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ICE AVALANCHES AND A LANDSLIDE ON GROSSER ALETSCHGLETSCHER

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With 14 figures

ABSTRACT

Ice avalanches with volumes between 50 m^3 and 3.5·10^5 m^3 (and perhaps even larger) and which descended over firn surfaces containing few or no crevasses, had average slopes of at least 17°. There seems to be no correlation between the avalanche volumes and the extremely small slope. Morphological features of avalanche paths and deposits indicate that sliding friction at the firn surface is the dominant process in decelerating and stopping the avalanche and that there is little friction within the descending ice mass. Some landslides, when descending over firn, may behave quite similarly to ice avalanches. Predictions of extreme runout distances of ice avalanches on certain firn areas are easier than for other terrain situations since the potential avalanche volume does not have to be known.

EISLAWINEN UND EIN BERGSTURZ AUF DEM GROSSEN ALETSCHGLETSCHER

ZUSAMMENFASSUNG

Eislawinen mit Volumina zwischen 50 m^3 und 3,5·10^5 m^3 (und möglicherweise sogar noch mehr), die über Firnoberflächen mit wenig oder keinen Gletscherspalten niedergingen, hatten Pauschalgefälle von mindestens 17°. Es scheint kein Zusammenhang zwischen diesen extrem kleinen Pauschalgefällen und den Volumina zu bestehen. Die Morphologie der Eislawinenablagerungen und Spuren in den Sturzbahnen weisen darauf hin, daß Gleitreibung an der Firnoberfläche der dominierende Bremsprozeß ist und daß nur wenig Reibung innerhalb der Lawine auftritt. Bergstürze, die über Firnoberflächen niedergehen, können sich ähnlich verhalten. Prognosen der Extremreichweiten von Eislawinen in bestimmten Firngebieten sind einfacher als bei anderen Geländesituationen, da das potentielle Sturzvolumen nicht bekannt zu sein braucht.

AVALANCHES GLACIAIRES ET UNE CHUTE DE ROCHERS SUR GROSSER ALETSCHGLETSCHER

RÉSUMÉ

Les avalanches glaciaires avec des volumes entre 50 m^3 et 3.5·10^5 m^3 (et probablement même plus) qui glissent sur une surface de névé avec peu ou pas de crevasses, ont des déclivités globales d'un minimum 17°. Il ne semble pas exister de rapport entre les volumes et ces extrèmement petites déclivités. La morphologie des cônes des avalanches et les traces de glissement laissent supposer que le frottement sur la surface de névé est le principal process de freinage et que les frottements internes de les avalanches sont faibles. Les chutes de rochers, qui tombent sur des névés peuvent avoir des comportements similaires. Le prognostic de la protée d'une avalanche glaciaire sur des zones de névé est plus facile que sur l'autres terraines car le volume potentiel n'a pas besoin d'être connu.

1. INTRODUCTION

Catastrophies caused by ice avalanches in the Alps have been documented since the 16th century (Röthlisberger 1978, Alean 1984 and in press). Ice avalanche accidents on glaciers have become frequent as a result of the massive increase in climbing activity over the last few decades. Various popular climbing routes go through the runout zones below hanging glaciers and have been the scene of fatal accidents (e. g. "Corridor" on Grand Combin, Festijoch on Dom, both Valais, Switzerland; cf. Alean 1984, p. 205). In recent years, various cable cars and ski lifts have been constructed and these facilitate the access to glacier surfaces. Several of these installations are near areas with potential ice avalanche hazards and some ski pistes are situated in such areas.

Ice avalanche hazards on glacier surfaces have had to be assessed in several cases, for example near Chli Titlis, Engelberg, Switzerland (VAW 1984), at Chli Matterhorn and Felskinn, both Valais, Switzerland. Predicting runout distances of ice avalanches has become possible on the basis of empirical studies (Alean 1984 and in press). A detailed study about ice avalanches on firn surfaces was carried out since it was realized (a) that certain terrain configurations in connection with firn as a sliding surface lead to extremely small friction i. e. extremely long runout distances, and (b) that the behaviour of such far reaching avalanches can be understood on the basis of a particularly simple one parameter model of avalanche motion.

The aim of this study is (a) to document some far reaching ice avalanches on firn surfaces, (b) to explain the extreme reach of these ice avalanches on the basis of field evidence and (c) to provide a simple empirical rule about lengths of runout distances over firn areas. In addition, similarities with a landslide which also descended over a firn surface are pointed out.

2. THE OBSERVATION PROGRAMME

Most ice avalanches which are presented in this study occurred in the accumulation area of Grosser Aletschgletscher, Bernese Alps. Avalanches which occurred prior to 1982 were mapped using aerial photographs with an approximate scale of 1 : 10,000. In addition, from May 1982 to September 1983 terrestrial photographs of the southern hanging glacier of the Mönch (cf. fig. 1) were taken daily by personnel of the Hochalpine Forschungsstation Jungfraujoch whenever the visibility was good; such photographs were also taken less frequently until 1984. The author was notified of exceptional events such as the fall of an ice block on May 13/14th, 1982 and a large avalanche on July 5th, 1984 (see below). In these cases, ground surveying was undertaken within one and two days respectively of each fall. Oblique aerial photographs taken on July 7th were used in addition to the ground survey to map the large avalanche. Maps at a scale of 1 : 10,000 are available for the entire area of Grosser Aletschgletscher.

3. DESCRIPTION OF THE ICE AVALANCHES

In this section only ice avalanches with small frictional coefficients will be described i. e., avalanches with particularly long reaches; in reality, many more events were documented. The frequency and seasonal distribution of all known ice ava-

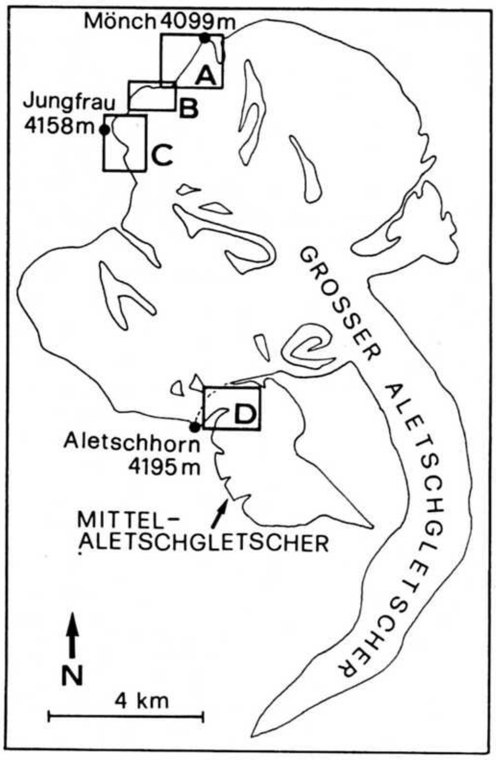

Fig. 1: Key map showing the location of other maps (identified by the letters A, B, C and D) shown below

