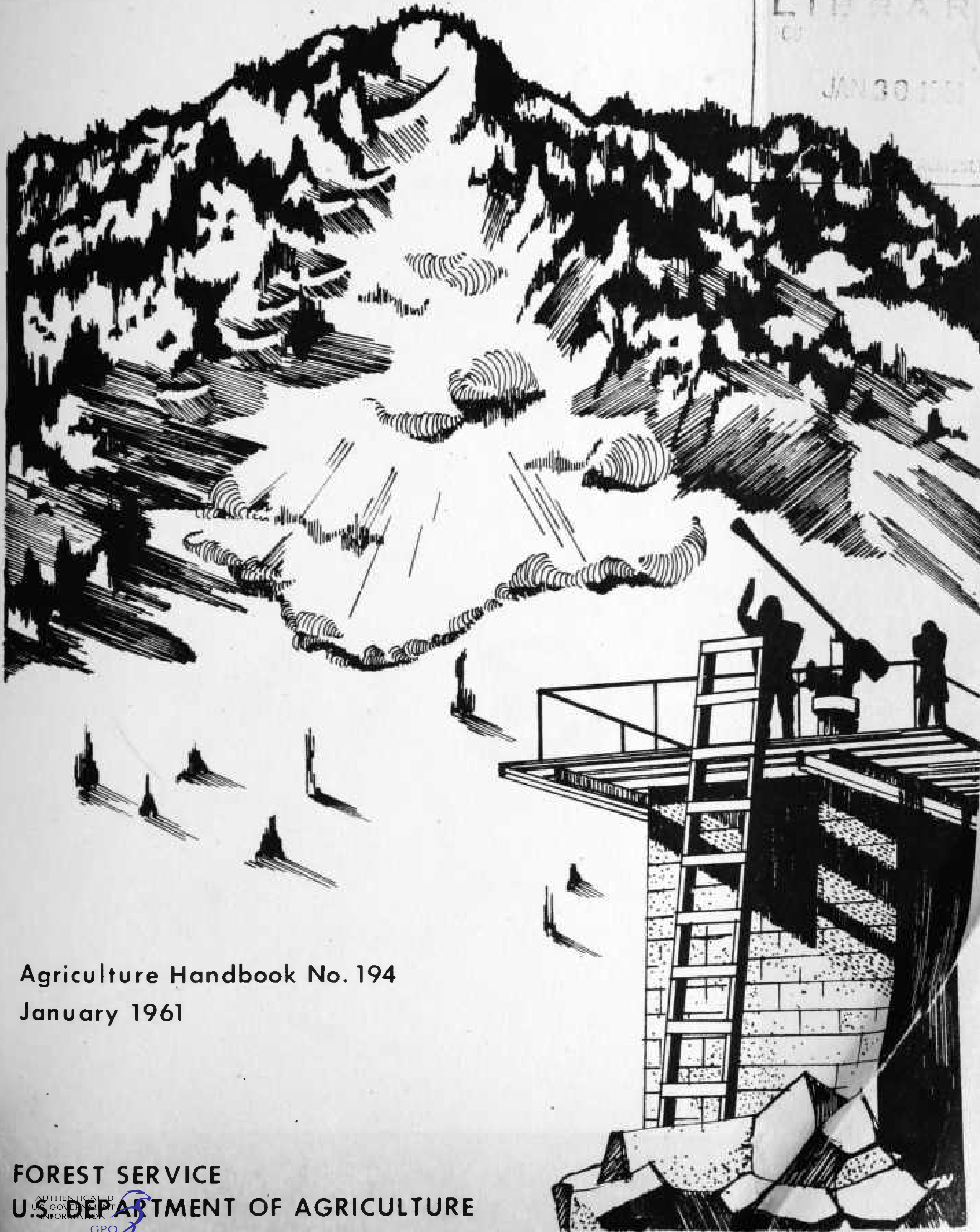
Snow Avalanches

A HANDBOOK OF FORECASTING AND CONTROL MEASURES



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Introduction

The first publication by the U.S. Forest Service dealing with snow avalanches, "Alta Avalanche Studies," appeared in 1948. This booklet reported the results of experiences and studies at Alta, Utah, where the problem of snow safety for the skiing public had confronted forest officers since the area had been established 10 years previously.

The study program at Alta continued, and experience was rapidly gained in methods of avalanche control which made possible increasing use of excellent alpine slopes without compromising public safety. Study stations similar to that at Alta were also established at Stevens Pass in Washington and at Berthoud Pass in Colorado, where the investigations and tests of control methods could be extended to encompass a wider range of climatic conditions. In 1952 the experience of forest officers working in these areas was compiled and published as the "Forest Service Avalanche Handbook." This was designed to be a manual of instruction for foresters confronted with snow safety problems following the rapid postwar expansion of skiing and development of new ski areas on national forest lands. It also served as a general text on the nature, characteristics, and formation of snow avalanches. The extensive appendix included a report on avalanche studies and research programs then in progress.

The "Forest Service Avalanche Handbook" was the only text in English on this subject widely available in the United States, and it was soon accepted by the public for use far beyond that for which it was designed. The training program of the National Ski Patrol System alone generated a heavy demand for it. Requirements of other groups, such as ski instructor associations, plus interest of the general skiing and mountaineering public, soon exhausted stocks at the Government Printing Office.

Eight years have passed since the first "Forest Service Avalanche Handbook" was published. During this period much practical experience has been gained, both through study programs and through the ever-widening practical application of snow safety measures. Many techniques proposed or described as innovations in 1952 are now routine procedures used by Forest Service snow rangers. For example, the use of artillery (fig. 1), which was barely out of the experimental stage in 1952, has now become a widely accepted and effective means of avalanche control in the Western United States. On the other hand, the basic principles of snow mechanics and avalanche formation, and the commonsense rules for safe conduct in avalanche terrain have not changed, though an understanding of snow mechanics increases with passing time and longer experience.

This new handbook provides an opportunity to bring forest officers up-to-date instructions on the most modern methods of avalanche hazard forecasting and control, and to recast the general text on avalanches in a more informative and concise pattern. This handbook is intended as a textbook, as a training aid, and as a field manual for the use of forest officers and others whose duties involve avalanche hazard.

Directly, or indirectly, many persons and organizations have contributed to this handbook. We acknowledge a particular debt to our European colleagues for material on the physics of snow and avalanche defense structures.

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FIGURE 1.—105 mm. recoilless rifle mounted on a Forest Service truck. This is a highly mobile weapon for avalanche control.

Chapter 1

1 AVALANCHE HAZARD AND PAST STUDIES. The remote mountain areas of America are the scene of hundreds, perhaps thousands, of avalanches each winter. No man witnesses them, and they have no measurable effect on civilization. But in certain locations, which are increasing in number, avalanches and mankind do meet. This creates avalanche hazard—a threat to life and property from the cascading snow (fig. 2).

The avalanche is a great natural force, not inferior in power to the tornado, the flood, and the earthquake. It is not so well known as a destroyer of life and property more because of timing and location than lack of potential. In the first World War, on the Austro-Italian front in December 1916, thousands of soldiers lost their lives in snowslides during a single 24-hour period. Total casualties from avalanches during the war on that front were greater than from military action. This was the greatest avalanche disaster in recorded history; it was brought about by an abnormal concentration of men stationed in the mountains, abetted by an abnormal winter. It demonstrates the difference between avalanches themselves and avalanche hazard.

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FIGURE 2.—A climax, hard slab avalanche (HS–AE–5—meaning of abbreviations is given in figure 38). This slide nearly buried a lift terminal, but lost its momentum just in time to prevent any damage. Such large slides have not been observed on this slope since it has been stabilized by routine artillery fire during and after every storm

During the Gold Rush period, from about 1860 to 1910, the mountains in the Western States were much more heavily populated than they have been at any time since then.

From the Sierras and the Cascades to the Rockies, miners swarmed into the high country and built their camps wherever they found silver and gold. Telluride and Aspen in the Colorado Rockies, Atlanta in the Sawtooths, Mineral King in the Sierras, Alta and Brighton in the Wasatch—to name a few—were famous in their day for fabulous riches. They were known also for the sudden, dramatic, and complete destruction by snowslides that often obliterated both miners and their camps.

The mining era was the first time that human beings in large numbers invaded the alpine zones of the United States. The consequences were often disastrous. Verifiable records of avalanche accidents in the vicinity of Alta, for instance, go back as far as 1874, when the mining camp was practically obliterated by avalanches; more than 60 lives were lost. During the next 35 years, avalanches killed 67 more persons. Three slides in three different years wiped out more than 10 persons each.

Demonetization of silver plus exhaustion of the richest claims ended the mining rush, and miners vanished from their alpine camps almost as suddenly as they had appeared. Except for a few trappers and prospectors, the mountains were deserted again in the winter. The avalanches remained, but the avalanche hazard was sharply reduced because the number of potential victims was reduced.

Other targets quickly developed after the mining camps were deserted—transcontinental railroads and highways. The railroads far excelled the highway builders in establishing all-year traffic through the western mountains. Even so, it was on a railroad that the greatest avalanche disaster in United States history took place. In March 1910, three trains were snowbound at Wellington in the Cascade Mountains of Washington. A single avalanche swept all three into the bottom of a canyon at a cost of more than 100 fatalities and a million dollars' property damage (fig. 3). This tragedy forced the railroad underground. Millions of dollars were spent on the tunnel that bypassed the slide area.

The succeeding quarter century saw a reversal of the downward trend of avalanche hazard in the United States. Industrial and agricultural development of the West led to construction of cross-country highways and their maintenance the year round. Mines reopened; logging operations pushed to higher elevations; reclamation and flood control projects sought the headwaters; power, telephone, and pipe lines competed with highways and railroads for room in the steep canyons and passes. Finally, the sport of skiing attracted into the mountains a horde of human beings greater than Gold Rush days ever saw.

Alta, with its grim history of death and destruction at the hands of the "white death" was reborn as a winter recreation area and the site of the first avalanche observation and research center in the Western Hemisphere.

In 1960, avalanche hazard threatens more persons and more enterprises than ever before, and the number is increasing. The spectacular increase in winter sports activities throughout the United States in the decade ending 1960 has been responsible for the greatest increase in hazard. The number of skiers in the national forests of the Intermountain Region has increased two and one-half times since 1950. The number of persons exposed to possible danger continues to increase yearly.

With the skier have come businesses, hotels, private cabins, and heavier highway traffic, all contributing to the economy and development of the West. As new highways are planned and use of the older ones increases, more and more nonskiers are also exposed to possible snow hazards in the many mountain passes. The development and increasing population in the Western States is bringing more and more people in contact with snow avalanches. Much of this contact occurs on national forest lands, so the safety problem becomes an ever-increasing concern of the Forest Service.

Large sections of Alaska are first-class avalanche country, comprising as they do some of the world's most spectacular alpine terrain covering thousands of square miles. Alaska so far is very sparsely populated and the hazard in most places is not yet large, but the high mountains are a dominant part of the landscape, and even now the few roads and railroads connecting the scattered population centers are endangered by avalanches. If Alaska fulfills its promise as a new frontier for rapid development, the avalanche hazard will rise rapidly in the next few decades. Much of the accessible mountain terrain near the seacoast is within the national forests (fig. 4).

There is no possibility that exposure to avalanche hazard in the United States will again decline. The pressure of traffic, communications, recreation, and industry is too great. Neither is hazard the product of climactic winters only. Injury, death, and property damage are an annual toll which merely rise to a peak in years of abnormal severity.

The oldtime answer to avalanche hazard—"either stay out of the mountains or take your chances"—is no longer good enough and the winter techniques developed by the Forest Service to cope with this hazard are providing a new answer.

The study of avalanches is difficult and expensive. Necessity is the main reason for undertaking it. The Swiss, pioneers in snow research, have lived with avalanche hazard for centuries, and have avalanche defense works as old as the towns they guard.

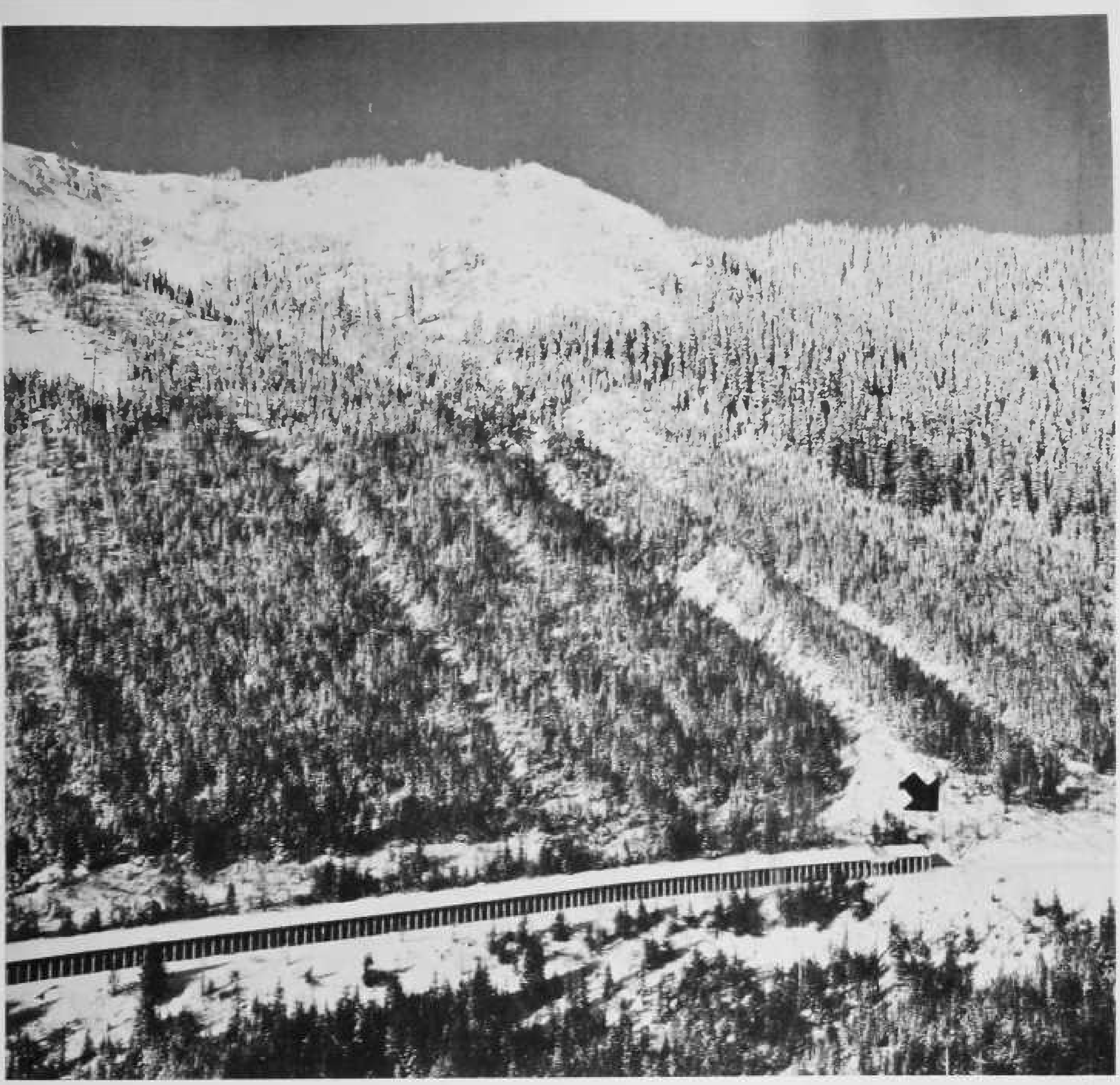

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FIGURE 3.—An example of avalanche hazard and protective measures. Here a series of slide paths descend through timber and cross the old railroad grade leading over Stevens Pass, Washington. A long snowshed has been constructed to protect the grade. The arrow points to the site of the Wellington slide disaster of March 1, 1910. A major avalanche overwhelmed 3 trains at this point and carried over 100 persons to their deaths. The railroad has since been rerouted through a tunnel under the pass.

In 1931 a national commission was established in Switzerland to coordinate all of the work being done by various groups and organizations. This resulted in the famous Avalanche Institute with its snow laboratory and staff of technicians and engineers. The Institute engages in all forms of snow study from basic research in snow mechanics to the development of avalanche barriers.

Avalanche study in the United States began in the winter of 1937–38 with the assignment of the first snow ranger to Alta, Utah. Again the reason was necessity. This abandoned mining camp with its history of death and destruction by avalanche was being developed as the first true alpine winter sports area in this country. Forest officers recognized an ideal combination of terrain and climate near a large city of potential skiers within easy driving distance. They further reasoned that safe use by the public was possible only under the supervision of a snow ranger armed with power to close slopes under avalanche hazard conditions.

Actually it is surprising that the study of avalanches did not begin 30 years earlier, after the

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FIGURE 4.—A striking example of avalanche hazard. Here an important highway and railroad are threatened by a series of slides which fall over unbroken slopes from a height of 3,000 feet. Turnagain Arm, on the Chugach National Forest, near Anchorage, Alaska.

disastrous winter of 1909–10. Two official reports were published. One, by a forester, noted the fact that forest fires had recently denuded the slopes above the railroad, creating avalanche paths which had previously been protected by timber cover. The other, by a meteorologist, described the weather patterns which led to severe avalanche conditions. While neither of the writers was a trained avalanche observer, their analyses contain some very acute observations. In fact, one statement by the meteorologist has become a motto in the avalanche profession:

"It was not only the quantity of snow that fell that caused so many avalanches but also the manner in which it fell."

Lacking any means of combating them, the miners endured avalanches as one more hazard in a hazardous occupation. The railroads retired into their tunnels and snowsheds and until recent years, the law of averages has been a defender of the highways. The odds against a moving car and an avalanche arriving at the same point at the same moment are good. But the odds are getting poorer every year with increasing winter travel by bus, truck, and private automobile.

The Forest Service inherited the avalanche hazard problem because so much of the desirable alpine skiing terrain was on national forest land. There was strong demand for the development of these areas, but the cost in lives and damage the gold miners were willing to pay was not acceptable for public recreation. Thus the Forest Service in the interest of public safety found itself in the business of combating avalanches.

The Forest Service undertook to obtain maximum public use of alpine ski areas with adequate public safety. It was obvious from the start that snow and avalanche research in this country would take a course different from that being carried on in the Alps. There was neither the time, the funds, nor the trained personnel to engage in basic research. Efforts had to be directed toward the rapid development of field techniques for the recognition and reduction of hazard.

Geography was also responsible for a different approach. Ski areas scattered throughout the West were located in widely different climatic zones and in varied types of terrain. In contrast to the compact areas of the Swiss Alps, the mountainous zones of the United States are spread out over a large territory, exposed both from north to south and east to west to different weather patterns and storm tracks. It was obvious that local methods would have to be developed in different areas, for no one location could be taken as representative for all at any given time. The Northwest mountains might be experiencing rain, the Intermountain ranges snowfall, and the Colorado Rockies basking in sunshine.

Until 1950 the snow safety program was confined to winter sports areas under the jurisdiction of the Forest Service. The principal objective was the protection of human life.

It was soon learned that about 80 percent of the slides large enough to endanger life and property run either during or immediately after storms (fig. 5). Therefore, it was decided that efforts should be concentrated on analyzing the weather factors which produce these direct-action avalanches. But the importance of structural changes in the snowpack which cause delayed-action avalanches was still kept in mind. Delayed-action avalanche hazard is an acute problem in the high alpine zone. Studies of this hazard were initiated

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FIGURE 5.—The destructive force of a large avalanche. This car was carried several hundred feet off a highway and completely demolished by a large soft slab avalanche (SS–N–4).

in 1950 with the establishment of the observation station at Berthoud Pass, Colorado.

Publication of the "Alta Avalanche Studies" brought about widespread interest in the avalanche hazard problem in this country. This interest was further stimulated by a series of severe winters beginning with 1948–49, attended by numerous avalanche fatalities and much property damage. No losses occurred at ski areas protected by Forest Service snow rangers. This led to requests for assistance on avalanche hazard problems from many sources. The development of numerous alpine-type ski areas following World War II led to the establishment of observation stations covering the full range of alpine climate in this country. With the assistance of the U.S. Weather Bureau, a number of weather instruments were installed—Alta 1937, Berthoud Pass 1950, Stevens Pass 1951, Squaw Valley 1956.

Alta is the central collecting station for avalanche data. Office space was added in 1955, providing accommodations for Forest Service avalanche files, an avalanche library, and modest research facilities. The recent study program at this station has included instrumentation development, compilation and review of records, tests of artillery and explosives for avalanche control, and literature review and translations. The U.S. Forest Service Alta Avalanche School, initiated in 1949, is held every other year. It was originally designed as a training course for forest officers, but has since attracted students from a wide number of private and Government agencies concerned with snow safety problems.

Chapter 2

2 PHYSICS OF THE SNOW COVER. The physical properties of snow and the processes of change which it undergoes are complex subjects being explored by research scientists. This chapter can be no more than a short introduction to the behavior of snow. The reader is referred to the bibliography at the end of this handbook for additional sources of information.

The serious student of snow behavior and avalanches is urged to give careful attention to these fundamentals before proceeding to the practical aspects of avalanche hazard forecasting and control. Though a purely empirical knowledge of snow can serve in many instances, a thorough understanding of the basic physical processes involved is essential to the intelligent interpretation of observations. This is particularly true of the more complex forecasting problems concerned with delayed-action avalanche hazard.

2.1 The Solid Phase of the Hydrologic Cycle. The conditions of geology, climate, and life on this planet are immensely influenced by the existence of a temperature range wherein water, one of the most common substances on the earth's surface, exists in all three states of matter—solid, liquid, and gas. It is difficult to conceive what the face of the earth would look like if the cycle of evaporation, condensation, and runoff were eliminated by temperatures high enough to keep all of the water in the form of vapor, or low enough to keep it in the form of ice. A complex hydrologic cycle exists because the temperatures that do prevail permit water to pass readily from one state to another. The liquid and vapor states of water are the active participants in the hydrologic cycle of nature, while the solid state—snow or ice—represents water that has been temporarily withdrawn from the cycle and placed in a natural storage reservoir. This withdrawal occurs mainly in the form of precipitated snow (fig. 6). The amount of water contained in this natural reservoir has varied during the history of the earth as great climatic changes of unknown origin have brought a succession of ice ages and tropical climates.

Storage in the polar ice caps and continental ice sheets is on a long term basis, and water so stored is withdrawn from the active hydrologic cycle for hundreds or thousands of years. This withholding of water from the hydrologic cycle during ice ages, and its return during climatic optima, has had profound effects on the climate of the earth, but these effects are measured on the scale of geologic time, and their influence is so slowly felt that they are obscured to human perception by short term climatic variations.

A similar withdrawal on a much more accelerated scale takes place with the deposit of a transient winter snow cover throughout the temperate and arctic zones each year. This annual storage exercises a strong effect on the yearly amount of free water available to arid or semiarid regions in these zones. In either case, the storage phenomenon owes its existence to the fact that vast quantities of energy are required to return water to liquid state once it has been deposited as a solid. The amount of heat required to melt, without change in temperature, a given weight of ice is seven times that reqnired to melt the same weight of iron, and thirteen times that for the same weight of lead.

2.2 Formation of Snow in the Atmosphere. Whenever atmospheric conditions favor precipitation of water vapor at temperatures below the freezing point, precipitation occurs as snow. Snow crystals are known to form around nuclei of foreign matter in the air, such as microscopic dust particles. The first step is the formation of a small ice crystal around the nucleus. This crystal grows by the deposition of additional ice from water vapor in the atmosphere. (The transfer of water directly from the vapor to the solid state, or vice versa, is known as sublimation.) Recent investigations suggest that minute water droplets (diameter around 1 micron) may also contribute to the growth of snow crystals. These crystals in general assume a hexagonal pattern, but, beyond this, the variations in size, shape, and form are almost infinite. A general classification according to form is given in figure 7. The particular form developed in the atmosphere depends on the air temperature and the amount of water vapor available. When a snow crystal falls through different air masses with different temperature and vapor conditions, the more complex or combined types may develop. Crystals formed at the freezing point, or falling through air whose temperature is near it, stick together to become aggregates of individnal crystals or snowflakes.

When snow crystals fall through air which contains water droplets, these droplets freeze to the crystals as a rime deposit. As the amount of rime on a crystal increases, the original shape is obscured and a rounded ball results, giving rise to the type of snow commonly known as pellet or tapioca.

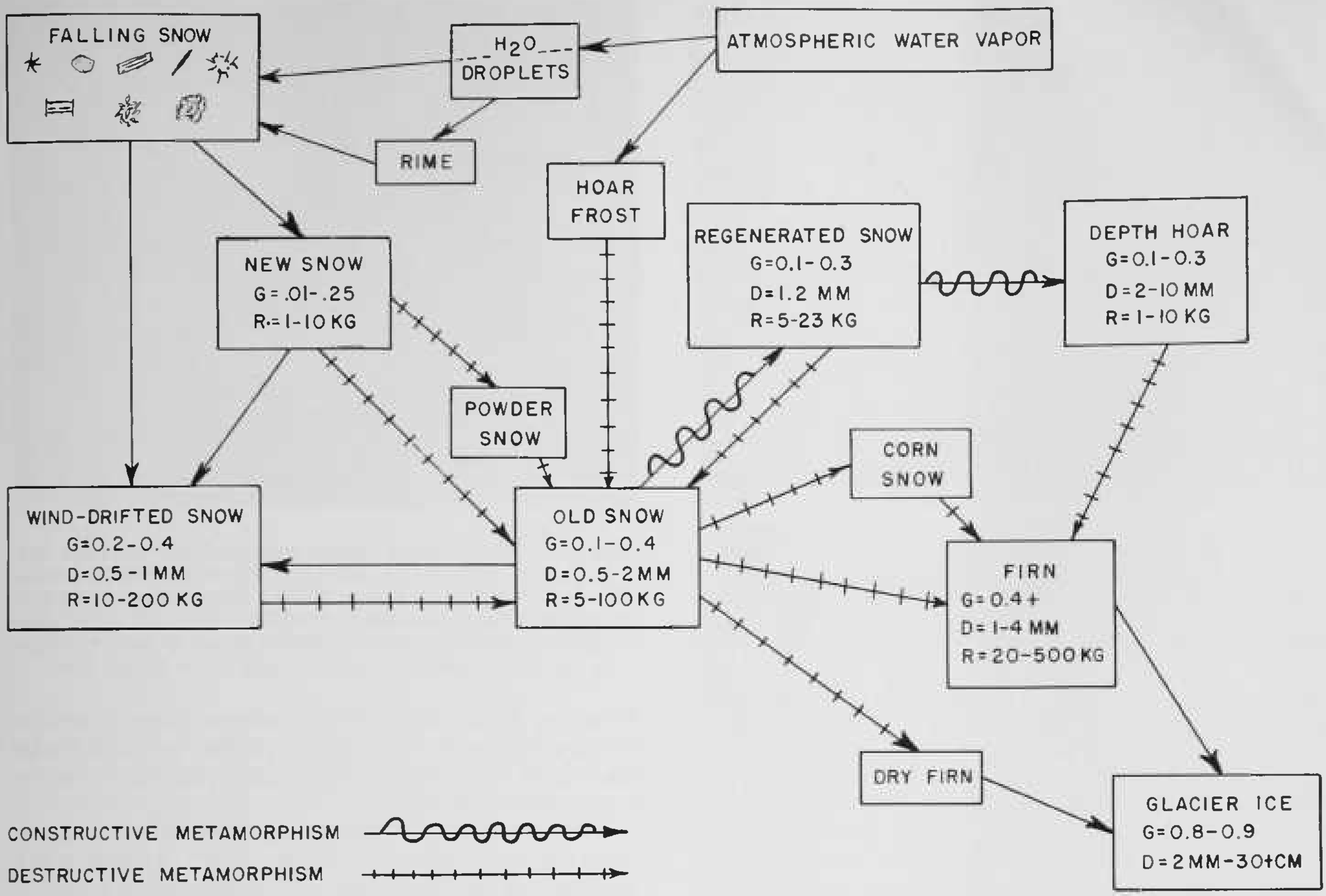

FIGURE 6.—The solid phase of the hydrologic cycle, showing the various paths by which water vapor is deposited as a solid on the earth's surface. The ice so deposited may at any time revert to the liquid phase by melting; only in certain favorable climatic conditions does it reach the final stage of glacier ice. This chart shows the terrestrial part of the cycle only, sea ice having been omitted.

The technical term for these rimed crystals is graupel (fig. 8).

A relationship has been noted between air temperature and density of newly fallen snow. In general, new snow density increases with air temperatures. The relationship appears to be at least partially independent of snow type. The percentage of water in new-fallen snow may range from 1 to as high as 25 percent, with the average value around 10 percent. The lightest snow is deposited under cold and very still conditions. The highest new snow densities are associated with graupel and needle crystals falling at temperatures near freezing.

2.3 Formation and Character of the Snow Cover. Formation of the snow cover is in some ways analogous to the geology of sedimentary rocks. Solid precipitation from the atmosphere (sedimentation) builds up the snow cover layer by layer, with a resulting stratification that displays the history of the weather variations which occurred during its buildup. With the passage of time, structural and crystalline changes within the snow cover (metamorphism) erase the original stratigraphic differentiation and convert the snow into new forms.

Graphing snow depths on a time (months and days) base provides a general record of the snow cover behavior throughout the course of a winter. Periodic observations of density, snow type, hardness, thickness, and other characteristics of individual layers can be plotted as profiles on the same time base. Pits dug from time to time provide information about internal changes taking place, and plotting meteorological data on the same graph allows the effects of various weather elements to be studied. This technique is described in detail in chapter 6, items 6.3 and 6.4.

Metamorphism within the snow cover is a continuous process which begins when the snow is deposited and continues until it melts. The normal path of metamorphism tends to destroy the original crystalline forms of the deposited snow crystals and gradually convert them into rounded, isometric grains of ice (destructive metamorphism). The physical process causing these changes is not entirely clear, but transfer of water vapor by sublimation from the points of the crystal branches to the more central portions of the crystal appears to play an important role. The process is strongly influenced by temperature, and proceeds at a rapid rate when the temperature

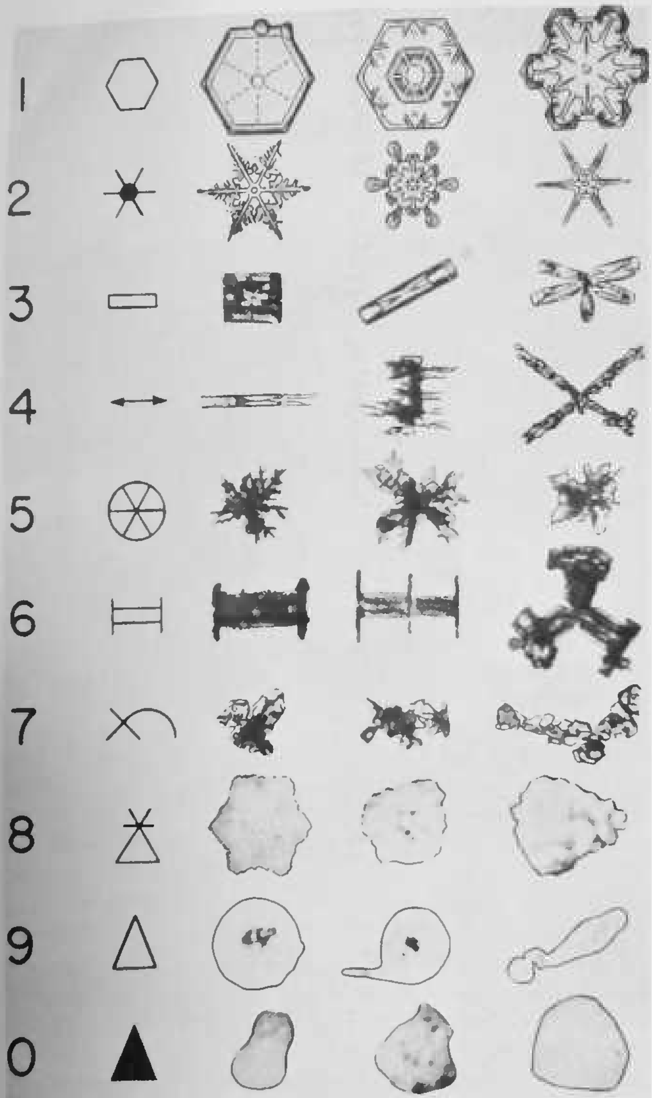

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FIGURE 7.—Types of solid precipitation (International Snow Classification):

1. Plates .... also combinations of plates with or without very short connecting columns.
2. Stellar crystals. also parallel stars with very short connecting columns.
3. Columns .... and combinations of columns.
4. Needles .... and combinations of needles.
5. Spatial dendrites. spatial combinations of feathery crystals.
6. Capped columns. columns with plates on either (or one) side.
7. Irregular particles. irregular compounds of microscopic crystals.
8. Graupel .... pellet snow, or soft hail, with isometric shape. Central crystal cannot be recognized.
9. Ice pellets .... ice shell, inside mostly wet (sleet).
0. Hail

is near the freezing point. At extremely low temperatures metamorphisim is very slow, and practically stops below −40°. As this process takes place with all types of snow crystals, they tend to approach the uniform condition of rounded ice grains, and the snow cover becomes more homogeneous. The rate of metamorphism is influenced by pressure as well as temperature (pressure metamorphism), and the weight of additional snowfalls over a given snow layer causes its metamorphism to accelerate.

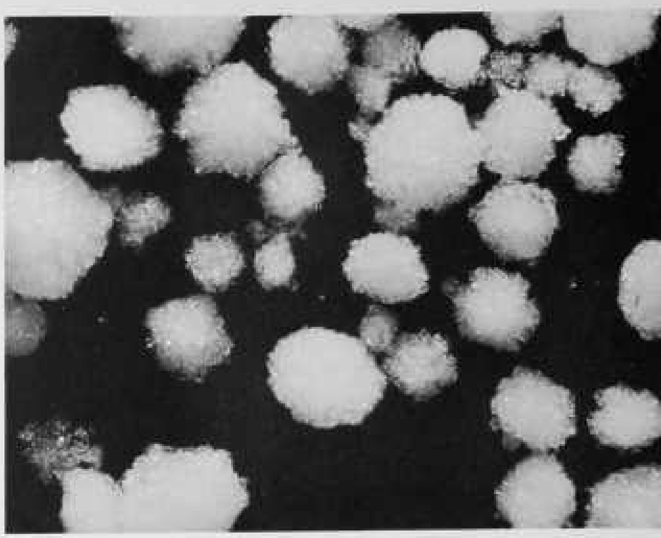

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FIGURE 8.—Graupel, or pellet snow, which has been subjected to destructive metamorphism within the snow cover. Magnified about 2.5X. The pellet characteristic has been retained, making layers of this snow type identifiable for a long time after incorporation in the snow cover. (Note: There is no figure 9.)

The destructive metamorphism of the snow crystals results in a reduction of the space a given amount of ice occupies. This causes an increase in density to accompany metamorphism, and the snow cover to shrink, or settle. This settlement is a continuous, visible evidence of metamorphism. When the process is accelerated by rising temperatures, the settlement rate of the snow cover increases.

A process known as constructive metamorphism may also take place in the snow cover. This occurs when water substance is transferred from one part of the snow cover to another by the vertical diffusion of water vapor. This vapor is deposited around new centers of crystallization and forms ice crystals with quite a different character from those of the original snow. These crystals tend to assume a scroll or cup shape, appear to be layered, and often grow to several millimeters in diameter (figs. 10 [1] and 11). They form a very fragile mechanical structure which loses all cohesion upon collapse and becomes very soft when wet. The snow form produced by this type of metamorphism is known as depth hoar, and is popularly referred to as sugar snow. The conditions required for its formation are a rapid change of temperature with depth (steep temperature gradient) to cause diffusion of water vapor within the snow cover, and a sufficiently high air permeability to permit this diffusion to take place. These conditions are most common early in the winter, when the snow cover is shallow and unconsolidated.

[1] There is no figure 9.

