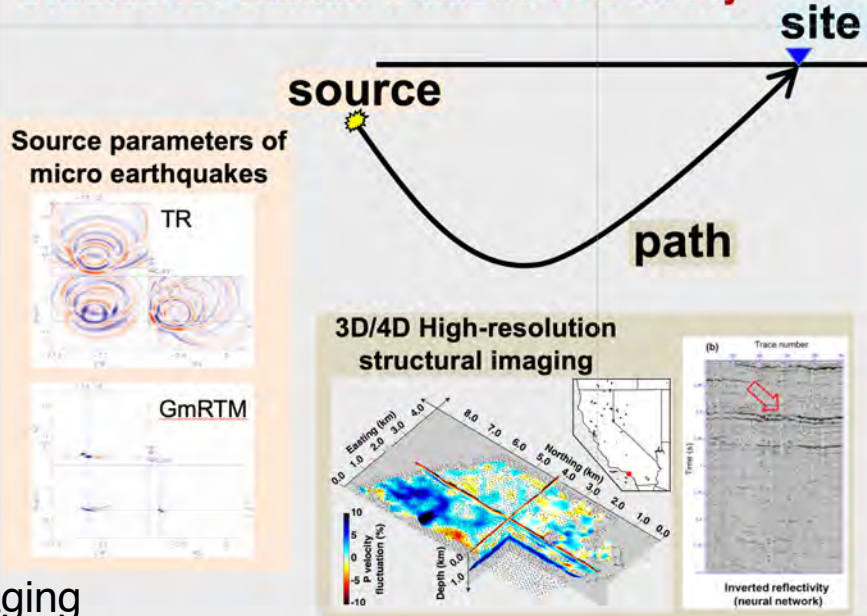


# Towards high-resolution seismic imaging and monitoring

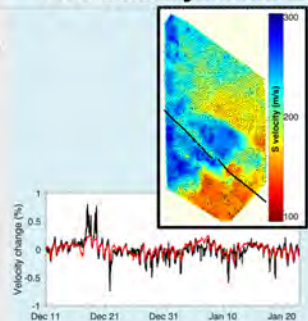
## Studies for human-induced seismicity



Microseismic  
wavefield imaging

Ambient noise imaging

## Near surface velocities and their dynamics



Ambient  
noise imaging

Machine learning

Publications:  
<http://www.mit.edu/~nnakata>

# Nori Nakata (MIT)

# **Towards high-resolution seismic imaging and monitoring using ambient noise, machine learning, and microseismic events**

**Nori Nakata (MIT)**

**Yuji Kim, Jianhang Yin, Bin Lyu (Univ. Oklahoma)**

**Yuwei Wang (Southwest Petroleum Univ)**

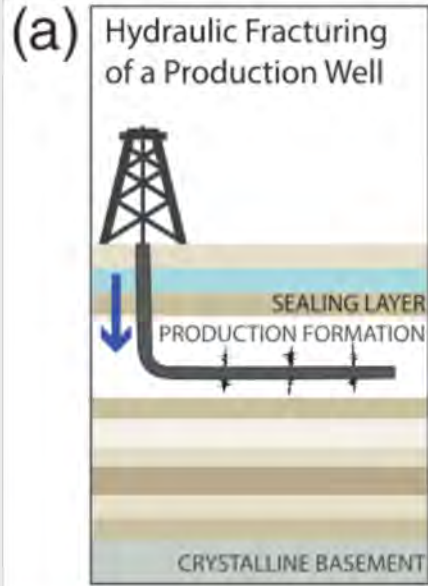
**Rie Nakata Kamei, Zack Spica (Univ. Tokyo)**

**Greg Beroza (Stanford)**

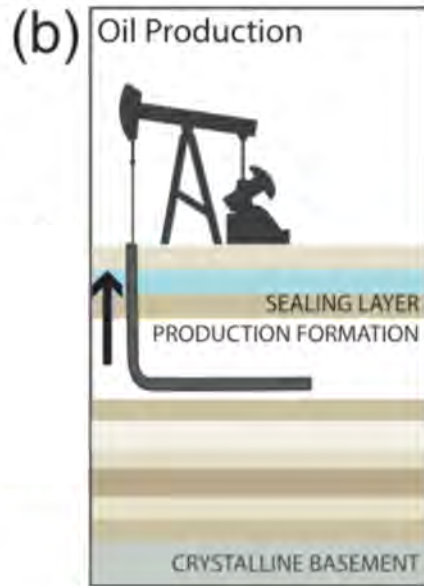
**David Shelly (USGS)**

# Human-Induced Seismicity

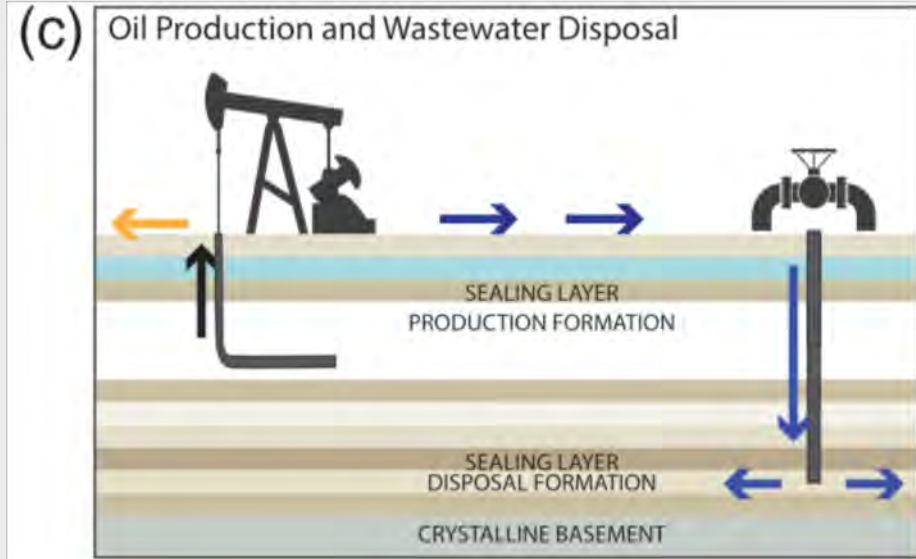
## Fracking



## Production



## Wastewater disposal



- EOR
- Geothermal
- Mining

# Human-Induced Seismicity

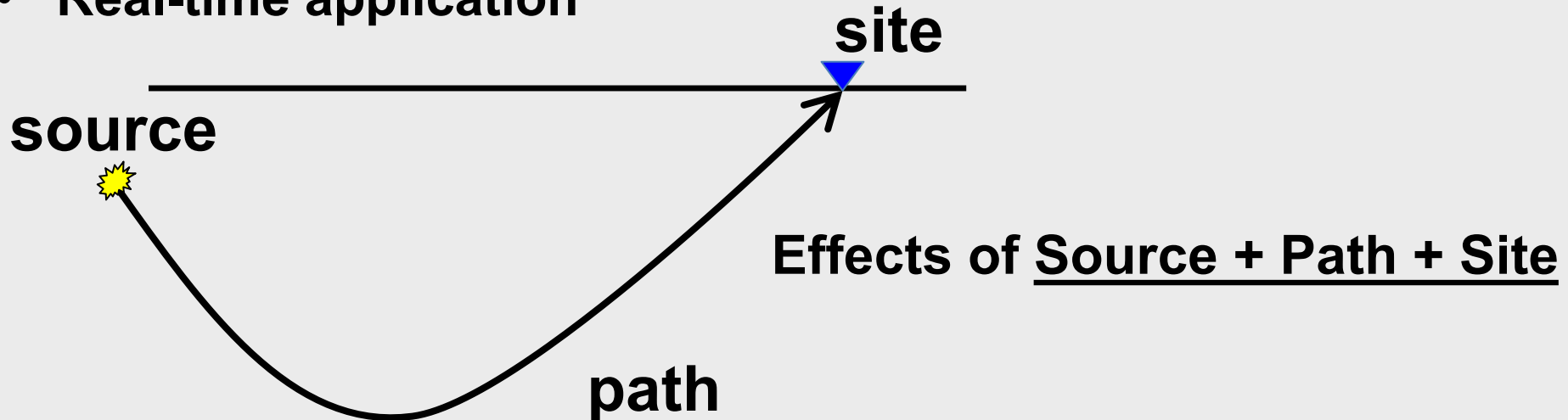
## Tasks

- **Assessing seismic hazard**
- **Understanding seismic sources**
- **Understanding physics of seismicity**
- **Effectively enhancing production**
- **Real-time application**
- **...**

# Human-Induced Seismicity

## Tasks

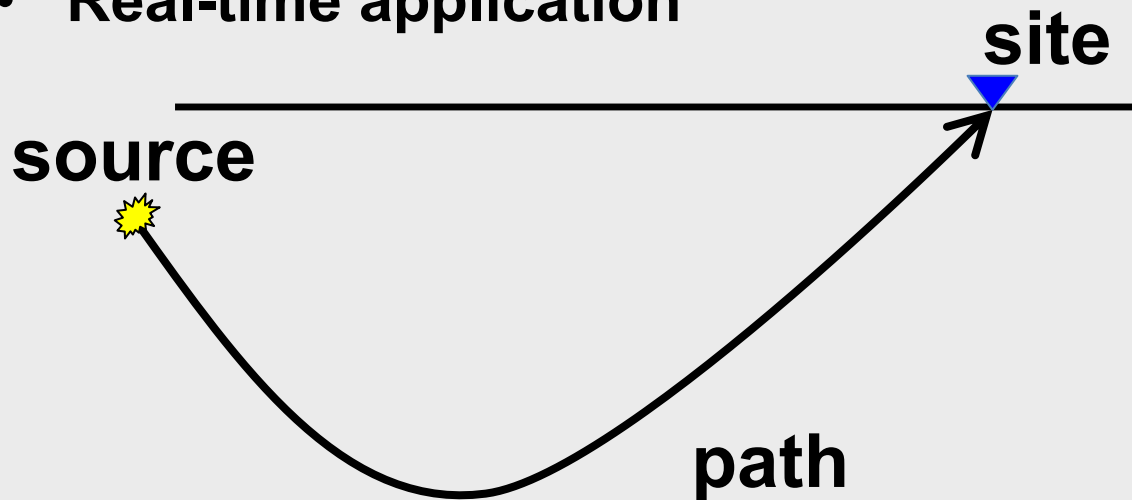
- Assessing seismic hazard
- Understanding seismic sources
- Understanding physics of seismicity
- Effectively enhancing production
- Real-time application



# Human-Induced Seismicity

## Tasks

- Assessing seismic hazard
- Understanding seismic sources
- Understanding physics of seismicity
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- Real-time application



## **My approach**

### Unique datasets

- Ambient noise
- Microseismic events
- Repeated active surveys
- Tube waves
- ...

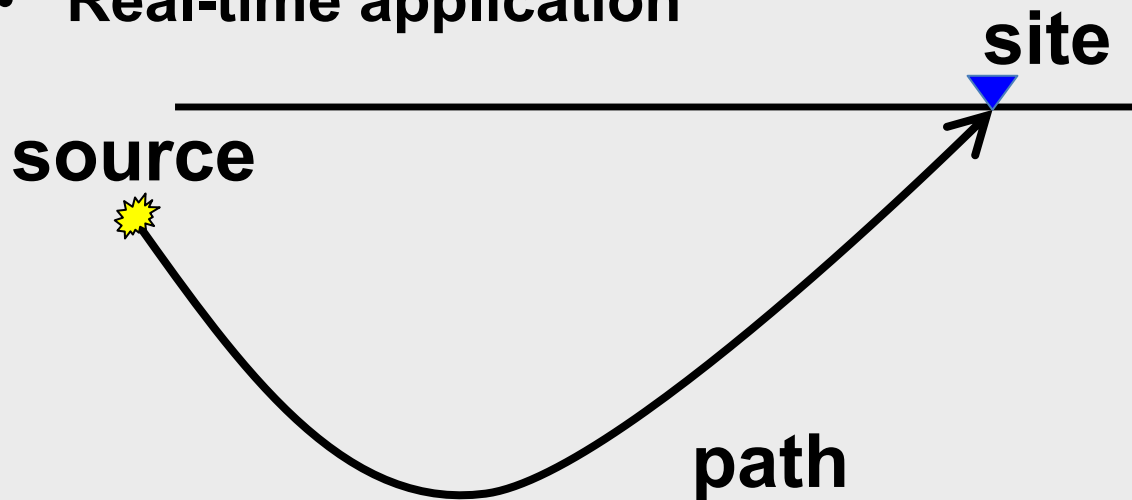
### Advanced techniques

- Time-lapse FWI
- Machine learning
- Stochastic modeling
- Wavefield migration
- ...

# Human-Induced Seismicity

## Tasks

- Assessing seismic hazard
- Understanding seismic sources
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## **My approach**

### Unique datasets

- Ambient noise
- **Microseismic events**
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- ...

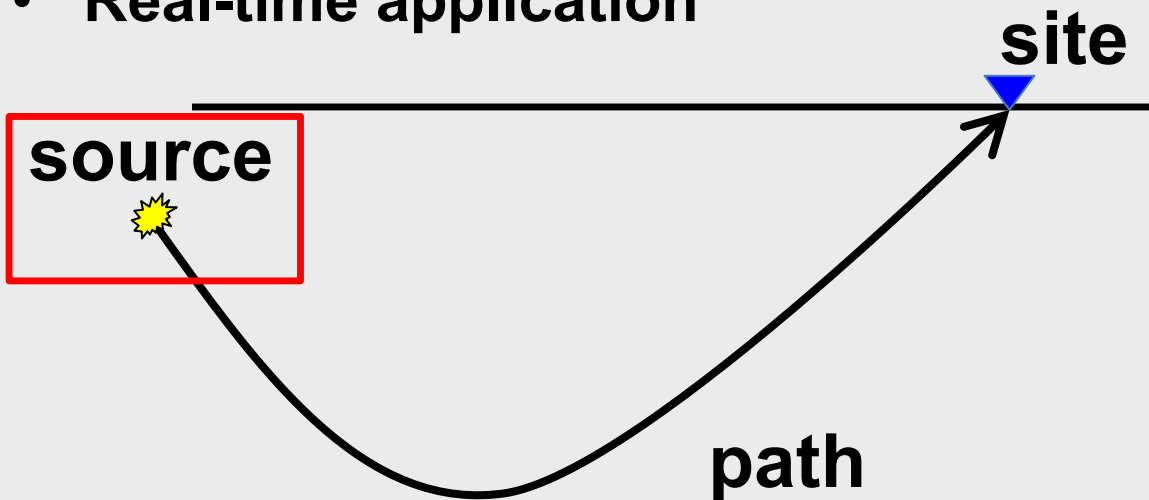
### Advanced techniques

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- **Wavefield migration**
- ...

# Human-Induced Seismicity

## Tasks

- Assessing seismic hazard
- Understanding seismic sources
- Understanding physics of seismicity
- Effectively enhancing production
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## **My approach**

### Unique datasets

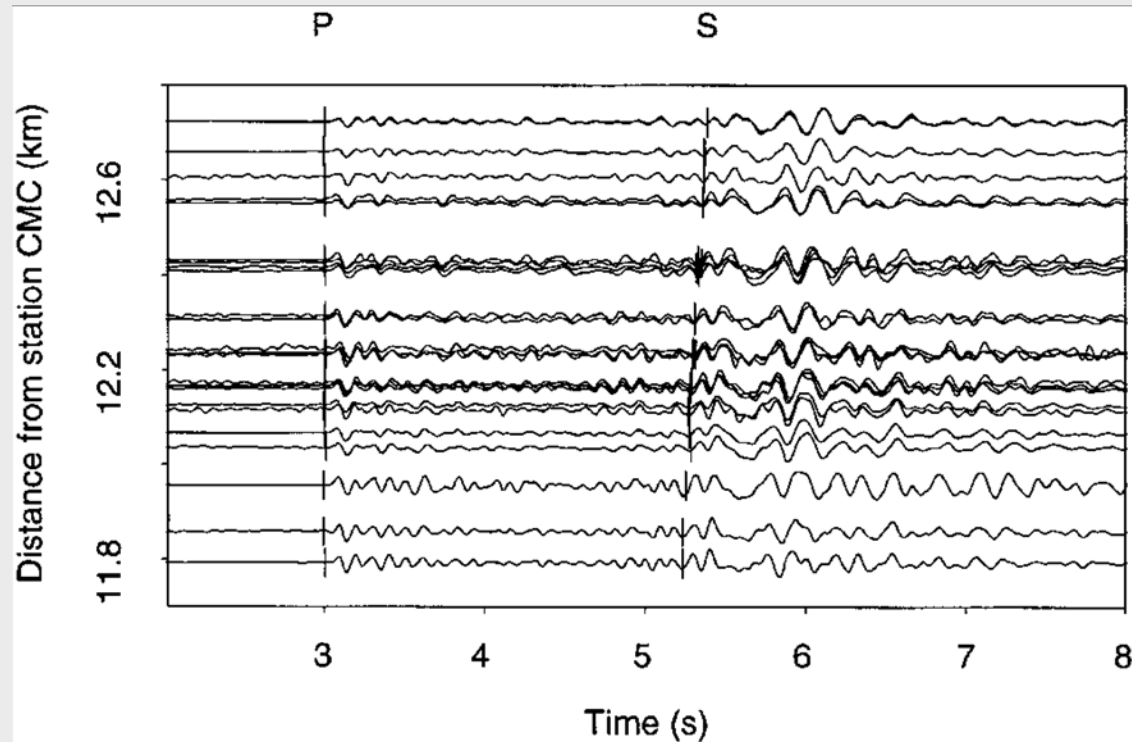
- Ambient noise
- **Microseismic events**
- Repeated active surveys
- Tube waves
- ...

### Advanced techniques

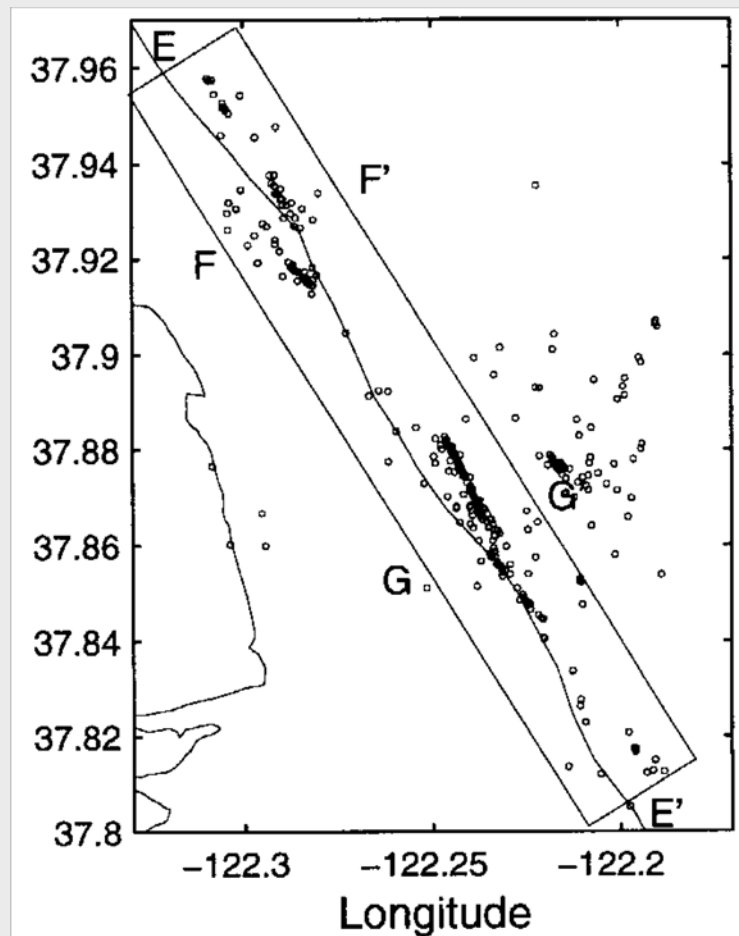
- Time-lapse FWI
- Machine learning
- Stochastic modeling
- **Wavefield migration**
- ...

