

A REVIEW OF AVALANCHE RELEASE MECHANISMS: FROM ANTICRACK PROPAGATION TO SUPERSHEAR FRACTURE

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ABSTRACT: Dry-snow slab avalanches are responsible for most avalanche fatalities, making understanding of release mechanisms essential for forecasting and hazard assessment. Slab avalanche release is now understood as a sequence of coupled mechanical processes: failure initiation in a buried weak layer, onset of crack propagation, dynamic crack propagation, and ultimately slab fracture, crack arrest, and release. Over decades of research, conceptual models of avalanche release have emerged, ranging from weak layer shear failure to collapse-driven anticrack propagation, often treated as competing explanations. In this review, we bring together laboratory experiments, field observations, numerical simulations, and analytical models, from which a unified perspective on slab avalanche release emerges. Across these approaches, consistent evidence shows that the type of crack propagation depends on the situation, in particular slope angle. On gentle terrain and in propagation saw tests, propagation is typically slow ($< 60 \text{ m s}^{-1}$), associated with weak layer collapse and slab bending. On steep slopes, the propagating crack can accelerate and become dominated by weak layer shear failure, with characteristics consistent with supershear fracture. Crack speeds may then exceed the slab shear wave velocity ($> 100 \text{ m s}^{-1}$). This suggests that these two propagation regimes, collapse-driven and shear-dominated, appear to describe different situations of the same dynamic process. The relative importance of collapse and shear depends on slope angle, the resulting stress state, and the weak layer failure envelope. Together, these findings help reconcile previously competing theories of slab avalanche release and highlight the need to consider both collapse-driven and shear-dominated crack propagation regimes. Further work is needed to assess whether this framework applies to natural avalanche release, or whether slab viscoelastic relaxation and weak layer ductile-to-brittle transition lead to partly different release mechanisms.

KEYWORDS: dry-snow slab avalanche, avalanche release, weak layer, failure initiation, crack propagation, anticrack, supershear fracture, slab fracture.

1. INTRODUCTION

Dry-snow slab avalanches are responsible for the vast majority of avalanche fatalities, making a sound understanding of avalanche release essential for forecasting and hazard assessment (McClung and Schaerer 2006; Schweizer et al. 2016). A slab avalanche forms when a cohesive snow slab detaches from the underlying weak layer and starts to slide downhill. Although this process may appear instantaneous, avalanche release is now understood as a sequence of fracture processes occurring over a wide range of spatial scales, from the failure of individual snow grains to crack propagation over tens or even hundreds of metres (Figure 1).

A useful framework to understand the underlying processes divides avalanche release into four

successive stages: (1) failure initiation in a buried weak layer; (2) onset of crack propagation; (3) dynamic crack propagation across the slope; (4) slab fracture and crack arrest (i.e., the end of propagation), finally leading to slab sliding and avalanche release. Failure initiation and crack propagation are the central processes leading to slab avalanche release. They describe how a local failure in the weak layer forms, for example beneath a skier, and can spread over tens or even hundreds of metres, ultimately causing an entire snow slab to detach. Whether crack propagation continues or eventually stops determines the size of the detached slab and, on sufficiently steep slopes, whether an avalanche is released.

Over the past decades, different conceptual models have emphasized different stages of this release sequence. Early mechanical models described crack propagation primarily as a shear failure process within the weak layer (McClung 1979). While these models captured important aspects of slab release on steep slopes, they could not fully explain common observations, including crack propagation on nearly flat terrain, audi-

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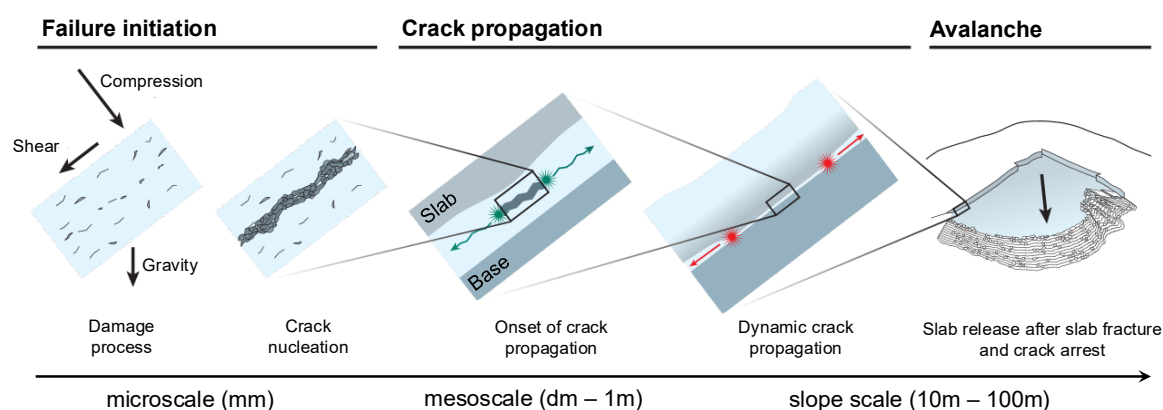


