A new insight into slab avalanche triggering: a combination of four basic phenomena in series.

François Louchet[1] and Alain Duclos[2]
[1] Laboratoire de Glaciologie et de Géophysique de l'Environnement, UJF/CNRS, BP96 – 38402 Saint Martin d'Hères, France, louchet@lgge.obs.ujf-grenoble.fr

[2]ALEA Sarl, 73500 Aussois, France, a.duclos@wanadoo.fr

1 Introduction

Pompon was born and lives in Aussois, a small village located in the french Alps. On february 14th, 2005, he climbs once more with a backpack full of explosives in order to trigger avalanches in the wide bowl of "les Balmes". The bowl was probably loaded with a significant amount of snow, due to the strong wind period started the day before. This is part of his job: he is a mountain guide (IFMGA), and a ski patroller in charge of avalanche control. He has been working for about twenty years in the ski resort just above the village. The access to the firing spots is easy, first taking the ski lift, and then crossing the plateau that directly leads above the slopes. The bowl is about 300m wide, and is divided in its upper part into small thalwegs with widths around 30 m each. Despite a strong snow accumulation in the first thalweg, the firing does not seem to have any effect. Observation results difficult, owing to bad weather conditions. In order to further check the result, and maybe test the snow resistance, Pompon slightly enters the second thalweg, a few meters below the convexity (from flat to slope), at a place where the slope gradient is still less than 30°. His mate suddenly sees him disappearing in the quasi-simultaneous release of the whole bowl. The involved snow quantities are impressive, and travel more than 600m of vertical drop. Pompon died a few months later after suffering a deep coma. This casualty, dramatic for the whole village, illustrates once more how an avalanche specialist, with a perfect knowledge of the field, may eventually be trapped. It also raises questions about many avalanche programs, that either provide mechanical explanations limited to a simplistic balance between load and resistance[1], or are based on the belief that everything is too much complicated to allow any type of prediction. A new insight into this problem is brought by concepts from both rupture mechanics and statistical physics. These theoretical approaches now perfectly fit field observations: they are able to explain why some unexpected avalanches may release, and also (and this is the most common case) why nothing happens, even if most conditions for avalanche triggering seem to be met.

The present paper aims at giving the main principles of these approaches, and to discuss their consequences on the basis of field observations.

2 A few basic concepts:

Avalanche release phenomena may be classified into two main categories: spontaneous avalanches and artificially triggered ones. It is generally agreed that spontaneous failures are of ductile nature, i.e. result from a strain rate increase during

[1] A simple balance between load and resistance cannot predict the failure of heterogeneous materials. In a same way as a paper sheet with a preexisting crack is easier to tear off than a defect-free one, a heterogeneous snow cover fails more readily than predicted considering an average homogeneous medium.

snow creep, up to a critical point at which failure suddenly occurs (Narita 1983, Gubler 1989, Louchet 2001a). By contrast, we shall focus here on accidental and artificial avalanches. Such failures, that occur within a much shorter time scale, i.e. correspond to a rapid change in the controlling parameters, are therefore of brittle nature.

Any physical evolution process needs a driving force, which may be or not balanced by a "resistance". Understanding the phenomenon needs to identify both the driving force and the resistance.

2.1 Driving force:

A process is likely to occur spontaneously if it contributes to decreasing the energy of the system, down to a stable state. In the avalanche problem, the available energy is the snow weight. The weight of a skier (some 80 kg) is extremely small as compared to the weight of the snow involved in the avalanche triggering mechanism (several billions of kg). The skier weight obviously cannot contribute to the driving force.

2.2 Resistance:

The reason why the snow cover remains on mountain slopes is snow cohesion, that provides resistance to rupture. This is not the case for water, that would immediately flow downslope as it has no cohesion. Snow cohesion contributes in keeping the snow cover in a metastable state[2].

Two types of resistance have to be overcome in order to release an avalanche:
i) the shear resistance of the bonding between the slab and the older snow substrate, known as "weak layer", and ii) the rupture stress of the cohesive slab. The local action of a skier may gradually damage the weak layer, that should be considered as a brittle house of cards rather than a ball bearing. It may also contribute in some cases in opening a crown crack across the slab thickness. Therefore, the skier's action only deals with possible changes in the resistance of the weak layer or of the slab, and not with the driving force.

2.3 A simple sketch of the system:

In the case of accidental or of artificial triggerings, both the cohesive slab and the weak layer are elastic/brittle bodies: they may deform elastically under stress, and fail in a brittle way if the stress exceeds a threshold value.

The system can therefore be schematized as in Figure 1. The elastic/brittle slab is represented as a series of blocks linked by brittle springs, that can extend or contract depending on the stress they experience, or split into parts if the stress exceeds a threshold value. In a similar way, the slab is connected to older snow by elastic/brittle bonds, represented as some kind of flexible (i.e. elastic) and brittle flat house of cards, that may fail and collapse if the stress it experiences is large enough.

The different steps involved in the avalanche triggering chronology, and based on the above mentioned properties, are detailed hereafter.

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[2] Powder snow, that is usually not considered as a cohesive medium by the skier, is actually a cohesive one for the physicist, as it may withstand and transmit all types of stresses, as shear or tension.