Table 1: Important parameters of ice avalanches with small average slopes in firn areas

Area	Date of fall	Date of photos	Reach (m)	Area of deposit (m²)	Volume of deposit (m³)	Estimated accuracy of volume value (±)	Average slope (α) (deg)	tan α
On Grosser Aletschgletscher and Mittelaletschgletscher:								
South of Mönch		13. 8. 1980	620	40,000	88,000	50 %	17	0.31
South of Mönch	15. 5. 1982	16. 5. 1982	470	24	55	25 %	18	0.32
South of Mönch	5. 7. 1984	6. 7. 1984	690	107,000	340,000	25 %	19	0.34
East of Jungfrau		4. 10. 1968	630	21,000	63,000	50 %	20	0.36
East of Rottalhorn		11. 8. 1971	465	5,500	18,000	60 %	20	0.36
East of Aletschhorn		6. 7. 1984	1060	175,000	350,000	50 %	21	0.39
On other glaciers:								
Brunegg Glacier, VS		6. 7. 1984	1300	200,000	300,000	70 %	20	0.36
Festigletscher (1)		10. 9. 1971	525	31,000	47,000	50 %	17	0.31
Marvine Glacier (2)		15. 7. 1983	2600	600,000	3,000,000	50 %	17	0.31

(1) West of Dom, Valais; from Alean 1984, p. 156

(2) Hitchcock Hills, St. Elias Range, Alaska; from Alean 1984, p. 176

lanches which originated within a certain period of time at the southern hanging glacier of the Mönch have been presented earlier (Alean 1985). Data on all the ice avalanches discussed in this paper are summarized in table 1.

3.1 TERMINOLOGY

The reach (horizontal distance from the top of the starting zone to the farthest point of the deposit) of an ice avalanche is influenced by the gradient of the terrain along the avalanche path. Therefore, the average slope (α), rather than the reach is a more appropriate parameter when comparing ice avalanches from different topographical settings. α was introduced by Heim (1932; "Pauschalgefälle") in connection with landslides. It represents the (constant) slope of a line which starts at the top of the starting zone of the landslide or avalanche and ends at the farthest point of the deposit. The line is drawn directly above the central line of the avalanche path (cf.,

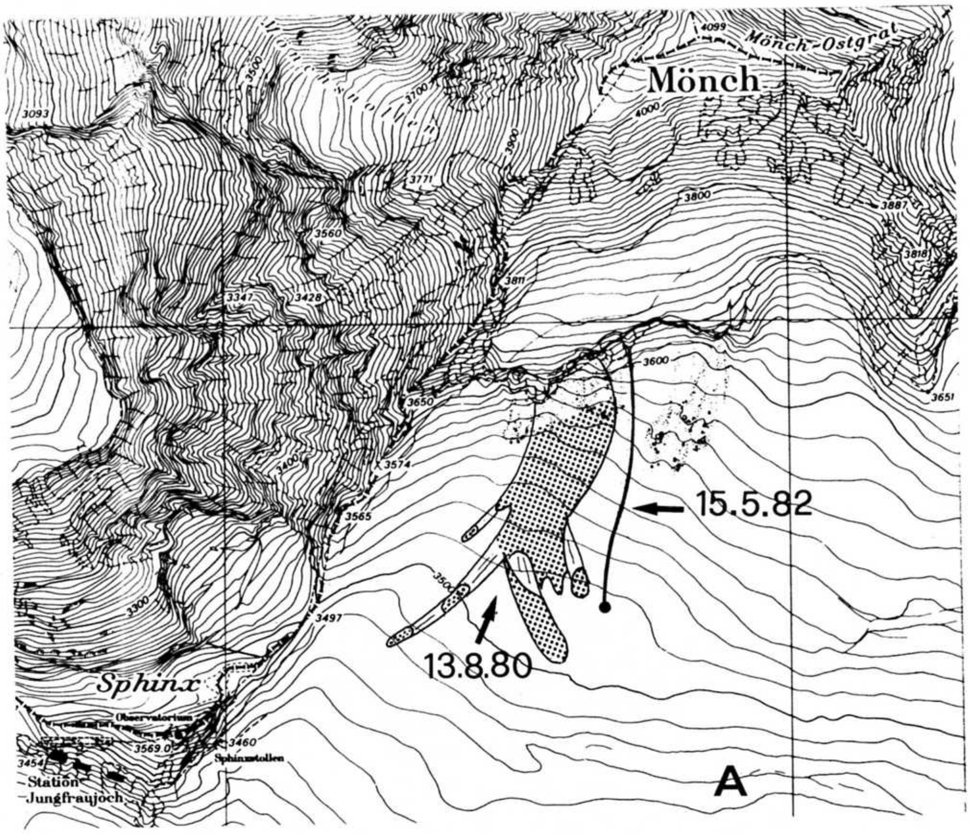

Fig. 2: Ice avalanche in 1980 and track of the ice block which descended from the southern hanging glacier of Mönch on May 15th, 1982. The resting position of the ice block is indicated by a circle, the diameter of which is larger than the one of the ice block (cf., figs. 3 and 4). Dotted areas show ice avalanche debris. The scale is the same as in fig. 5

fig. 10). Usually, a longer avalanche reach leads to a smaller average slope. The value of the average slope parameter is discussed further in section 4.

3.2 ICE AVALANCHE FROM THE MÖNCH, SUMMER 1980

The date of fall of this avalanche (fig. 2) is unknown; on the aerial photograph from August 13th, 1980 it appears fresh. Experience with other ice avalanches in this altitude range, however, indicates that the deposit may be several weeks old. In fig. 2, it can be seen that from the main part of the deposit, compact heaps of ice debris had separated and slid farther thus producing prominent, diverging, fingerlike extensions. The debris heaps are clearly separate from the main deposit and they have left distinctive trails in the firn. The trails suggest that the heaps slid in a manner comparable to a sledge and not in a chaotic or turbulent way. The heaps are therefore termed "sliding masses".