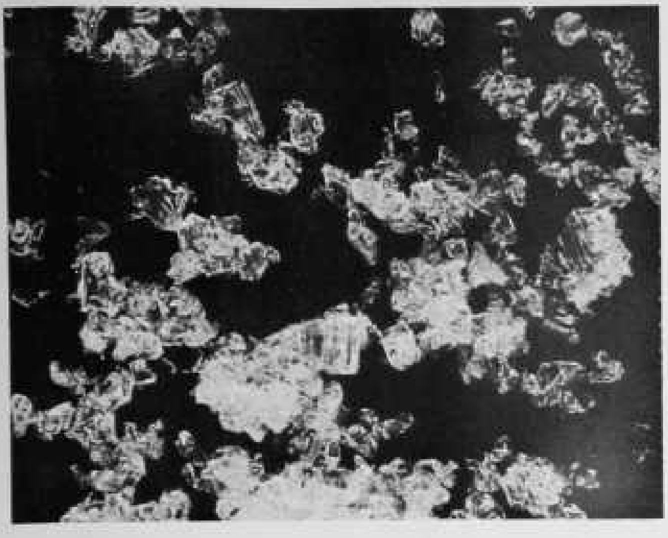

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FIGURE 10.—Depth hoar crystals from the bottom layer of a snow cover 65 cm. deep. This snow has undergone partial constructive metamorphism, and only some of the crystals display the distinct layering and cup-shaped form of mature depth hoar. Magnification about 2.5X.

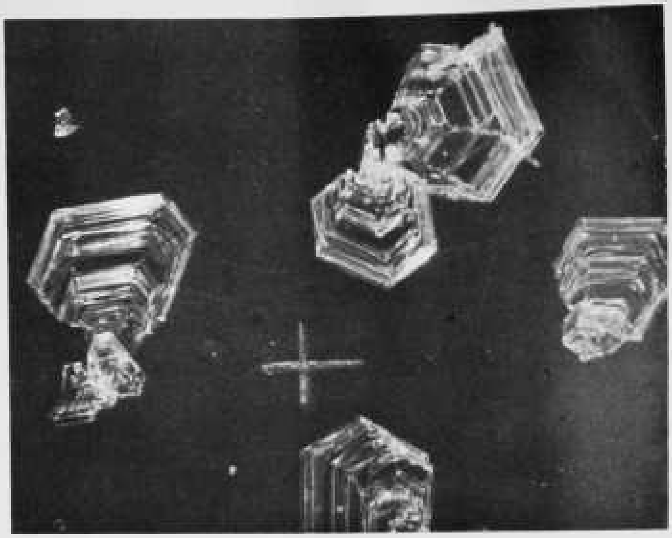

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FIGURE 11.—Surface hoar crystals, formed by sublimation of water vapor from the atmosphere onto a cold snow surface. These display the same characteristic layering and crystal form as depth hoar, but usually are flat instead of cup-shaped. Magnification about 2.5X.

Snow is an essentially plastic material. Because of its plastic nature, any snow cover situated on a sloping surface tends to flow downhill under the influence of gravity. This behavior is known as creep, and is highly dependent on temperature, since snow is very plastic near the freezing point and becomes increasingly brittle at lower temperatures. If the ground surface of a slope is smooth (grass, for instance), the snow cover will slide at its base as well as flow plastically within itself. The creep process is usually very slow, and goes unnoticed by the casual observer; but it can exert tremendous pressure against solid objects located within the snow cover. Even on flat ground, settlement alone can exert great force. These forces can be computed, and must be taken into consideration when constructing such installations as avalanche barriers, lift towers, and snowsheds. The tensile and shear stresses produced by uneven creep of snow are an important factor in avalanche formation.

Variations in the strength characteristics of snow are among the widest found in nature. The hardness of wind-packed old snow or frozen firn may be as much as 50,000 times that of light, fluffy powder snow. Strength characteristics continually change as a result of metamorphism, and are also dependent on temperature for a given snow type. When snow is disturbed mechanically, then allowed to set, it undergoes a process known as age-hardening. This process results in a gradual hardening of the snow for several hours after it is disturbed. The process is more pronounced at lower temperature. The greatest source of mechanical disturbance in nature is the wind, and an increase in hardness is always associated with wind-drifted snow. Age-hardening by the artificial disturbance of snow slopes such as skiing or foot packing is an important factor in avalanche prevention.

2.4 Mechanical Properties of Snow. Snow belongs to that class of solid materials which are termed "visco-elastic." That is, it exhibits the properties of both viscous fluids and elastic solids in varying combinations which depend on density, crystal type, and very profoundly on temperature. When a force is applied to snow it may deform elastically, flow as a viscous liquid, or react as a combination of the two (fig. 12). The rate and duration of force application will also determine the relative importance of the elastic behavior. Snow which is brittle is able to remain in a stressed state for long periods, resulting in persistent avalanche danger. Snow which behaves more nearly as a viscous liquid is able to relieve stresses rapidly by plastic flow, and will more quickly approach a stable condition.

The degree to which snow behaves as a viscous liquid is described by the quantity known as the coefficient of viscosity; the higher the value of this coefficient the stiffer and less liquidlike is the snow. Figure 13 displays in generalized form the dependence of this coefficient on temperature and density. The very great sensitivity of viscosity to temperature in snows of higher density is an important factor in slab avalanche formation. The viscosity of snow also increases with increasing grain size.

In contrast, however, the elastic properties of snow, described by a quantity known as the elastic modulus (usually the shear modulus) are only slightly dependent on temperature. The elastic modulus does increase exponentially with density over the range of densities found in winter snow covers.

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FIGURE 12.—The plastic character of snow has permitted it to flow off this roof and develop a large overhang without breaking.

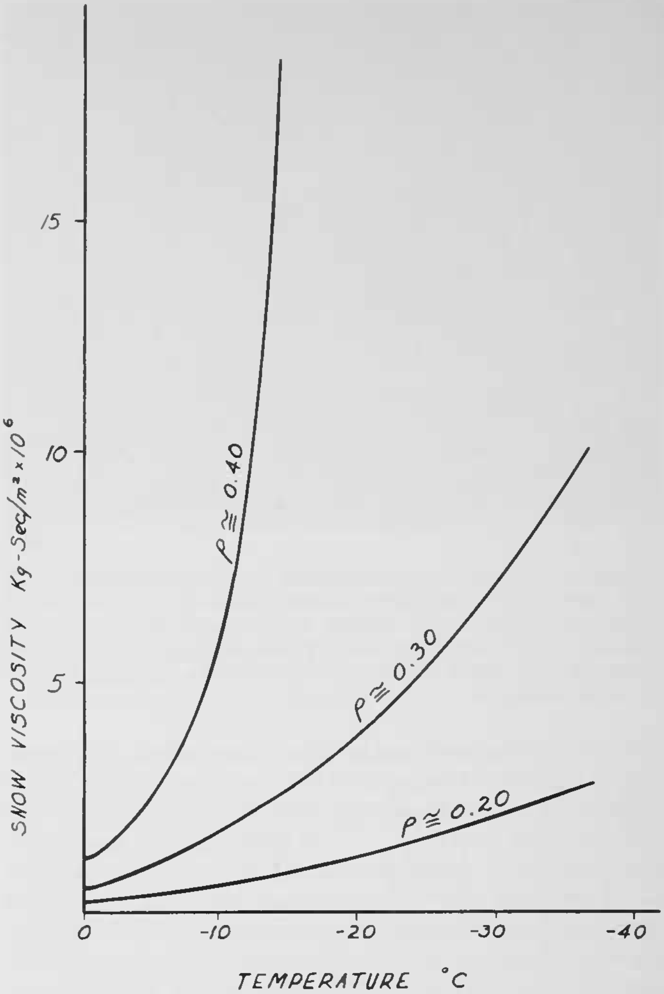

FIGURE 13.—The dependence of snow viscosity on density and temperature. As density increases, changes in viscosity become very sensitive to temperature.

The strength properties of snow, already mentioned, are also determined by density, temperature, and grain type. The magnitude of such properties as shear or tensile strength determines the ability of a given snow mass to remain anchored on a mountainside in opposition to the forces of gravity which are trying to pull it down. The changes of the strength properties with time are important in avalanche formation, and, taken together with time changes of stresses, determine when the moment of critical instability may be reached. A generalized picture of the dependence of tensile strength on the three principal variables is given in figure 14. Note that the strength reaches a maximum for fine-grained old snow, and then decreases as the grain size increases. This is one of the dangerous effects of constructive metamorphism and depth hoar formation already mentioned.

These mechanical properties of snow will be referred to again in the discussion of slab avalanche formation.

2.5 Thermal Properties of the Snow Cover. The common characteristic of the various properties of the snow cover just outlined is their dependence on temperature. Accordingly, the manner in which temperature of the snow cover is controlled by heat loss or gain is of primary importance to its whole behavior. In addition, the melting of the snow cover each spring is controlled by the supply of heat. An understanding of the relative importance of the various meteorological factors which affect the heat supply is thus important to forecasting snow behavior and avalanches.

There are three basic characteristics of snow which strongly influence its thermal properties. First is the high heat of fusion of ice already mentioned. For each gram of ice existing at the freezing point, approximately 80 calories are required to convert it to liquid water without any change in temperature. The second is the very low heat conductivity of snow which ranges from about 0.0001 to 0.0007 calorie/cm.-sec./°C., or up to 10,000 times as great as that of copper. The third characteristic is the presence of water in the vapor and/or liquid phases as well as the solid phase. Vapor and liquid water play an important part in heat transfer within the snow cover.

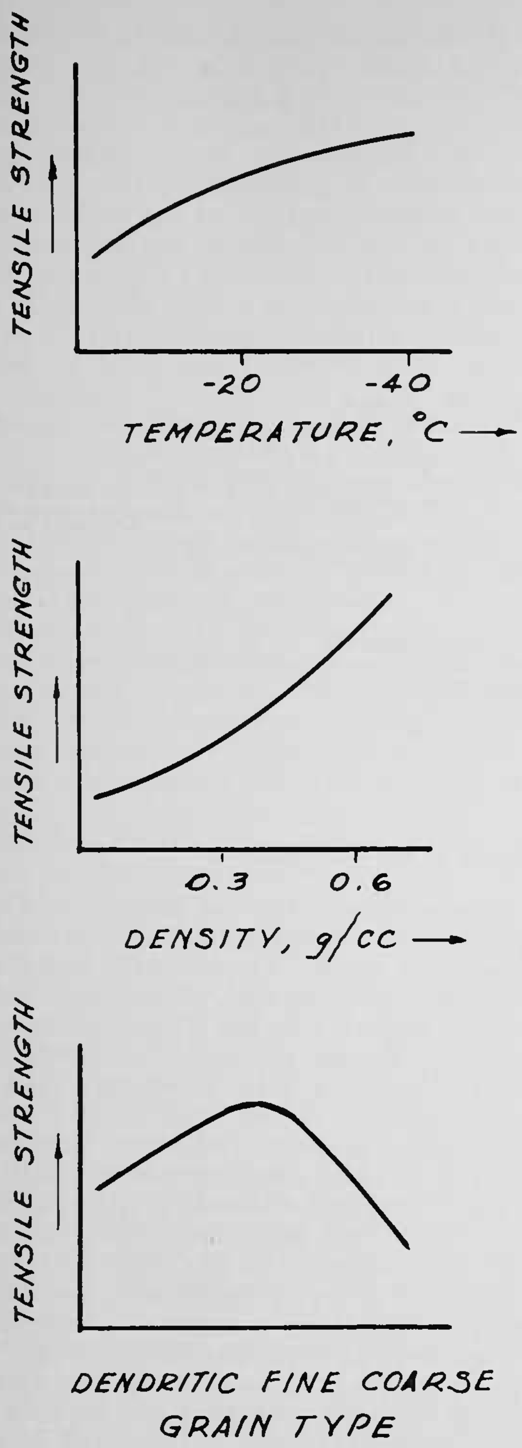

FIGURE 14.—Dependence of snow tensile strength on temperature, density, and grain type (generalized relations). The decrease of tensile strength with the formation of coarse crystals (constructive metamorphism) is an important source of instability.

The heat supply at the bottom of the snowpack is relatively limited. A certain amount of heat is stored in the surface layers of earth each summer, and this heat will melt some of the snow deposited during the winter. If cold weather precedes the first snowfall, however, some of this heat may already be dissipated by frost. The internal heat of the earth also provides a small but steady heat supply at the surface, and is sufficient to melt about 1 cm. of ice each year. In any case, an appreciable snow cover serves to insulate the ground surface from external heat exchanges; and the internal and stored heat, though it may be relatively small, is sufficient to melt small quantities of snow throughout the winter. The occurrence of melting means that the temperature must be kept at freezing point. For this reason, the snow-earth interface is almost always at a temperature of 0° C. or 32° F. in snow covers throughout the temperate zones. This is not the case in higher latitudes where very low temperatures, shallow snow cover, and permafrost are the rule. The temperature may also remain below freezing for a short time at the bottom of temperate zone snowpacks early in fall, when there is frost in the ground and the snow is shallow.

Heat is both lost and gained in much larger quantities at the snow surface, and the temperature undergoes wide fluctuations below the freezing point. The temperature of the snow surface, which is composed of particles of solid ice, can never be higher than 32°F. because water cannot exist in a solid state above that temperature. A thermometer placed on the snow surface will often give a misleading value higher than 32° because of solar radiation. The principal media of heat transfer at the snow surface are turbulence of the air, long and short wave radiation, condensation-evaporation-sublimation, rainfall, and internal conduction. The air, radiation, and vapor exchanges, and internal conduction may either add or subtract heat, while rainfall can only add it, since liquid water must always be at a temperature equal to or higher than that of ice. These media are shown diagrammatically in figure 15.

The medium of heat exchange with the largest potential is the air. Heat may be conveyed to or removed from the snow surface in large quantities by the process shown as eddy conduction, or the turbulent transfer of heat. This process depends on the motion of air over the snow surface, and does not occur with completely calm air. Under this latter condition heat is transferred within air only by molecular conduction and in very small quantities. When the air is warmer than the snow surface, heat is transferred to the snow, and as the difference in temperature increases, so does the amount of heat transferred. With air colder than the snow surface, heat flow is in the opposite direction. The laws governing the turbulent transfer of heat are not yet clearly formulated, but it is known that the quantity of heat transferred depends on difference between air and surface temperatures, the wind velocity, and roughness of the surface. The amount of snow that can be melted by a strong, warm wind, such as a Chinook wind, is much greater than can be melted by any other natural source, including solar radiation.

Large amounts of energy arrive at the earth's surface in the form of short wave (visible) radiation from the sun, but only a small portion is avail-

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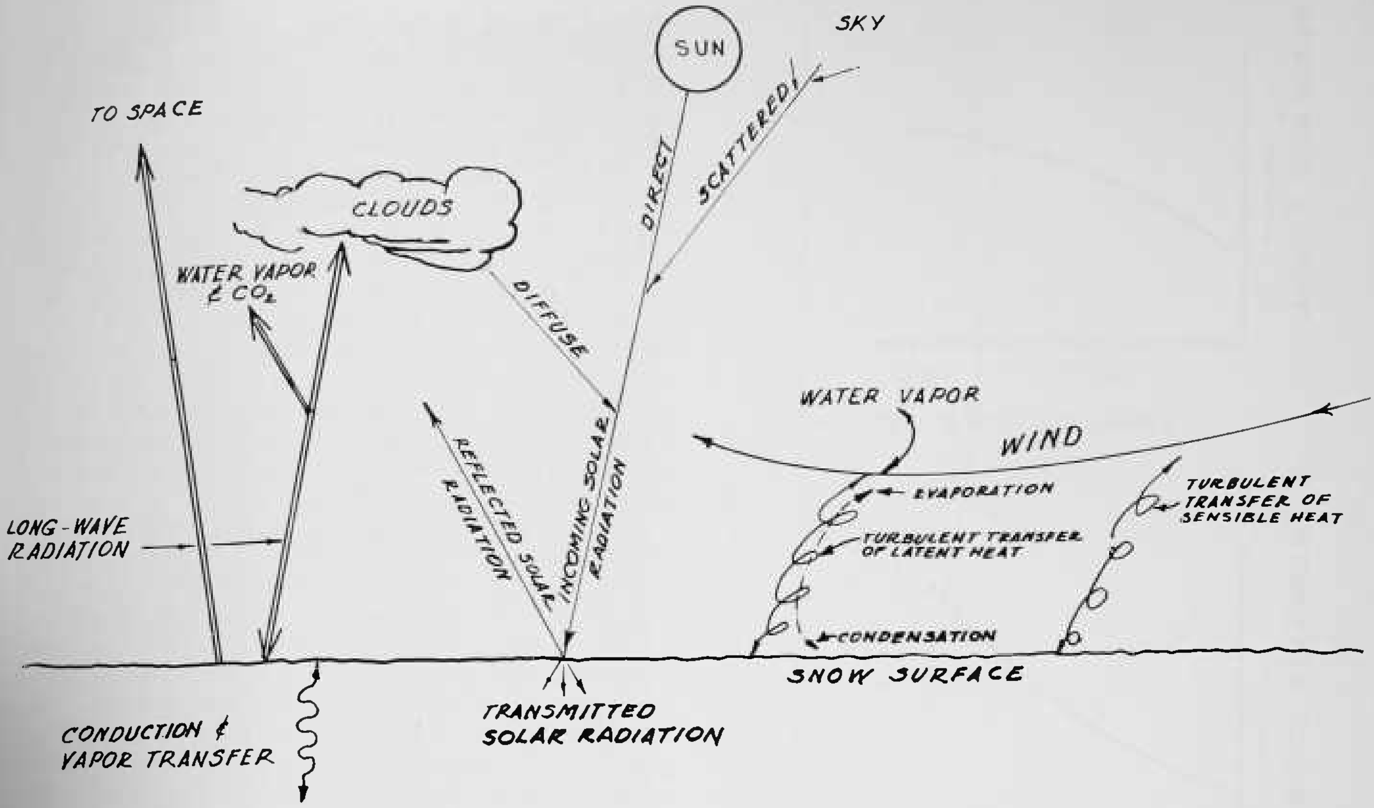

FIGURE 15.—The principal media of energy exchange at the snow surface.

able to snow because of its high reflectivity. Up to 90 percent of the short wave radiation arriving at the surface of freshly fallen snow is turned back by reflection. This figure drops to about 60 percent for wet spring snow, and may be even lower if there is appreciable dirt on the snow surface.

In contrast to its behavior under short wave radiation, snow reacts to long wave (infrared) radiation as though it were black. In fact, among all substances in nature, snow approaches the nearest to an ideal black body for long wave radiation. This means, for one thing, that snow is an excellent radiator of infrared, and that it can lose heat through this medium as well as gain it. When skies are clear, snow loses heat to space by long wave radiation. The amount of heat lost depends on the quantity of water vapor and carbon dioxide in the air, both of which strongly affect long wave radiation. Under overcast conditions, snow will also lose heat by long wave radiation to clouds if the cloud temperature is lower than that of the snow surface. Clouds of any appreciable thickness also behave as black bodies to infrared, and if temperatures of cloud and snow surfaces are known, the amount of heat exchanged can be calculated. When the clouds are warmer than the snow surface, the process is reversed and the snow gains heat by long wave radiation. This condition occurs most often in spring or summer when the air and clouds are warm and the snow remains at 32°.

The effects of long and short wave radiation add algebraically to produce the net radiation balance of the snow surface. The net balance in winter is usually positive (snow gains heat) in the day and negative at night. Occasionally under conditions of clear skies at high altitudes in winter, when the sun angle is low, the outgoing long wave radiation may exceed the short wave radiation absorbed by the snow even at midday, and the snow will actually be cooled while the sun is shining. Maximum positive radiation balance is achieved, not on clear days, but under conditions of thin fog or low broken clouds in spring or summer, when both long and short wave radiation contribute heat strongly to the snow surface.

The behavior of water vapor as a medium of heat exchange at the snow surface is determined by the high heat of vaporization of water. The conversion of 1 gram of water from liquid to vapor without change in temperature requires 600 calories of heat. If water is converted directly from solid to vapor (sublimation), the heat fusion must be added to this figure to give a heat requirement of 680 calories per gram. It is thus seen that, even though the heat of fusion is large, the heat of vaporization or sublimation is very much larger. Accordingly, addition or subtraction of material at the snow surface through the medium of water vapor must be accompanied by the exchange of large quantities of heat. This means, first, that evaporation can take place only if enough heat is available to supply the heat of vaporization. Heat in such quantities is not ordinarily available to the snow cover, and evaporation losses are generally quite small. Significant amounts of evaporation can occur only when extremely dry air with temperature well above that of the snow surface is accompanied by high winds, provided that the condition for evaporation described below is satisfied. A second corollary is that condensation of water vapor on a snow surface can be a large source of heat, for when condensation occurs, the heat of vaporization is given up to the snow. The transport of water vapor to or from a snow surface is governed by laws similar to those governing the turbulent transfer of heat, and increases with increasing wind velocity.

Whether the condition for evaporation or condensation prevails depends on a simple physical law. When the dew point of the atmosphere is lower than the snow surface temperature, condensation can take place. If the air and snow surface temperatures are below freezing, the exchange takes place as sublimation. Conditions most frequently favor condensation in spring or summer when air temperatures (and dew points) become higher, while the snow temperature remains at 32° F. Conditions favoring evaporation are more common in midwinter, but very little takes place because the available quantity of heat is small.

Rainfall ordinarily can deliver only a limited quantity of heat to the snow surface. The specific heat of liquid water is 1.0; that is, 1 calorie of heat is involved in changing the temperature of 1 gram of water 1°C. Thus, each gram of rain which falls on a snow surface and is cooled to the freezing point gives up only 1 calorie for each degree centigrade it is cooled. It is seen that large quantities of rain are required to melt any significant amount of snow (ice) requiring a heat of fusion of 80 calories per gram. Heavy snowmelts sometimes associated with rainstorms can usually be attributed to the warm winds and condensation which accompany such storms. Very warm rain in large quantities can cause appreciable melting, but such conditions are rare in the high mountains, and mountain snow covers seldom experince much ablation (melting) due to rainfall.

The flow of heat within the snow cover is a complex phenomenon due to the presence of all three phases of water; part of the heat is transferred by simple molecular conduction and part is transferred by circulation of air in the spaces between the snow grains. The air itself carries some heat, but the water vapor with it carries more. It is estimated that up to a third of the heat flow in snow is due to sublimation and diffusion of water vapor. Because of the high heat of sublimation of water, only small quantities of water vapor are required to transport appreciable heat in this manner. In any case, the total amount of heat transferred within the snow cover is quite small, due to its overall low conductivity. This situation is altered when appreciable amounts of liquid water are present. The downward percolation of liquid water through a snow cover transports heat very rapidly, and a sudden thaw or rainfall which produces free water at the surface will quickly warm the whole snow cover up to the freezing point. This process would take a long time by conduction alone. When water percolates into snow below the freezing point, the water refreezes and gives up its heat of fusion. Heat is thus transported through the snow by the physical penetration of water, circumventing the otherwise low conductivity of snow.

2.6 Examples of Weather Influence on the Snow Cover. A discussion of actual effects of weather on snow as obtained from the records will serve to illustrate some of the foregoing principles.

1. *Radiation.* The maximum amount of heat available to the snow from solar radiation can be calculated. The following tabulation gives the amount of heat available to a level snow surface exposed to the sun from sunrise to sunset at approximately the latitude of Alta, Utah.

Clear day in JANUARY (reflectivity of snow 0.9)	*cal/cm.² available to snow*
Sunrise to sunset	29
1000–1400	18
1100–1300	9.4
Clear day in APRIL (reflectivity of snow 0.7)	
Sunrise to sunset	200
1000–1400	93
1100–1300	48

These figures actually will be reduced somewhat by various factors in nature, and the heat losses due to long wave radiation on clear days will reduce them further. In January these reductions leave very little heat available to the snow. In April the increased sun elevation provides much more heat from solar radiation, and this source becomes important to snowmelt.

A good example of the effects of long wave radiation loss occurred at Alta in February 1954. A weeklong period of dry, clear, and calm weather brought air temperatures as high as 50° F. during the day and no lower than 30° at night. The snow remained light, crystalline, and fluffy during this warm spell, and even on south slopes there was only very limited melting and metamorphism at the surface. Snow temperature 2 centimeters below the surface was 25° even at the end of this period. Very strong long wave radiation losses almost completely neutralized heat supply to the snow even at midday, and cooled it strongly at night.

2. *Temperature Gradient.* The month of January 1955 at Alta was marked by many large avalanches. Some of these removed the snow cover on certain slopes so that only a thin icy layer remained next to the ground. Late in January a fall of more than 40 inches of powder snow occurred, and in many places avalanched again off this icy layer. One place that it stuck to the icy layer was on the west face of Greeley Mountain. Where this heavy snowfall was deposited on a deeper snow base which had not previously ava-

lanched, it quickly settled into a very hard and cohesive layer. This settlement also occurred on Greeley Mountain, but because the snow layer rested practically on the ground, it was subjected here to a much more severe temperature gradient by cold weather early in February than was the same layer which rested over a deep snow cover. This gradient was high enough to initiate constructive metamorphism, which gradually weakened the mechanical structure of the snow. As a result, a large and dangerous avalanche came down the west face of Greeley Mountain more than a week after the storm had ended. Given the same temperature conditions at top and bottom of the snow cover, and the same snow layer in question, the shallow snow cover became dangerously weak, while the deeper one became stable. The only differences were the magnitude of the temperature gradient and the character of the bond to the underlayer.

3. *Heat Transfer Within the Snow Cover.* The effects of liquid water on heat transfer within the snow cover were clearly demonstrated at Alta in December 1955. Cold and early storms had built up a fairly heavy snow cover that was at temperatures well below the freezing point. On the morning of December 22, the snow cover was 157 cm. deep. Internal temperatures were −1.2° C. at 60 cm., −2.4° C. at 92 cm., and −3.3° C. at 122 cm. Three-fourths of an inch of rain fell during the day, and by the morning of December 23, these temperatures had started to rise. Then during the day and evening of December 23, 3½ inches of rain fell, and by next morning the entire snow cover was isothermal at the freezing point. Temperatures of such points deep in a snow cover ordinarily change only very slowly, but the percolation of rainwater through the cover caused large changes within a few hours. This rain fell at temperatures close to freezing, and actually melted an insignificant amount of snow. In fact, later water-content measurements of the snow cover showed that more water had been retained by freezing of the rain in the cold snow than had been lost by melting. The effects of this rainstorm on snow temperatures are displayed graphically in figure 16.

4. *Turbulent Transfer of Heat From the Air.* As might be expected, heavy melting of snow by warm air often occurs over glacier surfaces in the summer. A clear example of such melting was observed in July 1955, on the Lemon Creek Glacier in Alaska. The ablation (melting) season commenced early in June, and wastage of the snow surface amounted to an average of about 5 cm. of snow each day through June and most of July. However, on July 21–22 a period of clear weather arrived, accompanied by a Chinook or foehn wind. Air temperature was near 50° F., higher than the daily means up to this time, and high winds to 40 mph. were noted. During this 2-day period, 45 cm. (1½ ft.) of snow were melted away. Density of the snow was about 0.5 gm./cc., so this represented the melting of about 22 cm. of water, requiring 1,760 calories supplied to each square centimeter of the snow surface. As soon as the foehn blew itself out, the ablation returned to about 5 cm. of snow each day. Similar high ablation rates have also been observed in this area when storm conditions are accompanied by high winds well above the freezing point. Warm winds such as these in the mountains are often the cause of extensive spring wet-snow avalanche cycles.

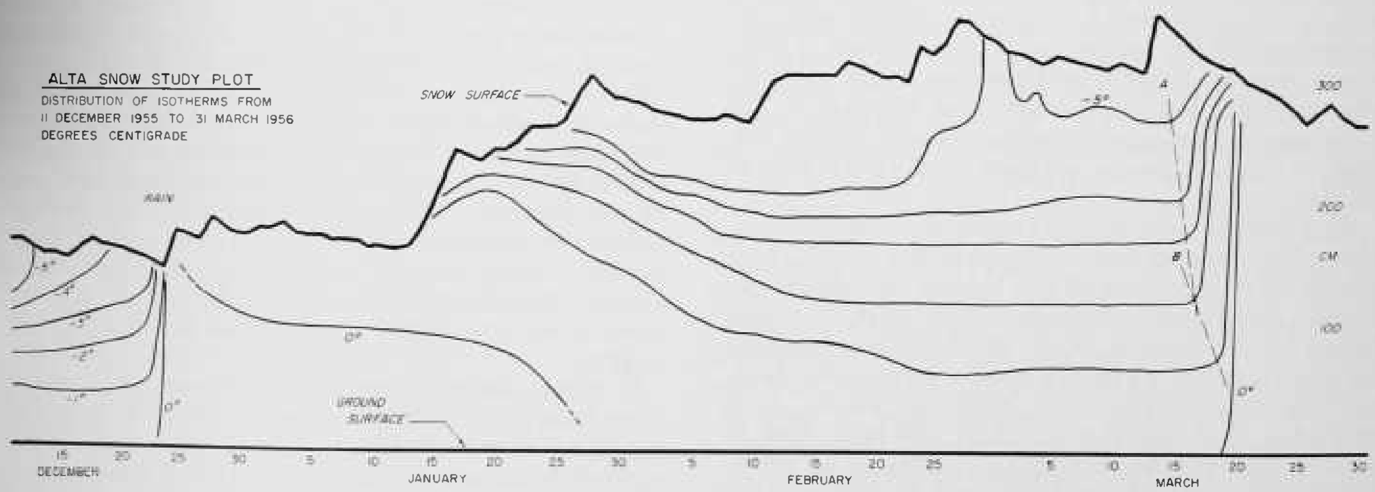

FIGURE 16.—Temperature changes in the snow cover throughout the winter. The gradual temperature changes due to conduction and the rapid changes due to melt-water percolation are both shown. The rainstorm of late December is discussed in the text. Slopes of the lines marked A and B indicate the rate of melt-water percolation in the spring. The lower layers of this snow cover had been made very hard and dense by refreezing of water from the December rain, and offered greater resistance to the downward flow of spring melt water.

Chapter 3

3 AVALANCHE CHARACTERISTICS. Avalanches which fall over long distances and varied terrain may involve more than one type of snow, or more than one method of motion. To permit a uniform means of description, the primary classification of any given avalanche is always based on conditions prevailing at the point of origin. The description may be modified if necessary to clarify the character of the avalanche over the length of its path.

3.1 Avalanche Classification. Two principal types of avalanches are recognized. These are loose snow and slab avalanches. The distinction is based upon the mechanical character of the snow at the point of origin. Loose snow has relatively little internal cohesion and tends to move as a formless mass. Loose snow slides start at a point or over a small area. They grow in size and the quantity of snow involved increases as they descend. A clearly distinguishable sliding layer is not always present, and the line of demarcation between the sliding snow and that which has remained in place is often indefinite. Slab avalanches, on the other hand, are characterized by internal cohesion of the snow involved. This cohesion may vary from only a very slight tendency of the snow crystals to stick together up to extremely hard snow which is broken apart only with great difficulty. Regardless of the degree of hardness of the snow slab, the common characteristic is that a large area of snow begins to slide at once, instead of starting as a small point as does the loose snow avalanche. A well-defined fracture line where the moving snow blanket breaks away from the stable snow is the positive identifying characteristic. This fracture line forms an irregular and often arc-shaped line across the top of the avalanche path with the face of fracture perpendicular to the slope. A definite sliding layer is usually distinguishable (figs. 17, 18, 19).

F–495198

FIGURE 17.—Skier-released small dry slab avalanche (HS–AS–2). The arrow points to the tracks where the skier entered.

F–495199

FIGURE 18.—Medium-sized dry soft slab avalanche (SS–N–3) released naturally by a cornice fall. The broken cornice is visible at the apex of the fracture line. The slide originated as a shallow slab which triggered a deeper layer of snow some 25 or 30 feet below the cornice (arrow).

F–495200

FIGURE 19.—Large, dry, hard slab avalanche (HS–?–4). Manner of release unknown. Fracture line extends under the lee side of a ridge, where heavy wind deposition has in places created an exceptionally thick slab (upper center of picture). Presence of angular blocks in deposition zone identifies this slide as a hard slab. The ridge running across center of the picture, the upper edge of the stable snow which was overridden by the falling slab, is a characteristic feature of the slab avalanche.

Slab avalanches are subdivided into soft and hard slabs. Soft slabs slide away with the typical fracture line, but have the general appearance of a loose snow avalanche until they actually slide and reveal the soft slab characteristics. The snow debris deposited by a soft slab avalanche is usually a formless mass like that from a loose snow avalanche. A hard slab is characterized by snow of sufficient cohesion to retain its form in motion. The principal feature identifying the hard slab avalanche is the presence of angular blocks or chunks of snow in the debris (figs. 20 and 21).

3.11 Loose Snow Avalanches. Loose snow avalanches arise when snow accumulates on slopes of steeper angle than its natural angle of repose. The snow on a given slope is placed in a state of unstable equilibrium by: (1) deposition of light, fluffy snow under conditions of little wind; (2) reduction of internal cohesion among the snow crystals by metamorphic changes; or (3) lubrication from percolating melt water.

Any small disturbance is propagated downward from crystal to crystal, causing the snow to slump downhill towards its natural angle of repose, or, if any momentum is attained, to slide onto slopes of lesser angle. Disturbance of the unstable equilibrium proceeds in the nature of a chain reaction, confined to the downward direction by gravity and laterally by the character of the snow and the terrain. More and more snow is collected in the sliding mass until sufficiently gentle slopes are reached for the moving snow to lose its momentum and come to rest.

F–495201

FIGURE 20.—Typical debris deposition from a hard slab avalanche (HS–AE–3 or 4). Artificial release by cornice blasting. The snow has sufficient internal cohesion to preserve the large, angular blocks of the original slab.

F–495202

FIGURE 21.—Debris blocks from a large hard slab avalanche (HS–AE–4).

The quantity of snow involved in a loose snowslide depends on the depth of unstable snow, the degree of instability, and the length and inclination of the slope. The size ranges all the way from the very common loose or powder snow sluff during or after a snowstorm to the rare, very large loose slide accompanied by destructive windblast. In terms of number, loose slides are probably the most common and generally are minor in size and significance. As will be noted in the discussion of avalanche hazard forecasting, these small, loose snow sluffs are actually a stabilizing factor which inhibit development of the more dangerous slabs. Dry loose snowslides (wild snow) of large size are very rare; most of those which might be so classified actually originate as soft slabs.

The most dangerous loose snow avalanches are those which involve wet snow in the spring or summer. Originating often high on the mountain as a true loose snow avalanche starting at a point, these may gather large quantities of snow by the time they reach the valley floor. The weight of the wet snow gives them large destructive power even though the velocity may be low.

3.12 Slab Avalanches. The slab avalanche is of major concern because it forms the most important source of winter hazard in the mountains. In fact, a review of avalanche accidents recorded both in this country and in Europe shows that the dry, loose snowslide may for all practical purposes be dismissed as a source of hazard. Slab avalanches, in most cases triggered by the victims themselves, are responsible for the overwhelming majority of accidents.

Slab avalanches may originate in snow types ranging from soft, fluffy new snow through compacted, hard old snow to the heavy wet snow of spring. Snow crystals may include almost every stage in the metamorphic processes from newly deposited stars or dendrites to completely metamorphosed old snow, as well as the forms of constructive metamorphism. It must therefore be clearly emphasized that slab avalanches are not exclusively associated with any particular snow type, and especially cannot be correlated with some particular visible characteristic of snow. True, certain types of fresh-fallen snow, noticeably those of higher density, tend to favor slab formation, but this is as much a property of their water content as of their crystallography. Wind drifted snow very commonly develops unstable slabs, and wind is one of the predominant natural factors in slab formation. But wind alone is neither a necessary nor a sufficient factor to cause these dangerous slides. Unstable slabs may develop through processes of internal change alone. This is especially true of climax avalanche development involving several layers of snow, any one of which may be stable when considered by itself, but which taken together may fall as a large slab avalanche.