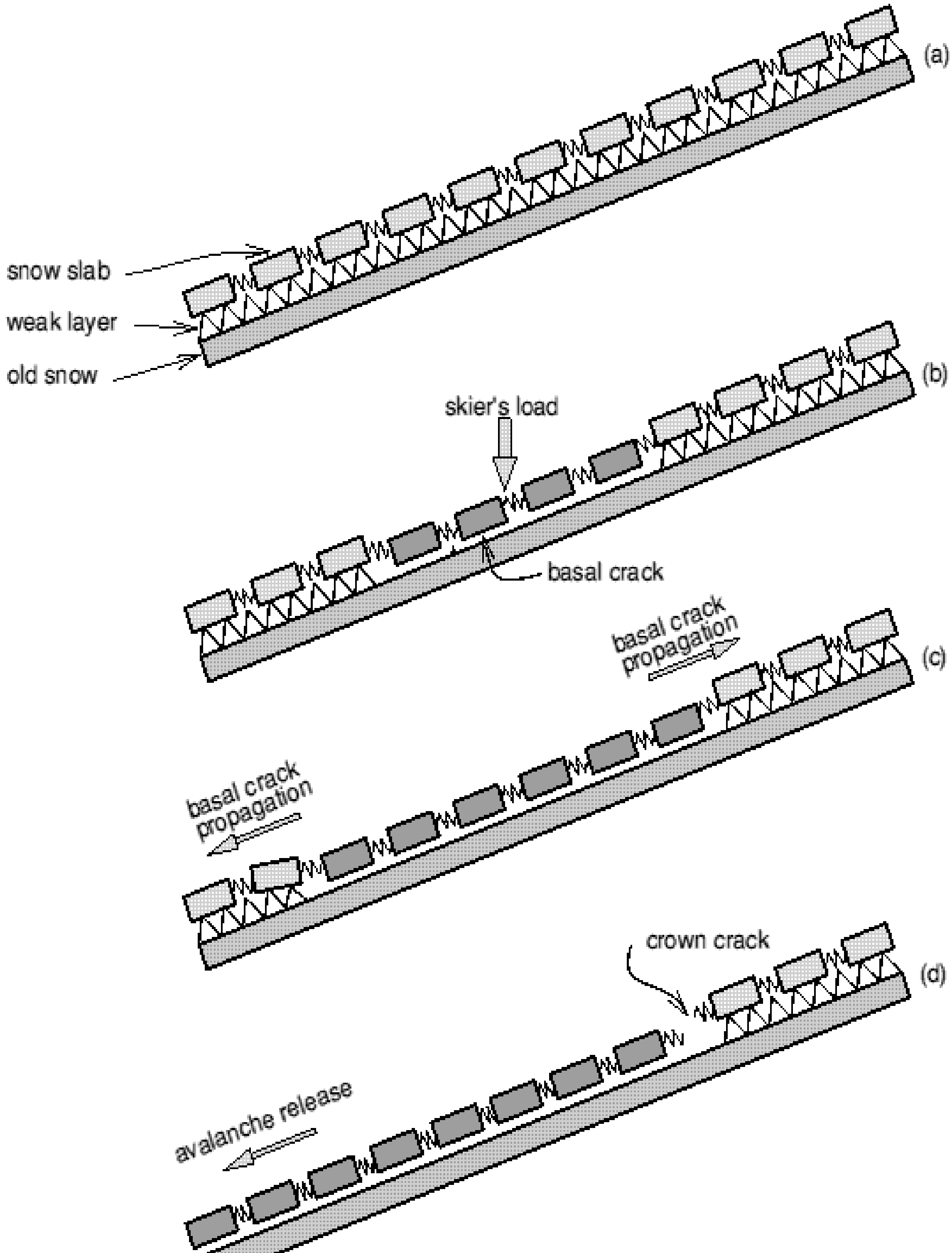

Figure 1. (a) A slab on a weak layer may be schematised as a series of blocks linked by elastic/brittle springs, lying on a collapsible house of cards; (b) the skier's load may collapse part of the house of cards (basal crack); (c) driven by either the skier's action or the snow weight, the basal crack may extend; (d) when the extension of the basal crack is large enough, the weight of the hung part of the slab initiates a crown crack at the top, resulting usually in the avalanche release.

3 A combination of four basic steps in series

Based on the concepts described above, we propose that accidental or artificial avalanche release stems from 4 mechanisms: i) collapse of the weak layer that results in the nucleation of a basal crack, ii) extension of the basal crack, iii) opening of the crown crack at the upper rim of the basal crack, and iv) extension of the crown crack, that leads to the avalanche release (Figure 2). These mechanisms operate in series; this means that if any of them does not occur, the avalanche is not released. These four steps are analysed now in more details.

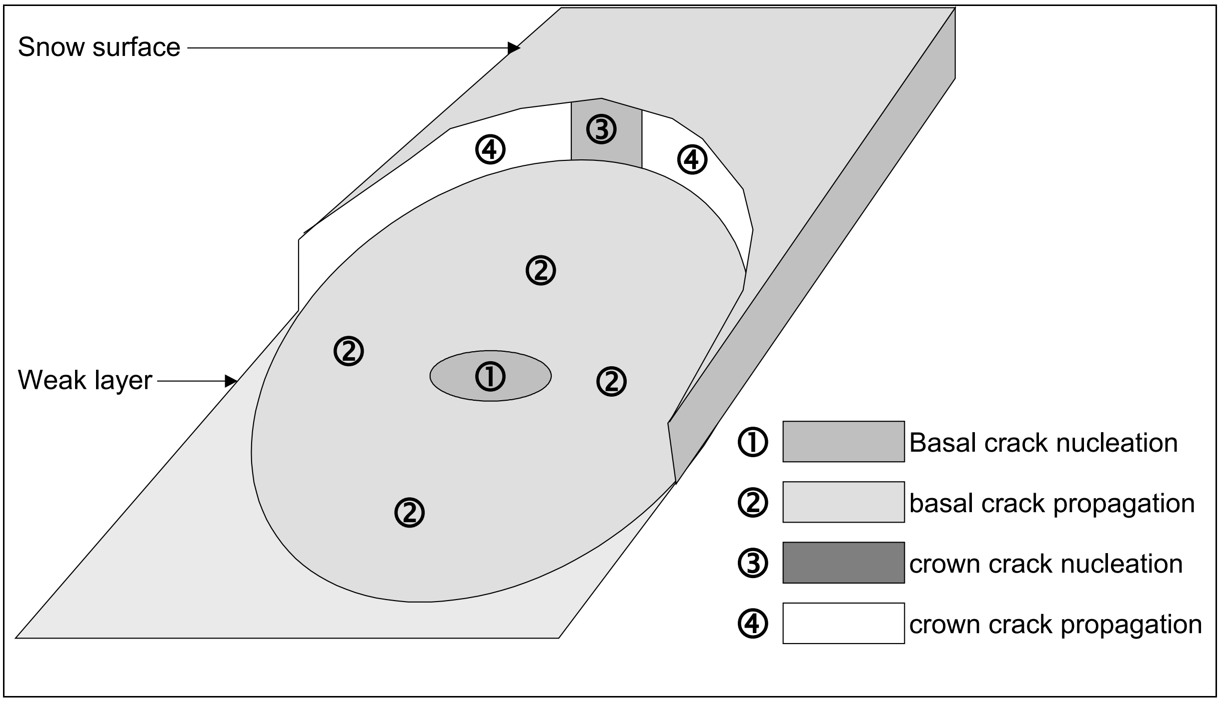

Figure 2. The four successive steps involved in avalanche release.

