AN APPROACH TO THE MECHANISM OF AVALANCHE RELEASE

By ANDRÉ ROCH[1]

(*Four illustrations: nos. 14–17*)

1. *Snow as a material*

The ice-crystals which originate in the atmosphere and which are deposited on the ground in snowfall have different shapes according to the conditions in which they are formed.

Among these shapes one may distinguish stars, needles, plates, prismatic columns, which may be independent or may join two stars or two plates, spatial stars or spatial dendrites, and stars of irregular shapes. All of these may be either dry or rime-covered or wet. The mechanical properties of layers of snow depend to a certain extent upon the *original shape of the crystal*. They are also affected by the *atmospheric conditions* which prevail during and after the actual snowfalls. Wind, for example, breaks the crystals and rolls them along, so that they accumulate in compact layers. At low temperatures and in calm weather, snow settles in a layer of very light consistency, while at high temperatures the crystals, being softer and more malleable, pack more closely and form a layer of denser consistency.

The *amount of snow which falls* also plays some part. The lower strata of heavy falls of snow become compacted by the weight of snow above. In low temperature and calm weather, a slight fall packs very little and produces a snow layer of light consistency and of thin density.

On the ground the crystals, being relatively near melting point, change shape continually. The points of the stars and needles sublime[2] and the resultant water vapour is deposited along the branches of the crystals, which become enlarged. The fine detail of the branches tends to disappear. This phenomenon is called *destructive metamorphism*. From being new, the snow becomes powdery, then granular. The more dendritic the crystals are, and the higher the temperature, the swifter is

[1] I should like to thank M. André Roch, of the Swiss Institute for Snow and Avalanche Research (Weissfluhjoch), and of course a member of the Club, for contributing this authoritative article.

M. Roch wishes to express his gratitude to Dr. de Quervain for making suggestions on the original French text of the article, and I join him in thanking Mr. Colin Fraser (who is himself writing a book on the subject of avalanches) for his invaluable help with technical points of translation. Any errors surviving from the first draft of the translation are the responsibility of the Editor.—Editor.

[2] The process of sublimation is the changing of a substance from its solid to its gaseous state, or *vice versa*, without passing through its normal liquid state.

the transformation of the crystals. At low temperatures and when the snow is already granular, metamorphism is more gradual. This kind of resorption of the original star-crystals produces a settling down and packing of the layers.

Within the snow cover the temperature at ground level is in the neighbourhood of 0° Centigrade. But the temperature in the surface layers of the snow is determined by the average air temperature. The temperature gradient—the difference of temperature between ground and snow surface—is steepest at the coldest time of year and when the snow cover is thin. The air in the pores of the snow, which is warmest near the ground, rises and becomes chilled. It is saturated with water vapour, indeed becomes over-saturated, with the result that the water vapour is deposited in the form of ice on suitably orientated crystals. These crystals therefore grow—at first by acquiring new facets, and later by growing into the shape of prisms or tiny cups. The growth of these crystals is called *constructive metamorphism*; and it takes place at the expense of other crystals, which disappear.

During cold winters, when there is little snow, almost the whole snow cover is transformed into a scaffolding of these crystals shaped like prisms or tiny cups.

In the same way, crystals which stay on the surface for any considerable time without melting become larger.

Unlike sand, whose grains for practical purposes do not change their shape, the properties of snow are not only very different according to the different types of crystal, but also they change all the time under the combined effects of metamorphic processes, of temperature and of the pressure of fresh falls of snow, all of which affect the shape of the crystal and the state of the snow.

Cohesion between crystals similarly takes place in different ways. In fresh snow, it is a *felt-like cohesion*, resulting from the interlocking of stars and needles. In granular snow, the grains are more or less touching, and freeze together at their points of contact. This is a *contact cohesion*. The presence of water produces a *capillary cohesion*.

The *compressibility and viscosity* of the snow depend on the temperature, on the state of consolidation of a stratum, and on the shape of the crystal which gives the snow its structure. Fresh snow, with its dendritic crystals, is highly compressible, because the delicate branches of the crystals bend and get broken. The more massive the crystals, the less compressible is the snow. At high temperatures, the snow is more compressible and less viscous than in intense cold, which makes the ice of the snow-crystals firm and hard.

With knowledge of these factors, one can already foresee what the characteristics of the different strata of the snow cover will be. The lower strata of heavy falls of snow, as well as layers which have been on

the surface for a short while—three or four days only, and at a low temperature—and which have subsequently been covered by a heavy fall, are pressed down and become very much compacted. They nevertheless remain more compressible and more malleable than layers in which metamorphism has enlarged the crystals into grains, into prisms, or into cups; such layers are not as compressible and are rather fragile, so may easily break under the effect of a shock or of any extra weight. The snow of layers which have been on the surface for a considerable time without melting becomes granular, and similarly forms strata which are rather resistant to compression and are more liable to break away.

