3 ICE AVALANCHES

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3.1. INTRODUCTION

Ice avalanches form when a large mass of ice breaks off from a glacier, drops down slope driven by gravity and bursts into smaller pieces of ice. In most cases, ice avalanches are the normal process of mass wastage of high altitude, alpine glaciers on steep slopes, so called hanging glaciers. A typical feature of hanging glaciers **is *the*** absence of **an** ablation area where ice can melt and the process by which ice mass is being removed is the release of chunks of ice (typically 10^3-10^5m3) at the glacier front. Such events can happen at any time of the year and have often been observed in the Alps and in other high mountain regions of the world.

The detachement of larger ice masses from a steep glacier is an extremely rare event and characteristically occurs during an active phase with enhanced sliding motion, which usually lasts for a few weeks during the melt season. The slip off of a large ice mass can also occur if the stability of a steep glacier reaches a critical state. The failure of one of the retaining forces can then lead to an ice fall. The typical mass is 10^5-10^6 m^3 and has sometimes the potential to impinge on settlements and other fixed installations in high mountain areas.

The effect of ice avalanches is comparable to that of snow avalanches, the main difference being that they can occur at any time of the year. The most destructive ice avalanches happen in winter when they release or entrain additional snow masses. Such combined snow/ice avalanches can cover very long run-out distances.

3.2. HISTORICAL ICE AVALANCHES

The largest known ice fall in the Alps happened on 11 September 1895 in the Bernese Alps in Switzerland, where the major part of a glacier (five million m3) slipped off from the summit area of Altels and fell onto an alpine pasture killing six people and 158 cows (Fig.3.1) (Heim 1896, Rothlisberger 1981). Both authors have attempted to analyse the possible causes of this detachment. The prominent curve-shaped fracture line at the head of the niche left by the avalanche indicates failure under tensile stresses. Basal and shear adhesion and shear resistance at lateral abutments were the stabilizing forces. The gravitational pull and the sum of the retaining forces have reached a critical equilibrium from which the spontaneous release of the avalanche occured when one of the retaining forces failed. Probably this occured by warming of a frontal zone frozen to the bedrock. **As** a consequence, the aerial extent of this zone became reduced and the loading on the still frozen parts increased up to the shear strength of ice. Very warm summers in the years preceding the ice fall support this hypothesis.

More recently, on 30 August 1965 a major portion of the terminus of Allalingletscher (Valais, Switzerland) detached unexpectedly, slid down a rock slope of some 27° over a vertical distance of 400 m and continued for further 400 m across the flat bottom of the valley, claiming 88 victims at the Mattmark construction site (Fig.3.2). The volume of the ice avalanche was estimated at 0.5-1 million m^3. Subsequent glaciological investigations showed that the ice avalanche had occured during a phase of enhanced motion **as** a result of intensive bed-slip of an even larger mass than that which broke off. It could be inferred that enhanced sliding on the rock substratum must have occured already some **2-3** weeks prior to the sudden slump of the avalanche. It could be observed that such active phases with enhanced sliding motion took place quite regularly at intervals of one to three years, starting usually in late summer or in fall, but always ending at the beginning of winter without any significant ice fall occurence. Similar movement irregularities can be obseived on many other steep glacier tongues. This active phase was a necessary bur riot a sufficient condition for the lower part of the Allalingletscher tongue to slide off. The convex bed topography and an unfortunate mass distribution, combined with the active phase, played a major role in that catastrophe (Rothlisberger 1981, Rothlisberger and Kasser 1978).