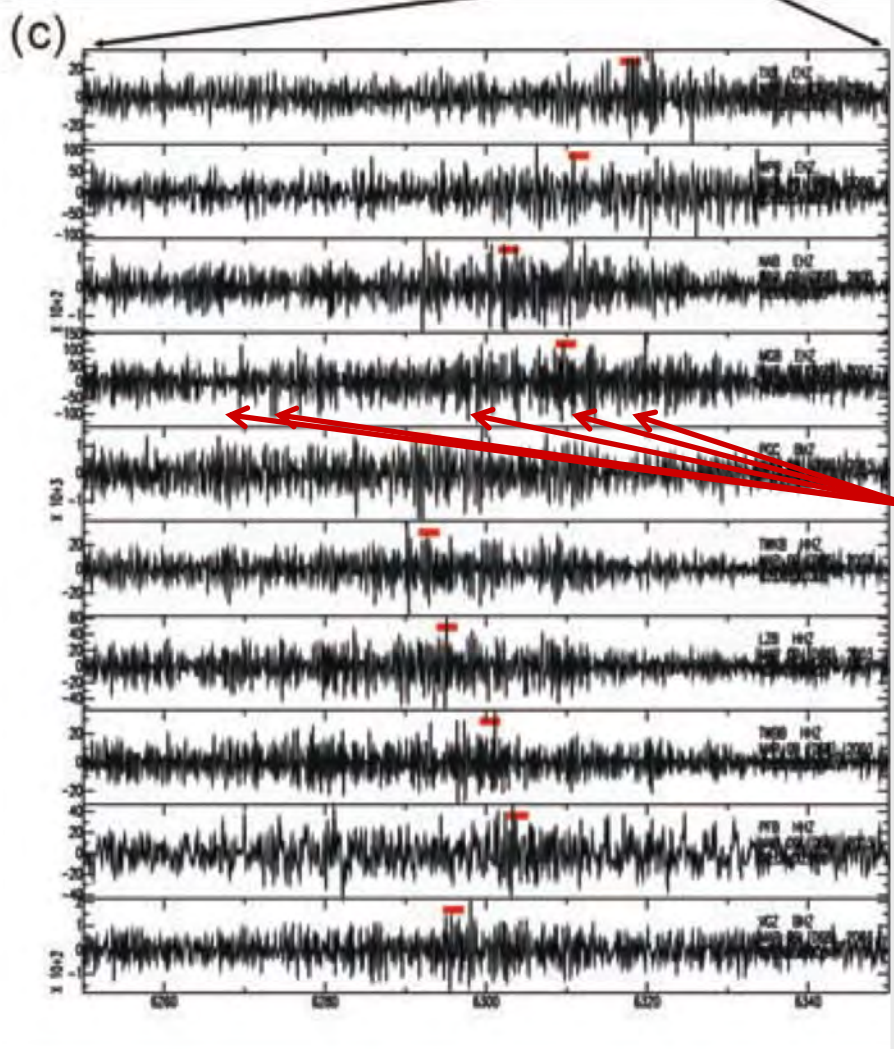


# Arrival time is useful if clearly identified



**Arrival time picks are used to locate source.**





**Small, weak, and  
extended events are  
hard to detect/locate**

**Wave arrivals?**

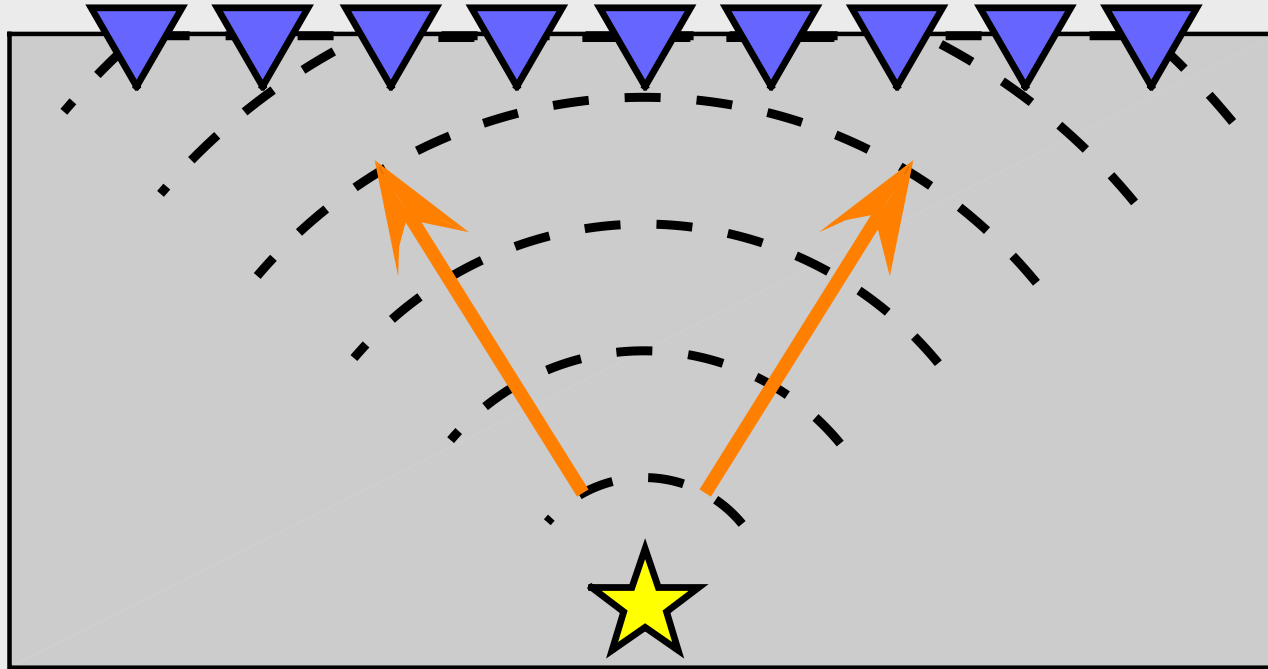


**We can't pick arrival times accurately**

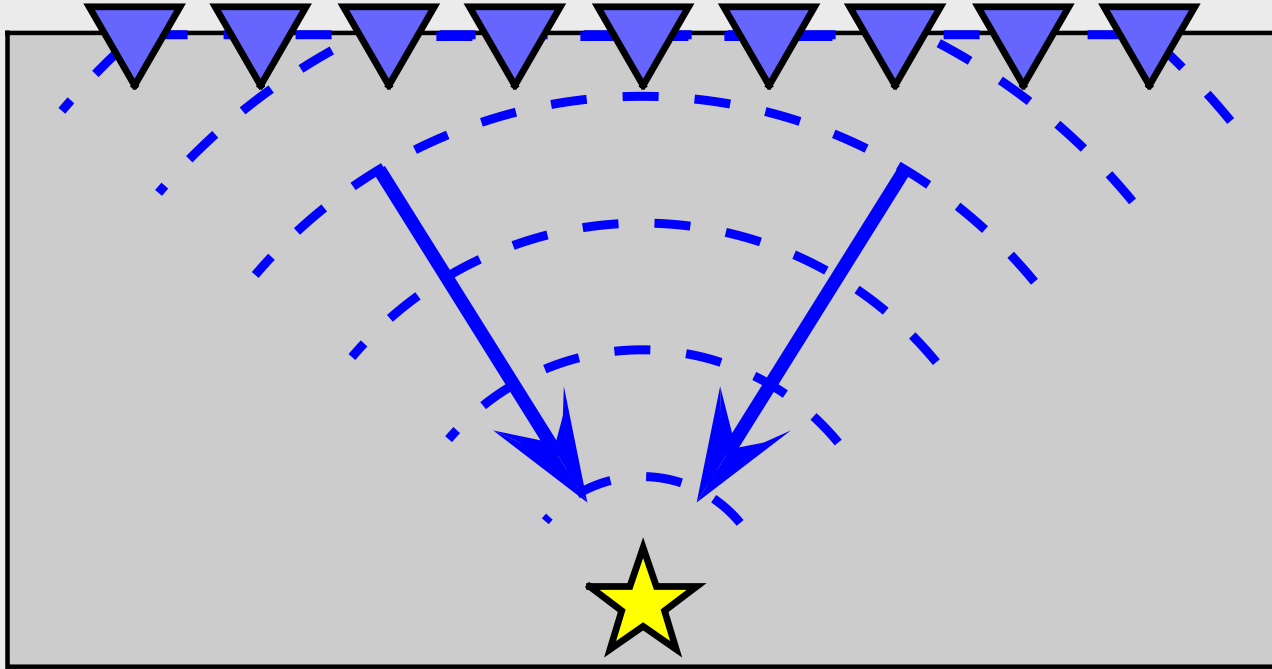


**Migration-based processing**

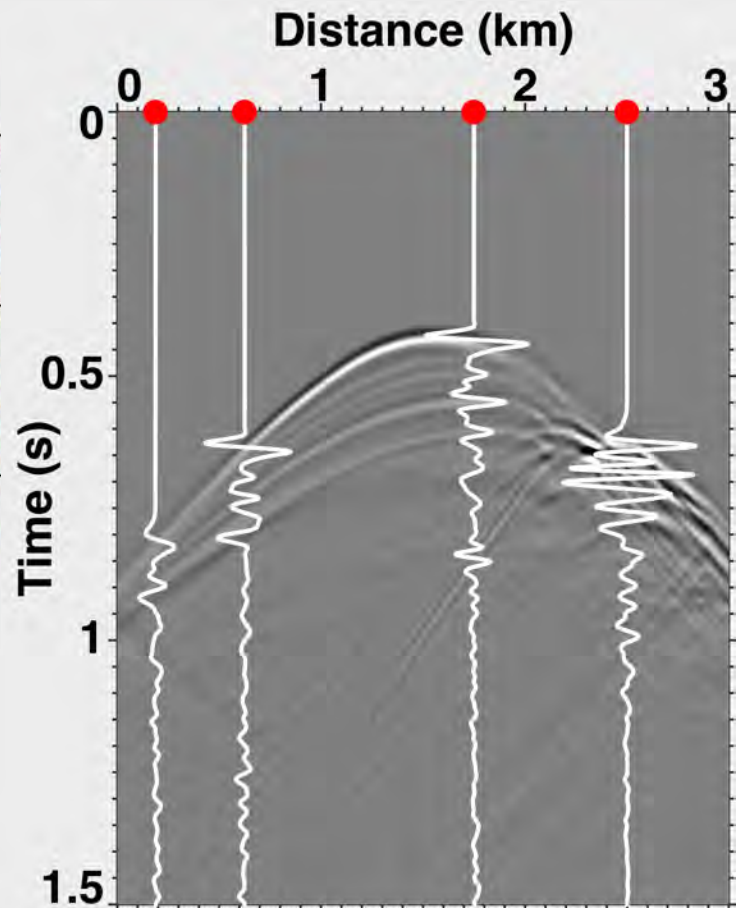
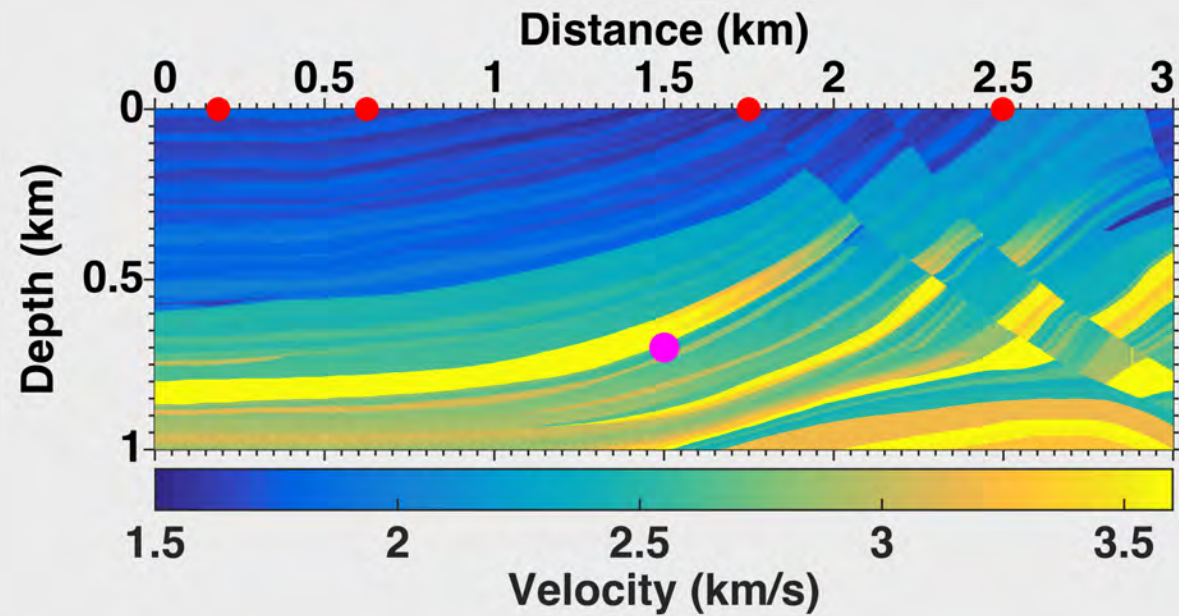
# Recording microseismic data



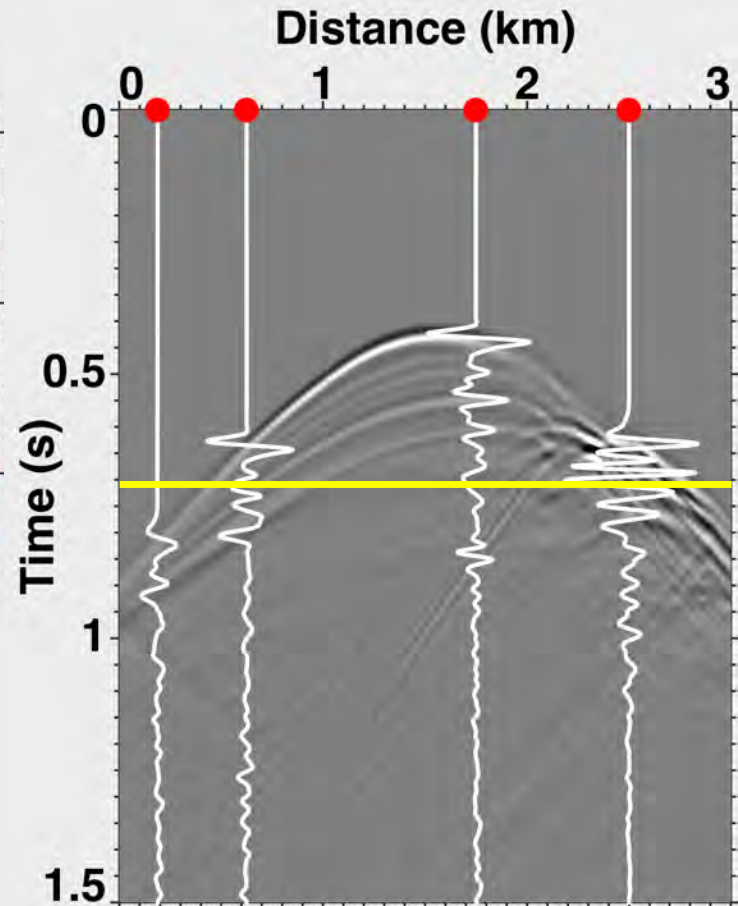
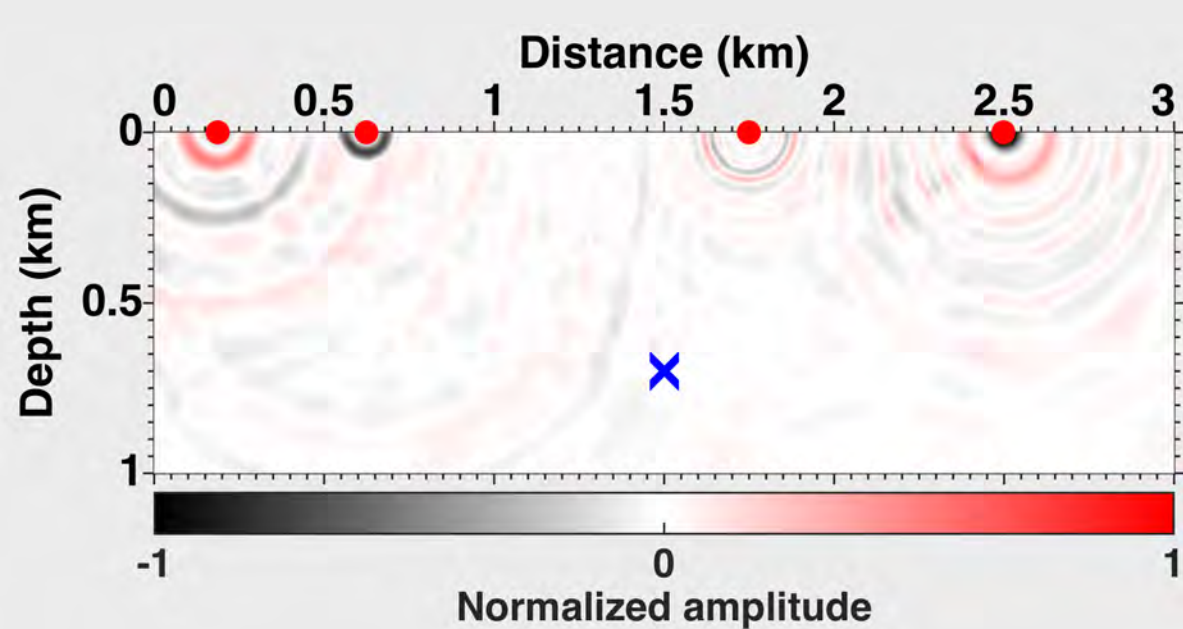
# Time-reversal imaging



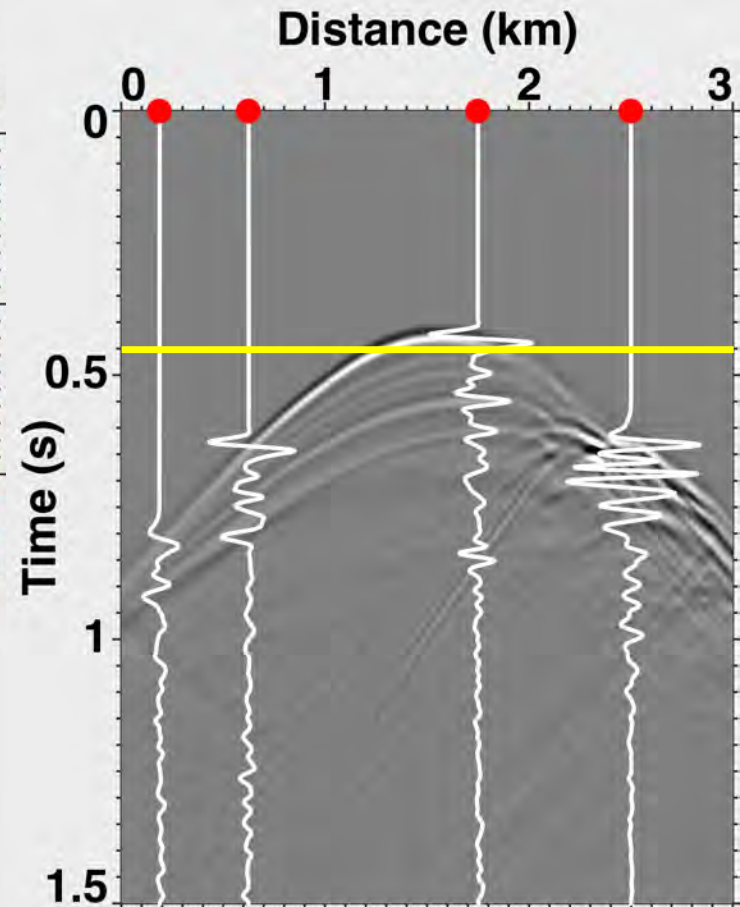
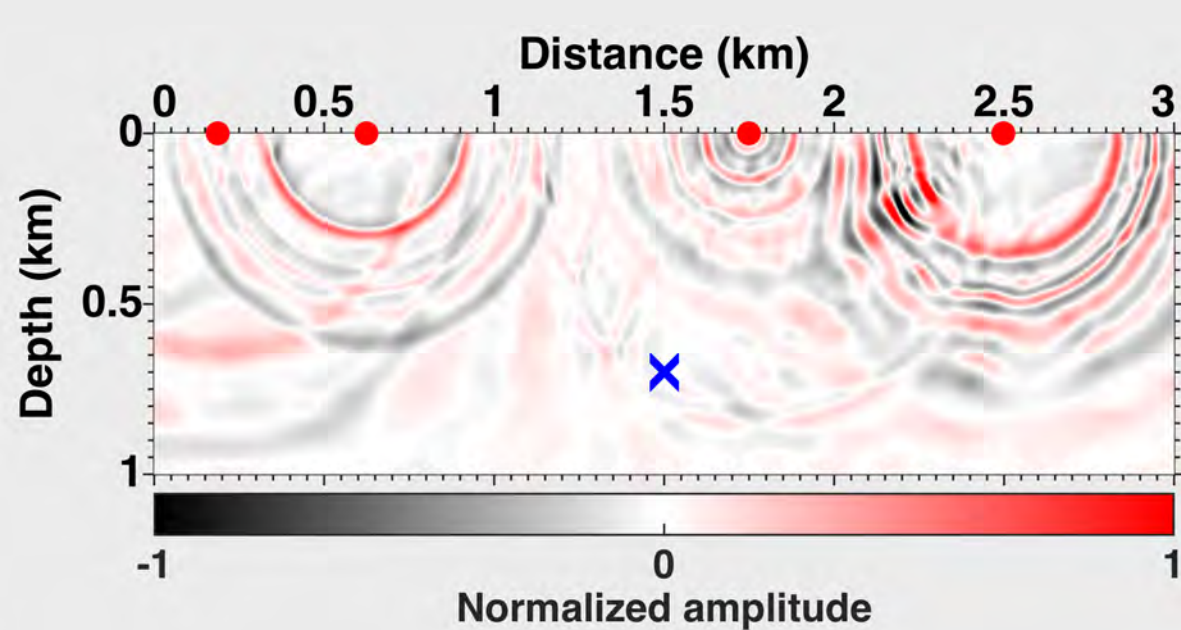
# Numerical example



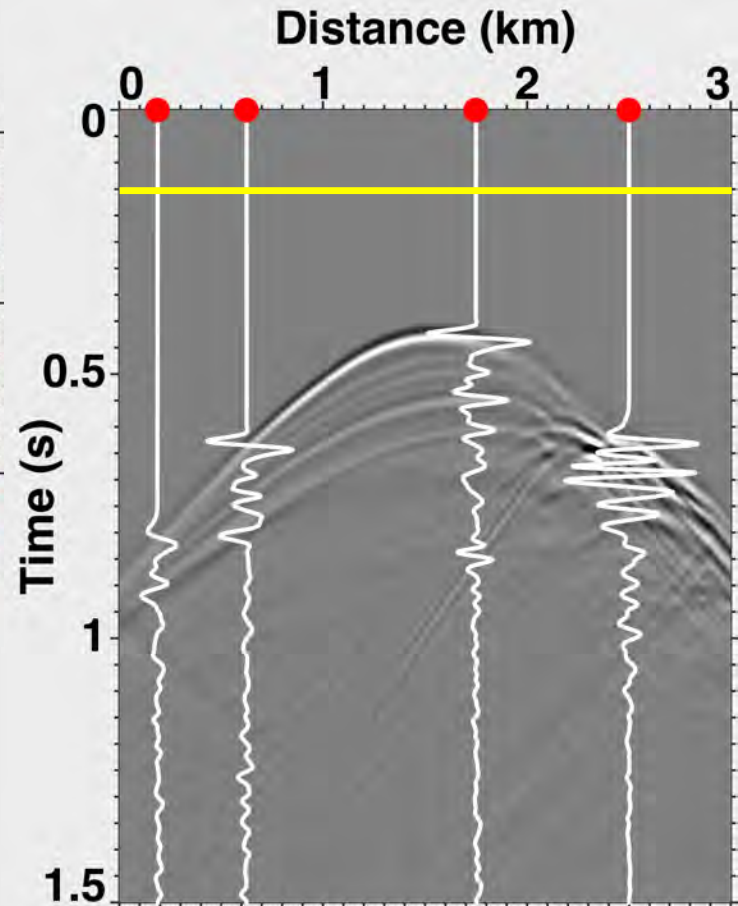
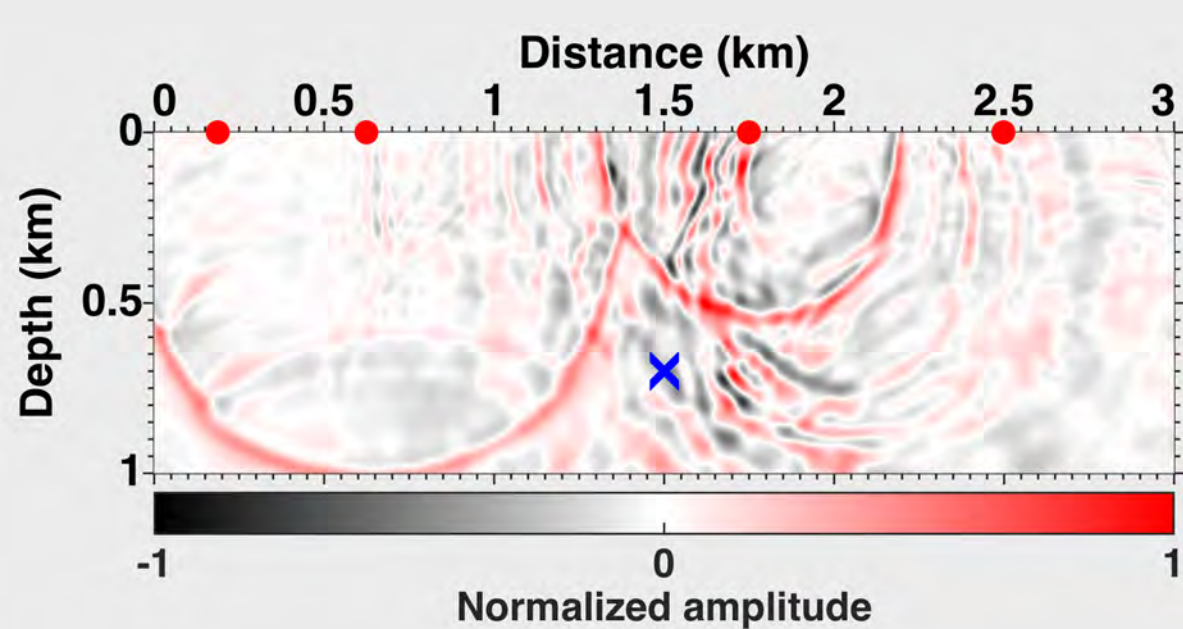
# Time-reversal imaging



