Snow Avalanches of the Wasatch Front

By R. I. PERLA

ENVIRONMENTAL GEOLOGY OF THE WASATCH FRONT, 1971

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Missing 1 Jan 1879 1 fatal
@ Alta, Emily Gulch (N. side)
via Charles Kelly Faint Trails

in

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SNOW AVALANCHES OF THE WASATCH FRONT

By R. I. PERLA[1]

INTRODUCTION

Each winter the "white death" thunders down from the great snow bowls, ravines, and gullies of the Wasatch. Indeed, the Wasatch Mountains have all the ingredients for avalanche disaster: steep alpine terrain, plenty of snow, and proximity to a large population center. Historically, the greatest toll from Wasatch avalanches was suffered by the early miners. Bowman (1967) estimates that 250 lost their lives between 1865 and 1939. The largest single disaster was the 1885 destruction of Alta City, the mining camp in Little Cottonwood Canyon, when avalanche followed by fire took over 15 lives. During that disaster avalanches dumped 15 meters[2] of snow on Alta's Main Street.

As shown in table 1, avalanche death and destruction in the Wasatch and other parts of northern Utah continued with 167 recorded deaths during the 1860-1939 period. Seventy-five percent of these deaths occurred in the Wasatch Mountains.

In recent years the death rate has been lower, but the avalanche disasters have continued. No deaths were recorded in 1940, but during the 1941-July 1971 period, 11 lives were lost in 9 avalanches (fig. 1).

Perhaps some lives were lost during the early days with a full understanding of the perils of living and working in avalanche paths; avalanches were just one more hazard in a traditionally unsafe life. However, most tragedies

Table 1.–*Avalanche deaths and property damage in northern Utah, 1860-1939*

County and area	Date	Number of people killed	Property damage
Cache:			
Logan Canyon	Feb. 6, 1884	2	No.
Do	Feb. 10, 1889	1	Yes.
Davis:			
Centerville Canyon	Jan. 25, 1860	1	No.
Farmington Canyon	Jan. 1, 1939	1	No.
Do	Jan. 31, 1939	1	No.
Juab:			
Tintic (Eureka)	Feb. 8, 1899	0	Yes.
Salt Lake:			
Big Cottonwood Canyon	Feb. 5, 1872	2	No.
Do	Jan. 20, 1875	6	Yes.
Do	Mar. 3, 1875	1	No.
Do	Feb. 17, 1882	7	Yes.
Do	Feb. 8, 1899	0	Yes.
Do	Jan. 31, 1911	3	Yes.
Bingham Canyon	Feb. 12, 1885	2	Yes.
Do	Feb. 8, 1899	2	Yes.
Do	Feb. 17, 1926	40	Yes.
Do	Feb. 9, 1939	4	No.
City Creek Canyon	Feb. 15, 1865	4	No.
Do	Jan. 17, 1899	0	Yes.
Little Cottonwood Canyon	Dec. 26, 1872	10	Yes.
Do	Jan. 11, 1875	4	Yes.
Do	Jan. 19, 1875	6	Yes.
Do	Dec. 25, 1875	1	Yes.
Do	Dec. 29, 1876	2	No.
Do	Mar. 11, 1877	2	No.
Do[1]	Jan. 12-17, 1881	15	Yes.
Do	Mar. 7, 1884	12	No.
Do	Feb. 13, 1885	15	Yes.
Do	Mar. 2, 1889	0	Yes.
Do	Jan. 20, 1906	6	Yes.
Do	Jan. 31, 1911	1	No.
Mill Creek Canyon	Apr. 1, 1864	2	No.
Do	Apr. 1, 1869	3	No.
Summit:			
Park City	Feb. 18, 1884	3	No.
Do	Jan. 21, 1886	3	No.
Tooele:			
Ophir Canyon	Mar. 14, 1876	1	Yes.
Do	Feb. 17, 1926	0	Yes.
Do	Feb. 26, 1939	3	No.
Utah:			
American Fork Canyon	Jan. 12-17, 1881[2]	------	------
Provo Canyon	Feb. 8, 1899	0	Yes.
Do	Jan. 30, 1911	0	Yes.
Do	Feb. 16, 1926	0	Yes.
Summit Canyon	Jan. 16, 1875	1	Yes.
Weber:			
Ogden Canyon	Mar. 2, 1899	0	Yes.

[1] Includes American Fork Canyon, Utah County.

[2] Included under Little Cottonwood Canyon, Salt Lake County.

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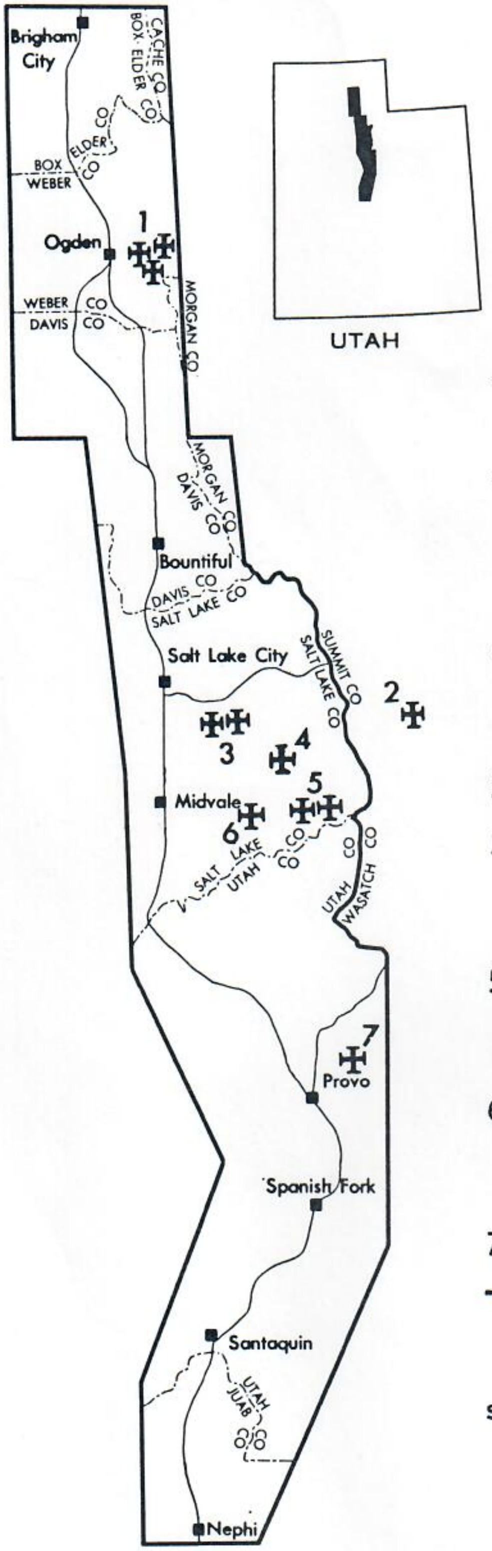
[1] Avalanche Hazard Forecaster, U.S. Forest Service, Alta Avalanche Study Center, Alta, Utah 84070.

[2] In avalanche studies, the metric system of measure is used internationally. Metric units used in this paper, their abbreviations, and their approximate equivalents in inches, feet, and miles are as follows:

10 millimeters (mm) = 1 centimeter (cm) = 0.394 inch.
100 centimetrs = 1 meter (m) = 39.4 inches or 3.28 feet.
1,000 meters = 1 kilometer (km) = 3,281 feet or 0.62 mile.



EXPLANATION

Locality[1]	Date	Number of deaths
1 Snow Basin	Mar. 9, 1958	2
	Mar. 29, 1964	1
2 Park City ski area[2]	Dec. 31, 1965	1
3 Grandeur Peak	Feb. 12, 1967	2
4 Big Cottonwood Canyon	Mar. 21, 1943	1
5 Alta ski area	Jan. 1, 1941	1
	Jan. 29, 1970	1
6 Little Cottonwood Canyon	Mar. 27, 1950	1
7 Rock Canyon	Feb. 19, 1968	1

[1] Identified by number on map. Death sites are shown by Maltese cross.

[2] On east slope of Wasatch Range.

Figure 1.–Map of Wasatch Front showing locations of avalanche deaths, 1941 to July 1971.

were probably due to the early settler's inexperience with the forces of moving snow—forces which can tear buildings apart, snap off 200-year-old trees as though they were toothpicks, and even pick up and move railroad cars. Certainly, it is easy now, as it was then, to underestimate the energy stored in the soft white blanket while it rests peacefully on the mountainside. The energy is great. For example, it is common for Superior Peak to unleash a slope of snow, the size of a football field and a meter thick, across the Little Cottonwood road at a speed of 200 km per hour. Such a moving mass of snow carries enough energy to momentarily supply the electrical needs for a city of more than 3 million people (fig. 2).

With the depletion of high-grade ores and the demonetization of silver, the high mining camps of the Wasatch became virtually deserted. Then, in 1938, with the advent of the Little Cottonwood Canyon road, a more determined breed than the miner became noticeable in the high country—the skier. In 1939 the Wasatch ski industry was inaugurated with the Collins lift at Alta and, since World War II, the industry has been growing steadily with the addition of a new lift almost every year. To appreciate the rapidly expanding winter usage of the Wasatch, compare for example, that 50,000 cars entered Little Cottonwood Canyon from January to March, 1965, while the usage for these months jumped to 80,000 in 1970. Because of the concentration of Wasatch canyons, especially in the Big Cottonwood-Little Cottonwood area, the possibility of a large interconnected ski complex may become a reality, and the Wasatch ski resorts, as much a result of their excellent snow conditions as their linked terrain, may be able to absorb an increasing proportion of the country's exploding ski population.

Of course, the growth in winter usage is a growth in public exposure to the avalanche hazard. The above-mentioned 80,000 cars, for example, traversed beneath a dozen large avalanche paths, each one a potential producer of an avalanche capable of destroying a car and its occupants (figs. 3 and 4). Today, the havoc once risked by the Wasatch miner is now risked by skiers on slopes in ski areas; skiers, snowshoers, snowmobilers, and hikers traveling in the back country; highway users; autos parked in avalanche paths; and winter and summer resort facilities and included people.

