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SNOW-AVALANCHE MAPS FOR USE BY THE NORWEGIAN ARMY

by

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ABSTRACT

Mapping of areas exposed to avalanche hazard for the Norwegian Army was started by the Norwegian Geotechnical Institute in 1986. The background to this mapping is that large-scale military exercises are held annually in northern Norway, in terrain where there is a high danger of avalanche activity. Avalanche areas are divided into two zones: potential starting zones, and potential run-out zones. All potential avalanche areas are indicated on maps, and mapping is carried out by computer using a terrain model and digital maps. An interactive graphic work station is used to outline danger areas. Starting and run-out zones are identified by using terrain parameters which may be extracted from digital maps. The usual scale of the avalanche maps is 1 : 50 000, with 20 m contour intervals.

INTRODUCTION

Military exercises are held in Norway each winter and, especially in northern Norway, there are many exercises. The exercises involve large numbers of participants and spread over a considerable geographical area; NATO training exercises with participants from six to seven countries alternate with annual national exercises, and a force ranging in number from 15 000 to 25 000 individuals participates. Most training takes place in Nordland and Troms counties, generally in the area between the cities of Narvik in the south and Tromsø in the north (Fig. 1). The size of the training area varies but it is usually about 2500 km^2.

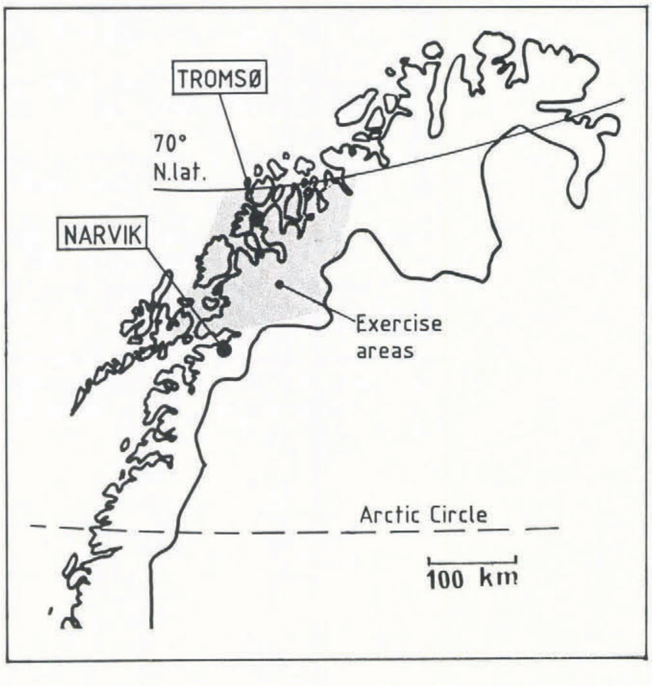

Fig. 1. Location of exercise area in northern Norway.

THE AVALANCHE ACCIDENT AT VASSDALEN

The NATO training exercise, Anchor Express, took place in March 1986. It involved 25 000 land-based soldiers and its location lay immediately north of Narvik in an area which had the topographic and climatic features typical of avalanche-activity danger zones. A battalion from the North Norway Brigade was in the process of carrying out a large flanking operation when a troop from the Engineers Company which was working on a snowmobile track on a steep mountainside at Vassdalen was struck by an avalanche. The entire troop of 31 men and two snowmobiles was dragged along by the avalanche and 16 people were killed.

A Civil Board of Inquiry, which was established after the accident, pointed out that planning of this type of exercise had not adequately take into consideration the potential dangers in avalanche-exposed areas, and that the information that had been made available during the exercise did not provide sufficient insight into the possible avalanche sites in an acute situation (Report from the Civil Board of Inquiry, 1986). It was admitted that during the course of several years the army had used training maps on which avalanche areas and other specialized information had been indicated. However, it was concluded that these maps were inadequate, and that methods used for indicating avalanches were unsystematic and often illogical. The maps had not been drawn up by specialists and it was impossible to establish what criteria had been used in marking areas of potential avalanche activity. Many officers who used the maps during training exercises therefore regarded them as inadequate for their need to evaluate exposed terrain.

