

Permafrost





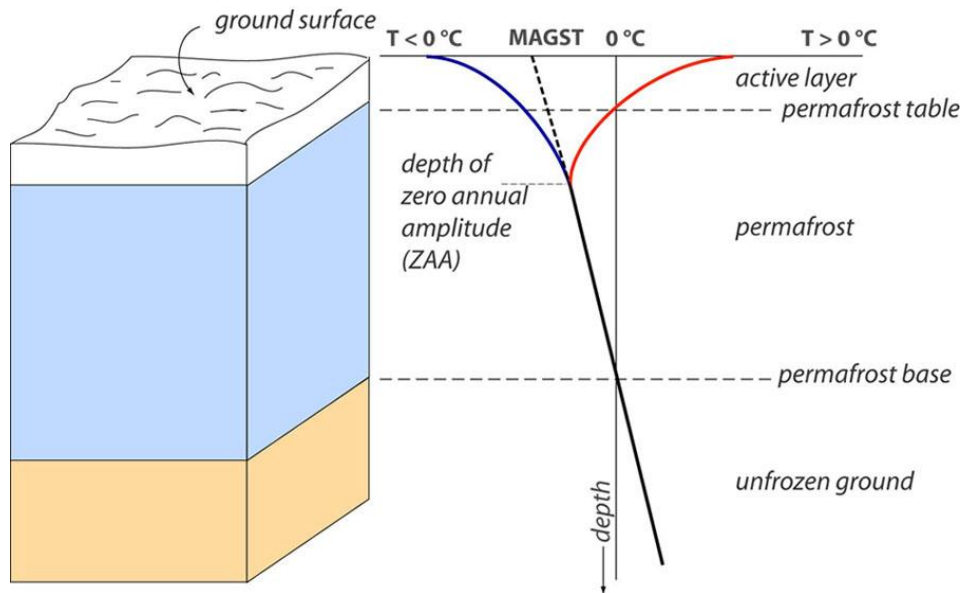
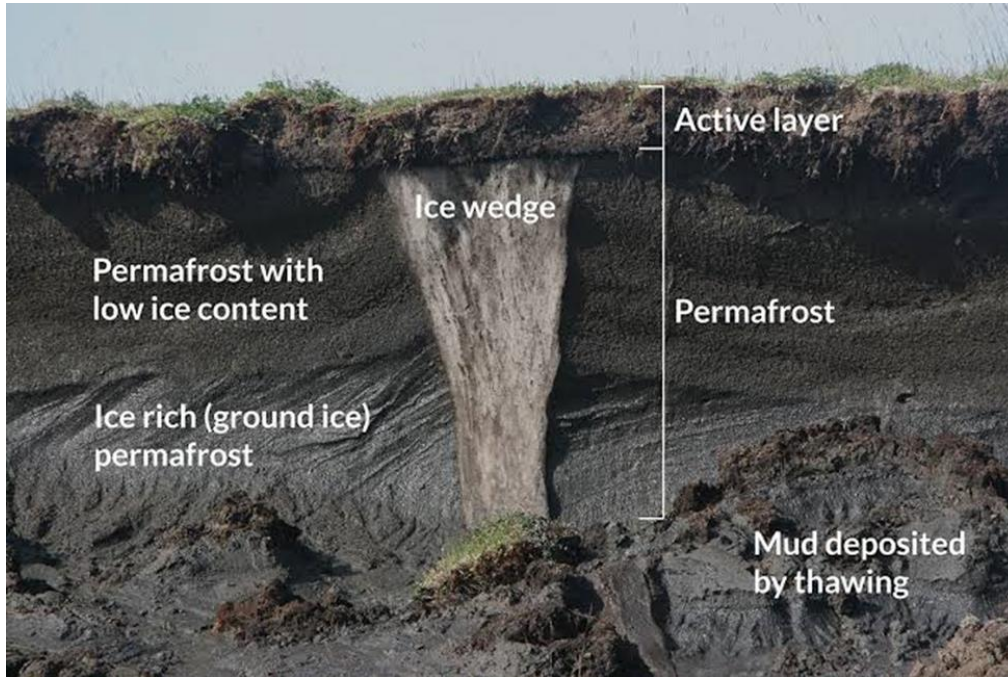
- What is permafrost?
- Active layer thickness (ALT)
- Permafrost on the global scale
- Permafrost in the Alps
- Permafrost and snow
- Permafrost research
- Thawing, dangers and impacts
- What helps to preserve permafrost?
- Take home messages



Permafrost is an invisible thermal phenomenon, soil or underwater sediment which continuously remains below 0° C for two years or more.

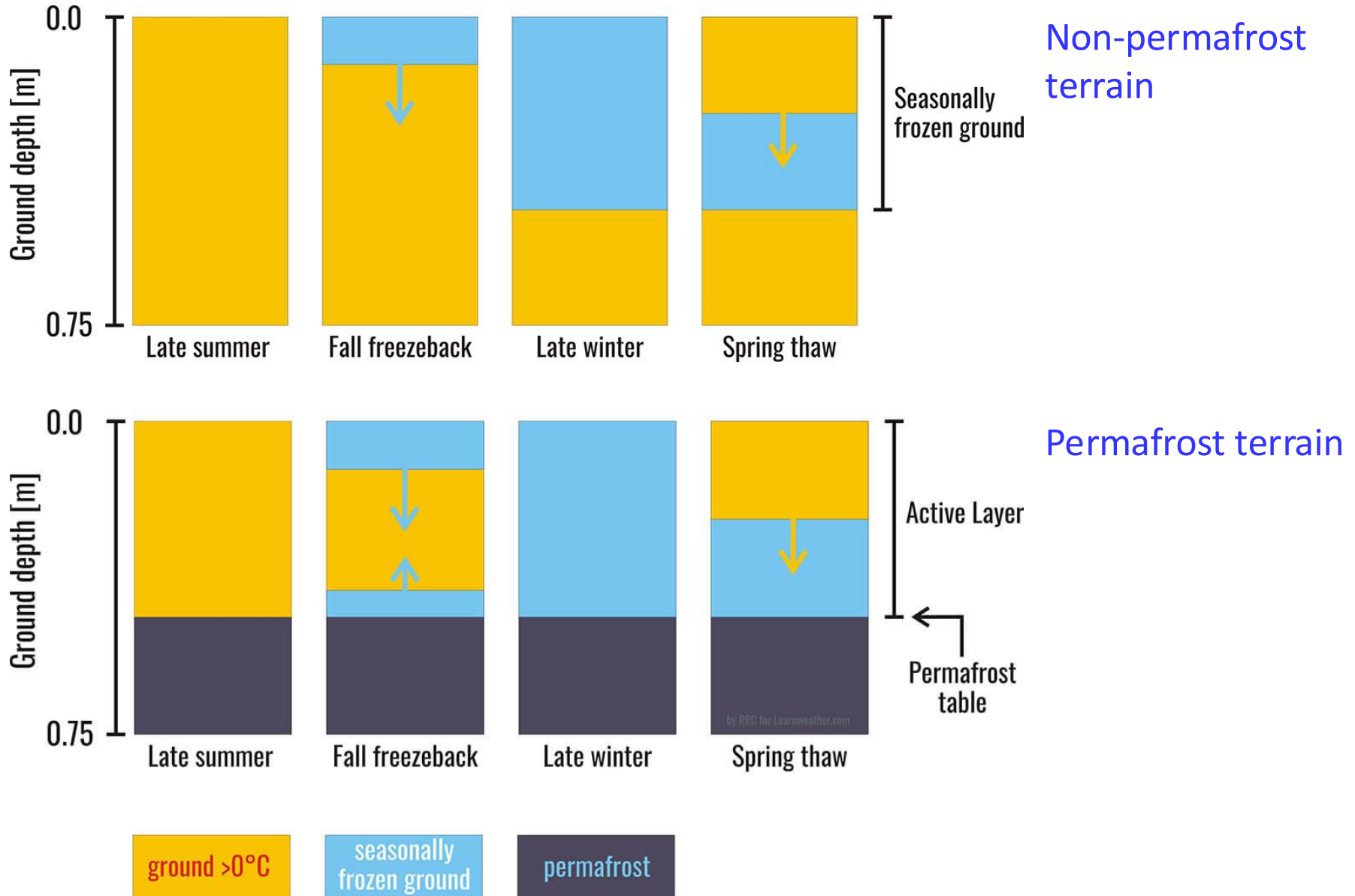
- The oldest permafrost has been continuously frozen for around 700,000 years (Siberian village of Batagay).
- The shallowest permafrost has a vertical extent of below a meter, the deepest is greater than 1,500 m.
- Permafrost has a significant influence on the stability of construction substrates or steep rock walls
- Research on permafrost is particularly useful for planning infrastructure or determining potential natural hazards.

