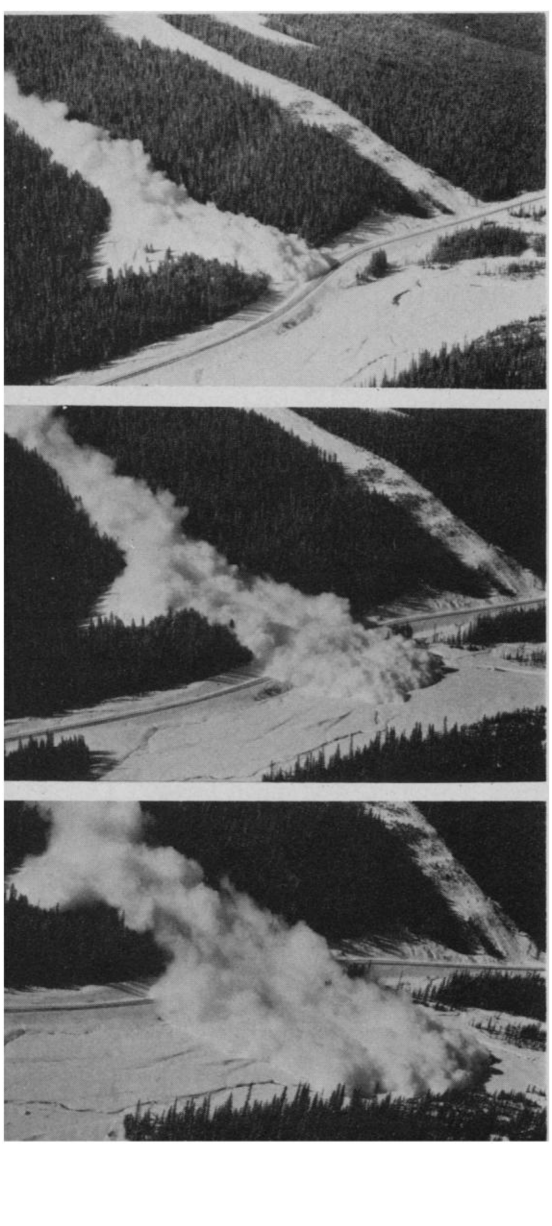
Snow Physics and Avalanche Prediction

Field studies and computer models provide insights into the mechanisms of snowslides.

Much of the fascination with avalanches derives from their transience, power, and seeming unpredictability. A hundred tons of snow may take a minute to descend a steep mountain slope, leaving only a scar to record the extent of the initial slab. Individual avalanches are still quite unpredictable in that no one knows at what moment a particular slide will occur, yet avalanches are not a major winter killer. In ski areas, for example, explosives are used to control snowslides by triggering them artificially when ski lifts and trails are closed. Nonetheless, forecasting avalanches and all other natural hazards is of scientific interest because the ability to predict is the ultimate test of understanding.



An avalanche in Kootenay National Park (British Columbia) appears as an advancing snow cloud in these photographs taken a few seconds apart. Part of an avalanche control project, this slide was triggered by explosives thrown by helicopter onto an avalanche-prone snow slope above the highway. New results suggest that the current control practice of detonating explosives in or on the snow may not be the optimal way to initiate avalanches. Hans Gubler (Federal Institute for Snow and Avalanche Research, Davos, Switzerland) finds that explosions in the air, 1 to 2 meters above the snow surface, may trigger avalanches more effectively. [Photos by Jim Davies, Bow Helicopters, Ltd., Banff, Alberta]

Statistical correlations between weather conditions and avalanche occurrence are serving as the basis for computerized schemes to estimate regional avalanche danger. Some investigators now report 80 percent success at forecasting avalanche activity—a respectable score for natural hazard prediction; but knowledgeable mountaineers and field workers such as snow rangers are said to do at least as well.

