



# Temperature distribution in a permafrost-affected rock ridge from conductivity and induced polarization tomography

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*Rock Slope Stability 2021*

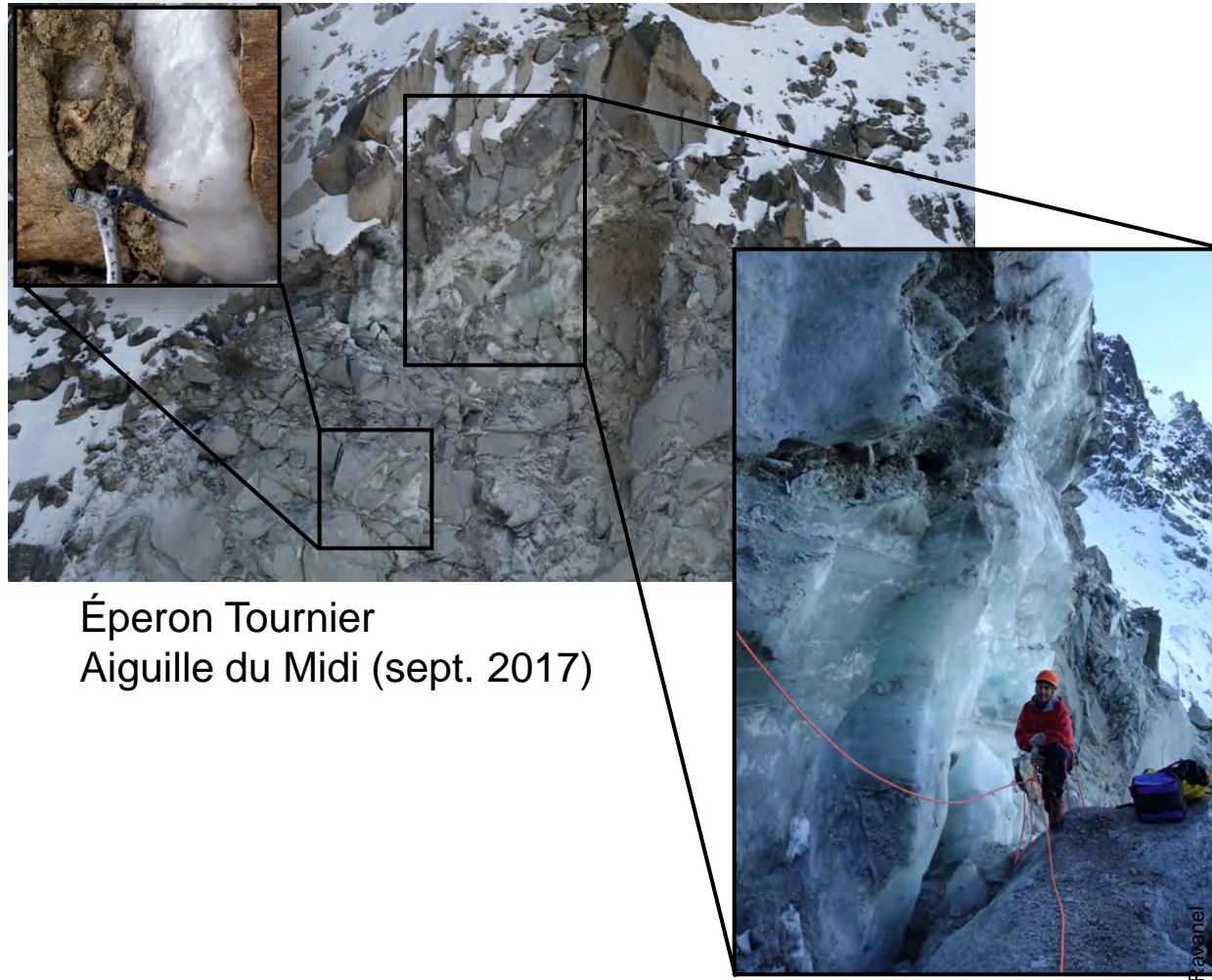
*Chambéry, 17 november 2021*



# Mountain permafrost definition

*“Ground material (soil, sediment or rock) that remains at or below 0 °C for more than two consecutive years” (French 2015)*

## Bedrock / rock walls



Éperon Tournier  
Aiguille du Midi (sept. 2017)

## Surficial deposits

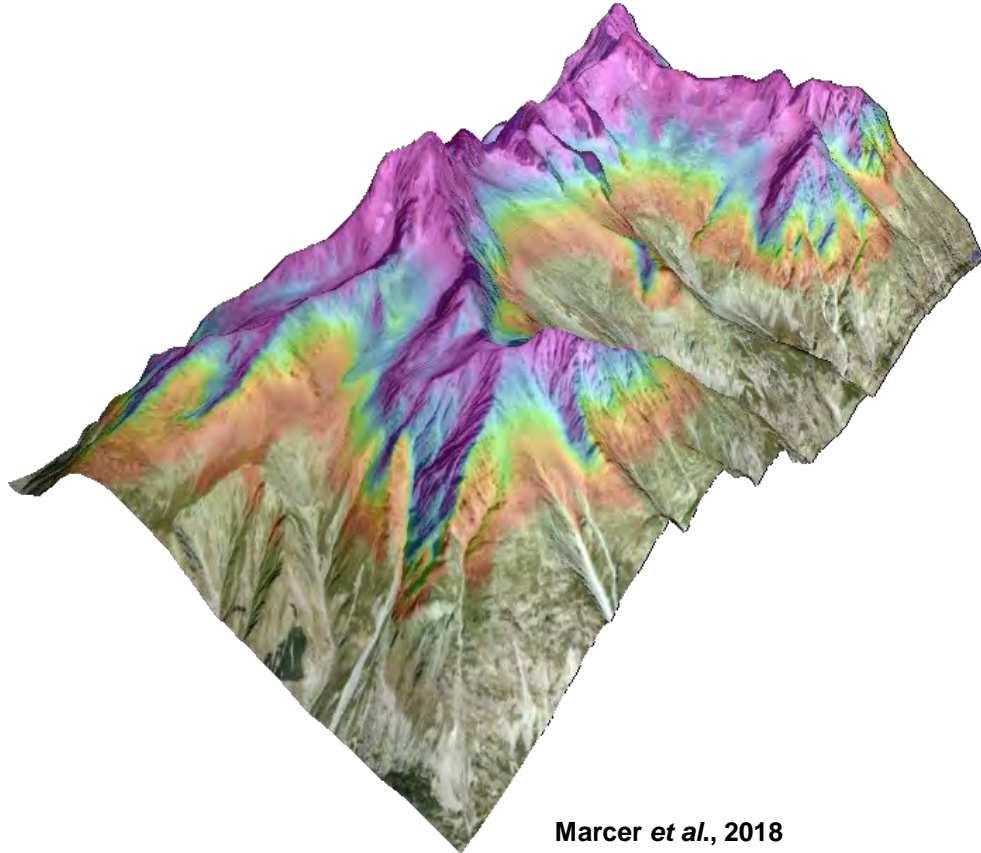


Bérard rock glacier, South Alp (2008)



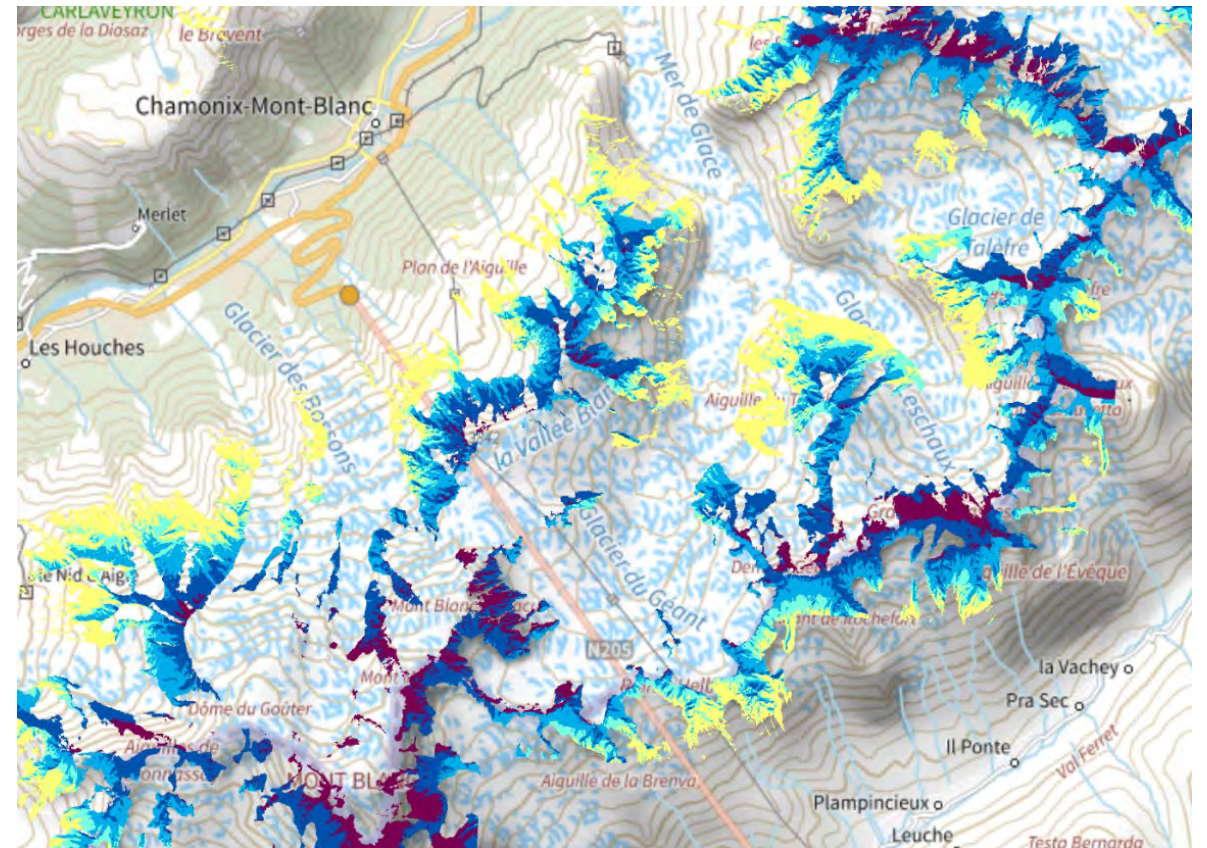
# Studying the presence of permafrost (1/2)

