# GLACIAL HAZARDS

## UNIT-7

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**Glaciers and ice sheets both affect and are affected by changes in Earth's climate. They are frozen fresh-water reservoirs that change volume in response to changes in temperature and snowfall. Were the ice sheets in Greenland and Antarctica to melt entirely, global sea level would rise about 75 meters (250 feet).**

**Glacial hazards frequently affect populated high mountain regions. Hundreds or even thousands of lives can be lost in catastrophes related to glaciers. Annual economic loss is estimated to be in the order of 100 mill. EUR worldwide.**

**Glacial hazards represent a major risk to life and property in densely populated high mountain areas such as the European Alps. In this context, risk is defined by a hazard and a damage potential component.**

**Long-term atmospheric warming since the end of the Little Ice Age with an ongoing trend (1) and increasing human settlement of mountain areas (2) are two important components which govern the risk posed by glaciers.**

## *The impact of climate change*.

**The glacial and periglacial environment is very sensitive to atmospheric warming, and thus quickly affected by melt conditions, as evidenced in the strong retreat of mountain glaciers**

**The 2001 IPCC report, mountain glaciers retreats were declared among the best natural indicators of atmospheric warming (IPCC, 2001)**

**Significant glacier recession can influence the development of related hazards**

**For example, potentially unstable glacial lakes often form in glacier forefields dammed by frontal moraines (Evans and Clague, 1994).**

**UNESCO recently issued a strong warning regarding lake outburst hazards in the Himalayas**

**Steep slopes of unconsolidated debris no longer covered by glaciers are a potential cause of debris flows (Zimmermann and Haeberli, 1992)**

## The influence of human activity on damage potential

**In the last few decades, human settlements and activities have greatly increased in high mountain regions such as the Himalayas, European Alps, etc.**

**Infrastructure has been expanded into areas which had not been developed previously. Hence, there was a parallel increase in damage potential and vulnerability of mountain communities**

# Glacial Hazards

- Glacier floods
- Ice avalanches
- Glacier advance and retreat
- Periglacial debris flows
- Rockfall
- Glacier-clad volcanoes
- Process interactions

# Glacier floods

**Generally, glacier floods represent the largest and most extensive glacial hazard, i.e., the hazard with the highest potential for disaster and damage**

**A GLOF (Glacier Lake Outburst Floods, GLOF) is characterized by a sudden release of a huge amount of lake water that rushes along the stream channel downstream in the form of dangerous flood waves.**

**These floods waves comprise of water mixed with morainic materials and cause devastating consequences for riparian communities, hydropower stations and other infrastructure.**

**The severity of flood wave depends upon the amount of water released, debris load and on basin characteristics of the watershed. Discharge rates of such floods are typically several thousand cubic meters per second.**

# Glacier floods

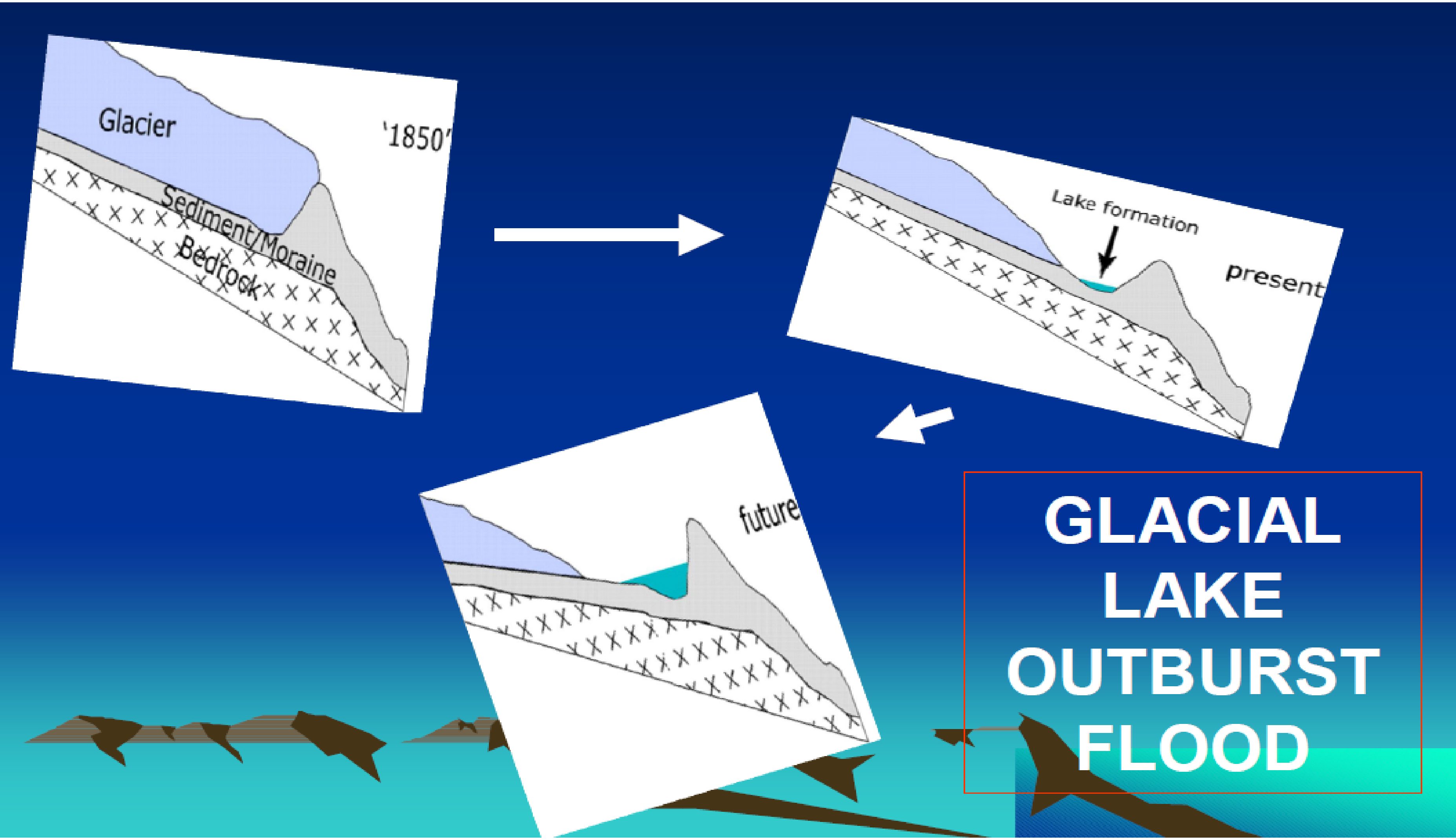
Glacier floods (in the Himalayas often termed Glacier Lake Outburst Floods, GLOF) occur in most glacierized mountains of the world

Glacier floods are triggered by the outburst of water reservoirs in, on, underneath and at the margin of glaciers (Haeberli, 1992).

Ice dams, particularly when formed by ice avalanche deposits or by the fractured ice of surging glaciers, can also fail through a sudden break producing very high peak discharges

Outbursts from moraine-dammed lakes can be triggered by overtopping, piping, slippage on steep slopes or a combination thereof, potentially initiated by an ice/snow jam

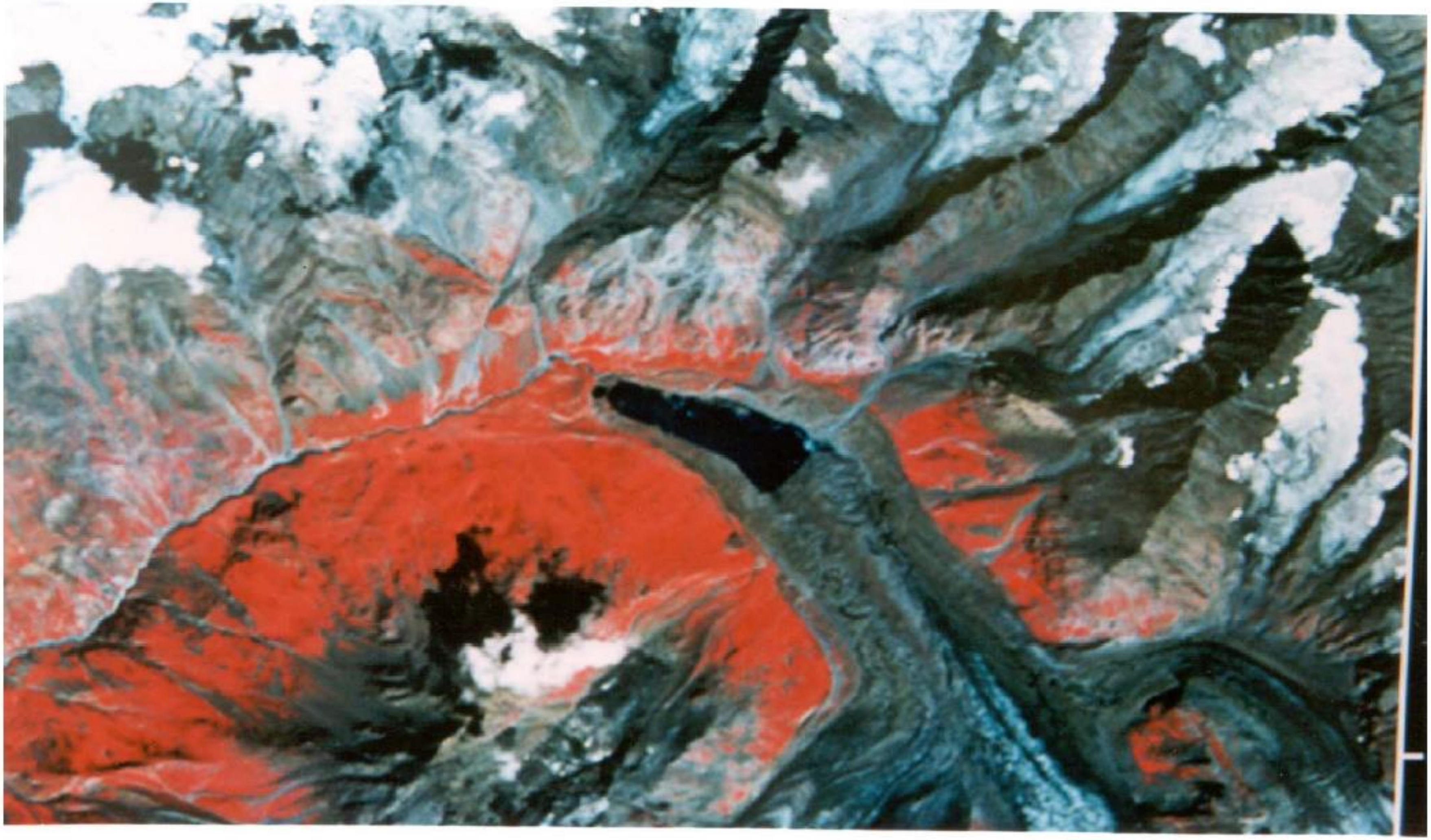
Bedrock-dammed lakes are commonly considered as safe from failure. However, impact waves from mass movements (e.g., ice avalanches, debris flows, rockfalls) can cause dam overtopping which then may trigger a flood or debris flow


Glacier
'1850'
Sediment/Moraine
Bedrock
Lake formation
present
future
GLACIAL
LAKE
OUTBURST
FLOOD

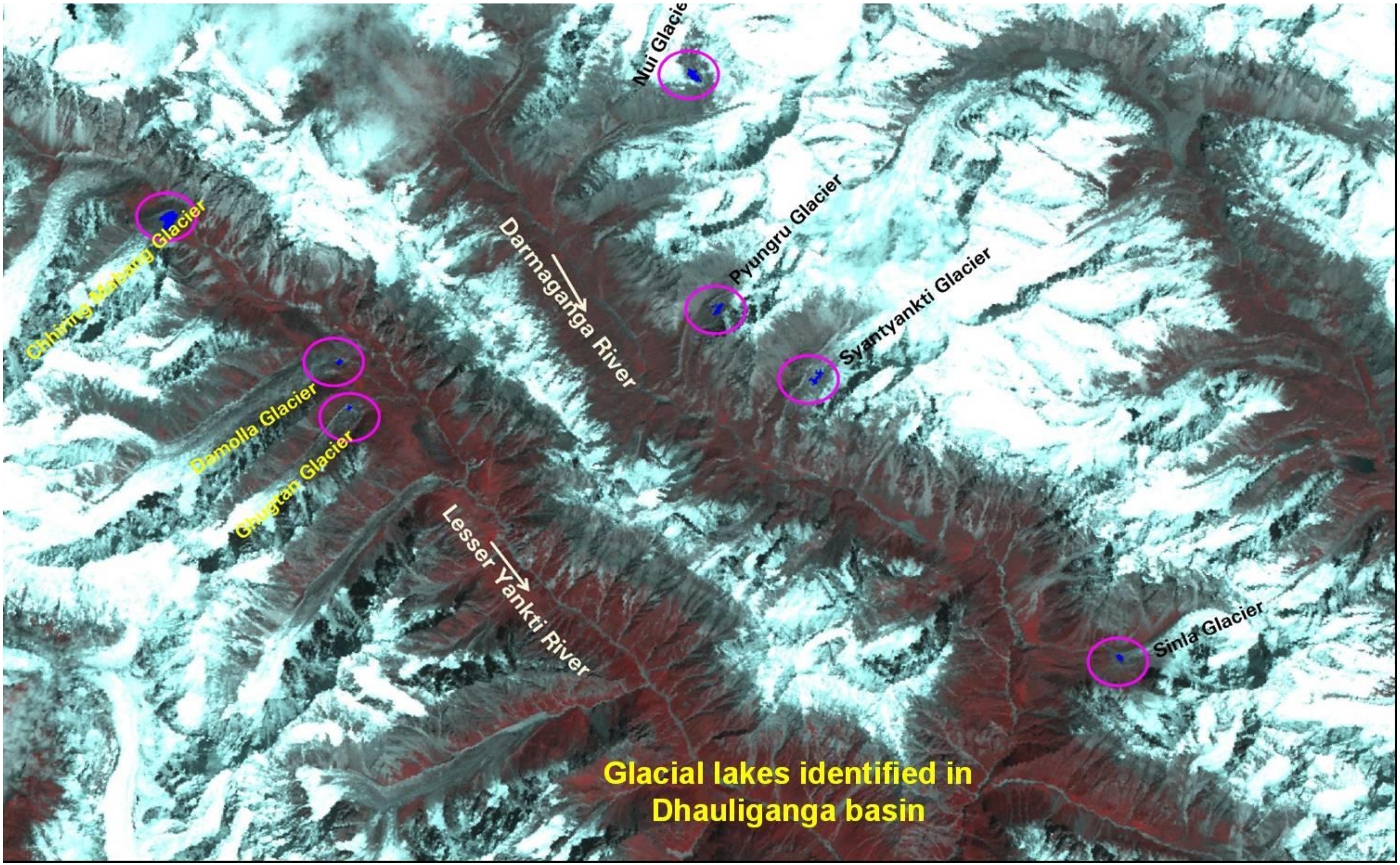
A **supraglacial lake** is any pond of liquid water on the top of a glacier. Although these pools are ephemeral, they may reach kilometers in diameter and be several meters deep. They may last for months or even decades at a time, but can empty in the course of hours.

Fig. 2: Belvedere glacier, Monte Rosa massif (Italy), with supraglacial 'Lago Effimero' on June 11, 2003, with a volume of ca. 2.5 mill. $m^3$ of water, a few days before the subglacial outburst. Note the avalanche deposits at the lower right end of the photo, and the elevated ice surface in relation to the lateral moraines (photo: M. Chiarle).

**supraglacial lake**



SATELLITE VIEW OF MORAINE DAMMED LAKE NEAR THE SNOUT OF GEEPANG GATH GLACIER IN THE CHANDRA RIVER BASIN,HIMACHAL PRADESH



Nui Glacier
Chhiring Mabang Glacier
Darmaganga River
Pyungru Glacier
Syantyankti Glacier
Damolla Glacier
Ghugtan Glacier
Lesser Yankti River
Sinla Glacier
Glacial lakes identified in Dhauliganga basin

# Impact of GLOFs

The impact of GLOF events downstream can be evastating in terms of damage to roads, bridges, hydro-power plants, trekking trails, villages, agricultural land, natural vegetation, as well as the loss of lives, property and infrastructure.

Much of the damage created during GLOF events is associated with the large amounts of debris that accompany the floodwaters.

Damage to settlements and farmland can take place at great distances from the outburst source.