Figure 1: General sequence of mechanical processes leading to dry-snow slab avalanche release, from weak layer damage and crack nucleation to dynamic crack propagation, slab fracture and release. The sequence spans scales from grain-scale failure to slope-scale avalanche formation; adapted from Schweizer et al. (2016).

ble whumpfs, and remotely triggered avalanches. These phenomena were accompanied by a rapid settling of the snowpack, often visible, caused by the collapse of the highly porous weak layers following their failure (e.g., (J. B. Jamieson and Schweizer 2000; Johnson et al. 2004)). The collapse was also evident in the fracture experiments (Johnson III 2000; Johnson et al. 2004; Herwijnen and B. Jamieson 2007; Sigrist and Schweizer 2007; Gauthier and B. Jamieson 2006), which also showed bending of the slab prior to crack propagation. The so-called anticrack model of Heierli et al. (2008) incorporated these observations and explained crack propagation in low-angle terrain. Bending of the slab due to weak layer collapse provides an additional driving mechanism for crack propagation even in the absence of substantial gravitational shear stresses. Because the crack closes rather than opens as it propagates, this process became known as anticrack propagation.

Recent field observations, laboratory experiments, numerical simulations, and analytical models suggest a more unified picture. Rather than representing competing explanations, collapse-driven and shear-dominated crack propagation appear to describe different propagation regimes that emerge under different conditions. At short propagation distances, such as those observed in standard propagation saw tests (PSTs), and on low-angle terrain, crack propagation is typically governed by weak layer collapse and slab bending. On steep slopes, however, cracks can accelerate and become dominated by weak layer shear failure. When crack speeds exceed the shear wave speed

of the slab, this is referred to as supershear crack propagation. The identification of this supershear propagation regime provides a framework for reconciling the anticrack and shear failure descriptions of slab avalanche release.

In this review, we summarize the current understanding of slab avalanche release, from weak layer failure to slab sliding. Rather than presenting historical theories as competing explanations, we argue that they describe different stages or propagation regimes within the same physical process. We discuss the evidence from laboratory experiments, field observations, analytical models and numerical simulations, and highlight how the interaction between these approaches has transformed our understanding of avalanche release over the past two decades.

2. FAILURE INITIATION

Failure initiation, the first phase in natural release, begins with damage at the scale of snow grains and intergranular bonds, eventually leading to a macroscopic loss of strength in the weak layer. Damage may result from gradual loading by snowfall, or from localized loading by a skier, explosives, a cornice fall, or other perturbations (Schweizer et al. 2003). Understanding the strength of weak layers is therefore fundamental to understanding how slab avalanches are initiated. The corresponding strain rates are important because snow strength is strongly rate-dependent and exhibits a ductile-to-brittle transition (Mellor 1975; Narita 1980; Fukuzawa and Narita 1993;

Schweizer 1998). At low strain rates, bond healing, sintering, and creep can compete with bond breaking; at higher strain rates, brittle fracture and abrupt post-peak softening dominate (Löwe et al. 2020).

Early studies of weak layer failure primarily focused on shear strength, measured, for example, using the shear frame, implicitly assuming that failure could be described by a single shear strength value. A major advance in recent years has been the recognition that weak layer failure is inherently multiaxial – consistent with the stress state in a sloping snowpack. Laboratory experiments have shown that snow strength depends on the combined shear and normal stress state (Reiweger and Schweizer 2010), with failure envelopes that cannot be reduced to a single shear strength value (Reiweger et al. 2015; Chandel et al. 2015). While Mohr-Coulomb-cap descriptions have been proposed, more recent experimental and numerical work suggests that weak layer failure is often better represented by an ellipsoidal or critical-state-type yield surface (Ritter et al. 2020; Mede et al. 2018; Gaume et al. 2017b; Bobillier et al. 2020; Blatny et al. 2021; Schöttner et al. 2025). These experiments provide a direct link between laboratory observations and the constitutive descriptions used in modern analytical and numerical models of avalanche release.