## Regionally → Permafrost modelling by massif



Marcer *et al.*, 2018

~ 1500 rock glaciers



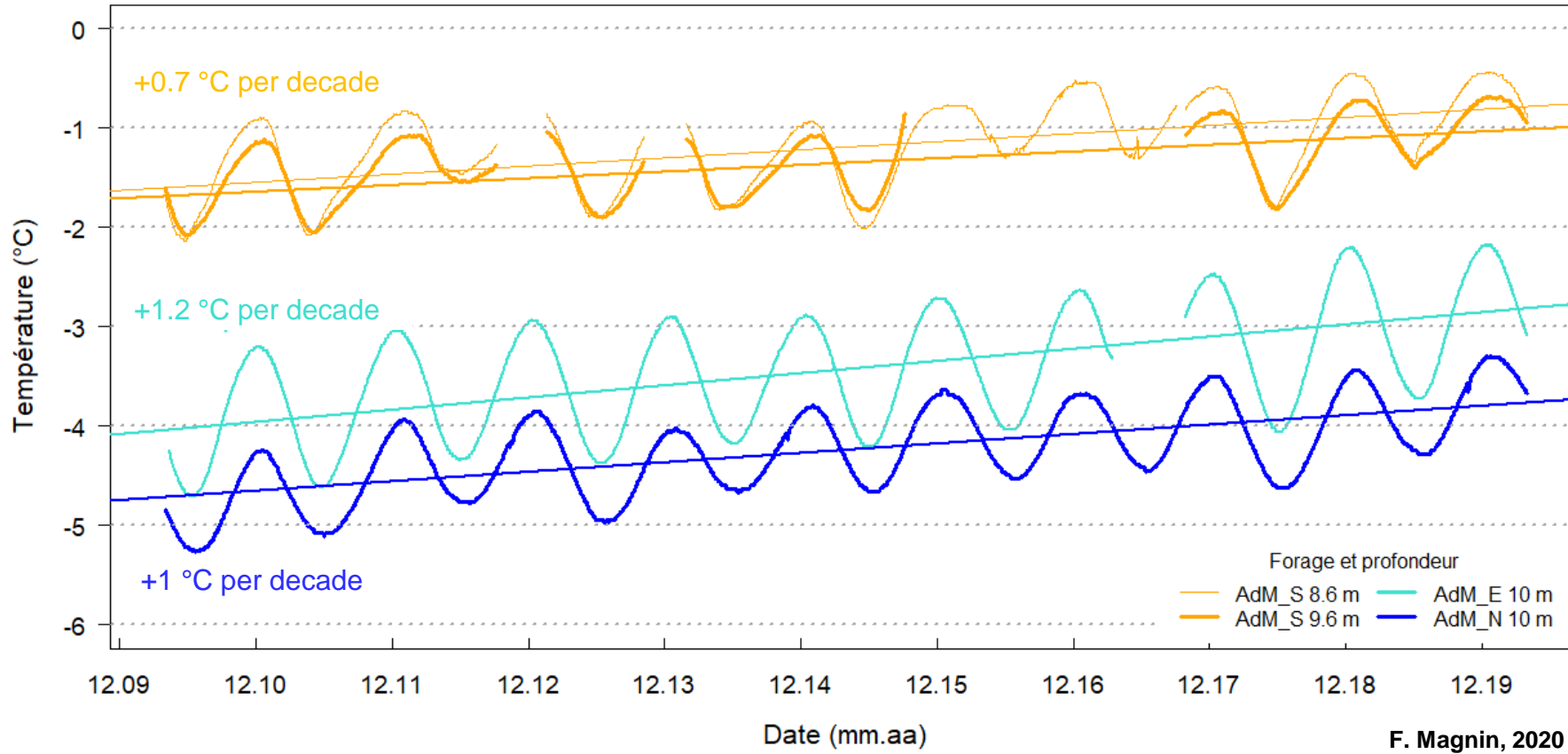
Magnin *et al.*, 2015

- 700 km<sup>2</sup> of permafrost ≠ 275 km<sup>2</sup> glacier in 2006-2009



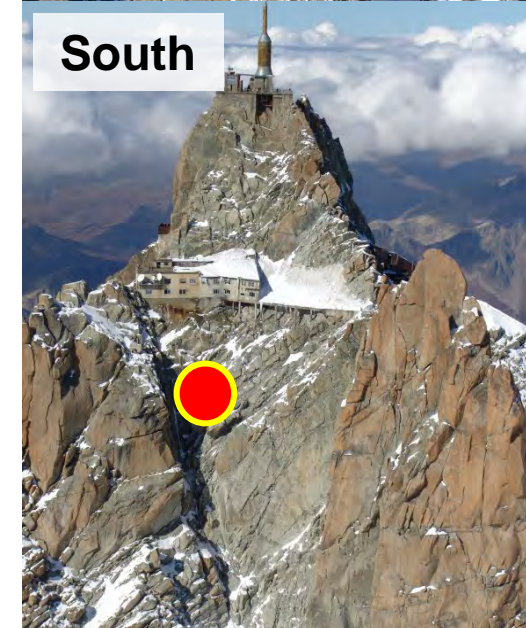
# Studying the presence of permafrost (2/2)

**Very locally** → Borehole temperature monitoring (EDYTEM Lab. )



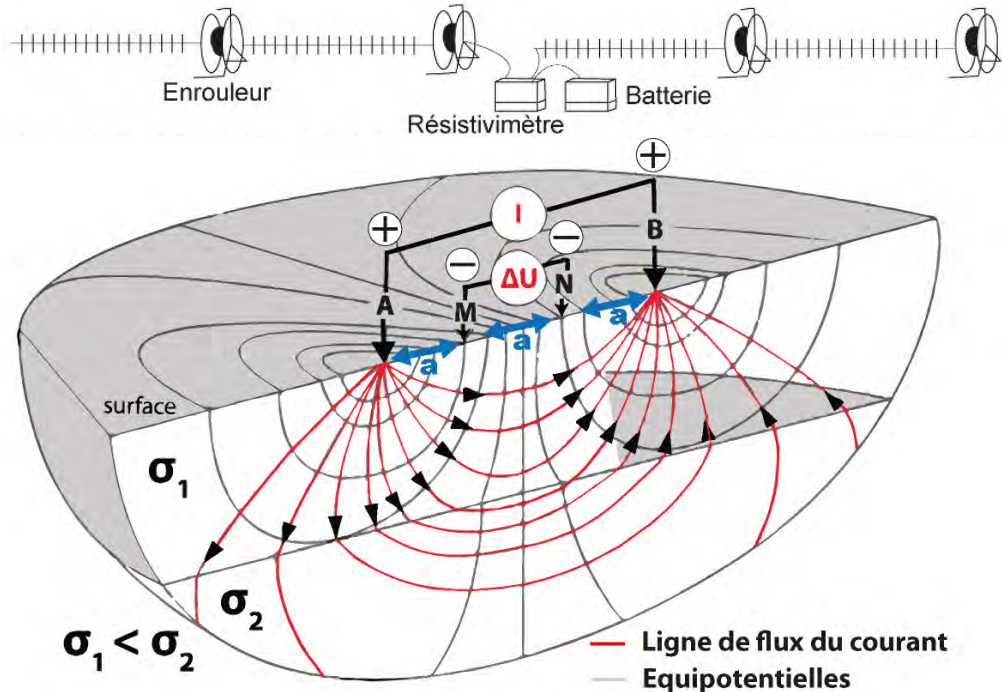
F. Magnin, 2020

Temperatures measured at -10 m at the Aiguille du Midi (3842 m)



