, law enforcement groups, and government officials and for handling the public-relations problems of the rescue. Throughout the rescue, he usually remains stationed at the summit terminal; he appoints an accident site commander to be in charge in the field.

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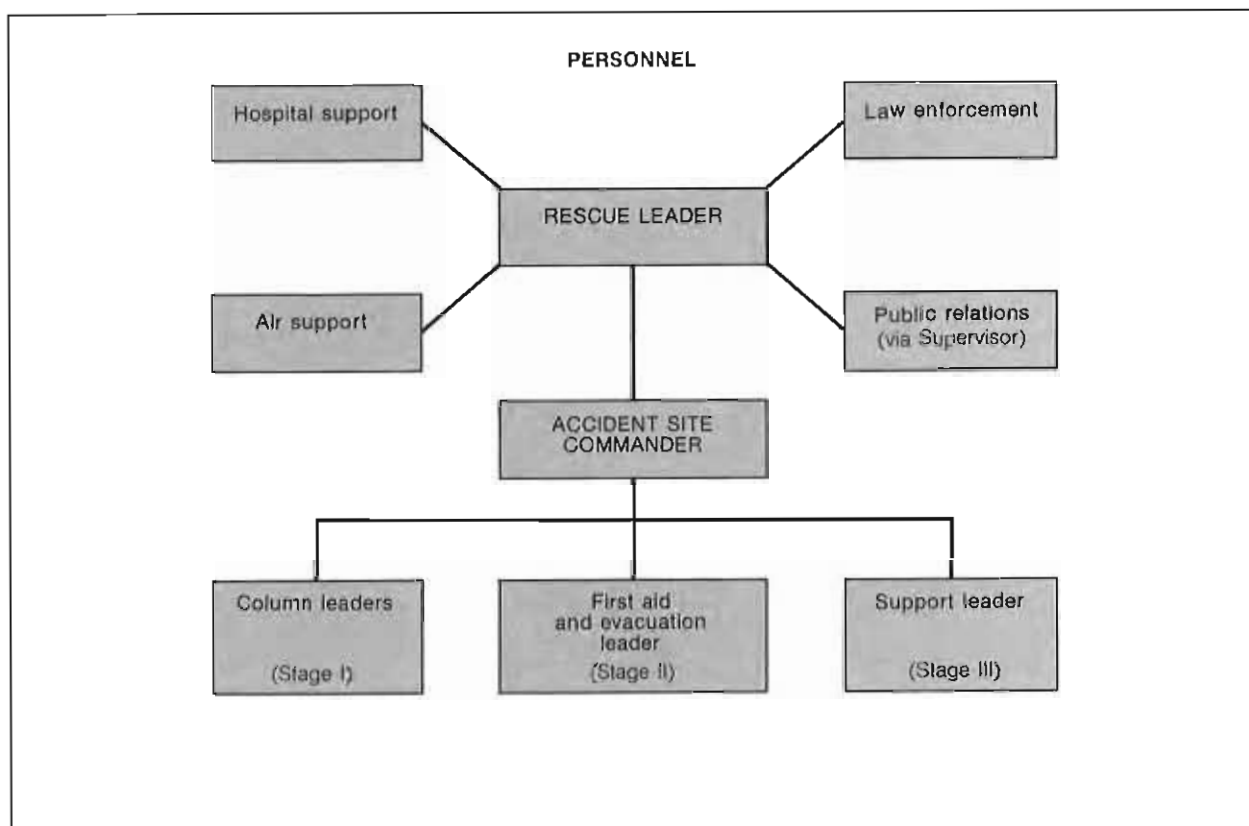
PERSONNEL

Figure 225.—Personnel requirements for organized rescue in ski area.

Accident site commander. He is sent as quickly as possible to the accident site and relieves whomever is temporarily in charge. He decides where to search and arranges probe lines accordingly. His badge is a power-operated megaphone through which he calls out instructions to column leaders.

Column leaders. These are experienced patrollers who lead rescue columns of five to ten professionals or volunteers to the accident site. Column leaders screen volunteers, equip them with probes and shovels, and lead the columns by a safe route to the accident, where they report to the accident site commander. A column leader may be asked to join an existing probe line or to direct the formation of and lead a new probe line. The first column should consist of professionals on standby at the top terminal; later columns can be formed of patrollers, instructors, and competent skiers who arrive at the top terminal. The first column leader is temporarily in charge at the accident site until relieved by an appointed accident site commander. Each column leader is responsible for checking in the members of his column at the end of the rescue.

Most rescues in ski areas proceed according to three stages:

Stage I—Immediate action. This stage consists of speedy dispatch of columns equipped with probes, shovels, light first-aid equipment, and personal gear. Their objective is to locate the victim by a fast surface search or vigorous coarse probe. They are not equipped for a long, drawn-out rescue, since they travel fast and light to the accident site.

Stage II—Revival and evacuation. Although patrollers in Stage I columns have first-aid kits for dealing with immediate problems, they cannot be slowed down by transporting the bulkier equipment needed for resuscitation and evacuation. Thus, a special team of three to five patrollers (plus one physician, if possible) is organized to transport toboggans, blankets, sleeping bags, resuscitation equipment, tent, stove, physician's kit, and other equipment needed to revive and evacuate the victim. As soon as the alarm is received, the rescue leader will have appointed an experienced patroller to organize Stage II and collect the necessary equipment. In a well-organized rescue, the Stage II column is only a few minutes behind the first stage columns.

Stage III—Support. The first two stages are dispatched with a speed which hardly leaves time to prepare for a prolonged rescue. The support stage is

organized to transport hot beverages, food, warm clothing, illumination equipment, and extra manpower. The extent to which the support stage is activated varies widely according to the size of the accident, weather conditions, and terrain problems. In some cases, it may hardly be necessary to provide support. In other cases, usually prolonged searches in major avalanches aimed more at body recovery than saving lives, the third stage may be the main component of the operation.

One of the essentials for a speedy rescue is to have equipment fully organized and ready for distribution as soon as the alarm is sounded. There are many ways to organize equipment caches, depending on the area layout; details must be specified exactly in the rescue plan. In general, a major cache containing equipment for all three stages should be maintained at the summit station. Small caches containing equipment for Stage I should be set up at each lift terminal or in the vicinity of each potential slide path. The rescue plan should also include a list of sources for Stage III equipment and manpower.

In summary, rescue organizations should use practice sessions to reduce lost time and improve efficiency. Four areas where time can be saved are in reporting the accident, responding to the alarm, traveling to the site, and carrying out procedures on the site. Good on-the-hill communications and public education help reduce reporting time. Response time is reduced if key rescue personnel are prepared to go into action immediately, equipment caches are completely stocked and well placed, and the group is well enough trained to avoid false starts. Travel time can be shortened if crews are in good physical shape, know the terrain well, and are experienced enough to make accurate field decisions about the route quickly and efficiently. Finally, procedural time can be minimized if the crews know what needs to be done, have proper equipment, and have enough practice performing the necessary jobs to do them without undue delay or fatigue. Repeated drills and dry runs are needed to perfect the individual steps and to blend them all into an efficient rescue effort.

Following is a list of equipment to be stored in caches for organized rescues in ski areas:

Stage I caches (at lift terminals near avalanche paths)

One or more rucksacks, each containing ten collapsible probes and one aluminum shovel (grain-scoop design)

Single-piece probes about 3 m long. The number of probes should be chosen to match the hazard (10, 25, or 50, arranged in bundles of 5). Either steel tubing (about 11 mm o.d.), or aluminum pipe similar to ¼-in, 6061-IT6, Schedule 40 (13.7 mm o.d., 9.3 mm i.d.).

Main cache (at summit station)

Several rucksacks as described above
Bundles of one-piece probes as described above
Extra shovels (some for heavy-duty work)
Revival and evacuation equipment (Stage II)
Toboggans (sectional and one-piece)
Blankets
Sleeping bags
Tent
Headlamps for night operation
Floodlights (gas or propane)
Flares
Megaphone (battery-powered)
String line
Flagging and wands
Climbing skins (as needed)
Rope, ice axe, etc. (as needed).

Special rescue problems

Speed is essential, but safety must not be compromised. Rescuers have been buried and killed on approach marches and at accident sites. In a classic case near Snow Basin, Utah (March 27, 1964), a rescue column crossed a slope above another column and released a slab that killed a volunteer below. In a worse tragedy, 62 workers perished in an attempted rescue of a train stalled by an earlier avalanche (Rogers Pass, B.C., March 5, 1910).