Failure initiation also depends on the behaviour of the weak layer after reaching its peak strength. At moderate to high loading rates, weak layers typically show pronounced softening followed by a residual frictional regime, as observed in experiments and reproduced by microstructure-based or continuum numerical models (Gaume et al. 2018a; Bobillier et al. 2020; Ritter et al. 2020; Mede et al. 2018; Schöttner et al. 2025). This softening, the progressive loss of strength, controls how a local damage zone can evolve into a macroscopic crack. Failure initiation is therefore not an isolated strength exceedance, but the beginning of a coupled localization, softening and fracture process. While natural release may involve slow crack growth to a critical size, artificial triggers such as skiers or explosives can directly create a macroscopic crack that is sufficiently large for self-sustained propagation.

3. ONSET OF CRACK PROPAGATION

The onset of crack propagation marks the transition from local failure to self-sustained growth of a crack within the weak layer. While failure initiation is primarily governed by the global stress state and

strength of the weak layer, crack propagation also depends on how stresses are redistributed around an initial defect or crack. Because the failed zone can no longer fully support the slab load, this load must be transferred to the surrounding intact weak layer, increasing stresses near the crack tip. This redistribution is controlled by characteristic length scales which depend on the elastic and geometrical properties of the slab and the weak layer. Depending on the formulation, the propagation condition can then be expressed either in terms of local stresses and strength, or in terms of effective fracture toughness and critical energy release rate. In stress-based formulations, propagation occurs when the stress state at the crack tip satisfies the weak layer failure criterion. Equivalently, in fracture mechanics formulations, it can be expressed in terms of fracture toughness and critical energy release rate. Crack propagation becomes self-sustained once the elastic energy released by extending the crack exceeds the energy required to propagate it, and does not require any additional external loading.

The mechanical driving force for self-sustained crack propagation arises from the deformation of the slab-weak-layer system around the growing failed zone. In snow slab avalanches, this driving force is mainly associated with slab deformation under gravitational loading, with slab bending promoted by weak layer collapse, and slab stretching becoming increasingly important on steeper slopes as downslope gravitational loading increases. These effects can be expressed either in terms of released elastic and gravitational energy, or in terms of stress redistribution and local loading at the crack tip. Depending on the dominant deformation mode and modeling framework, different mechanical descriptions have been developed. For instance, while McClung (1979) treated crack propagation as strain-softening shear failure within the weak layer, Heierli et al. (2008) used an energy-based approach that emphasized weak layer collapse and slab bending.

Field experiments, employing the propagation saw test, mimic the conditions for the onset of crack propagation. While some early studies with the propagation saw test related the critical cut length, which integrates weak layer and slab properties, to crack propagation propensity (Gauthier and B. Jamieson 2006), others combined field experiments with mechanical models to estimate the critical energy release rate of weak layers (Sigrist and Schweizer 2007; Herwijnen et al. 2016). While the PST is instructive, the setup with a fully unsup-

ported slab (cantilever) above the artificial crack may not fully reproduce the conditions of natural release on steep slopes. More recently, mixed-mode fracture experiments demonstrated that not only strength but also fracture toughness depends on the relative contributions of compression and shear loading (Adam et al. 2024).

The current view is increasingly unified. The onset of self-sustained propagation results from the coupling between weak layer failure, gravitational loading, slab deformation, weak layer collapse, and dissipation. This understanding has emerged from the complementary use of field observations, laboratory experiments, analytical models and numerical simulations (Gaume et al. 2017a; Bobillier et al. 2021; Gaume et al. 2018a; Gaume et al. 2018b; Guillet et al. 2023; Rosendahl and Weissgraeber 2020a; Rosendahl and Weissgraeber 2020b; Weissgraeber and Rosendahl 2023; Meloche et al. 2024; Adam et al. 2024; Gaume et al. 2026).

Together, these approaches show that crack propagation is a mixed-mode mechanical process that cannot be described from stress and strength alone. It also depends on how the slab and weak layer deform around the crack, and therefore on their elastic and geometric properties. These properties control stress redistribution around the crack and the mechanical energy available for propagation. The relative importance of collapse and shear then depends on slope angle, the resulting stress state, and the weak layer failure envelope.

4. DYNAMIC CRACK PROPAGATION

Direct measurements of dynamic crack propagation became possible through high-speed imaging of propagation saw tests and full-scale field experiments (Herwijnen et al. 2016; K. W. Birkeland et al. 2018; Bergfeld et al. 2021). In standard PSTs, measured crack speeds typically range from about 15 to 60 m s⁻¹ and increase with slab density (Gaume et al. 2015; K. W. Birkeland et al. 2018). These values are consistent with earlier estimates of around 20 m s⁻¹ from seismic and displacement observations of whumpfs (Johnson et al. 2004). These speeds are below the Rayleigh wave speed of the slab.

