Helicopter-borne ground-penetrating-radar (GPR) surveys on alpine glaciers

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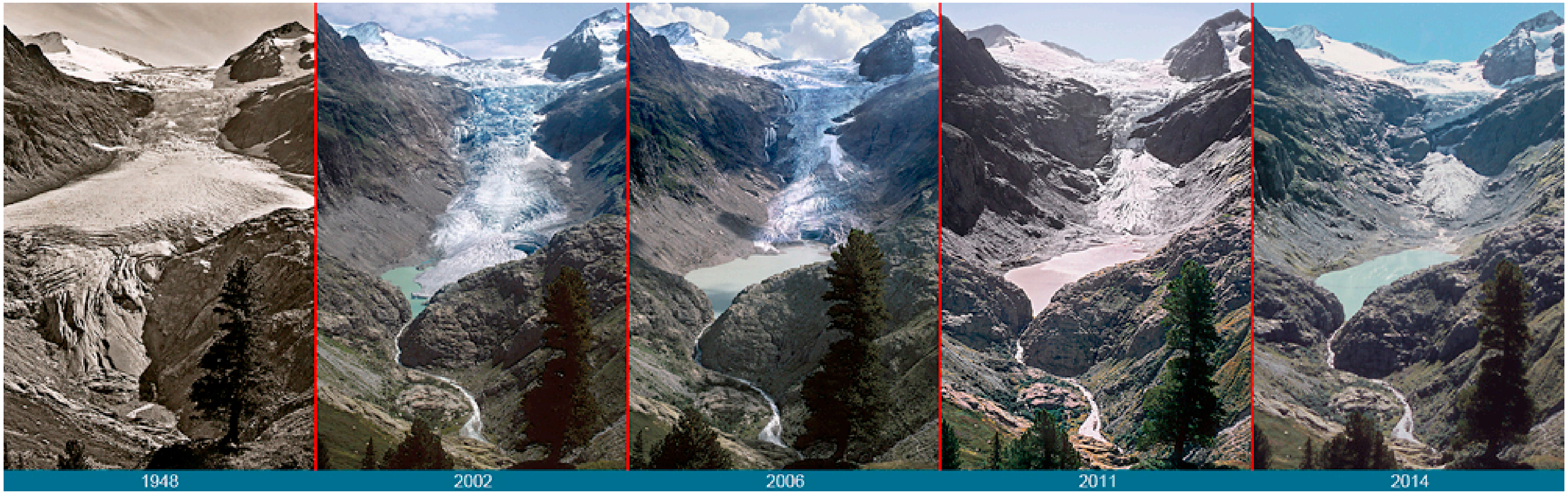
Overview

- Why studying glaciers?
- A few important features of alpine glaciers
- Helicopter-borne GPR surveying
  - Data acquisition
  - Data processing
  - Data interpretation
  - Applications to Swiss Alpine Glaciers
  - The road ahead

Why studying alpine glaciers?

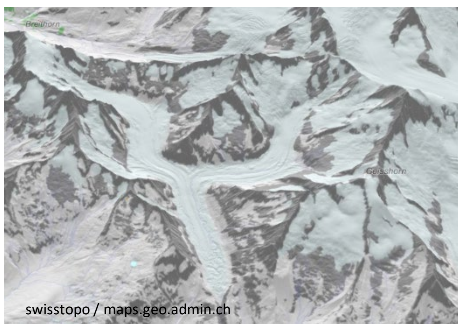


Extent of the Trift Glacier in 1948, 2002, 2003, 2011 und 2014 (www.gletscherarchiv.de)

Why studying alpine glaciers?

Energy Sector

- Loss of water storage at high altitudes
- Change of the seasonal river runoff in the forelands
- New sites for water reservoirs?



Example Oberaletsch

Tourism

- Loss of tourist attractions
- Increased natural hazards
- Problems with ski slopes / lifts on falling glacier surfaces

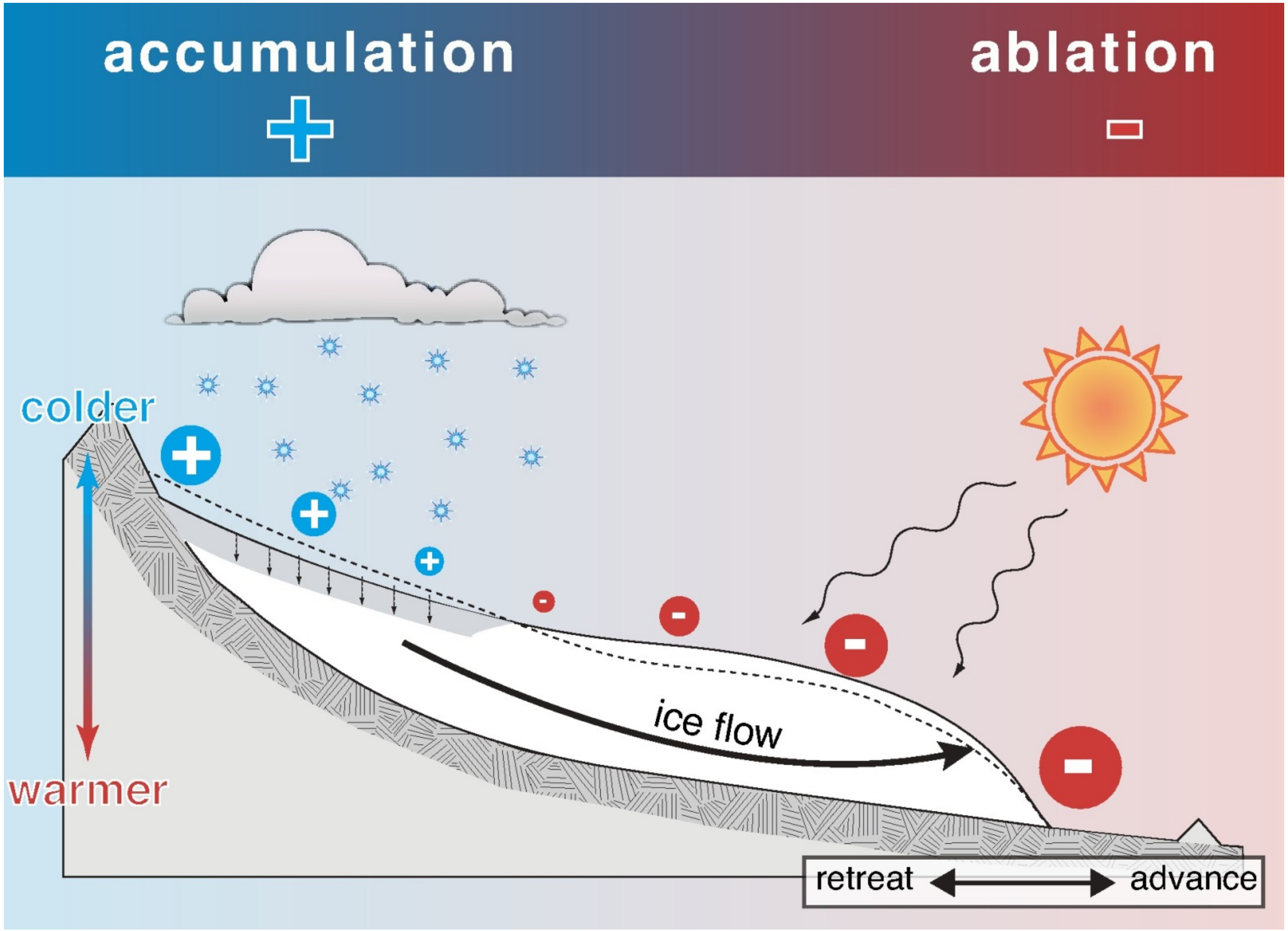
Examples: Ski resorts Nendaz, Flims-Laax-Falera

Natural Hazards

- New occurrence of slope instabilities, rock falls and ice falls
- Glacier lake outbursts

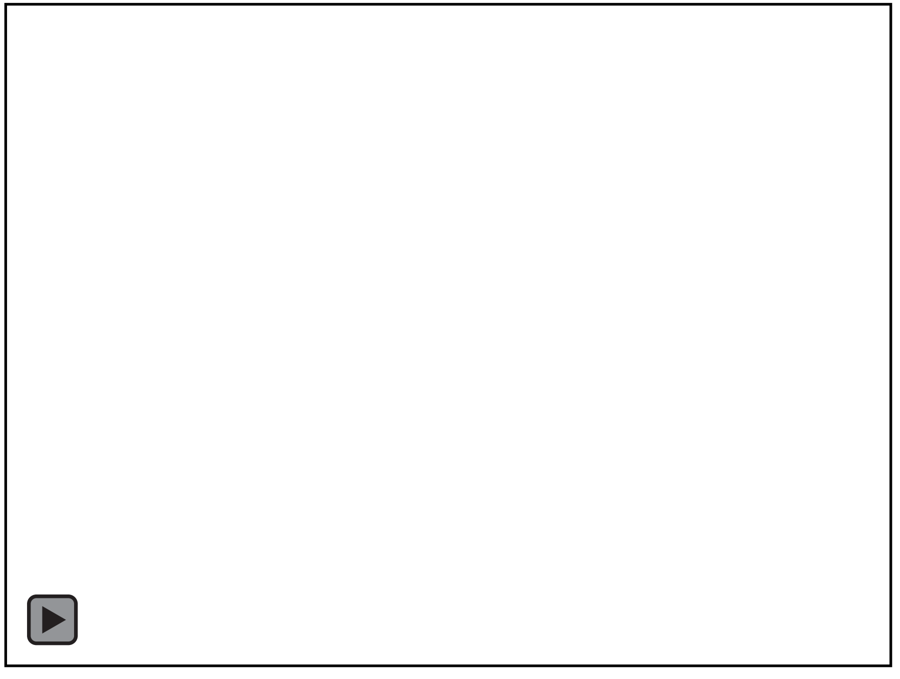
Examples: Cambrena- Bernina, Plane Morte-, Planpincieux-Glacier

How the ‘’glacier system’’ works:



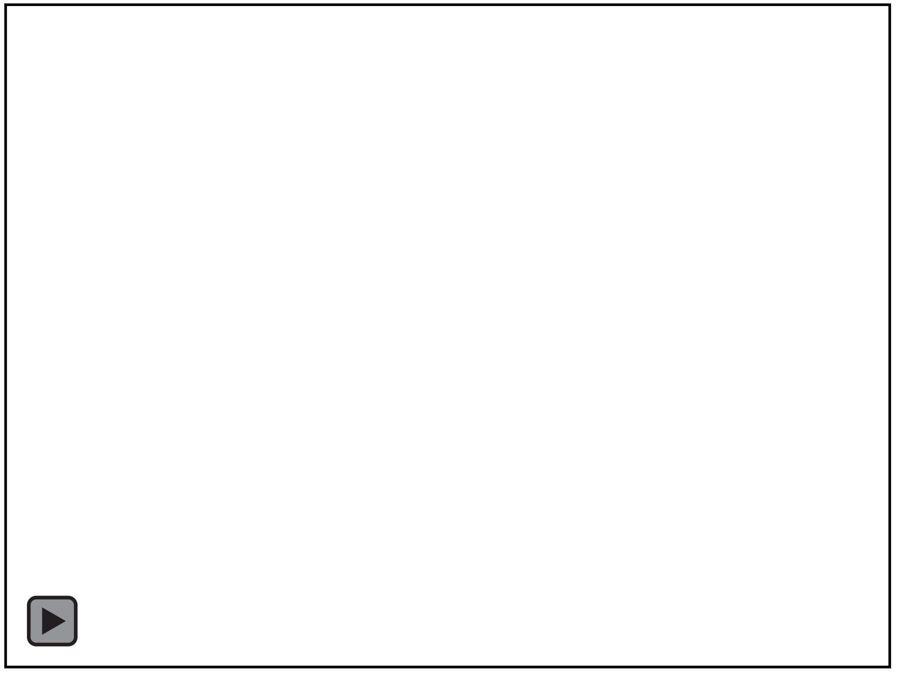
How do glaciers move?

Ice deformation (creep)



https://www.youtube.com/watch?v=1ai9Q27J2vc

Basal motion



http://www.moreauluc.com/index.en.htm

Cold and temperate glaciers

- Cold glaciers include no or very small amounts of unfrozen water.
- Temperate glaciers include a significant amount of unfrozen water.
- Glaciers can consist of both, cold and temperate ice.
- Most alpine glaciers are temperate glaciers

Electromagnetic (GPR) properties of glacier constitutents

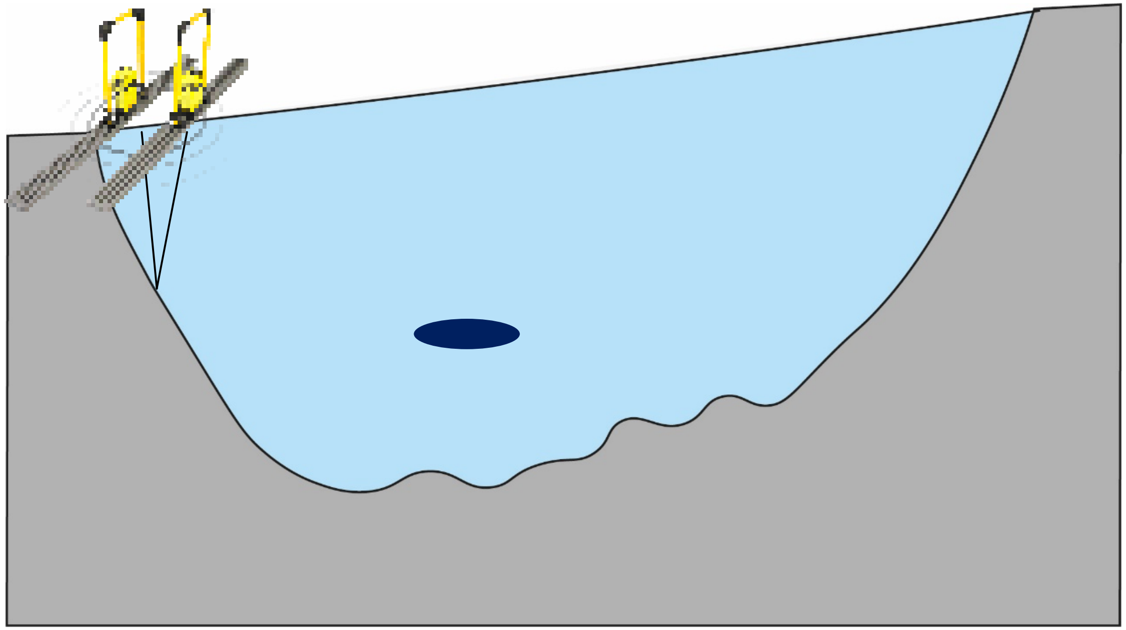
$$v_{GPR}^{ice} \approx 0.17m / ns$$

$$v_{GPR}^{water} \approx 0.03m / ns$$

$$v_{GPR}^{bedrock} \approx 0.12m / ns$$

Geophysical Methodology
Ground Penetrating Radar (GPR)

Estimate subsurface properties from **reflected electromagnetic (EM) waves**.