3.1 Basal crack nucleation:

On a slope, the weak layer experiences both the shear (parallel to the slope) and compression (perpendicular to the slope) components of the slab weight, that increase with its depth and density. The weak layer may be damaged when the load locally exceeds its mechanical resistance. The weight of a skier or a snowmobile does not significantly increase the total load experienced by the weak layer, but this load is applied on a very small surface (e.g. the base of skis), and results in a significant pressure that may locally participate to the damage of the weak layer. The local effect of the skier may significantly increase in dynamic conditions (additional pressure as the skier takes a sharp curve, or landing of a free-rider after a jump). A similar effect is obtained with an explosive.

The resulting collapse of these zones reduces their shear resistance to almost zero, depending on the nature of the weak layer. The damaged zone (basal crack) then extends along the skier path.

The weak layer may also collapse on a flat ground: the whole slab weight is now along its compression component. Similar damage effects are expected, also resulting in basal crack nucleation.

3.2 Basal crack expansion

Basal crack expansion may result from one of two different mechanisms (Figure 3)

- ✓ Owing to the gradual damage produced by the skier's additional and local pressure, the crack may extend step by step in an area around the skier's path (Figure 4)
- ✓ ii) The crack initiated by the skier may in some cases further extend over much larger distances under the effect of the snow weight itself.

In this last case, on a slope, the driving force consists of the compressive and shear components of the stress due to the slab weight. In other words, it results from the energy release experienced by the slab as the weak layer collapses. The possible skier's weight has no more effect at this stage, as the involved snow mass is enormously bigger.

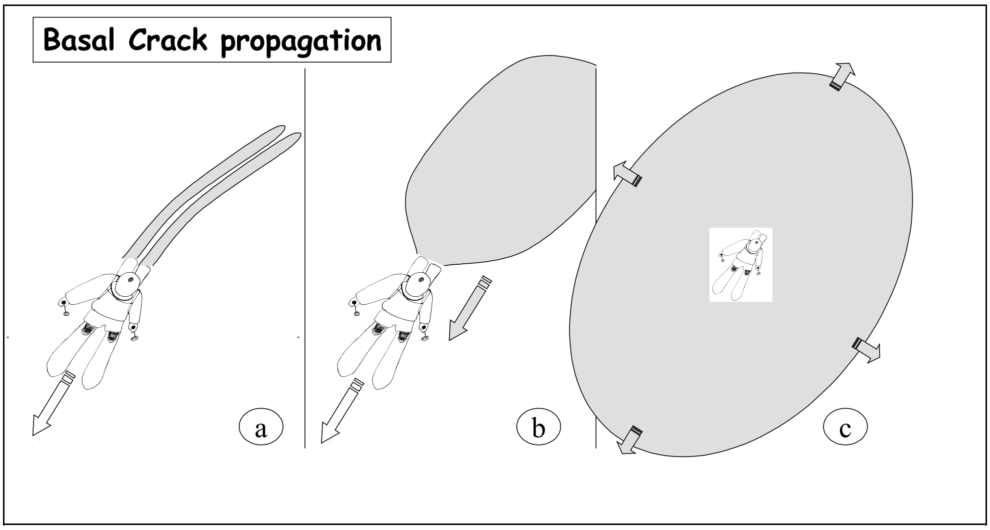

Figure 3. Basal crack propagation. (a) A weak layer covered by a fluffy shallow slab may collapse only along the ski tracks without further expansion; (b) the bending of a stiffer slab under the skier helps a wider collapse of the weak layer, resulting in a wider basal crack (artificial growth); (c) reaching a critical size, the crack may extend rapidly under the load of the snow itself (spontaneous growth).

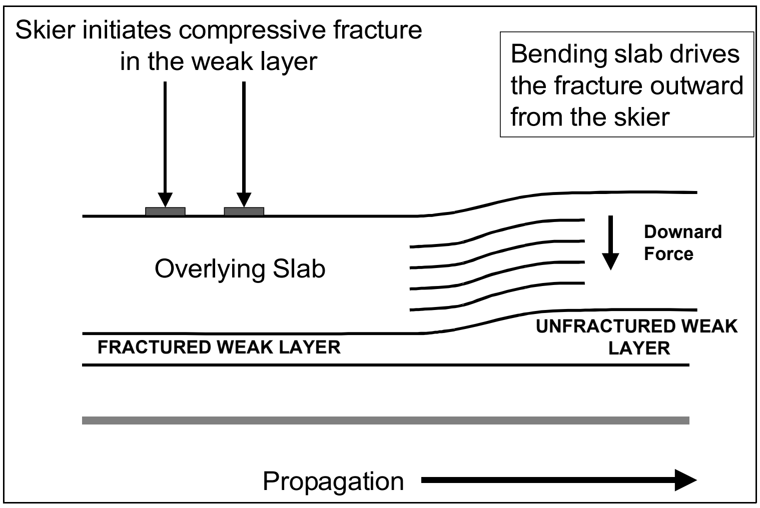

Figure 4. Diagram showing the collapse of the weak layer and the expansion of the basal crack. The overlying slab is bent, providing the downward force to progressively fracture the weak layer [after B. Johnson et al. 2000]

More precisely, such a spontaneous propagation of an existing crack obeys a specific law, known as Griffith's criterion (Griffith 1920)[3]. In spite of possible modifications related with slab geometry and stiffness, Griffith's criterion basically states that under a given stress, a large crack is more likely to expand than a small one. This is also the case for a sheet of paper, that tears off more readily if it contains a large crack. More quantitatively, spontaneous propagation takes place when the product of the stress by the square root of the crack size exceeds a threshold value K_c, called fracture toughness. As a consequence, for a given load, spontaneous propagation of the basal crack only occurs if the crack reaches a critical size. The larger the load, the smaller the critical size. Beyond this critical size, the energy release rate of the slab cannot be balanced any more by the resistance to slab propagation: the basal crack extension velocity is now much faster[4]. Velocities of the order of 20 m/s have been reported (Johnson et al. 2004).

