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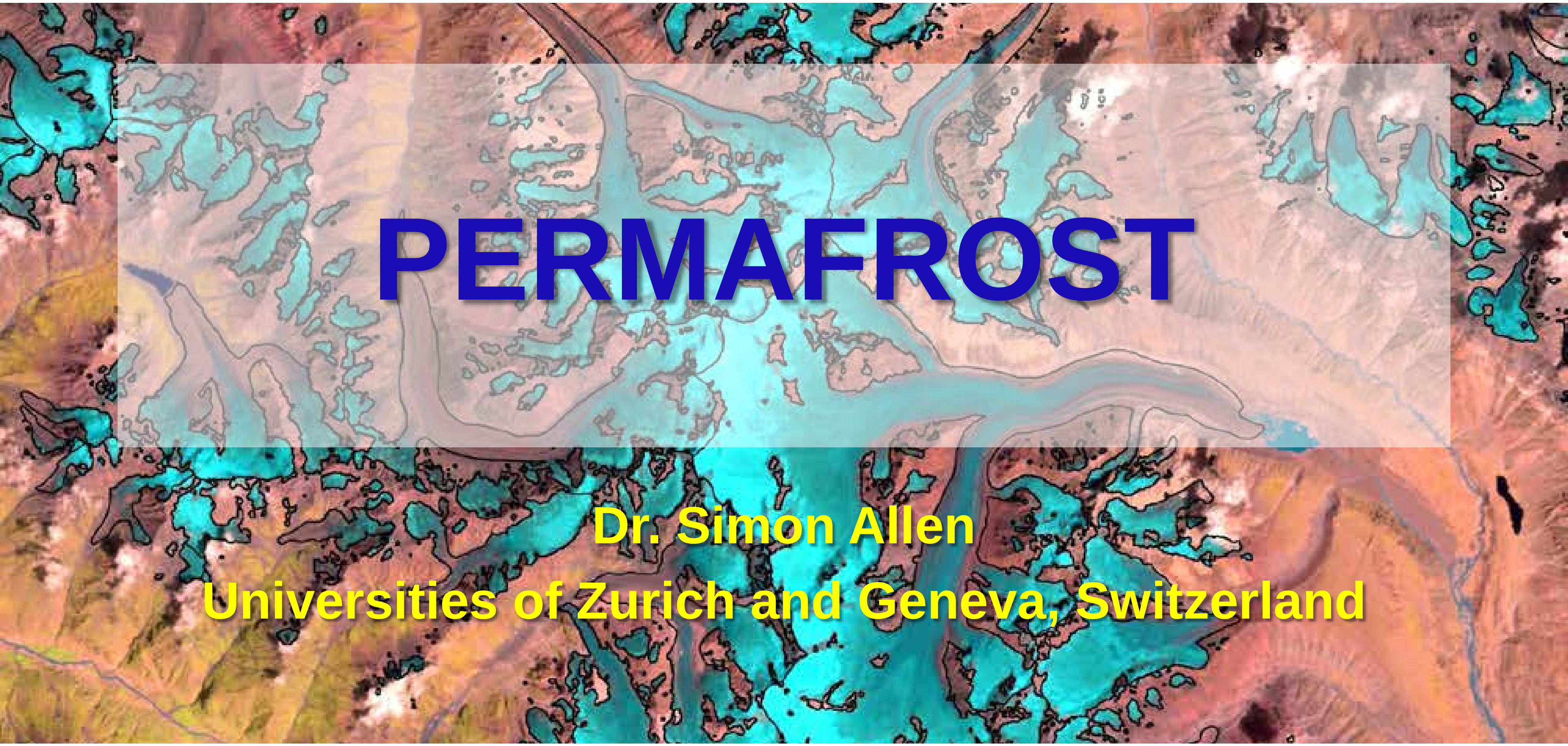


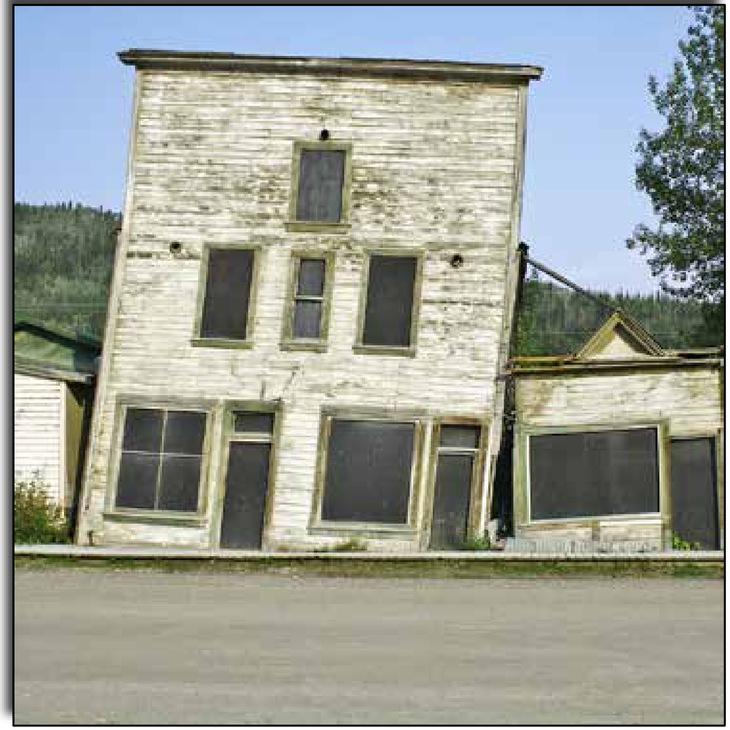
PERMAFROST

Dr. Simon Allen

Universities of Zurich and Geneva, Switzerland

IHCAP – Indian Himalayas Climate Change Adaptation Programme
Capacity building programme “Cryosphere” Level-1 (August 18 – September 15, 2014)

Earthquake?



Wind?

Man made?

A glacier?

Collapsing mountains?

Permafrost – part of the cryosphere

Program of the day

- An introduction to permafrost and terminology
- Conditions and occurrence of permafrost
  - High latitude permafrost
  - High altitude permafrost (mountain permafrost)
- Importance of permafrost, globally and locally
- Detecting and monitoring permafrost
- Modelling and mapping of permafrost distribution
- Rock glaciers
- Permafrost and rockfalls
- Permafrost in India

Permafrost Exercise

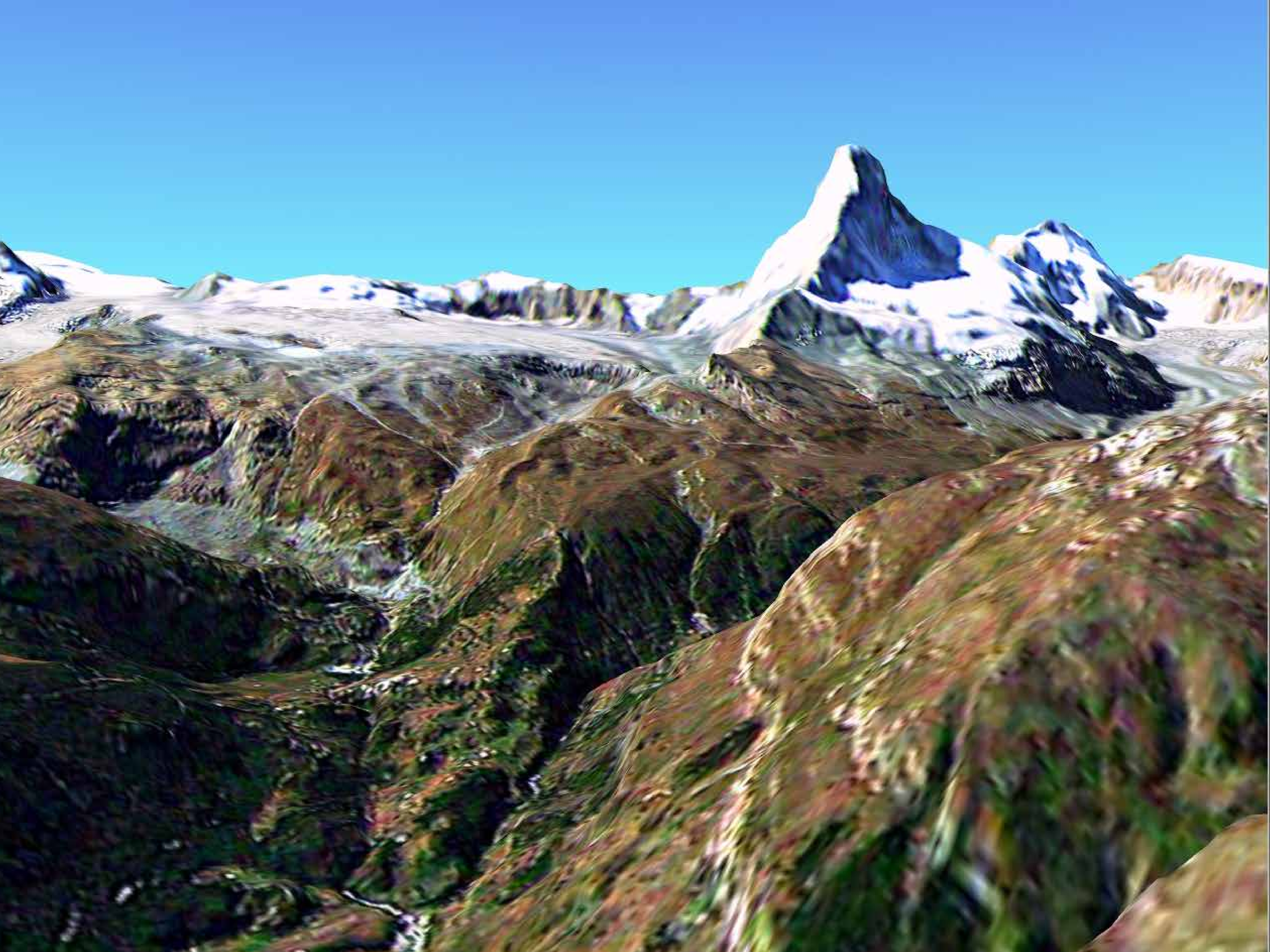
Introduction

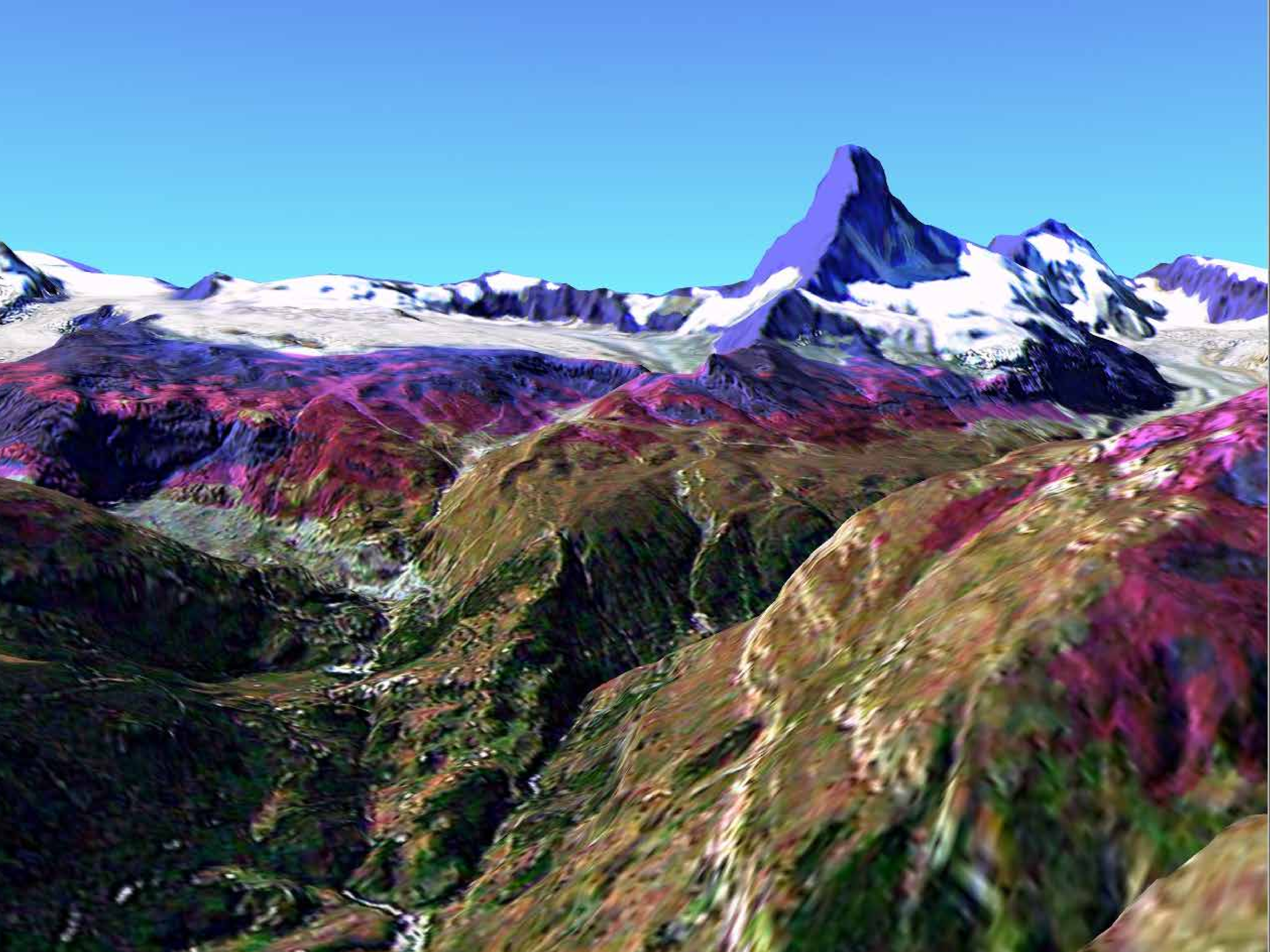
Definition :

Permafrost is a **thermal phenomena** and is defined as ground (soil or rock and included ice or organic material) that remains **at or below 0°C** for at least **two consecutive years**. The occurrence of permafrost does **not necessarily require the existence of ice**.

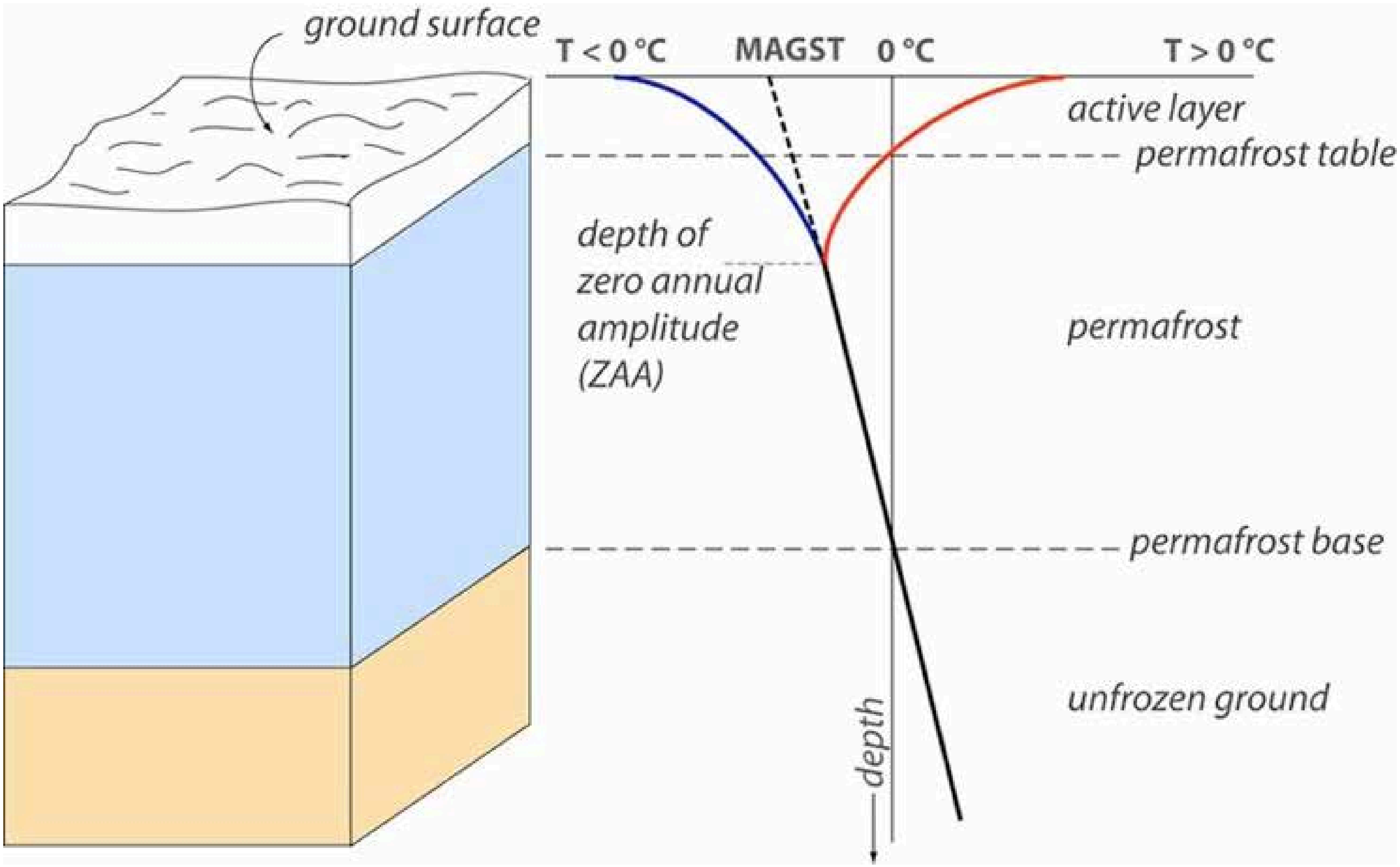
(International Permafrost Association)

- Defined through temperature not ice content!
- Not a glacier (but a transition zone glacier-permafrost exists)
- Invisible (observations and monitoring difficult!)