Avalanches in the Wasatch Mountains are related directly to climatic conditions, which are summarized in table 2 from 25 years of climatological measurements taken at Alta, Utah, elevation 2,700 m. As a result of the acute lifting effect exerted by the Wasatch peaks (general elevation 3,000-3,600 m) on moist layers of air,

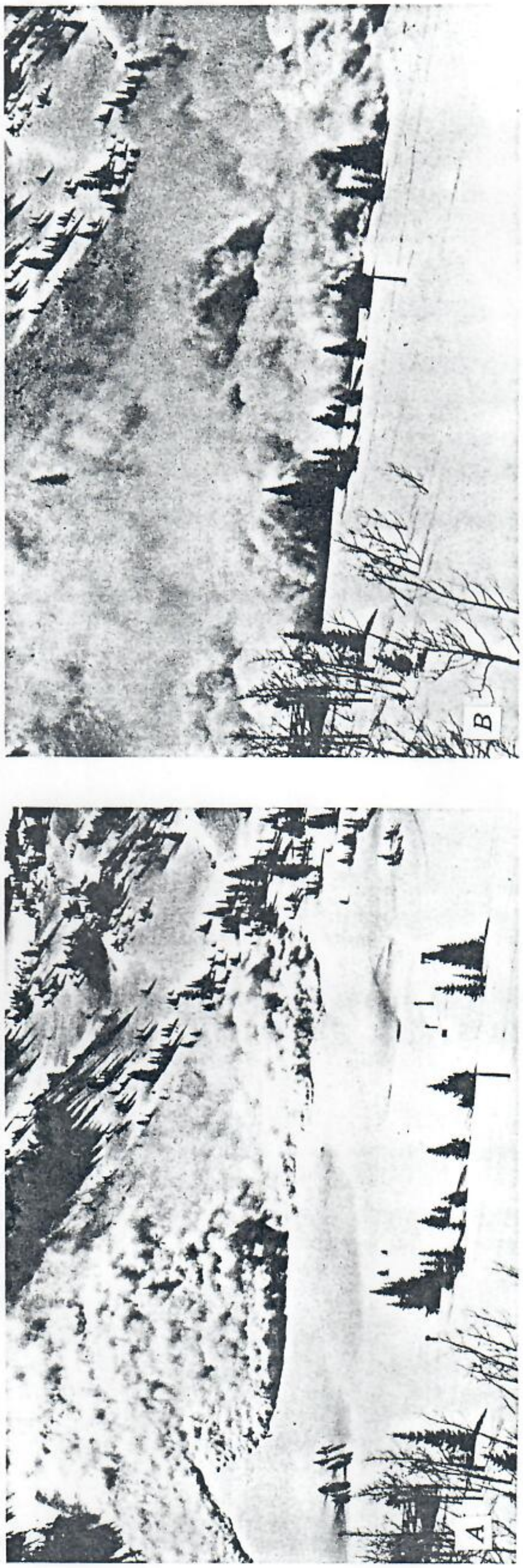


Figure 2.—Avalanche descending near Alta, Utah. Wave front in left view, *A*, is 10 to 30 m high and about 200 m wide. Note the explosive power shown in right view, *B*, as avalanche reaches canyon bottom. Some avalanches reach velocities of 300 km per hour.

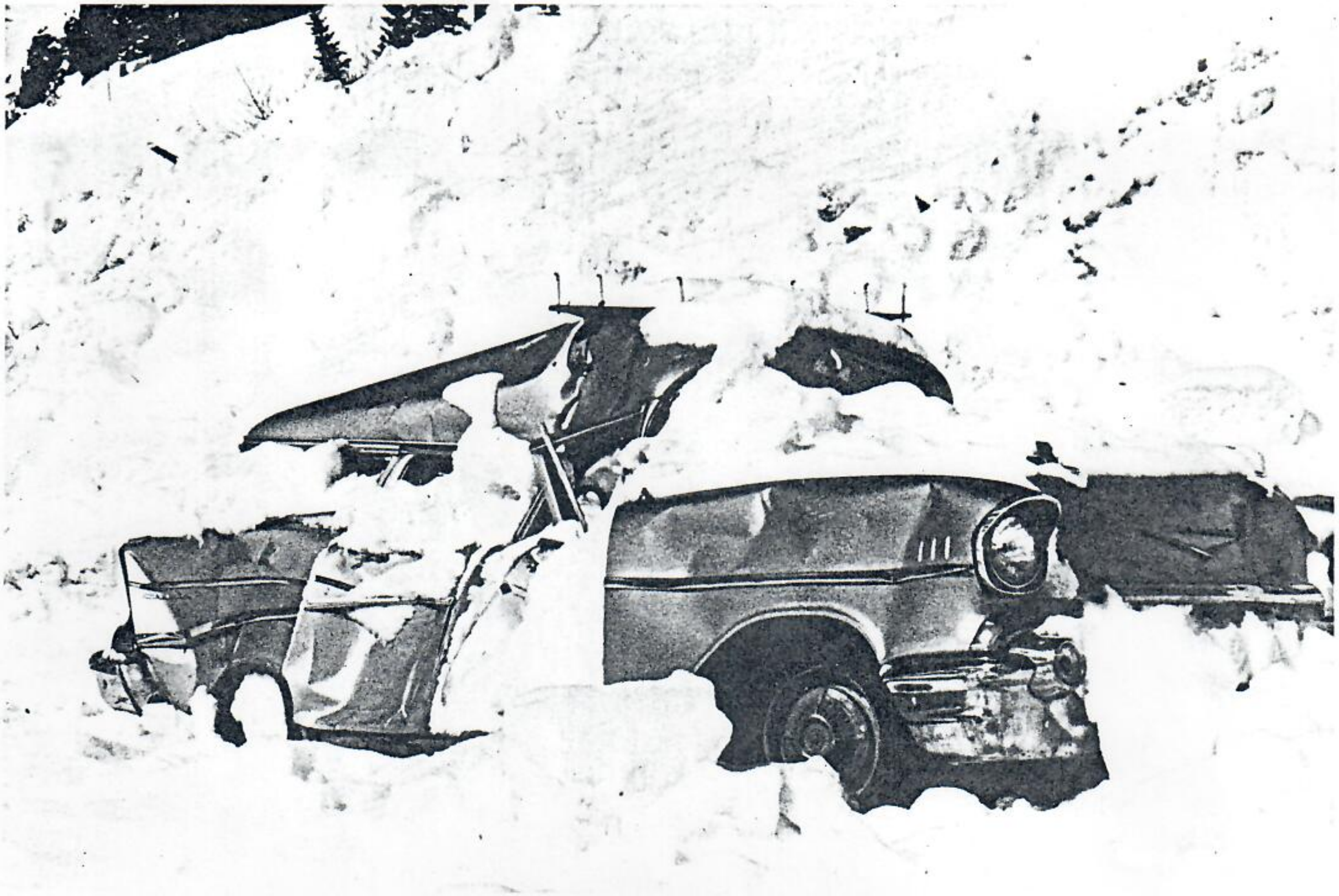


Figure 3.–Destruction of auto in February 1969 avalanche at Alta, Utah.

the high stations of the Wasatch, typified by Alta and Brighton, receive an abundant supply of winter precipitation, roughly an order of magnitude more than falls at the Salt Lake Valley stations (elevation about 1,350 m). Compared with other mountain ranges in the United States, the Wasatch receives more snow than the Colorado Rockies, but less snow than Pacific Coast ranges. Temperaturewise, the Wasatch Mountains are again in between, being somewhat colder than the Pacific ranges, but warmer than the Colorado Rockies. The Wasatch avalanche potential is greatest during January through April, but large avalanches are observed sometimes as early as mid-November, and avalanches from the flank of Superior Peak have crossed the road as late as June 1. Normally, a meter of snowpack, as measured at the Alta Ranger Station, is required before the terrain is covered enough for the avalanche hazard to become widespread. Usually this minimum depth is not achieved until mid-December.

As shown in table 2, the average water content of the Alta snow is slightly less than 1 part water to 10 parts snow. Lightweight snow would have a water content closer to 1 to 20; hence, Alta snow is not particularly light, and is in fact slightly heavier at time of deposition than snows observed in other ski areas. Thus, the fine powder skiing conditions of the Wasatch must be traceable to other factors than the average weight of the newly fallen snow. One explanation of Alta's unique ski conditions, which is also instructive with respect to avalanche conditions, pertains to the structure of the Wasatch storms.

Generally, storms begin at relatively warm temperatures and, consequently, start with relatively high snow densities. The wind initially has a strong south component, but as the storm progresses, the wind veers toward the north, the temperature drops, and the snow falls at relatively low densities. Thus, the new snowpack is a light fluffy layer resting on a heavier layer. It is the heavy layer which gives flotation to the skis and enables the skier to manip-

Figure 4.–Avalanche on Little Cottonwood Canyon road, at foot of Tanner Gulch, January 1965.

Table 2.–*Climatic data related to avalanche conditions at Alta, Utah, 1945-70*

Month	Snowfall (cm)	Water content (cm)	Maximum snow depth on ground (cm)	Number of days snowfall was $\geq$ 30 centimeters	Avalanche days	Mean daily temperature (°C)[1]	
						Maximum	Minimum
December..........	224	20.6	153	2.16	8.14	+0.3	–9.5
January..............	232	22.2	226	2.12	10.34	–1.1	–11.0
February............	200	18.2	266	2.00	9.04	–0.4	–10.3
March................	214	20.2	306	1.92	10.49	+0.4	–9.5
Totals.....	870	81.2	......	8.20	38.01	....	....

[1] Centigrade (Celsius) scale: 0°C corresponds to 32°F and 100°C corresponds to 212°F, the freezing and boiling points of water, respectively. To convert the above-listed numerals to the Fahrenheit scale, multiply by 1.8 and subtract from 32.

ulate in the lighter surface layer. At the concluson of the storm, the atmosphere returns to a dry, clear state. Low atmospheric humidity coupled with the high elevations enables the snow to lose heat to the atmosphere through radiation loss and thus enables the snow to remain light and dry. It is interesting, as well as fortunate, that the same density distribution that is conducive to fine skiing also is conducive to stable avalanche conditions.