On a flat ground, the reasons mentioned above are still valid; the basal crack may expand in a similar way if the snow weight is large enough. However, a basal crack on a flat ground can trigger an avalanche only if it extends up and propagates along a neighbouring slope (Figure 5). A simple calculation (Louchet, unpublished results) shows that a basal crack initiated by a skier of 80 kg on a hard slab thicker than 15 cm, with a density of 500 kg/m^3, may spontaneously propagate on a flat ground. If the central part of the slab does not totally collapse on the older snow surface, the crack may reach a neighbouring slope, expand upwards, and possibly trigger an avalanche. An estimate of the maximum distance at which the crack may reach the bottom of the slope before collapse can be obtained taking a maximum slab stiffness to density ratio: in the worst conditions (thick weak layer, thick slab) the crack will reach the slope if it is located at a distance up to a few ten meters from the skier.

Avalanche release may significantly differ depending on whether basal crack propagation was of the gradual or of the spontaneous unstable type. This important point will be discussed hereafter.

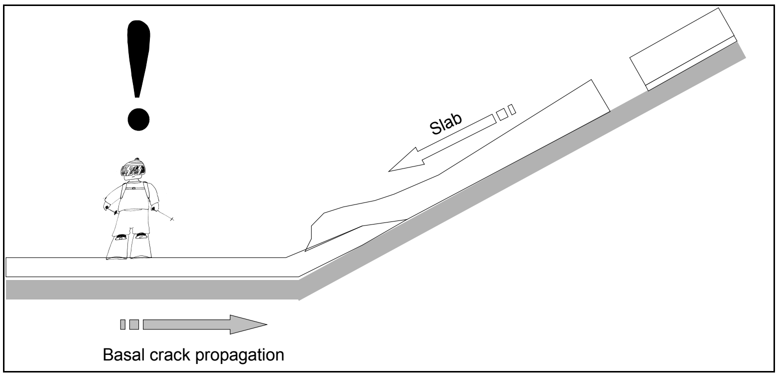

Figure 5. A basal crack on a flat ground can trigger an avalanche if it extends up and propagates along a neighbouring slope.

[3] The applicability of this criterion to the avalanche problem has been discussed elsewhere (Louchet et al., 2002).

[4] Velocities ranging from 6 to 330 m.s^{-1} were predicted on the basis of the propagation of a solitary wave in metastable snow stratifications, driven by the free-fall collapse of the weak layer (Heierli 2005). In real life, possible energy dissipation associated with weak layer collapse may further slow down the propagation velocity: energy dissipation accounts for much slower crack propagation in marzipan or in Xmas pudding for instance than in glass. These remarks qualitatively explain the values of crack propagation velocities measured by (Johnson et al. 2004).

3.3 Crown crack nucleation:

As the basal crack extends along the slope, the slab weight that was balanced by the weak layer resistance is now transferred into the slab itself at the crack rims. It takes the form of a tensile stress at the top cross section of the slab, at which the freed part of the slab is hung. This stress turns into a compression stress at the bottom rim, and into shear stresses on both sides. These stresses obviously increase with the weight of the "hanging" part of the slab, i.e. with the basal crack size. The failure stress of snow is usually smaller in tension than in compression, the shear failure being between these two. Therefore, as for basal crack nucleation, a crown crack nucleates at the top of the basal crack when the tensile stress in the slab reaches a threshold value.

As mentioned in section 3.2, two different basal crack growth mechanisms can operate. As a consequence, two different types of avalanche triggering are expected to occur (Figure 6).