A change of temperature in snow causes a variation in its strength. A rise of temperature makes snow less resistant, and *vice versa*. This effect can be expressed as an empirical relation, based on numerous experiments made to determine the tensile strength of snow.[3] The characteristics of this effect are:

(a) The stronger the snow, the greater the effect of a change of temperature.
(b) The nearer the temperature of the snow to 0° Centigrade, the greater the effect of a change of temperature.

It follows that, in the depths of winter, variations of temperature, which only penetrate slowly into the snow cover, have no important effect except in the snow's surface layers; while later in the season, when the temperature of the whole snow cover is in the neighbourhood of 0° Centigrade, a slight rise in temperature will produce a much greater loss of strength. This in turn is more liable to cause fractures in the snow cover, and these fractures can sometimes run great distances.

Experiments show that the *strength of different strata* of the snow cover varies according to all sorts of influences; but that two of these are generally preponderant. These are, firstly: the *pressure due to the weight of the snow*, which, by bearing down on the various layers, forces the crystals into contact, and causes them to freeze together more tightly, so increasing strength; and, secondly, *destructive metamorphism*, which tends to lessen resistance, the extent of its effect varying according to the shape of the crystal. These two factors are always competing against each other. For example, destructive metamorphism has a very marked effect on the dendritic crystals of new snow, which are morphologically unstable. The lower part of a slight fall of snow therefore develops little strength, because there is too little weight of snow pressing on it and because destructive metamorphism is very active. On the other

[3] $H_T^\circ = H_0^\circ + T^{0.26}$

(H_T° = tensile strength in kg/dm² at a temperature T° below 0° Centigrade; H_0° = tensile strength in kg/dm² at 0° Centigrade; T = temperature in °C below zero, but without the minus sign.)



Photo: A. Roch]

PLATE I : SLOPE SHOWING THE STATES OF STRESS IN AN AREA OF SNOW.

Above: Tensile stress which has caused fractures.
Left: Lateral shearings and avalanche.
Right: Lateral shearings and compressive stresses which have caused folding.
Below: Compressive stresses.

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hand, in the lower strata of a heavy snowfall the pressure of the snow is the preponderant factor, and these lower layers, which are highly compressible, develop great strength. The fine particles of snow are forced together into a compact mass, in which air cannot circulate well, and this reduces the effect of metamorphism and allows the snow to retain its characteristics of compressibility and low viscosity. That is why, later on, the pressure of a further fall of snow has more effect on these strata, which are already compacted and are still made up of relatively fine crystals, than on layers which have become granular and are less compressible—unless, of course, the structure of these larger granules shatters under the pressure, thus producing a compaction.

But after the increase in strength of the layers, as a result of a fall of new snow, an equilibrium is established; then, after a certain period (ten to twenty days, according to the strata and the conditions), strength decreases in all layers. These continual changes in strength may result in the release of avalanches without apparent explanation. Not only does the strength of the snow vary, but also the direction in which the weakest breaking resistance is found may change its orientation under the effects of crystal metamorphism, of compression of the layers and of the downward creep of snow on a slope.

2. *The stability of snow on a slope*

On a slope, snow, being a viscous and compressible material, packs, and also creeps downhill. It is in a *state of stress*, which depends on its viscosity, its compressibility, on the weight of snow above it and also on the configuration of the ground. Obviously, snow creeps downhill more quickly in places where the slope is steepest. As a result, there are zones of tension on the convex parts of slopes, of compression on the concave parts and of additional shearing in places where the incline varies laterally. A variation in the thickness of the snow similarly causes stresses, creep being more rapid in spots where the thickness is greater. (Plate 1.)

The states of stress and strength in the snow cover are extremely complex matters. Starting from certain simplified propositions, we can analyse what ought to occur for an avalanche to be released; and in accordance with the different processes and changes which take place in the properties of snow we can establish a classification of avalanche release mechanisms.

