

# Ground Penetrating Radar

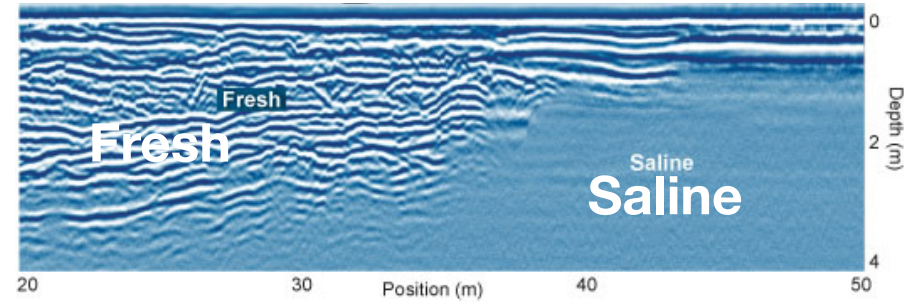


# Motivation

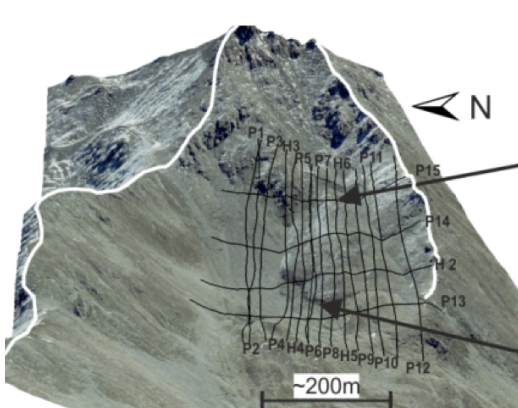
Sink holes



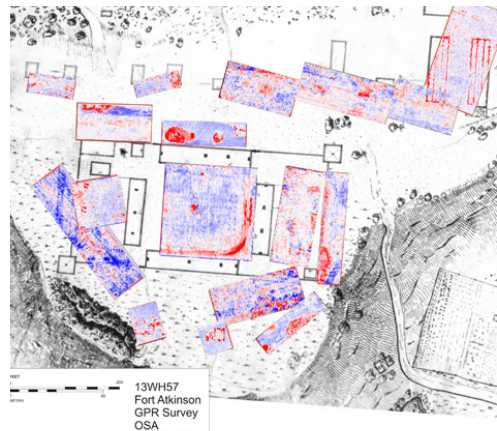
Salt Water Intrusions



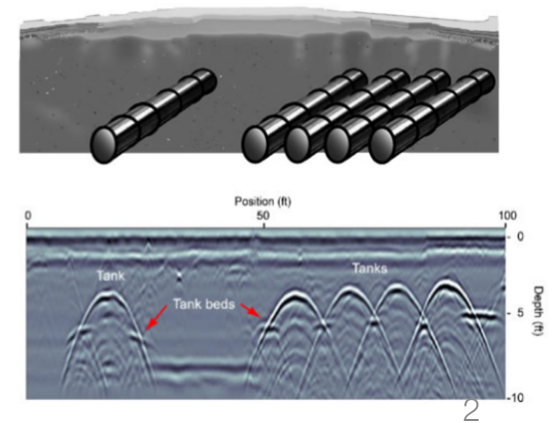
Rock glacier



Archeology



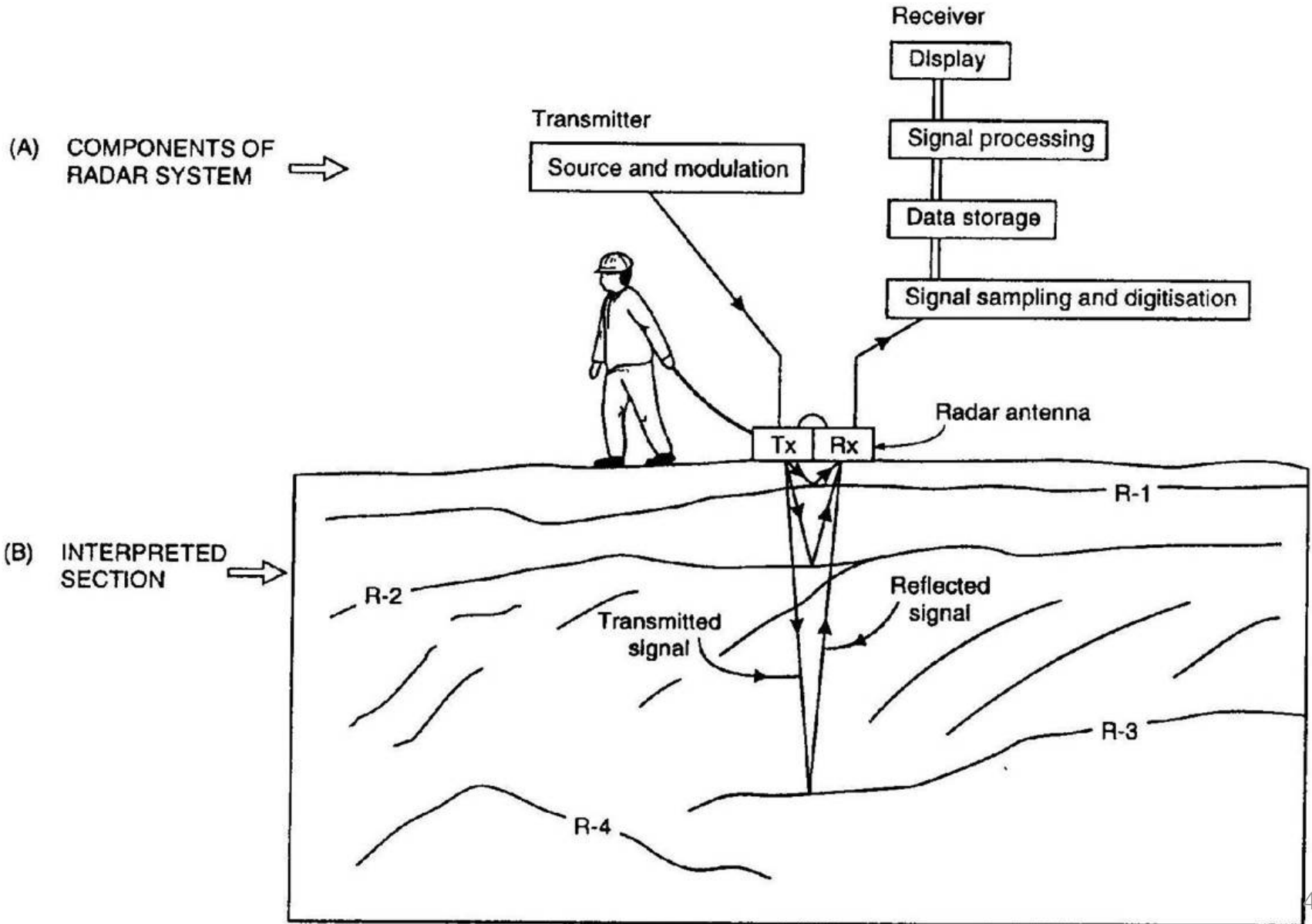
Underground tank



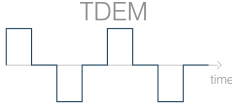
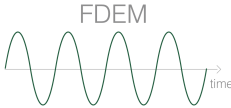
# Outline

- Basic experiment
- Physical property
- Physics
- Data and Processing
- Field examples
- Driverless Vehicles
- 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

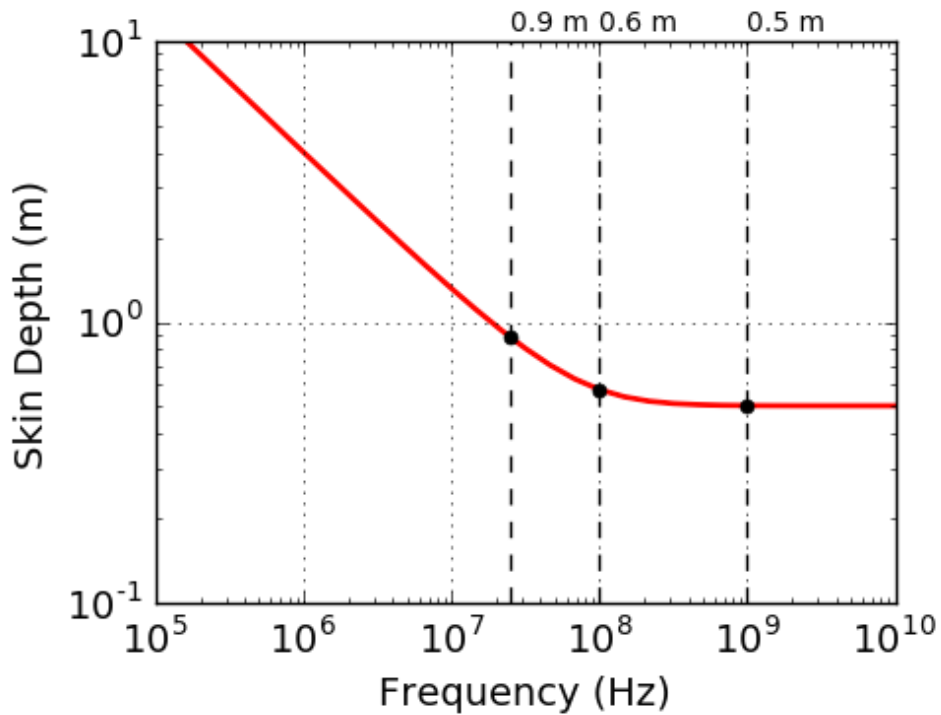
$$\begin{aligned}\nabla^2 \mathbf{H} + k^2 \mathbf{H} &= 0 \\ k^2 &= \omega^2 \mu \epsilon - i \omega \mu \sigma\end{aligned}$$

