The Relation of Crystal Riming to Avalanche Formation in New Snow

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Abstract

New snow avalanches are forecast by a study of contributory snow and weather factors. This method can be refined by considering effects of riming on snow crystal types and its variation during storms. Rime-free crystals form unstable snow layers which avalanche readily. Partial riming leads to greater initial stability, but this can allow dangerously thick snow layers to accumulate before a soft slab is released. Thick layers of graupel have a peculiar disposition to form slab avalanches due to the high density and large effective grain size. The empirical basis for these conclusions is illustrated by examples from storm and avalanche case histories. Theoretical speculation is developed to account for these effects of snow crystal riming in terms of the sintering process.

I. Introduction

This paper concerns the problem of forecasting direct-action avalanches in new snow. These run during or immediately after a snowfall; they are most commonly, but not necessarily, soft slabs (de Quervain, 1965). The forecasting of climax avalanches, which depends on investigation of structural weaknesses in the snow cover, will not be discussed.

Criteria in the form of contributory factors have been used as a basis for anticipating direction-action avalanche hazard from observable snow and weather conditions (U.S. Forest Service, 1952, 1961; LaChapelle, 1965). A number of factors were identified as significant (see below) at an early date. Experience in the United States during the past two decades has confirmed their validity. Many of these factors are interrelated, although new snow depth, precipitation, wind velocity and air temperature are probably the dominant ones. All were chosen empirically, though there are reasons to believe that some would be significant from a theoretical standpoint. Each has survived on the pragmatic basis of demonstrated usefulness.

From the start it has been explicitly recognized that other factors may also be significant, or that the present ones are inadequately evaluated. Specific notice has been taken of the unexplored possibilities in *new snow type* (U. S. Forest Service, 1961). Importance of this factor has recently been restated, in general if not in specific terms, by Zingg (1965). Lack of specifics, in fact, has persistently characterized consideration of this factor. Broad and somewhat loose terminology like "pellet", "powder", or "granular" is used to classify the types of new snow. An accumlating body of evidence suggests that new snow type may play a more important role than hitherto assigned to it. Accuracy of direct-action avalanche forecasting can be substantially enhanced by specific knowledge on this point. It is the thesis of this paper that the character of the falling crystals during a storm plays an important part in new snow stability. Specifically, the degree of *riming* on falling snow crystals influences mechanical properties of deposited snow in a recognizable fashion.

II. The Evidence and Its Interpretation

Rimed snow crystals. The accretion of rime particles (frozen supercooled water droplets) on falling snow crystals appears to be a common phenomenon. Yosida (1955) reports that most of the snow falling at Sapporo, Japan, exhibits rimed crystals. A comparable condition is found at Alta, Utah, USA, where completely rime-free snow crystals may occur only in one snowfall out of ten. There is little information available on the climatology and geography of crystal riming, for observations of this phenomenon is not a part of standard meteorological records. The percentage of occurrence may well be much lower in some localities. The famous collection of snow crystal photographs by Bentley in Vermont, USA, contains very few examples of rimed crystals, although the degree of selection that was exercised has not been stated (Bentley and Humphreys, 1931). The required presence of a super-cooled water cloud eliminates the possibility of crystal riming at temperatures below $-40°C$. Riming appears to be most common when precipitation at moderate temperatures is generated from pre-frontal clouds by strong orographic lifting. The observed effect ranges through a complete spectrum from a few scattered rime particles per crystal to the dense pellets of graupel.

Data sources. The following observations on the effects of snow crystal riming on avalanche formation have been made over a period of 13 years, largely at Alta, Utah. This site is located in the Wasatch Mountains of Utah, which rise abruptly along the eastern margin of the Great Basin. Snowfall varies from 9 to 15 m per year. Winter temperatures are relatively mild but periods of mid-winter thaw are rare. Most snowfall occurs at temperatures between -5 and $-15°C$, although storms at both colder and warmer extremes occur from time to time. The climate lies between the maritime conditions of the Pacific Coast and the continental climate of the high Colorado Rocky Mountains to the east. Character of the snow cover varies widely from year to year, reflecting at one time a continental regime, at another a semi-maritime condition. Large snow avalanches are widespread and frequent, occurring in a wide range of types.