## Ice avalanches

**They are flows which move under the influence of gravity**

**They can be channelized or unconfined**

**In this sense, they are similar to pyroclastic flows, debris flows, etc**

**Direct effects:**
- **impact**
- **burial**

**Indirect effects:**
- **tsunamis generated if an avalanche enters a lake**

# Avalanche zones

a) <u>Starting zone:</u> where an avalanche is initiated

b) <u>Avalanche track :</u> where it goes

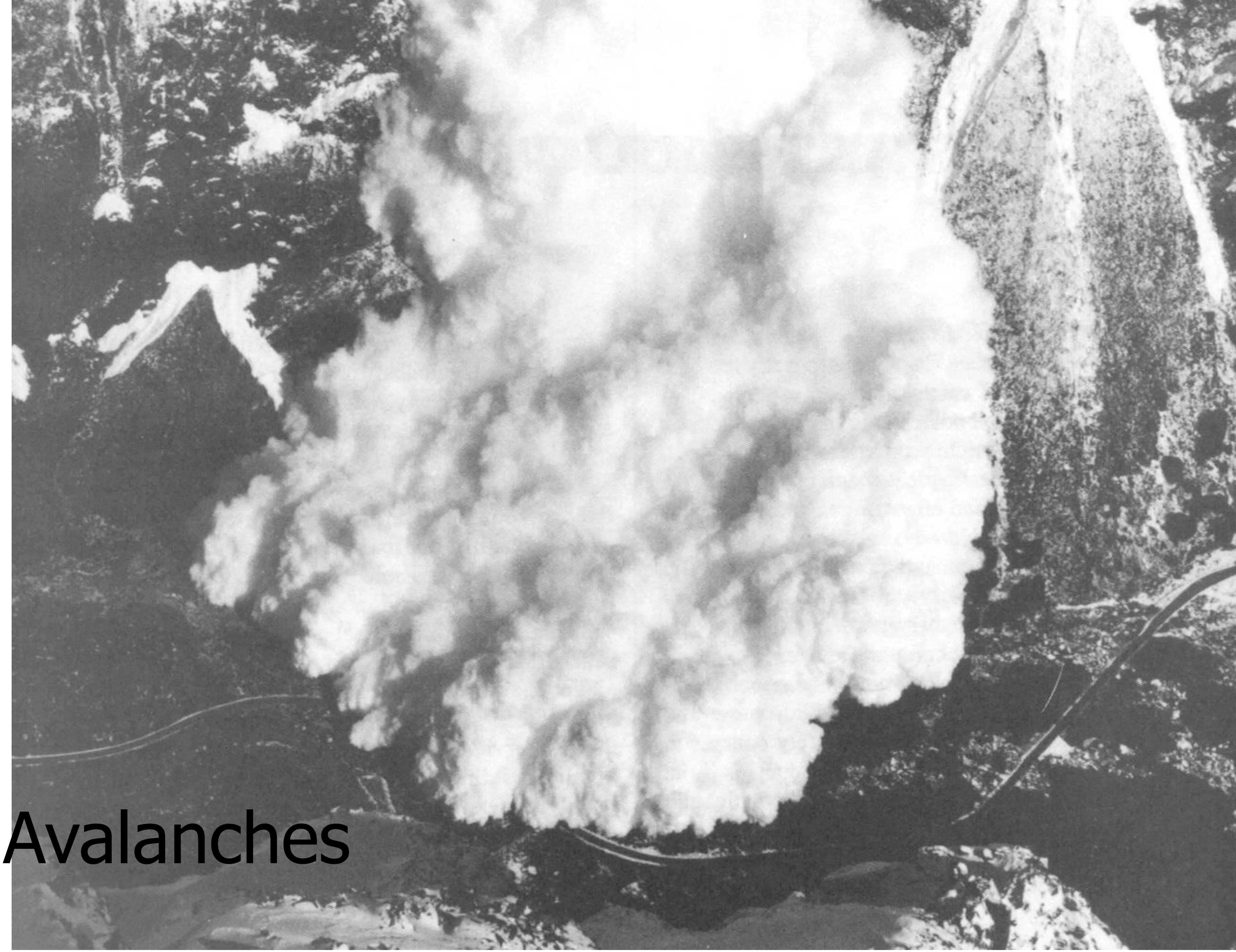
c) <u>Runout area:</u> where it dissipates

Fs = Safety Factor

Fs = (shear strength)/(shear stress)

<u>shear strength:</u> internal resistance to movement
<u>shear stress:</u> force causing movement parallel to slope; increases with slope angle

If Fs is less than 1, then the slope is unstable and prone to failure



# Avalanches

# Layering of snow

# Two weak layers within a slab

# Initial failure - two types

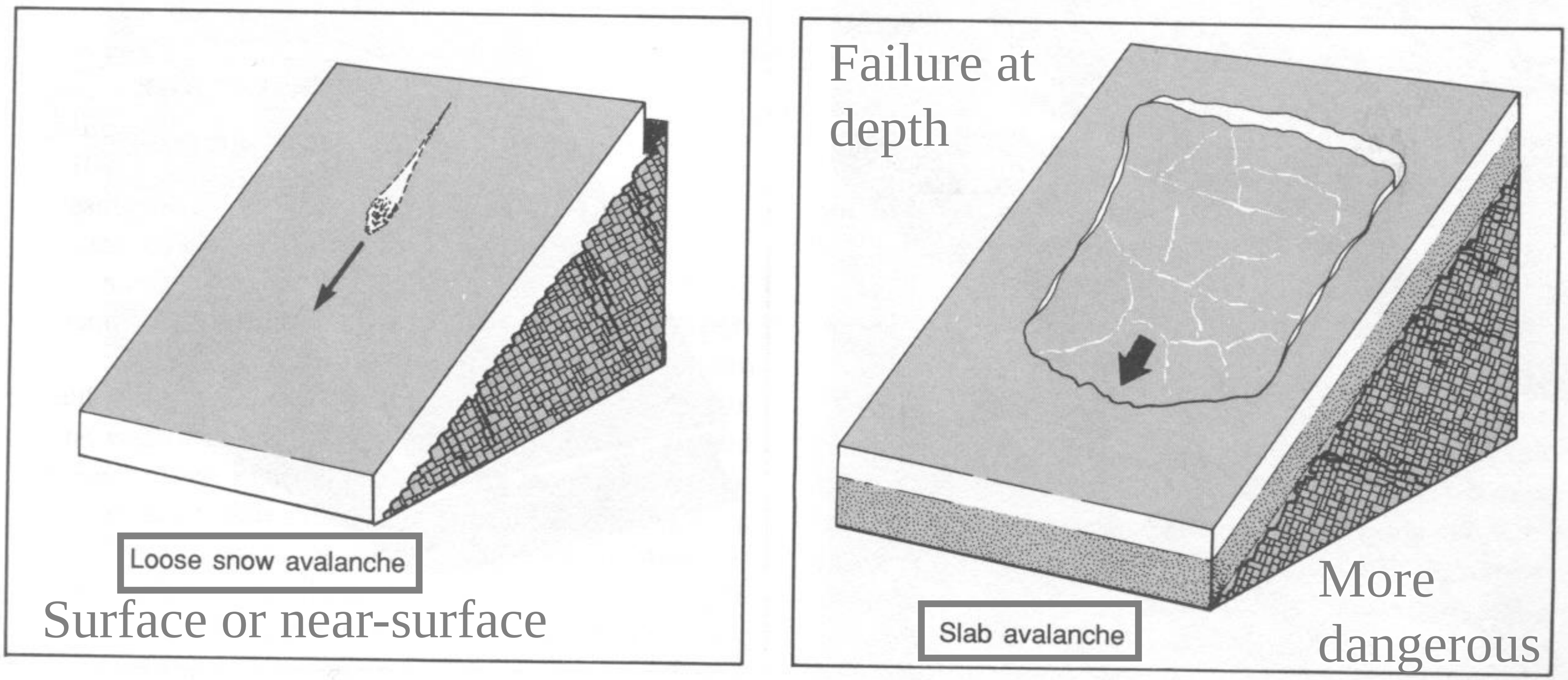
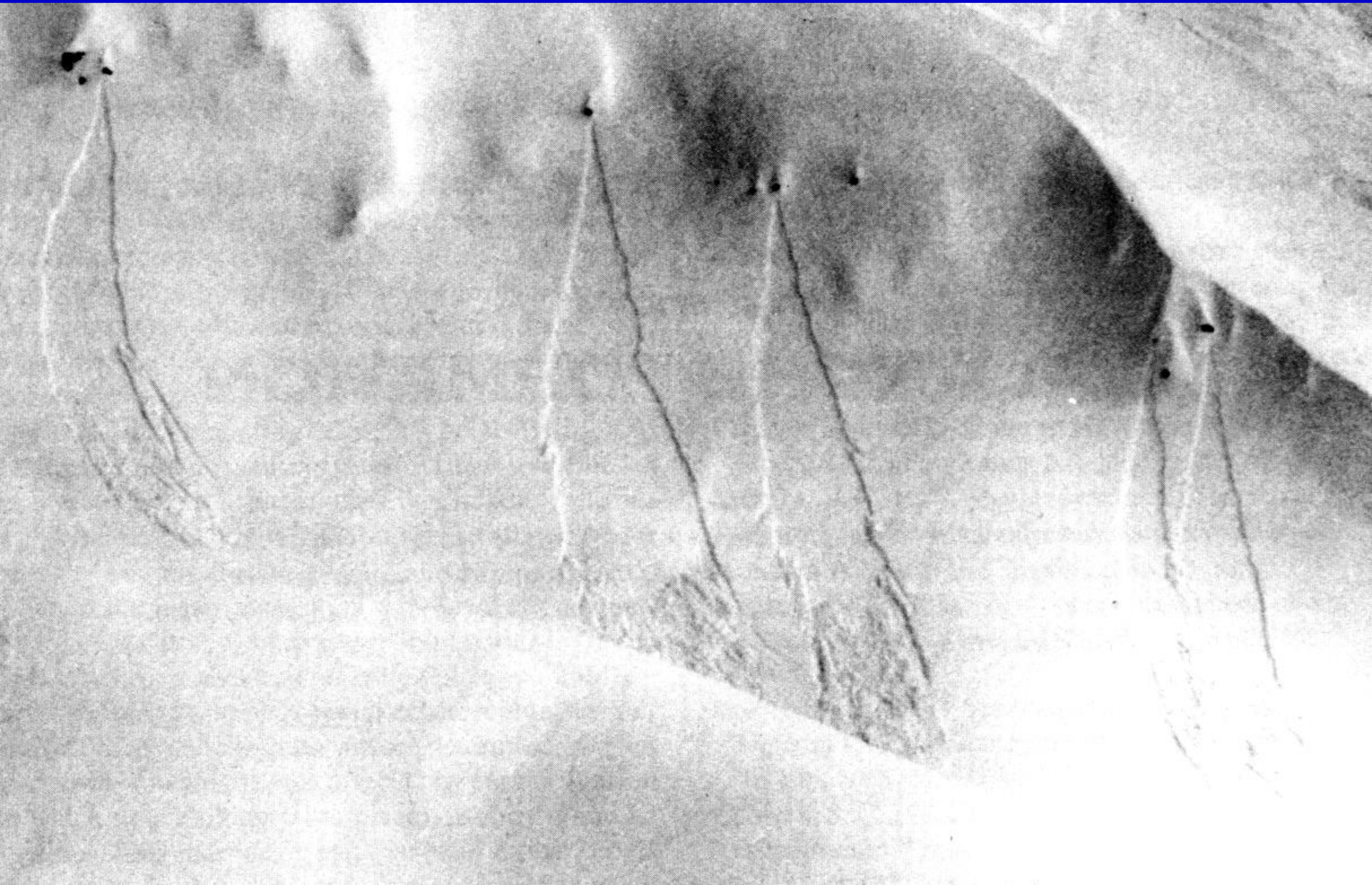



*Figure 4.1. Illustration of loose (left) and slab (right) avalanche failure types.*

# Loose snow failure




Slab failure

- 2 types of snow avalanche
  - Flow avalanches
  - Airborne powder snow avalanches

# Flow avalanches

- **Velocities up to 216 km/hr (60 m/s)**
- **Flow heights 5-10 meters**
- **Collisions of particles - granular flow**
- **Initially tends to slide as a rigid body (similar to a landslide)…**
- **…but rapidly breaks up into smaller particles and becomes a granular flow**

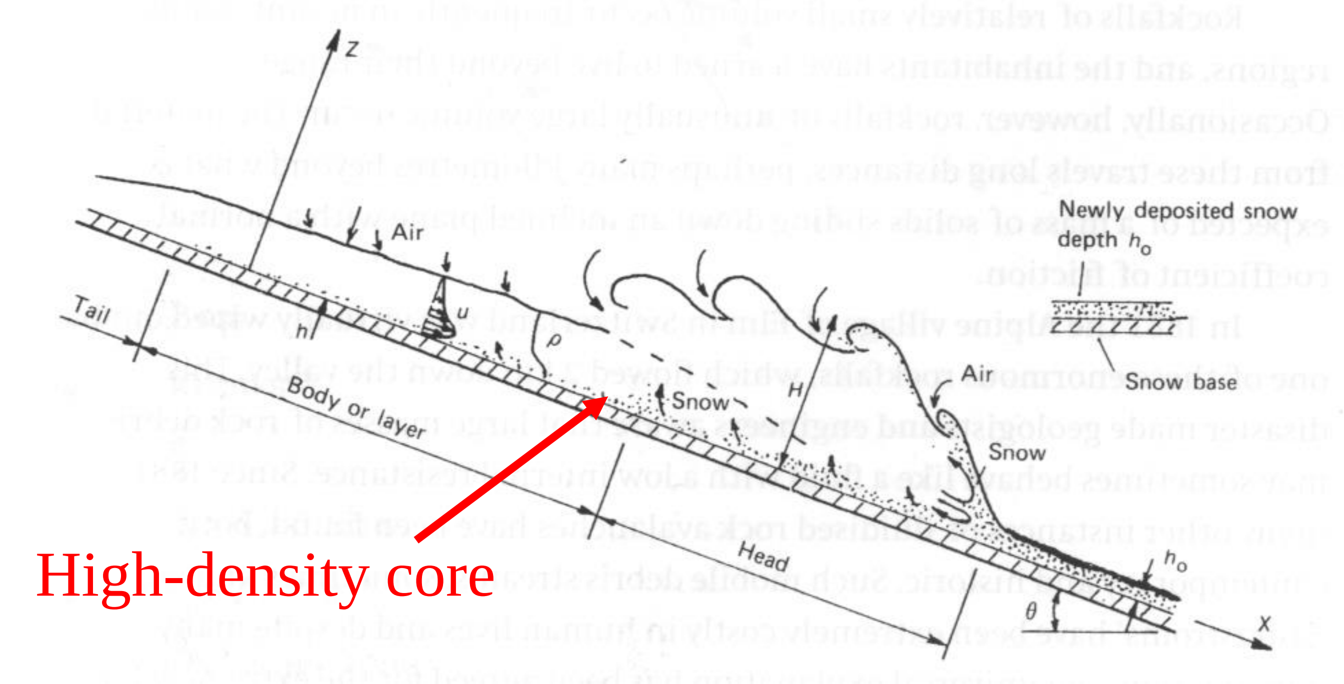
# Interior of the flow

-There is a **high-density core** near the base of the flow

-In this zone, particles collide, resulting in friction and producing **heat**

-When the avalanche flow stops, freezing can occur, making the deposit very **hard**

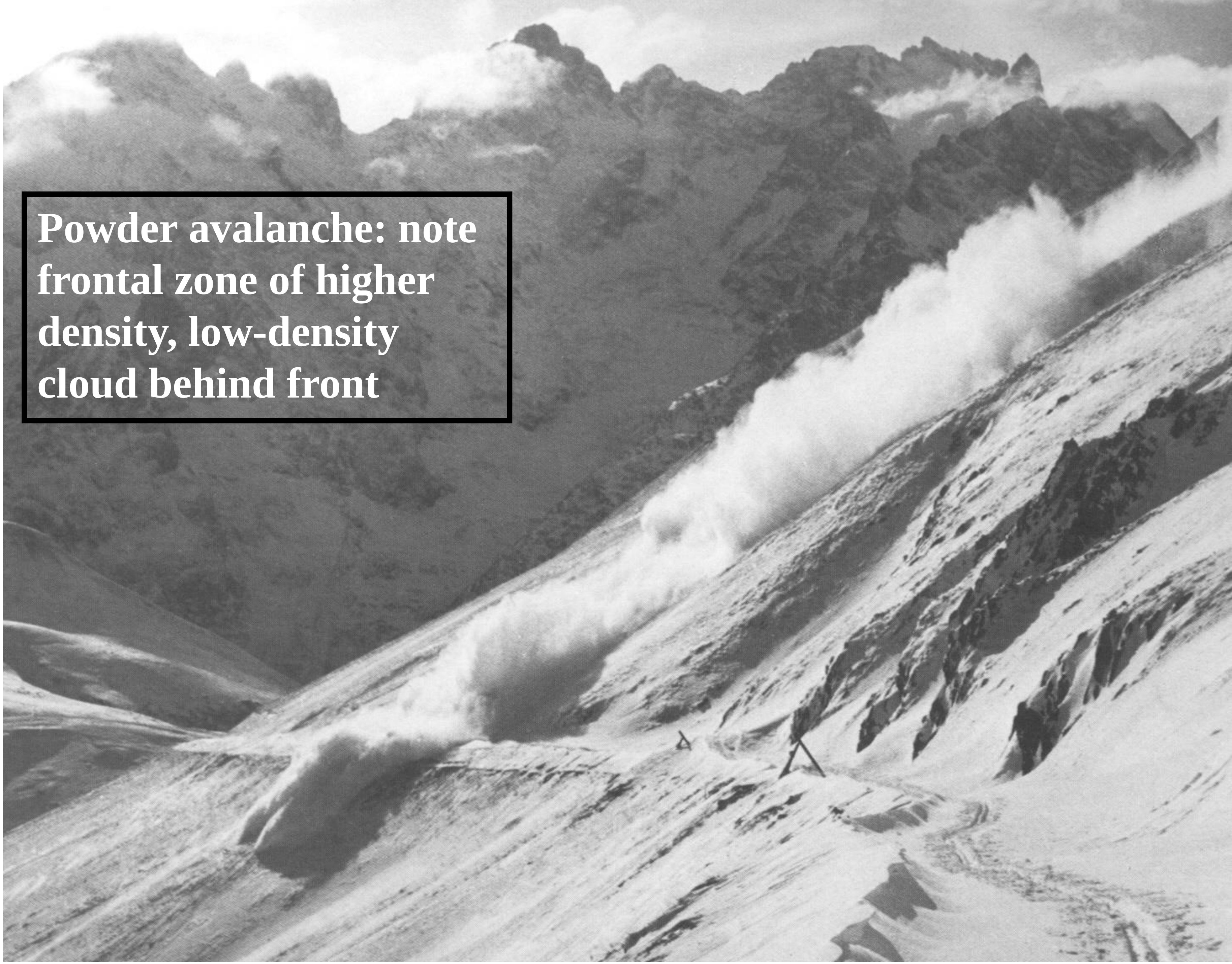
-sets like **concrete**



## Airborne powder snow avalanches

- **Velocities can exceed <u>360 km/hr</u> (100 m/s)**
- **Flow thicknesses may exceed <u>100 meters</u>**

