Snow Avalanches in a Nutshell: A Brief Phenomenology for Non-Specialists

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Why are snow avalanches interesting?

- Practical reason: Avalanches are a real threat to many mountain communities, 50–100 deaths/year in the Alps, significant economic losses.
- Scientific reason #1: Gravity mass flow with many different flow regimes due to wide variability of snow properties, flow size and terrain conditions.
- Scientific reason #2: Full-scale experiments are feasible, may serve as model for other gravity mass flows.
- Non-scientific reason: People are simply fascinated by the power and beauty of this natural phenomenon...

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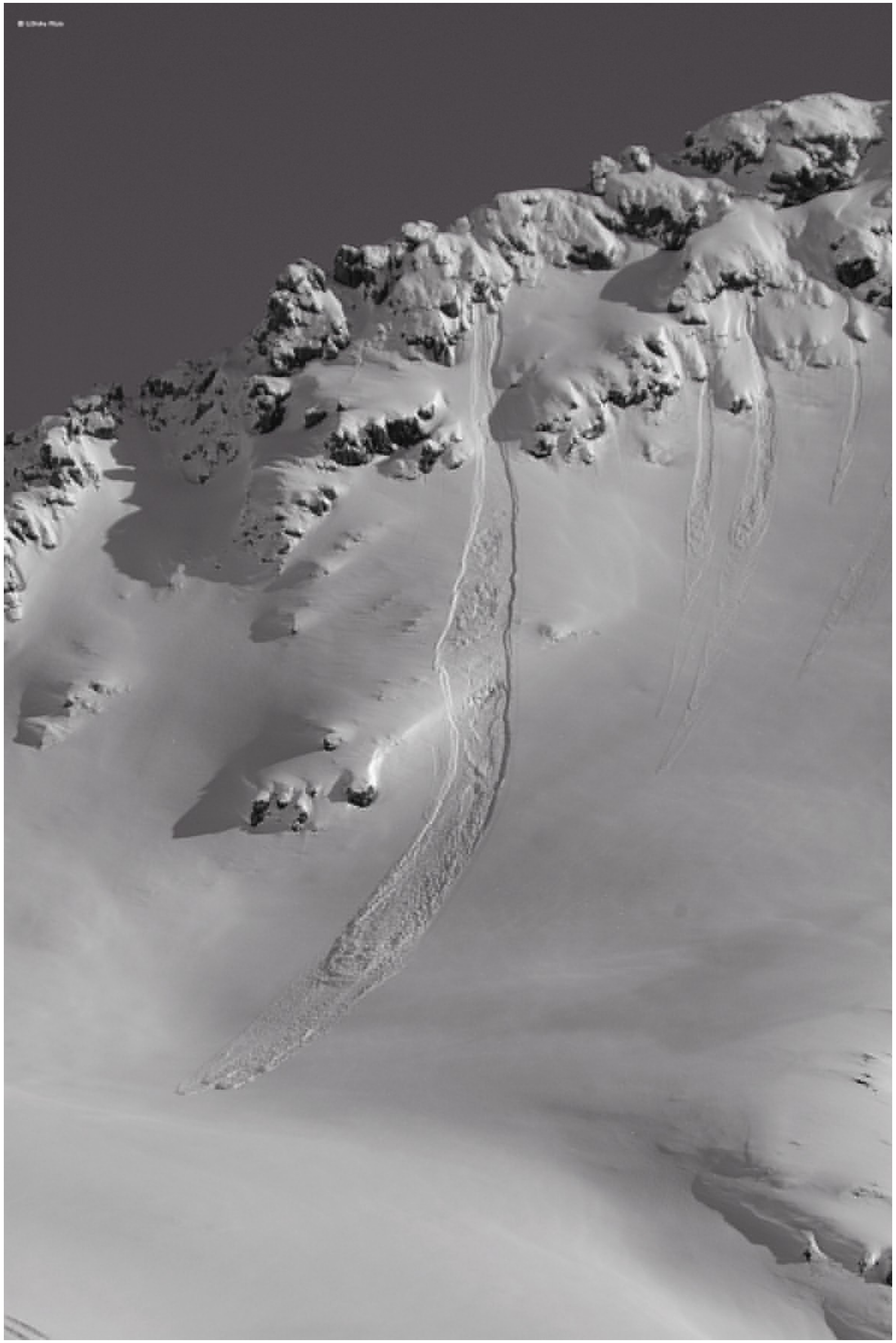
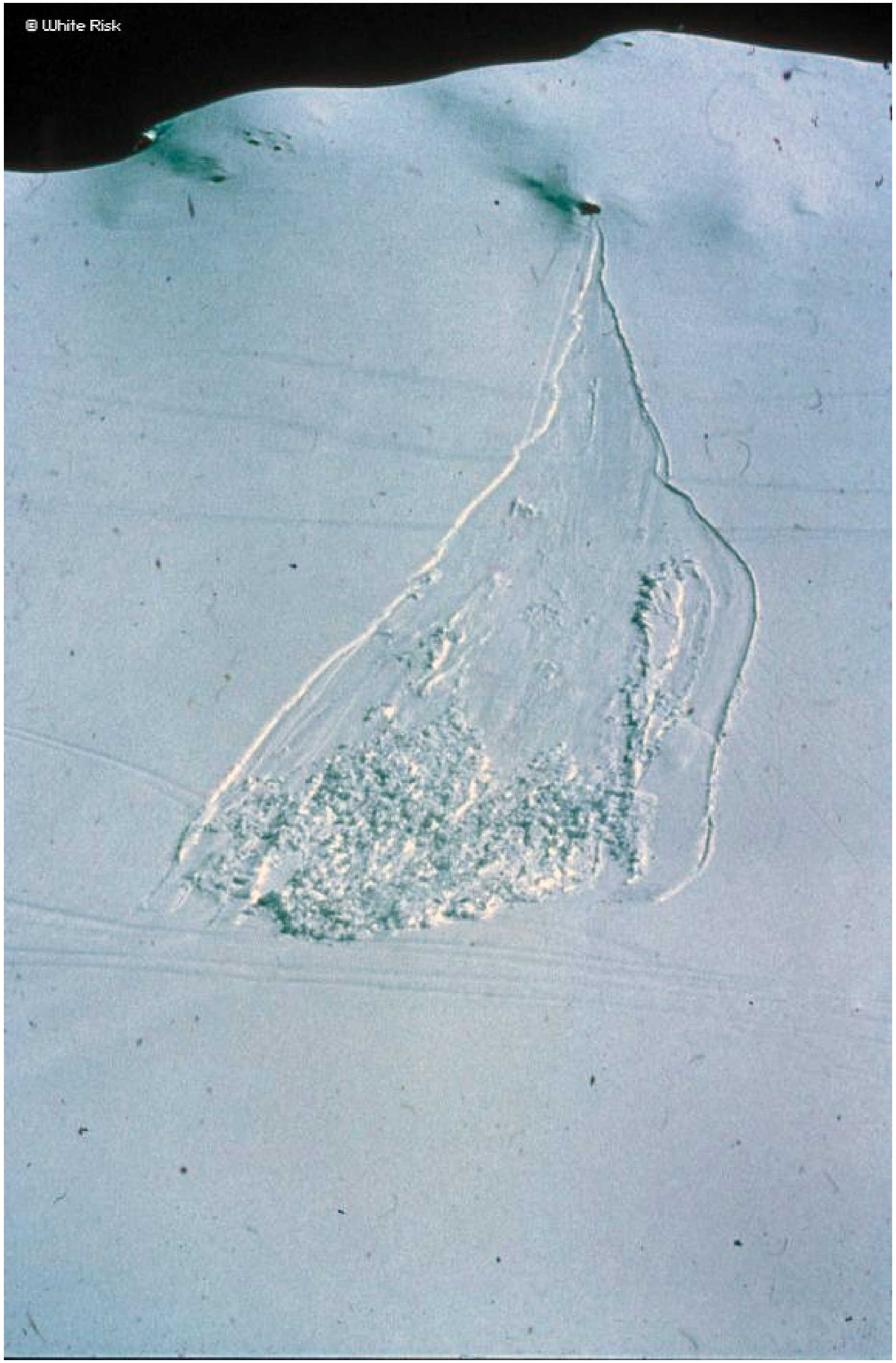
2. Snow metamorphism and avalanche formation
3. More on flow regimes
4. Entrainment and deposition
5. Avalanche classification by release type
6. Multi-phase problems in avalanche science

1. Avalanche classification by release type

- *Point-release or loose-snow avalanches:*

  Occur in early winter or spring, usually small and of restricted practical importance. Not very well studied.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- *Slush avalanches:*

  In water-saturated snowpack on gentle slopes (3–10°), mostly in (sub-)arctic areas or on glaciers. Share some features with slab avalanches. Few dedicated studies exist.

Telemark, East Norway. 28.04.1984

Illhullbekken, Rana, North Norway. 28.04.1994

Fivelstad, Stranda, West Norway. 05.02.1990

Tystigen, western Norway, 2005-06-21

Photo K. Kristensen, NGI


Tystigen, western Norway, 2005-06-21

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2. Avalanche classification by flow regime

- *Sliding wet-snow avalanches:*

  Viscoplastic plug flow sliding on the bed (hard layer in snow pack or soil), possibly lubricated by water film. Slow.

Längenboden near Davos, Switzerland. Photo Thomas Wiesinger, SLF

Dorfberg, Davos, Switzerland

Photo SLF

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  High density, coalescing particles, frictional flow regime. Slow.

