Locating and characterizing seismic events in Los Humeros (Mexico) using time-reverse imaging

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Motivation for seismicity analysis in geothermal projects

spatio-temporal distribution of seismic events:

- mapping of fault networks
- assess and mitigate seismic hazard
- reservoir characterisation

focal mechanisms (beachballs, fault planes, …):

- estimate local stress regime
- kinematic processes in the subsurface
- distinction between tectonic and anthropogenically induced events?

informed understanding of geological and geophysical processes in the subsurface

Why Time-Reverse Imaging (TRI)?

TRI is a method for locating and characterising seismic events.

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- full waveform → usage of all available data
- no picking → quasi-simultaneous & low SNR events
- all scales (lab, field, …) → non-destructive testing, micro-seismicity, tremors, …
- no a priori assumptions about sources → may be used to infer unknown subsurface processes

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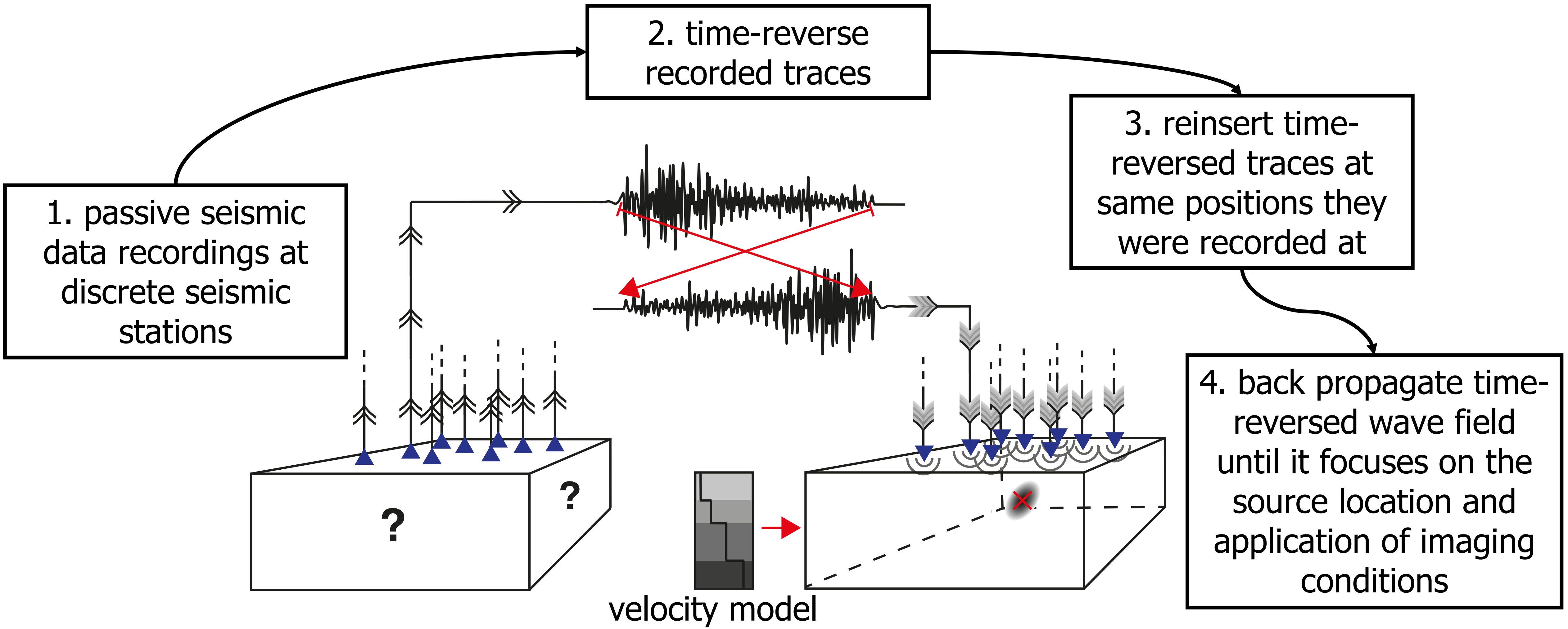
- well-constrained high-resolution velocity model is needed
- computational costs may be high
- constraints on station network

The principle of TRI



Imaging Conditions used for TRI

Imaging conditions are used to quantify the convergence of the time-reversed wave field. They are based on different characteristics of the wave field and are thus used simultaneously to obtain a more complete source image.

Maximum displacement: $$\mathbf{I}_d(\mathbf{x}) = \max_{t\in[0,T]} \|\mathbf{u}(\mathbf{x},t)\|$$

Maximum P-wave energy density: $$\mathbf{I}_p(\mathbf{x}) = \max_{t\in[0,T]} (\lambda + 2\mu)[\nabla \cdot \mathbf{u}(\mathbf{x},t)]^2$$

Maximum S-wave energy density: $$\mathbf{I}_s(\mathbf{x}) = \max_{t\in[0,T]} \mu\,[\nabla\times\mathbf{u}(\mathbf{x},t)]^2$$

Maximum total energy density: $$\mathbf{I}_e(\mathbf{x}) = \max_{t\in[0,T]} \sum_i \sum_j \left[\sigma_{ij}(\mathbf{x},t)\,\varepsilon_{ij}(\mathbf{x},t)\right]$$

$\mathbf{x}$: space vector – t: time – $\mathbf{u}$: displacement – λ,μ: Lamé parameters – σ_{ij}: stress – ε_{ij}: strain

Saenger (2011): Time reverse characterization of sources in heterogeneous media, *NDT&E International*, https://doi.org/10.1016/j.ndteint.2011.07.011

Challenges when using TRI

most influenced

↓

least influenced

1. Station Distribution → solvable by:

Irregular and sparse station distributions lead to under-sampled wavefields and thus incomplete reconstruction of time-reversed wave field.