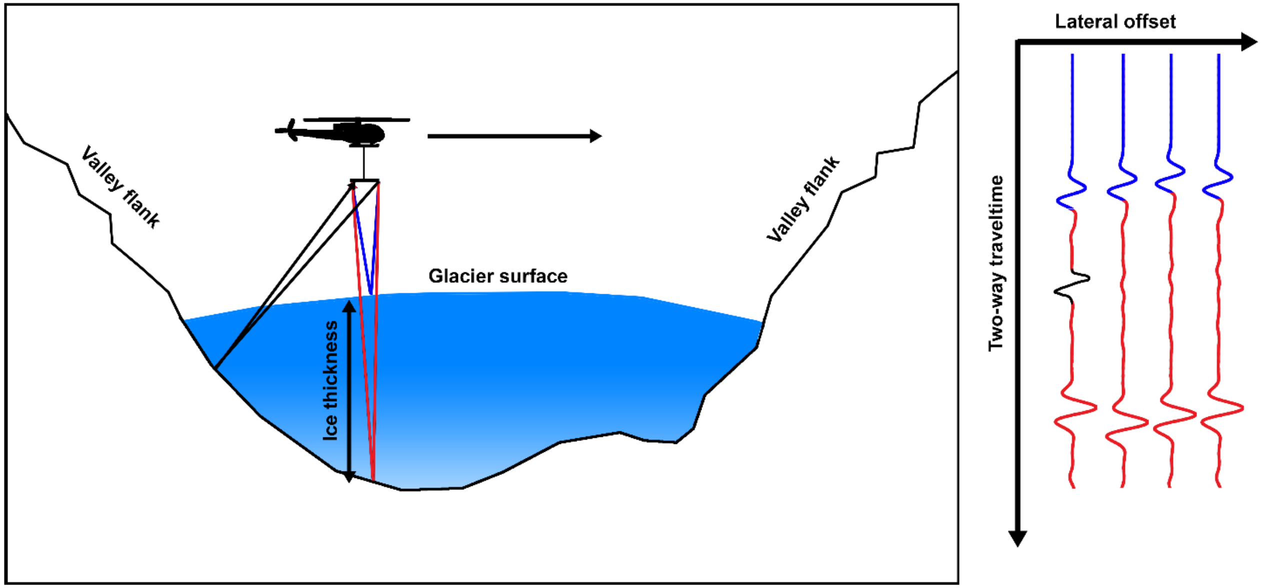


EM Waves: Sensitive to material properties such as **electrical permittivity**, **electrical conductivity** and **magnetic permeability**.

Helicopter-borne GPR

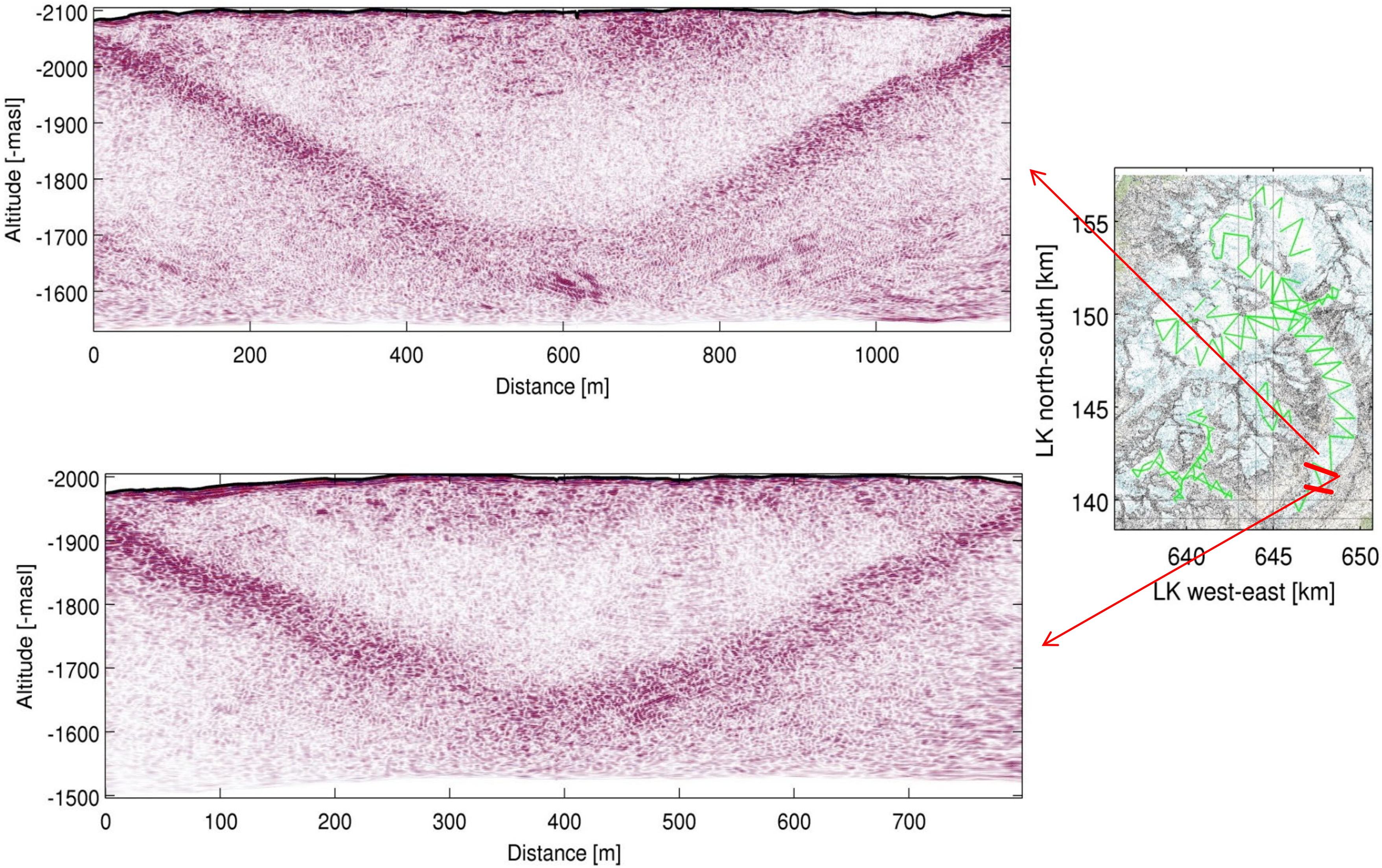
Surveying principle

- Glacier bed topography and current state of ice-thickness from helicopter-borne GPR