- **Essentially a highly dilute density current flowing down an incline:**
  - **partial entrainment of underlying snow by turbulent, erosive flow**
  - **dense core small or absent**
  - **powder avalanches may develop from flow avalanches, but the mechanisms are not well understood**


Powder avalanche: note frontal zone of higher density, low-density cloud behind front

# Runout area

- Powder snow avalanches flow around obstacles, while flow avalanches do not

- When powder snow avalanches hit a barrier, the lower dense portion of the flow is **stopped**, while the more dilute cloud behaves like a **fluid** which can flow around or over the obstacle

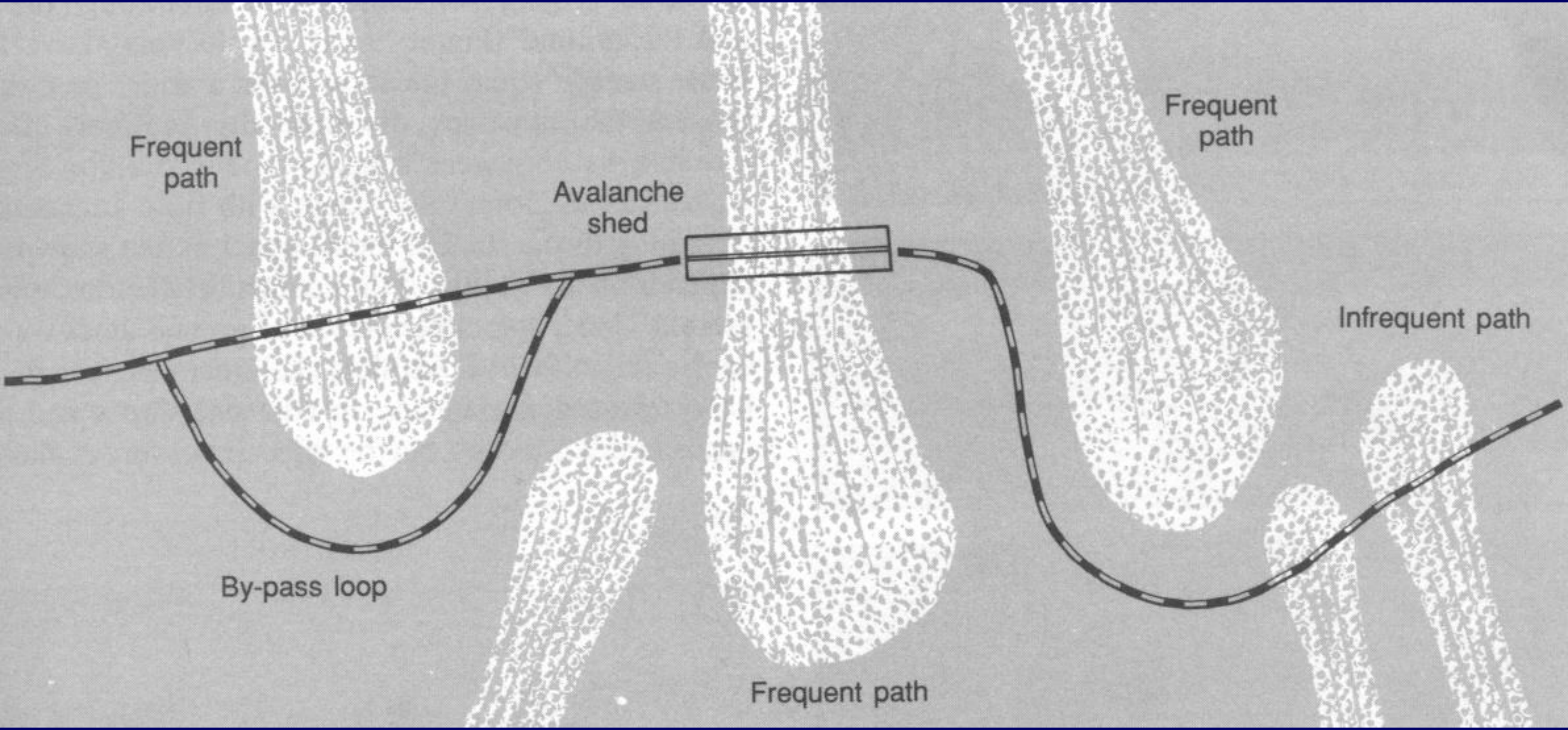
Fully-developed powder avalanche due to cascading down near-vertical cliffs

# Mixed flow and powder avalanche

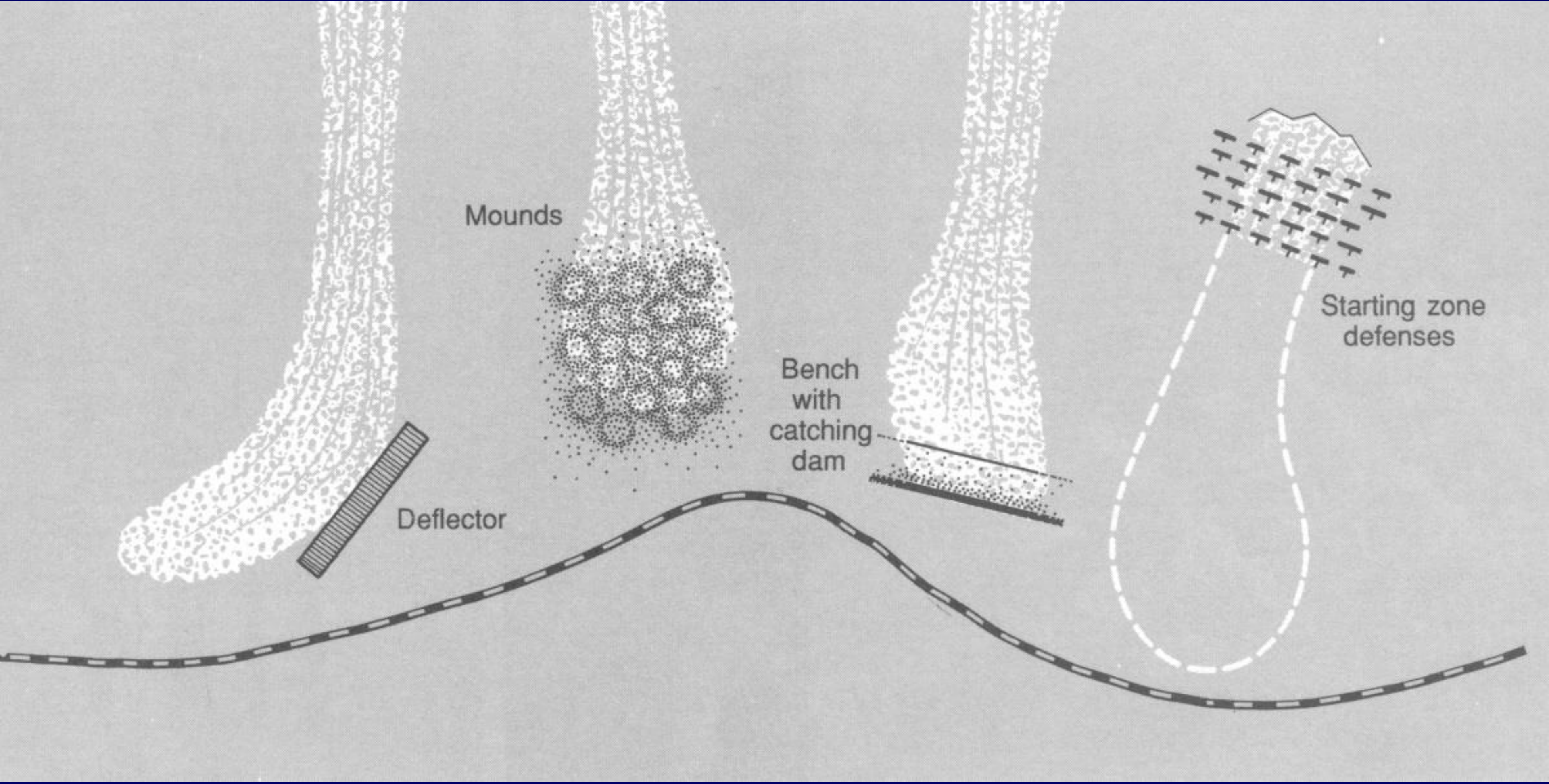
# Mitigation Strategies

- **<u>Reforestation:</u>**
  - to stabilize slopes and snow
- **<u>Highways:</u>**
  - locate to avoid avalanche tracks
  - use of defense structures: deflectors, mounds, benches with dams

# Avalanche avoidance



# Use of defense structures



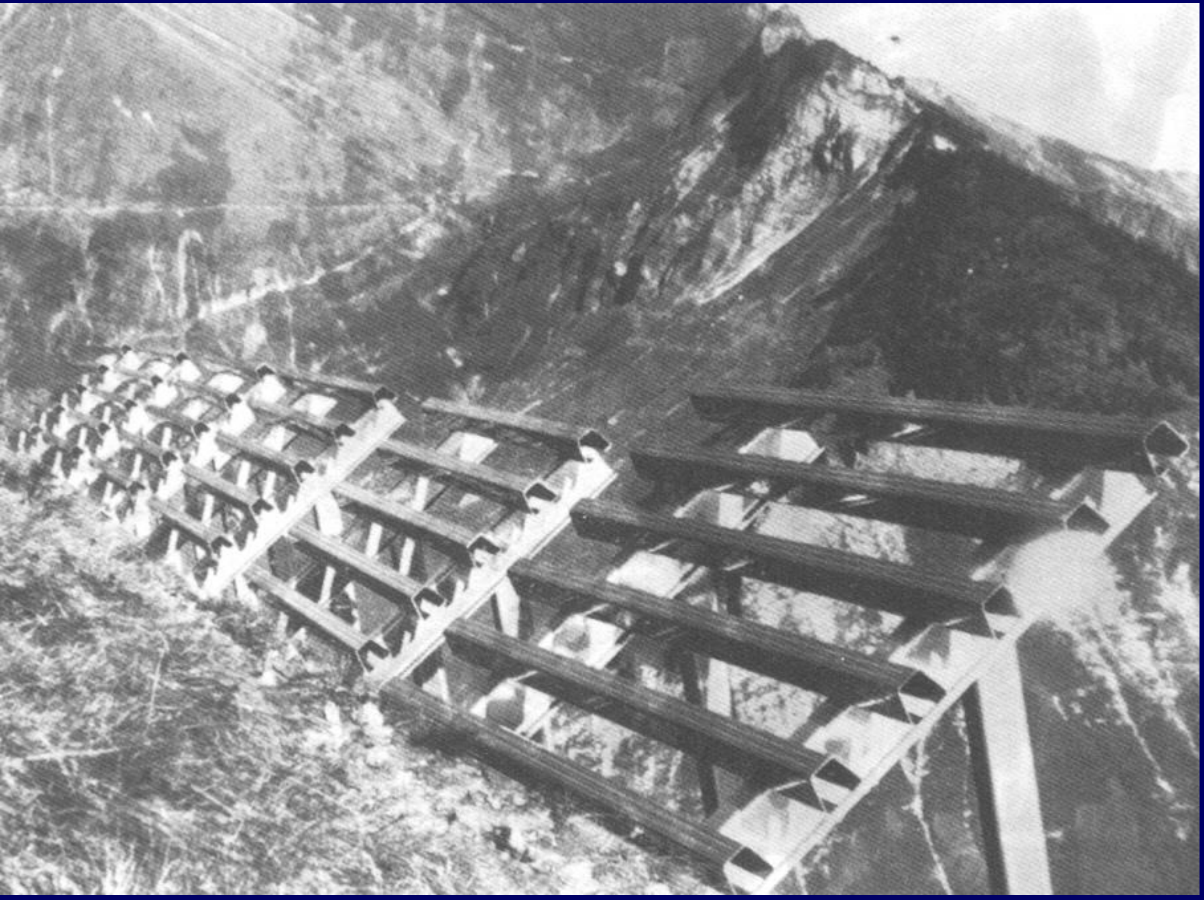
# Starting zone defenses

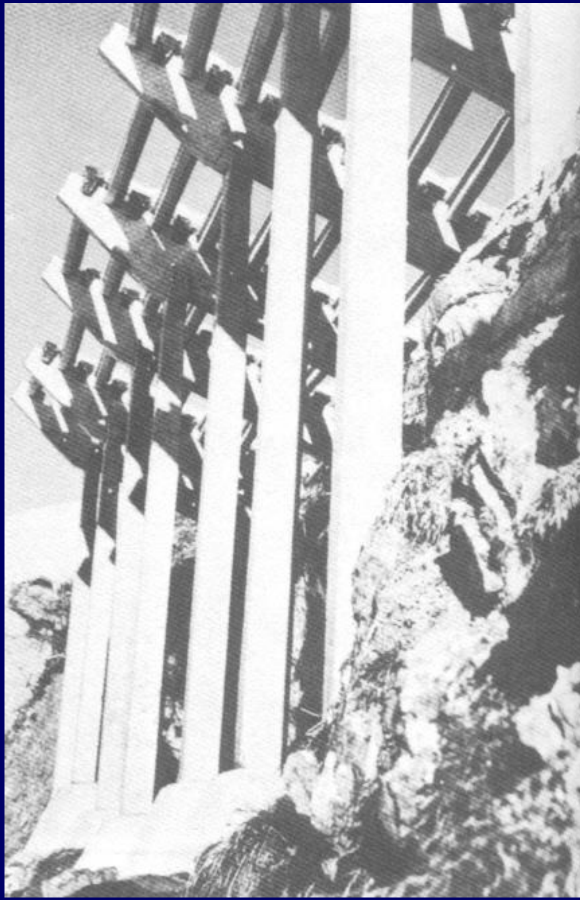
Terracing in avalanche starting zones

- To help reduce avalanches from forming:
- use of terraces
- use of supporting structures

# Supporting structures

# Details of supporting structures



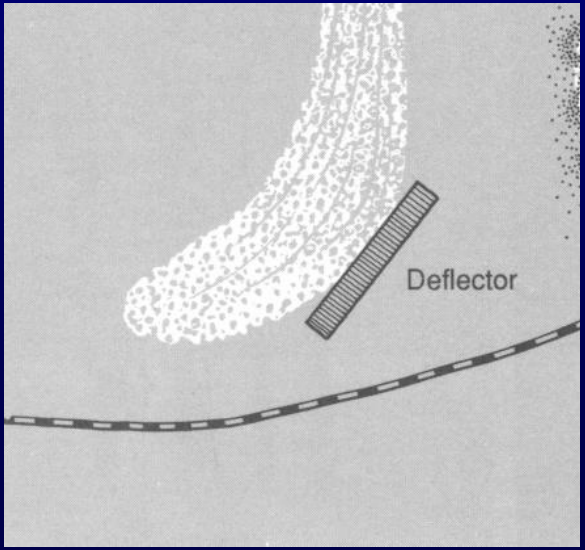


## Some specific examples of mitigation attempts

**<u>Deflectors:</u>**

- must be gradual, otherwise the avalanche will overflow the deflector

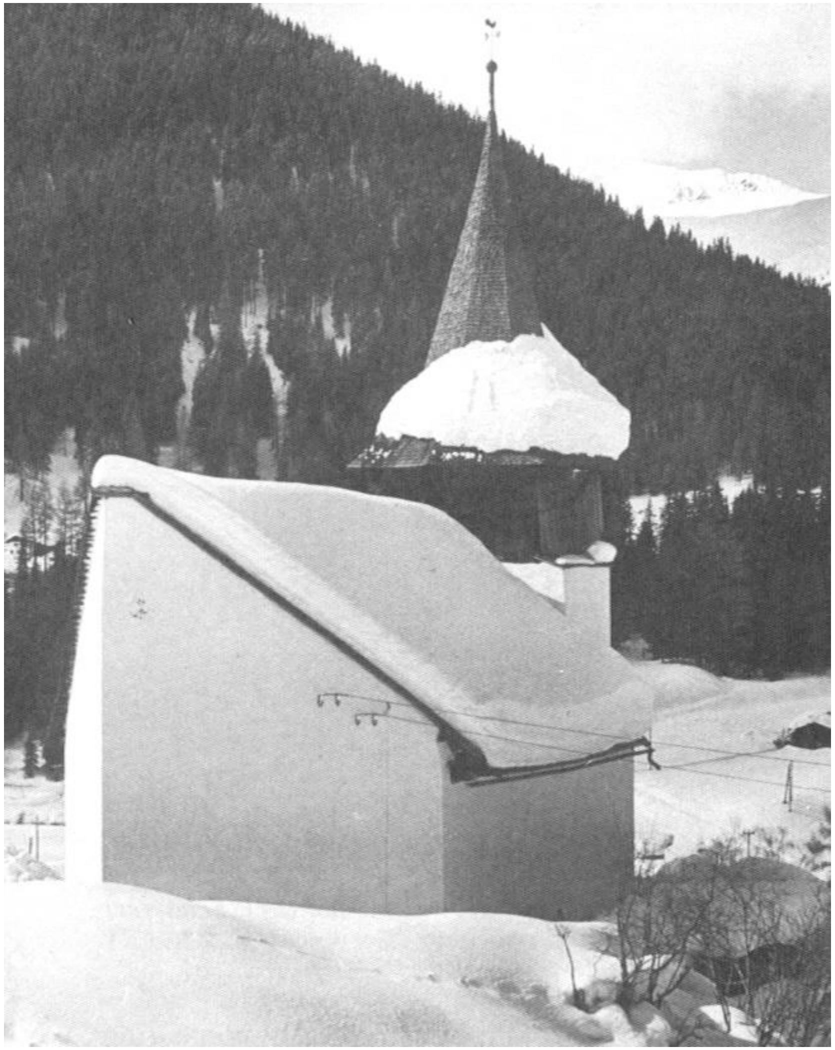
- **<u>Arresters</u>** are used to slow or stop avalanches
- need adequate height; if too low, flow can **<u>accelerate</u>** above barrier, increasing damage