# 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



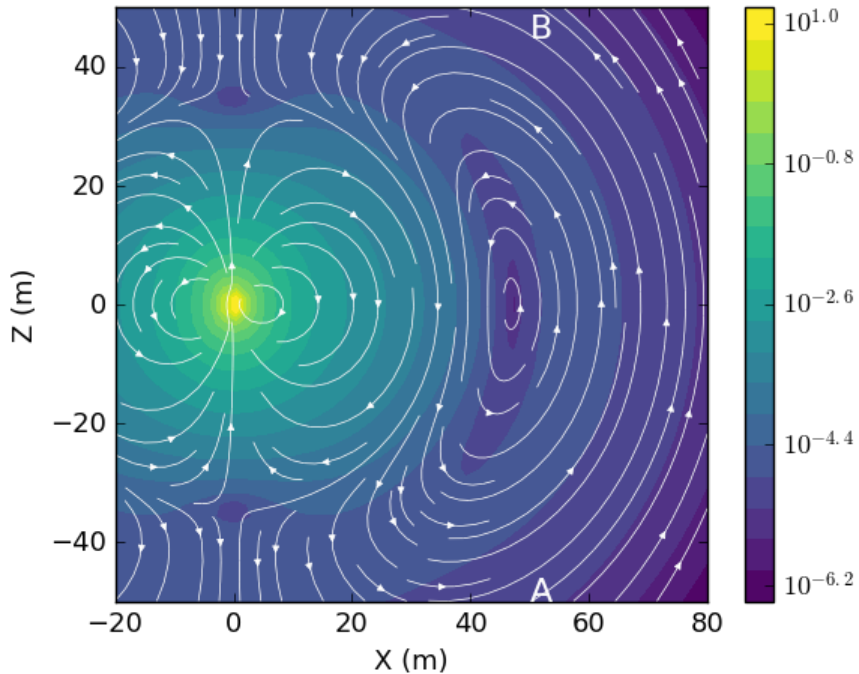
$\delta$  : skin depth

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

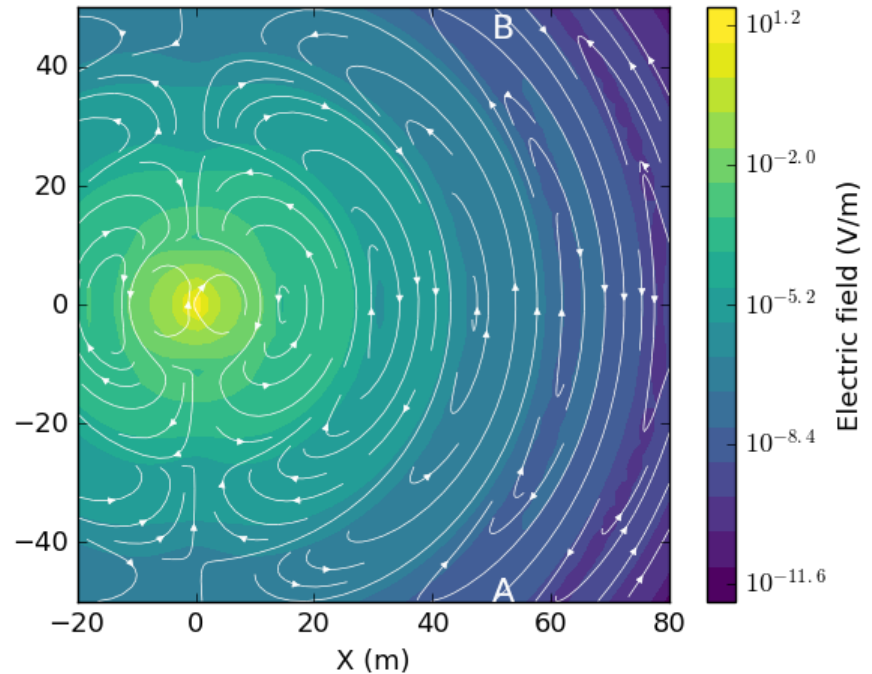


# Electric Dipole in a Whole Space

$10^5$  Hz



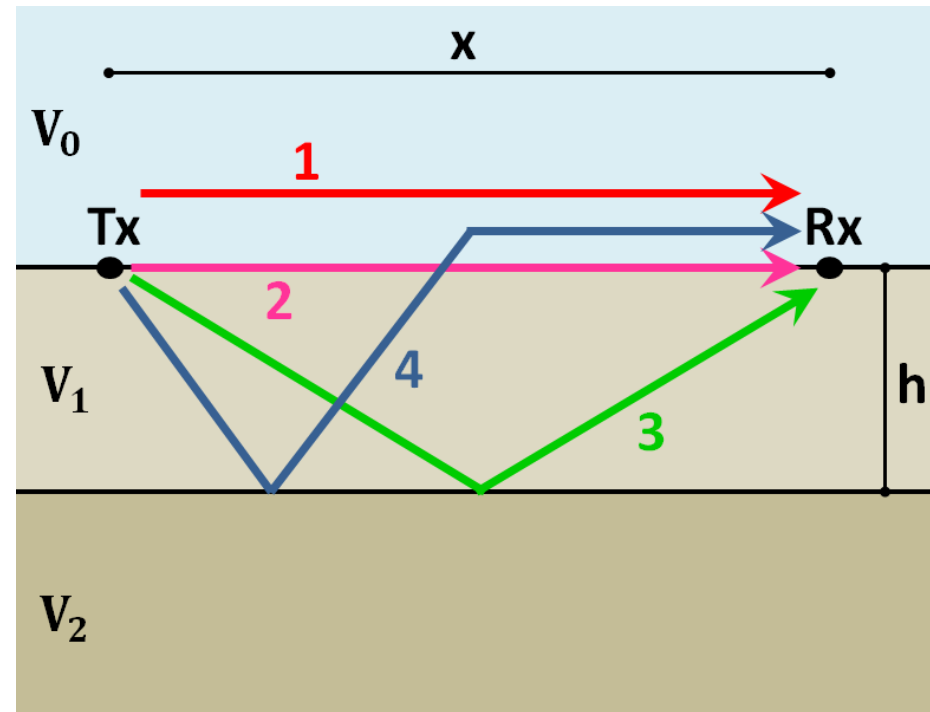
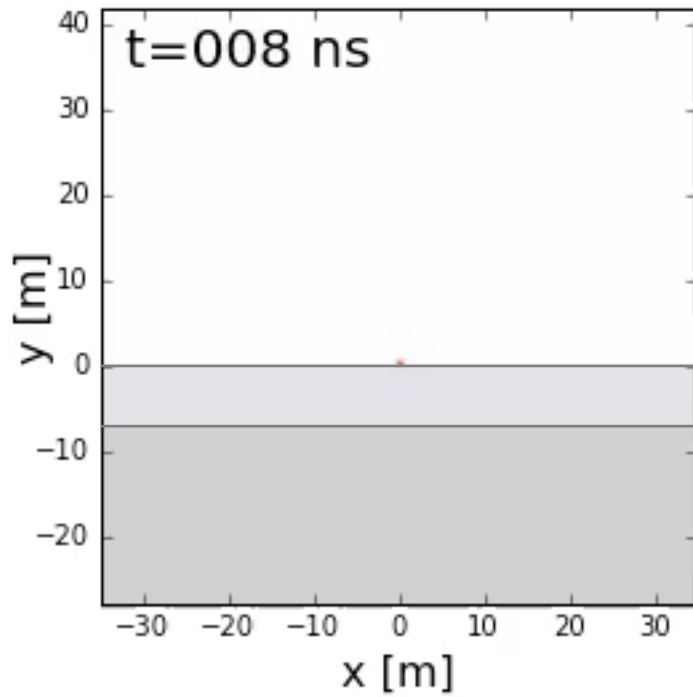
$10^6$  Hz



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

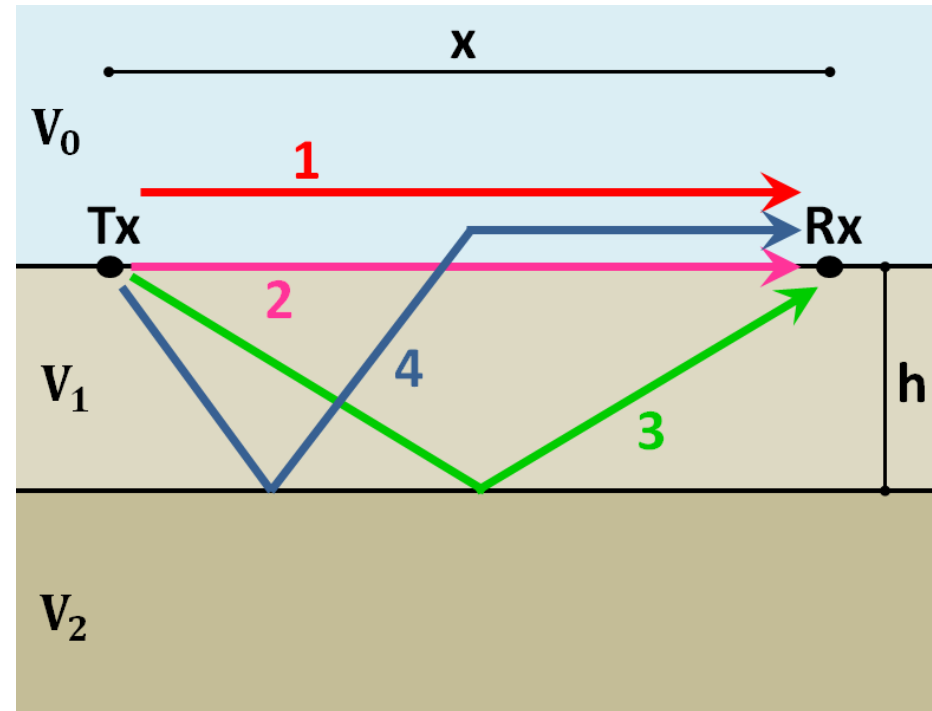
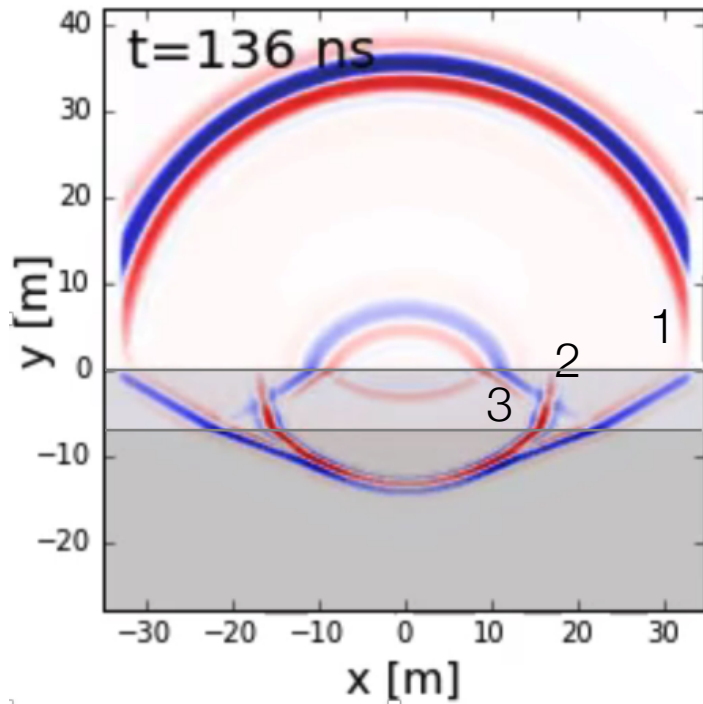
# Waves and Rays