But the powder skiing in the Wasatch is not always excellent and avalanche conditions are not always stable, as there are deviations from the normal pattern of light snow falling on heavy snow. More important, internal changes, called *metamorphisms,* occur within the snowpack to upset the stability balance. Before discussing in more detail the conditions of avalanche formation, it may be profitable to look first at what constitutes an avalanche zone.

LOCATION OF AVALANCHE ZONES

Although it is usually possible to determine if an avalanche has recently overrun an area, it is not always possible to decide with certainty whether a particular site is safe from avalanches. Had all the avalanche paths been recorded since the pioneer settling of Utah, there would still not be a complete catalog of Wasatch avalanches. In this connection, much can be learned from the alpine countries of Europe. For example, a Swiss church was completely destroyed after standing for 655 years (Fraser, 1966), and also consider that it is yet common for 100-year-old Swiss buildings to be demolished. Disasters such as these have led the Swiss to zone their land into three groups: (1) Categorically exposed to avalanches, (2) marginal, and (3) categorically safe from avalanches (Frutiger, 1970). After much debate, the Swiss authorities concluded that development on marginal land, as well as on categorically exposed land, should be protected against avalanches, even if it was uncertain that an avalanche could overrun the proposed development. One has only to watch the newsreels of villagers recovering the bodies of their relatives from the wreckage of buildings and snow to sympathize with the stand of the Swiss authorities.

An avalanche zone consists of three subzones: The *starting zone,* the *track,* and the *runout-damage zone* (fig. 5). Starting zones are high, steep mountain faces where the initial snow failure takes place. Dangerous avalanches originate on slopes which have an inclination from 30° to 50°. Above 50°, the slope is too steep to accumulate large amounts of snow.

After initial failure, the snow runs down its *track,* knocking loose more snow according to a complex loss and gain of energy. The length, inclination, terrain irregularities, and vegetation of the track determine the snow energy that will be delivered to the runout zone where the fixed facilities or proposed developments are located. It must be emphasized that where human life, as opposed to a structure, is endangered the avalanche zone need not be large to be devastating. From available U.S. statistics (Gallagher, 1967), nearly half of the ski area fatalities occurred in runout zones having a length of less than 100 m, which is an order of magnitude smaller than the zones which threaten entire villages.

In planning new construction, all sites in the Wasatch which are below mountain faces and gullies should be suspect and examined by persons experienced in avalanche problems. Gullies are especially dangerous since they tend to concentrate the flow of moving snow. Clearly, the most dangerous combination is the high, steep bowl which empties into a gully. It is necessary to inspect a proposed site for avalanche hazard in the winter as well as summer. Winter inspections show how the high terrain tends to fill in with snow, and to what extent the seemingly protective vegetation is covered. Of course, intense avalanche cycles may be associated with unusual winters so that it also is necessary to extrapolate for additional contingencies. A summer inspection for tree damage provides many clues for identifying an avalanche zone. One should look first for outright destruction of trees at the base of a suspected path (fig. 6). Further information on the size and frequency of avalanches is given by the age and type of trees. Aspens grow relatively quick so that a mature aspen stand may represent only a 25-year period of grace between destructive cycles (fig. 7). On the other hand, alpine firs tend to grow in the shade of aspens and to reach maturity much more slowly. Thus, the presence of large firs may indicate as much as 100 years since the last destructive avalanche. A sign of less complete destruction is the lack of branches on the uphill side of trees. A striking example of this effect is shown in figure 8, a photo taken near a recent commercial development in an avalanche area of Little Cottonwood Canyon. Tall, flexible trees, however, are not always a sure sign of safety, as they may be bent over by an avalanche and later return to an upright position little worse for the ordeal.

Contrasted against the total number of avalanche zones in the Wasatch, which must be a very large number indeed, many zones have become well known mainly as threats to existing facilities and thus stand out in importance. For instance, in the northern part of the Wasatch Mountains, in Logan Canyon, U.S. Highway 89 crosses beneath several large avalanche paths. During the January 11-15, 1971 period, an avalanche cycle struck this area; although no human lives were lost, the damage was as follows: (1) 70 m of highway guardrail and roadside vegetation destroyed,

Figure 5.–View down avalanche zone of Tanner Gulch, Little Cottonwood Canyon. Barren path through young aspen growth beyond gulch defines the runout zone to where it crosses road in canyon bottom.

Figure 6.–Destruction of young aspen trees from avalanche off south buttress of Superior Peak. Trees are prevented from maturing by repetitive avalanches.

(2) $10,000 damage to the City of Logan water supply, (3) 270 m of telephone line destroyed, (4) U.S. Forest Service campground land and wildlife habitat damaged and two deer killed, and (5) three summer homes destroyed (total loss $21,000).

In the southern part of the Wasatch Mountains, large avalanches are regularly observed as far south as Mt. Nebo, near Santaquin.

In the central Wasatch, avalanches run into the American Fork and Provo Canyon areas, but facilities along the Big Cottonwood and Little Cottonwood roads, especially near Alta, are subject to intense avalanche hazard. The following is a description of some of the well-known slide zones in the Big and Little Cottonwood Canyons area.

The *Storm Mountain* slide (fig. 9, avalanche zone 1) is the westernmost threat in Big Cottonwood Canyon. Starting at 3,500 m elevation, high on Twin Peaks, the slide generally runs down Stairs Gulch, across the Big Cottonwood Canyon road, and onto the Storm Mountain picnic area (elev. 1,900 m), for a total drop of 1,600 m—a full mile! This spectacular slide is active down Stairs Gulch several times each season, but fortunately runs its full track only about once in 10 years. After a run, avalanche deposits can be found in Stairs Gulch throughout the summer.

Several slides of moderate size cross Big Cottonwood between Storm Mountain and Mill A Gulch (fig. 9, avalanche zones 2 and 3), but in the vicinity of Mill A Gulch, three large slides converge on the road: *Circle Awl* (zone 5) strikes from the north, down from the ridge between Butler Fork and Mill A Basin; *Argenta* (zone 4) and

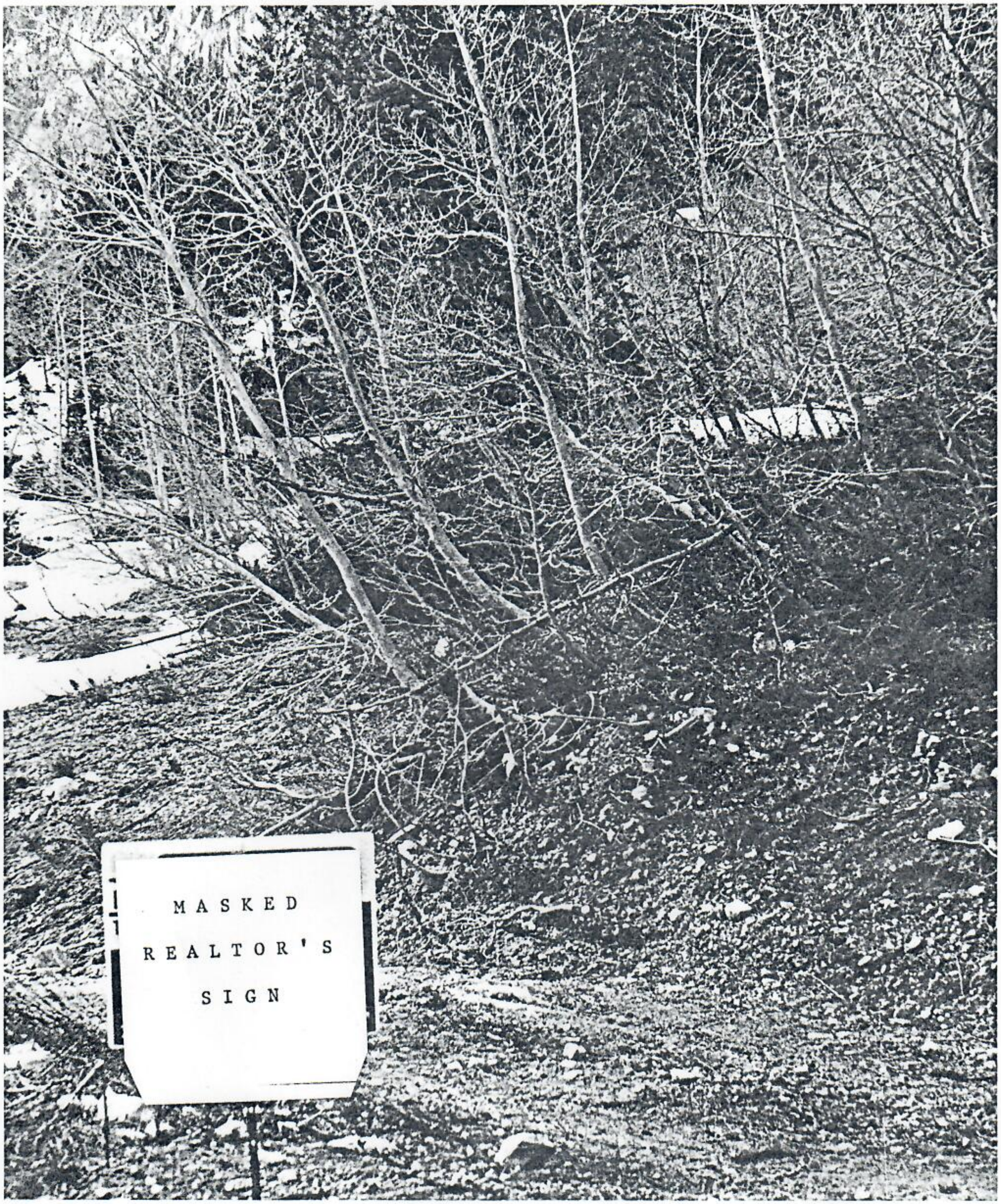


Figure 7.–Young aspen trees at base of avalanche path, Wasatch canyon area. These trees are younger than 25 years, indicating destruction of previous growth. Realtor's sign promotes land sale presumably for building development.

Figure 8.–Avalanche damage to alpine firs near commercial development. Larger trees may be as much as 100 years old. Note severe damage on uphill, left side, of mature trees.