Measurements of crack speeds in real avalanches are rare and are limited to artificially triggered avalanches. Video analyses suggested crack speeds exceeding 100 m s⁻¹, i.e., beyond the Rayleigh wave speed (Hamre et al. 2014).

Numerical simulations have reconciled these con-

trasting observations of crack speed and revealed the corresponding propagation regimes. On flat or low-angle terrain, DEM and MPM simulations showed that self-sustained propagation is driven by slab bending and weak layer collapse (Trottet et al. 2022; Bobillier et al. 2024a). The crack tip travels with a speed of < 60 m s⁻¹, i.e., in the sub-Rayleigh regime, controlled by slab elasticity, weak layer properties, and the energy dissipated during collapse.

In contrast, on steep slopes (> 30 degrees), the simulations suggest a transition from sub-Rayleigh collapse-driven crack propagation to shear-driven crack propagation with speeds that may exceed 100 m s⁻¹, i.e., larger than the shear wave speed. This transition to supershear propagation occurs once a supercritical propagation distance is reached, typically of the order of 2–5 m (Trottet et al. 2022; Bobillier et al. 2024a; Bobillier et al. 2024b). Therefore, this transition has not been observed in traditional, several-meter-long PSTs. Subsequent long fracture experiments (up to 20 m), field observations, and numerical simulations have provided growing evidence that this supershear propagation regime is not a numerical artifact, but can occur during slope-scale avalanche release (Bobillier et al. 2024a; Bobillier et al. 2024b; Simenhois et al. 2023; Bergfeld et al. 2025; Hamre et al. 2014).

Rather than representing competing mechanisms, the collapse-driven and the shear-driven propagation regimes appear to describe different situations of the same dynamic process (Figure 2). At short propagation distances or on gentle slopes, crack propagation is dominated by slab bending and weak layer collapse. On steep slopes, however, propagation becomes shear-dominated. Classical PSTs therefore primarily probe the onset of crack propagation and the very early stages of propagation, whereas longer fracture experiments are required to investigate the later dynamic evolution of slope-scale cracks (Bergfeld et al. 2022; Meloche et al. 2025).

In skier-triggered avalanches, however, the relevant initial conditions may differ from those imposed in classical fracture experiments. Because the skier acts as a moving load, they may progressively damage the weak layer over a distance exceeding the supercritical crack length before autonomous crack propagation begins. The system may therefore enter directly into a supershear regime, bypassing much of the early sub-Rayleigh anticrack stage and therefore possibly reducing its relevance for skier-triggered releases on slopes. In addition, the prevalence of supershear transi-

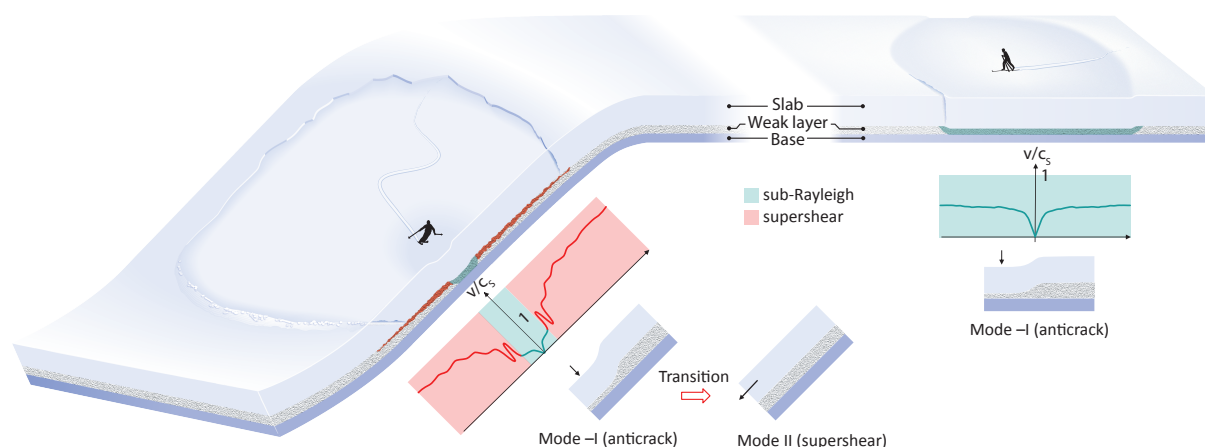


Figure 2: Propagation regimes after weak layer failure. On flat or low-angle terrain, crack propagation remains collapse-driven and sub-Rayleigh. On steep slopes, propagation is shear-dominated and may transition to supershear propagation (from Bobillier et al. 2024b).

tions and the role of cross-slope crack propagation in determining release area geometry remain important open questions, as does the more fundamental question of how initial cracks form and evolve in natural slab avalanches, including the relative importance of slab bending and longitudinal deformation.