MAJOR TOPOGRAPHIC AND CLIMATIC FEATURES OF EXERCISE AREAS

Most of the exercise areas in northern Norway are characterized by alpine, fjord, and valley terrain. Alpine areas are largely found in the vicinity of fjords, whilst in areas further east the mountains are not so high and the valleys are wider. Extensive mountain areas are located between 1000 and 1500 m a.s.l. The mountainous areas within the exercise areas are separated by a dense network of valleys. Many of the larger valleys are broad and wide with a U-shaped profile, but there are also some narrow mountain valleys with a more V-shaped appearance. In addition to valleys, large flat basins are found between mountains. Extensive plateaux on the tops of mountains are characteristic of the area, especially on the mountains near the Swedish border. The highest mountains in the exercise areas are located on Lyngen peninsula, east of Tromsø, and attain heights of up to 1800 m a.s.l. Figure 2 shows typical terrain formations of the area. Large tracts of land are above the tree line, at 400–600 m a.s.l. The low tree line and the open forest cover lead to avalanche activity even on short slopes and at low altitudes.

The exercise areas lie between lat. 68° and 70°N but, in spite of this northerly location, the climate is relatively mild because of proximity to the coast. There are, however, considerable differences between coastal areas with a maritime climate and the more continental eastern parts of Troms, which are situated up to 150 km from the sea.

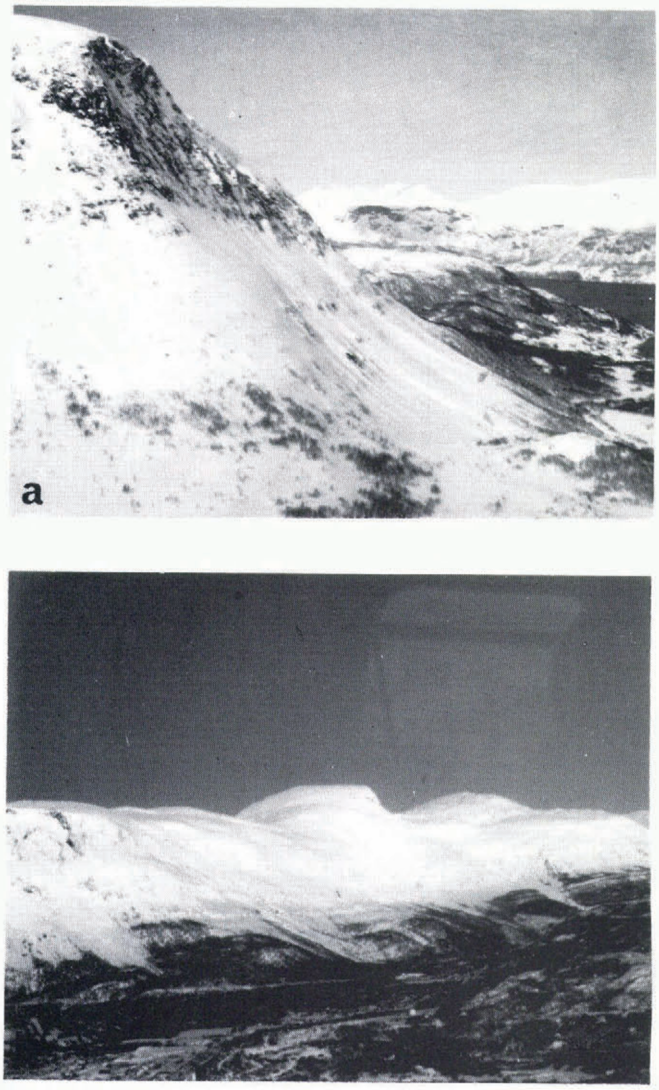

Fig. 2. Examples of topography in exercise areas.

The city of Tromsø, which is approximately 20 km from the sea, has a maritime climate and a normal winter (November–April) precipitation of 514 mm. Further east, the meteorological station Dividalen, about 100 km from the coast, has 105 mm precipitation.

There is also a considerable difference in air temperature between the maritime and continental tracts; in Tromsø the coldest winter month, February, has a mean temperature of $-4\,^{\circ}$C, whilst the parallel figure for Dividalen is $-9\,^{\circ}$C.