The sliding masses of this avalanche had a maximum thickness of at least 4 m or twice the average thickness of the whole deposit (2 m; thickness determinations from aerial photographs are considered rather inaccurate thereby setting the limit of the accuracy of the volume determination, cf., Alean 1984, p. 39—41). The deposit has a volume of 88,000 m^3 ($\pm 50\,\%$) and an average slope of 17° (the average slope angle of this and the other avalanches described below are considered to be accurate within 2 or 3°).

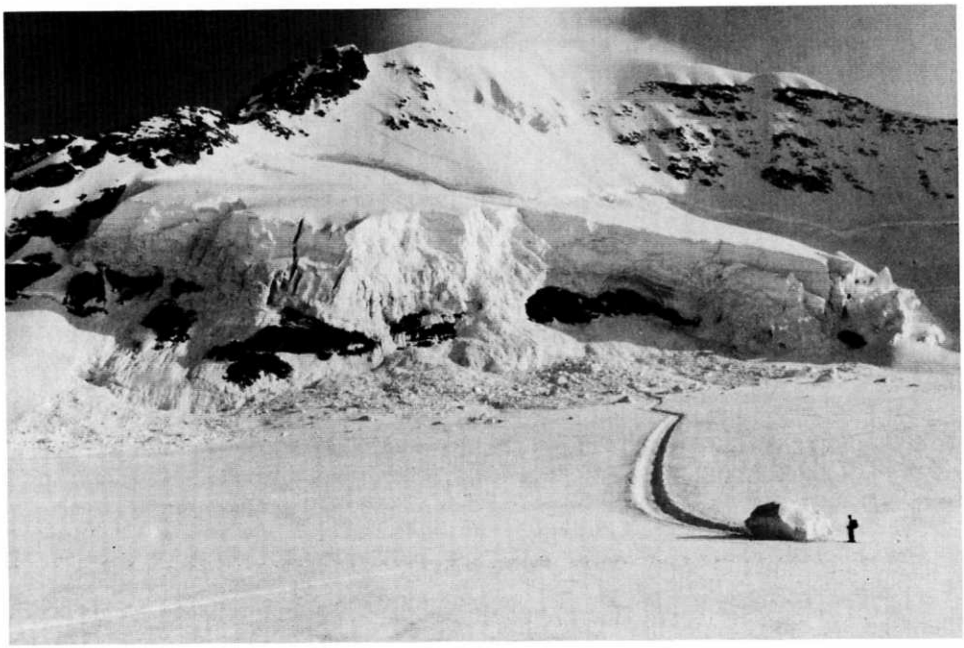

Fig. 3: Ice block of 55 m^3 volume and its track below the southern hanging glacier of Mönch. The ice cliff is between 40 and 50 m high. The block did not travel parallel to the steepest gradient of the terrain. Date of photograph: May 16th, 1982

3.3 ICE BLOCK FROM THE MÖNCH, MAY 15TH, 1982

A most unusual event occurred on May 15th and was documented by field photography and surveying on May 16th, 1982. It seemed that one individual block of ice had broken off the ice cliff at the lower end of the southern hanging glacier of the Mönch and slid for 470 meters over the fairly solid surface of Grosser Aletschgletscher (figs. 3 and 4). The path is shown in fig. 2 in which the block is represented by a circle with an exaggerated diameter. The path did not follow the steepest terrain gradient.

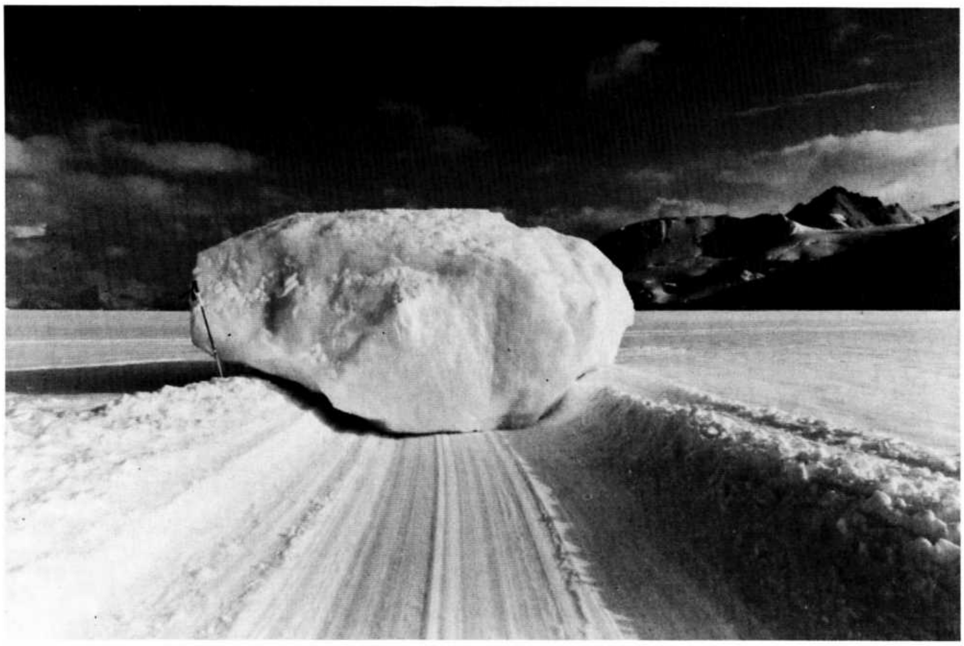

Fig. 4: Same ice block as shown in fig. 3, seen from within its track. The block is 2.8 m high and 4.5 m wide (length: 6 m)

The block had a maximum vertical thickness of 2.8 m, a width of 4.5 m, a length (parallel to path) of 6 m and a volume of 55 m^3 (±25 %). The trail was imprinted into the firn surface to a depth of 0.3 m. The average slope of the path is 18° — roughly the same as that of the large avalanche which descended in 1980.

Whereas individual blocks have occasionally been found on other glaciers, where they had slid away from a larger main ice avalanche deposit, there is only scant evidence for similar events of a single block falling off an ice cliff and sliding in a comparable manner for such a large distance.

3.4 ICE AVALANCHE FROM THE MÖNCH, JULY 5TH, 1984

The thundering noise produced by the descent of this avalanche woke up F. Gabriel of the nearby Hochalpine Forschungsstation Jungfraujoch at 3 a. m. The ice avalanche crossed a 300 m long section of a standard route used frequently by climbers. Some of the ice stopped 80 m from the area regularly used by a dog sledge team and 140 m from a ski lift (cf., figs. 5 and 7).