Where a second avalanche is a problem, the rescue leader or accident site commander often faces a difficult decision: Should artificial release by explosives be attempted on a slab that overhangs the accident site? If the answer is yes, the victim's chances are reduced considerably by the time spent in postponing the rescue for explosive control, and also by the deeper burial that may result should the avalanche run. Each case must be considered individually. If the avalanche is small and the victim has not been buried for a long time, then a team of experienced rescuers may gamble on a fast rescue before resorting to artificial release of the remaining hazard. The rescue attempt should not persist for long, especially if storm conditions intensify the hazard. If it is possible to gamble briefly that a natural release will not occur, it may be necessary to post guards to ensure that no one enters the starting zone above the rescue operation. For some terrain configurations, the guards may have time to sound an alarm via megaphone or whistle if
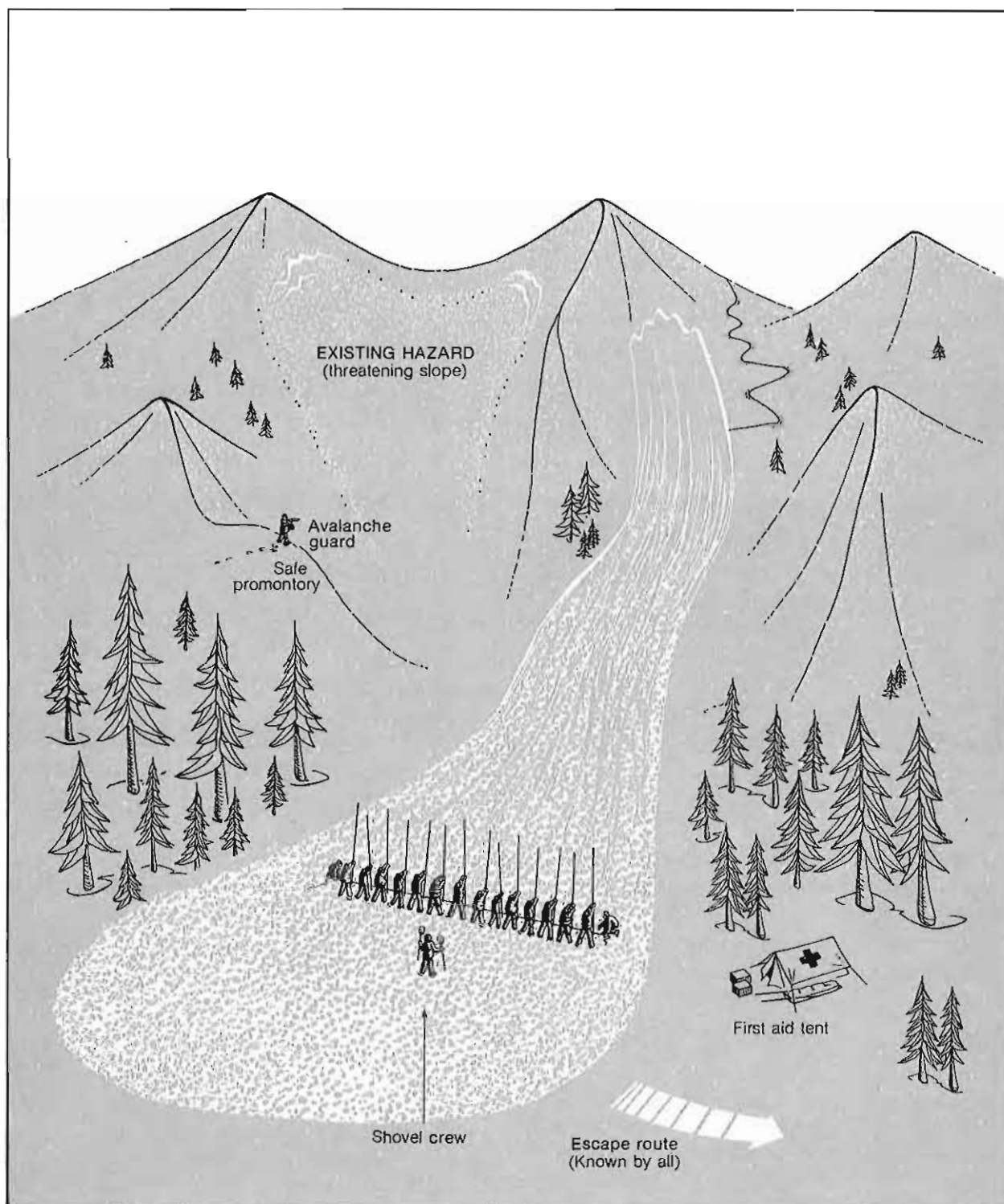
Figure 226.—First aid and support facilities are set up in a protected area. An avalanche guard is posted to warn the rescue team of further avalanches.

Labels within figure:
- EXISTING HAZARD (threatening slope)
- Avalanche guard
- Safe promontory
- First aid tent
- Shovel crew
- Escape route (Known by all)

Figure 227.—Weber County sheriff's patrol illuminates slope during avalanche rescue near Snow Basin, Utah, March 29, 1964.

the slab releases, whereupon rescuers could break for cover. All Stage II and support equipment should be in a safe location to begin with.

The well-being of the rescue columns is the first consideration on approach marches into the back country. It is foolhardy to take risks in the interest of speed, since the object is most likely body recovery. Approach routes should be chosen carefully, and rescuers should be led by experienced column leaders. All personnel should be properly equipped for travel and prepared to withstand conditions on the approach march and at the accident site. Volunteers should be screened for fitness, experience, and personal gear. Well-meaning volunteers from a ski area should not be permitted to set out for an extended rescue under severe winter conditions if they are equipped only with downhill ski equipment (plastic boots, racing garments, no heel lifts).

When weather conditions are favorable, helicopter transport has an overwhelming advantage over a land approach. The most efficient combination is helicopter transport of avalanche dog and leader. If an avalanche dog is available, dog and leader should be transported to the accident ahead of probing columns, which remain on standby in case the dog fails.

The first flight from a heliport usually requires daylight conditions; however, landing places and floodlights may be set up so that flying operations may continue into the evening. Heliports should be equipped with strong canvas bags containing rescue equipment. These may be arranged according to the three stages of rescue.

Volunteers should receive instructions in helicopter procedures before joining the operation. Even then, the pilot and accident site commander must be

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Figure 228.—Evacuation of victim from accident near Snow Basin, Utah, March 30, 1964.

on the alert for carelessness caused by hypothermia or fatigue.

Air transport is needed when large-scale disaster strikes remote mountain settlements. Quite often, road access is either cut off completely or limited to oversnow vehicles. In preparation for emergency, any threatened mountain settlement should select and maintain a safe heliport area complete with floodlights for night operation. The community via its sheriff should be aware of procedures for contacting the nearest center for coordinating air rescue, including avalanche dog service. Victims buried amidst building debris may survive lengthy burials, and rescue operations should continue until all victims are found.

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Converting units of measure

General conversion technique

There are many ways to convert from one system of units to another. One of the simplest is cross-multiplication to cancel out undesired units. Three examples of increasing difficulty illustrate this technique. The reader is urged to work the given examples.

Example 1. Convert 24 inches to feet.

Solution:

$$24 \text{ in} \left(\frac{1 \text{ ft}}{12 \text{ in}} \right) = 2 \text{ ft.}$$

Note that multiplication is by a fraction equal to one. The numerator and denominator are chosen to cancel out the undesired units.

Example 2. Convert 10 miles per hour to feet per second.

Solution:

$$\left(\frac{10 \text{ mi}}{1 \text{ h}} \right) \left(\frac{5280 \text{ ft}}{1 \text{ mi}} \right) \left(\frac{1 \text{ h}}{3600 \text{ s}} \right) = 14.7 \text{ ft/s.}$$

Example 3. Convert 100 ounces per square inch to pounds per square foot.

Solution:

$$\left(\frac{100 \text{ oz}}{1 \text{ in}^2} \right) \left(\frac{1 \text{ lb}}{16 \text{ oz}} \right) \left(\frac{12 \text{ in.}}{1 \text{ ft}} \right) \left(\frac{12 \text{ in.}}{1 \text{ ft}} \right) = 900 \text{ lb/ft}^2.$$

The metric system

There is a worldwide trend toward expressing all measurements in one system of units, the metric system. Two basic metric units commonly used in avalanche work are the *meter* and the *kilogram,* which are respectively units of *distance* and *mass.* These two basic units are the building blocks for more complex units of such quantities as speed, density, and stress.

Distance and speed. A meter (m) is a little more than a yard; more precisely, 3.28 ft or 39.37 in. Meters are used for measuring mountain elevations, thicknesses of slab fractures, runout distances of avalanches, artillery range, etc.

Problem 1. The range of a 105-mm HE round fired from a howitzer is 11,300 meters. Convert this to miles. (Problem solutions appear at the end of Appendix A.)

Large distances are measured in kilometers (km), which are equal to 10^3 m, and small distances are measured in millimeters (mm), which are equal to 10^{-3} m.

Problem 2. How many inches in diameter is a 75-mm projectile?