1. *Mechanical State.* It is therefore apparent that we must regard the slab avalanche condition as a mechanical state of the snow cover. *The tendency of a snow layer to slide is dependent not only on the character of that layer itself, but on its relation to adjacent layers and on the size and shape of the slope.* The primary requirement for slab formation is snow which has sufficient internal cohesion among the crystals to stick together as a united mass which can be set in motion as a blanket over some definite area. When the internal cohesion is very low, the slide behaves like a loose snow avalanche but the dividing line is not always clear. When the internal cohesion is high, the snow layer in question cannot be broken loose and stability prevails. It thus might be said that a certain amount of strength in the snow bears with it the seeds of hazard. In practice, the very unstable snow types of low mechanical strength actually offer less source of danger, for they slide off the mountain long before avalanches of dangerous size can form.

Assuming that a given snow layer has sufficient internal cohesion to behave as a slab, the question of whether or not it will slide is answered by the mechanical character of its attachment to the mountainside. This character is determined by the so-called static relations.

2. *Static Relations.* The primary anchorage of a snow layer on the mountainside is its bond to the underlayer. Strength of this bond depends on the strength properties of the two layers, the nature of the underlayer surface—smooth, windblown, etc.—the temperature at the interface, and the age of the bond. Gravity acting on the slab layer which lies on an inclined plane develops a component of force parallel to the undersurface. This shear stress tends to break the bond between the slab and underlayer. Opposed is the shear strength of the bond, which ordinarily increases with time in the course of destructive metamorphism and decreases with rising temperature. The primary condition of instability is reached when the shear stress exceeds the shear strength. This may be achieved either by a rise in the stress (increased snow load) or decrease in strength (e.g., constructive metamorphism or crust disintegration). This stress can be calculated rather simply if the slab thickness, its mean density, and the slope angle are known (fig. 22). The shear strength, on the other hand, cannot be readily calculated, and is difficult to measure in the field. The general relation for primary instability can be formulated, but a quantitative determination cannot be readily made. The natural law which governs can be recognized, but numerical values can be assigned only with difficulty.

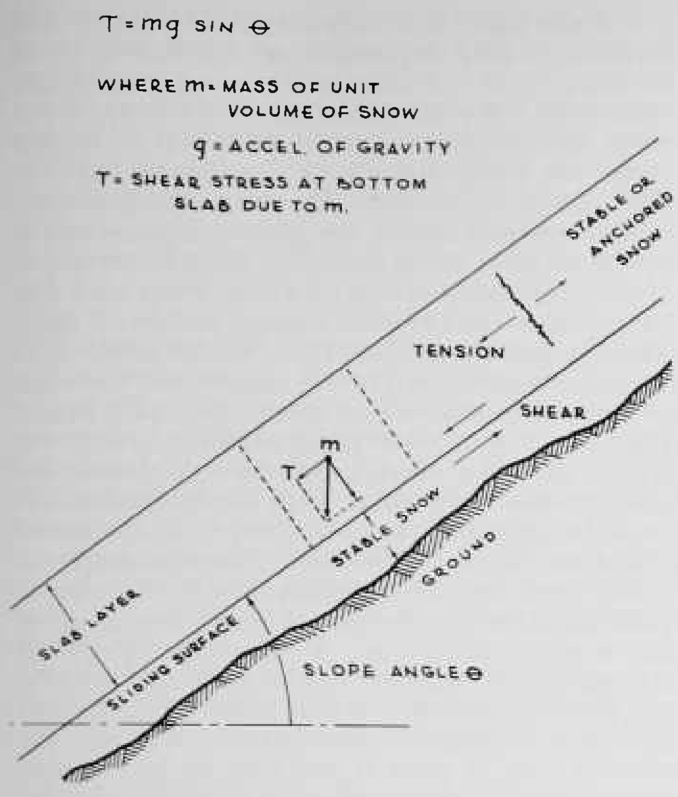

FIGURE 22.—The primary condition for slab avalanche release is achieved when weight of the slab exerts a component of force parallel to the sliding surface (shear stress) greater than the shear strength of the bond.

A shear stress which exceeds the shear strength of the bond is a necessary but not sufficient condition for a slab to slide. The snow layer is also anchored to the slope at the top, bottom, and sides as well as at the undersurface (fig. 23). The strength of these anchorages must also be less than the stress applied to them if a slide is to be released. As with the bond between layers, the critical point may be reached either by a rise in stress or a decrease in strength. Most important of the anchorages is that at the top of the slope where the snowslab is subjected to tensile (stretching) stress, for this is where a rupture is most likely to be initiated, either naturally or artificially. The applied tensile stress can be estimated from measurable properties of snow and slope, though not quite so simply as the shear stress mentioned above. The tensile strength cannot be readily calculated, and must be measured in the field, again with considerable difficulty.

If all the forces acting to release the slab exceed the strength of the anchorages, it obviously will not remain in place. In practice only certain anchorages may be dangerously stressed, or some or all of them may be stressed close to but not exceeding the breaking point. Any outside triggering force, natural or artificial, which cuts or breaks part of the slab then initiates a sudden redistribution of stresses which may break the anchorages and release an avalanche. The same thing probably happens when a gradual increase in load or decrease in snow strength causes one of the anchorages to rupture; suddenly increased stresses are then thrown onto the other supports of the slab and they too break.

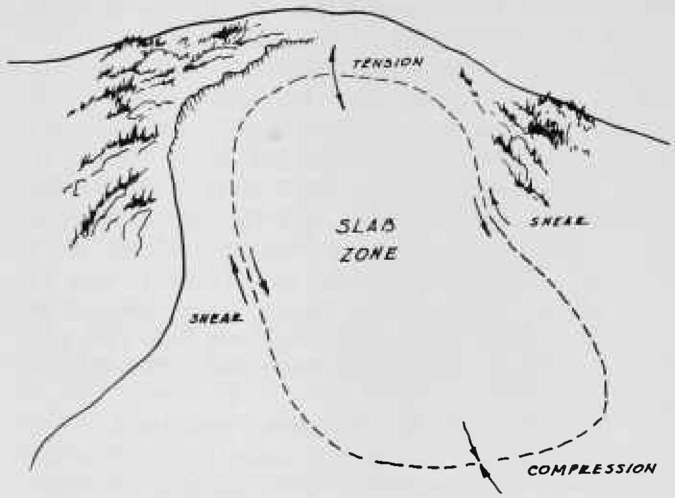

FIGURE 23.—The secondary condition for slab release is reached when stresses at top, bottom, and sides of the slab exceed strength properties of the snow.

If some of the anchorages are sufficiently strong, they may sustain the slab even if other supports are removed. This behavior is clearly seen in the common case of a snow slope which cracks but does not slide. In this case the tensile strength of the slab layer has been exceeded, and it breaks, but bonds to the undersurface, or other supports at sides or bottom, hold it in place.

3. *Dynamic Relations.* The discussion of the static relations assumed that the snow slab was an inert mass lying on the mountainside. In practice this is not the case. The slab and the snow layers beneath constantly experience the slow downhill motion of snow creep, which introduces additional complications to the problem of snow stability. It is the additional combination of stresses created by this creep motion that gives to the slab avalanche its dangerously unpredictable and unstable character.

Under the force of gravity, snow on a slope is continually trying to move toward the valley, both by sliding on the ground and by internal deformation. On level ground the only expression of this motion is the snow settlement. On a slope the motion results from both creep parallel to the slope and vertical settlement.

Zones of stress are formed when one part of a snow slope is free to flow by creep while another part is anchored and cannot move, or one part of a slope creeps faster than another. The most dangerous of these zones are those where tensile stresses occur, frequently found near the top of the slope.

The visco-elastic character of snow has already been described in chapter 2. The reaction of a snow layer to applied creep stresses depends on this visco-elastic character. As the viscosity of snow increases, it becomes more and more brittle (the elastic behavior becomes important only for high rates of stress application). Such snow is less able to relieve stresses by plastic (viscous) deformation or flow, and may remain in a highly stressed state for a long time. A slab so stressed is said to be subjected to creep tension.

When some triggering agent breaks a slab and relieves creep tension, the reaction of the snow may be very rapid. A whole slope may suddenly shatter into blocks before the slab has a chance to be set in motion. If the snow is very dense and cold, such as in hard slab, the release of tension may be signaled by a sharp cracking sound like a rifle shot. The propagation of a fracture line in snow which is subject to heavy creep tension is extremely rapid, and such fractures may run for many hundreds of yards across a slope faster than the eye can follow.

If enough time is available, the snow will eventually relieve or redistribute these stresses by internal deformation. The amount of time required depends on the viscosity of the snow. Snow of low viscosity (near the freezing point) can flow quite readily, and dangerous stresses do not persist for long periods. Thus direct action slab danger from warm snowstorms (25–32° F.) is usually of short duration and the snow quickly stabilizes. As temperature falls, the viscosity increases rapidly and creep tension becomes more persistent (fig. 13, ch. 2). This explains the basis for the general rule that the lower the temperature, the longer avalanche danger may persist.

A quantitative realization of this behavior may be obtained by referring to the concept of relaxation time introduced for the general class of viscoelastic materials by the famous English physicist James Clerk Maxwell. If a fixed initial stress is applied to such a substance, the time required for internal deformation to reduce this stress to approximately 38 percent ($1/\epsilon$) of the initial value is the relaxation time. For the range of densities and temperatures commonly found in nature, the relaxation time for snow may vary from less than 1 second to nearly 2 weeks. Thus it is seen that, on a seasonal basis, creep action will eventually cause the snow cover to deform in any case, but it is during the few days or hours when the snow is at first unable to accommodate this creep that the slab avalanche danger may be at its highest.

An illustration of the temperature influence on slabs is the behavior of hard slabs often found at high altitudes in a continental climate. On such slopes a slab may appear to be quite stable during a sunny day, but will become very sensitive to triggering as soon as it falls into shadow in the late afternoon. The very marked drop in snow temperature due to radiation cooling when the sun goes down is presumed to increase the brittleness of the surface snow layer. This is then easily fractured, and the break propagates throughout the entire slab. A fatal accident occurred on just such a slope that had been used all day by skiers.

4. *Layering.* The formation of unstable slab layers is highly dependent on discontinuities in the snow cover. A completely homogeneous snow cover with an even gradation of density, crystal types, and other properties from top to bottom would not likely form a slab avalanche. A possible exception is where the very strong discontinuity represented by the ground surface causes the entire snow cover to slide. Each interruption of snowfall, each advent of a new storm with different snow conditions, causes a change in snow characteristics from one layer to the next. The interface between two layers usually will have less strength than that which exists internally within a layer. This creates an opportunity for instability. It is therefore a general rule that an inhomogeneous snow cover with sharp discontinuities in stratigraphy is more likely to be the source of slab avalanche danger than a homogeneous one.

The formation of discontinuities in layering is quite sensitive to even minor variations in snow and weather conditions. Frequently a short lull or cessation of snowfall in the middle of a storm will result in the snow of that storm being divided into two distinguishable layers. Though the snow in each of these layers may be for all purposes identical, they will have a weakened bond at the interface which marked the lull. In such cases the upper, more recent layer sometimes can be dislodged as a shallow slab while the lower layer remains stable.

The major discontinuities from one snowfall to the next are of course much more strongly developed. The exposed snow surface in the interim between storms can readily be altered and aged by the various meteorological factors. Many slab avalanches, and especially direct action slides that occur during a storm, avalanche on such a surface.

The surface of discontinuity from which a slab layer may be dislodged is called the sliding surface. It is the top of the older, stable snow which remains in place. Hard crusts, such as those formed by sun melt or rain, are particularly good sliding surfaces which may be the source of repeated avalanche formation. There often exists between the sliding surface and the slab layer proper a shallow, weak layer deposited by a light snowfall or surface hoar sublimation. Such a layer, which provides a region of low shear strength, is called the lubricating layer.

3.2 Types. Both loose snow and slab avalanches are further classified as dry, damp, or wet, according to the amount of liquid water present in the snow involved. Knowledge of snow conditions at the time the slide occurred will help determine this, as will a study of the snow debris and pattern of flow of the slide. Damp or wet slides usually deposit snow in rounded balls or lumps as distinguished from the angular blocks of the hard slab avalanches. The wetter slides tend to flow in grooves and channels, often leaving snow ridges between the grooves and displaying the feature of "wheeling," or curving off in different directions, when they reach flatter ground (fig. 24).

Another feature of classification, and also a general basis of distinguishing wet from dry snow avalanches, is the form of motion of the slide. Three general types of motion are recognized; motion mostly in the air (dust cloud), motion purely on the ground, and mixed motion where both forms are present. Motion through the air alone is rather rare, and usually occurs when dry snow flows over cliffs or very steep terrain. Mixed motion—some on the ground and some in the accompanying dust cloud—is the most common form encountered with the dry avalanche of midwinter, both loose snow and slab (fig. 25). Motion mostly on the ground, with little or no accompanying dust cloud, is peculiar to the damp or wet avalanche of spring and summer. Wind blast, the strong wind which rushes ahead of the sliding snow, is caused by the dust cloud accompanying air motion.

Avalanches are also classified according to whether they slide upon an underlying snow layer (surface avalanche) or on the ground (ground avalanche).

Figure 26 illustrates the more important features of various types of avalanches.

3.3 Size. The dimensions of a slide would seem to be the logical method of determining its size. But to be of any value, the measurements should be accurate and these are often difficult, dangerous, even impossible to obtain. The shape of an avalanche is irregular. Wind action, sun action, and snowfall quickly disguise it. Dimensions do not always indicate the momentum, one of the most important features of a slide.

F–495203

FIGURE 24.—The path of a large wet snow avalanche (WS–N–4), showing the grooving and channeling of the path and the snow boulders in the deposition zone, both characteristic of this slide type.

Classification of avalanches as to size is based on the observer's estimate of threat to life and property:

1. Large or major—highly dangerous to human beings and property. A person caught would be killed or severely injured. Slides in this class destroy buildings, trees, or structural facilities.
2. Medium—dangerous to human beings but not likely to cause property damage.
3. Small—harmless to humans or property.

Abbreviations for the convenient description of avalanches in reports of snow and weather records are listed in chapter 6. (These abbreviations are used throughout this handbook whenever a specific avalanche is described, especially in the photo captions.)

3.4 Avalanche Triggers. Direct action avalanches occur during or immediately after a storm as the result of a new fall of snow. Delayed action avalanches do not result directly from a fresh snowfall, but are caused by wind action, temperature changes, melting, or internal structural changes in the snow. Climax avalanches are caused by the accumulation of snow from a number of storms until an unstable state is reached. This latter type ordinarily involves a large part of the snow cover, and occurs infrequently (fig. 27). Their occurrence depends on the character of weather and snow cover development. The conditions leading to a climax avalanche situation on a given mountain may occur only once in 5 or more years.

When snow reaches a critical state of instability, there often is some definite triggering force which actually sets it in motion as an avalanche. There are many unstable slabs in the mountains each year which never fall as avalanches because no trigger was present to cause their release. Such snow eventually stabilizes and the hazard disappears. In some instances, one period of critical instability may pass without release, only to be followed by another from a different cause—such as thaw in the spring—which starts a slide.

External triggers are those involving some disruptive force exterior to the slab or loose snow layer. Common natural triggers in this class are falling cornices, rolling snowballs, lumps of snow falling from trees, icicles, rockfall, or small slides. Small avalanches or loose snow sluffs which might otherwise be harmless frequently apply enough dynamic stress on the layers over which they slide to dislodge a larger slab avalanche. Large avalanches and massive cornice falls are very effective triggering agents, for they usually develop enough force to carry with them any snow layers which have even the remotest inclination to instability.

The involuntary artificial release of avalanches is a common cause of accidents. Most avalanche accidents involve snow slabs released by the artificial external trigger furnished by the victims themselves. Many such avalanches no doubt never

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FIGURE 25.—Dust cloud accompanying a dry avalanche (HS–AA–4) released by artillery firing in midwinter. The cloud indicates mixed motion that distinguishes this from a wet avalanche.

would fall if they had not been artificially triggered. Artificial external triggers are often deliberately supplied by skiing, artillery fire, or explosives for the purpose of avalanche control.

Changes in the stress-strength relationship of a slab layer, such as temperature changes, overloading by snowfall, or constructive metamorphism, are regarded as internal triggers which carry some part of the mechanical relationship of the slab beyond the breaking point and so effect release. The operation of these agents is less obvious than the external triggers, but they nevertheless are responsible for the natural release of many slides. The most common one is overloading by fresh snowfall. In this connection it may be noted that the rate of overloading or deposition of a slab layer also appears to play an important part in avalanche formation and release. This rate is expressed practically by the measurable meteorological factor or precipitation intensity. The importance of this factor to forecasting techniques is discussed in chapter 5, item 5.1.

Tradition has long regarded the sound of a human voice as an avalanche trigger. However, it has not been clearly demonstrated that such a weak force as the sound waves from voices can cause an avalanche. The possibility cannot be entirely dismissed because stronger sound waves, such as the concussion from explosions, have been observed to dislodge slides. It is therefore conceivable that much weaker sounds could trigger a slide when extreme instability exists. Evidence, on the other hand, seems to indicate that many cases where the fall of an avalanche has been attributed to sound may actually have occurred because the collapse or fracture of the snow cover was propagated over long distances. It has been observed that such a collapse can travel far, even over level ground. Local mechanical disturbance of unstable snow, instead of sound waves in the air, may thus at times be responsible for distant avalanche releases.

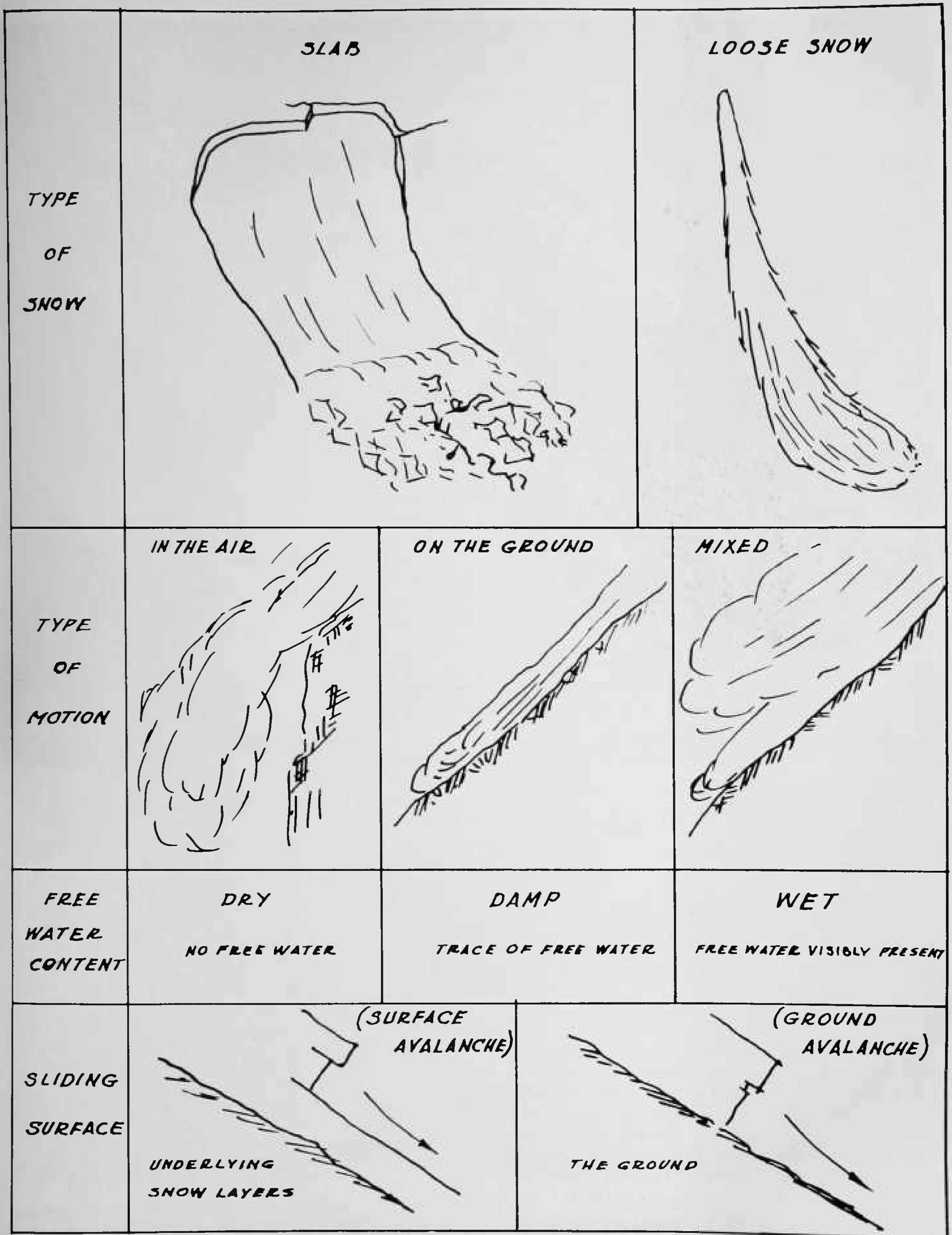

FIGURE 26.—Avalanche classification chart.

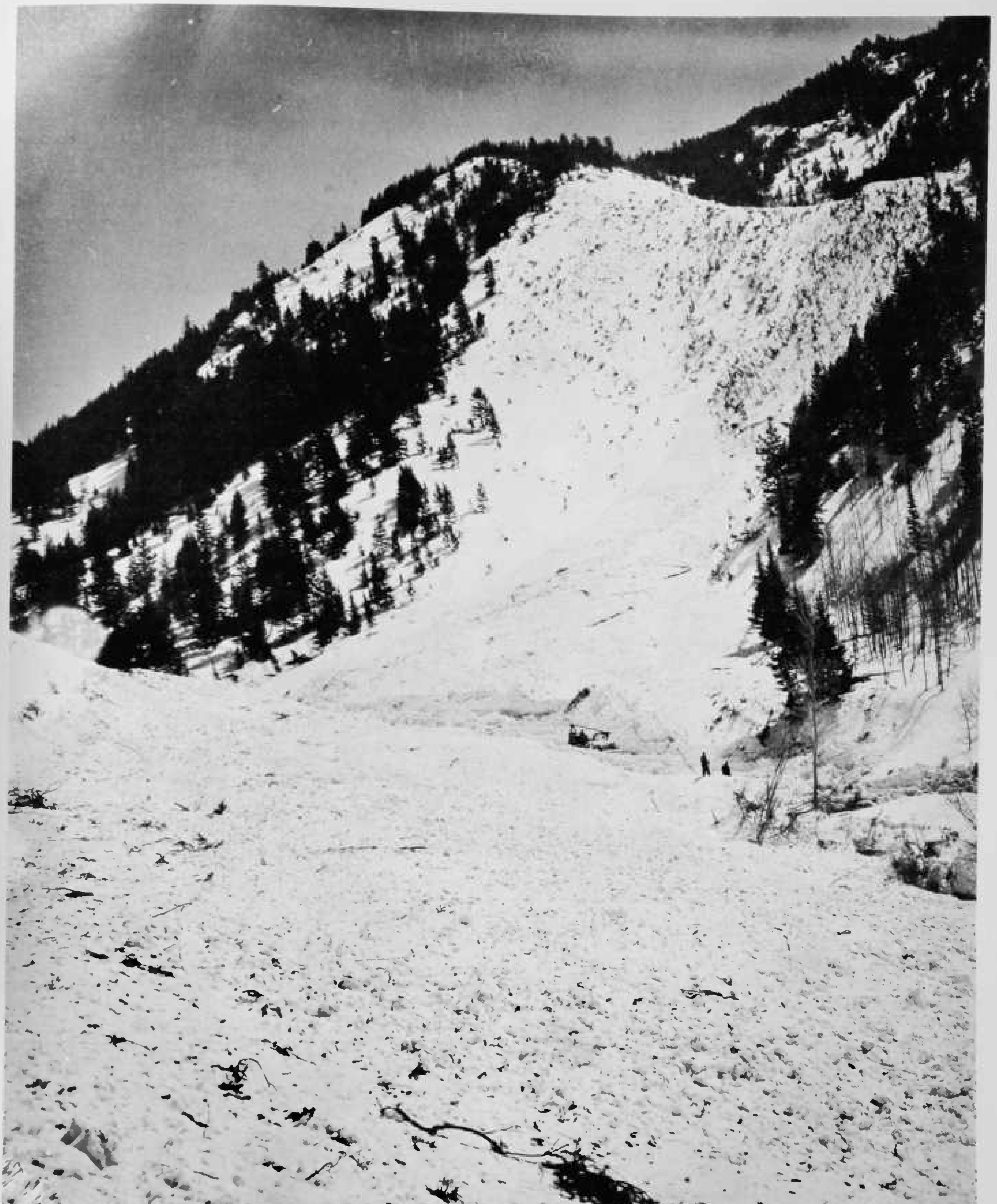

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FIGURE 27.—Major climax slab avalanche which overran a highway located in the bottom of a canyon (HS–N–5). Origin of the slide was far above the slope shown in this picture. Smaller slides on this path are normally arrested on the bench seen near the top of the picture. Argenta Slide, Big Cottonwood Canyon, Utah.

Chapter 4

4 TERRAIN. There are two fundamental requirements for snow avalanche formation—snow and a mountain for it to slide on. Terrain is the fixed factor, important but more amenable to description and classification, for it remains unchanged in any given locality. Avalanche barriers are no more than the artificial modification of terrain.

Steep gullies and steep open slopes are natural avalanche paths. Ridges, outcrops, and terraces are natural avalanche barriers. Ridges parallel to the fall line set definite boundaries to an avalanche path, while those running across the fall line halt, slow down, or divert the moving snow. As a practical matter, ridges are always the safest route to travel in avalanche terrain. On the other hand they modify the orientation of a slope so that one side may be stabilized by sun and wind while the other is an accumulation zone for slab.

Rock outcrops make effective diversion barriers or islands of safety which attract the eye of the area planner as likely locations for structures.

Terraces provide a zone of transition where the slope angle changes rapidly. They slow an avalanche down and give it a chance to spread out. Many major avalanche paths include one or more terraces which retain most of the annual slides and only avalanche to the full length of the slope under unusual conditions. The snow ranger takes full advantage of terrain features in preparing and carrying out his area safety plan.

Terrain variations are as wide as nature itself. The following are the most important.

4.1 Slope Angle. Critical slope angles for avalanche formation have been the subject of many and varied pronouncements in handbooks and manuals. Several sources have set the arbitrary figure of 22° as the critical angle above which slides are apt to occur. Avalanches in fact have been observed on slopes as moderate as 15°, though this is an unusual condition. The probability of avalanching increases with slope angle up to a certain steepness, and then decreases as slopes get steeper and approach the vertical. The reason for this decrease is the failure of snow to adhere in large quantities to extremely steep slopes; it simply runs off in small, harmless sluffs before any great depth can be accumulated. Occasionally, certain snow conditions will permit the formation of avalanches on very steep slopes, but this is not the general rule. It does not seem reasonable to draw any sharp dividing lines, but rather to recognize that there is a zone of slope angles within which dangerous avalanching is most common. Figure 28 has been drawn with this in mind.

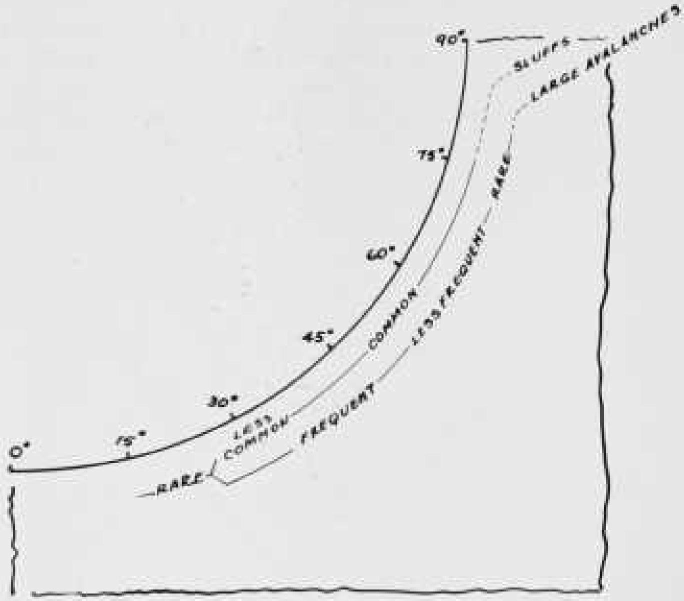

FIGURE 28.—The relation of slope angle in the release zone to probability of avalanche release.

Avalanches of large size may originate on slopes steeper or gentler than 25° to 60°, but the probability gets smaller as the slope angle approaches 0° and 90°. Slope angles at the fracture lines of major avalanche paths within the Alta ski area range from 35° to 40°.

Practical field experience by the snow ranger leads to a certain intuitive "feel" for the steepness of slope above which slides are commonly released in the course of test and protective skiing. Actual check of this intuition against an Abney level suggests that the common danger zone lies above 30–33°.

4.2 Slope Profile. Slopes whose profiles are convex in the vertical plane definitely favor slab avalanche formation (fig. 29). The reason for this can easily be understood in terms of slab mechanics discussed in chapter 3, item 3.12, for the increase of angle downslope on a convex surface results in an increase in creep velocity downslope. The tensile stress from differential velocity is thus added to that between creeping and anchored snow. On concave slopes, differential velocity tends to form compressive stresses which oppose the basic tensile stress near the top of the path. This should not, however, be construed to mean that avalanches are unlikely on a concave slope, for many large avalanche paths are concave in vertical profile. Actually, the concavity (rate of change of slope angle) near the top of natural concave slopes is frequently low. Since such slopes do not differ greatly from a plane surface, the stress modifications due to slope curvature are small. Creep tension is apt to be more strongly developed on convex slopes. This may also be true of slopes which are convex in horizontal profile.

4.3 Ground Cover and Vegetation. Roughness of the ground surface has two important effects. One is to determine how much snow is needed to fill in the terrain irregularities and present a smooth sliding surface; the other is to control the amount of creep motion of the snow over the ground and the ability of the snow to avalanche on the ground itself.

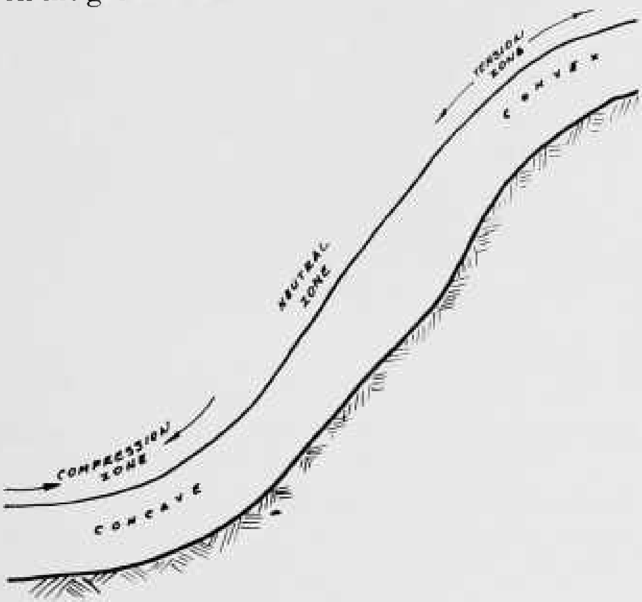

FIGURE 29.—The influence of slope profile on stress distributions within the snow cover.

Smooth, grassy slopes favor avalanche formation, for very little snow is required to smooth over the irregularities. Wet grass also provides an excellent sliding surface which encourages the release of ground avalanches. Snow creep is particularly rapid over a grass surface.

The opposite extreme in ground cover is a field of large boulders which may take 6 feet or more of snow cover before a smooth sliding surface is presented. Creep is low on such a slope, and ground avalanches practically unknown.

Certain types of bushes—willows, for example—provide a stabilizing influence early in the winter. They effectively retain the snow while it is still shallow. Such light vegetation, however, is quickly flattened by snow creep and settlement. By midwinter, or earlier, it is usually covered and offers no further stabilizing influence for surface avalanches.

Heavy stands of timber are usually positive assurance of stabilized snow. Avalanches do not ordinarily originate in a thick stand of trees high enough to remain well above the maximum snow depth, though loose snow slides here are possible under the rare condition of extremely unstable wild snow deposition. Scattered large trees are not proof against avalanche formation. Open, alpine parklands, even where many large trees are present, are the sites of numerous avalanche paths. An avalanche fatality in Colorado in 1960 occurred in just such terrain which, though the many trees made it appear safe to the casual observer, was long known as an active avalanche path.

Heavy timber inhibits the release of avalanches, but is not necessarily a protection against slides falling from open slopes above. Well-developed avalanche paths originating above timberline usually have obvious paths cut through timbered slopes below, where forest growth has been prevented by repeated slides year after year. Occasionally an abnormal situation will bring about large climax slides which break new paths through the heaviest timber. Traces of destruction from such slides can be found in most mountain areas of the Western United States. The catastrophic avalanches in Switzerland during January 1951 furnished several examples of unusual climax slides which fell through heavy timber where none had been observed for hundreds of years.

The presence of trees on a slope also has an important influence on wind currents and the deposition of snow during storms. This influence may either inhibit or encourage avalanching, depending on relation of the trees to a given slope and prevailing winds. Artificial control of snow deposition is possible either by cutting the trees or duplicating their effect with snow fences.

4.4 Slope Orientation. Orientation of a slope in respect to the sun and prevailing storm winds has a prime influence on avalanche development. The amount of heat the snow surface receives from the sun is directly dependent on both orientation and slope angle. The importance of heat transfer to snow behavior has already been emphasized in chapter 2. Slopes which face the northern quarter receive very little energy from the sun during the winter, and those above a certain angle, depending on latitude, receive no sunlight at all during part or most of the winter. Such snow surfaces receive maximum cooling by radiation losses, thus remaining colder and in a less metamorphosed state than snow that can be warmed by the sun. North exposures are the most favored locations for depth hoar formation early in the winter. In general, avalanche danger from the dry slides of winter can be expected to be most frequent and persistent on north exposures, other factors such as snow deposition being equal.

South exposures, on the other hand, receive the full benefit of solar radiation. Surface of the steeper slopes lies nearly at right angles to the rays from the sun when it is low in the winter sky, so that maximum concentration of radiant energy per unit area is obtained. Destructive metamorphism and settlement are thus accelerated by higher snow temperatures, and snow stability is more easily achieved in the winter snow cover. As the sun rises higher in the sky with the approach of spring, heat supply increases to the point where substantial melting occurs, and then south-facing slopes become the site of instability and wet snow avalanching (fig. 30).

The lee slopes, those which receive the heaviest deposition of snow by winter storms, are frequently the site of avalanche paths. In such locations the snow lies deeper, accumulates rapidly during storms, and is most apt to be deposited as unstable slabs. In addition to this combination of favorable factors of avalanche formation, lee slopes are often overhung with cornices which may fall and provide effective triggers. Those parts of a mountainside which lie to the lee of prevailing winds are thus very likely to be the most dangerous avalanche slopes. This applies to the individual lee aspects of gullies, ridges, and other terrain features subordinate to the principal mountain faces. Such lee slopes may receive snow deposits even during fair weather by wind drifting.

Windward slopes ordinarily are much less likely to avalanche, for they receive less snow deposition, and this snow is apt to be more firmly compacted by the wind. Wind pressure no doubt plays a part in this compaction, but the cementing of snow crystals by rime during storms is also considered an important factor in stabilizing windward slopes. The windward exposures should not be considered as completely avalanche proof, because under certain conditions of heavy snowfall, slides may occur without respect to slope orientation.

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Figure 30.—A small, wet, loose snow avalanche (WLS–N–2). Released on a south exposure by natural sunball activity.

Chapter 5

5 AVALANCHE HAZARD FORECASTING.

The "art" of forecasting is not sufficiently advanced to predict the exact time a slide will release on a given avalanche path. It is possible to estimate the probability that slides will occur on a slope. Such an estimate is a hazard evaluation.

When the effects of snow and weather developments are projected into the future, the evaluation is a hazard forecast.