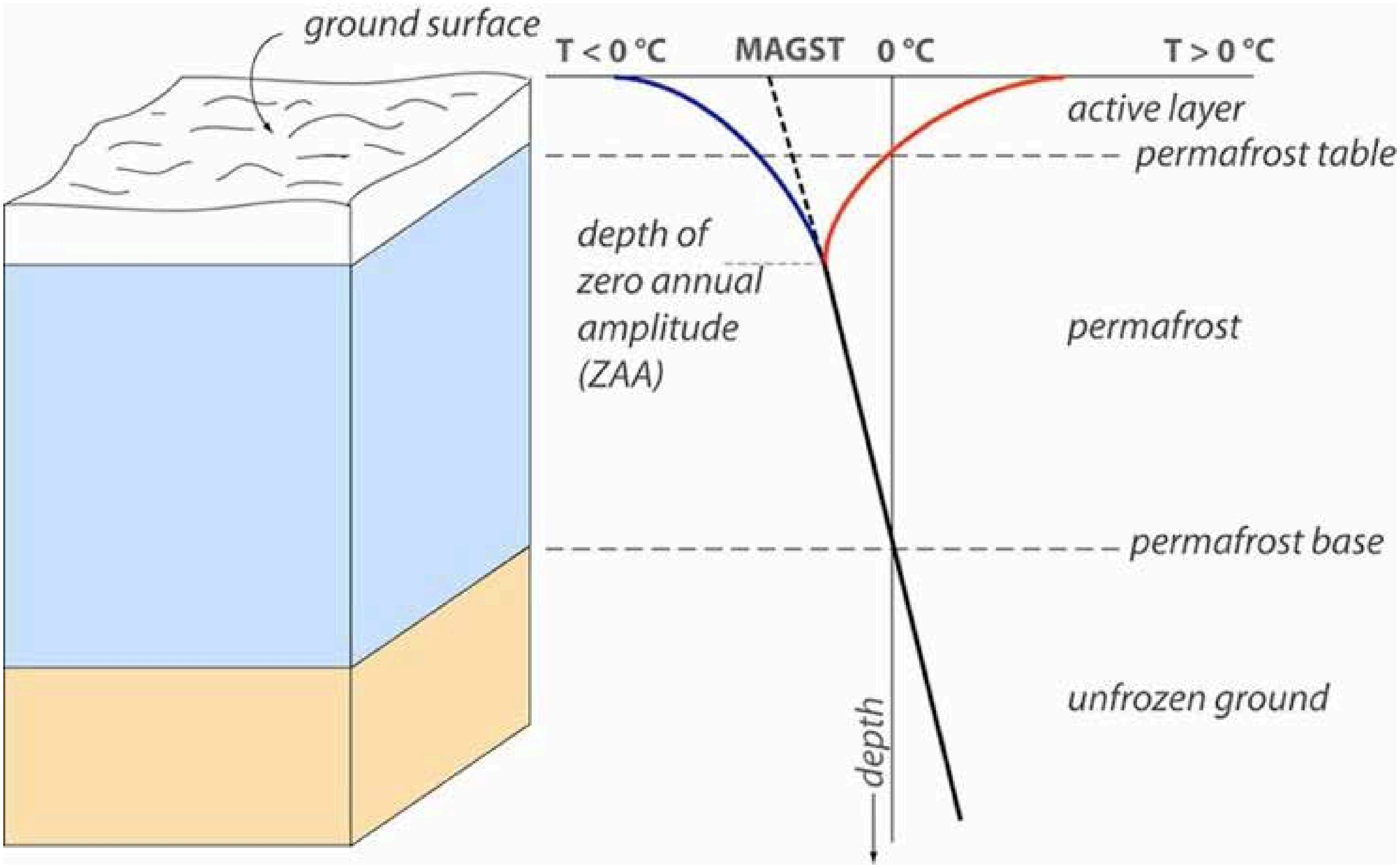




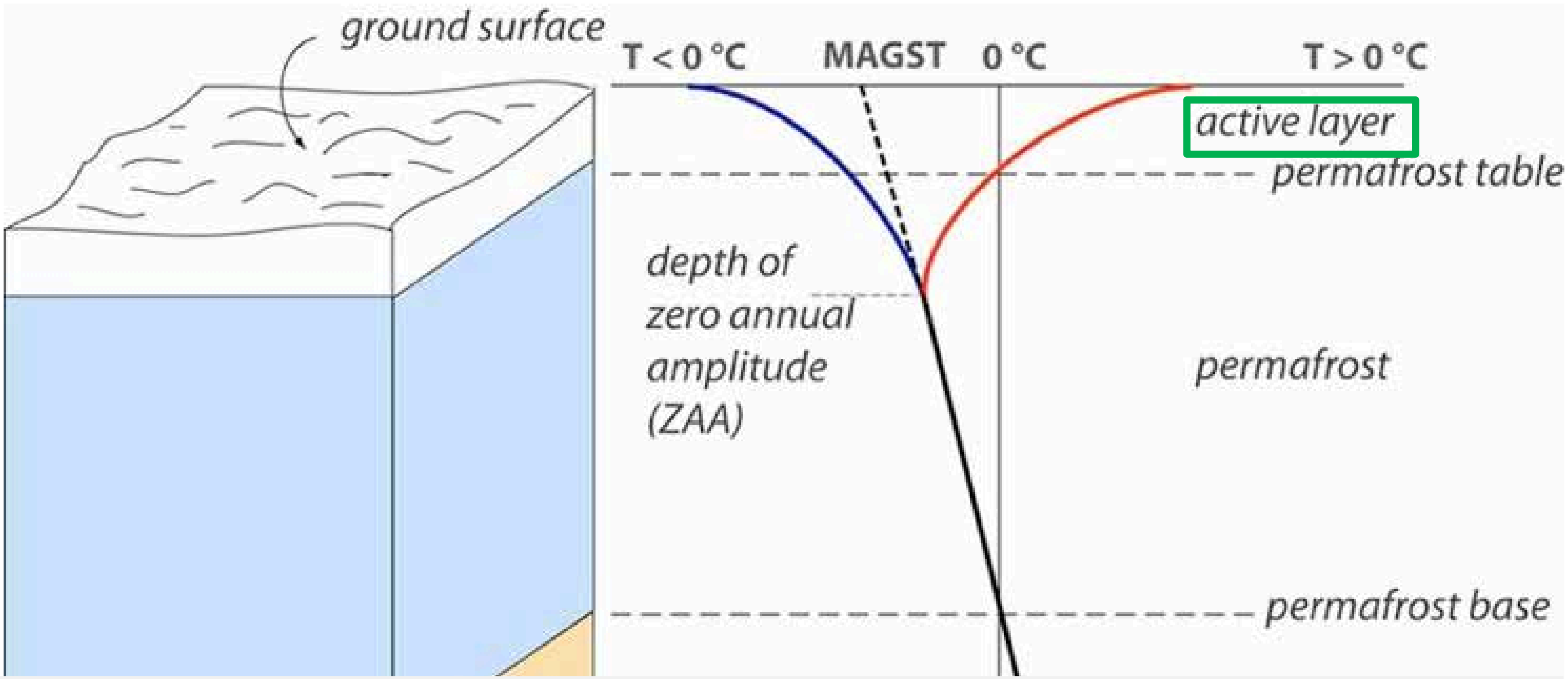
Introduction - terminology



Permafrost terms

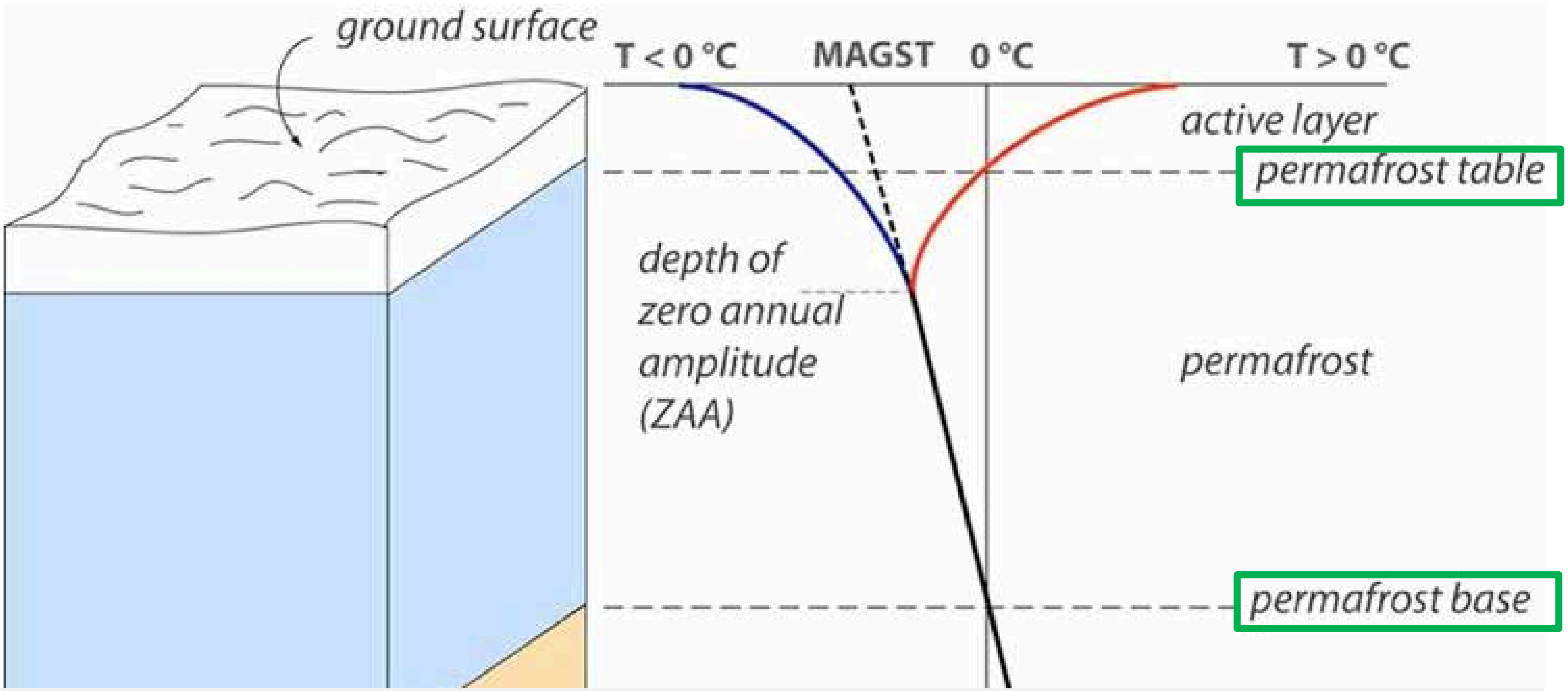


Introduction - terminology



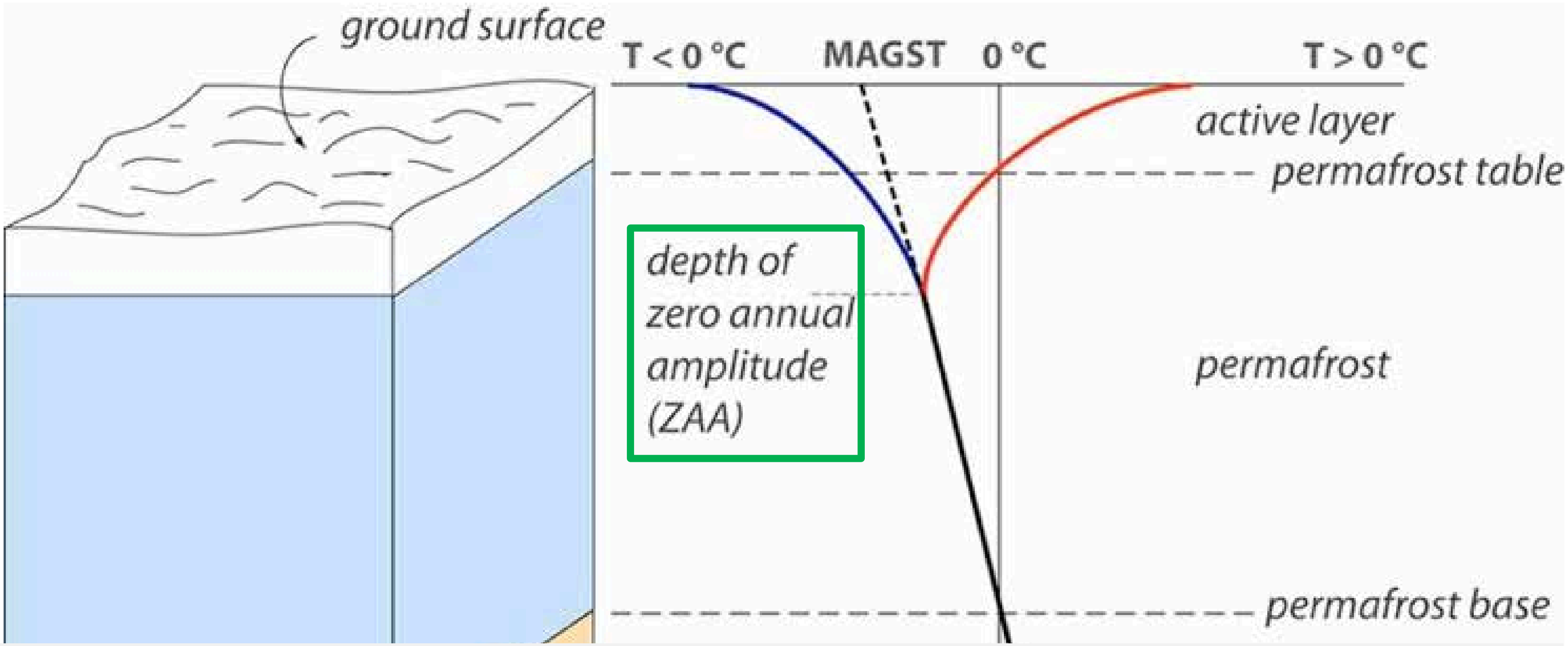
- The **active layer** is the top layer of ground surface that thaws during the summer and freezes again during the autumn (cm to a few metres thick)
- Changes in active layer thickness are influenced by many factors, including surface temperature, physical and thermal properties of the surface cover and substrate, vegetation, soil moisture and duration and thickness of snow cover.

Introduction - terminology



- Permafrost is bounded on the top by the **permafrost table** and on the bottom by the **permafrost base**.
- The depth to the permafrost base depends on a balance between freezing from the surface and warming from the Earth's interior.

Introduction - terminology



- The depth of **zero annual amplitude** is where the permafrost temperature has no seasonal variation at all. Permafrost temperatures below the depth of zero annual amplitude reflect long-term changes in average climate conditions.

- The depth of zero annual amplitude varies from a few meters in discontinuous permafrost to 20 meters or more in continuous permafrost or in bedrock.

Conditions and occurrence

- The distribution of permafrost is controlled by air temperature (latitude, altitude) and to a lesser extent by site specific surface and subsurface characteristics (e.g. snow depth, vegetation, topographic exposition and soil properties)
- Any location with mean annual air temperatures (MAAT) below freezing can potentially build permafrost.
- About 20% of the global surface is characterized by permafrost.
- The thickness of permafrost varies from less than one meter to more than 1500 meters.
- The presence of permafrost is often creates impressive landforms (‘indicators’).

Conditions and occurrence

- -> high latitudes:

  e.g. Pingos

- -> high altitudes:

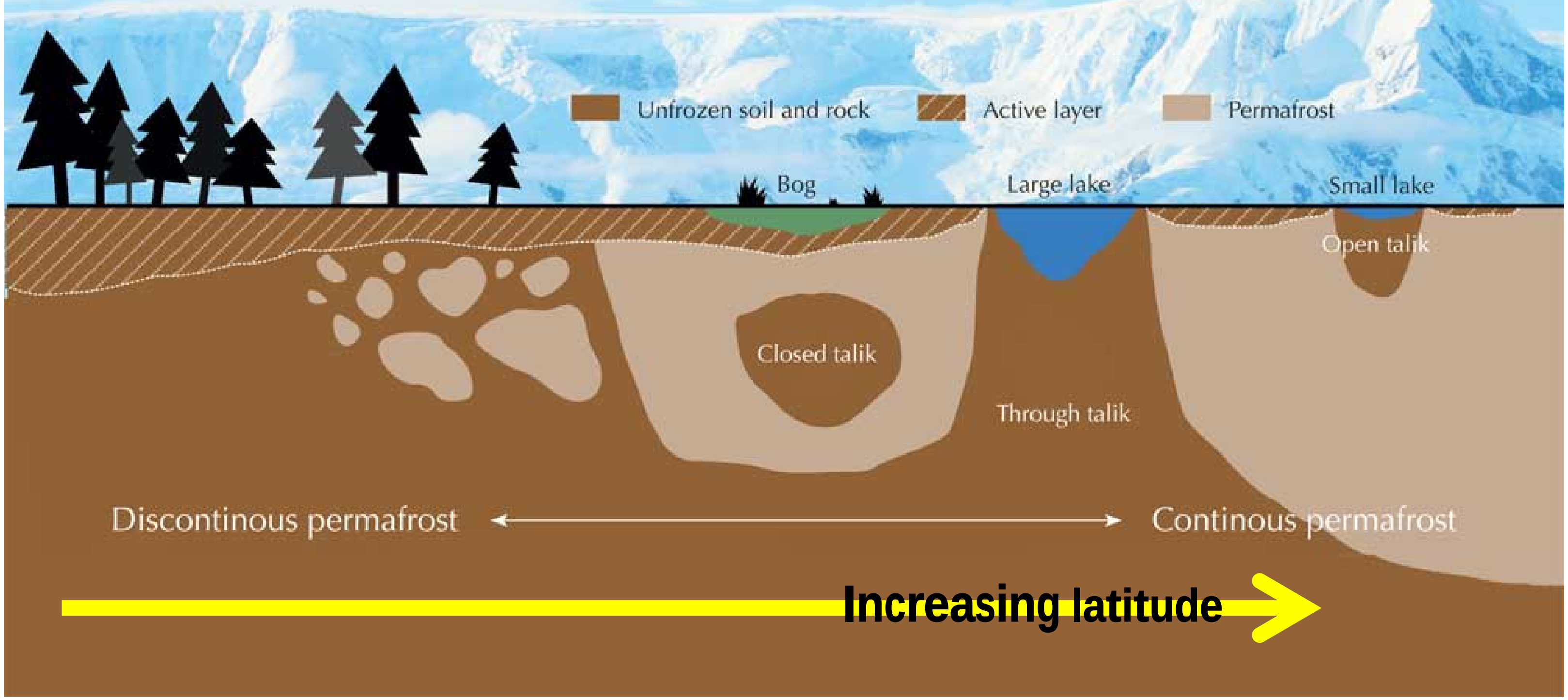
  e.g. rock glaciers

Occurrence – global perspective

Permafrost regions are classified into three zones:
Continuous permafrost *zones have permafrost underlying 90-100%* of the land area; ***discontinuous permafrost*** *zones have* 50-90%; and ***sporadic permafrost*** *10-50%.*
Isolated patches *refer to regions where permafrost underlies less* than 10% of the land area.

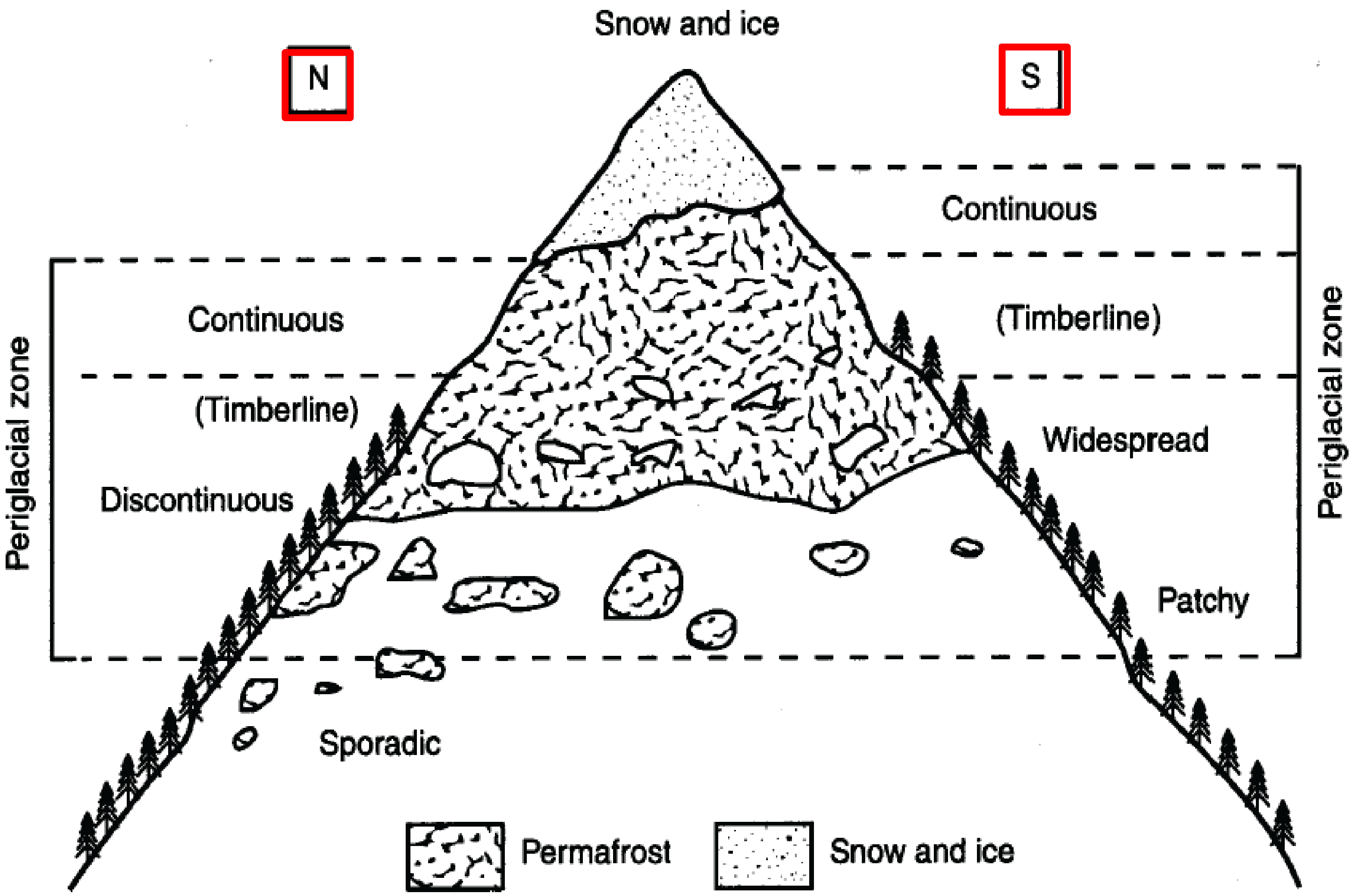
Occurrence – high latitude permafrost

- The coldest, and deepest permafrost generally occurs at the highest latitudes where air temperatures are lowest



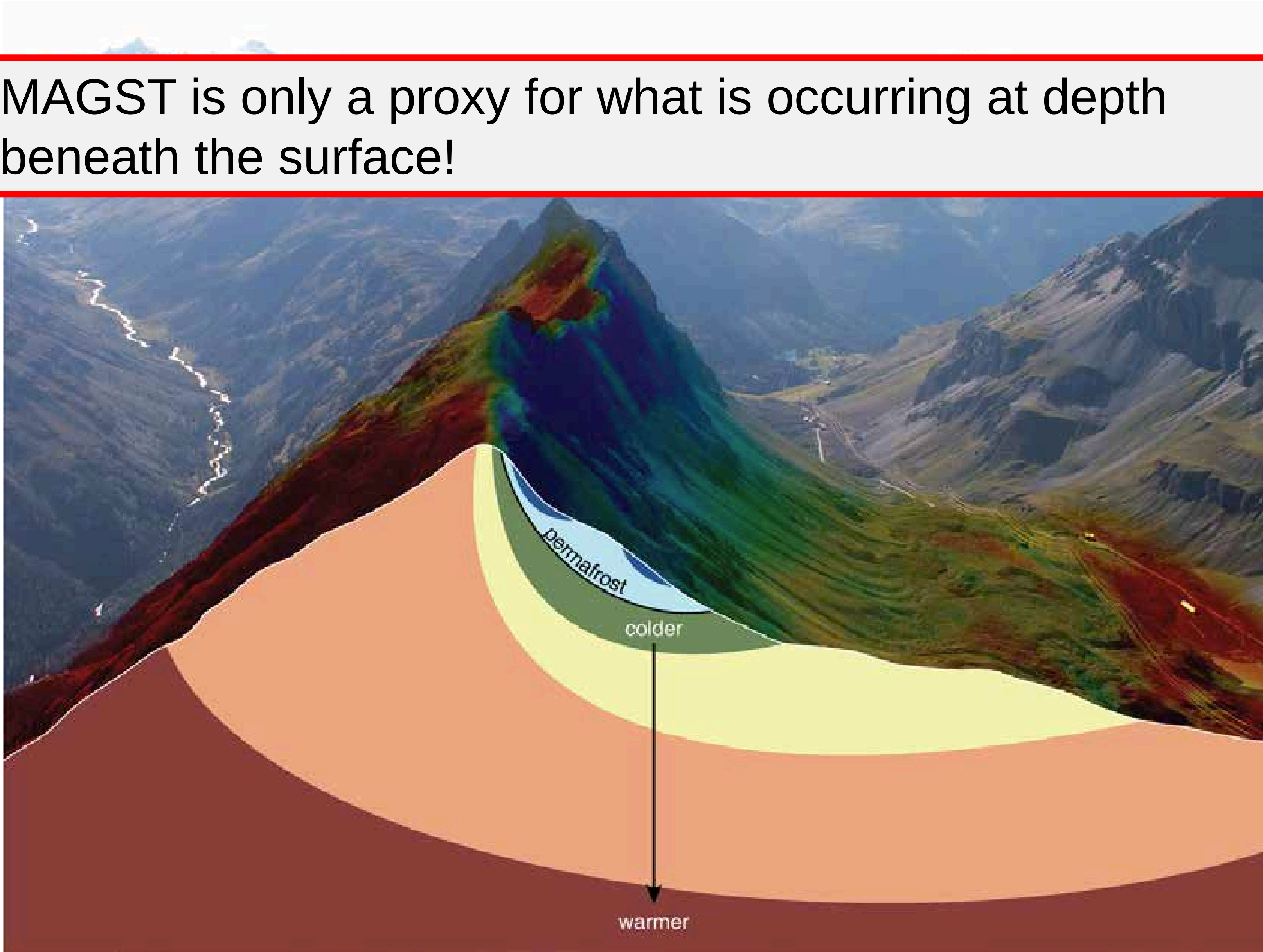
- A **talik** is a layer or body of permanently unfrozen ground in a region of permafrost

Occurrence – high altitude permafrost



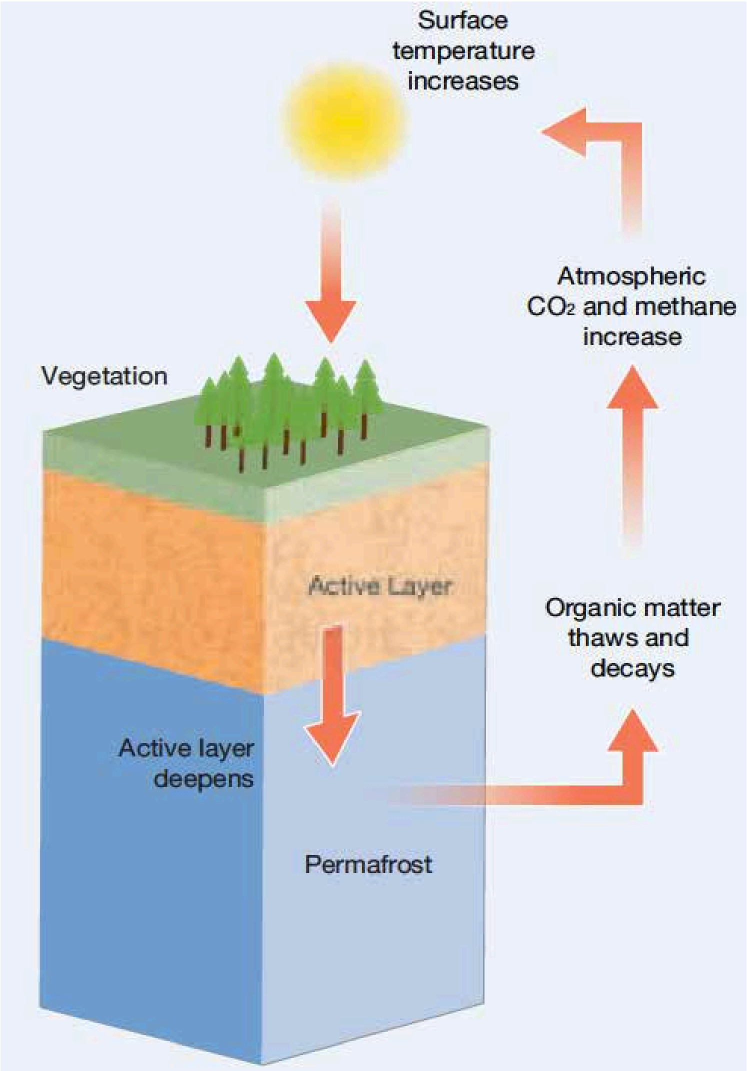
Occurrence – high altitude permafrost

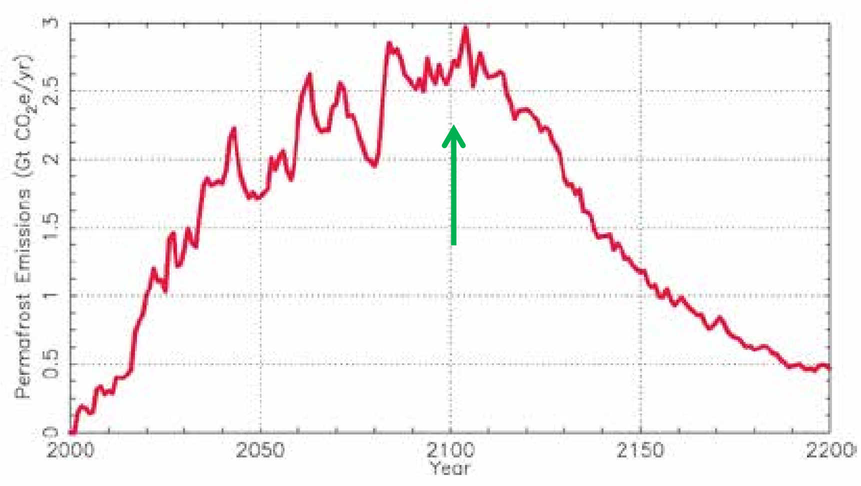
MAGST is only a proxy for what is occurring at depth beneath the surface!