Dorfberg, Davos, Switzerland, 2005-03-20. Photo Hansueli Gubler

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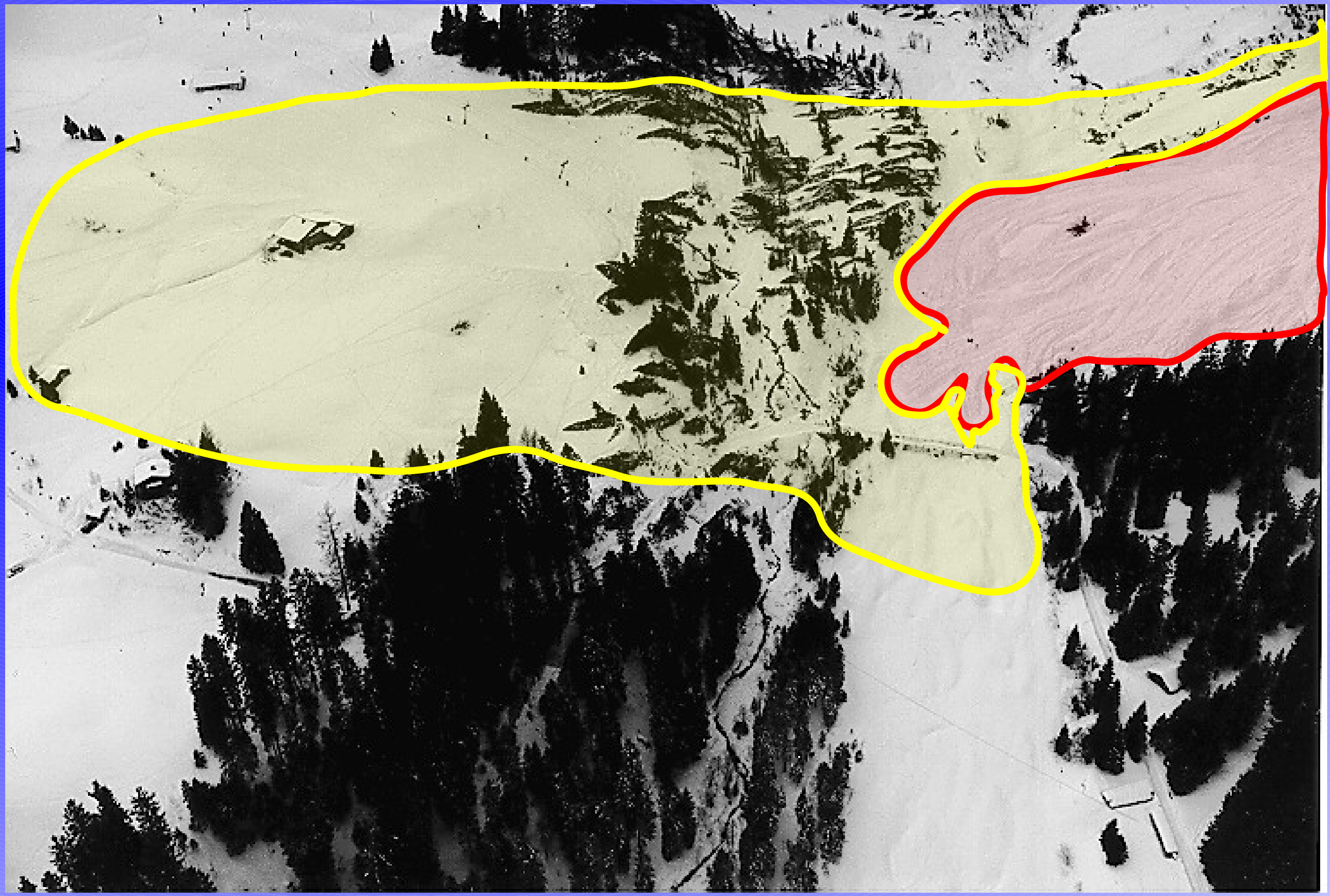
  Medium density, various particle sizes, collisional to inertial flow regime. High velocities.

Example: 1995 Albristhorn avalanche, Switzerland

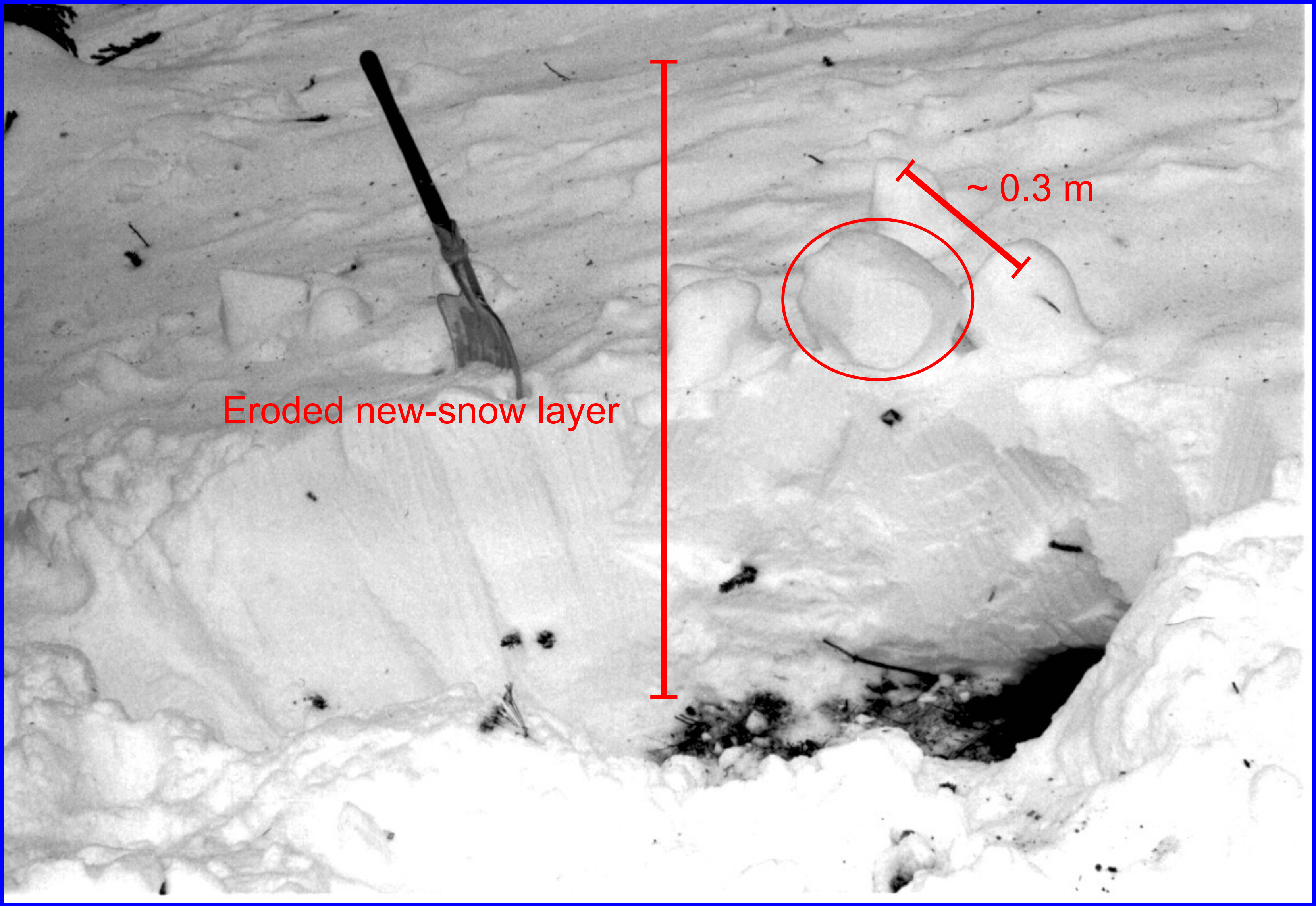
Deposit area of dense flow

Approximate deposit area of fluidized layer

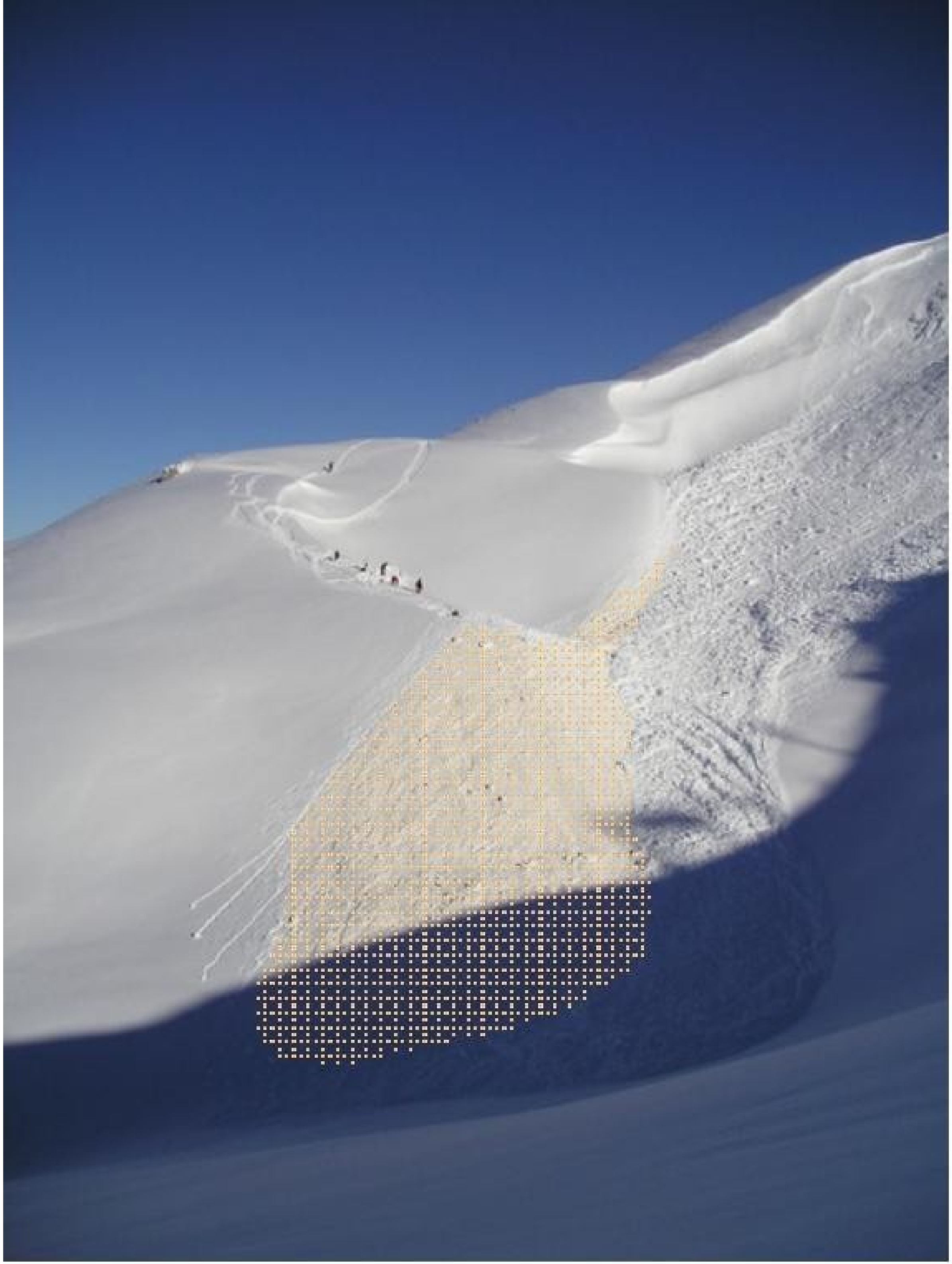
Powder-snow avalanche deposits extend approx. 500 m to the left (uphill).