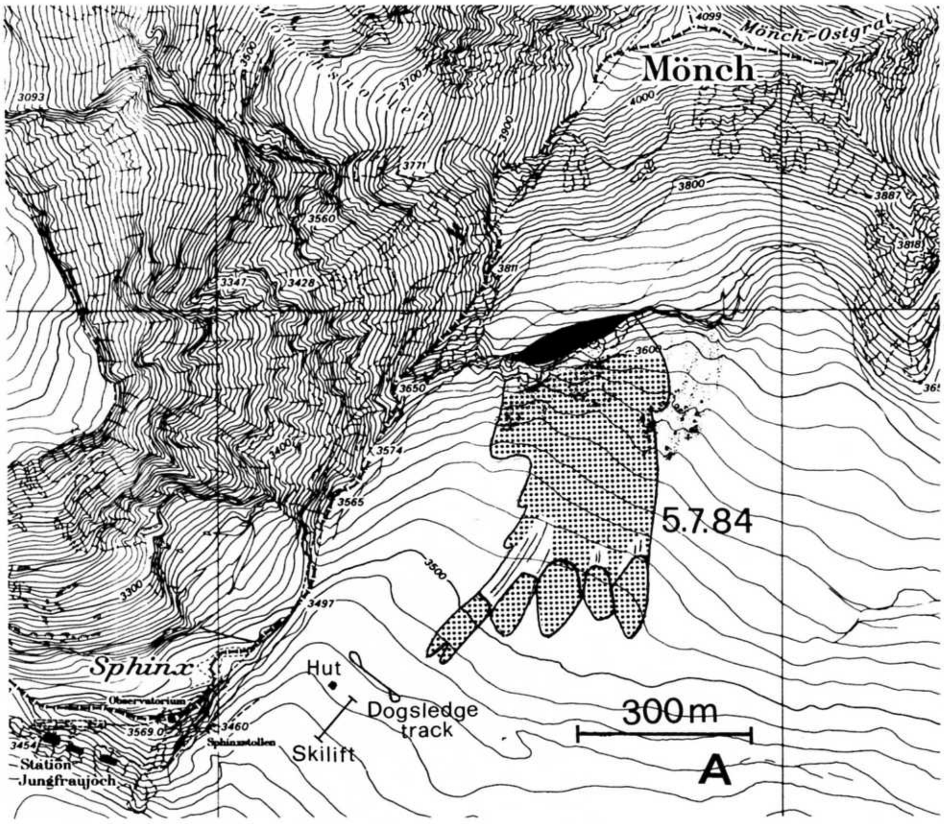

Fig. 5: Ice avalanche from the southern hanging glacier of Mönch (date of fall: July 5th, 1984). The starting zone is shown in black. This avalanche is shown at a larger scale in fig. 6

The volume of the deposit was determined as 340,000 m³ (± 25 %) and was the largest of any ice avalanche from the Mönch recorded to date. Five spectacular sliding masses (M_1 to M_5) can be seen in the large scale map (fig. 6). These sliding masses account for almost half of the deposit volume (M_1: 30,000, M_2: 25,000, M_3: 50,000, M_4: 25,000 and M_5: 15,000 m³). They had average thicknesses of 4 to 6 m and contained the largest number of very big ice blocks found in the deposit. Although dozens of blocks in the sliding masses must have been larger than 500 m³, a typical block size was 0.5 to 1 m³. At least two blocks labelled B_1 and B_2 in fig. 6, (cf., also fig. 9) had volumes of approximately 1000 m³. B_2 was 10 m high, 9 m wide and 15 m long. It contained relatively compact firn which showed distinctive stratigraphy, and probably originated in the higher parts of the falling ice mass.

The front parts of the sliding masses pushed up ridges of snow some 10 to 20 m wide and 1 or 2 m high. The backs of sliding masses M_1, M_2 and M_4 were almost exactly vertical. The trails left by the sliding masses were extremely smooth and showed parallel grooves up to several hundred metres long (cf., fig. 8); the sliding