What is permafrost?



From Noetzli and Gruber (2005)

Permafrost: Active Layer Thickness (ALT)

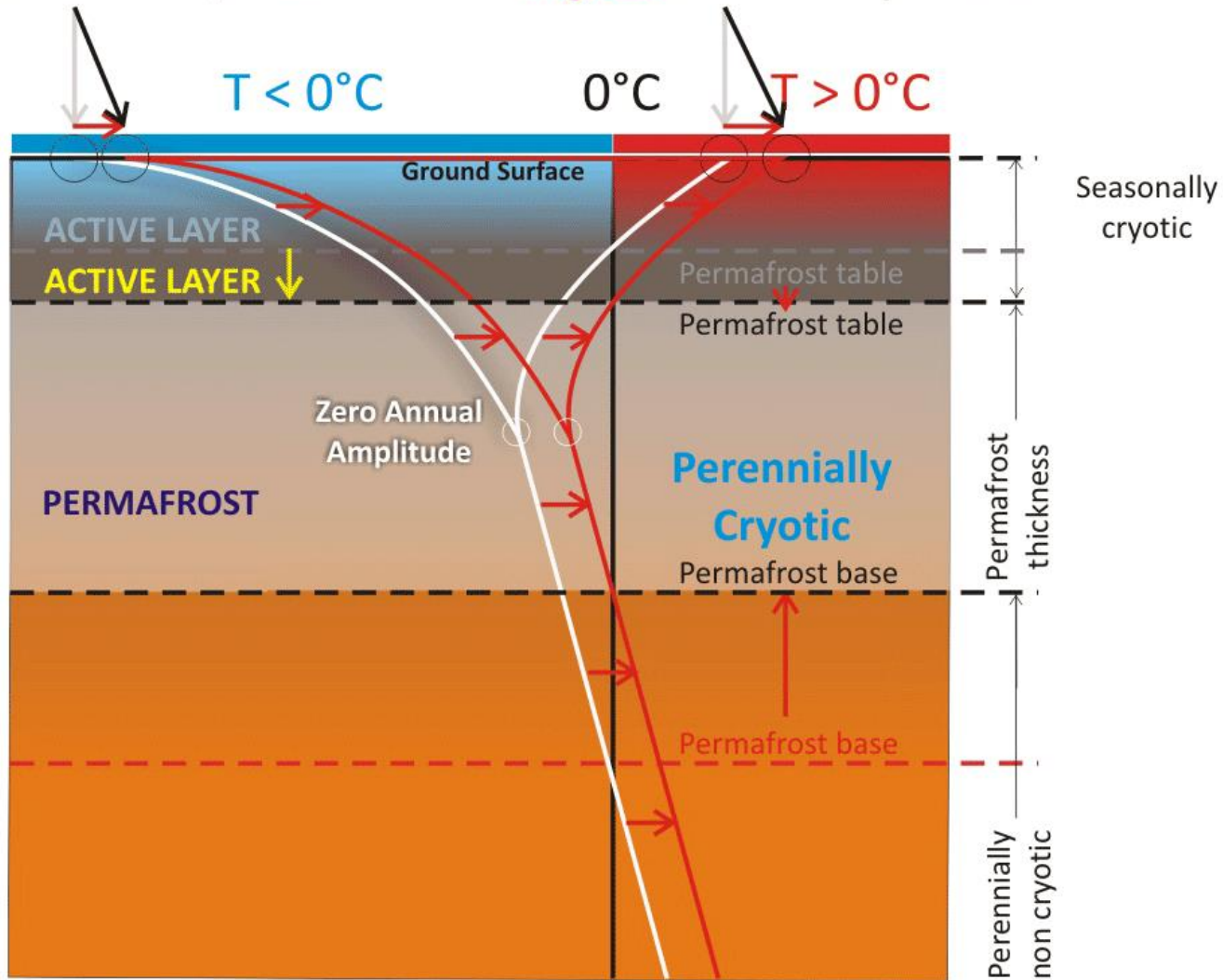


Permafrost: Active Layer Thickness (ALT)