Separation of fluidized layer from dense flow:



Deposit of a small mixed avalanche, photo taken in a region not reached by dense flow (after sharp bend of gully).



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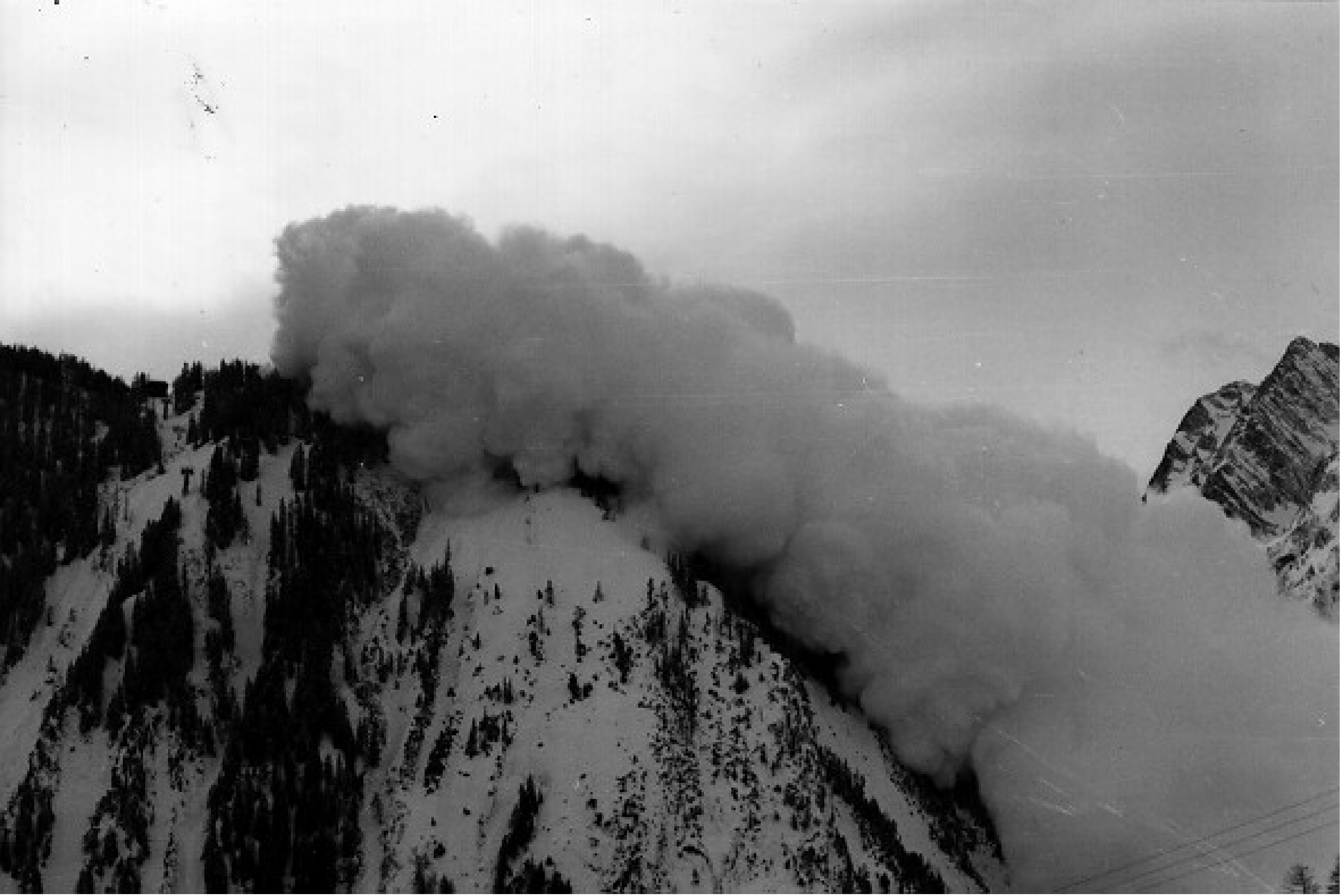
- *Powder snow avalanches:*

  Low density, small particles suspended by turbulence in the air. Particle collisions negligible. Boussinesq or non-Boussinesq.


Foto: G. Kappenberger



3. Snow metamorphism and avalanche formation

Snow crystals

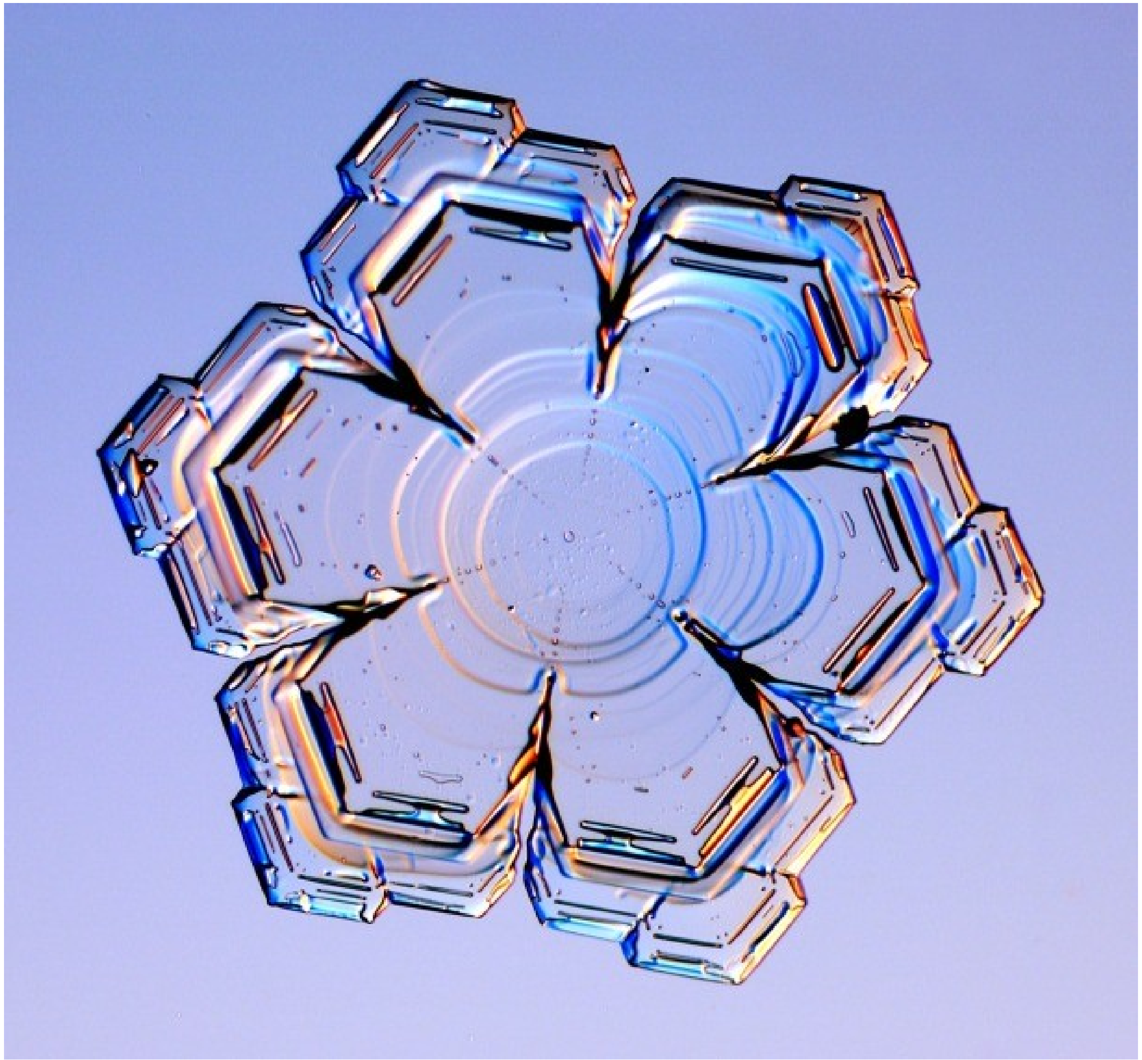
Growth of snow crystals depends sensitively on