Making the predictions more specific in time and place requires a detailed knowledge of avalanche physics. How does the snow pack evolve? How do snowslides break loose? And how do avalanches flow down the mountainside? Avalanche researchers are answering these questions slowly. One new result indicates that snow fractures more easily after it has been deformed a little, a characteristic that may help to explain the sudden release of a large snow slab.

In looking for clues preceding avalanche release, investigators are using a number of techniques for monitoring snow slopes. One technique is based on acoustic emissions from the deforming snow pack. William St. Lawrence at the Cold Regions Research and Engineering Laboratory in Hanover, N.H., has observed that stressed snow emits signals in the ultrasonic frequency range (30 to 200 kilohertz). He has correlated these signals with the deformation of ice crystals and with the breaking of bonds between individual grains of snow. Microscopic crystal deformations and fractures are thought to precede the sudden, large-scale failure of a huge snow slab; thus, recording an increase in the ultrasonic emissions could provide the desired prognostic. Unfortunately, snow is an excellent muffler of acoustic energy, and therefore these high-frequency signals are hard to detect even very near their source.

In a variation of the technique, seismic signals (5 to 100 hertz) that travel farther through snow are used. St. Lawrence has monitored these with some geophones installed in an avalanche-prone area. He identifies distinctive seismic signatures for two recognized classes of avalanches. Slab avalanches begin with a spike; then there is a quiet period of 0.5 second, after which the signal amplitude slowly increases. Loose snow avalanches, in contrast, are characterized by a gradually increasing signal amplitude alone. Whereas the seismic signatures are interesting after the event, they do not provide any warning to threatened individuals.

Richard A. Sommerfeld at the Rocky Mountain Forest and Range Experimental Station has also been monitoring avalanche slopes seismically. He observes what he calls "snow noise," and finds that increased snow noise sometimes seems to precede avalanche activity by several hours to a few days.

If seismic precursors are an unreliable indicator of impending avalanche activity, meteorological conditions and snow pack stratigraphy may not be. Empirical correlations between selected meteorological parameters and avalanche occurrence have been discerned with the use of computers. Although not all investigators agree, some believe that this approach holds promise for estimating regional avalanche danger on a given day and eventually may serve as a basis for making specific avalanche predictions.

Computer-based, statistical-empirical avalanche forecasting is based on the association of past avalanche activity with several meteorological and snow-pack factors. Thus, the success of the "model" is tied to the quality and amount of data available. Preferably several years' records are used.

For each day, the computer stores the meteorological data (for example, air

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temperature, wind velocity, and new precipitation) and snow-pack data (including depth, temperature at various depths, and stratigraphy) along with the record of avalanche activity. Then the days are separated into at least two classes, based on avalanche occurrence. Finally, the computer performs statistical tests, known as discriminant analysis, to identify the variables that best distinguish between the two or more classes.

Richard L. Armstrong and others at the Institute of Arctic and Alpine Research (INSTAAR) at the University of Colorado have "trained" their computer in this way, using a few years' data from the San Juan Mountains of Colorado. In order to obtain a more sophisticated discrimination they have examined the data for each day in combination with that from the preceding 1, 2, or 4 days. They obtain the most clear-cut separation between avalanche and nonavalanche days when only a 2-day record is considered. INSTAAR's routine has been tested with new data from the same locale. The forecasts have been over 80 percent accurate, suggesting significant links between the weather and avalanche occurrence.

As a by-product of this analysis, Armstrong and his co-workers have confirmed the different associations for wet and dry slab avalanches, long suspected by field workers. Wet snow slab release appears to correlate best with the mean and maximum air temperature (warming) during the previous several hours. But dry snowslides are linked with heavy snow fall just before release and with the air temperature history over longer periods of time. Although dry snow avalanches are often stimulated by large amounts of new snow, the fracture almost always occurs along a weak plane in the older snow.

In the Parsenn area of the Swiss Alps, meteorological, snow-pack, and avalanche conditions have been monitored since 1960. The large data base has allowed the testing of several different methods of statistical-empirical avalanche forecasting. In this venture, French scientists Charles Obled and Philippe Bois, at the University of Grenoble, are cooperating with Walter Good and others of the Swiss Federal Institute for Snow and Avalanche Research in Davos. Among other things they find that avalanche-prone situations seem to develop over a few days.