Importance of permafrost

1) Permafrost carbon-climate feedback:





- CO_2 and methane emissions from thawing permafrost can continue for decades or even centuries after anthropogenic emissions have stopped.
- One recent study has estimated permafrost thawing could result in an additional global warming of 0.13–1.69 °C by 2300

Importance of permafrost

2) Construction and infrastructure:

Importance of permafrost

3) Natural hazards from thawing:

- Rockfalls and other mass movements in mountain areas

Permafrost important both in a global and local context!

- Erosion of coastlines in high latitude permafrost areas

TO REMEMBER:

- Permafrost found in both high latitudes (eg, Arctic), and in high alpine environments (eg, Alps, Himalaya).
- Permafrost zones defined as continuous, discontinuous, sporadic, or isolated patches.
- Permafrost terrain has a vertical structure which includes:
  - Active layer
  - Permafrost table and base
  - Depth of zero annual amplitude
- Permafrost thawing may enhance climate change, hazards, and engineering problems.

Permafrost monitoring

Direct methods:

- Digging and uncovering ground ice
- Boreholes and temperature measurements

Semi-direct methods:

- Geophysical methods
  - Geoelectric: ERT (Electrical Resistivity Tomography)
  - Seismic: RST (Refraction Seismic Tomography
  - Radar: GPR (Ground Penetrating Radar)

Permafrost monitoring

Direct methods:

- Digging ground ice (mostly during construction work)

Permafrost monitoring

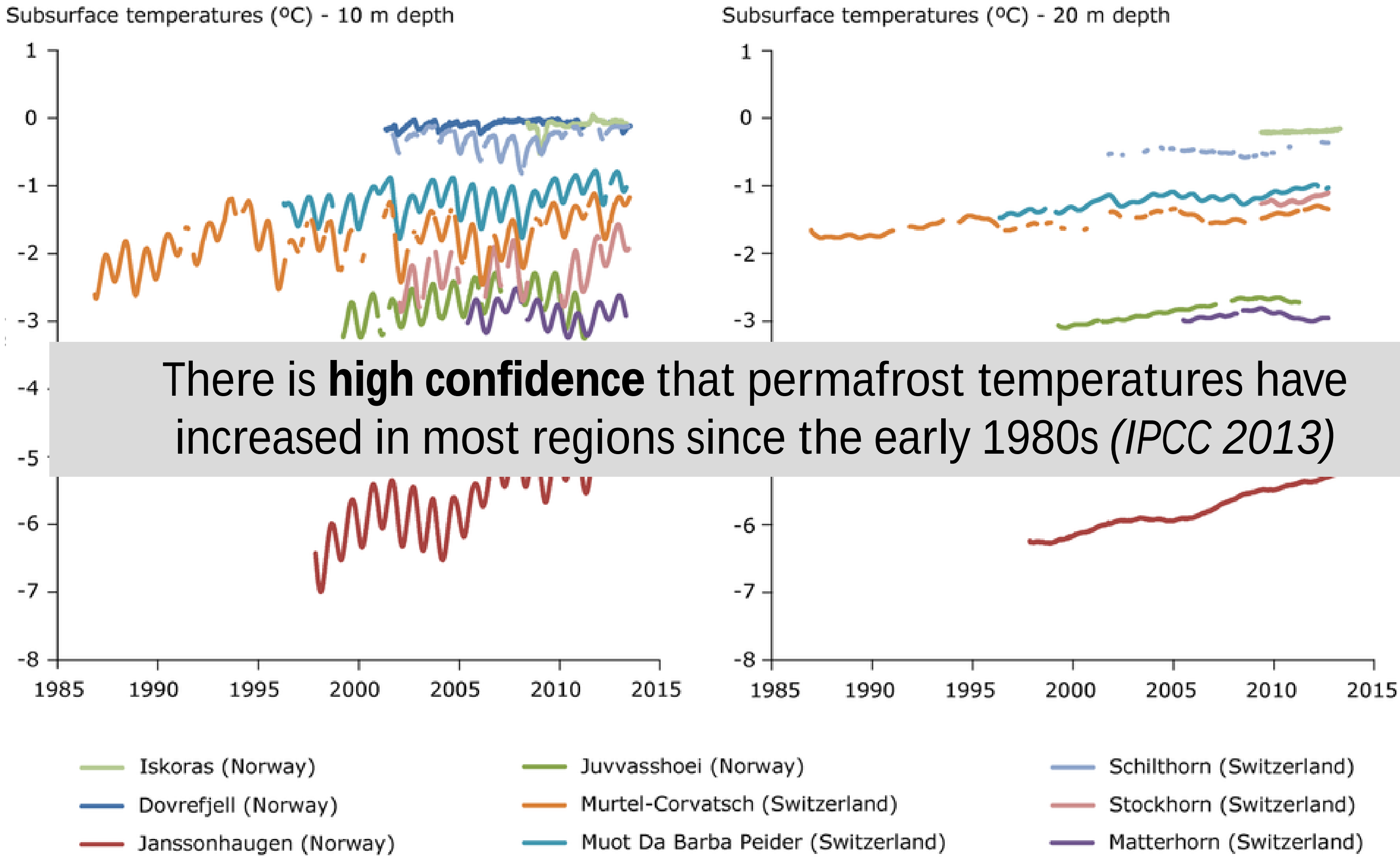
Direct methods:

- Drilling boreholes (temperature chain)

Permafrost monitoring

Direct methods:

- Drilling boreholes (temperature chain)



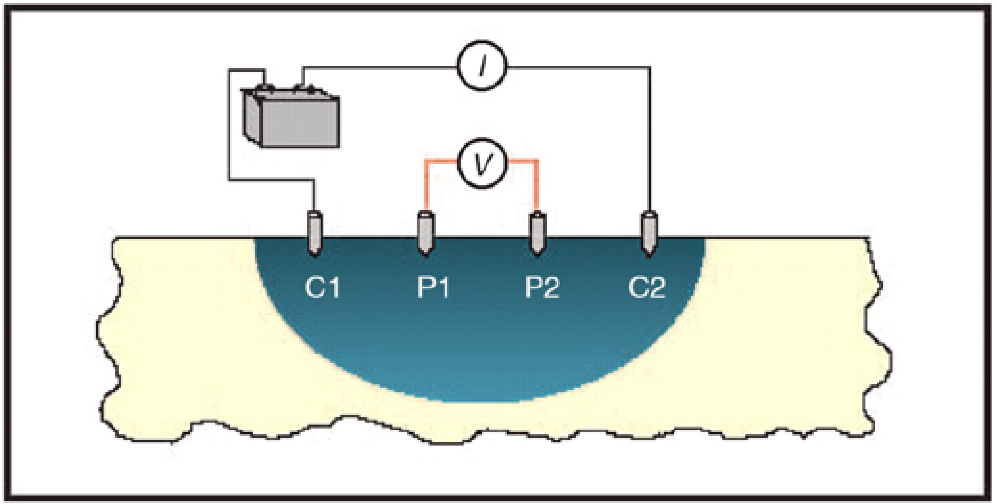
There is **high confidence** that permafrost temperatures have increased in most regions since the early 1980s *(IPCC 2013)*

Permafrost monitoring

Semi-direct methods:

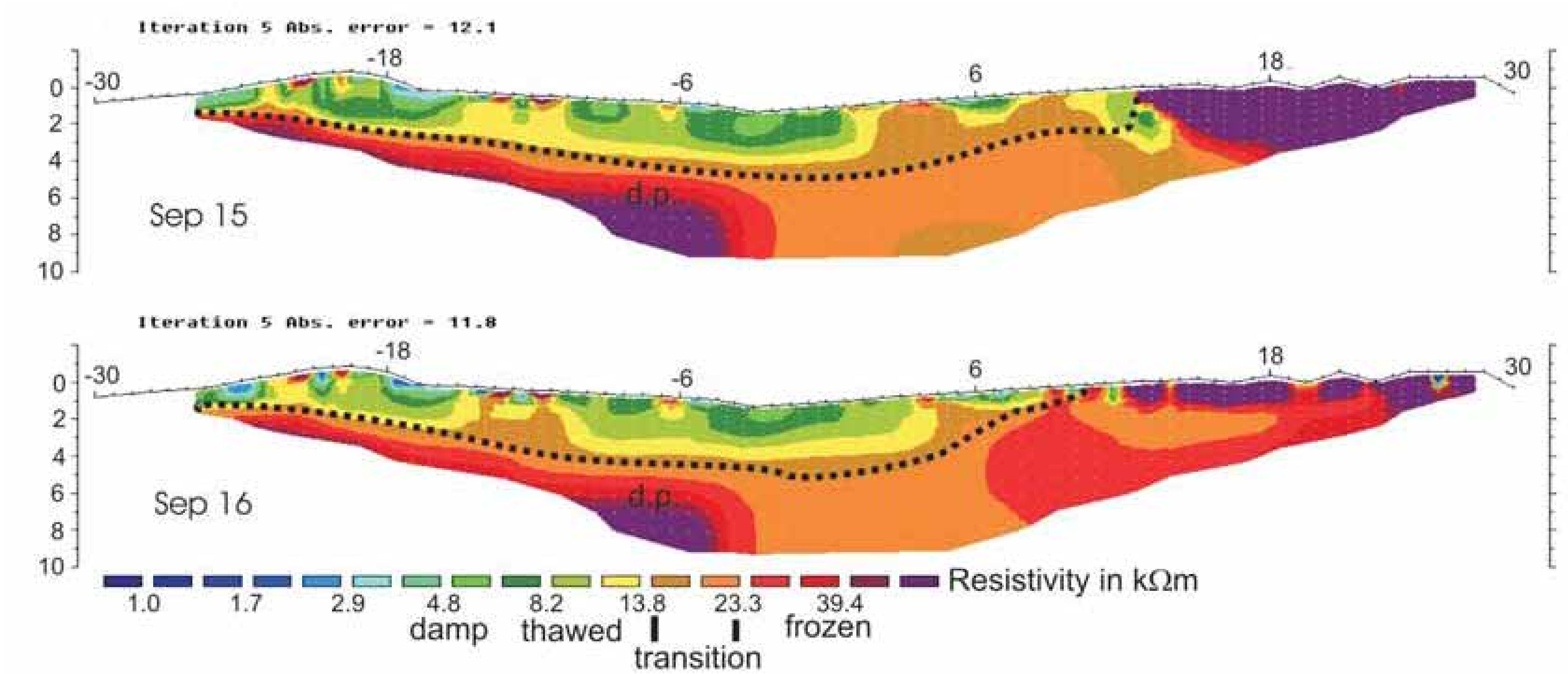
- Geophysical methods

  1) Geoelectric: ERT (Electrical Resistivity Tomography)



- ERT is a geophysical technique for imaging sub-surface structures based on electrical resistivity beneath the surface.
- Basically tells us how difficult it is to pass an electrical current through the sub-surface material.

ERT (Electrical Resistivity Tomography)

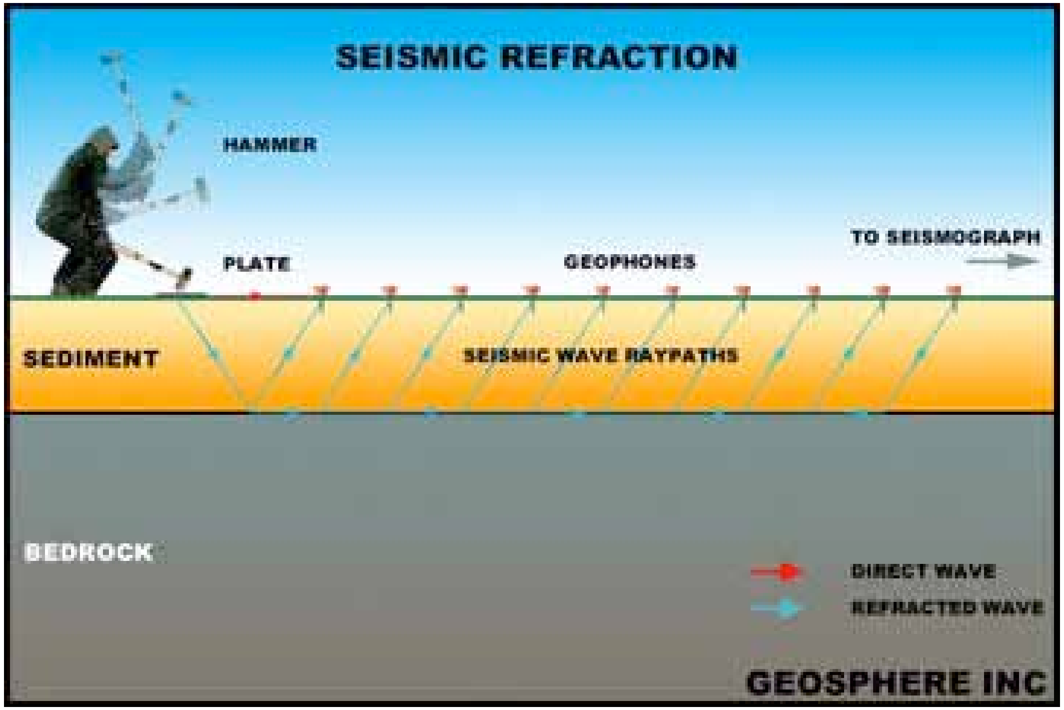


- Detection and mapping of horizontal extent of discontinuous permafrost and the depth of the active layer.
- Indication and delineation of massive ground ice.
- Estimation of ice and unfrozen water content.
- Monitoring the temporal evolution of permafrost and transient processes.
- Has the broadest potential from all applied methods.

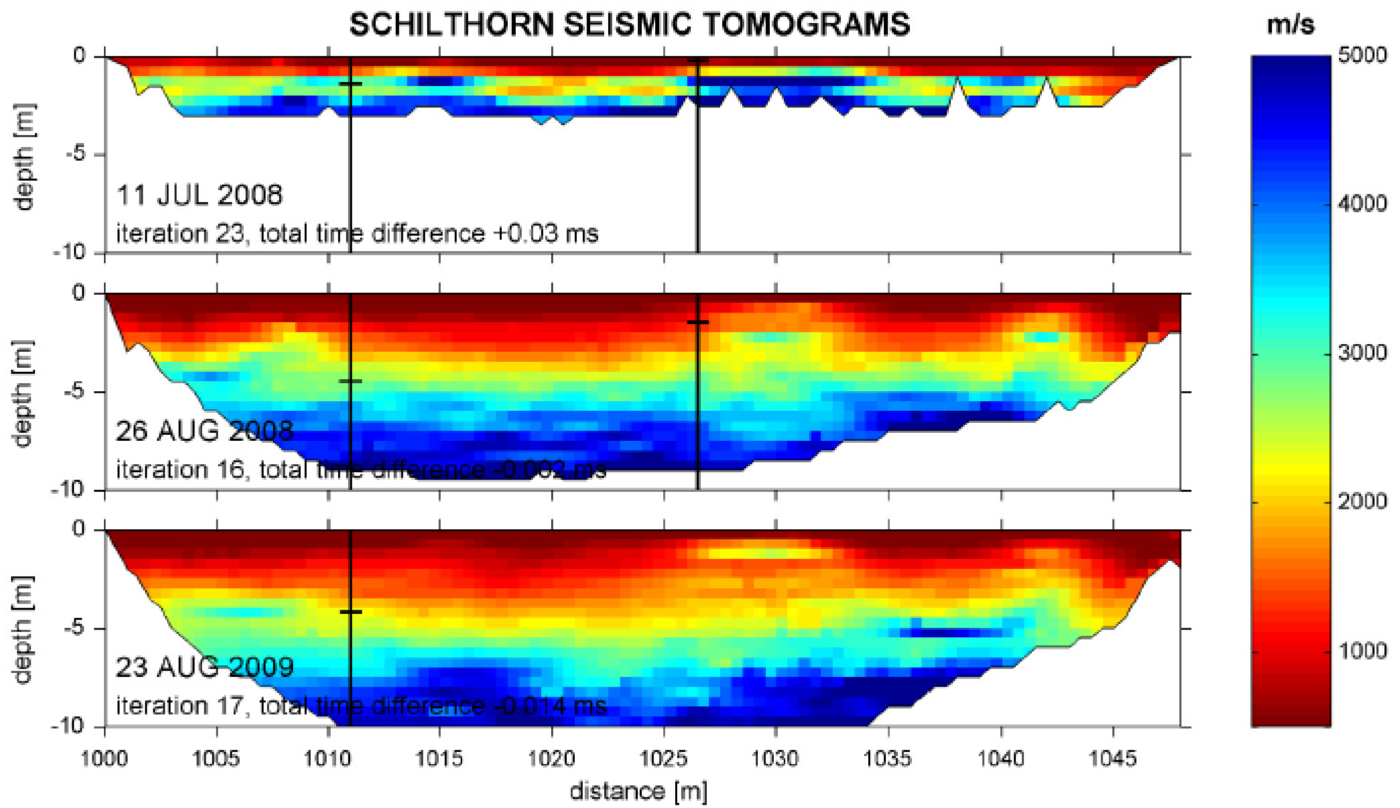
Permafrost monitoring

Semi-direct methods:

- Geophysical methods
  2) Seismic: RST (Refraction Seismic Tomography)



RST (Refraction Seismic Tomography)



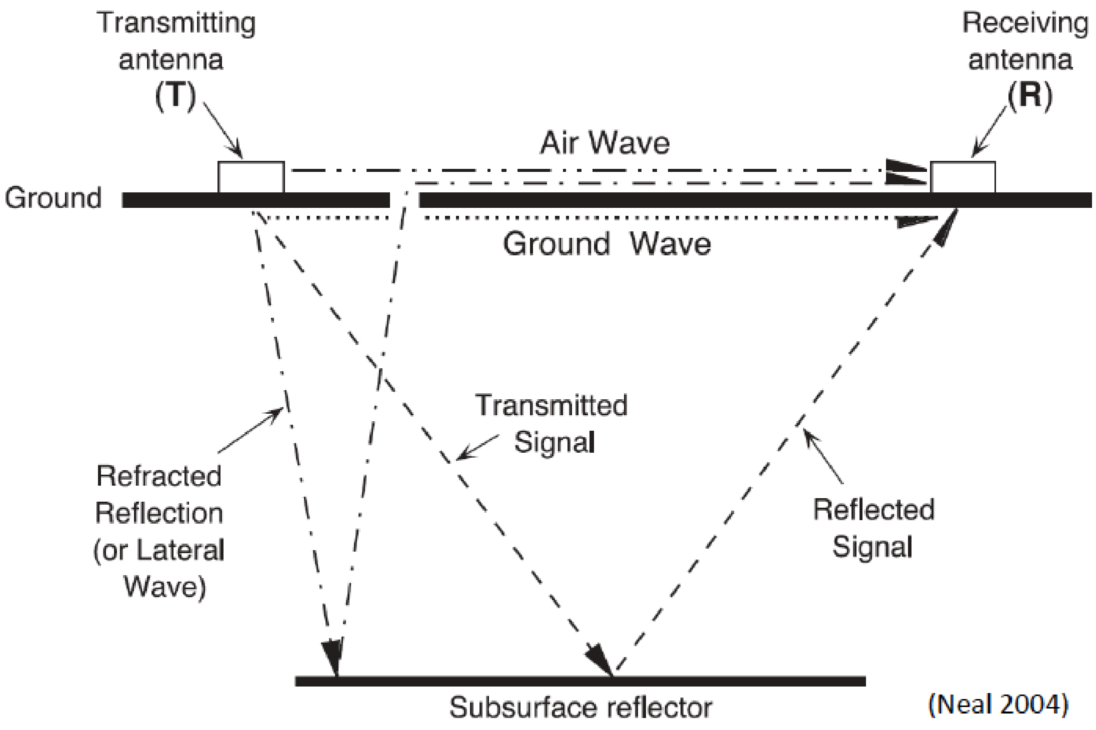
- Considered to be a valuable additional method to verify subsurface structures identified by ERT.
- Determination of the lateral distribution of frozen ground and active layer thickness.
- Greater depth resolution than ERT.

Permafrost monitoring

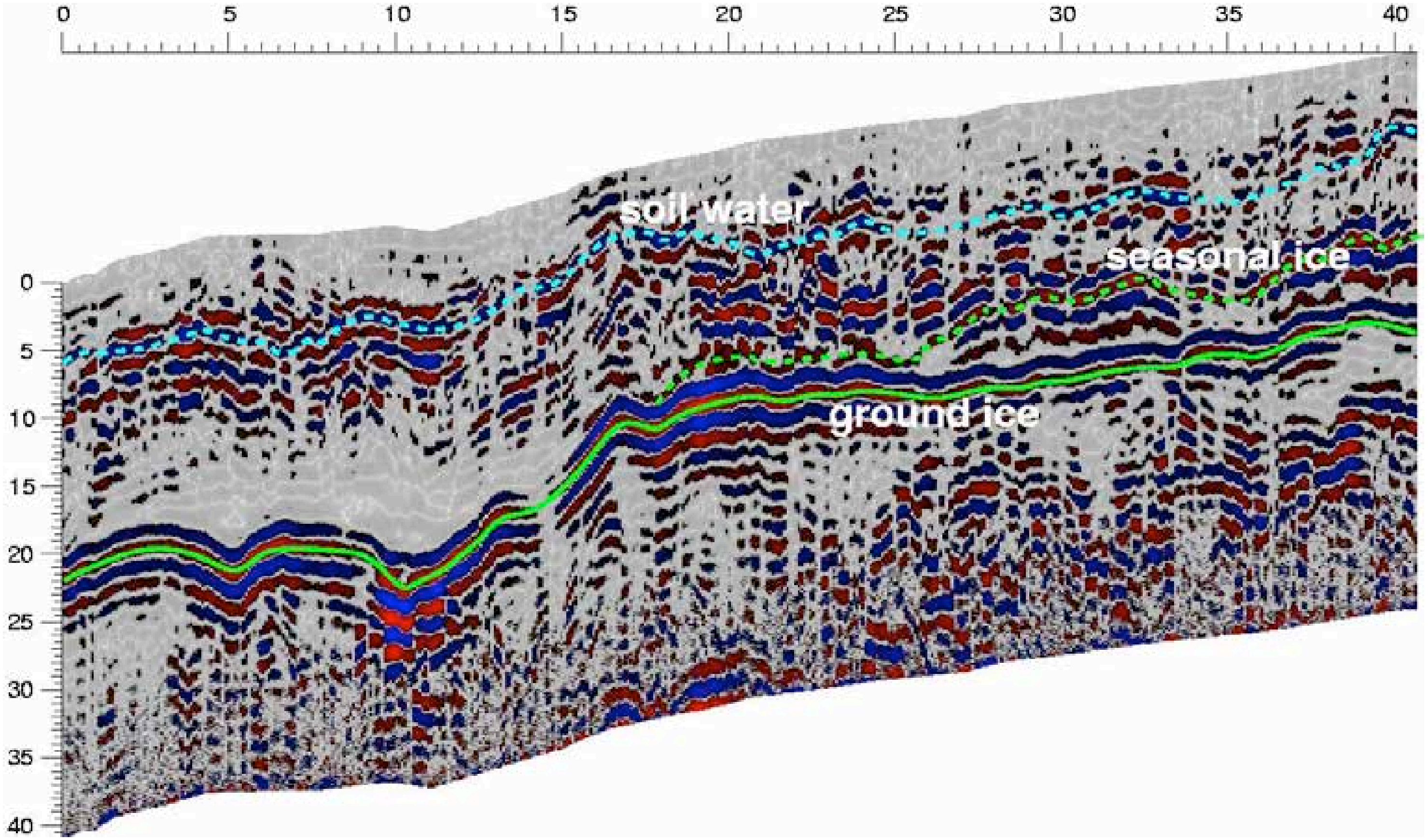
Semi-direct methods:

- Geophysical methods

  3) Radar: GPR (Ground Penetrating Radar)



GPR (Ground Penetrating Radar)



- A fast (cheap) survey method that does not need direct contact to the ground.
- Can identify massive ground ice.
- Depth limited by subsurface structure (clays, moisture, etc).