- Temperature (at snowflake's location)
- Air humidity
- Vapor diffusion rate (influenced by air density, thus altitude)
- Availability of nucleation seeds
- Permanence time in cloud (scale: minutes to hours)

Large variety of sizes and shapes, based on hexagonal pattern

- Fresh snow often with feathered dendrites
- Have a look at the site http://snowflakebentley.com !

http://www.its.caltech.edu/~atomic/snowcrystals



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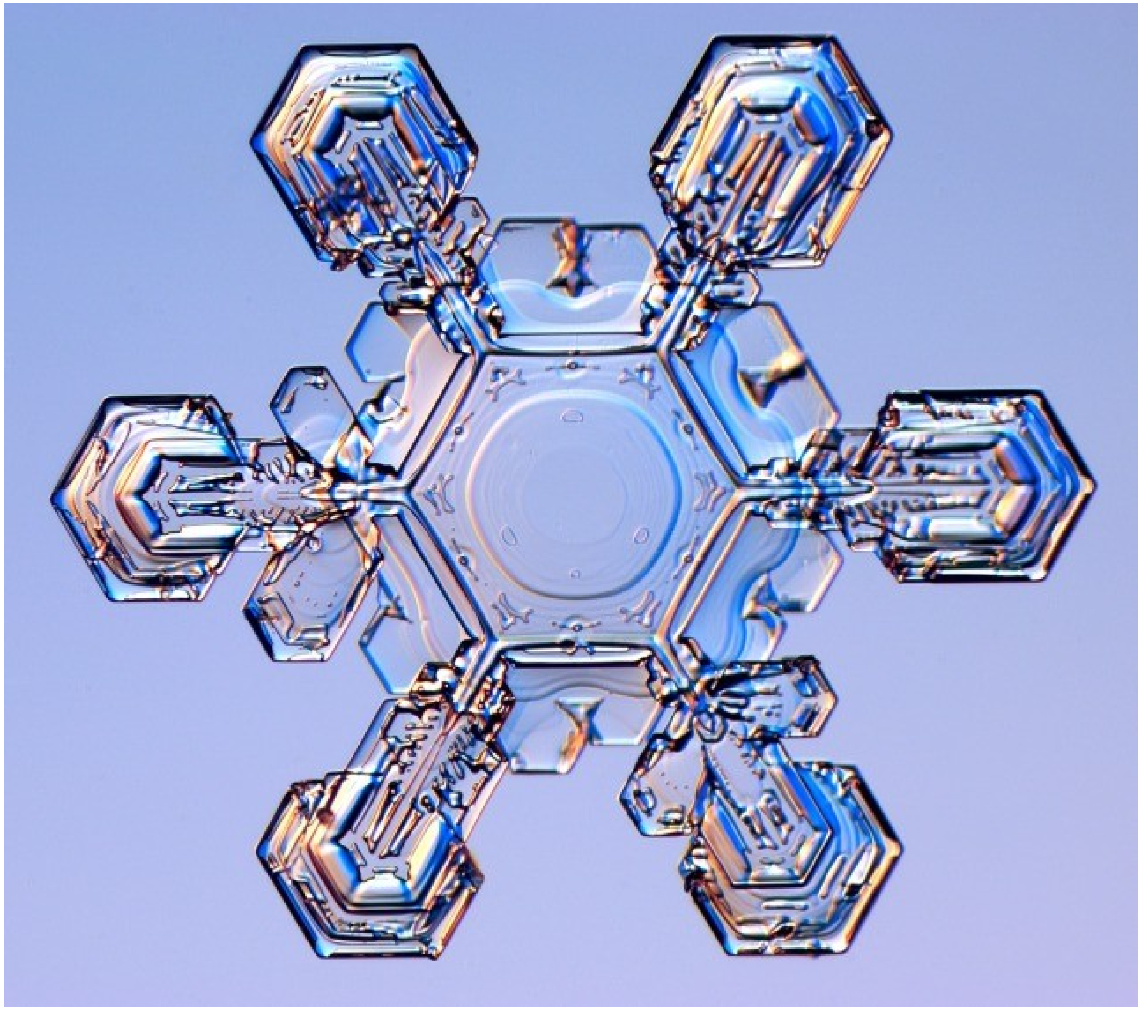

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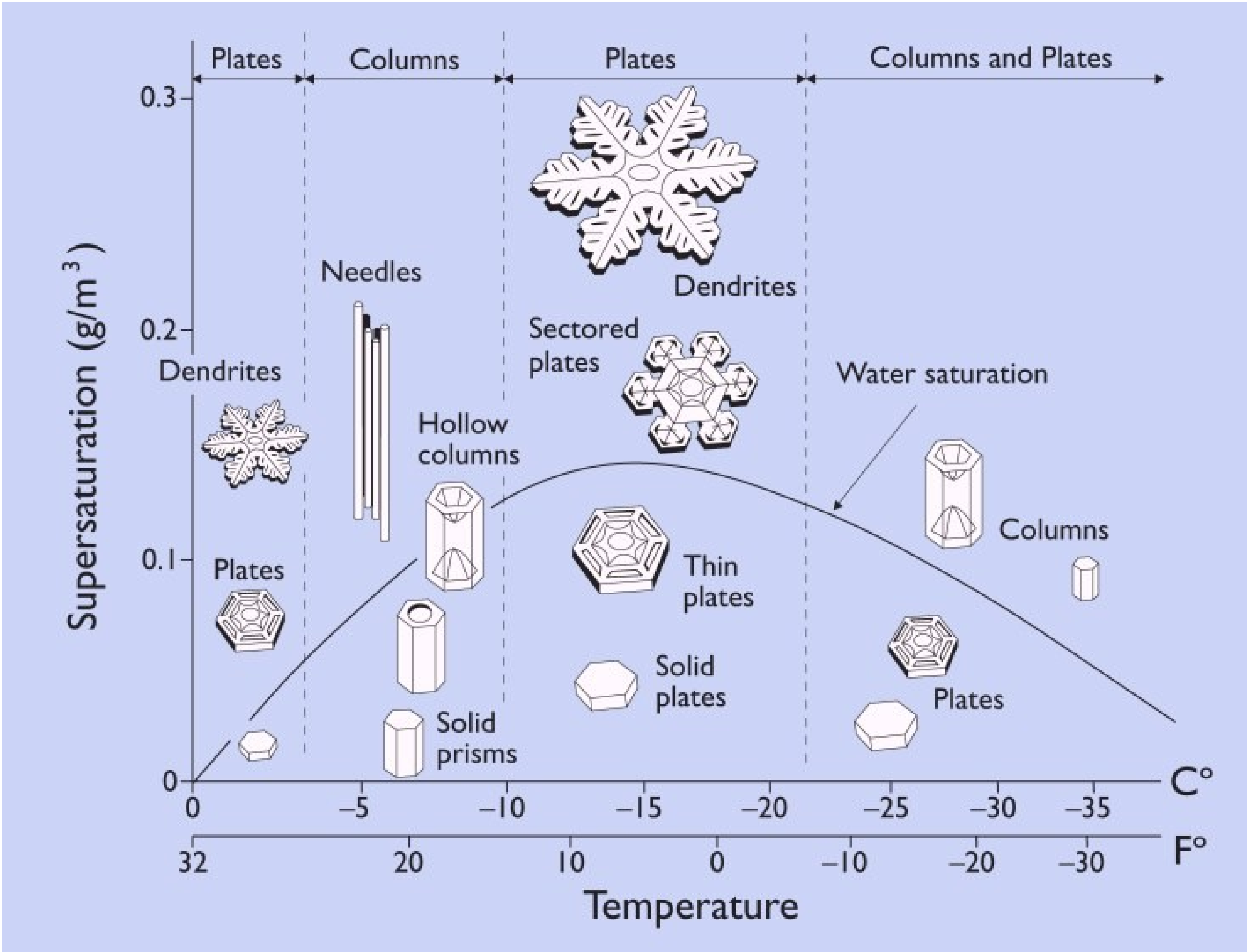

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Snow on the ground: metamorphism

- Transport by wind breaks arms off the dendrites.
- *Vapor diffusion* from convex to concave regions rounds crystals in the course of days to weeks
- Temperature in the snowpack:
  - Ground near 0°C, surface between −30°C (clear night, strong outgoing long-wave radiation) and 0°C (overcast during the day, absorption of long-wave radiation)
  - Temperature gradient typically a few degrees per meter

➔ *Vapor diffusion* from warm to cold, from bottom to top

➔ Constructive metamorphism: faceted crystals, depth-hoar gobelets in the course of weeks

Formation of depth hoar:

- During clear nights: Long-wave radiation cools snow surface far below air temperature

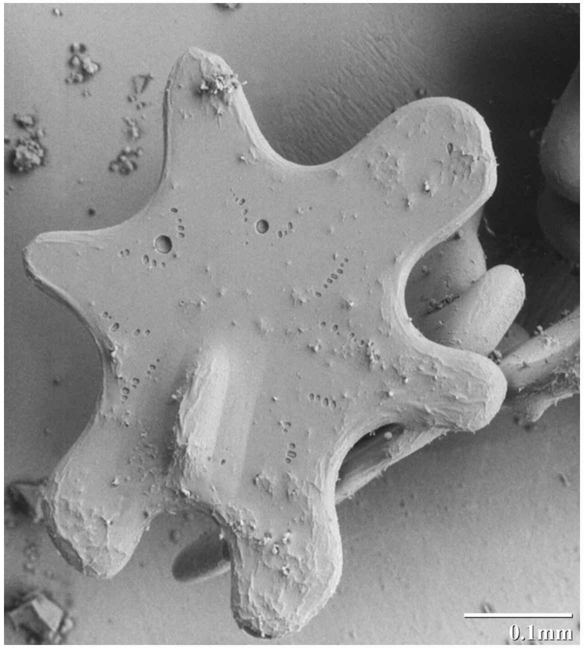
➔ Water vapor from air condenses onto surface of snow crystals