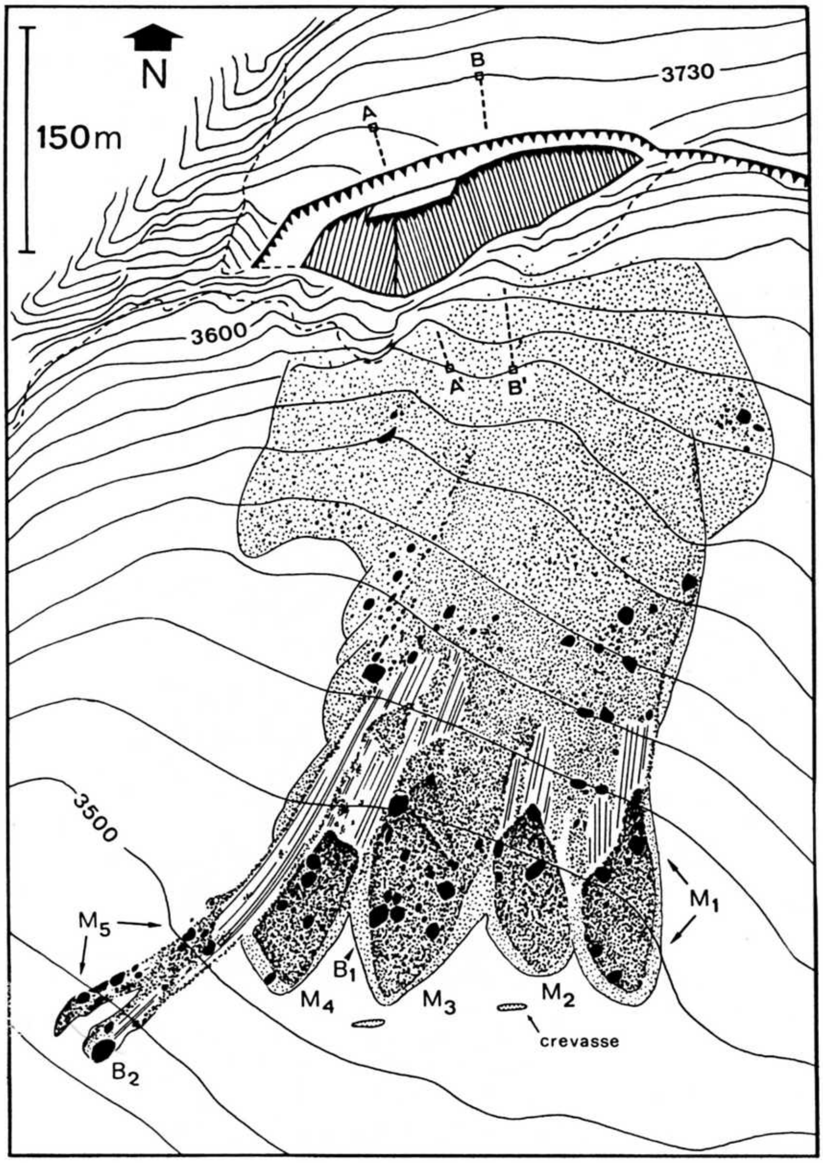

Fig. 6: Ice avalanche of July 5th, 1984, as in fig. 5, but at a larger scale. M_1 to M_5 are sliding masses as explained in the text, B_1 and B_2 are ice blocks, each of approximately 1000 m^3 volume. Other large blocks are also shown in black (see also figs. 7, 8 and 9). The sliding masses are, on average, 5 to 6 m thick; the upper parts of the ice avalanche deposit are about 2.5 m thick. The dashed lines A—A′ and B—B′ show the location of the profiles given in fig. 11. Contour lines (altitudes in m a. s. l.) show the terrain before the descent of the avalanche. The mapping was done by triangulation of prominent features and by interpolation of other detail using oblique and terrestrial photographs

Fig. 7: Ice avalanche of July 5th, 1984. The southern hanging glacier of Mönch is seen at upper left. The prominent block (B_1) at the lower end of the avalanche deposit is also shown in fig. 9 and is 80 m from the dog sledge tracks (two loops, one around hut). Note the track visible in the lower part of the avalanche (close up in fig. 8). Photograph July 7th, 1984, from Sphinx observation platform, Jungfraujoch

masses moved as a and did not rotate. Characteristics of the deposit behind these trials (above 3520 m a. s. l.) are less well known since the danger of further (smaller) avalanching prevented access on the ground.

Despite its large volume, the average slope of this avalanche (19°) is not smaller than those described in sections 3.2 and 3.4. The exceptional size of the avalanche was caused as a result of the fact that a 240 m long lamella had fallen from the cliff of the southern hanging glacier of the Mönch in one single event. The situation before the fall could be reconstructed with reasonable accuracy on the basis of terrestrial photographs taken on June 12th (cf., fig. 11). The lamella had become separated from the main part of the hanging glacier by an archshaped crevasse, the depth of which is not known. The volume of ice which fell is estimated to be 280,000 m^3 in good agreement with the deposit volume. That the volume of the deposit is larger is a consequence of the fact that the material is loosened during the fall and that snow is incorporated in the ice mass along the path of the avalanche; how much these factors influence the deposit volume cannot be estimated since the volume determinations are too inaccurate.

The location of the bedrock as shown in fig. 11 is hypothetical except in the small section where rock is exposed below the ice cliff. Nevertheless, it appears that a relatively sharp step in the bedrock surface is responsible for the formation of the cliff. Consequently, this can be classified as type II starting zone as explained in Alean (1984 and in press). From this type of starting zone very few ice avalanches are known

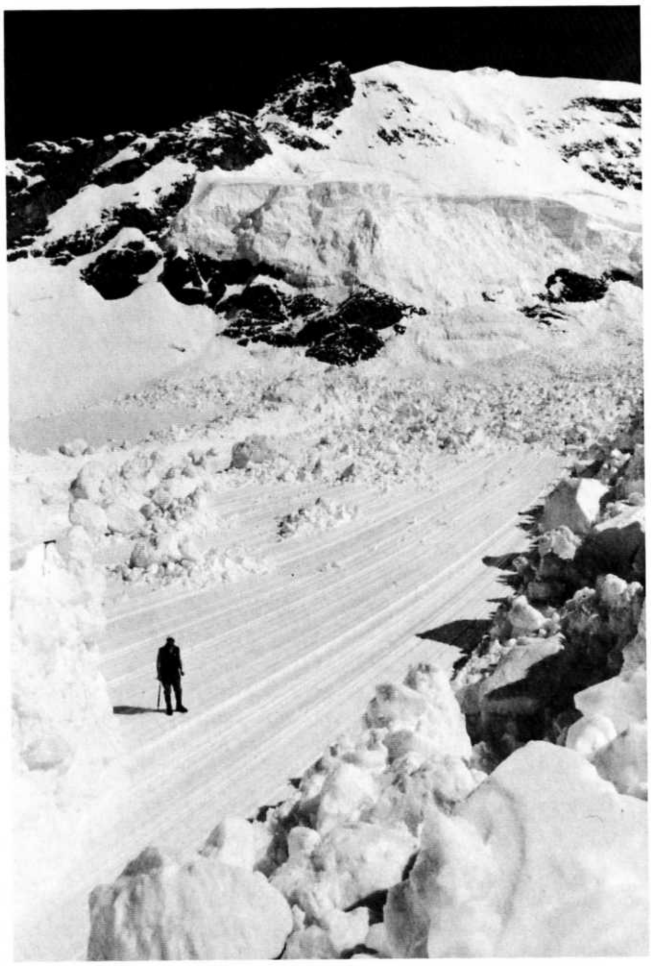

Fig. 8: Track left behind by sliding mass M_4 as seen from a point about 120 m north of the center of block B_1 (cf., fig. 6). The southern hanging glacier and the summit of Mönch are visible at upper right (photograph: July 7th, 1984)

which have volumes as large as the one described here. It is noteworthy that an almost identical lamella had developed in this starting zone in spring 1982. However, instead of falling down in one dominant event, it caused many individual smaller avalanches, the largest of which having a volume of 60,000 m³.