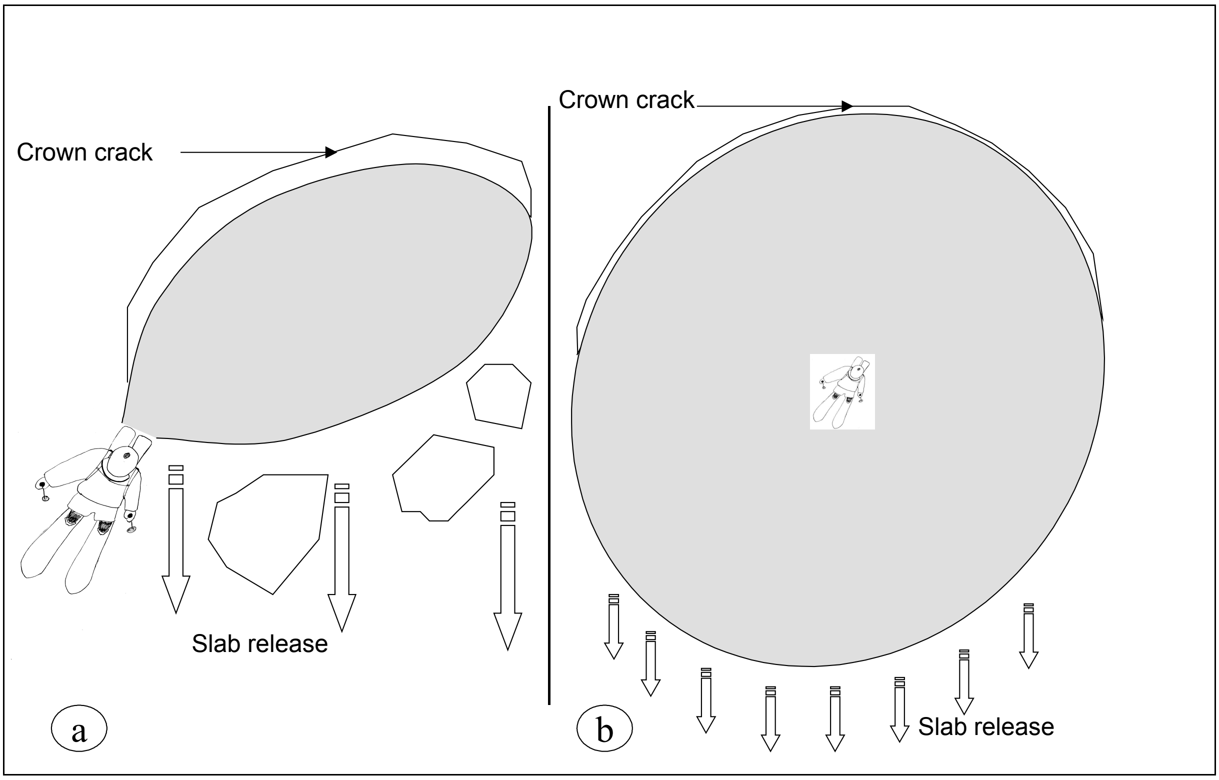

Figure 6. (a) subcritical triggering: the starting zone is limited roughly to the area damaged by the skier; (b) supercritical triggering: crown crack opening occurs at a large distance from the skier.

3.3.1 Subcritical triggering:

In this case, the basal crack gradually extends step by step in an area around the skier's path. At some stage of this extension, the tensile stress experienced by the slab at the upper rim may exceed the slab rupture stress. In this case, the starting zone is limited to the area actually damaged by the skier, who is likely to be located at the boundary of this zone when the avalanche is released. This scenario is likely to happen when the slab cohesion is low: a small sized basal crack is sufficient to reach the slab tensile rupture stress. The cut made by the skis in the soft slab may also help the slab failure along the skier's path. By contrast, in the case of stronger slabs, the slab rupture stress may not be reached, the crown crack does not open, and the skier gets out of the hazardous area without triggering the avalanche.

3.3.2 Supercritical triggering:

Now, the slab is significantly stronger (i.e. crown crack opening becomes more difficult), and (or) the driving force for basal crack expansion is larger (i.e. the slab is heavier). The basal crack size may reach the critical value for spontaneous expansion before a crown crack can open. At this point the basal crack starts expanding with a significantly larger velocity (Johnson et al. 2004). Crown crack opening occurs a short time later, often at quite a large distance from the skier, when the weight of the freed part of the slab has become large enough to trigger the failure of the tough slab. The starting zone is much bigger than in the previous case, and the skier is trapped somewhere in the middle of it. In some conditions, it may result in a "bang" at slab failure, as mentioned further (section 4.4). A simple calculation (Louchet 2001 b) shows that supercritical triggering is favoured by large slab weights, and that conditions for its occurrence are more readily met on slopes around a universal angle of 35.3^{o}.

3.4 Crown crack expansion and avalanche release

Provided some modifications are made, Griffith's criterion may also apply to the crown crack. If the tensile load is large enough to nucleate an incipient crown crack, it will necessarily be large enough to propagate it, as the increasing crack size requires a decreasing propagation stress. The crown crack grows very rapidly (brittle failure), until the stress concentration at its tips reaches the shear failure stress on both sides. The bottom rim usually fails in turn at this stage, as the whole slab weight is now transferred to it, and the avalanche is released. As a consequence, in most cases, the nucleation of the crown crack is immediately followed by the avalanche release.

However, as for the weak layer, the slab rupture threshold may have scattered values. An incipient crown crack usually appears at one of the weakest places. Its subsequent propagation may meet a tougher zone, which may hinder its growth. In this case, the basal crack goes on extending up further. Such stable incipient crown cracks are often observed.

4 The theory explains avalanches which are released...and those which are not

In the present section, we discuss several field situations and examples of avalanche release from "real life", in the light of the four basic steps developed above. We try to show on these examples that the conditions for avalanche release are that all the 4 conditions are fulfilled. If at least one of them is not, the avalanche will not be triggered.

4.1 Are huge snow accumulations favourable or unfavourable for avalanche release?

According to the above scenario, a thick snow cover may favour basal crack expansion. This is true for both natural, artificial or accidental triggerings. But basal crack nucleation by a skier or by explosives results impossible if the involved slab is too thick (Fohn 1987). This is probably why accidental releases are more frequent during the early winter: weak layers are indeed easily formed during this period, and frequently covered with shallow slabs. Basal cracks are therefore more likely to be nucleated in this case.

The influence of step 1 (basal crack nucleation) can also be illustrated by an accident that happened just after climbing skiers had taken their skis off, in order to climb straight up in the slope. The reason is that, for a similar stratigraphy, the weak layer fails more easily under a larger pressure, that corresponds to a smaller contact surface of the climber with the ground.

People sometimes deplore the poor efficiency of artificial triggerings in spite of huge snow accumulation. The snow depth is probably too large to allow artificial triggering, and not large enough to drive a natural avalanche release.

Finally, skiers happened to glide right across a heavily loaded bowl without any problem, and to trigger the avalanche as they popped out of it, at places where the snow covering the weak layer turned to be shallower.

4.2 Why should skiers cross a hazardous area one after the other rather than in groups?

This recommendation is supported by at least two reasons. The first one is obviously that if one of them is caught in an avalanche, he (she) may be rescued by the other ones. The second reason is that, in the case where the weight of a single skier is insufficient to nucleate a basal crack (e.g. thick slab), the combined weight of several of them crossing simultaneously the area may be large enough to nucleate it.