Snow depth in the area varies considerably from year to year, especially in coastal areas where mild weather and rain may occur several times during the winter. In continental areas the winter climate is more stable. The normal snow depths in these areas range from 300 to 500 mm, and deep hoarfrost frequently occurs in association with low temperatures, making the snow cover unstable. The relatively low amounts of precipitation contribute to a lower frequency of avalanche activity in the course of a winter than is noted for areas nearer the coast. However, when avalanches do occur, they usually consist of dry, light snow and have a long run-out distance.

In areas characterized by a maritime climate, snow cover varies more in composition and extent. There are usually several avalanche situations in the course of a winter, and both wet- and dry-snow avalanches occur. The prevailing wind direction accompanied by precipitation during the winter is from south-west to north-west. Southerly wind is usually associated with warm-front precipitation, and tends to lead to temperatures higher than $0\,^{\circ}$C at sea-level. Avalanches occurring under these conditions encounter wet snow in the lower parts of their paths and this results in a short run-out distance. Wind originates from the westerly to northerly sector during cold-front passage. During such conditions the air temperature is below $0\,^{\circ}$C at sea-level, and dry-slab avalanches with long run-out distances may occur in all areas including those located near the coast.

High-pressure situations are often accompanied by cold, easterly drainage winds which follow valleys and fjords and do not result in significant precipitation. The winds are particularly noticeable at lower altitudes, that is up to 500–600 m a.s.l. They may result in heavy drifting of snow, and subsequent release of dry-slab avalanches in eastern continental areas as well as in coastal areas to the west.

Briefly summarized, large expanses of the military exercise areas in the countries of Nordland and Troms are climatically and topographically vulnerable to avalanches.

DISCUSSION OF AVALANCHE-MAP ALTERNATIVES

In accordance with recommendations by the Civil Board of Inquiry, the Chief of Defence decided to replace older avalanche maps with newer maps of better quality. There was some doubt as to which type of map could best replace the older maps, and this was the cause of considerable discussion.

There are two main map series in Norway:

(1) Topographic Map Series at a scale of 1 : 50 000 with 20 m interval contours.
(2) Norwegian Economic Map Series at a scale of 1 : 5000 with 5 m interval contours.

When considering that the area which needed to be mapped was between 25 000 and 30 000 km^2, it was obvious that snow-avalanche mapping would have to be based on map series (1), that is at a scale of 1 : 50 000 because a snow-avalanche mapping system using maps at a scale of 1 : 5000 would involve such a large number of maps that they could not reasonably be used by troops in the field. The Chief of Defence expressed the desire that maps should be drawn up to include relatively frequently occurring avalanches. However, the frequency to be taken into consideration was not explicitly expressed (Report to the Norwegian Parliament, No. 68, Appendix 5, 1987).

The frequency limit is a difficult topic for two reasons:

(1) The Chief of Defence would have to choose risk levels. The common definition of risk (R) is: $R = P \times C$, where P = probability of an accident and C = consequences of an accident. If the consequences of an accident are great, the probability must be low if the risk level is to remain constant. Potential avalanche accidents in the Army may result in a variety of consequences, from insignificant injuries to individuals to considerable loss of life. This situation alone makes it difficult, if not impossible, to decide which avalanche frequencies should be included on the maps. Should annual avalanches, those occurring at 10 year intervals, or 100 year avalanches be considered as relevant? In principle, decisions and responsibility concerning the appropriate degree of security, or risk levels, to which the inhabitants of a community might reasonably be exposed are political. However, political authorities and official departments are often reluctant to make statements about such subjects, and are cautious in undertaking the unpleasant task of using precise numbers when discussing "acceptable" probabilities for loss of human life. Government or official replies to such questions are often limited to assertions that security measures should be "maximal", or "as good as possible".
(2) The identification of the frequency of an individual avalanche is technically difficult. It may be possible in inhabited areas below the tree line, where information from year-round residents may supplement visible signs of avalanche activity in forest vegetation, but most avalanche terrain in military exercise areas in northern Norway is located above the tree line, far from inhabited areas. In the majority of these areas, identification of avalanche frequency with a sufficient degree of accuracy would be difficult without undertaking detailed investigations of each avalanche area over several winters. This type of mapping

procedure would be nearly impossible to execute considering the size of the area involved (30 000 km^2) and the extent of the terrain likely to be vulnerable to avalanche activity.