Permafrost monitoring

Some general conclusions:

- Only point or local scale measurements
- Generally expensive and requiring specialized equipment and expertise
- Time consuming
- Often dangerous (steep rock walls)
- For large remote areas not applicable

https://www.youtube.com/watch?v=LmEC0NwqSSY

Modelling permafrost distribution

Overview:

- Permafrost models estimate the ground temperature, either by using relationships between the MAGST and scale-depending factors governing permafrost distribution (**empirical-statistical models**) or they calculate the ground temperature directly (**physically based process-oriented models**).

Modelling – Empirical approaches

Empirical-Statistical models (evidence based):

- Empirical-statistical models directly relate documented occurrences of permafrost to topo-climatic factors which can be easily measured or computed (altitude, slope, aspect, MAAT, potential solar radiation).
- These models can be easily applied, have limited input parameters and are quite reliable if well calibrated locally or regionally.
- Mostly provide only yes/no information about the occurrence of permafrost, and no direct information on the temperature conditions.

Modelling – Empirical approaches

1) Simple Empirical Rules:

The most simple approach uses empirical rules for permafrost mapping based on *rule of thumbs* from Haeberli (1975) for the European Alps.

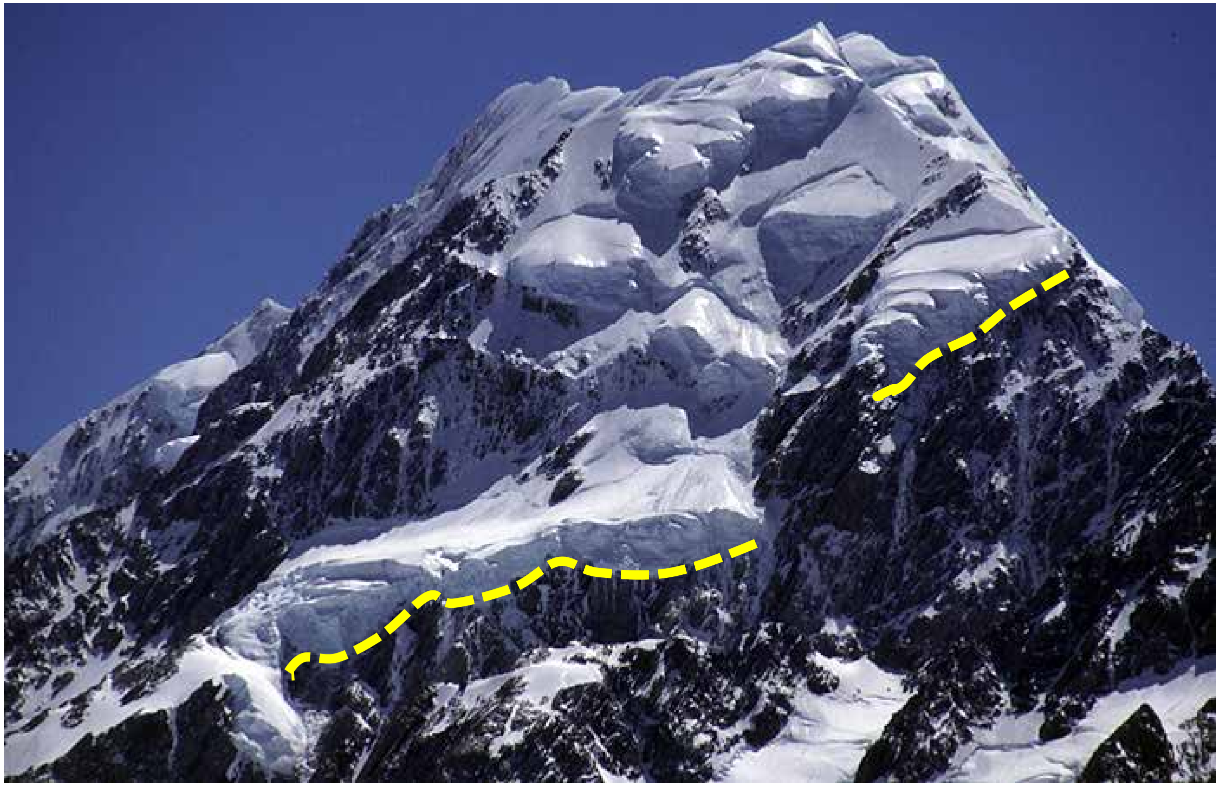
Based on field evidence:

1. Visible indicators: rock glaciers, perennial snow patches and avalanche deposits which frequently last over summer and keep the ground cooler, hanging glaciers etc.
2. In general, the probability for permafrost is higher in course blocky material than in fine grained and water circulated material.
3. In areas with closed vegetation (alpine meadow), the probability for permafrost is lower than in non-vegetated blocky slopes
4. Below timberlines permafrost is possible only in very shaded areas, above timberline permafrost is in principle possible.
5. Animals (marmots) do not hibernate in permafrost areas.

Modelling – Empirical approaches

The creeping behavior of a rock glacier requires high subsurface ice-content, and clearly indicates permafrost conditions. However, non-creeping bodies might also contain ice-rich permafrost, but movement may have stopped due to changes in stresses.

Modelling – Empirical approaches



Hanging glaciers indicate that the frontal ice is stuck "frozen" to the rock surface, requiring MAGST at or below zero degrees.

Modelling – Empirical approaches

Foot-of-slope areas are covered by long-lasting snow caused by avalanches. These long-lasting snow insulate the ground surface from spring and early summer warming, leading to generally lower permafrost boundaries.
In such cases, on the most shaded slopes, permafrost may even occur where MAAT is positive.

Modelling – Empirical approaches

In most high mountain environments, vegetation can not grow where the ground is permanently frozen.

Modelling – Empirical approaches

Animals don't like sleeping where the ground is permanently frozen!

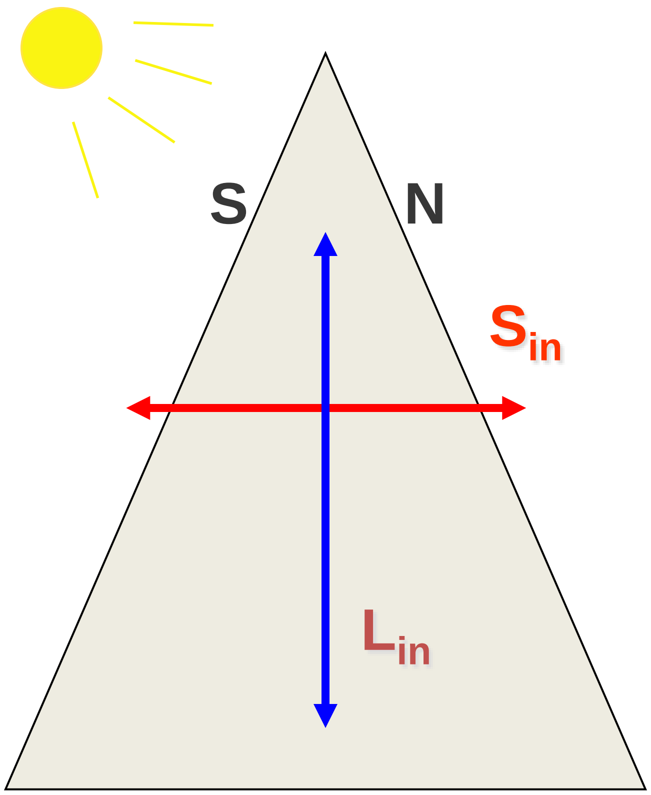
Modelling – Empirical approaches

2) Topo-climatic empirical approaches

- Haeberli (1975) developed one of the first systematic approaches for mapping permafrost distribution
- Topo-climatic key estimates zones of probable and possible permafrost
- Permafrost modelled as a function of:
  - Aspect – solar radiation
  - Elevation – MAAT
  - Slope morphology
    - Steep slopes (solar radiation dominant)
    - Flat slopes (air temperature and snow cover dominant)
    - Foot of slopes (late-lying avalanche snow important)
- Has become the fundamental basis for many more recent GIS based permafrost distribution models.

Modelling – Empirical approaches

Topographic Effect:



S_{in}: Aspect (radiation effect)

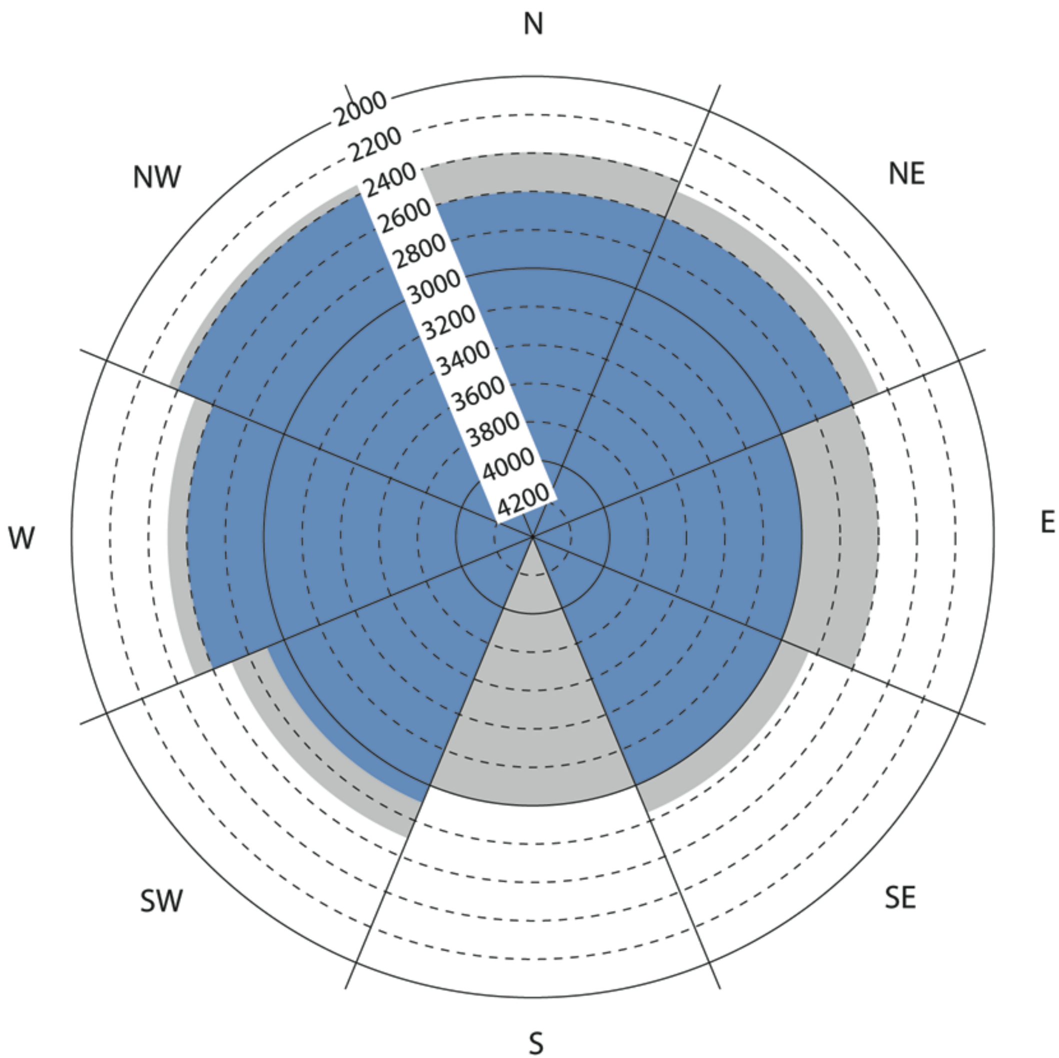
L_{in}: Altitude (air temperature)

Slope: (snow cover)

S_{in}: 6-8 °C north/south (**ALPS**!!)

L_{in}: 6 °C per 1000 m elevation difference

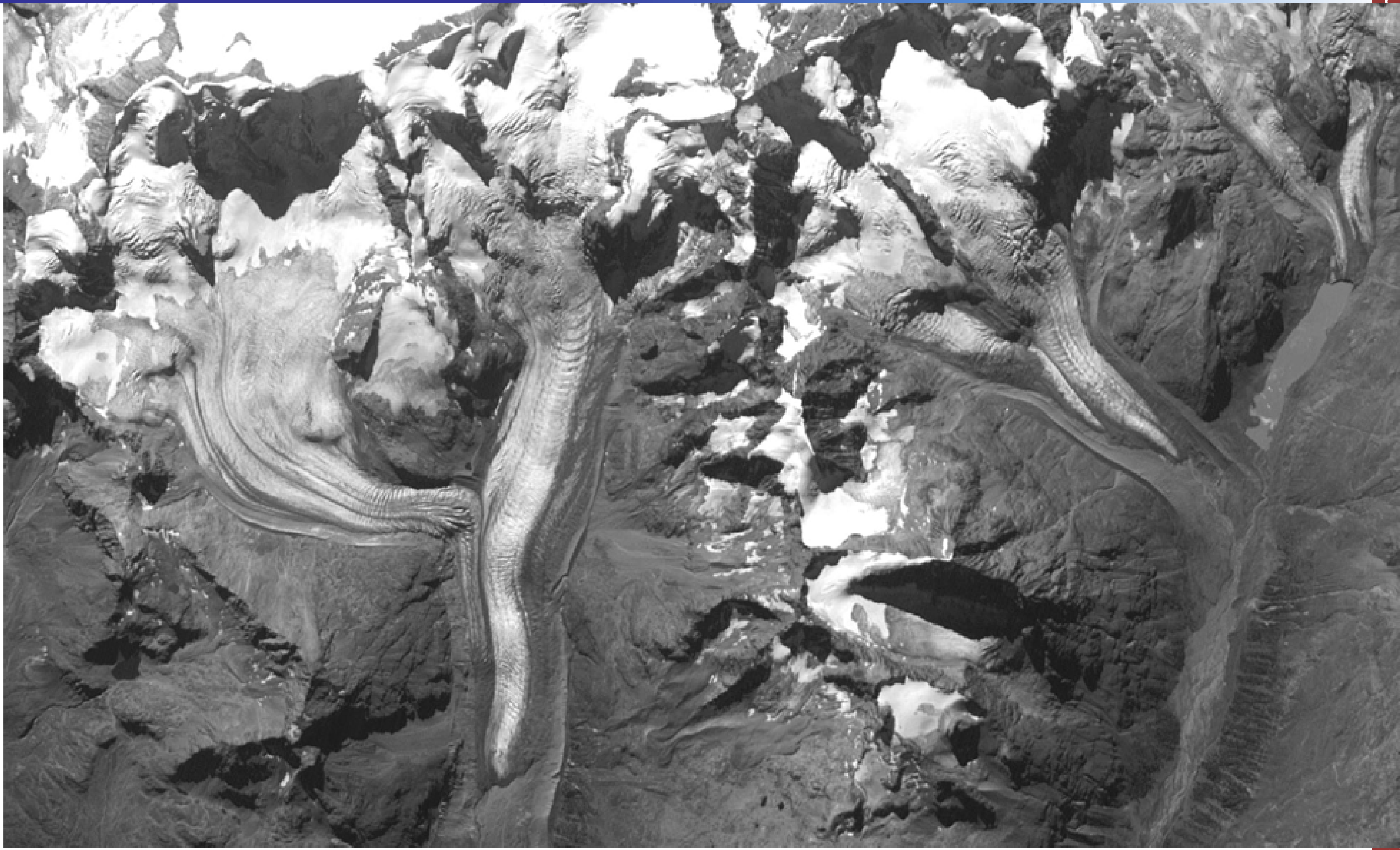
Modelling – Empirical approaches



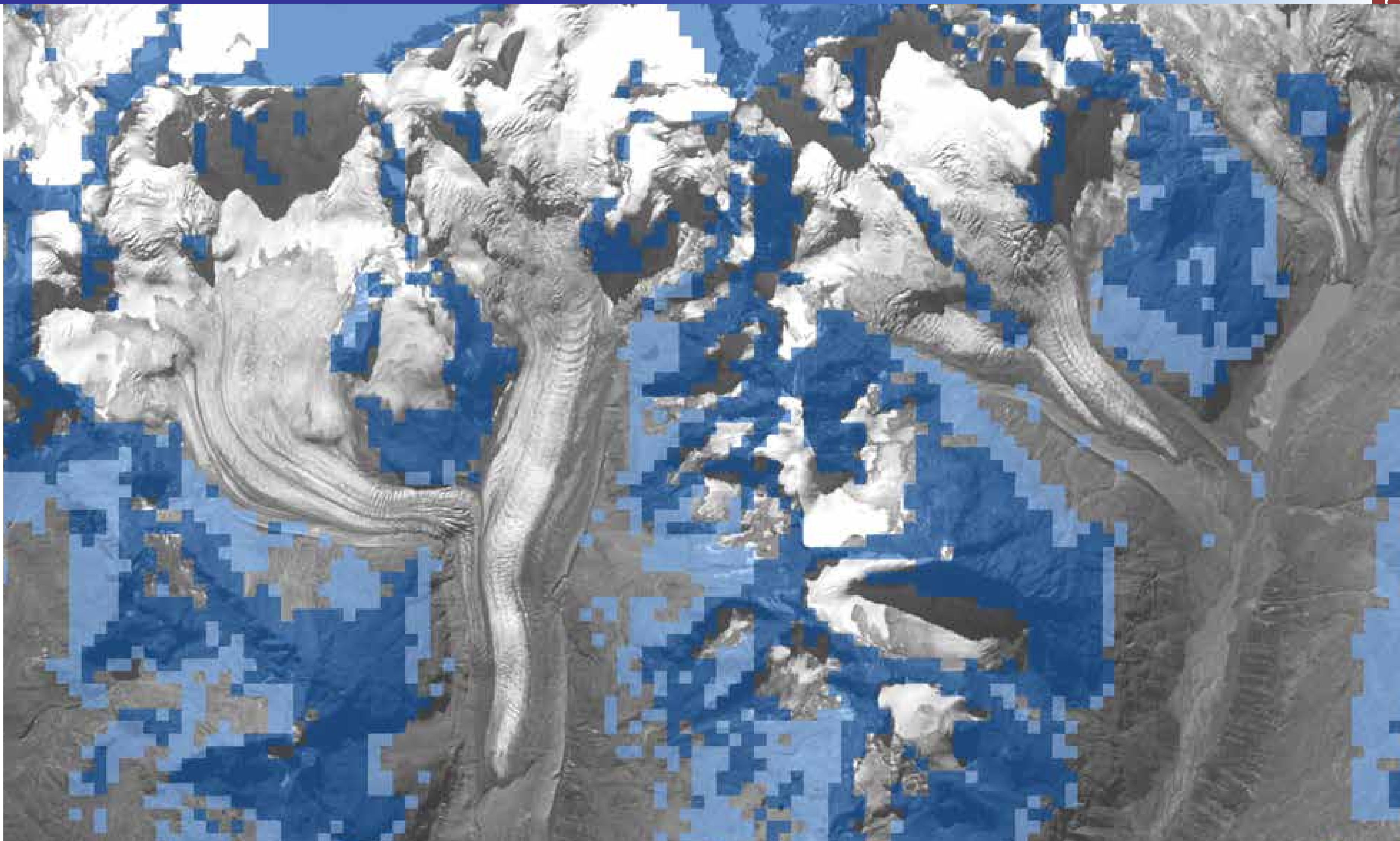
Permafrost probable   Permafrost possible

- Hand drawn maps possible
- Easily applied in a GIS using a digital elevation model.