# Time-reversal imaging

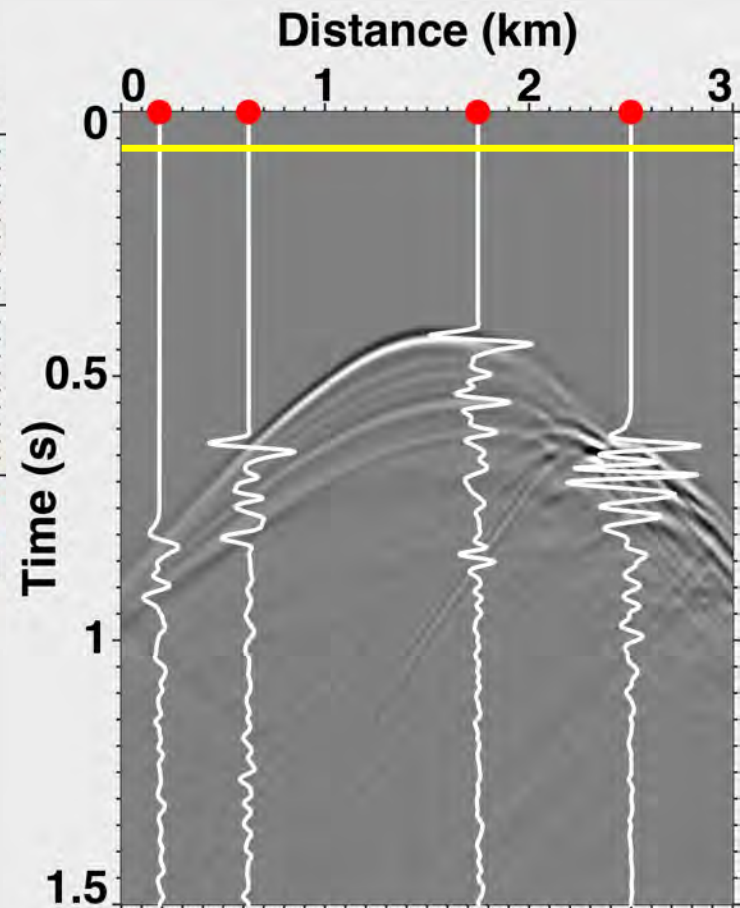
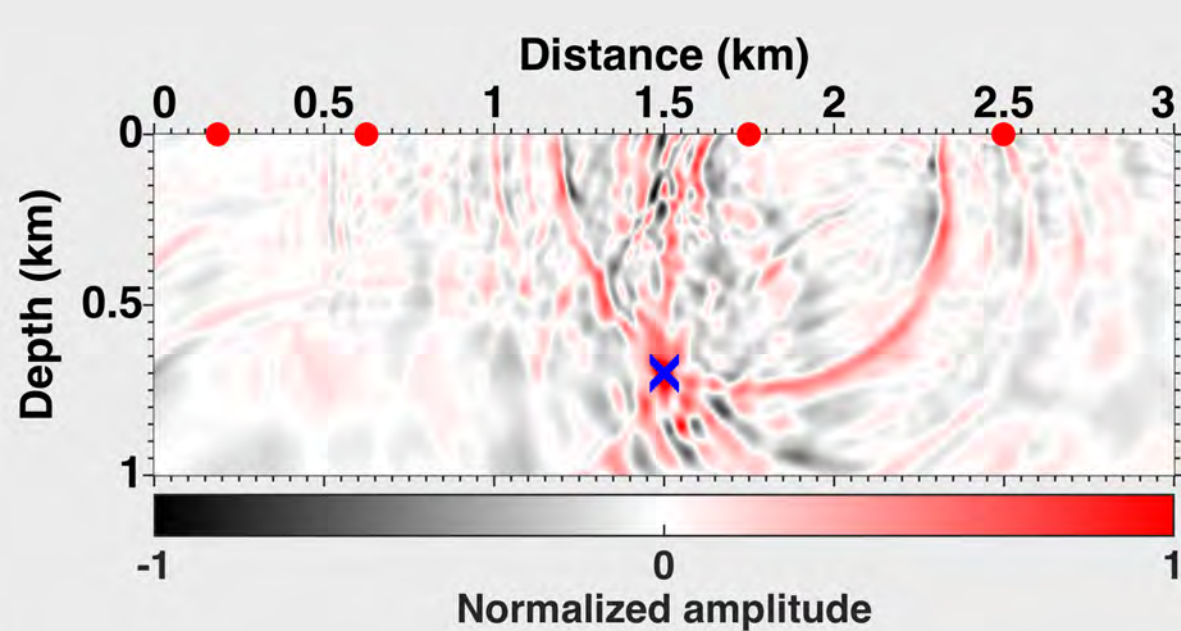


# Time-reversal imaging

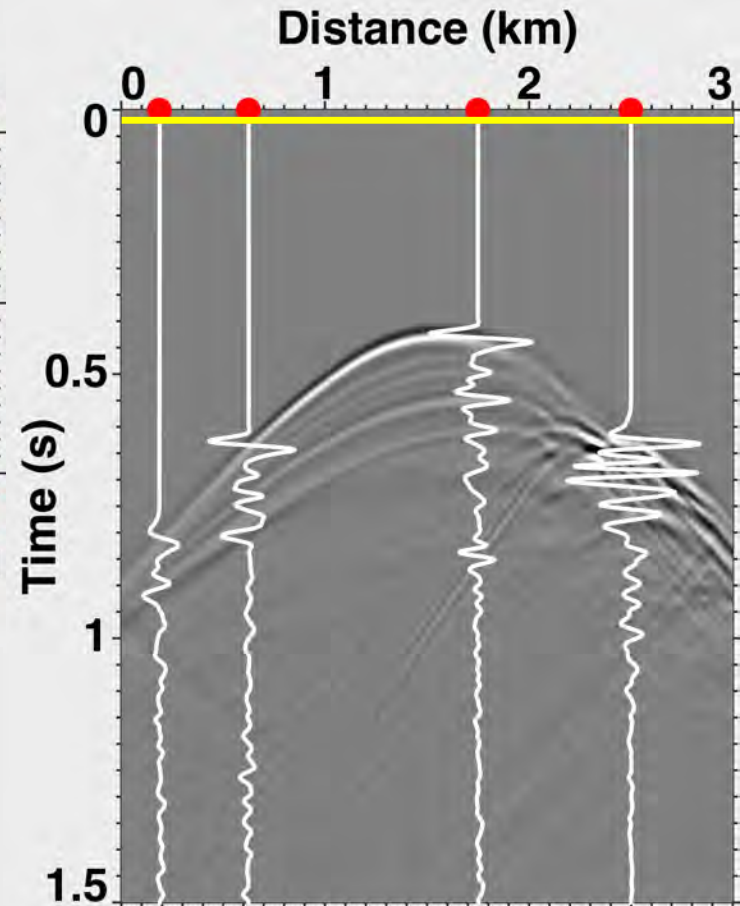
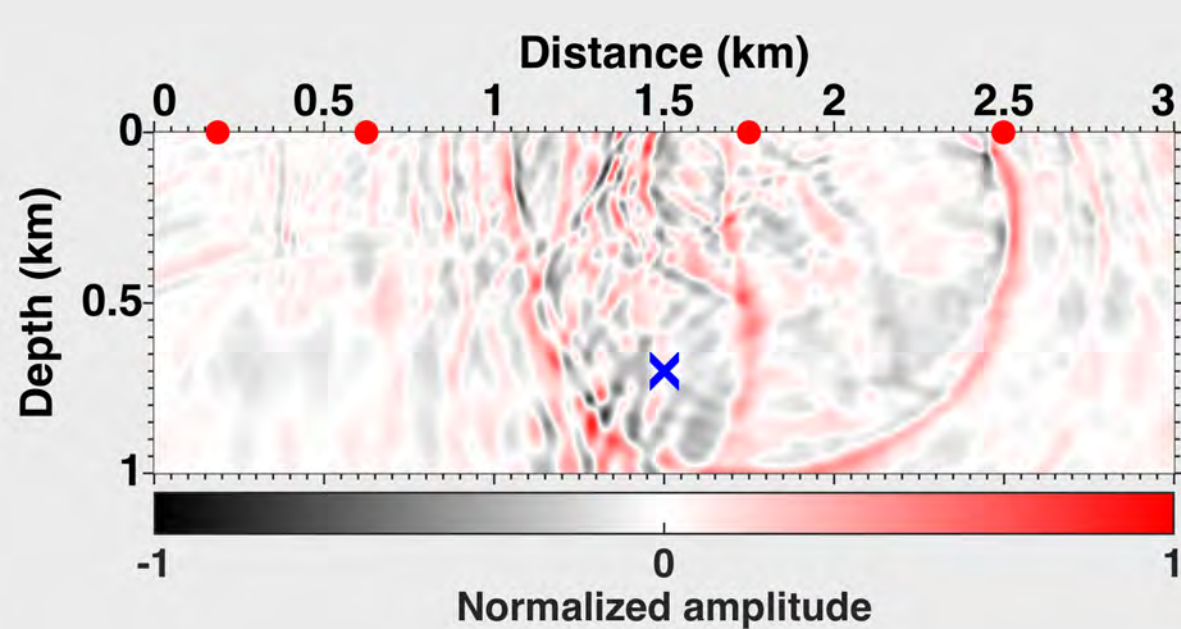




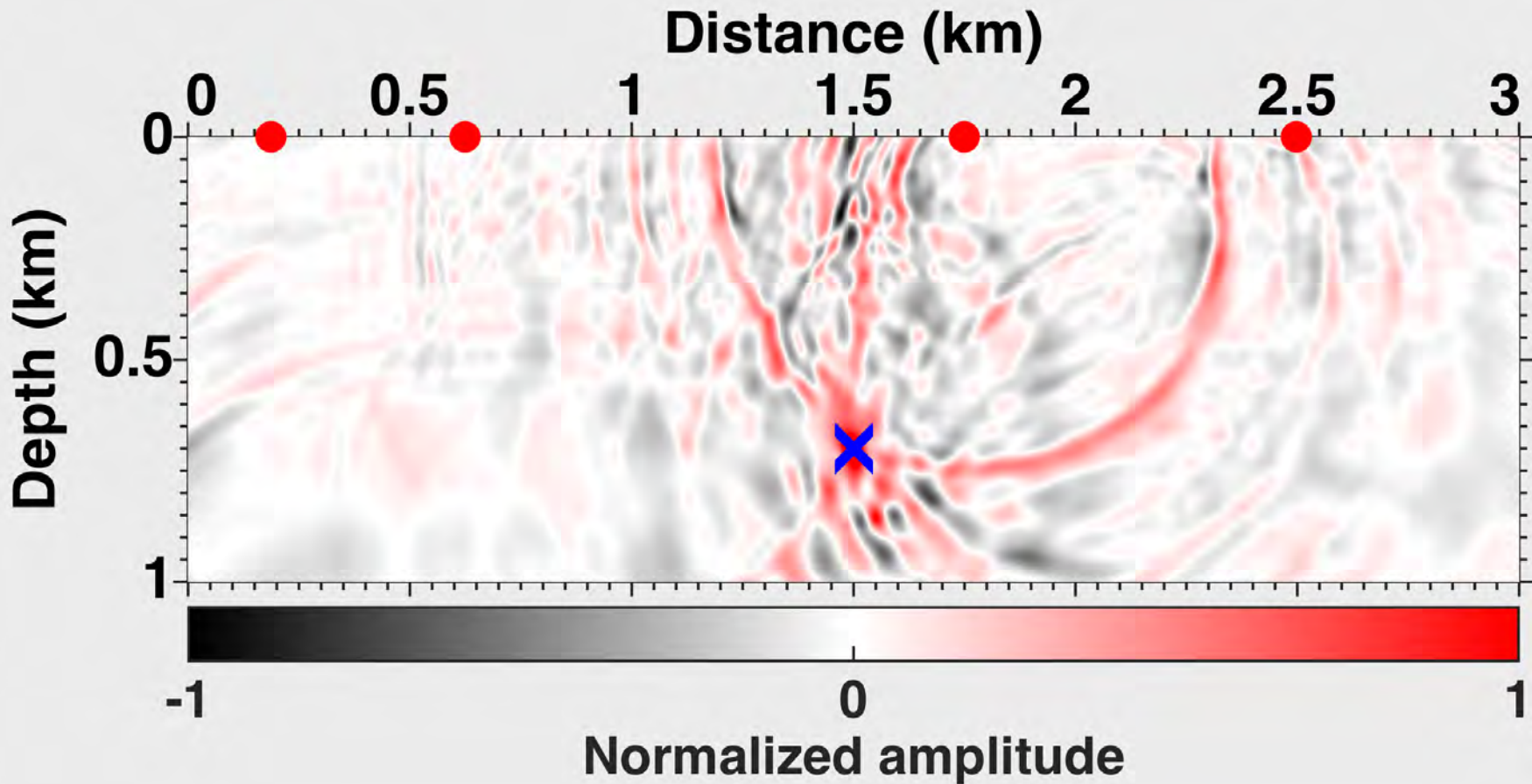
# Time-reversal imaging



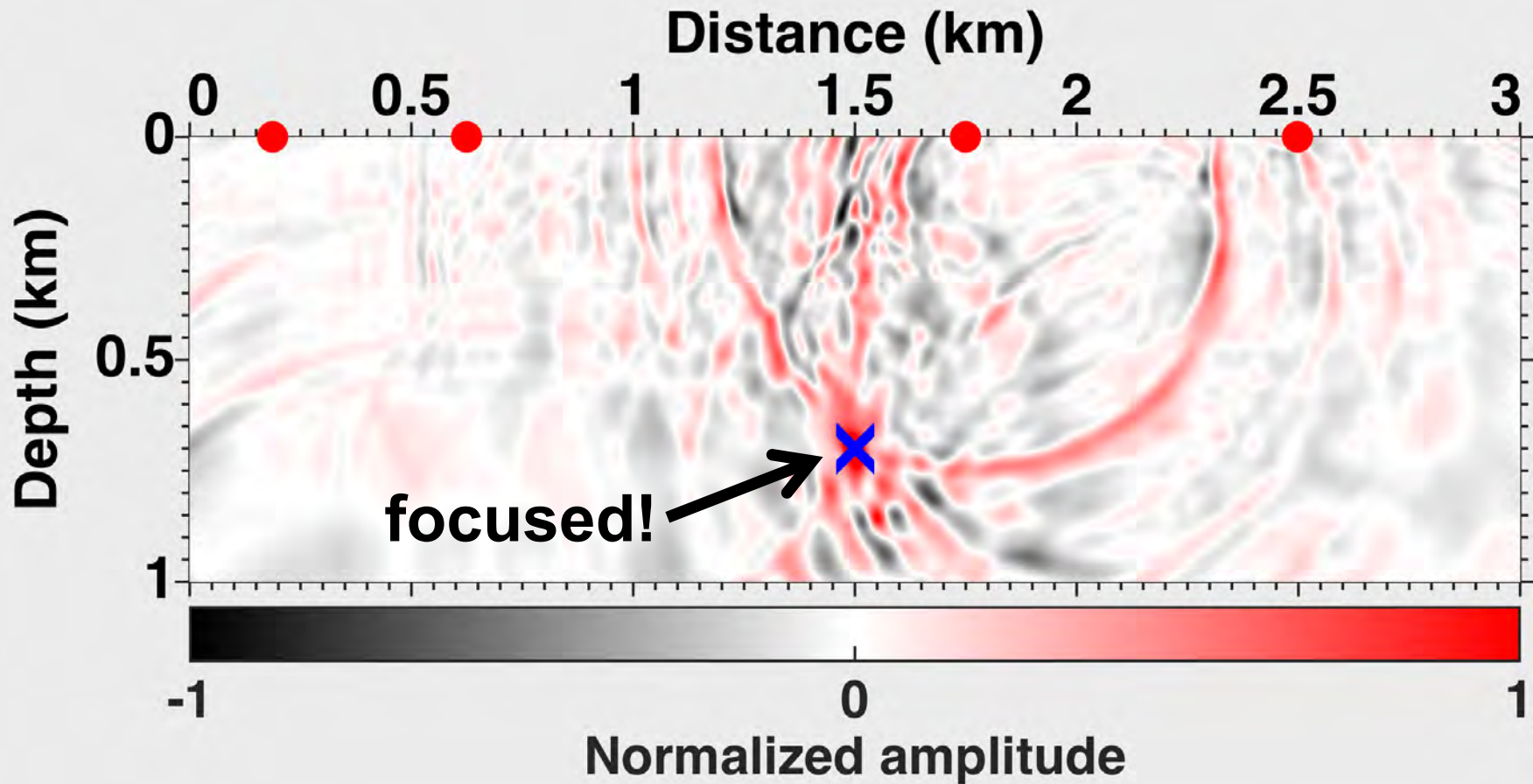
# Time-reversal imaging



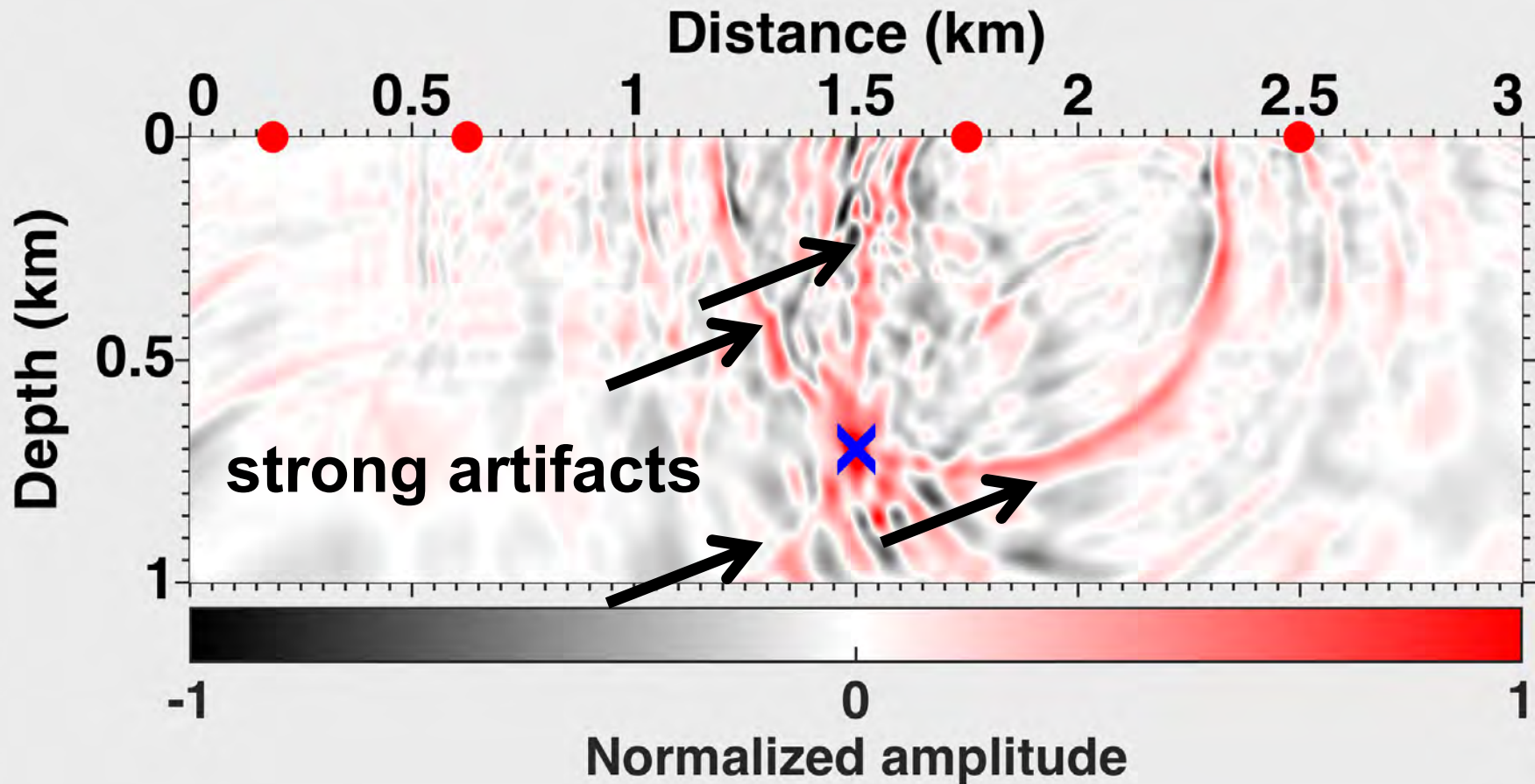
# Time-reversal imaging



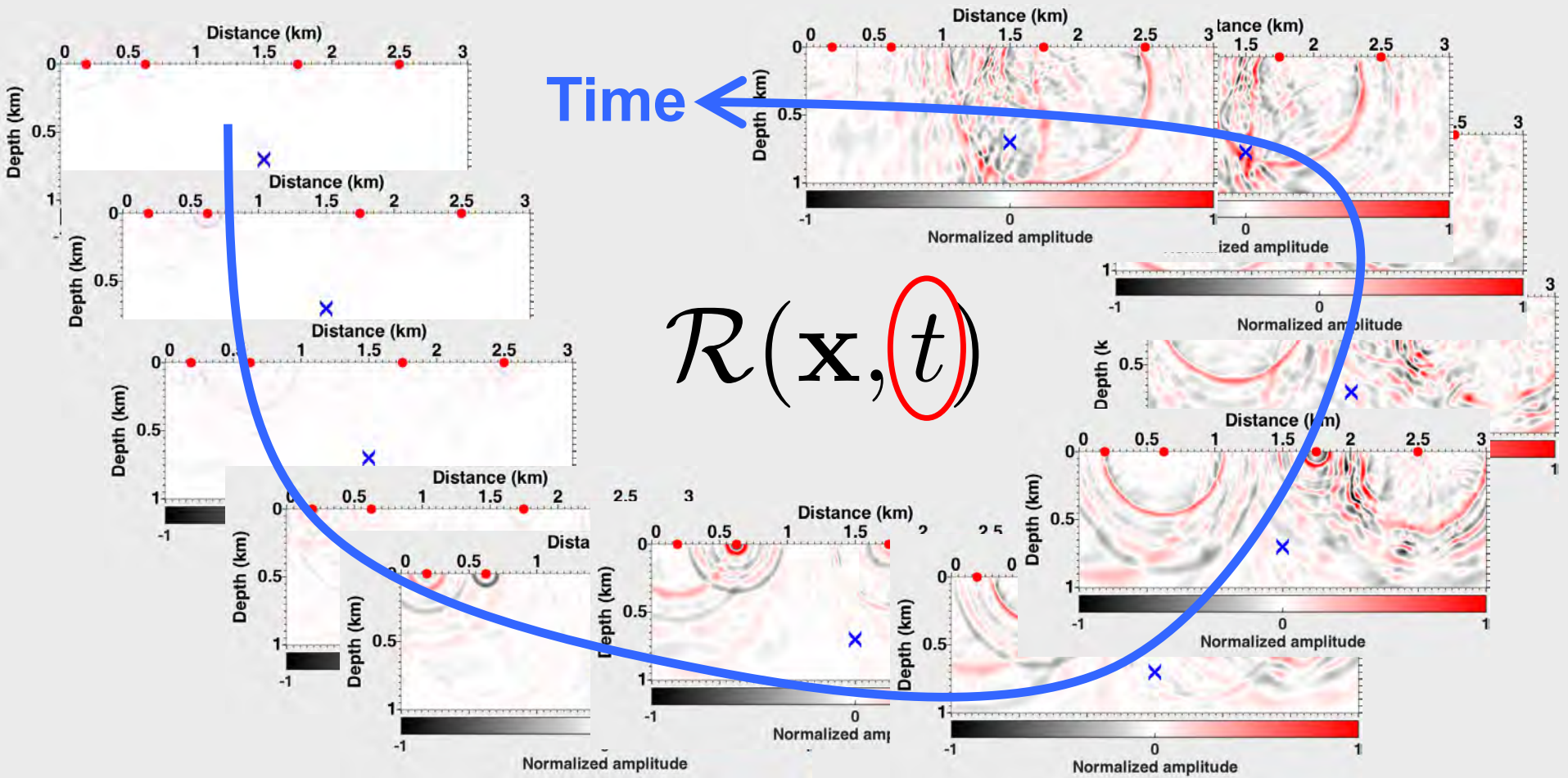
# Time-reversal imaging



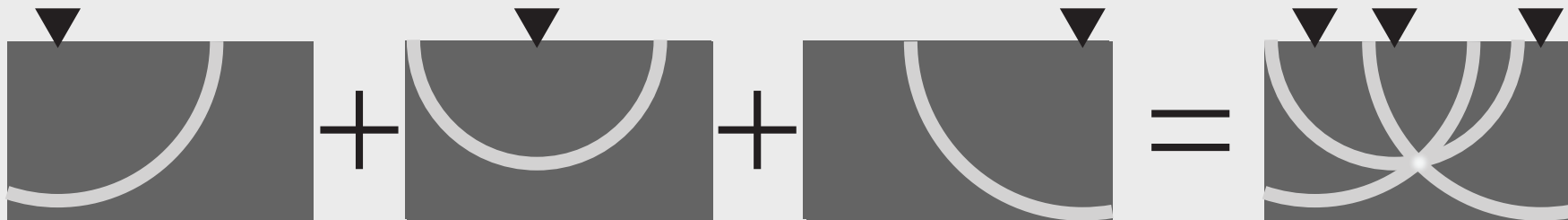
# Time-reversal imaging



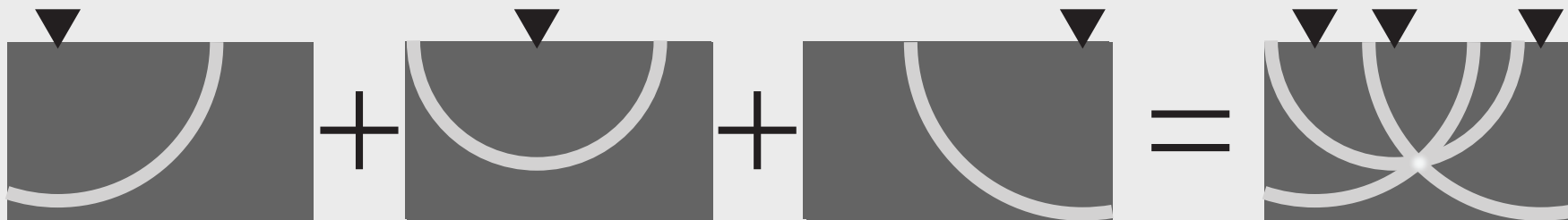
# Time-reversal imaging



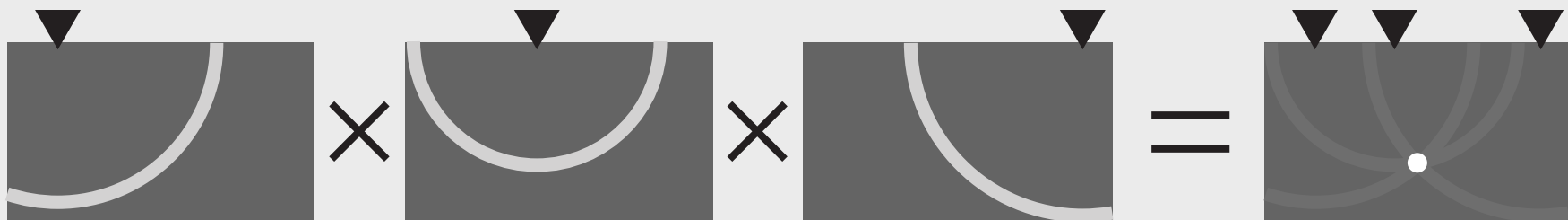
# Time-reversal image (conventional method)