A layer of snow can be anchored at the top of the slope, supported from below, and also secured laterally. The effectiveness of these anchorages varies according to the degree of compactness of the snow layer; but in any case their influence is only felt over a relatively short distance. One may therefore say: *when a slope is of reasonable area, the principal criterion of whether the snow will avalanche is the stability of the layers, one upon each other, or upon the base on which they are lying.*

In order to eliminate peripheral influences, let us assume a layer, or several layers, of snow on a slope of infinite length and breadth; or rather, a parallelepiped[4] with a square base of unit side length made up of these several layers. Stability depends on the most delicate balance between stress and strength in any particular direction. A practical and measurable approximation to this balance is given by the shear strength of a stratum divided by the shear stress produced by the weight of the layers on top of it. The scientist E. Bucher has taken the symbol s to indicate a stability factor, this being the ratio of shear stress to shear strength in the direction parallel to the slope, thus:

$$s = \frac{\tau_s}{\tau}$$

τ_s being the shear strength of a stratum, τ being the shear stress for the same stratum caused by the weight of the layers above it.

In the snow cover, the stability of the stratum in which s is smallest is generally what decides whether an avalanche will start.

Shear strength is composed of two elements, cohesion and static friction—this element of friction being proportional to the pressure perpendicular to the slope. When the weakest stratum breaks down, cohesion is eliminated and, once movement has started, the only resistance left is the lesser one of kinetic friction.

The static and kinetic frictions of various kinds of snow, disaggregated and unconsolidated, have been measured, thus eliminating the factor of contact cohesion. For new snow this is not possible, however, because one cannot eliminate felt-like cohesion without breaking the fine branches of the crystals and thus changing the nature of the snow. The results of these experiments are shown in Diagram A, and they are correlated to an approximate time of metamorphism, given that the temperature has remained in the range $-5°$ to $-10°$ Centigrade.

When a structural fracture in whatever direction is produced in a stratum of snow on a slope, cohesion between the grains is eliminated, and static friction is replaced by a much slighter resistance, that of kinetic friction. *But, for an avalanche to slide, the angle of the slope must be greater than the kinetic friction angle of the type of snow in the layer which has broken away.* To clarify this: it can happen that a whole layer breaks down, but that an avalanche does not start because the slope is less steep than the kinetic friction angle of the snow.

In Diagram A, one notices that fresh snow is the most dangerous because its angle of kinetic friction is the smallest, viz., 17°. Among the different types of dry snow, it may be called the best lubricant for starting avalanches. But, apart from this, at a certain speed the ice-particles can

[4] A parallelepiped is defined as 'a solid contained by parallelograms'.

swirl up and form a fine suspension with the air: this becomes a so-called 'airborne powder avalanche', in which, because the snow/air suspension flows and behaves like a heavy gas, the friction is much smaller still. Yet