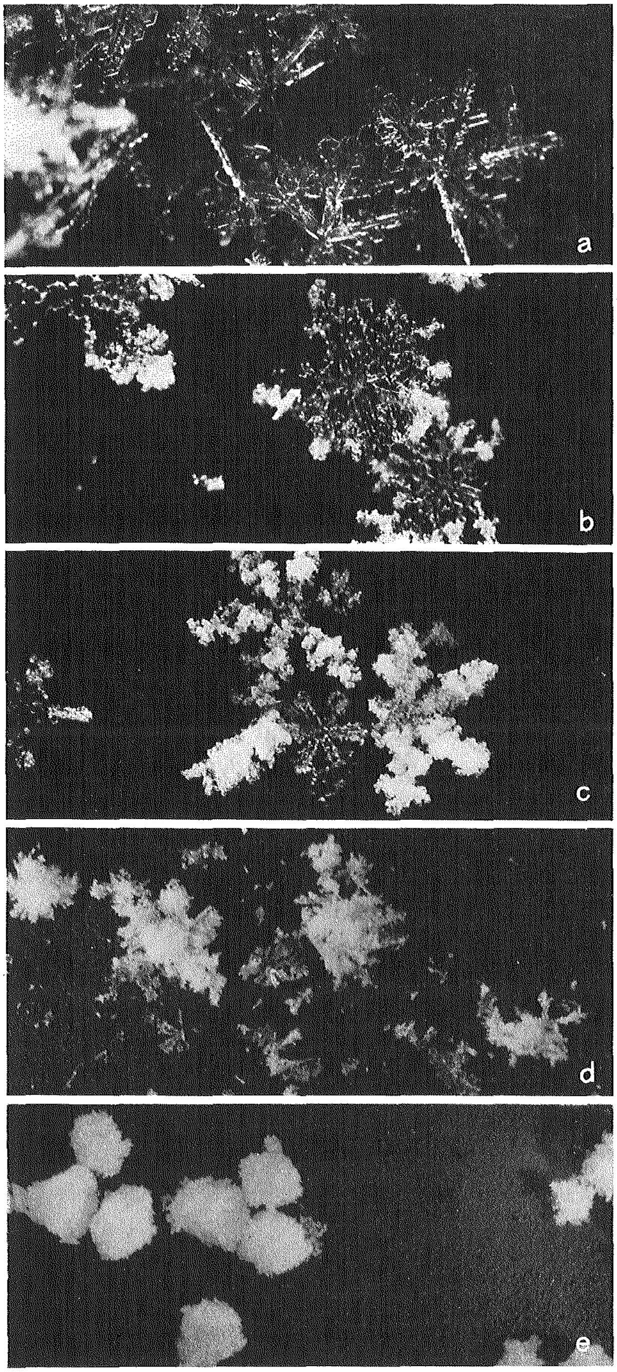
It is not easy to evaluate contributory avalanche factors, for many are interrelated. This is especially true for statistical analysis, because adequate data samples collected by reliable observers are hard to obtain. Even if they were available, the significance of a statistical analysis for such complex relations might be difficult to appraise. A rational interpretation of physical cause-and-effect which is first suggested and later confirmed by field observations is more fruitful for such problems as the interaction between variable weather and ephemeral snow conditions. Such is the approach adopted here. Observations serving as a basis for the present interpretations are of three types: (1) Routine records of weather, snow, and avalanches maintained by U. S. Forest Service snow rangers. These records at Alta, Utah, date from 1945; they are complete but vary widely from year to year in quality of technical details. (2) A careful study of individual storms, including macrophotography of falling snow crystals, since 1959. These provide excellent technical detail, but an erratic and sometimes poor sampling of storms in the normal course of a winter. (3) Habitual field observations by the author of falling snow crystal types (hand lense examination) for more than a decade.

The formation of soft slab avalanches. This avalanche type forms from snow of relatively low cohesion which still exhibits the formation of tension cracks and slides away from a fracture line as a distinct layer characteristic of slab avalanches. Adhesion of a new snowfall to the previous snow surface is one of the determining variables. Precipitation intensity, the rate at which the snow load is deposited, often plays a dominant role. Some wind drifting is required, but soft slab formation is not strictly confined to lee deposition areas. The minimum critical wind velocity is around 6 to $7\,m\cdot sec^{-1}$. The probable occurrence of a maximum critical velocity, above which avalanching is rare, has also been observed at around $30\,m\cdot sec^{-1}$. Temperature trends have a subtler effect, often exerted indirectly by influencing new snow density. The latter factor is important, soft slab formation being strongly related to the higher new snow densities. A significant negative influence is exerted by "sluffing", the natural release of many small, loose-snow avalanches which tend to stabilize the steeper slopes against the formation of thick slabs. Sluffing is most common at new snow densities below about $0.07\,g\cdot cm^{-3}$. Soft slab avalanche hazard seldom persists for long periods, for metamorphism and settlement rapidly alter the snow conditions prevailing at the time of deposition. Constructive metamorphism in a soft slab may occasionally precipitate a delayed avalanche, but more frequently these slabs are stabilized by settlement.