- optimised station network **SLIDE 7**
- identification of areas with low or insufficient source-location accuracy **SLIDE 10-11**

2. Velocity Model → solvable by:

Incorrect velocity models result in incorrect travel paths of the time-reversed wave field and thus hinder the convergence at the source location.

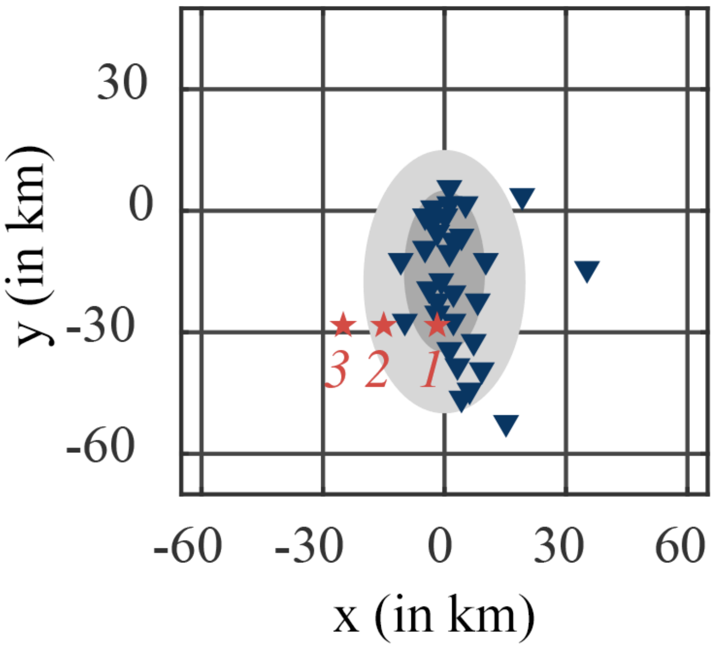
- identification of areas with low or insufficient source-location accuracy **SLIDE 10-11**
- improved velocity models

3. Ambient Seismic Noise → understand limits of method **SLIDE 8**

Low SNR (< 1) may introduce artificial convergence spots overshadowing the convergence spot at the source location.

Optimise station network for TRI

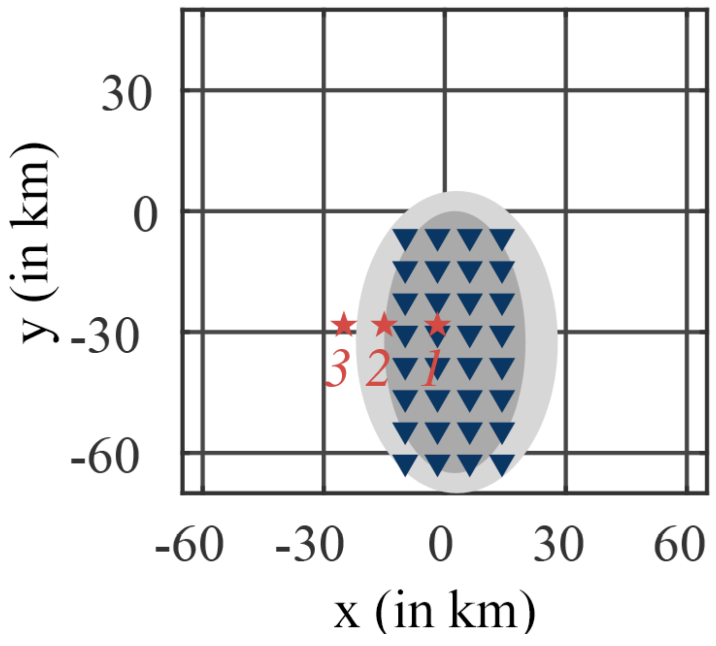
station network in Southern California



guidelines for optimised station network:

- inter-station distance < source depth
- aperture of network > 2 x source depth
- most accurate when sources are beneath the network
- regular station networks improve accuracy for shallow sources

station network optimised for TRI



dark grey circle: In this area sources can be located accurately in the target depths