Example: Bernina area (Switzerland)



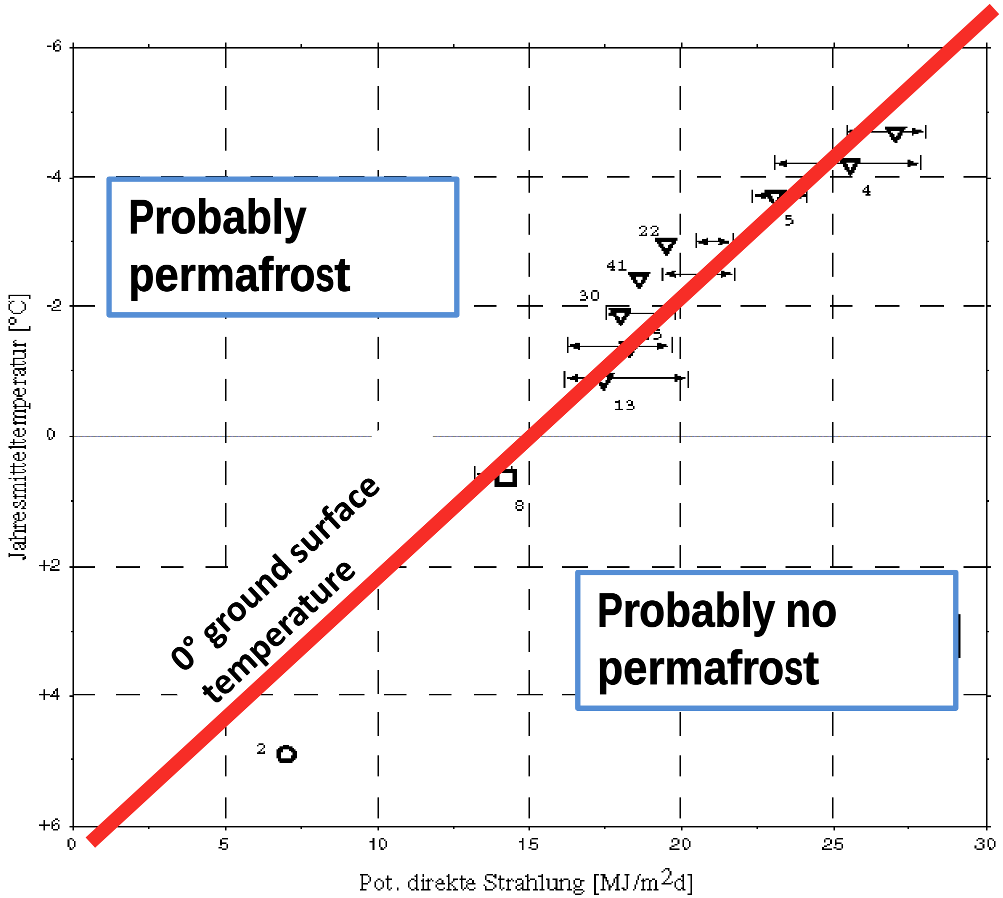
Permafrost: Bernina area (Switzerland)



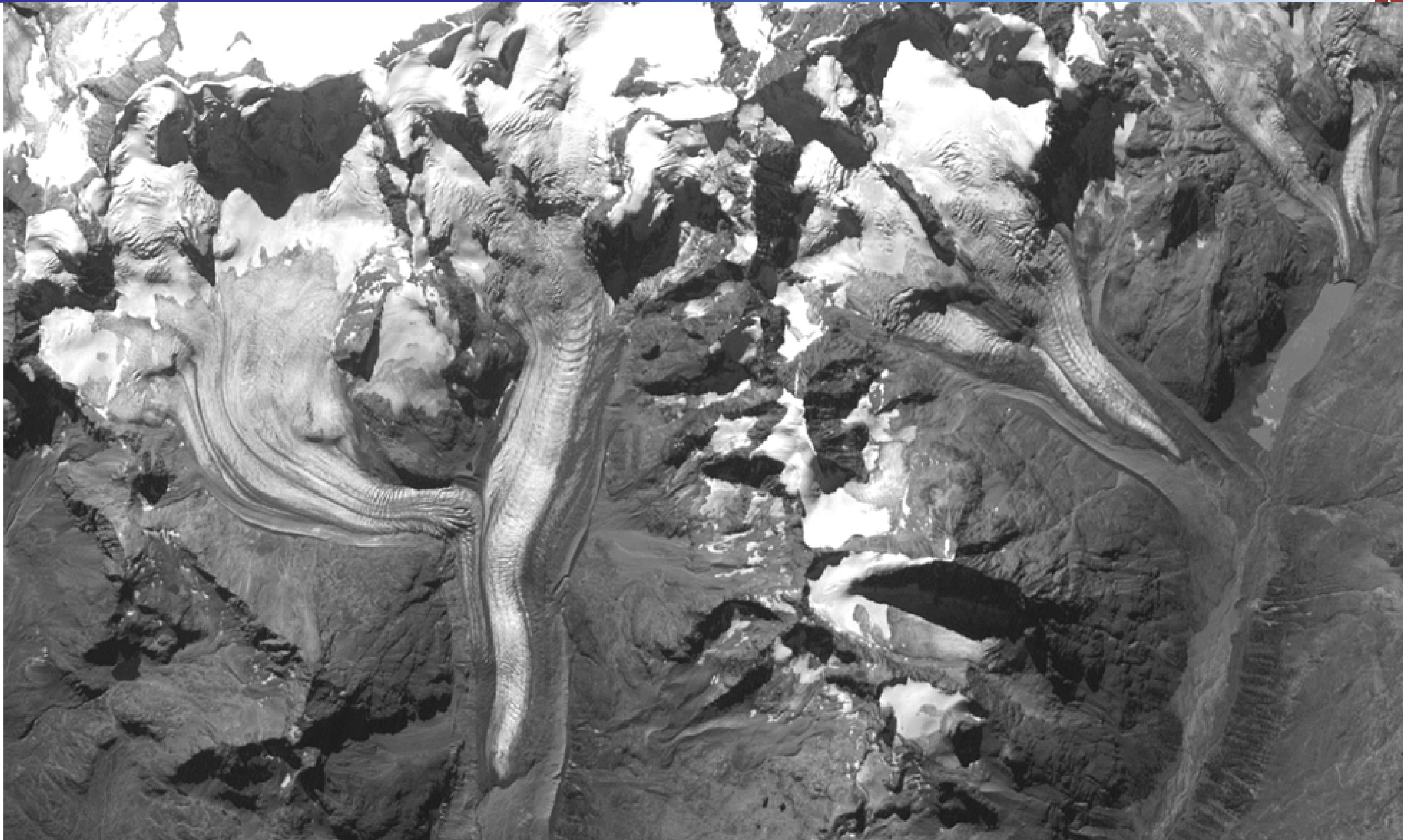
Modelling – Empirical approaches

3) Empirical-statistical models

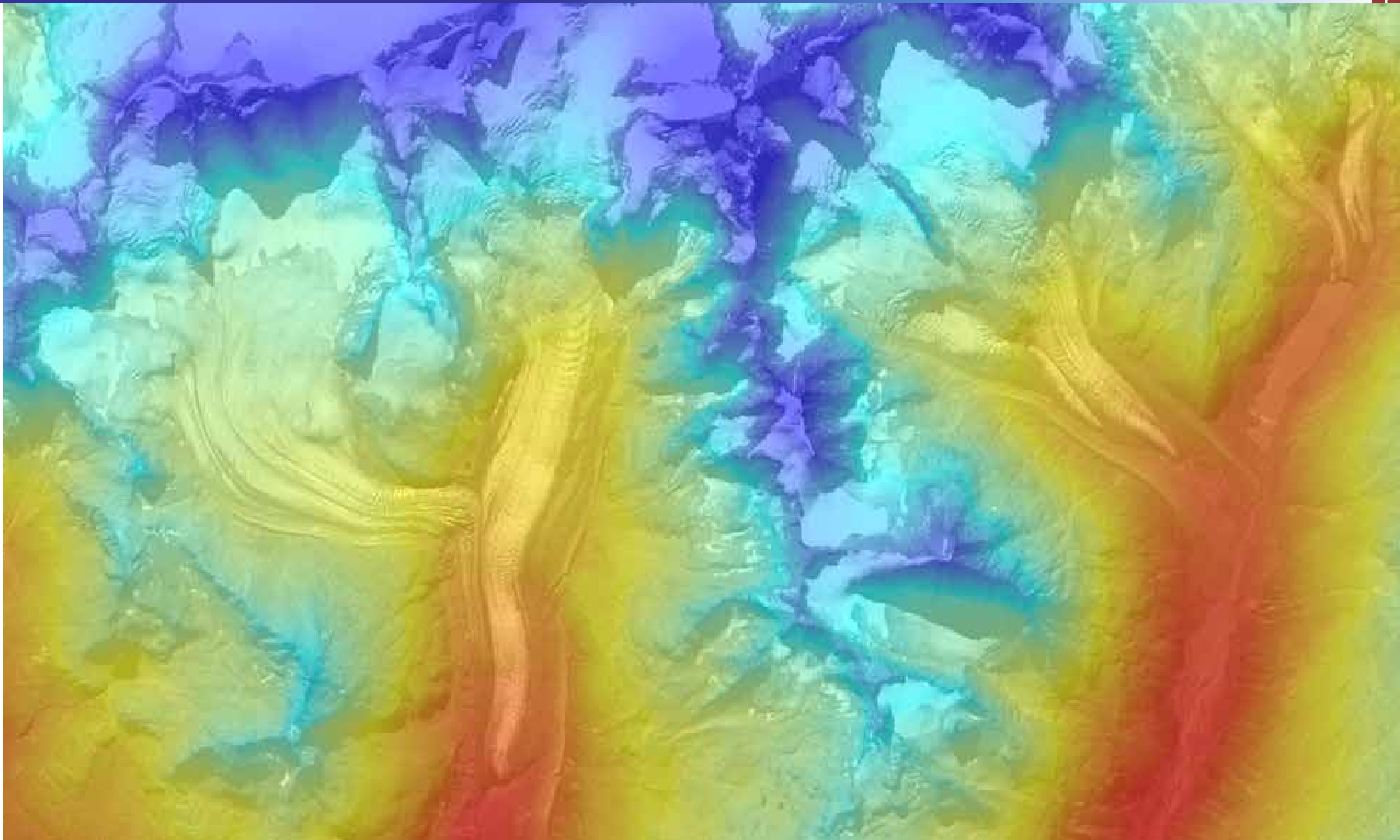
- Based on the relationship between potential solar radiation, mean annual air temperature (MAAT), and ground surface temperature



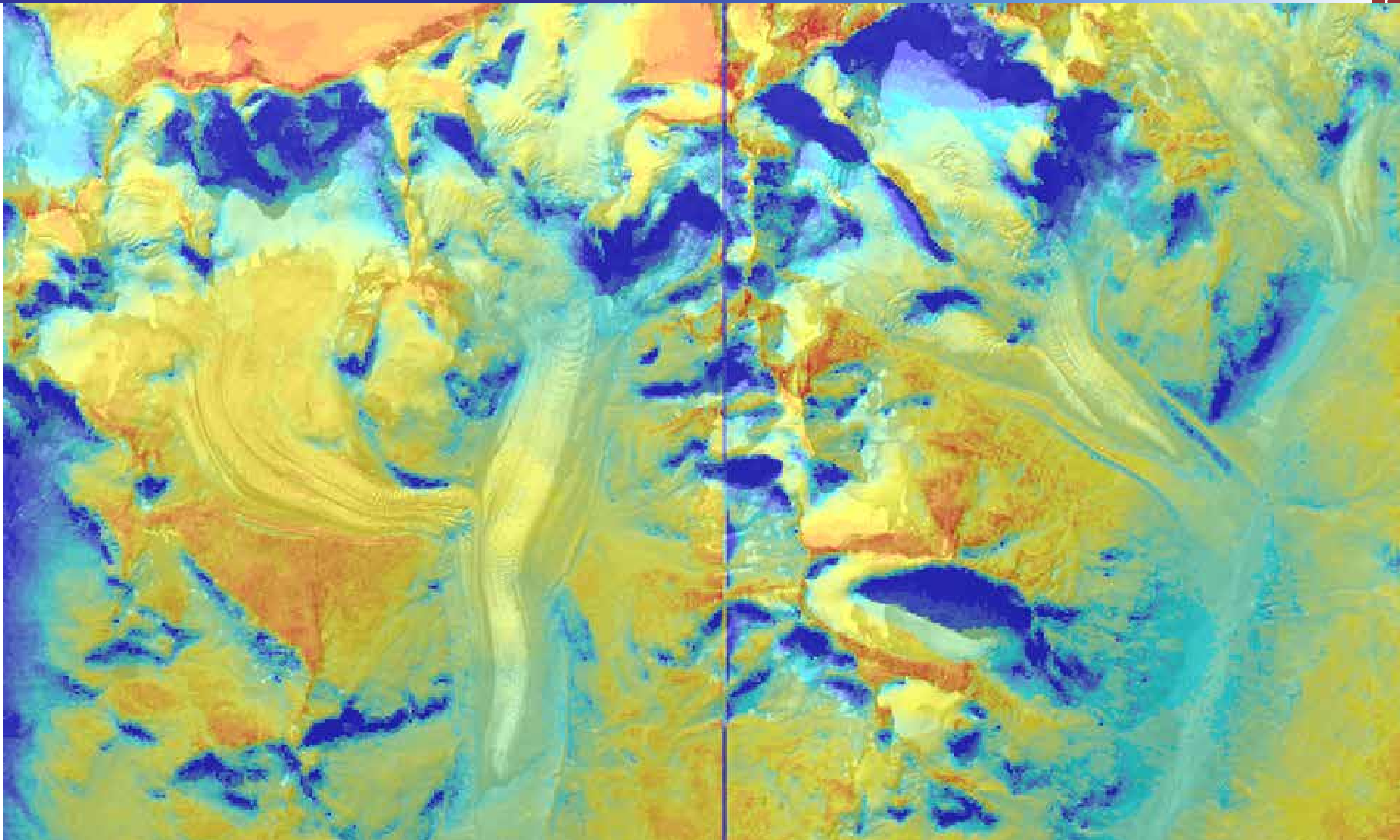
Example: Bernina area (Switzerland)



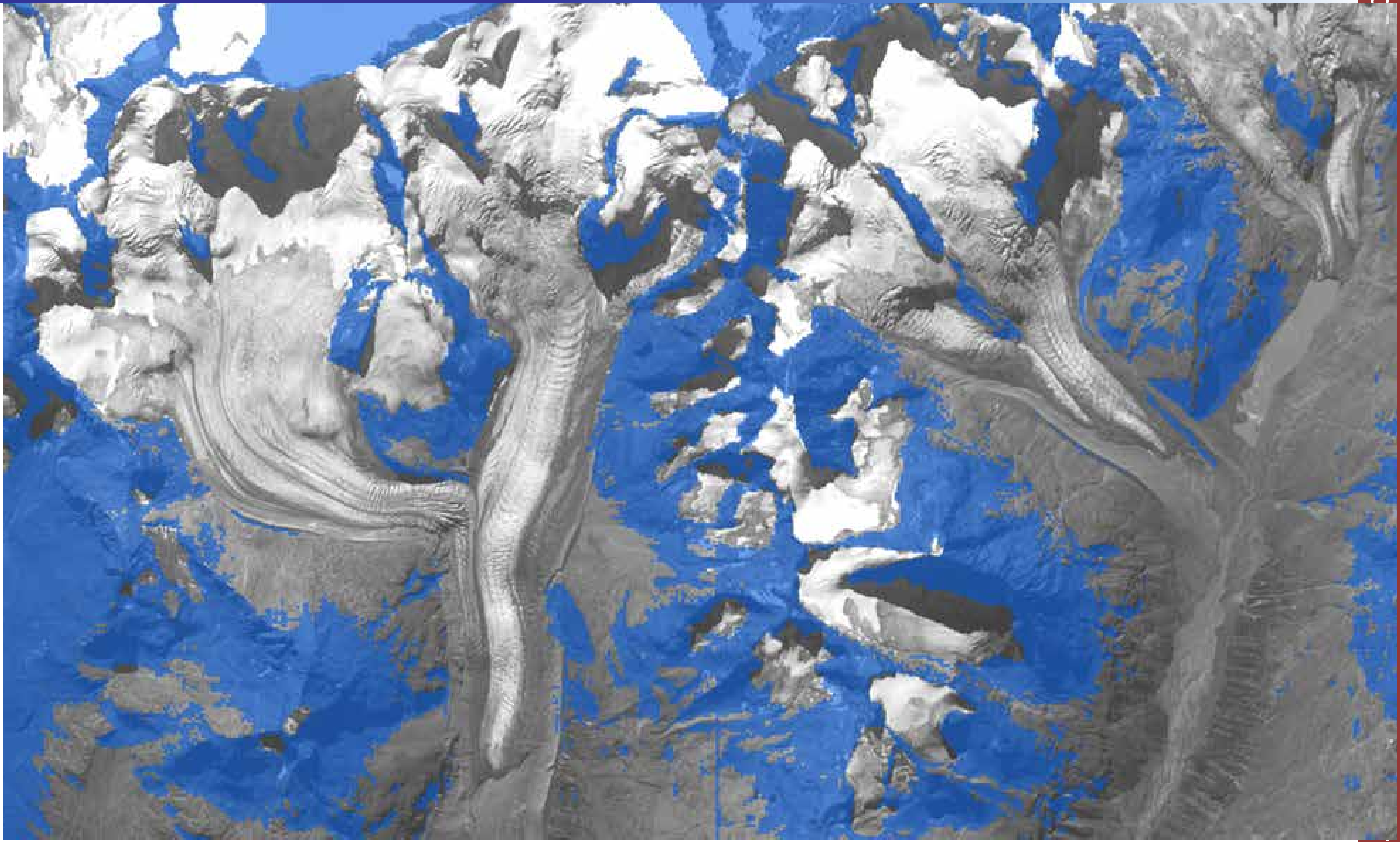
MAAT



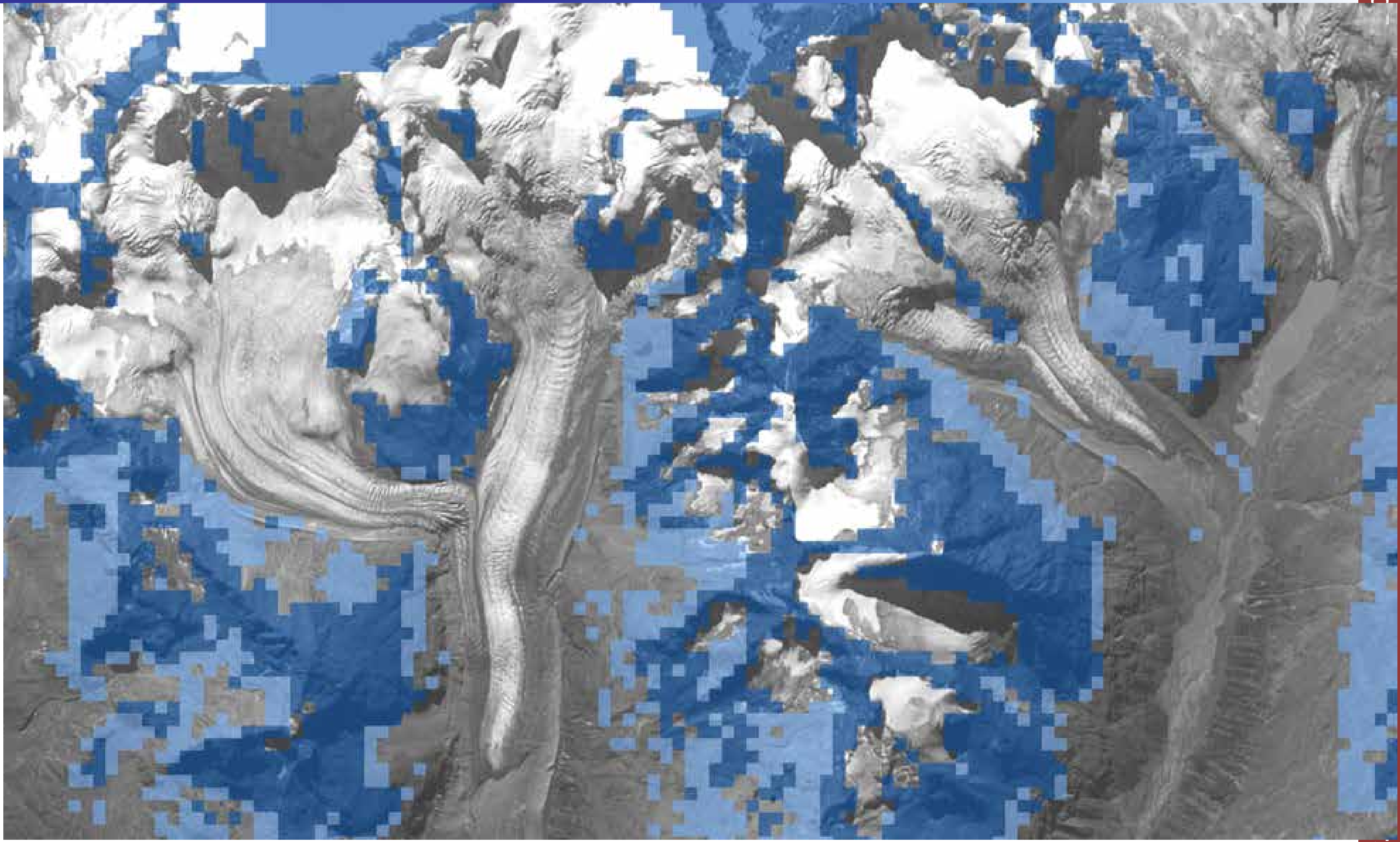
Potential shortwave incoming radiation



Permafrost: Bernina area (Switzerland)



Permafrost: Bernina area (Switzerland)



Modelling – Process-based

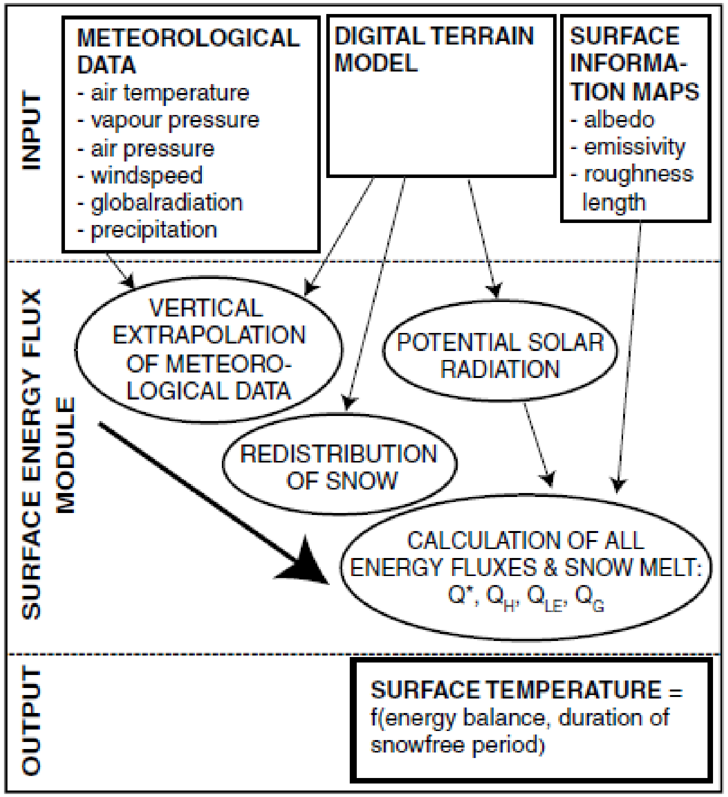
Energy balance model

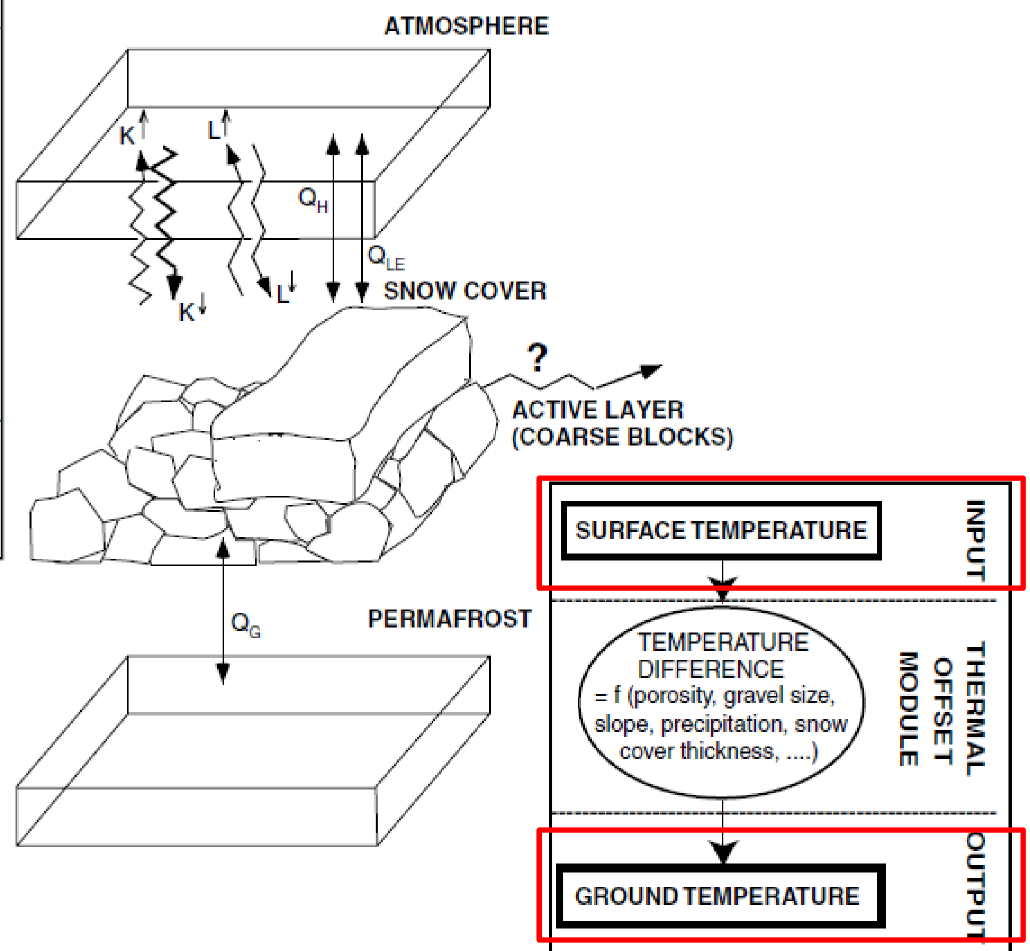
- The energy balance model is based on a description of the main energy exchange processes between the atmosphere and the surface. It includes calculations of short-wave net radiation, long-wave incoming radiation and turbulent fluxes as well as of snow distribution.