It is sometimes convenient to express certain measurements, such as the amount of new snow, in centimeters (cm). A centimeter is equal to 10^{-2} m, or about 0.39 in. This means 1 in equals 2.54 cm.

Problem 3. John Doe wants to sell his old 7-foot skis. What size should he advertise?

We all want to minimize confusion by using the smallest possible number of different units. It is argued that all our purposes are served if we stick to units based exclusively on factors of 1,000; for example, megameters (10^6 m), kilometers (10^3 m), meters (1 m), millimeters (10^{-3} m), and micrometers (10^{-6} m). Hence, the centimeter (10^{-2} m) is not a preferred unit. Nevertheless, it is a handy unit in avalanche work.

Units of area and volume are based on distance units raised to the second and third powers, respectively (for example, m^2 and m^3).

Problem 4. A standard density sample tube has a volume of 500 cm³. What is its volume in cubic inches?

Units of speed are based on distance divided by time. Avalanche speed, for example, is expressed in meters per second (m/s). A brisk walking pace is about 2 m/s.

Problem 5. An avalanche is clocked at 50 m/s. What is its speed in miles per hour?

Problem 6. An avalanche is triggered by a sustained precipitation intensity of 1 mm/h. What is this in inches per hour?

Mass and density. The amount of material, mass, is based on the fundamental unit, the kilogram, which is equal to 2.20 lb. Density is mass per unit volume and is properly expressed in kilograms per cubic meter (kg/m^3). The density of water is 1,000 kg/m³.

Problem 7. The average density of a slab is measured as 200 kg/m³. What is its density in pounds per cubic foot?

Snow density is sometimes expressed in grams per cubic centimeter (g/cm³). In these units, the density of water has the convenient value of 1.0 g/cm³.

Problem 8. Show that 1,000 kg/m³ equals 1 g/cm³.

Force and stress. The preferred unit of force is the newton (N). The preferred unit of stress (force per unit area) is newtons per square meter (N/m²). Unfortunately there is much confusion over force units. Although it is not possible in this short appendix to resolve the confusion, the reader should understand that some of the confusion is due to the fact that force-measuring devices such as spring scales are calibrated in units of mass (kilograms, grams) rather than units of force (newtons). Thus, it is a common (although poor) practice to speak of avalanche impact pressures, shear stress, ram strength, etc., in units of mass per unit area (for example, kg/m² for pressure).

Problem 9. Use the equation on page 56 to calculate the shear stress of a 2-m slab of density 250 kg/m³ on a 38° slope (sin 38° = 0.616).

Problem 10. Use the equation on page 86 to calculate the impact pressure of an avalanche that has a speed of 50 m/s and a flowing density of 100 kg/m³.

Although the newton may not be familiar to many readers, it is handy in force and stress computations. For example, the impact force equation on page 86 is simply

$$\text{Impact pressure} = \rho V^2$$

where the impact pressure is now in N/m², if density is in kg/m³, and V (speed) is in m/s. Note that the newton is equivalent to (kg) (m/s²), a result that is derived from Newton's second law of motion: force = (mass) (acceleration).

Problem 11. Use the data of problem 10 to compute impact pressure in N/m².

The common unit of atmospheric pressure is the millibar (mb), which is 10² N/m². One bar (1,000 mb) equals 29.5 inches of mercury.

Problem 12. What is the atmospheric pressure in inches of mercury at the 750-mb level?

Temperature. Snow and avalanche observations are based on the Celsius temperature scale. A com-

fortable room temperature is slightly over +20° C. Snow melts at 0° C and is cold enough to squeak at −20° C. The formulas for converting from Celsius to Fahrenheit and vice versa are:

$$F = \frac{9}{5} C + 32$$

$$C = \frac{5}{9} (F - 32).$$

Problem 13. Convert −20° C to the equivalent Fahrenheit temperature.

Solutions to problems

Problem 1

$$(11,300 \text{ m}) \left(\frac{3.28 \text{ ft}}{1 \text{ m}}\right) \left(\frac{1 \text{ mi}}{5,280 \text{ ft}}\right) = 7.02 \text{ mi.}$$

Problem 2

$$(75 \text{ mm}) \left(\frac{1 \text{ m}}{1,000 \text{ mm}}\right) \left(\frac{39.37 \text{ in}}{1 \text{ m}}\right) = 2.95 \text{ in.}$$

Problem 3

$$(7 \text{ ft}) \left(\frac{12 \text{ in}}{1 \text{ ft}}\right) \left(\frac{2.54 \text{ cm}}{1 \text{ in}}\right) = 213.4 \text{ cm.}$$

Problem 4

$$(500 \text{ cm}^3) \left(\frac{1 \text{ in}}{2.54 \text{ cm}}\right)^3 = 30.5 \text{ in}^3.$$

Problem 5

$$\left(\frac{50 \text{ m}}{1 \text{ s}}\right) \left(\frac{3,600 \text{ s}}{1 \text{ h}}\right) \left(\frac{3.28 \text{ ft}}{1 \text{ m}}\right) \left(\frac{1 \text{ mi}}{5,280 \text{ ft}}\right) = 112 \text{ mi/h.}$$

Problem 6

$$\left(\frac{1 \text{ mm}}{h}\right) \left(\frac{1 \text{ cm}}{10 \text{ mm}}\right) \left(\frac{1 \text{ in}}{2.54 \text{ cm}}\right) = 0.039 \text{ in/h.}$$

Problem 7

$$\left(\frac{200 \text{ kg}}{\text{m}^3}\right) \left(\frac{2.2 \text{ lb}}{1 \text{ kg}}\right) \left(\frac{1 \text{ m}}{3.28 \text{ ft}}\right)^3 = 12.5 \text{ lb/ft}^3.$$

Problem 8

$$\left(\frac{1,000 \text{ kg}}{\text{m}^3}\right) \left(\frac{1,000 \text{ g}}{1 \text{ kg}}\right) \left(\frac{1 \text{ m}}{100 \text{ cm}}\right)^3 = 1 \text{ g/cm}^3.$$

Problem 9

$$\text{Shear stress} = \rho \text{ D } g \sin \Theta$$

$$= \left(\frac{250 \text{ kg}}{\text{m}^3}\right) (2 \text{ m}) \left(9.8 \frac{\text{m}}{\text{s}^2}\right) (0.616)$$

$$= 3018 \text{ N/m}^2$$

Problem 10

$$\text{Impact pressure} = \frac{\rho V^2}{g}$$

$$= \frac{\left(\frac{100 \text{ kg}}{\text{m}^3}\right) \left(\frac{50 \text{ m}}{\text{s}}\right)^2}{\left(\frac{9.8 \text{ m}}{\text{s}^2}\right)}$$

$$= 25,510 \text{ kg/m}^2 = 25.5 \text{ t/m}^2.$$

Problem 11

$$\text{Impact pressure} = \rho V^2$$
$$= \left(\frac{100 \text{ kg}}{\text{m}^3}\right)\left(\frac{50 \text{ m}}{\text{s}}\right)^2$$
$$= 25 \times 10^4 \text{ N/m}^2.$$

Problem 12

$$(750 \text{ mb})\left(\frac{1 \text{ bar}}{1,000 \text{ mb}}\right)\left(\frac{29.5 \text{ in Hg}}{1 \text{ bar}}\right) = 22.1 \text{ in Hg.}$$

Problem 13

$$F = \frac{9}{5}(-20) + 32 = -4°.$$

Conversion tables

TABLE A1.—Distance

Inches	Feet	Yards	Miles	Centimeters	Meters	Kilometers
1	0.083333	0.027778	—	2.540005	0.0254	—
12	1	0.33333	0.000189	30.48006	0.304801	0.000305
36	3	1	0.000568	91.44018	0.914402	0.000914
—	5280	1760	1	—	1609.347	1.609347
0.3937	0.032808	0.010936	—	1	0.01	—
39.37	3.280833	1.09361	0.000621	100	1	0.001
	3280.83	1093.61	0.62137	—	1000	1

TABLE A2.—Area

Square inches	Square feet	Acres	Square centimeters	Square meters	Hectares	Square kilometers
1	0.006944	—	6.451626	0.000645	—	—
144	1	0.000023	929.034	0.092903	—	—
—	43560	1	—	4046.87	0.404687	0.004047
0.155	0.001076	—	1	0.0001	—	—
1,549.997	10.76387	0.000247	10,000	1	0.0001	—
—	107,638.7	2.471044	—	10,000	1	0.01
—	10,763,867	247.104	—	1,000,000	100	1

TABLE A3.—Weight

Ounces	Pounds	Grams	Kilograms
1	0.0625	28.34953	—
16	1	453.592	0.453592
0.035274	0.002205	1	0.001
35.27396	2.204622	1000	1