MAPPING PROCESS

The Norwegian Geotechnical Institute has developed a method for mapping areas of potential avalanche hazard. The method was briefly described in the report by the Civil Board of Inquiry on the accident at Vassdalen (1986) and approved in 1986 by the Norwegian Military Geographic Service for use by the armed forces.

Mapping principles

The following basic mapping principles are employed:

All potential avalanche areas are mapped, regardless of their frequency. By including all potential avalanche areas on a map the complicated question of which avalanche frequencies are to be considered is avoided.

Avalanche areas are divided into two zones: (1) avalanche starting zones, (2) avalanche run-out zones (that is areas below zone (1)).

Standard topographic maps of Norway at a scale of 1 : 50 000, with 20 m contours, are used (map series M711).

Zone (1): avalanche starting zone

This zone includes all areas on a map which are steeper than 30° to the horizontal and are not covered by dense forest. The upper limit for slab-avalanche rupture is 50–55°. The presence of ordinary military unit traffic on terrain steeper than 50–55° is unusual, and the extent of the avalanche-fracture area over steep terrain is therefore of little consequence to the Army. By specifying terrain which has a slope angle steeper than 30°, areas where personnel or vehicles may trigger avalanches can be clearly identified, and in addition, all naturally rupturing avalanches originate in these areas.

It is important to bear in mind that the basic features of the map, such as the distance between contour lines, determines whether an area is defined as a starting zone. A 20 m interval between contours implies that some slopes (with a difference in altitude of up to 40 m) where dangerous avalanches may occur may not be identifiable from a map with this contour interval. Attention should be directed to this inherent weakness.

Forested areas are coloured green on the topographic maps, and are easily identified. In most cases the forest is so large and so dense that avalanches do not cause rupture below the tree line, except in some areas of bare rock face. In the vicinity of the tree line, forest is often sparse and trees stunted in growth, and this may complicate decisions as to whether the forest is sufficiently large or dense to prevent avalanche ruptures in areas where slopes have angles greater than 30°. In such areas, only rough evaluations of potential rupture zones can be made.

Zone (2): avalanche run-out zone

The run-out distances of snow avalanches are calculated by using terrain parameters which are identified from a map. This method of calculating probable maximum run-out distances was first described by Lied and Bakkehøi (1980), and later revised by Bakkehøi and others (1983). Terrain parameters shown in Figure 3, worked out on the basis of data from 206 known avalanches where maximal reach was assumed to have occurred, are used to describe run-out distances by reference to the following regression equation:

$$\alpha = 0.92\beta - 7.9 \times 10^{-4}\, H + 2.4 \times 10^{-2}\, H y'' \theta + 0.04. \qquad (1)$$

In this equation α is the angle of the straight line between the other end of avalanche debris and the starting point; H is the vertical distance from the starting point to the low point in the parabola that best fits the longitudinal profile (see Fig. 3); θ is the terrain slope in the upper 100 m of the starting area; β is the line of sight from the point on avalanche path where slope of terrain is 10° to the top of the starting zone; y'' is the curvature of the terrain profile

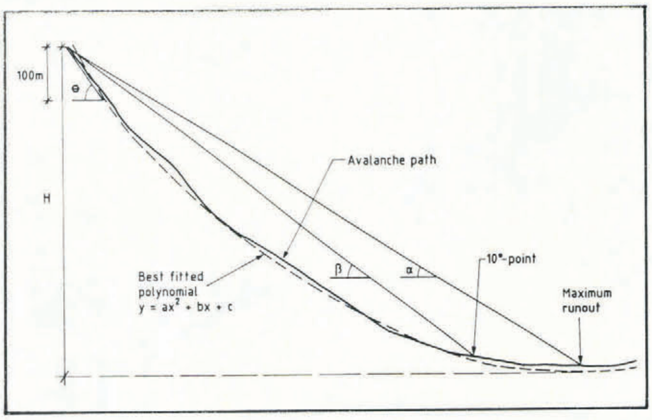

Fig. 3. Terrain parameters used for avalanche run-out calculations.