## Time-reversal image (conventional method)



## Geometric-mean RTM (new approach)





**At time-lag = 0...,**

**Time-reversal imaging**

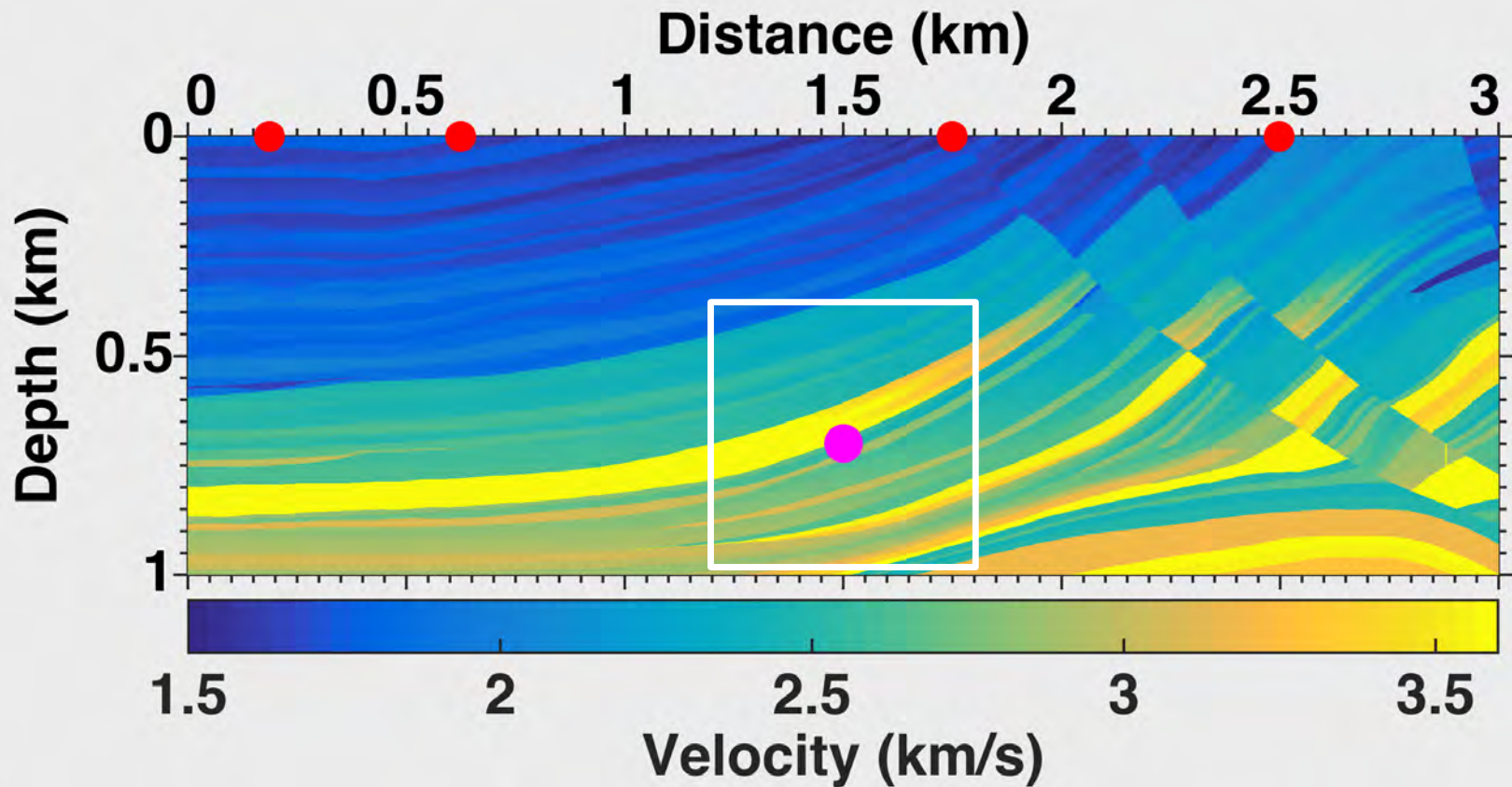
**= Arithmetic-mean reverse-time imaging**

$$\mathbf{R}(\mathbf{x}, \mathbf{t}) = \mathbf{W}_1(\mathbf{x}, \mathbf{t}) \oplus \mathbf{W}_2(\mathbf{x}, \mathbf{t}) \oplus \mathbf{W}_3(\mathbf{x}, \mathbf{t}) \oplus \mathbf{W}_4(\mathbf{x}, \mathbf{t})$$

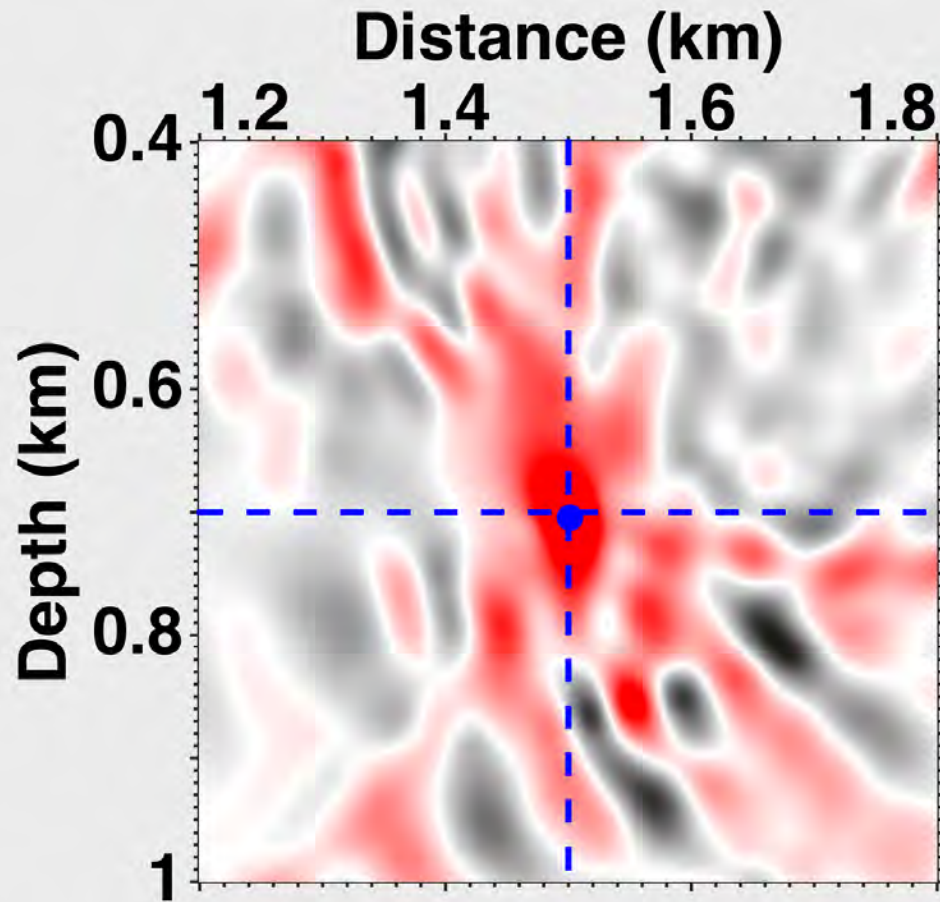
**Geometric-mean reverse-time migration**

$$\mathbf{R}(\mathbf{x}) = \left( \sum_{\mathbf{t}} \right) \mathbf{W}_1(\mathbf{x}, \mathbf{t}) \otimes \mathbf{W}_2(\mathbf{x}, \mathbf{t}) \otimes \mathbf{W}_3(\mathbf{x}, \mathbf{t}) \otimes \mathbf{W}_4(\mathbf{x}, \mathbf{t})$$

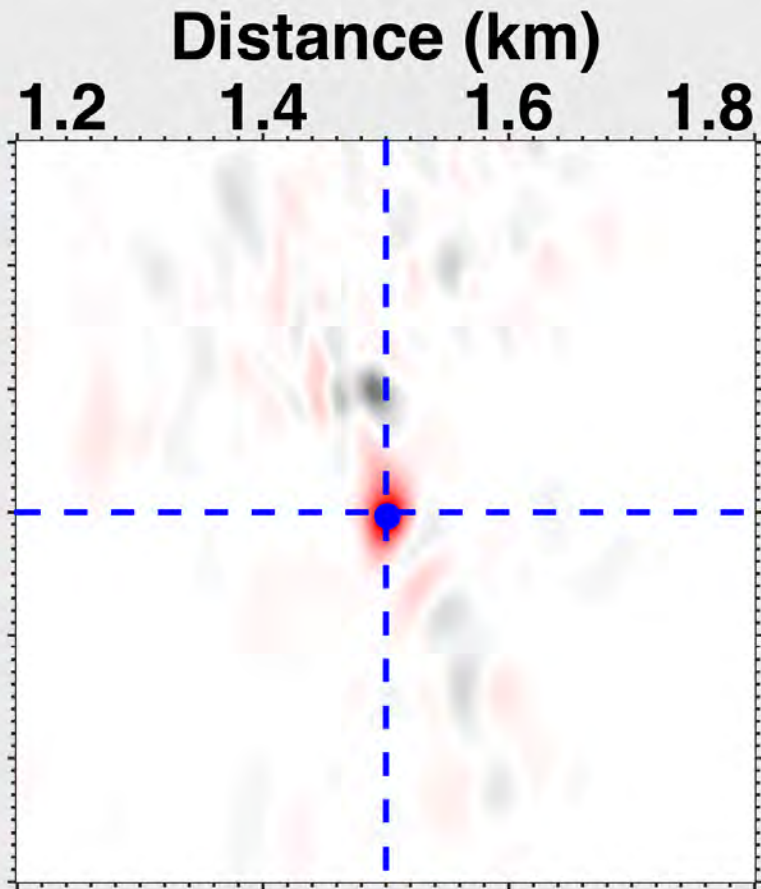
# Comparison



# Time reversal



# GmRTM

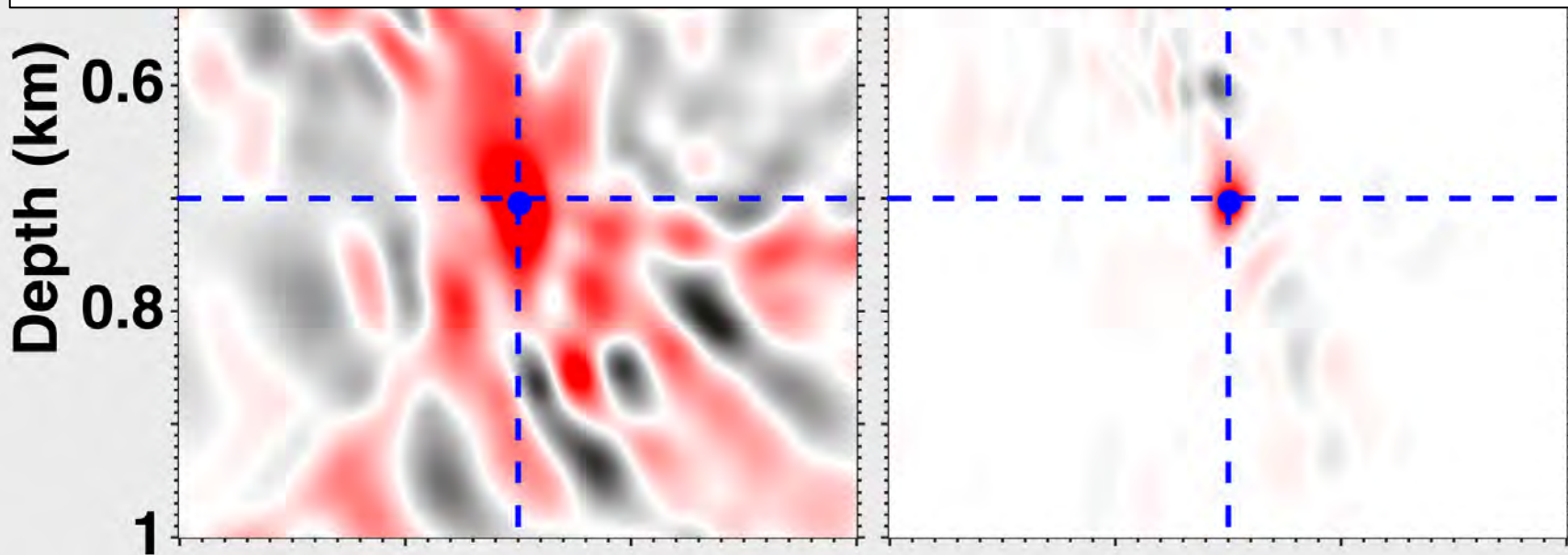


# Time reversal

# GmRTM

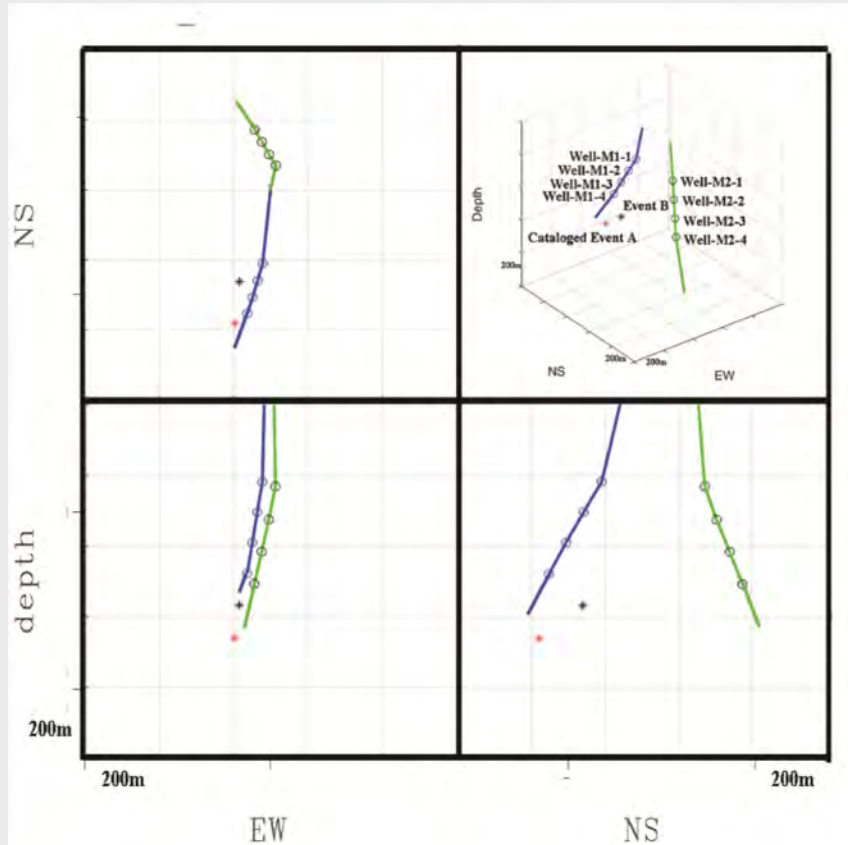
**GmRTM is efficient for :**

- locating with higher spatial resolution
- using long-duration signals (fracking, tremors...)
- enhancing weak signals (i.e., noisy signals)



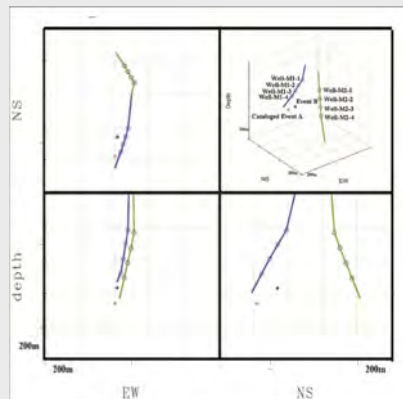
# Field data example (Fracking)

An oil field in Japan

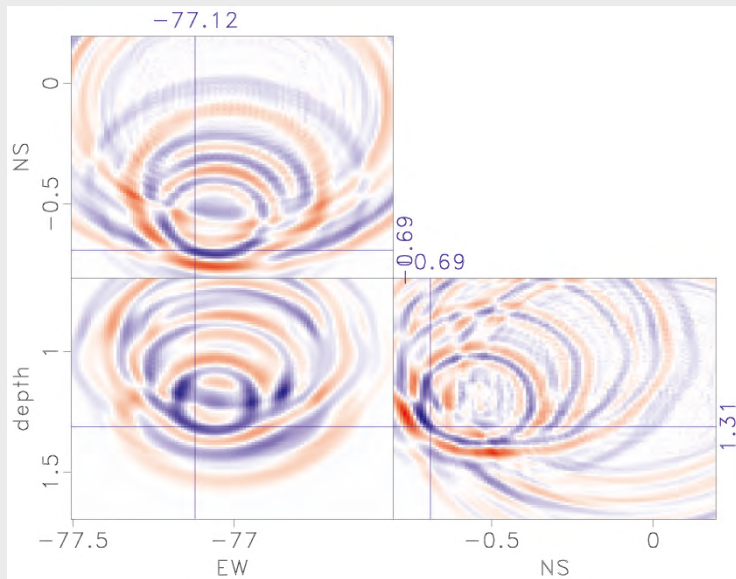


- Only 8 receivers available
- Challenging geometry

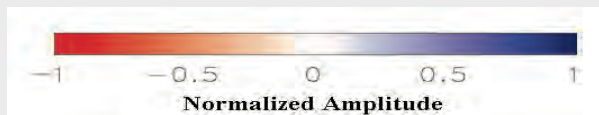
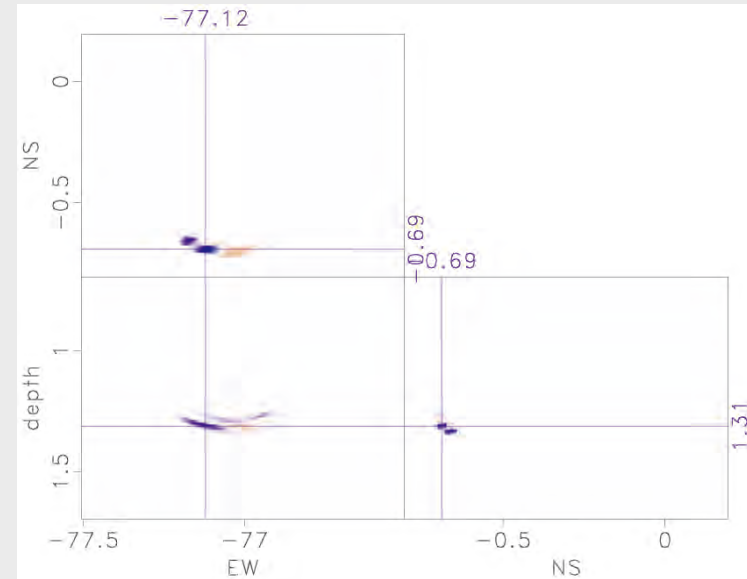
# Field data example (Fracking)