➔ Growth of vertically oriented, feathered surface hoar crystals

➔ Surface hoar forms very-low-density snow layer

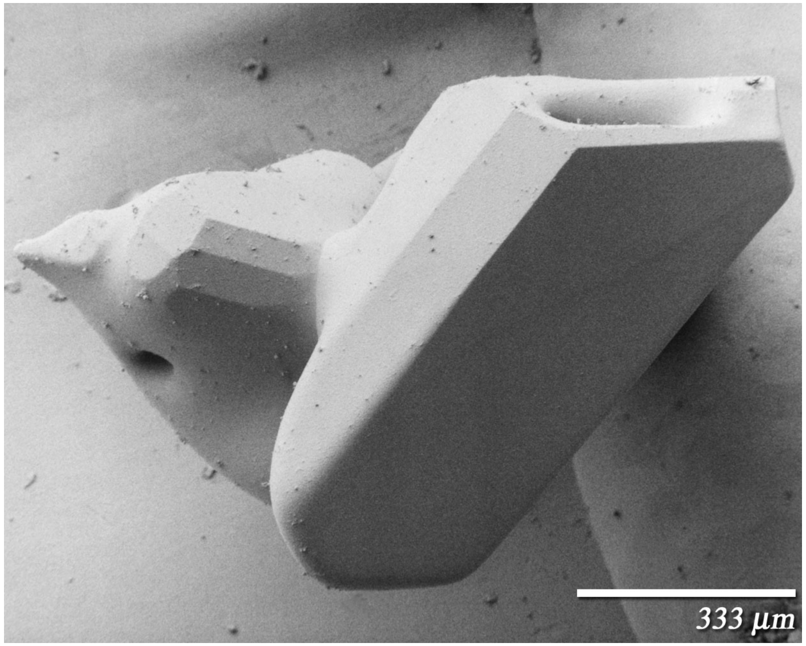
➔ Low mechanical strength against shear,may collapse

➔ Potential failure plane if new snow buries the depth hoar!



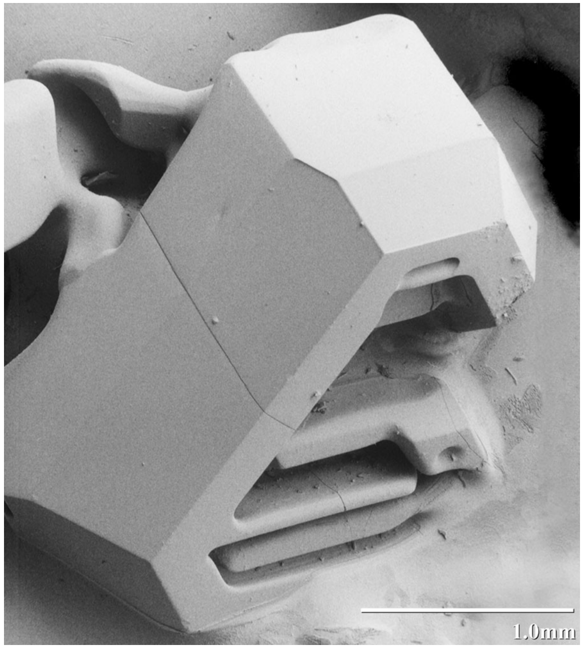
Destructive metamorphism, low temp. gradient: rounded crystal

Contructive metamorphism, moderate temp. gradient: faceted crystal



Constructive metamorphism, strong temp. gradient: goblet (depth hoar)

Melting, no temp. gradient: grain cluster with free water



http://emu.arsusda.gov/snowsite

The layered snowpack

Alpine snowpack consists of dozens of layers from different snowfalls (or different phases during a single snowfall), with different mechanical properties.

- Under overburden weight, slow compression from 50–150 kg/m³ to 300–600 kg/m³
- Strength grows ~ exponentially with density O(0.1–1 kPa) → O(10–100 kPa)

Weak layers or interfaces may be due to

- depth hoar
- buried surface hoar
- poor bonding to thin ice layers (from surface melt and refreezing)

Mechanical properties of snow

Snow is close to water–ice phase transition, thus its mechanical and thermal properties depend strongly on temperature

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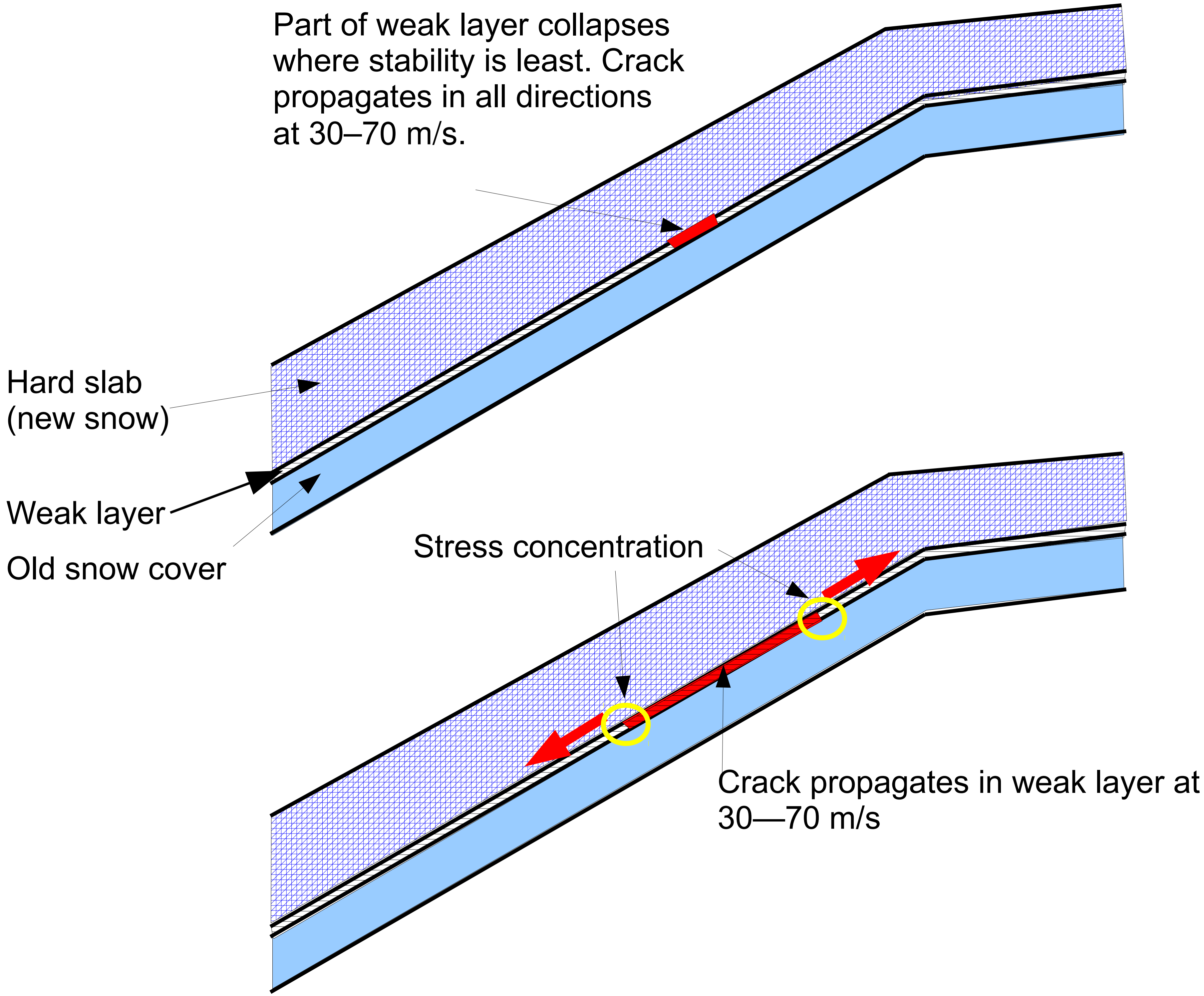
Two main release mechanisms