TABLE A5.—Volume

Cubic inches	Cubic feet	Cubic centimeters	Cubic meters
1	0.000579	16.3872	—
1728	1	28,317	0.028317
0.061023	—	1	0.000001
—	35.3145	1,000,000	1

TABLE A4.—Weight per unit area

Pounds per square foot	Pounds per square inch	Kilograms per square meter	Grams per square centimeter
1	0.006944	4.88241	0.488241
144	1	703.067	70.3067
0.204817	0.001422	1	0.1
2.04817	0.01422	10	1

TABLE A6.—Speed

Feet per second	Miles per hour	Knots per hour	Meters per second	Kilometers per hour
1	0.681818	0.592086	0.304801	1.0973
1.46667	1	0.868393	0.447041	1.60935
1.68894	1.15155	1	0.514791	1.85325
3.28083	2.236932	1.94253	1	3.6
0.91134	0.621370	0.539593	0.27778	1

Converting units of measure

TABLE A7.—*Grade percent and equivalent degree of slope*

Grade (percent)	Slope (degrees) °	'
5	2	51.7
10	5	42.6
15	8	31.8
20	11	18.6
25	14	2.2
30	16	42.0
35	19	17.4
40	21	48.1
45	24	13.7
50	26	33.9
55	28	48.6
60	30	57.8
65	33	1.4
70	34	59.5
75	36	52.2
80	38	39.6
85	40	21.9
90	41	59.2
95	43	31.9
100	45	0

TABLE A8.—*Degree of slope and equivalent grade percent*

Slope (degrees) °	'	Grade (percent)
1		1.746
2	30	4.366
5		8.749
7	30	13.165
10		17.633
12	30	22.169
15		26.795
17	30	31.530
20		36.397
22	30	41.421
25		46.631
27	30	52.057
30		57.735
32	30	63.707
35		70.021
37	30	76.733
40		83.910
42	30	91.633
45		100.0

TABLE A9.—*Natural trigonometric functions*

Degree °	Sin	Cos	Tan
1	.0175	.9998	.0175
2	.0349	.9994	.0349
3	.0523	.9986	.0524
4	.0698	.9976	.0699
5	.0872	.9962	.0875
6	.1045	.9945	.1051
7	.1219	.9925	.1228
8	.1392	.9903	.1405
9	.1564	.9877	.1584
10	.1736	.9848	.1763
11	.1908	.9816	.1944
12	.2079	.9781	.2126
13	.2250	.9744	.2309
14	.2419	.9703	.2493
15	.2588	.9659	.2679
16	.2756	.9613	.2867
17	.2924	.9563	.3057
18	.3090	.9511	.3249
19	.3256	.9455	.3443
20	.3420	.9397	.3640
21	.3584	.9336	.3839
22	.3746	.9272	.4040
23	.3907	.9205	.4245
24	.4067	.9135	.4452
25	.4226	.9063	.4663
26	.4384	.8988	.4877
27	.4540	.8910	.5095
28	.4695	.8829	.5317
29	.4848	.8746	.5543
30	.5000	.8660	.5774
31	.5150	.8572	.6009
32	.5299	.8480	.6249
33	.5446	.8387	.6494
34	.5592	.8290	.6745
35	.5736	.8192	.7002
36	.5878	.8090	.7265
37	.6018	.7986	.7536
38	.6157	.7880	.7813
39	.6293	.7771	.8098
40	.6428	.7660	.8391
41	.6561	.7547	.8693
42	.6691	.7431	.9004
43	.6820	.7314	.9325
44	.6947	.7193	.9657
45	.7071	.7071	1.0000

Degrees Fahrenheit | Degrees Celsius

210 — 100
200 —
— 90
190 —
180 —
— 80
170 —
160 —
— 70
150 —
140 — 60
130 —
120 — 50
110 —
100 — 40
90 —
— 30
80 —
70 — 20
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50 — 10
40 —
30 — 0
20 —
10 —
— -10
0 —
— -20
-10 —
-20 — -30
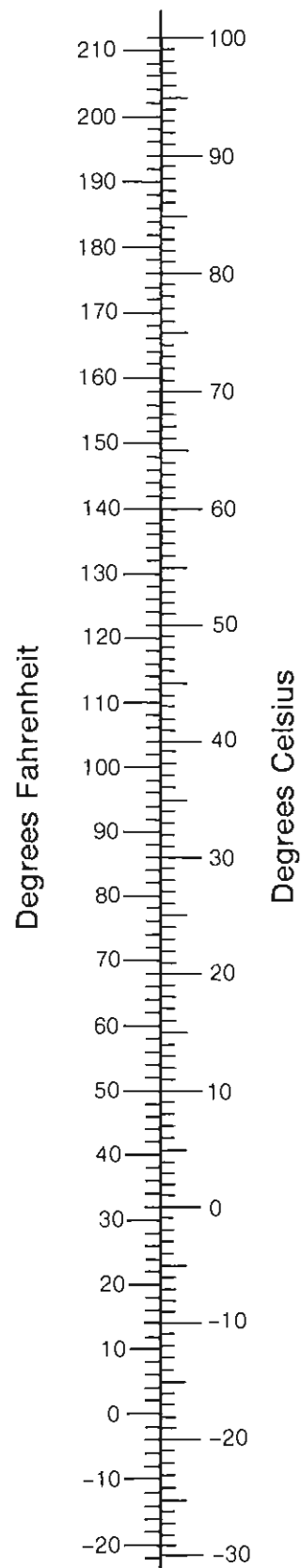
Snowpit data

As mentioned in chapter 3, much information can be gathered from a snowpit and a few simple instruments. A spiral-bound pocket notebook with waterproof paper is a convenient way to record the data. It is good to write column headings and other preliminary information and reminders in the book before going to the field. This reduces the chances of omitting vital information and speeds up fieldwork.
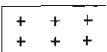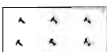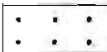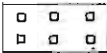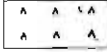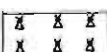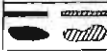
The data are often converted to a graphic display called a snow profile, using symbols and a procedure that are internationally understood and accepted (UNESCO/IASH/WMO 1970). Notice that the vertical scale against which the various features are plotted is height above the ground; the snow surface is not a suitable long-term reference for features in the snowpack.
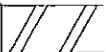
This appendix presents the international symbols and measurements used to describe snow features, a typical set of field notes, and the snow profile plotted from the field notes.

International symbols and measurements

Grain type

Symbol	Description
+ + + + + +	Freshly deposited snow. Initial forms can be easily recognized.
ʌ ʌ ʌ ʌ ʌ ʌ	Irregular grains, mostly rounded but often branched. Structure often feltlike. Early stages of ET metamorphism.
. . . . . .	Rounded, often elongated, isometric grains. End stages of ET metamorphism. Grains usually less than 2 mm in diameter.
□ □ □ □ □ □	Angular grains with flat sides or faces. Early stages of TG metamorphism.
ʌ ʌ ᴸʌ ʌ ʌ ʌ	Angular grains with stepped faces; at least some hollow cups. Advanced stages of TG metamorphism.
○ ○ ᵭ ○ ○ ○	Rounded grains formed by MF metamorphism. Grains usually larger than 1 mm and often strongly bonded.
ⱷ ⱷ ⱷ ⱷ ⱷ ⱷ	Graupel. Occasionally appreciable layers of this form of solid precipitation can be identified in the snow cover.
▬▬	Ice layer, lens, or pocket.

Hardness

Symbol	Description	Hand test*	Ram number (kg)**
□	Very soft	Fist	0–2
⟋⟋⟋	Soft	Four fingers	3–15
⋉ ⋊	Medium hard	One finger	16–50
⟋⟋	Hard	Pencil	51–100
⋈⋈	Very hard	Knife	Over 100
■	Ice	—	—

* In the hand test the specified object can be pushed into the snow in the pit wall with a force of about 5 kg. In hard snow, for example, a pencil can be pushed into the snow, but with the same pressure, a finger cannot.

** Ram number is from a cone penetrometer with a 60° apex and 4-cm diameter.

Grain size

(Average maximum grain diameter in millimeters)

Diameter	Term
0–0.5 mm	Very fine
0.5–1.0 mm	Fine
1.0–2.0 mm	Average
2.0–4.0 mm	Coarse
More than 4.0 mm	Very coarse

Free water content

Symbol	Term	Description
	Dry	Snow usually, but not necessarily, below 0° C. Grains have little tendency to stick together in a snowball when lightly pressed in gloved hand.
	Moist	Snow at 0° C. No water visible even with hand lens. Snow makes good snowball.
	Wet	Snow at 0° C. Water visible as a meniscus between grains but cannot be pressed out by moderate squeezing in the hand.
	Very wet	Snow at 0° C. Water can be pressed out by moderate squeezing in the hand. There is still an appreciable amount of air confined within the snow.
	Slush	Snow at 0° C. Snow flooded with water and containing relatively small amounts of air.