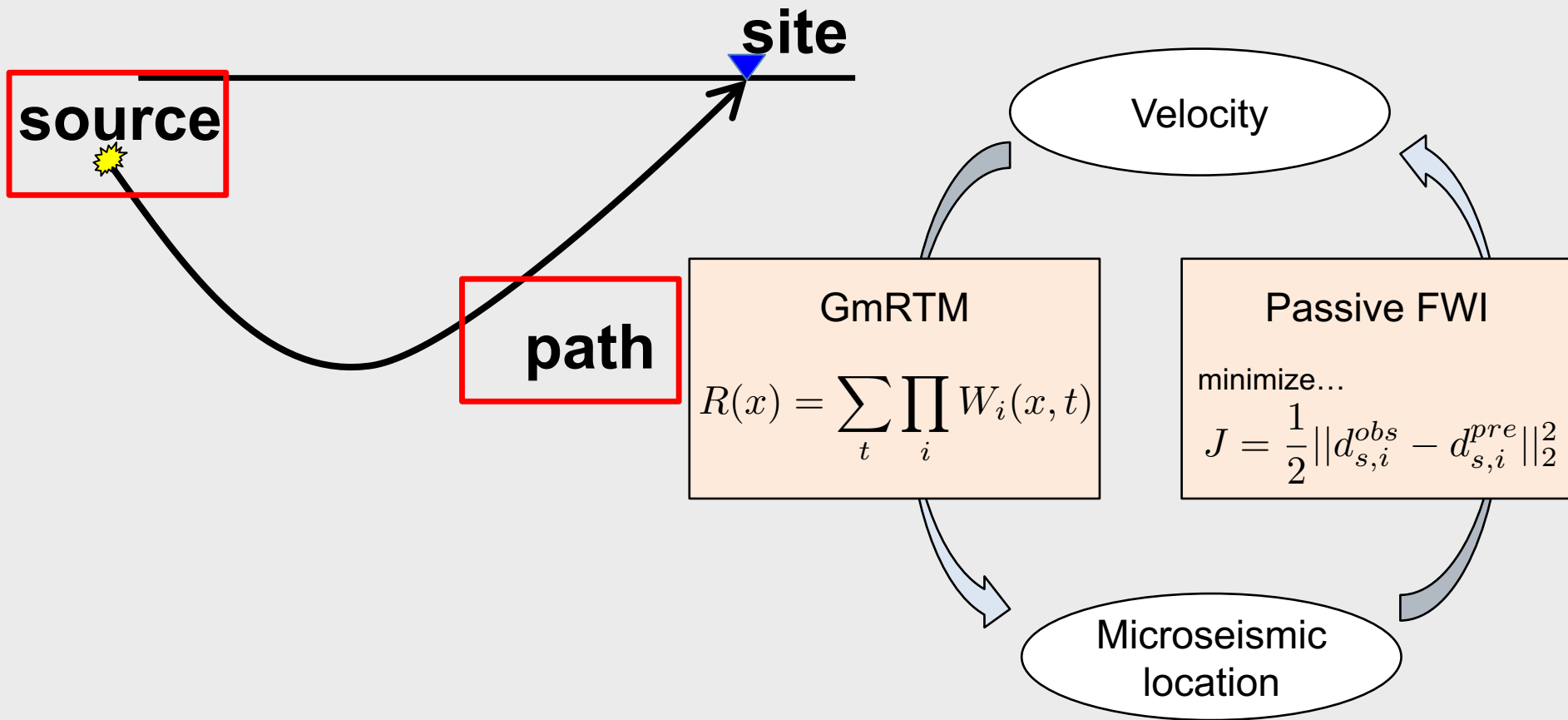
## Time reversal



## GmRTM

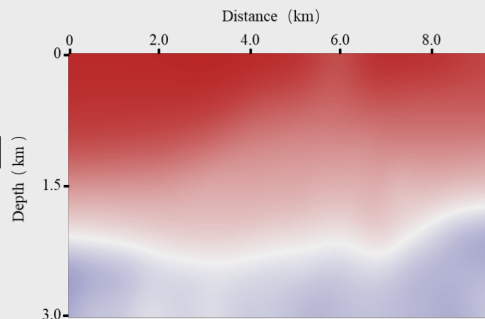


# Velocity update with microseismic data



# Velocity update with microseismic data

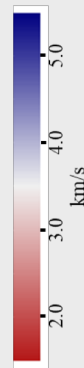
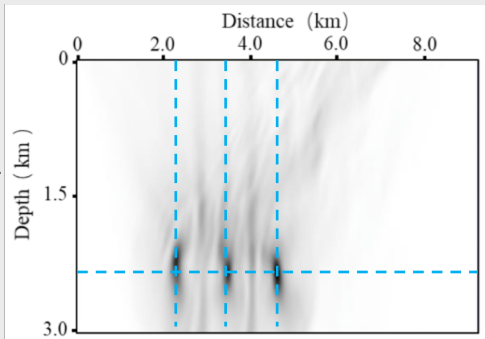
Initial velocity model



GmRTM

FWI

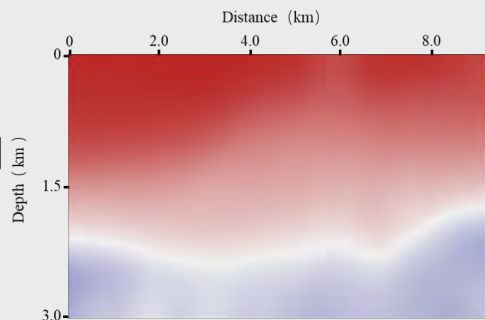
Initial source locations



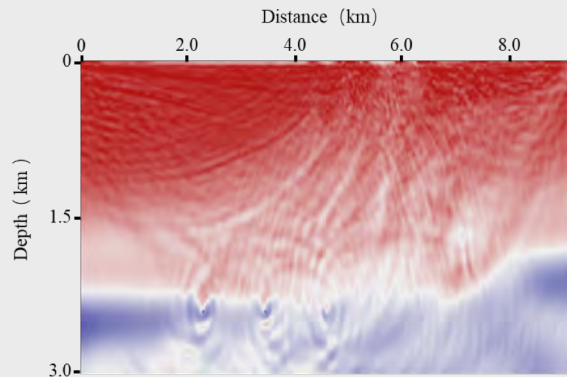


# Velocity update with microseismic data

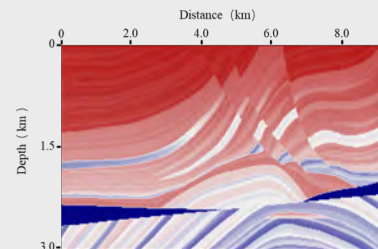
## Initial velocity model



## Inverted velocity model



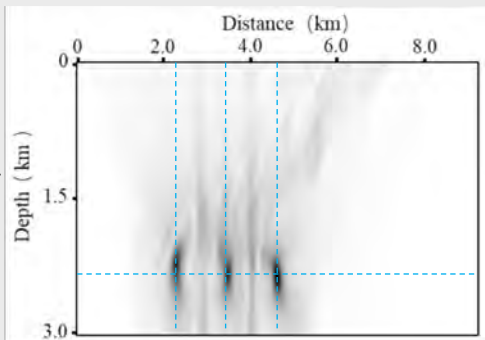
## True velocity model



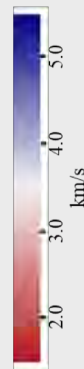
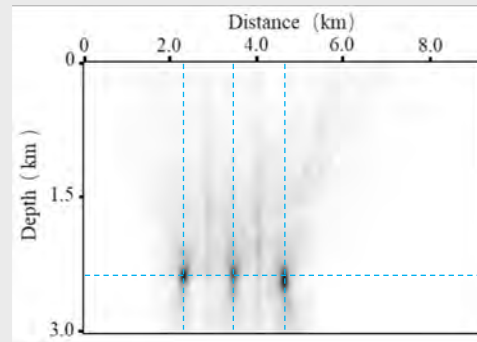
GmRTM

FWI

## Initial source locations

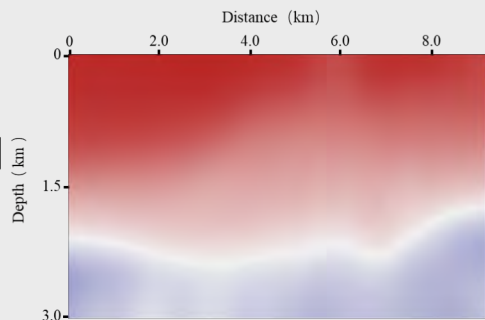


## Inverted source locations

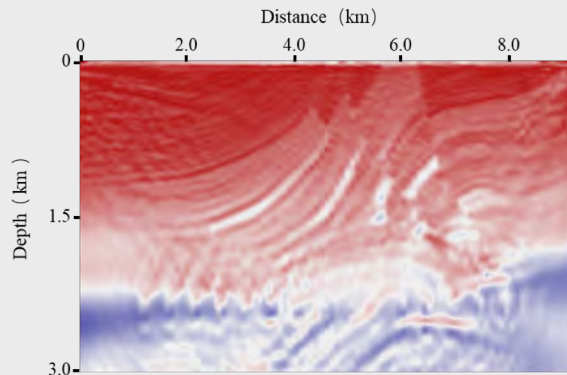


# Velocity update with microseismic data

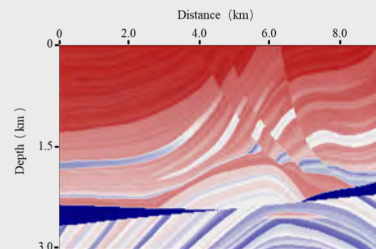
## Initial velocity model



## Inverted velocity model



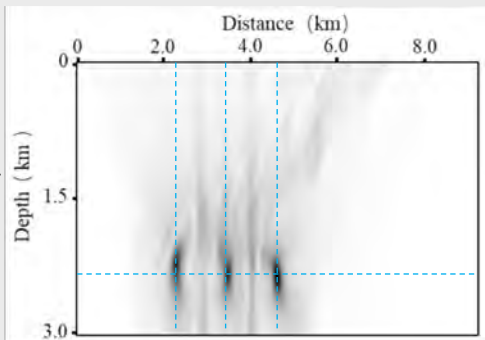
## True velocity model



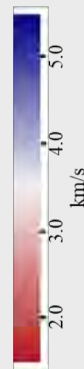
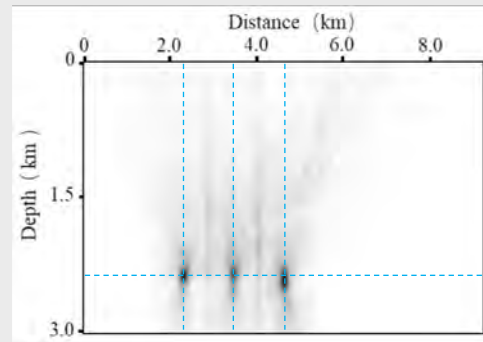
GmRTM

FWI

## Initial source locations



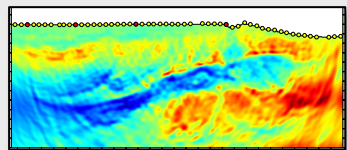
## Inverted source locations



# FWI for source parameter estimation

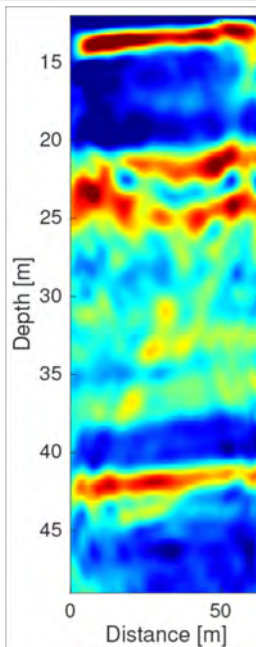
Cost function

$$E(\mathbf{v}_p, \mathbf{v}_s, \sigma_{xx}, \sigma_{zz}, \sigma_{xz}, w) = \sum_{i=1}^{N_s} \sum_{j=1}^{N_r} \sum_{k=1}^{N_t} (d_{mod}(\mathbf{v}_p, \mathbf{v}_s, \sigma_{xx}, \sigma_{zz}, \sigma_{xz}, w) - d_{obs})^2$$

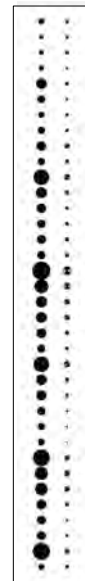


Field data example (crosswell active survey)

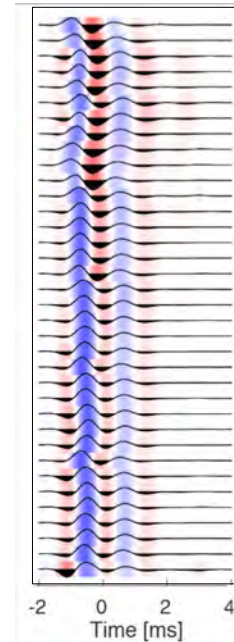
Vel model



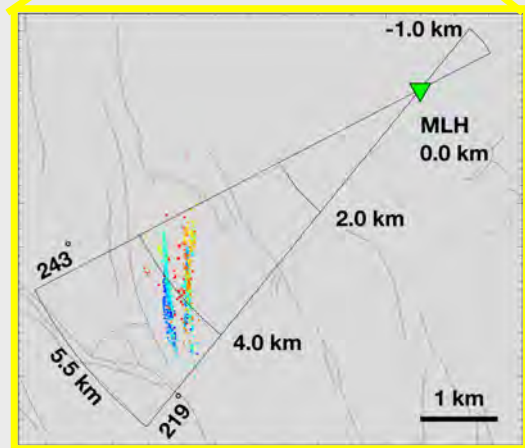
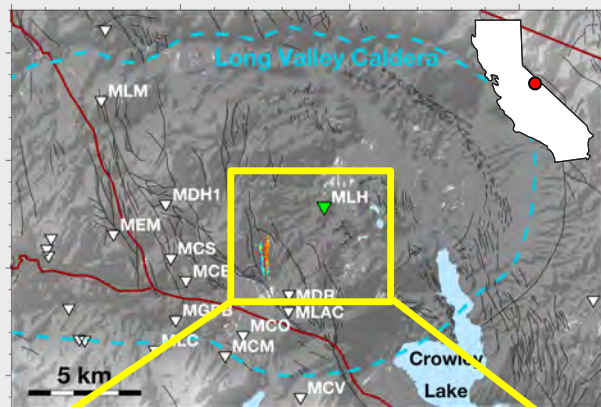
Radiation



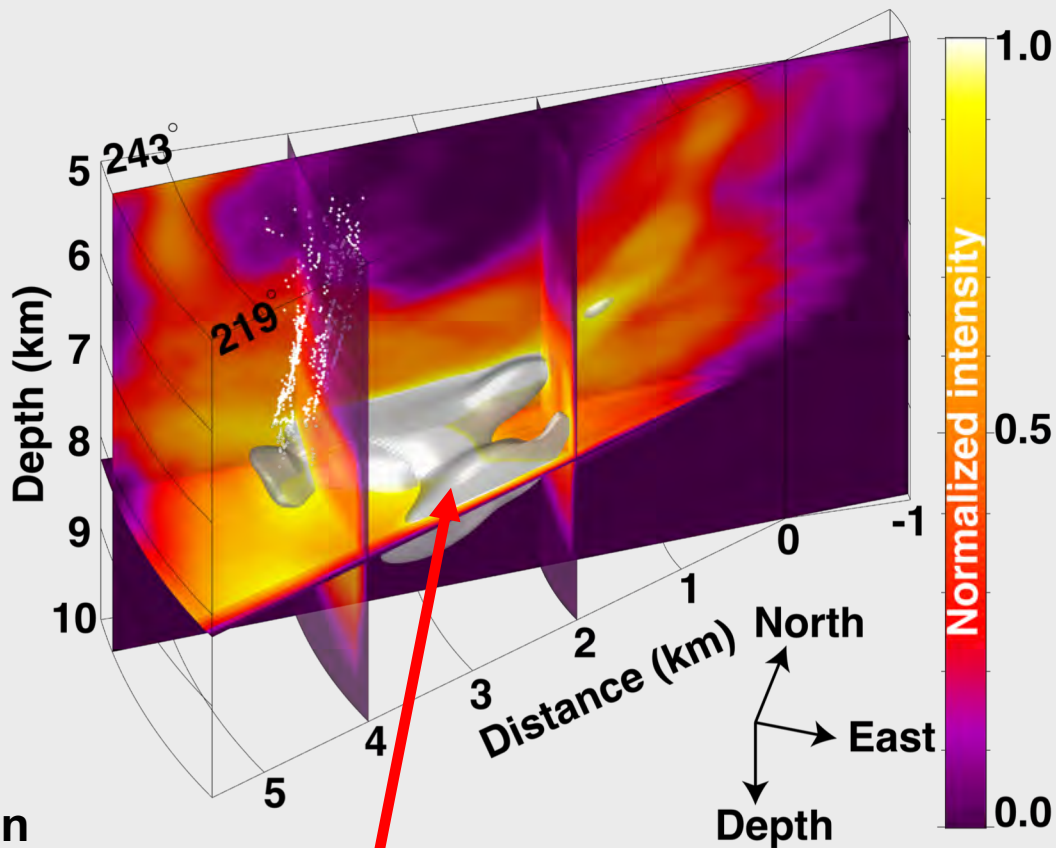
Source time func.



# Structure imaging with small earthquakes

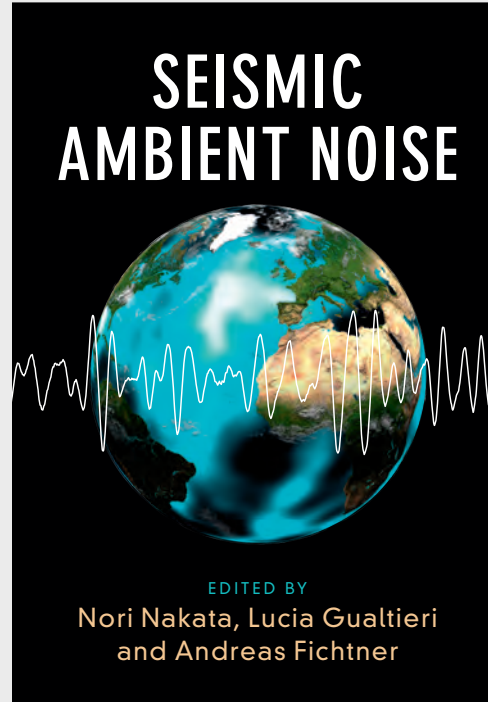
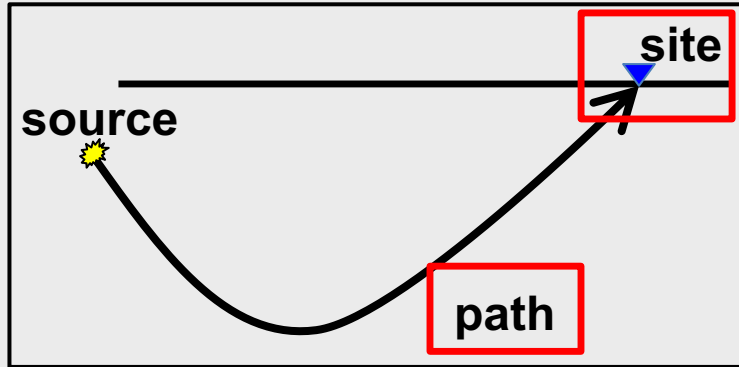