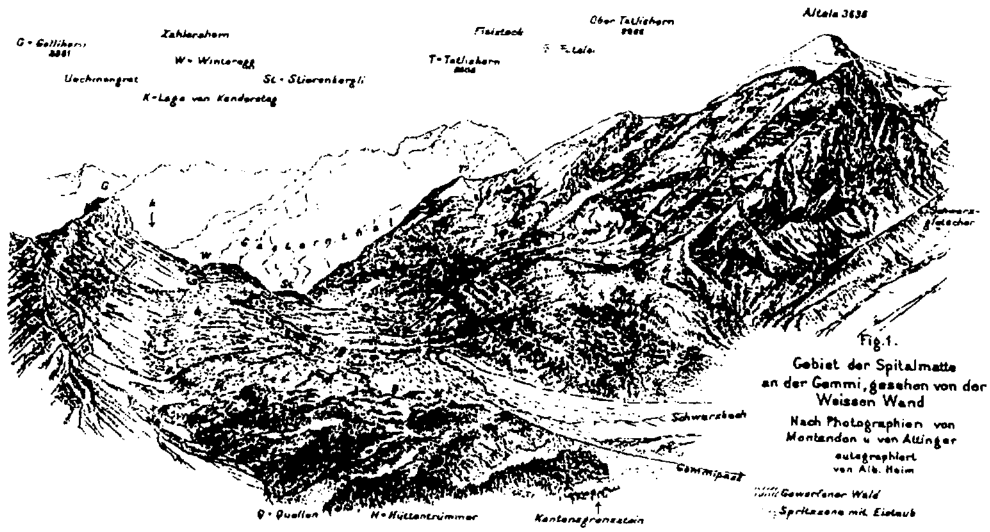

Fig.3.1 The ice avalanche from Altels. The curve-shaped line of rupture is visible immediately under the Altels summit (after Heim 1896).

On 5 September 1996 large ice masses (0.25 million m^3) broke off from Gutzgletscher (above Grindelwald, Bernese Alps, Switzerland) and dropped down as two major powder and dense flow avalanches in the direction of the road that connects Grindelwald to Grosse Scheidegg (Fig.3.3).

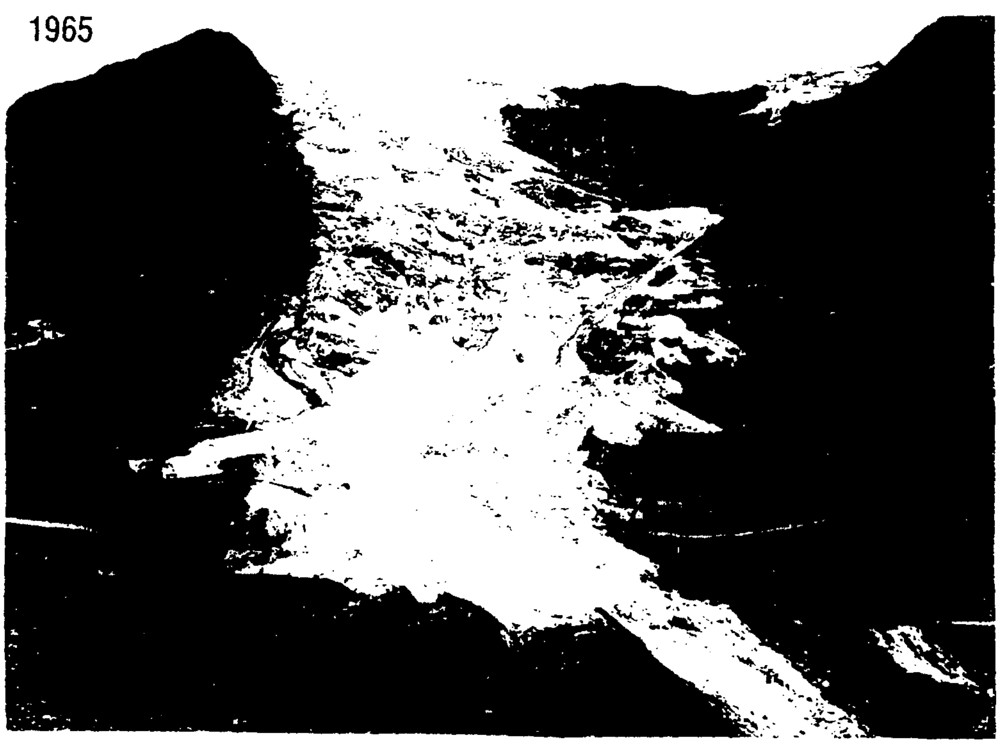

Fig.3.2 The ice avalanche from Allalingletscher.