Under many conditions, especially those for direct action slab avalanches discussed below, the period of high hazard (high probability of slide occurrence in an area) can be evaluated with reasonable accuracy. These periods can also be forecast with good accuracy if the weather trends—particularly storm behavior—can be foreseen. The practicing avalanche forecaster will soon learn that this "if" is the biggest stumbling block. The application of fundamental knowledge of snow and avalanche behavior, qualified by local experience, often makes it possible for the forecaster to say with confidence, "If certain weather conditions persist, large avalanches will almost certainly fall"; or "If a thaw does not set in within the next 24 hours, the snow may be considered stable." Neither he nor the professional meteorologist can say with an equal degree of assurance, "Precipitation intensity will be 0.15 inch per hour tonight," or "Heat balance of the snow cover will not exceed a given number of calories per square centimeter per hour this afternoon." Unfortunately the art of mountain weather forecasting, especially where precipitation quantities are concerned, lags behind that af avalanche forecasting. The degree to which a snow ranger is able to forecast avalanche hazard largely depends on his shrewdness in estimating mountain weather. In actuality, his forecast is more often an evaluation of present conditions. Mindful of the adage that "only fools and amateurs try to predict mountain weather," the avalanche forecaster is in an uncomfortable position. Nevertheless, "hazard forecasting" will continue to be referred to in this chapter while recognizing the limitations of this expression.

Understanding of the various contributory factors used to forecast direct action dry slab avalanches has improved. Experience has demonstrated that direct action dry slabs represent the greatest source of hazard in ski areas. This is the type of avalanche which is encountered throughout the winter, storm after storm. Delayed action and wet slides may be just as dangerous when they fall, but they occur less frequently.

There is absolutely no substitute for field experience as training in avalanche hazard forecasting. A thorough practical knowledge of snow behavior and an understanding of the basic principles outlined in this handbook are essential to successful hazard evaluation. Moreover, each region and locality has its own peculiarities of terrain and climate which must be learned by actual observation. The principles of snow behavior are the same everywhere, but the individual variations are endless.

5.1 The Contributory Factors. The analysis of contributory factors is a method of estimating the development of avalanche hazard. This method applies primarily to direct action dry slab avalanches which fall during or immediately after a snowstorm. Delayed action climax avalanches and the wet slides of spring are not readily predictable from a contributory factor analysis; danger from these can be foreseen only by the careful study of structural, crystalline, and temperature conditions within the snow cover.

In the Western United States, weather and climate produce three alpine zones, each with its dominant type of avalanche:

The High Alpine Zone, such as the Colorado Rockies, is characterized by comparatively low temperatures, light and very dry snowfall, very strong wind action, and hard slab avalanches associated with depth hoar.

The Middle Alpine Zone, such as the Wasatch Range in Utah, is characterized by fairly cold temperatures, heavy and dry snowfall, strong wind action, and dry, soft slab avalanches.

The Coastal Alpine Zone, such as the Cascades in Oregon and Washington, is characterized by moderate temperatures, heavy and damp snowfall, strong wind action, and damp soft slab avalanches.

The zones overlap and may produce slides having similar characteristics, but the dominating types of avalanches are distinct enough to warrant identification of these zones.

The forecasting factors which follow were developed primarily in the Middle and Coastal Alpine Zones.

Experience at the Berthoud Pass avalanche station in the High Alpine Zone has shown that the critical values of some of the factors listed below have to be modified for the conditions prevailing at high altitudes and low temperatures. Storms in this zone generally bring higher winds and lighter snowfalls than those in the other zones. The result is a tendency for localized formation of hard slabs instead of the more widespread soft slab development encountered when snowfalls are heavier and the areas in question are nearer to or below timberline.

The ten factors which are used in this method of hazard forecasting have been selected empirically on the basis of experience and snow, storm, and avalanche records over the years. There may well be other factors, or aspects of the present ones, which have not yet been clearly recognized. For instance, the exact type and percentages of the different kinds of snow crystals in a fresh snowfall are believed to have some bearing on the formation of snow slabs, but this relationship has not yet been exactly determined. At present the practice is to give all ten factors somewhat equal weight in the analysis. Actually, they do not all have equal effect, but the relative importance of the different factors has not been measured.

Experience has shown that this method of hazard forecasting is reasonably accurate. A general direct action avalanche cycle almost always coincides with a predominant number of factors favoring avalanche formation; and, conversely, when most are unfavorable, a general slide cycle seldom is observed. In practice, the observer's analysis should always be checked by actually testing the snow on steep slopes, either by explosives or by skiing, to see if unstable conditions actually are developing. This is particularly true in borderline situations when the contributory factor analysis does not give a clear indication one way or another.

1. *Old Snow Depth.* The primary contribution of the old snow, without reference to its character, is to fill in the terrain irregularities and provide a smooth, even surface upon which an avalanche may start. The amount of snow it takes to cover up the irregularities—rocks, stumps, bushes, etc.—obviously will depend on the nature of the terrain, so the exact value of old snow depth which begins to contribute toward avalanche formation will depend on the locality. On smooth, open grass slopes as little as 6 inches might be a favorable factor, while in a field of large boulders it may take 6 feet before everything is covered and a smooth snow surface is present. In the usual mountain terrain a depth of 2 to 3 feet might be taken as an average value. The general rule in evaluating this factor is that the deeper the old snow, the more likely avalanches are to form. However, given the proper type of old snow, even a few inches might be a dangerous indication.

2. *Condition of the Base.* The nature of the old snow surface determines in part whether a new fall of snow will form a good bond. A crust on the old snow may provide a smooth sliding surface and favor avalanches. A crust covered with a few inches of unconsolidated light powder is more likely to contribute to avalanche formation when fresh snow falls, because the intervening layer of loose snow provides a lubricant between the new snow and the crust. New snow may sometimes make a firm bond to even a very hard crust; whether or not this happens is controlled primarily by new and old snow temperature. If the new snow falls at temperatures near the freezing point, or if the old snow surface layers are warm, then a good bond is possible. A surface of very loose or fresh snow may sometimes form a poor bond, while firm or settled old snow is more apt to offer a good bonding surface. Extremely rough windblown snow (sklaver) offers sufficient irregularities to provide bond for the new snowfall, so that slide formation is hindered.

The character of the old snow also determines the amount of support it can give to subsequent fresh layers, and whether or not it will itself become involved in slides originating in the new snow. Unstable slabs in the old snow may in themselves be the primary source of an avalanche, for the weight of the new snow may provide a trigger for their release, even if the new snow is not inclined to slide. Weak or poorly bonded layers, old crusts, or air spaces within the old snow may all be considered favorable to avalanche formation. A particular type of weak layer which is especially disposed to cause avalanching is depth hoar (chapter 2, item 2.3). This type of crystal forms a very weak and fragile mechanical structure and offers little support to successive layers of snow. Even a very shallow layer of old snow which consists mainly of depth hoar may induce avalanching.

3. *New Snow Depth.* The single most important cause of direct action avalanches is a large quantity of new snow. Deep falls may not necessarily produce avalanching, and even small quantities of new snow can cause large slides under the right conditions; but as a general rule, deep new snow is a warning of possible hazard. The deeper the new snow, the more likely that unstable conditions exist. New snow of a foot or more may cause avalanches of significant size. New snow of less than a foot does not usually build up a general hazard, except in the High Alpine Zone where 4 or 5 inches of new snow with high winds may produce a general hazard. A few inches accompanied by high winds may produce localized danger from slabs on lee exposures in the other zones.

4. *New Snow Type.* The type of snow crystals which make up new snow considerably influence the type of avalanche which may develop or whether any develop at all (chapter 6). Pellet snow, or graupel, for instance, is peculiarly disposed to form slab avalanches, both because it is usually denser than normal snow types and because it easily forms a stiff and slablike layer. A snowfall composed entirely of needles also leads to a dense slab formation, while granular snow (fine, rime-coated crystals) is another type asso-

ciated with this kind of avalanche. The fluffy, feltlike snow built up primarily from star crystals and spatial dendrites does not usually lead to a slab formation unless subjected to heavy wind drifting. However, there appears to be relationship between this snow type and soft slab formation when there is some rime coated on the crystals. Stellar or dendritic snow, if deposited in appreciable depth under cold, calm conditions favors loose snow avalanches.

5. *New Snow Density.* Avalanche occurrence is definitely associated with new snow densities which depart widely from normal. Careful measurement of the density of new fallen snow is therefore one of the standard observations for hazard forecasting. What constitutes the limits of normal density is open to some interpretation. Annual average new snow densities computed from several years of data may range from 0.07 to 0.10 gm./cc. (7 to 10 percent water content) or higher, depending upon climatic conditions. Wide departures from this range are sometimes observed; and the greater the departure, the more likely is the snow to be prone to avalanche. The higher densities, which may range up to 0.25 or 0.30, are associated with slab avalanches. Low densities, as low as 0.01 when snow falls under very cold and calm conditions, generally lead to loose snow avalanches. New snow densities must be measured in the surface layers within a short time after the snow is deposited; otherwise settlement will have altered the original density, especially at warmer temperatures.

6. *Snowfall Intensity.* Snowfall intensity is the rate at which snow is deposited during a storm, expressed in inches of snow per hour. Two feet of new snow deposited over a period of 2 or 3 days may cause little trouble, but the same amount falling in a period of 10 or 12 hours can precipitate widespread avalanching. The influence of snowfall intensity appears to be related to the ability of the snow to stabilize itself by settlement. High rates of snowfall create instability faster than settlement can reduce it. Observations indicate that for most conditions a snowfall intensity of 1 inch per hour is about the critical rate above which heavy avalanching often occurs, especially if this rate of fall continues for several hours. In the High Alpine Zone a snowfall intensity of one-half inch per hour is favorable for avalanching.

7. *Precipitation Intensity.* Precipitation intensity is the rate at which water, in the form of snow, is deposited by snowfall or wind drift. It is thus a measure of the rate at which mass is being added to a snow slope and is probably a more basic factor for avalanche formation than is snowfall intensity, though the latter is easier to measure in the field. High precipitation intensity is associated more definitely than snowfall intensity with avalanche occurrence and notably with the formation of slab avalanches. Experience has shown that a rate of water deposition greater than 0.10 inch per hour, accompanied by winds above the critical level for an extended period, has a high correlation with avalanche occurrence. Short periods of high precipitation intensity do not necessarily lead to avalanches, but the deposition of 1 inch or more of water (as snow) at a high rate is a favorable factor. Extensive direct action slab avalanches are almost always associated with high precipitation intensity coincident with high wind.

The effects of rate of mass deposition may be expressed in terms of the precipitation intensity factor. This factor has a numerical value equal to the amount of water, expressed in inches, which has been deposited for a continuous period at a rate of 0.10 inch per hour or greater, while winds are above the critical level. Thus a sustained precipitation rate of 0.15 inch per hour for a period of 10 hours while the wind is at high levels would yield a precipitation intensity factor of 1.50. This factor expresses the coordinate influence of wind and precipitation. Values in excess of 1.00 in the Middle and Coastal Alpine Zones and 0.50 in the High Alpine Zone are taken as warning of possible avalanche development. Extensive and destructive avalanche cycles are often associated with a P.I. factor of 3.00 to 4.00 or greater. The catastrophic avalanches in Switzerland in January 1951 coincided with development of a P.I. factor greater than 4.80.

8. *Settlement.* Settlement is a process of stabilization in the snow cover, the rate of which is more or less proportional to temperature. Snow which has undergone strong settlement is less likely to slide than snow which has not. Of especial importance is the settlement that takes place in new snow during and immediately after a storm. Even very deep snowfalls may create little avalanche activity if the new snow settles very rapidly while it is still being deposited. Settlement in the old snow during a storm indicates to what degree it is stabilizing and compacting under the weight of the new snow. This settlement is also significant in hazard forecasting. The actual numerical values of settlement which are significant for avalanche formation are widely variable and it is difficult to give precise figures. In general, new snow settlement in excess of 15 to 20 percent indicates a trend toward stabilization.

There is one situation in which settlement is not a stabilizing factor. An underlying snow layer may settle away from a stiffer layer above, even to the point of leaving an air gap when the latter is strong enough to be self-supporting.

9. *Wind.* Wind is the primary agent in formation of slab avalanches. The presence of wind during a storm, or at any time when strong enough to cause snow transport, is a warning sign of avalanche danger. Below a certain critical velocity, apparently no extensive slabs are formed. Study of many storms, snow, and avalanche records suggests that the average figure for this critical value is in the neighborhood of 15 miles per hour, although the figure may vary considerably.

Some light wind can occur without development of hazard. Prolonged periods of high wind cause dangerous conditions. When average wind velocities are 25 or 30 miles per hour or more for any length of time, some sort of slab formation is almost certain. The magnitude and extent of slab formation, however, is highly variable and some of the factors affecting it are not clearly understood. At one time wind action may develop only highly localized slab avalanches in certain lee exposures; while at other times, especially during heavy snowfalls, slabs may form everywhere regardless of wind direction. The only safe rule is to beware of avalanche danger whenever high winds blow.

There also appears to be an upper critical wind level, not clearly defined, above which snow tends to form windpack rather than slab. This phenomenon has been observed but not in sufficient detail to be of use in hazard forecasting. Scanty data suggest that winds above 60–70 m.p.h. may fall in this category.

10. *Temperature.* Temperature has more ramifications in avalanche formation than any other single factor. Both air temperature and the temperatures within the snow cover must be considered in estimating hazard development. The deposition of snow, the changes it undergoes on the ground, and consequently the formation and persistence of avalanche conditions, are all highly dependent on temperature. As a broad rule, avalanche hazard varies inversely with temperature during the winter when snow and air temperatures are generally below freezing. Under warm conditions, near the freezing point, the period of instability in snow is quickly reached and passed. Either slides follow directly from storms or wind action, or else the snow quickly stabilizes and offers little further source of hazard. Avalanche danger thus can be high when temperature is near the freezing point, but the period of instability is usually short. As temperatures decrease snow tends to persist in an unstable state for longer periods of time, and at very low temperatures (below 0° F.) avalanche conditions may last for many days or even weeks. Low temperature coupled with high wind is particularly favorable for formation of the unpredictable hard slabs. Such slabs may remain dangerous for long periods if the temperatures remain low. Slab formation may also be slower to develop in very cold weather, and the danger may not develop for several days or weeks after the snow layers involved are deposited. Low temperatures may also create snow instability by forming depth hoar.

Snow and air temperatures are also important keys to wet snowslides in the spring. During most of the winter, snow temperatures remain below freezing; but with the coming of warm winds and strong solar radiation in the spring, melt water forms at the snow surface, percolates downward, and rapidly warms the snow to the melting point. Excess free water provides a lubricating action causing wet slides, but this cannot occur until after the snow has been warmed. Snow temperature is thus an important clue to wet slide occurrence. Wet slides will not fall while the snow is still cold. It is often observed in early spring that the snow remains stable on clear, sunny days, but that wet slides of considerable size fall as soon as a hazy or cloudy day occurs, particularly if accompanied by a warm wind. In clear weather the heat supply from solar radiation is counteracted to some extent by long wave radiation loss from the surface, especially at high altitude; the snow thus gains little heat during the day and freezes hard at night. Warm winds can melt the snow both day and night, and clouds reduce the radiation loss; under these conditions much greater melting can take place and provide large amounts of melt water to trigger wet slides.

The trend of temperature during a snowstorm affects avalanche formation. Snowstorms which start with damp, sticky snow near the freezing point, then gradually become colder and end with lighter snow, generally leave a stable deposit of new snow. The warm, damp snow at the start often bonds well to the underlying layer, and the lighter, drier snow coming later does not add a heavy burden. Storms starting with low temperatures and light, dry snow, followed by rising temperatures and wetter snow, are more likely to lead to avalanching. The dry snow at the start forms a poor bond with the older snow surface and often has insufficient mechanical strength to support the heavier snow deposited later in the storm.

5.11 Factor Analysis. It must be remembered that these contributory factors are not isolated elements of avalanche formation. Many of them are interrelated, and, though they may be treated one at a time in the analysis, it is their effects as a whole that produce avalanche action. In the method of factor analysis described below, the forecaster can exercise a certain amount of judgment concerning these interrelationships and express them in his hazard estimate. Even so, the result of analyzing the contributory factors is no more than an approximation of a complex natural phenomenon that is far from being completely understood.

In order to sum up the results of the contributory factor analysis for a given storm, one possible method is to assign to each factor a plus, minus, or zero value, indicating that the factor is favorable, unfavorable, or neutral to avalanche formation. A preponderance of pluses among the factors will then indicate possible hazard development. If most of the factors are found to be minus, the snow is likely to be stable. Another method, which gives the observer wider latitude in expressing his judgment and experience, is to assign to each factor a number between 0 and 10, with 0 indicating minimum contribution to avalanche formation and 10 indicating a strong disposition toward avalanching. By this method more exact degrees of influence are expressed for each factor than by the simple plus and minus method. The numbers so chosen are then summed to give a single number, between 0 and 100, to express the degree of hazard development expected in a given situation.

The higher the "hazard factor," the stronger the indication is that avalanches may be expected. A hazard factor falling in the midrange—40 to 60—would indicate a borderline situation, or limited slide activity; while a high number—75 or more—would be a definite warning of impending hazard.

The analysis of contributory factors is a useful aid in estimating avalanche danger; but it does not give the whole answer nor a positive one. There is no substitute for actual testing of snow conditions in the field; and decisions involving public safety should, whenever possible, be based on such tests as well as on general hazard forecasting procedures.

5.2 Delayed Action and Climax Avalanches. These are the avalanches which fall as the result of cumulative factors working over longer time intervals than those associated with single storms. The most common type of climax avalanche probably is that which occurs because successive snow accumulations finally overcome the support of some weak layer within the snow cover (fig. 31). Successful assessment of approaching danger from such slides depends on the recognition of unstable configurations of snow stratigraphy and the processes which weaken the snow, especially constructive metamorphism.

Dangerous stratigraphic weaknesses cannot be recognized by casual inspection. Excavation of a pit is one means of gaining insight into the snow structure, but to be most useful, such a pit should be dug near the release zones on the avalanche paths. The ram penetrometer discussed in chapter 6, item 6.3, can be used to obtain part of the necessary structural information without digging a pit, but evidence gathered by this method is far from conclusive. The day-to-day record of snow, weather, and avalanche conditions throughout the winter in a given area is another means of determining whether an unstable condition may be forming. The most satisfactory information comes from a combination of all three methods, estimates from the daily observations being checked by periodic pit excavations and by ram profiles on the actual avalanche paths. This ideal is achieved only in certain areas where trained observers are on the ground all winter to observe and record snow and weather developments. Elsewhere, climax avalanche danger can only be crudely estimated, especially if the history of snow and weather conditions is missing.

A knowledge of early winter weather conditions is essential to anticipate many climax slides. The character of the lowest layers of the snow cover and their subsequent evolution largely determine the stability of the snow cover as a whole. The most frequent cause of instability is a layer of

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FIGURE 31.—Major climax avalanche (HS–N–5) which crossed a small canyon, covered a highway, and ascended 300 feet up the opposite slope. Channeling in the deposition cone indicates damp snow was involved in this slide. Scale is given by the tractor in the foreground, working directly over the highway. Coalpit Slide in Little Cottonwood Canyon, Utah.

depth hoar formed by periods of clear weather early in the winter when the snow is shallow and easily subjected to steep temperature gradients. This condition is most common on northerly exposures which receive little sunlight. The mechanically weak layer of depth hoar near the ground is unable to support a very large overburden, so that the first heavy snowfall is likely to trigger widespread avalanching. If the depth hoar is only partially formed (incomplete constructive metamorphism), the layer may not fail mechanically until several storms have deposited their loads. Once an avalanche occurs in such a condition, exposure of the remaining depth hoar next to the ground sometimes results in a hard crust formation which provides an excellent sliding surface for subsequent avalanches.

Formation of a smooth crust or ice layer next to the ground early in the winter by rain or thaw is another frequent source of climax avalanches. This layer provides a good sliding surface, but unlike depth hoar, has high strength. The critical factor then becomes the character of the bond between the ice layer and subsequent snowfall. Such a bond, though weak, is generally stronger than the support offered by depth hoar alone, and accumulation of much snow may be required before critical instability is reached. An ice crust exposed by avalanching may also serve as a sliding layer once again as more snow accumulates. Like depth hoar, it can be the cause of repeated avalanche action, either direct or climax in character. By late winter or early spring rising temperatures eventually cause a bond to form between new snow and such layers, so that the hazard from this source diminishes as the season progresses.

The existence of marked inhomogeneities, especially those caused by weak layers or crusts, is apt to introduce the possibility of climax avalanches at almost any stage of snow cover evolution. Those of early winter have been emphasized because they are most frequently associated with the large and destructive avalanches.

A reduction of tensile or shear strength within certain snow layers can lead to eventual avalanching of layers which may at one time have been entirely stable. The most common form of this weakening is that resulting from melt water intrusion, details of which are discussed under item 5.4. At this point we are concerned with the more subtle influences of constructive metamorphism and crust disintegration.

The internal diffusion of water vapor and recrystallization which characterizes constructive metamorphism leads to reduction in strength properties of snow, whether or not the process is carried through to the end product of fully developed depth hoar. A reduction in tensile or shear strength so effected can create dangerous instability in a snow slab; hence this weakening process must always be watched as a possible source of hazard. As pointed out in chapter 2, a steep temperature gradient is the prime cause of constructive metamorphism, so the temperature influences on the snow cover must be accurately estimated if hazard development is to be foreseen. Long periods of cold weather without precipitation should be a warning sign, as should periods of clear weather which permit strong radiation cooling on shaded slopes. If the snow cover is deep, strong surface cooling will usually affect only the surface layers. These might either become dangerous in themselves, or else serve as a weak layer, inadequate to support a subsequent snowfall. When the snow cover is shallow, steep temperature gradients throughout the snow cover are possible. Even when winter is well advanced, the latter conditions may be found on avalanche paths which have lost part of their snow cover by sliding. The surrounding undisturbed snow may be deep enough to forestall development of strong gradients, but this will not be the case on the partially denuded avalanche path (chapter 2, item 2.6, example 2).

Icy crusts tend to disintegrate under these same influences. The individual crystals lose their strong cohesion to one another and become loose grains which may provide a lubricating layer for a slab resting on them.

A series of light snowfalls, especially at low temperatures, will form a much more unstable stratigraphy than will heavy snowfalls. In the former case, the bond between snowfalls is often poor, and the individual layers never develop very high mechanical strength unless subjected to reworking by wind drift. Very deep falls of dry, loose powder snow usually attain high mechanical strength once they have undergone settlement and incorporation within the snow cover.

5.3 The Ram Profile. Snow and weather observations, snowpit techniques, and operation of the ram penetrometer—all necessary for the estimation of climax avalanche hazard—are described in detail in chapter 6. The following paragraphs illustrate some of the principles used in interpreting ram profiles in terms of potential avalanche danger. These interpretations are based on work conducted at Berthoud Pass.

At Berthoud Pass the studies have been focused on identifying the characteristics which indicate a snow slab that will fracture and become an avalanche. The principal test area is "The Roll," a slope prone to the formation of slab in snow transported from the surface by wind.

During one observed 36-hour period, wind averaging 27 m.p.h. deposited 6 feet of snow on "The Roll." This high rate of deposition indicates that a delayed action slab avalanche condition can develop in a very short time in areas similar to the test area. In fact, the development is so rapid that stabilization by skiing could not be effective unless done day and night. Incidentally, the test area is an area of concentrated public use.

The following profiles and interpretations illustrate the methods used to reach certain preliminary conclusions regarding the stability of slab as revealed by the penetrometer. The profiles were all taken directly in the slide path either just before or just after the occurrence of an avalanche. In two cases the avalanches were triggered by explosives. In one case blasting produced extensive fracturing with stabilization in place. In two cases avalanches were produced by protective skiing.

1. *Interpretation: Chart No. 3 (fig. 32).* Profile was taken in the Berthoud Pass test area. The sections of particular interest are marked *A*, *B*, *C*, and *D*. *A* was slab deposited during a storm when there was wind action on snowfall and on snow transported from the surface. *B* was a weak layer of older snow. *C* was an old comparatively thin slab of high resistance. *D* was a very weak layer of cup crystals.

Under explosives, the low-resistance slab layer *A* fractured. The break penetrated weak layer *B*. Significantly, high-resistance layer *C* withstood the shock of the explosion and supported the vibration and weight of the avalanche until it had attained full momentum. Layer *C* eventually collapsed and the fracture penetrated weak layer *D* to the ground.

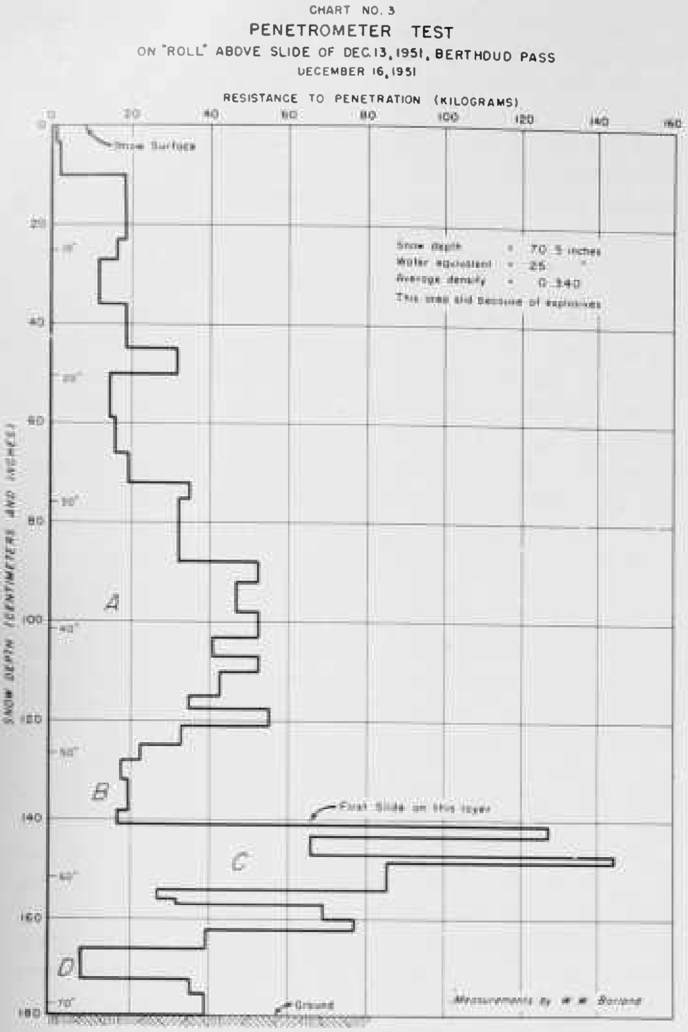


FIGURE 32.—Chart No. 3, penetrometer test.

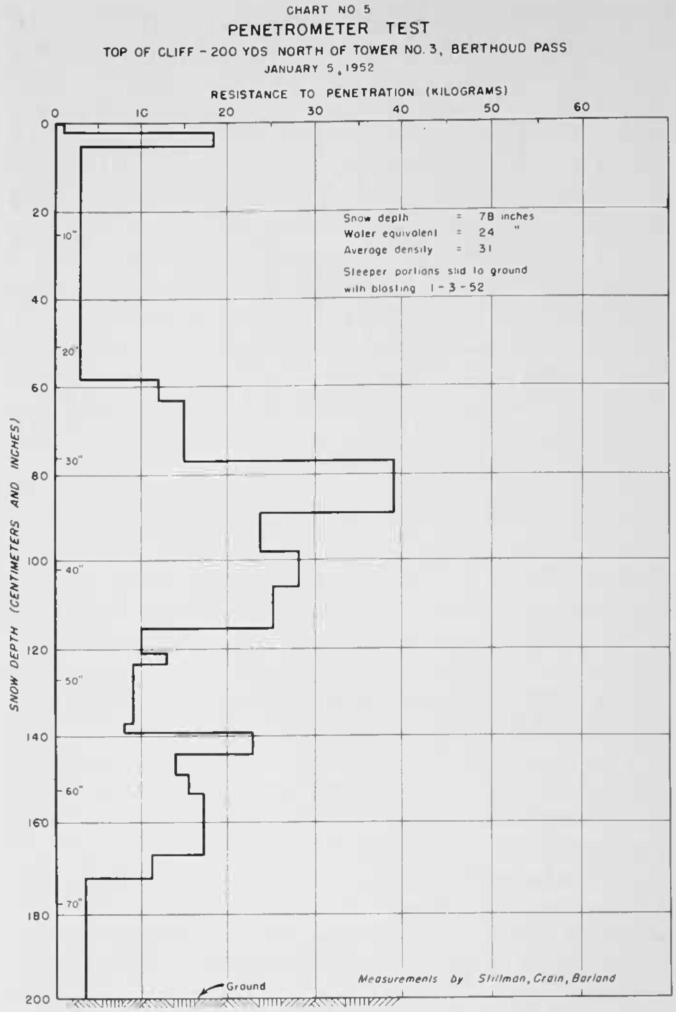


FIGURE 33.—Chart No. 5, penetrometer test.

This profile illustrates several important points. The snowpack contained two slab layers, each lying above a zone of minimum support. The upper slab layer had low resistance, the other high resistance. The low-resistance layer was 33 cm. thick, the high-resistance layer only 13 cm. thick. Layer *C* was subjected to a blast and a moving load which amounted to 108 pounds per square foot, deadweight. Nevertheless it was able to maintain its position on a 40-degree slope until the avalanche from layer *A* attained full speed.

2. *Interpretation: Chart No. 5 (fig. 33).* This profile was taken in an area similar to the test area, and located near it. To the observer it indicated a situation comparable to that on Chart No. 3—a slab layer of low resistance over a zone of little support. Under explosives, the area avalanched to the ground.

3. *Interpretation: Charts Nos. 7 and 8 (figs. 34 and 35).* These profiles illustrate similar conditions in two areas of similar aspect but a number of miles apart. Again we have two slab layers, each lying over a zone of weakness.

In both cases an avalanche was triggered by protective skiing. Chart No. 7 shows that the fracture penetrated both slab layers but only the upper layer avalanched. The observer concludes that the lower layer stabilized in place due to its strong anchorage at the toe of the slope. It was buttressed by the debris from several earlier slides.

Chart No. 8 indicates that only the upper layer avalanched at first. Eventually the lower, high-resistance layer did break and carry with it the remainder of the snowpack.

5.4 Wet Snow Avalanches. Of the various types of slides, those originating with wet snow sometimes may be predicted with the greatest precision as to time and place, because their formation depends on measurable formation of melt water and its penetration into the snow cover. The absence of wet slide hazard can be rather firmly established by the observation of snow temperatures below the freezing point. The presence of liquid water in snow means that its temperature has been raised to 32°F. Cold (subfreezing) snow will not contain water in the liquid phase and does not participate in the origin of wet slides. Snow temperature readings provide a useful guide to wet snow avalanche hazard, but the measurements should be made at the fracture zone to be effective. The positive heat balance of the snow cover which

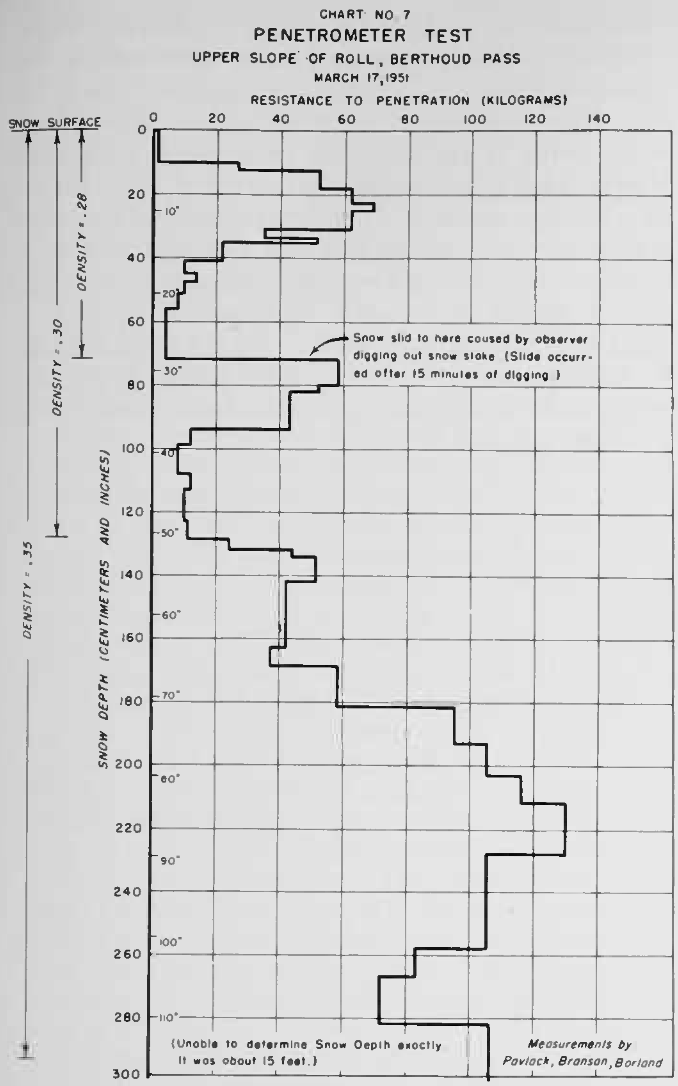


Figure 34.—Chart No. 7, penetrometer test.

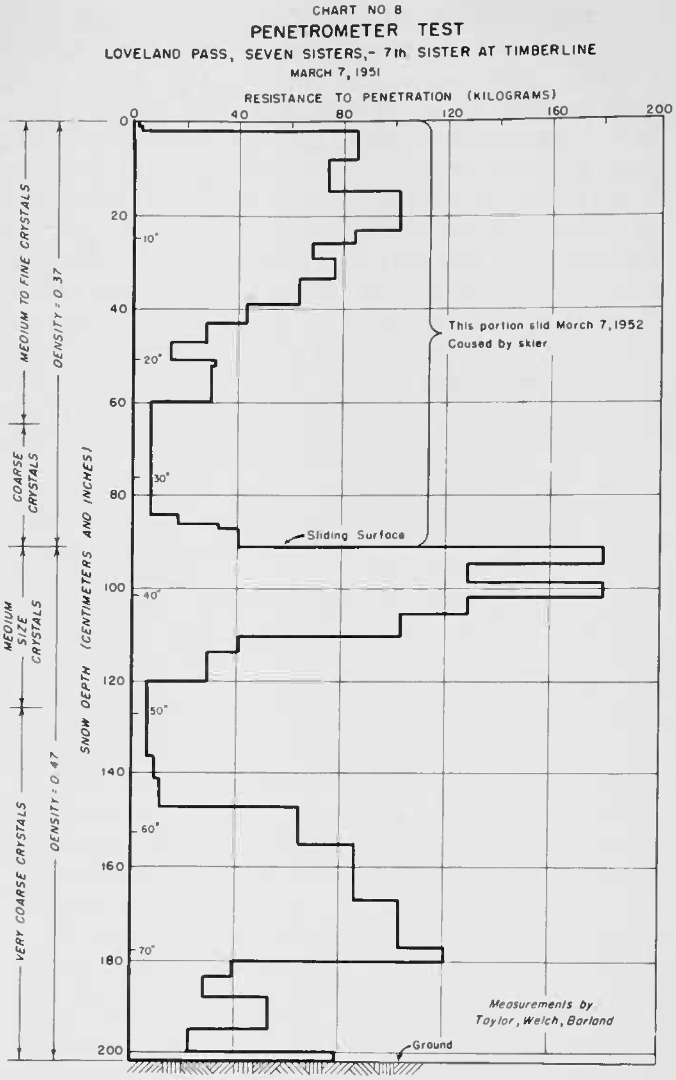


Figure 35.—Chart No. 8, penetrometer test.

leads to melting may differ greatly between valley floor and ridge top, between north exposure and south. Moreover, penetration of percolating melt water can alter snow temperatures very rapidly. A slope which appears safe because of cold snow one hour may be ready to avalanche the next.