5. SLAB FRACTURE, CRACK ARREST and RELEASE

The final stage of the fracture process involves the end of crack propagation, namely crack arrest, slab fracture, the formation of the detached slab, and finally its release. How far the cracks propagate determines the potential amount of snow available for avalanche release. The slab tensile strength is a key factor for slab size (J. Jamieson and Johnston 1992). Subsequent field observations, laboratory experiments, analytical models and numerical simulations have considerably improved our understanding of the processes controlling crack arrest. They show that propagation may stop because of slab fracture, material heterogeneity, topographic variations, or slab touchdown following weak layer collapse (Failletaz et al. 2004; Fyffe and Zaiser 2004; Kronholm and K. Birkeland 2005; Gaume and Puzrin 2021; K. Birkeland et al. 2014; Schweizer et al. 2014; Rosendahl et al. 2024). These mechanisms reduce the energy available for further crack growth and ultimately determine the size and shape of the detached slab. Recent numerical studies further suggest that crack speed may play an important role in determining release area dimensions. Faster cracks

generally propagate farther before arrest, increasing the likelihood of larger release sizes (Gaume et al. 2015). Analytical work provides a possible explanation by showing that slab tensile stresses decrease with increasing crack speed, reducing the tendency for slab fracture to arrest propagation (Meloche et al. 2025). These findings suggest that, once cracks transition to a supershear regime, crack arrest may become increasingly controlled by topography and lateral arrest conditions rather than slab fracture (Trottet et al. 2022).

Despite this progress, slab fracture and arrest remain the least understood stage of the fracture process. In particular, the prevalence of supershear propagation in natural avalanches, the mechanisms controlling crack arrest, and the factors determining final release area geometry remain important open questions.

Failure initiation, crack propagation, slab fracture, and arrest can all occur on nearly flat terrain. For an avalanche, however, the detached slab must overcome friction to slide downslope. Measurements of crack-face friction indicate that the critical slope angle for avalanche release is about 30 degrees, primarily controlled by the friction between the detached slab and the bed surface, with a weaker dependence on snow properties such as slab and weak layer characteristics (Herwijnen and Heierli 2009; Simenhois et al. 2012; Herwijnen et al. 2016). Consequently, topography ultimately determines which parts of a detached slab will slide and contribute to avalanche release.

6. CONCLUSION

Dry-snow slab avalanche release is best understood as a sequence of coupled mechanical processes, from failure initiation and crack propagation to slab fracture and slab sliding. Each stage is governed by different physical mechanisms and controlled by different combinations of snow properties and terrain. Failure initiation depends primarily on the stress state and weak layer strength. The onset of crack propagation also depends on how the slab and weak layer deform around the initial failure or crack, and therefore on their elastic and geometric properties. Depending on the formulation, this propagation condition can be expressed either through local stress redistribution and weak layer failure properties, or through effective fracture toughness and critical energy release rate. Once propagation becomes self-sustained, its dynamic evolution is governed by the same coupled system, but inertia and propagation distance become increasingly important, allowing transitions from collapse-driven sub-Rayleigh propagation to shear-dominated supershear propagation. Slab fracture, crack arrest, and subsequent sliding then depend on slab tensile failure, topography, crack speed, and the balance between gravity and friction. Together, these factors determine whether a local failure ultimately develops into a slab avalanche.

This process-oriented framework also helps reconcile several theories that have been presented as competing explanations of avalanche release. Rather than representing competing theories, shear failure and collapse-driven propagation increasingly appear to describe different situations or propagation regimes of the same fracture process. Likewise, the complementary use of field observations, laboratory experiments, analytical models and numerical simulations has greatly advanced our understanding by revealing processes that cannot be captured by any single approach alone.

Despite this progress, important questions remain. In particular, the questions of the prevalence of collapse-driven and shear-dominated propagation regimes in natural avalanches, cross-slope crack propagation, the mechanisms controlling crack arrest, and the influence of friction on slab release require further investigation. Addressing these challenges will require continued integration of field observations, laboratory experiments, and physically based modeling across the wide range of spatial scales involved in avalanche release.

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