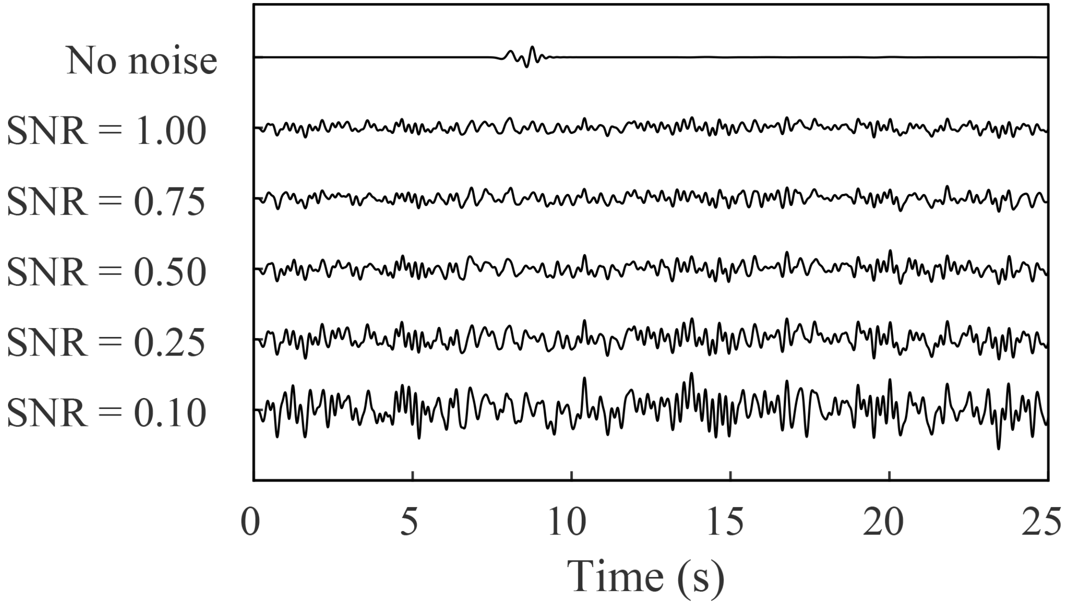
light grey circle: In this area sources may be located with decreased accuracy

blue triangles: stations
red stars: sources

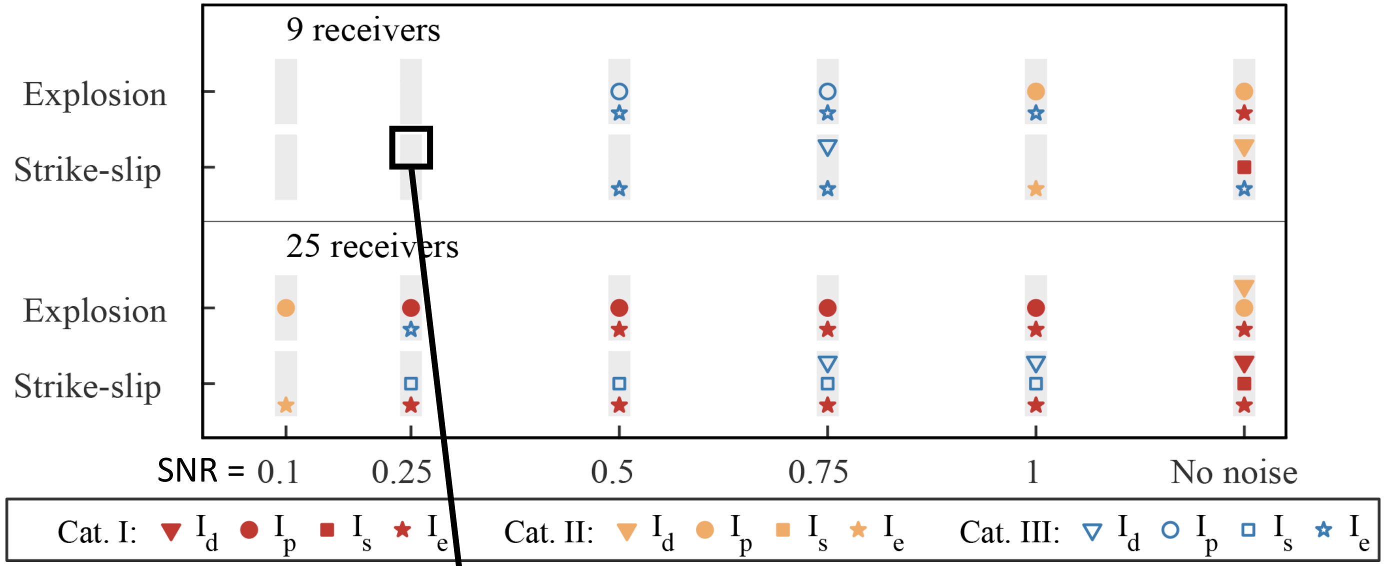
Werner and Sanger (2018): Obtaining reliable source locations with time reverse imaging, *Solid Earth*, https://doi.org/10.5194/se-9-1487-2018

Handling low noise levels with TRI

Example traces for a synthetic source with noise



TRI handles low SNR well if the station network is well enough (i.e. enough stations). Depending on the imaging condition, sources may be located with an SNR as low as 0.1.



