

# Ground Penetrating Radar

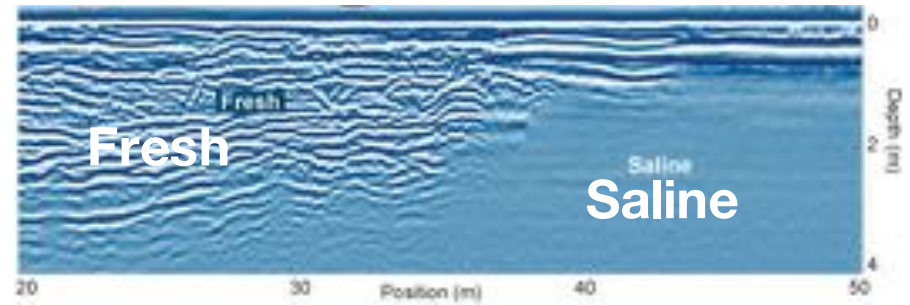


# Motivation

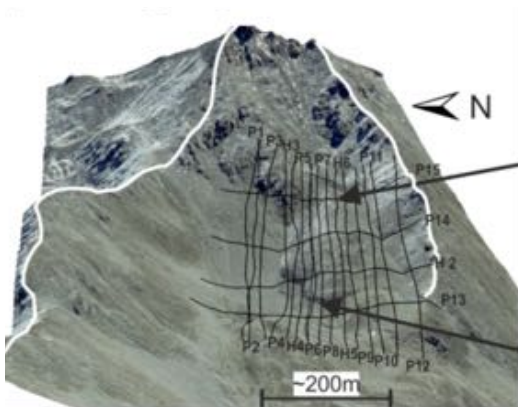
Sink holes



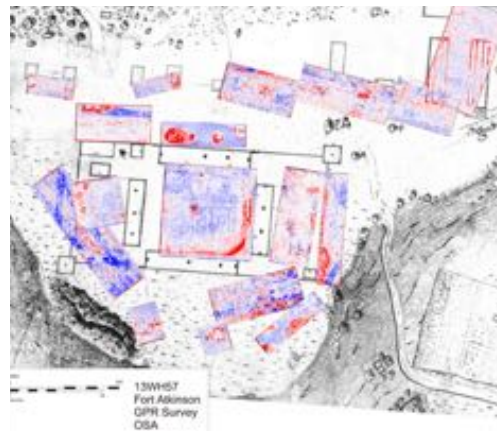
Salt Water Intrusions



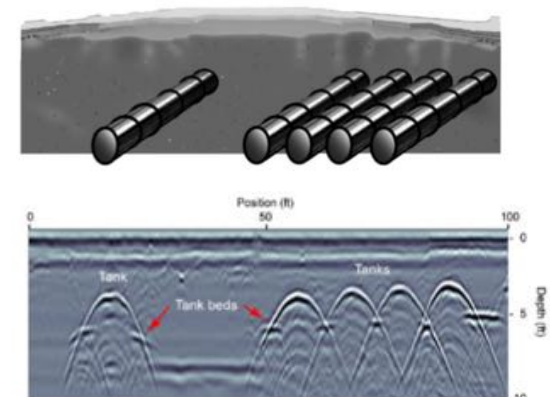
Rock glacier



Archeology



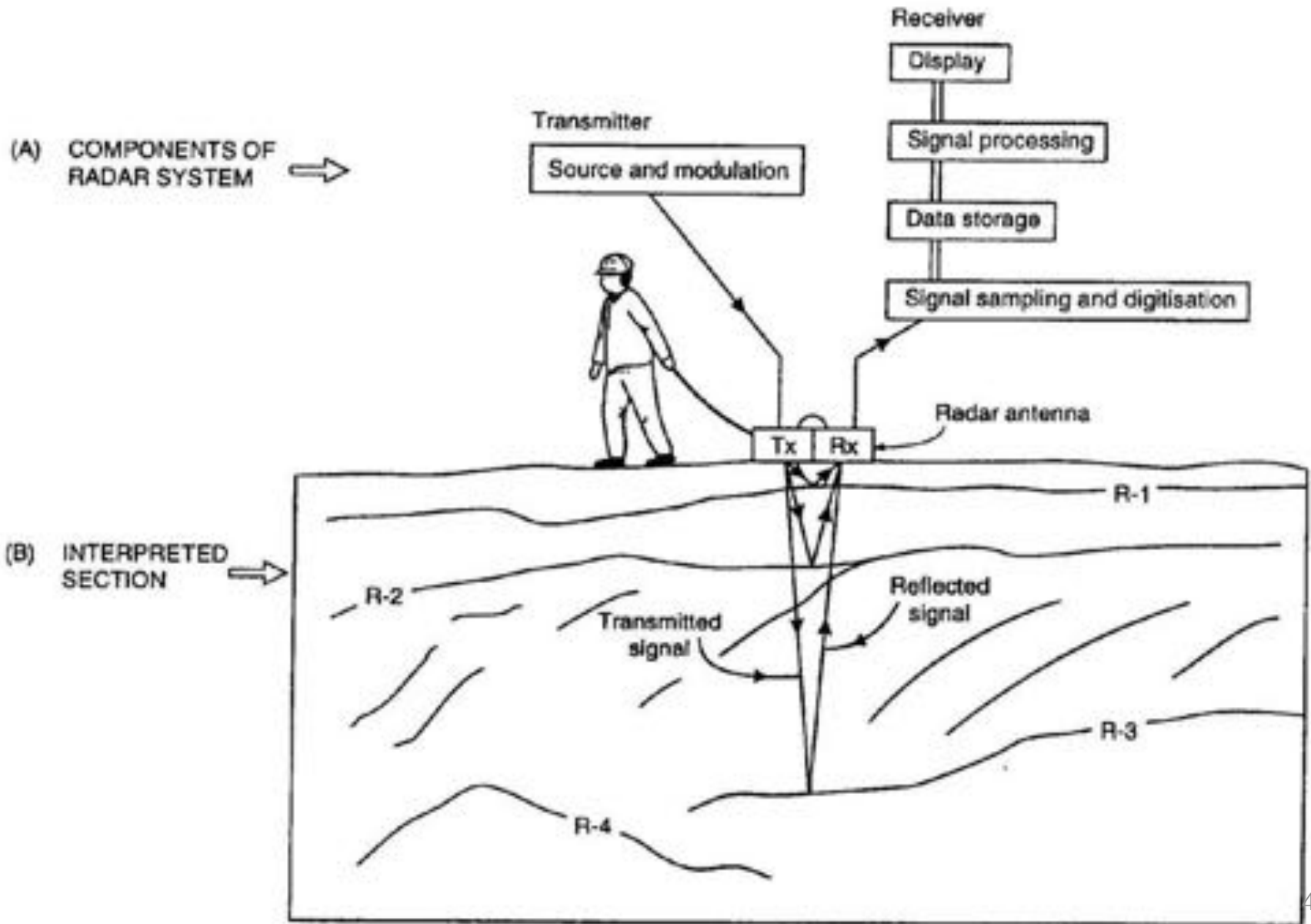
Underground tank



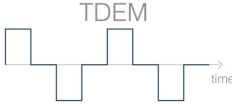
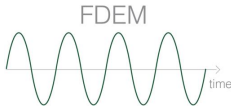
# Outline

- Basic experiment
- Physical property
- Physics
- Data and Processing
- Case history: rock glacier