Kessler (zone 6) strike from the south down from the slopes of Kessler Peak. *Argenta*, in particular, can deposit large amounts of snow. After a 1948 avalanche cycle, it took two seasons for Argenta's snow debris to melt completely. The *Grand Central* (zone 7) slide strikes from the north in the vicinty of Mill D Gulch (Mill D North Fork). Farther east, the Big Cottonwood road is relatively free from avalanche hazard.

In the Little Cottonwood Canyon area, the westernmost threat runs down an alluvial fan, from the south, just west of Coalpit Gulch (zone 8). This slide runs only a portion of its track each season, and has not crossed the canyon road since 1948. However, in March 1948 it filled the road so full of debris that the plows had no place to push the snow, and it was necessary to bridge the slide. In spite of the rather obvious peril, in 1967 a housing development was planned directly in the path of the runout zone.

Farther east on Little Cottonwood Canyon road, many steep gullies descend from the left (north) directly onto the highway. These are in fact the most concentrated group of large avalanche paths in the Intermountain Region.

A high shoulder of Sunrise Peak (across from Maybird Gulch) is the starting zone for the first habitual path (zone 9) which runs directly onto the road. This path may either cross the road in a relatively narrow band, or, as was observed in 1965, bend and follow the road for about 0.5 km.

The next path, *Tanner Gulch* (zone 10), originates just below the summit of Dromedary Peak (elev. 3,700 m), runs down to Tanner Flat (elev. 2,370 m), and occasionally runs across Tanner Flat onto the road (see figs. 4 and 5), sometimes leaving a 10-m-high pile of snow debris.

Sunrise, *Tanner*, and several smaller slides just east of Tanner, will each run by *natural release* across the road about once in 5 years. However, these slides can be activated more frequently by explosives (*artificial release*).

Whereas the avalanche hazard diminishes at the eastern and higher part of Big Cottonwood Canyon, the hazard becomes greater at the eastern and high part of Little Cottonwood Canyon. Two large gullies (zones 11 and 12) opposite White Pine Fork run naturally to the road one or more times per season. The high bowls under the west

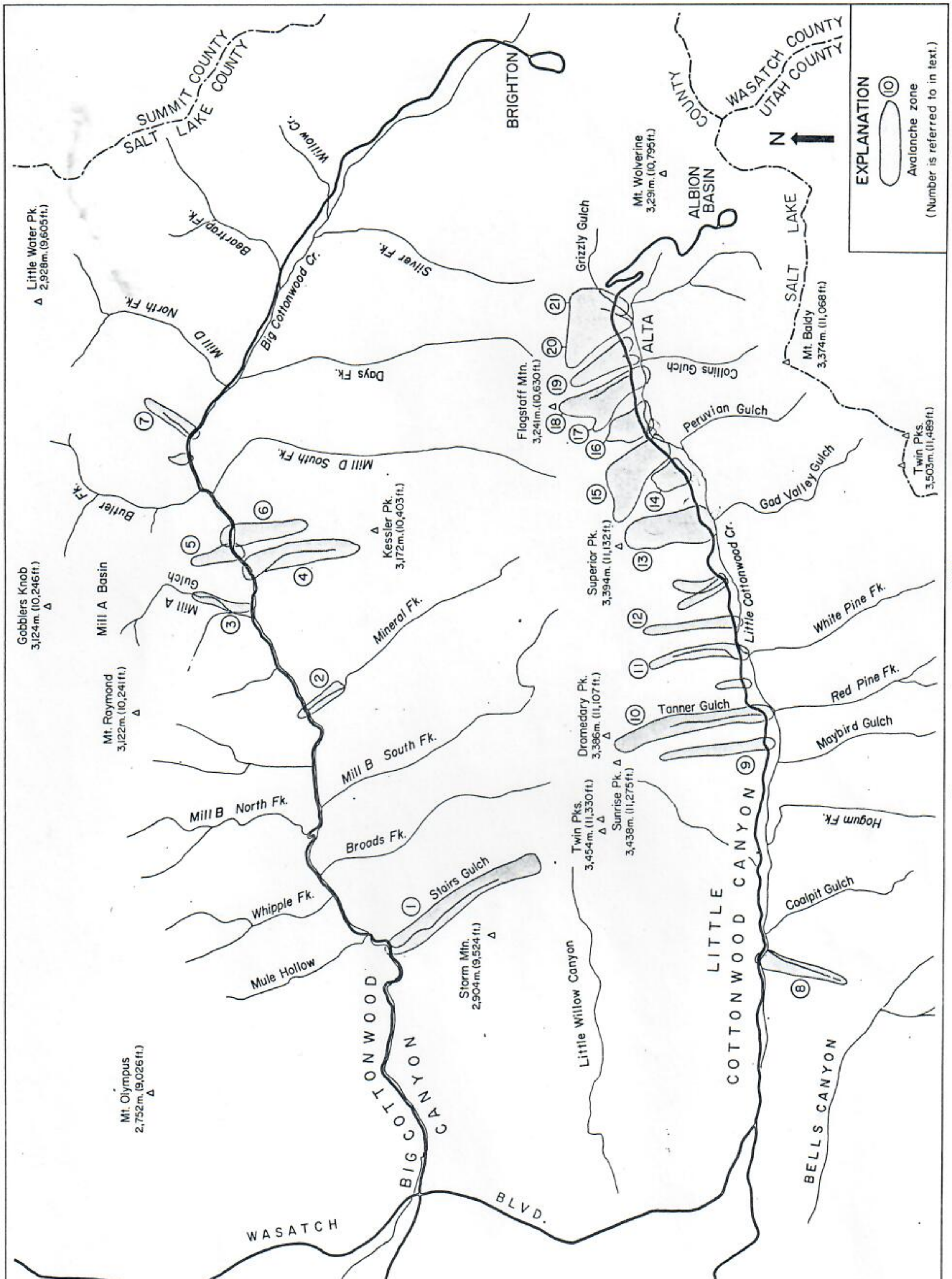


Figure 9.–Map of Big and Little Cottonwood Canyons area and some well-known avalanche zones.

summit (zone 13) of Superior Peak form a very large snow catchment area and a starting zone for several large avalanches which run down gullies in the vicinity of Number Ten Spring. A house was recently constructed on the east margin of this slide area.

Farther east is the *Superior Peak* slide area. Under normal conditions, the south buttress (zone 14) of Superior Peak is blown free of snow, and hence will pose only a minor threat, during most seasons, to a housing development that presently is under construction at its base. Across from the south buttress, on the south side of Little Cottonwood Canyon, a new ski area is being developed, which, with the tramway lift line, is interlaced with serious avalanche problems. Still farther east, one can look up the 1,000-m mountain face to the east summit of Superior Peak. From this face, at least three avalanches per season can be counted on to crash directly onto the road at the foot of Superior Peak's many slide paths (zone 15). Attesting to this avalanche frequency is the runout zone, at elevation 2,700 m, which is nearly devoid of trees.

Immediately east of Superior one enters the *Hellgate* slide area (zone 16). Here, the starting zones are high bowls above the Hellgate cliffs. The impact of the snow pouring down over the cliffs can set off secondary avalanches along a wide area. In 1965, the Hellgate avalanches completely destroyed one residential cabin, did minor damage to another, and several old mining cabins were totally destroyed.

East of Hellgate one enters the Alta area, a precariously situated village which is under avalanche threat from all sides. Two large avalanche-producing slopes, situated on the south-facing side of Flagstaff Mountain (zones 17 and 18), release slides which converge down a single gulley. The runout-damage zone of this gulley contains a parking lot and a ski lodge. About once in 5 years, snow strikes the ski lodge—so far, fortunately, causing only minor damage. Another avalanche, which also runs its full track about once in 5 years, originates on the shoulder of Flagstaff Mountain (zone 19) and drops down a series of gullies directly into the center of the present Alta village. So far, avalanches in this zone have split up, passing on both sides of a cluster of buildings but, nevertheless, repeatedly causing minor damage to Alta's oldest ski lodge. Needless to say, the avalanche debris adds greatly to the congestion of an already cramped complex of roads, parking areas, and lodges. In spite of the congestion, and avalanche danger, an element of luck has staved off disaster. Recently, for example, a new residence was planned in a site which was supposedly free of Flagstaff's reach. Fortunately, an avalanche overran the proposed site just before construction, thus heading off development, at least for the present.

Across from Flagstaff, Alta ski lifts lead up directly into the avalanche country on the south side of the canyon. So far, one ski lift has been destroyed by avalanches (fig. 10), and two lifts have been hit, but suffered no damage. In the 1964 cycle, a large avalanche released by explosives from the shoulder of Mt. Baldy stopped within 100 m of the warming shelter, and engulfed a large portion of Alta's most popular ski runs. This avalanche was released artificially as part of the Forest Service's protective program. Had such an avalanche released naturally on a weekend ski crowd, it could have killed hundreds. In 1967, three U.S. Forest Service officers (including the author) nearly lost their lives in an avalanche accident which occurred while they were blasting a cornice which was overhanging the ski area. There have been many other close calls in the main ski area and along the back-country touring routes. The avalanche zones can be perilous and must be respected, or lives will be lost needlessly.

Historic Alta City, located at the eastern end of the present Alta village, was harassed by avalanches from both north- and south-facing slopes. The deathblow was delivered in 1885 by an avalanche from the south-facing Emma Ridge (zones 20 and 21), a long ridge which connects Flagstaff with Grizzly Gulch. In that avalanche, and from the fires that followed, more than 15 people lost their lives and much of the village was destroyed. In later years, Alta has fared better but the peril remains. In 1941, the Emma avalanche neatly removed the second storey of a lodge which was under construction. A slanting, reinforced concrete roof added to the surviving first storey successfully withstood a repeat performance when Emma ran in 1964. Another cabin, built below Emma in the presumed safety of a clump of aspens, however, was cut in half during the 1964 cycle.

CONDITIONS OF AVALANCHE FORMATION

Snow avalanches can be classified into two categories: The *point release* and the *slab release*. Both categories are observed in all mountain ranges, including the Wasatch. In the nomenclature of the more well-known mechanisms of land-slope instability, the point release is related to the *rotational* failure of soil bodies, while the slab release is related to *block-glide* failure of cohesive strata over a weak substratum, or discontinuity (fig. 11).