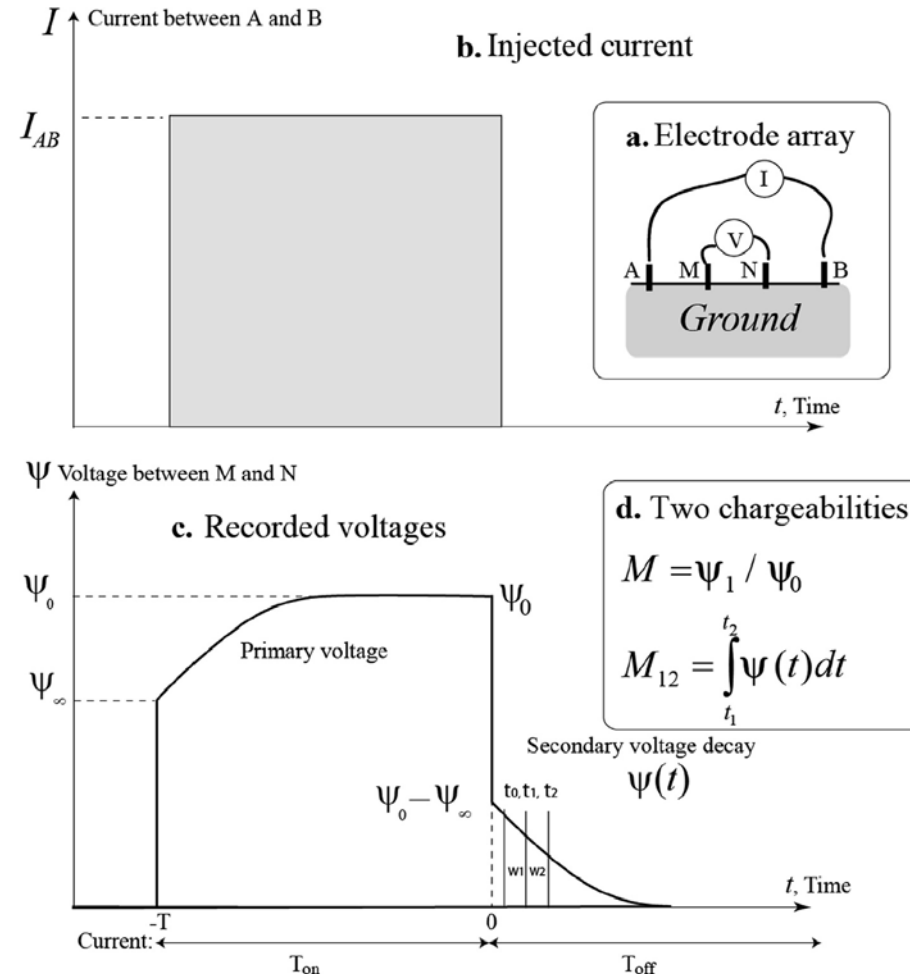
# Locally → Geophysical measurements

## Electrical conductivity tomography



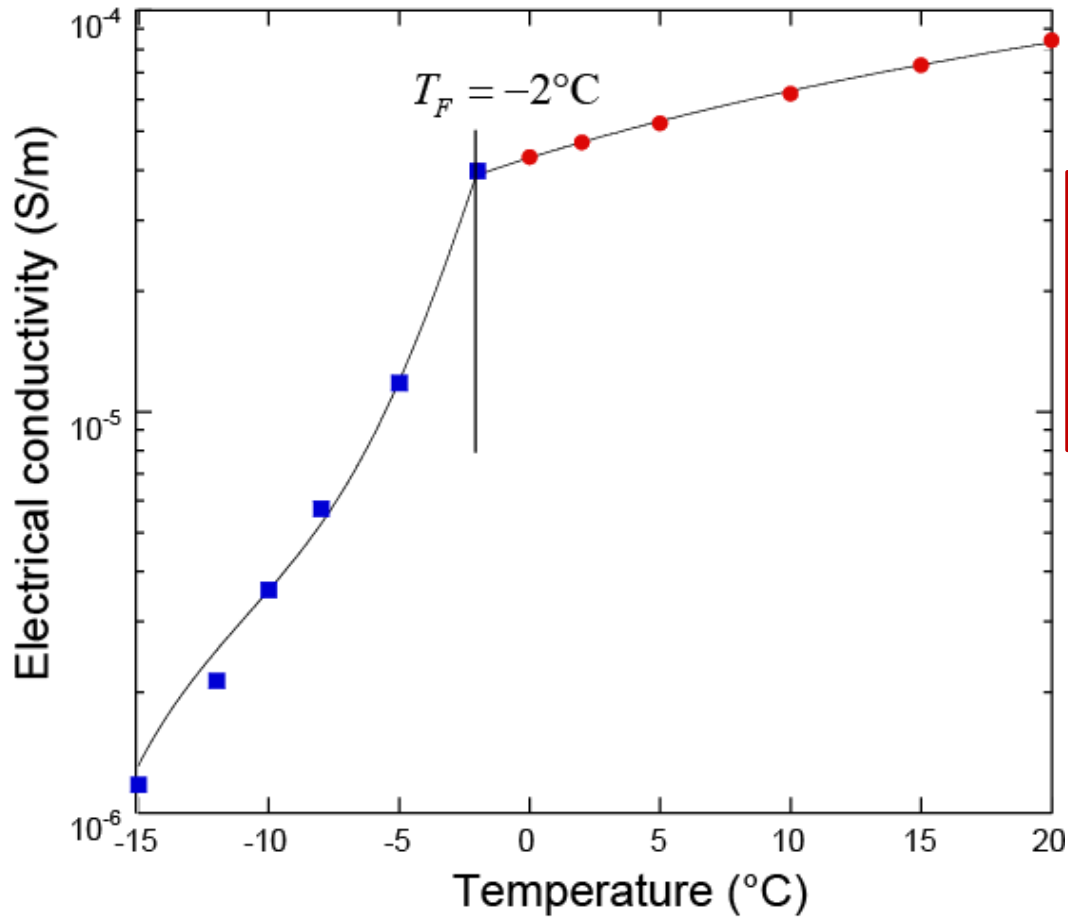
- Specific injection parameters
- Improve electrode / rock face contact

## Induced polarization tomography (or chargeability & complexe conductivity)



# Laboratory investigation

Temperature ranges between -20 / +15°C



Exemple: Granite sample

Development of a petrophysical model

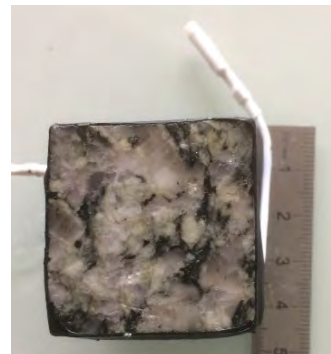
$$\sigma(T) \approx (\phi - \theta_r) \exp\left(-\frac{T - T_F}{T_C}\right) + \theta_r \left| \frac{\sigma(T_0)}{\phi} [1 + \alpha_T (T - T_0)] \right|$$

Relationship between T°C and electrical conductivity

Freezing curve Relationship between :

- Porosity,
- Water content,
- T°C ,
- T°C freezing point,
- T°C controlling the frozen/non-frozen state,
- Residual water content