# Basic Experiment



# Basic Equations

	Time 	Frequency 
Faraday's Law	$\nabla \times \mathbf{e} = - \frac{\partial \mathbf{b}}{\partial t}$	$\nabla \times \mathbf{E} = - i\omega \mathbf{B}$
Ampere's Law	$\nabla \times \mathbf{h} = \mathbf{j} + \frac{\partial \mathbf{d}}{\partial t}$	$\nabla \times \mathbf{H} = \mathbf{J} + i\omega \mathbf{D}$
No Magnetic Monopoles	$\nabla \cdot \mathbf{b} = 0$	$\nabla \cdot \mathbf{B} = 0$
Constitutive Relationships (non-dispersive)	$\mathbf{j} = \sigma \mathbf{e}$ $\mathbf{b} = \mu \mathbf{h}$ $\mathbf{d} = \epsilon \mathbf{e}$	$\mathbf{J} = \sigma \mathbf{E}$ $\mathbf{B} = \mu \mathbf{H}$ $\mathbf{D} = \epsilon \mathbf{E}$

\* Solve with sources and boundary conditions

# Basic Equations: Wave Equation

First order equations

$$\begin{aligned}\nabla \times \mathbf{e} &= -\frac{\partial \mathbf{b}}{\partial t} & \mathbf{j} &= \sigma \mathbf{e} \\ \nabla \times \mathbf{h} &= \mathbf{j} + \frac{\partial \mathbf{d}}{\partial t} & \mathbf{b} &= \mu \mathbf{h} \\ & & \mathbf{d} &= \epsilon \mathbf{e}\end{aligned}$$

Second order equations

$$\nabla^2 \mathbf{h} - \underbrace{\mu \sigma \frac{\partial \mathbf{h}}{\partial t}}_{\text{diffusion}} - \underbrace{\mu \epsilon \frac{\partial^2 \mathbf{h}}{\partial t^2}}_{\text{wave propagation}} = 0$$

In frequency

$$\begin{aligned}\nabla^2 \mathbf{H} + k^2 \mathbf{H} &= 0 \\ k^2 &= \omega^2 \mu \epsilon - i \omega \mu \sigma\end{aligned}$$

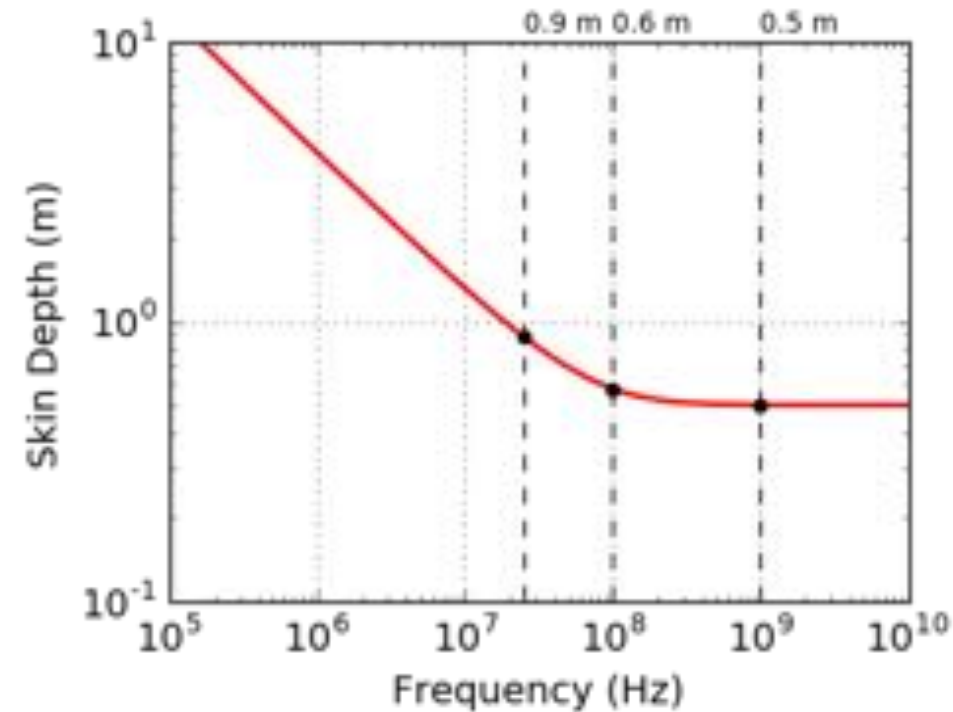
# Physical properties

$$v = \frac{c}{\sqrt{\epsilon}}$$



Material	$\epsilon_r$	$V_{avg}$ (m/ns)	$\sigma$ (ms/m)	Penetration Depth (m)
Air	1	3	0	$\infty$
Fresh Water	80	0.033	0.5	285
Sea Water	80	0.01	3000	< 0.1
Ice	3 - 4	0.16	0.01	3000
Dry Sand	3 - 5	0.15	0.01	3200
Saturated Sand	20 - 30	0.06	0.1 - 1	145
Limestone	4 - 8	0.12	0.5 - 2	30
Shales	5 - 15	0.09	1 - 100	1
Silts	5 - 30	0.07	1 - 100	1.3
Clays	5 - 40	0.06	2 - 1000	0.2
Granite	4 - 6	0.13	0.01 - 1	65
Anhydrites	3 - 4	0.13	0.01 - 1	55

# Attenuation: Skin Depth



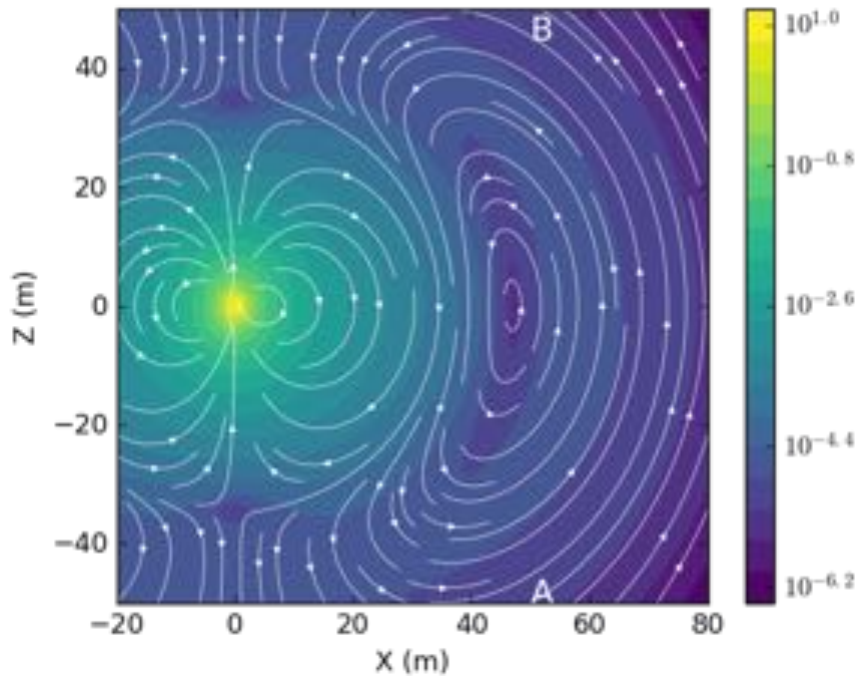
$\delta$  : skin depth

$$\delta \approx \begin{cases} 503 \sqrt{\frac{1}{\sigma f}} & \text{for } \omega \epsilon \ll \sigma \\ 0.0053 \frac{\sqrt{\epsilon_r}}{\sigma} & \text{for } \sigma \ll \omega \epsilon \end{cases}$$