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



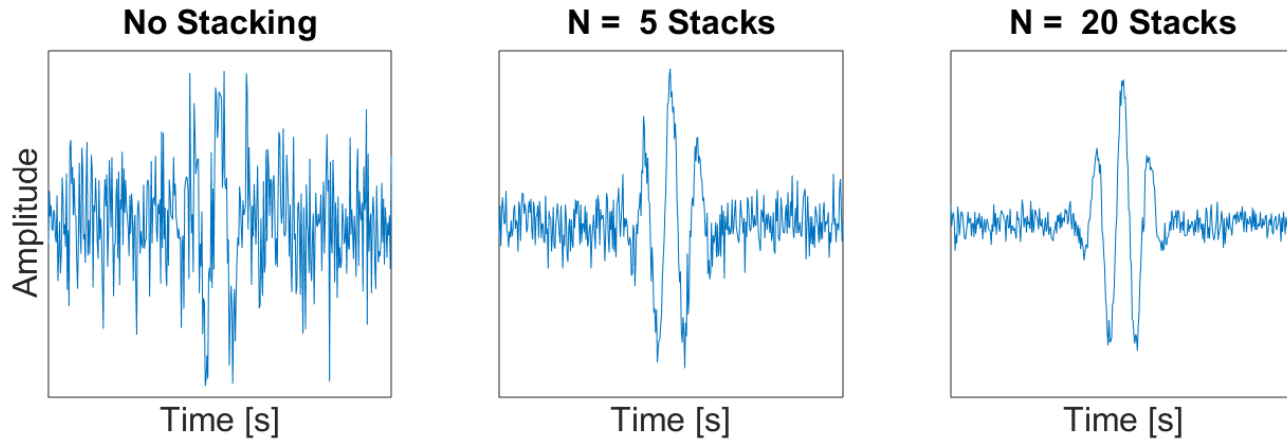
# Waves and Rays

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

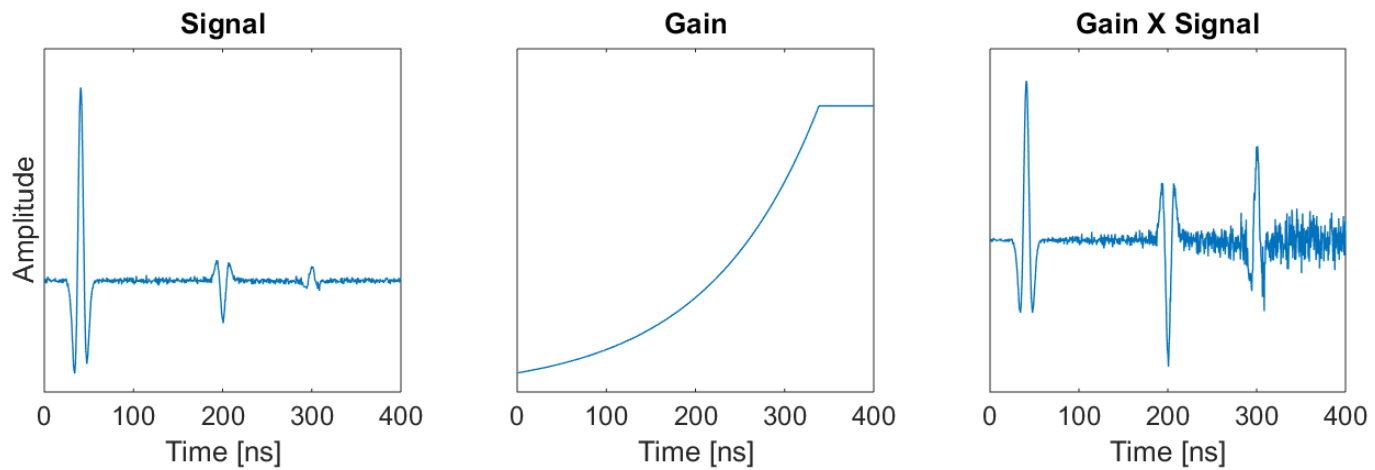


# Processing

## Stacking

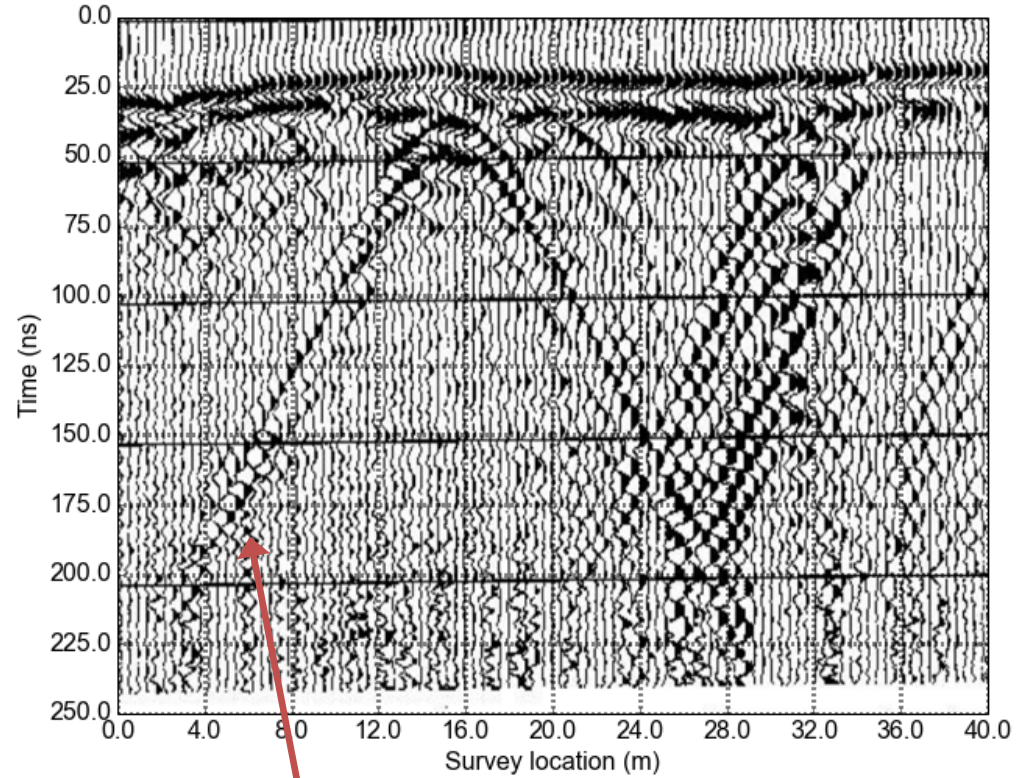
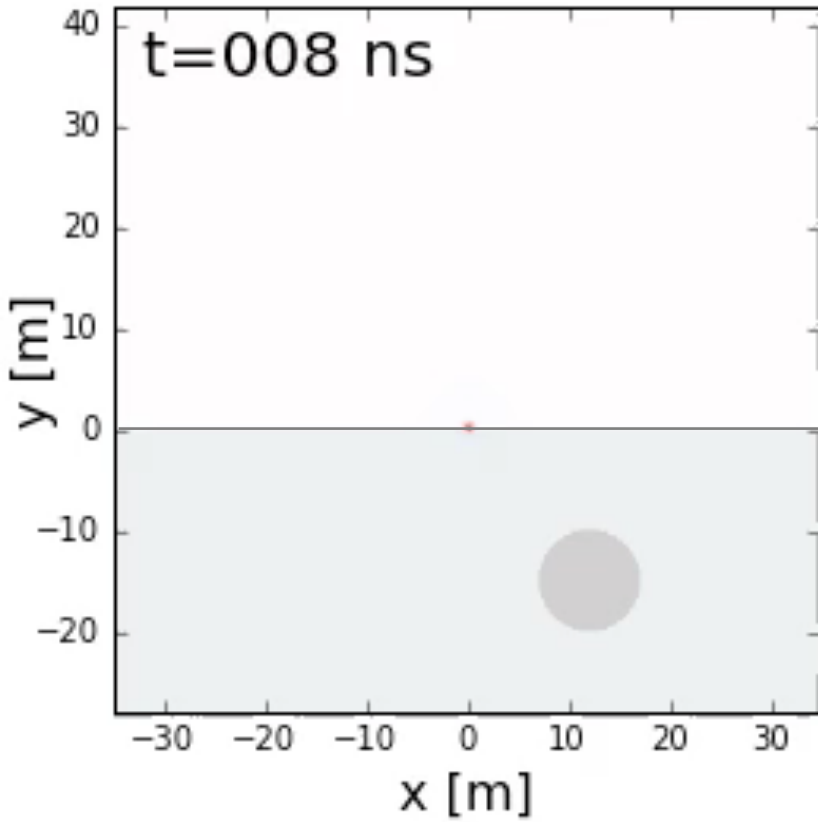