high accuracy

medium accuracy

low accuracy

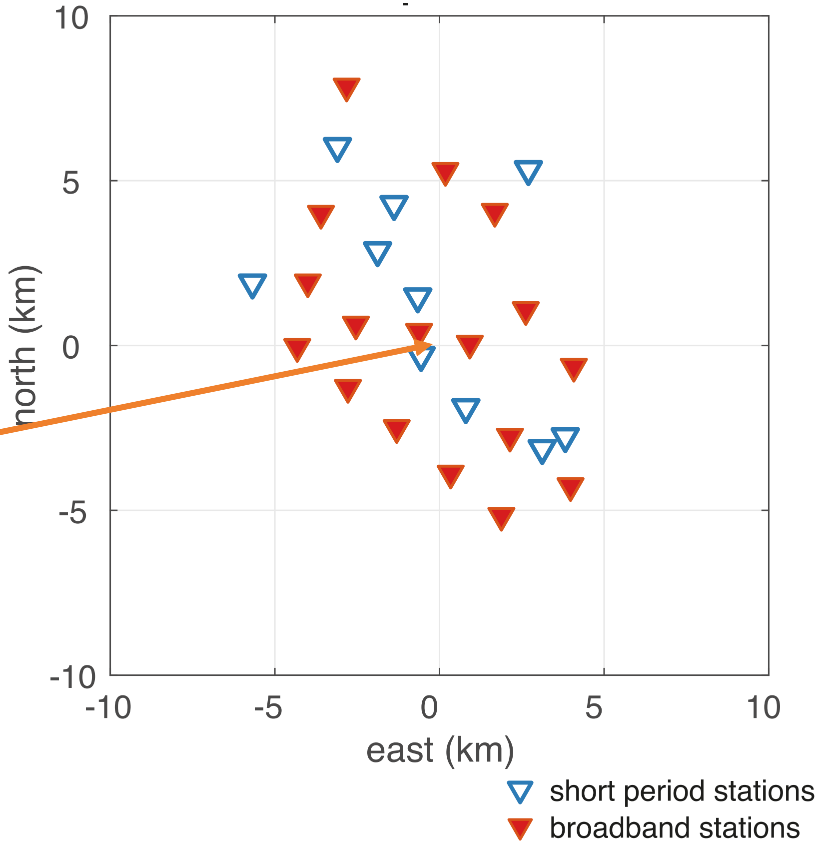
insufficient accuracy

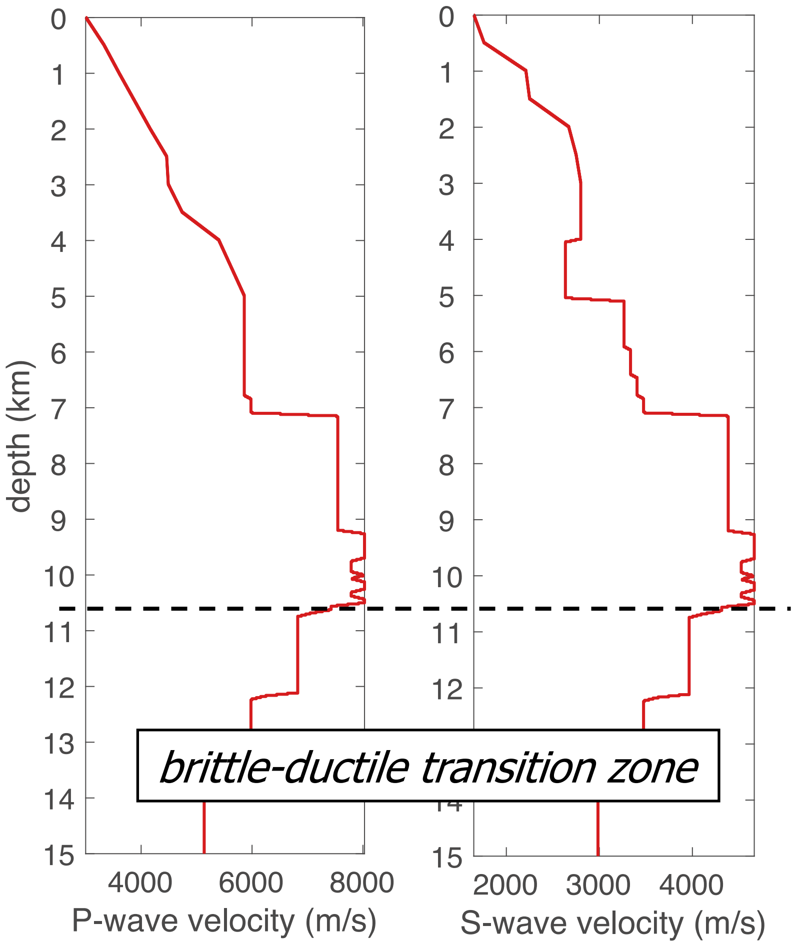
I_d : Maximum displacement imaging condition
I_p : P-wave energy density imaging condition
I_s : S-wave energy density imaging condition
I_e : Total Energy density imaging condition

Werner and Sanger (2018): Obtaining reliable source locations with time reverse imaging, *Solid Earth*, https://doi.org/10.5194/se-9-1487-2018

Los Humeros geothermal field (Mexico)

27 stations (deployed 09/2017 – 09/2018)





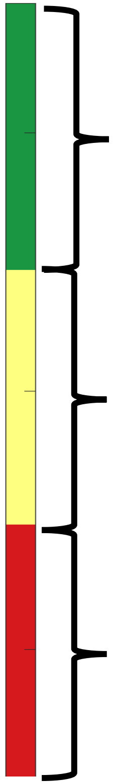
Toledo, T. et al., 2019. Dataset of the 6G seismic network at Los Humeros, 2017-2018, *GFZ Data Serv.,* https://doi.org/10.14470/1T7562235078

Löer, K. et al., 2020. Imaging the deep structures of the Los Humeros geothermal field, Mexico, using three-component ambient noise beamforming, Seismological Reseach Letter, *submitted*

Sensitivity maps reveal influence of stations and velocity model

Sensitivity maps highlight areas with low or insufficient source-location accuracy due to the combination of the station distribution and the velocity model. Convergence spots in these areas may be excluded from further analysis.