Wet snow avalanches are directly associated with a source of liquid water at the snow surface which can warm up the snow and then lubricate it to reduce internal cohesion, or the adhesion between layers. An obvious source of liquid water is rain. Rainstorms in winter or spring should always be regarded with suspicion until the snow has either slid or proved itself stable. Warm rains in midwinter immediately following a heavy fall of dry powder snow are a common cause of major avalanche cycles in the Coastal Alpine Zone of the Cascades and Sierras. Heavy melt at the surface is the other common source of liquid water which may precipitate slide action. A review of the discussion on thermal properties of the snow cover in chapter 2 is recommended at this point. The major sources of heat which might cause melt should be noted. In particular, observe that the heat balance at the snow surface may be more strongly positive on a hazy day than on a clear day, and that warm winds are an especially effective source of heat. These two conditions sometimes combine to form very marked thaw weather which may precipitate slide action. Remember that wet snow action on south exposures is often absent during clear, cold weather, even though sunlight is intense, but a slide cycle can follow when the weather turns warm, windy, and cloudy.

South exposures receive the full benefit of direct sunlight and are the ones most commonly associated with wet slide activity. North slopes are not immune, because a warm wind or rainstorm will affect all slopes alike without regard to orientation. Solar radiation has one additional property which makes it especially effective in warming and melting snow. The sun's rays can penetrate the snow surface to a depth of 4 to 8 inches and cause subsurface melting, even at times when the snow surface may be maintained at subfreezing temperatures by cold air.

Dangerous wet slide activity occurs most commonly when a sudden thaw or rainstorm affects a cold, unsettled snow cover. The very rapid metamorphic changes and melt water penetration in dry loose snow create serious instability. The same amount of rain or thaw that would generate large slides in soft, new snow would be less likely to cause trouble in settled, old snow which had already been warmed to the melting point by previous thaws. The first heavy thaw of late winter or early spring is likely to be the most dangerous one. The same conditions might be repeated later in the season after a fresh fall of new snow. Wet surface slides are likely to occur when a late spring snowstorm is followed by a bright, sunny day, even if new snow falls on settled, stable old snow.

Some of the largest and most destructive wet avalanches are the ground avalanches which result from prolonged thaw or rain. The entire snow cover is thawed and permeated with melt water, which lubricates the ground that serves as a sliding surface. The total depth of the winter snow cover is then released as a wet slab avalanche. Such slides are most common on smooth, grassy slopes or smooth rock which provide a good sliding surface when properly lubricated. In some situations a heavy ice layer located deep in the snow cover may serve the same function as a smooth ground surface.

Chapter 6

6 STANDARD SNOW OBSERVATIONS AND TERMINOLOGY. The importance of standardized, systematic observations of snow and weather phenomena cannot be too strongly emphasized. Estimates and forecasts of snow and avalanche conditions are based on the total experience of the observer and of others who have preceded him. To permit comparison of present conditions with this accumulation of knowledge and past experience and drawing valid conclusions, observations and records must all be expressed in the same terms and the same units of measurement, and to the extent feasible, measured and recorded in the same manner. One observer's experience and knowledge must be recorded in a manner that permits the next man to compare the results with his own observations if the information is to be useful to future workers in the field.

Systematic terminology and methods of observing and recording snow data have gradually been evolved by Forest Service snow rangers working every day in the field. The records they are accumulating are gradually being brought to a single standard. It is the purpose of this chapter to instruct Forest Service officers in these uniform methods of observation.

6.1 Snow Studies Chart (fig. 36). The fundamental record is that of the daily observations of weather, snow, and avalanche conditions entered in the Snow Studies Chart (fig. 36). The methods and terms for each item on this chart are discussed below.

1. *Temperature.* Accurate measurement of free air temperature, which requires that the thermometer be unaffected by radiation or local air variations, is extremely difficult. The best approximation is achieved with standard thermometers mounted in a properly designed and installed meteorological shelter. A proper shelter is the most important item of the temperature equipment; much more accurate and consistent records can be obtained with a dime store thermometer correctly mounted than with the finest instrument casually hung on the wall of a building. Whenever possible, a standard Weather Bureau meteorological shelter should be used, located, and mounted according to Weather Bureau instructions. Standard maximum and minimum thermometers, used according to instructions, are preferred. Where a station cannot be attended regularly every day, a thermograph mounted in a meteorological shelter may be used. This instrument does not give the accuracy of thermometers.

Maximum and minimum temperature readings are taken once daily and at the same time every day. The recommended time is in the late afternoon, but early morning readings are acceptable. The maximum and minimum temperatures are entered in degrees Fahrenheit each day on the Snow Studies Chart.

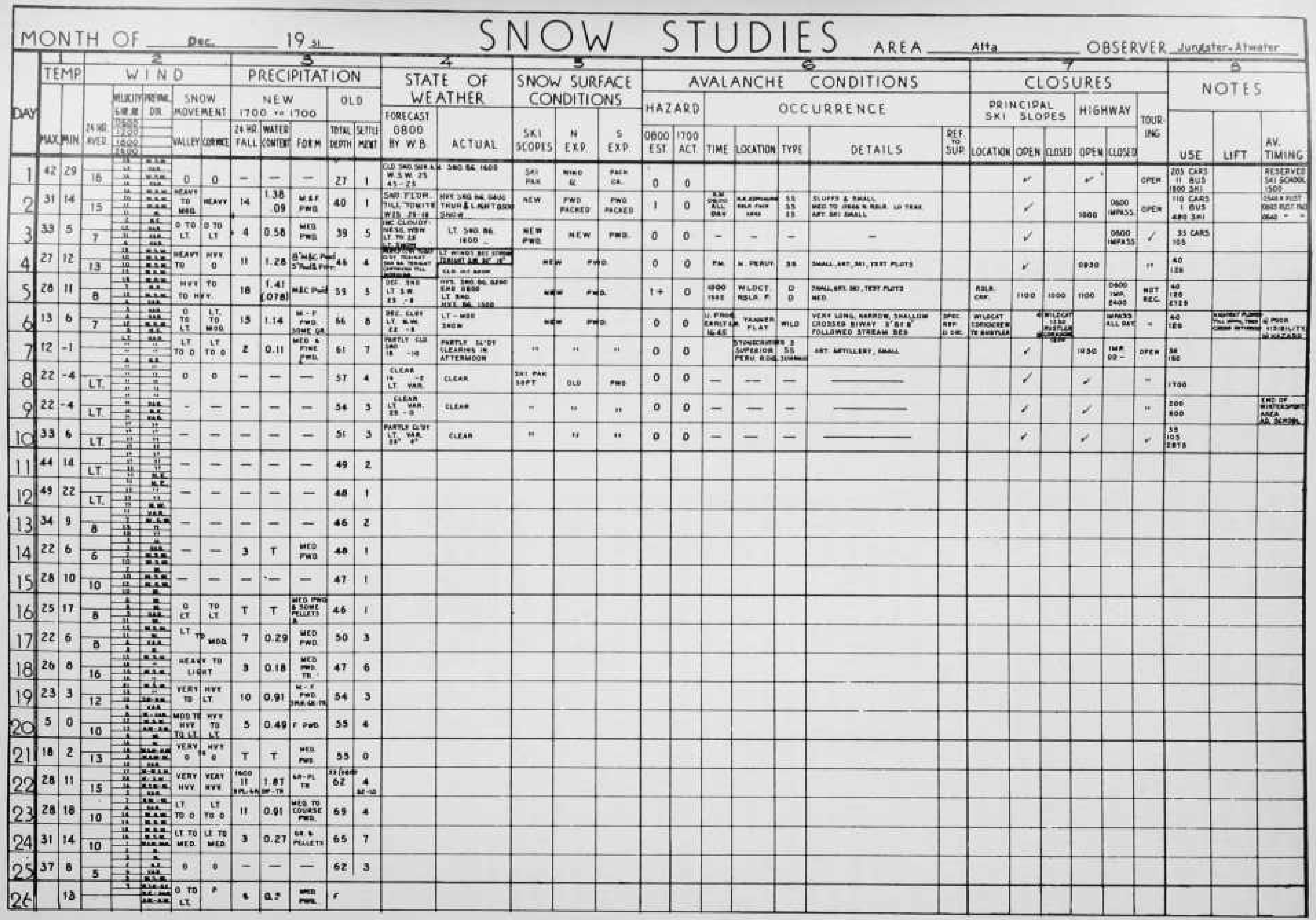
2. *Wind.* The preferred information is the number of miles of wind past the station each 24 hours, to be entered in the 24-hour total column. Either a dial anemometer which displays miles of wind directly, or a continually operated wind recorder is required to obtain this information. The dial is the easiest to operate but requires that the observer climb up the anemometer mast to get the reading. A remote recorder can be read inside of a building but is more complicated and requires continuous power.

When an indicating or recording anemometer is not available, the observer must enter his estimates for the different periods of the day under the 6-hour average velocity column, and indicate the direction. Velocities are given in miles per hour and estimates may encompass a range of velocities, such as "3–5 mph." or "10–15 mph."

Whenever terrain, building location, and other considerations permit, the wind record should be obtained from an anemometer mounted on a high, exposed ridge or peak. The wind behavior at higher elevations is of primary concern in avalanche hazard forecasting.

Snow movement refers to the amount of snow observed drifting each day. Drifting snow can develop avalanche conditions on lee slopes just as a storm can. An estimate of wind-transported snow is an essential part of hazard forecasting. Where the drifting is not directly observed, evidence such as fresh deposits in lee areas can serve as the basis for estimating what may have happened behind clouds or during hours of darkness. Widely different conditions between ridges and the valley floor may be noticed. A separate record should be kept for each area.

3. *Precipitation.* Regular, accurate, daily measurements of snow depths are the backbone of these records. In addition, more frequent measurements of new snowfall—as often as once every hour in some cases—are an important part of storm records and hazard forecasting.



MONTH OF Dec. 19 51 — SNOW STUDIES — AREA Alta — OBSERVER Jungster-Atwater

DAY	TEMP MAX	TEMP MIN	WIND 24 HR. AVER.	NEW 24 HR. FALL	NEW WATER CONTENT	OLD TOTAL DEPTH	OLD SETTLEMENT	HAZARD 0800 EST.	HAZARD 1700 ACT.
1	42	29	16	—	—	27	1	0	0
2	31	14	15	14	1.38 .09	40	1	1	0
3	33	5	7	4	0.58	39	5	0	0
4	27	12	13	11	1.28	46	4	0	0
5	28	11	8	18	1.41 (.078)	55	5	1+	0
6	13	6	7	15	1.14	66	8	0	0
7	12	-1		2	0.11	61	7	0	0
8	22	-4	LT.	—	—	57	4	0	0
9	22	-4	LT.	—	—	54	3	0	0
10	33	6	LT.	—	—	51	3	0	0
11	44	14	LT.	—	—	49	2		
12	49	22	LT.	—	—	48	1		
13	34	9	8	—	—	46	2		
14	22	6	6	3	T	48	1		
15	28	10	10	—	—	47	1		
16	25	17	8	T	T	46	1		
17	22	6	8	7	0.29	50	3		
18	26	8	16	3	0.18	47	6		
19	23	3	12	10	0.91	54	3		
20	5	0	10	5	0.49	55	4		
21	18	2	13	T	T	55	0		
22	28	11	15	[illegible]	1.87	62	4		
23	28	18	10	11	0.81	65	4		
24	31	14	10	3	0.27	65	7		
25	37	8	5	—	—	62	3		
26		13		6	[illegible]	[illegible]			

FIGURE 36.—Snow studies chart.

A minimum of four snow stakes are customarily used for standard observations. One is a fixed stake used to measure total snow depth on the ground. It is usually a length of clear 2 x 2 inch lumber, painted white, with zero at the ground level and each inch of height clearly marked with dark paint. This stake is bolted to an angle iron driven deep enough into the ground to provide permanent support, and is long enough to record total snow depth in the area. This stake should be labeled with total inches from bottom to top, rather than in feet and divisions thereof. The others are short, portable stakes made of a yardstick firmly bolted in an upright position to the center of a 2 x 2 foot platform of 1/4-inch plywood. The plywood bases must be painted white, both to protect the wood and to reduce radiation melting of the snow.

The snow observation site where the stakes are to be located must be as free as possible from wind drifting and snow creep. The best location is in a level opening in heavy timber. Where such a site cannot be found, a compromise must be made, but the stakes should be kept as far as possible from buildings and other large objects which influence the deposition pattern of snow. The site should not be located so far away from the observer's dwelling that daily observations are apt to be neglected because of inconvenience.

Snow observations should always be made in the early morning. Erroneous values may be obtained if snow depths are read in the late afternoon or evening, because the new snow depth will be reduced by settlement, or possibly melted away if the sun has come out during the day following a snowfall the previous night.

The first of the three short stakes is known as the storm stake. This is set out on the surface of the old snow and is left undisturbed for the duration of any one storm period. When the storm is over it is dug up and reset on the surface to be ready for the next storm. (The total depth of snow deposited on the ground from a single storm lasting more than 24 hours cannot be measured without the storm stake. Summing the readings of the 24-hour stake gives a different value because of settlement.) The second yardstick is used as the 24-hour stake. At each morning's observation the depth of new snow which has fallen in the past 24 hours is read from this stake; it is then cleared of snow and reset on the surface. The third stake serves as the interval stake. It is used to obtain snowfall measurements over intervals shorter than 24 hours or during a storm, being reset on the surface after each observation. The use of observations with the interval stake is discussed in more detail under item 6.2.

Water content of the new snow which has fallen during the past 24 hours is measured at each morning's observation. The overflow can of the standard 8-inch Weather Bureau rain gage is used to collect a snow sample from the 24-hour stake platform. The can is held upside down and vertically over the platform adjacent to the yardstick and pushed down through the snow until it rests against the platform. Both can and platform, carefully held together, are turned over. The platform may then be removed and the core of snow collected allowed to slide down into the 8-inch can. The can is carried inside a building and the snow melted. This may be done by pouring onto the snow a measured quantity of hot water, which is later subtracted from the measured precipitation; or the can may be set over a low source of heat until the snow is melted. Holding the can in a sink so hot water runs over the outside is a quick way to melt the snow. The water obtained in the can is then poured into the narrow collecting tube of the rain gage and the amount of water measured with the regular 10:1 rain gage dipstick.

Exactly the same procedure is used to collect and measure water content samples from the interval stake for use in computing precipitation intensity (see under item 6.2). Instead of collecting the 24-hour core from the 24-hour stake platform, a separate plywood sheet may be put out on the snow surface and reset each day like the 24-hour stake. Both new snow depth and new snow water content are entered each day in the appropriate columns on the snow studies chart.

The specific gravity of the new snow measured is obtained by dividing the water content, in inches, by the snow depth, also expressed in inches. This figure is also known as the water ratio, which may be expressed as a decimal figure the same as specific gravity, or as percent of water (multiply specific gravity by 100). For instance, a 15-inch fall of new snow which contained 1.20 inches of water would have a specific gravity of $1.20/15=0.08$, which is the same as a density of 0.08 gm./cc. or a water content of 8 percent. Though it is actually specific gravity that is determined when snow depth and water equivalent are measured, this figure is usually referred to as the density for the sake of convenience. The correct symbol for density is the Greek letter Rho, ρ.

The form, or type of snow, in a fresh snowfall is entered each day on the snow studies chart. A general description such as "powder," "pellet," or "granular" is given. In addition, the exact type or types of snow crystals should be recorded according to the system of the International Snow Classification, Types of Solid Precipitation (fig. 7, ch. 2). The number or numbers corresponding to the type of crystals observed are noted immediately following the written general description. Special care should be taken to note whether or not the individual crystals show a coat of rime. The presence of any rime should be noted on the chart. Most crystals can easily be identified with the naked eye, but occasionally a low-power magnifying glass may be required.

The following explanations of crystal types associated with the broad snow classifications will aid the observer.

Powder snow. Fluffy, feltlike new snow consisting mostly of stars and spatial dendrites, with occasional admixture of some plates or needles.

Granular snow. A collection of small crystals made up of stars or plates which are partly coated with rime. It may also consist of irregular crystalline aggregates. Snow that is almost all needle crystals will likewise appear granular.

Pellet snow. Also known as graupel, or soft hail, is made up of crystals (most often stars) which have become completely and heavily coated with rime so that they form individual round balls.

Snow flakes. Aggregates of individual crystals which stick together at warmer temperatures. Examine carefully to see what kinds of crystals are actually present.

Windblown snow. Either during or after a snowfall, may often consist of fragments of such crystalline forms as stars or spatial dendrites. The original crystal type is difficult to identify.

The settlement column under "Precipitation" on the chart refers to old snow settlement. Old snow in this context means snow which as been on the ground for more than 24 hours. This settlement is computed for each day according to the following expression:

$$\left[\left(\begin{array}{c}\text{Total snow}\\\text{depth of pre-}\\\text{vious day}\end{array}\right)+\left(\begin{array}{c}\text{new snow in}\\\text{past 24 hours}\end{array}\right)\right]-\left[\begin{array}{c}\text{total depth}\\\text{at time of}\\\text{observation}\end{array}\right]$$

4. *State of Weather.* Report the daily weather conditions concisely and accurately. The term "clear" should be reserved for days with cloudless skies; a sunny day with high scattered clouds should be reported as such. To give more accurate information, report cloud cover as scattered, broken, or overcast. Scattered clouds cover less than half of the sky, broken clouds cover more than half but not all, while overcast means that no blue sky is visible. When changes in weather occur during the course of a day, note them. Record times and duration of precipitation on the storm records (see item 6.2). When Weather Bureau forecasts are available, they should be entered in the column provided.

5. *Snow Surface.* This record is important both for evaluating avalanche conditions and for collecting data on skiing conditions. Follow the terminology of this handbook and be careful to distinguish between the different conditions on north and south exposures. This record should be the source of accurate information to the public on the actual state of skiing conditions (fig. 37).

6. *Avalanche Conditions.* The degrees of hazard should be entered in the appropriate column. The "1700 actual" column is the record of avalanche conditions that actually occurred, to be entered at the end of the day. The "0800 estimated" column is for entering the anticipated hazard in the morning. There may often be a wide difference between the two entries for the same day, resulting from changes in snow and weather conditions or forecasting errors. Every effort should be made to keep the "1700 actual" record as accurate as possible.

The time and location of each avalanche observed in the area are entered in the appropriate column. Where a large avalanche cycle has occurred and there is not enough space on the chart for all the slides, enter a reference to the storm report where the avalanches are described in detail. Descriptions of the avalanches are entered according to the "Avalanche Abbreviations for Snow Study Chart" (fig. 38). When these abbreviations are used, an avalanche is assumed to originate in dry snow unless the letters for damp or wet conditions are included in the description.

Avalanche types and classification are discussed in detail in chapter 3.

It is important to record all snow movement. This includes minor activities such as sunballs on south exposures and small loose snow sluffs. These are indications of changes taking place in the snow and are significant in evaluating future avalanche hazard.

6.2 Storm Plot and Storm Report Records. The methods of observing and recording snow conditions described above apply in many cases to the storm plot and storm report forms (figs. 39 and 40). These more detailed records of snowfall will be kept whenever avalanche hazard is a problem and forecasting activity must be undertaken. Certain refinements of observations are required when reporting on storms. They are discussed as follows:

1. *New Snow Density.* Snow density determinations have already been described in connection with the daily snow observations. Density values determined from the 24-hour records, however, are an average for the total amount of snow that has fallen in that period. In the course of 24 hours snow type and density can change widely. Even if they do not, settlement will make the average value for the total quantity of snow different from that of the snow most recently deposited on the surface. For this reason, accurate new-snow densities must be measured at the surface almost as soon as the snow falls. One way to get an undisturbed sample is to put a shallow container such as a 1-pound coffee can on the snow surface and allow it to fill full of snow. The snow is then carefully scraped smooth over the top of the can and weighed. If the weight and volume of the can have been previously determined, the snow density can be obtained by dividing the volume of the snow so collected into its weight. For example, a can with a volume of 1,000 cc. and a weight of 100 gm. which, when filled with snow, weighed 170 gm., would show that the snow density was:

$$\frac{170-100}{1{,}000}=0.07 \text{ gm./cc.}$$

Snow Conditions Reports

Where reports of snow conditions are made to the public, particularly for winter recreational purposes, only major classifications would be used.

The following items are of interest to the general public:

1. Total depth of snow.
2. Depth of snow fallen in previous 24 hours.
3. Type of new snow: Dry, damp, or wet.
4. Condition of the surface; new snow, old snow, ski-packed, crushed, etc.
5. Condition of the undersurface as it affects skiing conditions.
6. Weather conditions and forecast.
7. Avalanche hazards (if any). Closures.
8. Condition of highways.
9. Classification of skiing conditions, which may vary on different parts of the area.

Skiing conditions are classified as follows:

I. Excellent

1. New powder
2. Old powder
3. Skipack dry or damp
4. Corn snow

II. Good

1. Damp new snow
2. Damp old snow
3. Skipack wet
4. Unbreakable crusts
5. Windpack dry or damp

III. Fair

1. Variable crusts
2. Icy crust unbreakable
3. Windpack wet
4. Wet new snow
5. Wet old snow

IV. Poor

1. Breakable crusts
2. Slush

FIGURE 37.—Snow conditions reports.

Avalanche Abbreviations for Snow Study Chart

HS ---	hard slab	N ---	natural
SS ---	soft slab	A ---	artificial
WS ---	wet slab	AA ---	artificial, artillery
L ---	loose snow	AE ---	artificial, explosives
WL ---	wet loose snow	AS ---	artificial, ski
D ---	damp (prefixed to HS, SS, or L)	O ---	surface avalanche
B ---	sunballs	G ---	ground avalanche
		J ---	windblast

1 ---	sluffs	T↑ ---	temperature rising
2 ---	small	T↓ ---	temperature falling
3 ---	medium		
4 ---	large		
5 ---	major		

Example: A large, dry, soft slab avalanche released by artillery fire would be entered on the Snow Study Chart as SS-AE-4.

FIGURE 38.—Avalanche abbreviations for snow study chart.

If available, a standard 500-cc. snow sample tube may be used to collect a core of snow from near the surface and the density determined by weighing as above. The tube should be chilled and very carefully inserted into the snow to get an accurate sample of light, fluffy new snow.

2. *Gross and Net Snowfall and New Snow Settlement.* The amount of snow measured on the storm stake is the net snowfall for the storm. This is less than the amount of snow which actually fell because the new snow is continuously settling. The amount which actually fell, without settlement, is called the gross snowfall, a quantity determined with the aid of the interval stake. When only 2 or 3 inches of snow are allowed to build up on the interval stake each time before it is reset, there is little chance for any settlement to take place. If the interval stake is reset frequently during a snowfall, a number of small increments of accumulation will be obtained. The gross snowfall is the sum of these increments. The more frequently the interval stake is reset, the more nearly will the sum of the increments approach the true value of the amount of snow which actually fell, free of settlement.

The settlement in the new snow during the time of its deposition is the difference between the gross and net snowfall. This difference divided by the gross snowfall and multiplied by 100 gives the percent settlement of the new snow during deposition. Once snowfall has ended, further settlement of the new snow can be observed directly by watching the drop of the surface level on the storm stake. (An example of these computations is given in figure 40, sheet 1.)

3. *Snowfall Intensity.* Snowfall intensity (S.I.) is the rate at which snow is deposited, expressed in inches per hour. Divide the amount of snow which has fallen in a given interval of time by the length of that interval. To be correct, this

Storm Plot No. 1 Date 12/25/59 Area Alta

Time	Snow Depth					New Snow			Old Snow	P. I.		S. I.			Wind			
	Total	Storm	24 Hr	#1	#2	Type	Density	Sett	Snow Sett	T.B.	Gage	Core	Stake	Instr.	Speed	Direc.	Temp.	Notes
25 December																		
0800	17	6	6/0	6/0		Dmp.	0.12					0.10	1.1		15	W	27°	
1215	--	12	5	5/0		Dmp.	0.10	0	--			0.12	1.2		15-20	W	23°	
-- a sharp temperature drop around 1200, wind and storm intensity picking up.																		
1520	28	16	9	4/0				0	0			--	1.3		9	W	--	
26 December																		
0600	37	25	19	19/0		lt. pdr.	0.08	0	0				0.6		lt. & variable		8°	Density from 24-hour core, clouds now breaking, snowfall light.

FIGURE 39.—Storm plot form.

amount of snowfall should be the gross snowfall during the interval. Measurements should be made over short intervals whenever possible so that variations in the snowfall intensity during a storm can be recorded. If this cannot be done, then the average S.I. for each day can be obtained by dividing new snow depth of the 24-hour stake by 24.

4. *Precipitation Intensity.* Precipitation intensity (P.I.) is the rate at which water (which may be in the form of snow) is deposited, and is expressed in inches per hour. Divide the water equivalent of the snow that has fallen in a given time interval by the length of that interval to get precipitation intensity. The customary method of obtaining the water content of the snow that falls over short intervals is by collecting samples from the interval stake platform with the 8-inch rain gage can, as previously described. A recording precipitation gage may also be used. The slope of the precipitation curve on the chart is the P.I. Such a gage should always be equipped with a scoop for obtaining accurate sampling of snowfall; core samples with the rain gage must also be collected to check the catch in the gage.

The average value of P.I. for a 24-hour period can be obtained from the regular morning snow observations, by dividing the total amount of water collected from the 24-hour stake platform by 24. Variations in P.I. during a storm, however, are highly significant for avalanche formation. P.I. values for shorter intervals should be determined whenever possible.

5. *Precipitation Intensity Factor.* The Precipitation Intensity Factor is an index of possible hazard due to direct action soft slab avalanches. The first criterion is that winds must be above the critical level of velocity. When this is so, the P.I. Factor is the amount of solid precipitation, (expressed in inches of water) which fell during any given interval when the precipitation intensity was continuously above 0.1 inch of water per hour. Two inches of precipitation at a rate of 0.05 inch per hour obviously would not fit this definition, and for such a situation the factor would be nonexistent and inapplicable. If 2 inches of precipitation fell continuously at 0.15 inch per hour while winds were high, this factor would exist as an index of hazard, and the "P.I. Factor" would be 2.00.

6. *Snow Settlement.* Settlement of old snow during all or parts of a storm period may be determined just as it is for 24-hour periods.

6.3 Snowpit Studies. Periodic study and recording of subsurface snow conditions to show snow cover evolution through the winter has become standard procedure at Forest Service avalanche stations. This section gives instructions for collecting, plotting, and interpreting snow pit data.

Storm Report Instructions

Storm No.: Number the storms of each season consecutively.

1. Record the hour of beginning and ending of snowfall as closely as possible. Record the duration, or durations, of the intense storm period in hours.
4. The snowfall according to measurements taken at the shortest intervals in use at your station. Record this interval: 2 hrs., 4 hrs., 24 hrs., or whatever.
5. The amount of snowfall at the end of the storm. Should be taken from a platform stake set on the old snow surface and not reset during the storm.
7. Average S.I. for the major storm period. Maximum S.I.: Record periods of S.I. at 1"/hr. or more.
8. Amount of water per inch of snow. Computed from the snowfall of each 24 hr. period.
9. Average P.I.: for the major storm period. Maximum P.I.: Record all periods when P.I. was .10"/hr. or more. The gage record must be reasonably close to the precipitation according to the snow core method. If a recording gage is not in use, P.I. can be computed directly from the snow core, but the snow should be sampled not less often than every 4 hrs.
10. Record any period when P.I. was continuously at or near .10"/hr. with strong wind action. Example: 6 hrs. at .18: P.I. Factor 1.08.
11. Average wind speed for major storm period. Maximum: Record periods when wind speed averaged 15 m.p.h. or more.
12. Sample computation assuming that you have a total snow depth stake, a storm stake, and an interval stake:

Old snow depth- - - - - - - -	12" (total stake)
Gross snowfall - - - - - - -	12" (from interval stake summation)
Net snowfall- - - - - - - - -	10" (storm stake)
Total depth at end of storm -	21" (total stake)

New snow settlement was 2 inches and old snow settlement was 1 inch.

13. Percent of settlement is computed by dividing gross snowfall into the amount of settlement.
14. Record general trend and any marked changes.
15. Record time, type, size, and location. Give best estimate of the trigger.
16. As above; also record method of release: Ski, explosives, artillery fire, etc. Record stabilization in place if it occurs.

    It is important for the observer to record his personal opinions, also any unusual or unfamiliar developments.
17. Sufficient copies of the Storm Report should be made so that one is available to forward to the avalanche study center at Alta, Utah. Reports should be made promptly following the storm.

FIGURE 40.—Storm report (sheet 1).

STORM REPORT

Storm No. 1 Date 12/25/59 Area Alta Observer Havens and LaChapelle

TECHNICAL DATA

1. Began 0100 25 December 1959 Ended 0600 26 December 1959
Duration Major Storm Period 29 hrs.

2. Old Snow Depth 8"

3. Old Snow Surface depth hoar on N. slopes, bare ground on S. slopes

4. Gross Snow Fall 25"

5. Net Snowfall 25"

6. New Snow Type 13" damp new snow followed by 12" dry powder

7. Snowfall Intensity
Average 0.9 in/hr.
Maximum 1.3 in/hr.

8. Water Ratio 0.09 Total Precipitation 2.14"

9. Precipitation Intensity
Average 0.075 in/hr.
Maximum 0.15 in/hr.

10. P.I. Factor never reached 1.0

11. Wind
Speed Average 10 mph Max. 18-20 mph (short periods)
Direction W & SW

12. Old Snow Settlement negligible

13. New Snow Settlement Inches

14. Temperature began 30°, falling to 10° at end of storm

15. Avalanche Occurrence - Natural
General cycle of small, medium and large soft slabs of northerly exposures.

16. Avalanche Occurrence - Artificial
Extensive ski and explosive releases--see gun report and analysis.

Observer's Analysis

Trouble had been expected on north exposures with the first storm to deposit much snow over the existing shallow depth hoar. The danger was further heightened by the existence of a crust layer in the depth hoar resulting from a November salt storm. The early part of this storm brought damp, heavy snow which favored slab formation, and avalanche activity began early, when little more than 6 to 8" of snow had fallen

FIGURE 40.—Storm report (sheet 2).

Test skiing on the morning of the 25th revealed highly unstable conditions, and the skiers were restricted to minimum hazard areas on the Collins lift for the rest of the day. A test release in one of the chutes of the Peruvian Ridge resulted in release of a soft slab extending all the way from Peruvian Bowl to Westward Ho. Very extensive cracking of the snow was observed even early in this storm, and persisted for a day or two afterwards.

Artillery fire on the morning of the 26th brought down several large slides, the most extensive being those on Baldy Shoulder and Sunspot-Race-Course. Many small patches of slab existed throughout the ski area, and test skiing and blasting in the Peruvian Ridge-Wildcat areas proved these to be sufficiently dangerous that they were kept closed throughout the day. A small part of the ridge around the top of the Wildcat Lift was left open to permit use of this lift, but even here the snow was unstable, and two small slabs were dislodged by skiers, one of them burying another skier who had the misfortune to fall just as the slab patch was released. The latter was quickly dug out and was uninjured. A heavy influx of skiers out to take advantage of the first good skiing of the winter made the area control problem difficult, and there was considerable complaining about the restrictions until it became obvious to even the most careless skiers that a serious hazard situation existed.

It is interesting to note that the slopes of Stonecrusher and Lone Pine, which had been previously foot-packed, did not slide, though adjacent slopes slide vigorously following artillery release. Increasing evidence confirms that foot-packing is an effective countermeasure against the hazards of depth hoar. Peruvian Bowl also did not slide, for it had been thoroughly side-stepped with skis several days prior to the storm.

Blasting and artillery fire continued for two days after the storm, and danger in the outlying ski runs was eventually reduced. A serious condition of instability continues on north slopes, however, and more trouble may be expected from future storms. At the date of this writing (3 January), occasional patches of unstable slab have continued to be uncovered in the ski area, and a general hazard condition is presumed to exist in the back country where no control measures have been taken.

Figure 40.—Storm report (sheet 3).

1. *Preliminary Requirements.* The prerequisites of a site for snow profile investigations are few, but important. For practical use, the study plot must be accessible to the observer throughout the winter. It must be an area free from avalanche danger, disturbance by unnatural deposition of snow (such as the discharge from rotary snowplows), and foot or ski traffic. If disturbance by passing skiers is likely, the area must be roped off. The study plot should be reasonably level and free from exposure to snow creep pressure from adjacent slopes. It should be located away from ridges, cliffs, or other terrain irregularities that would tend to modify the normal conditions of snow deposition and metamorphism, and should be protected from the scouring action of high winds. The ideal location is a level opening in a stand of heavy timber. It should be such size that the distance from the edge of the study plot to the nearest trees is at least as great as the height of the trees. Normally, the study plot should be located close to the total snow stake where accumulation and snow depth records are obtained. If this is not feasible, a separate total depth stake must be provided at the study plot. A number of pits will be required in the course of a winter; therefore the test area must be staked out and the sites of future pits planned in advance. Each pit is refilled with snow after the studies have been made, to keep the snow cover in the test area as homogeneous as possible. The limits of the area which has been dug up for study must be clearly marked, so that fresh undisturbed snow can be excavated from each succeeding pit. Excavated snow must be thrown away from any area which may subsequently be studied.

In shallow snow covers, a square pit dug through to the ground is usually the quickest and most convenient. For deep snow, a long narrow pit increasing in depth by steps from one end to the other provides easier access; or a vertical shaft can be dug with the snow hoisted up from the lower levels by bucket. A D-handle shovel with a square blade is the best for all-around use. A short shovel with a pointed blade may be needed to break up very hard snow.

In practice the ram profile is taken first, and the penetrometer left in place to guide the pit excavation and to serve as a scale of reference. The subsequent tests are then made in more or less the order given below.

2. *The Ram Penetrometer.* The ram penetrometer (Haefeli cone penetrometer), or "rammsonde," was developed in Switzerland over 20 years ago. It has become a very useful tool in various kinds of snow investigations. This instrument measures the resistance snow offers to penetration of a cone-shaped point, and indicates the relative degrees of hardness and cohesion in various snow layers. The method of use provides a graph of ram resistance against depth without digging a pit. The stratification of the snow is readily apparent from the graph and provides the snow investigator with clues to the various conditions existing in a given snow cover.

The penetrometer consists of an aluminum alloy tube approximately 3 cm. in diameter, 1 m. long, and weighing 1 kg. The 4-cm. diameter point is a 60° cone tipped with steel for wearing quality. A scale in centimeters is engraved on the tube, reading upward from the point. Depths over 1 m. may be probed by the addition of successive 1 m. lock-connected lengths of tube.

A sketch of the ram penetrometer, together with the formula used to compute ram resistance, appears in figure 41.

The force of penetration is developed by the fall of a weight along a guide rod supported on the upper end of the penetrometer tube. The force may be varied by varying the height of fall and size of weight. The calculated value of ram resistance, given in kilograms, is an arbitrary figure depending on the dimensions of the penetrometer. Readings taken under different conditions and by different observers can usually be compared. Operation of the ram penetrometer is as follows:

a. Hold the penetrometer tube vertically with point at the snow surface and allow it to sink by its own weight into the snow. Read and record penetration.

b. The 1 kg. ram weight and guide rod are then carefully set on the tube and any further penetration due to the increased weight is recorded.

c. Raise the ram weight and let it fall from a height sufficient to produce at least 1 cm. penetration. Note scale reading at the snow surface and the fall height of the weight. As the process is continued and firmer snow layers are reached, the distance of fall for the weight will have to be increased. When maximum possible fall height is insufficient to produce at least 1 cm. penetration, then two or more falls must be used between successive readings. A greater sensitivity to small variations in ram resistance and to thin snow layers is usually obtained if short fall heights and a number of falls between penetration readings are used as regular practice. If heavier ram weights are available, they may be substituted for use in very hard snow.

d. When the first tube has penetrated to approximately 80 cm. a second tube is added, as is a third tube when the depth has reached about 180 cm., and so forth. Addition of the extra tubes must be noted in the record. Changing the total weight of the penetrometer changes the calculated value of ram resistance for given conditions. When the point has penetrated through the snow cover and reached the ground, a sudden increase in ram resistance is usually observed, and the ram weight makes a duller sound when it falls.

e. From the quantities recorded (fall height, ram weight, penetrations, etc.) the ram resistance for each snow layer can be calculated with the formula given in figure 41.