Relationship T°C / conductivity below freezing point



Model development on 12 samples of rock and soil



# Refuge des Cosmiques (massif du Mont Blanc, 3613 m)





# Refuge des Cosmiques (massif du Mont Blanc, 3613 m)



A. Sage

P. Batoux



**1990**

Construction of the hut

Massive ice

**1998**

Rock fall

Renovation works

**2009**

Monitoring of instabilities

**2016**

Geophysic

Températures de subsurface

**2019**

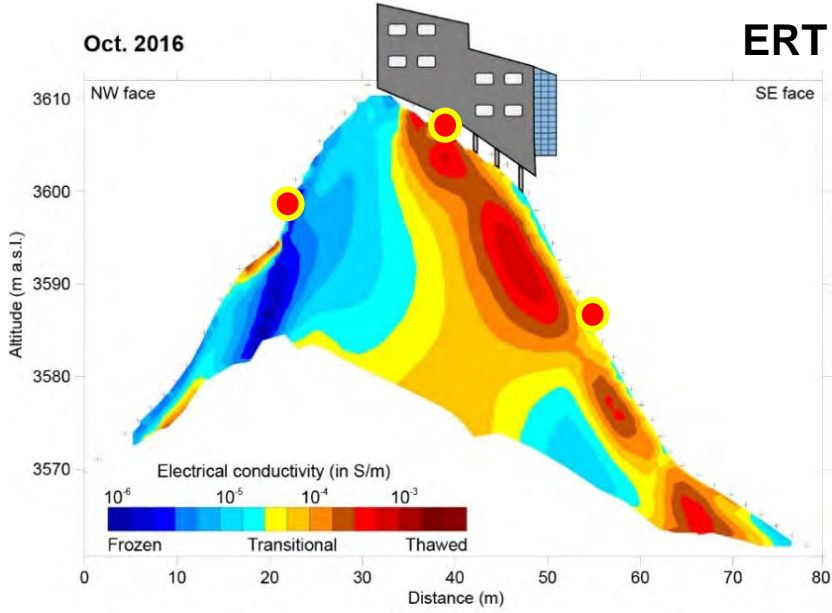