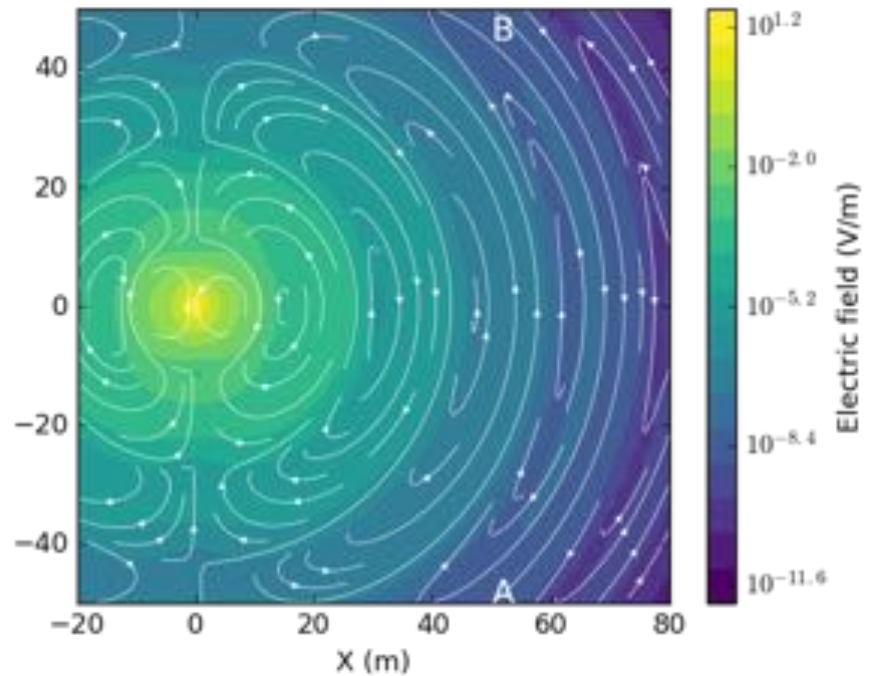


# Electric Dipole in a Whole Space

$10^5$  Hz



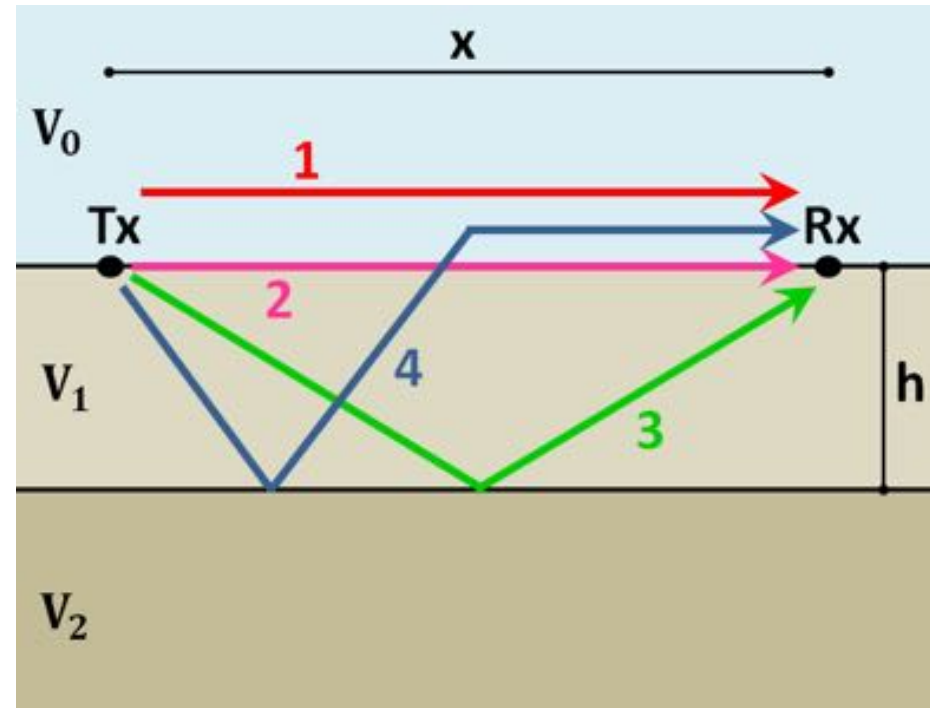
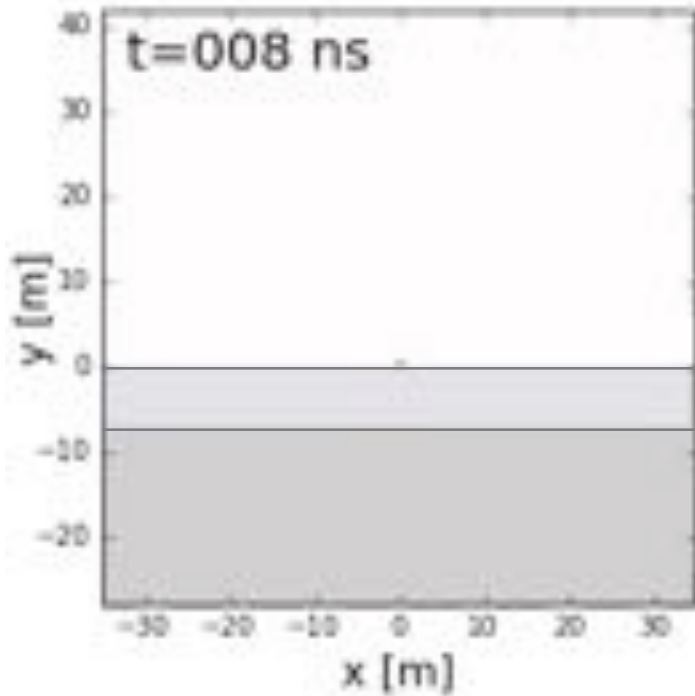
$10^6$  Hz