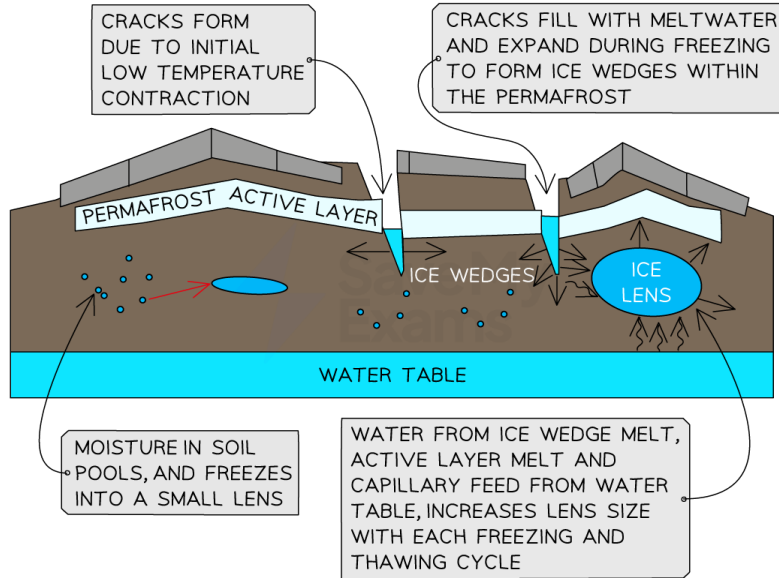


Lowest Annual Temperature

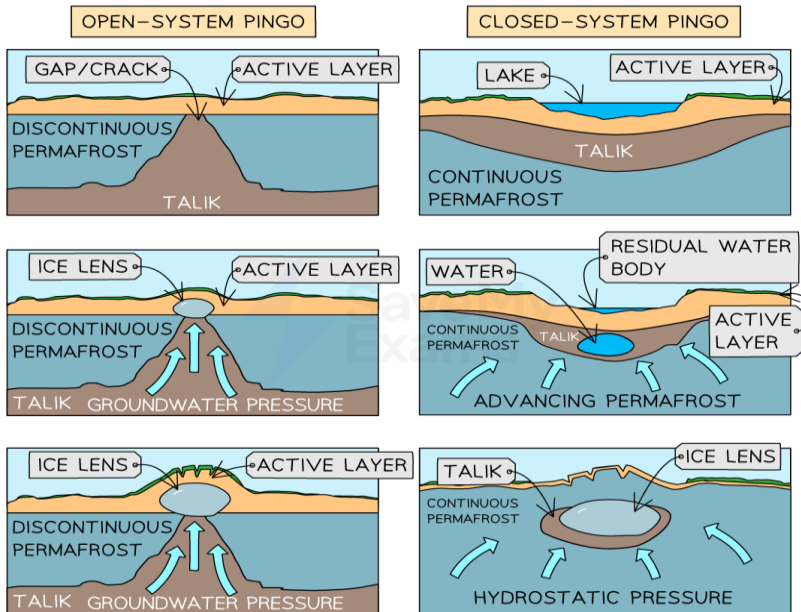
Highest Annual Temperature



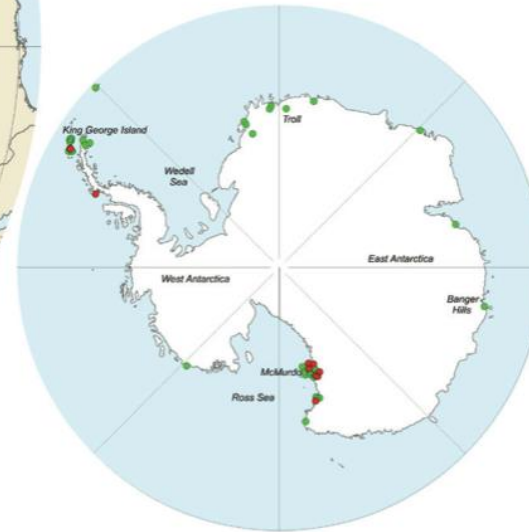
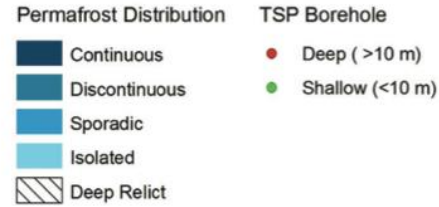
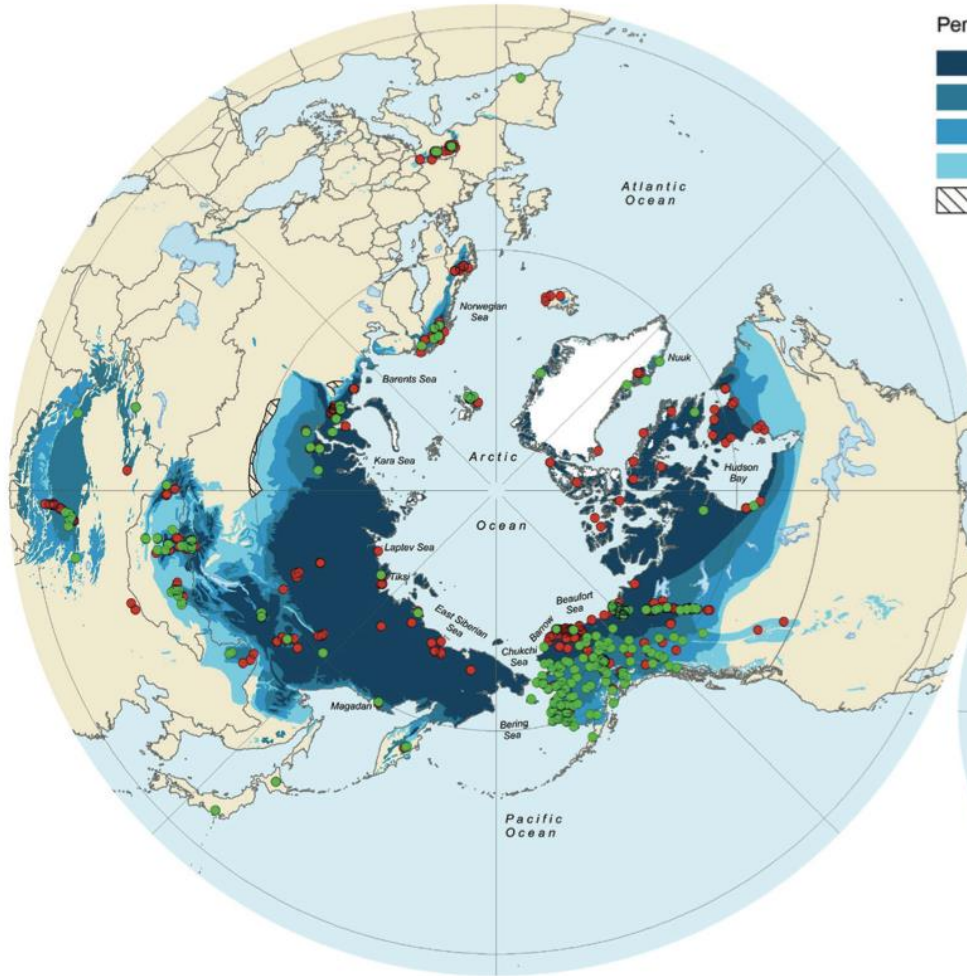
Permafrost: Different processes



- **Ice wedges** – Formed by repeated freeze–thaw cracking and ice infilling
- **Pingos** – Dome-shaped hills formed by ice pushing up the ground surface.
- **Ice lenses** – Thin layers of pure ice forming within soil.



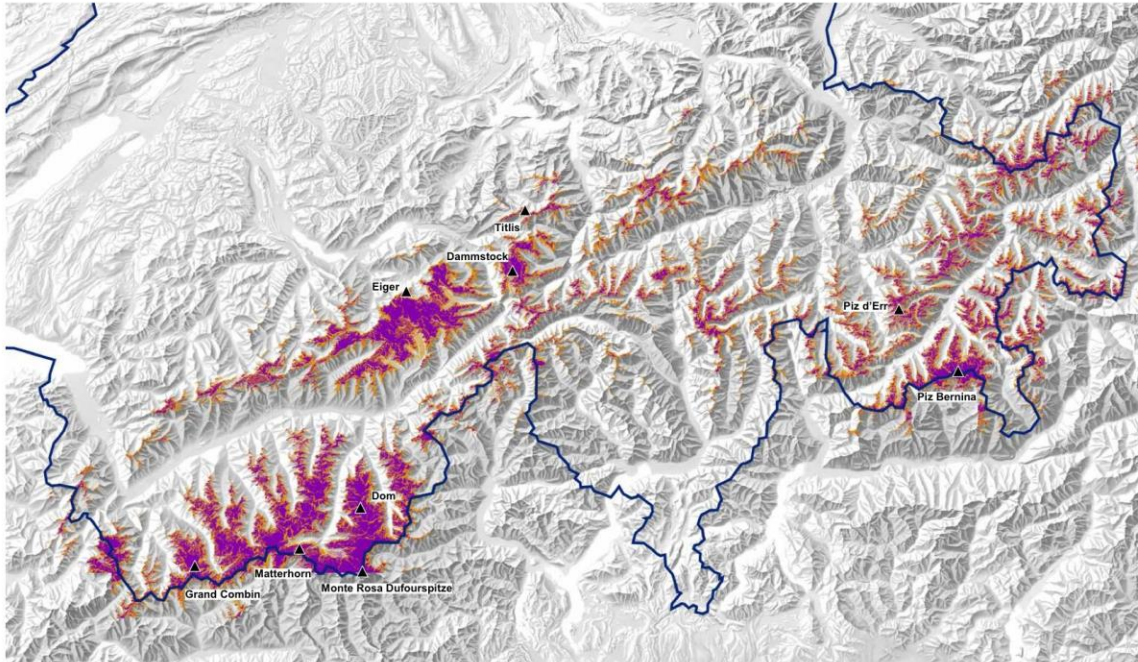
Permafrost on the global scale



Covers about 25 % of the land masses of the Northern Hemisphere

Hinweiskarte Permafrost Schweiz

Potentielle Permafrostverbreitung aufgrund von Modellierungen mit dem DHM25 (BAFU 7/06)



Legende:  Permafrost lokal möglich  Permafrost flächenhaft wahrscheinlich

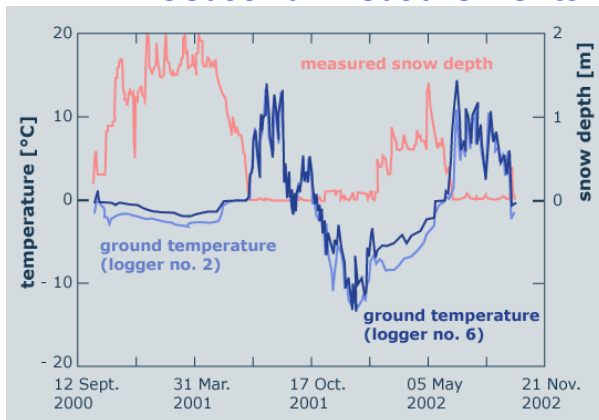
PERMOS
Swiss Permafrost
Monitoring Network



- Begin somewhere above 2400–2 600 m a.s.l. in many locations
- Permafrost covers around 6% of the Swiss Alps

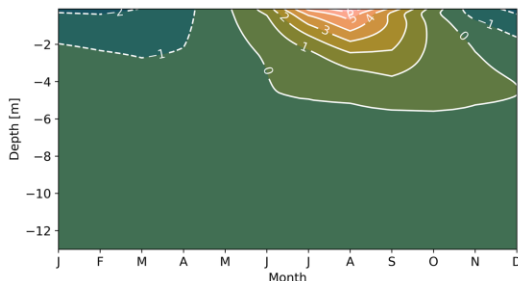


Seasonal measurements

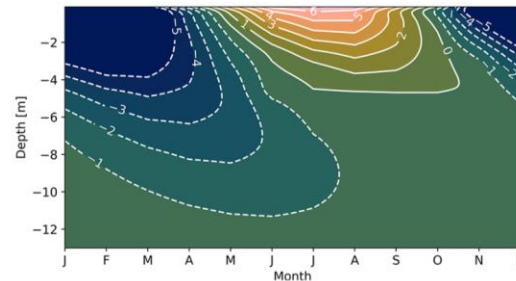


- Snow as a thermal insulator:
 - Low thermal conductivity (fresh snow)
 - Thicker snow → warmer permafrost (reduced winter cooling)
 - Thinner snow or wind scouring → colder permafrost
 - Seasonal snow cover controls ground heat flux
 - Contrast between early/late snow onset: early snow insulates (warmer permafrost); late snow allows deeper cooling
 - Snow ↔ Permafrost
- Snow as a water source:
 - Spring melt infiltration → affects active layer thaw depth
 - Role of refreezing and ice lenses in the active layer

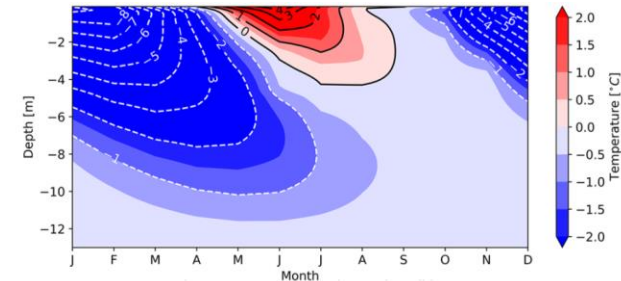
Ground temperature profile numerical modeling over the year. Example for the Alps (Schilthorn).