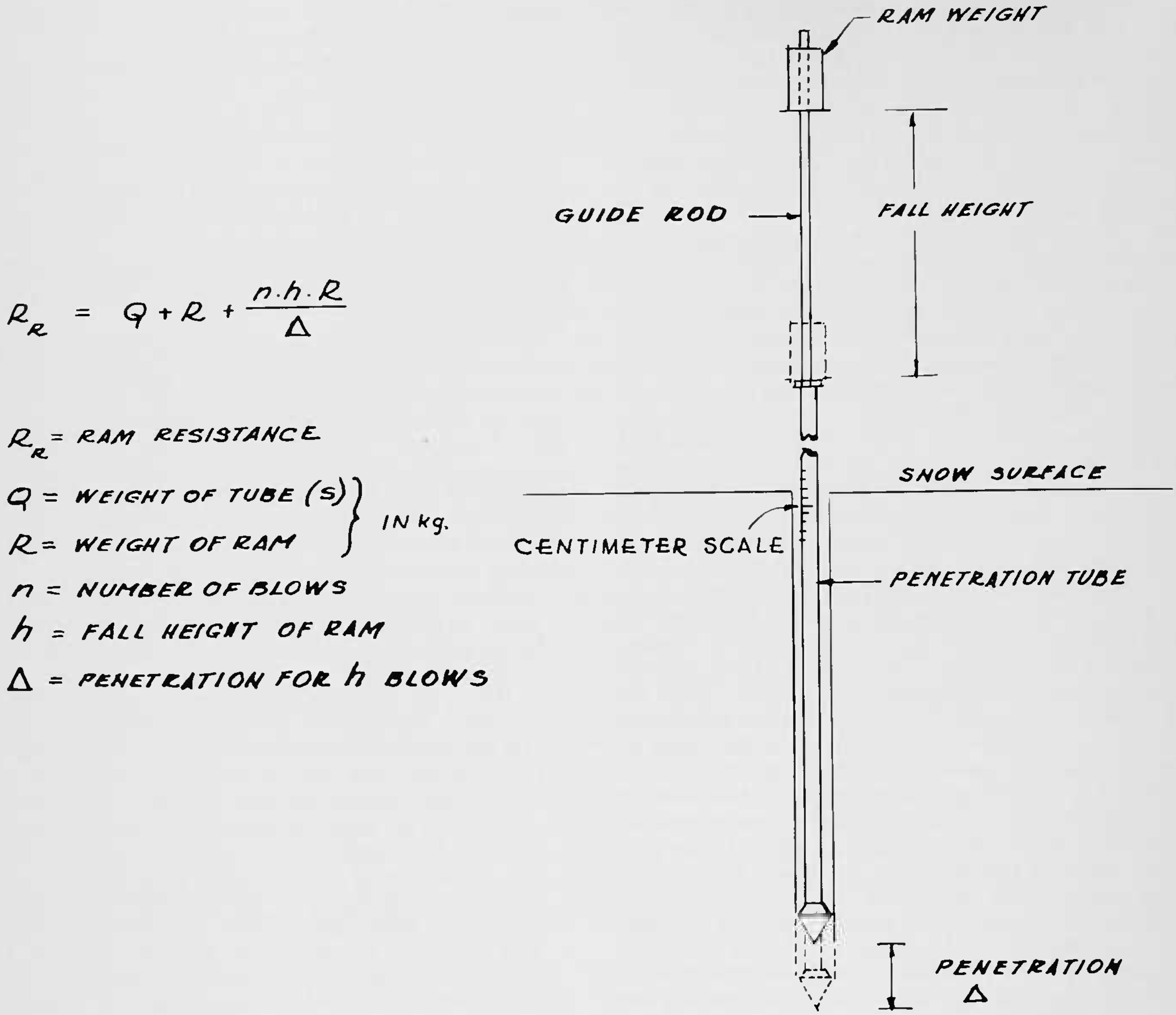


FIGURE 41.—The ram penetrometer.

3. *Temperature.* The simplest way to determine temperature profile is to insert thermometers at regularly spaced intervals in the wall of a freshly dug pit. Reliable temperature records cannot be obtained in this manner after more than an hour or so of exposure of the pit wall. A usable curve of temperature against depth can be obtained if a few precautions are taken. The best method is to measure the temperature from the pit wall as the pit is being dug. This insures minimum disturbance of the natural temperature gradient. Where more accurate records are required, resistance thermometers, thermistors, or thermocouples must be allowed to accumulate with the snow cover during the winter so that they are surrounded by undisturbed snow.

The thermometers may be inserted in the pit wall at 20-cm. intervals, unless more detailed studies of snow temperature changes near the surface are being made. If glass thermometers are used, a metal punch should be kept handy to make holes for the thermometers in all but the softest snow. The Weston dial thermometer is more rugged, and is recommended where great precision is not required. A punch should also be used for it in very hard snow. Care must be taken to avoid parallax when reading the dial thermometer. After the thermometer is inserted in the snow, it should be allowed to remain there for a few minutes to approach equilibrium. Then it should be shifted to a fresh spot of snow at the same level and once more allowed to approach equilibrium before being read. This is necessary because the thermometer initially inserted in the snow is usually at a different temperature than the snow, and the first equilibrium temperature reached will be appreciably different than the surrounding snow temperature.

An accurate temperature of the snow surface is very difficult to obtain. An approximation may be obtained by sliding the thermometer just under the snow surface, and shielding it from direct solar radiation.

4. *Stratigraphy.* The stratigraphic, or layer, profile is derived from detailed observations of grain size, grain type, layer boundaries, hardness, and other special features in the snow cover being investigated. The results as plotted show the various layers of snow and their characteristics. See the pit profile plot in figure 42.

The snow crystals observed are classified according to the outline given in the Types of Deposited Snow chart, and the appropriate graphic symbols are used for plotting the results.

A few general remarks about visual observations will aid the field worker. One of the quickest ways to locate the various layers, where large differences in hardness are present, is to draw the finger or a pencil tip down the pit wall at an even rate from top to bottom. The variations in resistance offered by the different layers will be quite apparent. Where the difference is slight, careful horizontal stroking of the pit wall with a soft brush will model out the layers. When applied to new snow near the surface, this technique will even reveal the variations in wind velocity which occurred during deposition. Care should be taken, however, to make a close visual inspection for the layer boundaries, because a change in grain type or size will sometimes occur with very little change in hardness.

In the absence of a hardness gage or penetrometer, a rough estimation of hardness may be obtained by noting the size of common articles which may be easily pushed into the snow. The following table will serve as an example:

	Hardness	*Approx. ram resistance*
Mittened fist (sidewise motion possible).	very soft	0–3 kg.
Flat hand pushed endwise	soft	3–15 kg.
Single outstretched finger	med.-hard	15–50 kg.
Sharpened pencil	hard	50–150 kg.
Knife blade	very hard	over 150 kg.

Special features such as sun or rain crusts, thin layers of surface hoar crystals, the presence of depth hoar, ice laminations, and ice lenses, should be noted.

Individual snow layers may be marked by stretching colored thread on the surface after each snowfall when profiles are to be taken throughout the winter at a single site for the purpose of plotting a time profile of snow cover evolution (see item 6.4). The threads become incorporated in the snow cover and plainly mark layer boundaries which might otherwise be difficult to distinguish.

5. *Density.* Snow density is determined by the familiar method of weighing a sample of known volume. The snow specimen is collected by inserting a standard 500-cc. sampling tube horizontally in the pit wall. The snow is cut away around the tube, and the snow at the ends of the tube is carefully cut or scraped flush with the tube, and it is weighed. The tube weight is deducted from the total weight to get the snow weight, and the density is computed from this known weight and volume. If a large number of sample tubes are available, the specimens from an entire profile may be collected at once and weighed at a convenient indoor location. If the tubes will be exposed to melting temperatures before being weighed, they must be capped with rubber caps to prevent loss of any meltwater formed.

Density samples should be collected from each separate snow layer in the profile large enough to admit the sample tubes. Several samples should be obtained from the thicker layers. The height of each sample collected in the snow cover must be recorded. The density values are plotted against snow depth to give the snow density curve for the profile, as illustrated in figure 42.

6. *Plotting the Profiles.* The general technique in plotting a complete snow profile from pit data is suggested in the accompanying example (fig. 42). The direction of the axis on which any given characteristic is plotted is merely a matter of convention; the example shows the method of plotting found convenient after considerable use. Millimeter graph paper used with a scale of 1 : 10 (one millimeter for each centimeter of snow depth) gives a convenient and easily manageable profile.

6.4 Time Profile. The end product of snow profile determinations is the time profile, from which the investigator may observe the overall character of snow cover evolution throughout the winter. This time profile is prepared by plotting (on a time base) a series of pit profiles obtained from a sequence of pits dug at the same study plot throughout the winter. Daily snow depths, settlement data, and meteorological records are also incorporated in the time profile. If care is taken to identify individual layers in each pit profile, the behavior of these layers can be followed throughout the winter. The desirable interval for collecting pit data is every 2 weeks.

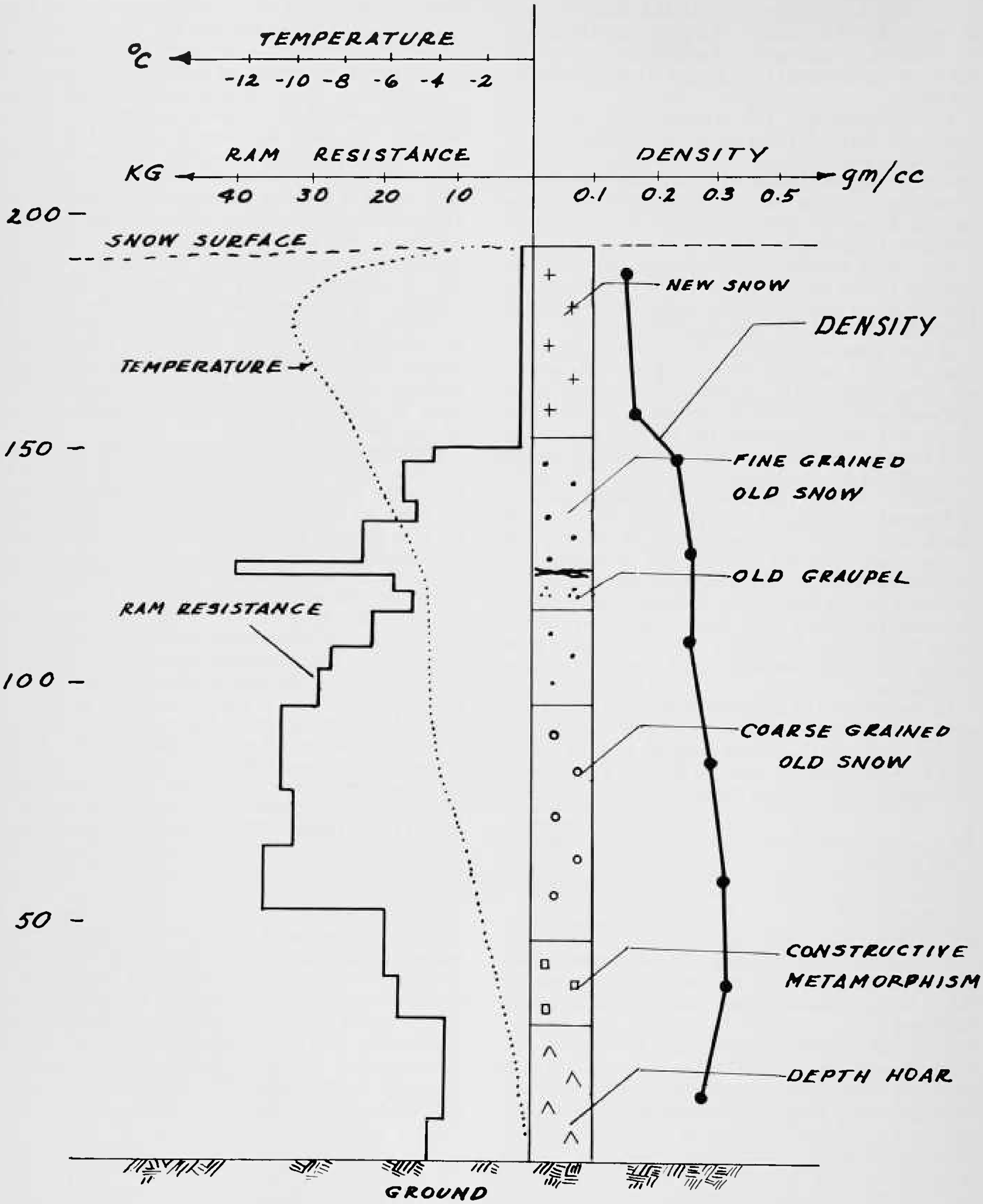


FIGURE 42.—Typical plot of pit profile data, showing symbols for various deposited snow types.

Chapter 7

7 SNOW STABILIZATION. Snow may be stabilized and avalanche hazard consequently reduced or eliminated by the following methods. These represent measures of avalanche control and prevention as applied to the snow itself, in contrast to such defense measures as retention barriers which permanently alter the nature of the terrain.

Mechanical disturbance of the snow with one exception results in a trend toward greater stability. This works in two ways. One is the process of age-hardening already mentioned in chapter 2, item 2.2. Whenever snow is disturbed and then allowed to set, its final hardness is greater than if left undisturbed. This effect is accentuated at lower temperatures. The other method of stabilization is by relief of creep tension or inhibition of its development. Existing creep tension is relieved if the homogeneous layer of a snow slab is broken. Once the slab is broken into segments, there is much less likelihood that such tension will again develop. Slabs which have been broken without an avalanche release tend to become a well-attached part of the snow cover.

The one exception to the stabilizing effect on snow of any mechanical disturbance is wind, for it transports the snow from place to place as well as disturbs it. It is a potent natural stabilizer when it forms windpack and windcrust. When it constructs a slab or transports an overload of snow from one part of the area to another, the reverse is true.

Skiing is the most obvious means of mechanical disturbance available in a ski area. It is a well-established general observation that slopes which receive heavy ski use are much less likely to avalanche than those which do not. Light skiing—a few tracks criss-crossing a hill—also has a stabilizing influence. First, it may relieve creep tension in a soft slab. Second, each ski track and each area of snow displaced in a turn, represents an island of harder snow which will impart strength to the upper snow layers. In short, a little skiing is better than none, and a lot of skiing is even better. Breaking up the snow will improve its stability; compacting it will assure a solid, well-anchored layer.

When snow reaches a certain degree of hardness, caused by high winds and low temperatures, the ski is no longer able to penetrate the surface. In such cases more violent means of breaking the snow are required, such as foot-packing or the use of vehicles.

High explosives represent another effective means of introducing mechanical disturbance in the snow. Explosives are safer when large avalanche paths are involved, because they may be delivered from a distance either by hand-throwing or by an artillery shell. The shock of an explosion is extremely effective in relieving creep tension, even in the hardest slab. Intense age-hardening is also initiated in the immediate vicinity of the blast crater, but this effect is confined to the snow which is physically displaced by the explosion. For this reason it is not efficient to depend on explosives to create widespread age-hardening over a slope. Rather, they are used primarily to initiate avalanche release and/or to relieve creep tension. The use of explosives is discussed in detail in item 7.2.

An avalanche release also stabilizes the snow. An avalanche in motion represents a major mechanical disturbance of both the sliding snow and that nearby which falls under its influence. The consequent age-hardening thus eliminates large quantities of snow from the probability of being responsible for a later release. Instead of stabilizing snow in place on an avalanche path, a slide removes a large quantity of unstable snow and carries it to more gentle slopes below where it can cause no harm. The immediate hazard on a given path is eliminated, and the future hazard is reduced, for there is less snow available for subsequent slides. Avalanching is frequently a less desirable protective measure than stabilization in place. In a ski area good skiing snow is removed from attractive slopes, and on a highway a slide on the roadbed means extra labor and cost of clearing. Nevertheless, avalanches are frequently precipitated to insure public safety, and the beneficial effects should be recognized.

7.1 Test and Protective Skiing. Protective skiing is the deliberate, day-to-day disturbance of snow on avalanche slopes in order to encourage stabilization as described above. Test skiing is an attempt to artificially release avalanches on selected small slopes by skiing. It serves as a field test of snow stability to check the conclusions of hazard forecasting. The two functions of test and protective skiing are so often combined that they are treated here together. The safety precautions for both are identical.

The reaction of snow under the snow ranger's skis constantly provides him with information on the physical processes which are taking place in the snow cover. This technique provides warning of snow which is tending to form slabs and create an impending hazard, particularly during storms. An important key to successful test skiing is the selection of test slopes which accurately represent the snow conditions found on the larger and more dangerous avalanche paths. In most areas it is possible to locate some of these small, short avalanche paths where slides may safely be dislodged by skiing. It is very desirable to find such paths which have the same orientation and approximately the same slope angle as the larger paths. Configuration, relation to timber, and altitude must also be considered. Safe routes of approach, access, and exits are essential.

Cracks which form in the snow with the passage of skis are the best indicators of developing slab avalanche danger. Breaks in the snow immediately adjacent to the skies are not necessarily a danger sign; the weight of the skier may simply be cracking the snow locally. Breaks or cracks which run ahead of the skies are more clearly a warning of hazard. A crack which may appear for just a few feet ahead suggests that slab conditions are forming and caution is indicated. Cracks which run far ahead of the ski (e.g., 50 feet or more) indicate serious instability. Under these conditions avalanches on steep open slopes are almost certain. Occasionally conditions will be found in which cracks appear everywhere in the snow at the slightest disturbance—on gentle slopes and among trees—as well as on obvious avalanche paths. Snow in such a condition is very "touchy" and avalanches are often released unexpectedly on slopes where they normally do not occur.

If snow actually avalanches on a test slope following the passage of a skier, the character of the slide will furnish additional information on the degree of instability. Considerable external force may be required to initiate an avalanche, if only the snow dislodged by the skier slides away. If the fracture line propagates for some distance, and the slide gains mass and momentum as it descends, the triggering of large slides obviously will be much easier. When relating these observations to larger avalanche paths, remember that differences in location, slope, angle, etc., will cause different paths to behave in different fashions. The test skiing procedure offers an additional check on snow conditions, but it does not furnish all the answers. When done by an experienced observer, however, test skiing does often furnish accurate evidence on the approach of dangerous conditions.

The experienced snow ranger will enlist the aid of the skiing public in his program of snow stabilization and avalanche prevention. Once a slope has been adequately tested (usually with explosives) and proved safe, skiers should be encouraged to use it and get the snow broken up and packed into a solid layer. Closure of ski runs is not a satisfactory avalanche defense measure. Neither is it an acceptable substitute for approved control measures which can be used to safeguard a slope and open it to use. Closures are a temporary measure intended to protect the public during periods of high avalanche danger, especially during storms. They should be lifted as soon as possible after the critical period passes, so that full benefit of stabilization by use may be achieved. It should be the objective of a snow safety program in any ski area to keep all the slopes open just as much as possible without exposing the public to hazard. Safety precautions to be observed by men engaged in test and protective skiing are outlined in chapter 8, item 8.3.

Depth hoar requires special attention for proper stabilization. When a shallow, early-winter snow cover has been converted to depth hoar, the base for subsequent snowfalls is dangerously unstable. Unlike freshly fallen snow, depth hoar is not readily stabilized by skiing. It is not easily compacted into a hard layer, and tends to reform if steep temperature gradients persist. Repeated sidestepping with skis tends to compact it sufficiently to harden the layer, but breaking down the structure by skiing alone is not sufficient. The same slope must be tramped over several times by a number of skiers to insure adequate stabilization. Foot packing is a more reliable method. The higher specific pressure of a boot appears to provide satisfactory compaction and hardening. Experience has demonstrated that foot packing will satisfactorily stabilize early season depth hoar, while adjacent slopes not so treated persist as a source of avalanche hazard. Increased safety and ease of control warrant the work involved to foot pack slide paths which threaten a busy ski area.

The initial formation of depth hoar is inhibited by thoroughly packing each fresh fall of snow as it occurs. This will not prevent depth hoar from developing, but a reduction in the porosity and increase in density will restrain free circulation of water vapor within the snow cover and reduce the adverse effects of steep temperature gradients.

7.2 Explosives. The use of explosives to stabilize snow—either hand placed or as projectiles—has been routine in the United States for a number of years. Techniques and equipment have steadily improved.

Before the explosives techniques were developed, the only avalanche defense the snow ranger had was the closed area sign. The signs did nothing to deter avalanches and very little to deter the people.

Explosives have numerous advantages as a means of avalanche hazard control. They are a logical extension of the test and protective skiing techniques which seek a definite answer to the question "Is this slope stable?" A heavier shock can be delivered to the snow, and it can be done quickly and safely. Explosives are the only means of getting a definite answer where hard slab conditions prevail.

Where projectiles are available, large areas can be controlled from a few firing positions. The savings in time and labor are notable. At Squaw

Valley, during the 1960 Winter Olympic Games, 30 different and widely scattered avalanche paths were controlled as a matter of routine in less than 2 hours. Where a highway crosses the area, the rifle can be hauled along it and deliver projectiles to avalanche paths otherwise inaccessible.

Contrary to the belief of the general public, the objective of using explosives in avalanche hazard control is not to start avalanches. The objective is to determine if the snow is stable or unstable and eliminate hazard. The latter does not necessarily require that an avalanche fall.

Education of the public is important because it leads to the cooperation and acceptance by the public, without which no snow safety program can be successful. Accordingly, avalanche control operations are often performed in full view of spectators, and all personnel engaged in avalanche control work are encouraged to explain the objectives.

When an explosive charge is detonated in an avalanche area, one of three things happens:

1. An avalanche occurs. This proves that the snow is unstable and further control action is needed on other slopes.
2. The snow cracks and either slides only a short distance or stabilizes in place. This indicates a moderate degree of instability. It calls for further control action, since some other slope may be ready to slide. Stabilization in or nearly in place is a better outcome than an avalanche, for there is no debris to roughen a ski slope or fill a highway.
3. Nothing happens except the formation of a crater in the snow. This suggests stability. If confirmed by several more shots on key avalanche paths, it may be taken as evidence that the area as a whole is stable. This is the best answer of all.

Any one of the three answers is satisfactory, for it is definite. If there was a hazard, it has been removed; if there was no hazard, this has been demonstrated.

Continuity of avalanche hazard control operations is also important. The routine and frequent stabilization of avalanche paths by all methods—from protective skiing to explosives to skiing use—is the best guarantee that no deepseated, climax-type hazard can develop. In the educational aspect, people become accustomed to the operation, understand what it is all about, and even identify themselves with the program if they are allowed to help out in small ways.

7.21 Hand-Placed Charges. For slope avalanches, explosives with a high rate of detonation such as military demolitions and seismograph powder are the most effective. For cornice removal, the slower explosives such as 40 percent gelatin dynamite are more effective. The faster explosives deliver a maximum blow to the surface and also propagate a shock wave which counters the marked absorptive powers of snow. Cornice removal, on the other hand, is like a quarrying operation which requires a strong push rather than a sharp blow (fig. 43).

F–462503

FIGURE 43.—Removal of cornice by a heavy charge of tetrytol.

For a soft slab, a 2½-pound block of tetrytol (military demolition) is generally a sufficient charge. If the slope is wide it is better to fire a multiple charge strung out along the fracture line than to increase the size of a single shot. If the slide path is unusually large it may be necessary to blast at several different trigger points. For the hard slab-depth hoar combination, the size of the shot may be increased to 5 or even 10 pounds. The ignition type detonator (blasting cap) saves time and is approved for avalanche blasting. (For winter work such as this, the fuse is most easily lit with a pullwire igniter.) With this type of detonator slide paths under a lift line have been successfully blasted by dropping the charge from a moving chair.

For cornice removal, the standard procedure is to drill shotholes along the expected sheer plane at 6- to 8-foot intervals and to a depth that will place the explosives in the center of the snowmass. The holes are loaded with 3 or 4 sticks of dynamite and well tamped with snow. The charges are linked together with primacord and fired as a multiple blast (figs. 44 and 45). The shotholes can be dug with a snow sampler. A handier tool is a sectional avalanche probe with a casehardened cone-shaped head, the same diameter as a dynamite stick, which can be screwed on to the bottom section of the probe.

F—495208

FIGURE 44.—Dynamite release of massive cornice at Twin Lakes Pass, Alta, Utah. This cornice is about 75 feet long and 25 feet high at the face. Ten shot-holes were used, spaced 8 feet apart along a straight line and drilled 6 feet deep. Each hole was loaded with two sticks of 40 percent gelatin.

A cornice which forms every year or several times during the winter may be precharged. Explosives are placed on the ground as near as possible to the shear plane, or placed after the cornice is partially formed. The charge can then be fired whenever the overhang becomes dangerous and the procedure repeated as often as necessary. The precharging technique has advantages: it effects more complete removal and permits placing the charge in favorable weather. Moistureproof and frostproof explosives must be used. Military demolitions, seismograph powder, and bangalore torpedoes are suitable. Such charges must be very securely anchored against snow creep, and should be armed with primacord—never with blasting caps. Where the cornice is inaccessible, projectiles have been used effectively. The technique is to get "on target" by the ladder method with point-detonation fuse; then to fire delay-fuse rounds into the cornice to get the burst inside the snow-mass.

7.22 Artillery. Fundamentally, artillery represents an extension of the snow ranger's throwing arm. A projectile launcher must be accurate, mobile, reliable, simple to operate and maintain, and have adequate range.

Of the numerous weapons listed, the 75 and 105 mm. recoilless rifles and the 75 mm. pack howitzer have proved to be best adapted for avalanche control operations. Weapons larger than 105 mm. are not recommended.

The 75 mm. recoilless rifle is especially suitable. It weighs 167 pounds, is readily mobile, and has a range of 7,000 yards with pinpoint accuracy up to 3,000 yards. This rifle is easily operated and maintained and can be fired from any platform which will support its weight (fig. 46). Its only drawback is the "backblast" common to all recoilless rifles. Gun crews should use air-valve type ear plugs because of its sharp concussion.

The 75 mm. pack howitzer is similar to the recoilless rifle of the same calibre in range, reliabil-

F–495209

FIGURE 45.—Sequel to figure 44, after cornice has fallen. Arrows point to location of shot-holes. Note the hard, smooth surface of an older cornice underneath the one removed.

ity, and shock power. However, it is considerably more complicated. It weighs approximately 500 pounds and is therefore much less mobile. Unlike the recoilless which fires fixed ammunition, the pack howitzer has a variable powder charge. Unless fired with Charge No. 4 (full propellant charge) there may be a problem with duds or deep bursts in soft snow. Since there is no backblast, it can be fired from restricted areas such as the doorway of a shelter. It is well suited for use in a ski area where it can be fired from a fixed position, or along a highway where it can be towed.

The 105 mm. recoilless rifle (fig. 47) is similar to the 75 mm. in accuracy and reliability. It has greater range and shock power. It weighs 700 pounds and is not mobile over snow, but it can be mounted in and fired from a wheeled vehicle. Concussion and backblast are heavier than with the 75 mm. recoilless but not so sharp. Ear plugs are required. The 105 mm. recoilless is recommended particularly for use on highways where ranges may be extreme.

Firing position. The selection of firing positions requires careful study. They must be accessible under all conditions of weather and hazard and protected from avalanches. The safety of habitations, parking areas, and other facilities must be taken into account. With all these limitations in mind, the snow ranger chooses firing positions from which the maximum number of targets can be reached. They may be strung out along a highway or concentrated in the vicinity of the ranger station, or located on a ridge if a lift provides access. With proper care, rifles and other weapons can be left in the open all winter.

In a ski area, gun platforms raised above the maximum snow level are essential. They also make it possible to fire on short notice without delay. They provide the fixed position for blind firing. Where the rifles are to move along a highway, fixed positions can be provided by marking the wheel positions of a mounted vehicle or a towed weapon.

F—495210

Figure 46.—Typical fixed position for a 75 mm. recoilless rifle. Here the rifle is on a pedestal mount, which is interchangeable with the normal tripod mount. An aiming stake for blind firing is visible in front of the platform. The elevated position gives ample clearance for the backblast with all snow depths.

Targeting. The estimated range should be determined from a topographical map when firing at target for the first time. The first shot should be visually aimed so that it will land well down on the slope; then proceed upward, ladderwise, until the burst is on target. At all times, be sure that there is enough dead space behind the target so that an "over" will not endanger life or property. A range card should be prepared for each gun position showing both the range in yards to each target as determined by visual firing, and the elevation of the barrel as measured by the gunner's quadrant.

Firing projectiles into or over areas occupied by people is not permitted. For this reason most firing in ski areas is done in the early morning. On highways a blockade system is essential.

Projectiles should not be used where the target is close to structures, because of fragmentation. Shrapnel dispersion from the 105 mm. shell is particularly dangerous.

Blind firing often starts a premature avalanche cycle or stabilizes the snow in place. Whether in a ski area, along a highway, or for any other purpose, it is extremely effective in shortening closure time, preventing the development of major avalanche conditions, and reducing the volume of snow and amount of avalanche debris in a ski area or piled upon a highway. Blind firing can be done safely during blizzards when it would be unsafe to use hand-placed explosives. With proper blind firing data, the gunner can hit any target he can see during clear weather.

F—495211

Figure 47.—105 mm. recoilless rifle permanently mounted on a tower for avalanche control in a major ski area. A winter's supply of ammunition is stored in the base of the tower. With such an installation, accurate blind firing data can be acquired so that control measures can be taken during storms. Alta, Utah. Note lightning grounds as safety measure.

At each fixed gun position, the snow ranger sets up aiming stakes which determine the line gun-target. Elevation is set by the gunner's quadrant as taken from the range card.

Training. Personnel assigned to use artillery or hand-placed explosives must receive special training. (See Forest Service Safety Regulations, chapter 8, item 8.3.)

Chapter 8

8 **SAFETY.** By now it should be obvious to the reader of this handbook that avalanches are a dangerous and sometimes unpredictable force of nature. It cannot be emphasized too strongly that the artificial release of this natural force involves considerable danger unless carried out in strict conformance with established safety procedures.

8.1 **Safety Objectives.** The three principal objectives of avalanche control safety regulations are to:

1. Carry out avalanche control without endangering forest officers or others participating in the control operation.
2. Assure that control operations do not endanger skiers or others who may be in the vicinity.
3. Prevent damage to lifts, buildings, automobiles, powerlines, and other facilities.

To attain these objectives, the Avalanche Control Safety Regulations in this chapter have been promulgated. These have the official status of a supplement to the Forest Service Safety Code, and should be so respected.

8.2 **Safety Principles.** The following general safety principles are based on accumulated experience.

1. Avalanches must never be artificially released unless it is absolutely certain there are no humans on the slopes below. If these slopes are not visible to the man effecting the release, a system of guards and signals must be arranged. Normally, release should not be attempted during poor visibility (fog, snowstorm, etc.) except when blind firing with artillery and then only if rigorous safety precautions are taken.

Merely walking or skiing along a ridge or near an avalanche path may effect release during conditions of exceptional instability. With such conditions, artillery fire or blasting may cause the sympathetic release of large slides at great distances from the actual target point. Fracture lines or the collapse of an unstable snow structure may be propagated for a very long distance. In one recorded case an artillery shellburst started sympathetic release of one adjacent slide path after another until a large avalanche fell on the opposite side of the mountain from the target point. When such conditions are suspected, great care must be exercised to see that there are no people in possible danger zones.

2. Avalanche accident statistics illuminate one important point which should be a constant source of caution to men engaged in control work and to anyone traveling in avalanche terrain. *Almost all accidents involve slides which are started by the victims themselves.* Accidents which result from naturally released slides falling on an unsuspecting victim are rare. The time it takes for even a large slide to fall is measured usually in seconds. The chance that this time will coincide with the passage of a traveling party across an avalanche slope is very small, unless an artificial trigger is supplied. The moral of this lesson is very plain: don't cross avalanche slopes and provide the trigger for a slide which may overtake you. If necessary, go below the slide path—this is safer than being on it. Better yet, go above the slide, even if this means a long detour.

3. It should become a matter of habit among men engaged in avalanche control work to avoid using wrist loops on ski poles. Once a man gets caught in a slide, his chances of survival, or escaping injury, will be greatly enhanced if his hands are free to protect his face, excavate breathing space, or dig himself out. He may be in trouble if his arms are pinned by buried ski poles.

4. Small avalanches, which ordinarily would be harmless to a man caught in them, can be dangerous if they fall over cliffs or into gullies or ravines. Burial and suffocation are usually thought to be the common fate of those caught in avalanches, but practical experience has shown that mechanical injury from striking trees, stumps, or rocks are as responsible for death or injury as burial. Early winter slides running on a depth hoar layer next to the ground are particularly dangerous in this respect. Their paths are often studded with rocks exposed by the sliding snow.

5. Safety rules for handling explosives are treated in detail in the Forest Service Safety Code and handbooks prepared by explosive manufacturers. Strict observance of these blasting regulations must be enforced in avalanche control work the same as in any other blasting operation. Modern explosives and blasting equipment are manufactured to a high standard, and misfires due to defective manufacture are very rare. Most misfires can be traced to improper handling, storage, or preparation of the charge. Since there is more than normal chance for these to occur under the often adverse field conditions of avalanche blasting, special care must be taken. Do not allow frozen toes, cold fingers, or an unpleasant blizzard

to encourage short cuts or careless preparation of a charge. A few extra minutes spent in doing the job right is always easier and safer in the long run.

6. Never work alone. The minimum group for any avalanche control work is two men. They must conduct themselves so that never more than one is exposed to possible danger. The primary purpose is to have someone around to aid you if you get caught in a slide, or to go for help if necessary. This amounts to applying the general rule of never traveling alone in the mountains, and exposing only one man at a time to possible avalanche danger. It is a very elementary precaution that must always be observed.

7. The administration of an area where avalanche dangers can threaten should never become a matter of habit or routine. Snow conditions exist in many forms and are subject to change. Their prediction cannot be reduced to a fixed set of rules. The most important safety rule of all is always to THINK.

T rain for the job.
H ave good equipment.
I nsist on correct procedure.
N ever get in a rush.
K eep on thinking.

8.3 Safety Regulations. Avalanche control operations by means of protective skiing and explosives are highly specialized. The following safety instructions will govern all forest employees whose duties include such work.

8.31 Personnel.

1. *Qualifications.* Any Forest Service employee who conducts avalanche control operations must:
   a. Be a competent ski mountaineer.
   b. Have received special training.
   c. Hold an avalanche blaster's card, if he conducts operations with explosives. Requirements:
      (1) General training in use, transportation, and storage of explosives.
      (2) Special training in avalanche blasting techniques.

8.32 Avalanche Test and Protective Skiing.

1. *Test Skiing:*
   a. Is a field test to determine actual stability of snow.
   b. Is done on very steep slopes, short enough so that a slide will not endanger the tester.
   c. Is carried out by not less than two men, working as a team, one testing, one observing.
   d. Precedes protective skiing.
2. *Protective Skiing:*
   a. Is carried out to:
      (1) Hasten stabilization.
      (2) Remove avalanches from the slope.
   b. Must be repeated often so that:
      (1) No unstable layer becomes hidden in the snowpack.
      (2) Only the top layer can avalanche.
   c. Snow safety leader decides whether or not to employ from:
      (1) Hazard forecast.
      (2) Results of test skiing.
      (3) His familiarity with the area.
      (4) Size and steepness of the slope.
      (5) Amount of snow that may avalanche.
      (6) Observation of natural avalanche activity.
   d. May follow use of explosives to:
      (1) Clean out small pockets of avalanche snow.
      (2) Complete stabilization of adjacent slopes.
      (3) Encourage stabilization by use.
   e. May be employed during a storm to prevent major hazard from developing on key slopes.
   f. Is effective if slope is thoroughly cut up, though not ski-packed (exception: depth hoar and hard slab).
   g. Must be repeated for every radical change in snow conditions.
   h. Protective skiing team:
      (1) Not less than two.
      (2) Only one man on the slope at a time.
      (3) Begin work at top of slidepath and cross from anchor point to anchor point.
      (4) On cornices or very steep slopes, tester will be belayed.
   i. Is not to be employed when hazard is higher than Condition 2 (moderate).
   j. Once the safety of a slope is established, stabilization of the surface is improved use by the skiing public.