and is defined as the second derivative of a second-degree polynomial best fitted to the terrain profile. The method is simple, easy to use, and, in our opinion, the best way of calculating the probable run-out distance of snow avalanches (Fig. 3). It is extensively used by the Norwegian Geotechnical Institute in both detailed evaluations of snow-avalanche run-out distances and in survey mapping of avalanches. The advantages of this method are that it is independent of individual snow parameters and that the bases for calculations of run-out distances are built on a set of objective parameters which are to be found on maps. The computation method, where run-out distance is calculated using regression analysis, necessitates decisions as to whether it is desirable to correct the calculated reach for one or several standard deviations. During mapping for the Army, run-out distances are established by subtracting one standard deviation (2.3°) from the estimated mean value for the α angle, which means longer run-out than the mean value.

As already mentioned, maps do not provide information about frequency of avalanches in a particular zone. Avalanche frequency may vary considerably, from areas where avalanches occur every winter to areas where 100 or more years may elapse between each occurrence. Older buildings may be situated within or near the predicted run-out distances of avalanches in several areas and, although calculations indicate that an avalanche may strike or pass by such buildings, we have chosen to terminate run-out areas above them. This is done because the probability that an avalanche will strike older buildings is considered slight. The risk encountered by military units located in the immediate vicinity of buildings of this kind is therefore considered to be acceptably low.

Mapping techniques

The Norwegian Geotechnical Institute has conducted survey mapping of areas exposed to the potential danger of rock and snow avalanches for the National Fund for Natural Disaster Assistance since 1980 (Hestnes and Lied, 1980). This mapping project is also based on the M711 series. When the M711 maps became available in digital form, in 1982, NGI decided to computerize the avalanche-mapping process. The terrain-model system TERMOS was developed by Stabell and Toppe for this purpose (Toppe, 1987) and has been used in survey mapping of snow- and rock-avalanche danger since 1984. The system is also used in the production of Army snow-avalanche maps described in this paper. Mapping is performed using a Prime or VAX computer on which a terrain model is created on the basis of a digital map. It has a bicurved surface, built by overlapping cubic spline functions, controlled by a regular grid with a cell size of approximately 30 m × 30 m, and a total of about 1 million cells. Elevation and normal vectors are stored for each grid cell.

The actual mapping of avalanche zones is conducted on Tektronix 4115 or 4125 graphical work stations. The work station has built-in zooming and panning functions, and all map handling during an interactive work session is performed locally in the work station. This substantially

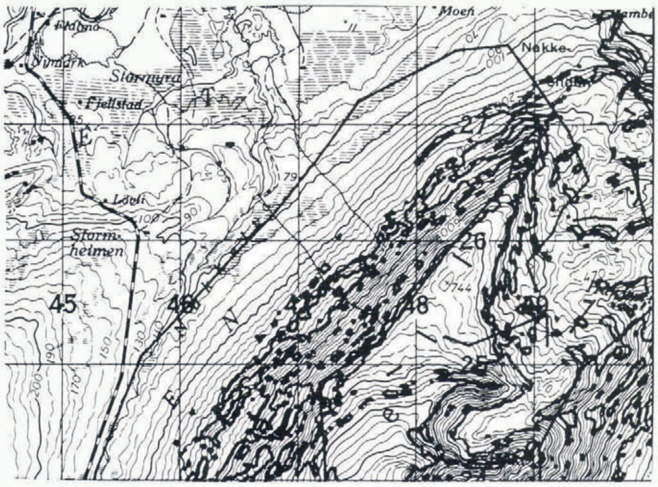

Fig. 4. "30-degree" areas.

reduces the time used in displaying sections of the map. The mapping itself is performed using on-screen hierarchical menus, together with puck and tablet. Mapping starts with the identification of all areas on the map sheet with slopes steeper than 30° to the horizontal. This is done automatically, using normal vector information, and on a map sheet for a surface area of 500 km^2 takes about 30 min. All "30-degree" areas are drawn over the contour lines (see Fig. 4). Several small "30-degree" areas may be located close to each other at many positions on the map. In order to make maps easier to read, these zones are simplified by manually sewing them together into larger areas on the work station using puck and tablet.