With snow cover



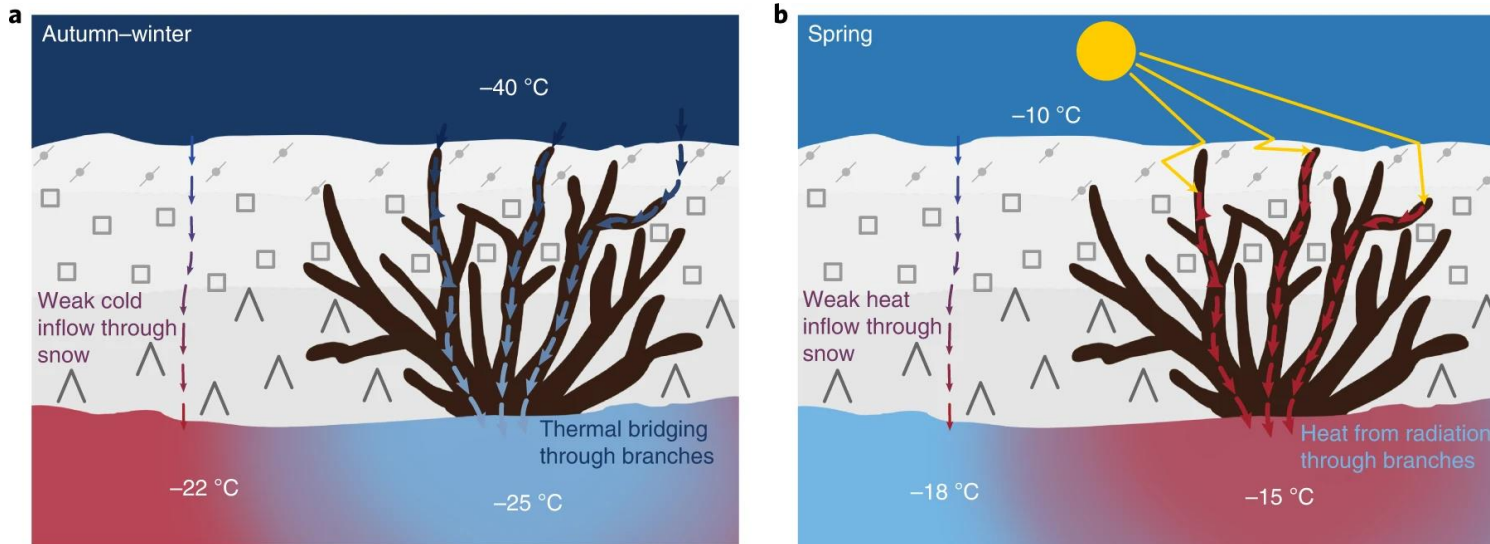
Without snow cover



Difference

Shrubs trap more snow → further insulation → permafrost warming.

Thermal bridging through shrub branches in winter and spring.



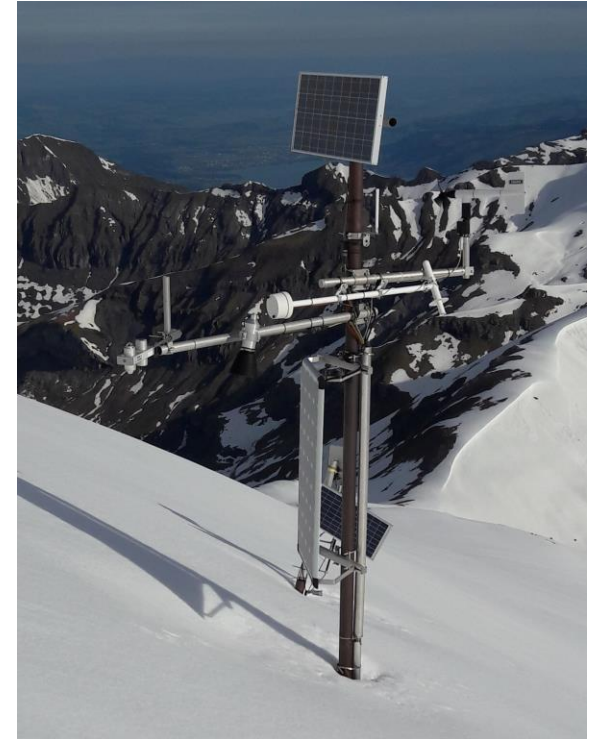
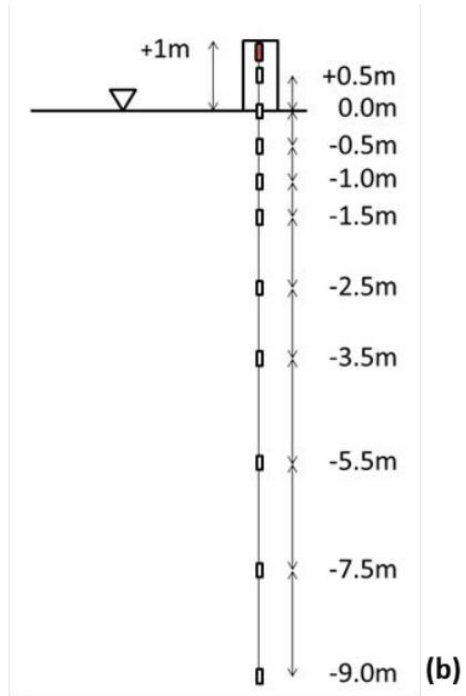
A) In autumn and winter, in the absence of sunlight, thermal bridging through frozen shrub branches cools the ground. B) In spring, light absorption by shallow buried shrub branches heats up the branches. The resulting heat is transferred through the branches to the ground, whose warming is thus accelerated.

More info: Domine, F. et al. "Permafrost cooled in winter by thermal bridging through snow-covered shrub branches" [Nature Geoscience](#) volume 15 2022

Field Observations

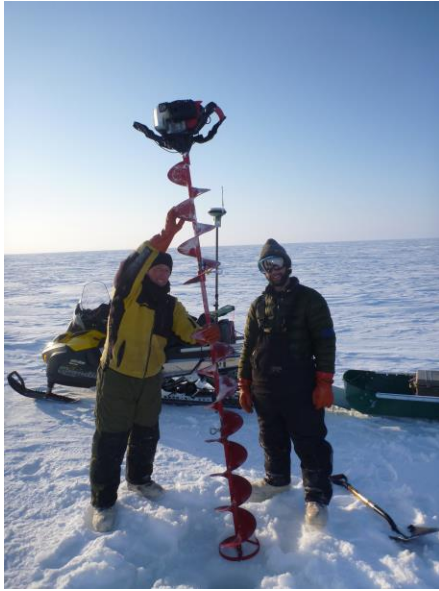


Ground Temperature measurements



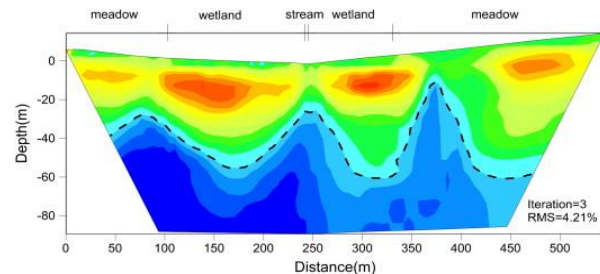
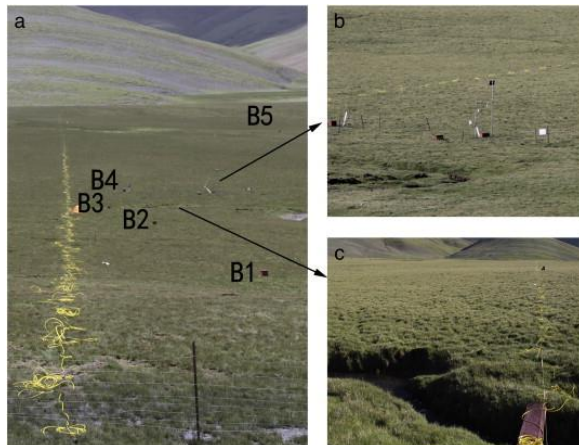
Meteorologic/Atmospheric measurements

Field Observations



Permafrost coring

Electrical resistivity tomography (ERT)



ERT uses direct current (DC)

- Injects electric current into the ground through two electrodes.
- Measures the resulting voltage at other electrodes.
- Uses Ohm's Law to calculate resistivity

Frozen ground contains ice, not liquid water.