Snow surface deposits

Symbol	Deposit	Description
⌣ or ∨	Surface hoar	Sublimation crystals formed directly on the snow surface.
∨	Soft rime	White, opaque deposit formed on objects by rapid freezing of supercooled water droplets.
∨	Hard rime	Formed the same way as soft rime but more compact and amorphous.
∽	Glazed frost (Verglas or glaze)	Coating of ice, generally clear and smooth but usually including some air pockets formed on objects by freezing of films of supercooled water. Denser, harder, more transparent than rime or surface hoar.

These symbols are also used in snow profiles if the deposits are identified inside the snowpack.

Snow density

Snow density samples are usually taken with cylindrical tubes. A tube 57 mm in diameter and 196 mm long gives a convenient volume of 500 cm³. The tube may be inserted parallel to the layering or vertical, depending on whether one is interested in layer properties or integrated snowpack properties. Tubes are weighed empty and then full of snow, and density is computed.

Snow temperature

Snow temperatures should be taken in the north-facing wall as the pit is being opened up. Dial thermometers are sturdy and fast to use. When taking readings near the surface, shade the area above the thermometer to keep penetrating light from heating the stem. It is good practice to insert the thermometer and allow it to reach apparent equilibrium, then withdraw it and insert it in another place before taking a reading. In crusty or very hard snow, use an ice pick to punch a guide hole for the thermometer.

Total snow depth or height

The amount of snow on the ground is measured vertically in centimeters, using the ground as a reference plane. On sloping terrain, slope angle must be given. When taking snowpit data, measure ram number first. Then leave the ram in place and dig the pit adjacent to it. This way the ram serves as a height guide for recording features of the pit wall.

New snow depth or height

The daily new snowfall measured vertically from the old snow surface.

Total snow thickness

The thickness of the snow cover measured in centimeters perpendicular to the slope, with the ground as reference.

New snow thickness

The thickness of the daily new snowfall measured perpendicular to the old snow surface.

Typical set of field notes

Rammsonde Data

Location: Pat's Knob   Date: 25 Mar. 1974
Time: 13:00   Obser: mm

$$R = T + H + \frac{nfH}{P}$$

(H) Hammer wt. = 1 kg

Wt.of Tube+ Hammer T+H	No.of Blows in	Fall Height f	Location of Point	Penetration cm P	nfH/P	Ram Number R	Height above ground cm	
			0 @ snow surface				190	
1	0	0	11	11	0	1	179	
2	0	0	11	0			179	Added Guide Rod + Hammer
	6	5	13	2	$\frac{30}{2}=15$	17	177	
	3	10	20	7	$\frac{30}{7}=4\frac{1}{2}$	$6\frac{1}{2}$	170	
	4	10	34	14	$\frac{40}{14}=3$	5	156	
	8	10	48	14	$\frac{80}{14}=5.7$	7.7	142	
	1	5	50	2	$\frac{5}{2}=2\frac{1}{2}$	4.5	140	
	15	10	62	12	$\frac{150}{12}=12\frac{1}{2}$	14.5	128	
	15	10	72	10	$\frac{150}{10}=15$	17	118	
	16	10	80	8	$\frac{160}{8}=20$	22	110	
	8	10	82	2	$\frac{80}{2}=40$	42	108	
3			82	0			108	Added 2nd section of tube
	12	15	90	10	$\frac{180}{10}=18$	21	100	
	6	20	95	5	$\frac{120}{5}=24$	27	95	
	5	20	103	8	$\frac{100}{8}=12\frac{1}{2}$	$15\frac{1}{2}$	87	
	5	20	118	15	$\frac{100}{15}=6.6$	9.6	72	
	1	20	138	20	$\frac{20}{20}=1$	4	52	
	30	10	144	6	$\frac{300}{6}=50$	53	46	
	35	25	160	16	$\frac{875}{16}=55$	58	30	
	2	25	174	14	$\frac{50}{14}=3.6$	6.6	16	
4			174	0			16	Added 3rd section of tube
4	1	10	190	16	$\frac{10}{16}=.6$	4.6	0	Ground

Snow Grain Data

Location: Pat's Knob   Date: 25 Mar. '74
Time: 14:00   Obser: mm

Ht. above ground cm	Size mm	Hardness	Free water	Grain Type	Notes
190					Snow Surface
190-184	1-2	v. soft	moist	Stars & plates wind broken	
184-178	0.5-1	v. soft	dry	mostly broken spatial dendrites	
178-176	1.5-2	ICE LAYER			old surface crust
176-170		soft	dry	melt-freeze grains	
170-143	0.5-1.0	soft	dry	Felted old snow ET started	
143-140	1.5-2.0	v. soft	dry	Buried surface hoar	Surface hoar from several days ago
140-112	0.5-1.0	med. hard	dry	small rounded grains	
112-110		ICE LAYER			
110-91	1-2	med. hard	dry	well bonded grains with flat faces & angles	
91-53	1-2	soft	dry	more angles & steps on faces	Aval. bed surface @53cm Slope of bed surface 34°
53-30	2-3	hard	dry	TG grains	This layer stayed in place
30-17	.3-3½	soft	dry	well formed TG grains some cups	Loose & poorly bonded
17-ground	3-4	v. soft	dry	Same type of grains only larger & looser	Grains fall out of pit wall

Location: Pat's Knob   Date: 24 Mar. '74
Time: 14:30   Obser. mm

Density					Temperature	
Ht. above ground (cm)	Wt. tube* + snow (gms)	Wt. of snow (gms)	Density Kg/m.³		Ht. above ground (cm)	Temp. 0° C
	*Tare wt. 500cc tube = 310 gms				187	0
182	369	59	118		182	-2
					170	-2
158	390½	80½	161		160	-3
					140	-4½
148	397½	87½	175		120	-8
					100	-8
134	415	105	210		80	-4½
					60	-4
115	410	100	200		40	-3
					30	-2
102	446	136	272		15	-1
					ground	0
76	416	106	212			
58	397	87	174			
38	465	155	310			
20	462½	152½	305			
5	470	160	320			

Air temp. +1°C

Snow profile plotted from field notes

Grain type	Hardness	Grain size (mm)	Free water	Density (kg/m³)
+ +		1-2		
+ +		0.5-1		118
o o	╱	1.5-2		
◄	╱	0.5		161
◄	╱	1.5		175
		1.5 2.0		
•	x	0.5		210
•	x	1.0		200
□	x	1-2		272
□	x			
□ᴧ	╱			
□ᴧ		1-2		212
□ᴧ	╱			174
□□		2-3		310
ᴧᴧ		3-3.5		305
ᴧᴧ		3-4		320

Snow surface

Crown face

Ice

Bed surface   34°

TEMPERATURE (T), °C

RAM INDEX (R), kg

T

R

◇ Air temperature in shade
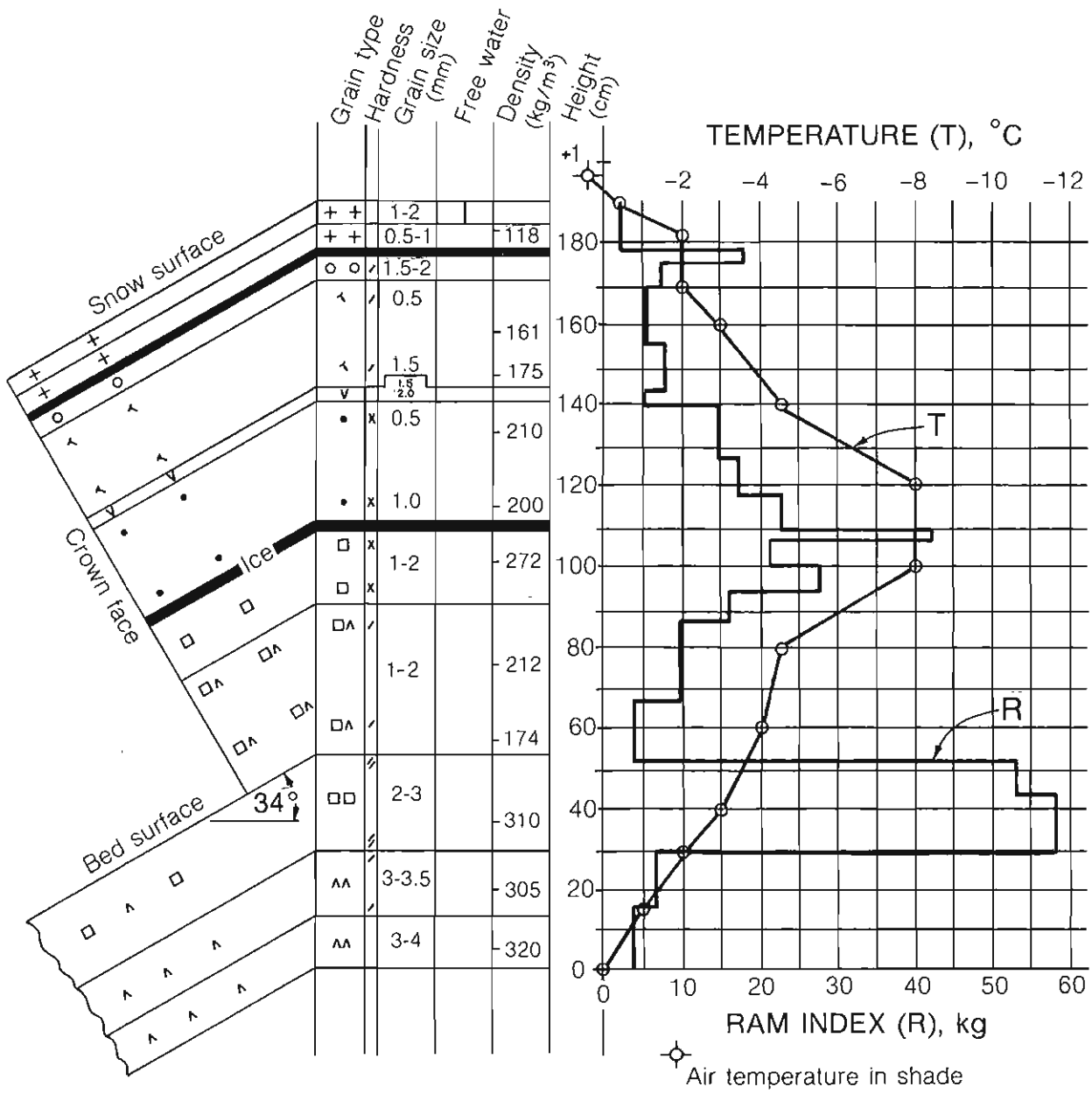
International avalanche classification