## Gain Control



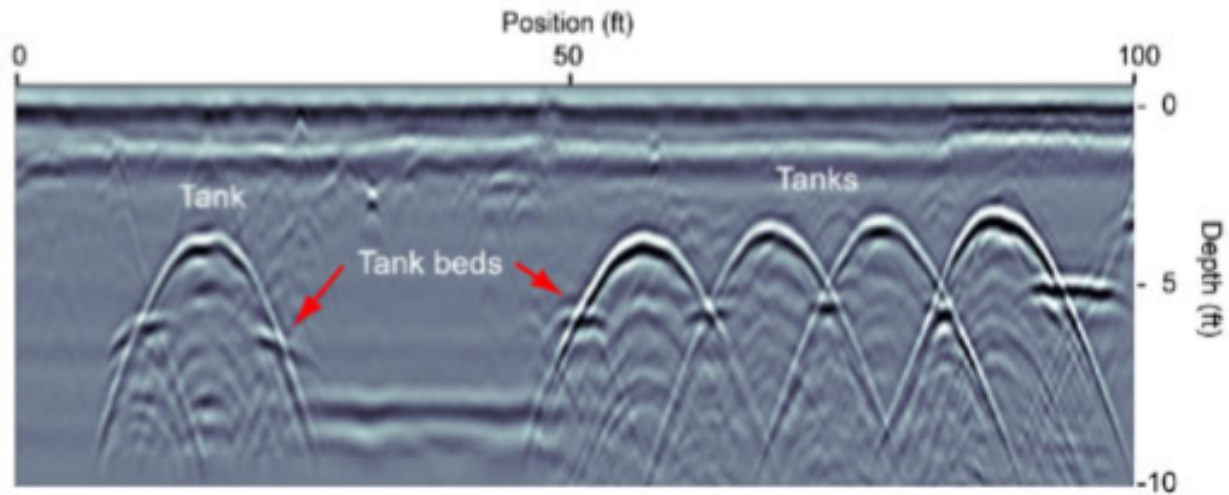
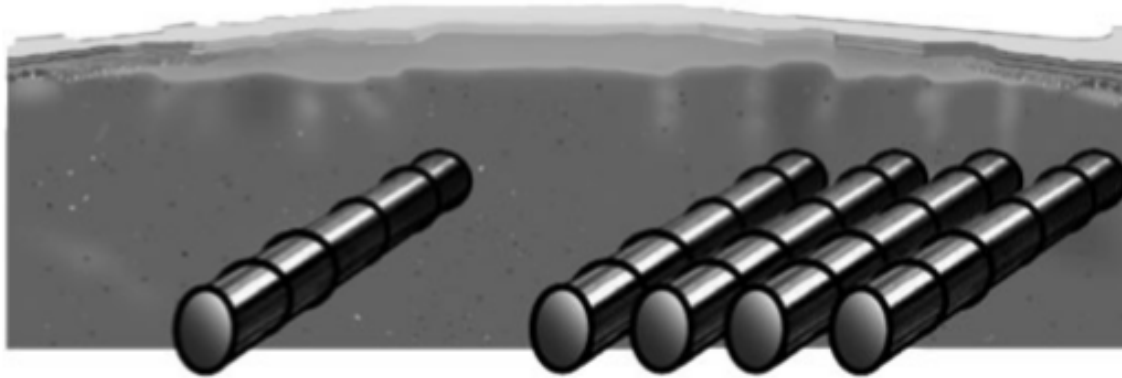
# Radargrams

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

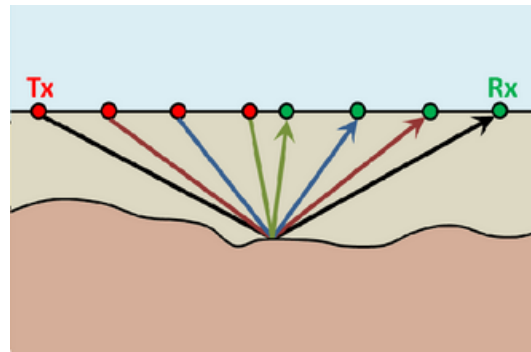


Hyperbola  
slope  $\sim 2/v$

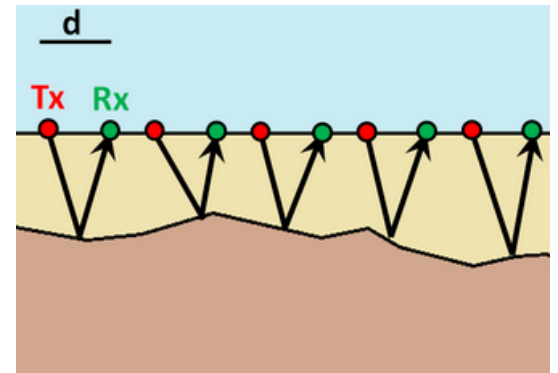
# Radargrams



# GPR systems



Common midpoint



Common offset

# Outline

- Basic experiment
- Physical property
- Physics
- Data and Processing
  
- Questions?
  
- Field examples
- Driverless Vehicles
- Case History: Rock Glacier



# Environmental Test Survey

## Problem

- Characterize soil and identify potential aquifers

## Why use GPR?

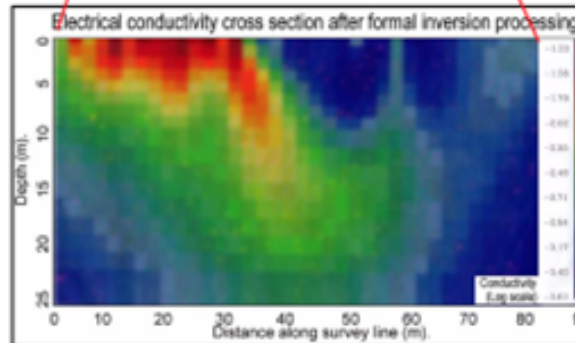
- Dielectric permittivity varies with
  - Water content
  - Lithologies

## Survey and Data

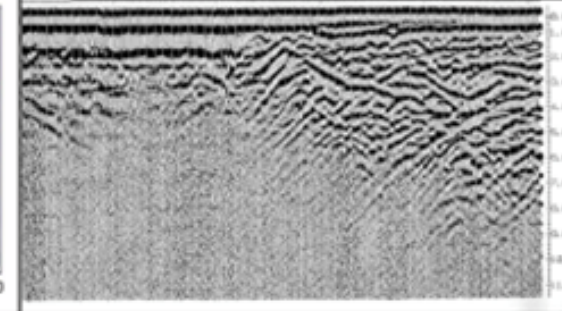
- Zero offset data colocated with DC resistivity

## Processing and Interpretation

- Attenuation of GPR signals on western side: higher conductivity
- Near surface structure from reflecting events



Ground penetrating radar cross-section



# Locating Underground Storage Tanks

## Problem

- Locate buried storage tanks and tank beds

## Why use GPR?

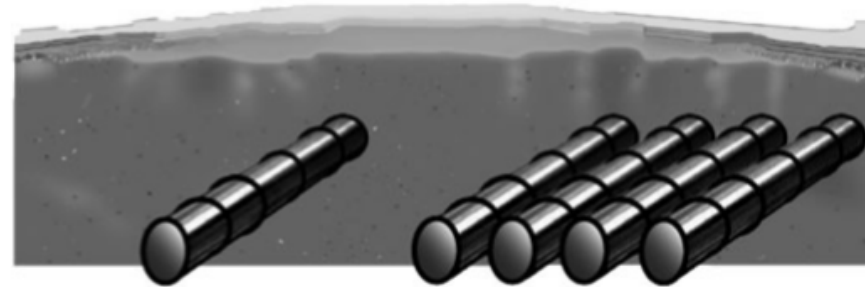
- Conductive tanks, tank beds are strong reflectors

## Survey and Data

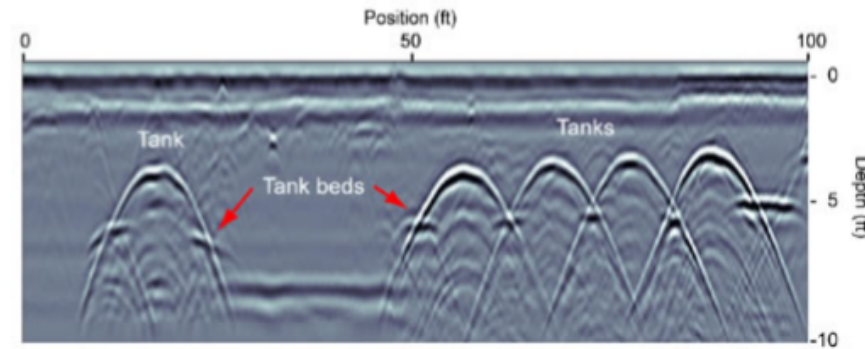
- Zero offset data (250 MHz)

## Processing and Interpretation

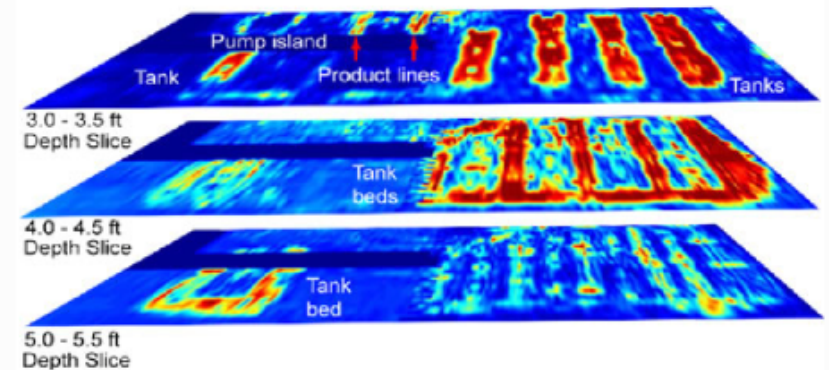
- Hyperbolic signatures from tanks
- Flat tank-bed reflectors
- 3D image constructed from radargrams