8.33 Avalanche Blasting.

1. *Authorized explosives:*
   a. For slope avalanches:
      (1) Military demolitions tetrytol, C–3, TNT blocks.
      (2) Commercial seismograph powder.
      (3) Military projectiles, not over 105 mm., HE, superqnick fuse.
      (4) In an emergency and in absence of the above, commercial dynamite.
      (5) For experimental and test purposes, other explosives may be used if authorized by forest supervisor.
   b. For cornice removal:
      (1) Commercial gelatin dynamite 40 percent, nonfreezing.
      (2) Military demolitions or seismograph powder
   c. For preplanting cornices:
      (1) Military demolitions.

d. Detonators:
  (1) Type: electrical, ignition, or primacord.
  (2) Size: for military demolitions—No. 8 or larger.
  For commercial explosives—as recommended by manufacturer.
  For primacord—No. 8 or two No. 6 taped together. When used as a detonator, primacord will be attached to the explosive as prescribed in Dupont Blaster's Handbook or Army Field Manual FM5–25.

2. *Storage.*
  a. Magazines for explosives and detonators will meet Forest Service Safety Code standards. They may be raised above ground to normal snow depth.
  b. Field caches: during operations season not more than 50 pounds of explosives—not detonators—may be stored in the field convenient to the blasting area. Requirements:
    (1) In a substantial, locked box.
    (2) Plainly marked.
    (3) Isolated location.
  c. Primacord is classed as an explosive and will be so stored. Distinguish carefully from safety fuse.
  d. Ignition type detonators require special protection from moisture. Use waterproof packaging in storage and ring or cutthroat type crimping tool in the field. Taping joint between cap and fuse is recommended.

3. *Transportation.*
  a. According to Safety Code except over snow.
  b. Over snow, vehicle or backpack, requirements:
    (1) Redflagging.
    (2) Physical separation of detonators and explosive.
    (3) Detonators in box individually wrapped or padded.
    (4) Projectiles in individual containers.
  c. Via lifts and tows:
    (1) Normally at times when not in use by the public.
    (2) 100-foot minimum separation between explosives and persons on the lift other than blasting party.

4. *Party Management.*
  a. Blasting party consists of the blaster and at least one assistant.
  b. Blaster organizes and conducts all operations:
    (1) Brief assistants and notify authorities.
    (2) Assemble, check equipment and materials.
    (3) Choose the targets.
    (4) Transport the detonators.
    (5) Personally arm, place, and fire the charges; aim and fire the gun.
    (6) Provide for party safety: routes, protection from blast, secondary avalanches.
    (7) Provide for area safety: closures, guards, communications, and signals.
    (8) Prepare report on each operation as required by forest supervisor or other authority: i.e., Army Gun Book.
  c. For training purposes, the blaster may supervise while an assistant performs any of the above.
  d. Assistants must:
    (1) Be competent ski mountaineers.
    (2) Have proper equipment as directed by blaster.
    (3) Obey blaster's instructions.
  e. Spectators. It is recognized that avalanche blasting operations have educational value. Spectators are permitted. They must be:
    (1) Briefed on safety requirements.
    (2) Controlled, by extra guards if necessary.
  f. Publicity:
    (1) Will be avoided.
    (2) Scheduled demonstrations may be held for press and public with prior approval of forest supervisor.

5. *Technique.*
  a. Preparing charges:
    (1) Use standard procedures outlined in Blaster's Handbook or Army Field Manual.
    (2) Make sure all materials and equipment are in working order.
    (3) Premature detonation of electrical caps by snow static is possible. Ignition caps are recommended for avalanche blasting.
    (4) When using electrical detonators, check firing circuit with galvanometer at each stage. Keep circuits shorted until ready to fire. If blowing snow is present, prepare complete firing circuit before inserting detonator in explosive.
    (5) When using ignition detonators, test at least 3 feet of each new lot of safety fuse for burning time. Fuse may be cut and cap crimped on before proceeding to the field. Cut fuse for minimum 3-minute delay, longer if necessary for protection of blaster.
    Pull-wire fuse igniters are recommended.
    Note the time when fuse is ignited.
    Be sure fuse is burning before leaving the charge.
    Replace igniter if fuse fails to ignite.

If blaster leaves the charge and it fails to explode, it must be treated as a misfire, even if he thinks the cause is the failure of the fuse to ignite.

(6) Primacord:

Is recommended for detonating multiple blasts.

Is required for 6-shot blasts or over.

Attach primacord pigtails to main line with 2 clove hitches, pulled tight.

An ignition cap crimped on the end of each primacord pigtail and inserted in the explosive is recommended.

Primacord mainlines over 50 feet long should be doubled.

(7) Amount of explosive to use:

Determined by blaster.

Four pounds demolition or seismograph powder generally sufficient for slope avalanche. For wider slopes use multiple shots at 100-foot intervals. Do not use less than 2 pounds per shot.

Where hard slab is prevalent, with or without depth hoar, increase size of charges, up to 10 pounds per shot.

Three to four sticks of dynamite per hole is generally sufficient for cornice removal.

Use too much explosive rather than too little. Get the answer.

b. Placing slope avalanche charges:

(1) May be lowered or tossed into position. The following precautions should be taken:

Detonator securely taped or fastened.

Charge securely packaged.

No strain on lead-in wires of electrical caps. Lower by blasting wire or separate line.

Belay charge if snow is hard and it might slide.

If blaster goes onto avalanche slope to place the charge, he will be belayed. Belay personnel working on cornices.

(2) May be dropped from ski lift, but lift must carry no other passengers besides the blaster.

Pullwire igniters required. Throw the charge to one side and behind the blaster.

c. Firing:

(1) Use approved warning signals.

(2) Establish a minimum party clearance of 50 feet plus substantial terrain barrier.

(3) Party location must be protected from secondary avalanches.

(4) Blaster must have visual observation of the slide path and adjacent danger areas, or fire upon signal from a guard.

d. Preparing cornice shotholes:

(1) Use coring tool or drill such as snow sampler.

(2) Place holes so as to split off overhang.

(3) Stem the holes with snow.

(4) Holes should be 6 to 8 inches apart, depth so that charge is in center of snowmass.

(5) Man working on the cornice must be belayed.

e. Preparing preplanted cornice charges:

(1) Primacord firing circuit required.

(2) Charges should be securely anchored againt snowcreep.

(3) Protect firing circuit from snowcreep.

(4) Fire the blast well before cornice might fall naturally.

f. Misfires:

(1) Electrical detonator: check the circuit and attempt to fire; rearm with a new detonator and fire.

(2) Ignition detonator: wait 30 minutes; without disturbing the charge, place a new charge alongside and fire.

(3) If unexploded powder goes down the slope in an avalanche, treat as a misfire.

g. Projectiles:

(1) Follow Field Manual instructions.

(2) Avoid firing over buildings, other structures.

(3) If necessary to fire over a structure, the distance gun-to-structure must be not more than two-thirds the distance, gun-to-target.

(4) If necessary to fire alongside a lift, the line of fire must diverge from the lift line.

(5) Area gun-to-target, to be clear of all personnel.

Exception—Personnel may be inside a fragmentation-proof structure, not less than 300 yards from the target area, not within the avalanche path, and not on the gun-to-target line.

(6) Safety limit, gun crew to target: 600 yards.

(7) Beware of damage from dispersion of fragments—especially with 105 mm. weapons.

(8) Provide traffic control if firing on or near a highway.

(9) Vehicle clearance from gun position, other than gun carriage, should be 100 yards for 75 mm. weapons and 200 yards for 105 mm.

(10) Prepare one round at a time. Keep other ammunition in containers.

(11) Conventional cannon: Provide clearance for muzzle blast. Keep personnel behind and to either side of the breech.

(12) Recoilless cannon: Provide clearance for back and muzzle blast. Keep personnel on a line at right angles to the barrel.

(13) Visual firing: Check sighting equipment by boresighting before each operation. Do not fire where an "over" endangers life or property. If range is unknown, use ladder method of getting on target. Place first sighting shot below target or on an adjacent, higher slope. Make a range chart.

(14) Blind firing: Target data must be predetermined by visual firing. Double check the lay of the gun. Provide a fixed gun position and aiming stakes. Recheck target data frequently by visual firing or aiming.

(15) Firing on slope avalanches: Use point detonation fuse. *Exception*—If an unstable layer within the snowpack is suspected, fire first with point detonation fuse, then with 0.05-second delay fuse.

(16) When firing on cornices: Point target weapons such as the recoilless rifle may be used effectively against cornices. Do not employ unless there is a backslope or sufficient dead space behind the target to take care of an "over." Use the ladder and burst-on-target method of getting the exact range, with superquick fuse. When a direct hit can be obtained on the cornice, use delay fuse.

(17) Misfires: Proceed as instructed in Army Field Manual. Dispose of defective ammunition by demolition.

(18) Duds: Note point of impact. Make search for dud as soon as possible. When found, dispose of in place by demolition. Be extremely careful not to disturb the dud. Secure military assistance if necessary.

(19) Care and maintenance: Follow Army Field Manual instructions. If rifles are left in the open remove the breechblocks when not in use. Inspect the rifle before using for defective parts, especially sight mount and obstructions in the bore. Check all moving parts for malfunctions before loading first round.

8.34 **Exceptions to Safety Code.** Due to the special conditions of avalanche blasting—absence of flying debris, danger from snow static, for example—certain exceptions to the Forest Service Safety Code are authorized; summarized as follows:

1. Hard hats are not required.
2. Metal cutters are permitted for opening boxes with steel strapping.
3. Ignition type detonators are authorized and recommended.
4. For electrical detonation, Army combat wire or equivalent is authorized as lead wire. Maximum length is 200 feet. Damaged wire should not be repaired or spliced.

Chapter 9

9 **AVALANCHE DEFENSES.** Avalanche barriers of all types are much more extensively used in Europe than in the U.S.A. In the Alps, towns, lines of supply and communication, farms, and factories are exposed to avalanche hazards (fig. 48).

The need for avalanche defense structures in the United States is increasing rapidly. Motor traffic on mountain highways is growing heavier and more passes are being kept open each winter. Dam builders, loggers, miners, and winter sports areas are moving farther and higher into the deep snow country.

In addition to some snowsheds and tunnels in the Western States, only a few barriers have been constructed by highway departments and lift operators in recent years. For the latest developments in this field a person must turn to Austria and Switzerland. Both countries maintain research establishments to develop and test new designs. Significant progress has been made recently.

The modern trend is away from avalanche walls and towards fencelike retaining structures which do the same job as well or better at less cost. The trend is also away from solid or continuous retaining structures.

9.1 Diversion Barriers. Diversion barriers give protection by diverting avalanches—over highways or railroads, away from villages, around electric transmission pylons (fig. 49). Walls, tunnels, snowsheds, and bulkheads are examples of diversion-type barriers. Although they have the effect of slowing down or halting an avalanche, they do nothing to prevent it from starting and little to limit either its size or penetration. Sometimes they are the only solution. The Flexenstrasse, access highway to the famous ski centers of Zurs and Lech in Austria, would be blocked or hazardous most of the winter without its elaborate system of snowsheds and tunnels. Stabilization of these slidepaths would be too expensive (fig. 50).

9.2 Stabilization Barriers. Barriers of this type attempt to control the avalanche hazard by holding the snow in place or reducing its movement to minor proportions. To be effective, they must go to the top of the avalanche path. In former years, design was limited to walls and terraces. Such structures are difficult and costly to build where the avalanche release point may be several thousand feet above the valley floor. Although long lasting, masonry deteriorates from the effects of frost and water seepage, and repairs are a major project in themselves. Walls and similar continuous barriers have other disadvantages. They are very costly and frequently increase the load on a slidepath or cause the development of cornices.

European engineers have studied the forces exerted by both avalanches and snowcreep. This has led to the development of fence-type structures which are cheaper to install and maintain, and are more efficient than masonry.

1. *Arlberg Fence.* This is the prototype for all designs, so-named because it was invented to protect the railroad in the Arlberg Pass (fig. 51). A typical installation utilizes railroad steel posts set in concrete 8 to 10 feet apart. Cables which support vertical poles spaced 4 to 6 inches apart are fastened to the posts, which are braced uphill with guy wires. The height seldom exceeds 12 feet.

This makes a very rugged structure that has proved itself over the years. Modern engineering has added many innovations in designs, materials, and layout. One of the most important advances has been to determine the optimum angle of inclination of the fence with respect to the slope. Originally, avalanche fences were built perpendicular, regardless of the grade. Modern practice is to set the fence at an angle slightly more than 90 degrees from the slope on the uphill side. This arrangement utilizes the full height of the fence and snow pressure drives it against, not away from its anchorage. It is also possible to brace the fence from the downhill side so that avalanche and snowcreep do not affect the supports (fig. 52).

Avalanche engineers are experimenting with treated and untreated wood, steel, aluminum, nylon, prefabricated concrete, and combinations of these. They are also testing various fence designs, including the spacing and arrangement of the bars (horizontal, vertical, lattice, or net type). The objective is to obtain maximum efficiency with a minimum amount of material. Regardless of how the bars are arranged, it has been found that if airgaps in the fence exceed a width of 6 inches, very dry and very wet snows flow through them.

The design of interrupted fence patterns coming into use takes into account that it is seldom possible to keep avalanches from starting under all conditions. The interrupted pattern requires

F–495212

FIGURE 48.—A century of avalanche defense at Davos, Switzerland. Ancient masonry walls and terraces with Arlberg fences added later, and flanked by modern fences. The six dots near the center of the picture are wind baffles controlling an adjacent slide path.

less fence to cover a given area and is less likely to act as a snow catcher (fig. 53).

2. *Nets, Hedgehogs, Triangles.* In their search for effectiveness at least cost in labor and material, European avalanche engineers have developed the avalanche net. In the Austrian version the net is hung on two posts of ingenious design, like very large ski poles. Eight to ten feet apart, these posts are driven into the ground and guyed above and below at an angle to the fall line (fig. 54). The net cables, located on each side and in the middle, are hung with considerable slack and anchored uphill. Among the fillers under test are cable mesh, wire mesh, and horizontal wooden poles. Results to date favor the wood poles, spaced 4 inches apart. The poles counteract the net's tendency to fold together when struck by an avalanche. The virtues of this net are simplicity, ease of construction, and flexibility. It can roll with the punch of an avalanche. An installation using nylon nets has recently been made in France.

F—495213

FIGURE 49.—Concrete bulkhead guarding an electric transmission pylon. Note diversion wall protecting houses to right, Arlberg fences above, and snowshed at upper left. Stuben, Austria.

F—495215

FIGURE 51.—Old style Arlberg avalanche fence. Installed for protection of pipeline in foreground.

F—495214

FIGURE 50.—The Flexenstrasse snowsheds.

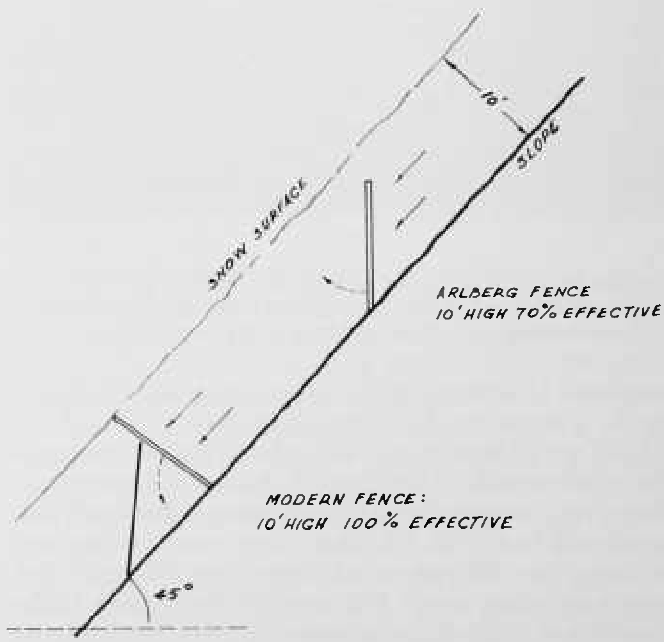


FIGURE 52.—The original Arlberg vs. modern avalanche fence, showing angle of inclination and effect of snow pressure (broken arrow).

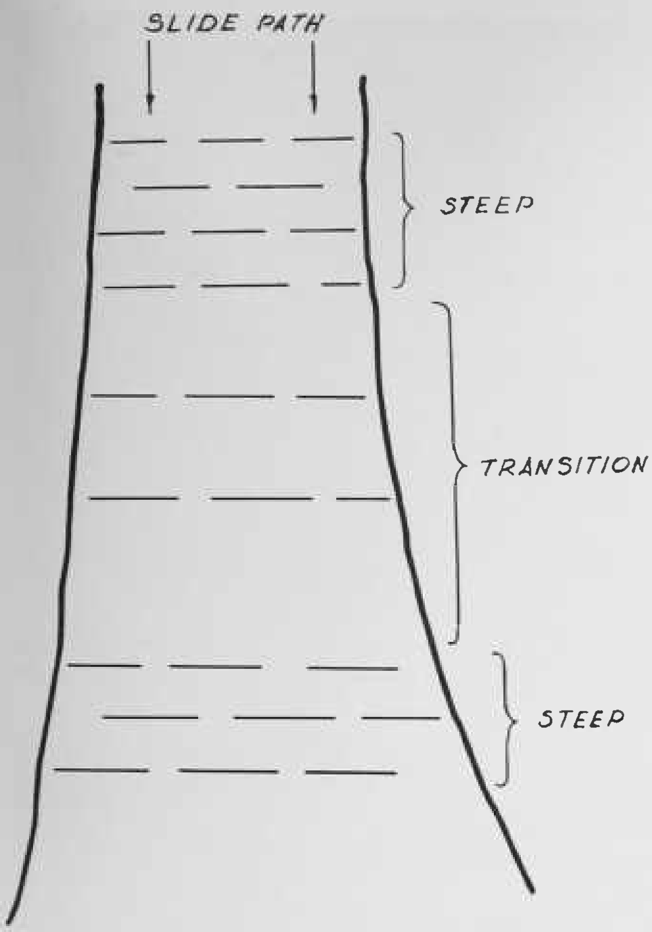


FIGURE 53.—Avalanche fence layout, interrupted pattern.

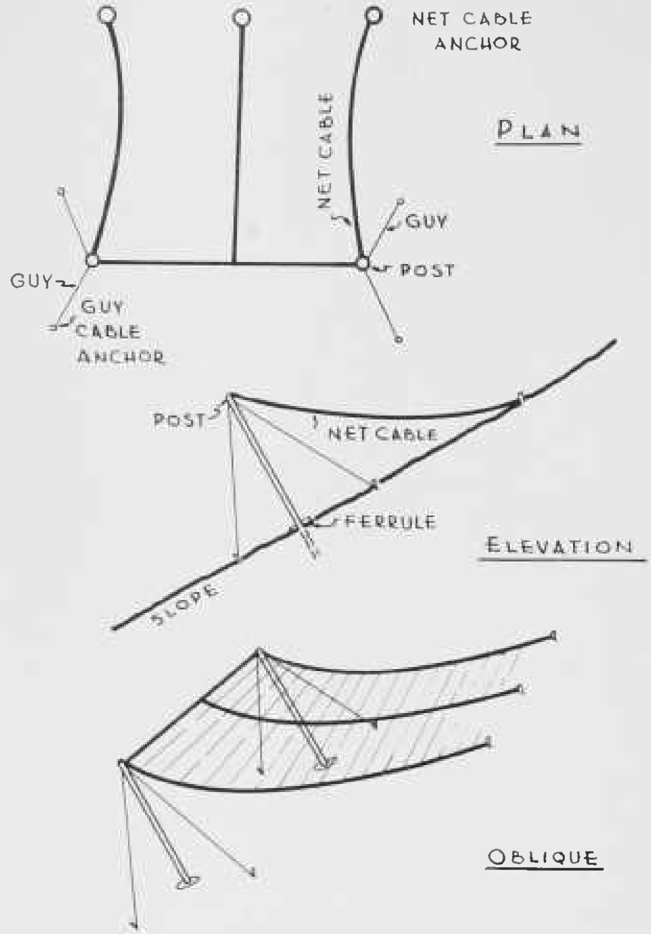


FIGURE 54.—Austrian avalanche net.

3. *Windbaffles, Drift Fences.* The windbaffle (Kolktafel) is a panel set at right angles to the prevailing wind in a slab area. It was based on the supposition that a system of these panels would break up the current of windborne snow and create islands of strength and discontinuity in any slab that did form and, perhaps, inhibit the formation of depth hoar. Baffles do some good but are not an absolute control. In Europe they are used to reinforce or supplement other defense measures (fig. 55).

Drift fences have long been used along highways to alter the fallout pattern of windborne snow. Strategically located fences can reduce the amount of snow deposited on an avalanche path by causing premature fallout. In a similar manner, a fence can modify the windflow over a ridge in such a way as to reduce or prevent the formation of overhanging cornices (fig. 56).

Conventional drift fences, made of wooden slats woven together with wire, are not strong enough for the winds that blow over the peaks. At the present time, the location, height, and spacing are a matter of trial and error on the ground. Every installation must be a tailormade job depending upon terrain, prevailing wind direction and force, amount of snowfall, vegetation, and nature of the hazard.

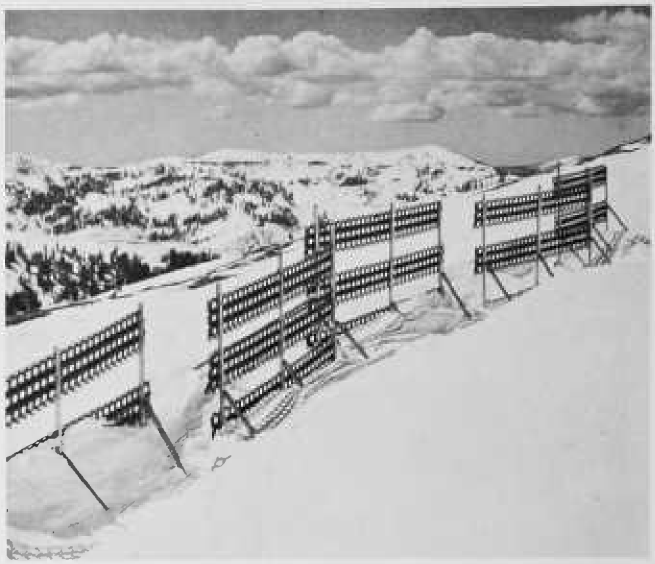
Emergency airfield mats have proved successful for fence material. They come in perforated steel panels 8 feet long and 18 inches wide, convenient to transport and erect. U-bolt fasteners make it possible to slide the panels up and down the posts for adjustments in height and airgap. With proper bracing they are strong enough to use as defense structures (fig. 57).

4. *Avalanche Mounds.* Mounds are a type of braking or diversion barrier. They are effective when installed on a slidepath that includes a transition zone. The crosscurrents, internal friction, and age-hardening process set up by the mounds in a falling avalanche reinforce the natural slowing down effect of the transition.

Avalanche mounds originated in Europe, where they have proved their value (figs. 58 and 59). A system of mounds has been constructed by the highway department on the Willow Swamp slidepath in southern Colorado that has proved to be successful. Mounds have effectively protected two lift towers and two lift terminals in Squaw Valley. In Alaska mounds have been installed to protect highways near Anchorage. These have proved very successful, including those constructed on a slope above Turnagain Arm where the mountainside falls steeply for about 3,000 feet without any transition slope. They have been particularly effective in arresting wet slides on these steep slopes (fig. 60).

F–495216
FIGURE 55.—Recently designed Austrian windbaffle, omnidirectional, tripod suspension, nose of baffle anchored to ground. The material is aluminum strips woven together with wire.

F–495217
FIGURE 56.—Arrow points to cornice on Squaw Peak, controlled by drift fence. Compare absence of overhang with adjacent, uncontrolled cornices.



F–495218
FIGURE 57.—Snow fences made of steel landing mats. These are used to prevent cornice formation near the summit of Squaw Peak, California (see fig. 56).

F–495219
FIGURE 58.—Arzler Alm and the original system of avalanche breakers. Arrow indicated the mound of waste material which was the model for present-day design. Note natural reforestation behind the breakers.

Where terrain favors the construction of mounds, they can be built economically and quickly with bulldozers out of the material at the site. Fill should always be taken from the uphill side of the mound. Spacing should be as close together as possible, leaving enough room between mounds so that equipment can work and get sufficient material. To be most effective they should be alternated as shown in figure 61, although exact layouts are not essential. The practical

F-495220

FIGURE 59.—Modern avalanche mound system, near Innsbruck, Austria.

height of mounds is generally 12 to 15 feet. However, 20 feet may be necessary in areas of exceptionally heavy snowfall.

Mounds have been successfully installed on grades up to 25 degrees and experimentally up to 35 degrees. The steeper the grade the longer the transition zone must be for an effective mound system.

9.3 Barrier Design Factors. Due to variations of terrain and climate, the following data must be taken as rules of thumb rather than exact formulas. Used in this manner, they are helpful guides in designing avalanche barriers.

1. The pressure exerted by snowcreep against a barrier, or any obstruction, can be estimated by using the formula in figure 62.

Experiments with pressure gages have revealed that the force exerted at the ends of a barrier is from two to two and a half times greater than at the center. These effects are due to the plastic nature of snow.

2. To determine the spacing of avalanche barriers, construct a right triangle using the slope as the hypotenuse (fig. 63). The perpendicular leg is a contant 45 feet. Project the horizontal leg until it intersects the line of the slope. The length of the hypotenuse determines the spacing of the barriers, under average conditions, for the particular grade. Once the profile of the slide-path is known it is possible to plot the barrier system on a map or diagram.

3. The following rules of thumb apply to the construction of barrier fences (fig. 64).

a. Distance between posts—8 feet to 10 feet

b. Distance between bars—4 inches to 6 inches

c. Fence angle—105 degrees on the uphill face

d. Support—35 to 40 degrees attached two-thirds height of fence

4. Under average conditions, the wind-shadow of a fence extends for a distance 11 times its height.

F–495221

FIGURE 60.—Earth mounds used as avalanche breakers near Girdwood, Alaska. Though a transition zone is absent on this slope, these mounds have proved an effective defense against wet slides.

9.4 Reforestation. From the long-range viewpoint all authorities agree that a forest is the best and most economical avalanche barrier. A century ago, according to Austrian engineers, there was no avalanche hazard at Innsbruck because of its screen of timber. The hazard has been created by forest fires and logging.

To be effective, the forest cover must be dense and extend to the avalanche release points.

Where forest cover has been destroyed by fire, logging, or climactic avalanche cycles, the problem is to reestablish the cover. Some great slidepaths are dormant for decades at a time and reforest themselves. Others are active every winter. Snowcreep often prevents the establishment of young trees. Reforestation on slidepaths, whether natural or by man, needs protection. Any avalanche defense project should include reforestation if feasible.

The practice in the Alps is to reforest immediately where mature timber has been destroyed by avalanche action and install barriers to protect the seedlings.

The Austrians and Swiss are experimenting with methods of protecting seedlings. Posts set on the uphill side give good results. Other protective devices include tripods and wickets. In many cases, trees are planted in the shadow of complete avalanche defense systems. The Austrians favor the "island method" of reforesting a denuded area or pushing timberline to higher elevations. They have learned from experience that the mortality rate is lower where seedlings are planted near established growth, even if it is no more than a bush.

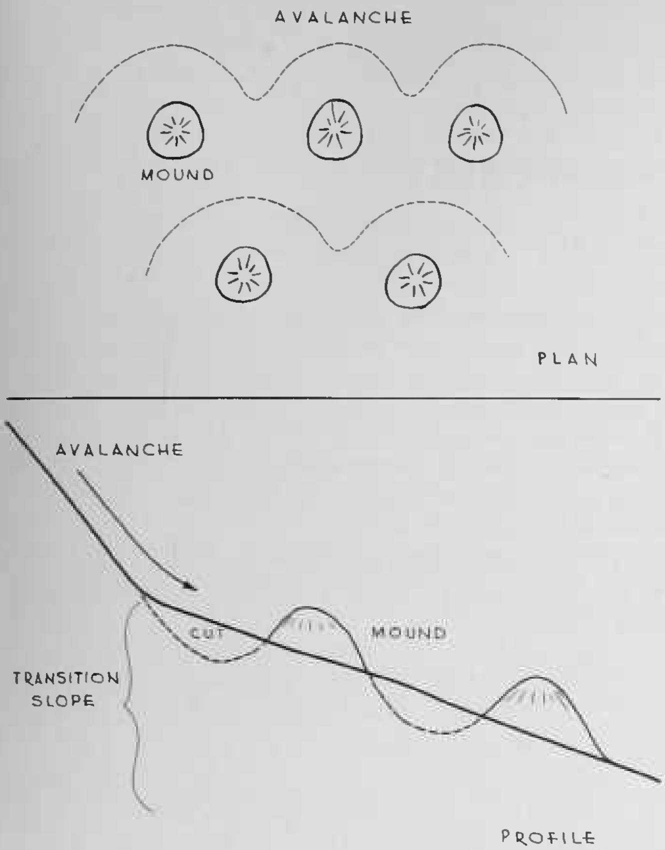


FIGURE 61.—Avalanche breakers.

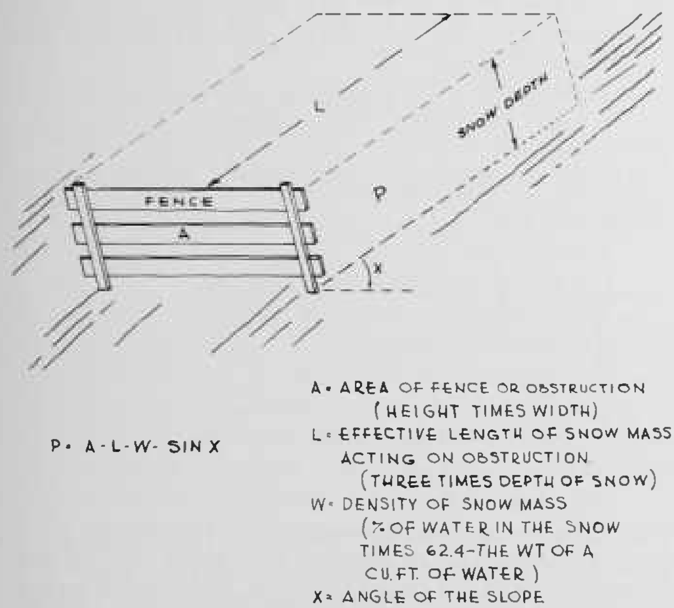


FIGURE 62.—The calculation of snowcreep pressure.

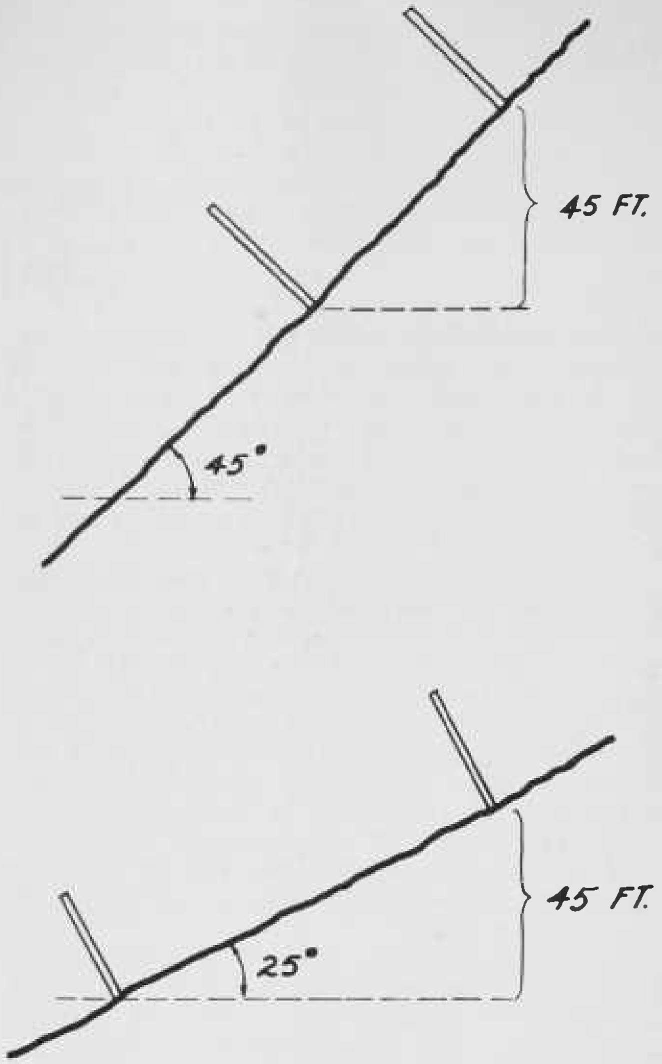


FIGURE 63.—Avalanche fence layout. The separation depends on the slope angle, the fences being located at 45-foot contour intervals.

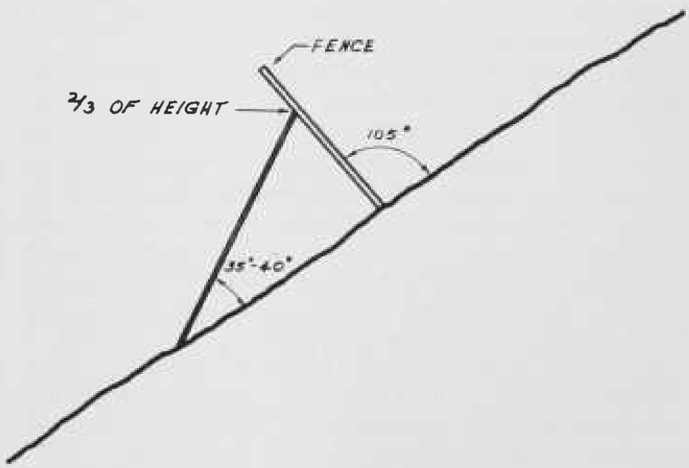


FIGURE 64.—Avalanche fence design, showing optimum angle of inclination and bracing arrangement.

Chapter 10

10 AVALANCHE RESCUE. Prompt and organized rescue operations are the only hope of getting the victim out alive if a human being is buried in an avalanche. There are records of persons who lived as long as 72 hours while buried. Ordinarily they are either killed instantly, or die within a short period from suffocation, bodily injury, or shock.

Investigations of a number of avalanche accidents, fatal and nonfatal, lead to the conclusion that 2 hours is the average survival limit. Snow is porous and ordinarily contains enough air to support life, though not consciousness. It appears that in about 2 hours an ice mask, from condensation of the victim's breath, forms an airproof seal around his face. Rescue operations are therefore designed to get the victim out within the 2-hour limit. Due to special circumstances which prolong the life of the victim—he may be in an air pocket—rescue operations must not be abandoned for at least 24 hours.

Successful avalanche rescue operations depend upon special equipment, trained leadership, and manpower. Darkness and storm are normal; parties setting out to participate in a rescue action must be prepared for the worst that weather and snow conditions have to offer. The rescue leader must dispatch only groups of men who are properly clothed, equipped, and in good physical condition to face the rigors of exhausting work in deep snow at high altitudes.

Obviously the accident would not have happened if avalanche hazard did not exist. This same hazard condition is a source of danger to the rescue party. Therefore, the highest degree of caution is required both during the march to the accident scene and while rescue work is in progress. In an avalanche rescue operation in 1958, two independent and uncoordinated parties set out for the scene. One of them, following high ground, dislodged a slide which buried a member of the other party below, resulting in a second fatality. The strictest observance of all precautions for traveling in avalanche terrain must be enforced to prevent such accidents.