# Splitters

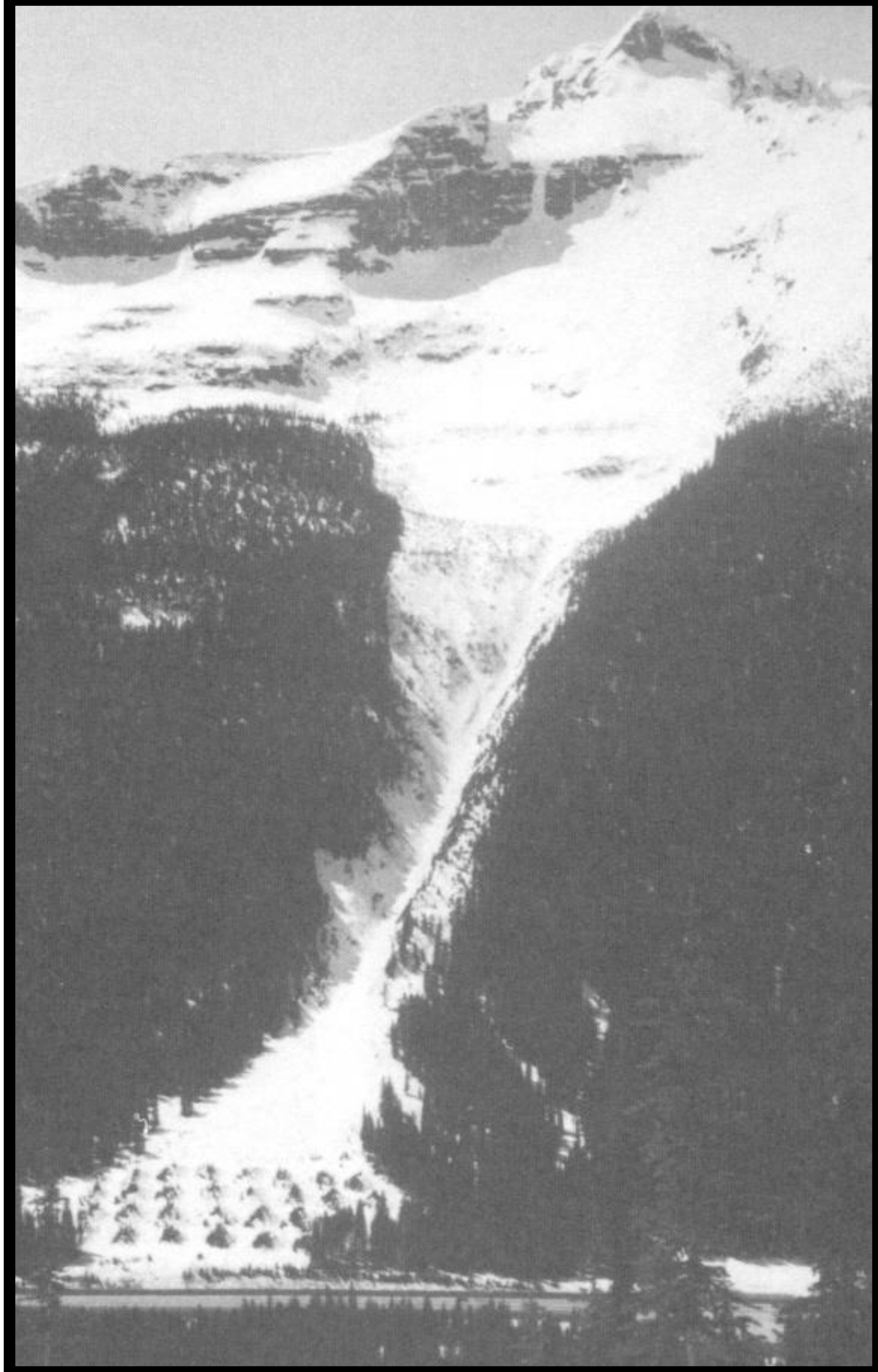
- These are placed directly in front of a single object

- They redirect and divert the avalanche flow around the structure



# Mounds

- These are used to retard flowing snow at the end of the runout zone



# Snow sheds

- These sheds allow the avalanche to pass <u>**over**</u> the structure

## Glacier advance and retreat

**The direct risk posed by advancing and retreating glaciers is the potential danger to mountain infrastructures and installations**

**Historically, glacier advances have been a major threat to forested and agricultural land in densely populated mountains**

**advancing glaciers have repeatedly given rise to the formation of ice-dammed lakes with subsequent dam failure**

**Glaciers retreat may lead to destabilization of steep rock slopes, exposure and potential erosion of large debris reservoirs, formation of ice and moraine dammed lakes, or change in glacier geometry with possible new formation or increase in ice avalanche activity**

**Working Group on Himalayan Glaciology (WGHG) of the International Commission for Snow and Ice(ICSI) stated: "glaciers in the Himalayas are receding faster than in any other part of the world**

**If the present rate continues, the livelihood of them disappearing by the year 2035 is very high"**

**Direct observation of a select few snout positions out of the thousands of Himalayan glaciers indicate that they have been in a general state of decline over, at least, the past 150 years**

**The prediction that "glaciers in the region will vanish within 40 years as a result of global warming" and that the flow of Himalayan rivers will "eventually diminish, resulting in widespread water shortages" (*New Scientist* 1999; 1999, 2003) is equally disturbing.**

**In the context of India this spells bigger trouble for the 500 million inhabitants of the Indus, Ganges and Brahmaputra river basins, who rely on the perennial supply of melt-water from the Himalayas (Sharma 2001)**

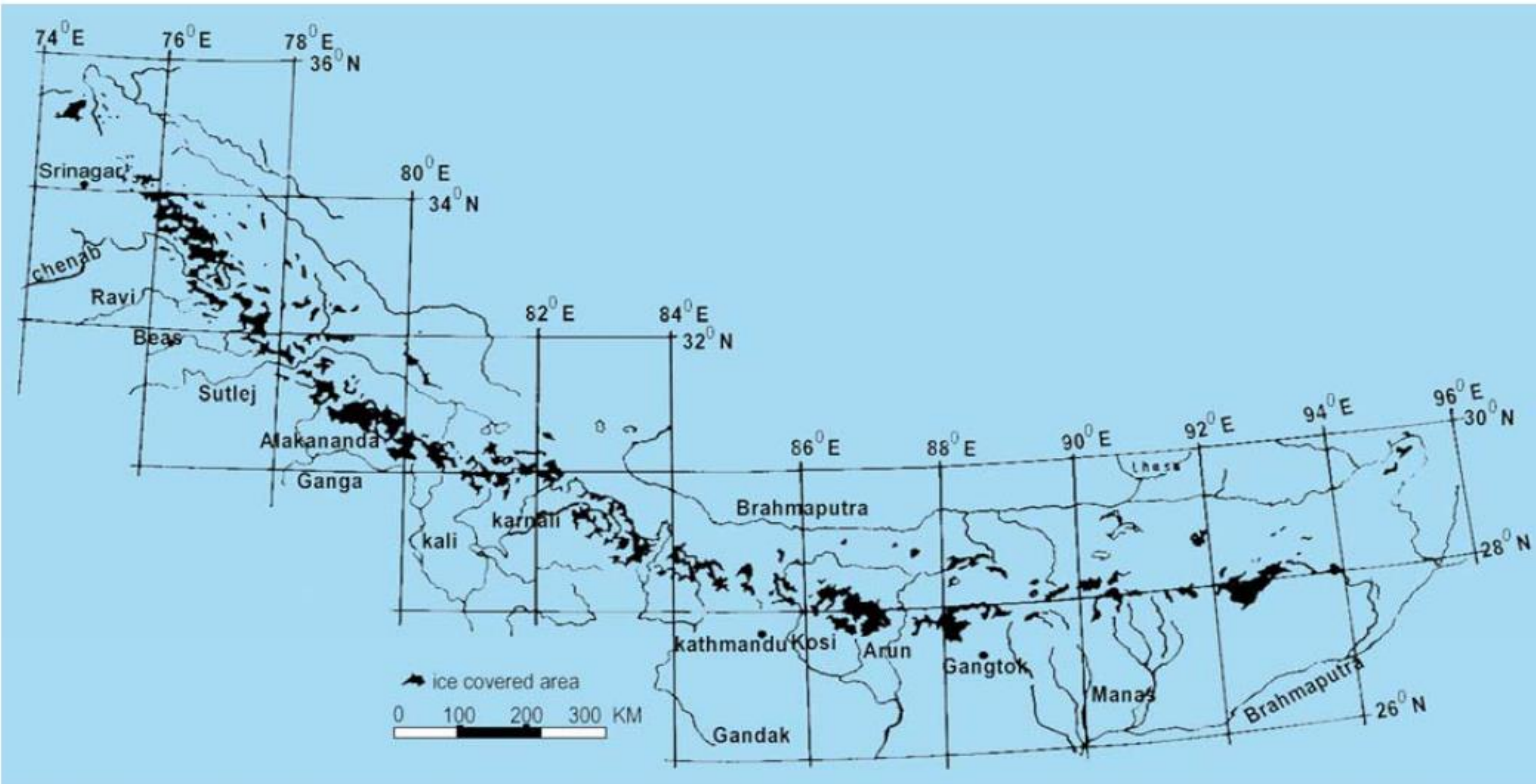



*Figure 19: Glacier distribution along the Himalayan arc*

*Table7 Retreats of Important Glaciers in the Himalayas*

| **Glacier** | **Location** | **Period** | **Avg. retreat (m/year)** | **Reference** |
|---|---|---|---|---|
| Milam | Uttaranchal | 1849-1957 | 12.5 | Vohra (1981) |
| Pindari | Uttaranchal | 1845-1966 | 23.0 | Vohra (1981) |
| Gangotri | Uttaranchal | 1935-1976 | 15.0 | Vohra (1981) |
| Gangotri | Uttaranchal | 1985-2001 | 23.0 | Hasnain, *et al.* 2004 |
| Bada Shigri | Himachal Predesh | 1890-1906 | 20.0 | Mayekwski & Jeschke (1979) |
| Kolhani | Jammu & Kashmir | 1857-1909 | 15.0 | Mayekwski & Jeschke (1979) |
| Kolhani | Jammu & Kashmir | 1912-1961 | 16.0 | Mayekwski & Jeschke (1979) |
| Machoi | Jammu & Kashmir | 1906-1957 | 8.1 | Tiwari (1972) |
| Chota-Shigri | Himachal Pradesh | 1970-1989 | 7.5 | Surender *et al.* (1994) |


*Figure 20: Retreat of the Gangotri Glacier (Garhwal Himalayas) snout during the last 220 years (Source: Jeff Kargel, USGS)*

**Himalayan glaciers form a unique reservoir that supports mighty perennial rivers such as Indus, Ganga and Brahmaputra, which are the lifelines of millions of people.**

**Recently the geologists of Geological Survey of India (GSI) counted 5,218 glaciers in the Himalayas (Puri 1994).**

**It is estimated that 33,200 km2 (Flint 1971) of the Himalaya is glaciated and glaciers occupy about 17 percent of the total mountainous area of the Himalaya (Vohra 1978)**

**Meltwater draining from these ice and snowfields is important in regulating the hydrology of the Indian sub-continent.**

**Though it contributes only to 5 percent of total runoff, it releases water in the dry season (Upadhyay 1995).**

# Glacier retreat and formation of Glacial Lake

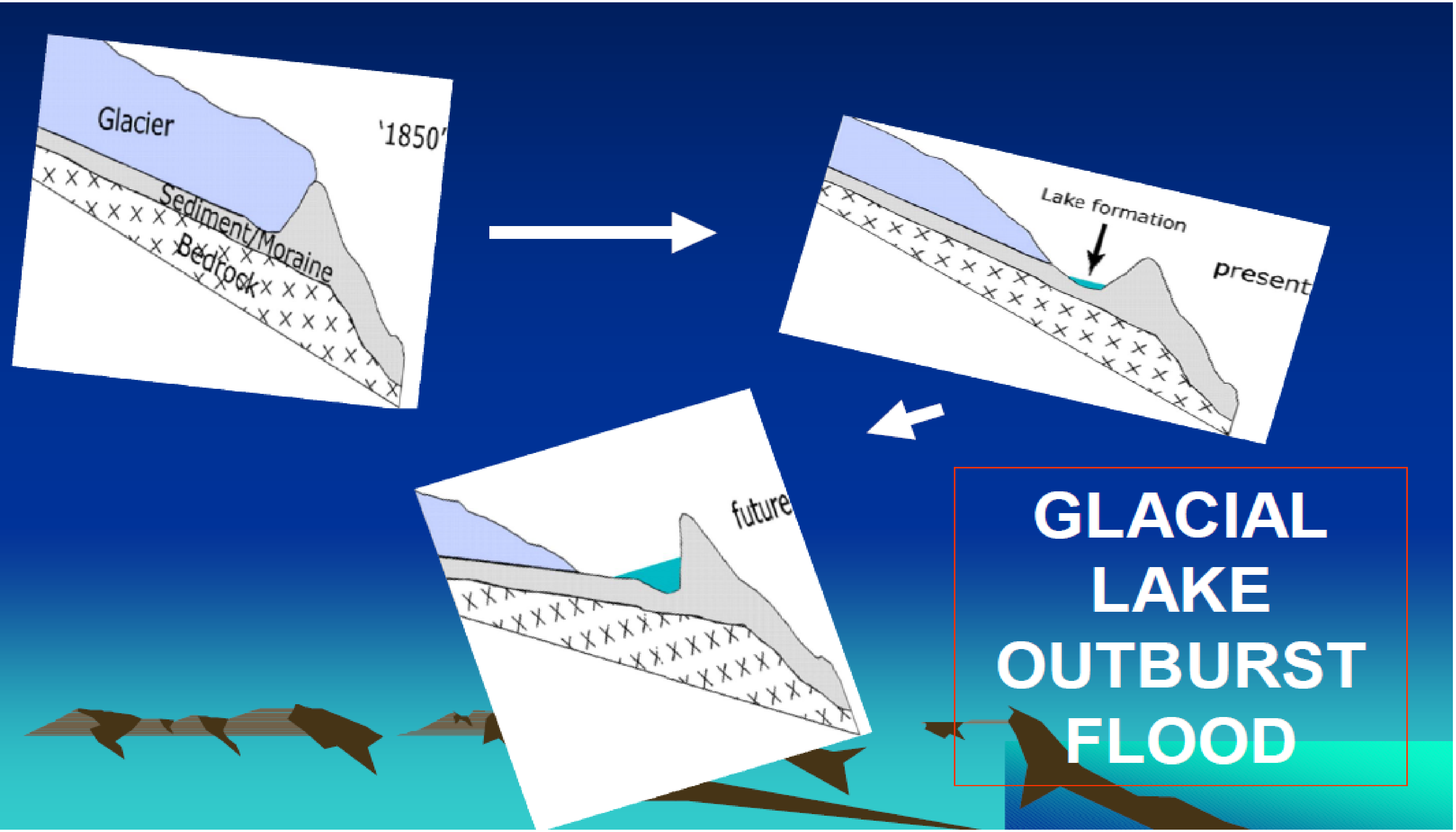
**The formation and growth of glacier lakes is a phenomenon closely related to deglaciation.**

**Valley glaciers generally contain supra-glacial ponds. Due to warming climate, these ponds grow bigger and merge.**

**This process is accelerated by rapid retreat of glaciers. As the glacier retreats it leaves a large void behind.**

**The ponds occupy the depression earlier occupied by glacial ice.**

**The moraine walls that act as dams are structurally weak and unstable and under go constant changes due to slope failures, slumping, etc. and are in danger of catastrophic failure, causing glacier lake outburst floods (GLOFs). Principally, a moraine dam may break by the action of some external trigger or self-destruction.**