The road was blocked over a distance of 20 m and the air pressure injured three persons and knocked down some hikers (Margreth and Funk 1998). The Gutzgletscher, a so-called hanging glacier, is situated on a moderately inclined bed in the very steep north-west face of Wetterhorn mountain and ends in a frontal ice cliff. Small ice avalanches occur there every year, but they never endangered the road during the summer season.

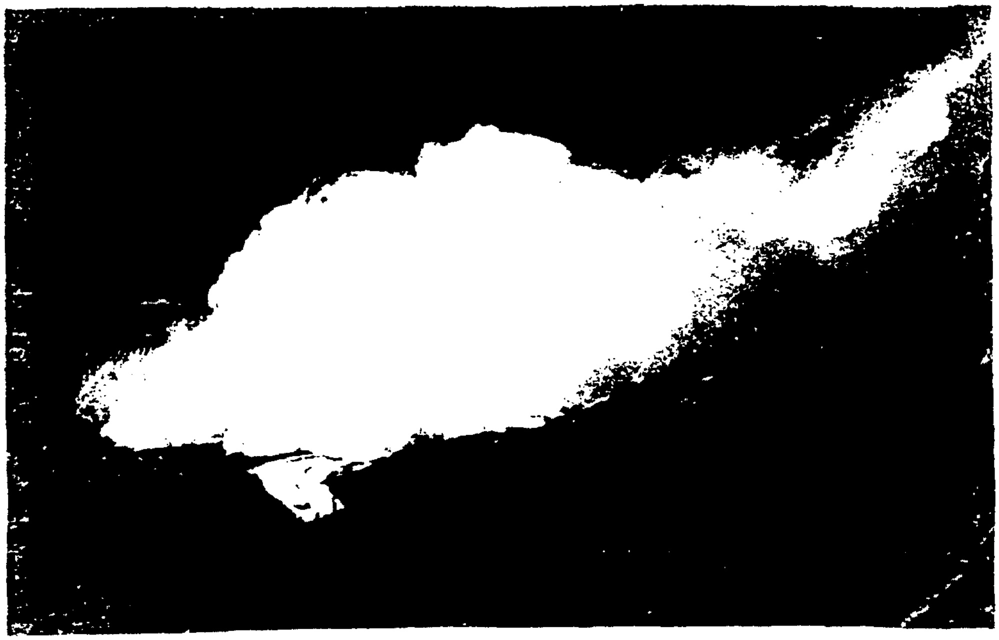

Fig.3.3 The ice avalanche from Gutzgletscher (Foto U. Schiebener).

3.3 STARTING ZONES AND RUN-OUT DISTANCES OF ICE AVALANCHES

A number of ice avalanche situations have been recorded and analysed by Alean (1985) in a comprehensive study, in which he discusses some of the morphological features of the starting zone and investigates the relation between ice volume, run-out distance, velocity and travel time. It is appropriate to distinguish between two main types of idealized **bedrock** morphologies with respect to potential starting zones affecting the failure process. According to Haefeli (1965) two different kinds of failure can occur: wedge failure (type I) and slab failure (type 11) (Fig.3.4):

- For glaciers with a *type* 1 starting zone (break-type), the underlying rock topography shows in general a sharp break in angle, so that the glacier (called hanging glacier) flows over a moderately inclined (< 10") bed and ends in a frontal ice cliff (e.g. Gutzgletscher). The temperatures at the bed of a type I starting zone can be either temperate (at pressure melting point) or cold (below pressure melting point). When the ice cliff becomes too steep or even overhanging, an ice lamella breaks off (Iken 1977). Typical ice volumes breaking off in this process are 10^3-10^5 m^3.