A system of classification by observable properties of avalanching snow has been proposed by the International Commission on Snow and Ice (De Quervain et al. 1973). This so-called *morphological* classification system takes into account three zones, which correspond to the starting zone, track, and runout zone:

Zone of origin. In this zone the appearance and movement of an avalanche are characterized by the manner of starting. For a slab avalanche the zone of origin extends down to the stauchwall fracture; for a loose-snow avalanche there is no sharp lower limit. The zone of origin is seldom more than 100 m long.

Zone of transition. In this zone flow is independent of the manner of starting. The speed may be increasing, steady, or decreasing. No particular avalanche deposit is visible in this zone after movement has stopped, except for snow retained by rough terrain or narrow gullies.

Zone of deposit. In this zone a natural deposit is produced by loss of energy due to friction and compaction. The zone of deposit can exhibit a wide range of slope angles; it may even extend uphill on the opposite side of the valley from the main part of the avalanche path. For powder avalanches the zone of deposit is the sediment zone of the snow dust cloud.

Letter-number symbols

Within each zone, several criteria are used in classifying avalanches. The list below gives the criteria for each zone, along with the characteristics important to each criterion. The letter-number symbols are used for coding purposes.

Zone of Origin

A   Manner of starting
    A1   Starting from a point (loose-snow avalanche)
    A2   Starting from a line (slab avalanche)
        A3   Soft slab
        A4   Hard slab

B   Position of sliding surface
    B1   Within snow cover (surface-layer avalanche)
        B2   New-snow fracture
        B3   Old-snow fracture
    B4   On the ground (full-depth avalanche)

C   Liquid water in snow
    C1   Absent (dry-snow avalanche)
    C2   Present (wet-snow avalanche)

Zone of Transition

D   Form of path
    D1   Path on open slope (unconfined avalanche)
    D2   Path in gully or channel (channeled avalanche)

E   Form of movement
    E1   Snow dust cloud (powder avalanche)
    E2   Flow along ground (flow avalanche)

Zone of Deposit

F   Surface roughness of deposit
    F1   Coarse (coarse deposit)
        F2   Angular blocks
        F3   Rounded clods
    F4   Fine (fine deposit)

G   Liquid water in snow debris at time of deposition
    G1   Absent (dry avalanche deposit)
    G2   Present (wet avalanche deposit)

H   Contamination of deposit
    H1   No apparent contamination (clean avalanche)
    H2   Contamination present (contaminated avalanche)
        H3   Rock, soil
        H4   Branches, trees

Below are explanations of some of the criteria in the list.

Manner of starting

Loose-snow avalanche. This type of avalanche starts at a point and may be triggered by a falling object (stone, ice chunk, etc.) or by a skier. In the latter case the point fracture mechanism is obscured.

Slab avalanche. This type of avalanche starts at a line. The origin of the movement may be propagated as an invisible fracture from a distant point of initiation. (The term *slab* is often used synonymously with *slab avalanche*. This should be avoided unless there is no doubt about the correct meaning.) Slab fracture may be observed without subsequent avalanche (often related to the slow gliding movement of wet snow on the ground).

Distinction between soft and hard slab may be based on testing the snow at the fracture site, considering any changes that might have occurred, or, less reliably, on the appearance of the avalanche.

- *Soft slab.* Broken snow layer is very soft, or soft and of low density. Slab disintegrates into loose material immediately after the start.

- *Hard slab.* Broken snow layer is medium hard, hard, or very hard and of high density. A hard slab preserves chunks or blocks over longer avalanche paths depending on their roughness.

Position of the sliding surface

Within snow cover. If the sliding surface is within the snow cover, it is called either a *new snow fracture* or an *old snow fracture*. A new snow fracture is in a uniform layer of snow deposited within 1 to 5 days before the avalanche. An old snow fracture takes place in the older snow layers. It thus contributes old snow to the avalanche at the fracture line. A fracture separating new snow from old snow is a new snow fracture, even if the surface condition of the old snow (surface hoar, sun crust, loose surface, etc.) favored the fracture.

On the ground. If the avalanche slides on the ground surface, *full depth avalanche* should be noted even if some snow patches are left on the ground because of roughness of the ground.

Liquid water

A *wet-snow avalanche* requires liquid water to be present throughout the avalanching layer; otherwise the avalanche would be dry or mixed. Discrimination may be difficult without considering genetic elements (development of temperature, rain).

The classical term "ground avalanche," often used as the opposite of "powder avalanche," is reserved for heavy, wet spring avalanches that drag along rock or soil material.

Form of path

Many channeled avalanches start as unconfined avalanches and are concentrated in a channel only in the lower part of their course. If the main part of the path is channeled, an avalanche is characterized as *channeled;* otherwise a mixed type is reported, describing the unconfined and channeled sections.

The *longitudinal profile* of an avalanche path is often very important (changes in slope angle, intermittent steps). A quantitative description of the profile is better than an elaborate classification of all possible terrain profiles.

Form of movement

Mixed types are very frequently observed. "Mixed flowing-powder avalanche," "powder avalanche with flowing component," and "flowing avalanche with powder component" are ways to characterize mixed avalanches. A movement detached from the ground—either of powdery or flowing type—may be called a "cascade."

Liquid water in snow debris

Large avalanches that are dry in the zone of origin may pick up wet snow in lower parts of the track and change their character. Wet snow in debris causes hard and solid deposits, practically impermeable to air, an important fact for rescue work and avalanche clearing.

Avalanche reporting in the United States

Observers at about 30 locations in the western United States and Alaska fill out forms to document avalanche control activity and avalanche occurrences within their area of interest. The reports may apply to ski areas, mining areas, sections of major mountain highways, or short stretches of secondary or private roads. The U.S. reporting system is described and illustrated below:

Symbol	Type avalanche
HS	Hard slab
SS	Soft slab
WS	Wet slab
L	Loose
WL	Wet loose

	Trigger (activating agent)
N	Natural
AS	Artificial, ski
AE	Artificial, hand charge
AA	Artificial, artillery
AL	Artificial, avalauncher
AO	Artificial, other

Size (based on volume of snow for the path in question)

1	Sluff	(Any slide running less than 150 feet (50 m) slope distance regardless of other dimensions)
2	Small	(Relative to the path)
3	Medium	(Relative to the path)
4	Large	(Relative to the path)
5	Major or maximum	(Relative to the path)

Running surface

G	Avalanche ran to ground in the starting zone
O	Avalanche ran on an old snow surface in the starting zone

Airblast

I	Airblast was observed with the avalanche.

To describe an avalanche these symbols are given in sequence as listed. For example:

HS-AA-2-G Hard slab avalanche released by artillery. It was of small size and ran to ground in the starting zone.

SS-AE-4-O-J Soft slab avalanche released by hand charges. It was large for that path and ran on an old snow layer. Airblast was observed.

L-N-1-O A loose-snow sluff that released naturally and ran on an old snow surface.

Avalanche classification is only part of the information routinely reported on avalanches in the United States. The full report form and instructions for completing it are on the next few pages.