$$\lambda = \frac{v}{f}$$

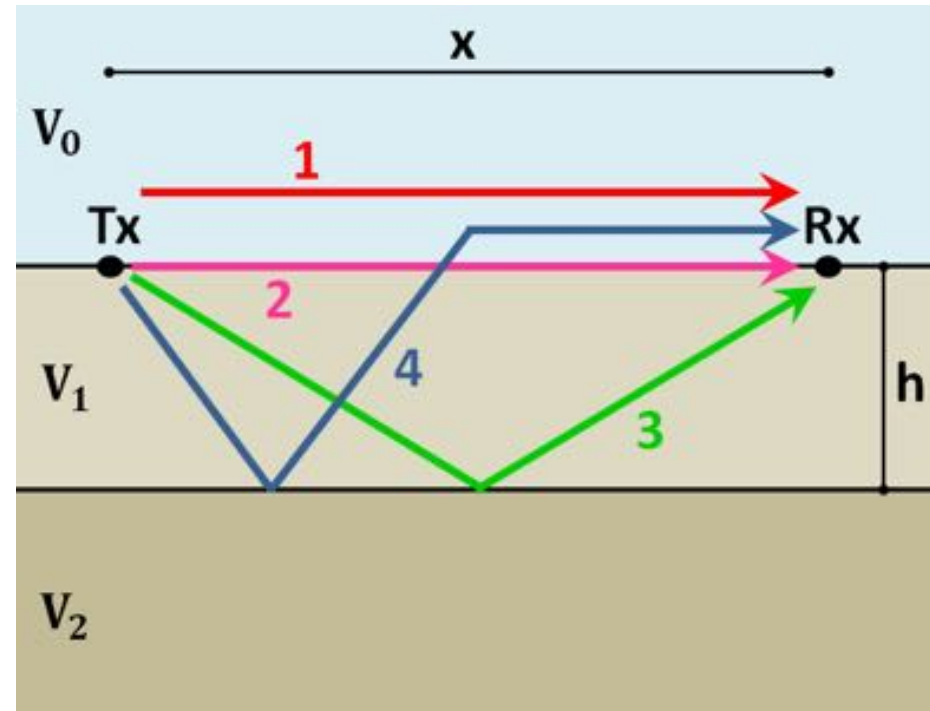
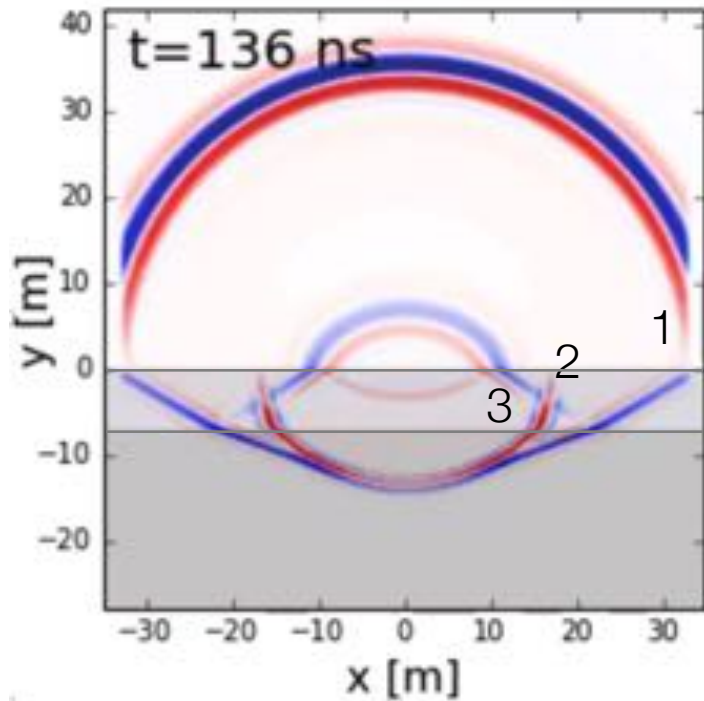
# Waves and Rays