Geophysic



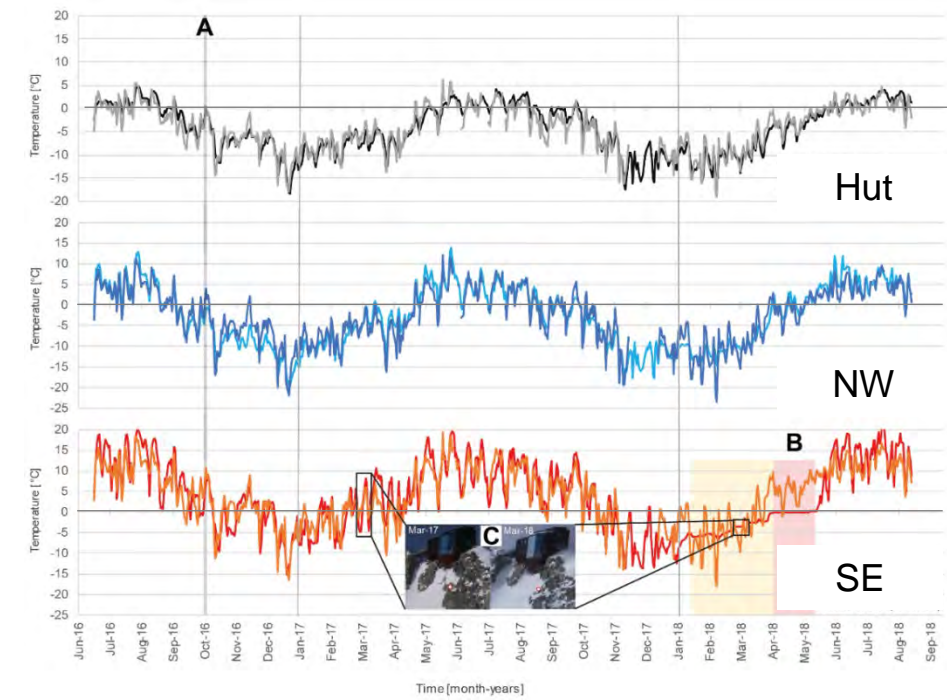
# Permafrost distribution

Oct. 2016

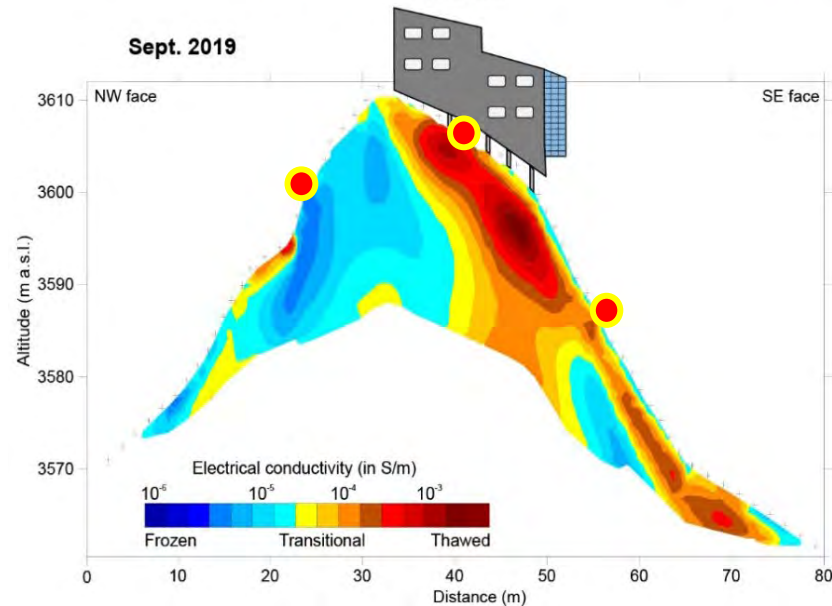
ERT



- Permafrost presence is restricted to the NW face with a vertical permafrost limit below the hut
- Absence of permafrost below the SE face

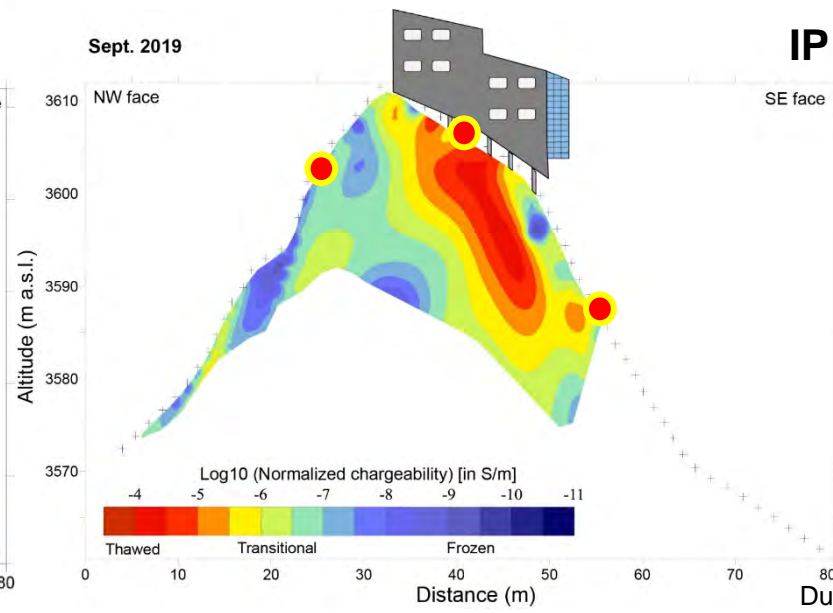


Sept. 2019



Sept. 2019

IP

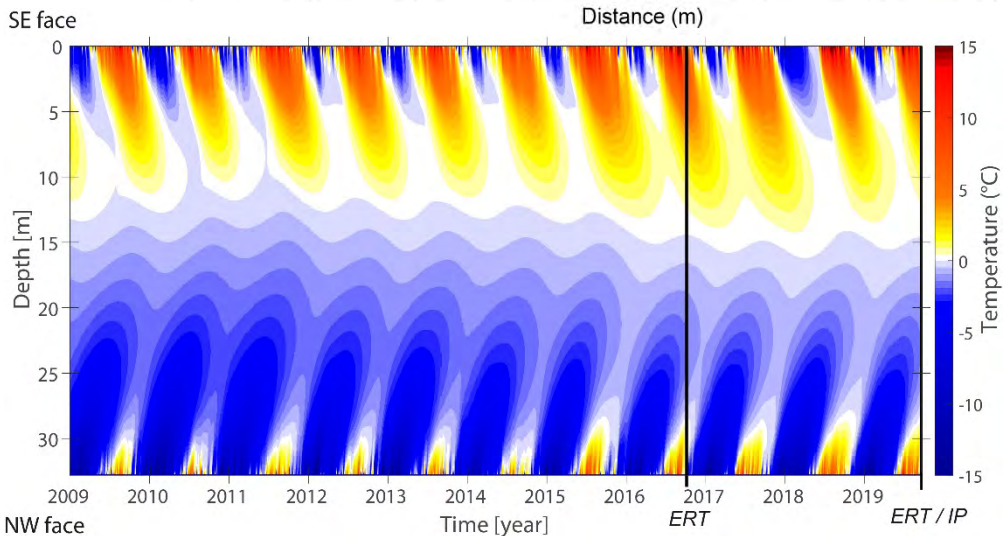
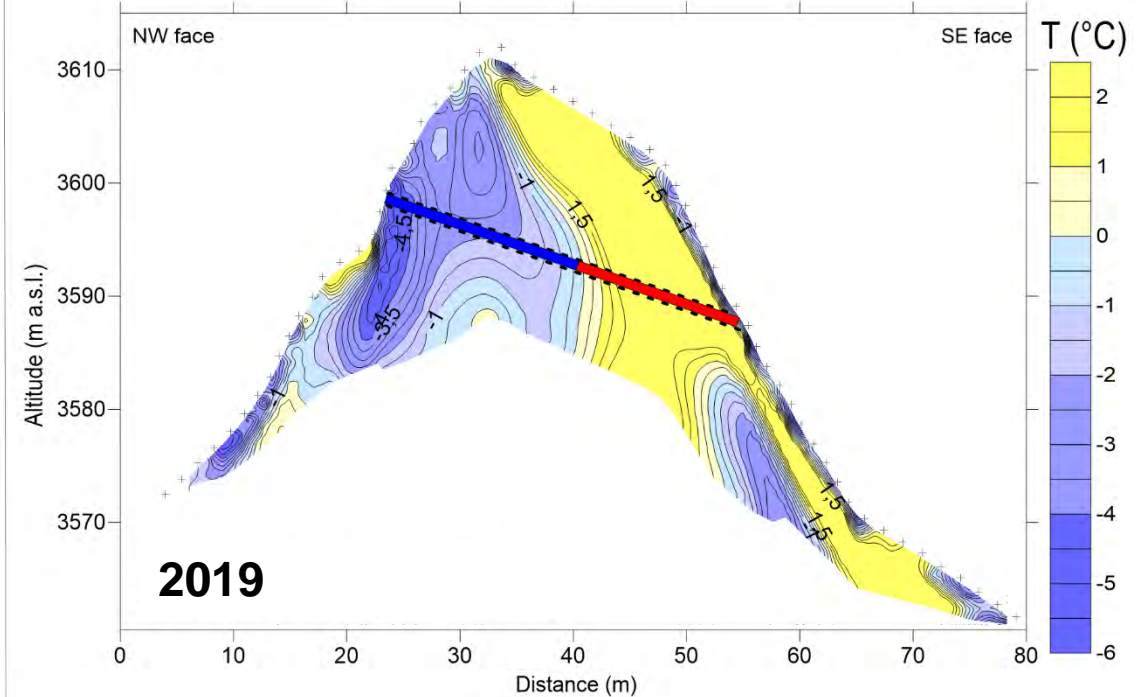
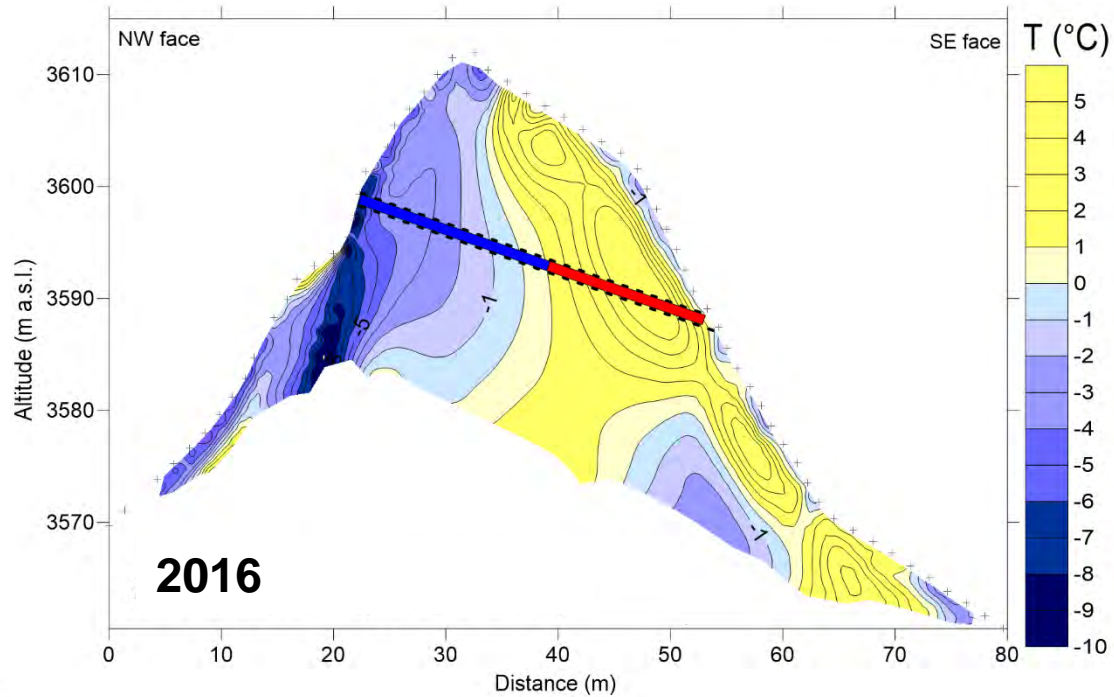