The importance of graupel (Fig. 1 e) to soft slab formation has long been noted. At times a shallow layer of coarse graupel deposited at relatively low temperatures (under $-6°C$) may occur as cohesionless pellets which offer poor anchorage to subsequent snowfalls and thus serve as the lubricating layer of a soft slab avalanche. More commonly, graupel forms a dense, cohesive slab layer. When such a layer reaches 20 to 30 cm in thickness, dangerous avalanches are common. The high density of newly-deposited graupel (up to $0.25\,g\cdot cm^{-3}$) in relation to its relatively low tensile strength causes readily-fractured soft slabs. Probably just as important is the high viscosity associated with effective grain sizes up to $8\sim10$ mm, for this would inhibit stress relaxation.

The type of new-fallen snow loosely described as "granular" also contributes to soft slab formation. Stabilizing loose-snow sluffs are rare. Deposited new snow density tends to be above $0.10\,g\cdot cm^{-3}$. Layers more than $25\sim30$ cm thick have a notable tendency to avalanche if deposited in the presence of wind. Microscopic examination of this snow type shows it to consist of small crystals or fragments or large ones, all heavily rimed but lacking the dense structure of large graupel pellets (Fig. 1 d).

Soft slab layers built up from strongly rimed but still recognizably stellar crystals (Fig. 1 c) retain some of the avalanching characteristics of those formed from graupel or "granular" snow. Under favorable circumstances (adequate wind, precipitation intensity, and new snow depth), large soft slab avalanches may be released. Tension cracks



×13.7

×13.7

×13.7

× 3.4

× 3.4

Fig. 1. The principal stages of riming on stellar crystals, from rime-free (a) to graupel (e). The new snow type sometimes called "granular" is illustrated by (d)

originate readily in mechanically disturbed slab layers of such snow, although they may have a soft, felt-like texture of very low bearing capacity and little apparent mechanical strength. Minor sluffing may occur. Avalanches in such snow still release by characteristic slab fractures, but resemble loose snow avalanches once they are in motion.

As the amount of rime on stellar crystals decreases (Fig. 1 b), so does the probability of large soft slab avalanches. Snow layers formed from such crystals appear much less able to sustain tensile stresses than the types described above. Sluffing is common. Occasionally, shallow and very soft slabs may form, but these run as generally harmless small avalanches. In respect to layers formed from heavily rimed crystals or graupel, such snow is unstable and very seldom builds up to dangerous thicknesses on steep slopes; it runs off as sluffs first.

Direct-action avalanches, especially soft slabs, exhibit a contradictory behavior of newly-deposited snow. The eventual formation of a slab avalanche hazard becomes more probable as the initial instability of the new snow *decreases*. Highly unstable snow does not form a serious hazard by virtue of the very fact that it slides so easily. The avalanches, small and mostly harmless, run long before the snow accumulates to a depth where they might be dangerous. As the degree of cohesion among crystals increases, the snow initially is more stable and has the opportunity to build up thick layers capable of temporarily sustaining stresses but eventually fracturing as slabs. Field evidence in the form of observed soft slab behavior strongly suggests that this degree of cohesion is directly related to the amount of rime on the falling crystals. In the absence of rime, the crystals cohere poorly, the snow layer they form avalanches easily, and a serious hazard from large avalanches seldom occurs.

Snow crystal characteristics do not, of course, hold the entire key to occurrence of such avalanches. The pre-requisite of suitable terrain is assumed. Other determining contributory factors must be favorable. A certain minimum new snow depth must be attained; 25～30 cm is the critical minimum for dangerous soft slabs. Precipitation intensity must be high enough (above 2.5 mm of water per hour, roughly) to surmount the stabilizing influences of metamorphism and settlement. But when these and other conditions are met, there still remains a highly variable behavior of newly-deposited snow*. At times large avalanches may occur widely, while at others, with very similar contributory factors, only extensive sluffing is observed. Evidence accumulated in the climate of northern Utah indicates that this difference is dictated by the degree of riming on falling snow crystals in the manner outlined above.