$$v = \frac{c}{\sqrt{\epsilon}}$$



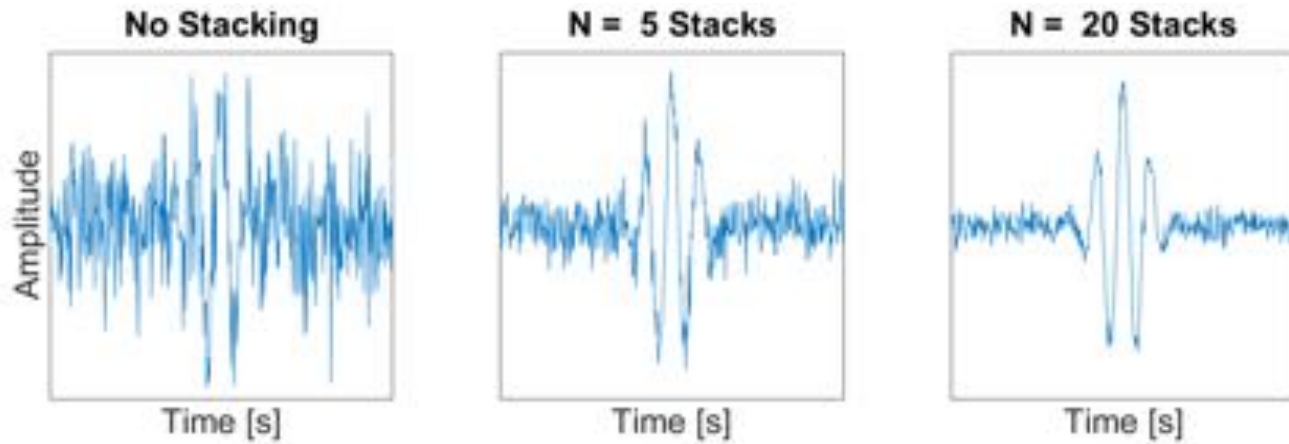
# Waves and Rays

$$v = \frac{c}{\sqrt{\epsilon}}$$

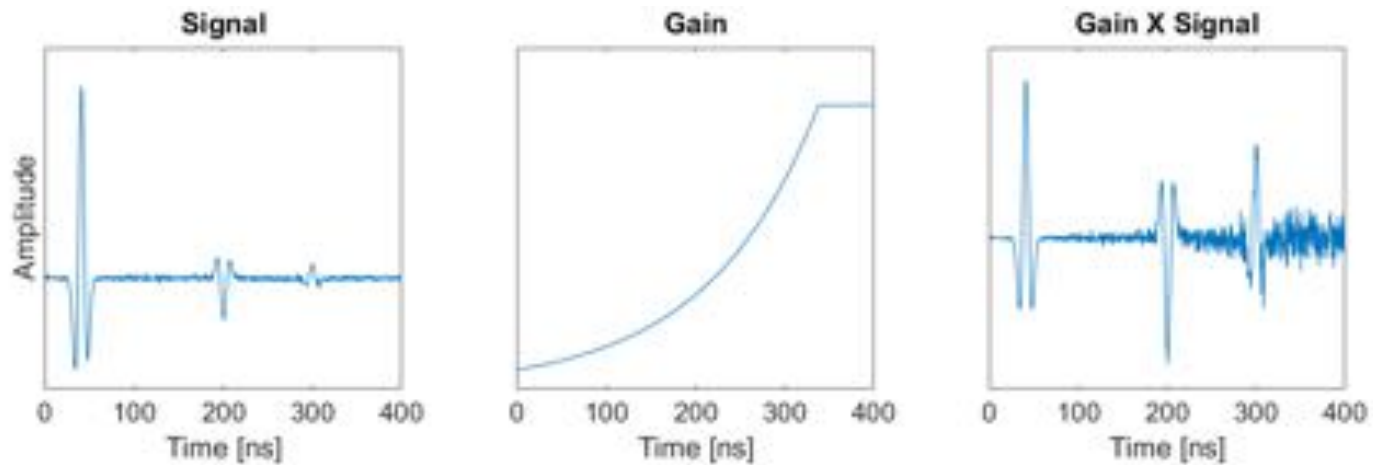


# Processing

## Stacking

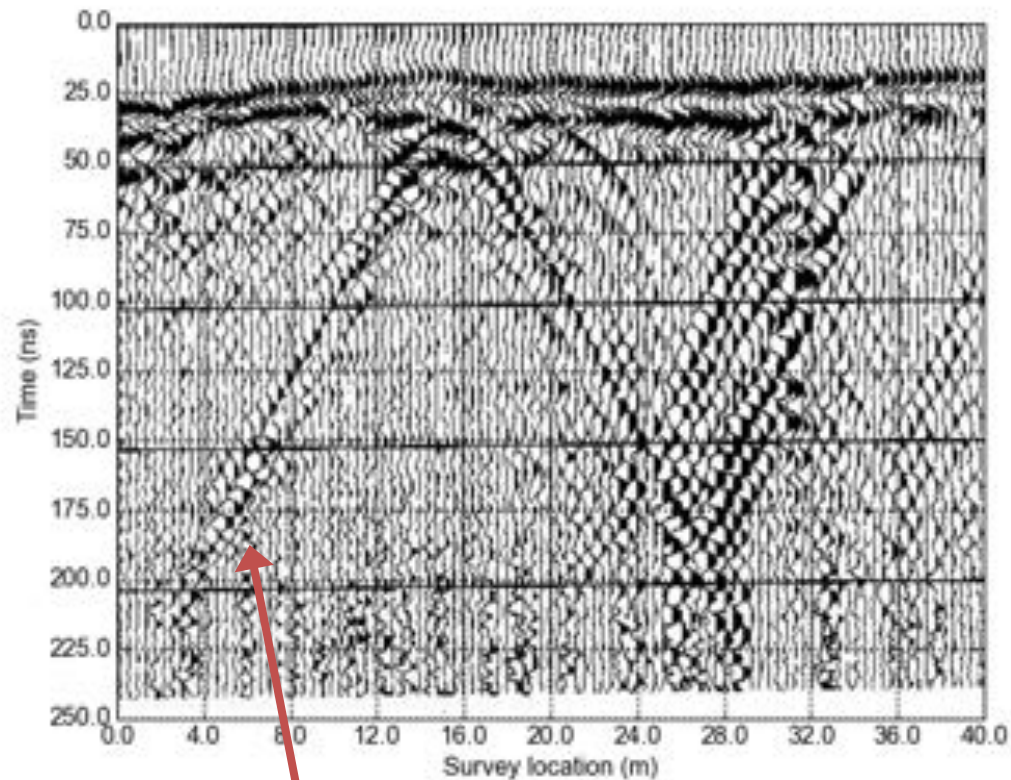
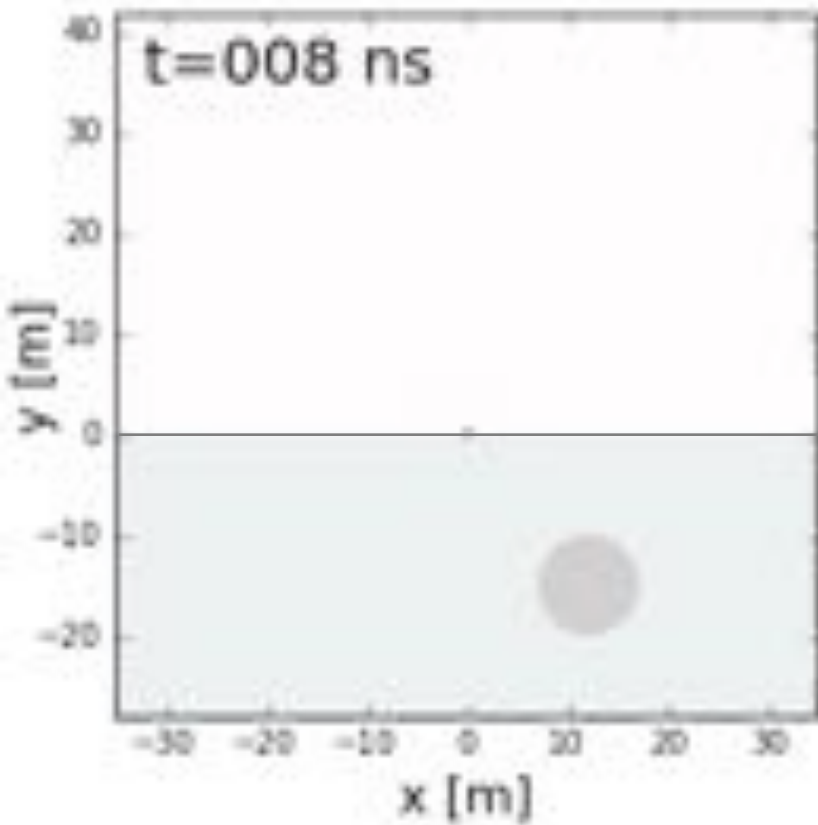


## Gain Control



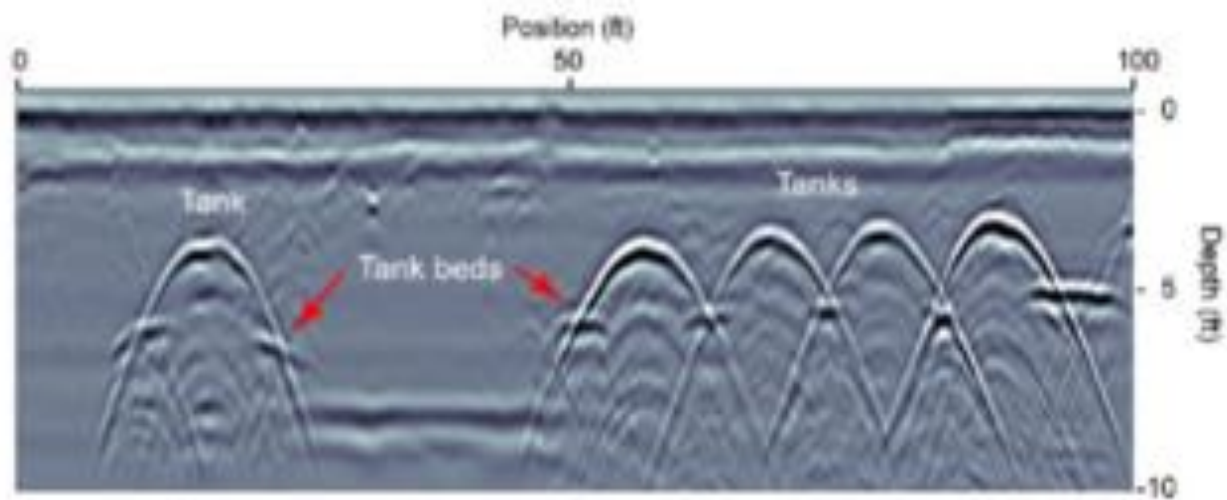
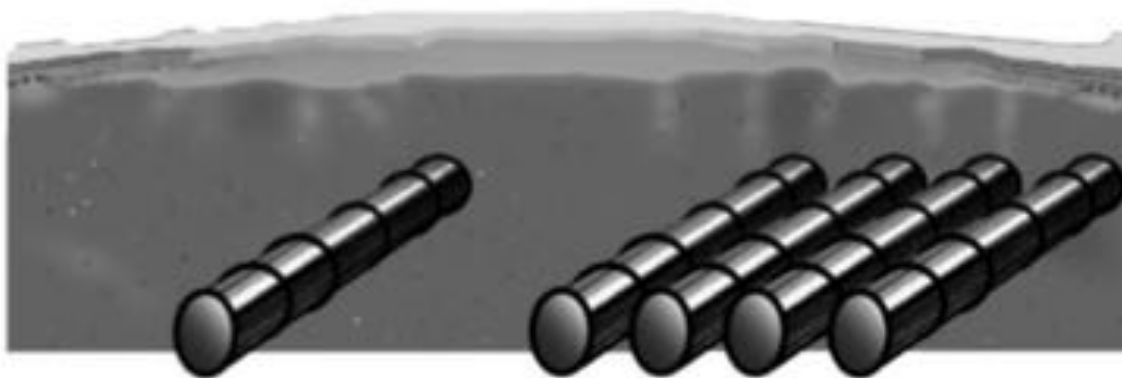
# Radargrams