MARST 2016-2019

- 3.7°C in NW face
- 5°C below refuge
- +2.4°C in SE face



# Distribution of the temperature determined from geophysics

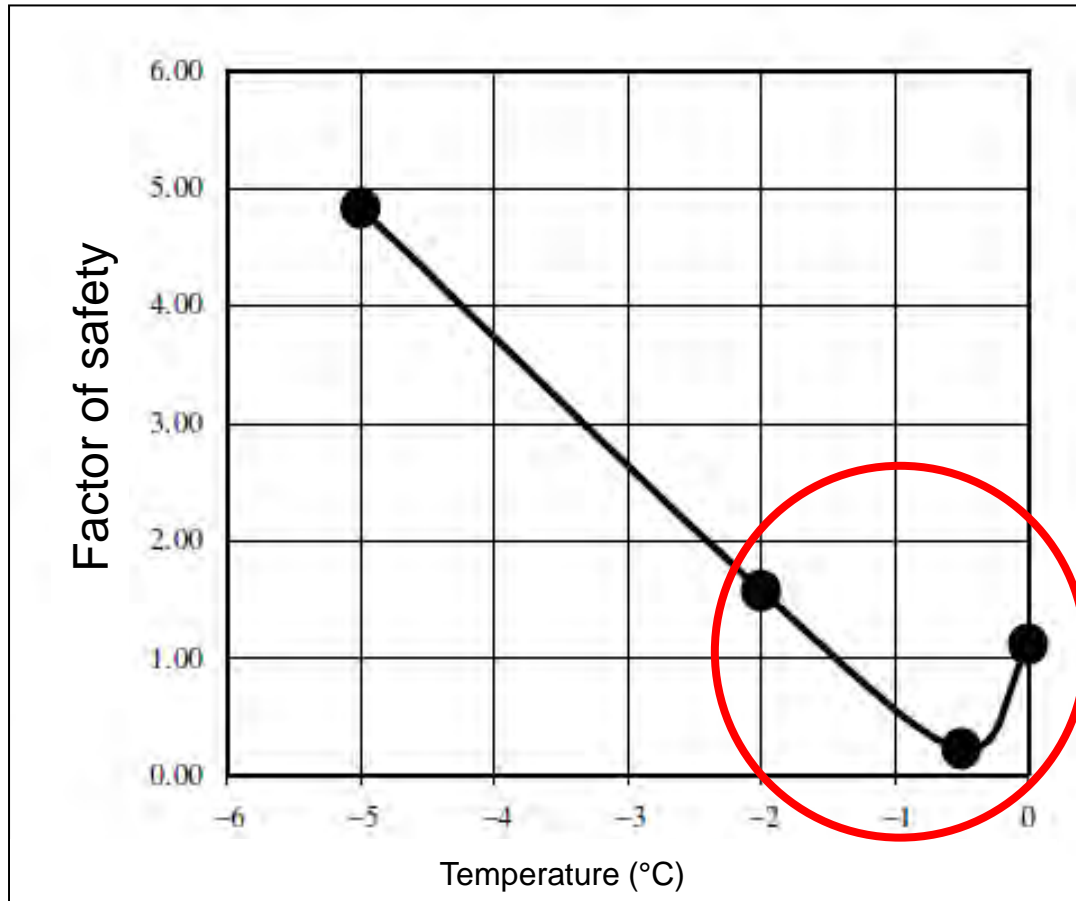


- Temperature around  $-2^{\circ}\text{C}$  in the NW face
- Relative increase of the lowest temperature between 2016 and 2019, suggesting permafrost warming within this 3-years period
- Consistent with the numerically simulated temperature from surface temperature logger

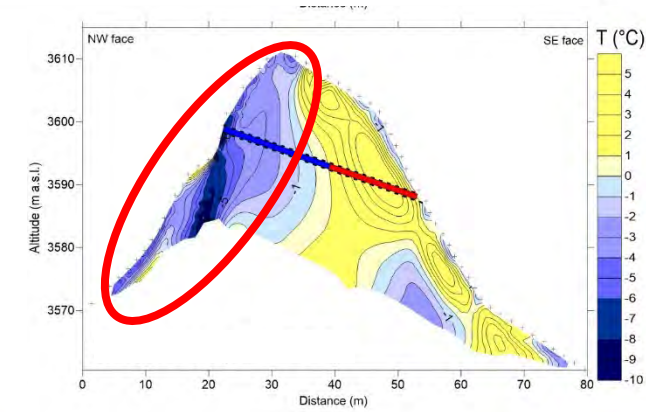


# Critical state of permafrost in NW face?

Decrease in stability due to melting of ice-filled discontinuities in a rock slopes

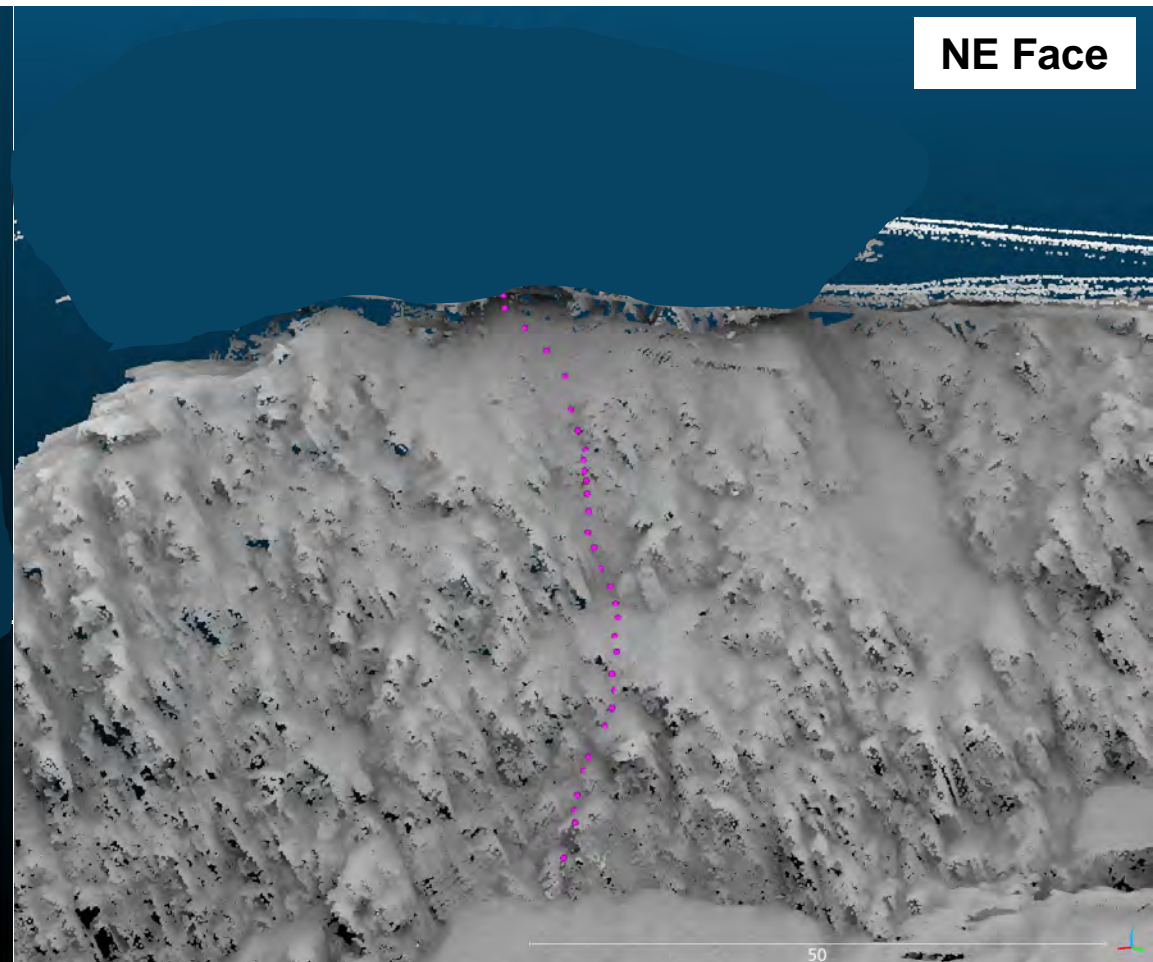
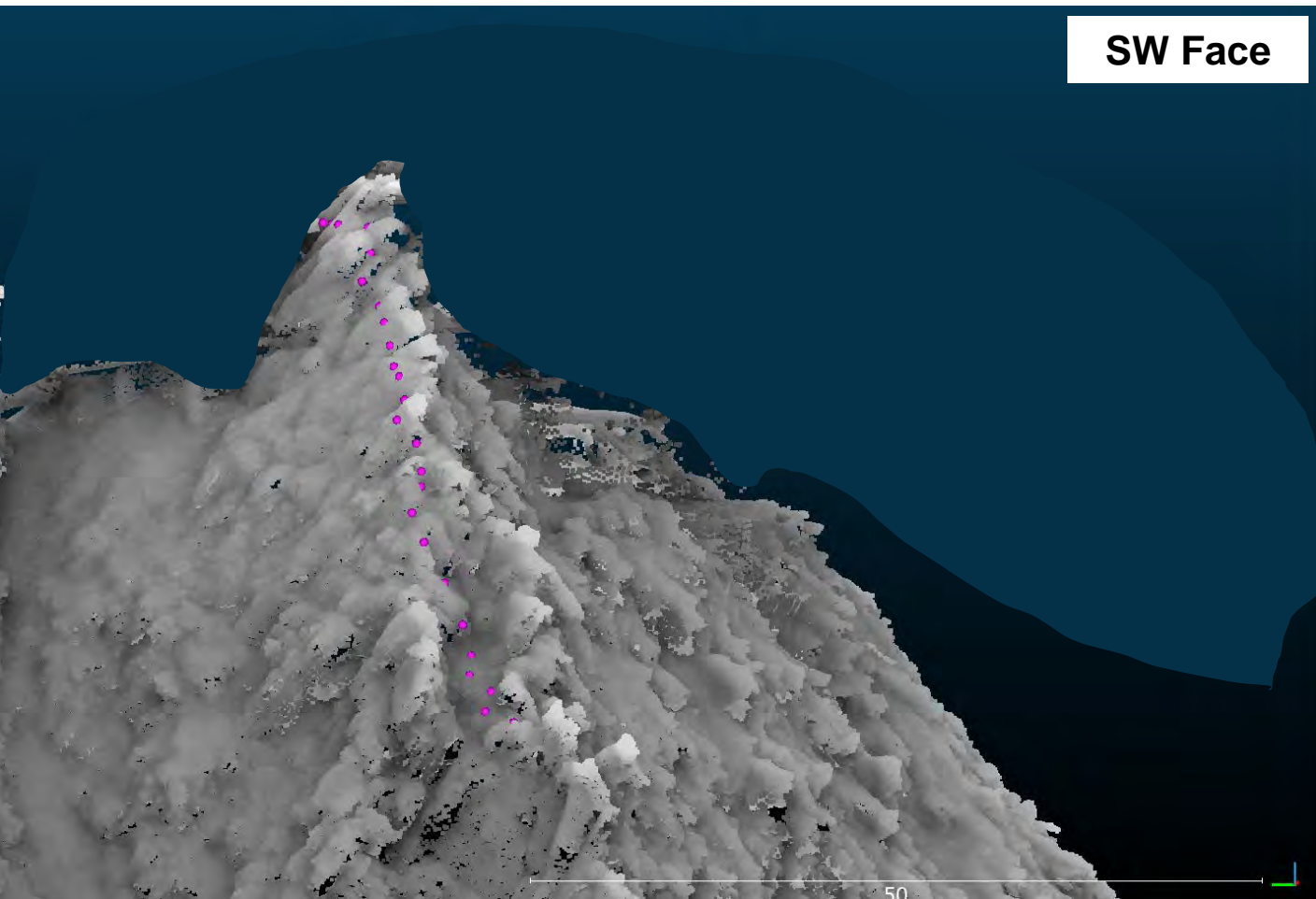