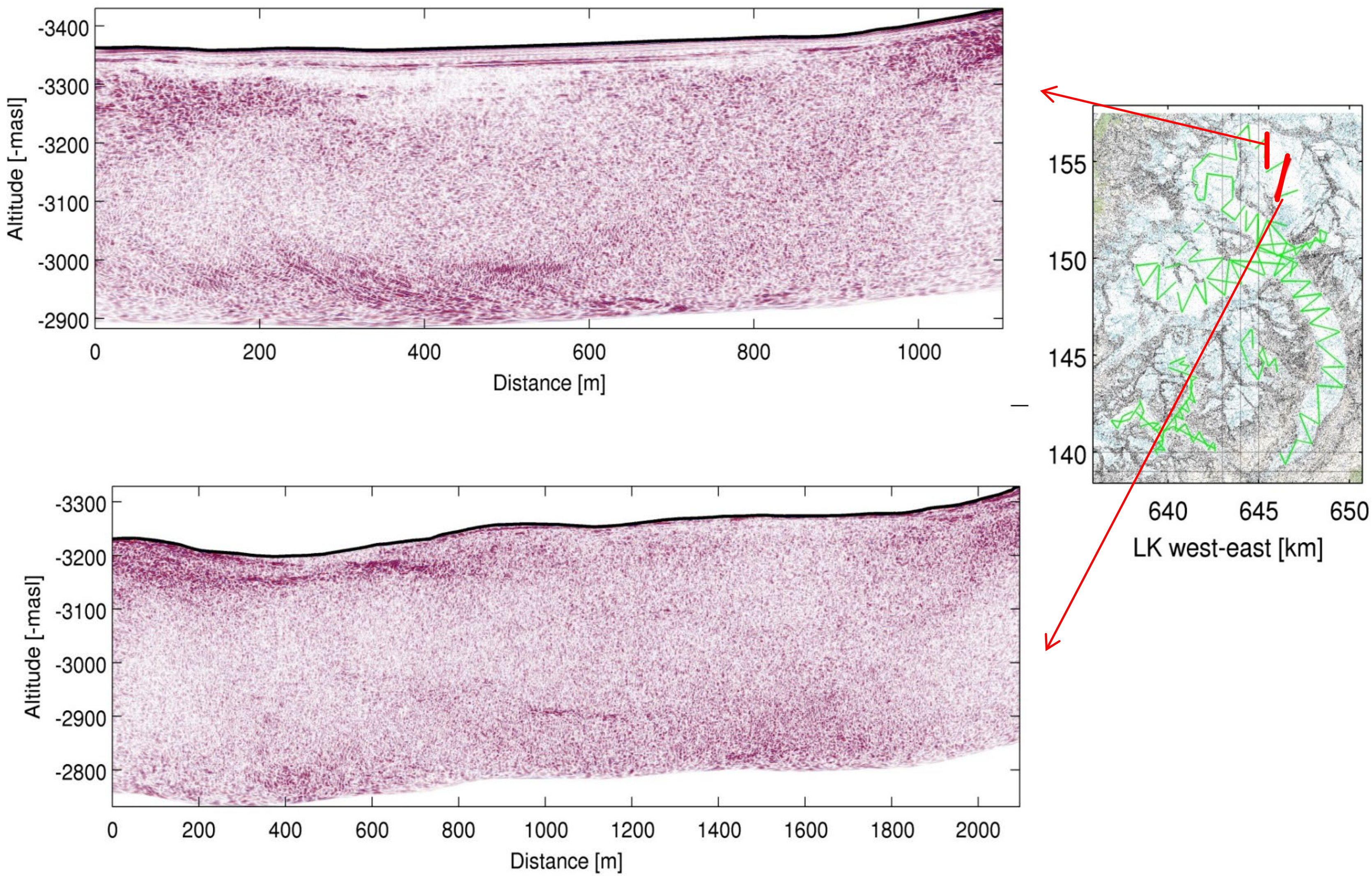


Helicopter-borne GPR data acquisition

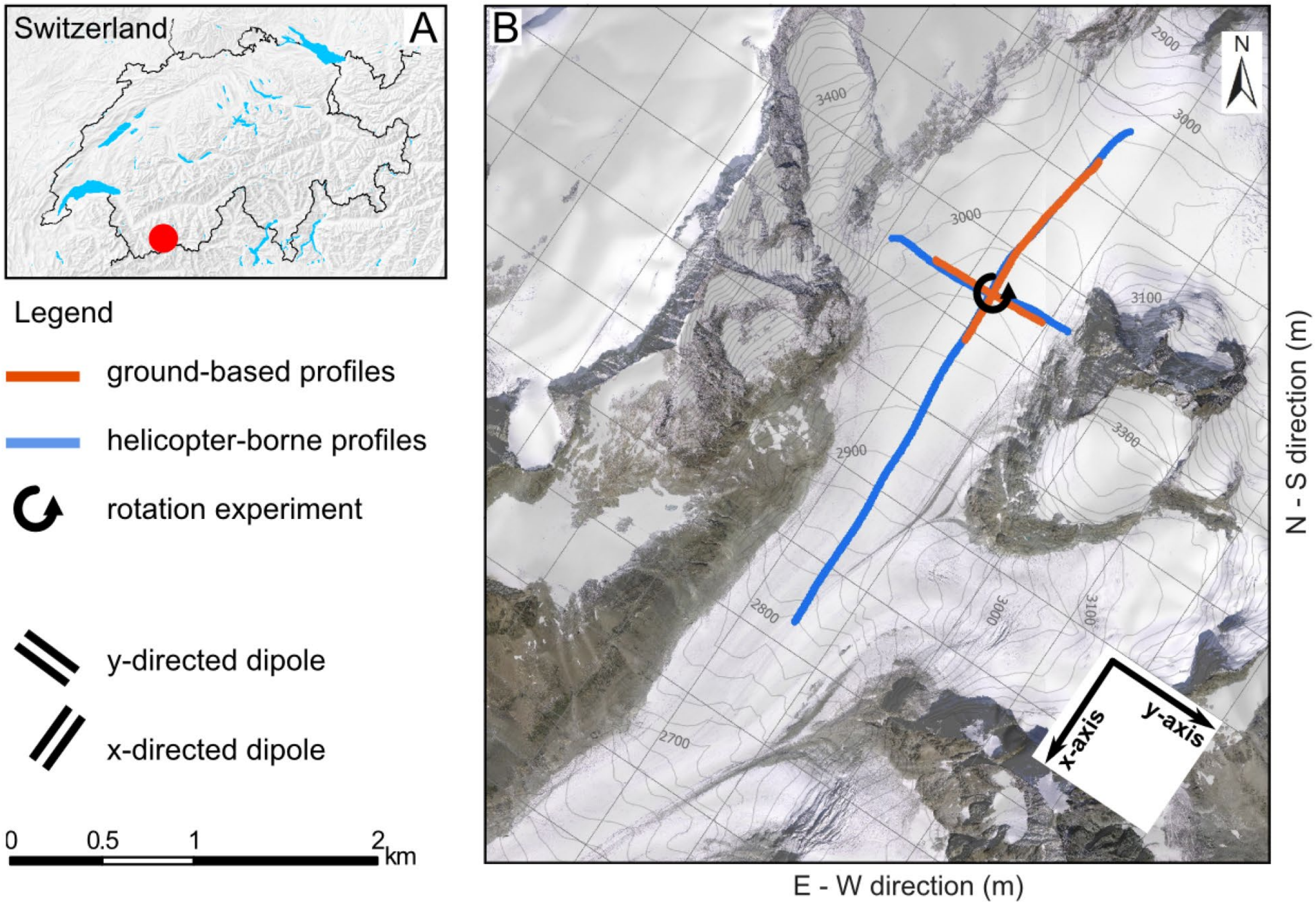
Example: Aletsch glacier frontal part



Example: Aletsch glacier accumulation zone



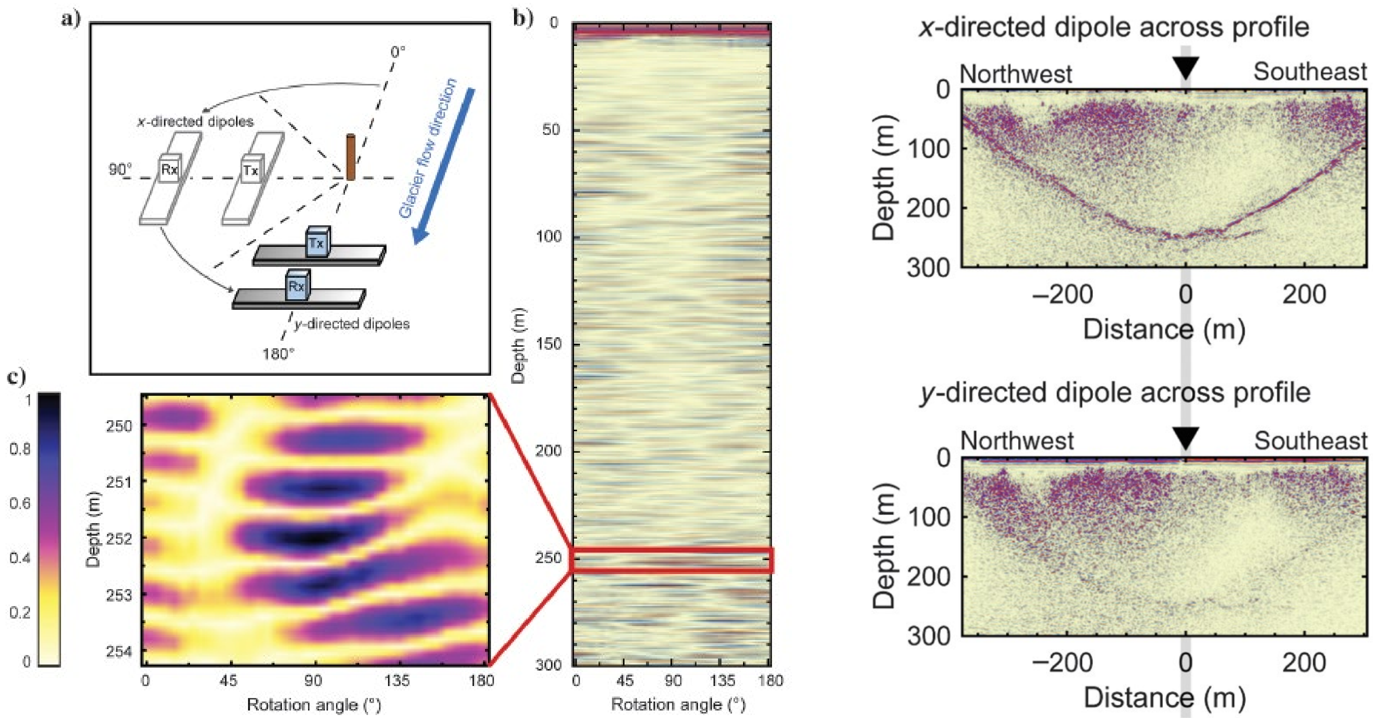
Directivity effects of GPR antennas



From Langhammer et al (2017)

Directivity effects of GPR antennas

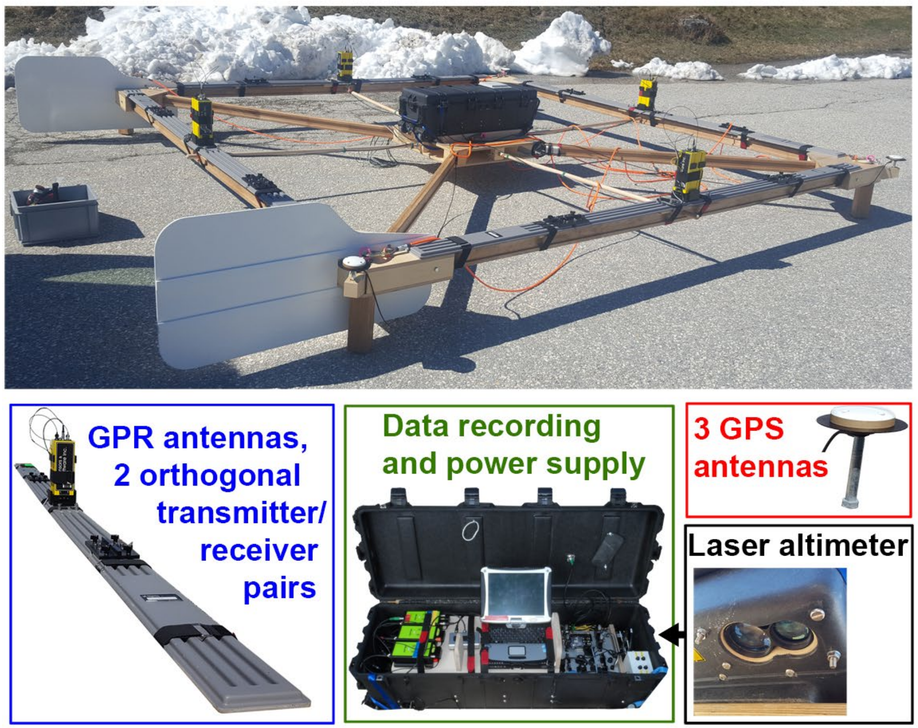
Rotation of GPR antenna pair by 180°. Maximum relfection amplitudes for antennas oriented parallel to glacier flow / valley



Langhammer, L., Rabenstein, L., Bauder, A., & Maurer, H. (2017). Ground-penetrating radar antenna orientation effects on temperate mountain glaciers. *Geophysics*

Data Acquisition with the AIR-ETH system

AIRETH-system: Air-borne Ice Radar – ETH Zürich

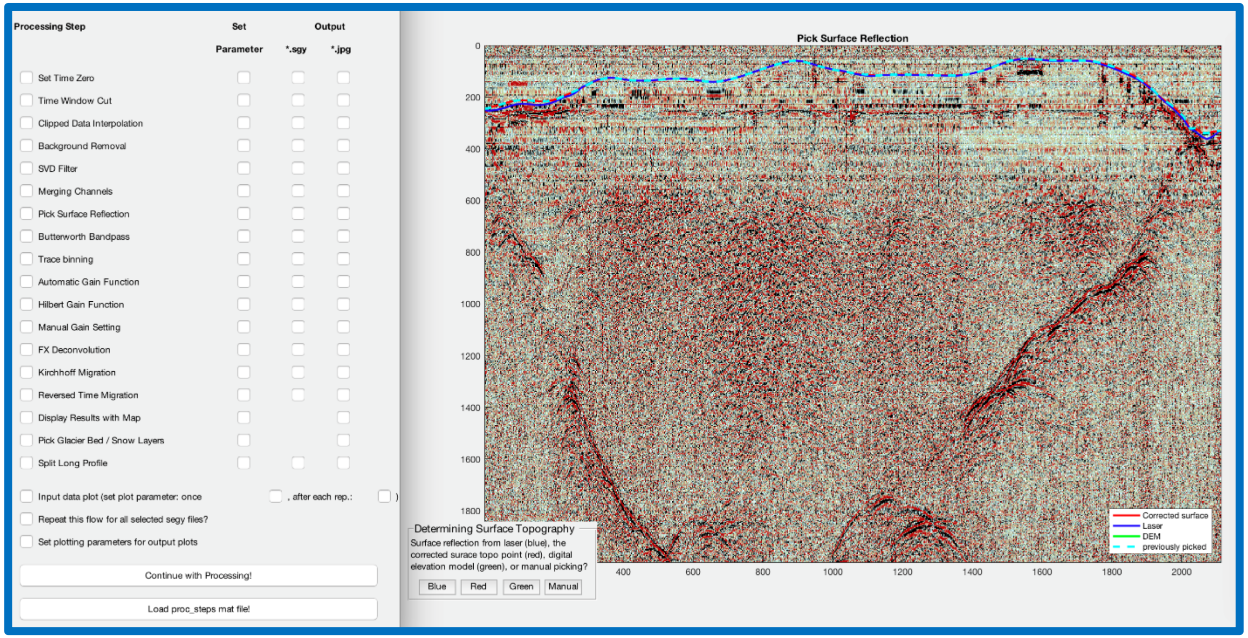


Components of the GPR-System

AIRETH in action

Helicopter-borne GPR data processing

Matlab-based processing package GPRglaz



Data Conversion

↓

Removal of (Ringing) Noise

↓

Channel Merging (Langhammer et al.)

↓

Frequency Filtering

↓

Altitude Allocation

↓

f-x Deconvolution

↓ / ↓

Data Binning

↓

Kirchhoff Migration | **Reverse Time Migration**

↓ / ↓

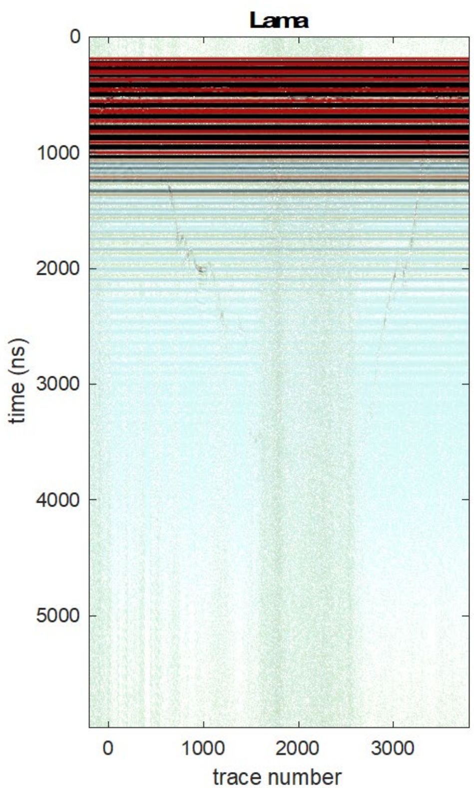
Time-to-Depth Conversion

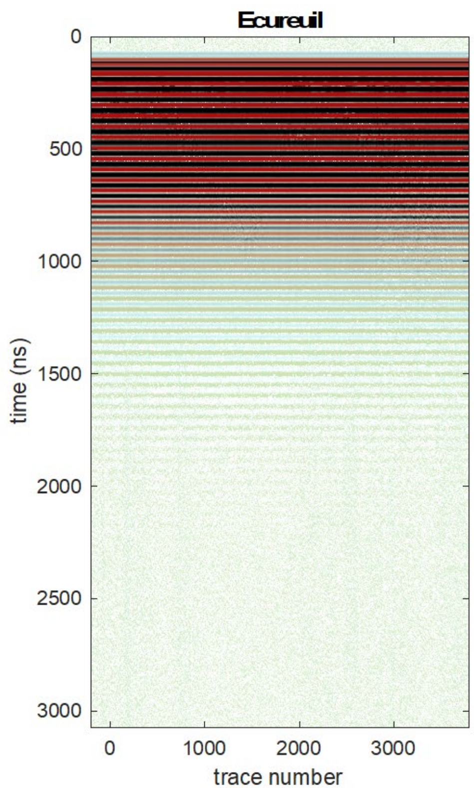
↓

Bedrock Reflection Picking

Ringing effects caused by helicopter

- Raw data recorded with our GPR-system
- Substantial ringing, mainly from the helicopter