- Ice is a very poor conductor → High resistivity
- Unfrozen soil and rock contain liquid water → Lower resistivity

Remote Sensing



Satellite observations

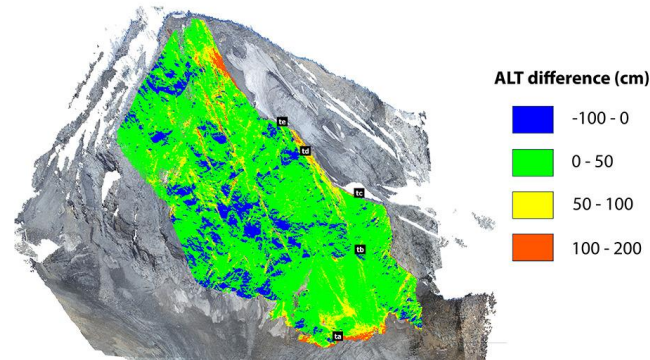
Thermal UAV photogrammetry



Thermistors in situ



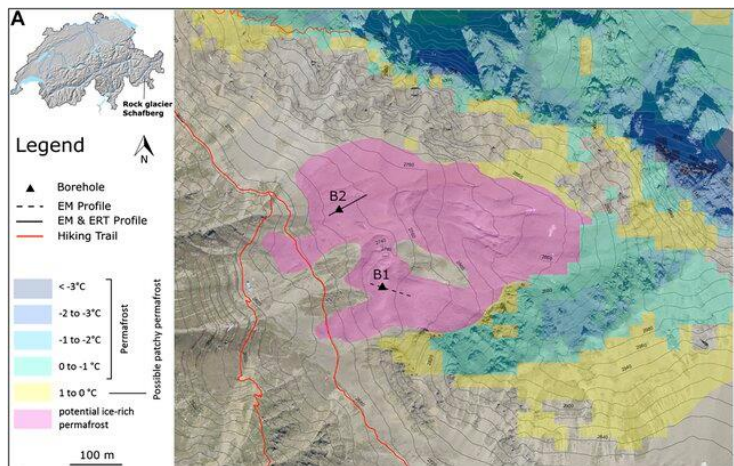
Rock wall permafrost modelling 2021-2022



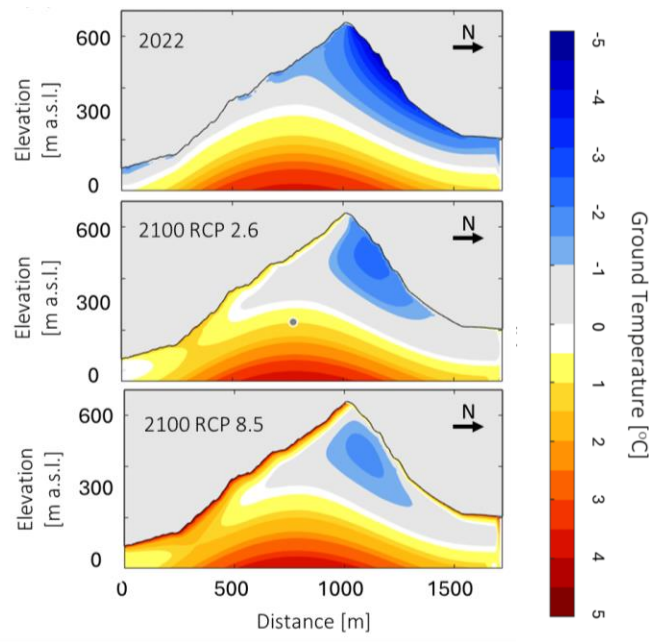
LiDAR and photogrammetry for surface topography changes

Picture: Central Italian Alps, Italy
Stefano Ponti et al. 2024

Modeling Permafrost



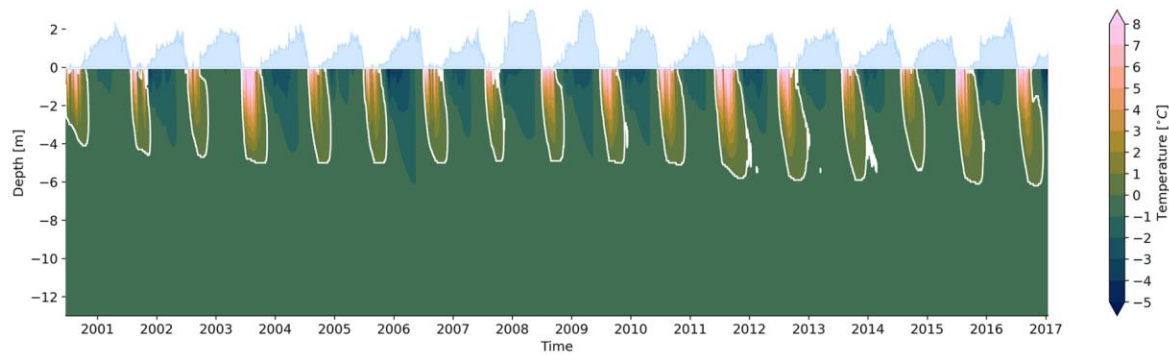
Modeled permafrost distribution (Kenner et al., 2019a) at the Schafberg site (Eastern Swiss Alps, near Pontresina). The approximate extent of ice-rich permafrost is mainly based on photogrammetric ground deformation measurements (Kenner et al., 2019b). (Aerial photograph: Swiss Federal Office of Topography, swisstopo).



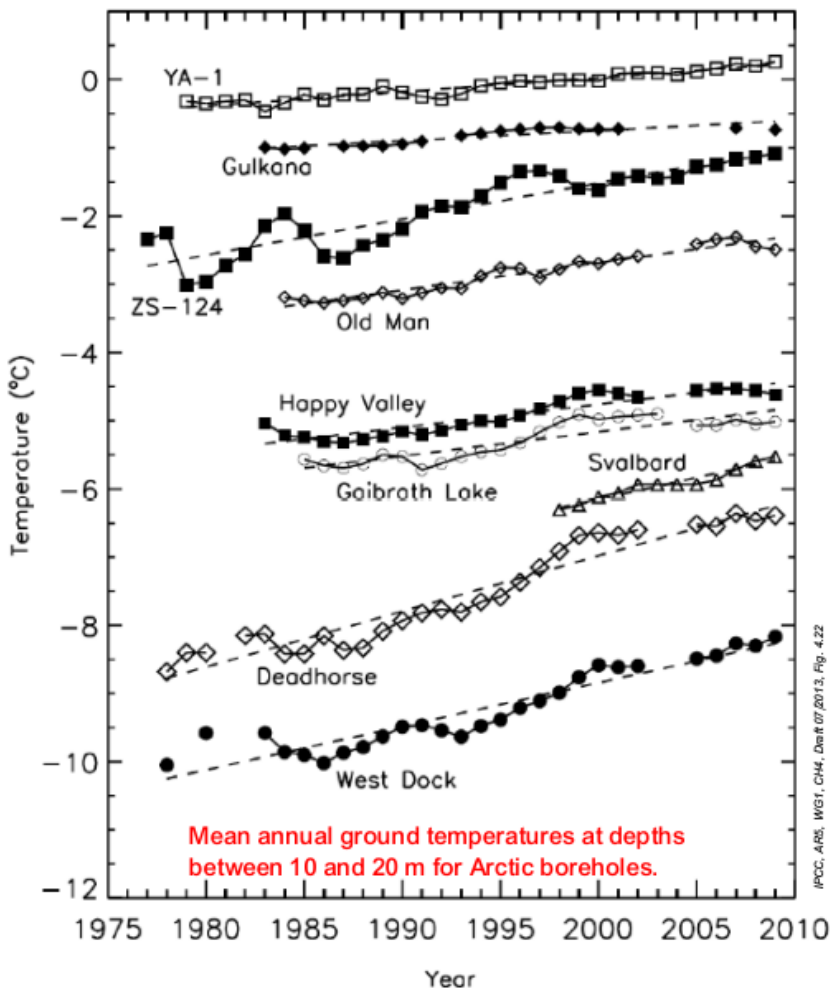
2D simulations for future scenarios.