*Fig. Geophysical problem*



*Fig. 2D Radargram profile perpendicular to storage tanks*



*Fig. 129 3D interpolation from several GPR survey lines.*

# Mapping Peat Thickness

## Problem

- Estimate peat thickness

## Why use GPR?

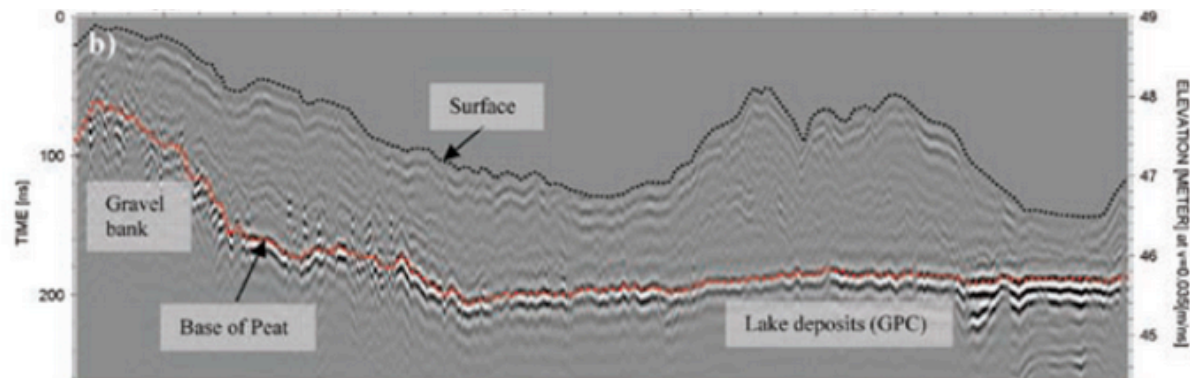
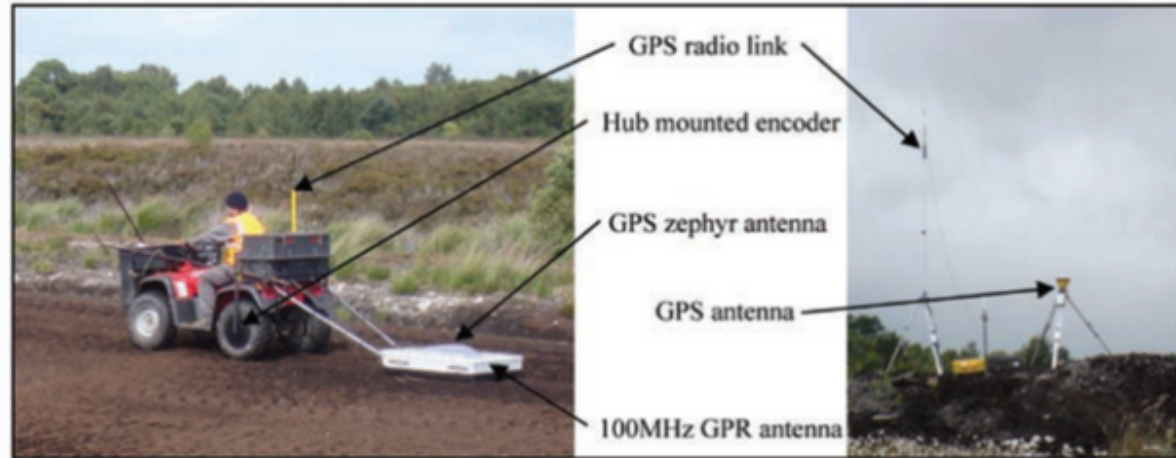
- Strong reflector at base of the peat

## Survey and Data

- Zero offset data (100 MHz)
- Profiles every 60m
- LIDAR collected for local topography

## Processing and Interpretation

- Arrival time to depth conversion
- Topography correction with LIDAR
- Peat layers up to 2m thick
- Additional reflectors indicate internal structure of peat



# Subsurface Utility Mapping

## Problem

- Locate iron-cased water pipes and PVC-cased gas lines at an intersection

## Why use GPR?

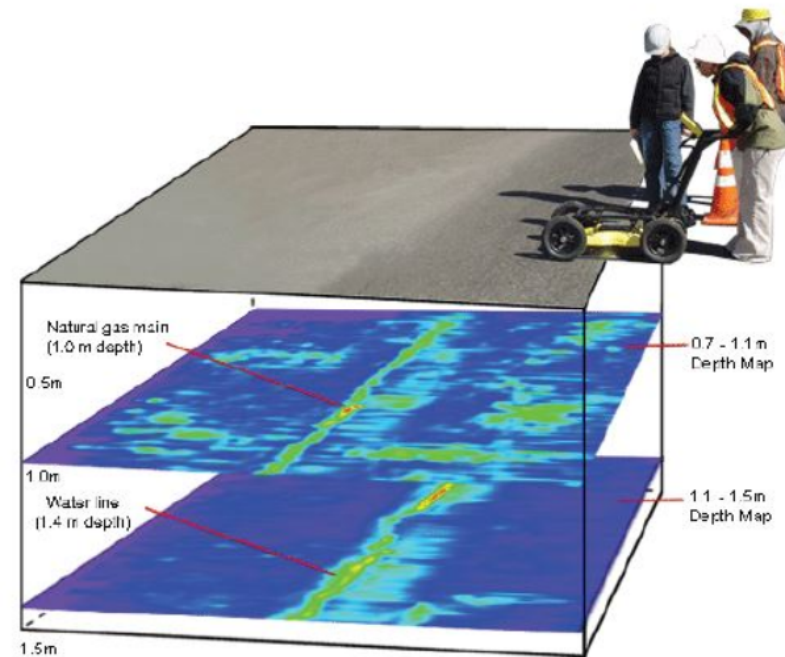
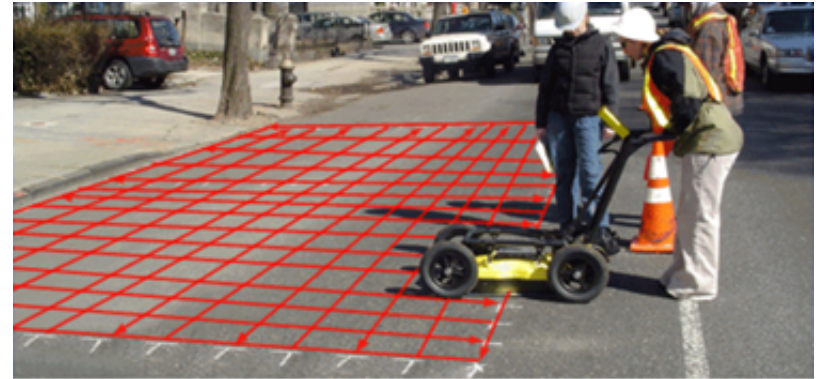
- Iron pipes very conductive → strong GPR reflector
- PVC v. low dielectric permittivity → GPR reflector

## Survey and Data

- Zero offset data (250 MHz)
- 0.5m line spacing, 8m x 23m grid

## Processing and Interpretation

- Arrival time to depth conversion
- Natural gas main at 1m depth
- Water line at 1.4m depth



# Underground Potash mines

## Problem

- Locate water/brine leaking into potash mine

## Why use GPR?

- Potash has low relative permittivity ( $\sim 5$ ).
- Water/brine has high dielectric permittivity ( $\sim 80$ ).

## Survey and Data

- Zero offset data along mine shaft

## Processing and Interpretation

- Arrival time to depth conversion using velocity of 0.13 m/ns for anhydrites



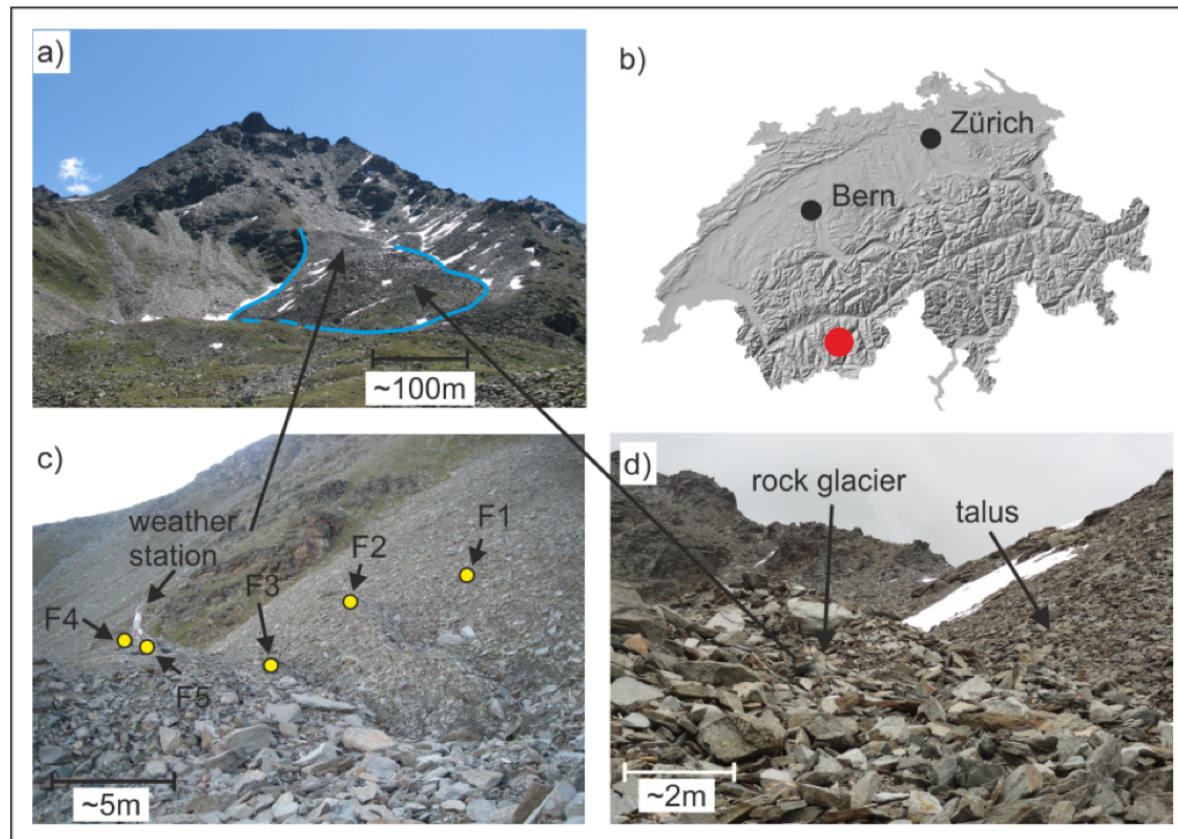
*Fig. Inflow problems in a mine*



*Fig. GPR survey along ceiling of a mine shaft. Courtesy of: <https://www.sensoft.ca/>*