$$v = \frac{c}{\sqrt{\epsilon}}$$



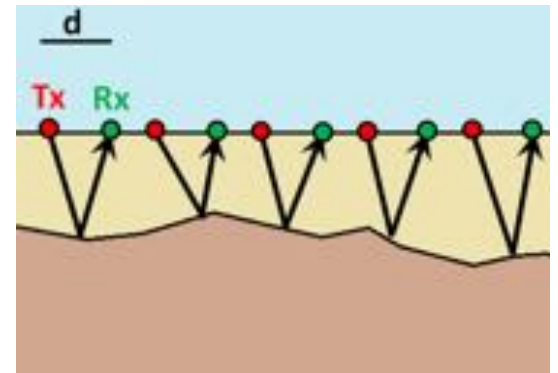
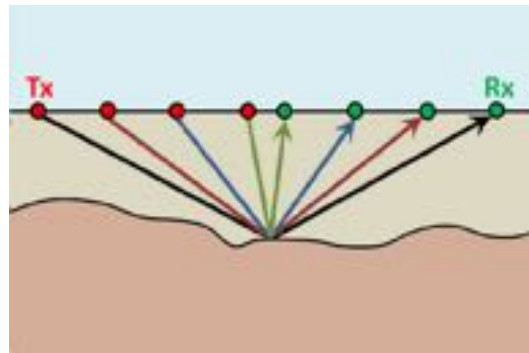
Hyperbola  
slope  $\sim 2/v$

# Radargrams





# GPR systems



# Outline

- Basic experiment
- Physical property
- Physics
- Data and Processing
  
- Questions?
  
- Case history: rock glacier

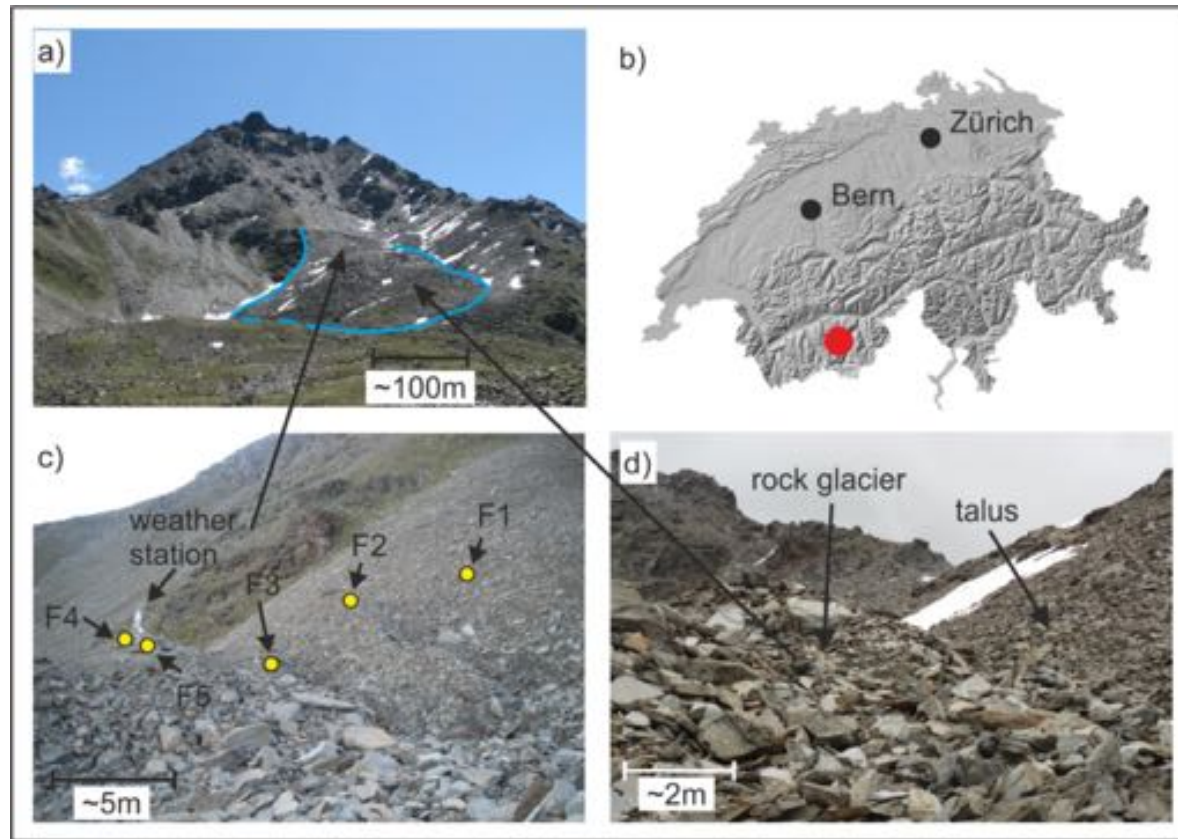


# Case History: Furggwanhorn

Merz et al, 2015

# Setup

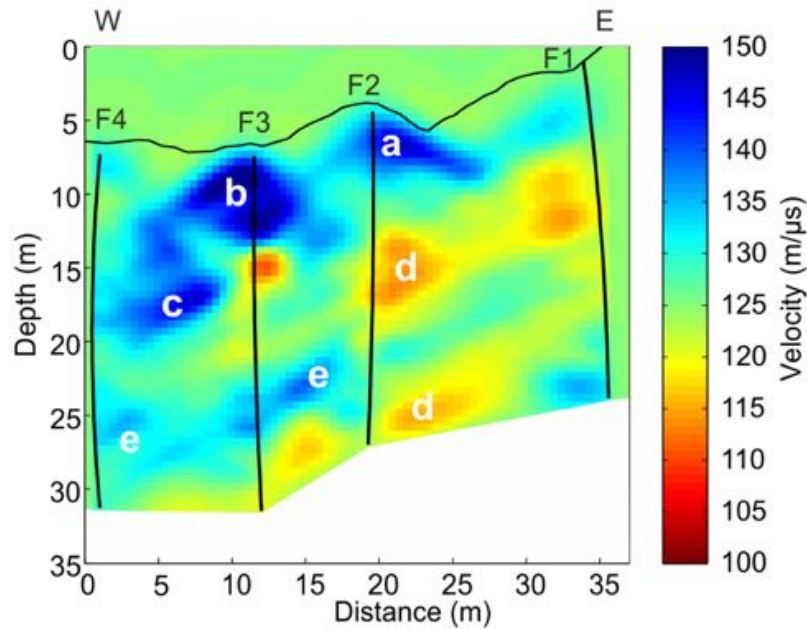
- Downslope movement shown to increase from 1.5 m/yr to 4.0 m/yr.
- Aim: characterize rock units and evolution of glacier
- Surface GPR: unsuccessful (too close to scatterers)
- Helicopter GPR used



# Properties

$$v = \frac{c}{\sqrt{\epsilon}}$$

Velocity from cross well GPR



Material	Velocity (m/μs)
(a & b) Unconsolidated sediments	> 140
(c) Ice	> 140
(d) Ice + partial melt	110 - 130
(e) Compact debris	130 - 140
Saturated sediments	80 - 100
Bedrock	110 - 130

# Survey

- Initial Ground-Based Survey
  - 2 systems
  - Frequencies: 25 MHz and 50 MHz
- Heli-GPR
  - Frequency: 60 MHz
  - Flight height: 15-20 m
  - Line separation ~15 m