1 station  
800 earthquakes



Magma roof

# Ambient noise



A book about  
Seismic Ambient Noise

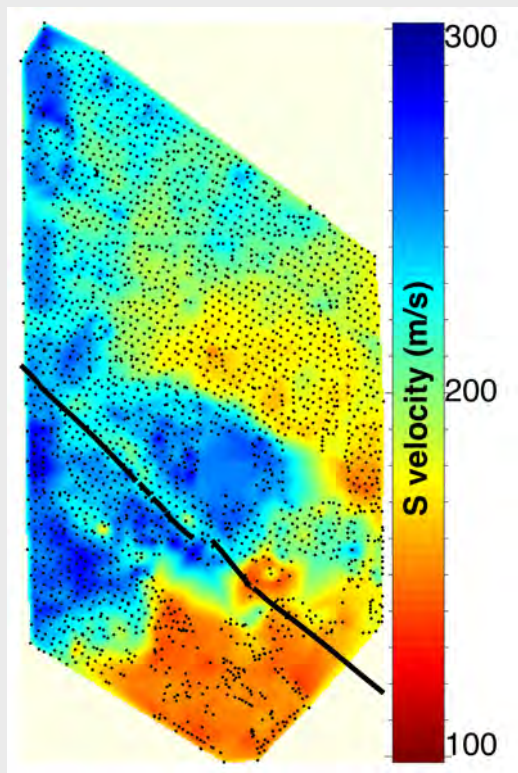
Cambridge University Press

370 pp

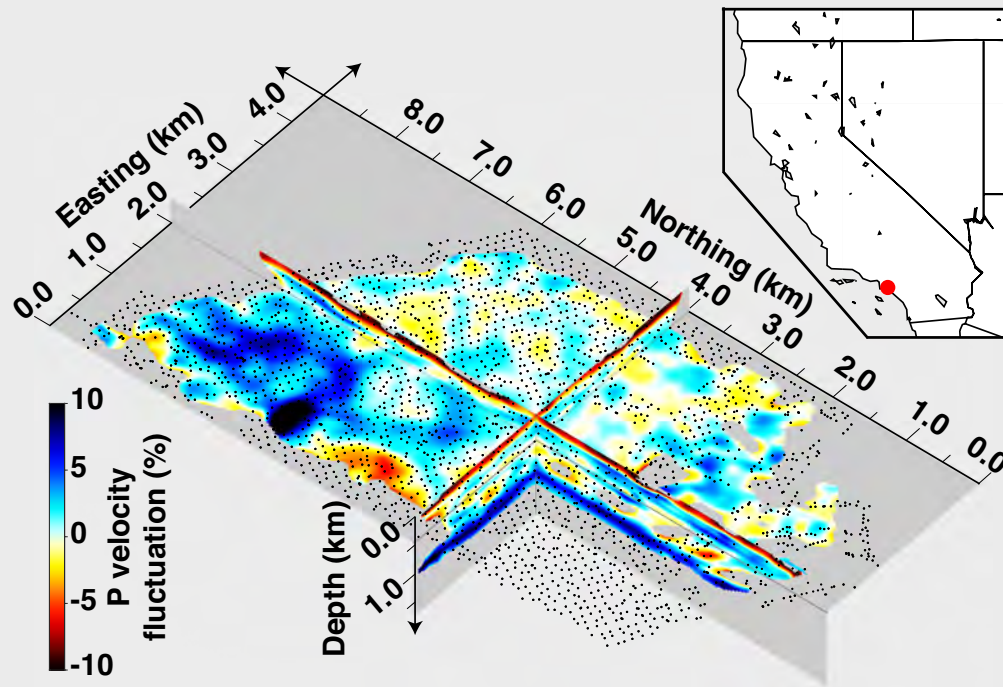
Published on May 2, 2019

# Velocity estimation

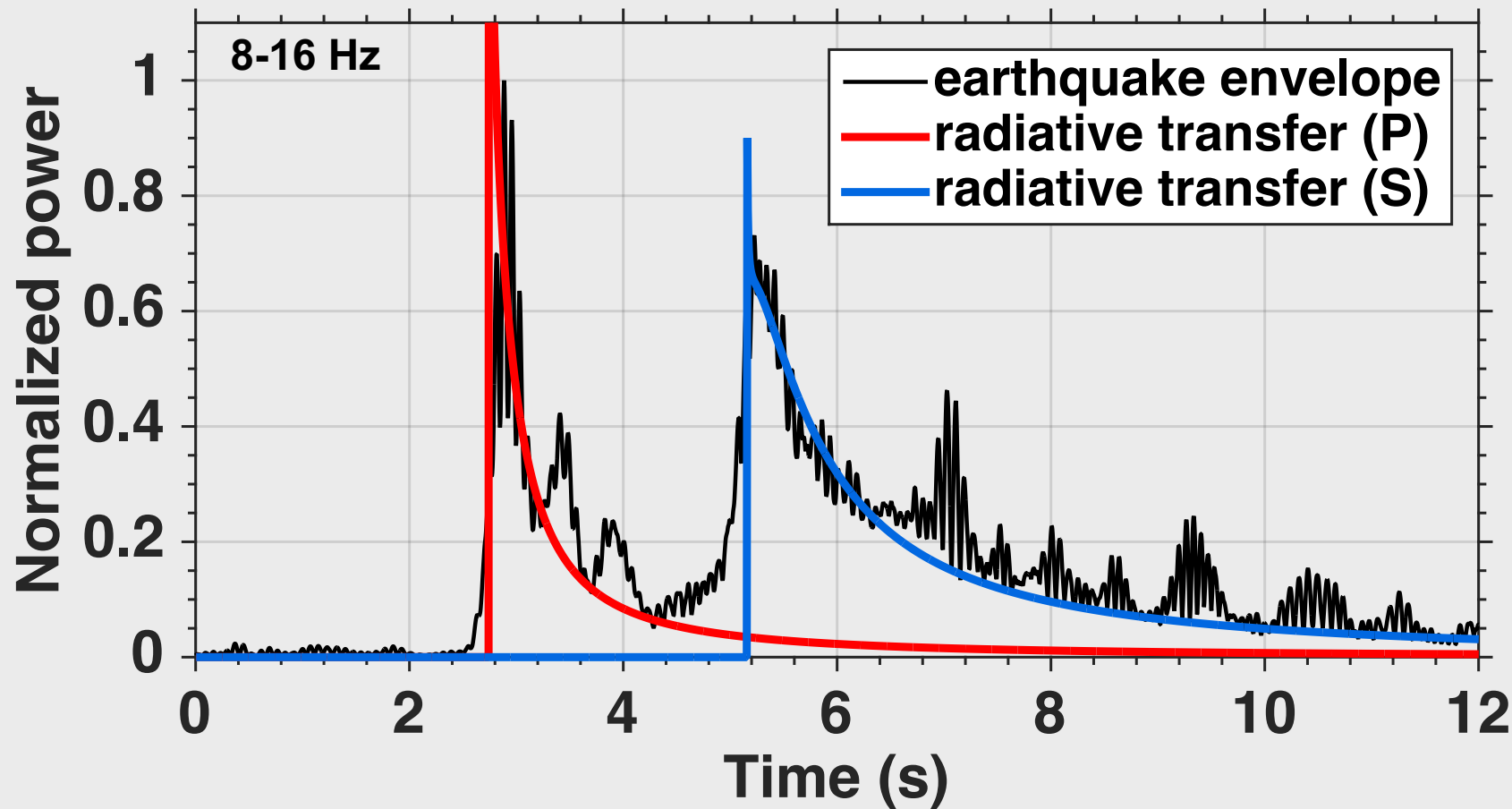
Near-surface  
S velocity



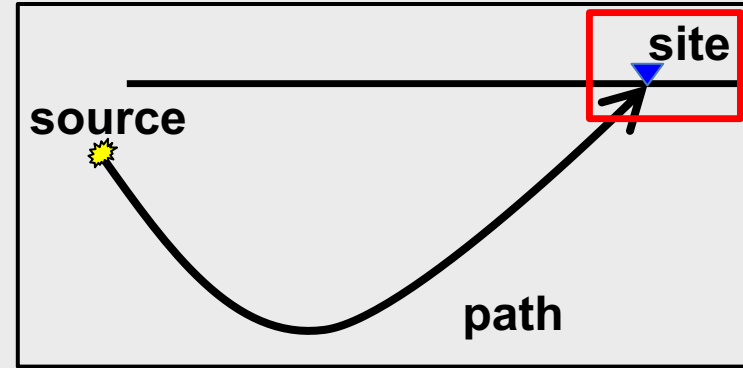
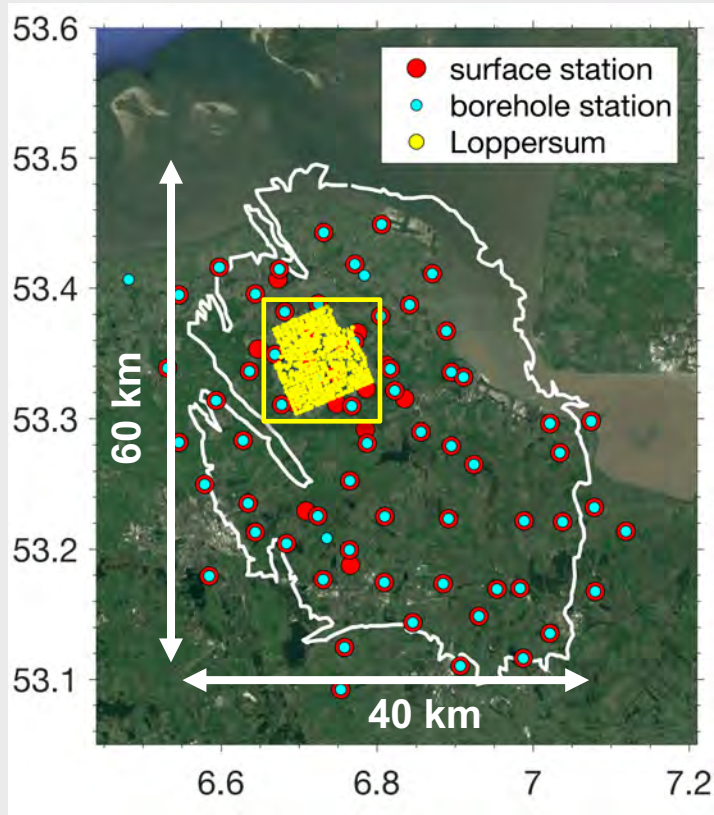
3D P velocity



# High-frequency ground motion prediction



# Groningen Gas Field



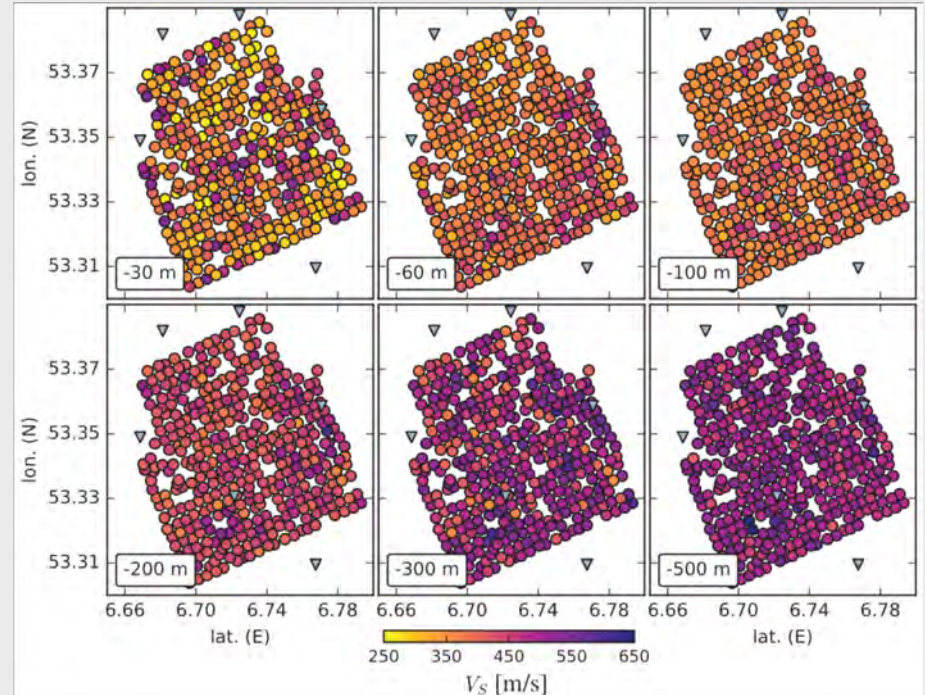
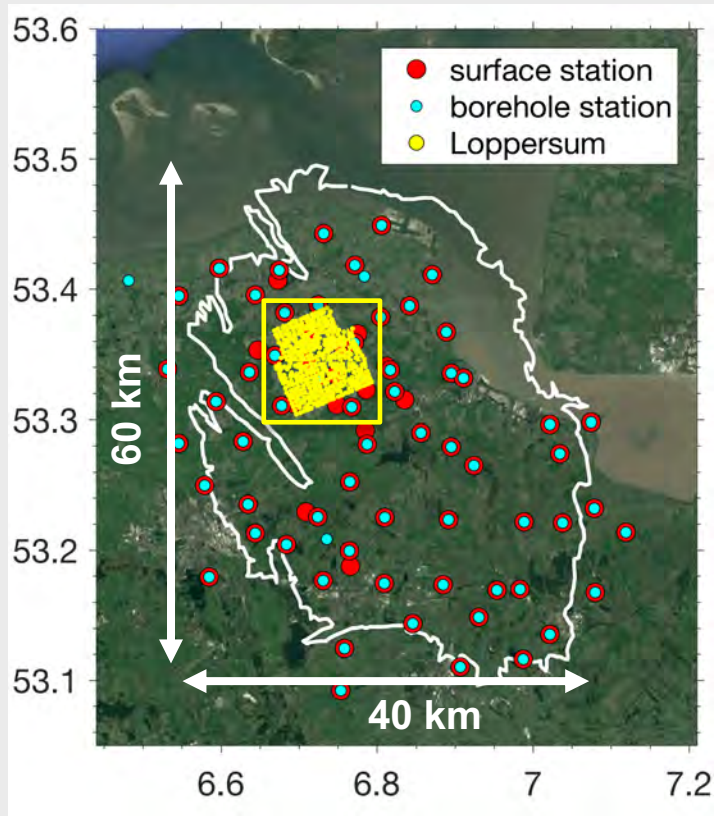
- **415 stations**
- **3 components**
- **Receiver spacing: 400 m**
- **One-month continuous record**



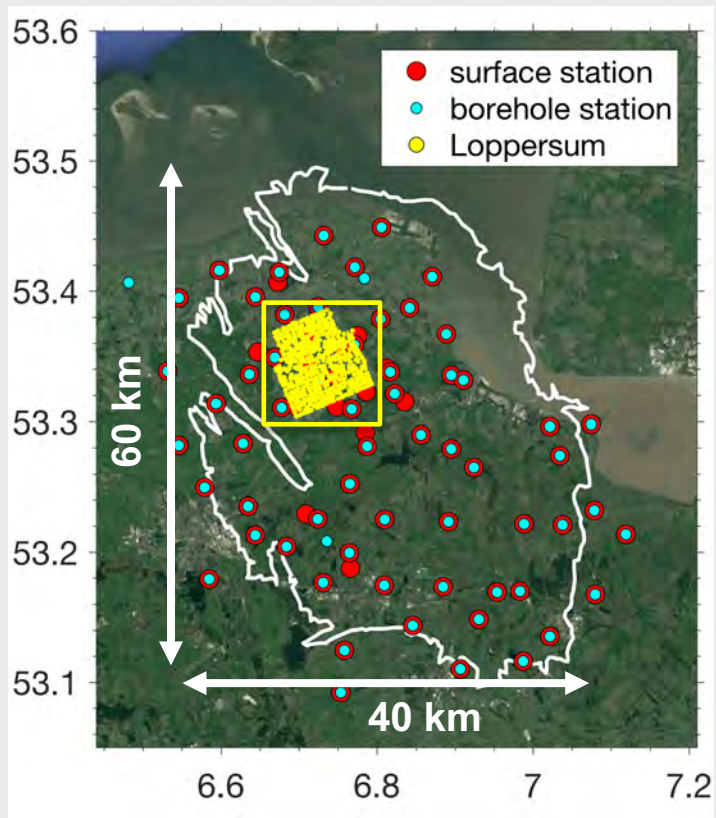
# Groningen Gas Field

Near-surface velocity model estimated from

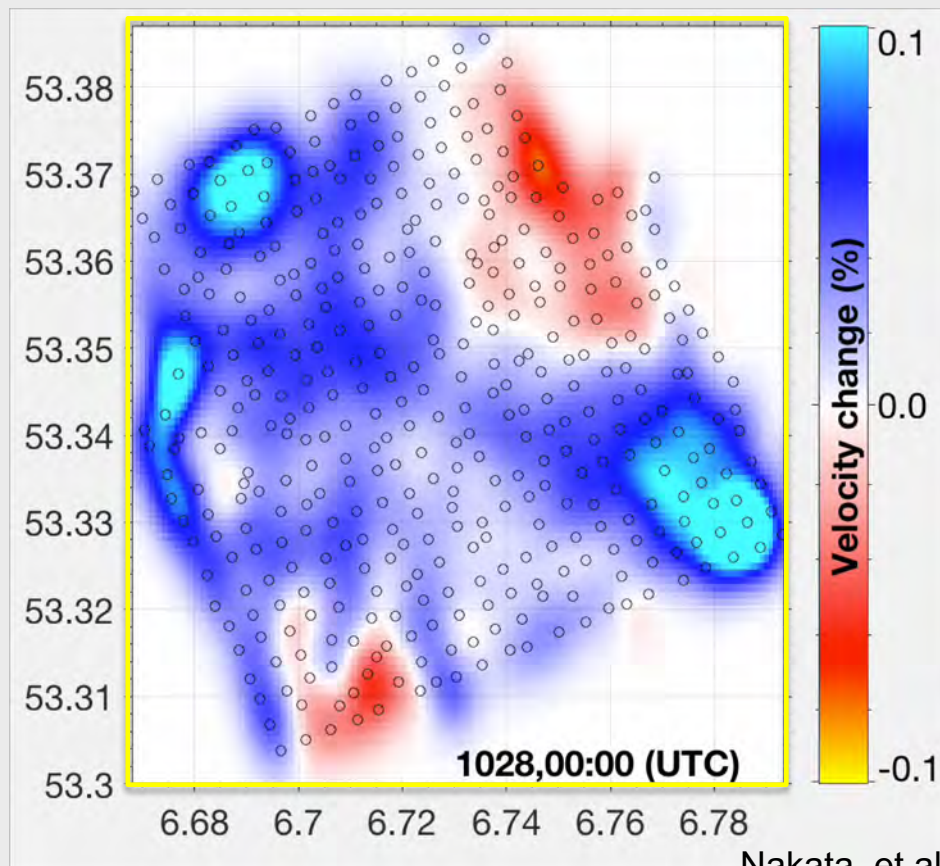
- H/V
- Rayleigh and Love waves



# Groningen Gas Field

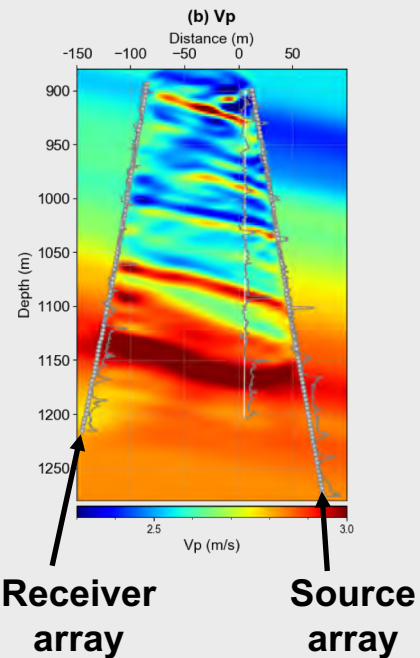


## Hourly seismic velocity change

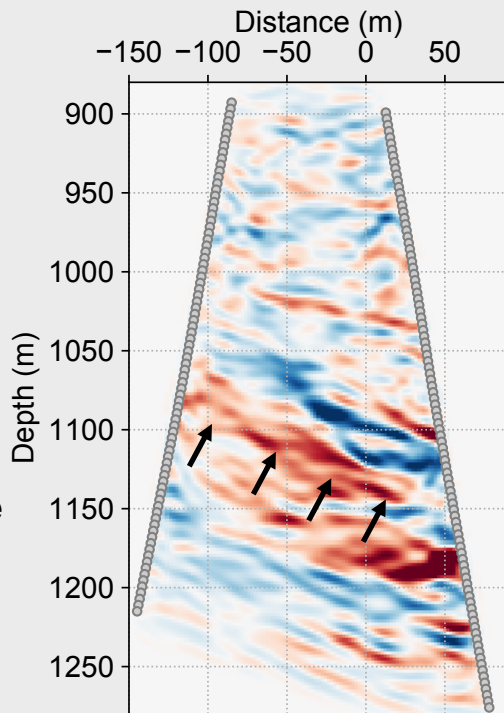


# Time-lapse FWI (CO<sub>2</sub> monitoring)

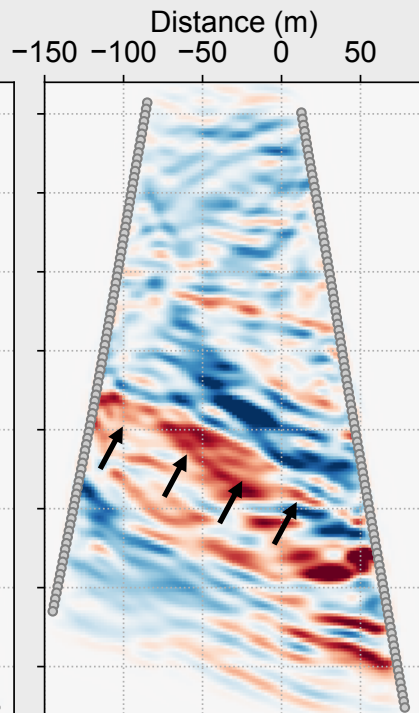
**Baseline**



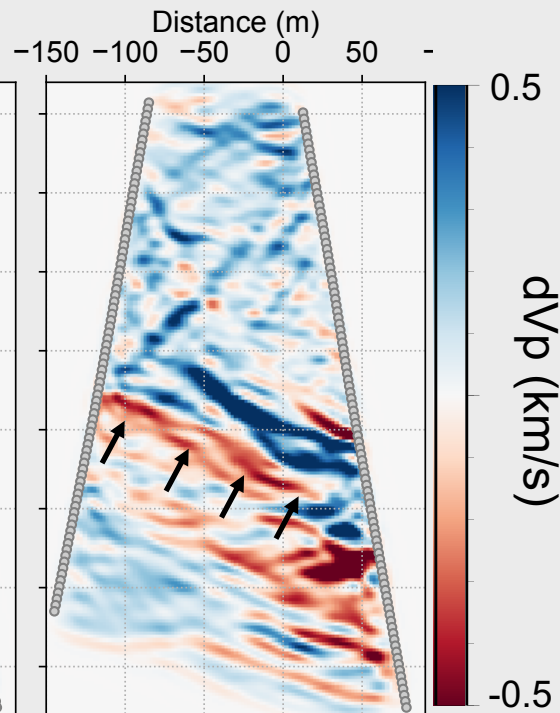
**MN1 – Baseline**  
**(3000 t injected)**



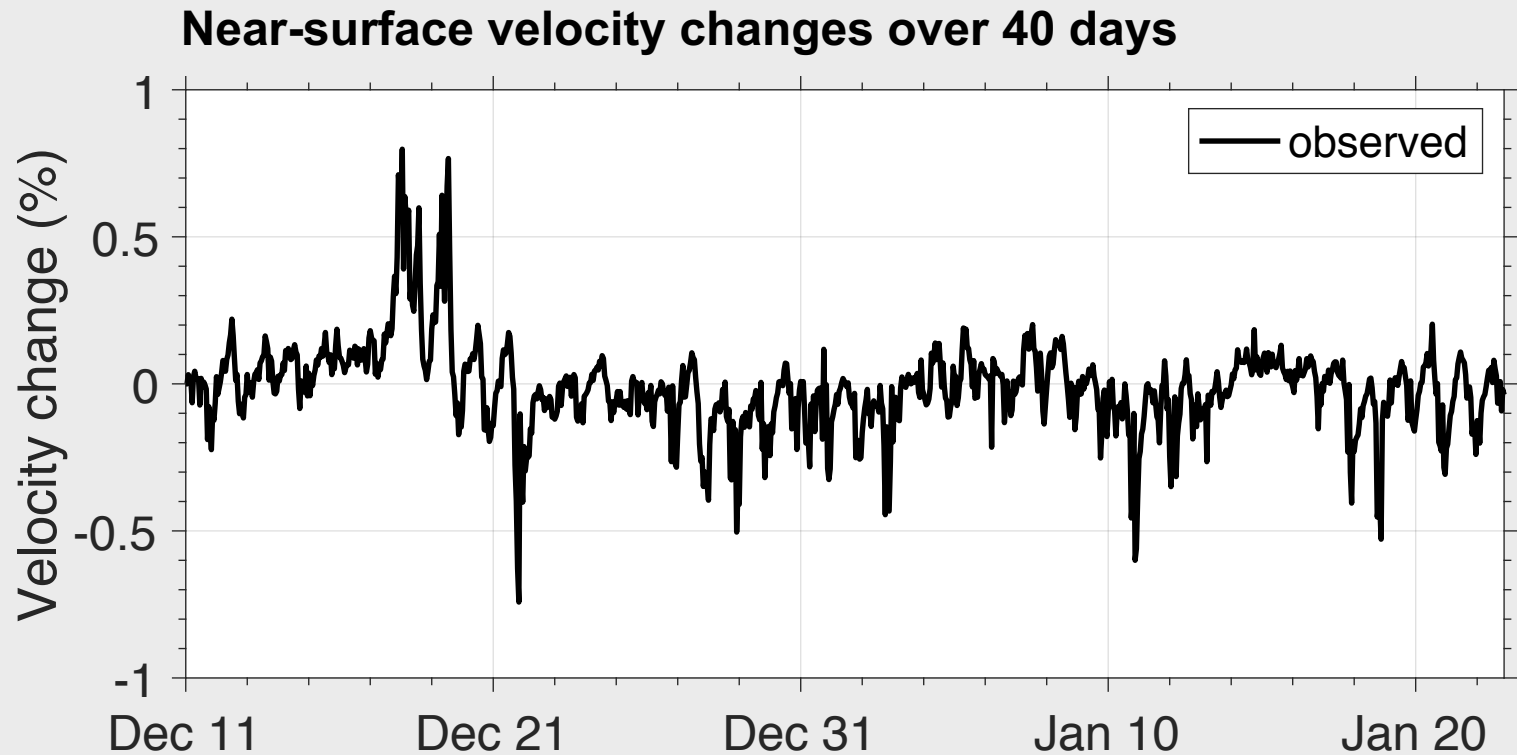
**MN2 – Baseline**  
**(6000 t injected)**



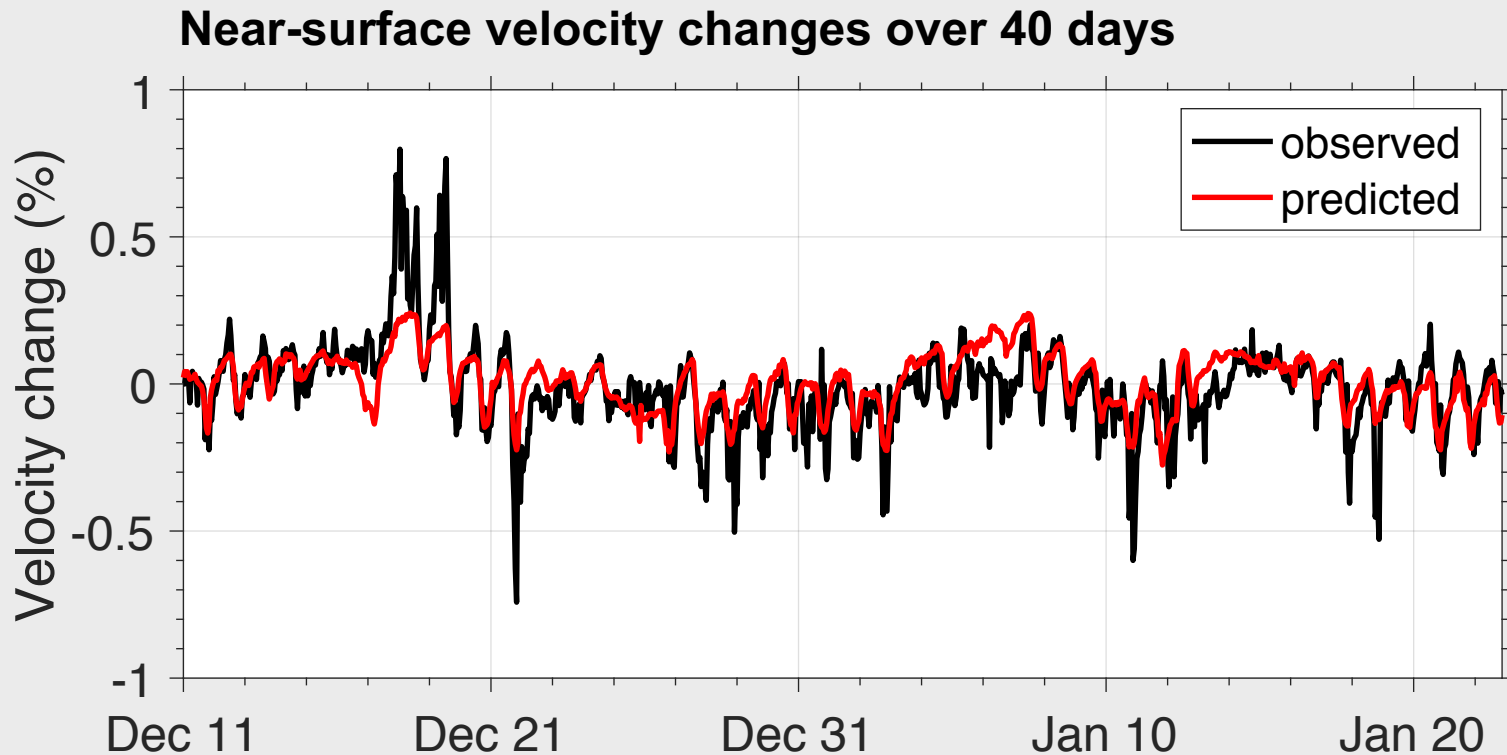
**MN3 – Baseline**  
**(9000 t injected)**