Interpretation. A community of deposited snow crystals gains its bulk strength from cohesion among the individual particles. As soon as the crystal branches touch one another without further disturbance, the sintering process begins to establish bonds at the contact points. Mass transfer, principally by vapor diffusion, deposits ice to bridge the contacts and welds them together (Hobbs and Mason, 1964). Bulk mechanical strength of the snow layer will be determined by the number of these bonds as well as

* Another aspect of this variable behavior is introduced when new snow falls on an unstable base such as depth hoar. All forms of snow will avalanche from a sufficiently unstable depth hoar layer. But this represents a climax avalanche situation reached by internal metamorphism of already-deposited snow, which is beyond the scope of this paper.

the structure of the original crystals. If the crystals are rime-free, there is an opportunity to form a single sintered bond at each contact between arms of adjacent crystals. In the case of stellar or dendritic crystals, mechanical interlocking is also possible, contributing to the felt-like structure of low-density new snow. Given the same crystals forming the same matrix, but rime particles coating each with a pebbled surface, each contact between arms finds more than one possible juncture or near-juncture between rime particles and thus the opportunity for multiple sintering bonds. If these bonds are favored at certain relative crystallographic orientations of the two contacting ice particles, then the multiple contacts of rimed particles will offer augmented probability for the encounter of favored orientations.

As the degree of riming increases, the branched crystals become filled and mechanical interlocking is no longer possible. Instead of a readily deformed felt-like structure, the snow takes on the character of a coarse-grained aggregate which culminates in the stiff, dense graupel layer. Although viscosity measurements related to different types of new snow appear to be scarce, presumably even the incipient forms of graupel associated with partial riming must exhibit a heightened viscosity serving to forestall stress relief through plastic deformation.

Conclusions. On the basis of empirical field experience, there appears to be a definite relationship between snow crystal riming and stability of the deposited snow layers. Rime-free crystals form highly unstable snow which sluffs readily and does not generate

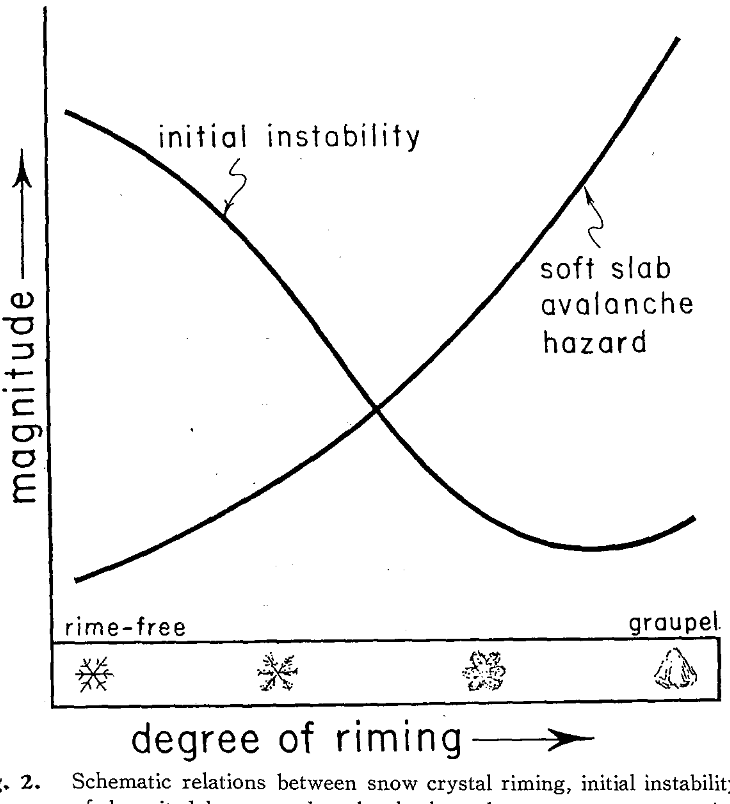


Fig. 2. Schematic relations between snow crystal riming, initial instability of deposited layers, and avalanche hazard

dangerous soft slabs. As the degree of riming increases, a pseudo-stability allows accretion of layers capable of sustaining stresses and forming large slab avalanches. Numerous illustrative examples of this relationship are available from the climate of northern Utah. There appears to be a rational explanation of the relationship in terms of sintering phenomena, but it has not been rigorously proved. The acquisition of a sufficiently large sample of data collected by reliable observers will probably require a number of years before a meaningful statistical comparison can be obtained. In the meantime, tests of mechanical properties of newly-fallen snow could either confirm or deny the validity of present speculation about reasons for the effects of riming. This type of snow is difficult to manipulate in the laboratory, but it should be possible to devise *in situ* field tests—for instance, large cone penetrometers or shear vanes—which would yield information on the relative strength properties of low-density new snow. Viscosity measurements would be more difficult.

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