At least part of the reason avalanches seem to take time to develop is that snow undergoes structural changes. In fact, under some conditions, a weak layer is formed within the snow pack by a process termed temperature gradient metamorphism. New evidence, however, suggests that the moisture gradient induced by the temperature gradient is crucial to the formation of a weak layer.

The upper edge of the snow-slab scar appears as a linear shadow along the ridge crest directly above the avalanche. This flow narrowly missed the truck, which was climbing toward Loveland Pass, Colorado. [*Photo by the Colorado Highway Patrol*]

The mechanism of weak layer formation is controversial. Some researchers favor small-scale water vapor diffusion in which snow grains grow at the expense of their warmer neighbors. Others contend that diffusion alone cannot account for the amount of material transported upward through the snow pack; another mechanism, like air circulation within the snow, must play a role.

When the air is cold (typical of dry continental interior regions like the Rocky Mountains), the snow is coldest on its surface and warmer, near freezing, at the ground. The water vapor pressure in the air near the deep, warm snow is higher than it is in the air in the cold surface snow. Furthermore, the cold air in the surface snow is more dense than the warmer air on which it rests. This unstable stratification can result in air convection through the low-density, highly permeable snow pack. Thus circulating air may transfer water, as vapor, from the deep layers toward the surface, where it would refreeze. As this process continues, the deep snow would be depleted of material and large vertically oriented crystals, known as depth hoar, would grow. These do not anchor the upper layers of snow well, and may fall like dominoes, releasing a slab avalanche.

The larger the difference between the moisture content of the air at the top and bottom of the permeable layer of snow, the more rapidly the temperature gradient metamorphism proceeds. Richard L. Armstrong at INSTAAR and Edward R. LaChapelle at the University of Washington report that they have identified a critical vapor pressure gradient below which so-called temperature gradient metamorphism does not occur.

Other avalanche research has focused on snow fracturing, in an attempt to reveal how snowslides are triggered. The initiation of slides is still not well understood, partly because snow is so variable. For example, the weak layers at the base of some avalanche slabs seem to be 100 times stronger than the layers that fracture to produce other snowslides.

Snow strength depends in a complicated way on the snow density, crystal structure, and temperature. For this reason, it varies greatly within a snow pack.

When a slab avalanche is released, a thick layer of snow slides along the surface of stationary snow, in a process known as shear. Ronald I. Perla and David M. McClung at Environment Canada in Canmore, Alberta, are studying the behavior of snow in shear. McClung has observed that snow becomes easier to fracture or deform after it has been deformed a little. This property may help explain why avalanches are precipitated suddenly, sometimes without apparent stimulus. By deforming slowly, the weak layer becomes weaker. When it becomes too weak to support the overlying snow, fracture occurs, and the released slab accelerates down the mountainside.

In the past few years, investigators have been able to make measurements on avalanches in motion. This has added another dimension to the characterization of snowslides since prior data came only from after-the-event studies of avalanche paths and destruction.

Peter Schaerer at the National Research Council, Division of Building Research in Vancouver, Canada, has monitored some known slide paths in order to measure avalanche velocities and impact pressures. These features are of interest to structural engineers designing buildings and bridges for mountainous areas. Average, moderate-sized avalanches travel about 30 meters per second, observes Schaerer; but he has measured speeds as high as 60 and as low as 10 meters per second. Investigators in France, Japan, and the U.S.S.R. also measure velocities in this range. However, researchers admit that huge avalanches, such as the earthquake-triggered one that buried the town of Yungay, Peru, in 1970, may travel much faster.