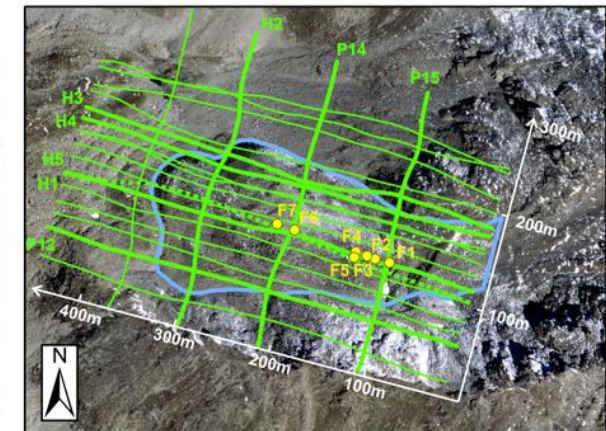
Ground-GPR



Heli-GPR

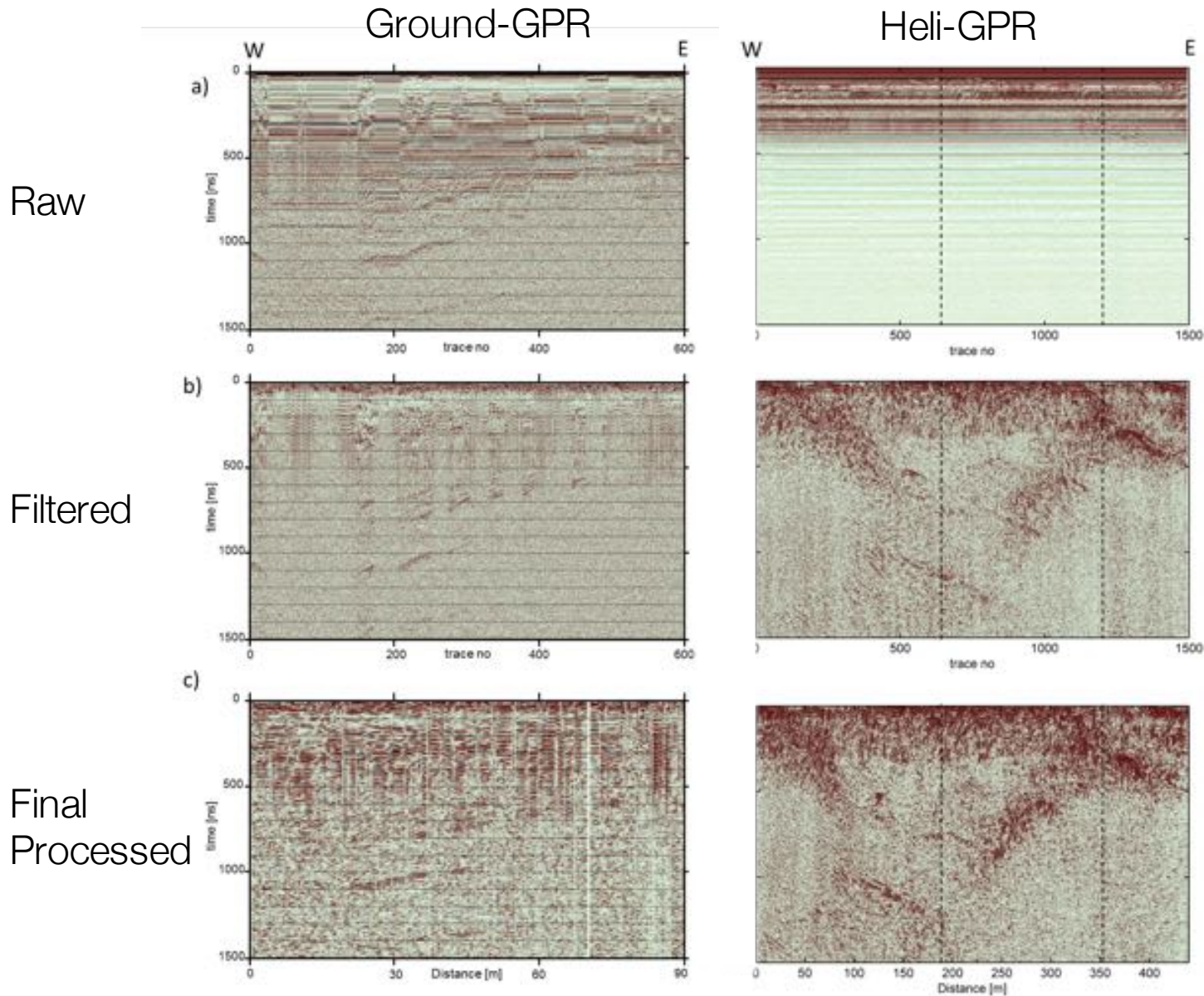


Survey lines

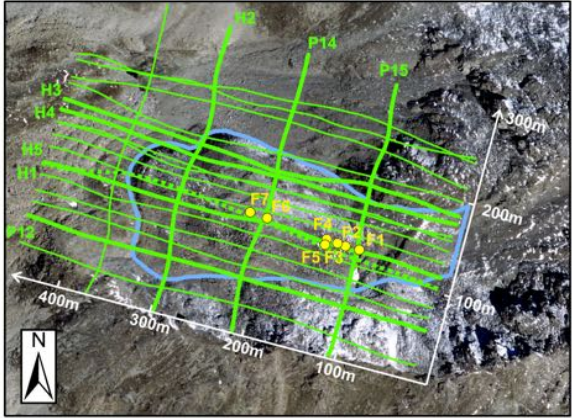




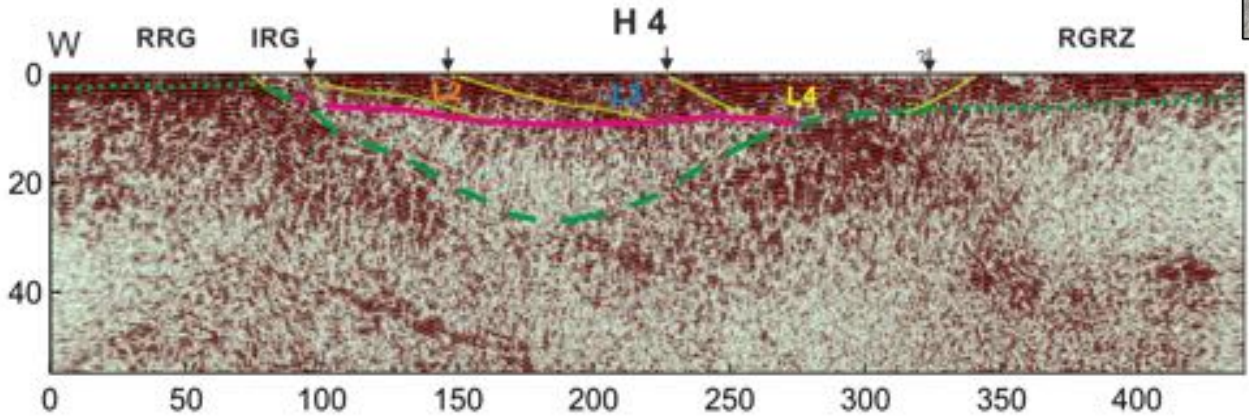
# Data and Processing



# Interpretation

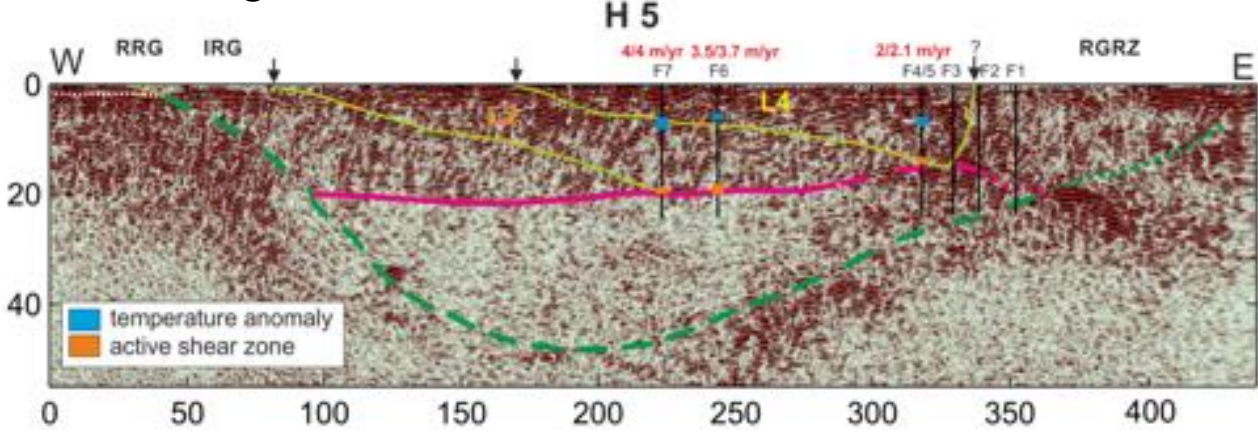


Profile along line H4



- Bedrock surface
- Major shear zone between ice-rich and ice-poor regions
- Fault zone boundaries of rock lobes

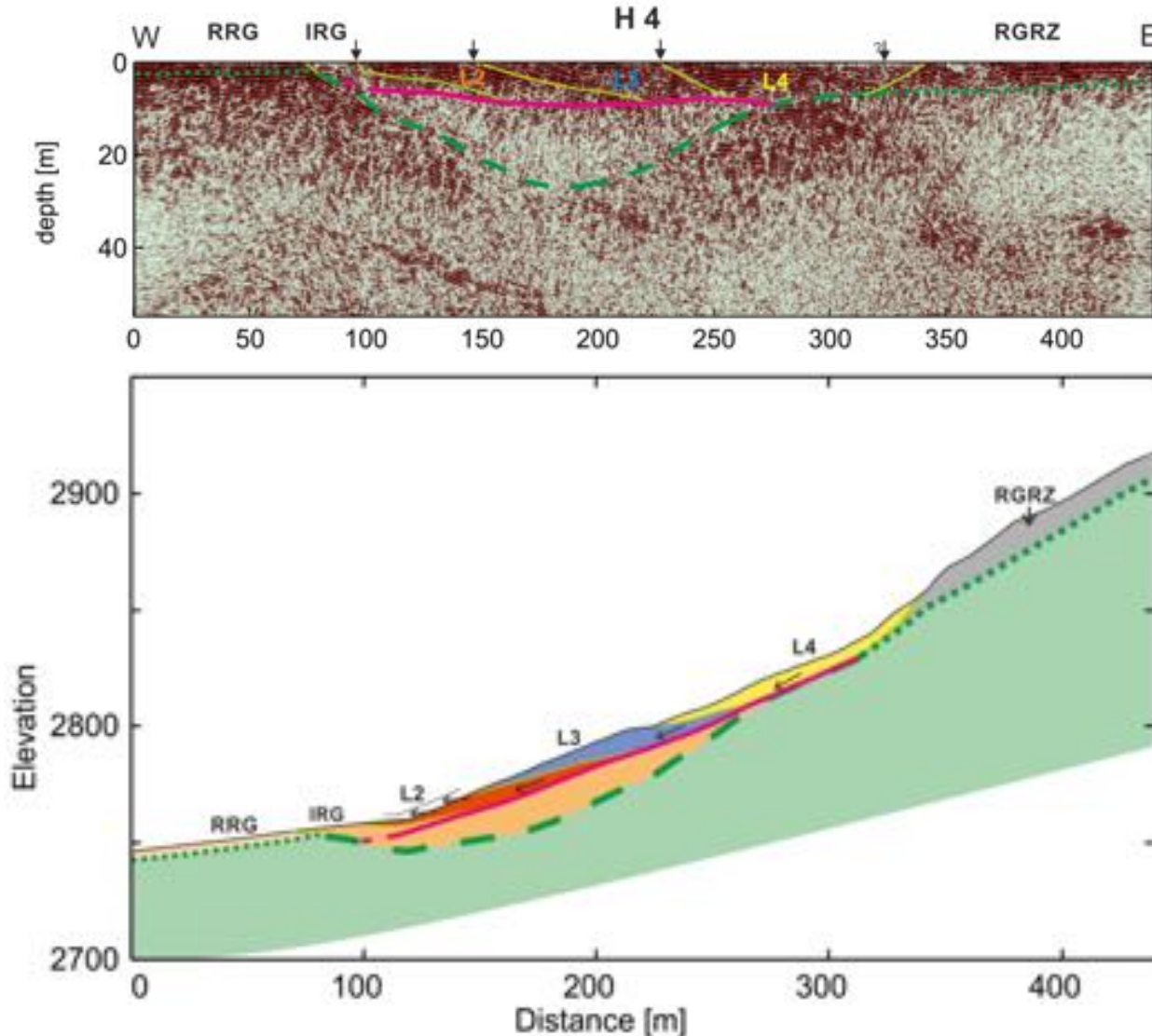