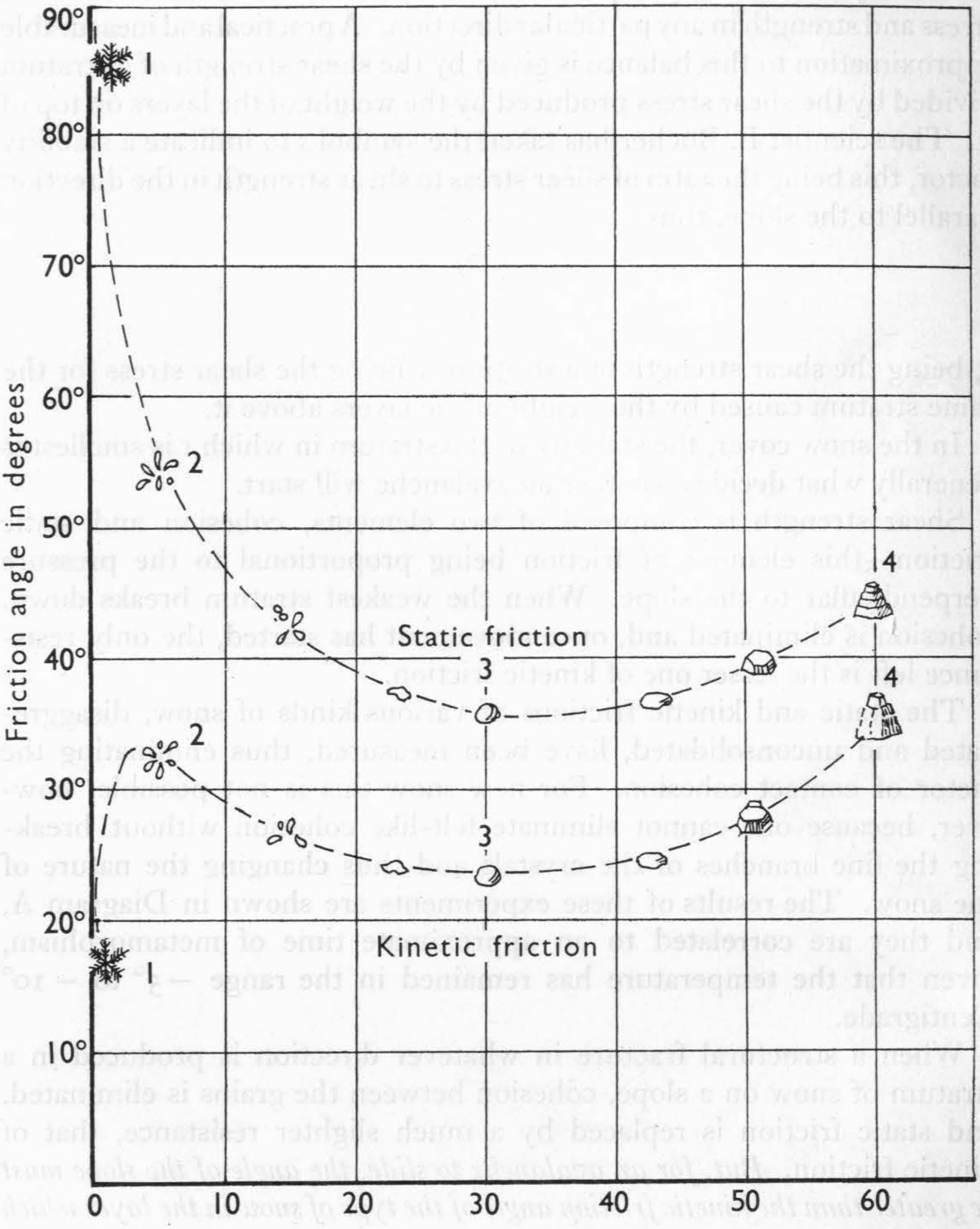


Diagram A: The change, over an approximate period of time, of the static and kinetic friction angles of loose and unconsolidated snow, brought about by the metamorphism of this snow when the temperature stays below 0°Centigrade.

fresh snow, however fragile the crystals may be, is difficult to set in motion as an avalanche because of its felt-like cohesion. This cohesion is hard to break down, owing to the shock-absorbing properties of new

snow. In addition, a slow increase of the combined forces of compression and shearing results in the packing down and consolidation of this fresh snow. But if it does start to move, the fine particles of the star-crystals become distorted and broken, and form a fine free-flowing powder with marked lubricating qualities.

In granular types of snow, the angles of friction depend on the shape of the crystal, which itself depends on metamorphism. The angle of kinetic friction is as low as 23° for spherical grains, but increases to as much as 35° for cup-shaped crystals.

We make a distinction between 'fracture' and 'release', and we shall see that, according to conditions, some types of fracture can sometimes, but not always, release an avalanche, while other types do so invariably.

In order to study why a fracture takes place in a stratum, we have to look for certain phenomena, which can either increase the stresses until they exceed the strength or reduce the strength until it is less than the stresses.

In a stratum, the stresses can be suddenly increased as a result of some incident, such as the fall of a lump of snow, the passage of a skier, or the shock of a peripheral fracture; but they can also be increased slowly through the extra weight of a fresh fall of snow or of rain.

The strength itself is always being gradually reduced under the effects of metamorphism and rises in temperature. A fracture occurs when strength becomes smaller than stress. Fracture in a stratum is followed by an abrupt lowering of resistance. In fact, shear strength gives place to the very small resistance offered by kinetic friction.

We call the release of avalanches by a progressive increase of stresses, or by a gradual reduction in strength, *spontaneous release*, as opposed to *release due to a sudden accident or occurrence*, because in the former case, once the movement has been initiated, the propagation of that movement usually presents no problem. The progressive increase in stress caused by the extra weight of a snowfall gradually brings the weakest stratum, lying at a given angle of inclination, to a state of extreme instability. The slightest extra load provokes a fracture and sets the snow on the slope in motion, unless the layers have some anchorage at the sides. When an avalanche is released in this way, the problem of the propagation of movement seldom arises. What happens is that the fracture eliminates cohesion between the grains of the stratum which breaks, and, from the moment that the movement begins, all that remains is kinetic friction, which is nearly always less than static friction. In general, the surface of a slope is much more important than the surface of the anchorages which hold a layer at its edges, for these only play a secondary role. It is a special and exceptional case when the fracture of an underlying stratum takes place without an avalanche being released, owing to the upper layers being anchored at their edges. In such a case, the fracture must be

considered in the same category as an outside influence or occurrence, which may or may not cause the start of an avalanche.