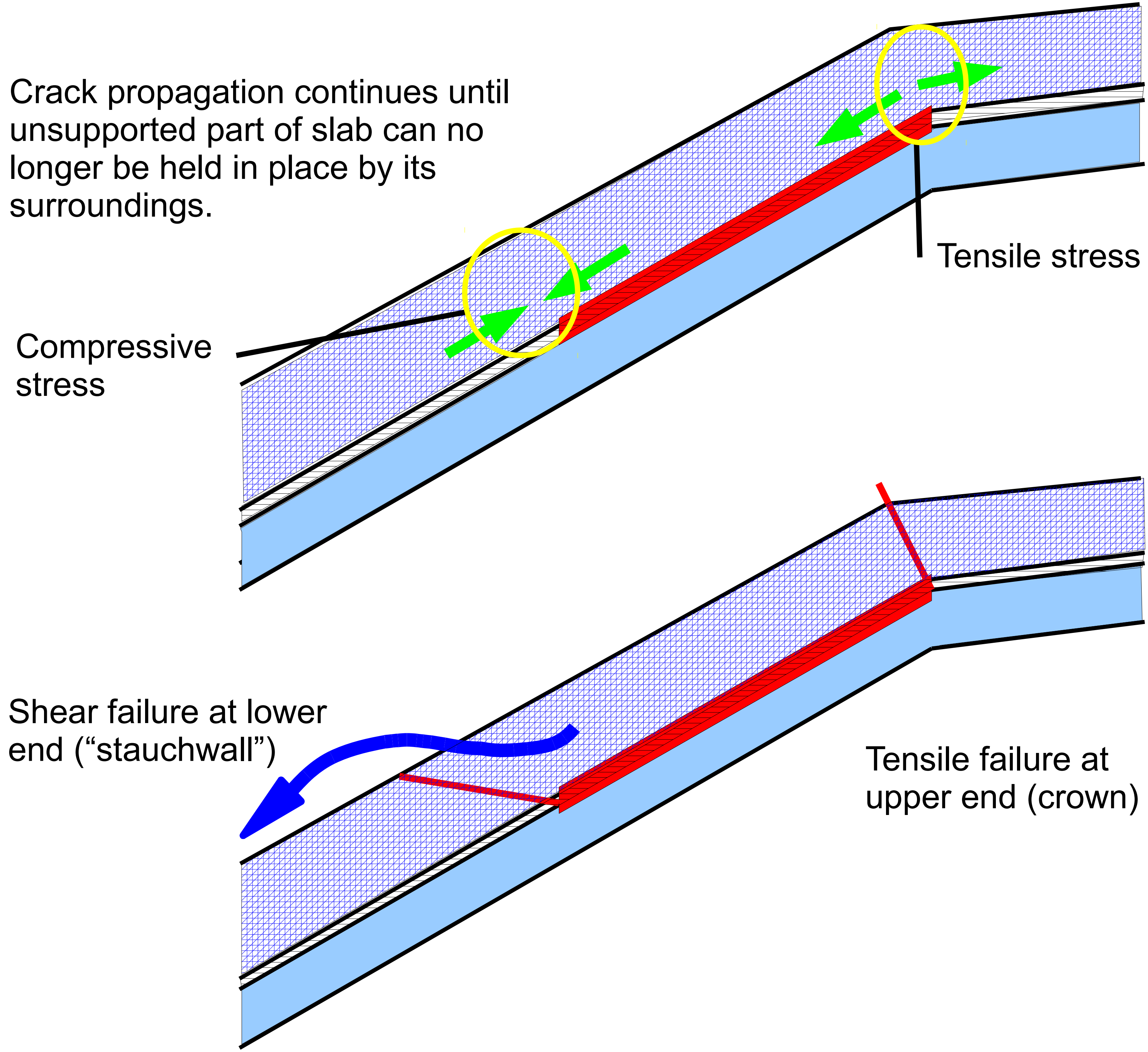
Slab avalanche:

- Major avalanches
- Occurs with relatively strong layer (slab) sitting on a thin weak layer
- Creep concentrated in weak layer → shear thinning!
- Shear failure along weak layer inside snowpack, followed by shear and tensile failure inside the slab
- Rupture surface perpendicular to gliding surface

Loose-snow avalanche:

- Either in early winter (unconsolidated fresh snow) or spring (wet snow losing cohesion)
- Starts from a point, conical shape
- Usually only small events, relatively harmless


Part of weak layer collapses where stability is least. Crack propagates in all directions at 30–70 m/s.
Hard slab (new snow)
Weak layer
Old snow cover
Stress concentration
Crack propagates in weak layer at 30—70 m/s


Crack propagation continues until unsupported part of slab can no longer be held in place by its surroundings.
Tensile stress
Compressive stress
Shear failure at lower end ("stauchwall")
Tensile failure at upper end (crown)


Stauchwall

4. More on flow regimes

Flow regimes correspond closely to those of granular flows:

- Dense flow – grains are in continuous contact
  Density 250–500 kg/m^3
  Speed up to 30–40 m/s
- Fluidized flow – grains collide often but do not have continuous contact
  Density 30–100 kg/m^3
  Speed typically 30–70 m/s
- Suspension flow – grains suspended in air by turbulence ("powder snow avalanche")
  Density 1–10 kg/m^3
  Speed typically 10–100 m/s

The granular view:

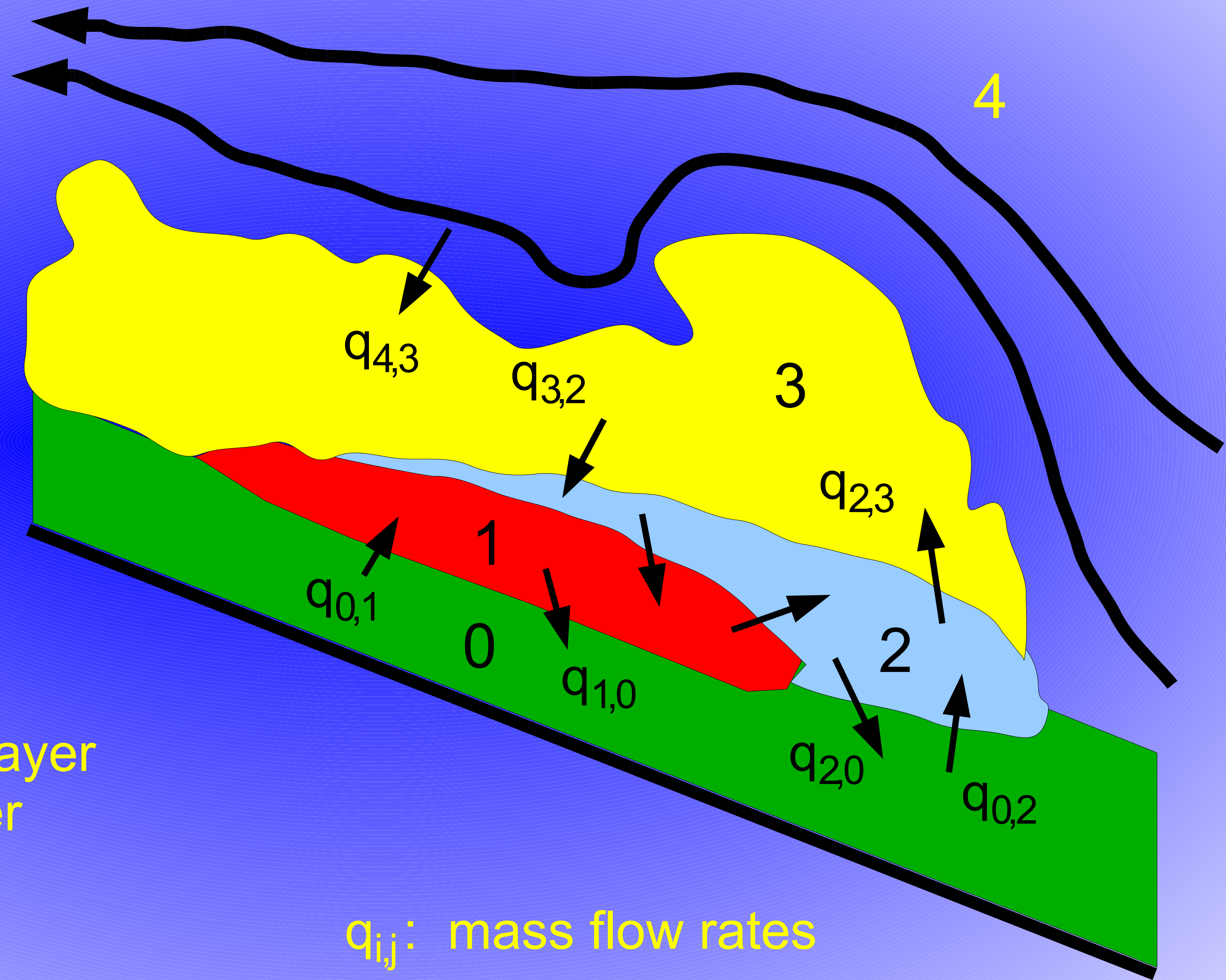
- At macroscopic scale, *frictional* and *collisional* regimes can coexist at same location.

- *Frictional regime:*
  Mean free path → 0, continuous contact between particles, Coulombian friction

- *Collisional regime:*
  Short-duration collisional contacts,
  dispersive pressure ~ (shear rate)^2, but also
  dispersive shear stress ~ (shear rate)^2

- *Fluidization* occurs when and where the dispersive pressure supports the avalanche weight.
  Seems to require slopes with tan θ ~ 1, however!

Present view of avalanche structure



4 ambient air
3 suspension layer
2 fluidized layer
1 dense flow
0 snow cover

$q_{i,j}$: mass flow rates

Remarks concerning the preceding schematic diagram:

- Much of this is the topic of ongoing research in Ryggfonn etc.
- Transitions between layers are probably more continuous than suggested by the schematic.
- Parts of the dense flow (front) fluidize when dispersive pressure from particle collisions and aerodynamic lift exceed the weight of the flowing mass.
- The mass fraction of the fluidized layer varies from 0 to ~ 30%., depending on snow cohesion, avalanche size and travel distance. It may contain rather large particles.
- The suspension layer is probably mostly alimented from the fluidized head. Usually only a small fraction of the total mass.