Lama

Ecureuil

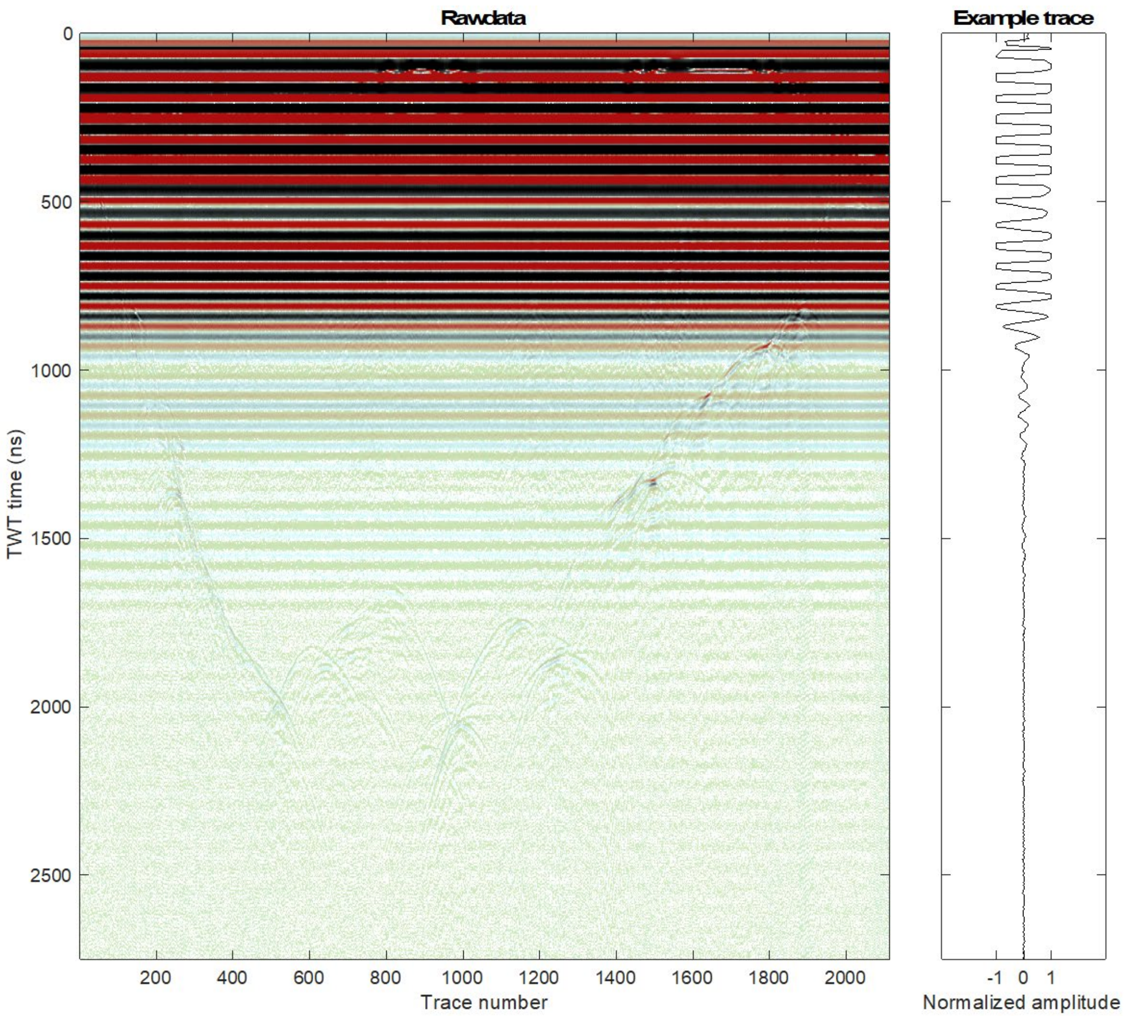
Photos: Air-glaciers.ch

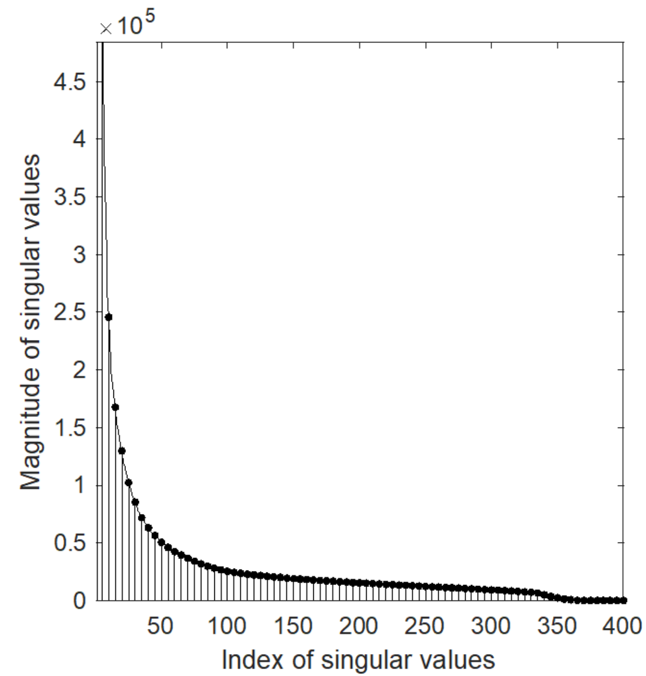
Data processing – ringing removal

- Singular value decomposition filtering of clipped data

$$D = U\,S\,V^T$$

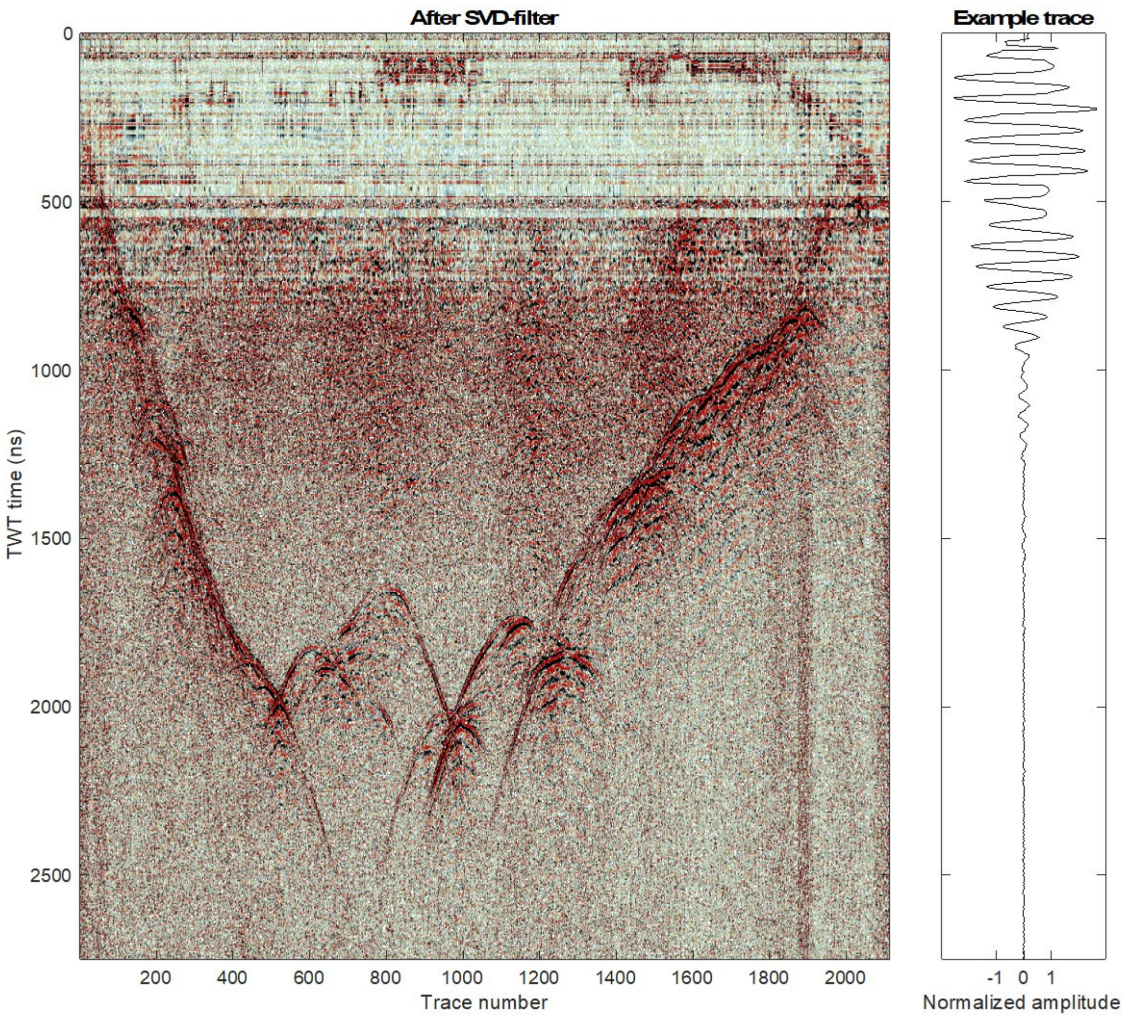
$$S = \begin{bmatrix} S_1 & 0 & 0 & \dots & 0 \\ 0 & S_2 & 0 & \dots & 0 \\ 0 & 0 & S_3 & \dots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & \dots & S_n \end{bmatrix}$$





Data processing – ringing removal

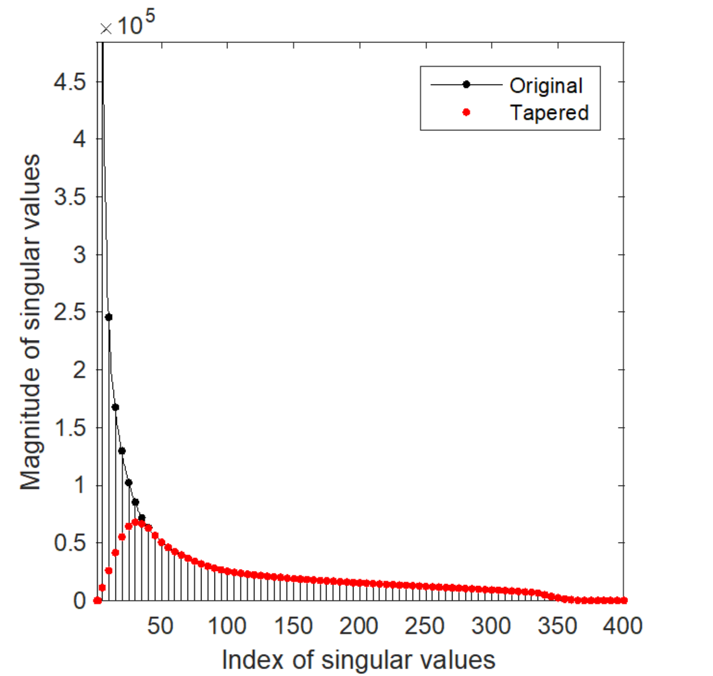
- Optimized singular value decomposition filtering of interpolated data



$$D = U\,S\,V^T$$

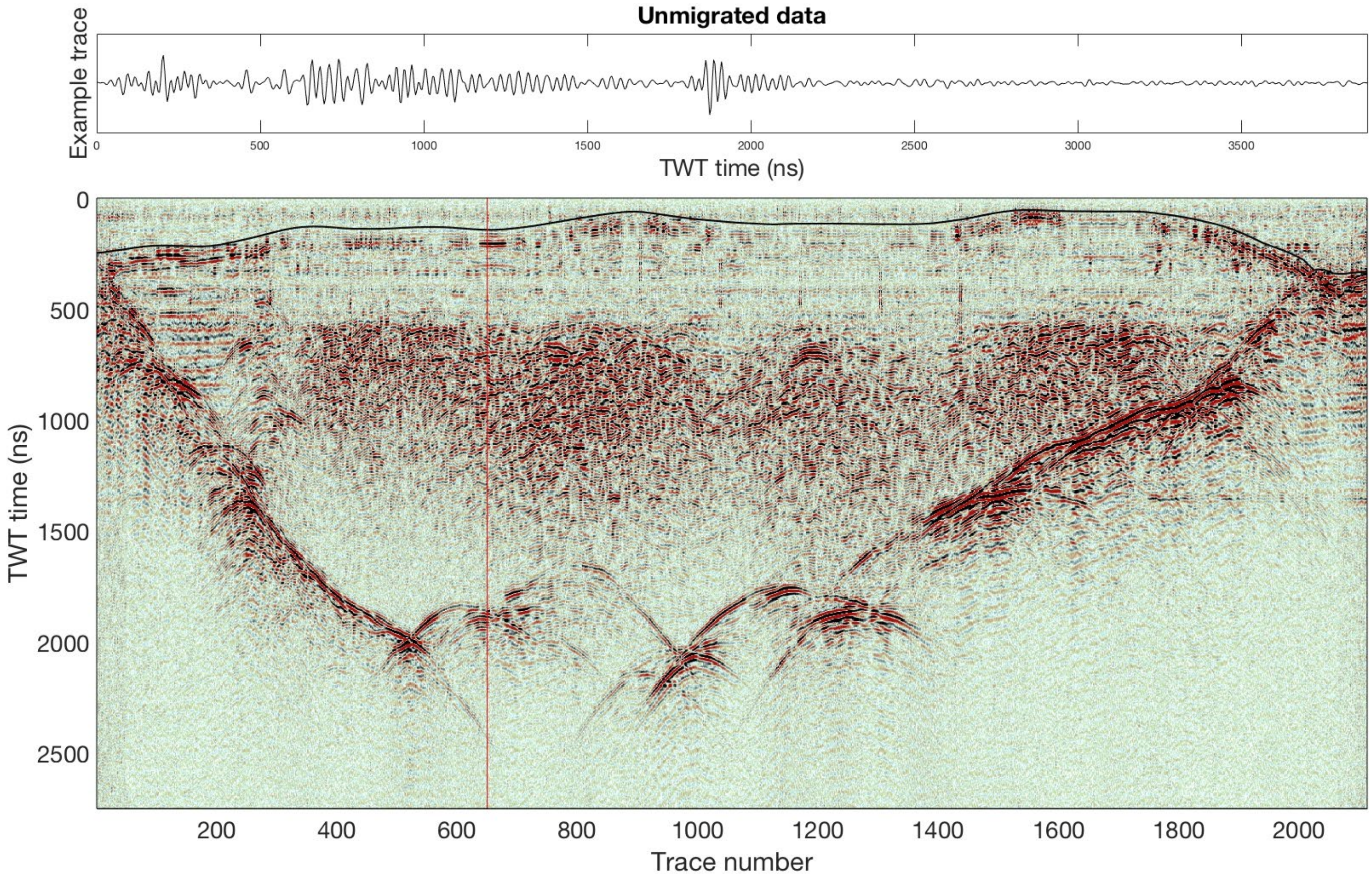
$$\hat{S} = \begin{bmatrix} x_1 S_1 & 0 & 0 & \dots & 0 \\ 0 & x_2 S_2 & 0 & \dots & 0 \\ 0 & 0 & x_3 S_3 & \dots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & \dots & S_n \end{bmatrix}$$