3. *Spontaneous release*

(a) *By the slow increase of stresses.* During a snowfall, the snow on steep slopes (40° to 50° and above) is set in motion as soon as stress exceeds strength. On less steep slopes (30° to 35°), some further accumulation of snow is needed for a fracture to be produced, the more so because the strata become progressively consolidated under the effects of pressure. But if a thick layer of new snow starts to move spontaneously, the avalanche can be terrible. In effect, the snow of a whole slope is in a state of precarious equilibrium, and it all slides at the same moment. When it reaches a certain speed, this snow mixes with the air and constitutes something like a heavy gas, whose viscosity and friction are very slight. Furthermore, the upper masses flow over and against the lower, which are themselves in motion, with the result that resistance to forward movement is slight. There is probably a compression of the heavy gas and an increase of frontal speed. Catastrophic avalanches are of this type, those which cause so much damage to forests, villages and houses. Luckily they are rare, because they occur only after huge snowfalls on slopes of a gentle angle where avalanches do not ordinarily happen (average 30°).

(b) *Spontaneous release by reduction of strength.* The second kind of spontaneous release is that which is provoked by gradual lessening of strength. For a first example we may take the destructive metamorphism of fresh snow. Here, briefly, the needle crystals and the star crystals interlock with each other and can hold even on a vertical plane, provided that the weight of the layer does not exert more stress than its strength can withstand. Destructive metamorphism produces a resorption of the delicate crystal-points and makes the main crystal-branches more massive. Felt-like cohesion disappears. The crystals which are produced by this transformation can hardly be said to be compacted together. They are only frozen together by very small contacts, and eventually can no longer retain their stability. They fall away, set other crystals in motion and form snow slides. After slight snowfalls, many slides are set in motion in this way spontaneously on steep slopes, as soon as the effect of metamorphism is sufficient. The first rays of the sun stimulate metamorphism, and so produce the start of numerous snow slides.

Another example of spontaneous release by lessening of strength comes from a rise in temperature. The effect of such a rise on the various strata of snow is particularly important in spring when, at the end of a cold winter in which there has been little precipitation (e.g. the winter of 1963/4 in the Alps), the snow cover is almost completely transformed into a fragile scaffolding of cup crystals. We have already seen that around 0°



Photo: E. Bucher]

PLATE 2: INSTANCES OF THE RELEASE OF LOOSE SNOW. NOTE THAT THE SNOW BEGINS TO SLIDE AS SOON AS THE MASS IS SUFFICIENTLY GREAT.

Centigrade a given rise in temperature results in a more marked reduction in strength than it would in lower temperature ranges. Therefore, without taking melting into consideration, it follows that it is the rise of temperature those last degrees before melting-point which most reduces the strength of snow. A spontaneous fracture may be produced, which can easily spread, because a layer of snow over a whole area is in a state of instability. A general collapse results, although no avalanche will be released except on slopes which are steeper than the kinetic friction angle of the crystals of the layer which has broken, that is to say (for cup crystals) 35° to 37°.

When the layers are more compact, a fracture in the structure of strata can result from melting, which destroys the contact cohesion between the crystals.

Spontaneous release takes place when the stability factor falls below 1 and, except in the special case of peripherally anchored layers, the problem of the propagation of movement does not arise.

4. *Accidental release, as a result of sudden occurrences or accidents and the propagation of movement.*

Experiments with avalanches show that a release can take place when the stability factor measured at the line of fracture is greater than 1, perhaps when $s = 3$ or even when $s = 4$; that is to say, when the shear strength of a stratum is three to four times greater than the shear stress exerted parallel to the slope by the weight of the layers of snow superimposed on the stratum.

For this to happen, some event must cause a sufficient increase in stress to break the fragile stratum. Even after this fracture, however, the conditions for an avalanche being released are not yet fulfilled. The movement still has to propagate.

The mechanics for the propagation of movement vary according to the compactness of the layers above the stratum in which the fracture has taken place. If these layers are of weak cohesion, peripheral anchorages have little effect, and all that is needed for the movement to propagate after the fracture is that the mass initially liberated be large enough to set the snow below it on the slope in motion.

One can oneself make the experiment of pushing loose snow, whether powdery or wet, downwards on a steep slope. Usually nothing happens, but if one continues to push, there comes a moment when the mass of accumulated snow is sufficient to set the snow lower down in motion, and so to propagate the movement. (Plate 2.)