# GLACIAL LAKE OUTBURST FLOOD

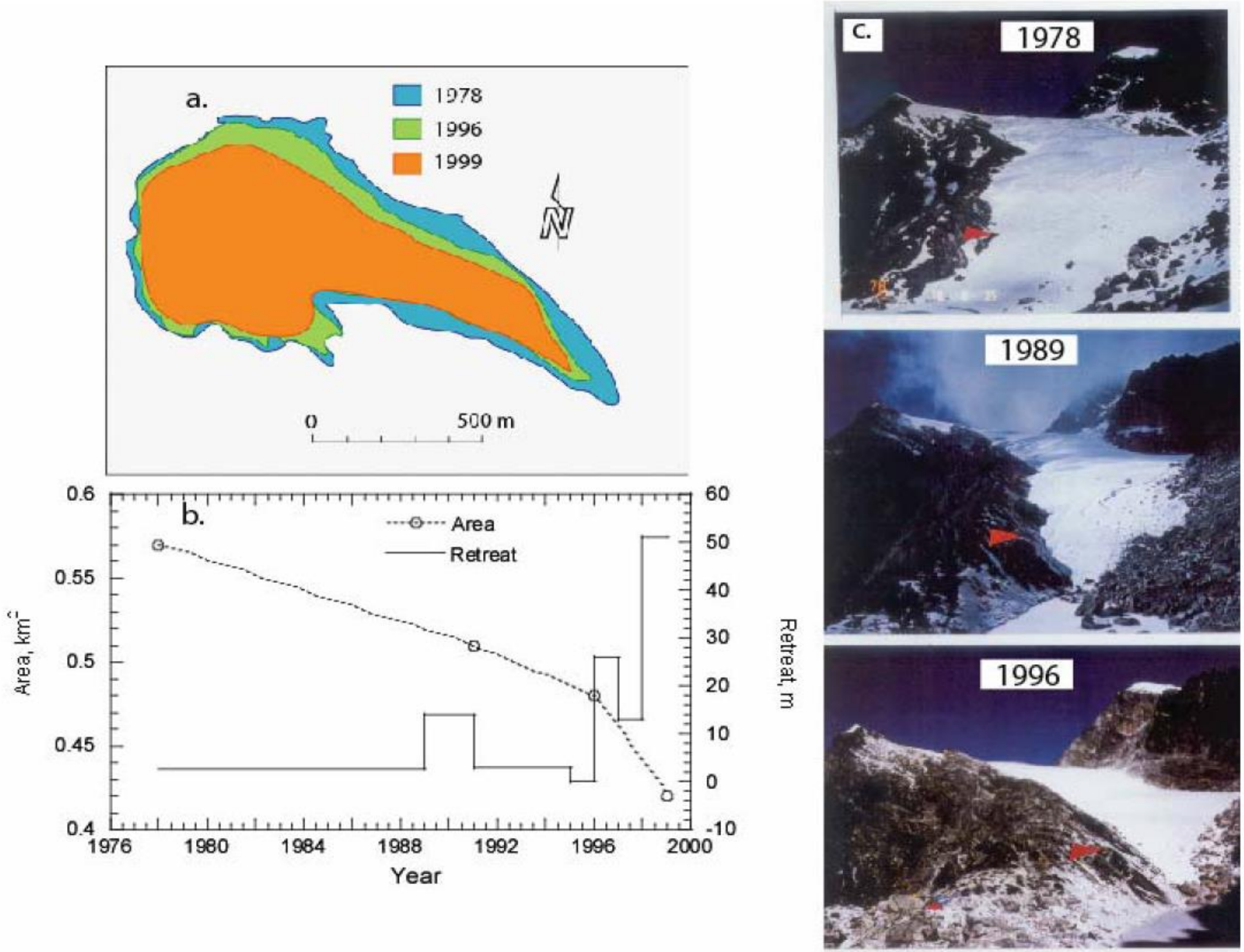



***Figure 9: Retreat of AX010 glacier: a. Map showing the changes in the glacier area b. Changes in the glacier and the rate of terminus retreat c. Photographs of glacier terminus between 1978-1996***


**Figure 5.1:** Retreat of Gangotri Glacier snout during the last 220 years from 1780-2001, India (cited ICIMOD/UNEP,2007)[2]

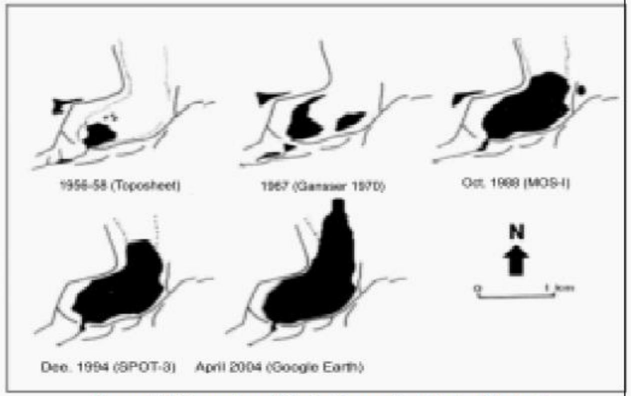



**Figure 5.2:** Expansion of Raphsthreng Tso Glacier, Bhutan[2]

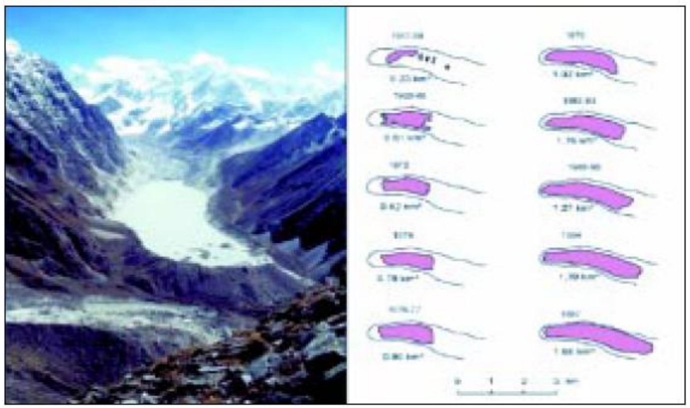


**Figure 5.3:** Growth of Tso Rolpa Glacier Lake 1957-1997 Nepal (cited Chaulagain 2006)[11]

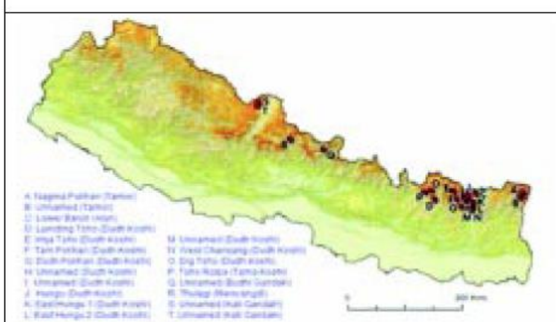


**Figure 5.4:** Potentially dangerous 20 Glacier Lakes, Nepal[5]

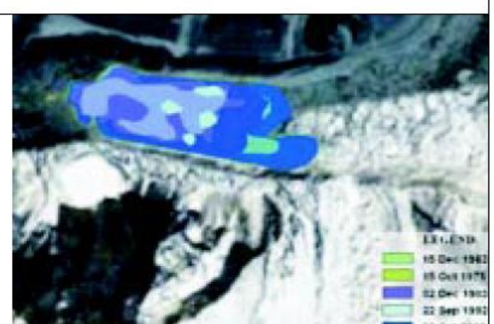


**Figure 5.5:** Development pf Glacier Lake 1962-2006 (ICIMOD/UNEP, 2007)[2]

# Glacier retreat and formation of Glacial Lake

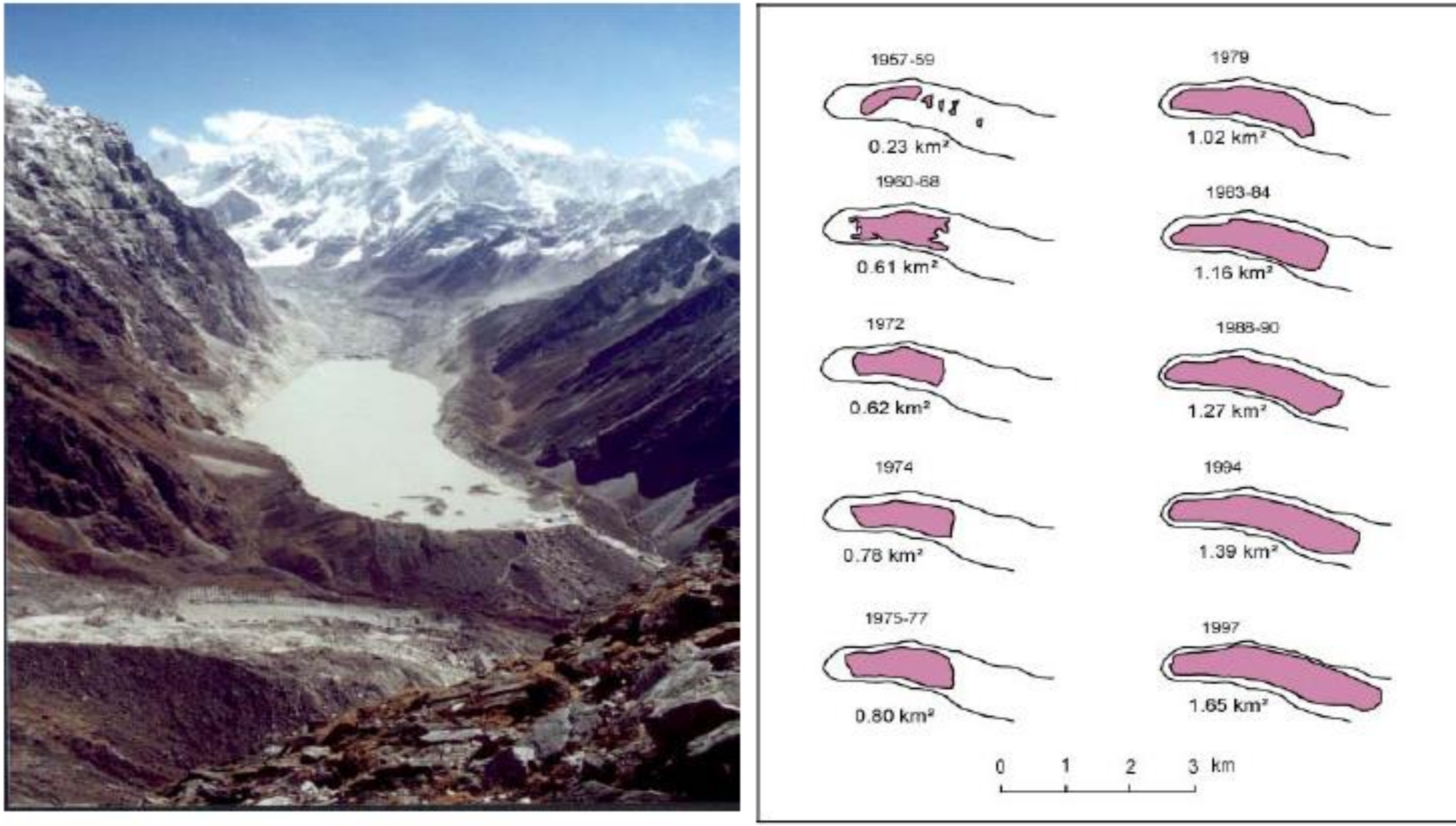
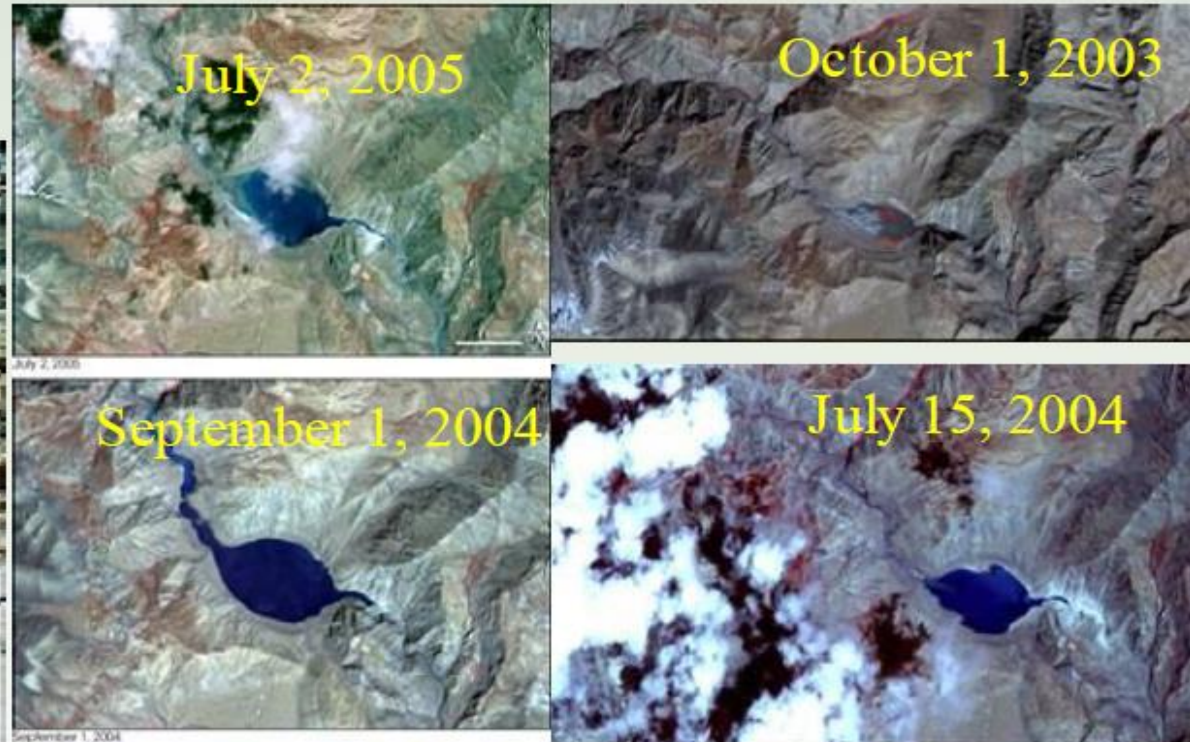
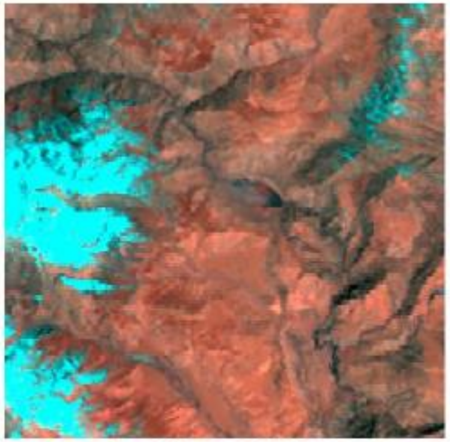



*Figure 18: Growth of Tsho Rolpa from the late 1950s to 1997, Photo © P.K. Mool, 2000*

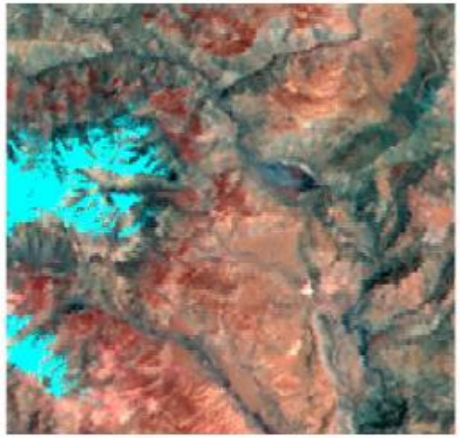
# Landslide Damburst

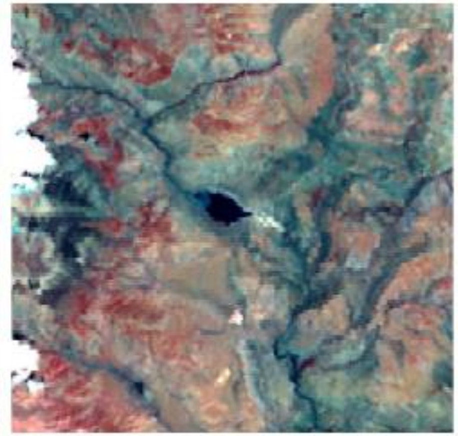

Landslide Dam Lake in Pare Chu Tibet Autonomous Region, China – 35 km upstream of India Sutlej basin



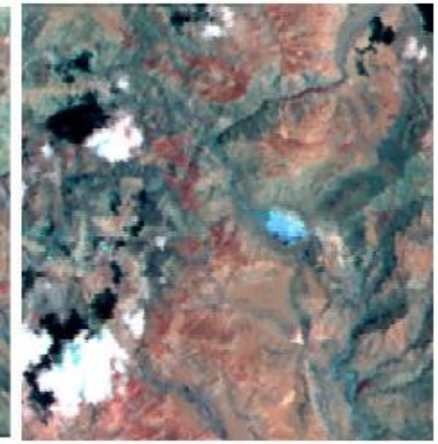
April 16, 2004



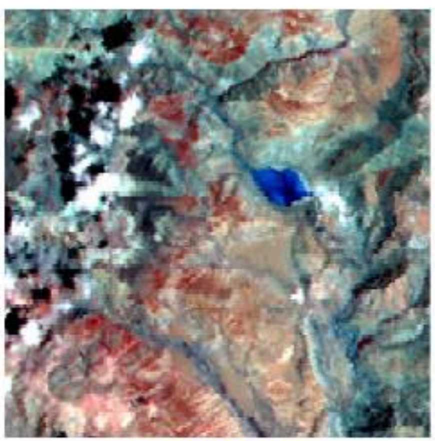
May 29, 2004



July 02, 2004



July 11, 2004



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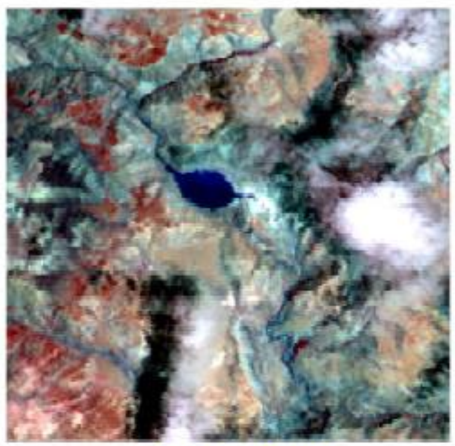

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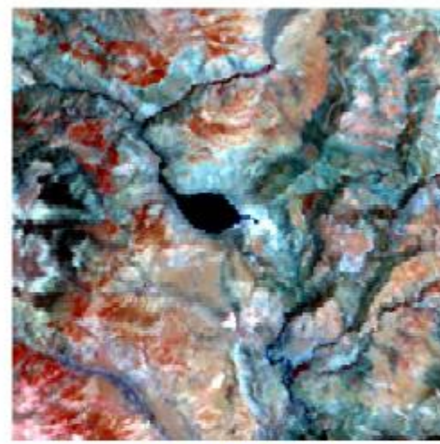


July 26, 2004

Temporal Variations of the Lake extent using AWiFS

Prepared By

Space Applications Centre (ISI
&
Himachal Pradesh Remote Ser

14th Aug. 2004

## Observations

# IRS-P6 LISS-IV MX satellite Image of 06-Sep-2006 showing the lake on Pareechu River

- There is no significant change in the water spread area of the lake when compared to 4th August 2006 image.
- Presently, the lake is free from ice/snow.
- Significant inflows and outflows are observed in the Pareechu river u/s and d/s of the lake.