Davies et al., 2001





## Study case n°2 – Infrastructure in high mountain

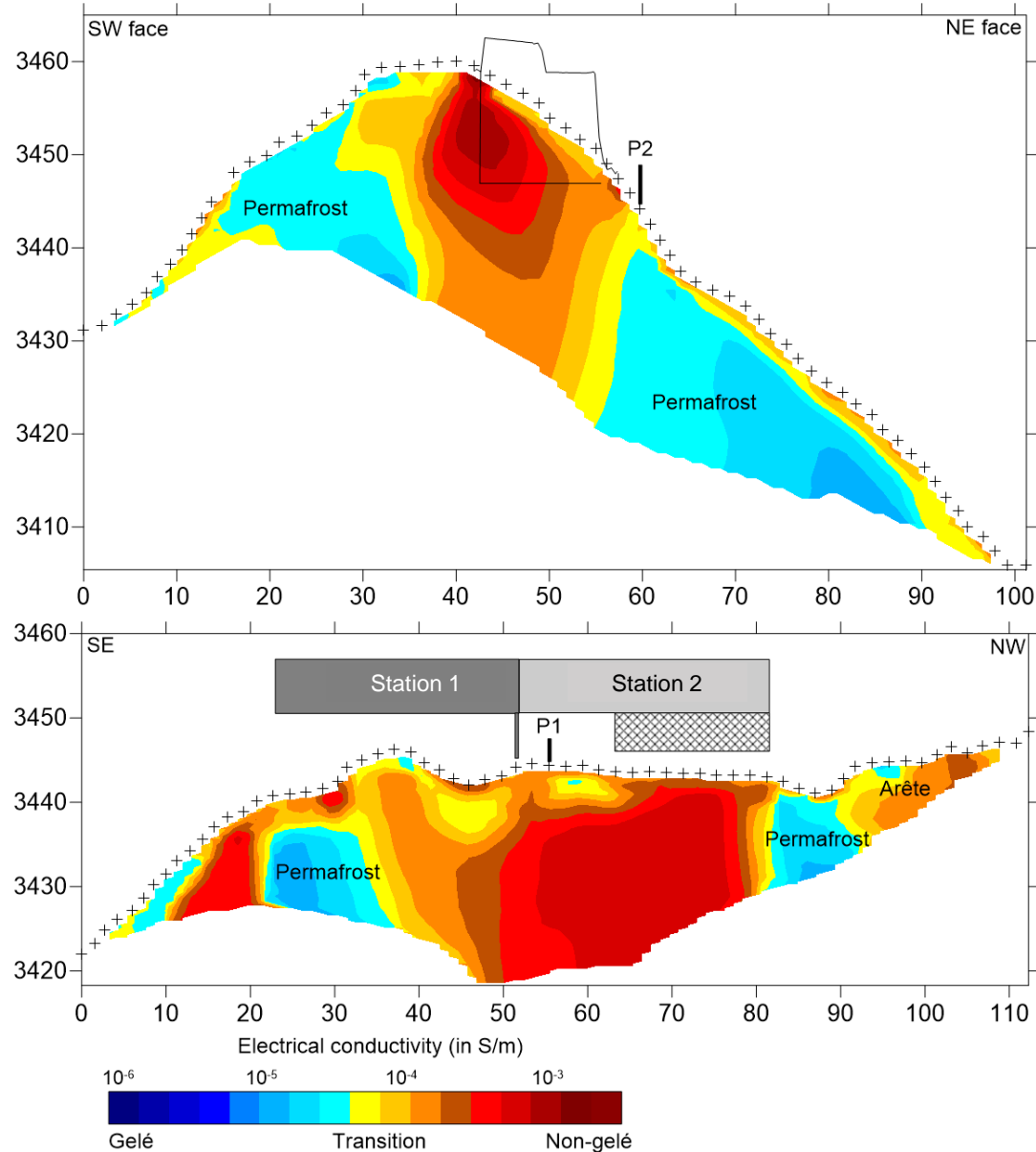


2 profiles survey in september 2021

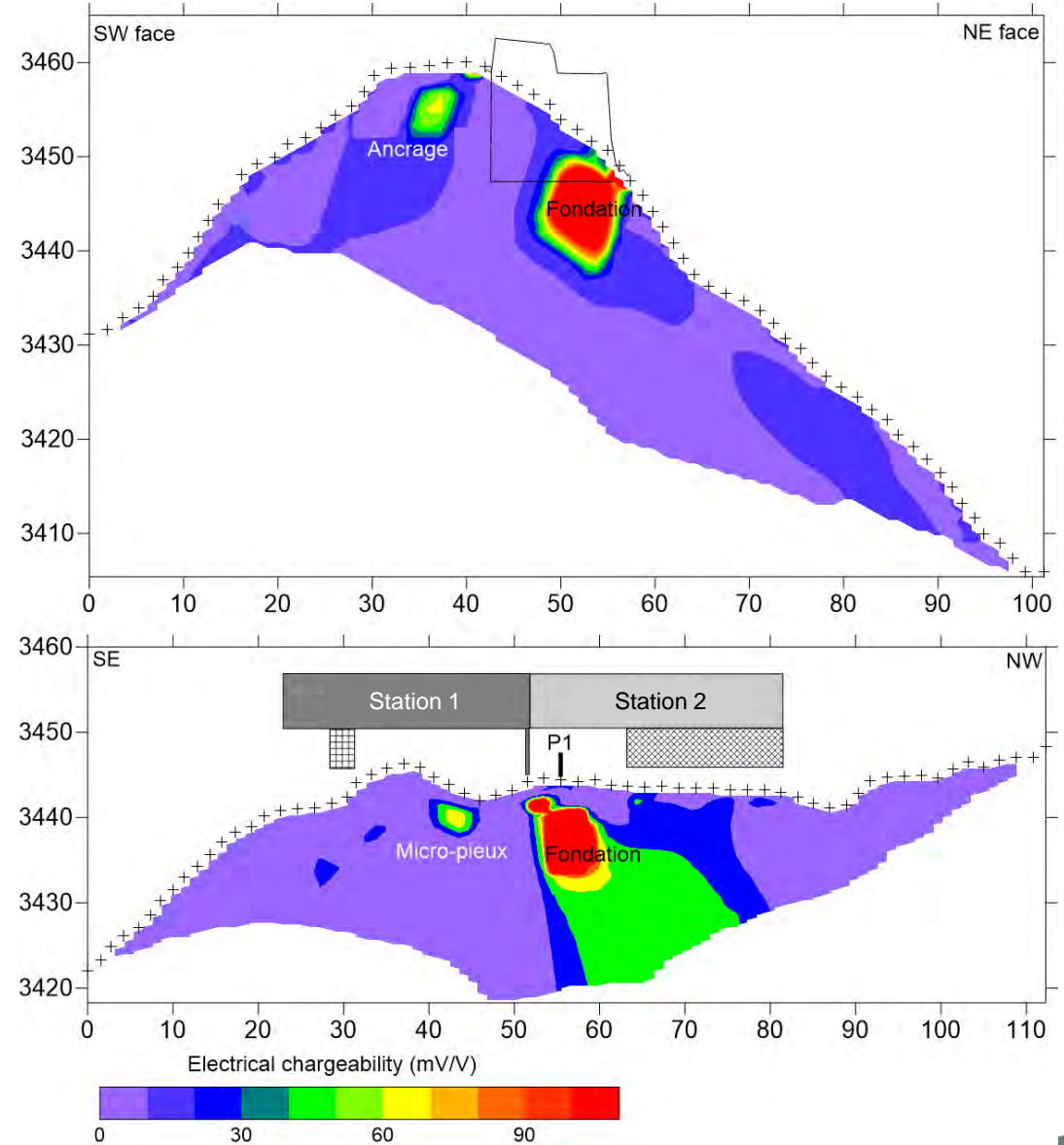


# Permafrost distribution

ERT

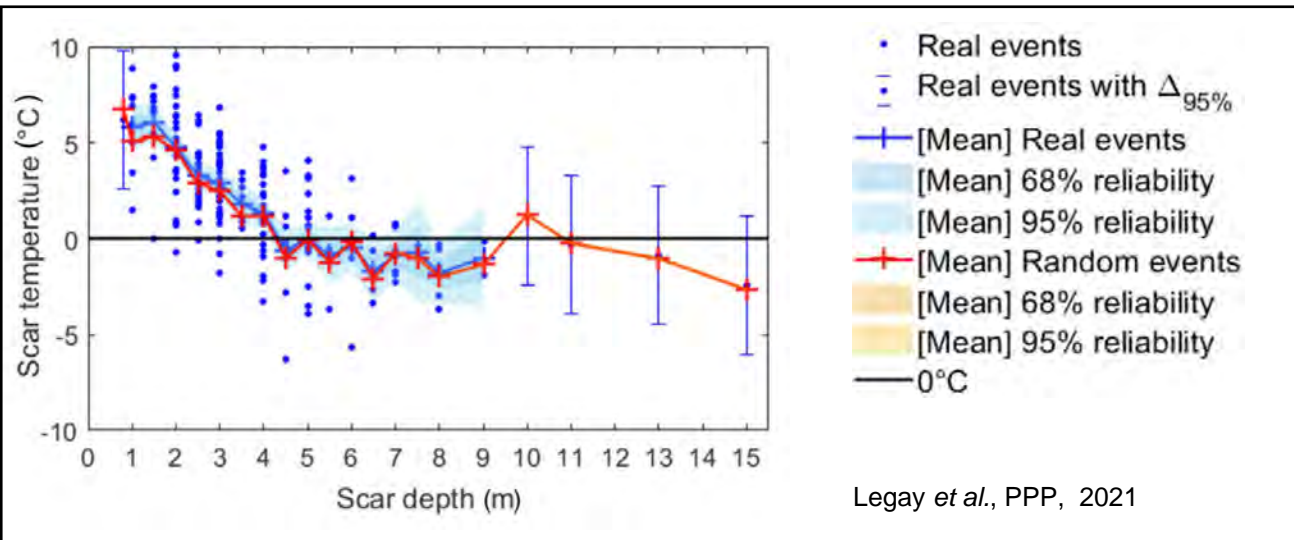
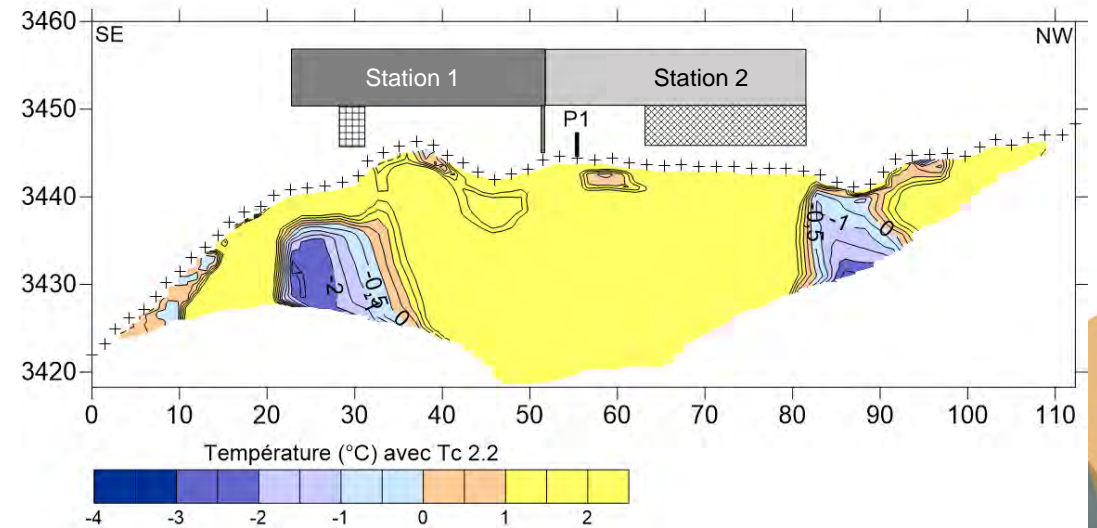
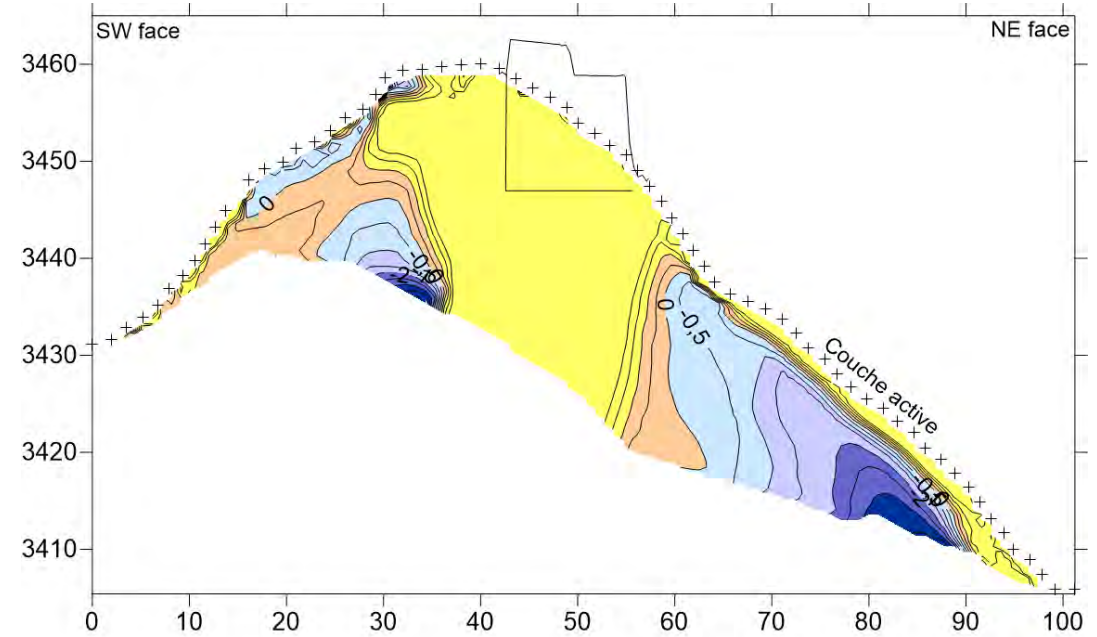