When calculating a run-out distance, the operator draws the avalanche path on the computer screen from the uppermost point in the starting area. The data system calculates both terrain profile along the path and also the maximum probable reach of the avalanche. Computation of avalanche reach is done by the data system on the basis of Equation (1). The starting and stopping points of the avalanche are automatically plotted on the profile. Correspondingly, the reaches of all potential avalanche paths on the mountainside being considered are calculated, and finally the run-out area of each individual avalanche path is drawn automatically as a continuous zone over the colour edition of the map. Three-dimensional images of the terrain map may be drawn and used as visual aids during the mapping process (Fig. 5).

USE OF AERIAL PHOTOGRAPHS AND FIELD WORK

Vertical aerial photographs are used in mapping, particularly to control forest density in areas steeper than the 30° slope used in diagnosis. Aerial photographs are also used when there is doubt as to the likely extent of a run-out zone. All avalanche maps are subsequently checked in the field; most field work is carried out from a helicopter or a car, with 2 days required by two people to cover each map sheet. During field work, most attention is concentrated on likely avalanche starting areas where there may be some doubt about the effectiveness of forest vegetation in preventing avalanche rupture. Terrain in the starting area is also monitored. Those terrain forms which may influence the extent of an avalanche may be located during field work, although they are not identifiable from a map. In such cases maps are corrected.

After the completion of field work, maps are edited and revised at the work station. The avalanche map is then plotted on a master copy which is used for printing. (A section of a printed map is shown in Figure 6.) Instructions for use are printed on each map. These instructions briefly explain what the map includes and indicate details which require particular attention during use. User instructions are given below:

"Most snow avalanches rupture during bad weather, i.e. when periods of heavy snowfall are accompanied by strong winds. A pronounced rise in temperature may also lead to the occurrence of a snow avalanche. Snow-avalanche hazard increases with:

Heavy snowfall (20 cm or more per day).
Winds resulting in drifting snow.
A rapid increase in snow temperature, caused by sunlight radiation, rain or warm air. The danger is usually greatest when snowfall is accompanied by wind.
Although the surface of the snow appears to be hard and firm, a loose layer may occur further down in the snow cover, which can lead to avalanche ruptures.
Such loose snow layers are often formed as a result of extensive cold spells with little snow.
Sudden booming noises in the snow are an indication of avalanche hazard.
Exercise extreme caution if you observe other avalanches in the terrain.
Mountainsides and slopes lying on the lee side of the wind accumulate the largest amounts of snow. Potential avalanche hazard is greatest in these areas. Avoid areas which appear to have more snow than other areas on a mountainside.
Choose a route in the vicinity of protruding rock, boulders, etc. Dense forest vegetation may also impede avalanche rupture."