Profile along line H5





# Synthesis

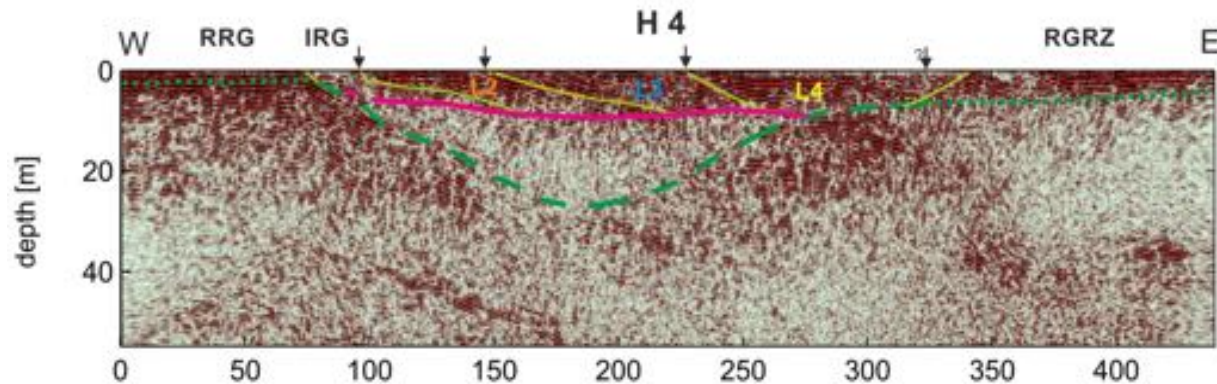
## Final Structural and Kinematic Model



- Interpreted with thin-skinned tectonic model
- Major shear zone acts as a décollement
- Rock glacier lobes act as nappes
- Lobes appear to move down-slope
- Tectonic model applicable to other glaciers

# Summary

- Basic experiment
- Physical property
- Physics
- Data and Processing
- Case history: rock glacier





# End of GPR