- As a physical model, the energy balance module requires an extensive set of input data describing meteorological conditions, and ground surface characteristics, and topography.

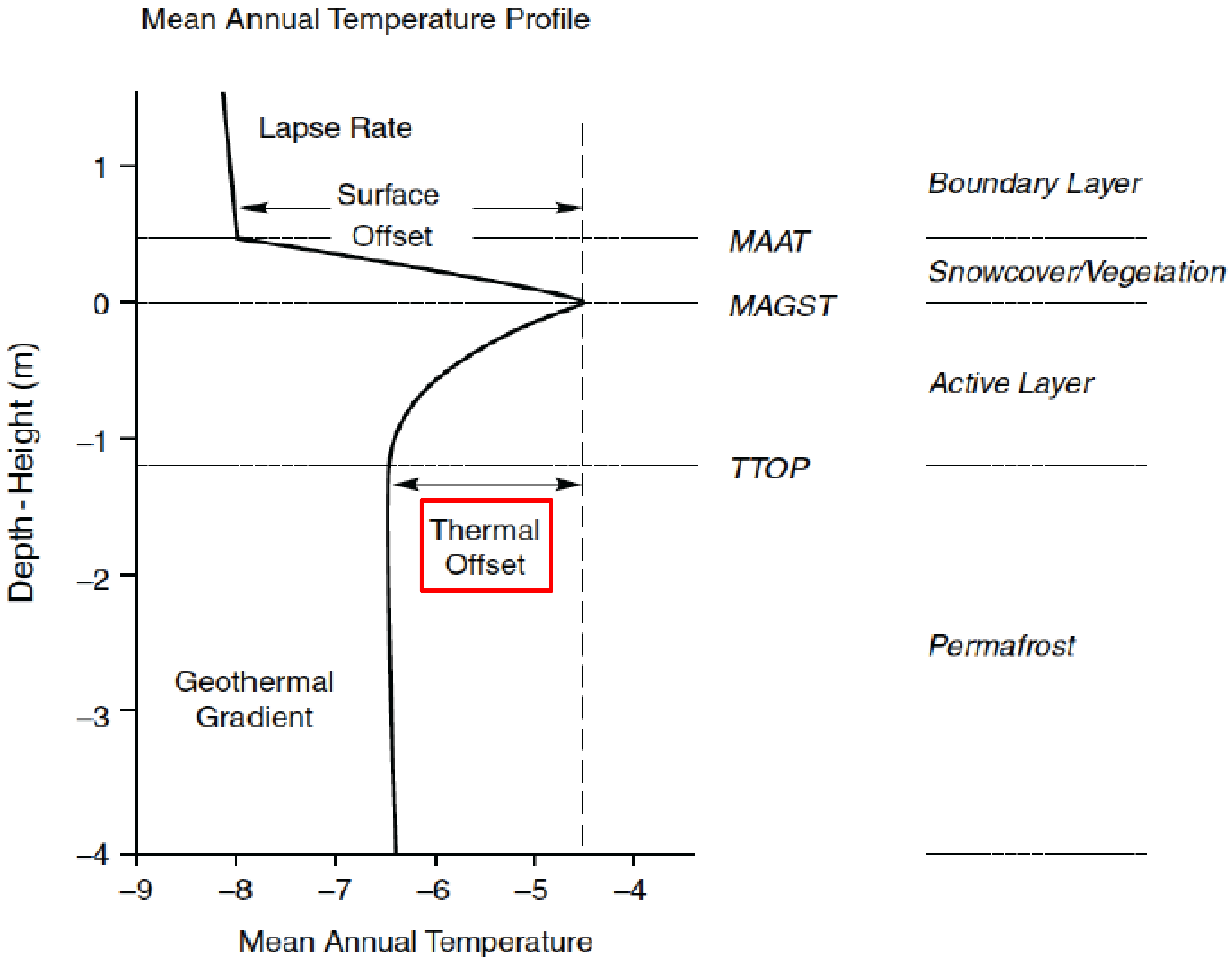
- These models enable surface temperatures to be computed and, hence, thermal conditions at depth and transient effects to be estimated. Such approaches are especially well suited for studies regarding climate change scenarios and regional climate modelling.

Modelling – Process-based





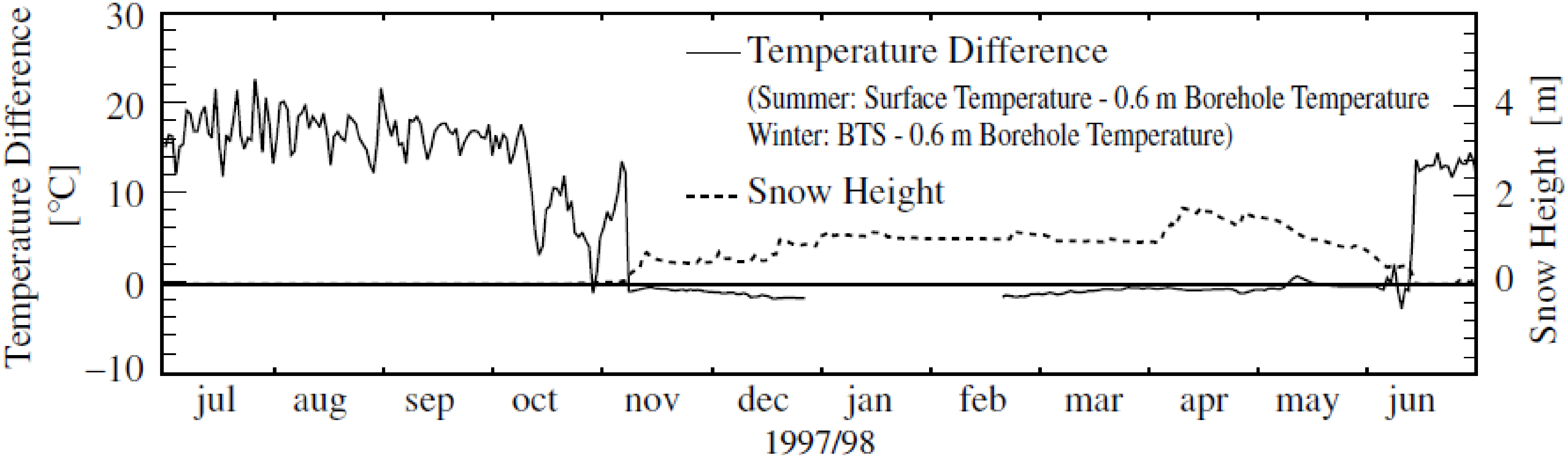
Modelling – Process-based



Modelling – Process-based

Effect of snow cover

- Important determinant of the thermal offset

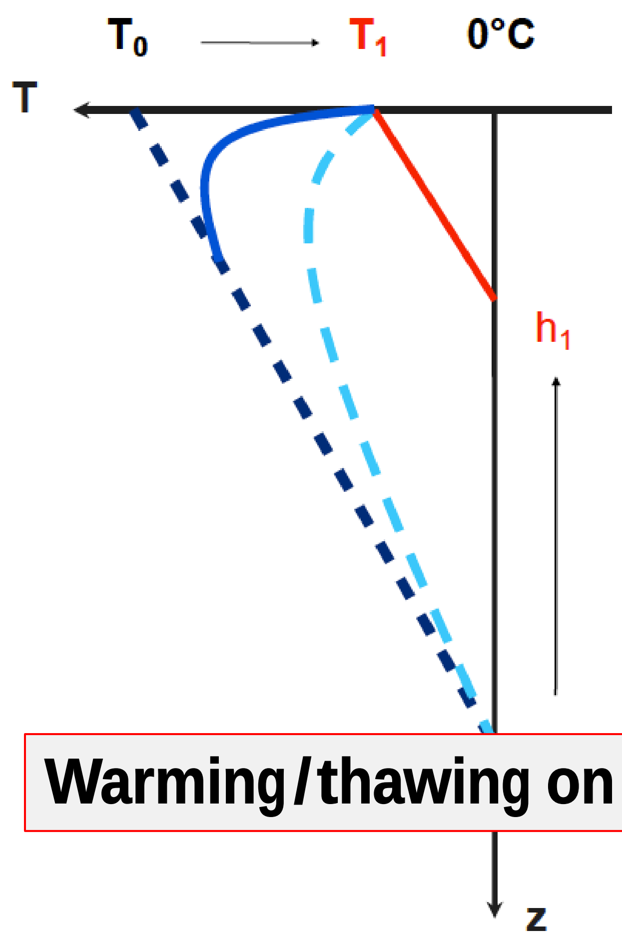


- Timing and duration of snow cover is very important
- There is a critical snow height to achieve insulating effect: ca. 30cm

Modelling – Process-based

Climate change – Heat conduction into the ground

- Very slow (lag) response to changes in surface-air temperatures



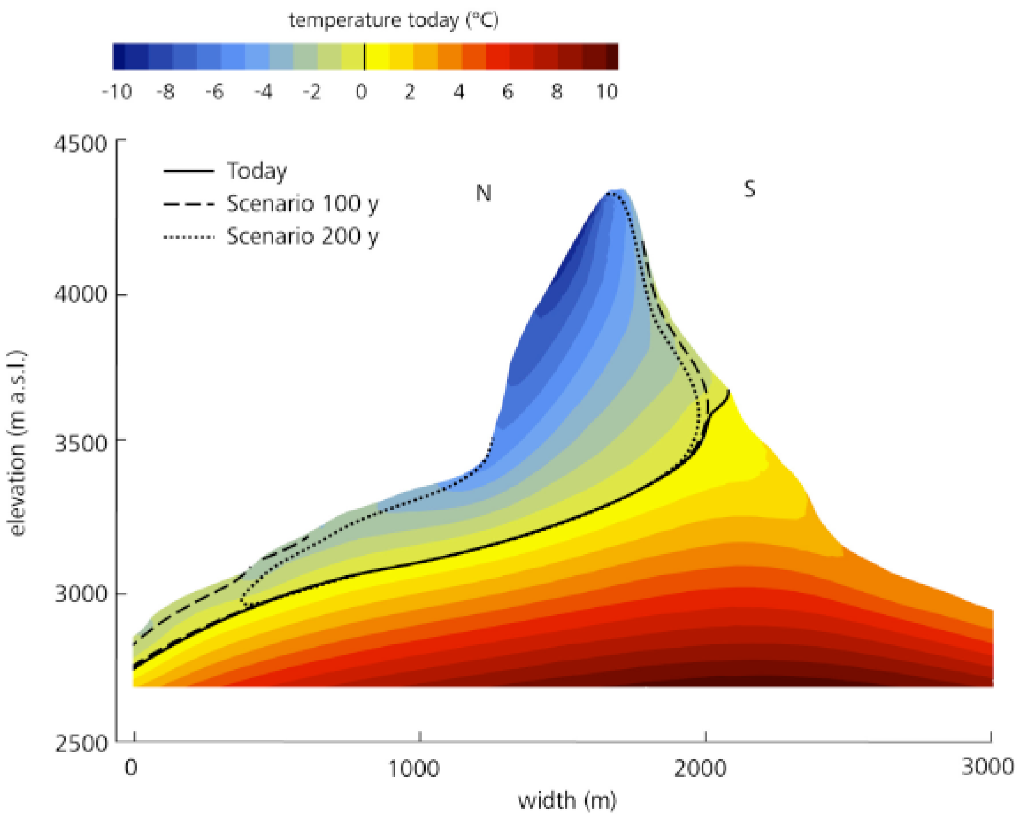
A ✳ Short-term (annual): Increasing active layer

B ✳ Mid-term (years, decades): Change of temperature profile in permafrost

C ✳ long-term (centuries): Shift of permafrost base, change of permafrost thickness

Warming/thawing on time scales from annual to centuries!

Modelling – Process-based



- Process based models provide a powerful tool for assessing current and future changes in permafrost conditions, in complex topography.

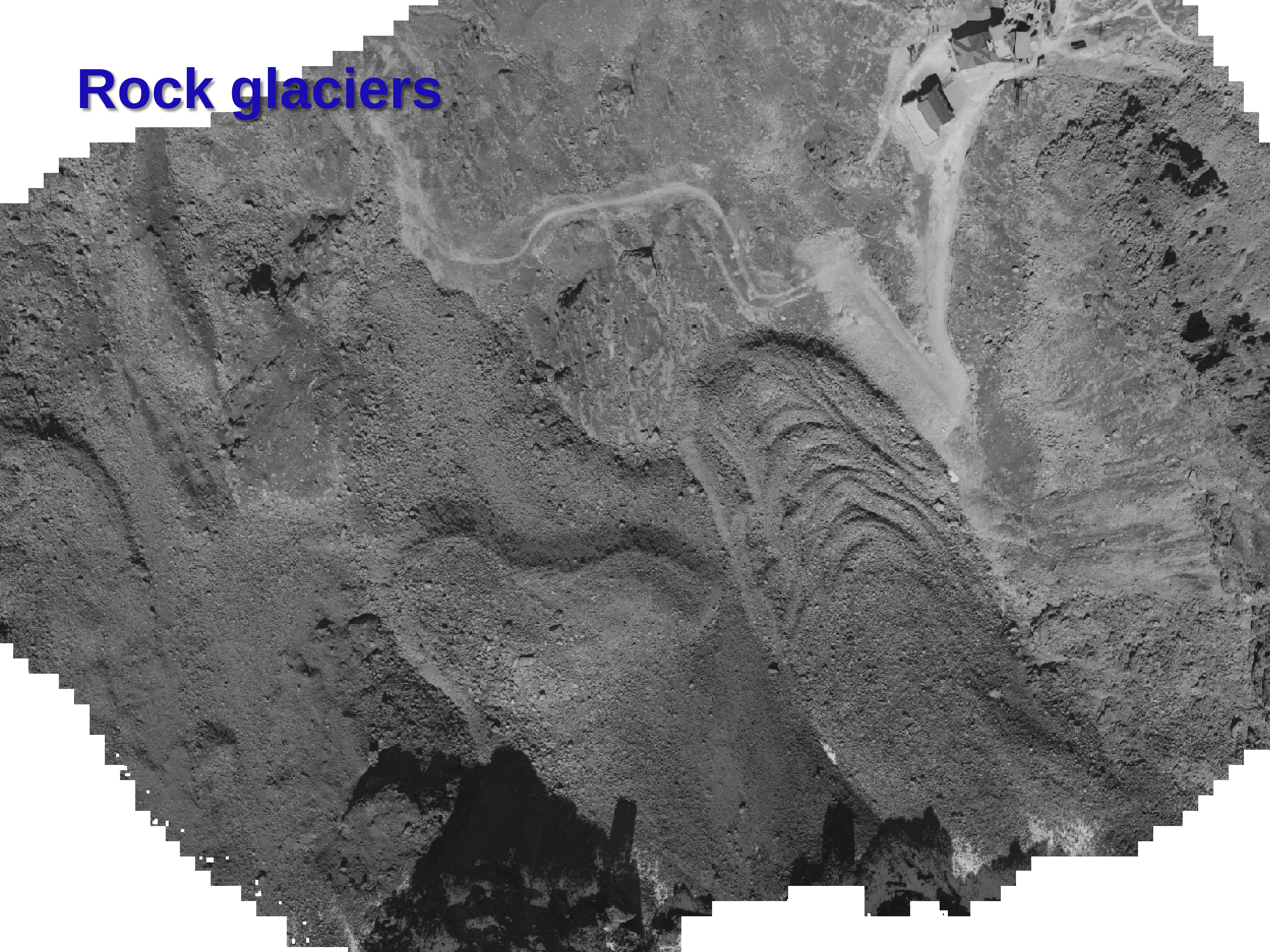
TO REMEMBER:

- Direct or semi-direct monitoring of permafrost is difficult.
- Evidence based models (empirical) are relatively simple, and provide a useful first overview of permafrost distribution for large, remote regions.
- Simple field indicators, and topo-climate factors form the basis for many permafrost distribution maps.
- Process based models are more complex, but provide direct information on ground temperatures in 3D, for current and future permafrost conditions.
- The influence of snow-cover, and the thermal offset are important factors in process based models.
- It takes a long time for surface warming to penetrate to depth (decades to centuries).

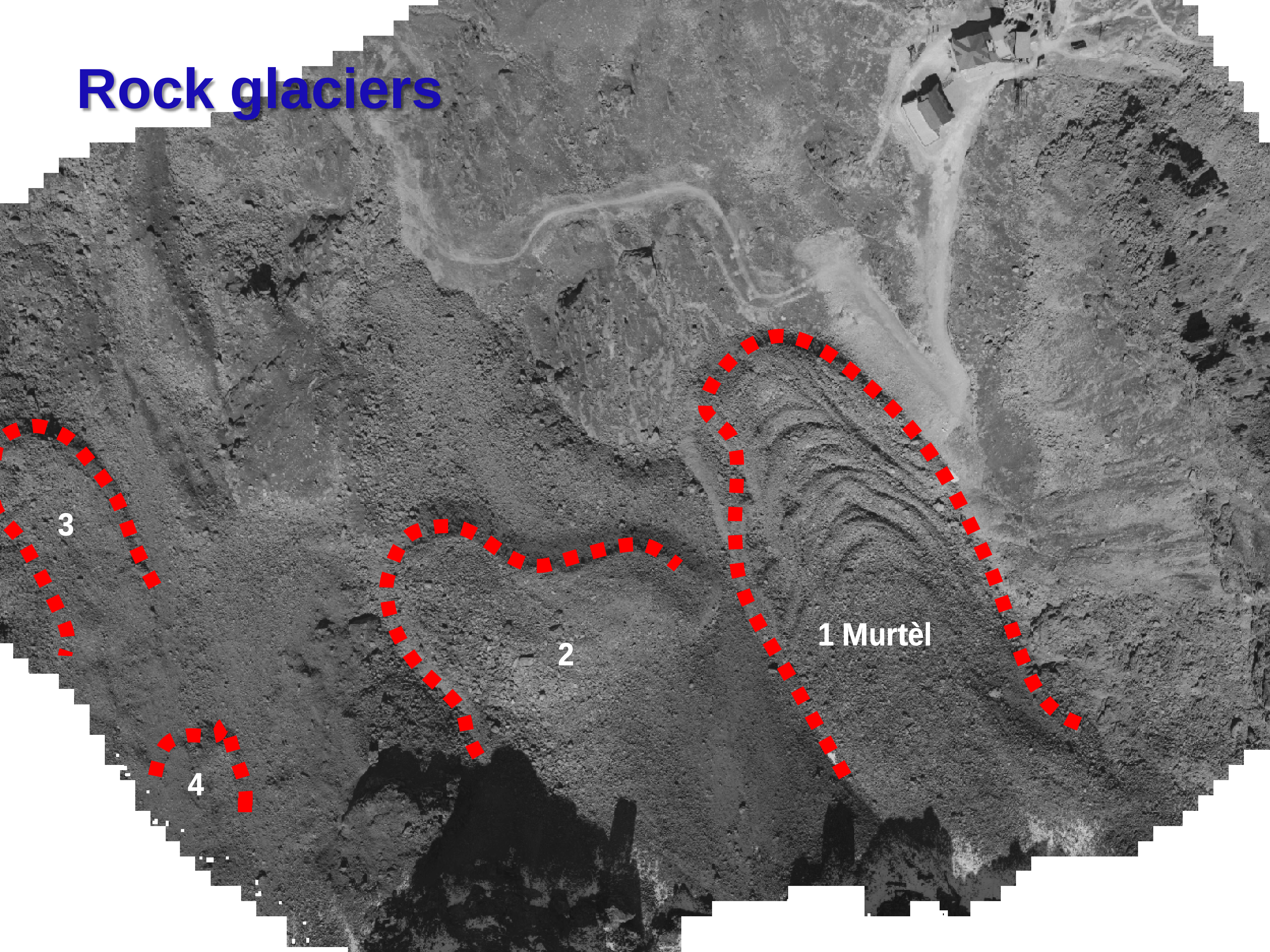
Rock glaciers

Active rockglaciers **are lobate or tongue-shaped bodies** of **perennially frozen** unconsolidated material **supersaturated with ice** that **move downslope by creep** as a consequence of slope and the deformation of ice contained in them.