2D models are run until 2100 for RCP 2.6 and RCP 8.5

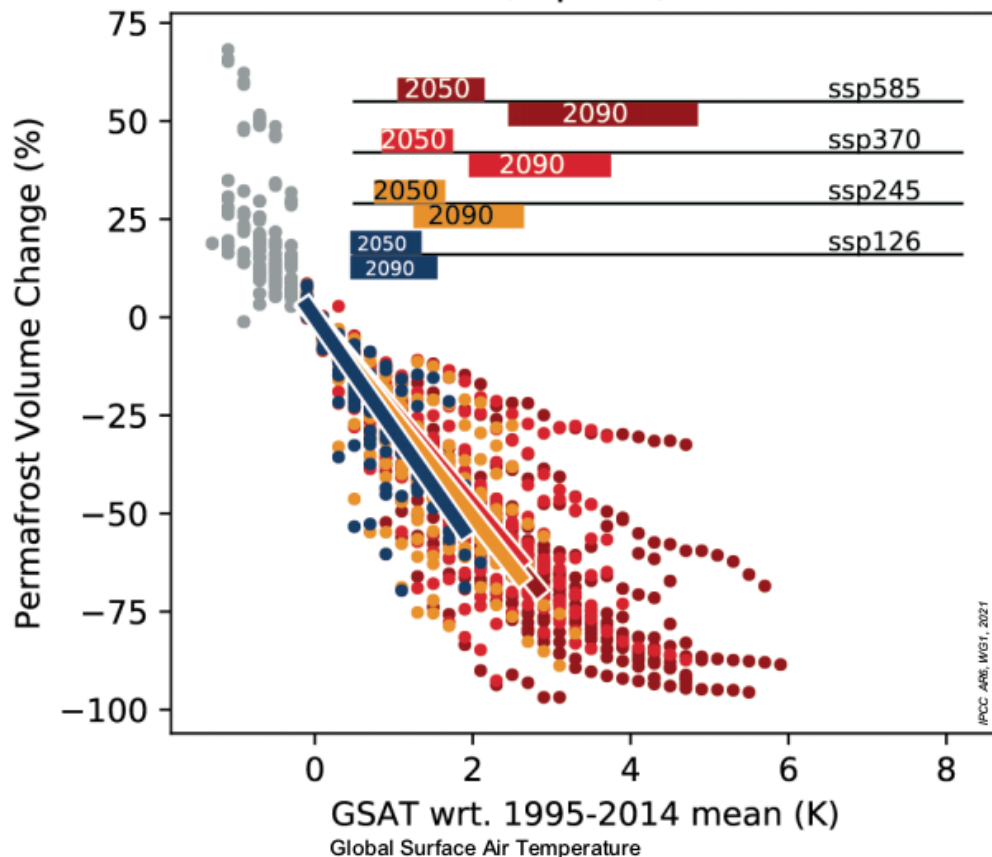
Greenland ice sheet
 Marcer, M. et al. 2024



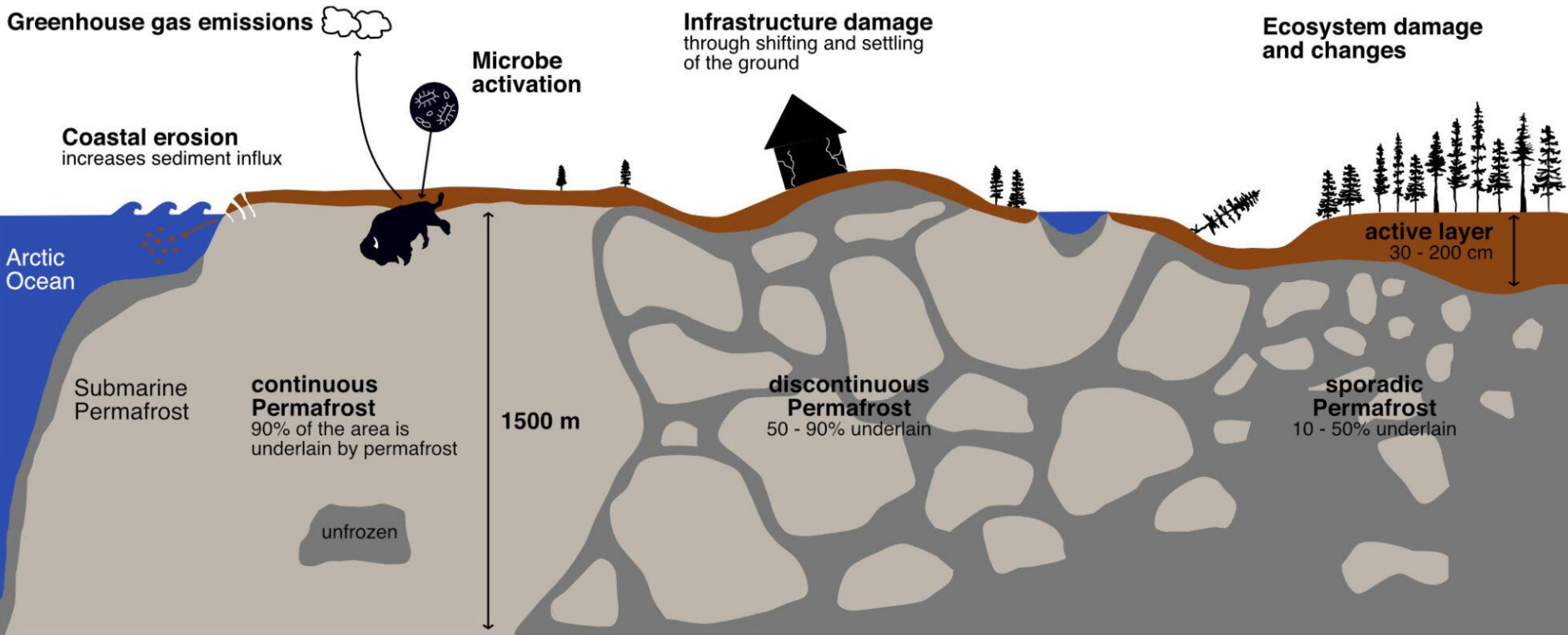
Time series of daily averaged modelled ground temperatures during natural undisturbed conditions at the Schilthorn (Bernese Alps CH) site from 2000 to 2017. (SNOWPACK modeling) Sharaborova et al. 2025



b) Global Permafrost Volume Change (top 3m)