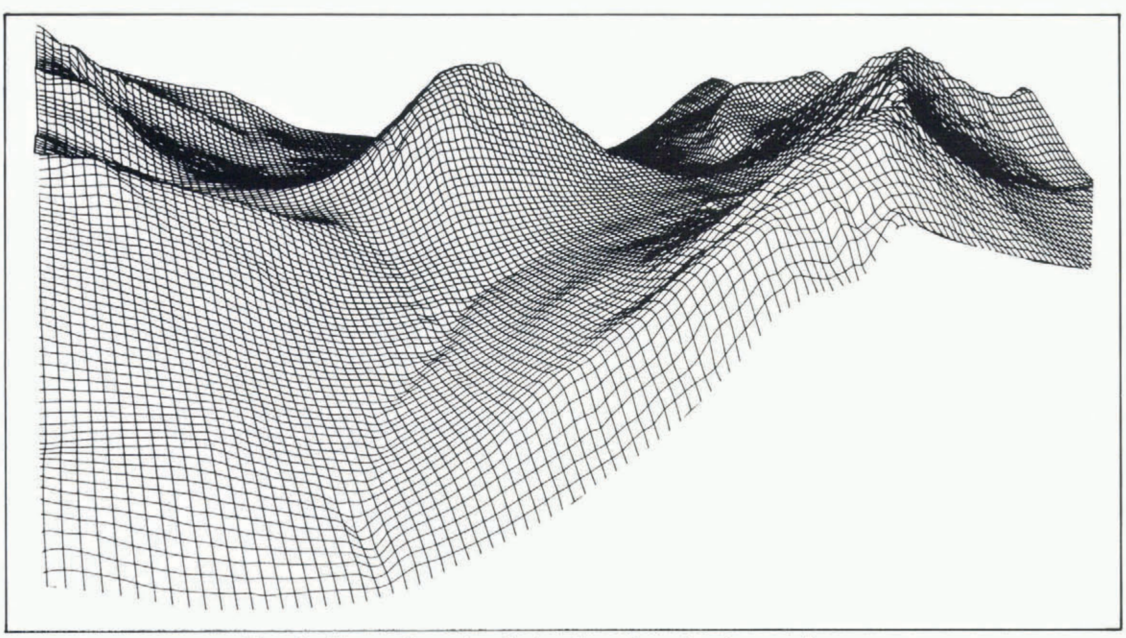

Fig. 5. Three-dimensional drawing of avalanche terrain.

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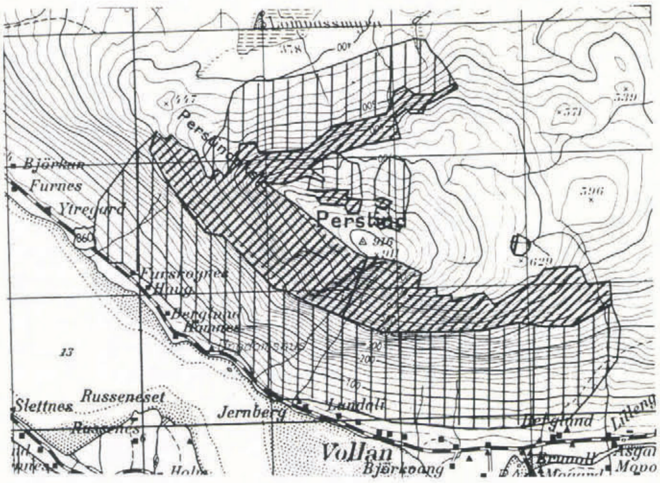

Fig. 6. Section of a completed avalanche map.

AVALANCHE FORECASTING ASSOCIATED WITH THE MAP DESCRIBED

During larger military exercises, an avalanche group responsible for avalanche forecasting is always organized. This group has direct communication with the exercise command and gives advice about areas in the exercise terrain which may be used without the problem of avalanche danger. The group also sends daily avalanche forecasts to all participating units. In order to simplify forecasting, the degree of avalanche danger is related to avalanche zones on the map. The following degrees of avalanche danger are referred to:

"Avalanche hazard 0: little or no avalanche hazard. Very low probability of avalanche rupture. No traffic restrictions in association with avalanche hazard.
Avalanche hazard 1: medium avalanche hazard. Danger of snow-avalanche rupture in steep terrain. Traffic prohibited in zone 1 on avalanche map.
Avalanche hazard 2: high avalanche hazard. Danger of snow avalanches in zones 1 and 2 on avalanche map. Hazard greatest on mountainsides and slopes lying on lee side of the currently prevailing wind direction. Traffic prohibited in zone 1. Areas in zone 2 may only be passed after clearance by avalanche group.
Avalanche hazard 3: extremely high snow-avalanche hazard in zones 1 and 2. All traffic is prohibited in these zones. Troops positioned in zones 1 and 2 must be evacuated immediately. Movement along public roads within zone only after clearance by avalanche group.
Avalanche warnings will be supplemented in greater detail according to the avalanche situation."

CONCLUSIONS

The avalanche maps now being produced for the Norwegian Army appear thus far to have functioned in accordance with expectations. However, more experience is needed before any final conclusions about their suitability can be reached. One of the most important reasons for this is that none of the larger military exercises have as yet been conducted under conditions of great or very great avalanche danger.

Five map sheets and 12 avalanche maps are produced each year, each costing 175 000 Norwegian Kroner (28 000 $US) have been produced up to the present time. In all, 60 map sheets will be produced. This work is conducted by the Norwegian Geotechnical Institute under contract from the Norwegian Military Geographic Service.

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