The point release usually begins with a rotational failure of a relatively small volume (less than a cubic meter) of cohesionless snow. Reduced cohesion may be a conse-

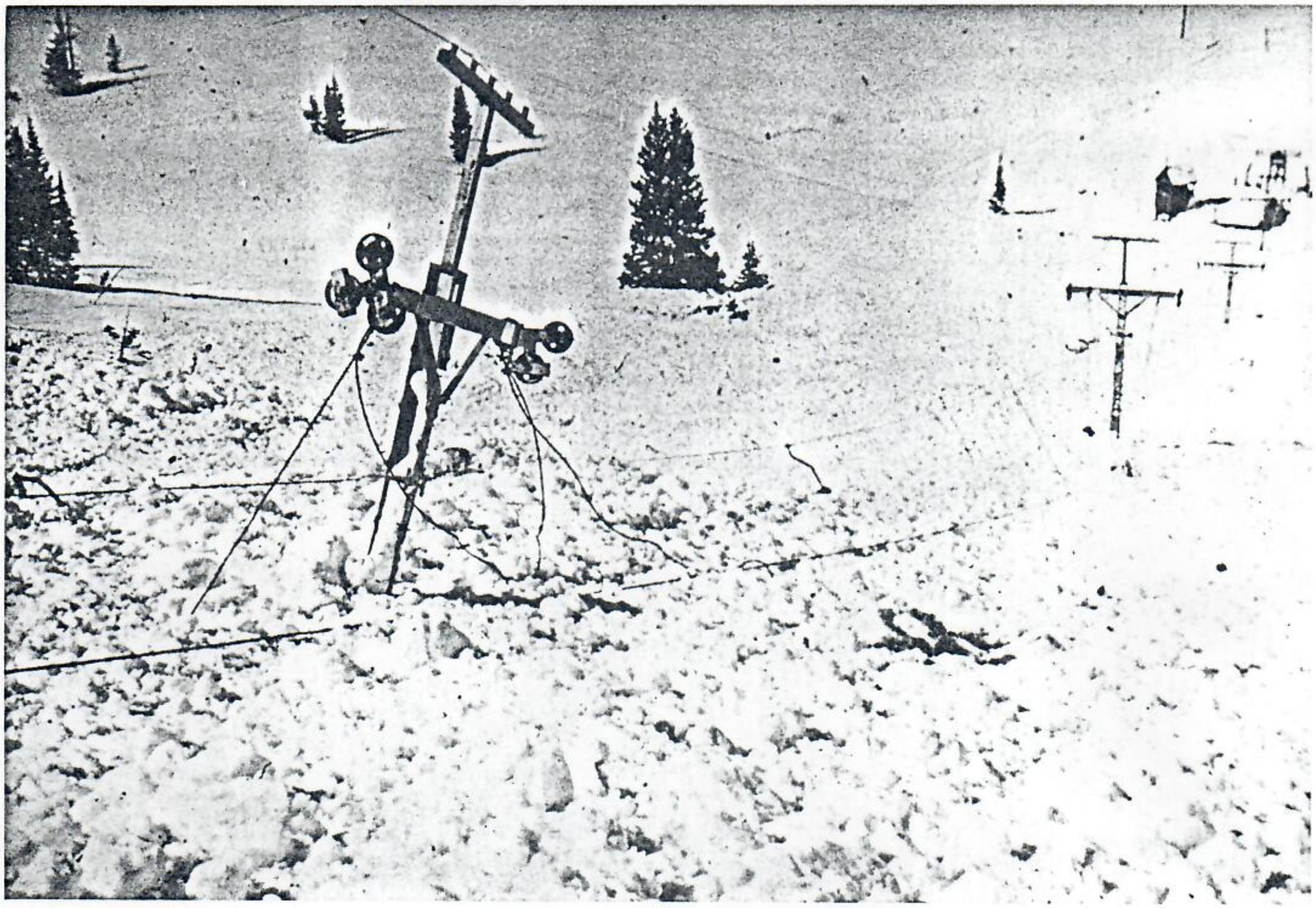


Figure 10.—Ski lift destroyed by avalanche, Alta, Utah, November 1955. Depth of avalanche in foreground is about 2 meters.

quence of a cold, dry pack of new snow or a consequence of, alternatively, a breakage of crystal bonds due to a warming of the snowpack. In either case, the released volume slides downslope bulldozing an everwidening mass of cohesionless snow. The failure pattern is clear that failure commenced and spread out downwards from a well-defined *point* (fig. 12). Generally, point releases stabilize avalanche paths by gradually redistributing loose, dry snow from high-angle slopes. In the Wasatch, point avalanches can be a threat in the late spring when intense radiation converts a large portion of the snowpack into a wet, cohesionless mass. Point releases can then lead to dangerous wet snow avalanches. It is also possible that the impact of small point avalanches may trigger the second and more dangerous category, the slab avalanche.

Slab release is characterized by an initial, spectacular propagation of cracks, followed by the crushing of a relatively large slab area (over 300 sq m) of the slope into numerous blocks, each about a cubic meter in size. These blocks are usually pulverized as they slide and topple down the avalanche track, and unless the avalanche track is relatively short, the blocklike forms are not recognizable in the debris. Sometimes a slab consists of relatively hard, high density snow; in such case, the blocks may survive a lengthy trip. The distinguishing feature of the slab avalanche is the sharp fracture surface which remains on the slope and outlines the original boundaries of the slab (fig. 13). Slab release has been exclusively responsible for avalanche death and destruction in the Wasatch Range.

Although the mechanism of slab release is not fully understood, it appears that slab formation is the result of a relatively cohesive layer resting on a weak substratum. The Wasatch climatology gives ample opportunity for the development of such a structural combination. Storms tracking over the Wasatch deposit relatively thick layers of new snow. During these prolonged storm periods, changes in atmospheric conditions, for example fronts which result in abrupt shifts in temperature and wind, can generate discontinuities in the newly fallen snow. After the storm period, the atmosphere usually recovers to a dry, clear state which is typical of a continental climate. At this time, structural changes, called metamorphisms, occur within the deposited snow layers and at the snow-atmosphere surface. If these metamorphisms substantially weaken the deposited layer or the surface of the deposited layer, then slab avalanches are likely to occur when the snowpack is loaded by subsequent storms. Thus, slab avalanche formation stems from the complex interaction of storms with snowpack metamorphism.

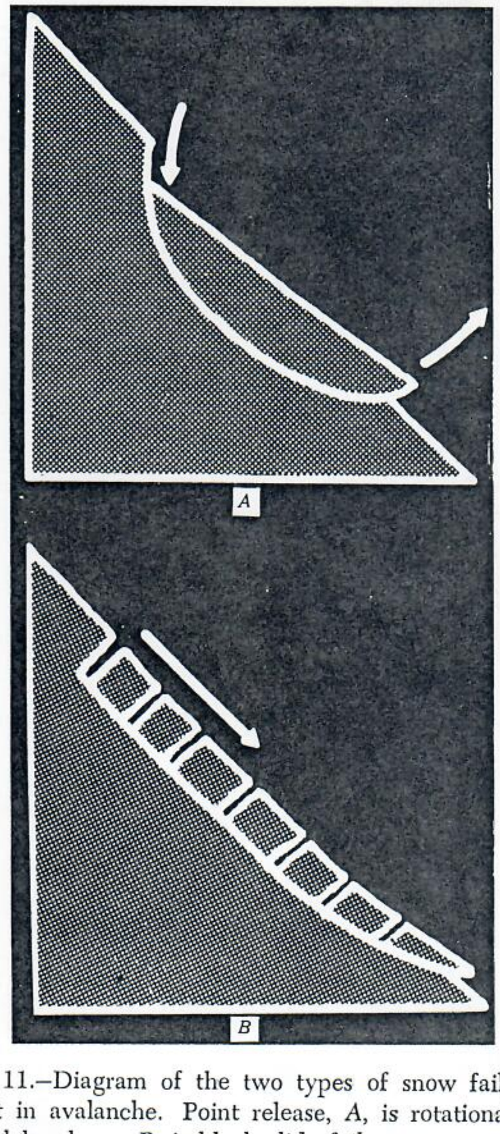


Figure 11.–Diagram of the two types of snow failure that result in avalanche. Point release, *A*, is rotational failure and slab release, *B*, is block-glide failure.

New snowfalls may consist of a variety of intricate crystals which have shapes that depend mostly upon atmospheric temperature during the storm period. In the Wasatch, the dominant crystal form is the *stellar dendrite*, a star-shaped crystal with many branches (fig. 14). Once on the ground, crystals are modified by initial metamorphisms which remove the starlike branches and build the crystal into a more rounded structure. Additional metamorphism of the crystal is dependent on the *temperature gradient* of the snowpack (the variation of snow temperature between layers). Because the ground temperature remains very close to the melting point (0°C) throughout the winter, temperature gradients for a given snowpack thickness are mainly controlled by surface temperature of the snow. When temperature gradients are relatively weak, the regulating metamorphism, called *equitemperature metamorphism*, tends to knit the individual crystals into a tight and strong network. Hence, equitemperature metamorphism builds increasing strength into snow layers.

In the presence of strong temperature gradients (above 0.1°C/cm), growth occurs on crystal faces; the crystals enlarge individually, but little bond growth occurs between crystals. This process, known as *temperature gradient metamorphism*, weakens the snowpack and is considered an important cause of slab instability. Examples of crystals grown in a strong temperature gradient are shown in figure 15. Temperature gradient metamorphism is certain to occur when a thin snowpack formed by an early winter storm is exposed to several weeks of clear, cold weather.

Figure 16 illustrates the stratification of a slab which was released by Forest Service artillery at Alta, Utah. Note that the failure surface consisted of temperature-gradient (abbreviated T.G.) metamorphosed crystals, while the bulk of the slab consisted of equitemperature (E.T.) metamorphosed crystals. The T.G. crystals were formed during a clear weather period in November and December following an early October storm. As shown in the temperature profile of figure 16, temperature gradients were reduced at the time of observation, December 27, owing to the increased thickness of the slab. The center of the slab contained a notably weak layer of *graupel* crystals, which are haillike pellets that form during frontal passage of a severe storm. These spherical-shaped crystals resist metamorphism and tend to retain their original form for relatively long periods. As shown by the *shear frame index*, which is a measure of strength determined by a boxlike instrument, both the graupel and T.G. layers were possible slide surfaces (in fact, several other avalanches on December 27 slid on the graupel instead of the T.G. layer). How-

Figure 12.—A point avalanche, Alta, Utah. Note how avalanche mass widens downslope from point at top.