Permafrost: Thawing dangers and impacts

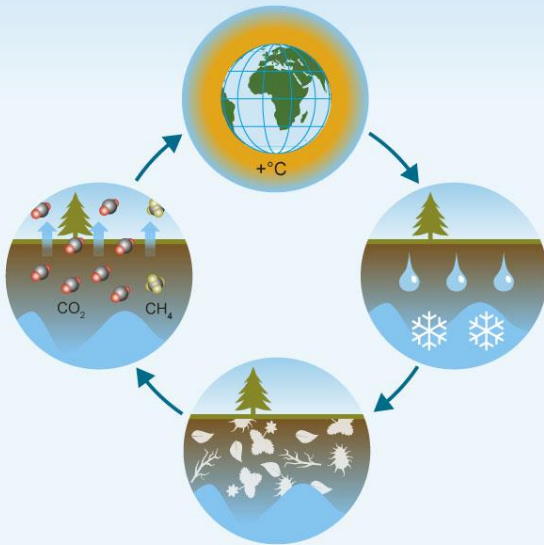


Greenhouse gas emissions

Permafrost thawing can intensify global warming

1. High levels of greenhouse gases, such as CO₂ and methane, in the atmosphere cause global temperatures to increase

4. As organic matter decays, CO₂ and methane are released into the atmosphere



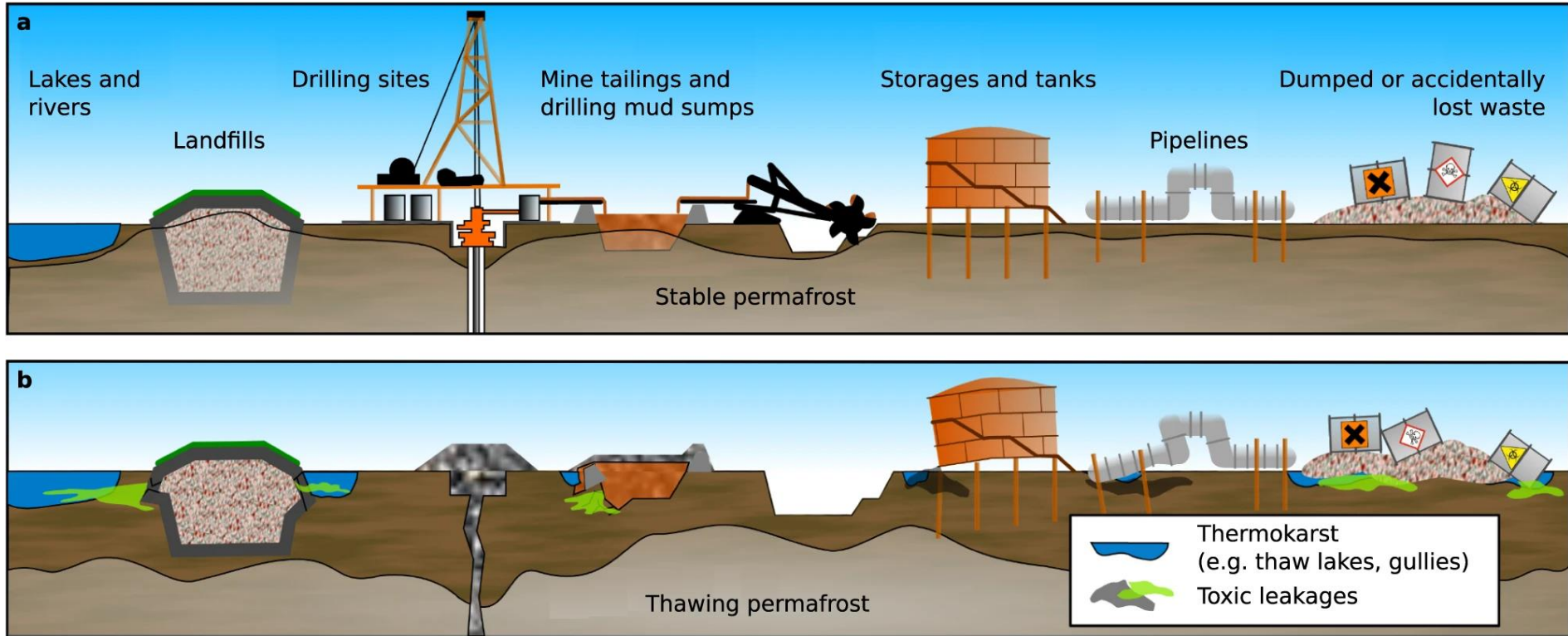
2. Increasing temperatures cause permafrost to thaw

3. Thawing exposes previously frozen organic matter to decay



- Organic matter has been preserved for thousands of years because it stayed frozen and microbes couldn't decompose it.
- Permafrost holds about half of the world's soil organic carbon.
- When permafrost thaws, microbes become active, the organic matter breaks down and releases CO₂ in dry soils (aerobic conditions), CH₄ (methane) in wet, thaw lakes, peat bogs (anaerobic conditions).
- Thawing permafrost can become a long-term amplifier of global climate change.

Impact on Infrastructure



Potential impacts of thawing permafrost on above- and below-ground industrial infrastructure containing toxic substances or waste.

- (a) Past and present industrial activities in the Arctic result in various accumulations of hazardous substances in the Arctic.
- (b) The warming and thaw of near surface permafrost unlocks frozen disposal sites and destabilizes foundations and containment structures.

Furthermore, permafrost thaw intensifies thermo-hydrological erosion and increases the lateral flow of water, fostering the dispersion of contaminants.

Permafrost: Thawing dangers and impacts



The fuel spill of May 2020 saw 21,000 tons of diesel pour from one of a company's storage tanks into rivers and lakes in Russia's Arctic North.



Effects of global warming as the permafrost thaws near Yellowknife in Canada's Northwest territories. The pavement is buckled and pot-holed.



The village of Blatten in the Swiss Alps was largely destroyed by a landslide that occurred as a result of the partial collapse of the Birch Glacier in May 2025.



Infrastructure in permafrost areas is threatened by riverbank erosion, Mackenzie River Delta, Canada.



Thermal Stabilization Systems

Permafrost thermal stabilization refers to engineering techniques used to maintain or restore frozen ground conditions, preventing permafrost thaw under infrastructure such as roads, buildings, pipelines, or runways.

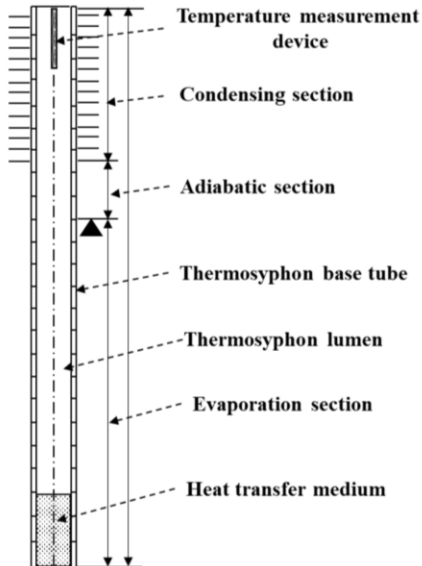
It's especially important in Arctic and mountain regions where permafrost degradation threatens structural stability and increases maintenance costs.

1. **Passive Cooling Systems:** Use natural thermal gradients (no external energy)
2. **Active Cooling Systems:** Use mechanical or powered systems

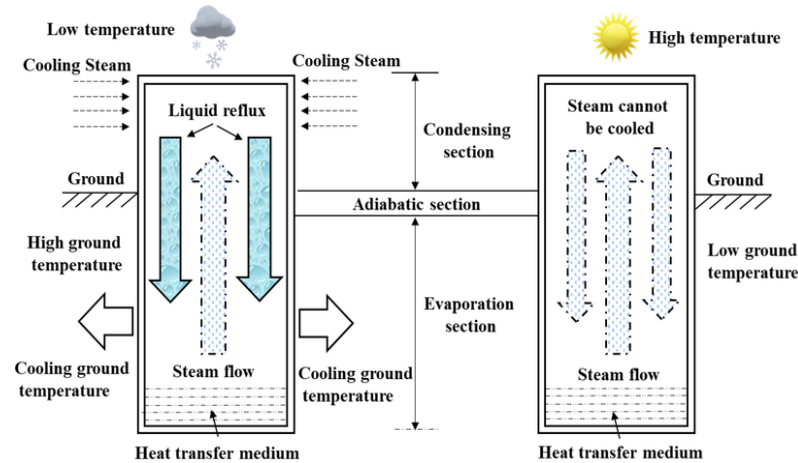
Thermosyphons

- Vertical or inclined sealed tubes filled with a working fluid (e.g., CO₂, ammonia).
- In winter: vapor carries heat upward and releases it to the cold air, cooling the ground.
- In summer: the system shuts down automatically (no heat input).
- Common under pipelines, buildings, and road embankments (e.g., Trans-Alaska Pipeline).

Schematic diagram



Work principle



Installation examples



Air convection embankments (ACE)

Rock-filled embankments that promote air circulation, enhancing ground cooling in winter.



Configurations used along permafrost zones.



Example of surface shading.

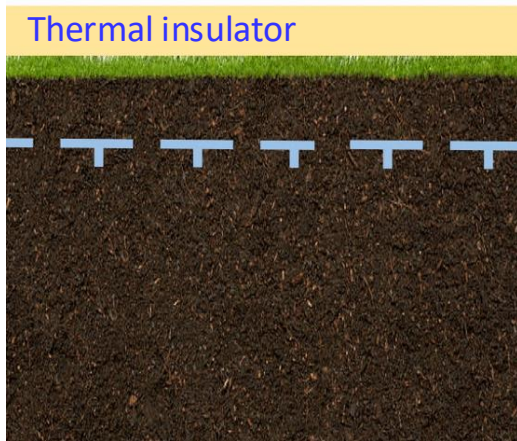
Shading

- Incoming solar radiation is a major source of ground warming during summer.
- By reducing direct sunlight, shading helps limit heat absorption at the ground surface and keep permafrost temperatures low.
- The technique modifies the surface energy balance, lowering both mean annual ground surface temperature (MAGST) and thaw depth.

Insulation layers

Use of foam boards or crushed rock to reduce summer heat transfer from above.

All year placement



- Thermal insulation creates a barrier with low thermal conductivity, limiting the heat transfer.
- Without insulation: summer heat penetrates deeply, permafrost thaws → road subsidence.
- With insulation layer: heat flux reduced, active layer stabilizes, and permafrost preserved.

active layer depth



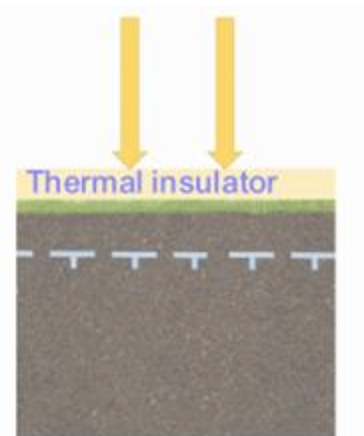
Insulation layers

Use of foam boards or crushed rock to reduce summer heat transfer from above.