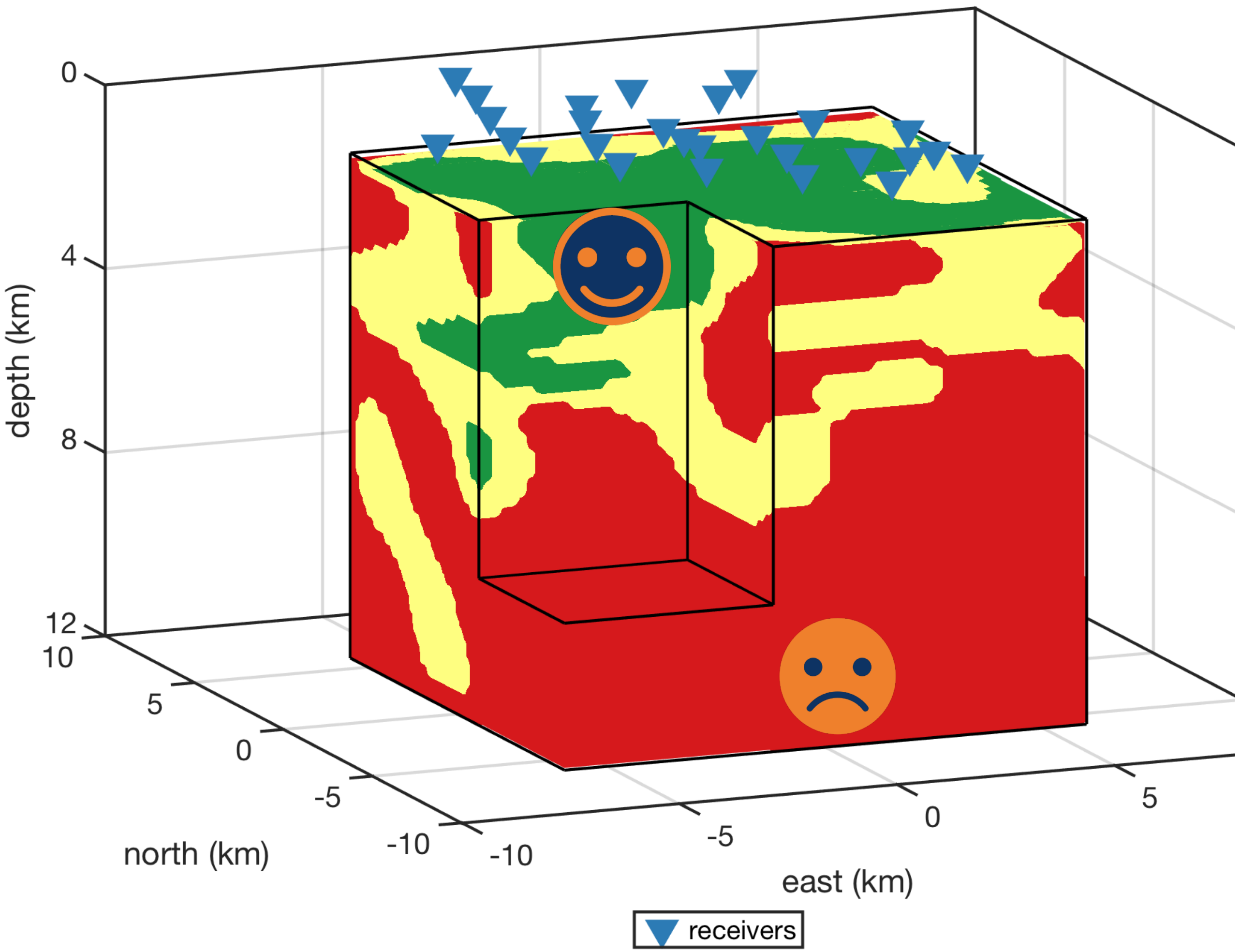
accuracy



high
spatial error < ½ S-wave wavelength
temporal error < ½ period of S-wave
focus size < spatial error