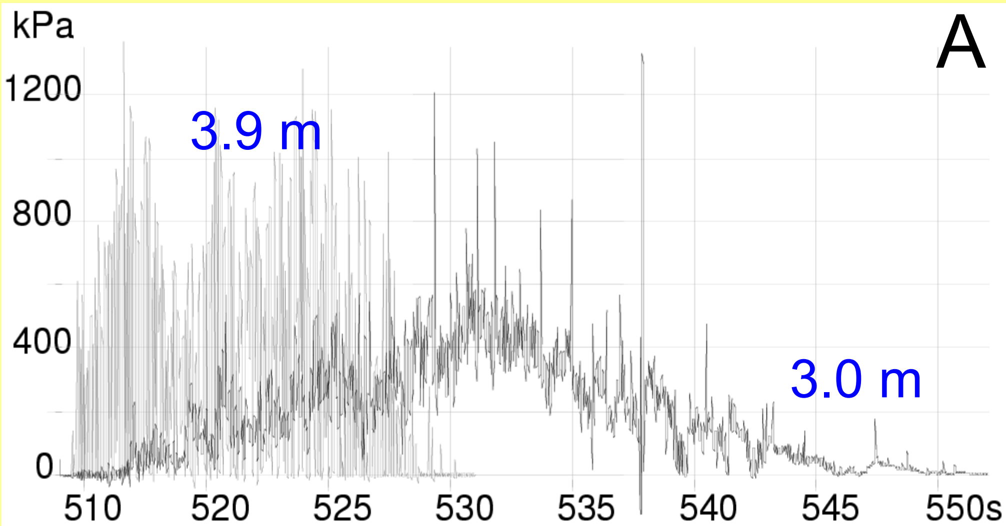
Order-of-magnitude estimates:

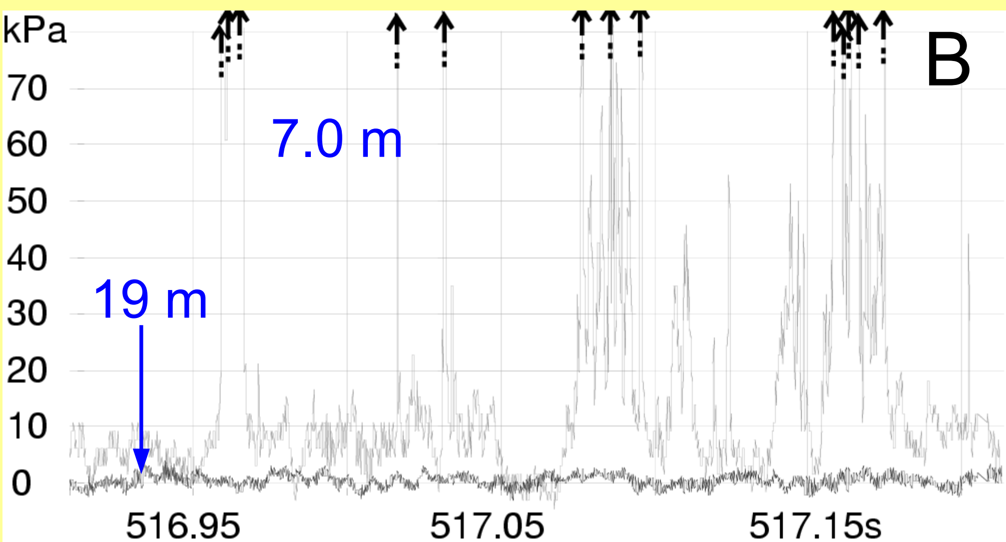
Flow type	*Density* (kg/m^3)	*Concentr.* (—)	*Mean free path* (particle diam.)	*Granular regime*
Dense	100–500	0.1–0.5	0–1	frictional / collisional
Fluidized	10–100	0.01–0.10	1–4	grain-inertial
Suspension	1–10	$< 10^{-2}$	> 4	macro-viscous (turbulent)

Physical properties and transport processes differ substantially between flow types!

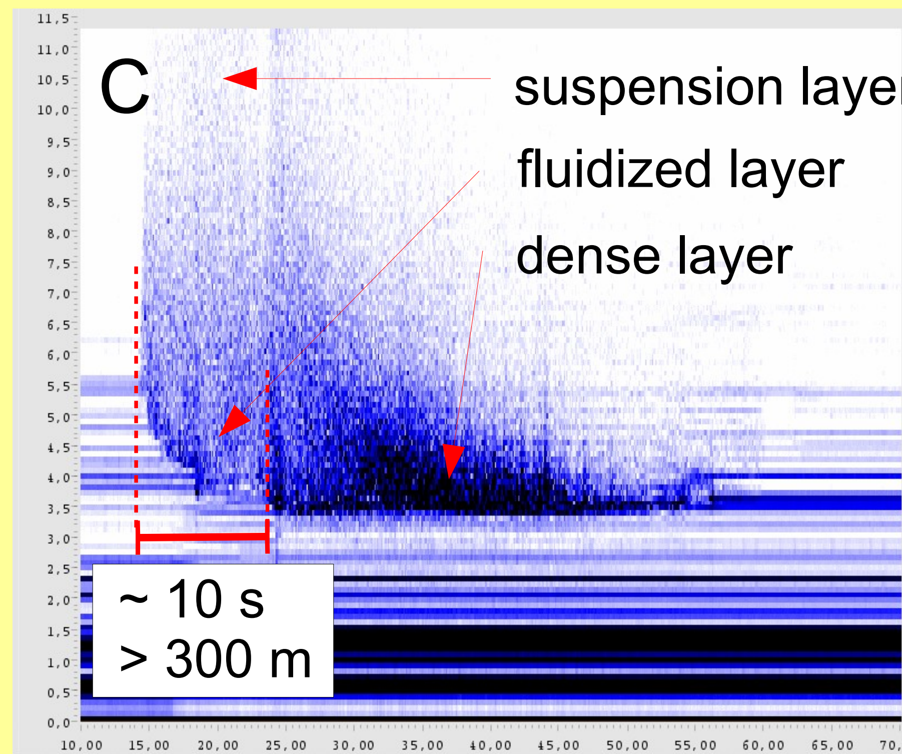
1999 measurements at Vallée de la Sionne

Load cell measurements





FMCW radar profile



(see next page for explanations)

Explanation of the preceding slide (1):

Plots A and B show the pressure time series during the passage of a large mixed dry-snow avalanche.

- At 3 m, very high mean pressures superposed by violent short-term fluctuations.
  ➞ Dense part arrives much later than the front.
- At 3.9 m, some pressure peaks exceed 1 Mpa, but pressure drops to near zero between impacts.
  ➞ Fluidized layer, moderate density, impact of snowballs up to 30 cm at ~ 40–50 m/s.
- At 7 m, intermittent swarms of impacts up to ~100 kPa. Fluidized layer, smaller particles and lower density.
- At 19 m, turbulent eddies O(1kPa) from the suspension layer.
  ➞ Small snow grains, low density, moderate velocity.

Explanation of the preceding slide (2):

Plot C is the time-series of the output of a profiling radar looking upwards from a cavern in the ground. Abscissa – time; ordinate – distance from ground; darkness – strength of echo from the respective distance.

- The echo strength is in agreement with the schematic avalanche structure proposed above.
  Dense part moves much more slowly than fluidized layer.
- Approx. 2 m of snow cover are eroded during the first 10 s, i.e. during the passage of the fluidized head. Erosion rate up to

Snow entrainment is a very important, but poorly understood process in avalanche flow.

Two causes for fluidization to consider:

A) *Purely granular mechanism:*

Dispersive pressure from collisions between particles overcomes normal load.

Conditions:
- ✓ high shear rates,
- ✘ sufficiently elastic collisions
- ? dispersive shear stresses large

B) *Pneumatic mechanism:*

Air flow over avalanche creates stagnation pressure at snout, underpressure on the head.

Conditions:
- ✓ high velocity
- **?** small cohesion in avalanche

Wet-snow avalanches

Sometimes viscoplastic flow, sometimes granular:

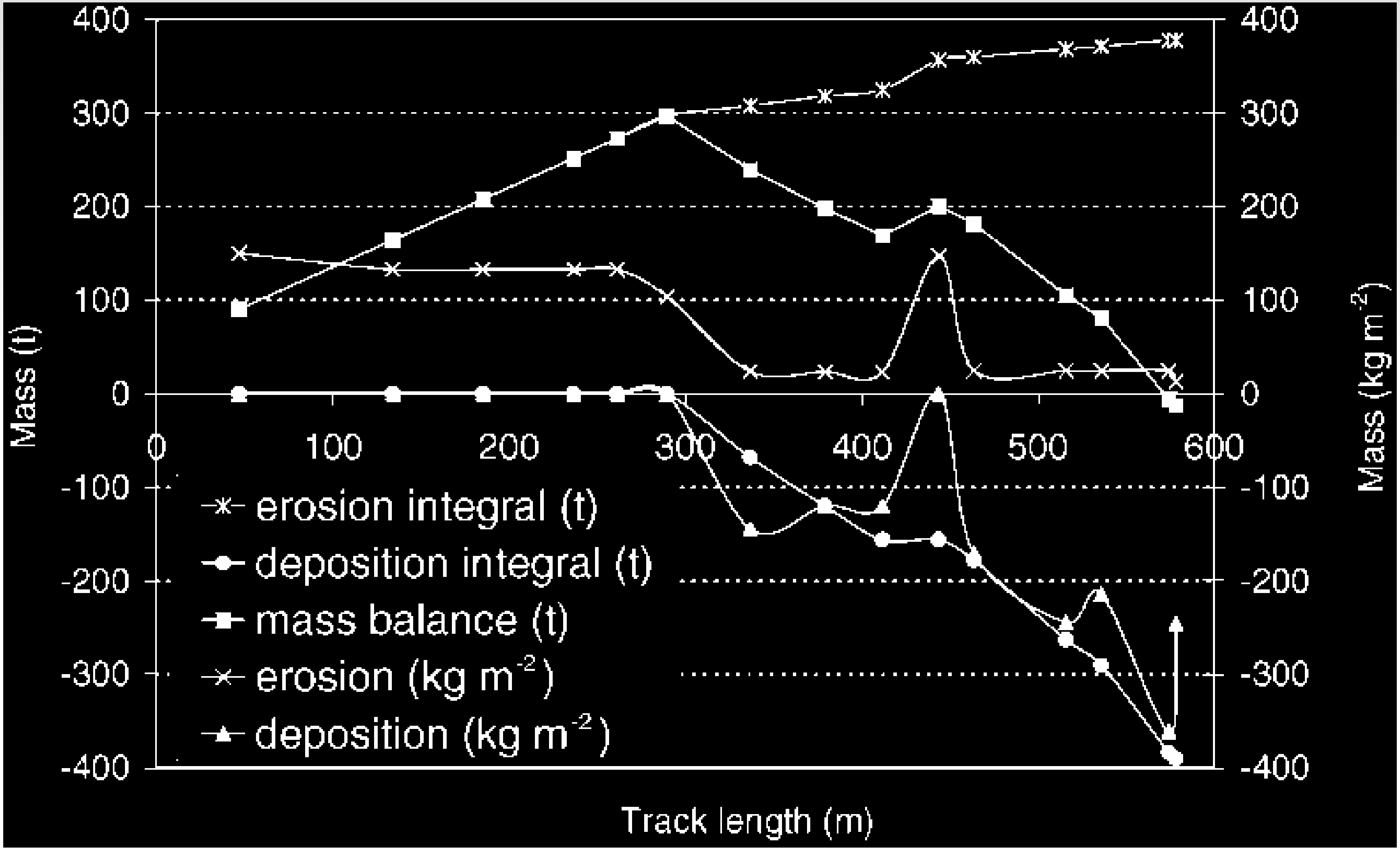
- Dense flow – grains are in continuous contact
  Density 250—500 kg/m^3
  Speed up to 30 m/s
- Lubrication effects due to the presence of liquid water possible → large runout distances despite low velocities
- Impact pressures much higher than stagnation pressure $\frac{1}{2}\rho v^2$ due to cohesion of snow

N.B. Much is still unknown!