The more compact the layers are, the more peripheral influences assume importance. *As soon as there is a stratum of low strength below layers which are more compact and strong, the mechanical conditions for the release of a slab avalanche exist.*

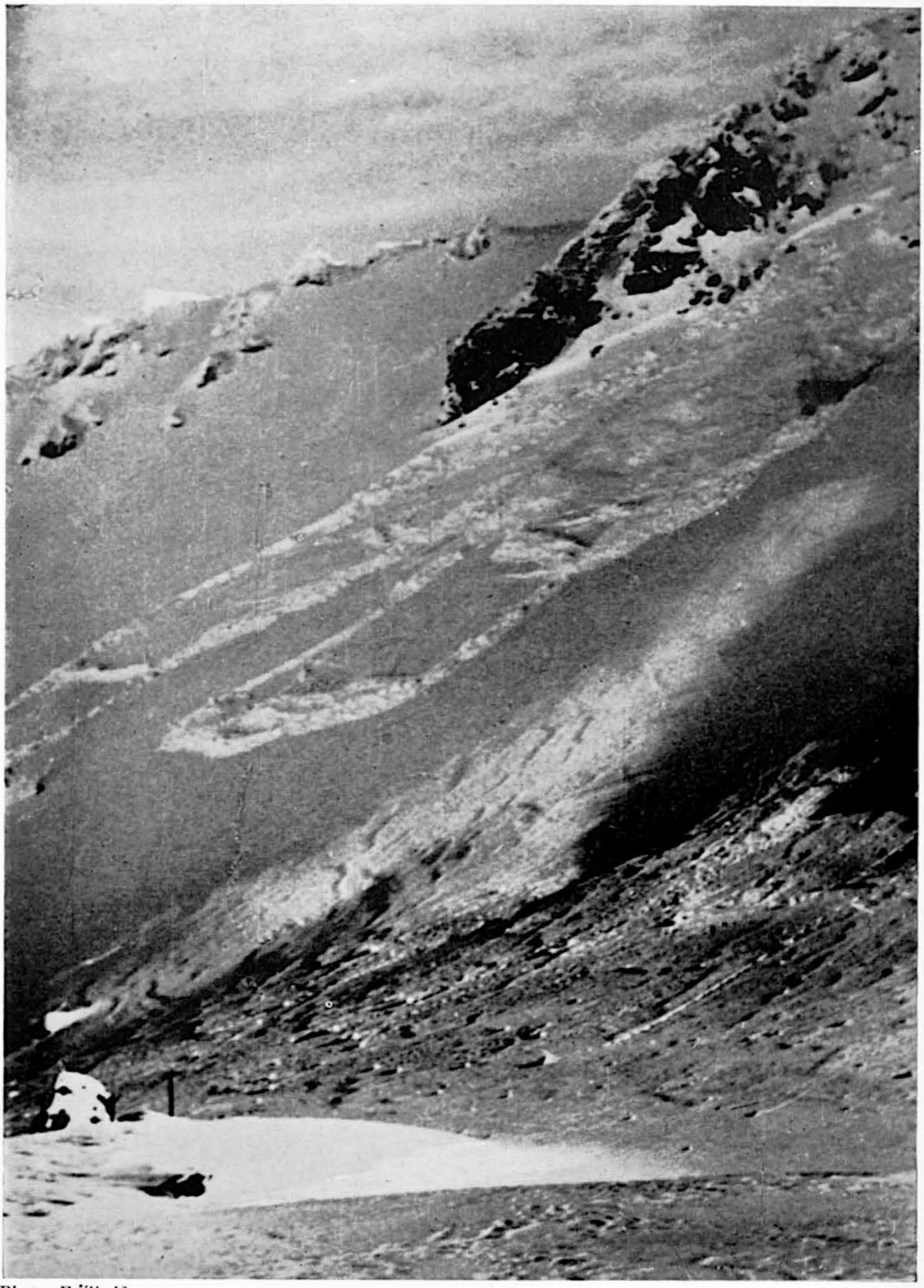


Photo: Frölisch]

PLATE 3: THE WAY IN WHICH MOVEMENT PROPAGATES. AN EXPLOSION (TOP RIGHT), WHOSE SMOKE IS VISIBLE, SETS TWO SLABS IN MOTION, EACH OF WHICH IN ITS TURN SETS IN MOTION A SLAB OF APPROXIMATELY THE SAME DIMENSIONS BELOW IT, AND SO ON IN SUCCESSION.

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Let us imagine compact layers of snow, anchored at the top of the slope, also laterally, and supported from below, and whose stability factor is higher than 1. This means in effect that they are still well anchored on their underside. That they may be released, the peripheral fractures, as well as a fracture along the underside, must take place. This slab therefore appears more stable than a comparable layer of loose snow whose moorings at the periphery are negligible. But this is not so at all, for in more compact snow the shock of the fracture of any one of its peripheral anchorages may lead to the fracture of all the others.

Thus it happens that, as a result of one peripheral fracture, a slab of snow, which is perhaps more stable along its underside (higher stability factor) than a layer of loose snow of equivalent weight, may be released while the loose snow would stay in place.