# Velocity change prediction by Machine learning

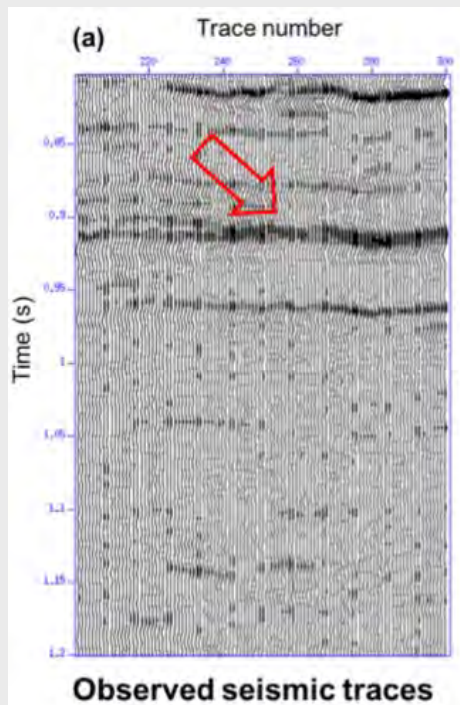


# Velocity change prediction by Machine learning



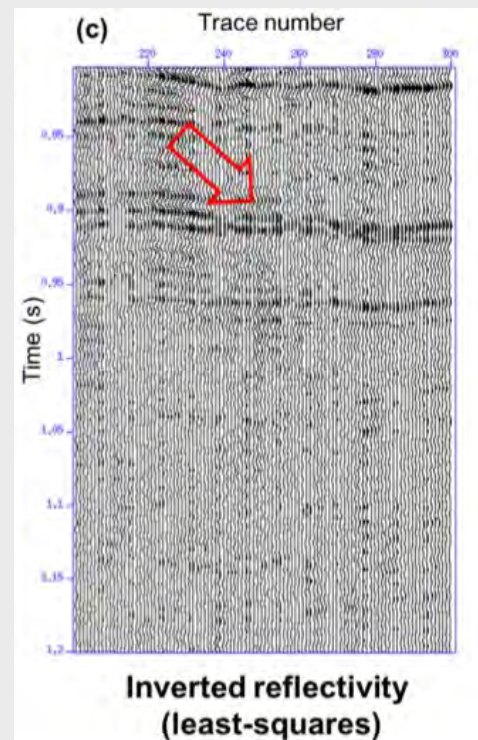
**Prediction using machine-learning regression analysis**  
***Input data: first 20 days & environmental parameters***

# Reflectivity inversion



Reflectivity inversion based on conventional deconvolution (least-squares inversion)

$$L = \frac{1}{2} \|s(t) - h(t) * r'(t)\|_2^2$$

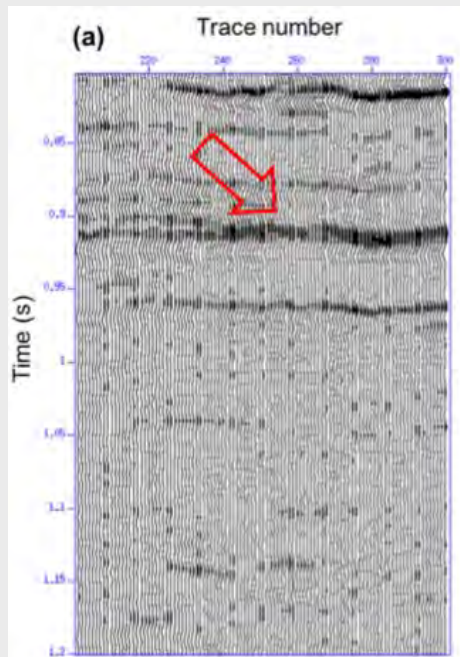


$$s(t) = h(t) * r(t)$$

observed data      source wavelet      reflectivity

$$r'(t)$$

# Reflectivity inversion with Machine Learning



$s(t) = h(t) * r(t)$   
↑ source wavelet  
↑ observed data

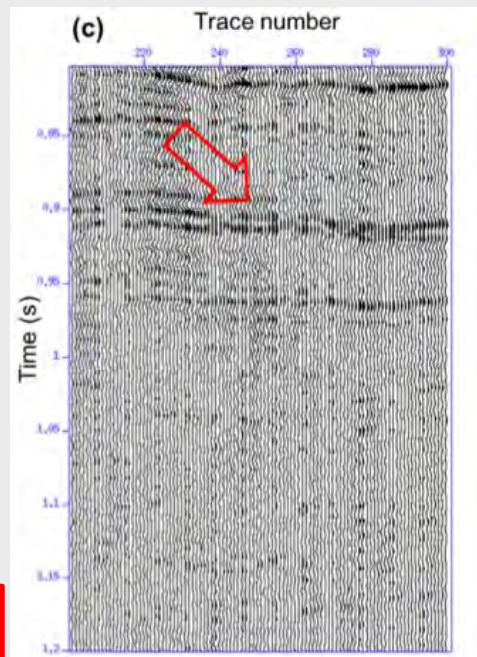
Reflectivity inversion based on conventional deconvolution (least-squares inversion)

$$L = \frac{1}{2} \|s(t) - h(t) * r'(t)\|_2^2$$

$$L = \frac{1}{2} \|\underbrace{r_s(t)}_{\text{synthetic data}} - \underbrace{h_{\Theta}^{\dagger}(t)}_{\text{Mapping operator}} * \underbrace{s_s(t)}_{\text{observed data}}\|_2^2$$

synthetic data

Mapping operator

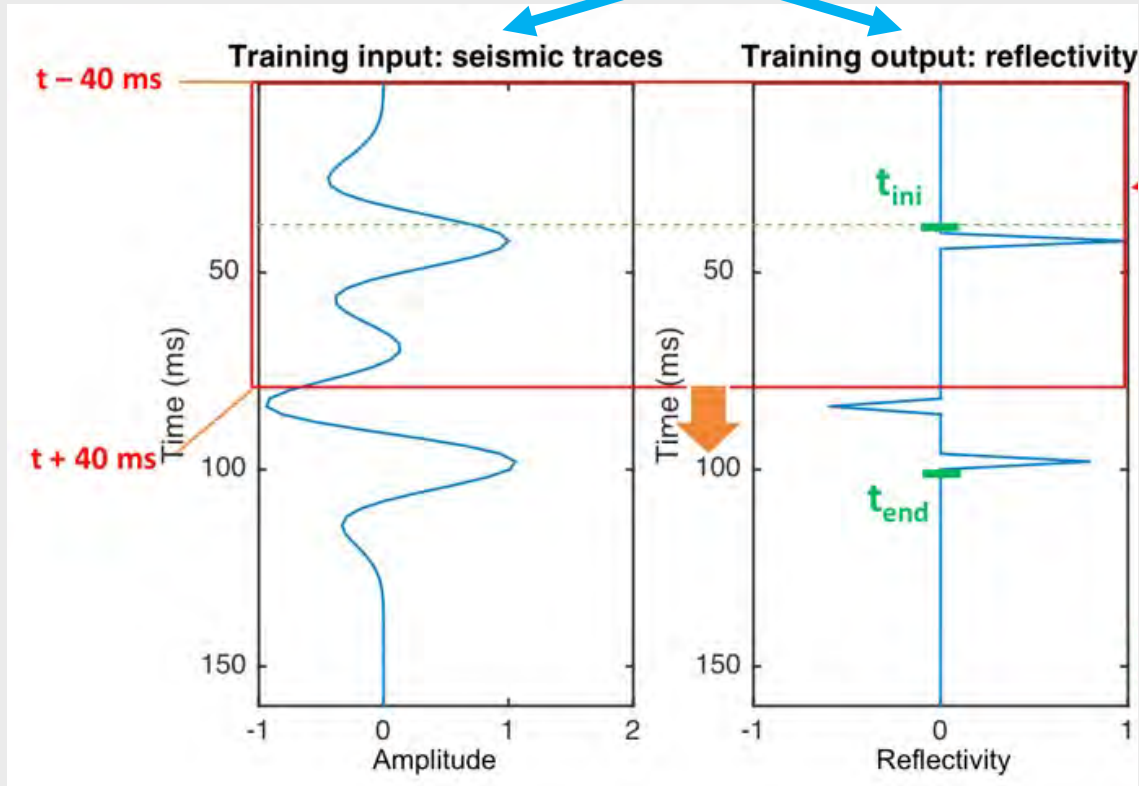


Inverted reflectivity (least-squares)

$r'(t)$

# Synthetic training set

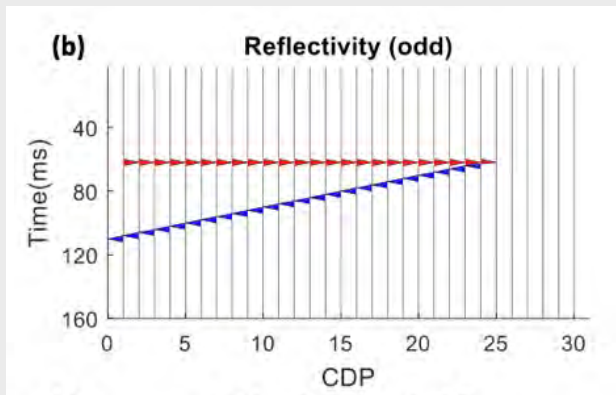
$$L = \frac{1}{2} \| r_s(t) - h_{\Theta}^{\dagger}(t) * s_s(t) \|_2^2$$



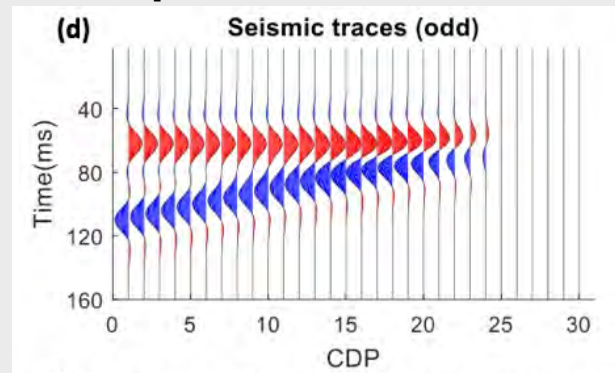


# Resolution test

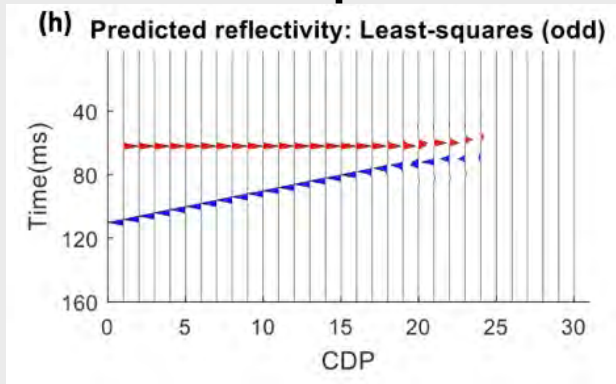
## True model



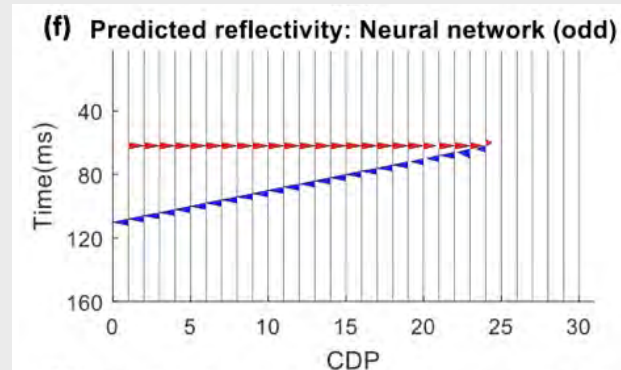
## Input seismic data



## Least squares

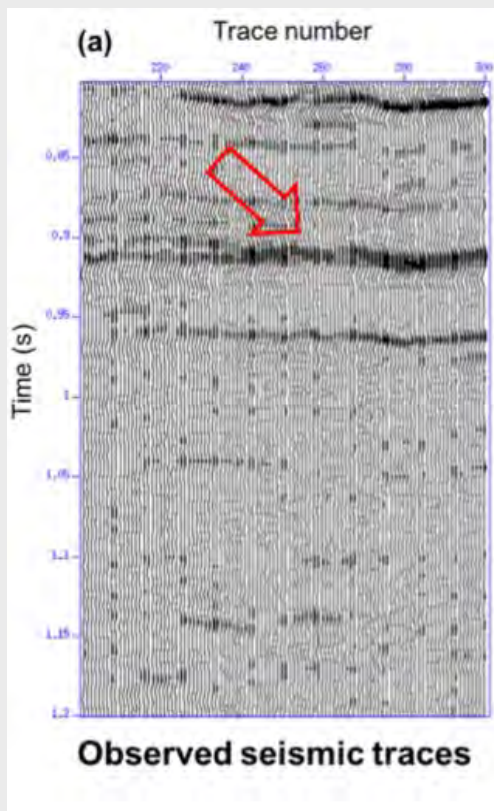


## Neural network

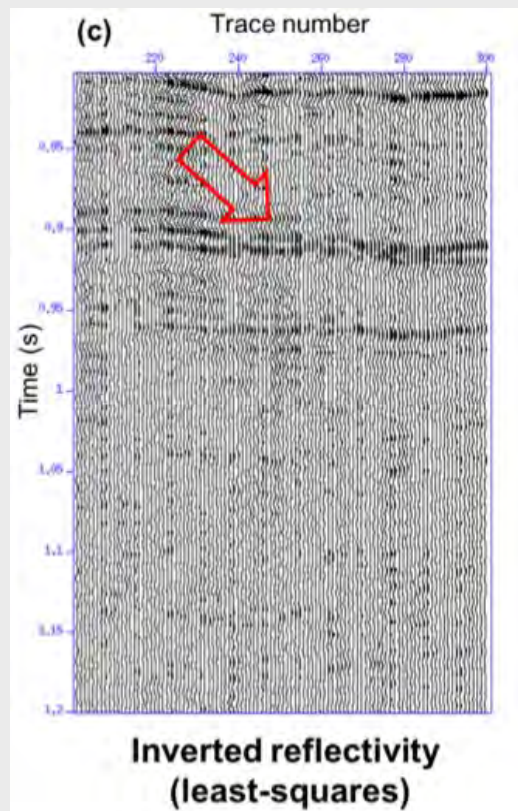


# Field data example

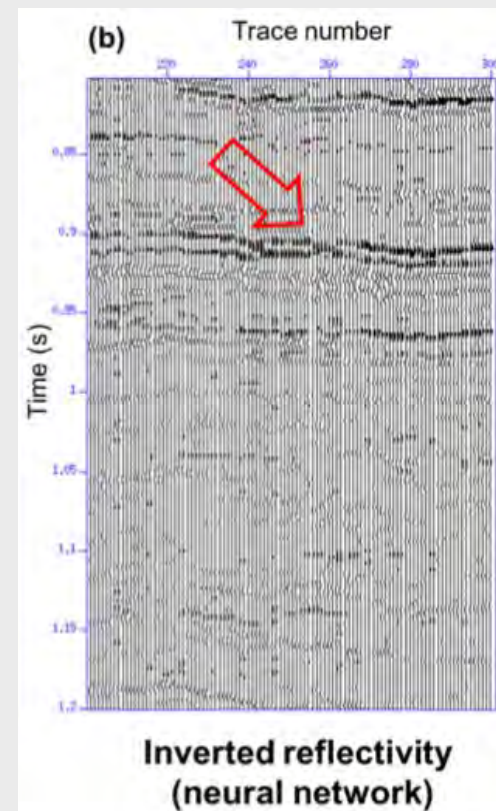
## Input seismic data



## Least squares



## Neural network



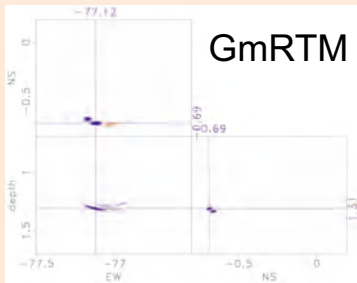
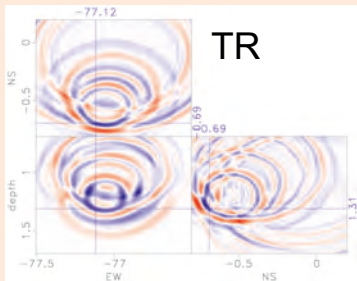
# Studies for human-induced seismicity

source

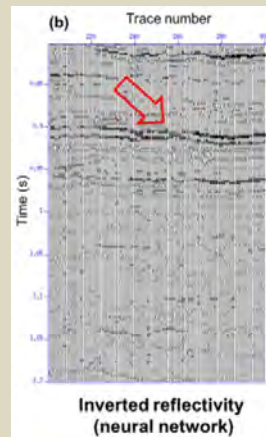
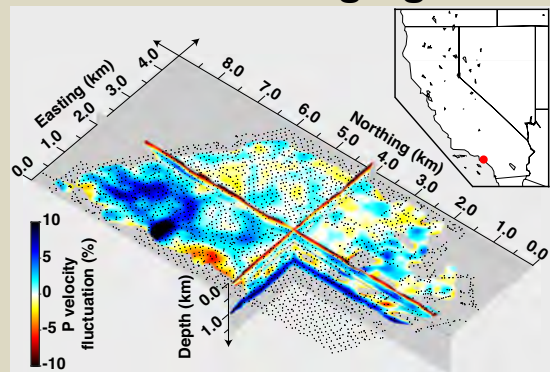
site

path

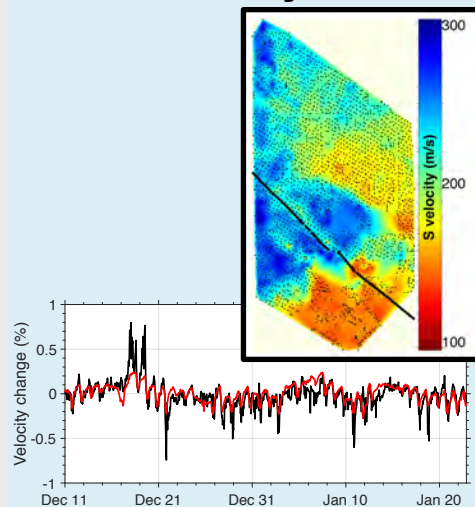
Source parameters of micro earthquakes



3D/4D High-resolution structural imaging



Near surface velocities and their dynamics



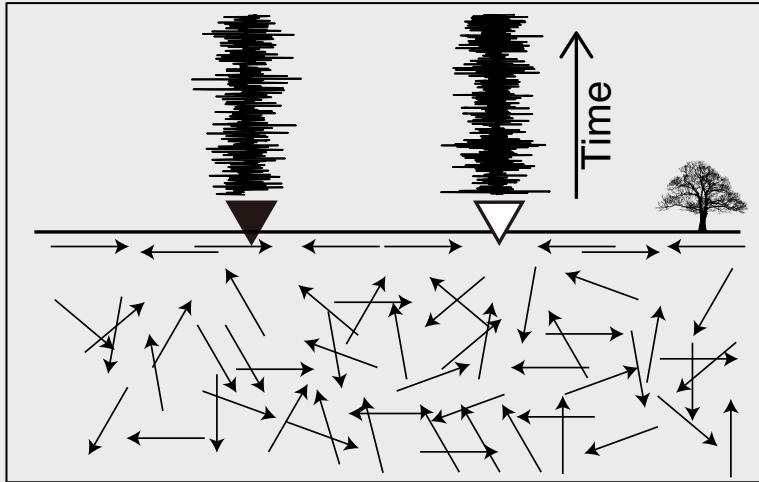
Publications:  
<http://www.mit.edu/~nnakata>



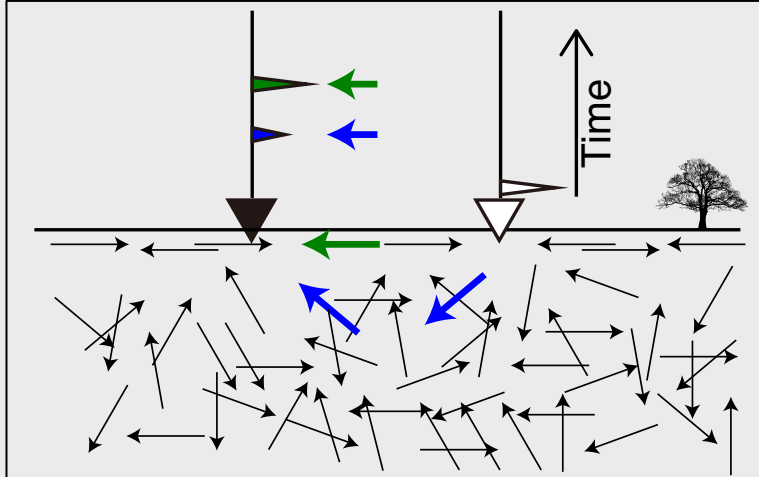




# Ambient noise correlation



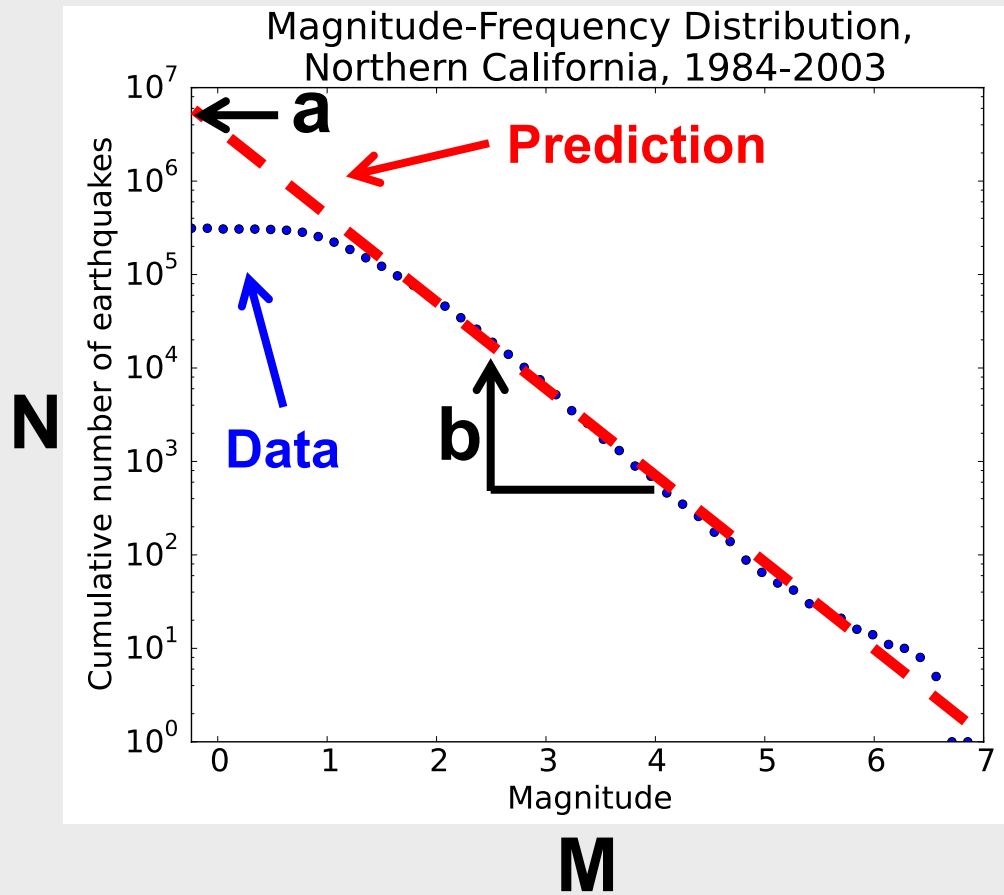
= ambient-field  
correlation  
∈ seismic interferometry



## Processing

- crosscorrelation
- spectral whitening
- time and/or space averaging
- normalization
- etc...