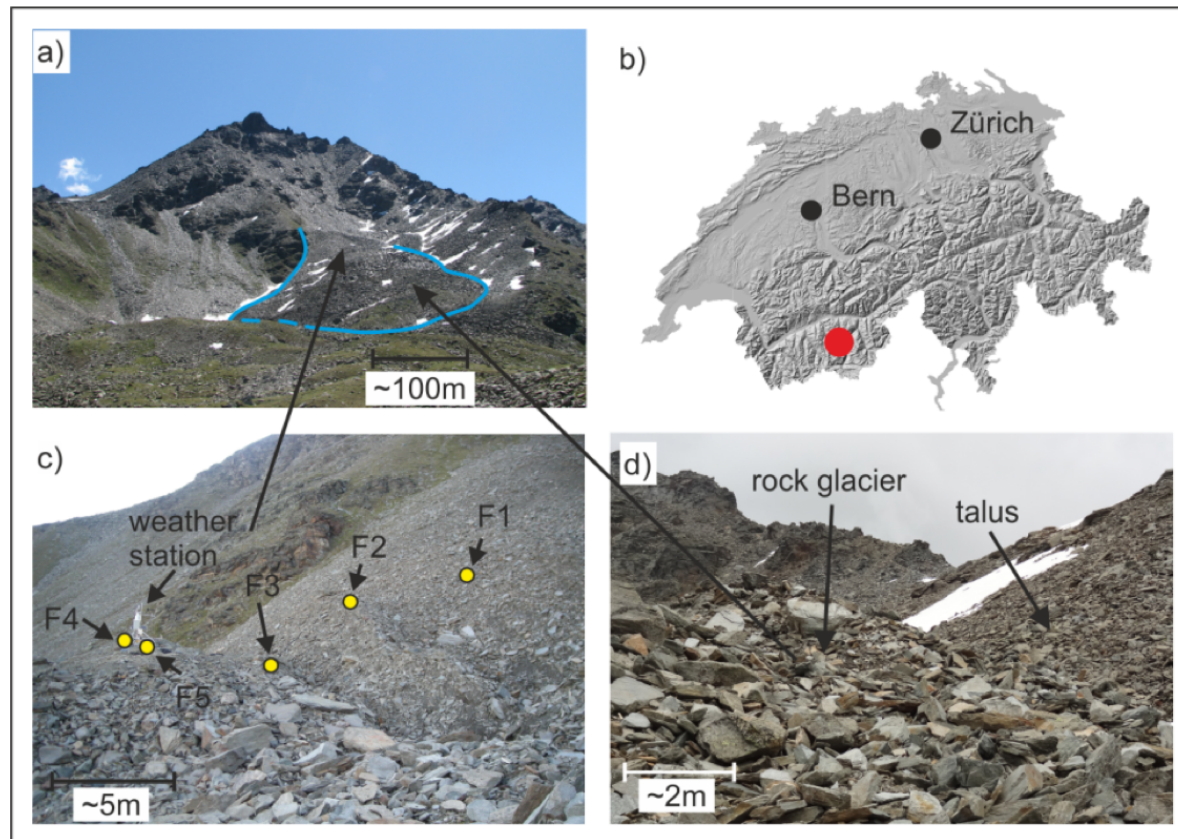
# Case History: Furggwanghorn

Merz et al, 2015



# Setup

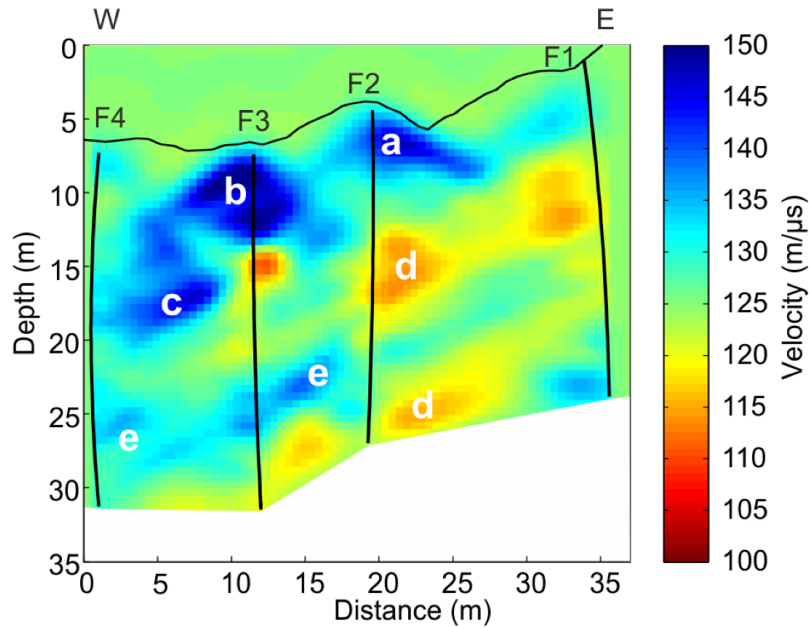
- Downslope movement shown to increase from 1.5 m/yr to 4.0 m/yr.
- Aim: characterize rock units and evolution of glacier
- Surface GPR: unsuccessful (too close to scatterers)
- Helicopter GPR used



# Properties

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

Velocity from cross well GPR



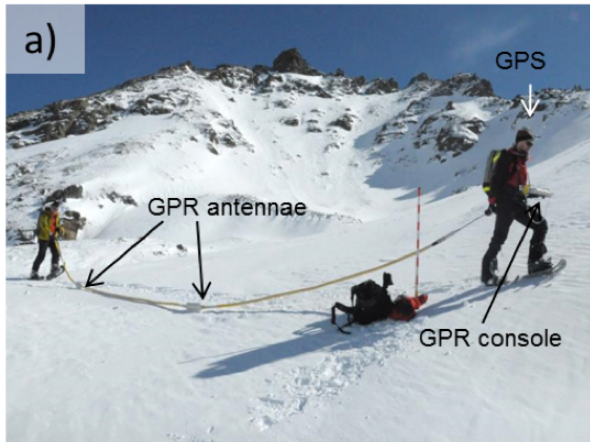
Material	Velocity (m/μs)
(a & b) Unconsolidated sediments	> 140
(c) Ice	> 140
(d) Ice + partial melt	110 - 130
(e) Compact debris	130 - 140
Saturated sediments	80 - 100
Bedrock	110 - 130