# Periglacial debris flows

Periglacial debris flows in combination with retreating glaciers, large and steep reservoirs of loose sediment (mainly of morainic origin) can become exposed and then represent a potential source of debris flows.

Analysis of the numerous debris-flow events in the Swiss Alps in 1987 has shown that about 50% of all events (with volumes larger than 1000 m3) originated in areas of loose sediment which have been uncovered in connection with the glacier retreat since 1850

Periglacial debris flows are not only released from glacial forefields but also from marginal permafrost sites, from the scree of debris cones and rock-glacier fronts.

**Permafrost strongly influences the stability and hydrology of steep debris slopes, since permanently frozen material acts as a barrier to groundwater percolation and can imply local saturation within the non-frozen debris**

**Permafrost thawing in non-consolidated material leads to a loss of cohesion and increase in pore water pressure.**

**Together with water-saturated fine material and formation of caverns originating from the disappearance of massive ground ice bodies, steep slopes may thus become highly susceptible to landslides and debris flows**

**Trigger mechanisms can be related to strong precipitation, intense snow/ice melt, or remain unclear**

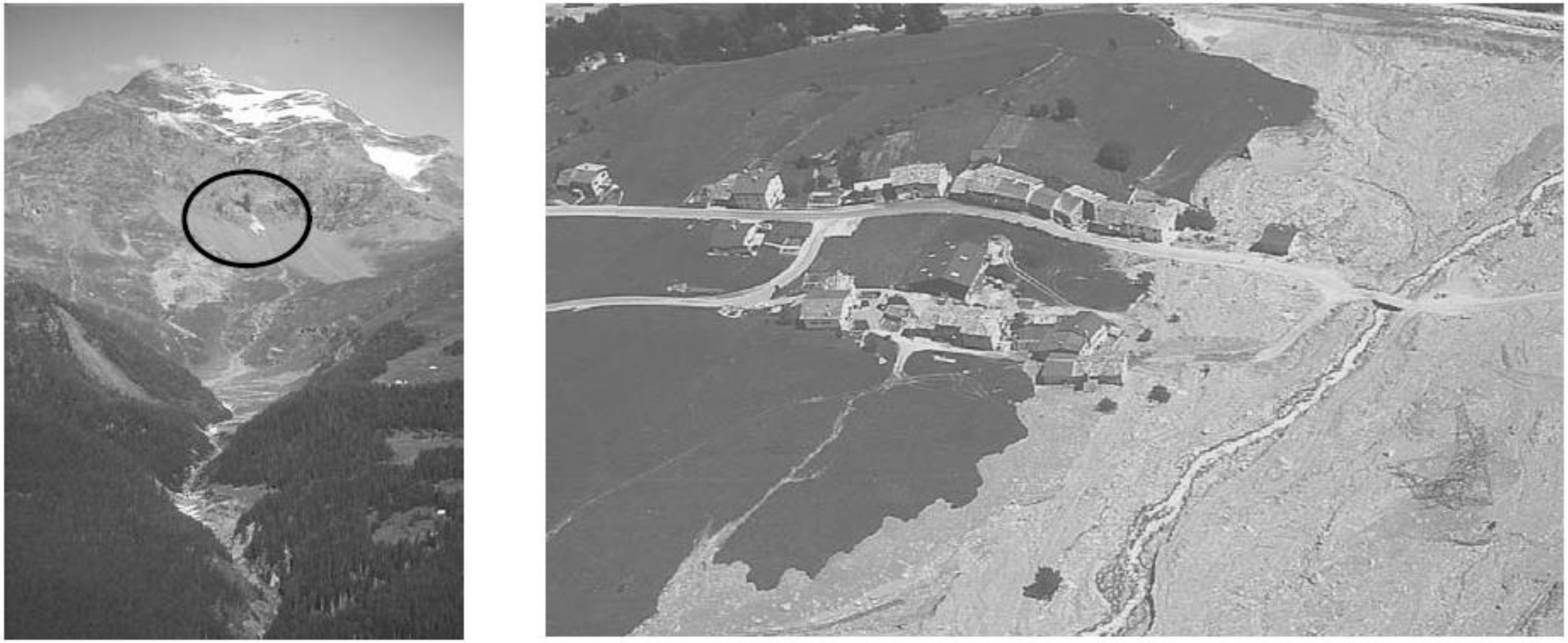


Fig. 4: One of the major flood disasters in the Swiss Alps in 1987 was related to a periglacial debris flow from the Varuna valley (southern Swiss Alps). The debris flow started from a talus slope below Varuna glacier (left image, indicated by circle), damaged the settlement of Privilasco by sediment deposition on the fan (right image), and finally dammed the main river valley. Subsequent flooding caused severe damages of about EUR 30 mill. in the city of Poschiavo (photos: W. Haeberli).

# Rock fall

**In glacial and periglacial environments, the significance of rockfall relates to the interaction with glacier retreat and permafrost changes, combined events with ice avalanches, and enlarged runout on glacier and snow surfaces.**

**Glacier retreat may induce changes in the stress field in rock walls, leading to destabilization processes**

**Shear laboratory tests have shown that a rise in ground temperature may result in a reduction of the shear capacity of ice-bonded discontinuities and eventually in a decrease in slope stability**

Fig. 5: Rockfall at the southwest face of the Matterhorn in August 2003, at about 3800 m a.s.l. near Carrel alpine hut. The event is one out of a rockfall series in the extraordinarily hot summer 2003, originating in permafrost areas (photo: L. Trucco).

# Glacier-clad volcanoes

**On a global level, glacier-clad volcanoes represent a further major glacier-related hazard.**

**For instance, lahars (volcanogenic debris flows) can impact downstream areas at a distance of more than 100 km.**

**The investigation of glacier-clad volcanoes was intensified and reinforced following the eruption of Mount St. Helens (Washington, USA) in 1980 and the Nevado del Ruiz catastrophe (Colombia) in 1985**

**Historically, lahars have been one of the deadliest volcano hazards. Lahars are mudflows or debris flows composed mostly of volcanic materials on the flanks of a volcano.**

**These flows of mud, rock, and water can rush down valley and stream channels at speeds of 20 to 40 miles per hour and can travel more than 50 miles.**

**Some lahars contain so much rock debris that they look like fast-moving rivers of wet concrete.**

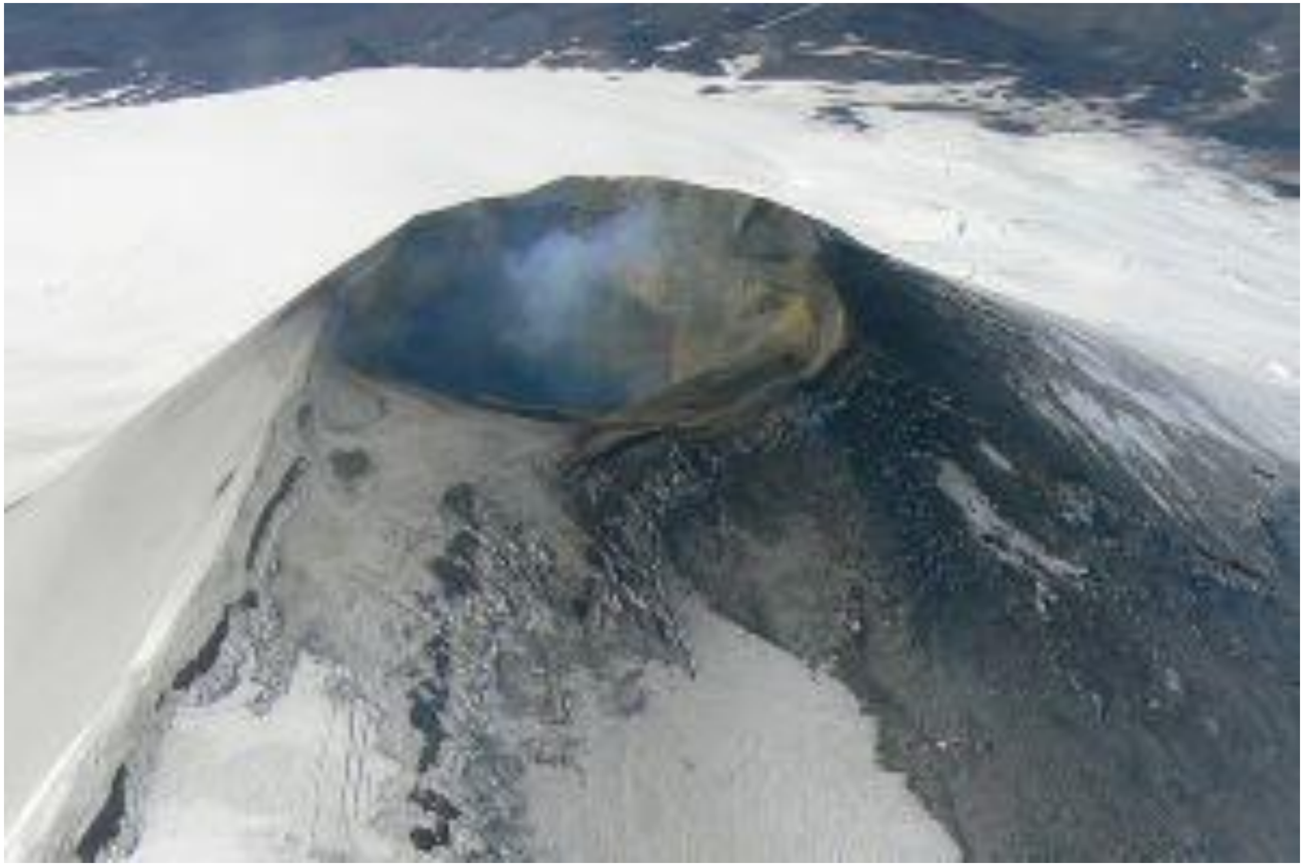
**They can occur both during an eruption and when a volcano is quiet.**

**The water that creates lahars can come from melting snow and ice, intense rainfall, or the breakout of a summit crater lake.**

**Large lahars are a potential hazard to many communities downstream from glacier-clad volcanoes, such as Mount Rainier in Washington.**

Fig. 6: Eruption of Popocatépetl volcano, central Mexico, with ash fallout on Ventorillo/Noroccidental glacier (marked by circle, photo: A. Boneta).

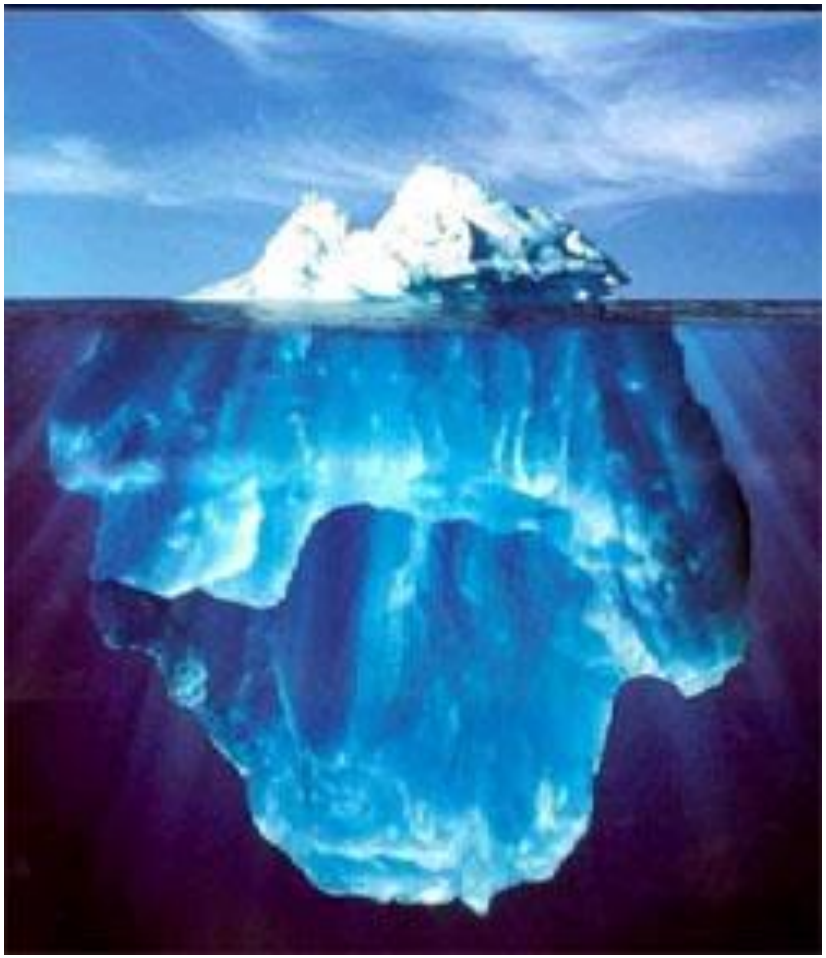
# Volcano Villarrica, Chile



# Process interactions

**Combinations and interactions between different hazard types can be highly hazardous. In fact, many of the largest known glacier catastrophes featured hazard combinations and/or process chains**

# Icebergs

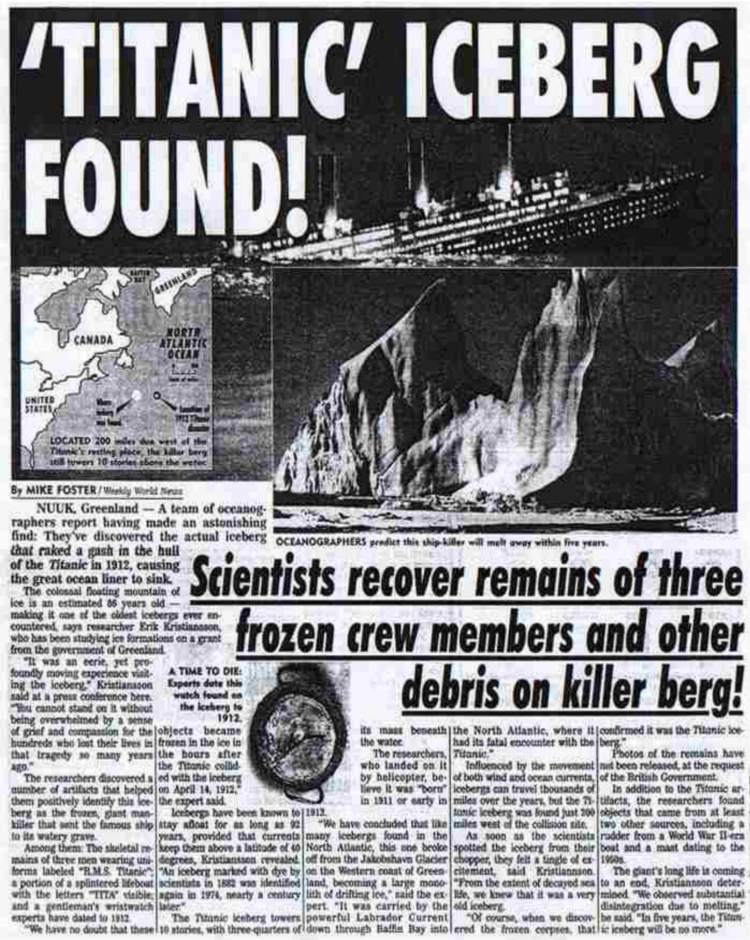


- Glaciers vs. icebergs
- Glaciers move over land and when they hit water they become an iceberg.
- 10,000 icebergs form every year from Greenland.

# Icebergs


- Only about 10 percent of an iceberg is visible.
- 90% of an iceberg lies below the surface.
- The underwater part is a hazard to ships because it is often much wider than the visible part of the iceberg.

# Icebergs



'TITANIC' ICEBERG FOUND!



LOCATED 200 miles due west of the Titanic's resting place, the killer berg still towers 10 stories above the water.

OCEANOGRAPHERS predict this ship-killer will melt away within five years.

By MIKE FOSTER / Weekly World News

NUUK, Greenland — A team of oceanographers report having made an astonishing find: They've discovered the actual iceberg *that raked a gash in the hull of the Titanic in 1912, causing the great ocean liner to sink.*

## Scientists recover remains of three frozen crew members and other debris on killer berg!

The colossal floating mountain of ice is an estimated 86 years old — making it one of the oldest icebergs ever encountered, says researcher Erik Kristiansson, who has been studying ice formations on a grant from the government of Greenland.