3.5 ICE AVALANCHES EAST AND SOUTHEAST OF THE JUNGFRAU

Fig. 12 shows two ice avalanches which were mapped using aerial photographs (October 4th, 1968 and August 11th, 1971). Most of the 63,000 m³ (± 50 %) of ice of the 1968 avalanche came down as one sliding mass, whereas only a small sliding mass left

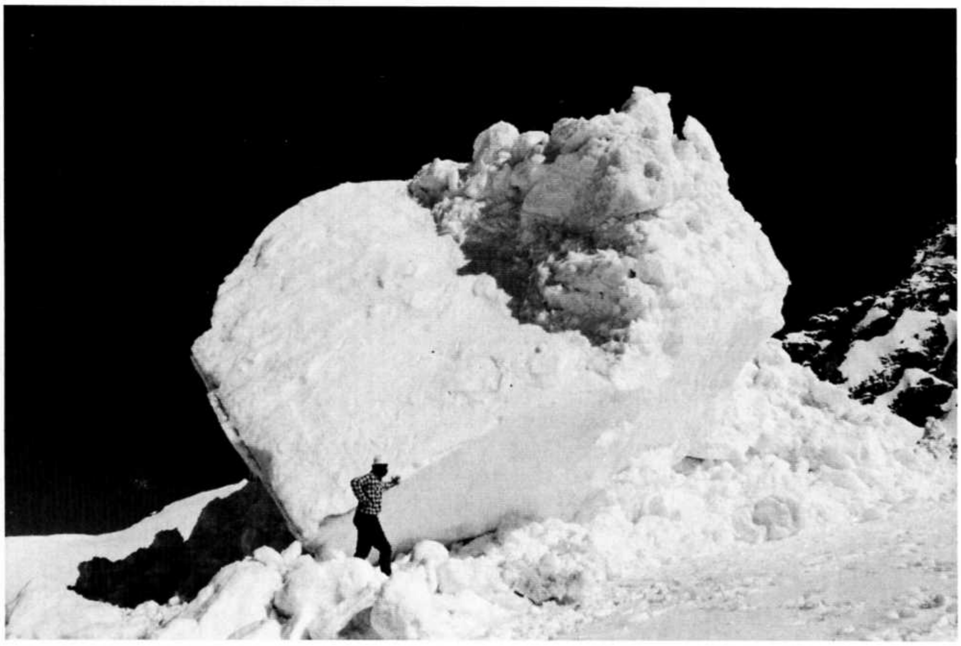

Fig. 9: Block B_2 from the southeast. It is 10 m high and 15 m from left to right. The volume is around 1000 m^3. Ice debris on its upper right did not fall off during the last part of the descent, thus confirming that the block did not roll. Photography by P. Müller, July 7th, 1984

the main deposit of the 1971 avalanche (total volume 18,000 m^3, ±60 %). Both avalanches had an average slope of 21°.

3.6 ICE AVALANCHE EAST OF THE ALETSCHHORN, SUMMER 1984

Fig. 13 shows an ice avalanche which was discovered coincidentally whilst flying north to photograph the large avalanche from the Mönch. This ice avalanche had descended at an unknown date over firn of the Mittelaletschgletscher (formerly part of the Grosser Aletschgletscher, cf. fig. 1). Convex terrain in the middle section of the avalanche path caused diverging flow. Somewhat lower down, the sliding masses reconverged on concave terrain. The farthest reaching sliding masses had partially fallen into a large crevasse. The total volume of the deposit was 350,000 m^3 (±50 %), and the average slope of the path is 21°.

4. MOTION OF ICE AVALANCHES IN FIRN AREAS

The occurrence of sliding masses with small average slopes (large horizontal reach compared to the altitude difference covered) appear to be unique properties of some ice avalanches with descend over firn surfaces. Sliding masses have not been observed in the deposits of ice avalanches which have descended over bare glacier ice, proglacial moraine fields, rock, stream gullies or even old ice avalanche deposits (Alean

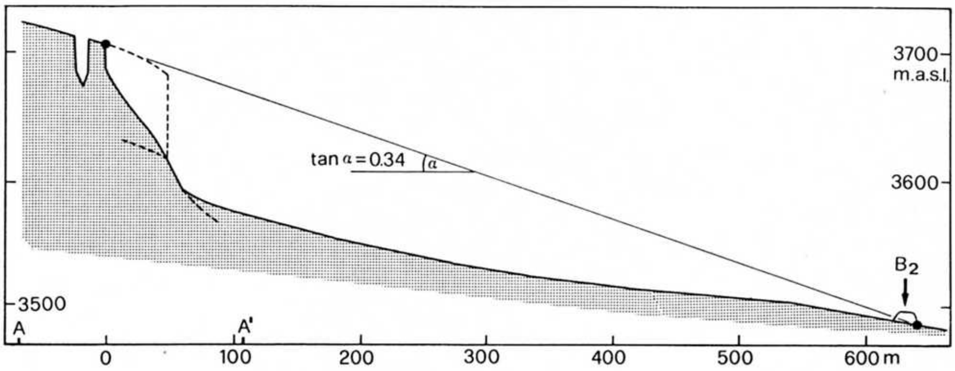

Fig. 10: Profile of the ice avalanche from Mönch, July 5th, 1984. The profile goes through the points A and A′ as shown in fig. 6 and then follows the trails left behind by block B_2. B_2 is shown in correct size relation. Other details of the avalanche deposit have been omitted. The dashed line in the starting zone shows the position and shape of the ice before breaking off. The significance of the oblique line is explained in the text

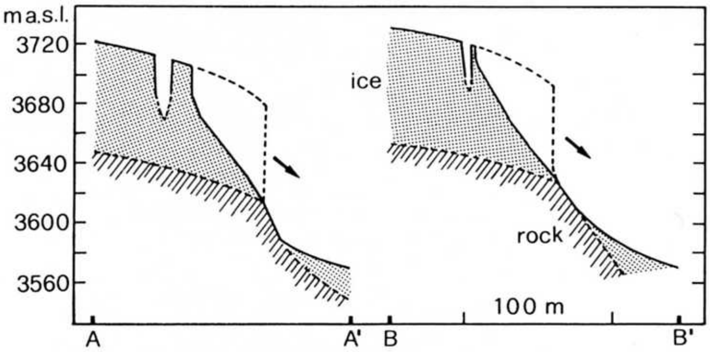

Fig. 11: Profiles through the starting zone of the ice avalanche from Mönch, July 5th, 1984. Points A, A′, B and B′ identify the location of the profiles in fig. 6. The shape of the ice cliff before the descent of the avalanche is indicated by dashed lines. The surface of the bedrock (hatched) is hypothetical (dashed line) except for the sections where it is exposed below the ice cliff

1984). Also, except on firn areas, only avalanches with volumes of at least 1 million m^3 had average slopes of less than 22°, such as the Mattmark ice avalanche from Allalingletscher (10^6 m^3, $\alpha = 21°$), the ice avalanche from the Altels ($4 \cdot 10^6$ m^3, $\alpha = 17°$; Heim 1896) or the colossal ice avalanche from Iliamna volcano, Alaska in 1980 (1 to $3 \cdot 10^7$ m^3, $\alpha = 12°$; Alean 1984 and in press).