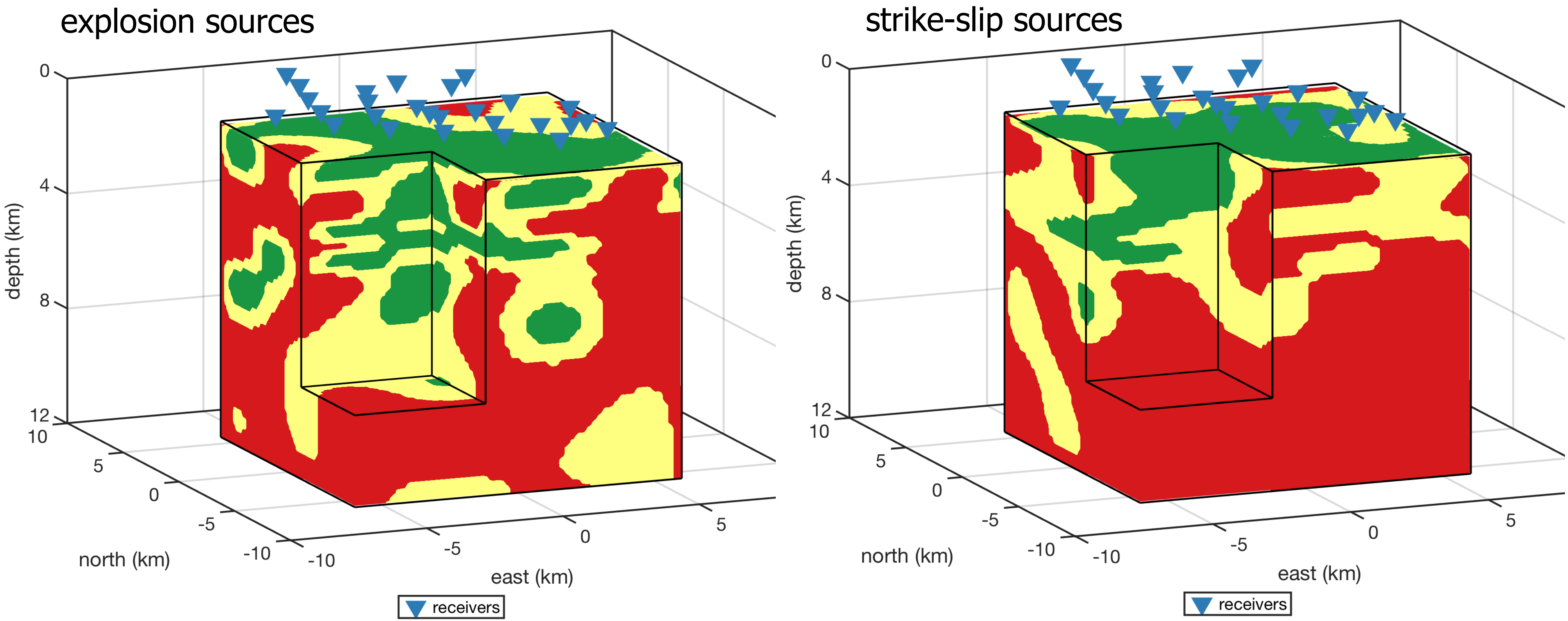
low
spatial error > ½ S-wave wavelength
temporal error > ½ period of S-wave
focus size > spatial error

insufficient sources can not be located



Finger and Sanger (2020): Sensitivity Maps for Time-Reverse Imaging, *GJI*, https://doi.org/10.1093/gji/ggaa160

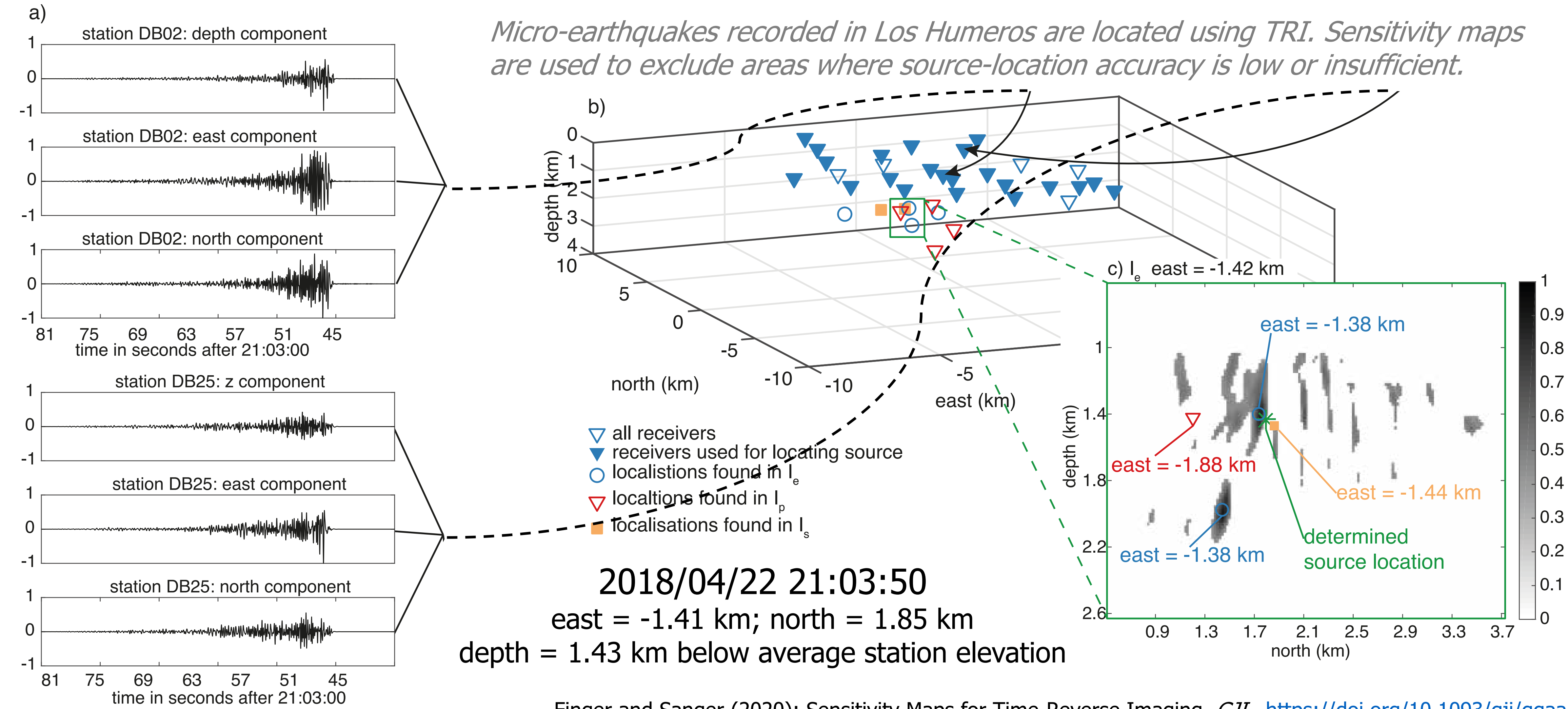
Sensitivity Maps are sensitive to the source type