However, in the case of shallower slabs, a single skier may nucleate a basal crack (step 1), gradually expand it on a limited area (step 2), and get out from the hazardous zone without triggering an avalanche: in this case, the 3^{d} step (crown crack nucleation) failed, because the hung part of the slab was too small, i.e. not heavy enough, to open the crown crack. But now, if a second skier, and a third one, and so on, cross the same zone along slightly different paths, the corresponding basal cracks may merge, resulting in a unique crack that may be large enough either to directly open a crown crack (step 3, subcritical mode), or to expand in an unstable way before opening a large crown crack far above (step 3, supercritical mode). The resulting triggerings do not depend on whether skiers have crossed the zone together or one after the other. A reasonable recommendation to minimise the risk should therefore be to cross the dangerous area successively, and along the same path (although by doing this, the skiers are more likely to initiate the basal crack if the deep weak layer is deep…).

4.3 Why are most avalanches observed on slopes around 35º?

There is a general agreement that the most favourable slopes for avalanche triggering are around 35º. This observation may be explained using the above considerations. A limited basal crack width as in fig. 3 a or b, that remains smaller than the critical size for spontaneous expansion (step 2, subcritical mode), may result either in a limited starting zone, or in no triggering at all. By contrast, if the basal crack is wide enough (or the critical size small enough), the resulting spontaneous expansion cannot be stopped (step 2, supercritical mode) unless stratigraphy changes; indeed, the tensile stress experienced by the slab at the upper crack tip continuously increases, until the slab rupture stress is reached, and the crown crack opens (step 3). The avalanche is more likely to be released at this stage, as compared to the case of a limited subcritical growth (step 4).

As the supercritical scenario is favoured for slopes around 35°, avalanches are expected to be preferentially triggered on such slopes, and not around the classical 45° expected from simple mechanical arguments. This particular observed feature is a strong argument in favour of the present approach. Avalanches on slopes around 45° are more likely to be triggered in the subcritical mode[5], whereas those on slopes around 35° in the supercritical one.

4.4 Why are tough slabs often associated with large avalanches?

The tougher the slab, the more difficult crown crack nucleation is. This is probably why tough slab avalanches are usually big. The amount of elastic energy stored in such big slabs can be huge[6]. Its sudden release at crown crack opening may result in an impressive "bang", as experienced a couple of times by both of us.

4.5 Why do crowncracks often open at outcrops or trees?

It is frequently observed that the crown crack starts opening (step 3) at an outcrop or a tree, or even on a ski or surf track. These features act as weak points in the slab, that help crown crack nucleation. The same mechanism takes place at convexities.

Such weak points play a double role: i) they facilitate slab triggering through crown crack nucleation, but ii) they prevent large scale propagation of basal cracks, that may have resulted in the release of very large slabs. In other words, large slab avalanches are likely to be found on wide and smooth slopes without weak points (field heterogeneities, trees, sparse rocks or outcrops). It happened to one of us (AD) to see a slab avalanche whose crown crack was initiated at avalanche barriers (bridges or rakes). These barriers were suspected to be responsible for the release, but one may reasonably presume that without them, the avalanche would have been by far bigger and harmful, as the preexisting basal crack should have propagated further up.

4.6 Why are some avalanches triggered by skiers on a flat ground?

The propagation of the basal crack (step 2) allows understanding all the accidents occurring as skiers were on gentle slopes, but neighboured by slopes steeper than the fateful 30°. The skiers are responsible for the nucleation of the basal crack, that may gradually expand to the steeper slopes; at this point, the driving force is more efficient[7], and the basal crack may become unstable and propagate rapidly in the supercritical mode, triggering one or several slabs.

Such a mechanism is probably responsible for slab triggered by a skier coming on a terrace, whereas the other ones are still on the steeper slope below, where the significant snow thickness hinders any basal crack nucleation.

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[5] a slope of 45° is a compromise between a large snow accumulation and a steep slope (Louchet 2000).

[6] Taking a slab of 150m in diameter, and 40 cm in depth, with a density of 300 kg/m^3, on a slope of 45°, this energy is of about 1MJ, i.e. the same as that released by a mass of 1ton falling from a height of 100m. A slab twice as large in diameter would have an energy 4 times larger.

[7] The driving force for basal crack expansion on a flat ground stems from the weak layer collapse. As a first approximation, such a collapse may be limited by the weak layer thickness. By contrast, on a slope, the driving force results from both a collapse of the weak layer and a downslope shift of the slab. This last contribution is not limited and results in a sustained driving force.