[handwritten: RON PERLA OBJECTED STRONGLY TO "RELATIVE" AS THE FIRST SIZE INDEX]

AVALANCHE CONTROL AND OCCURRENCE CHART
REVISED 10/71

DAY OF MONTH	TIME OF CONTROL OR OCCURRENCE (1)	AVALANCHE PATH AND/OR TARGET NAME	AVAL. PATH NUMBER (IF ASSIGNED)	CONTROL MEASURES (2)	TYPE HS/SS/WS/L/WL	TRIGGER N,AS,AE,AA,AL,AO	SIZE 1-5	RUNNING SFC 0 or G	AIRBLAST = J	TYPE OF MOTION	FRACTURE LINE (SLABS ONLY) DEPTH FT.	LAYERS	% OF TOTAL AVAL. AREA THAT SLID	LOCATION OF STARTING POINT (6)	VERTICAL FALL DISTANCE FT.
6	0700	STANLEY		4 2	SS	A	A	2	O	S	2		20	TR	300
6	0745	BERTHOUD FALLS		4 1	SS	A	A	3	O	M	4		30	TC	700
6	2417	DAM			SS		N	3	O		5		50	TR	700
7	2405	FLORAL PARK			SS		N	4	O		4	B	75	M	300
15	2405	CURRENT CREEK HDWL			SS		N	2	O		2		10	TC	200
30	0800	STANLEY		4 1	HS	A	A	4	O	M	6		75	TL	1500
30															
30	0900	DAM		4 3											
31	2417	HIGH TRAIL CLIFFS			L	N	1	O					5	T	50

(1) Use 24-hr clock — 0800, 0915, 1630, etc. When time is unknown, enter 2405 if event is suspected in A.M.; 2417 if suspected in P.M.

(2) Control Measures: Col. 36 - Type of control; 1 = Ski, 2 = H.E., 3 = 76mmR, 4 = 75mmH, 6 = 105mmR, 6 = 105mmH, 7 = Avalauncher, 8 = other. Col. 37 - No. of shots or ski passes or lbs. of H.E. If greater than 9, enter 9. Col. 38 - If snow fractured w/o avalanche, enter 1; otherwise, blank.

(3) Examples: HS-AA-2-G = Hard slab, artificial artillery, small size, ran to ground; SS-AE-4-0-J = Soft slab, artificial hand charge, large size, ran on old snow sfc with airblast; L-N-1-0 = Loose snow, natural, ran less than 150 ft. slope distance, ran on old snow sfc.

AREA BERTHOUD PASS U.S. 40   STA. NO. 142   WILLIAMS

MONTH JAN   YR. 71   PAGE 1 OF 2

OBSERVERS

LOC. OF DEBRS (7)	IF AVALANCHE REACHED A ROAD		AVALANCHE ACCIDENTS & DAMAGE (8)									REMARKS
	MAX DEPTH ON CENTER LINE FT.	LENGTH OF CENTER LINE COVERED FT.	PEOPLE				VEHICLES		DAMAGE TO			(Please use for clarifying statements about any entries. Note unusual or interesting events, give details on avalanche accidents, make dollar estimates on avalanche damage, etc. If necessary, use more than one line.)
			CAUGHT	BURIED	INJURED	KILLED	CAUGHT OR BURIED	DAMAGED	BUILDINGS	LIFTS	MISC.	
59	60 61	62 63 64 65	66 67	68 69	70 71	72 73	74 75	76 77	78	79	80	
B												Small slide confined to right side of path.
B												
B												Right hand slot.
C	3	3 0 0										Ran sometime before 6 A.M.; fracture line ~500' long; ran on old ice layer 4' deep which had formed in early Dec.
B												3 separate slides observed.
B	2 0	2 0 0					1	1				Hit upper road, did not reach lower road. Damaged a grader parked on road at edge of path. Grader was unoccupied. 3 shots fired, no action.
B												2 small sluffs.

(4) Type of motion: S = Sliding, F = Flowing or Tumbling, P = Airborne Powder, M = Mixed Air & Ground Motion.

(5) If fracture line is confined to new (storm) snow layer, enter A; if fracture line penetrated and includes old layer, enter B; if uncertain, leave blank.

(6) Location of starting point:
Col. 53 - T = Top, M = Middle, B = Bottom
Col. 54 - L = Left, C = Center, R = Right

(7) Where avalanche stopped:
A = Fracture Zone, B = Transition Zone,
C = Foot of Runout Zone

(8) Enter no. of people caught, partially or wholly buried, injured, and/or killed; no. of vehicles partially or wholly buried and/or damaged; and no. of buildings, lifts or miscellaneous damaged. Explain misc. in Remarks column.

U. S. FOREST SERVICE
AVALANCHE CONTROL AND OCCURRENCE CHART
Revised October 1971

General Instructions

1. The U.S. Forest Service Avalanche Control and Occurrence Chart is designed to give national uniformity to recordings of avalanche events. The chart is intended as an aid in snow safety and avalanche control programs and as a source of data for avalanche research.

2. The 80-column format facilitates data keypunching for computer usage. The observer needs to fill out columns 8-80 and enter all pertinent remarks.

3. These forms are printed on self-duplicating paper. Put the rear cover cardboard flap behind the second sheet to give an original and one "carbon" copy. Test to be sure that the sheets are in the proper order to give a "carbon" copy on the second sheet.

4. Use a medium-hard pencil. Please do not use a ballpoint pen. This way mistakes can be erased and rewritten. Entries must be neat and legible. Enter only one letter or number per column.

5. Use a separate line for each avalanche path controlled or for each avalanche reported. Feel free to use several lines in the Remarks column if necessary.

6. Use as many sheets per month as needed.

7. Start a new sheet on the first of each month.

8. Fill in only data of which you are reasonably certain; otherwise, leave the column(s) blank. Higher quality data are obtained if the entries are made quickly following avalanche control work or observation. A small notepad or tape recorder is useful for recording observations while outdoors. These can then be transferred to the avalanche chart indoors.

9. If several columns are available to make a certain numerical entry and the number of columns exceeds the number of digits to be written, the number should be right-justified with blanks appearing in the leftmost column(s). For example, if a 2-foot fracture line is observed, enter __2 in Cols. 47-48, not 2__. Or if an avalanche fell 80 feet, enter__ _80 in Cols. 55-58, not _80_ or 80__.

10. If an entry in a column or columns is the same for several consecutive lines, ditto marks or a continuous arrow pointing downward in all column(s) after the first is acceptable as long as legibility is maintained. For example, if 10 avalanche events are recorded (using 10 consecutive lines) on the 8th day of the month, enter __8 in Cols. 8-9 of the first line (for the first avalanche) and follow this either with ditto marks in Col. 9 for lines 2 through 10 or with a continuous arrow in Col. 9 extending from line 2 through 10. Either way will indicate that all 10 events occurred on day 8. This convenience can be used for any columns which have identical entries for several consecutive lines.

11. Upper left corner: Fill in names of the area, state (abbreviation), station number, month, and year. State and federal highways with avalanche problems are considered to be individual reporting stations, unless the control work on these roads is done specifically to safeguard travel to a particular ski area or mine, in which case the road bears the same station number as the ski area or mine. Mark the first sheet of each month Page 1. If all avalanche activity for the month can be recorded on one page, this will read Page 1 of 1. If 2 sheets are needed, the first will read Page 1 of 2 and the second, Page 2 of 2.

12. Upper right corner: Print the name of the observer or observers.

13. At the end of the month, keep the "carbon" copy for your reference and send the original to

Rocky Mountain Forest and Range Experiment Station
240 West Prospect Street
Fort Collins, Colorado 80521

Attn: Alpine Snow and Avalanche Project

14. The original must be received on or before the 10th of the following month to be included in the monthly summary.

Cols. 8-9: Enter the day of the month when avalanche control or occurrence took place. For days 1-9 make entry in Col. 9.

Cols. 10-13: Use 24-hour clock - 0800, 0915, 1520, etc. When time is unknown, enter 2405 if event is suspected to have occurred in the a.m.; 2417, if suspected in the p.m.

Cols. 14-32: Enter the name of the avalanche path. Please print; enter only one letter per column starting at the left, and abbreviate if necessary. When many paths responded in the same way and a general term is used here, list the actual slide paths in the Remarks column.

Cols. 33-35: If the avalanche paths have been assigned numbers, enter the 3-digit number which corresponds to the avalanche name, such as 003, 021, etc.; otherwise, leave blank.

Control measures: columns 36-38. For natural avalanches, leave blank.

Col. 36: Enter the number indicating the type of control: 1 = ski, 2 = hand charge or explosive, 3 = 75 mm. recoilless, 4 = 75 mm. howitzer, 5 = 105 mm. recoilless, 6 = 105 mm. howitzer, 7 = avalauncher, 8 = other (specify in Remarks).