- For glaciers with a temperate bed and a *type II* starting zone (ramp-type) very large ice volumes (typically 10^5-10^6 m3) can be released. The complex mechanisms leading to the failure of these large ice masses resting on ramp-type starting zone were discussed above for the cases of Allalingletscher and Altels. In case of glaciers frozen to the bed, observations showed that ice masses (typically 10^3-10^5 m3) become detached by progressive fracture at englacial interfaces.

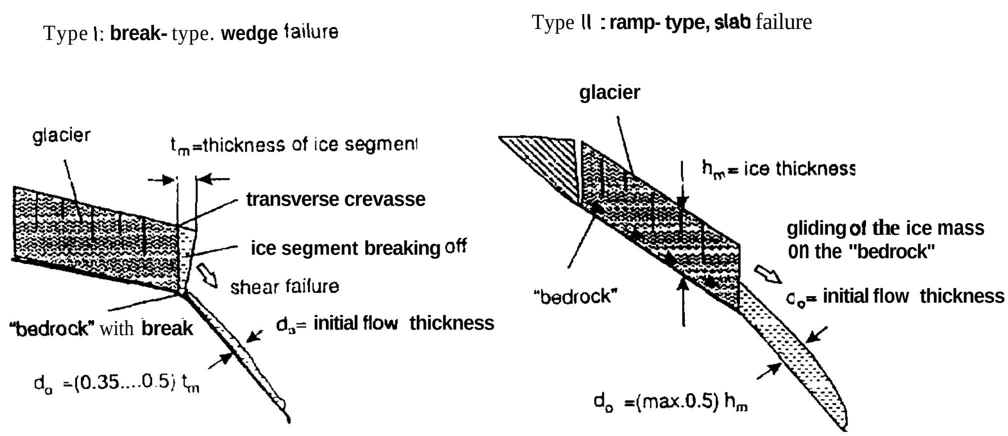

Fig.3.4 Types of starting zones (after Margreth and Funk 1998).

Major ice avalanches from cold ramps or hanging glaciers can occur during the whole year, whereas their occurence seems to be limited to the late melt season in the case of temperate ramps.

To obtain a rough estimate of the run-out distance of ice avalanches, Alean (1985) proposed to relate the average slope of ice avalanche trajectories to their volumes and characteristic terrain parameters (Fig.3.5). With a classification of terrain parameters, a grouping of the points in Fig.3.5 was possible (lines A1, B1, C1 and D1; Alean, 1985). The model proposed is not complete enough for detailed hazard mapping. This method is only justifiable for short reaches or for overview studies. In addition, the powder part is neglected in this model.

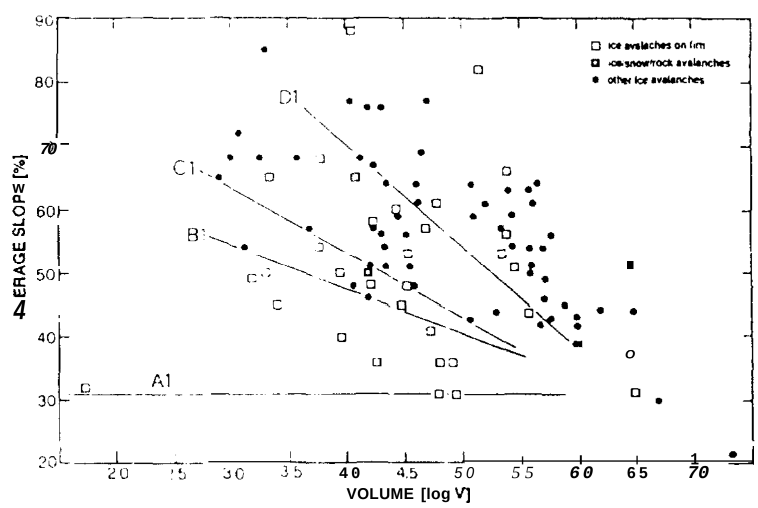

Fig.3.5 Average slopes (%) and volumes (V in m^3) of ice avalanches (after Alean 1985)