Figure 13.—Fracture face at the head of a slab avalanche. Note the angular break at head and flat glide surface where man is kneeling.

ever, since the shear frame and other field devices developed so far do not adequately measure the failure resistance properties of the snowpack, it presently is difficult to predict the failure layer in a multistratified slab that contains two or more weak layers. With present technology, an examination of the stratification of the slab of figure 16 before failure would have led only to the modest conclusion that failure is likely, but not certain, to occur at one of the observed weak layers.

In addition to the lack of a meaningful failure measurement, there are two other serious obstacles to precision forecasting of the "where and when" of slab avalanches. First, avalanche conditions vary rapidly in time. During a storm, instability can build up in a matter of hours, hardly enough time to set up and perform intricate tests. Second, avalanche conditions vary rapidly from place to place. The snowpack may be rock solid at a particular altitude and exposure, but 100 m away the pack may contain an unstable T.G. layer.

In view of these uncertainties, the decision that an unstable condition exists, and that some control action should be initiated, is based on broad qualitative guidelines. For the Wasatch Range, unstable conditions tend to fall into the following four categories: (1) Temperature gradient metamorphism, (2) high rate of loading due to new snow or windblown old snow, (3) unstable stratigraphy of newly fallen snow (including conditions at the new snow-old snow bond), and (4) thaw. Although these four categories are quite interdependent, in practice, recognition of any one of these categories has been cause to recommend caution and protective action. If several of the categories exist simultaneously, then avalanche activity is almost a certainty.

TEMPERATURE GRADIENT METAMORPHISM

Temperature gradient (T.G.) metamorphism is considered an important clue to the instability of a snowpack. Other deep stratigraphic discontinuities, such as ice crusts,

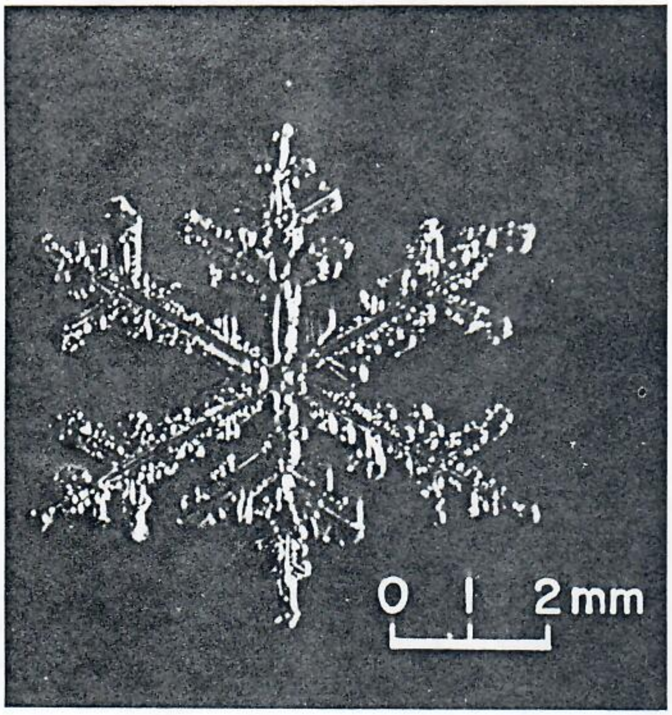


Figure 14.—A "stellar dendrite" snow crystal. Such crystals initially form in an almost infinite variety of hexagonal forms. Photo, courtesy of E. R. LaChapelle.

may be suspect, but their activation seems to depend largely on the effects of categories (2), (3), and (4). In contrast, hard experience in the Wasatch has demonstrated that T.G. substrata offer weak support to overriding slabs, and that instability of the slab substratum system may be activated by the slightest disturbing effect of the other three categories. The more complete the T.G. metamorphism toward a final stage, called *depth hoar*, the greater is the structural instability of the slab substratum system.

Important T.G. layers usually form in the first meter above the ground, and most often on northern or shaded slopes where snow surface temperatures are at a minimum. After severe and prolonged cold spells, T.G. layers are apt to be found on all exposures. Most T.G. layers are sufficiently thick to be detected by probing with a ski pole where the snow cover is thin, or with a special penetrometer, designed specially for avalanche work, where the snow cover is too thick for ski pole probing. If the preliminary sounding indicates a weak substratum, then a snow pit can be excavated to allow a visual inspection of the stratigraphy. Occasionally, thin T.G. layers form above or below ice crusts.

Should acute T.G. conditions develop in early winter, as occur in about 50 percent of the Wasatch winters, then the verdict is slab instability until about March when the combined effects of snowpack warming and high pressures of a thick overlying slab can consolidate and strengthen the T.G. crystals. Until then, serious avalanche activity can be expected from slopes which contain T.G. substrata during almost all storm periods. Control operations are especially critical during T.G. seasons as compared to non-T.G. seasons.

RATE OF LOADING OF NEW SNOW OR WINDBLOWN OLD SNOW

Qualitatively, the failure of a snow slab depends on a critical stress in combination with a critical stress rate

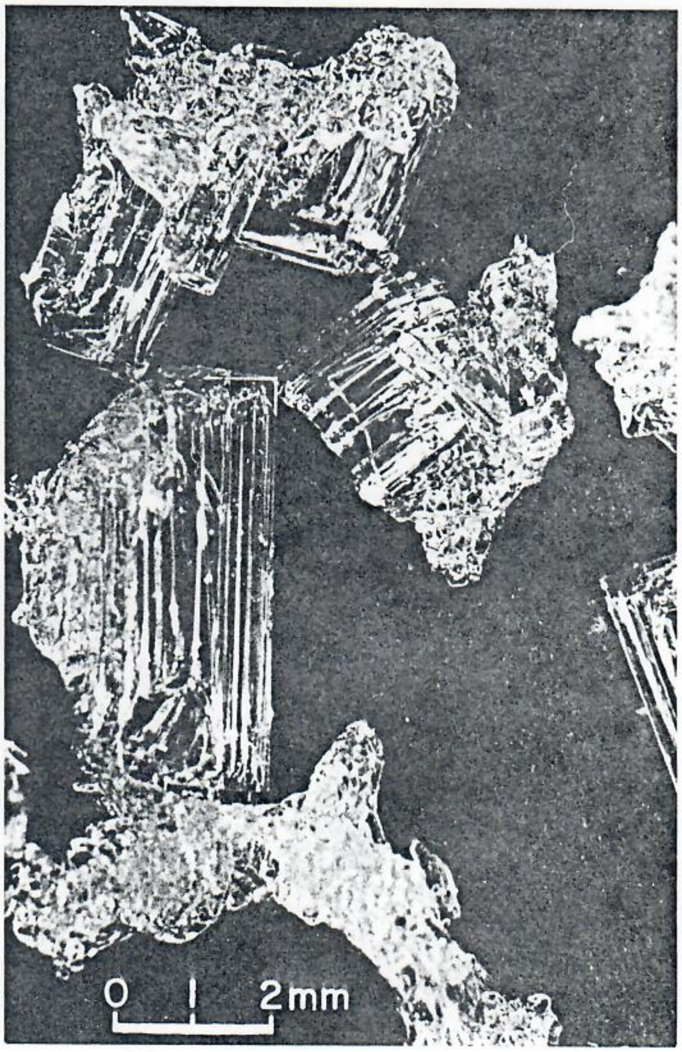


Figure 15.—Metamorphosed snow crystals resulting from a strong temperature gradient. Photo, courtesy of E. R. LaChapelle.

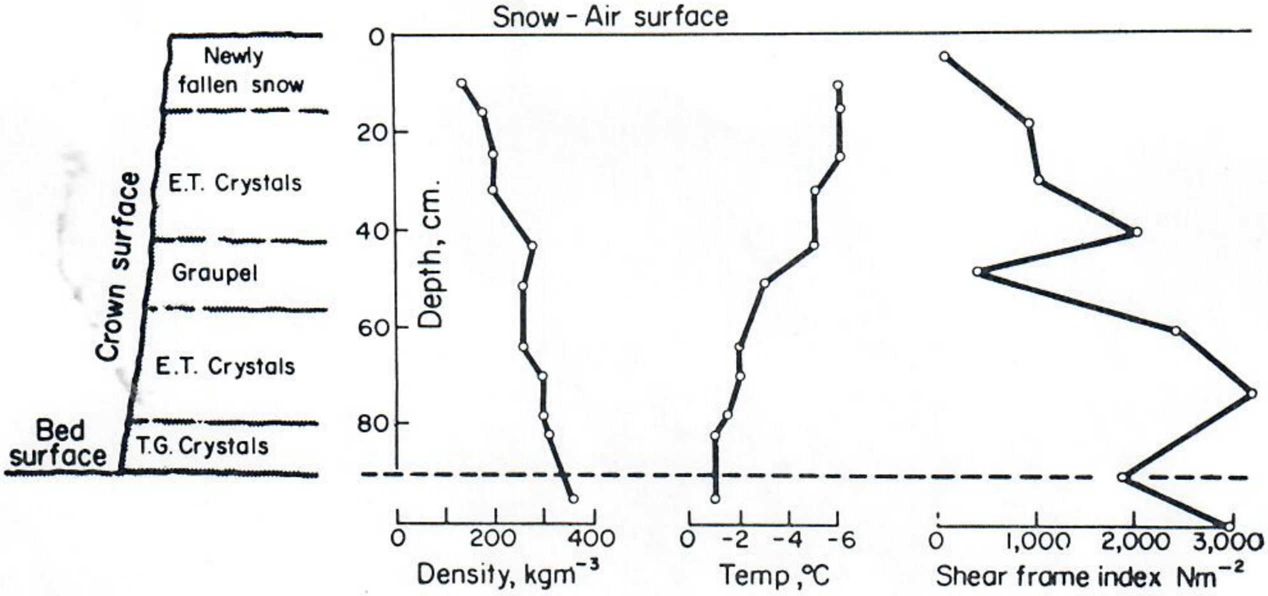


Figure 16.—Density, temperature, and shear relations within the strata of an avalanche slab at Alta, Utah.