$$D_{\mathrm{fil}} = U\,\hat{S}\,V^T$$



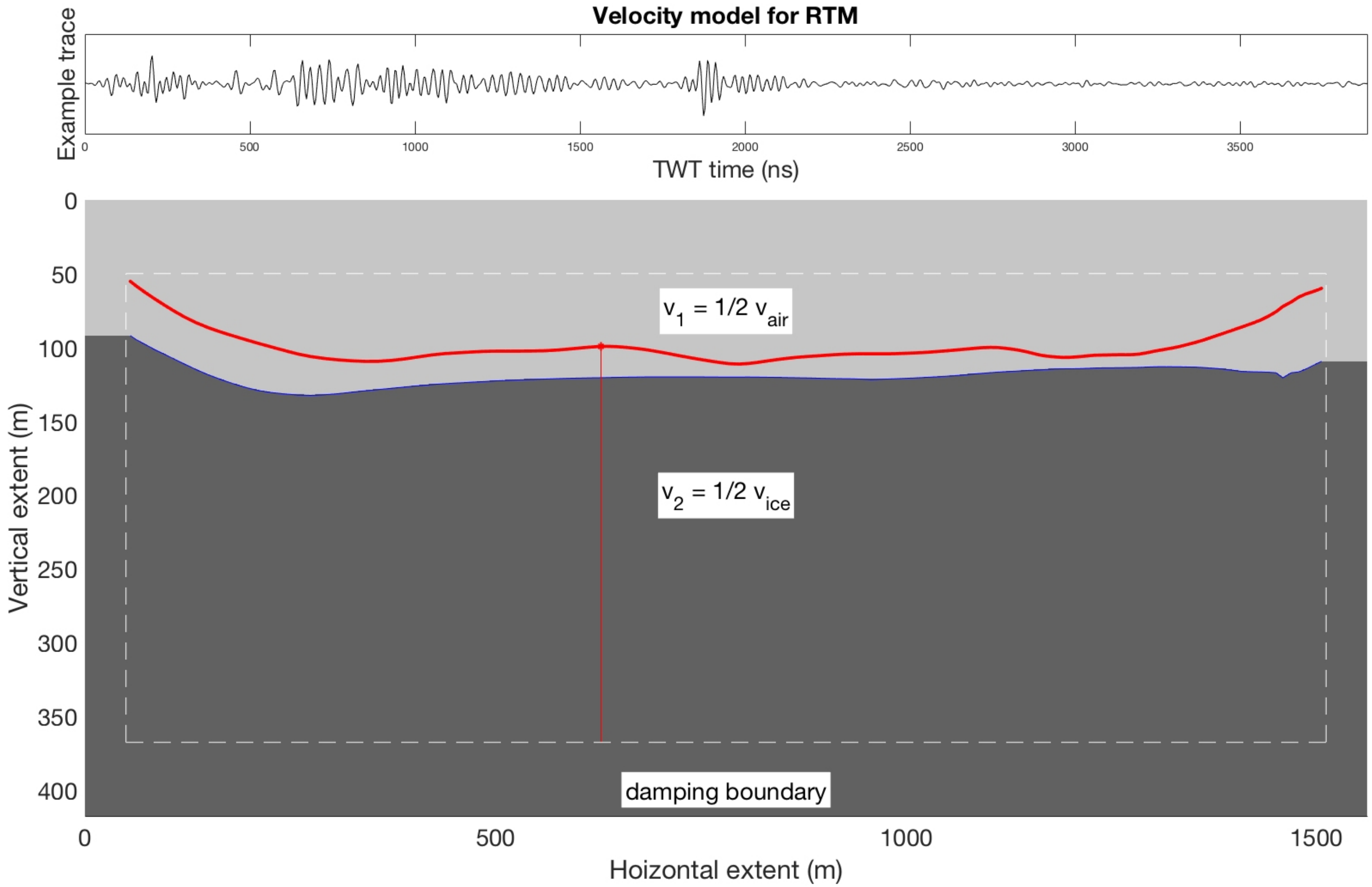
Data processing – reverse time migration

- Zero-offset data → modeling one-way travel paths



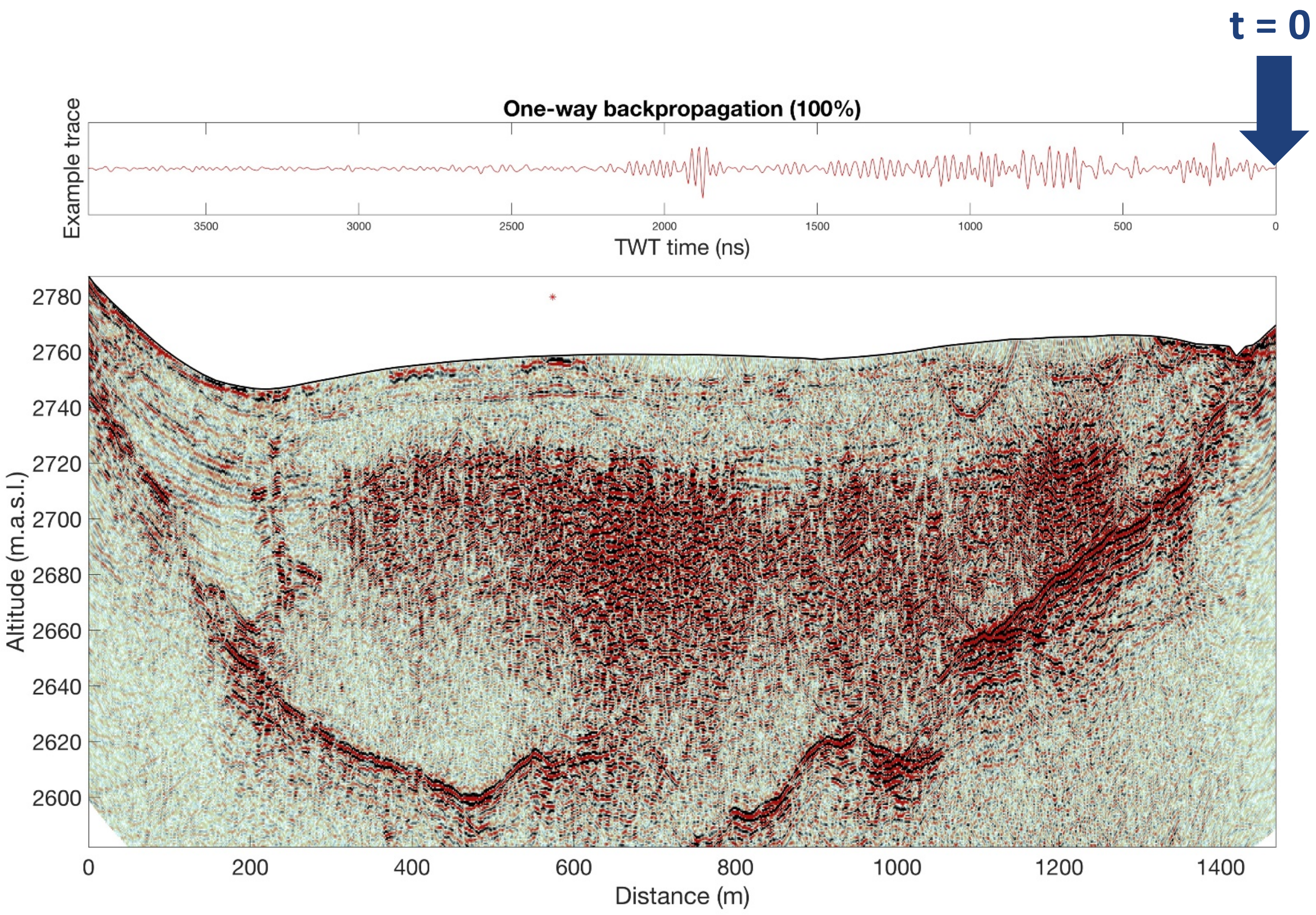
Data processing – reverse time migration

- Zero-offset data → modeling one-way travel paths
- Resolving bedrock reflections → two-layer medium is sufficient
- Half velocities because of one-way propagation
- Using time-reversed recorded traces as source signals



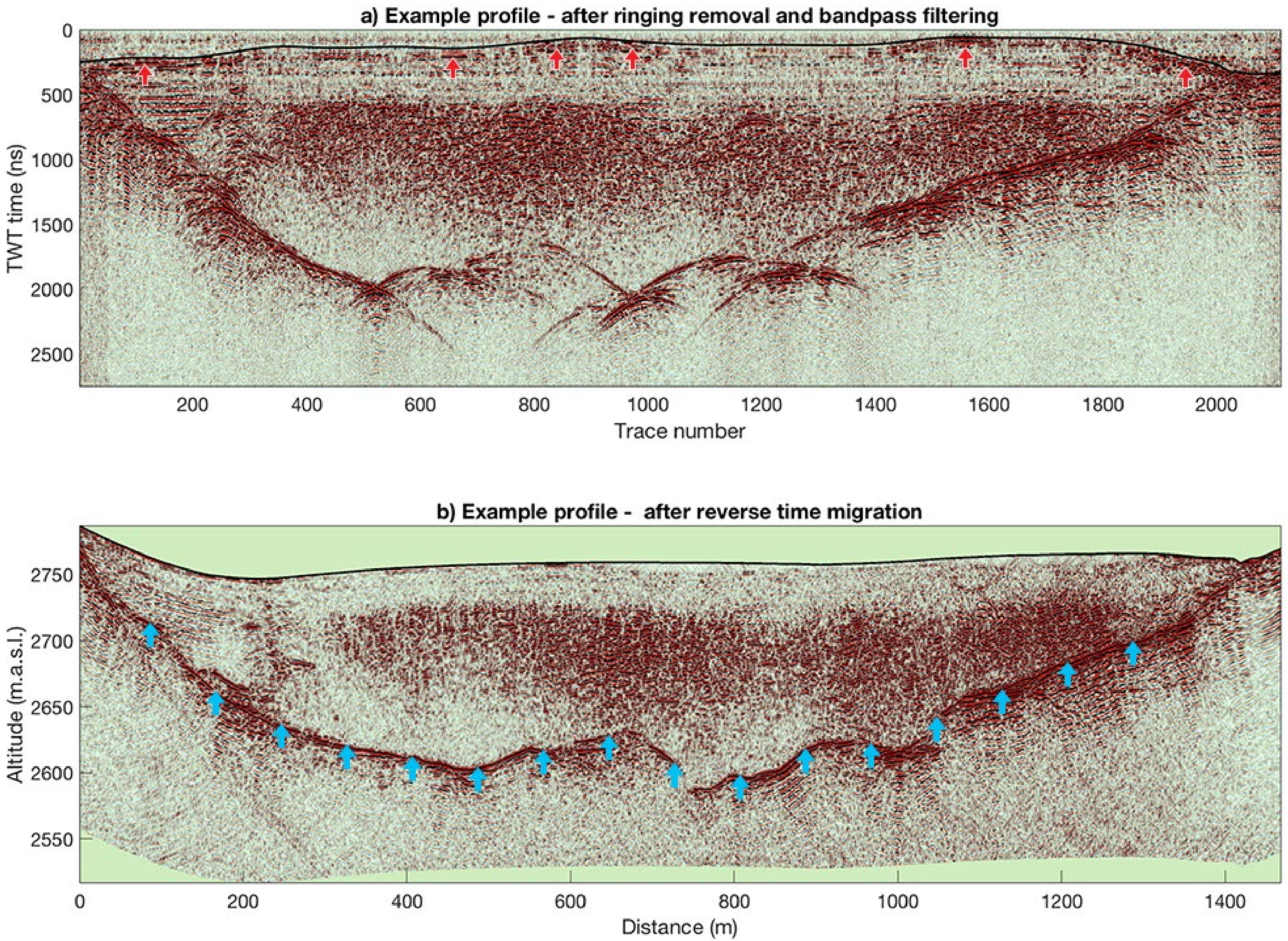
Data processing – reverse time migration

- Backpropagation to t = 0



Data processing – reverse time migration

- Picking bedrock on the resulting migrated section



Estimation of ice thickness/volume

- GPR data provide accurate ice thickness estimates along profile lines, but they do not provide information for areas not sampled by the profiles
- GPR profile network on glaciers is typically quite sparse
- Traditionally, glaciologists estimate ice thicknesses and ice volumes with numerical modeling approaches using glaciological constraints
- Glaciological modeling provides continuous 3D subsurface models, but they typically lack «ground truth» information

Glaciological ice thickness modelling in a nutshell

Here, we discuss the model described by Clarke et al. (2013), but it is important to note that many other approaches exist (ITMIX project, Farinotti et al., 2017).

The model by Clarke et al. (2013) estimates ice thickness $\mathbf{h}^{\mathbf{glac}}$ using

$$\mathbf{h}^{\mathbf{glac}} = \frac{\boldsymbol{\tau}^*}{\rho g \sin(\phi)}$$

where $\boldsymbol{\tau}^*$ is the basal shear stress. It is defined as,

$$\boldsymbol{\tau}^* = \left[\frac{(n+2)\rho g \sin(\phi)^2 \xi \mathbf{q}}{2A} \right]^{1/(n+2)}$$

n - exponent of Glen's flow law

ρ - ice density

g - gravity acceleration

A - creep rate factor

ξ - creeping contribution relative to basal sliding

q - specific discharge q = Q/l

ϕ = surface slope

Combining GPR data and glaciological constraints

It is our goal to determine a continuous ice thickness distribution that satisfies a number of constraints. For that purpose, we subdivide the investigation area in a regular grid including *M* cells. For each cell, try to find an ice thickness value. They are represented by the *M x 1* vector $\mathbf{h}^{\mathbf{est}}$.

First, we consider the GPR data constraints. They can be represented by the equation $\boldsymbol{G}\ \boldsymbol{h}^{est} = \boldsymbol{h}^{GPR}$, where $\boldsymbol{h}^{GPR}$ includes all GPR ice thickness estimates along the individual profile lines, and the *M x M* matrix $\boldsymbol{G}$ is a diagonal matrix including ones at cell indices, where GPR thickness estimates are available, and zeros at the remaining diagonal elements.

Obviously, such a system of equations does not constrain cells, where no GPR information is available.

$$\mathbf{G}\mathbf{h}^{\mathbf{est}} = \mathbf{h}^{\mathbf{GPR}}$$

Combining GPR data and glaciological constraints

Next, we consider the glaciological constraints $\boldsymbol{h}^{glac}$. Since there is considerable uncertainty in the various constants used to determine $\boldsymbol{h}^{glac}$, their magnitudes may be incorrect. We can account for this by introducing a correction factor a, leading to corrected values $\boldsymbol{h}^{glacc} = \alpha\, \boldsymbol{h}^{glac}$. Can be determined by minimizing

$$\sum_i \left(h_i^{GPR} - \alpha h_i^{glac} \right)^2$$

whereby the index i runs over those cells including GPR data.

The correction factor α accounts for some inadequacies of $\boldsymbol{h}^{glac}$, but it is still possible that there are still systematic differences between $\boldsymbol{h}^{GPR}$ and $\boldsymbol{h}^{glacc}$. To avoid the resulting inconsistencies, we consider not the absolute value of $\boldsymbol{h}^{glacc}$ but instead the spatial gradient $\nabla \mathbf{h}^{\mathrm{glacc}}$ as glaciological constraints, resulting in

$$\mathbf{L}\mathbf{h}^{\mathbf{est}} = \nabla \mathbf{h}^{\mathbf{glacc}}$$

where matrix ***L*** is a difference operator of size *M x M*.