The commonest peripheral fractures, and those most effective in releasing an avalanche, are tensile fractures at the convex parts of slopes. When the slab which breaks under tensile stress is compact, the shock of this fracture produces a concussion which breaks the cohesion of the weakest underlying layer over a certain area. If the slab of snow thus released along its top edge and along its underside is large enough, it breaks its lateral moorings and forces into motion the slab of snow below it on the slope. If on the other hand the snow which breaks under tension is of low strength, the smaller shock is absorbed and, dependent upon its stability factor, the snow downhill from the fracture may not move. Most frequently, the concussion of a peripheral fracture releases a slab of snow which slides out onto the surface of the snow downhill from it; and it may or may not start this snow moving as well. But it also happens that a slab in movement simply forces into motion the next slab downhill from it without sliding over its surface, and so on in succession. (Plate 3.)

Where the stability factor is low, the shock of a tensile fracture at the convex part of a slope may break the cohesion of a fragile underlying stratum right down to the bottom of the slope. Then all the snow is put in motion simultaneously. It can also happen that the collapse of an underlying stratum at the bottom of a slope propagates towards the top and thus releases an avalanche. The best example of this is that of a ski school at Davos which, on a level place at the foot of a slope, started to jump up and down on the snow at the instructor's signal. The skiers were next seen pushing themselves frantically downhill with their sticks to get out of the way of a superb slab avalanche which was released above them.

Peripheral fractures are in fact intrinsic and spontaneous incidents, but ones which we classify in the same category as occurrences and accidents, because their effects are of the same type and because they may also result in the sudden, incidental release of avalanches when the stability factor is in excess of 1.