Finger and Sanger (2020): Sensitivity Maps for Time-Reverse Imaging, *GJI*, https://doi.org/10.1093/gji/ggaa160

Locate examplatory event in Los Humeros with TRI

Micro-earthquakes recorded in Los Humeros are located using TRI. Sensitivity maps are used to exclude areas where source-location accuracy is low or insufficient.



2018/04/22 21:03:50
east = -1.41 km; north = 1.85 km
depth = 1.43 km below average station elevation

Finger and Sanger (2020): Sensitivity Maps for Time-Reverse Imaging, *GJI*, https://doi.org/10.1093/gji/ggaa160

Characterise events with TRI

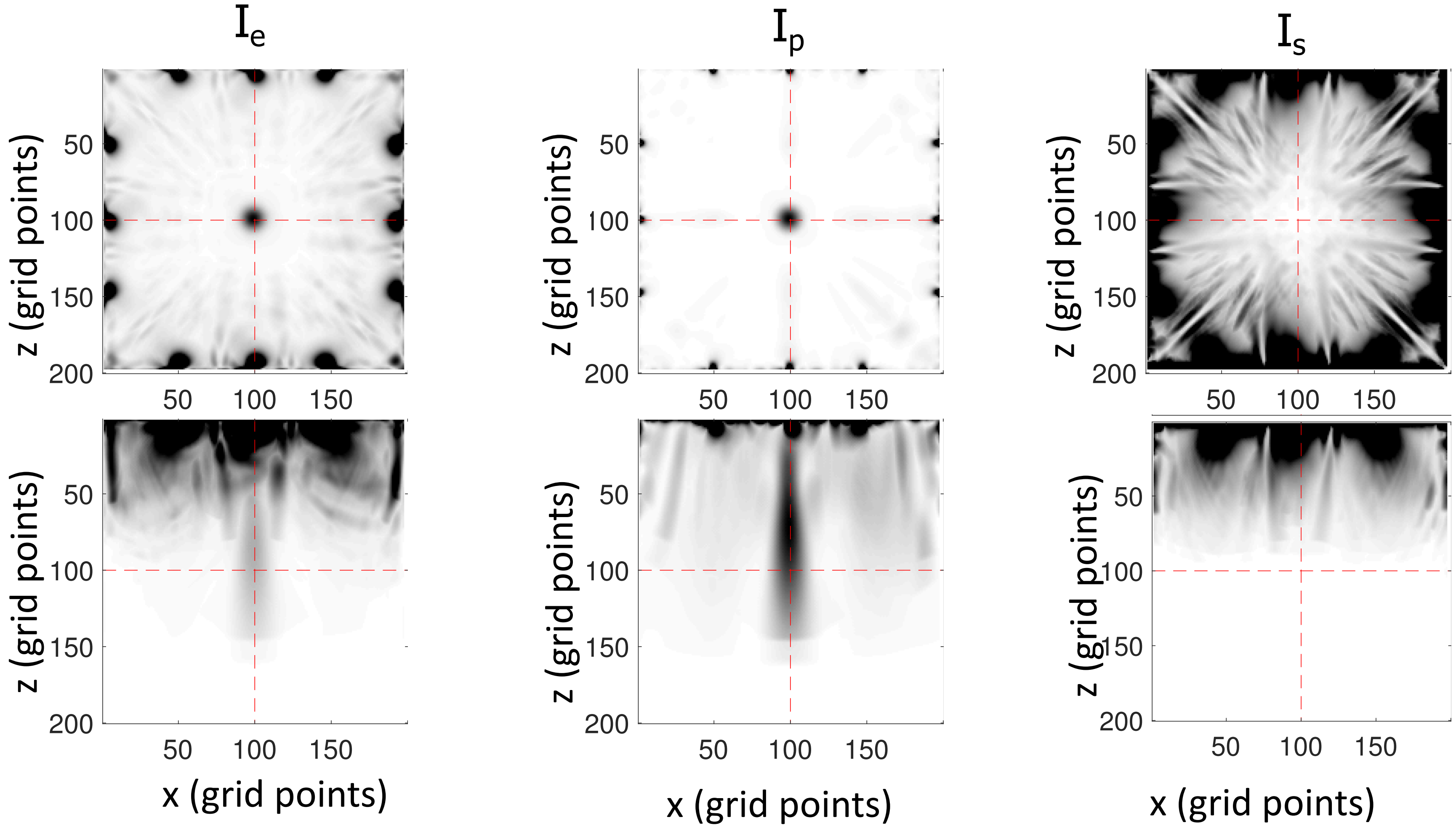
synthetic explosion source in a homogeneous cube

stations all around 3D cube

source location is recovered with I_e and I_p

stations only at surface

source location is smeared in z-direction



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Characterise events with TRI