Combining GPR data and glaciological constraints

Additional constraints can be imposed to better determine $\boldsymbol{h}^{est}$. When the outline of a glacier is known, we should request that all ice thicknesses outside of the glacier are zero. This can be achieved with the equation

$$\mathbf{B}\mathbf{h}^{\mathbf{est}} = 0$$

where matrix $\boldsymbol{B}$ is a diagonal matrix of size $M \times M$ including ones for cells outside of the glacier and zeros elsewhere.

Finally, we can impose smoothness constraints that enforce smooth spatial variations of $\boldsymbol{h}^{est}$ (Occam's principle). The smoothness constraints are written as

$$\mathbf{S}\mathbf{h}^{\mathbf{est}} = 0$$

where matrix $\boldsymbol{S}$ is a smoothing operator of size $M \times M$.

Putting everything together

- **G**: Diagonal matrix including ones, where GPR data are available
- **L**: Difference operator
- **B**: Diagonal matrix including ones, outside of glacierized areas
- **S**: Smoothing operator
- λ_1 to λ_4: Weighting factors

$$\begin{pmatrix} \lambda_1 \mathbf{G} \\ \lambda_2 \mathbf{L} \\ \lambda_3 \mathbf{B} \\ \lambda_4 \mathbf{S} \end{pmatrix} \mathbf{h}^{\mathbf{est}} = \begin{pmatrix} \lambda_1 \mathbf{h}^{\mathbf{GPR}} \\ \lambda_2 \nabla \mathbf{h}^{\mathbf{glacc}} \\ 0 \\ 0 \end{pmatrix}$$

How do we determine λ_1 to λ_4 ?

Choice of weighting parameters λ_1 to λ_4

- λ_3 is not critical (e.g. $\lambda_3 = 1.0$)
- $\mathbf{h}^{\mathbf{est}}$ should fit GPR data only within a prescribed accuracy (e.g. $\varepsilon^{GPR} = 0.05$), and 95% of the GPR data should be fitted within ± ε^{GPR}
- Only relative magnitudes of λ_1 and λ_2 are of interest
- λ_4 should be tuned, such that prescribed GPR data fit can be achieved

$$\boldsymbol{\varepsilon}^{\mathbf{GPR}} = \left\| \mathbf{h}^{\mathbf{est}} - \mathbf{h}^{\mathbf{GPR}} \right\| / \left(\mathbf{h}^{\mathbf{GPR}} + h^{\min} \right)$$

$$\begin{pmatrix} \lambda_1 \mathbf{G} \\ \lambda_2 \mathbf{L} \\ \lambda_3 \mathbf{B} \\ \lambda_4 \mathbf{S} \end{pmatrix} \mathbf{h}^{\mathbf{est}} = \begin{pmatrix} \lambda_1 \mathbf{h}^{\mathbf{GPR}} \\ \lambda_2 \nabla \mathbf{h}^{\mathbf{glac}} \\ 0 \\ 0 \end{pmatrix}$$

Choice of weighting parameters λ_1 to λ_4

1. Choose a high λ_1 / λ_2 ratio, and a high λ_4 value.

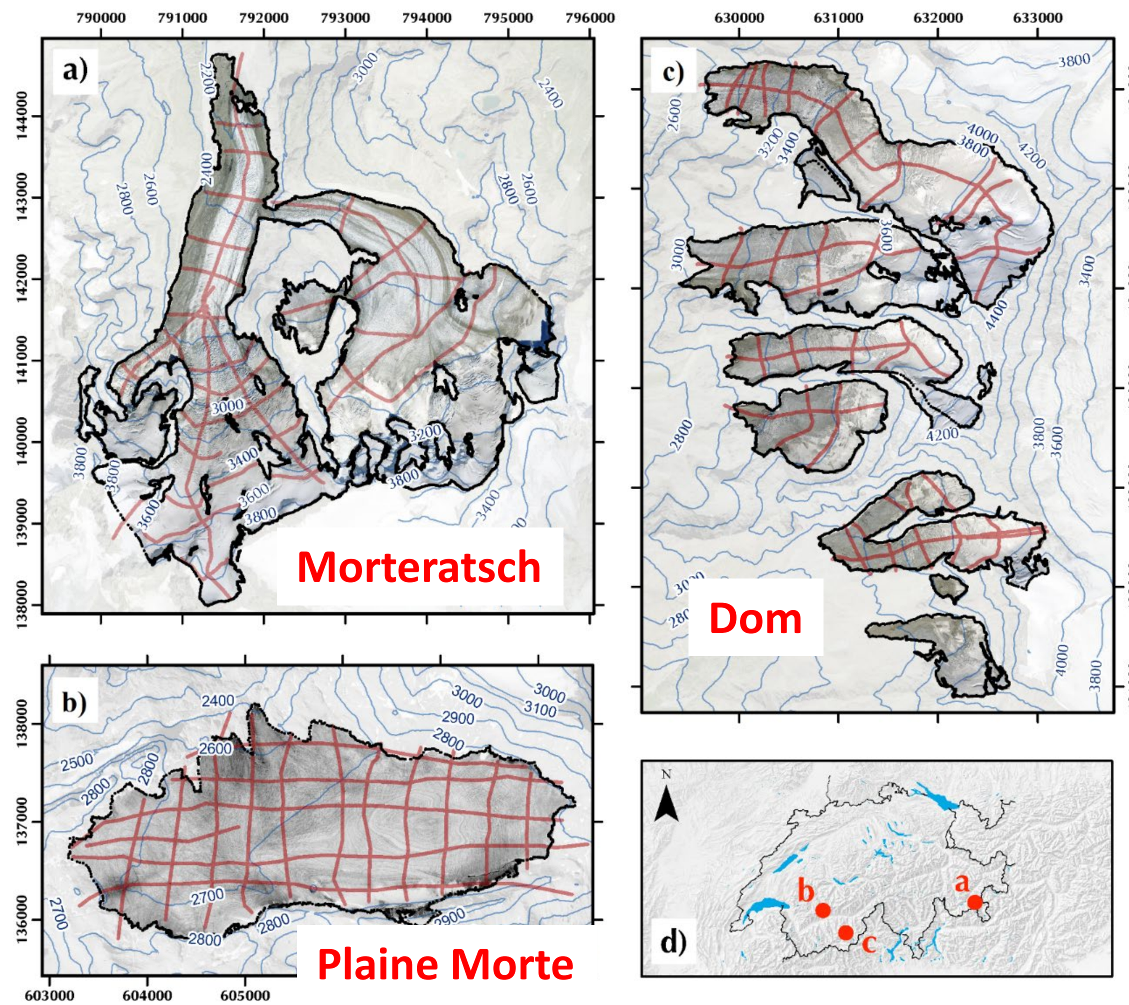
2. Solve system of equation.

3. If prescribed GPR data fit is not achieved, decrease λ_4 and repeat step 2, until data fit is achieved or λ_4 drops below minimum level

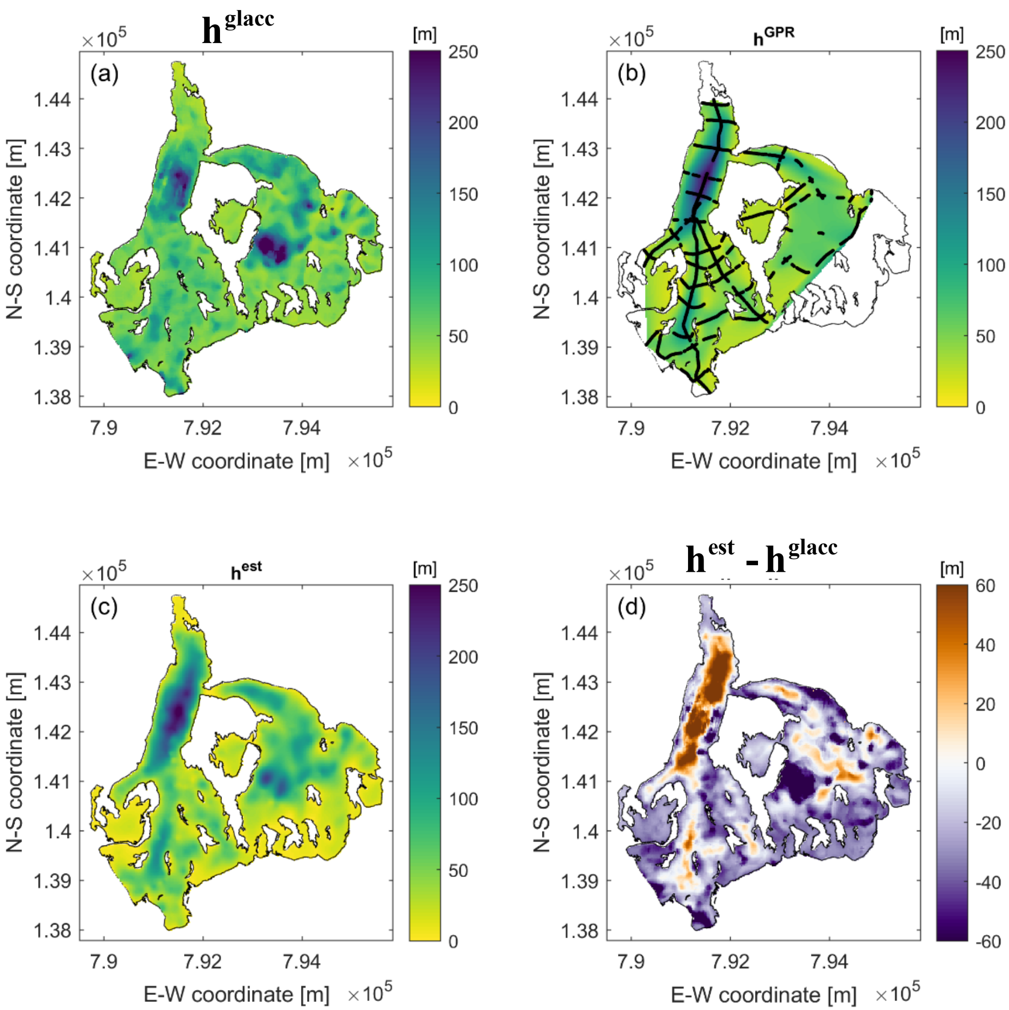
4. Decrease λ_1 / λ_2 ratio, and repeat steps 1 to 3 until
   - I. GPR data fit can no longer be achieved, or
   - II. λ_1 / λ_2 ratio drops below prescribed minimum value

$$\begin{pmatrix} \lambda_1 \mathbf{G} \\ \lambda_2 \mathbf{L} \\ \lambda_3 \mathbf{B} \\ \lambda_4 \mathbf{S} \end{pmatrix} \mathbf{h}^{\mathbf{est}} = \begin{pmatrix} \lambda_1 \mathbf{h}^{\mathbf{GPR}} \\ \lambda_2 \nabla \mathbf{h}^{\mathbf{glac}} \\ 0 \\ 0 \end{pmatrix}$$