Continuous records of avalanche impact pressure reveal sizable fluctuations several times a second as the snow streams past the sensor. Although some investigators attribute the pressure peaks to collisions of individual snow particles with the transducer, others are skeptical. However, there are not enough data to resolve a major controversy on the nature of avalanche flow. The question is what happens to a slab of snow after it breaks loose and begins to move down a slope. Does it retain enough coherence to have a dense "core" region? Or, as some researchers suspect, does the slide rapidly become a low-density, fully turbulent flow—a snow cloud?

A definitive answer could be obtained by recording simultaneously the impact pressure at several heights above the stationary snow surface and at several locations across the path. Such a recording has yet to be accomplished because field measurements of natural avalanche dynamics are inherently difficult to make. Instrumentation must be installed in an avalanche track and remain functional and exposed until a slide occurs.

Numerical and experimental modeling is being performed by some groups. However, only the dynamics of the slide can be simulated with any confidence since details of the release mechanism are poorly understood.

Theodore E. Lang and his associates at Montana State University report that they can produce runout distances and average impact forces that are similar to those observed by field workers. Lang's computer routine is a modification of a program developed at Los Alamos Scientific Laboratory for modeling the transient shock phenomena associated with atomic blasts. Lang treats the avalanche as a laminarly flowing fluid, with the important physical parameters being fluid viscosity and frictional drag at the base of the flow. Lang's model is criticized by those who believe that avalanche flow is entirely turbulent.

To test the numerical model and provide better data on avalanche dynamics, Lang's group has studied small-scale man-made avalanches. They have dug a small channel in a snow pack and poured snow into the chute to create a mini-avalanche that could be monitored thoroughly. Although only the velocity of an unrealistically slow snowslide (6 meters per second) has been achieved, the experimental results could be simulated successfully by the computer program.

Taken together, the computer simulations, statistical studies, and field measurements are beginning to provide new insights into the mechanisms of a long-standing winter hazard. However, much remains to be learned before specific avalanche prediction becomes a reality.

—Beverly Karplus Hartline

Update

Cancer and Estrogens

Late last year, criticism of the evidence linking the estrogen drugs used to treat menopausal symptoms to an increased risk of uterine cancer spurred the Food and Drug Administration to take another look at its policy regarding the use of the drugs (*Science*, 22 December 1978, p. 1270). That policy requires that the estrogens carry a label warning physicians that the agents are associated with an increased risk of the cancer and urging caution in their use. Now the agency has decided that no change in its policy is needed.

The criticism provoking the FDA review was advanced by Alvan Feinstein and Ralph Horwitz of Yale University Medical School. They maintain that the epidemiological studies on which the policy is based are all flawed by a bias in their design that favors the detection of uterine (endometrial) cancer in estrogen users but not in nonusers. The FDA disagrees.

One of the factors in the agency decision was the publication of the results of another study, the largest performed thus far, indicating that the link between estrogens and endometrial cancer is both real and substantial.* The results agree with those of several earlier studies in which estrogen users were found to have a risk of endometrial cancer several times greater than that of nonusers. The current study also finds, as have some of the others, that the risk increases as both the dosage and duration of drug administration increase.

According to Feinstein, the new study suffers from the same flaw as the previous ones. In contrast, the study coordinator, Paul Stolley of the University of Pennsylvania School of Medicine, says that the study addressed—and refuted—the Feinstein-Horwitz criticism and also other criticisms leveled at the epidemiological evidence in the past. In particular, Stolley points out that no evidence was found in the new study that estrogen use speeds up the diagnosis of endometrial cancer. Feinstein counters that speed of diagnosis is not at issue. Rather, the issue is that the cancer is more likely to be detected in the users simply because use increases medical surveillance of the women and not because the drugs cause the cancer. It is safe to say that neither side in the controversy is much convinced by the arguments of the other. But the FDA is convinced. And there the matter rests.—J.L.M.

*C. M. F. Antunes, P. D. Stolley, N. B. Rosenshein, J. L. Davies, J. A. Tonascia, C. Brown, L. Burnett, A. Rutledge, M. Pokempner, R. Garcia, *N. Engl. J. Med.* **300**, 9 (1979).