3.4 ICE AVALANCHE HAZARD MAPPING

Classical hazard maps are used for municipal landuse planning. For this type of hazard map the scenario of the extreme winter event is in general decisivo. The hazard zones are defined in terms of recurrence interval and potential impact pressure. In Switzerland the red zone means a high potential hazard with impact pressures of 30 kPa or more for recurrence intervals up to 300 years. In red zones building activities are prohibited. In the blue zone the potential hazard is considered to be moderate and there is a limited possibility to build reinforced buildings. Sometimes a yellow zone is added which accounts for the powder part of avalanches. In comparison to snow avalanches it is much more difficult to assign a realistic recurrence interval to extreme ice avalanche events.

Another type of hazard map is used as a tool for *avalanche warning* and evacuation during periods of imminent glacier fall. These hazard maps are prepared for specific ice fall scenarios with varying break off volumes. Closure of roads or evacuations are imposed according to the prevailing hazard situation. For the *hazard assessment* of ice avalanches similar procedures as for snow avalanches are used. The mapping requires as far as possible application of quantitative and objective criteria, including:

- *Avalanche history:* information from former ice fall events is very valuable especially for the calibration of avalanche dynamic models.

- *Analysis of topography and terrain parameters:* characteristic features in the terrain must be recognised. Therefore the starting zone, track and runout have to be examined. Often different flow directions are possible. Steep slopes below a hanging glacier can be starting zones for secondary snow avalanches. If there are cliffs in the track powder avalanches can form.

- *Glaciological analysis:* first, the: potential for ice falls of a dangerous glacier has to be identified. Unfavourable developments of a glacier and possible break off volumes can be detected by regular monitoring using aerial photographs and hotogrammetry. Typical scenarios with variable ice masses for winter and summer conditions are established. The most reliable method to predict the time of breaking off is based on glacier motion measurement.

- *Avalanche dynamics calculations:* the results from avalanche dynamics calculations can be used to quantify avalanche impact pressures and runout distances for different ice masses. As the physical processes of ice avalanches are largely unknown, no advanced numerical models exist. Therefore simple models developed for snow avalanches are also applied for ice avalanches. The model calculations are useful if the input parameters can be calibrated from well documented events. The initial conditions depend mainly on the starting zone type (Fig.3.4). Current avalanche dynamic models often fail for complex situations.

- *Expert knowledge and judgement:* in parallel to scientific reasoning, expert knowledge and judgement is fundamental. An important point is that the expert explains what is factual and firmly known and what are the consequences of the main uncertainties.

3.5 PREDICTION OF THE BREAK-OFF TIME

A warning by an expert is difficult to use for hazard mitigation unless it includes a forecast of the time of final detachment. The possibilities to forecast a major ice avalanche depend on the mechanisms leading to the detachment of a large ice mass. In this respect, the thermal conditions at the glacier bed are important. Measurements of the movement of ice masses on ramp-type starting zones (type 11) frozen to the bed or ending in a frontal ice cliff (type I starting zone) during the destabilization phase have revealed a regularity by which they accelerate for a long time prior to the actual breaking off (Rothlisberger 1981).Using a finite element computational model for the analysis of stress and flow of an ice mass breaking off from a cliff, Iken (1977) has shown that a stepwise crack extension alternating with viscous flow leads to the observed form of the velocity-time relationship. In the case of a lamella breaking off at the frontal ice cliff of hanging glaciers (type 1 starting zone), which are not always frozen to the bed, the volume of blocks or lamellae breaking simultaneously off from the cliff is limited. It seems that also in this case a particular movement versus ame relation is valid like that for cold ice.