Col. 37: Enter number of shots or ski passes or lbs. of H.E. If 9 or greater, enter 9. Note: if one man skis across the path, this is one pass; if two men cross, this is two passes.

Col. 38: If snow visually or audibly settles or fractures but does not avalanche, enter a "1"; otherwise, leave blank.

Standard avalanche classification: columns 39-45.

Cols. 39-40: Enter type of avalanche: HS = hard slab, SS = soft slab, WS = wet slab, L = loose snow (either column), WL = wet loose. Note: Slab avalanches release from a line; loose snow avalanches, from a point. A slab avalanche is soft slab if snow disintegrates into loose material immediately after the start; hard slab, if angular blocks of snow are preserved over long distances of the avalanche path depending on the ruggedness. The distinction between hard and soft slabs is based on the density and hardness of the snow, with hard slab avalanches consisting of higher density snow ($\geq.30$ grams/cm^3). It is often not clear whether an avalanche is hard or soft slab; in such a case, soft slab is probably the more correct entry. A slab or loose snow avalanche is called wet if free water can be seen or squeezed from the debris, or if the debris is obviously refrozen when inspected several hours after the event.

Cols. 41-42: Type of avalanche release or trigger: N = natural (either column); AS = artificial, ski release; AE = artificial, hand charge; AA = artificial, artillery; AL = artificial, avalauncher; AO = artificial, other, such as backblast, snowshoe, snowcat, snowmobile, sonic boom, etc. (specify in Remarks).

Col. 43: Avalanche size: The size of an avalanche is designated with a number scale ranging from 1 to 5. A size 1 avalanche, or sluff, is any snowslide running less than 150 feet slope distance (approx. 75 ft. vertical) regardless of its other dimensions such as width, fracture line, etc. All other avalanches are classified by a number 2 to 5 that designates their sizes. This size classification is based on the concept that size should convey an estimate of the volume of snow that is transported down an avalanche path rather than an estimate of threat to life or property. In addition, sizes 2 to 5 are reported relative to the slide path. A "small" avalanche is one that is small (moves a small volume of snow down the path) for the particular avalanche path; a "large" avalanche is large (moves a large volume of snow down the path) for that path.

With these specifications in mind, the avalanche size classification becomes:

1 = a sluff, or snowslide less than 150 ft. slope distance (approx. 75 ft. vertical) regardless of volume of snow

2 = small, relative to the avalanche path

3 = medium

4 = large

5 = major or maximum

Col. 44: Running surface: enter G if avalanche ran to the ground in the starting zone, O if avalanche ran on an old snow surface in the starting zone.

Col. 45: Enter J if airblast was observed with avalanche; otherwise, leave blank. Airblast should not be confused with the dust cloud observed with many dry soft slabs. True airblast is the potentially destructive strong wind that may extend well beyond the visible dust cloud or moving snow front.

Col. 46: Type of motion: Sliding (S) is when the snow breaks loose and moves downslope without rolling or tumbling. In flowing or tumbling motion (F), the snow, whether granular or in blocks, moves along the snow or ground surface in a rolling, turbulent action. Airborne powder (P) refers to snow that billows up in a dust cloud; motion is turbulent and very fast. Mixed air and ground motion (M) is probably the most common with some snow moving along the ground or snow surface in sliding or flowing motion, and the rest billowing up as a dust cloud. Leave this column blank unless the avalanche motion is clearly observed.

Fracture line data: columns 47-49. Fill in only for slab avalanches.

Cols. 47-48: Estimate thickness or depth of fracture line at right angles to the slope, to the nearest foot. If less than .5 foot, enter zero; .6 to 1 foot, enter 1. Remember only slab avalanches have fracture lines; loose snow avalanches start from a point, not a line.

Col. 49: The fracture line of a slab avalanche may penetrate only into newly deposited snow from the current or most recent storm, or it may penetrate deeper into an old snow layer or layers. Entries should be made in this column only if the observer is reasonably certain of the snow layers penetrated in the starting zone. If only new snow is involved, enter A. If an old layer is included, enter B. If uncertain, leave blank.

Cols. 50-52: Estimate the percent of the total avalanche path affected by the avalanche being reported. If, for example, an avalanche starts at the top of its path, covers the entire width of the path, and runs to the runout zone, 100 percent of the path is effected and should be recorded as 1 0 0. If an avalanche starts at the top of its path, covers only the right half of the path, and stops halfway down the track, only one-half the width and one-half the height of the path are affected. This is 25 percent and should be recorded as _ 2 5.

Cols. 53-54: This locates the starting area when the avalanche path is viewed from below. In Col. 53, enter T, M, or B for top, middle, or bottom, and in Col. 54, enter L, C, or R to indicate a fracture line left, center, or right of the midline of the path. T, M, or B with no suffix will indicate a fracture line extending across the entire width of the starting zone or avalanche track.

Cols. 55-58: Give an estimate in feet of the vertical fall distance of the avalanche, not slope distance. On most avalanche paths, vertical fall distances are considerably less than slope distances. For example, on a 30°(58%) slope, vertical fall distance is only half the slope distance. Topographic maps are helpful in making accurate estimates.

Col. 59: Location of debris or where avalanche stopped: A = fracture or starting zone; B = transition or bench partway down track; C = bottom of track or runout zone.

If avalanche reached a road normally kept open in winter: columns 60-66.

Cols. 60-61: Estimate in feet the maximum depth of snow on the centerline. Should this depth ever exceed 99 feet, enter 99.

Cols. 62-66: Estimate in feet the length of centerline covered by debris. Should this length ever exceed 9999 feet, enter 9999.

Avalanche accidents and damage: columns 66-80.

Cols. 66-67: Enter number of people caught by an avalanche. A person is considered caught if he is in any way involved in the moving avalanche snow. This can involve ski patrolmen or snow rangers doing control work, recreational skiers, people in automobiles or buildings, etc. If this person skis out of the avalanche or is thrown completely to the snow surface when the snow stops moving and is uninjured, he would be entered only in the "caught" category. (See examples below.)

Cols. 68-69: Enter number of people partially or wholly buried by an avalanche. A person is considered partially buried if he is covered by debris (after it has come to rest) anywhere from his ankles to his neck. He is also considered buried if trapped inside a vehicle or house which is buried. Every person entered in the "buried" category is by necessity entered in the "caught" category also. (See examples below.)

Cols. 70-71: Enter number of people injured by an avalanche. Every person entered in the "injured" category is by necessity entered in the "caught" category also. He may be entered in the "buried" category too, if he is both buried and injured, which is quite likely. (See examples below.)

Cols. 72-73: Enter number of people killed by an avalanche. Every person entered in the "killed" category is by necessity entered in the "caught" category also. He may be entered in the "buried" category too, if he is both buried and killed, which is likely. However, it is not possible for one person to be both injured and killed; being killed supersedes being injured.

Examples: Two skiers release a slab avalanche. One is momentarily caught by the moving snow but manages to ski out. The other is carried downhill partly or wholly submerged, but when the avalanche stops, he is completely on top of the snow and uninjured. Enter 2 caught.

Two skiers are carried downhill by an avalanche, both are partly buried, one is injured. Enter 2 caught, 2 buried, 1 injured.

A skier is caught by an avalanche, strikes a tree, and is injured but not buried. Enter 1 caught, 1 injured. If he has been killed, enter 1 caught, 1 killed.

A motorist is killed inside his car which is buried by an avalanche. Enter 1 caught, 1 buried, 1 killed, 1 vehicle buried, and possibly 1 vehicle damaged.

Ten people are inside a cabin when it is buried by an avalanche. Four people are injured and two others are killed. Enter 10 caught, 10 buried, 4 injured, 2 killed, 1 building damaged. Should one of those injured later die from his injuries, reduce the number injured from 4 to 3 and increase the number killed from 2 to 3.

Cols. 74-75: Enter number of vehicles caught, partially buried, or wholly buried by an avalanche. This includes automobiles, trucks, snowmobiles, snowcats, snowplows, bulldozers, graders, etc.

Cols. 76-77: Enter number of vehicles damaged by an avalanche.

Col. 78: Enter number of buildings of any kind damaged by an avalanche.

Col. 79: Enter number of ski lifts damaged by an avalanche.

Col. 80: Enter number of other structures damaged by an avalanche. This miscellaneous category includes bridges, roads, telephone lines and poles, transmission towers, etc.

Remarks: This part of the chart is less formal than the entries by columns; it is not keypunched, and therefore, remarks may be made in longhand.

Be generous with remarks. Use for clarifying statements about any entries. Note any unusual or interesting events such as extra large slides, the presence of an ice or depth hoar layer in the snowpack, etc. Give details on all avalanche accidents, and make dollar estimates on avalanche damage. Use as many lines as needed, skipping down that many lines before making the next avalanche entry.

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