# 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

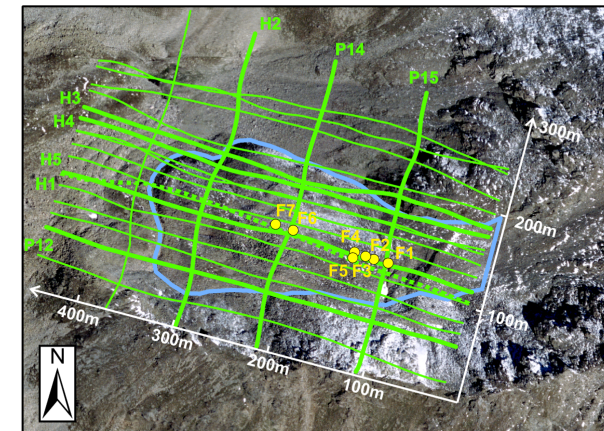
Ground-GPR



Heli-GPR

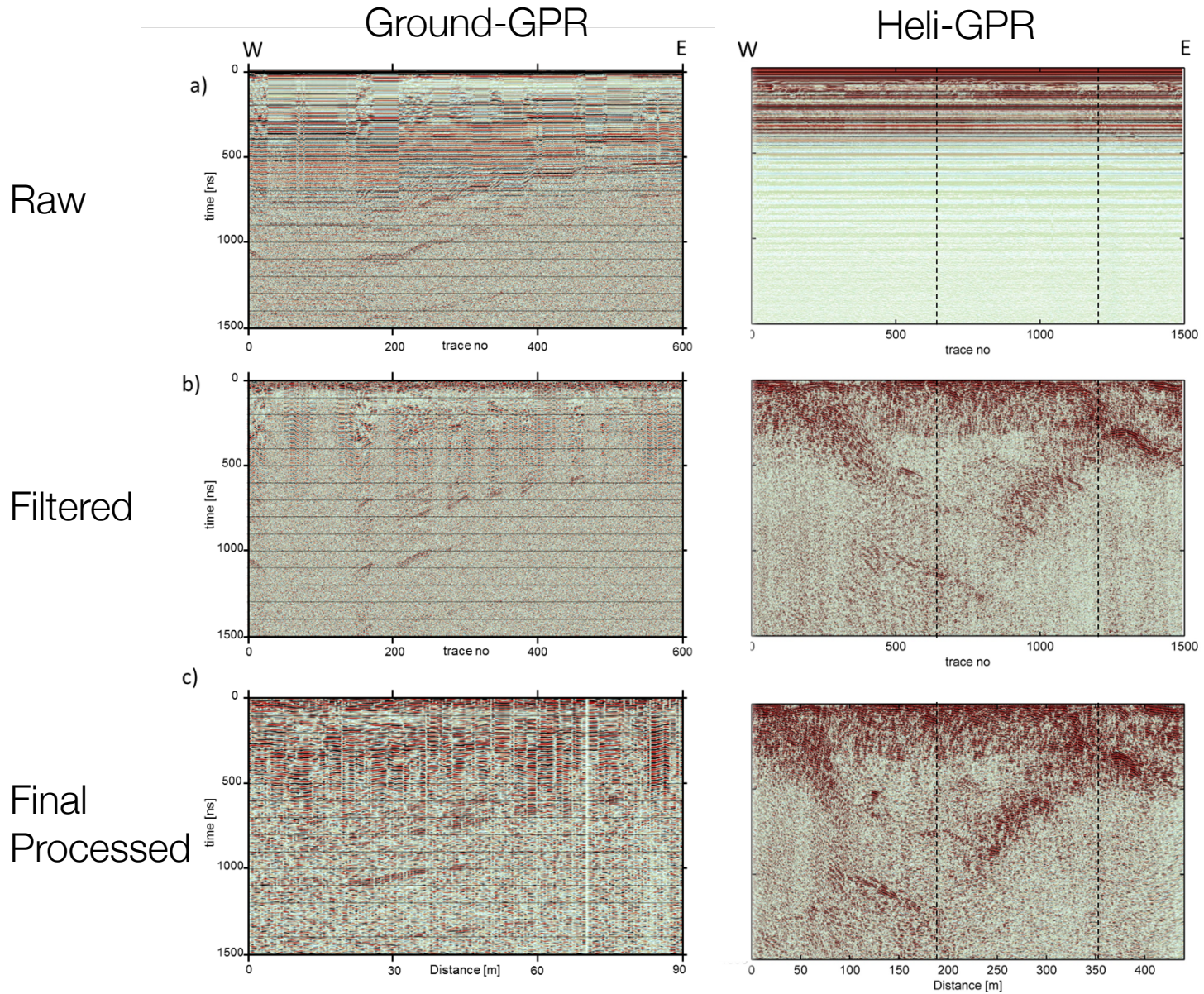


Survey lines

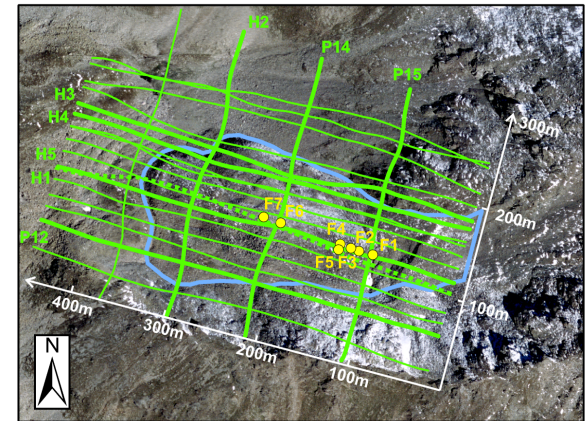


- Helicopter GPR Profiles
- Rock Glacier Outline
- Boreholes

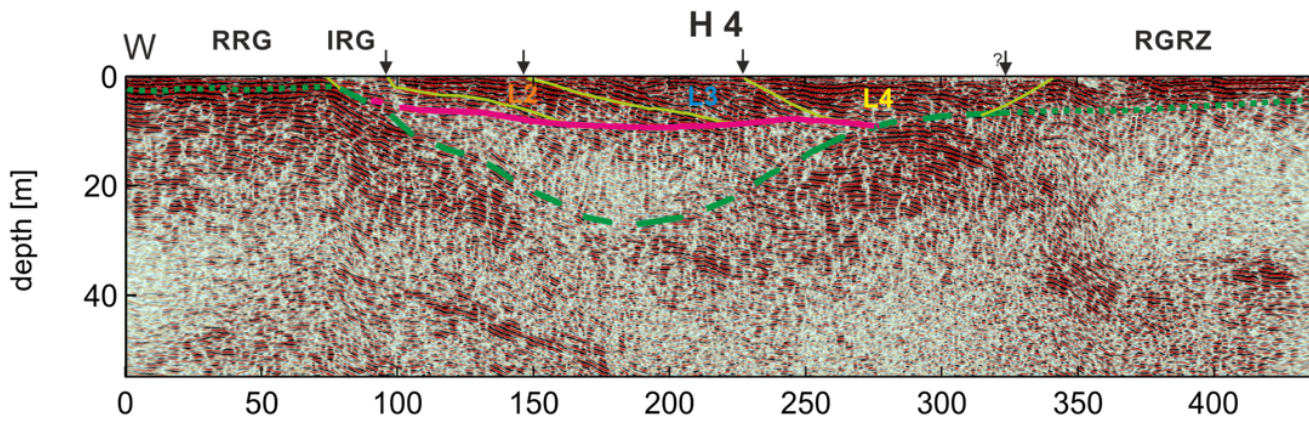
# Data and Processing



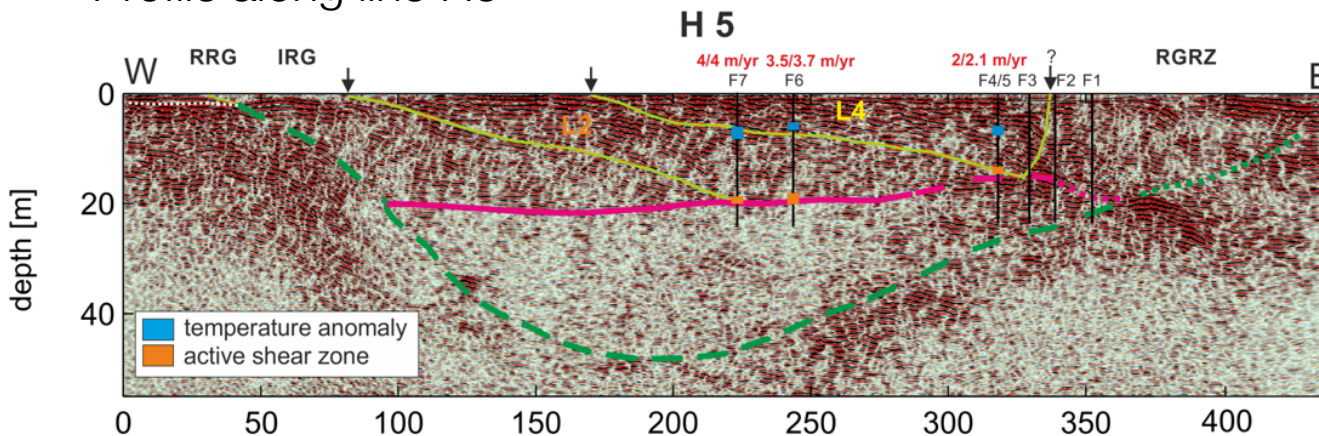
# Interpretation



Profile along line H4



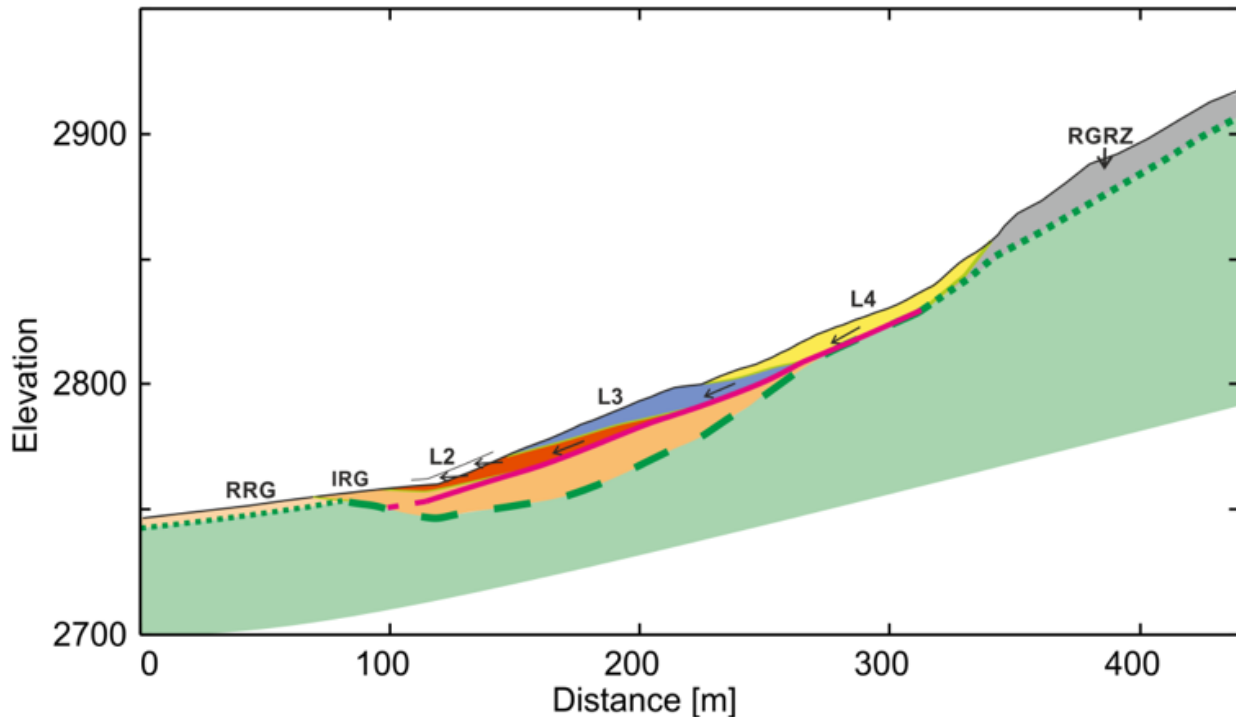
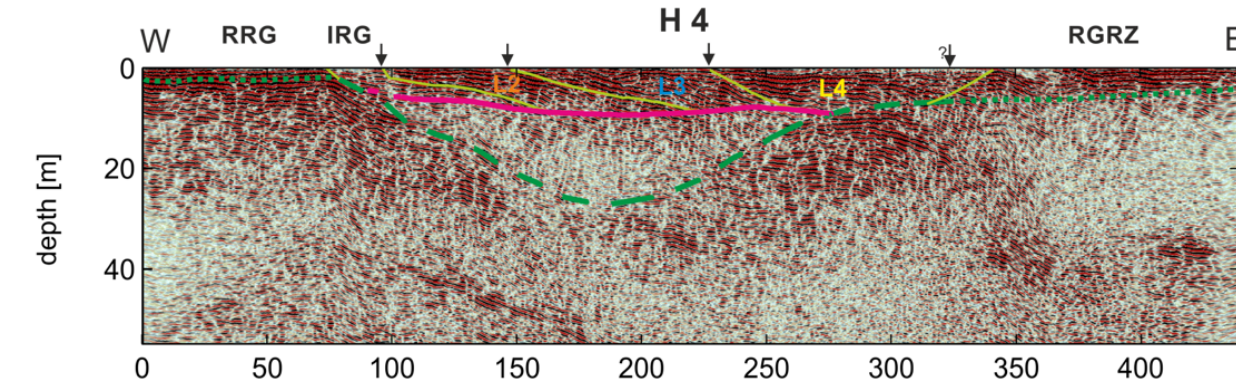
Profile along line H5