# Small EQs occur more frequently than large EQs



Gutenberg-Richter law (*b* value)

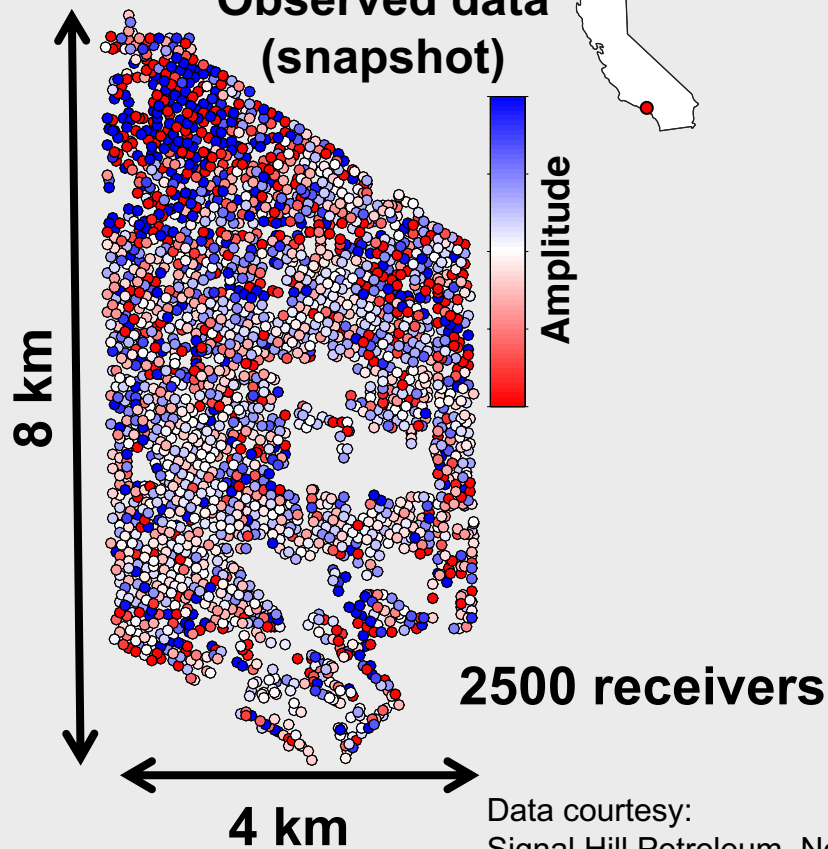
$$\log_{10} N = a - bM$$



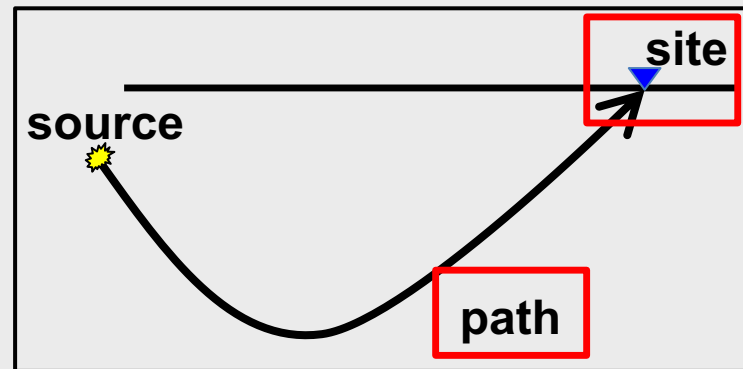
# Ambient noise

Long Beach array (2012)

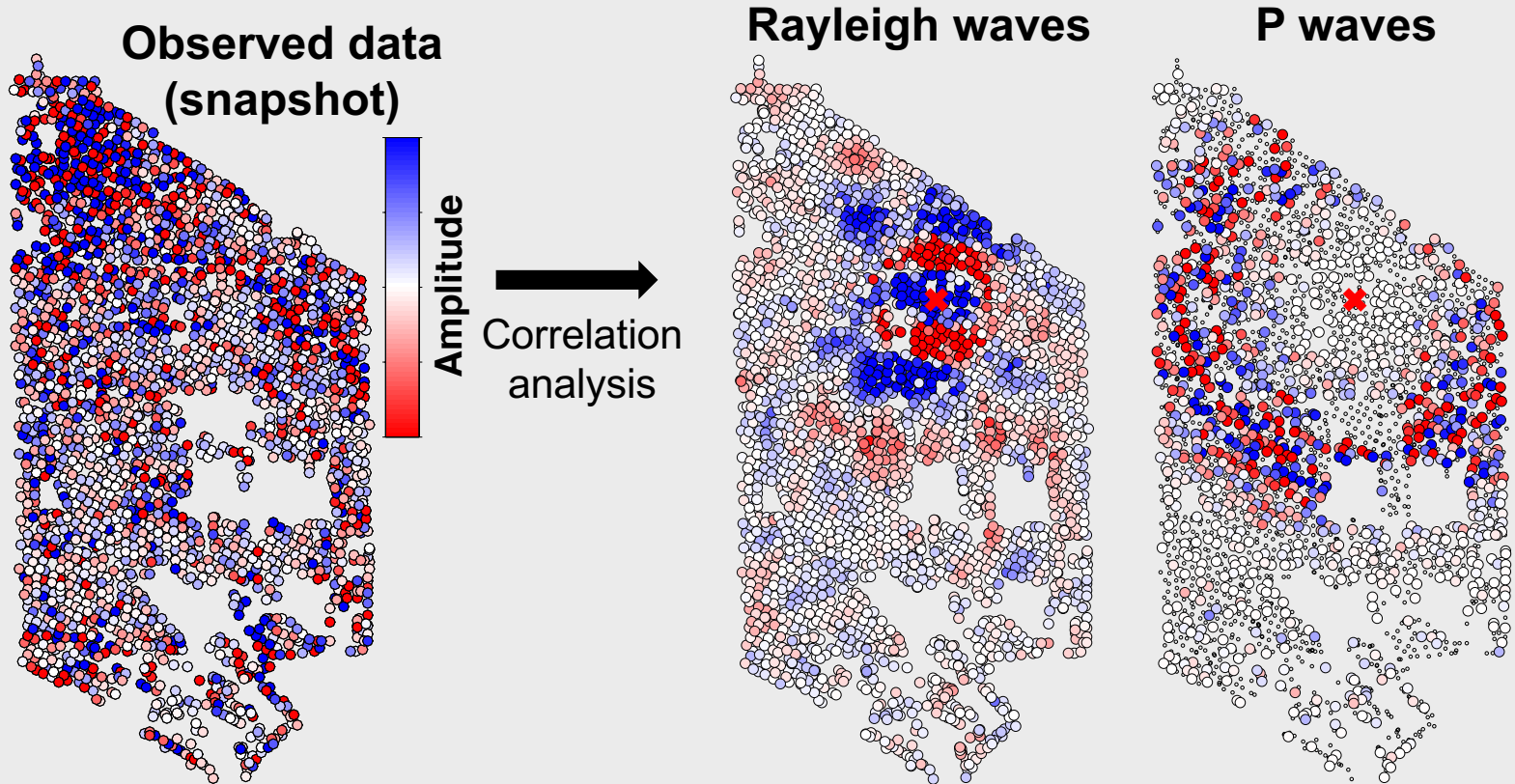
Observed data  
(snapshot)



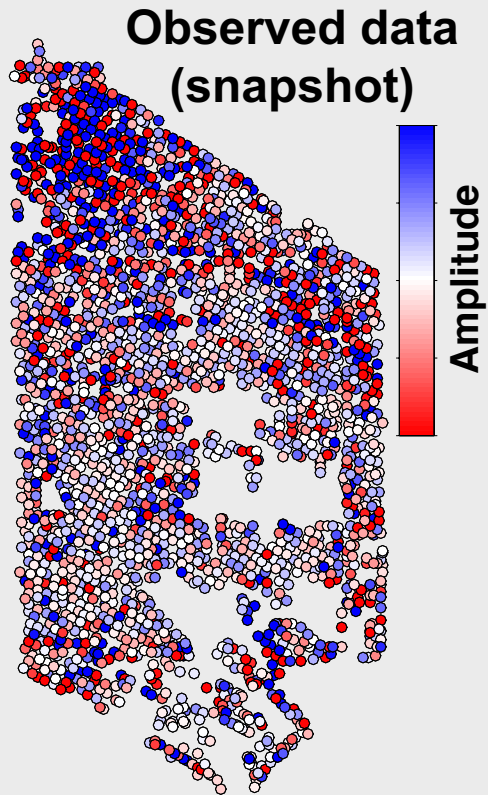
Data courtesy:  
Signal Hill Petroleum, NodalSeismic



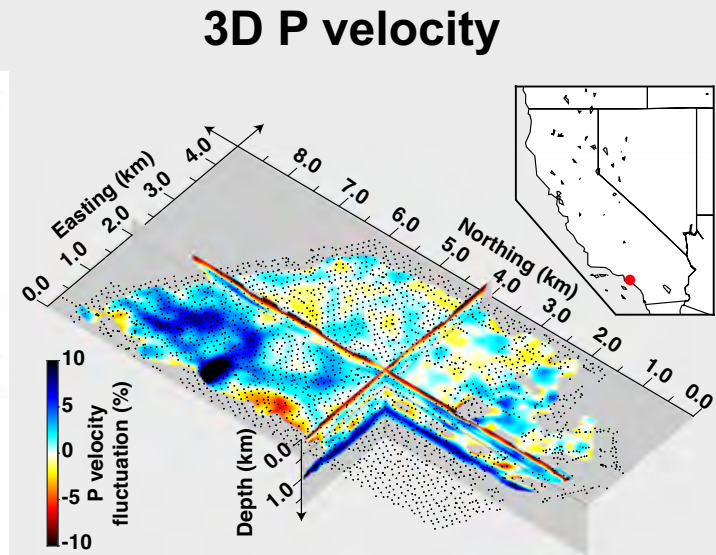
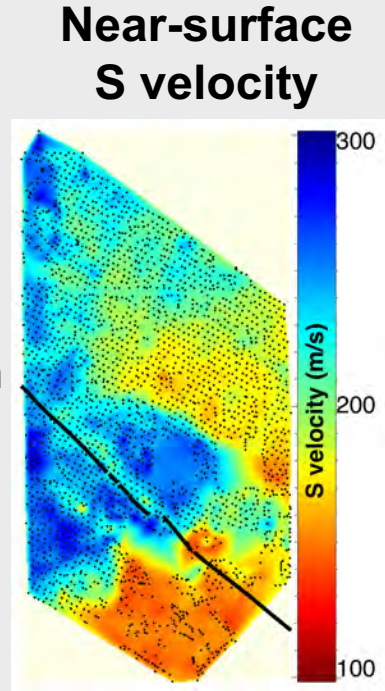
# Data mining to extract coherent waves



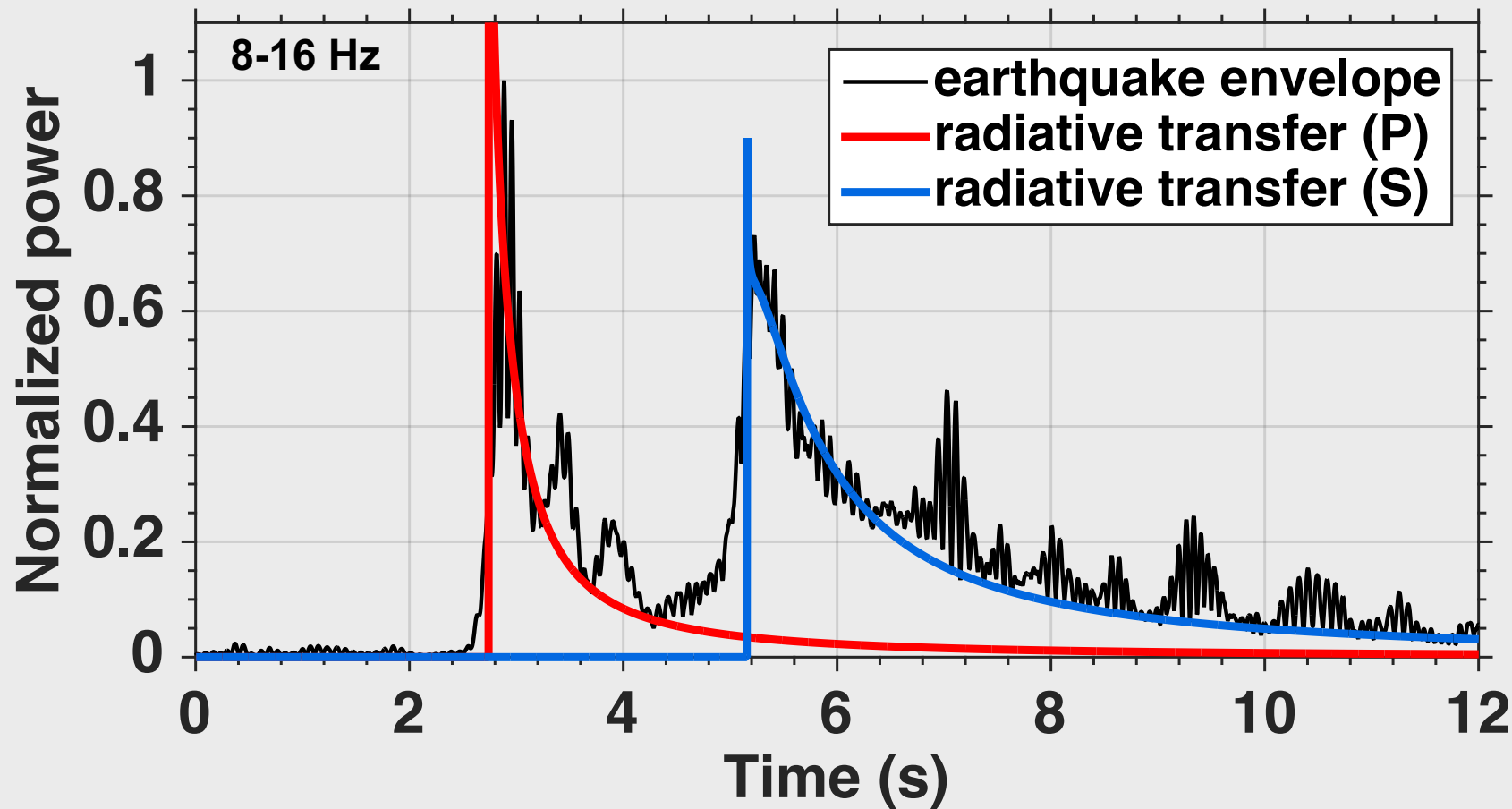
# Velocity estimation



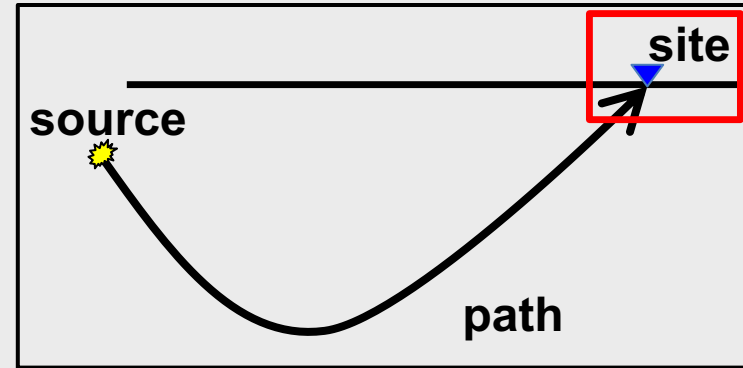
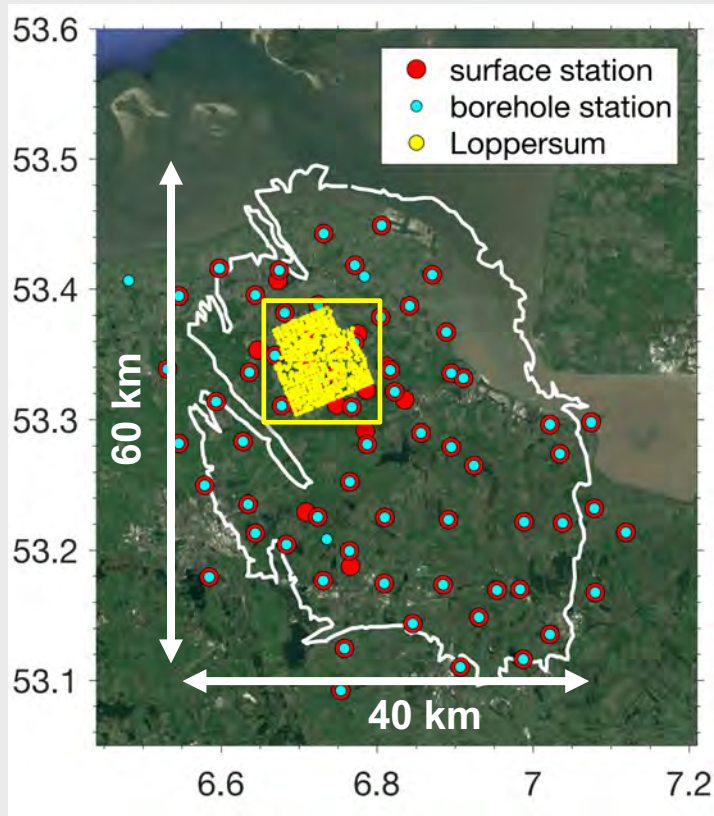
Correlation  
analysis



# High-frequency ground motion prediction



# Groningen Gas Field

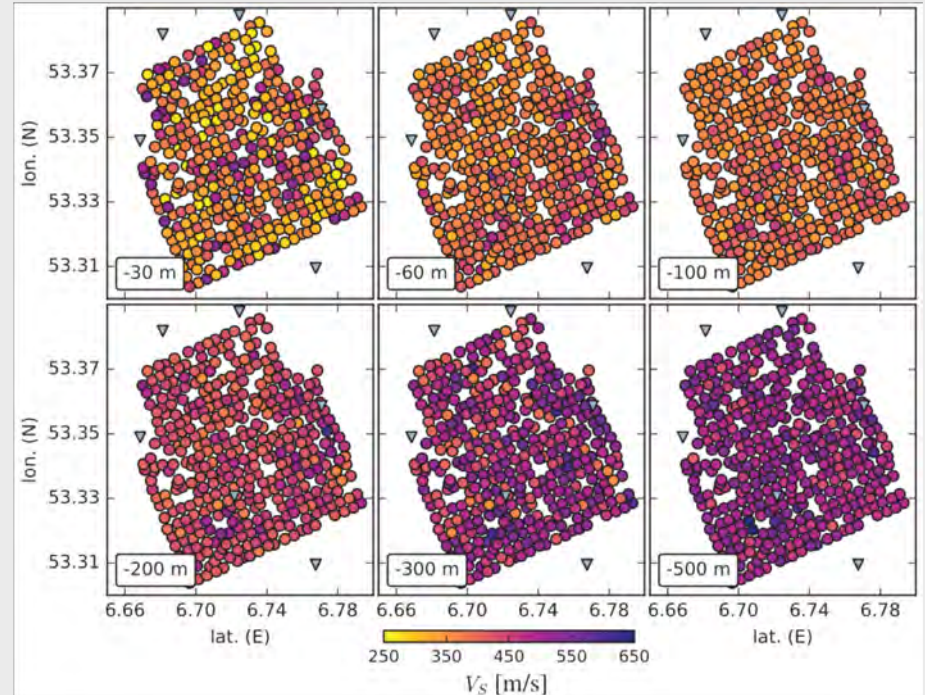
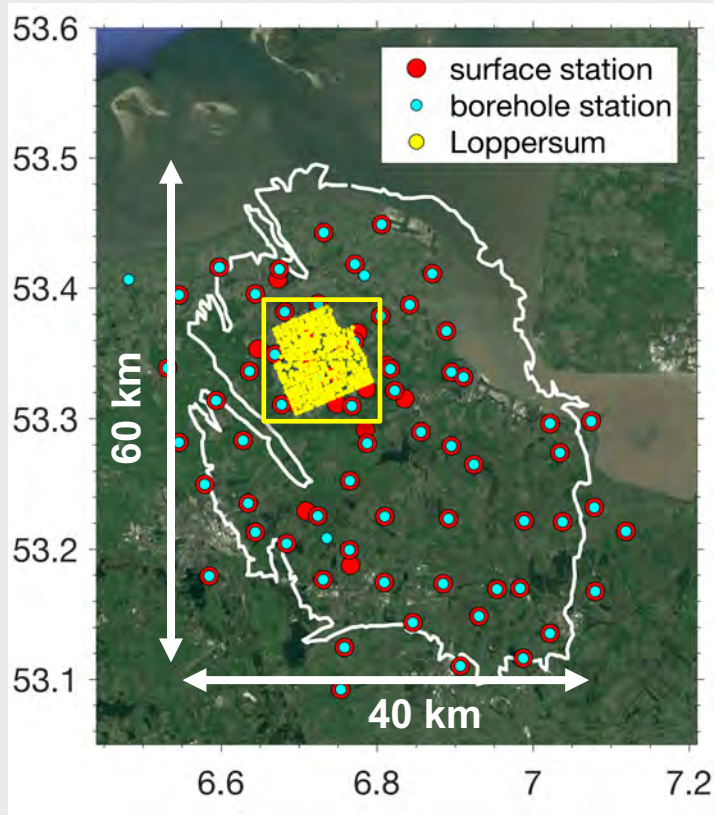


- **415 stations**
- **3 components**
- **Receiver spacing: 400 m**
- **One-month continuous record**

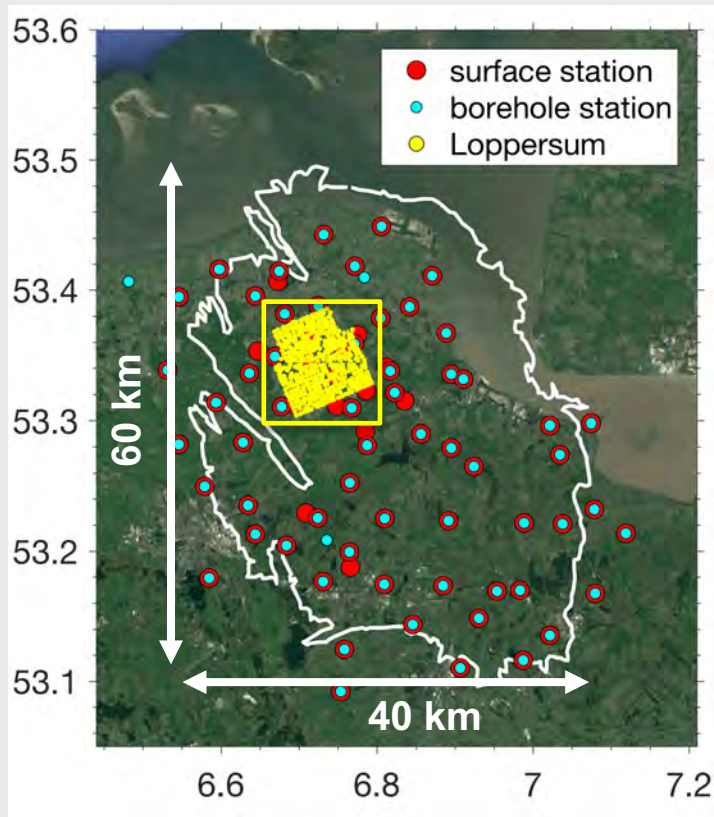
# Groningen Gas Field

Near-surface velocity model estimated from

- H/V
- Rayleigh and Love waves



# Groningen Gas Field



## Hourly seismic velocity change