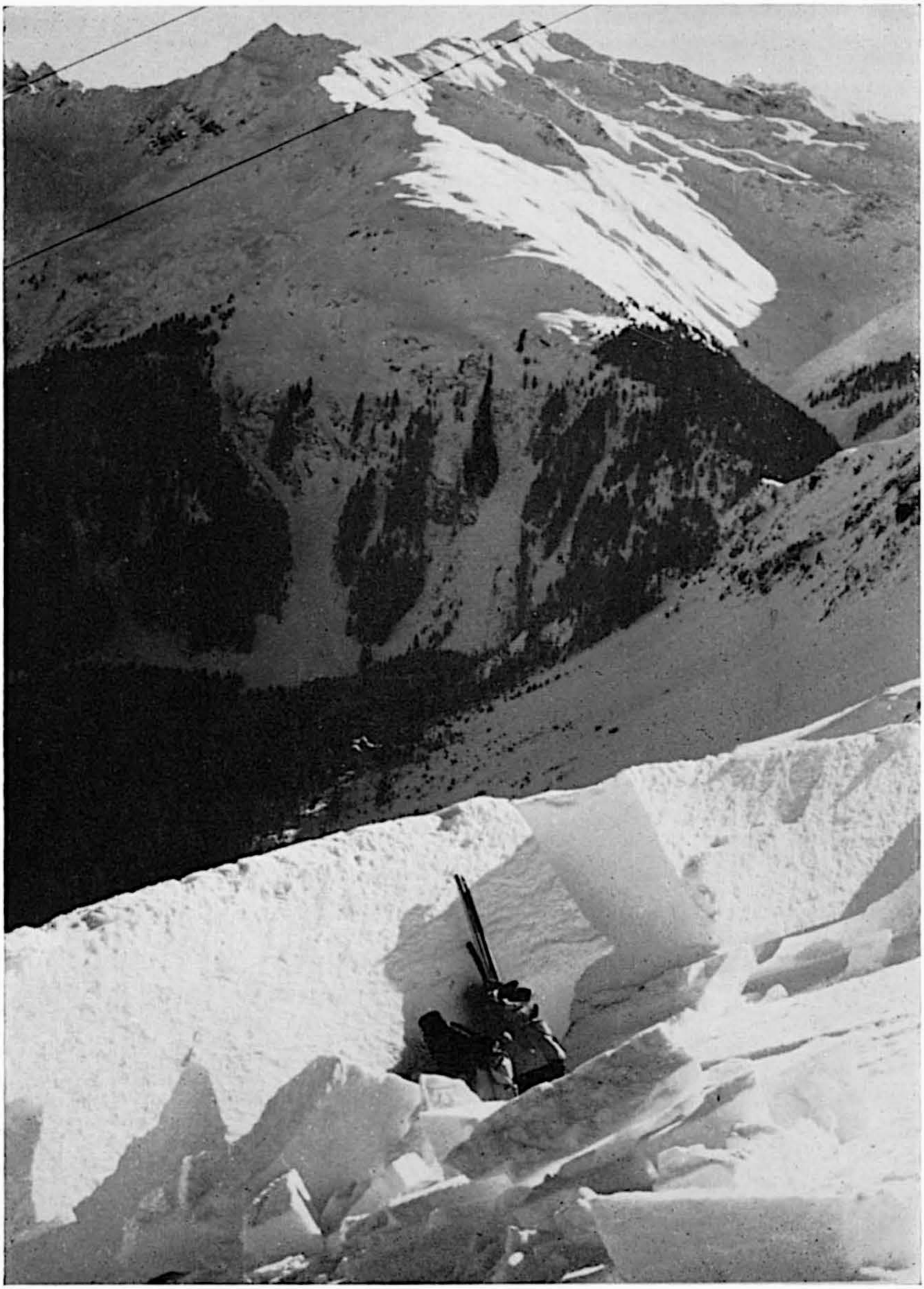


Photo: A. Roch]

PLATE 4: SLAB AVALANCHE AT HAGLAMAD ON THE GOTSCHNA ABOVE KLOSTERS, JANUARY 5, 1953. THE STABILITY FACTOR OF THIS SLAB IS 3. IT WAS FORMED OF WIND-DRIVEN SNOW, AND IT IS EXTREMELY COMPACT. THE TOTAL TENSILE STRENGTH OF THE SLAB IS 250 KG. PER 10 CM. RUN ALONG THE FRACTURE.

(No. 17)

It can also happen that a layer of snow which is thicker at one place on a slope—a snowdrift or a cornice—may be released spontaneously because at this place the stresses exceed the strength. If in its course this mass sets in movement another layer whose stability factor is higher than 1, this layer should be regarded as being released by an outside occurrence or by an accident.

It is probable that the fall of a lump of snow or the passage of a skier, which causes a local break in an underlying stratum on a uniform slope, will not release any avalanche, because the area over which the fragile underlying stratum is broken is insufficiently extensive. On the other hand, there is every likelihood that an avalanche will be released if these events cause the fracture of a slab of snow which is under tensile stress on the convex part of a slope. It therefore follows that a skier traversing the middle of a slope in a neutral zone, or the foot of a slope in a zone of compression, is less likely to release an avalanche than if he crosses the tension zone high up. However, if an avalanche starts, he has more chance of escaping from it if he is caught high up rather than in the middle of the slope or at its foot. He might be able to anchor himself and let the snow go on down. In addition, being on the upper part of the moving snow, he will be less deeply buried and less compressed when the avalanche stops.

When a long file of skiers crosses a slope, it may happen that an avalanche is only released with the passage of the third, even the tenth, man. The fractured area of the fragile stratum is increased a little as each man goes across, until it is sufficient to overcome the peripheral anchorages and to release the snow. It is possible too that a local fracture may be gradually extended by vibration, and so become much more significant.

Experiments made at the fracture lines of slab avalanches show that the greater the stability factor, the more compact the slab has to be before the avalanche can be released. The shock waves resulting from some occurrence or incident are transmitted better in compact strata than in loose snow. (Plate 4.)

The touring skier who has a certain degree of experience instinctively feels that, on snow whose cohesion is weak, an avalanche cannot be released except on a relatively steep slope, because the effects of shock are deadened; whereas, if the snow breaks up into blocks when he puts weight on it with his skis, the shock will spread and the situation is precarious. But it is possible that, under an excellent surface layer of loose snow, there may be a compact stratum which is itself lying on a fragile foundation. These conditions are ideal for the whole snow slab to avalanche, and the skier will not realise it. It was conditions of this kind which were met by Barbi Henneberger and Bud Werner, who were so tragically carried down and killed in the Val dal Selin, above Celerina (Engadine), on April 12, 1964. Snow which had melted in the sun had

its surface refrozen the night before. On the morning of the accident, the first rays of the sun softened a thin surface layer into spring snow, excellent for skiing and resting on a stratum which was still frozen. But below this stratum there was a completely rotten foundation, composed of a fragile scaffolding of cup-crystals, formed by constructive metamorphism during a cold winter in which little snow had fallen. This foundation, moreover, was already wet, the night frost having only consolidated the snow lying above.

It is related that the great Champex guide, Maurice Crettez, who loved to pull people's legs, used to tell his tourists that, in order to detect avalanche danger, he plunged his axe into the snow, put his ear to the axe-head and listened to ascertain the degree of danger! Personally, I doubt whether he heard anything. But, by plunging in his axe, he felt if there was a stratum of low cohesion lying below a compacted layer, and could at once, instinctively, detect slab avalanche danger.