"It was an eerie, yet profoundly moving experience visiting the iceberg," Kristiansson said at a press conference here. "You cannot stand on it without being overwhelmed by a sense of grief and compassion for the hundreds who lost their lives in that tragedy so many years ago."

The researchers discovered a number of artifacts that helped them positively identify this iceberg as the frozen, giant mankiller that sent the famous ship to its watery grave.

Among them: The skeletal remains of three men wearing uniforms labeled "R.M.S. Titanic"; a portion of a splintered lifeboat with the letters "TITA" visible; and a gentleman's wristwatch experts have dated to 1912.

A TIME TO DIE: Experts date this watch found on the iceberg to 1912.

"We have no doubt that these objects became frozen in the ice in the hours after the *Titanic* collided with the iceberg on April 14, 1912," the expert said.

Icebergs have been known to stay afloat for as long as 92 years, provided that currents keep them above a latitude of 40 degrees, Kristiansson revealed. "An iceberg marked with dye by scientists in 1882 was identified again in 1974, nearly a century later."

The *Titanic* iceberg towers 10 stories, with three-quarters of its mass beneath the water.

The researchers, who landed on it by helicopter, believe it was "born" in 1911 or early in 1912.

"We have concluded that like many icebergs found in the North Atlantic, this one broke off from the Jakobshavn Glacier on the Western coast of Greenland, becoming a large monolith of drifting ice," said the expert. "It was carried by the powerful Labrador Current down through Baffin Bay into the North Atlantic, where it had its fatal encounter with the *Titanic*."

Influenced by the movement of both wind and ocean currents, icebergs can travel thousands of miles over the years, but the Titanic iceberg was found just 200 miles west of the collision site.

As soon as the scientists spotted the iceberg from their chopper, they felt a tingle of excitement, said Kristiansson. "From the extent of decayed sea life, we knew that it was a very old iceberg.

"Of course, when we discovered the frozen corpses, that confirmed it was the *Titanic* iceberg."

Photos of the remains have not been released, at the request of the British Government.

In addition to the *Titanic* artifacts, the researchers found objects that came from at least two other sources, including a rudder from a World War II-era boat and a mast dating to the 1950s.

The giant's long life is coming to an end, Kristiansson determined. "We observed substantial disintegration due to melting," he said. "In five years, the Titanic iceberg will be no more."

- The International Ice Patrol was set-up to track icebergs alter the Titanic disaster.
- They use ships, planes, and satellites to track icebergs.
- Warnings by the patrol have saved many people from disasters like the Titanic.

At 2:17 A.M., the *Titanic*'s stern rose out of the water, reaching a near vertical position before the great ship disappeared under the sea. From the lifeboats, passengers heard a hideous noise as all the contents of the ship crashed forward. Several survivors reported seeing the ship begin to break apart.

# Role of Remote sensing in glacial hazard detection

**Synoptic View,**

**Spatial and Temporal data helpful in GLOF**

**Detection of Ice Movements using Optical and microwave data**

**Detection Recession using multidated satellite data**

**DEM (SRTM, ASTER DEM, or Photoogrammetric DEM) with satellite data very much useful hazards vulnerability mapping and Hazards preparedness**

**SAR interferrometry help in identifying deformation of ice sheets, amount of melt, rate of movements and associate with DEM, it is helpful to identify the direction of movement and what is the slope in the movement direction**

# Remote sensing techniques for glacial hazard detection

Several studies have demonstrated the suitability of multispectral satellite data for glacier mapping

Segmentation of ratio images (e.g., Landsat-TM channel 4 by 5) has proved to be a robust mapping method for firn and clean glacier ice

Difficulties arise in connection with debris-covered parts of a glacier or steep glaciers in shadow

To a much lesser degree, spectral properties have been used to detect certain features of the glacial and periglacial environment.

Thermal infrared ASTER channels were used to detect glacier ice partly covered by debris (Taschner and Ranzi, 2002).

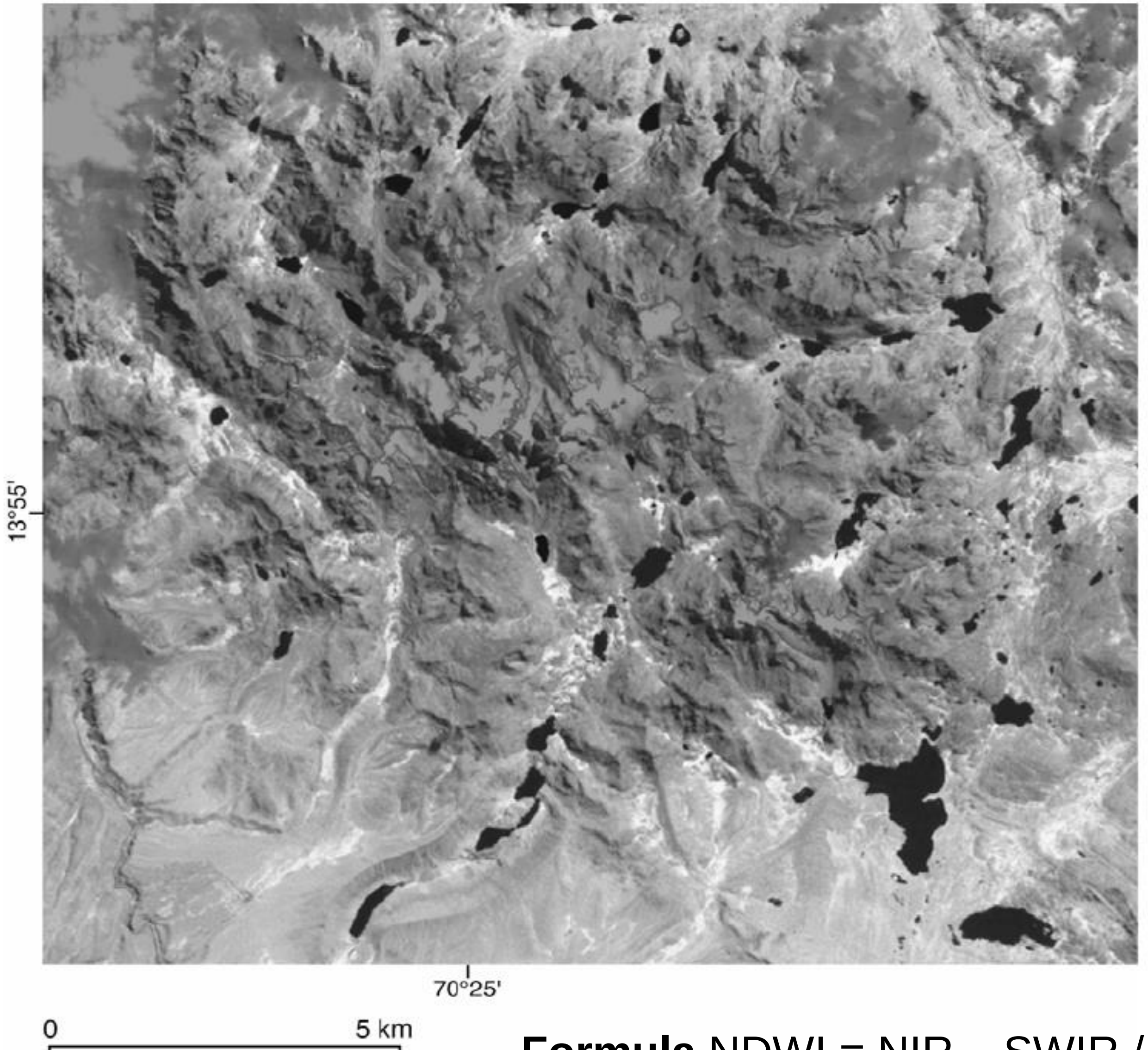
Air- and space-borne data in the microwave range of the electromagnetic spectrum have been used mainly for glaciological applications in the Arctic and the Antarctica and occasionally also for mountain glaciers.

A few SAR-based studies still exist on mass movements in high-mountain regions

| Type of hazard | Typical time periods involved | Examples of studies |
|---|---|---|
| Glacial lake | *Moraine-dammed lakes*: formation: years; trigger and outburst: days to minutes.<br><br>*Ice-dammed lakes*: formation: often seasonal cycles; trigger and outburst: days. | Monitoring of ice-dammed lakes (Kääb et al., 2003a; Paper II). |
| Ice avalanche | *Evolution of disposition*: years to seasons; acceleration of ice mass over weeks and days before failure; smaller events continuous. | Monitoring of hanging glaciers (Kääb, 1996; Paper IV); ground-based remote observations (Wegmann et al., 2003). |
| Debris flow | *Build-up of source zones*: decades to years; rainfall-related trigger and flow formation: hours to minutes. | Monitoring of rainfall for debris flow triggering (Wieczorek et al., 2003); source zone monitoring (Paper V); landslide motion (Yamaguchi et al., 2003). |

| | | |
|---|---|---|
| Rock slope instability | *Slowly accelerating rock masses*: years to months; *immediate failure*: days to hours | Space-borne remote sensing only for long-term monitoring (Strozzi et al., 2003); ground-based remote observations (Wegmann et al., 2003). |
| Glacier-clad volcanoes | *Immediate eruptive events*: weeks to days; *related glacier mass changes*: years to season. | Degassing and thermal monitoring, morphologic deformations (Harris et al., 2002; Wallace et al., 2003); related glacier monitoring (Huggel and Delgado, 2000; Julio and Delgado, 2003). |

Table 1: Different hazard types, relevant time periods and examples of related remote sensing-based monitoring studies.




**Formula** NDWI = NIR – SWIR / NIR + SWIR

Fig. 13: Example of lake detection using the NDWI, based on a 1999 Landsat ETM+ image of the Cordillera Carabaya in Southeast Peru. Lakes are marked black (from Huggel et al., 2003a).

**Detection of ice avalanche-prone glaciers starts with the classification of glacier areas. The ratioing algorithm dividing Landsat-TM channels 4 by 5 has proven to be a robust technique (Paul et al., 2002).**

**Paul (2004) has found that a channel ratioing of TM3/5 has better performance in areas of extended shadows**

**Debris flow activity of scree slopes can be evaluated by identification of existing debris flow channels, preferably using 1 to 2 m spatial resolution imagery (e.g., IKONOS or SPOT-5) due to small-scale flow structures.**

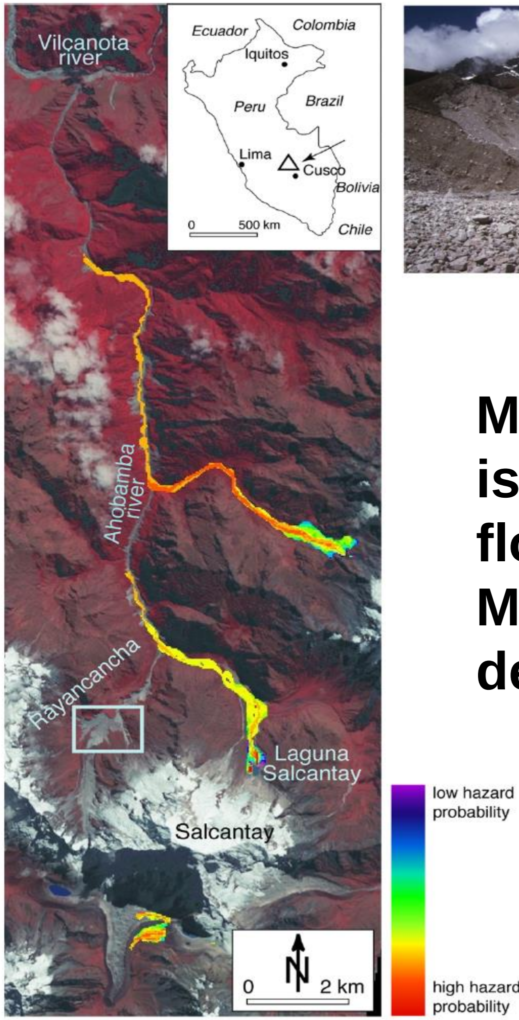
# Use of remote sensing-derived DEMs

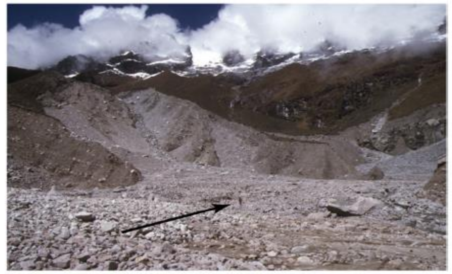
Terrain modeling significantly contributes to the detection of potential hazard zones in glacial and periglacial areas.

Satellite imagery-derived DEMs are of particular importance for remote regions

In a case study at Gruben, southern Switzerland, elevation errors of the ASTER-DEM (compared to a photogrammetric DEM) showed a root mean square error (RMSE) of about 18 m for a subset excluding mountain peaks and maximum error $< 25$ m around the debris flow trajectory

Potential ice avalanche trajectories and runout distances are modeled based on the detection of steep glaciers by remote sensing and terrain modeling techniques



**Modified Single Flow Direction (MSF) model, is based on the frequently used D8 single-flow-direction algorithm (O'Callaghan and Mark, 1984) which follows the steepest descent direction.**

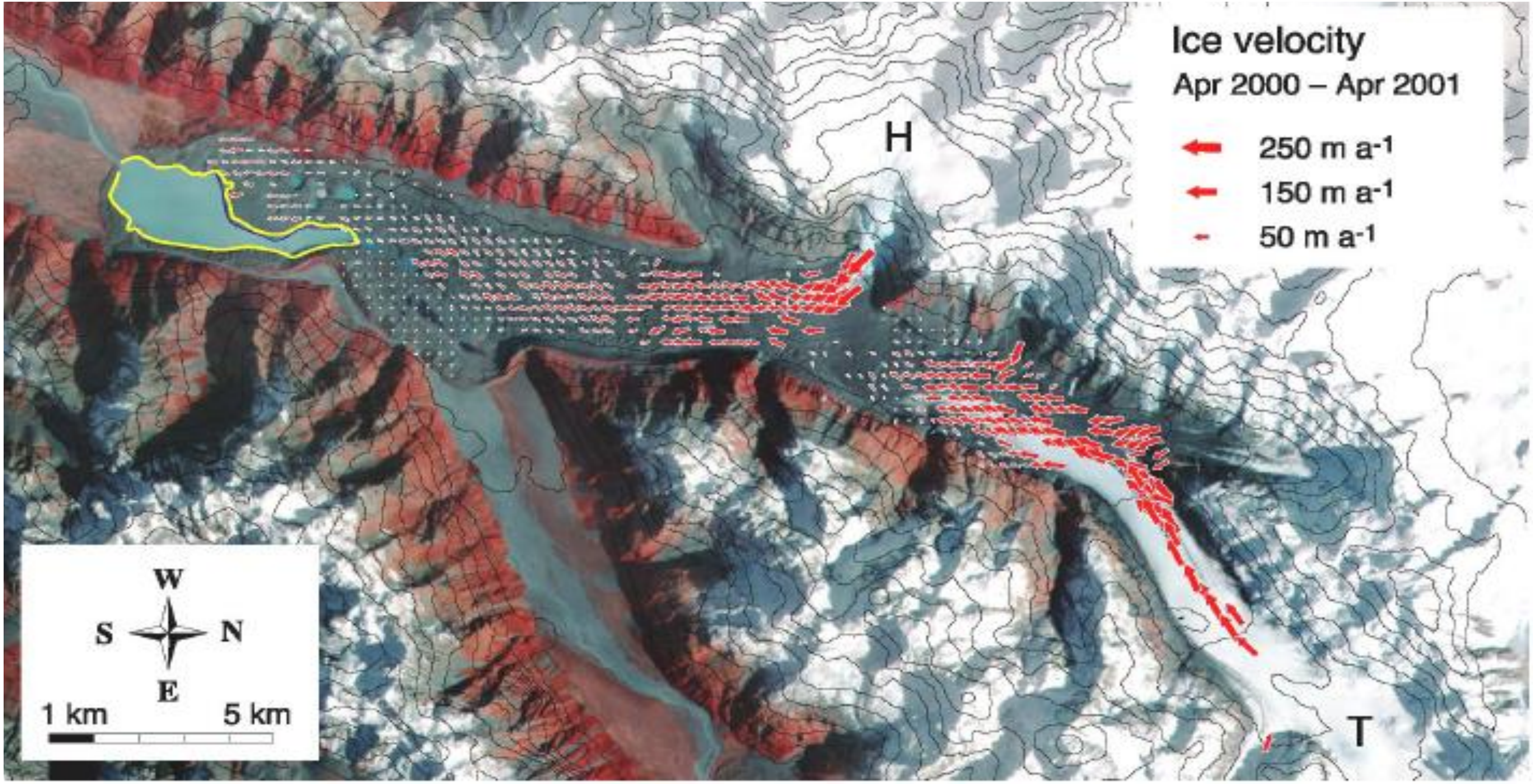
Fig. 14: Application of the MSF model in the Peruvian Andes based on ASTER image and stereo data showing two potential glacial lake outbursts. The models were part of a hazard assessment study for a hydro power plant (located at the upper end of the image), which was destroyed by a particularly large debris flow (in the order of 25 mill. $m^3$) in 1998. The event had its origin in the Rayancancha scar at ca. 4000 m a.s.l., traveled all along the Ahobamba river and eventually dammed the Vilcanota river. The Rayancancha scar is shown in the photo with a person indicating the scale. A glacial lake outburst is furthermore known from the Laguna Salcantay in 1996 (from Huggel et al., 2004; photo: Reynolds Geoscience Ltd., 2002).