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

# Synthesis

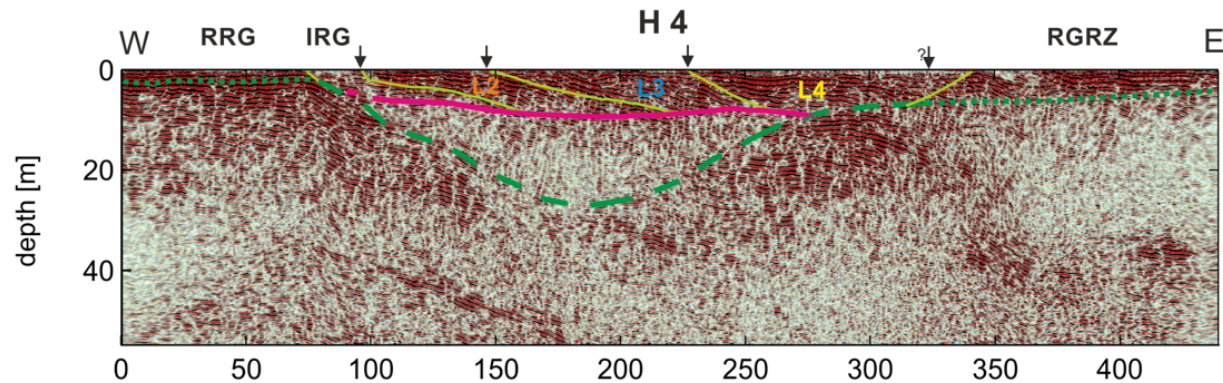
## Final Structural and Kinematic Model



- 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

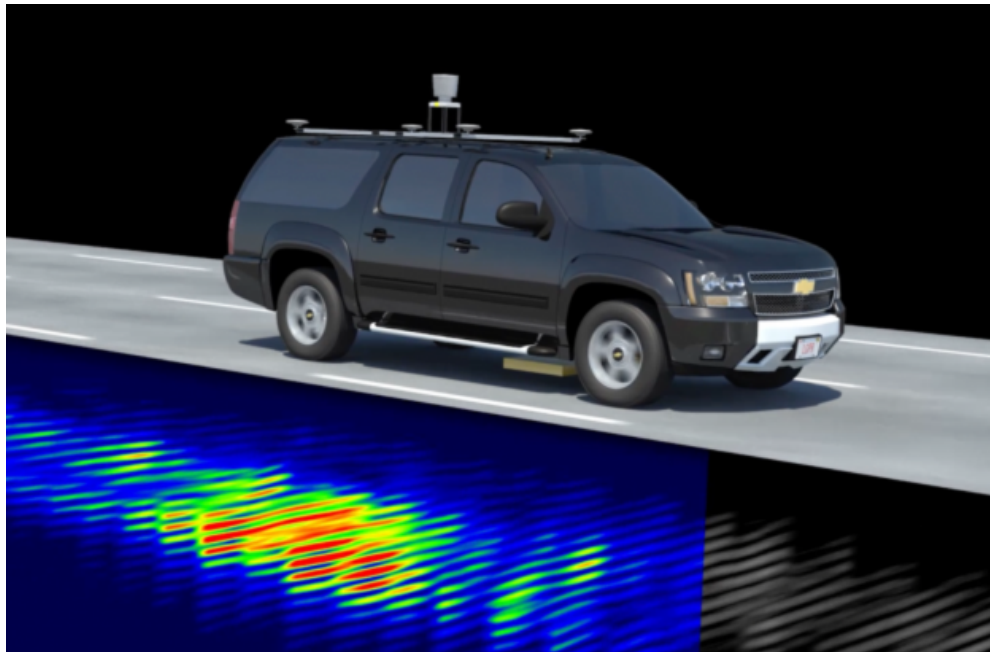
- Basic experiment
- Physical property
- Physics
- Data and Processing
- Case history: rock glacier



# LGPR

## Localizing GPR for driverless vehicles

MIT Lincoln Labs with GSSI



Journal of Field Robotics

Volume 33, Issue 1, pages 82-102, 27 MAY 2015 DOI: 10.1002/rob.21605

<http://onlinelibrary.wiley.com/doi/10.1002/rob.21605/full#rob21605-fig-0003>

# Typical Sensors

## Sensors

- GPS
- Lidar
- Camera
- Work fine in good weather

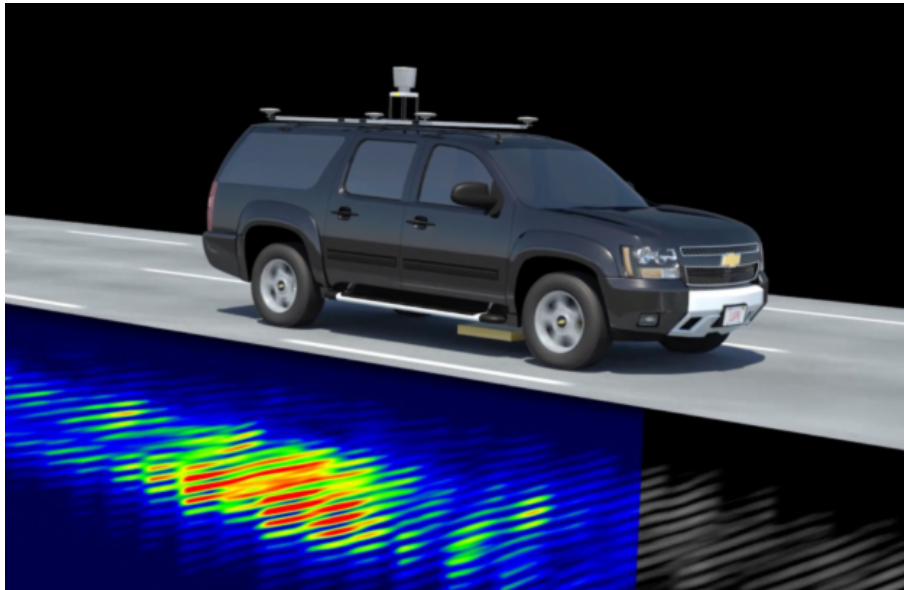
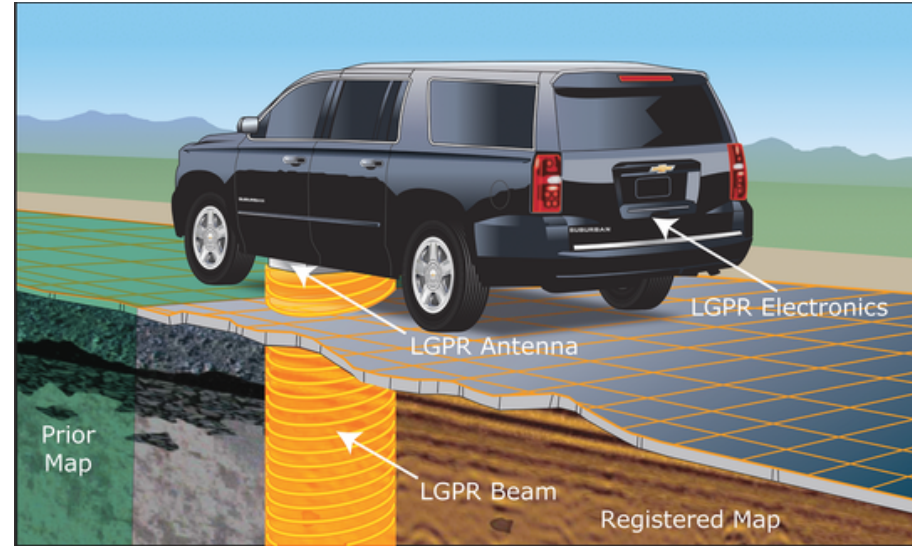
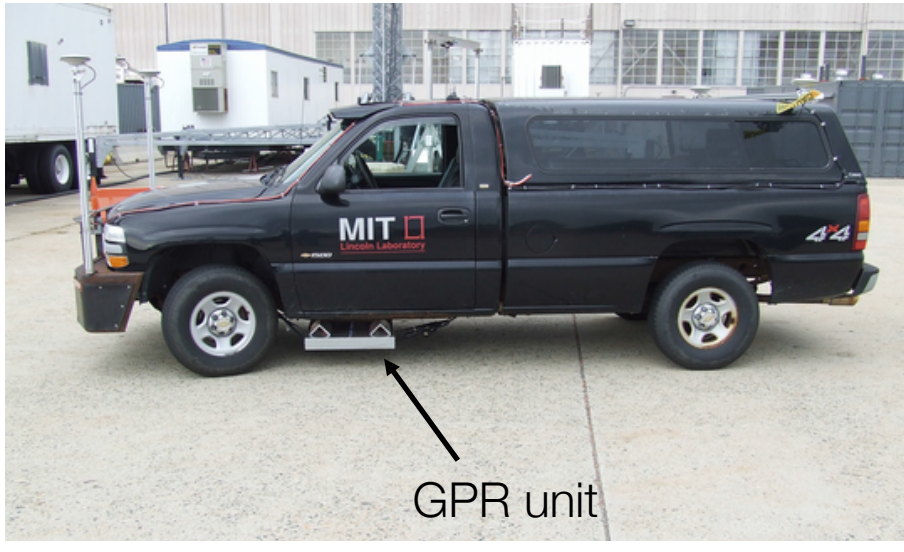
## What happens when

- Bad weather
  - rain, snow, sleet, fog, ...
- Changes
  - signs, road stripes, vegetation, ...

Need additional sensor data



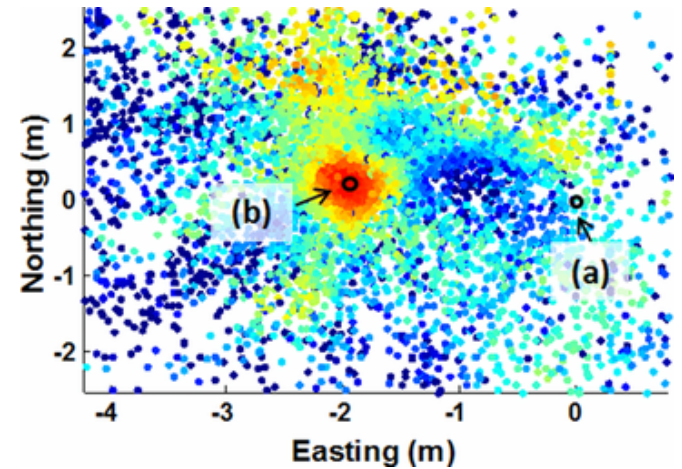
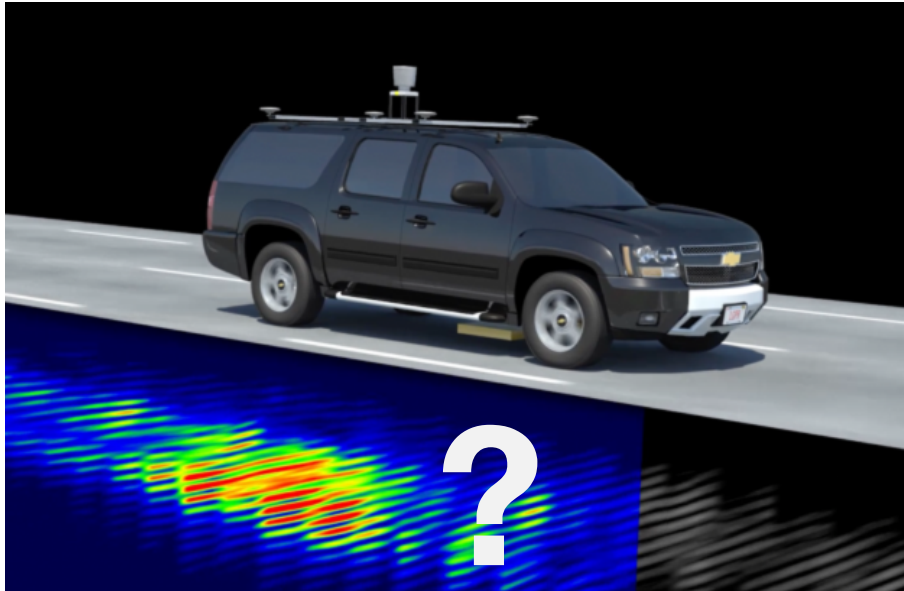
# Localizing Ground Penetrating Radar



- Collect reference GPR data on clear day
- Store reference data set



# Localizing Ground Penetrating Radar



Cross correlate real-time data with reference data to find location

*LGPR complements existing technology to achieve the vision of safe autonomous vehicles.*



<https://youtu.be/rZq5FMwl8D4?t=20s>

# End of GPR