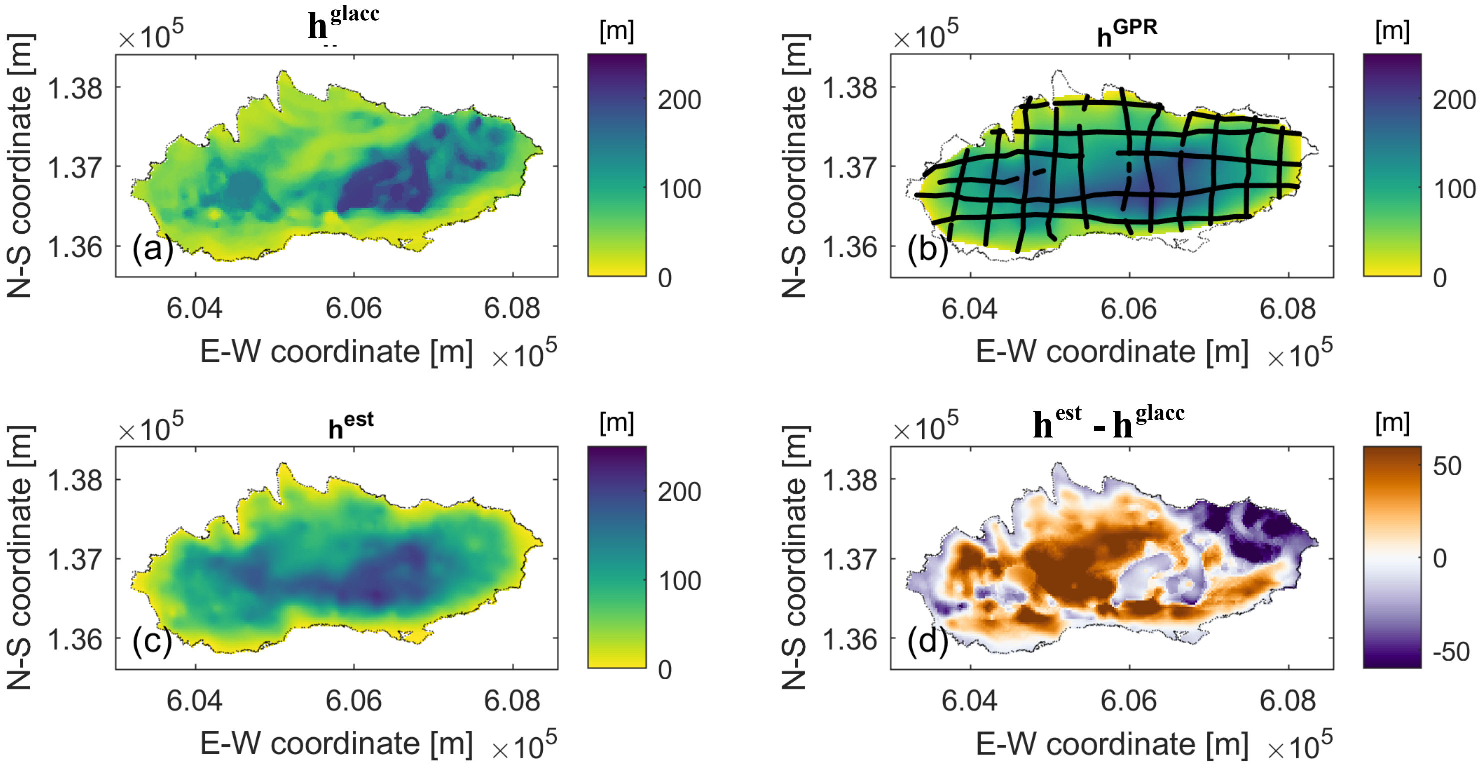
Case studies



Morteratsch



Plaine Morte



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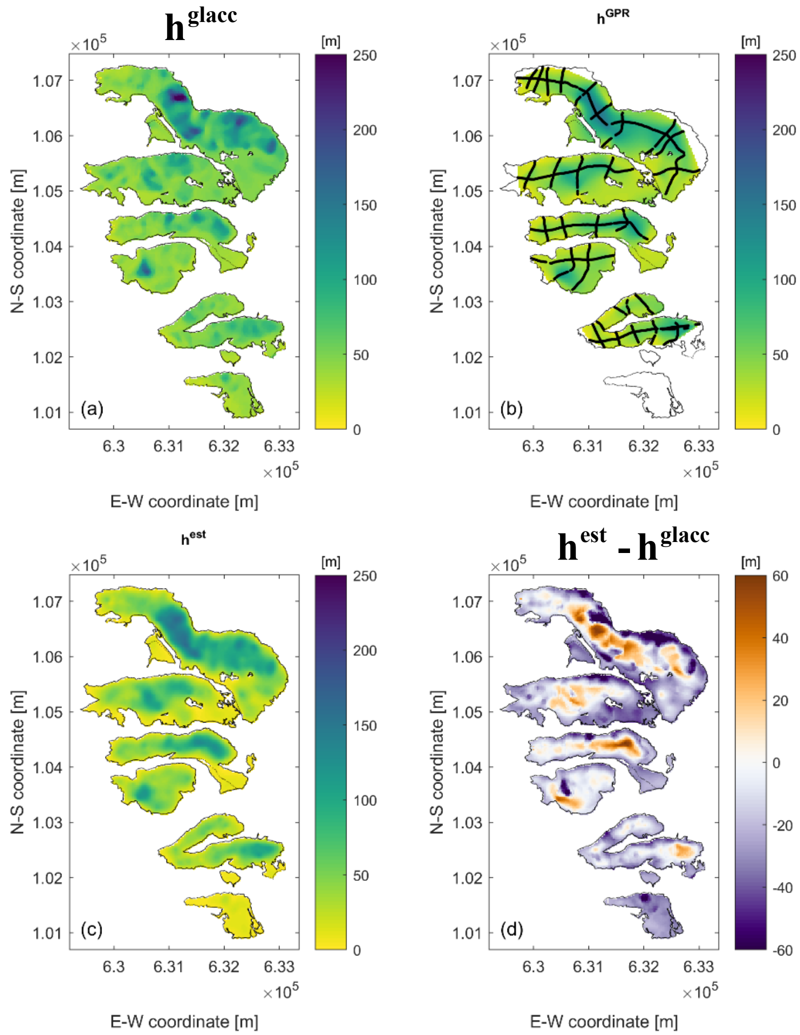
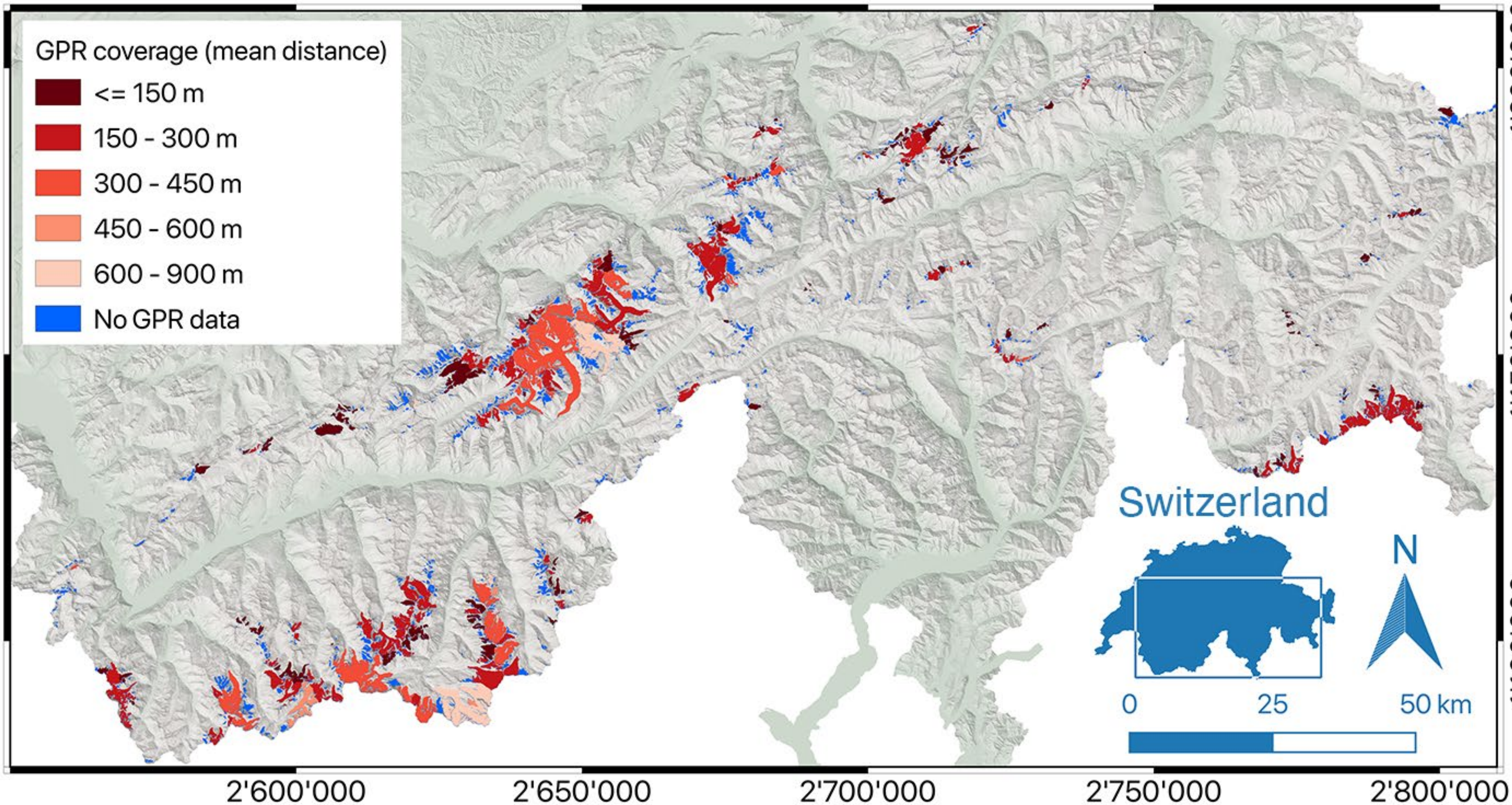


h glacc
h GPR
h est
h est - h glacc
(a)
(b)
(c)
(d)
[m]
N-S coordinate [m]
E-W coordinate [m]

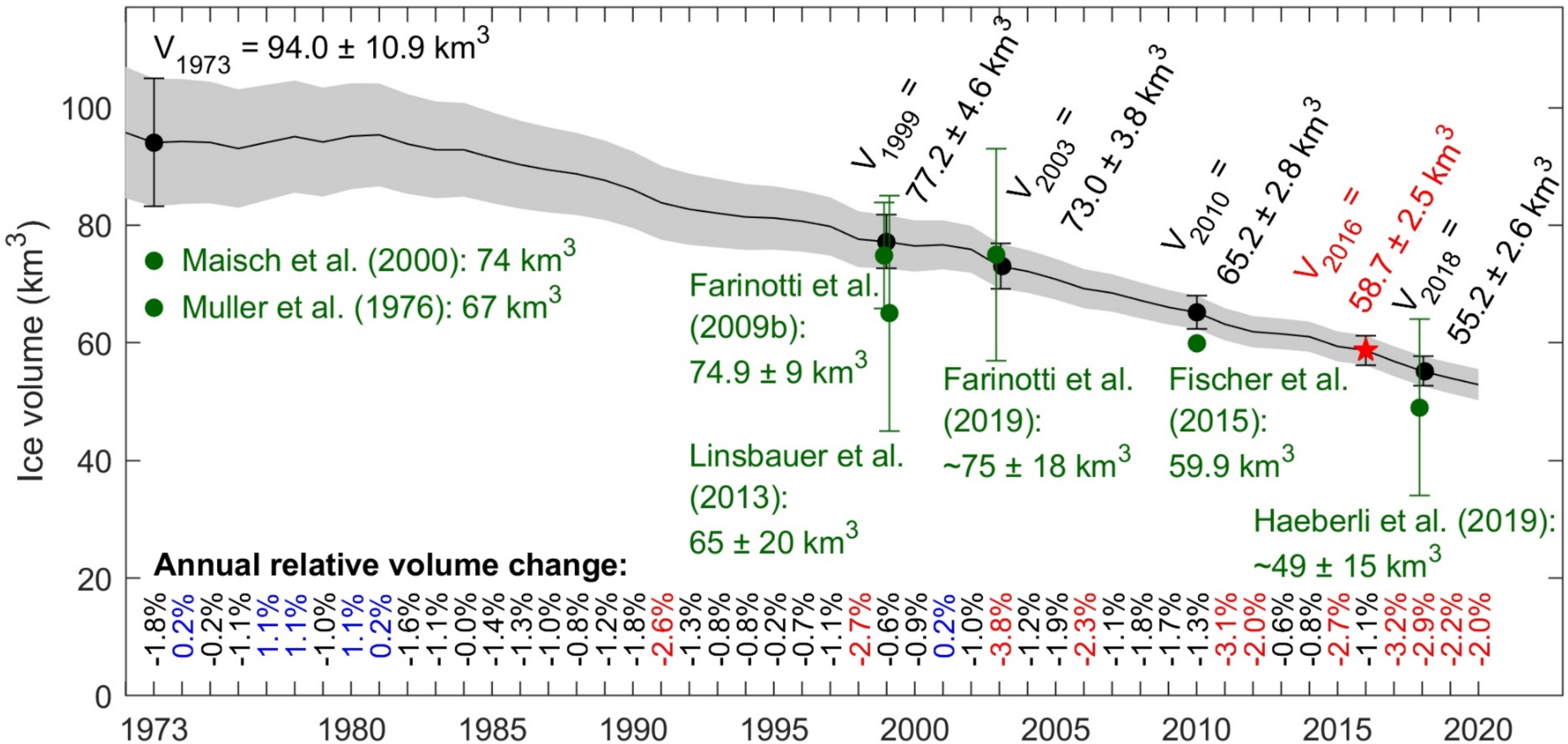
Establishing an inventory of Swiss glaciers



Main findings: Total ice volume in the Swiss Alps

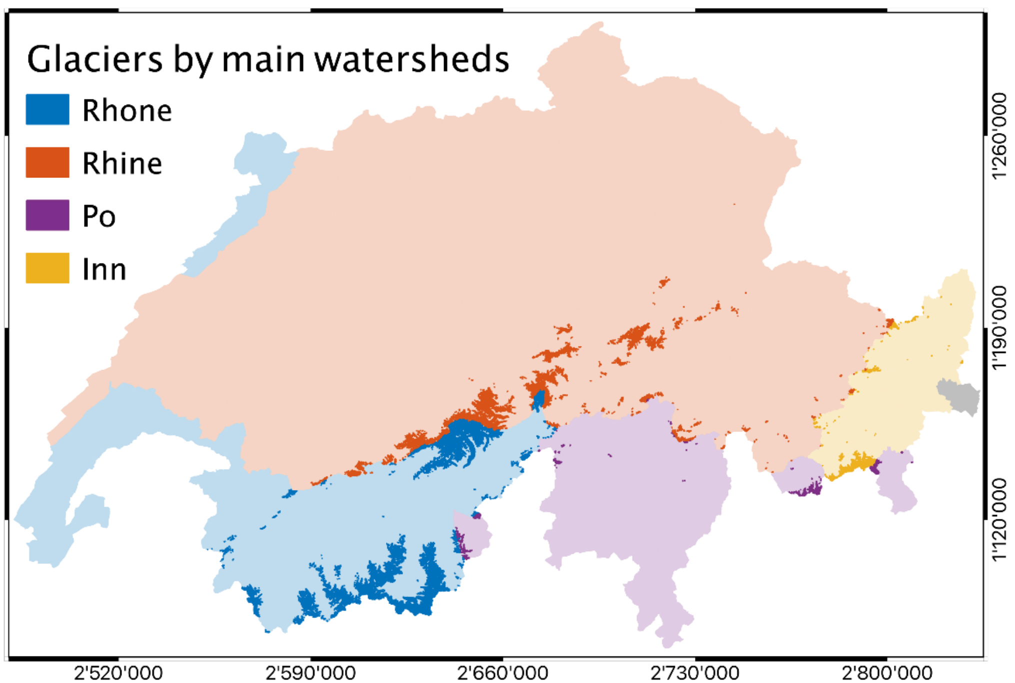
Total ice volume of all Swiss Glaciers: **58.7 ± 2.5 km³** (2016)

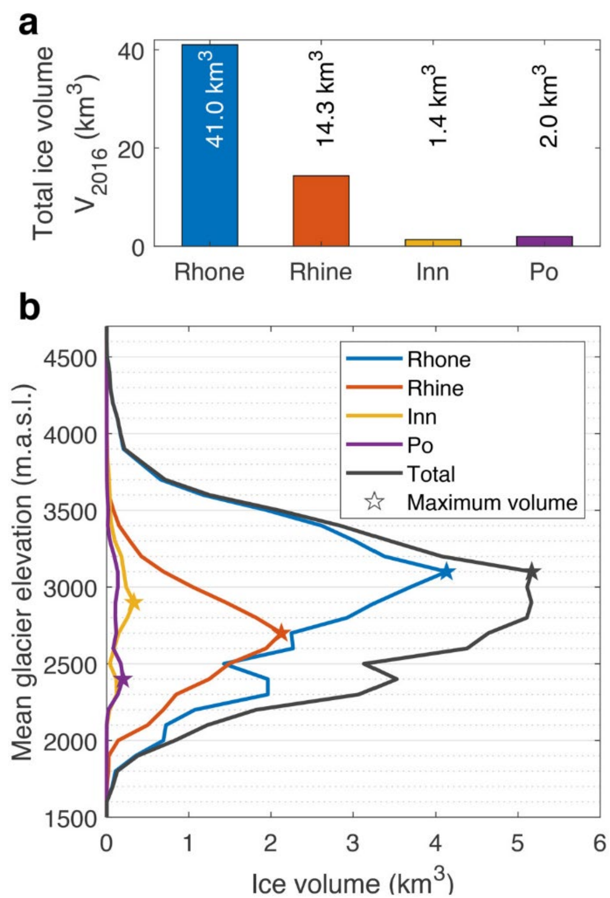
In 2020: 52.9 ± 2.7 km³ (2016)