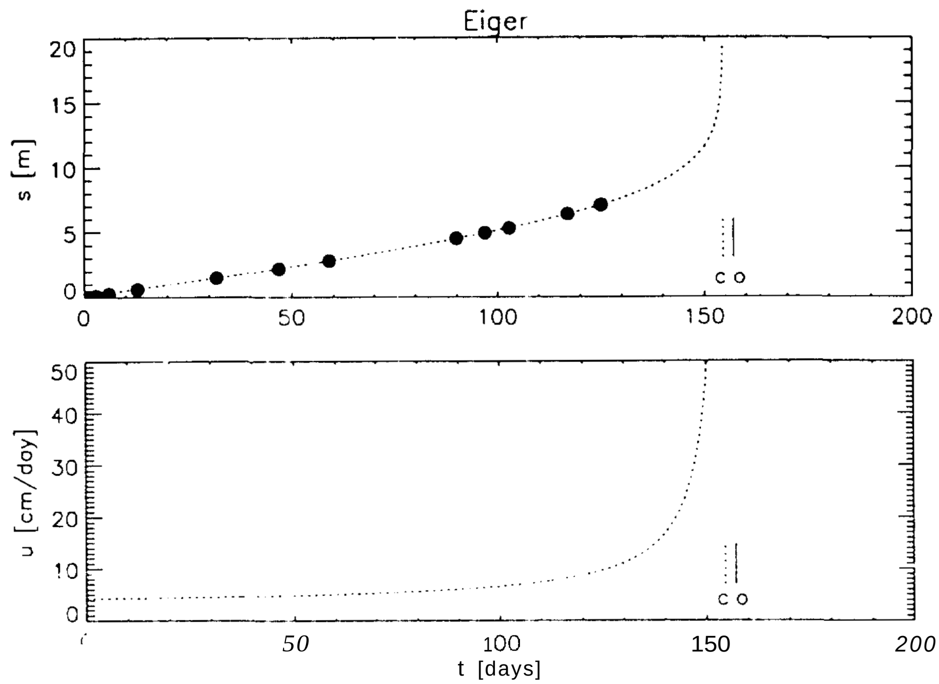

Fig.3.6 Upper panel: measured positions s_i (circles) and resulting hyperbolic function. Lower panel: velocity-time function. Day 0 corresponds to March 16, 1990.o: observed event (August 20, 1990) and c: calculated t_∞ (August 17, 1990).

The case of a type II starting zone with a temperate glacier bed is more complicated. When a large area of the bed is inclined at a critical angle, large amounts of ice may break off (Altels 1895 and Allalingletscher 1965). The processes leading to the slip off of the tongue of Allalingletscher during a particular sliding situation do not allow any predictions, except that a high rate of sliding is one of the observable factors. This active phase was only one of the necessary condition for the ice fall. While the gradual development of the active phase permits to forecast the growing avalanche **risk,** it remains impossible to predict the time of breaking off. No such experiences exist for Altels-type ice falls. The only reported observation was **a** progressive increase of the ice thickness in the frontal zone during the year prior to the catastrophe (Heim 1896).

The experience with hanging glaciers or steep glaciers frozen to the bed is much better. In the case of a cold ice mass on a 45° slope of Weisshorn above Randa (Valais, Switzerland), Röthlisberger (1981) and Flotron (1977) found that the curve representing the progressive increase in velocity with time can be closely approximated **by** the following hyperbolic function:

$$u = u_0 + \frac{a}{(t-t_\infty)^n}, \tag{3.1}$$

where u is the velocity at time t and the other parameters are constant. To determine the assumed time of breaking off t_∞, a least square procedure was applied with the integrated form of equation (1) and the displacement measurements s_i at different times t_i (Wegmann et al., 1998). Although theoretically breaking off occurs at $t=t_\infty$ experience has shown that rupture takes place for $t < t_\infty$ when high acceleration rates are reached. Recently, a large icefall from a hanging glacier situated in west facing slope of Eiger (Bernese Alps, Switzerland) could be forecast within three days based on 13 position measurements s_i, the last measurement s_n being performed one month prior to break off (Fig.3.6) (Funk, 1995; Lüthi and Funk, 1997). Chances of forecasting this type of ice avalanche are therefore fairly good.