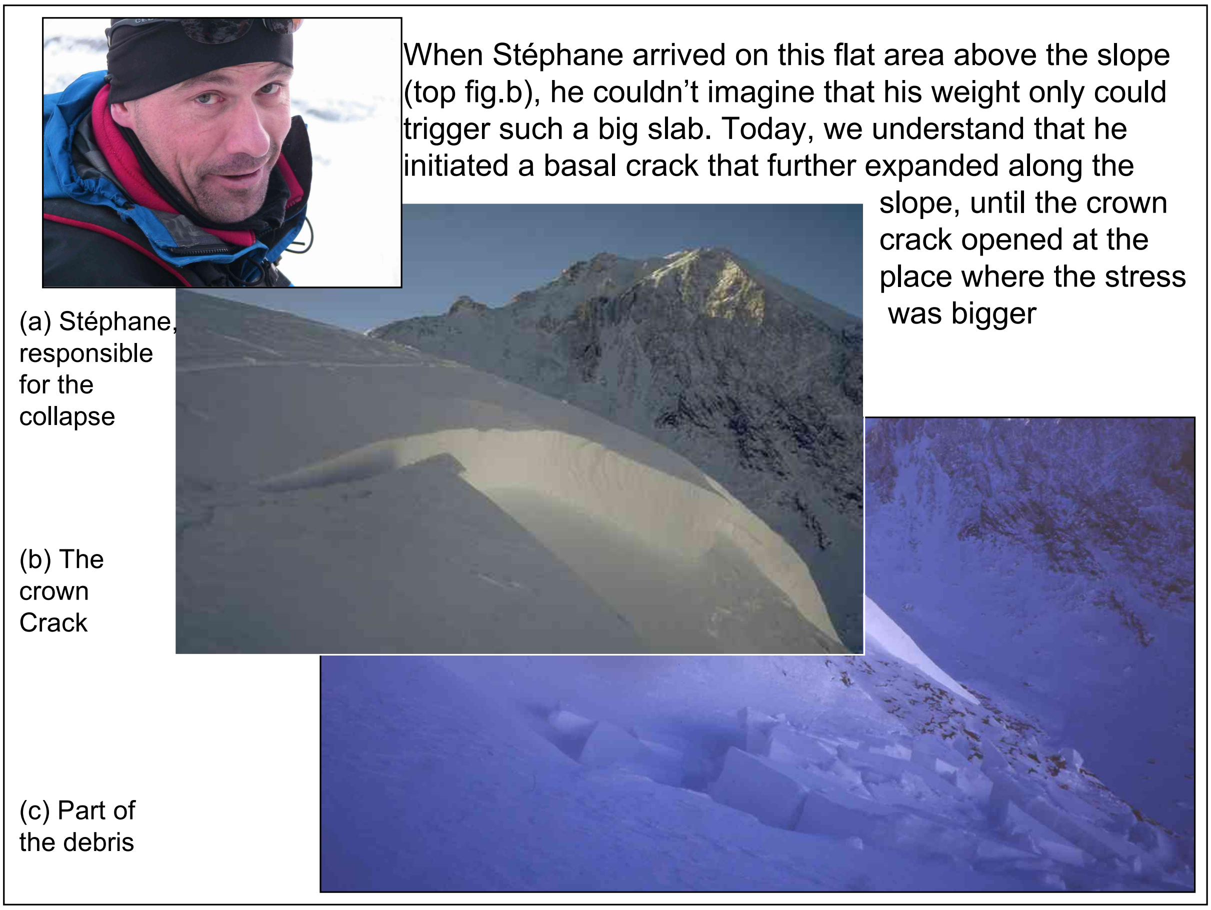

Figure 7. Crown rupture of a deep slab on a steep zone, triggered by a skier on the terrace just above.

4.7 Why whumpfs on steep slopes do not necessarily result in avalanche release?

It also happens that a "whumpf" is clearly felt on a rather steep slope (step 1), but without any further consequence. This case may correspond to a weak layer of small dimensions (blown out by the wind as it still was at the surface, or swept out by a previous avalanche), at the boundaries of which the basal crack propagation stops (step 2) before reaching the size necessary for unstable propagation or for directly opening a crown crack (step 3) and releasing the avalanche (step 4).

4.8 Snow cover variability and triggering scenarios:

The different triggering scenarios therefore depend on the spatio-temporal variability of the snow mechanical properties, that are involved during the four successive steps of the triggering process.

The snow cover is most often heterogeneous in thickness or (and) mechanical resistance. For this reason, the type of basal crack left along the skier's path may vary, for example from the case of fig. 3a to that of fig. 3b, or worse, that of fig. 3c. This may be the case for instance if snow evolves from fluffy to stiff. Another example is that of an artificial crack growth under a shallow slab (fig. 3b) that can quickly turn to the case of fig. 3c if the slab thickness becomes locally larger (Figure 8).This last case is specially threatening for experienced mountaineers, who usually take care of how snow may be like under their skis, but are less aware about the danger due to the snow variability in the neighbourhood. In both cases, a slope that seems to be quite safe may suddenly be swept out by a spanning avalanche.