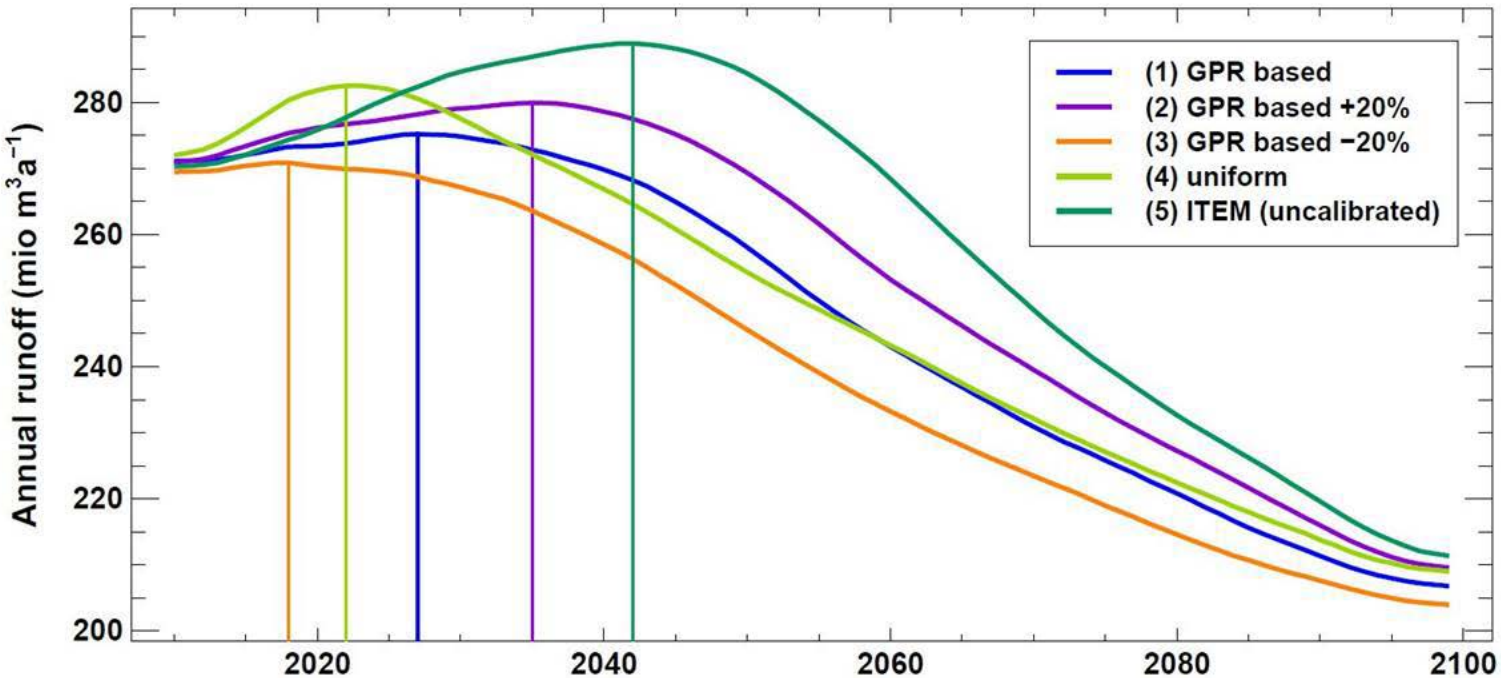
Main findings: Ice thickness distribution

Most important input data for predicting future river runoff behavior





Impact of GPR measurements on runoff projections
Mauvoisin case study (Gabbi et al., 2012)



Main findings: Glacier bed topography

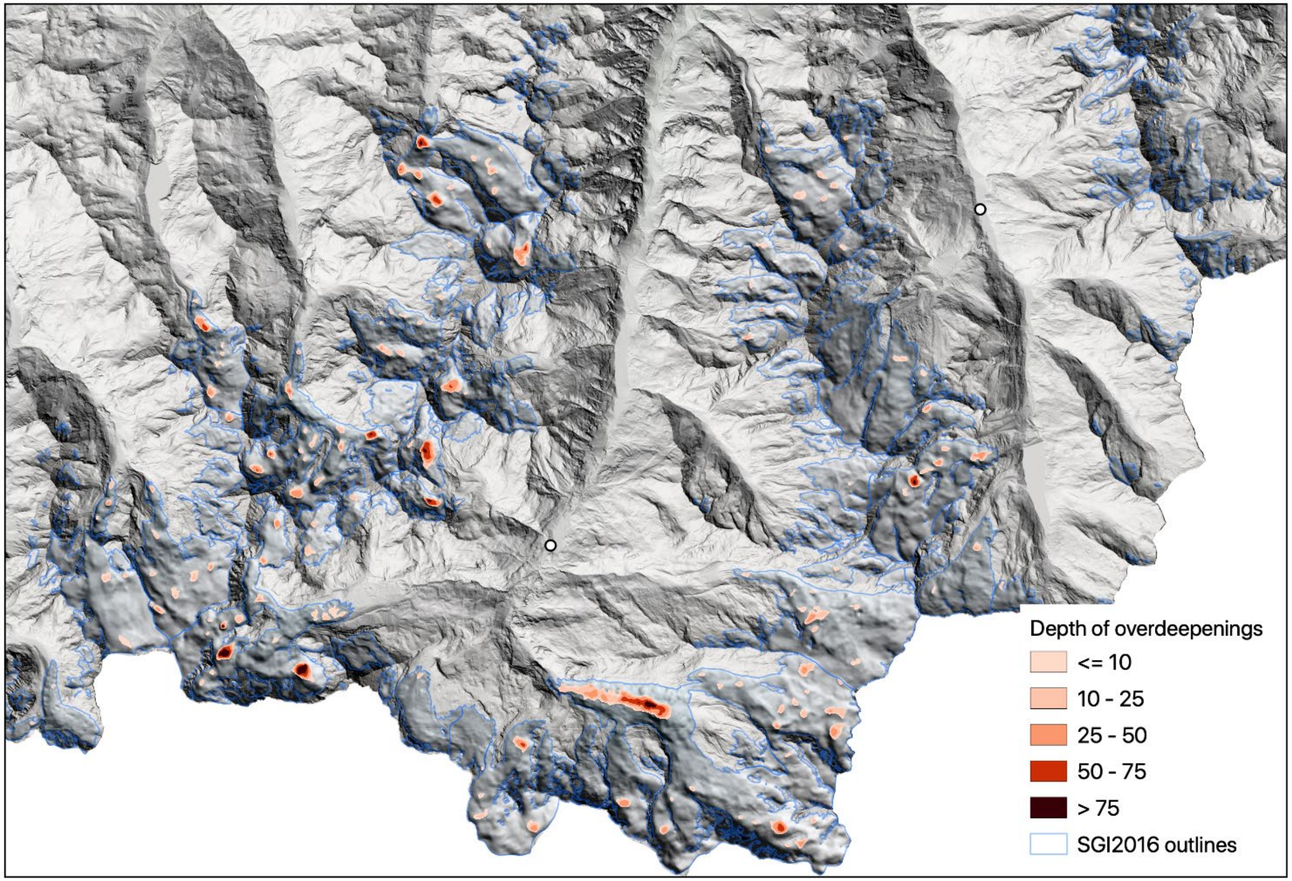
Morphology of the (hypothetically) completely deglacierized landscape.

Base data for example to estimate water volumes in future high-alpine lakes.

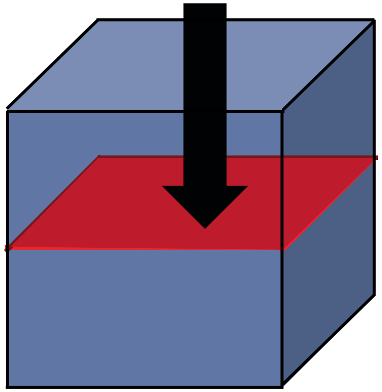
Lake volume estimate for Swiss Alps:

Linsbauer et al. (2013):
2 km^3

Our study:
1 km^3



Future of GPR on glaciers

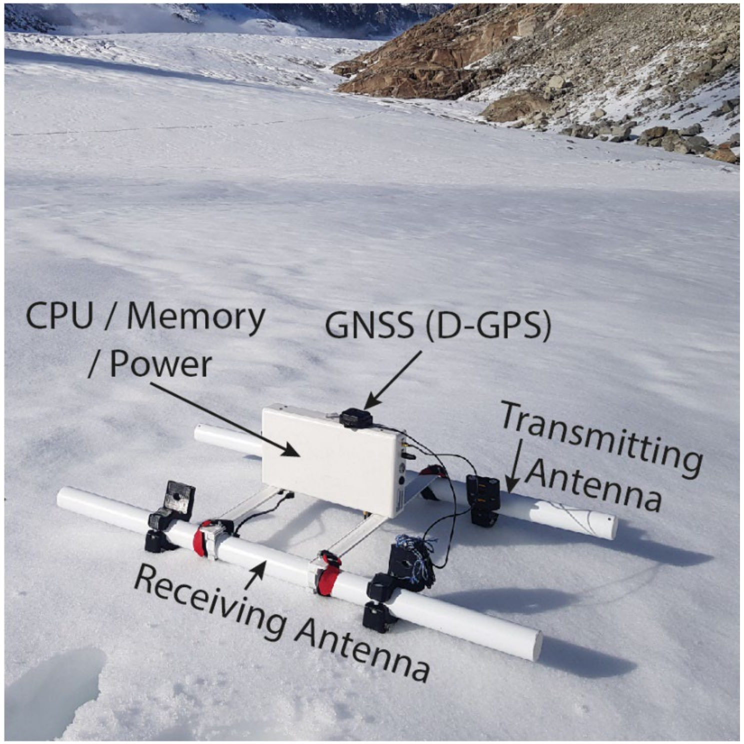


(courtesy of Greg Church)

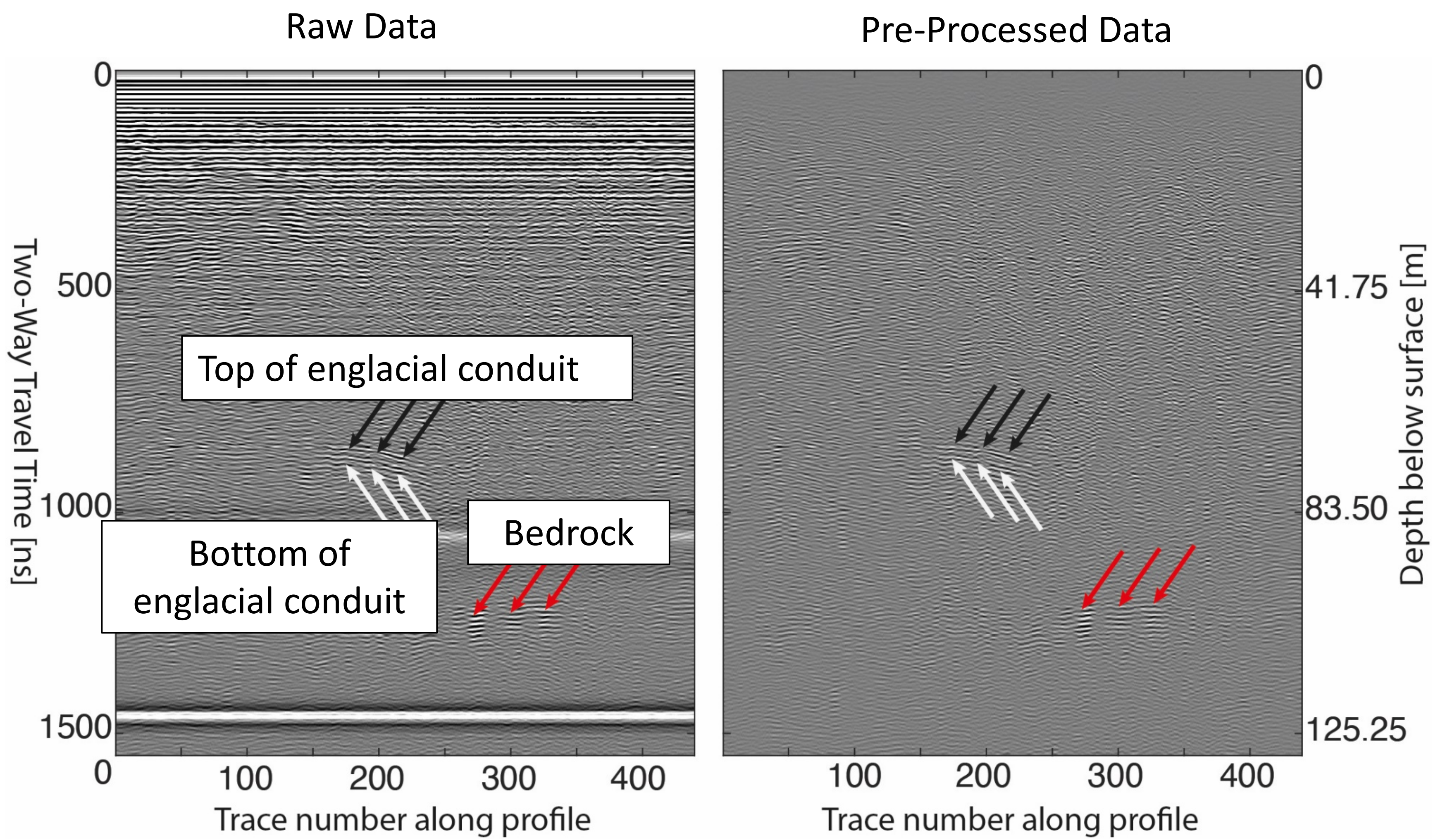
Future of 3D GPR on glaciers

- Unmanned aerial vehicles to carry GPR as payload.
- Fast and efficient acquisition over difficult to access terrain.

- 3D GPR: Walking – 9 days
- 3D GPR: Drone – 7 hours



Drone GPR Data




The end