3.6 OUTLOOK

The investigation of steep glaciers is of practical importance when they are the origin of hazardous ice avalanches. Expenence shows that very large ice avalanches are extremely rare events. Related to this scarcity, human activities tend to spread into endangered zones. A basic rule valid for large ice falls is, that if a particular one has occured once, it will happen again in a similar way. Unfortunately, our records do not extend sufficiently far back to enable an early warning of a dangerous situation. As a consequence, forecasts of imminent danger become necessary.

Chances of forecasting ice avalanches originating from cold glaciers or from glaciers ending on type I starting zones (break-iype, **Fig.3.4)** are fairly good if adequate displacement measurements are performed during the destabilization phase.Additional experience, especially immediately before final breaking off, is necessary to give more insight into the critical acceleration phase.

Temperate glaciers ending on type II starting zones (ramp-type, Fig.3.4) can release large ice masses. Expenence has shown that the risk is small during most of the year (quiescent phase). Only during a period of a few weeks with enhanced sliding during the late melt season a detachment can be expected.In view of the uncertainties concerning the mechanisms of the fast sliding phase, a successful prediction of individual avalanche events is very difficult. Further efforts to improve the understanding of the fast sliding process and the release mechanism of large ice avalanches are needed. As the physical processes of ice avalanches are largely unknown, no advanced numerical model exist. To improve the accuracy of ice avalanche hazard maps further progress in avalanche modeling is necessary.

REFERENCES

Alean, J. (1985). Ice avalanches: some empirical information about their formation and reach. *Journal of Glaciology* **31**(109): 324-333.

Flotron, A. (1977). Movement studies on hanging glaciers in relation with an ice avalanche. *Journal of Glaciology* 19(81): 671-672.

Funk, M. (1995). Glaciologie appliquée en Suisse: Deux cas récemment traités: Grimsel-Ouest et glacier suspendu dans la face ouest de l'Eiger. In *Gletscher im ständigen Wandel:* 179-188, SANW, vdf Hochschulverlag AG: Zünch.

Haefeli, R. (1965). Note sur la classification, le mécanisme et le controle **des** avalanches de glaces et des crues glaciaires extraordinaires. Symposium International sur les Aspects Scientifiques des Avalanches de Neige: Davos. In *Extrait de la publication de l'A.I.H.S.* **69:** 316-325.

Heim, A. (1896. Die Gletscherlawine an der Altels am 11. September 1895. *Neujahrsblatt der Naturforschenden Gesellschaft in Ziirich* **98,** 63 pages.

Iken, A. (1977). Movement of a large ice mass before breaking off. *Journal of Glaciology* **19**(81): 565-605.

Liithi, M., **Funk,** M. (1997). Wie stabil ist der Hangegletscher am Eiger. *Spektrum der Wissenschaft (5): 2*1-24.

Margreth, S., Funk, M. (1998). Hazard mapping for ice and combined snow/ice avalanches - two case studies from the Swiss and Italian **Alps.** In *International Snow Science Workshop ISSW98,* Sunriver, Oregon: 368-380

Rothíisberger, H. (1981). Eislawinen und Ausbrüche von Gletscherseen. In ***P.*** *Kasser* ***(Ed),*** *Gletscher und Klima - glaciers et climat, Jahrbuch der Schweizerischen Naturforschenden Gesellschaft, wissenschaftlicher Teil* ***1978***: 170-212. Birkhauser Verlag: Basel, Boston, Stuttgart.

Rothlisberger, H., Kasser, P. (1978). The readvance of the Allalingletscher after the ice avalanche of 1965. In *Proc. Int. Workshop on Mechanism of Glacier Variations,* 30.9.-11.10.1976, Alma-Ata,. Materialy Glyatsiologicheskikh Issledovaniy, Khronika, Osuzhdeniya **33:** 152-164.

Wegmann, M., Funk, M., Flotron, **A.,** Keusen, H. (In press). Movement studies to forecast the time of breaking off of ice and rock masses. In *Proceedings of the IDNDR-Conference on Early Warning Systems for the reduction of natural Disasters,* Potsdam, Germany.