5. Entrainment and deposition

- Typical shear strength of fresh snow: $\tau_s = 0.1-1$ kPa,
  Typical grav. traction on avalanche: $\rho g h \sin\theta = 0.5-3$ kPa.
  ⇨ Entrainment of snow cover is rule rather than exception!
- Typical starting zone is 5−30% of path length.
  ⇨ Avalanche mass may increase by large factor!
- Entrainment has a substantial effect on the flow dynamics (flow height, velocity, runout distance, impact pressure).
- Entrainment mechanisms are still poorly understood and crudely modeled (or neglected) in most models.

Spatial mass balance in a snow avalanche (measured at Monte Pizzac test site, Italy, in 1998)

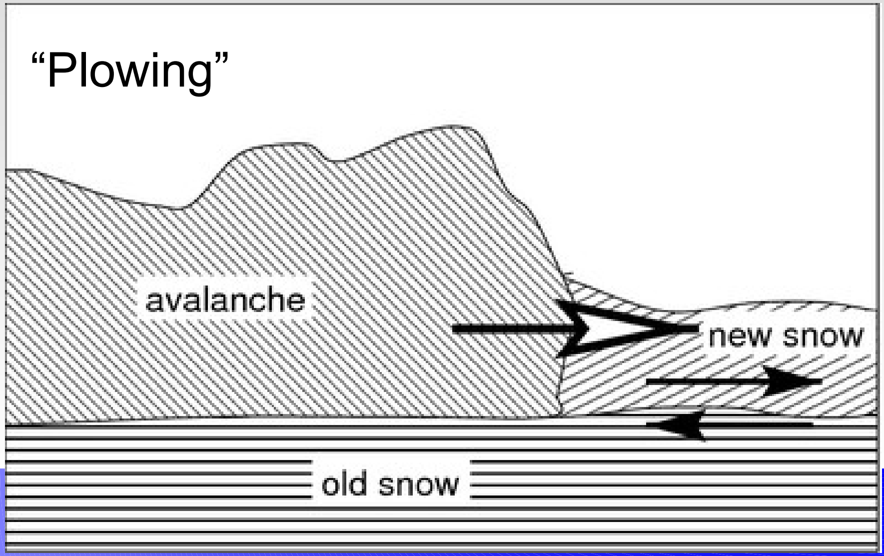


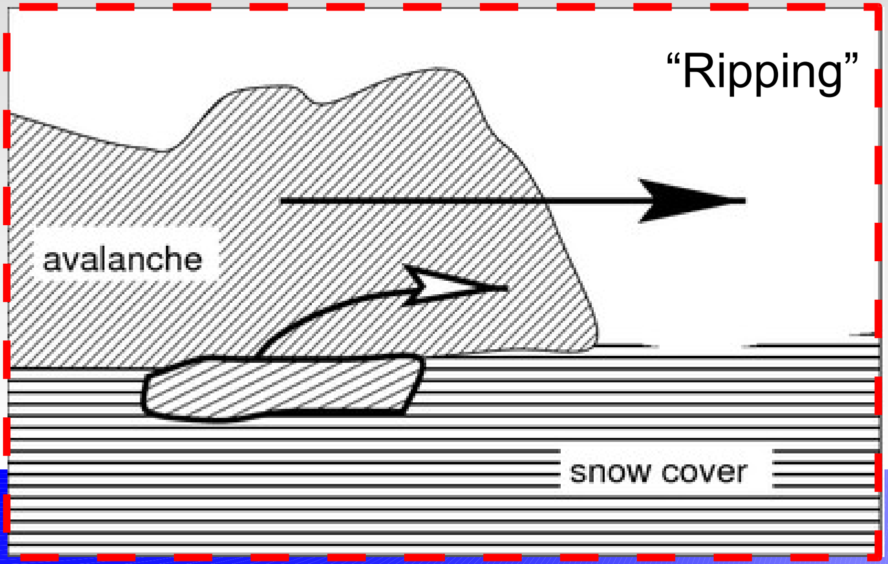
From Sovilla et al., Annals Glaciol. 32 (2001), 230–236.

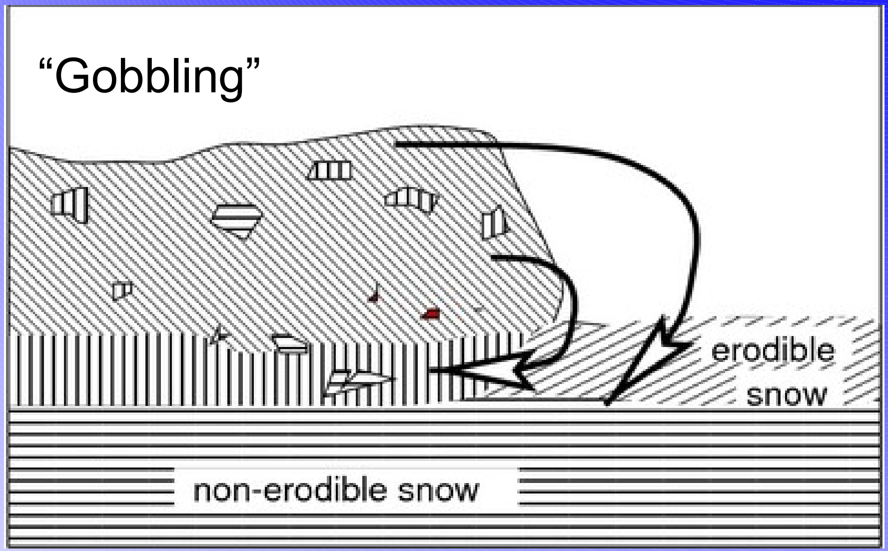
Erosion mechanisms in GMFs

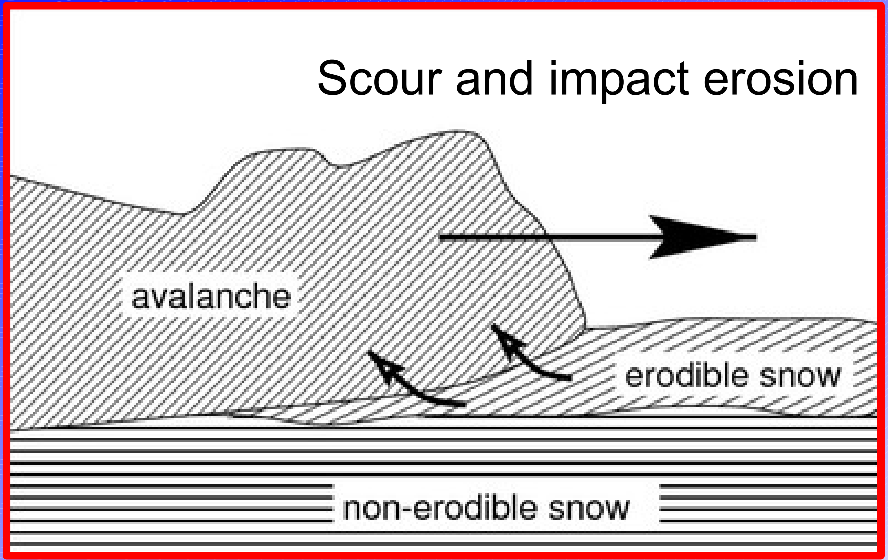
Frontal mechanisms

Mechanisms acting along bottom









Gobbling:

- No experimental evidence so far. Disregard it in the following.

Ripping:

- Experimental evidence in dry-snow avalanches from ground-radar measurements.
- Seems to occur in strongly stratified beds if there is a weak layer underneath a strong layer.
- Can be approximated by continuous entrainment along bottom with sufficient averaging over bottom area and time.

Scour (abrasion) and impact erosion:

- Experimental evidence strong.
- Can be treated by model for continuous entrainment along bottom.

Impact traces

Ryggfonn 04/06/2003

$\rho_s \approx 120$ kg m^{-3}

Abrasion traces

The plowing mechanism:

- Clearly dominant in wet-snow avalanches.
- Possibly important in dry-snow avalanches as well, but clear experimental confirmation is still lacking.
- Open question for debris flows and pyroclastic flows.
- Likely condition for plowing to be possible: Flowing material must have higher strength than bed and sufficient weight.
- In laboratory granular flows, length of plowing zone = *O*(flow height).

6. Multi-phase problems in avalanche science

- *Snow pack models:*
  Ice, water, vapor, air: Flow and phase transitions, modification of grain shapes and sizes, evolution of mechanical strength.

- *Pneumatic erosion of snow cover at avalanche front / Aerodynamic effects in fluidization:*
  Rapid air flow in a porous medium, forces on solid particles.

- *Slush avalanches and lubrication in wet-snow avalanches:*
  Water in snow matrix, evolution of excess pore pressure, mass balance including melting. (Similar problems as in debris flows.)

- *Powder-snow avalanches:*
  Particles suspended in turbulent flow, sedimentation and erosion, modification of turbulence. (Similarity with turbidity currents and pyroclastic suspension flows.)