It seems clear, therefore, that the uniform and smooth firn areas provide an ideal sliding surface for ice avalanches, in particular if there are no crevasses to be filled by the descending avalanche. In the general case it is not only the sliding friction at the base of the avalanche that is responsible for the observed reaches but also internal frictional dissipation of kinetic energy (Alean 1984 and in press). Such internal friction

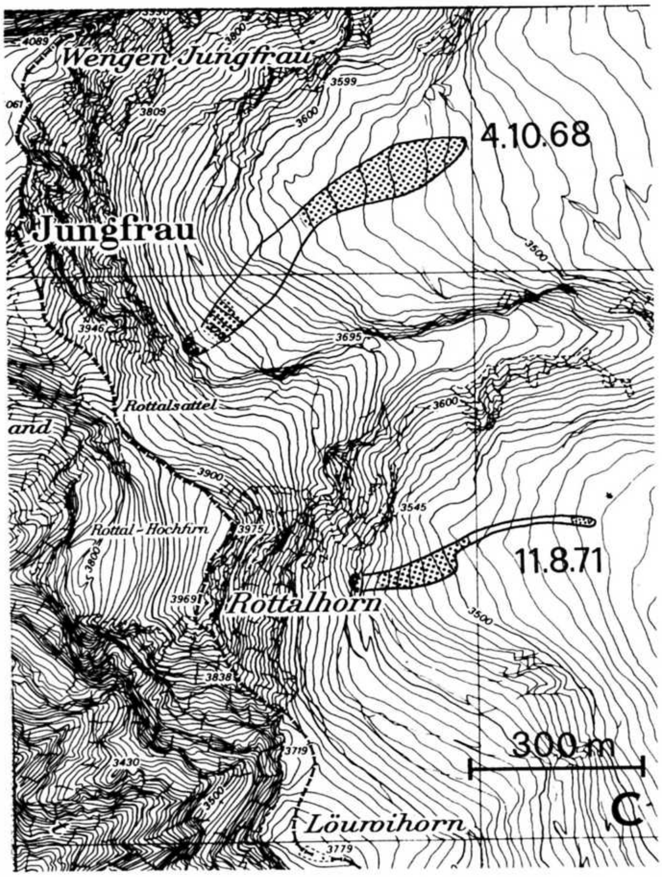

Fig. 12: Ice avalanches east and southeast of Jungfrau. Mapping on the basis of vertical aerial photographs taken on October 4th, 1968 and August 11th, 1971

has been termed "turbulent" in the case of snow avalanches and is assumed to increase with the square of the avalanche velocity (e. g., Voellmy 1955, Salm 1966, Körner 1976, 1980, Perla et al. 1980). In connection with ice avalanches, Scheiwiller and Hutter (1982) imagine blocks of ice colliding with each other within a descending ice avalanche. The effect of these collisions of ice blocks would also be one of braking the ice avalanche. It appears that this mechanism increases with the kinetic energy and thus with the square of the avalanche velocity. Indeed, rounded ice lumps embedded in a matrix of sintered ice dust found in many ice avalanche deposits outside firn areas are ample evidence for such collisions and, consequently, for v^2-proportional friction.

On the other hand, ice avalanches in firn areas such as the ones presented in this study often contain very large ice blocks. Smaller ice blocks are more abundant but have angular shapes. This is taken as evidence for avalanche motion with little "turbulence". Individual ice blocks have such small relative velocities that they can interlock soon after the break-off in the starting zone. These interlocked heaps of ice debris then slide downglacier in the form of the sliding masses observed. Consequently, such ice

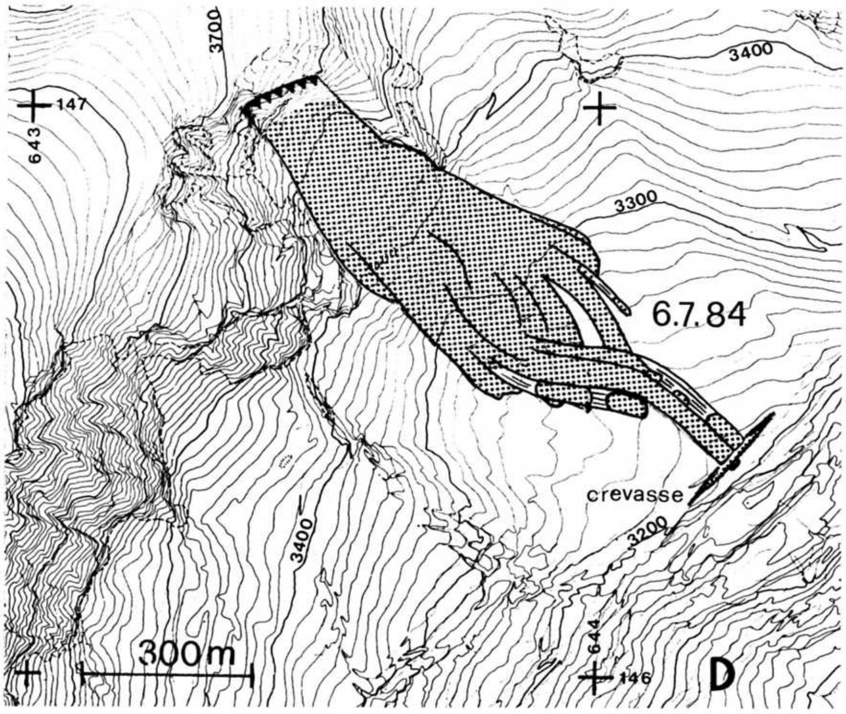

Fig. 13: Ice avalanche east of Aletschhorn as mapped on the basis of oblique aerial photographs taken on July 6th, 1984

avalanches (a) lose little of their kinetic energy in the process of breaking up the ice into very small particles and (b) the particles do not collide very often and consequently relatively little ice dust is produced.

Ice avalanche motion with comparatively little internal friction appears to occur only (a) if the path is very smooth (firn surfaces with few or no open crevasses) and (b) if the avalanche does not drop over too large an altitude difference onto a relatively flat runout zone. All the ice avalanches documented here dropped over a few tens of metres of altitude only, onto terrain which gradually became flatter and where deceleration of the avalanche started (cf., fig. 10). Total lack of internal friction made the surprisingly large reach of the ice block described in section 3.3 possible.