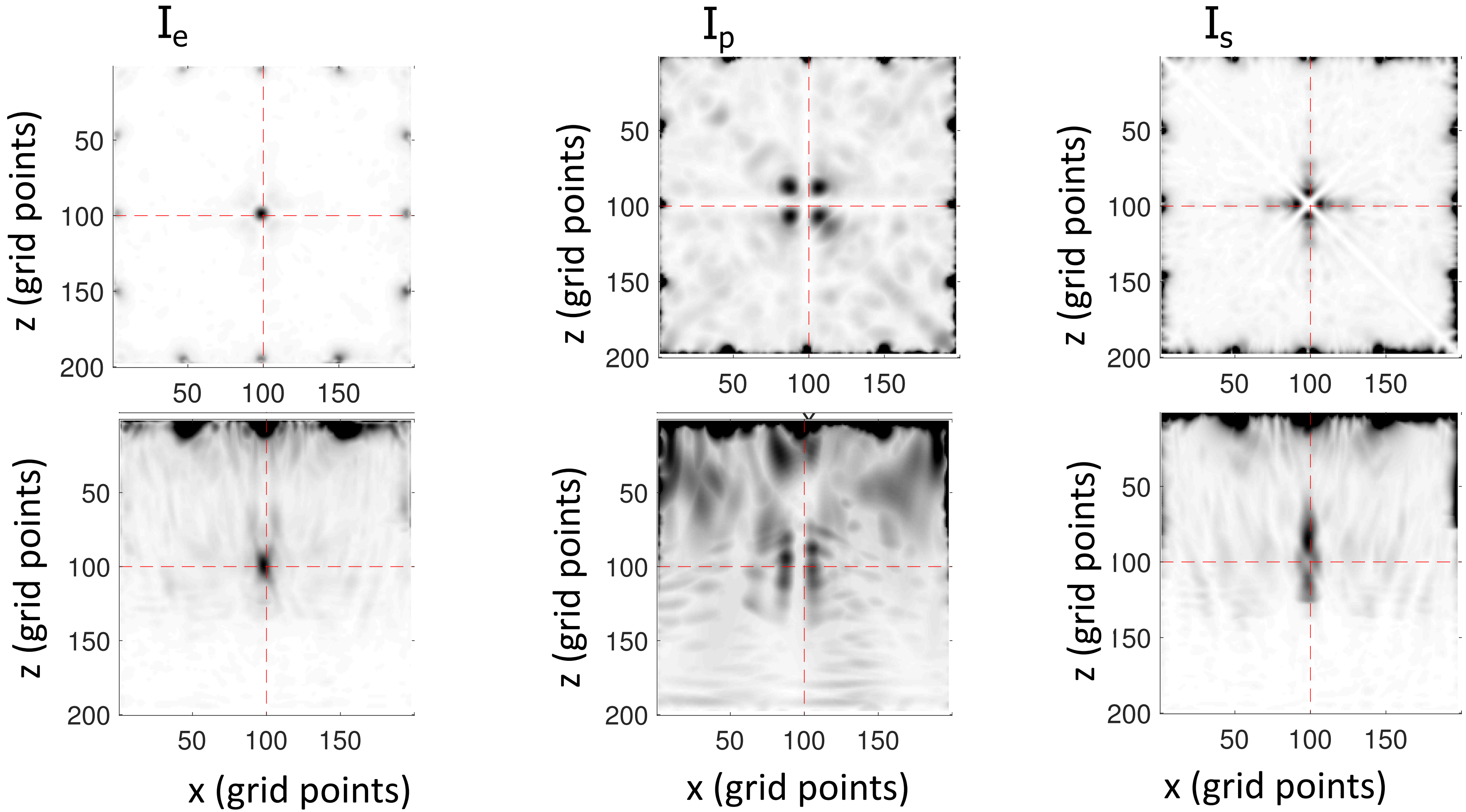
synthetic dip-slip source in a homogeneous cube

stations all around 3D cube

source location is recovered with I_e. Radiation pattern is recovered with I_p and I_s.

stations only at surface

source location is recovered with I_e. Radiation pattern is not clearly visible.



Summary and Outlook

- TRI is able to locate and characterise seismic events in low SNR conditions and is especially well-suited for applications such as aftershock sequences, induced seismicity due to fluid injection and hydro-fracture stimulation.
- TRI is a complementary method to standard analysis routines.
- An in-depth understanding of source mechanisms is possible.
- An automatic work flow for locating and characterising seismic events is being derived (manuscript in preparation)

Thank you for your Attention!

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