Rescue operations of all kinds can easily become disorganized unless they are directed with a firm hand. The most effective rescue is one which is carried out with military precision and rigid discipline.

10.1 Rescue Equipment. Rescue equipment is needed imediately when an accident occurs. Rescue caches must be properly stocked and easily accessible, and their location and contents known to all who might have occasion to use them. Caches must be kept sealed until actually needed for a rescue operation. The establishment of properly stocked rescue caches must be one of the first steps in developing a ski area where avalanche danger may exist.

1. The minimum equipment that should be available at all times in a readily accessible location is as follows:

   - 12 probes, sectional preferred; otherwise metal rods, ½-inch diameter, minimum 12 feet long. Aluminum thick-wall conduit is recommended.
   - 12 snow shovels
   - 12 electric headlamps with carton of spare batteries
   - 100-foot climbing rope
   - Five yards of red flagging cloth
   - 200 feet of ¼-inch nylon cord
   - First aid kit (standard ski patrolman's kit satisfactory)
   - Toboggan with blankets. Collapsible toboggan preferred, light enough to be back-packed

2. The following additional equipment is recommended:

   - Emergency rations
   - Chemical hot pads for toboggan
   - Ski climbers in assorted lengths
   - Additional probes
   - Gasoline stove
   - Camp cook kit
   - Mountain tent
   - Gasoline lanterns
   - Portable radio

3. Highly trained German shepherd dogs have come into widespread use in the Alps. Time and again they have located buried avalanche victims rapidly and efficiently. Avalanche case histories show that buried victims have sometimes been located by untrained dogs who happened to be on the scene and instinctively joined in the search. Therefore, whenever possible a dog should be taken on rescue operations, whether he has been trained or not.

Proposals to locate victims with mine detectors or other unusual means have not as yet proved practical.

10.2 Immediate Action.

1. Snow ranger will take charge of rescue operations and sound general alarm. He should not hesitate to requisition any needed equipment or call for volunteers. All ski patrolmen and experienced skiers will be ordered to report to a central location.

2. The informant or eyewitness should be questioned on exact location of accident. Even if in poor physical condition, eyewitnesses should return to the accident location with the first party to point out where the victim was last seen. This is extremely important.

3. Dispatch the first party. A snow ranger does not necessarily lead this party. It must be in command of a reliable ski mountaineer and first aid man, preferably trained in avalanche rescue. It consists of not less than three persons. Five is a desirable number, large enough to do the work, small enough to travel fast. This party should be dispatched within 15 minutes after receiving the alarm.

4. The first party travels light with whatever equipment can be picked up at once. Speed is the first consideration.

5. Upon reaching the location of the accident, the leader posts an avalanche guard, unless he decides this is not necessary. Leaders are responsible for the safety of their parties. Avalanche guards must be kept on duty if there is the slightest danger of another slide in the same vicinity. Rescuers must know where to go in case of an alarm. If the danger becomes critical, leaders must not hesitate to call off operations.

6. Locate the spot where the victim was last observed and mark the "last seen" point so that it cannot be obliterated by wind or snowfall. From this point downhill, the first party makes a hasty search of the slide surface for the victim or any of his equipment.

7. If any indication of the victim is found, begin probing in the vicinity. If no indication is found, begin to probe in likely locations. These places are obstructions in the slidepath such as trees, boulders, or transitions, also the tip and edges of the slide. A human body is bulky and all other things being equal, is likely to be thrown toward the surface or the sides.

8. If the victim is found, give first aid. Unless danger of further avalanches is acute, the first party should not attempt to move the victim out of the area. Regardless of physical injuries, the victim must first be treated for suffocation and shock. Get the snow out of nose and mouth. Apply artificial respiration if breathing has stopped. Get the victim warm, applying body heat if nothing else.

10.3 Followup Action.

1. In a well-organized ski area, the followup party can usually start in half an hour. It must start within an hour. It goes completely equipped for extended rescue operations with everything except food. It may be dispatched in groups with at least probes and shovels.

2. The snow ranger will serve as leader after notifying the county sheriff or designated disaster authority. People not physically qualified for the exhausting work of rescue should not be taken. They can help by preparing and transporting supplies.

3. In the 30 to 60 minutes at his disposal, the snow ranger will organize and equip the followup party, notify authorities outside the area of the accident and of possible need for further help. He will obtain, if possible, the correct name or names of victims and appoint a leader to take charge of any further reinforcements and equipment.

4. Before beginning to probe, the followup party must make a thorough search of the slide. They should form a single line, shoulder to shoulder, and march back and forth across the slide debris kicking and scuffing at the snow to uncover any additional clues and possibly the victim or his equipment, which might lie somewhere just under the surface. Systematic probing of the slide begins at the tip and works up the fall line toward the last-seen point (fig. 65). Rescuers are spaced shoulder to shoulder and probe every square foot (fig. 66 and 67). If the victim is not located on the fall line below the last-seen point, or the latter is not known, the entire debris cone must be systematically probed. It is very important to mark the probed areas as the search is completed, so that no effort is wasted by duplication (fig. 68). Flags or other markers for this purpose are an essential part of the rescue equipment.

5. The first party may be relieved and sent out of the area. Exhausted rescuers will become casualties themselves if allowed to remain. They can carry messages giving an estimate of additional equipment and assistance needed.

6. Shovel crews will accompany the probers, relieving them at intervals and digging in any likely spots. They should be prevented from digging haphazardly and wasting energy.

7. Small slides may be systematically probed in a few hours. Large slides may take much longer, especially if the snow is deep and hard. If the probing action is unsuccessful, the slide must be trenched. This work, where possible, should be under the supervision of the county sheriff.

8. Trenches are dug parallel to the contour down to ground level or undisturbed snow at intervals of 6 feet. If sectional probes are available the interval can be increased to 10 feet. Digging begins at the tip of the slide and proceeds uphill. It is best to space the shovel crews along one trench with frequent reliefs. In this way snow from one trench can be thrown into the one just dug.

9. The operation ceases to be of an emergency type if trenching is necessary. A constant system of relief crews must be organized.

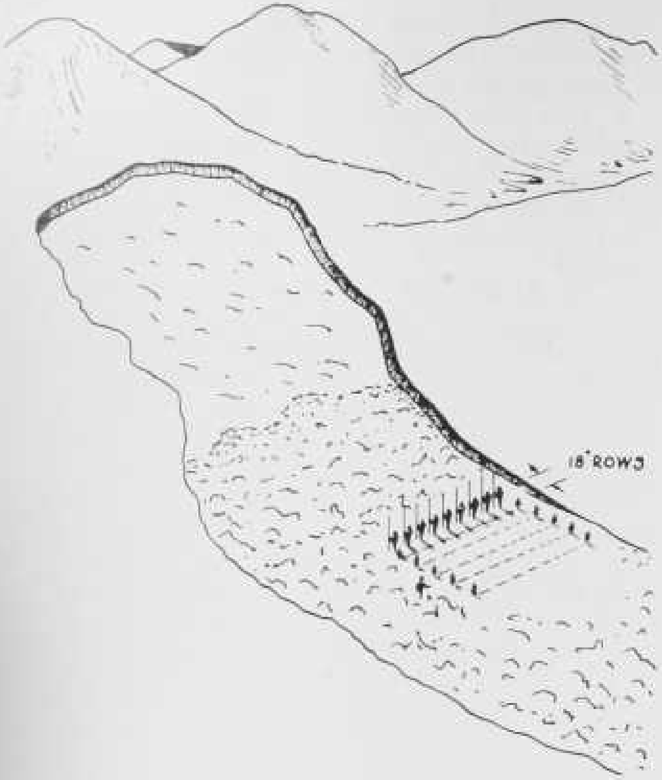


FIGURE 65.—Arrangement of a probing line on an avalanche path. It is much easier for the probers to keep in a straight line if two men hold a string to mark location for the probes, and move this marker forward each time the line advances.

F–495222

FIGURE 66.—Close-interval probing requires insertion of the avalanche probe by the right foot, between the feet, and then by the left foot. The prober then advances one step and repeats the sequence. Such close probing is especially important in deep avalanche debris (see fig. 67).

10.4 Avalanche Accident Report.

1. Date, time, and location of accident.
2. Names of victim and other members of party, with any information on their mountain experience.
3. Summary of events leading up to accident; departure point, route, and objective of party.
4. Eyewitness account of accident, if available. Otherwise, observer's deductions based on tracks and any other evidence. Important points are: location of skier in relation to release point of slide; how was slide released?
5. Summary of rescue operations. Times and names are important.
   Time of accident.
   Time report of accident received and from whom.
   Time first party dispatched. Leader. Number in party.
   Time first party arrived at scene of accident.
   Time followup party dispatched. Leader. Number in party.
   Time followup party arrived at scene of accident.
   Procedure at slide.
   Time and location of victim when found, injuries sustained.
   Cause of death or injury.
   Time operation was concluded.
6. Weather and avalanche hazard background; wind, temperature, and snow data; restrictions in force, if any; type of slide and extent.
7. Terrain data, including maps and diagrams.
8. Recommendations and conclusions.

10.5 Case Histories.

1. Case History No. 1 (fig. 69).
   a. *Members of party:* A and B, guests at ________________, excellent skiers; enthusiastic but inexperienced ski mountaineers. C and D, ski instructor and ski patrolman, respectively, excellent skiers and experienced mountaineers.

      Events leading up to accident: C and D were going to test the __________ Run, known to be dangerous at that time. A and B went along at their own request.

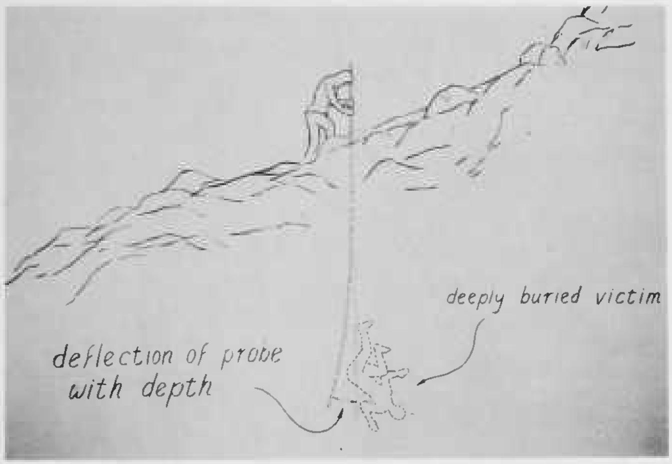


FIGURE 67.—Why a close probing interval is necessary.

F—495223

FIGURE 68.—String marker method used to guide probing operations. The string shown tied to the ski pole is moved one foot ahead after the complete line has been probed. The other string stays in place as a permanent marker for the area probed.

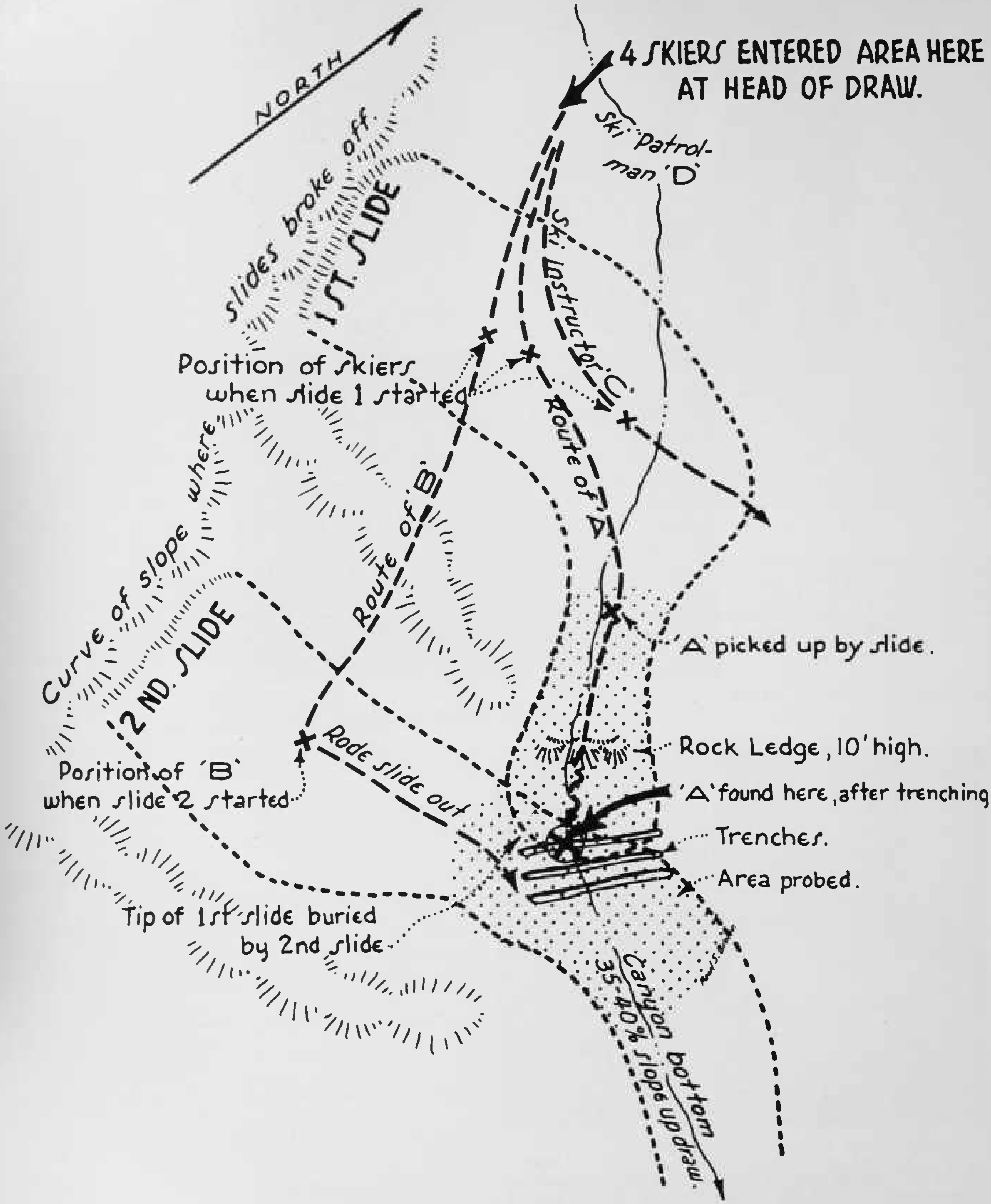


FIGURE 69.—Avalanche accident. Case 1.

b. *The accident:* C skied onto the slope, followed immediately by A and B. Slab, plus dry snow, avalanche fractured while all three were on the slope. C made an experienced mountaineer's typical test run of a doubtful slope: a short fast dip in and out of the danger zone. Only the edge of the slide touched him. B and A went farther out onto the slope. B, nearest to the release point, managed to ski out to one side. A attempted to outrun it straight down the gully. He went over a rock ledge, apparently fell, and was picked up there by the slide. B, looking for A, went out onto another avalanche slope and started a second slide which buried the tip of the first one.

c. *Rescue operations:* Rescue operations were prompt, considering the distance from help, and were well organized. Accident happened at 2 p.m. First party reached the scene at 3:30 p.m. Followup party reached the scene at 9:45 p.m. Victim was found at 5 a.m. the following morning. Elapsed time: 15 hours. Cause of death: suffocation. Immediate action was unsuccessful. Systematic probing was unsuccessful. Body was finally located by trenching.

d. *Weather and hazard data:* Successive storms followed by prolonged cold. Snow had not settled and was unstable.

e. *Conclusions:* The following errors were the direct cause of accident:

(1) A and B went onto the slope at once instead of waiting for C to complete his test run.

(2) A and B went too far onto the slope.

(3) A tried to outrun the avalanche.

(4) The second slide started by B complicated rescue operations. Under the conditions set, the only possible means of locating A quickly would have been a trained dog.

2. *Case History No. 2.*

a. *Location:* An alpine highway.

b. *Members of party:* A, highway crew foreman and B, in a pickup truck; C and D, plow operators in a rotary snowplow; E, supply truckdriver; 1, 2, 3, skiers traveling the highway on foot.

c. *Events leading up to the accident:* At high elevations a prolonged and severe storm was in progress. Because of the hazard the highway was closed to public travel, and it was blocked by snowslides. The weather was cloudy at the elevation where the pickup truck and the snowplows were operating. The plow was working in a slide; the pickup was parked a short distance behind. An avalanche observer had earlier warned the highway crew of the hazard and recommended no traffic of any kind.

d. *The accident:* An avalanche on the same track as the one that had already blocked the road buried both the plow and the pickup. The rotary plow, being higher and heavier than the pickup and close to the uphill bank, withstood the force of the slide. C and D were trapped in the cab but not injured. The pickup, parked near the downhill bank, took the full force of the slide. All glass was broken. A and B were packed in the cab as if in concrete. The avalanche was probably a temperature-released slab.

e. *Rescue operations:* E, the driver of the supply truck, arrived on the scene shortly after the accident. He saw the exhaust stack of the rotary, which projected out of the snow, and freed C and D. The three then departed to get help without attempting to locate the pickup. On the way out of the canyon they encountered the three skiers traveling on foot, and told them what had happened. The skiers proceeded to the avalanche, found the pickup by means of its radio mast, and dug out A and B with their skis and hands. A recovered quickly, but B was dead.

f. *Weather and hazard:* See above.

g. *Terrain data:* The accident happened where a known major avalanche path crosses a highway.

h. *Conclusions:* The accident was caused by failure to heed a definite hazard warning and failure to recognize the possibility of a repeater avalanche. It was faulty technique to have both vehicles and all members of the party exposed to the same slide. If C and D had remained behind to look for their companions while E went for help, there would probably have been no fatality.

i. *Recommendation:* All men working in hazardous areas should receive avalanche rescue training.

Chapter 11

11 AREA SAFETY PLANNING. Use of an area exposed to avalanche hazard requires a systematic snow safety plan. This plan is tailormade to fit the area. A safety plan for an isolated structure like a mine building could scarcely be applied to a highway extending for many miles. Neither plan would have much value for a complex development such as a winter sports area.

All safety plans, regardless of the type of use or character of the area, have the same objective—maximum use with adequate safety. Knowing the type of use contemplated or already developed, the observer proceeds according to the following:

1. Terrain analysis
2. Climate and weather analysis
3. Hazard classification
4. Operations plan.

11.1 Terrain Analysis. Terrain analysis should be made on the ground. It is desirable for the observer to see the area in both winter and summer (fig. 70). Photomaps of excellent quality are almost a necessity for this work. Topographical maps are of limited value for analysis, since they lack sufficient detail. They can be used to record the results after an analysis has been made. The low oblique photomap is the most desirable, followed by ground level panoramas and verticals. Vertical photomaps have a special value in locating cross-country routes. Generally it is possible to pick out the major slidepaths at once and make a tentative route selection.

The purpose of the terrain analysis is to identify the slidepaths and the zones of safety, to estimate the effect of natural barriers, and to determine the hazard pattern of the area. This pattern will govern the location of improvements. Buildings are placed to take advantage of the natural barriers. If this is impossible for any reason, the fact must be noted and recommendations made for protection by other means. It is seldom possible, for instance, to survey an alpine highway on an entirely protected route (fig. 71). However, a hazard reconnaissance prior to construction will suggest ways of reducing the number of avalanche paths which must be crossed.

For a winter sports development, the layout of the ski runs is as important as the location of buildings (figs. 72 and 73). Minimum hazard areas must be identified. Lift sites are chosen so that they not only open up desirable ski slopes but also make it possible to protect the people using them. The lift line itself requires careful study so that terminals and intermediate towers will not exposed to avalanche danger as in figure 74.

F–495224

FIGURE 70.—*Terrain analysis:* (1) Major slide paths. (2) Lesser slide paths. (3) Narrow gully. (4) Cornice formation. (5) Convex slope. (6) Concave slope. (7) Safe area, no avalanche danger. (8) Cliffs and steep lee slopes (fracture zone). (9) Gentle, open slopes—beginner's ski area. (10) Possible lift location. (11) Arrow points to existing lift terminal just beyond pass. Almost all slopes shown are accessible from this lift. Albion Basin, Alta, Utah.

F—495225

FIGURE 71.—An example of avalanche hazard. A major avalanche path, with vertical relief of nearly 4,000 feet, overhangs the access highway leading to a major ski resort. Protective measures used are road closures during high hazard, and artificial release of avalanches by artillery fire.

The trend in lift design is changing as a result of damage to lift lines caused by avalanches. It used to be thought necessary to install a lift on many towers so that the cable would closely follow the land profile. Numerous towers multiply the exposure to avalanche hazard—and snowcreep, which can be just as destructive. Modern design utilizes a minimum number of towers and long spans extending over the avalanche paths.

Protection of the lift line and structures from avalanche hazard and snowcreep should always be fully considered.

11.2 Climate Analysis. It is more difficult to make a climate and weather analysis than a terrain analysis. In a new area, the data are usually incomplete. The kind of information an avalanche observer wants generally is not recorded. Some information is always obtainable by studying the available records, by questioning inhabitants or people familiar with the area, and by studying the conditions on the ground. Persistence and ingenuity are required. In one case, a snow ranger recommended minimum lift clearances on the basis of snow course records at a station 20 miles away but in a similar location. The recommendation was generally thought to be excessive, but it was accepted and proved to be correct the next winter.

Ordinarily, an original climate and weather analysis must be based on superficial data: some temperature, maximum snow depth, and total precipitation records; some word-of-mouth history of avalanche occurrence. To these, the inspector adds his own observations in the field: prevailing wind directions, snow types, and storm characteristics. This information, even though fragmentary, should permit him to form some opinion on the predominating types of hazard.

11.3 Hazard Classification. After analysis of the terrain, climate, and weather, the next step is a hazard classification of the area (fig. 75). Identifications must be accurate and should be plotted on a map. All factors must be considered: grade, contour, and dimensions of the various slopes; natural barriers; exposure to wind and sun; type of use; the avalanche history of the location, and the protective measures that will be available. Four degrees of hazard are recognized:

1. *Minimum hazard.* This classification indicates practical absence of hazard. Examples: A building fully protected by natural or artificial barriers; a slope not likely to avalanche.
2. *Low intermittent hazard.* This indicates occasional exposure to avalanches of dangerous size. Examples: A slope not steep enough to avalanche in dangerous volume except under extreme conditions; a structure close enough to a slidepath to be damaged under climax avalanche conditions.
3. *High intermittent hazard.* This indicates areas frequently subject to avalanches of dangerous size. Example: A high-angle slope of sufficient dimensions so that hazard is likely to exist with every major storm or under delayed-action avalanche conditions. (The distinction between low and high intermittent hazard is frequency.)
4. *High intermittent hazard, not controlled.* Indicates highly hazardous areas which are not feasible to control.

The classification of an area may be changed if protective measures are applied. Thus an area would take a lower classification if it were put under stabilization by use, explosives, or barriers. The reverse situation is also possible.

11.4 Operations Plan. The final step in snow safety planning is to formulate a plan of operations. Where a number of different activities are involved, such as a ski area and a highway, with several cooperating agencies, the operations plan can be complex. Ordinarily it is a brief and simple outline of procedure. A snow ranger, well trained and thoroughly familiar with his area, seldom needs to look at it. He knows it by heart. The same is not true for his successor or a temporary replacement. Either could easily get into trouble without a systematic plan of action. The following is a plan outline:

Snow Safety Operations Plan

- I. Objective
- II. Responsibility
  1. Leadership and control
  2. Finance
  3. Personnel
  4. Equipment and facilities.
- III. Table of Organization
  1. Snow Safety Leader
  2. Assistants
  3. Reinforcements.
- IV. Table of Equipment
  1. Rifles
  2. Explosives
  3. Snow-Weather-Avalanche observation equipment
  4. Communications
  5. Rescue equipment
  6. Transportation, wheeled and oversnow
  7. Signs.
- V. Table of Facilities
  1. Explosives magazine and field caches
  2. Headquarters
  3. Gun towers
  4. Shelters
  5. Barriers
- VI. Procedures
  1. Area hazard classification
  2. Protective measures
  3. Opening and closing procedures
  4. Restrictions procedures: signs
  5. Sequence of avalanche control operations
  6. Search and rescue

Where national-forest land is involved, a snow safety plan approved by the forest supervisor is customarily a permit requirement. It covers ski patrol functions and plans for handling other

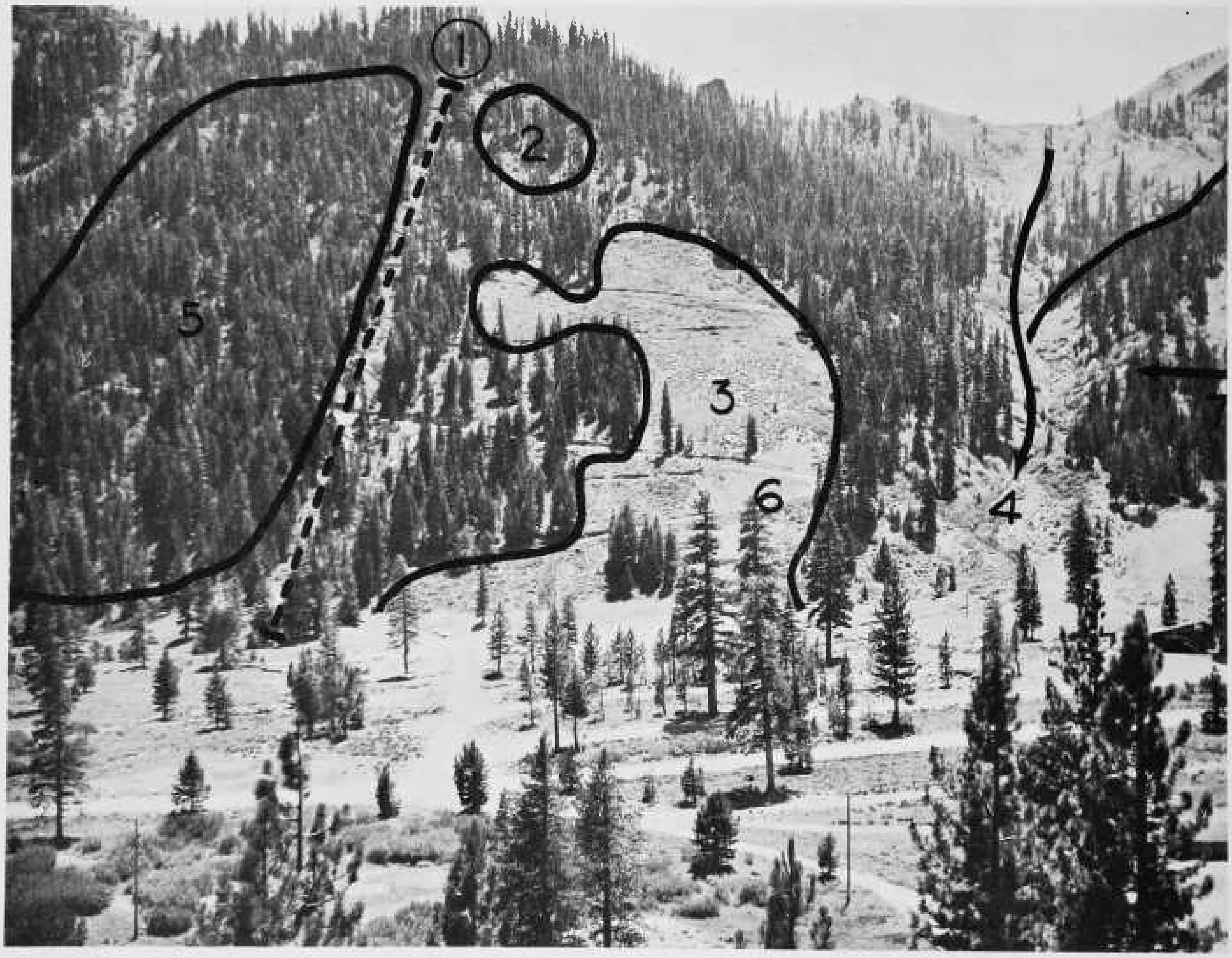


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FIGURE 72.—A new ski slope in the process of development. (1) Lift line partially cleared. (2) Only observed avalanches on the mountain originate in this area of scattered timber. (3) A natural clearing. (4) An avalanche gully flanking the new area. (5) Area of heavy timber, very steep but completely stable. (6) Construction road. Switchbacks screened behind timber. Arrow at right, prevailing wind direction. The slope faces north.

hazards related to ice, breakable crust, insufficient snow cover, high wind, low visibility, and lift operations.

Where possible a snow safety reconnaissance should be made in advance of development. This would insure a sound basic safety plan taking advantage of natural barriers for the protection of major installations, and reducing the need for expensive artificial protection measures to a minimum.

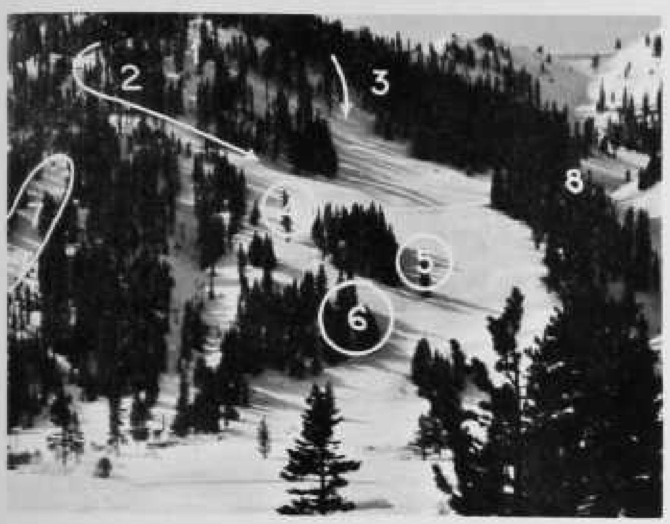

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Figure 73.—The slope shown in figure 72 after development. (1) The liftline, held to minimum width for wind protection. All defective trees removed. (2) A ski trail cut around the mountain. (3) Ski trail partially cleared around the other side of the mountain. Timber between trails left for avalanche protection. Tree clumps below are also left so that no avalanche path the full length of the slope is created. (4, 5, 6) These isolated trees and part of the clump were later removed. (7) Jumping hill. Tree screen retained for wind and avalanche protection and to act as a natural barrier between skiers and the avalanche gully.

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Figure 74.—Avalanche destruction of a lift tower.

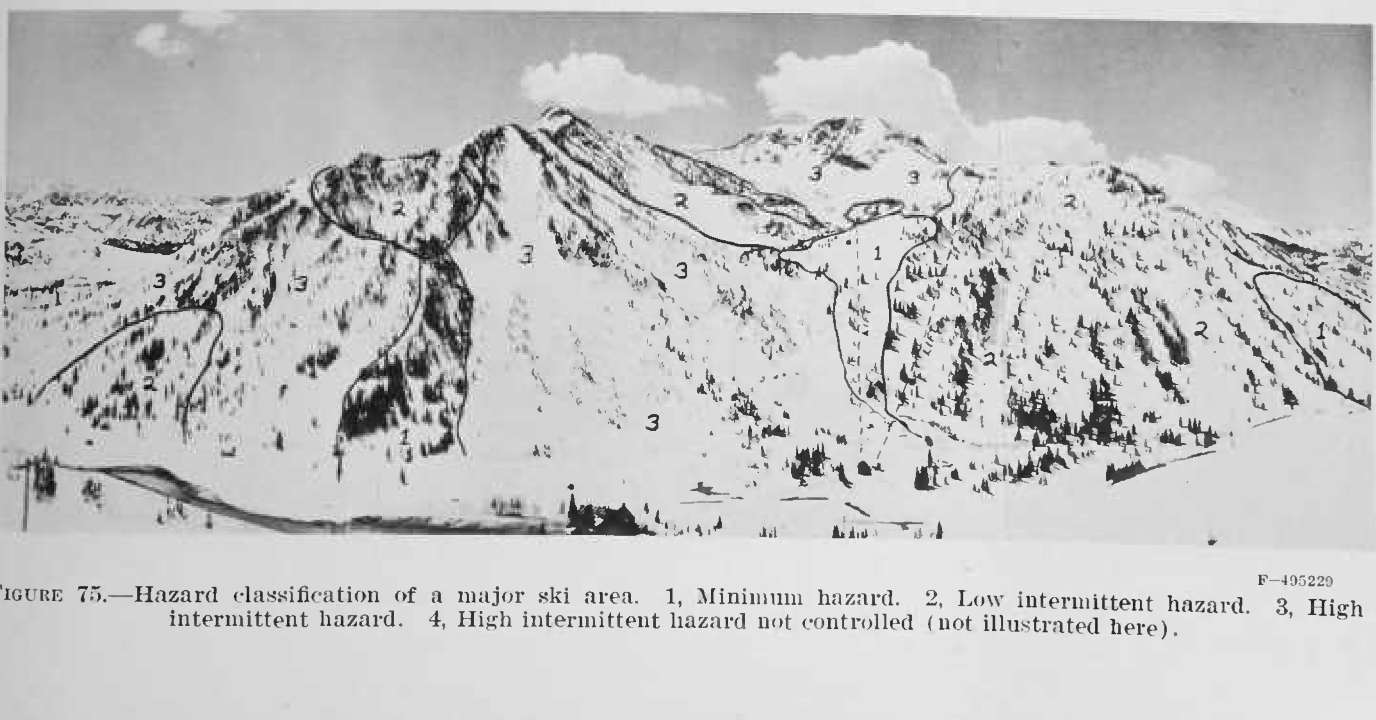

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Figure 75.—Hazard classification of a major ski area. 1, Minimum hazard. 2, Low intermittent hazard. 3, High intermittent hazard. 4, High intermittent hazard not controlled (not illustrated here).

Bibliography

The following list encompasses some technical references on snow and avalanches available in the English language. There exists a large body of literature in other languages—principally German, French, Italian, Russian, and Japanese—in the form of texts and articles or papers in periodicals. A more complete bibliography of this literature is available on request from the Forest Supervisor, Wasatch National Forest, Salt Lake City, Utah.

The classic work in English has long been "Snow Structure and Ski Fields" by Gerald Seligman. This well-illustrated book has been out of print for a long time, and accessible copies are rare.

Some of the more important Swiss texts have been made available in English by the U.S. Army Corps of Engineers' Snow, Ice and Permafrost Research Establishment (referred to below as SIPRE). Most important of these is "Snow and its Metamorphism," a standard reference on snow mechanics published in Switzerland in 1939.

Bader, H., R. Haefeli, E. Bucher, *et al.*
January 1954. Snow and its Metamorphism, SIPRE Translation No. 14.

Bucher, E.
February 1956. Contributions to the Theoretical Foundations of Avalanche Defense Construction, SIPRE Translation No. 18.

Fuchs, Alfred
July 1955. Avalanche Conditions and Avalanche Research in the United States with Recommendations for Future Work, SIPRE Technical Report No. 29.

Fuchs, Alfred
July 1957. Effects of Explosives on Snow. SIPRE Special Report No. 23.

Nakaya, U.
1954. Snow Crystals. Cambridge: Harvard University Press.

Rikhter, G.
August 1954. Snow Cover, its Formation and Properties. SIPRE Translation No. 6.

Roch, Andre
April 1956. Mechanism of Avalanche Release. SIPRE Translation No. 52.

Seligman, G.
1936. Snow Structure and Ski Fields; With an Appendix on Alpine Weather by C. K. M. Douglas. London: MacMillan and Co. Ltd., 555 p.

Yosida, Z.
1955 and 1956. Physical Studies on Deposited Snow, I. Thermal Properties II. Mechanical Properties. Contribution to the Institute of Low Temperature Science. Sappro, Japan: Hokkaido University No. 7 and No. 9.

Various authors
1951. Review of the Properties of Snow and Ice. SIPRE Report No. 4.

For additional papers and texts on the general subject of snow and ice, see List of Publications, U.S. Army; Snow, Ice and Permafrost Research Establishment; Corps of Engineers, July 1959.

The technical journal which carries papers on various aspects of snow physics and occasionally on avalanches is the Journal of Glaciology, published twice a year by the British Glaciological Society.

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