When sliding friction at the base is the dominant braking effect, the simple model of a sliding block can be used to describe the avalanche motion. This model was introduced by Müller in Heim (1932). In this model, the tangent of the average slope (α) of the block's path is equal to the average coefficient of sliding friction. The model helps to understand why larger avalanches need not cover longer distances than smaller ones on identical paths over firn. A larger avalanche is accelerated by a larger component of the gravitational attraction parallel to the avalanche path, but the braking force at the sliding surface is also larger.

However, ice avalanche deposits are many times longer than the ice body which broke off in the starting zone and the center of gravity of the ice before and, particularly, after the descent are usually poorly known. Consequently, the tangent of α of the ice avalanche cannot be expected to be more than a rough approximation of an "equivalent coefficient of friction" (cf., Scheidegger 1973).

It must be pointed out that in this study only those areas are considered "dangerous" over which the avalanche descends and where the ice debris is deposited. Direct observations of descending ice avalanches indicate, however, that even small ice volumes dropping over a few tens of metres of altitude can produce clouds of ice dust. These clouds move beyond the final position of the main deposit of the ice avalanche but do not settle in the form of measureable deposits. The total potential danger zone may, therefore, extend farther than the avalanche deposit.

5. THE LANDSLIDE FROM THE JUNGFRAU, OCTOBER, 6TH, 1937

Although this paper is primarily concerned with ice avalanches, the landslide from the northeast ridge of the Jungfrau, October 6th, 1937, should be briefly mentioned because it displayed features typically found in ice avalanches. Photographs (in Mercanton 1938, Zürcher Illustrierte, No. 43, 1937, and unpublished data) taken on October 11th show a large deposit with big boulders mixed with firn in an area approximately 300 m wide and 500 m long. The rock debris did not cover the firn surface entirely. From this main deposit, heaps of rock debris slid farther, leaving 3 prominent trails very much resembling the sliding masses found in some ice avalanches (cf., fig. 14).

The material which constituted these "sliding masses" travelled over smooth firn. It probably did not have to traverse a crevasse field as did the material of the southern

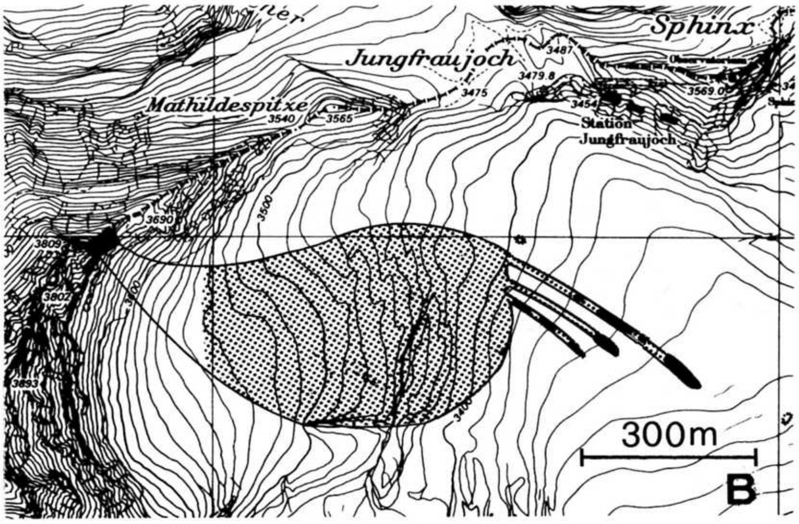

Fig. 14: Landslide from northeast ridge of Jungfrau, October 6th, 1937. The dotted area is partially covered by rocks, black areas at the lower end of the landslide indicate massive heaps of rock debris. Mapping was done on the basis of terrestrial photographs

half of the main deposit. The horizontal reach of the landslide was 1200 m, the vertical drop 435 m which corresponds to an average slope (α) of 20°. This value is remarkably similar to the one for far-reaching ice avalanches. The landslide probably did not flow in the manner described as being typical for larger landslides, for example by Hsü (1975 and 1978) or Davies (1982) who suggest "fluidized" or "turbulent" motion. Basal sliding was probably the main process for the dissipation of kinetic energy.

Volume estimations of the deposit are difficult because much firn was incorporated. 150,000 m³ may be a reasonable value (average thickness of deposit about 1 m) and corresponds well with the volume of the niche in the rock face still visible today (less weathering) below point 3809 m on the north east ridge of the Jungfrau.

6. CONCLUSIONS

Empirical data from ice avalanches which descended over firn areas indicate that these avalanches flow differently from those descending over other terrain types. Some avalanches may reach particularly far if the following conditions are satisfied: (I) the vertical or near vertical drop at the beginning of the avalanche path is not higher than a few tens of metres (internal "turbulent" friction does not develop to an extent where it significantly contributes to the braking of the avalanche), and (II) the terrain is a smooth firn surface, i. e. there are few or no crevasses, and no marked steps in the avalanche path (which increase basal friction). As opposed to ice avalanches which descend over rough moraine fields or highly crevassed terrain, perhaps making the path smoother for subsequent avalanches, it is conceivable that even rough avalanche deposits themselves may hinder the motion of subsequent ice avalanches.

If conditions (I) and (II) are satisfied, ice avalanches may reach average slopes (α) as little as but not smaller than 17° ($\tan\alpha = 0.31$). In other words, their reach is 3.3 times longer than the vertical drop. This rule appears to be followed by far reaching avalanches irrespective of their volume; even individual ice blocks may slide this far if the firn surface has the appropriate firmness. Only one individual avalanche with more than $3.5 \cdot 10^5$ m³ volume was observed (table 1); although this avalanche of $3 \cdot 10^6$ m³ also had an average slope of 17°, it cannot be considered to justify the validity of the rule for the volume range of millions of cubic meters.

Given that conditions (I) and (II) are satisfied, then predictions of maximum runout distances are particularly simple since seemingly the avalanche volume need not be known in advance. However, even accurate knowledge of the expected minimum average slope (α) may yield an unprecise prediction of the avalanche reach. This is the case if the terrain slope in the lowest part of the runout zone is similar to α. Inspection of fig. 10 helps to understand the reason for this; the oblique line with slope α then intersects the terrain at an acute angle and a slight change in α leads to a large change in the position of the expected stopping position.

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