# Ice velocity measurements

Concerning optical satellite data, horizontal displacements on glaciers have been measured mostly from repeated Landsat or SPOT data using different correlation techniques

For such work, the spatial resolution of the used images is the most crucial parameter, besides the time period between the acquisitions.

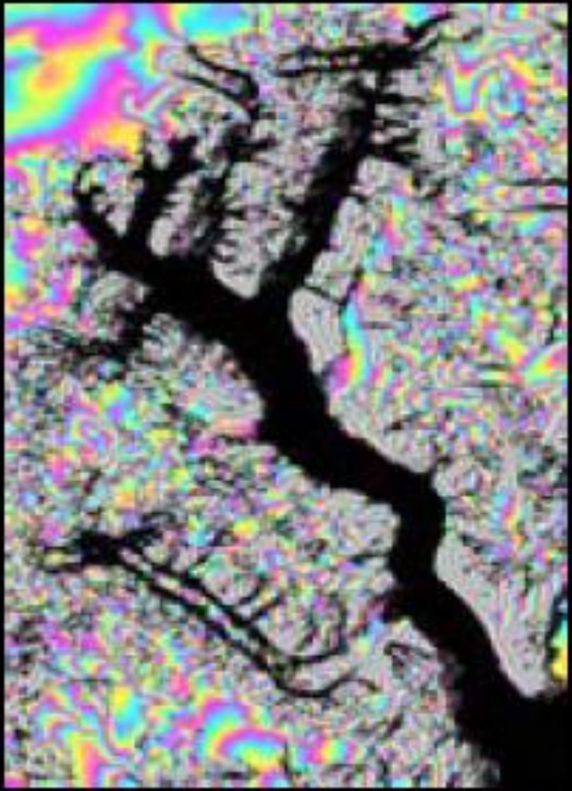
Multi-temporal orthoimages obtained from repeated ASTER imagery are used for measuring terrain displacements using a double cross-correlation technique (program CIAS)



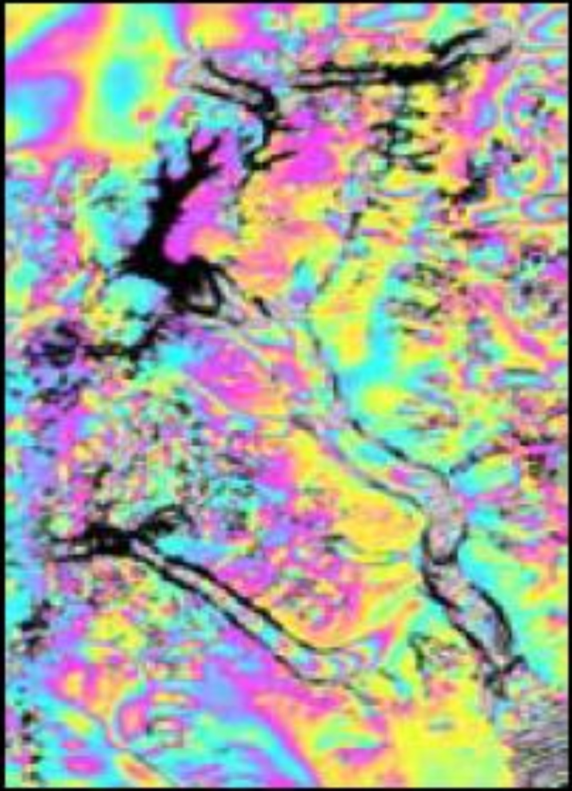

*Ice flow vectors for Tasman Glacier, New Zealand, superimposed on an ASTER image of 29 April 2000. Contour lines of 200m interval are computed from the according ASTER DEM. The ice-flow vectors have been derived from automatic image correlation between ASTER images of 29 April 2000 and 7 April 2001. Ice speeds amount up to 250 m $a^{-1}$. The striking decrease of ice flow for Tasman Glacier (T) at the confluence with Hochstetter Glacier (H) indicates a complex interaction between both glaciers. At the glacier terminus the yellow line marks the lake extent of 7 April 2001 superimposed on the 29 April 2000 orthoimage. The observed lake growth towards the ice front amounts up to 130 m.*

SAR DATA

# Interferograms



26 and 27 May 1995

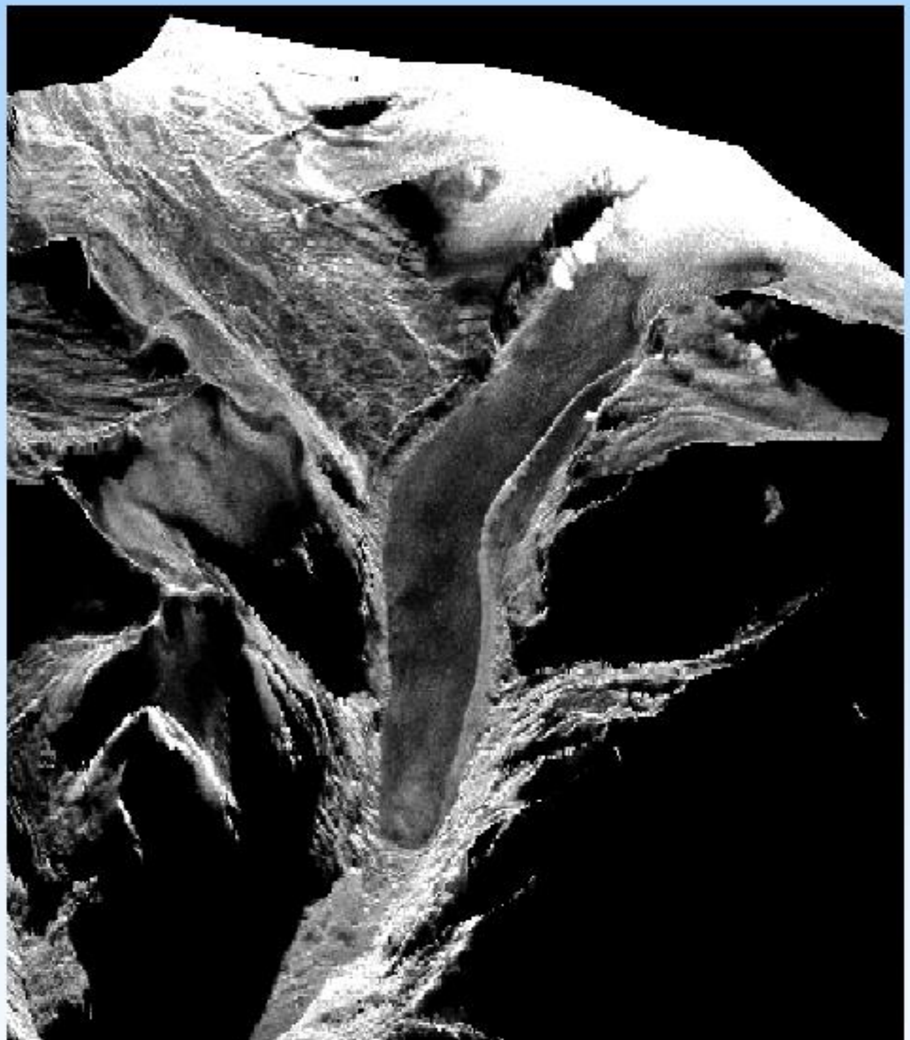


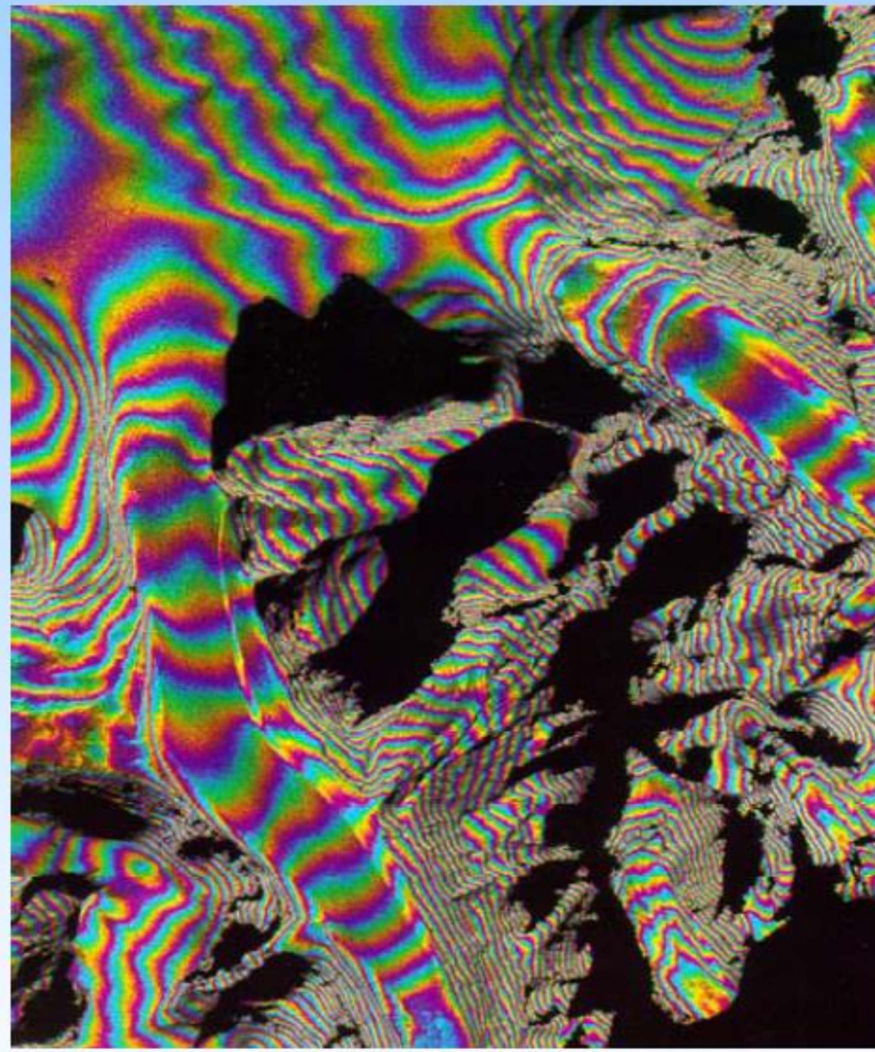
7 and 8 January 1996

Topography and displacement effects on the phase combined with coherence

Image 40 km x 60 km

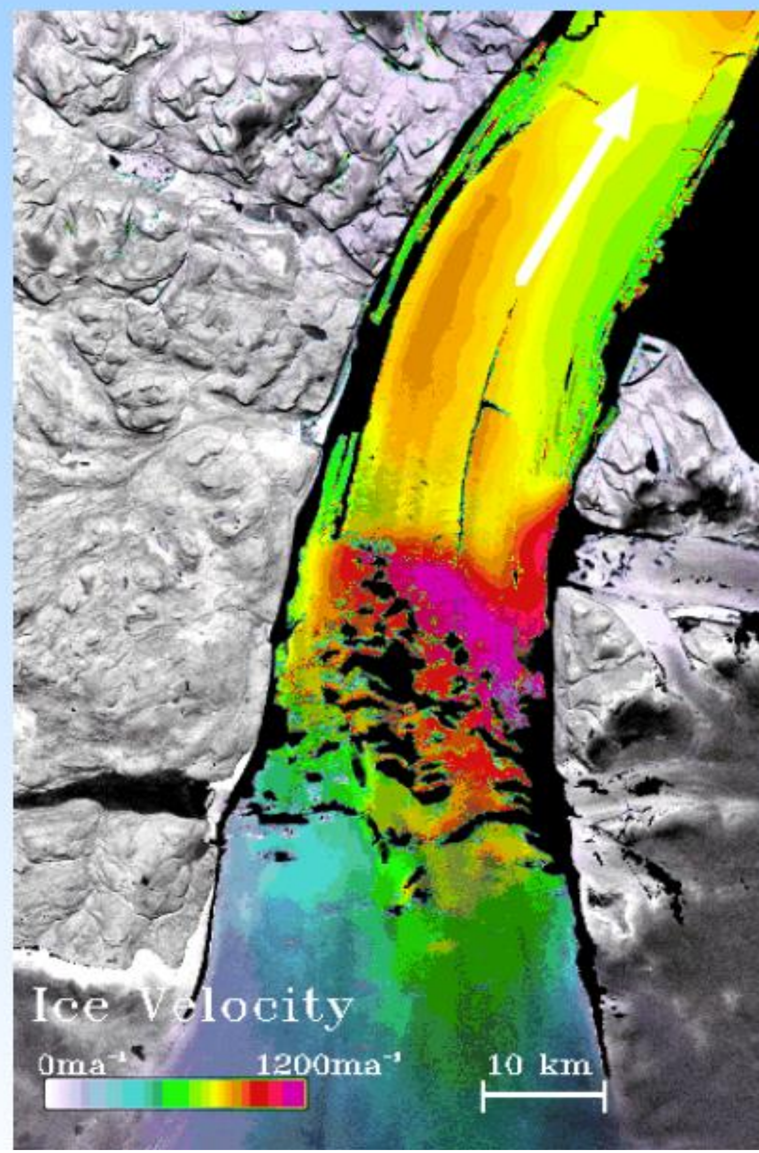
# Perspective View & DEM of Saskatchewan Glacier





**References:** Cumming, I., J.-L. Valero, P. Vachon, K. Mattar, D. Geudtner and L. Gray, 1996

# Glacier / Ice Stream Velocity Measurement

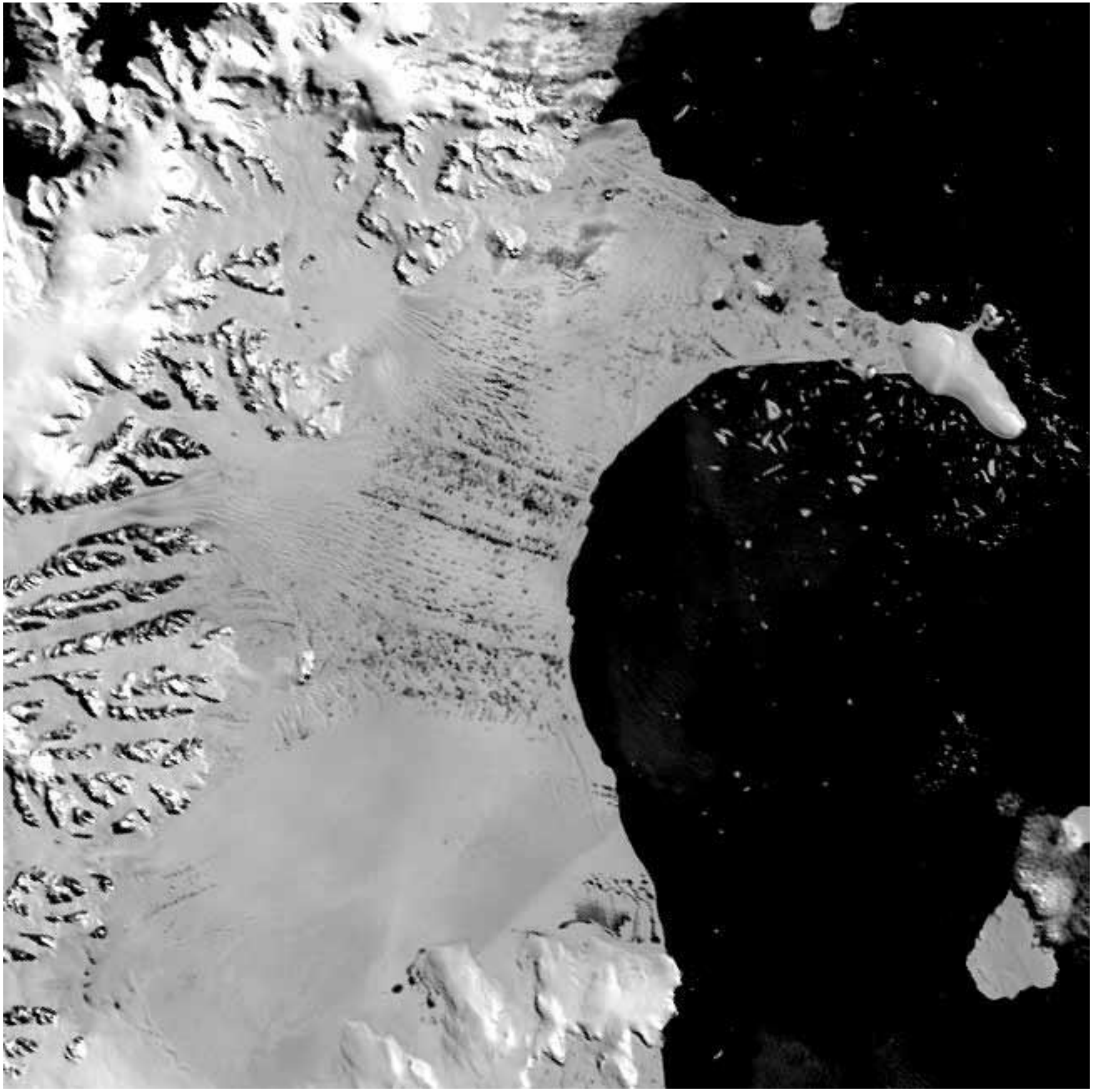



An outlet glacier in North-Eastern Greenland.

Only the moving parts of the scene have been coloured. The black areas are areas where the coherence was too low to process.

Image courtesy of
Prof. Howard Zebker,
Stanford University

***The Collapse of an Ice Shelf***
***Larsen B***
***Antarctic Peninsula***
***01/31/2002***



***The Collapse of an Ice Shelf Larsen B Antarctic Peninsula 04/05/2002***