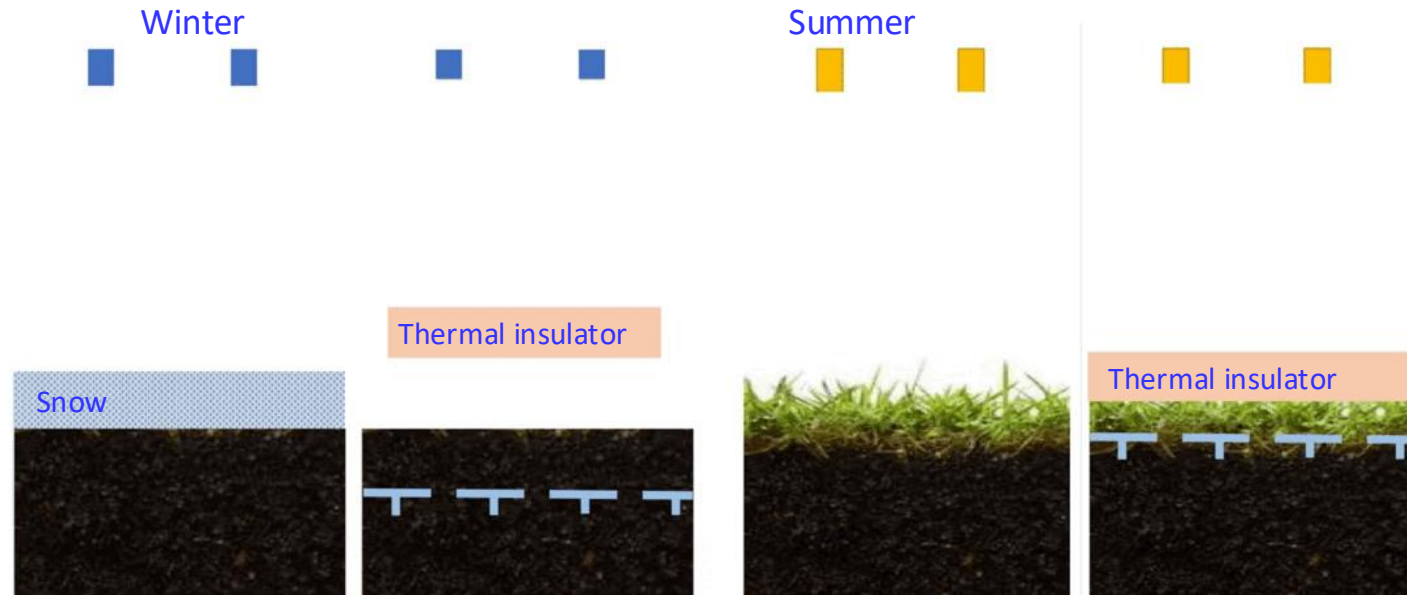
- Thermal insulation placement in summer creates a barrier, limiting the heat transfer.
- Thermal insulation lifting in winter cools the ground better, allowing the heat transfer.
- Without insulation: in winter, permafrost cools naturally.
- With insulation layer: in summer, the heat from winter is stored in the ground and permafrost is preserved.

Seasonal variation (Heat flux regulation)

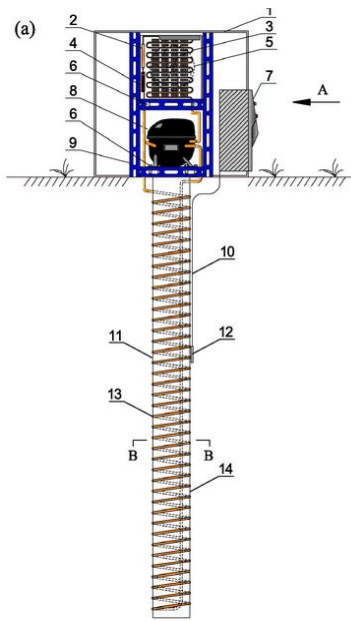
All year placement



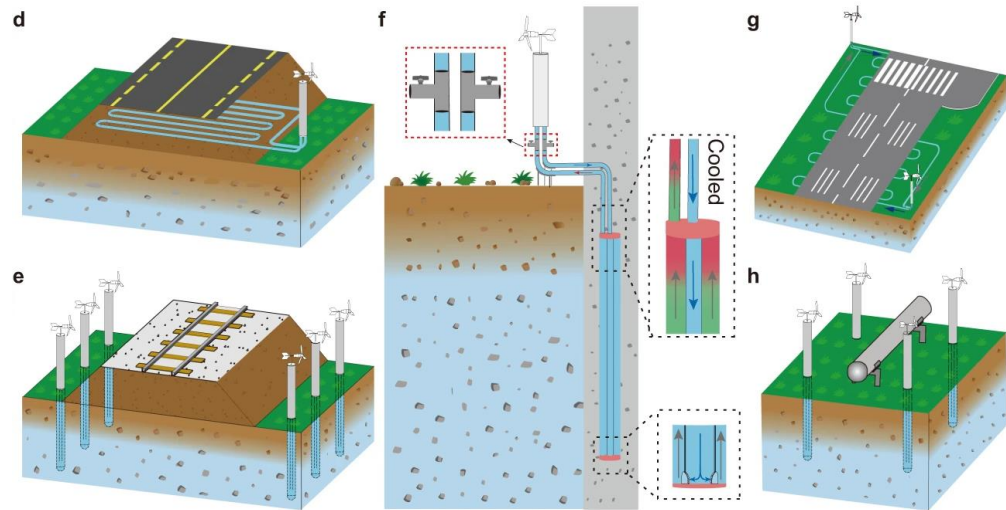
active layer depth



- Active systems use external energy (mechanical, electrical, or cryogenic) to actively remove heat from the ground or inject cold energy into it.
- Unlike passive cooling (which relies on natural temperature gradients), active systems operate year-round, and their effect can be controlled.
- Goal: maintain permafrost below 0° C, even under warming conditions or thermal stress from infrastructure.



Hu, T., et al. (2020). Design and experimental study of a solar compression refrigeration apparatus for embankment engineering in permafrost regions. *Transportation Geotechnics*, 22.

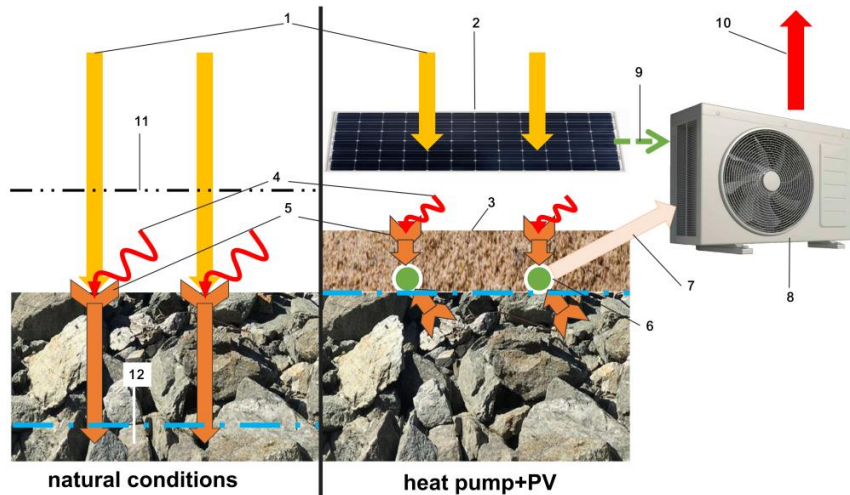


Qin, Y., Wang, T. & Yuan, W. Wind-driven device for cooling permafrost. *Nat Commun*

Combined Cooling System



- A combined system integrates two or more stabilization techniques (typically passive and active), to achieve enhanced permafrost protection.
- Each component targets a different heat-transfer process:
- Passive systems limit or redirect heat flow.
- Active systems extract heat or artificially cool the soil.
- They provide control even under variable climate and load conditions.
- Seasonal optimization: active cooling in summer + passive winter cooling.
- Cost optimization: active only where needed, passive elsewhere.



- 1 - solar radiation
- 2 - energy converter
- 3 - sand or gravel
- 4 - convection
- 5 - heat conduction
- 6 - cooling tubes
- 7 - heat transfer fluid
- 8 - heat exchanger
- 9 - converted solar energy
- 10 - heat sink
- 11 - snow level
- 12 - active layer depth



- Permafrost is ground below 0°C along > 2 yrs. The thermal balance at the ground surface controls its existence.
- Permafrost links climate, hydrology, ecology, and engineering, it is a sensitive component of the cryosphere.
- The active layer thickness indicates the thermal state of the permafrost and ongoing changes.
- It is found worldwide in cold or high-elevation regions.
- There is a strong interaction between snow and permafrost resulting in warmer/colder permafrost.
- Permafrost research combines field observations, remote sensing, and modeling. These all are essential for predicting its state and evolution.
- Thawing causes ground and slope instability, carbon release, and infrastructure damage.
- Protecting permafrost requires both scientific understanding and engineering innovation.
- In a warming climate, permafrost stability is not guaranteed, but informed management can mitigate impacts. Stabilization: passive, active and combined systems aim to preserve frozen ground.