Rock glaciers



Rock glaciers

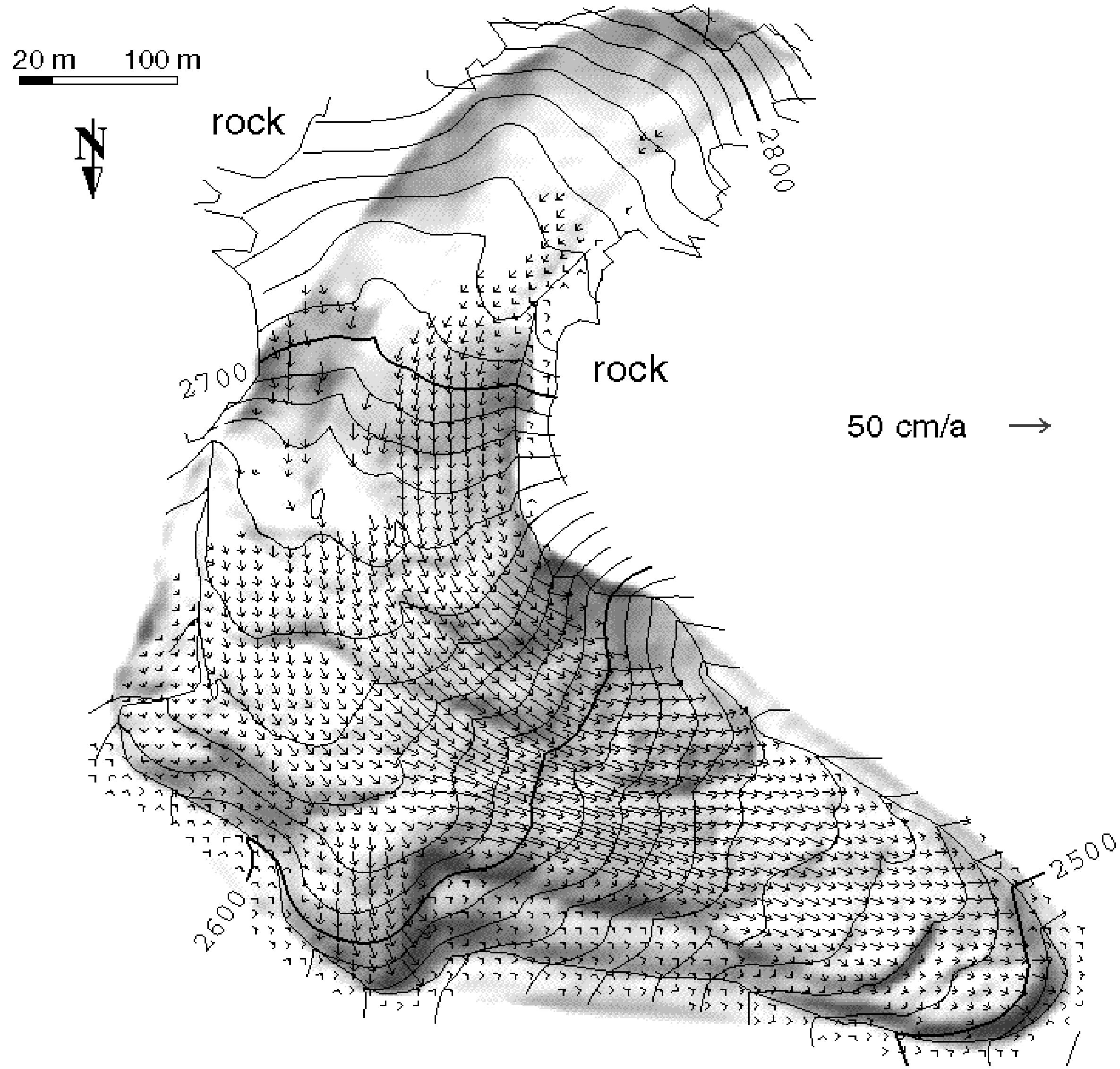


Rock glaciers – dimensions (Alps)

Rock glaciers – dimensions (Alaska)

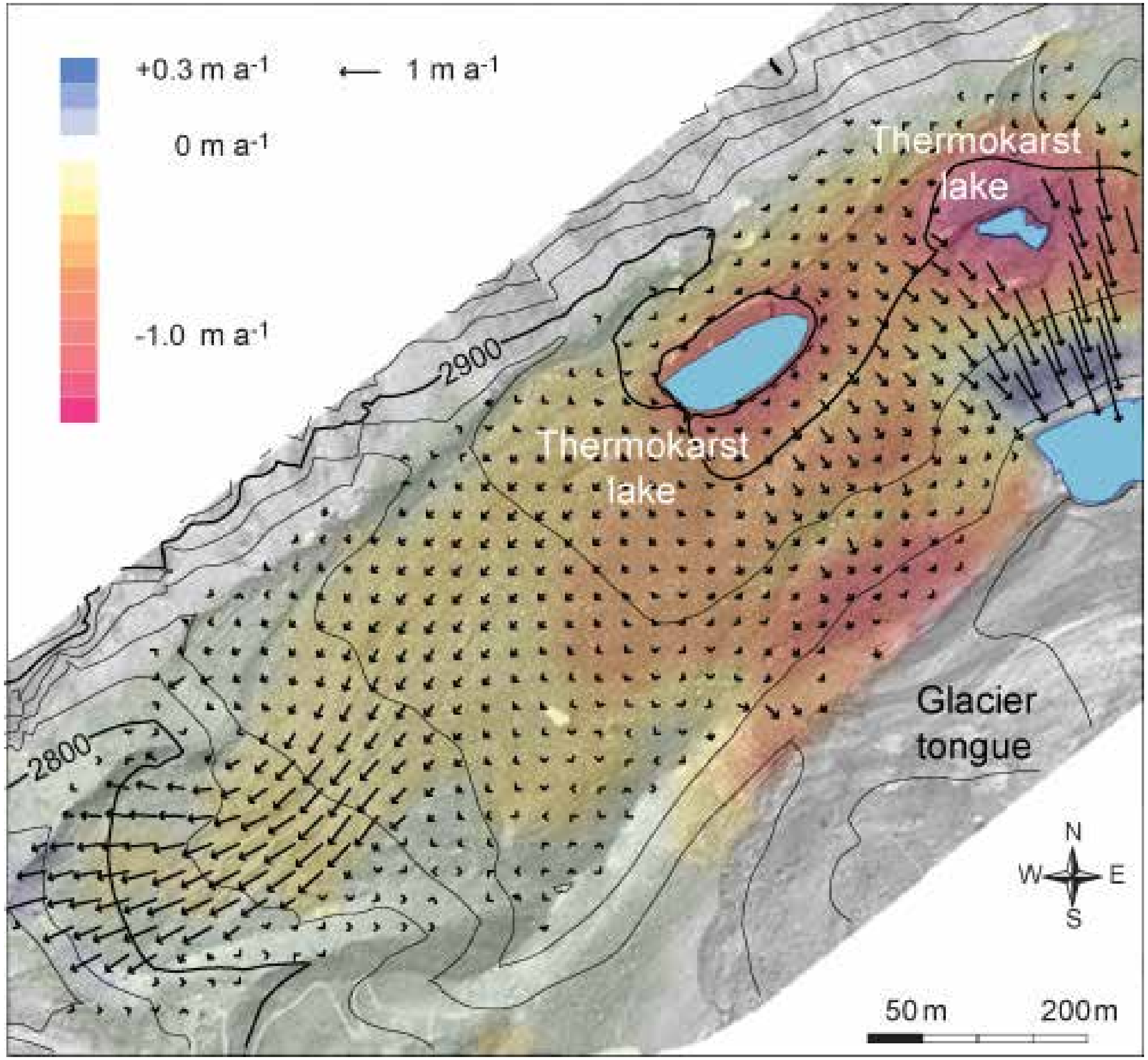
Rock glaciers - movement

Velocity
~ 0.01-1.5m/year
(-> slope angle)

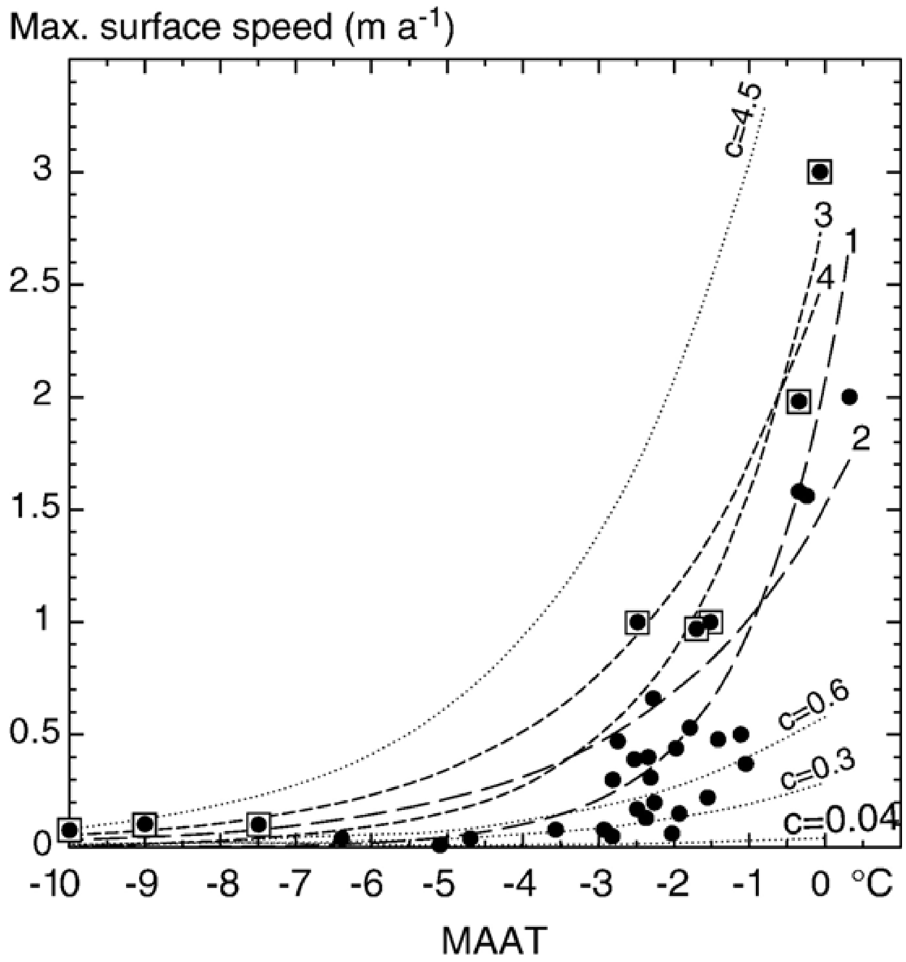


Rock glaciers - movement

Elevation
> 1 m/year

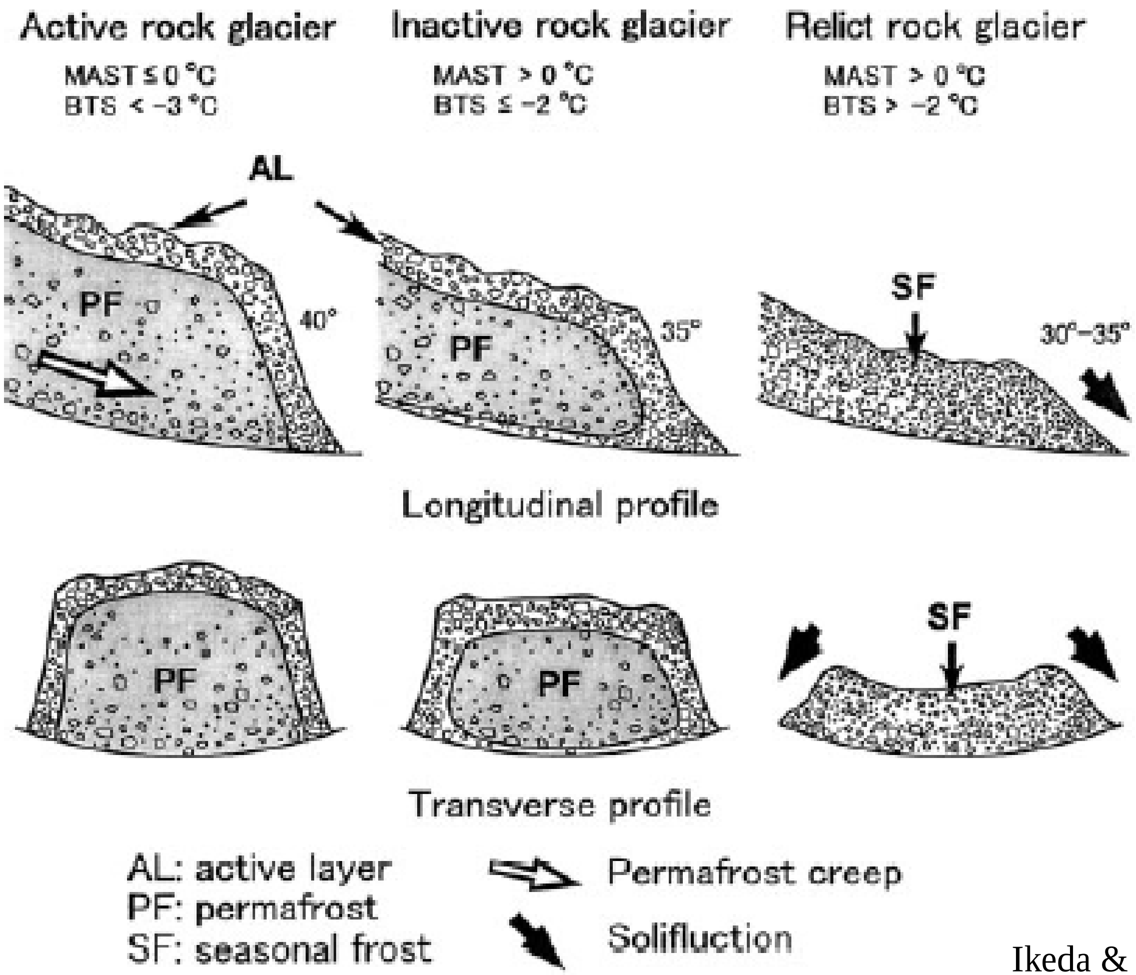


Rock glaciers - movement



- The movement of rock glaciers is closely related to MAAT.
- This implies a link with current and future global warming.

Active, inactive and relict rock glaciers



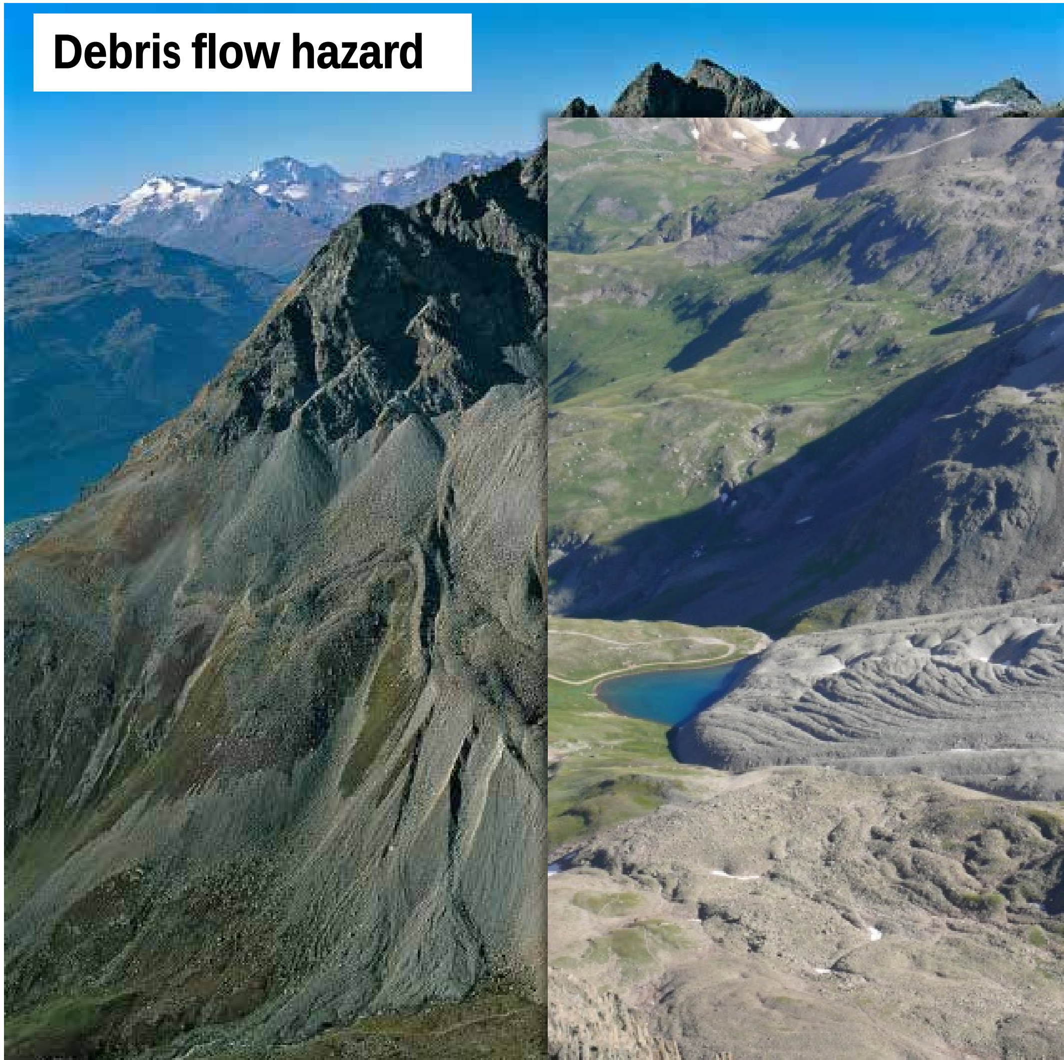
Ikeda & Matsuoka 2002: 158)

Active rock glacier

Inactive and relict rock glaciers

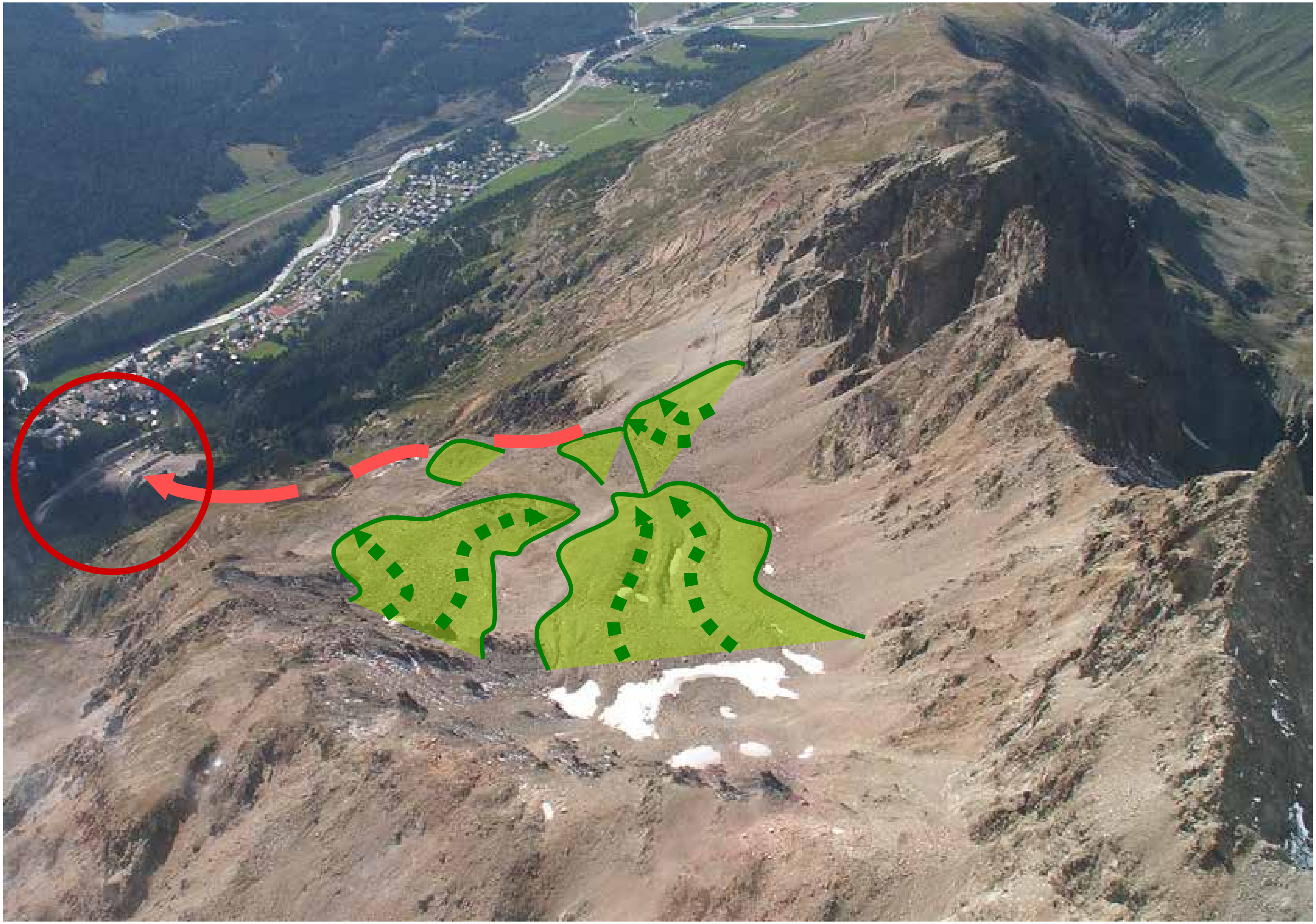
Rock glacier – Hazards

Debris flow hazard



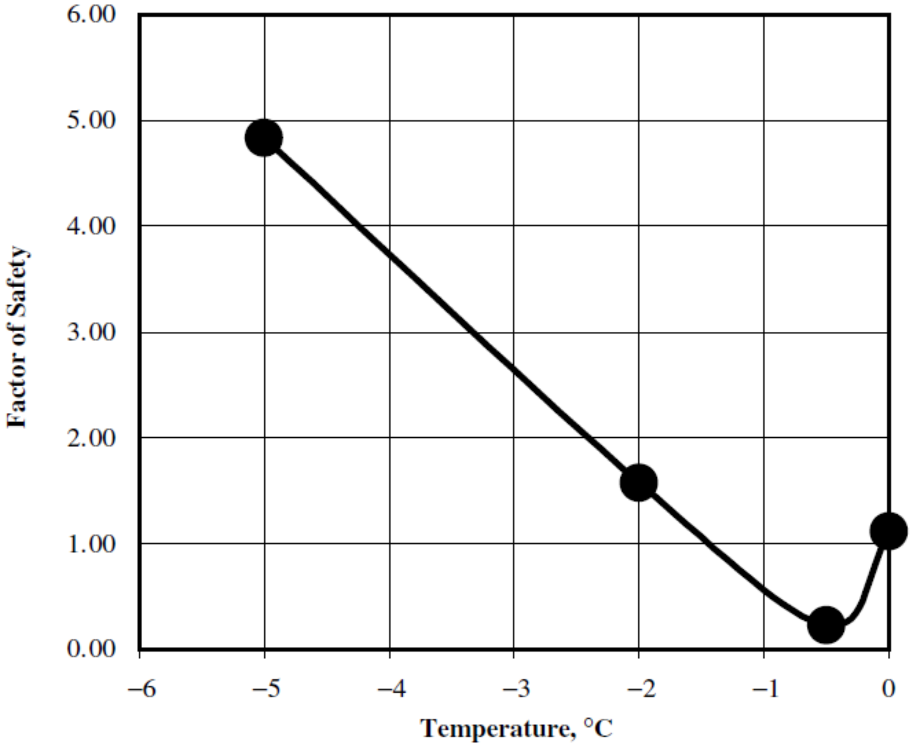
Lake outburst hazard

Rock glacier – Hazards



Permafrost and rockfalls

- In steep permafrost rock slopes, an ice filled rock fracture widens over time, owing to volume expansion of ice and ice segregation.
- Physical modeling has indicated that the shear strength of an ice bonded rock fracture decreases with warming – loss of bonding/adhesion.