(alternatively, a critical strain and strain rate); hence, the vast majority of slab avalanches occur during or immediately after deposition of new or windblown snow when slab loading rates are at their highest. As discussed earlier, quantitative approaches to the stress-strength evaluation of weak layers are unfeasible due to the lack of appropriate instrumentation and the wide scatter of data in space and time. For this reason, avalanche technologists, faced with uncertain data, attach special caution to the storm period, regardless of the substratum observations. It is of course possible to synthesize, at least in a qualitative way, storm and substratum effects, and to conclude, for example, that instability is achieved with less intense storms when weak substrata are present. On the other hand, storms of long duration and high intensity are almost certain to activate instability irrespective of substratum weaknesses.

Avalanche instability in response to storms has been studied in the Wasatch since 1945 (Perla, 1970). On the basis of more than 100 storm records, an evaluation was made of the probability of large avalanches occurring on the slide paths which affect the Little Cottonwood Canyon road and Alta (fig. 9) as a function of the storm behavior. In making this evaluation it first is necessary to distinguish between hazardous and nonhazardous avalanches.

On the U.S. Forest Service scale of avalanche size, 1 through 5 (U.S. Dept. of Agriculture, 1968), only sizes 3, 4, and 5 are large enough to be considered dangerous to the Little Cottonwood Canyon road and Alta. Next, it is possible to establish two classes of hazard probabilities for the road-village vicinity, the probability of a minor hazard, P_3, and the probability of a major hazard, P_{10}. These hazard probabilities are defined in the following way: P_3 is the probability that at least one avalanche of size 3 will run into the road-village vicinity; P_{10} is the probability that several avalanches, whose various sizes total 10, will run into the road-village vicinity. Figure 17 shows how P_3 and P_{10} vary with six storm factors: (1) Total precipitation during the storm period (fig. 17*A*), (2) maximum precipitation intensity (fig. 17*B*), (3) average wind speed (fig. 17*C*), (4) wind direction (fig. 17*D*), (5) Atwater Number (fig. 17*E*), and (6) maximum temperature change (fig. 17*F*).

As shown in figure 17*A*, both P_3 and P_{10} increase steadily with the total precipitation of the storm. In most cases, precipitation was measured by weighing a cylindrical sample of snow that was extracted manually from the new snow layer. Hazard probability could also be related approximately to total snowfall of the storm by recalling from earlier remarks that a 10-cm thickness of Wasatch snow has a water content of about 1 cm. The certainty of minimum avalanche activity ($P_3 = 1.0$) at large amounts of total precipitation (or large amounts of total snow) confirms that major storms can force avalanches irrespective of the structure of the snowpack.

As shown in figure 17*B*, the alpine snowpack is sensitive to the maximum precipitation intensity, or the maximum rate of loading of the storm. This sensitivity was verified in the laboratory by Kinosita (1967) who subjected snow samples to compression at various loading rates. At low rates of load application, the snow samples

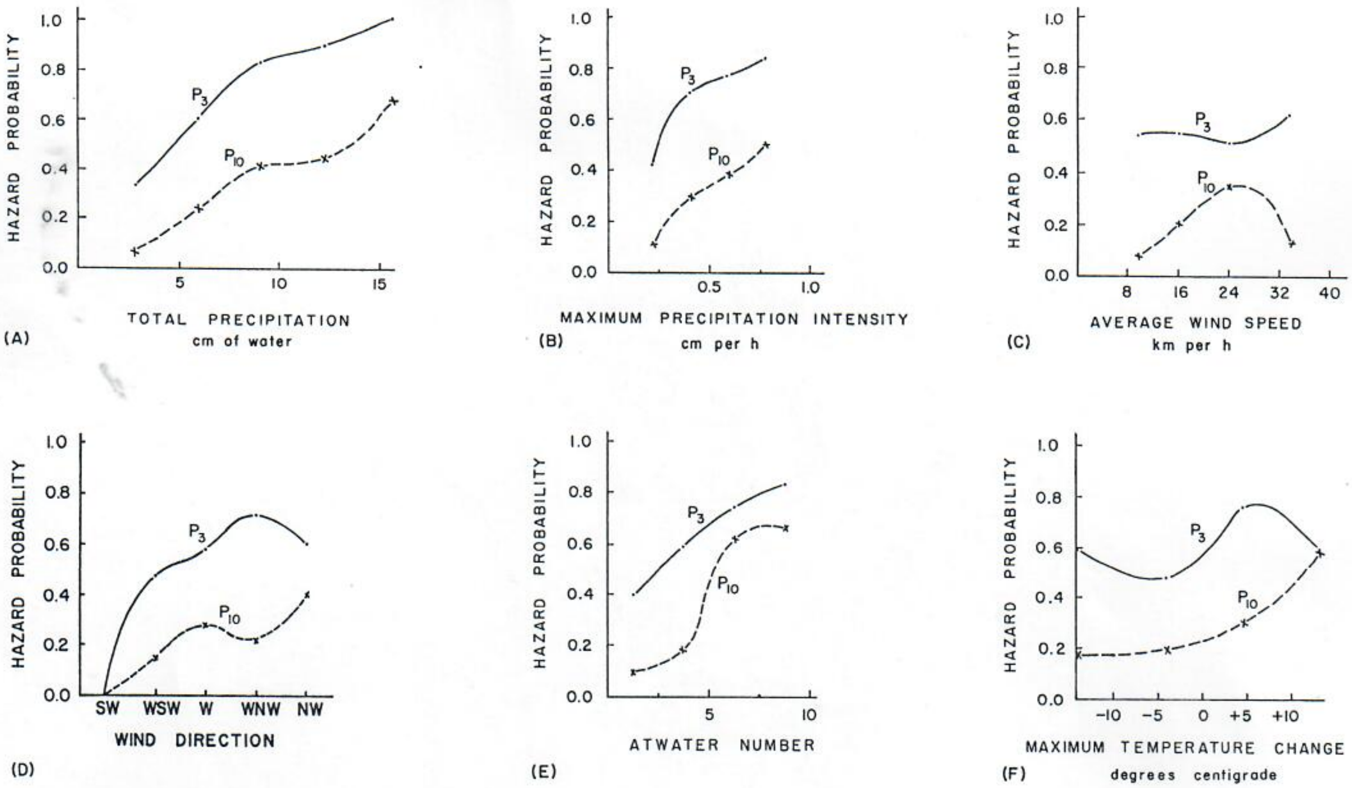


Figure 17.–Curves showing the hazard probabilities of two avalanche sizes (P_3, P_{10}) as related to six different storm conditions in the Alta-Little Cottonwood Canyon road area.

compressed substantially, resisting failure by internal deformation. But at high loading rates, the samples failed catastrophically. It is hypothesized that natural snow slabs behave similarly; at low precipitation rates (loading rates) the slab can absorb the new snow load by deforming internally, but at high rates the slab fails catastrophically.

As shown in figure 17*C*, hazard probability cannot be related definitely to wind speed, but this statement must be immediately qualified. What the storm reports indicate is that the large avalanches, which are threats to the road and village, are insensitive to wind speed, presumably because Wasatch storms most always occur with the minimum wind required to induce avalanche activity. However, it is an observed fact that small avalanche paths, which, for example, are threats within ski areas, can be loaded by strong winds that redistribute the snow, even when the measured amounts of new snow are comparatively sparse. Then, too, the data of figure 17*C* were derived from a low elevation anemometer (elev. about 3,300 m), which may only partly describe conditions in the high elevation starting zones (3,700 m). Recently, wind instrumentation was installed on a high elevation ridge above Alta, so that the results of figure 17*C* may be overruled in a revised study.

As shown in figure 17*D*, wind direction, in contrast to wind speed, seems to be the most reliable predictor of avalanche development on the south-facing slopes of this study. Large avalanches simply do not form on a given group of slopes unless the wind direction is favorable. By favorable is meant that the wind blows over the ridge crest as shown in figure 18.

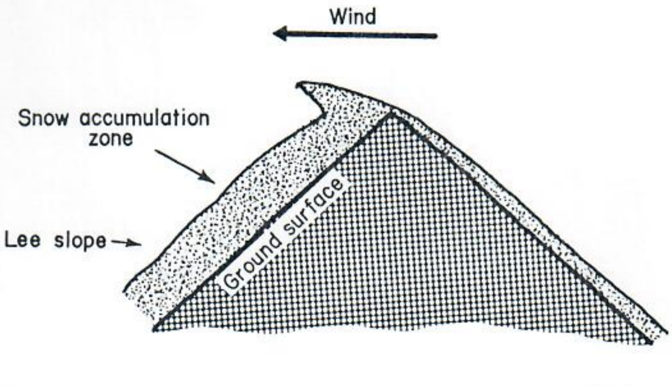


Figure 18.–Avalanche relations to a ridge, wind direction, and relative snow depths. Maximum depth is on lee side of wind and is most hazardous.

In figure 17, parts *A, B, C,* and *D* relate the hazard probability to individual storm factors. An important problem in avalanche technology is to somehow synthesize such factors into a combined parameter. One such combined parameter is the Atwater Number which has a numerical value equal to the centimeters of water that have been deposited during a continuous period in which the rate of precipitation was above 0.25 cm/hr and the winds were above 20 km/hr. Although the critical values of 0.25 cm/hr and 20 km/hr were chosen by Atwater (1952) on the basis of limited data and some arbitrariness, nonetheless, figure 17*E* shows that the Atwater Number, as originally proposed, is a meaningful indicator of major avalanche cycles. In retrospect, the instability of the large avalanche paths which affect the Alta road and village may be better described by basing the Atwater Number on wind direction instead of speed.