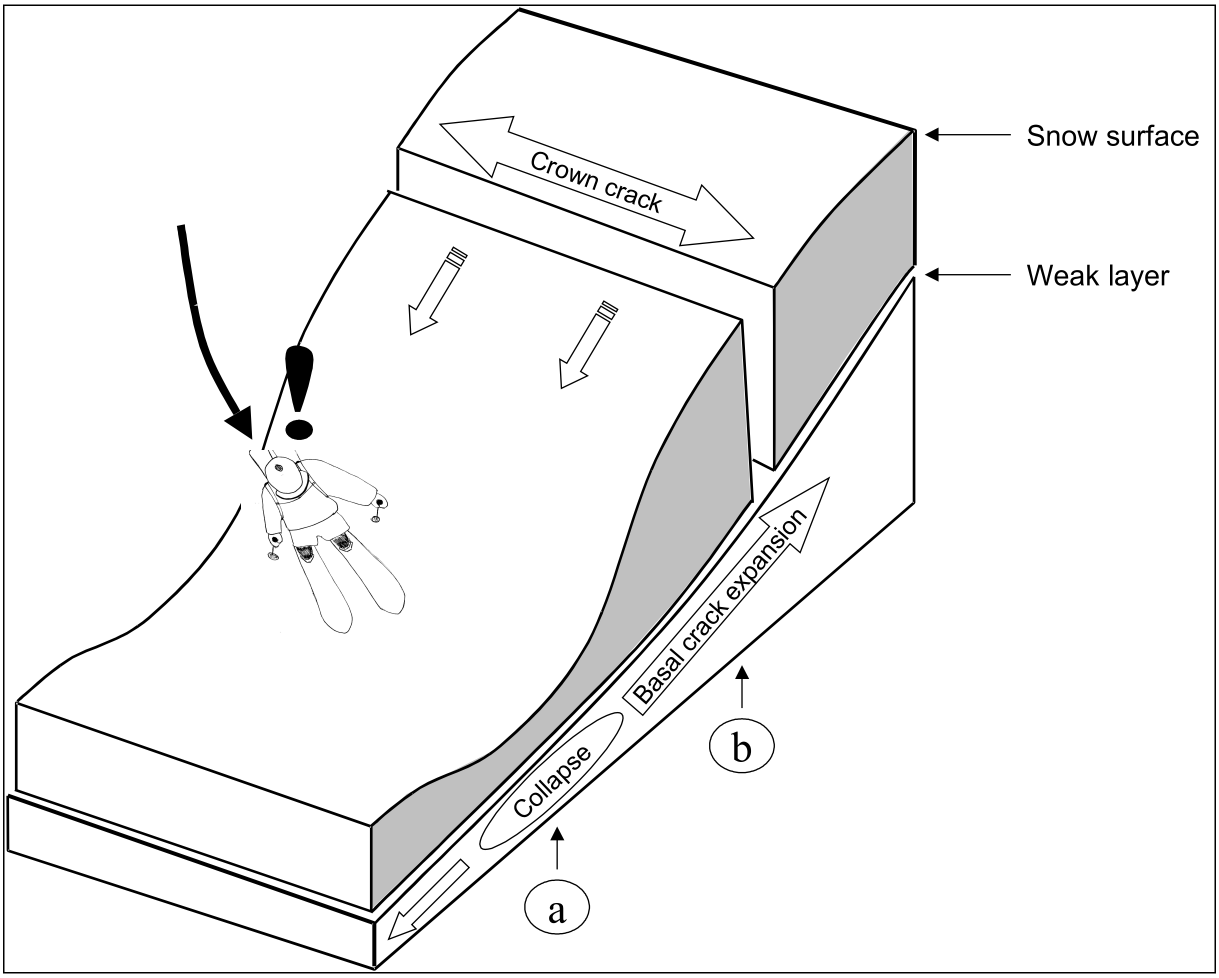

Figure 8. A particularly hazardous situation is found when a slightly loaded slope (where a skier can easily nucleate a basal crack (a)) is bounded by a more loaded and steeper slope. Both the larger load and the steeper slope favour basal crack propagation and further crown crack opening.

Skillful experienced skiers sometimes succeed in triggering slab avalanches without being caught in them. "Cutting slopes" was a current technique for patrollers before the systematic use of explosives or gas exploders. It may happen indeed that a skier triggers an avalanche of limited size. In most cases, this is a "subcritical triggering": the tensile stress in the slab resulting from the collapse of the weak layer on a limited area is large enough in this case to open a crown crack just above; the avalanche is released, but the skier can escape if he (she) is able to control his (her) trajectory. This is likely to occur for weak and shallow slabs made of loose snow.

This cutting slope technique usually works, but not always. This may be the reason why Pompon was caught as he was trying to trigger the bowl of "les Combes". On a same slope indeed, with exactly the same topography, a slab avalanche may largely exceed the “usual” size. We are in the case of a supercritical triggering. The weak layer collapse spontaneously and rapidly extends in all directions. The crown crack may open far above the skier, who gets trapped in the middle of a huge triggered slab that may reach widths up to several hundred meters. Finding a way out turns to be impossible, and the outcome is usually fatal. This scenario is more likely to take place in the case of tough and heavy snow. Being aware of the existence of these two modes is quite fundamental for practitioners. They should know that predicting which one of these two is likely to occur is risky, even if the supercritical mode is favoured by a continuous weak layer, a heavy, thick and tough upper snow layer, and slope angles around 35°.

The layout procedure for triggering devices (e.g. gas exploders) should also take into account these two different scenarios: the separation between two neighbour devices is not the same depending on whether sub or supercritical avalanches have to be triggered. Too frequent subcritical triggerings probably hinder the release of large slabs, whereas optimizing supercritical triggerings may lead to unexpected consequences, owing to the uncontrolled size of the avalanche.

5 From a basic understanding towards a possible prediction?

We showed that, despite the large variety of observed avalanche phenomena, their understanding does not require as many models, but may be described by using a few simple concepts. Too simple approaches, based on a balance between a global snow resistance and a supposed overload due to the skier, would not be able to describe the variety of observed triggerings. By contrast, such a variety of behaviours can be easily accounted for on the basis of the four step scenario described above.

However, the present approach is able to account for the observed phenomena only after they have occurred. The final result in terms of avalanche occurrence and size may vary indeed drastically, depending on the way in which these processes are connected. Human action modestly appears to be limited to a local change in the weak layer resistance, that may nevertheless lead to quite different scenarios depending on the local and global snow cover properties. This is reminiscent of the well-known butterfly wing problem: the snow cover is such a complex system, with such a large spatio-temporal variability, that a deterministic prediction of avalanche release turns out to be impossible, as it would require an army of patrollers measuring snow properties all the day long, and that a slight uncertainty in these measurements might lead to totally different behaviours.

Though, our ignorance can be dealt with in terms of randomness. It was shown recently indeed, from field measurements, that starting zones obeyed a specific size distribution, taking the mathematical form of a power law, also known as a "scale invariant" distribution. This means that there are many small avalanches, and a few big ones, but that the ratio between the number of avalanches of different sizes is perfectly well defined, and that there is no characteristic avalanche size.

We demonstrated using cellular automata simulations (Faillettaz et al. 2004) that such a scale invariance can be reproduced provided random values are used for rupture thresholds. The consequences are twofold:

i) scale invariant size distributions obtained from field measurements are a signature of the random nature of the snow cover, confirming the necessary use of statistical approaches.

ii) introducing disorder leads to a perfectly well defined statistical organisation, which provides some hope of "personalized" avalanche prediction using cellular automata fitted on particular gully topographies.

In the meanwhile, we believe that the basic concepts and mechanisms developed in the present paper will be of some help in improving decision making for both professionals and practitioners, through a better understanding of the possible underlying mechanisms.

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The authors:

François Louchet graduated as an engineer at "Ecole des Mines", and has a PhD in Solid State Physics. He is a professor of Physics of Materials and Geophysics at the University of Grenoble. He began trying to understand avalanche release after watching a huge slab avalanche triggering during a trek in the Galibier district, french Alps, in february 1997. He recently joined the Grenoble department of Glaciology to develop new research topics on dynamical aspects of deformation and fracture, and physics of complex systems.

Alain Duclos is an engineer. He got a PhD in Geography at Grenoble University in the aim to learn more about slabs. He spent many years as a IFMGA mountain guide and ski patroller. He presently rules the ALEA company, dedicated to avalanche risk mitigation and expertise, in Aussois (Savoie), and is seriously committed in road protection in the Savoie region.