IP



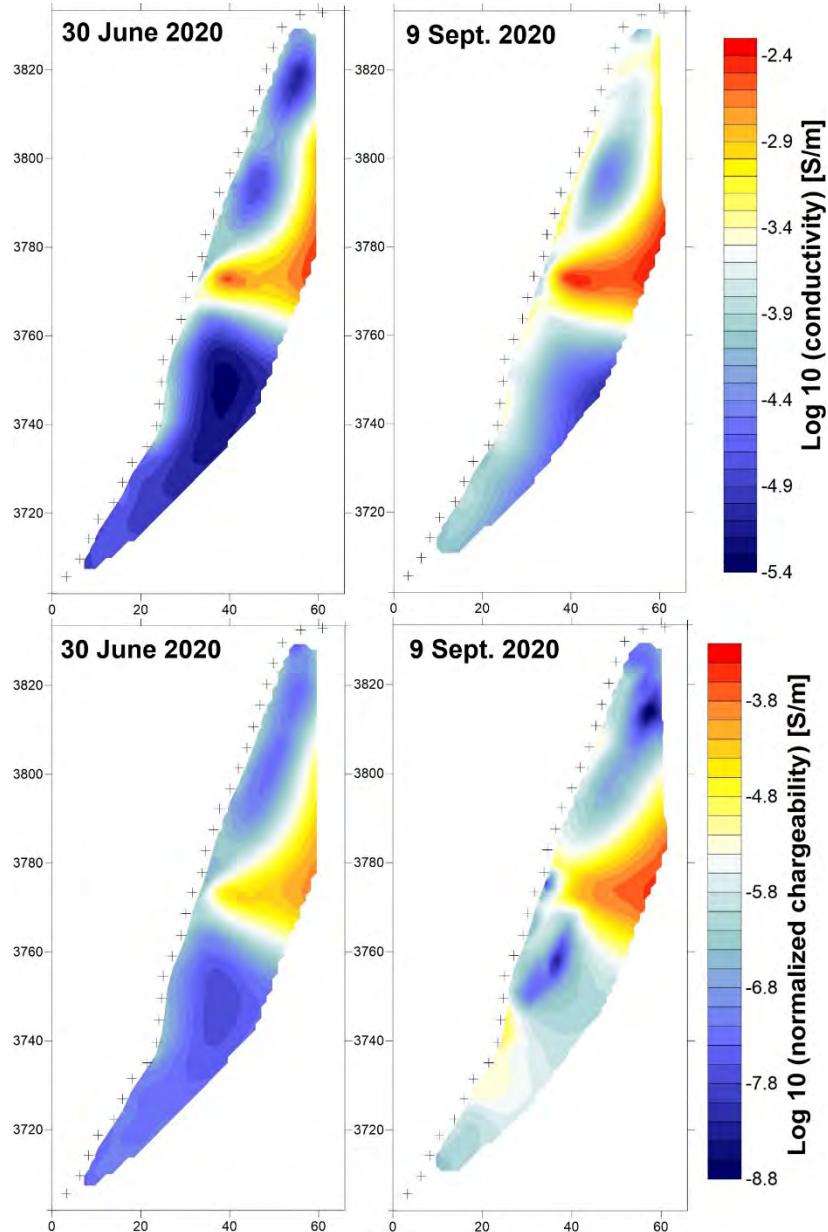
# Distribution of the temperature determined from geophysics

- SW face probably dried after summer with strong ridge effect
  - Infrastructure effect on permafrost distribution
  - Permafrost between 0 and -2°C
- Validation required with MARST

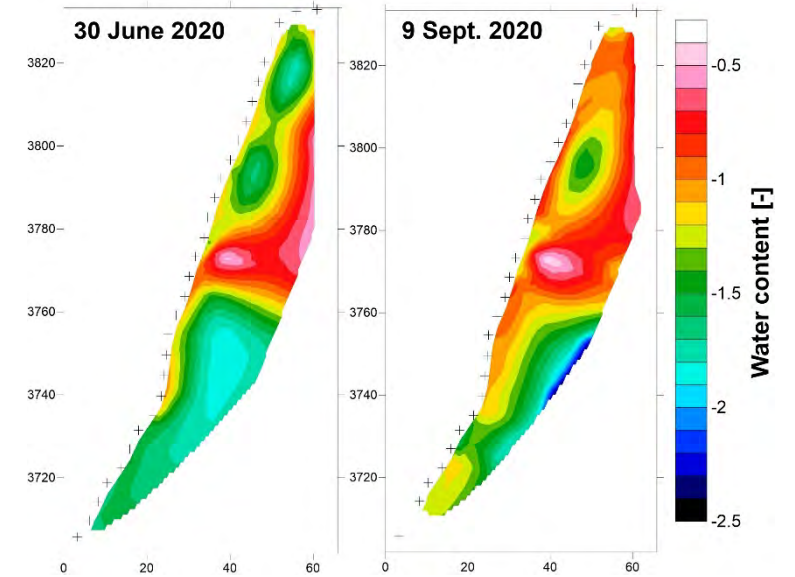




# Towards automatic monitoring and processing



ANR WISPER, Magnin F.



- Seasonal thawing and permafrost warming
- Touristic infrastructure (galleries in the rock mass, elevator) are clearly identified due to numerous metallic components
- Desiccation of the shallow layer of the north face in response to summer heating

- **Interest of ERT/IP coupling and petrophysical model**
  - Quantitative study of infrastructure elements built on permafrost
  - Wide spatial coverage and low costs
- **Outlooks**
  - Monitoring the ice/water phase evolution with IP and ERT
  - Joint inversion framework using T°C data (surface on borehole measurement)





# Thank you for your attention!



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Thanks to:  
Lab. EDYTEM  
Fondation FEREC  
CCVCM  
Gardiens des Cosmiques



## Géomorphologie Appliquée

- Permafrost / Glacier
- Torrent & Modélisation
- Suivi topographique 3D

**NĀGA**  
Geophysics

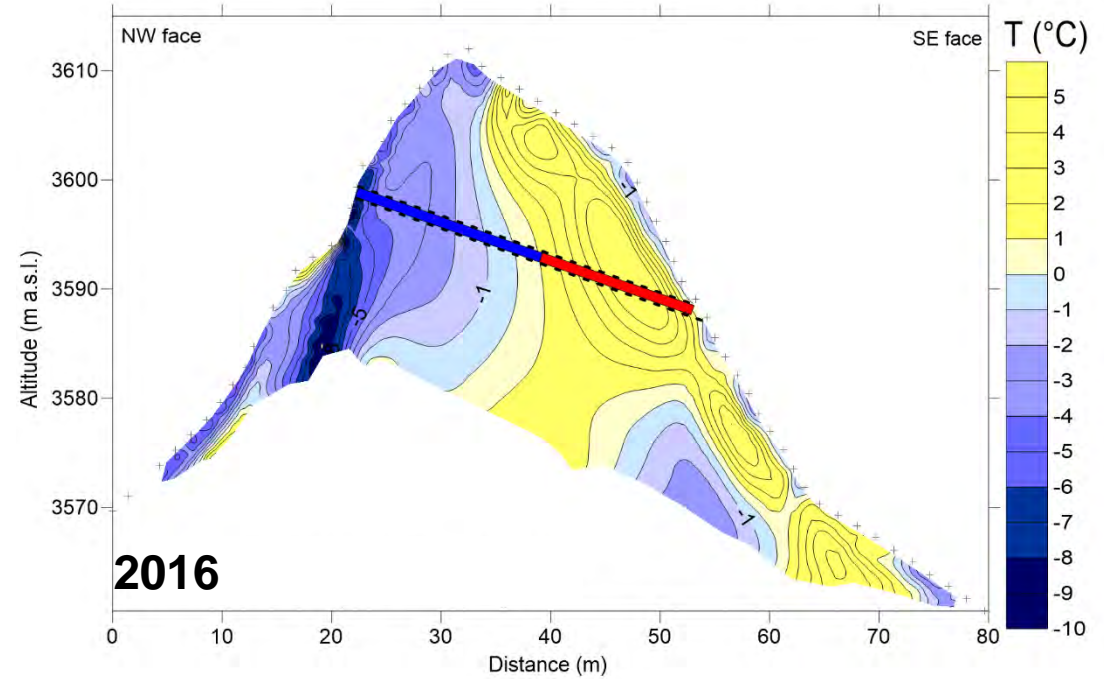
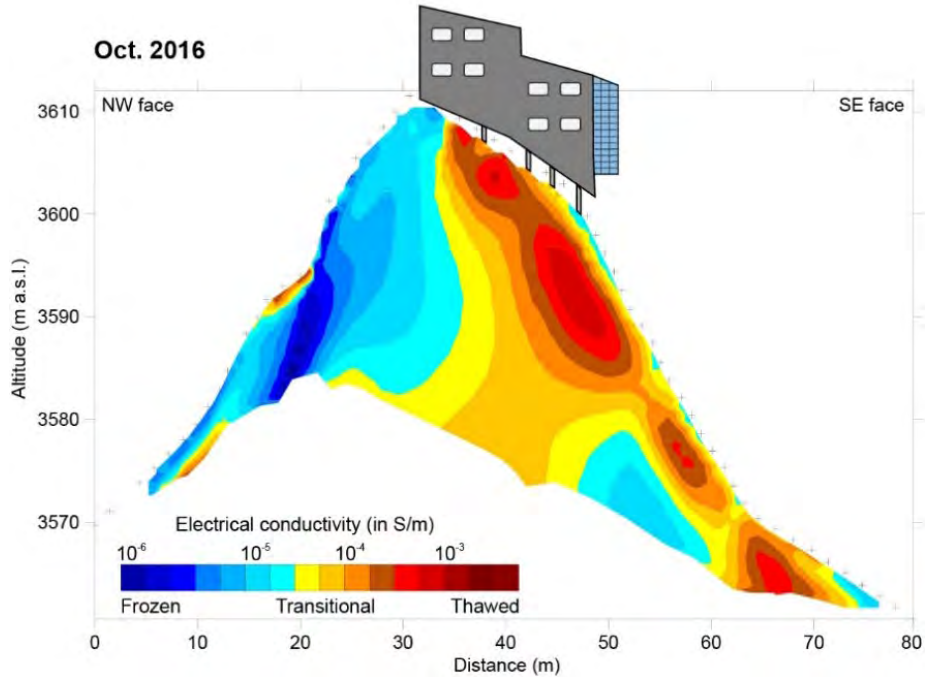
## R&D Géophysique

- Dignes / barrages
- Sites / sols pollués
- Glissement de terrain
- Circulation d'eau





# Quantitative geophysics



Residual water content

Freezing point

$T_0$  = conductivity at ref  $T^\circ\text{C}$  ( $25^\circ\text{C}$ )

$T^\circ\text{C}$  dependance of conductivity

$$\sigma(T) \approx \left[ (\phi - \theta_r) \exp\left(-\frac{T - T_F}{T_C}\right) + \theta_r \right] \frac{\sigma(T_0)}{\phi} [1 + \alpha_T (T - T_0)]$$

0.021°C (2% conductivity increase per °C)

Max volumetric ice content

Transition frozen/unfrozen ( $T^\circ\text{C}$ )