UNSTABLE STRATIGRAPHY OF NEWLY FALLEN SNOW AND CONDITIONS OF NEW-OLD SNOW BOND

Three prestorm surface conditions relating to the stratigraphy are especially important: (1) Ice crust, (2) surface hoar, and (3) a cold, weak layer of loose snow. Ice crust is formed by the freezing of a rain-soaked snowpack, or sometimes by a wet fog which deposits a thin ice glaze on the windward side of a cold slope. Surface hoar is an evening growth of frostlike, sparkling crystals on a radiantly cooled snow surface. This growth, which is nourished by the moisture of a humid atmosphere, forms layers that are exceedingly weak and cohesionless and therefore makes an excellent sliding surface. A similar, but less efficient sliding surface, can be formed by a weak layer of newly fallen snow. Such layers are deposited under low wind conditions and are kept dry and fluffy until the next storm period by cold air temperatures and reduced incoming radiation.

An unstable structure of newly fallen snow results from a relatively stiff, strong layer, deposited on a relatively weak layer. Such conditions may occur during an *inverted storm,* i.e., initial deposition of weak, low density, or fluffy snow at cold temperatures followed by heavy snow with rising temperatures. Normally, the temperature sequence of temperate zone storms is a drop in temperature as the storm progresses. As shown in figure 17*F*, inverted storms are statistical contributory factors to instability. Formation of a stiff layer on a weak layer can also result from the initial deposition of crystals at low wind speeds, that is, the deposition of a weak, uncompacted layer, followed by the deposition of a stiff, compacted layer at high wind speeds.

Although the mechanics of instability of this category are complex, an effective qualitative test, called test skiing, can be applied to the new snow when conditions are questionable. Taking necessary safety precautions, the observer simply skis across small avalanche slopes, referred to as test slopes, and checks for snow fracturing and the release of miniature slabs. The severity of the fracturing is a qualitative measure of instability. Thus, relatively large amounts of snow are subjected to a realistic failure test. It should be emphasized, however, that test skiing is only a measure of new snow instability and relates at the most to the top meter thickness of snow. It is not a measure of the deep instabilities that may remove by avalanches as much as a 5-m thickness of snowpack.

THAW

Thaw generally is thought to be caused by a warming and thus a loosening of the slab substratum attachment due to heat conduction, melt-water percolation down from surface layers, and a steady increase to criticality of the free water content of the entire slab. In the case of thin slabs, the warming can be caused by direct penetration of solar radiation onto a weak substratum. Thaw first of all depends on the warming of the snowpack to the melt point (0°C), a condition which is not achieved in the Wasatch until March. Energy balance at the slab surface is the important determiner of thaw instability; however, as everywhere else in avalanche technology, the variables that make up the energy balance are elusive and difficult to describe quantitatively. Qualitatively, it is possible to synthesize the effects of air temperature, long and short wave radiation, and winds to gain a rough idea of the direction and trend of the energy balance.

Thaws are of two types. The first tends to produce avalanches during the warming period immediately after a spring storm (in the Wasatch, March through June). Usually, at that season the slab layer consists of only newly deposited snow. The avalanching of small, innocuous point releases and slabs may give some warning of the impending hazard from this first type. The second type forms unstable slabs deep in the snowpack on substrata of ice crusts, T.G. crystals, or forms directly on the ground at the base of the snowpack. These deep thaws are usually not associated with a particular storm, but are due to the cumulative thaw effects of several days; hence, it is almost impossible to predict the "when and where" of this type.

Thaw instabilities are most prevalent in gullies where melt water is readily produced by the heat of rock walls and then collected in a narrow channel. Avalanches, so caused, are wet and move slowly, generally following the gully bottom, in contrast to the drier and faster moving avalanches of midwinter which tend to follow a straighter course, sometimes jumping over the gully sides at the bend points. In planning structures, one must keep in mind the alternate tracks that an avalanche might follow depending on whether it is wet or dry.

Due to the hardness of the spring snowpack, the Wasatch back country becomes more accessible to the hiker as well as the ski tourer during April, May, and June. As a general rule, gullies should be off limits as climbing routes until thaws have cleared the higher slopes. It is advisable to complete cross-country travel before midday. Hikers should also remember that gullies filled high with avalanche debris contain many traps of hidden or open snowpits which can lead to ground-level streams and death by drowning. Hazards related indirectly to avalanches are thus prolonged well into the summer.

PROTECTIVE MEASURES AND AVALANCHE CONTROL

Locations of the more recent avalanche deaths (1939 to July 1971) in the Wasatch are shown in figure 1. Although the record is imperfect, there has been a great gain over the toll of the mining era, especially in consideration of the much larger population using the mountain slopes in recent years. This gain is due to the protective efforts of ski patrols, snow rangers, State Highway crews, and ski area operators. Snow rangers are employed in the Cache and Wasatch National Forests. Avalanche threatened ski areas, which include almost every ski area in the Wasatch, maintain staffs of professional and volunteer ski patrolmen who keep close watch on the avalanche hazard. Protective measures involve the distribution of information on hazardous conditions to the public, controlling the hazard through artificial release of avalanches by explosives or artillery, and, when disaster strikes, in performing rescue operations and in giving aid to avalanche victims.

Public information is distributed in a variety of ways. In ski areas, *avalanche danger signs* are posted at hazardous ski runs until the conditions can be checked and cleared. Along highways, signs are posted to warn against parking or stopping in known avalanche zones. Special warnings also are broadcast on radio and television. Ski patrol and Forest Service personnel present educational films and lectures at schools and ski lodges, and avalanche training sessions are conducted for ski patrols and mountaineering clubs. Many gaps remain, however, in informing people of the avalanche hazard which is literally at the back door of a large part of the population of the Salt Lake and Utah Valleys.

Closure of roads and ski runs, followed by artificial release of avalanches by explosives or artillery (fig. 19), has become standard practice in avalanche threatened regions of the United States since the introduction of such techniques at Alta, Utah, shortly after World War II. Each winter, roughly 1,000 artillery shells and an equal number of hand-thrown explosives are fired into, or exploded on, the Alta slopes. Substantial amounts of such control also are carried out at the Brighton, Park City, and Snow Basin ski areas.

Because of the inexactness of avalanche hazard evaluation, control measures are usually taken whenever conditions are in doubt, which is essentially after every major storm. In consideration of safety of fixed facilities, economics, and forest ecology, control measures must be carefully timed. Ideally, avalanches should be released when they are small enough that they will stop short of the runout-damage zone. Within the limits of present technology, however, it is not yet possible to guarantee optimum timing. Also, artificial release causes far more avalanches than those that would run naturally. Furthermore, the first avalanche often fills in the depressions in the terrain and thus provides a natural ramp for a second avalanche to extend the runout-damage zone. Experience shows that this is particularly so if an avalanche path is activated early in the season, thereby making an ideal sliding surface for a slab release later in the season. Thus, once explosive and artillery control is initiated to release an avalanche from a slope, that slope must be watched closely for further avalanche development for the remainder of the winter.

Since present technology cannot guarantee the timing of explosive or artillery control so that avalanches stop short of the runout-damage zone, building developments which are located in categorically hazardous or marginal zones must be safeguarded by special construction techniques, by the erection of protective facilities, and by the production of structures or forestation practices that will prevent avalanche. In the runout-damage zone, construction techniques may be difficult, but are possible. Although it adds greatly to the cost, buildings can be constructed to withstand avalanche blows. In general, concrete must be substituted for wood, and the buildings must somehow be banked in the hillside, or protected by a diversion wall or wedge (fig. 20). Similarly, highways can be protected by concrete sheds, but the great initial expense of such structures has so far prohibited the use of them on the Wasatch highways. Sheds also introduce driving hazards in the form of icy road surfaces, restricted visibility, and restricted maneuvering space, which sometimes are more dangerous than the avalanche hazard.

Figure 19.—Snow ranger aiming howitzer at avalanche area on flank of Superior Peak, Alta, Utah. Little Cottonwood Canyon is beyond left edge of gun.

Prevention of avalanche is feasible in the starting zone through the erection of special structures and by reforestation or afforestation practices. Structures, which resemble large racks, are used extensively in the avalanche starting zones of the Swiss Alps. These structures must be solidly braced to support the forces of snow creep, and must be arranged in a dense enough network to hold the snow slab in place. Installation costs of these racks on a steep mountainside are quite costly unless, as is common in Switzerland, the installation is performed by volunteers. Reforestation, or afforestation, for aesthetic reasons, is preferred but is difficult to accomplish on the high and exposed starting zones of many avalanche paths. In tree planting experiments attempted above Alta, the survival rates of the trees have been disappointingly poor. Perhaps, special trees such as the limber pine will grow among the rocks on the south-facing slopes that are most troublesome to the Alta vicinity, but these trees are not available from nurseries and their cultivation from seeds will require some time and care.

When all preventive measures have failed, final protection is provided through avalanche rescue. In spite of the equipment (fig. 21) that is available and the manpower that rallies to the distress call (fig. 22), avalanche rescue

Figure 20.—Ancient Swiss church, protected by an avalanche diversion wedge. Photo, courtesy of E. R. LaChapelle.

Figure 21.–U.S. Forest Service avalanche rescue cache, Alta, Utah. Cache includes probe poles, shovels, first aid set, and rescue sled.

Figure 22.—Part of human chain from a mountain community making a rapid and preliminary search for surface clues to avalanche victims while awaiting arrival of long poles for probing. Only 20 percent of completely buried victims survive.

tends to be more of a body recovery operation than a rescue. This saddening situation is directly related to the length of time a victim can survive while buried under the snow. After 1 hour of burial over 50 percent of the victims are found dead, and rescues completed within 2 hours save only 20 percent of the victims. This re-emphasizes the importance of a greater public awareness of avalanche conditions and the taking of effective steps to prevent and control avalanches.

Among the serious avalanche problems of the Wasatch Range is the present entanglement of public and private lands, crisscrossed rights-of-way, and concessions which operate under permit. Under such conditions it is difficult to establish responsibility for avalanche control, preparation of zoning maps, supervision of construction in marginal avalanche areas, dispatch of information to the public, etc. In spite of these conditions it is vitally necessary that a way be found to combine and share the responsibility in a cooperative effort. The precedent for such an operation has been set by other cooperating projects concerned with, for example, water, wildlife, or fire. It can be done if there is a will to do it.

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