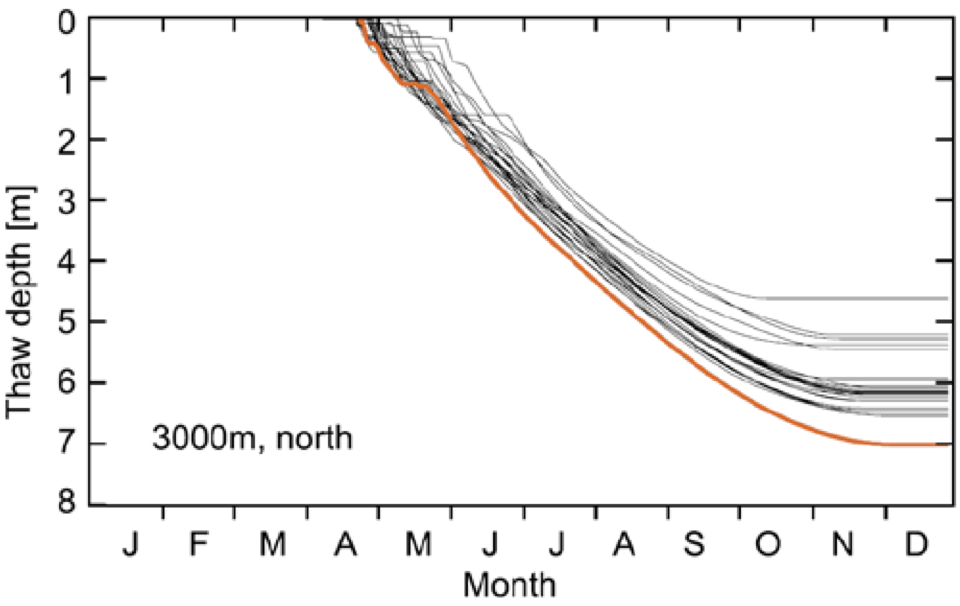


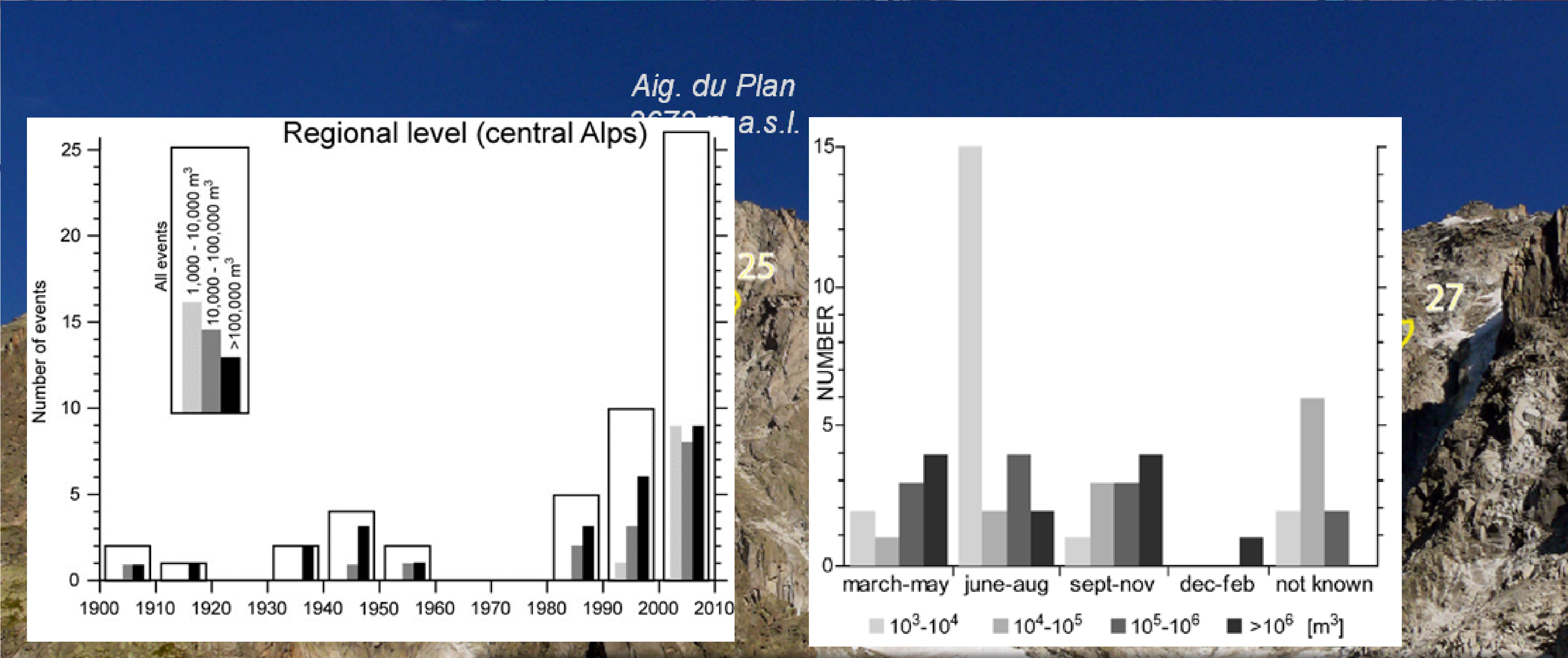
Permafrost and rockfalls

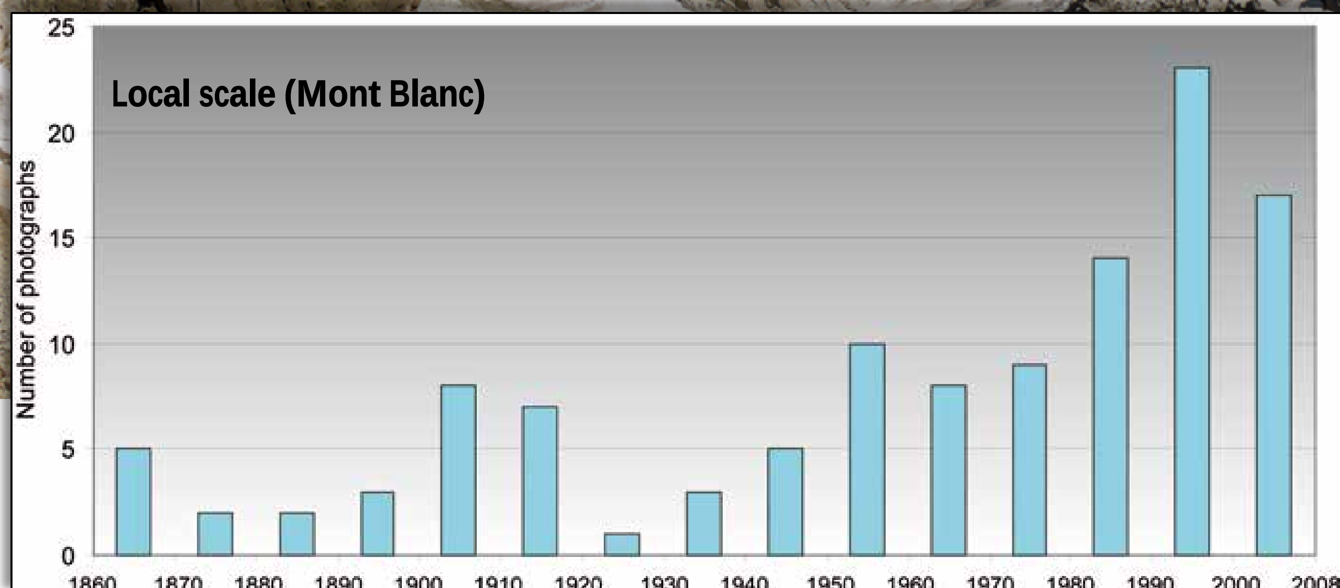
- Meltwater or ground water flow into a previously frozen bedrock can elevate water pressure and reduce frictional strength.

- Lack of snow or debris cover on a steep bedrock slope means that sub-surface temperature will respond rapidly to atmospheric warming -> there is a direct coupling with the atmosphere.

Extreme thawing during European summer heatwave 2003

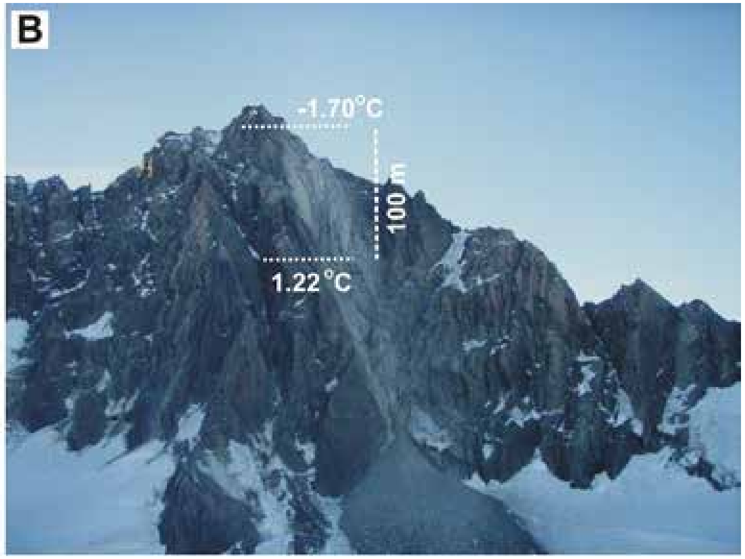






Increasing rock fall frequency!

Permafrost and rockfalls



Recent rockfall occurring from within the zone of marginal, thawing permafrost:

- Active layer thickening
- Ice filled fractures gradually weakening

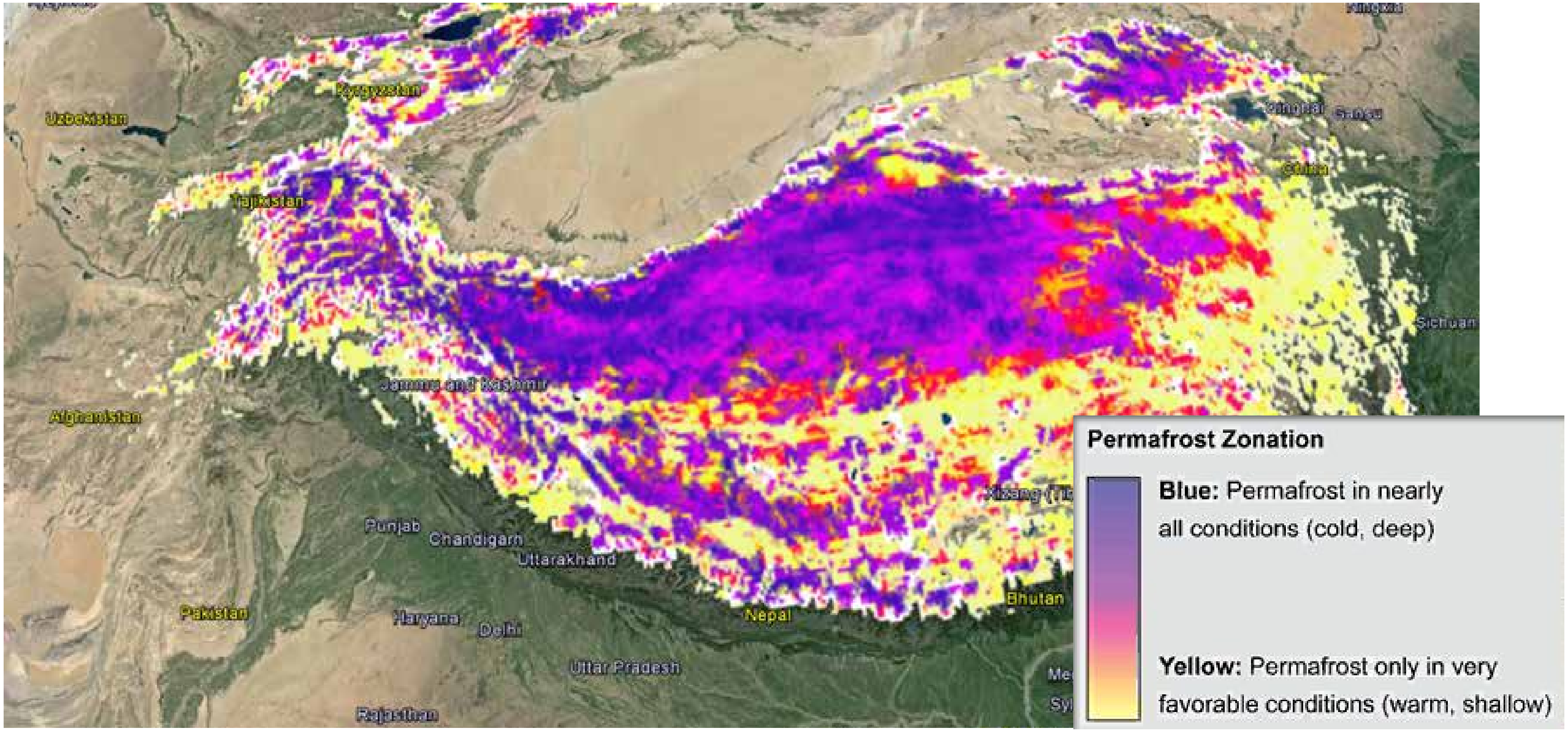
Permafrost in India

Where is the permafrost?

Are there rock glaciers?

Are there hazards from permafrost?

Permafrost in India



- Discontinuous and sporadic permafrost is found through much of the Indian Himalaya.
- For example, MAAT 0° isotherm in the Kullu district of Himachal Pradesh is approximately 4000 – 4200 m a.s.l.
- There are no monitoring studies, and only basic global scale model results.

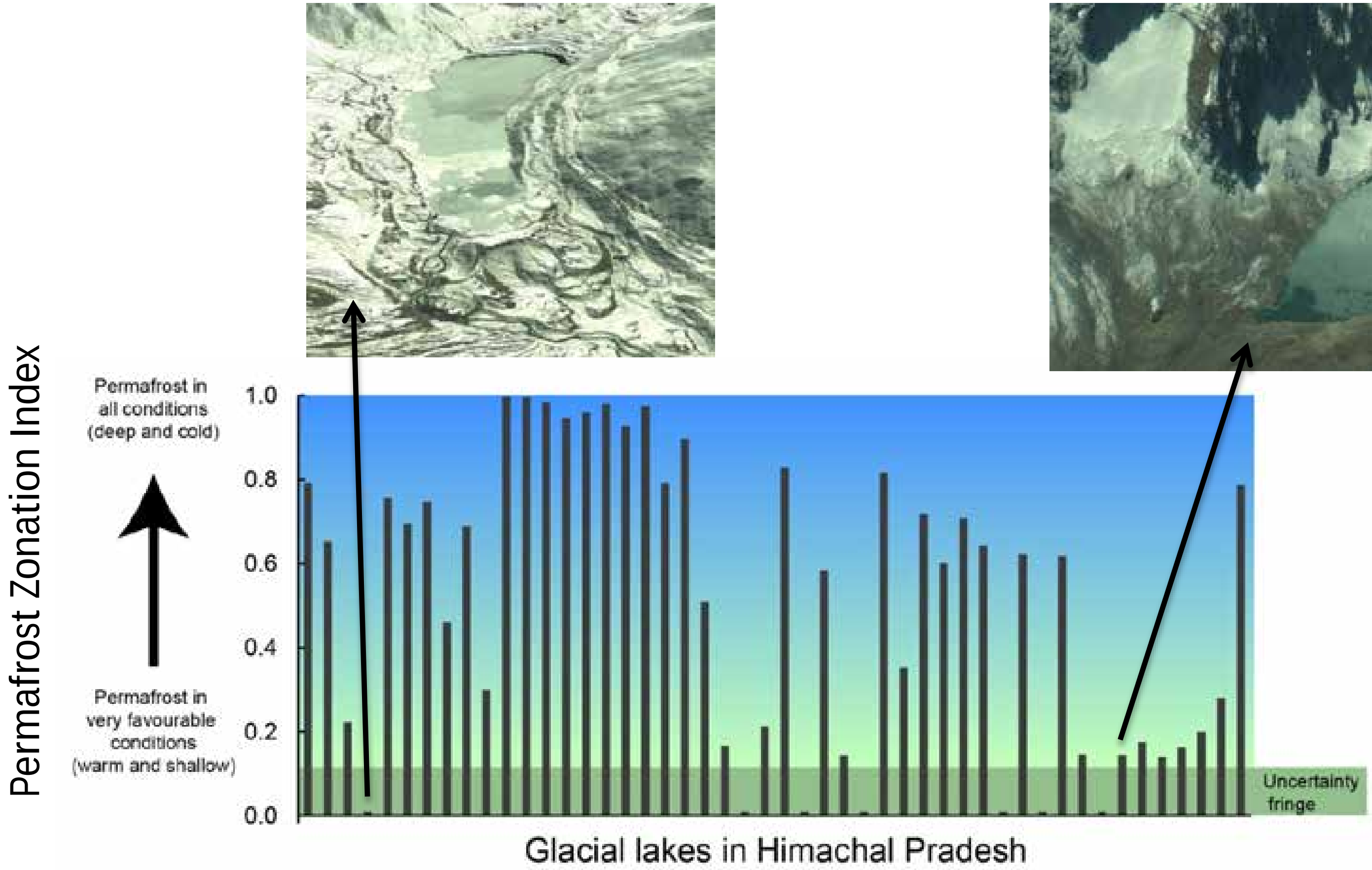
Permafrost in India – rock glaciers

Lahul and Spiti

Beas Kund Glacier, Kullu district

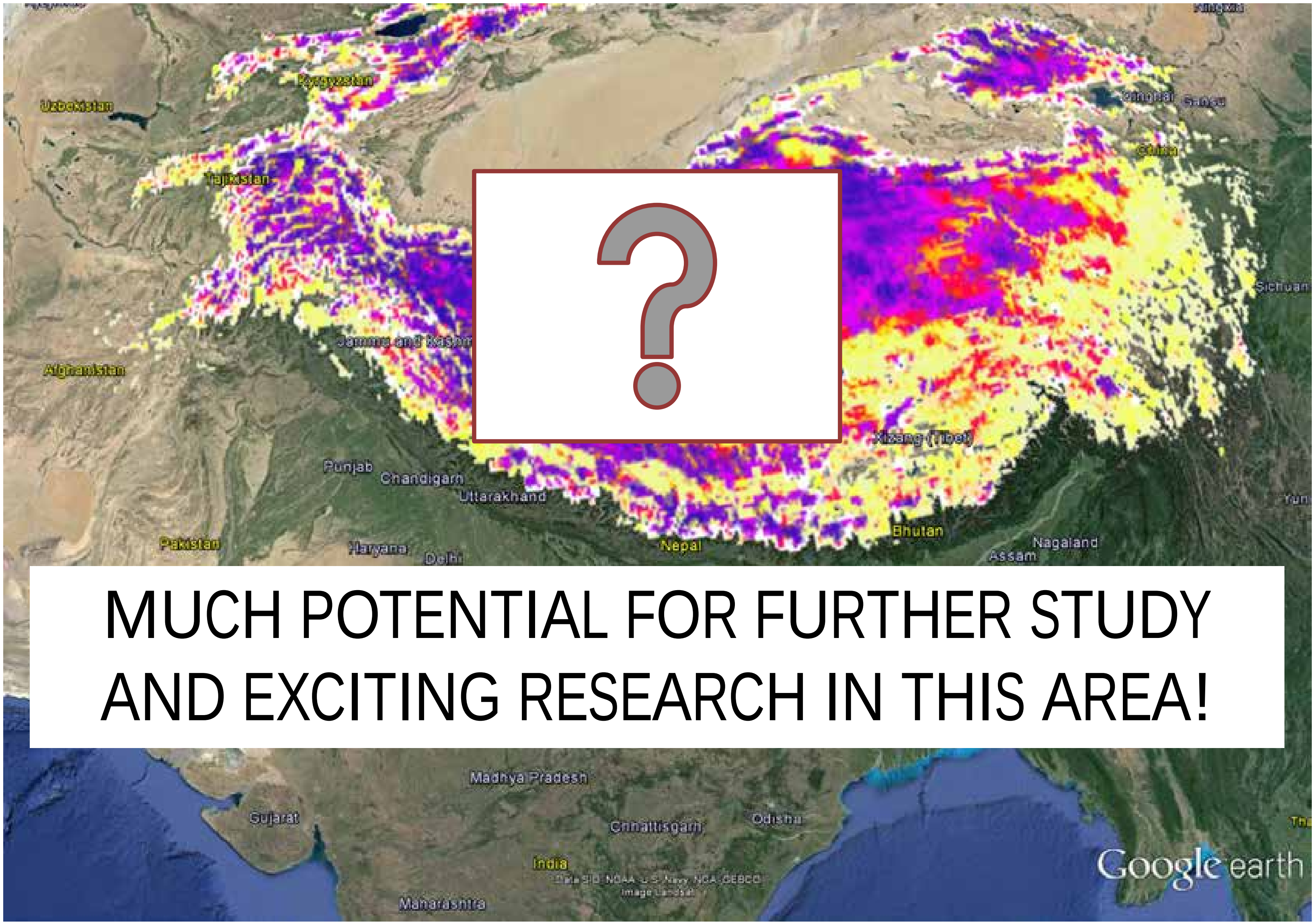
- Both active and inactive rock glaciers are observed throughout the Indian Himalayan states.
- There has been no mapping or long term monitoring of rock glaciers in India.

Permafrost in India – Hazard

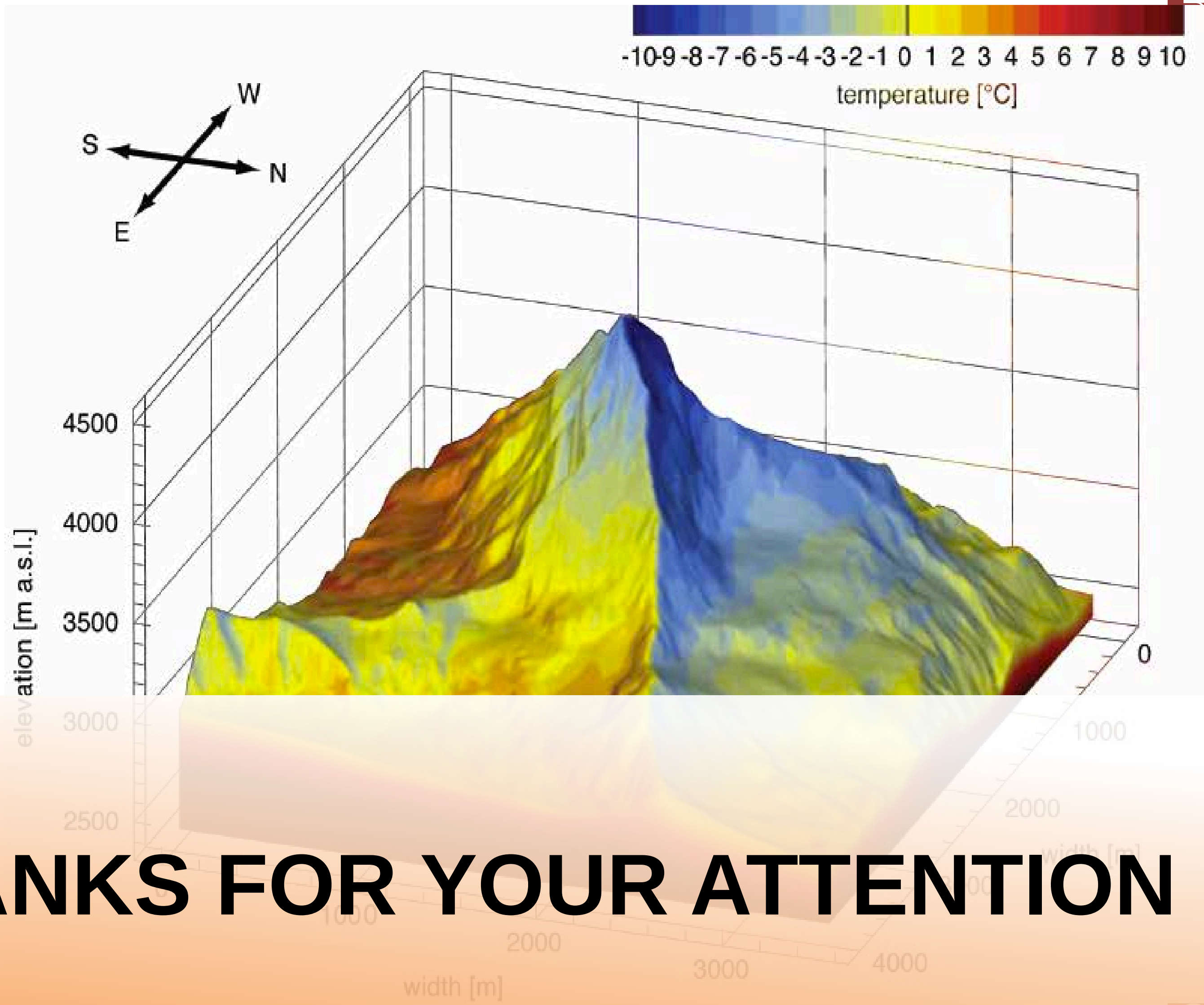


- Many lakes in India are formed within or below permafrost slopes -> potential for thawing and GLOF hazard.
- Very likely rockfall and debris flow hazard associate with thawing permafrost, but limited evidence for this.

Permafrost in India



MUCH POTENTIAL FOR FURTHER STUDY AND EXCITING RESEARCH IN THIS AREA!



MANY THANKS FOR YOUR ATTENTION

Permafrost Exercise (1)

- Your objective:
  - Create a first assessment (map) of permafrost distribution for an area of the Garhwal-Himalaya.

- Your tools:
  - Topographic map of the region (pdf and hardcopy)
  - Some mean climate data (xls. and hardcopy)
  - Google Earth

- Challenge:
  - Use the empirical information (rules) you have learnt in the lecture.
  - Document carefully your methods -> There is NO right or wrong approach to the exercise. The challenge is to use your new knowledge and explain your approach.

Permafrost Exercise (2)

- Your objective:
  - Interpret and describe data from Swiss permafrost boreholes.

- Your tools:
  - 4 borehole plots (depth profiles and long-term trends)
  - Select only THREE sites!

- Challenge:
  - On the depth profiles, indicate layers and terminology you have learnt in the lecture (active layer, permafrost table, permafrost base, ZAA, etc)
  - Based on the profiles and long term trends, describe how the borehole temperatures are evolving over time, the role of surface and topography effects, and possible weather and climate conditions.