Numerical Investigation of Surface Wave Anisotropy for Fault Characterisation in Geothermal Fields

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Aim:

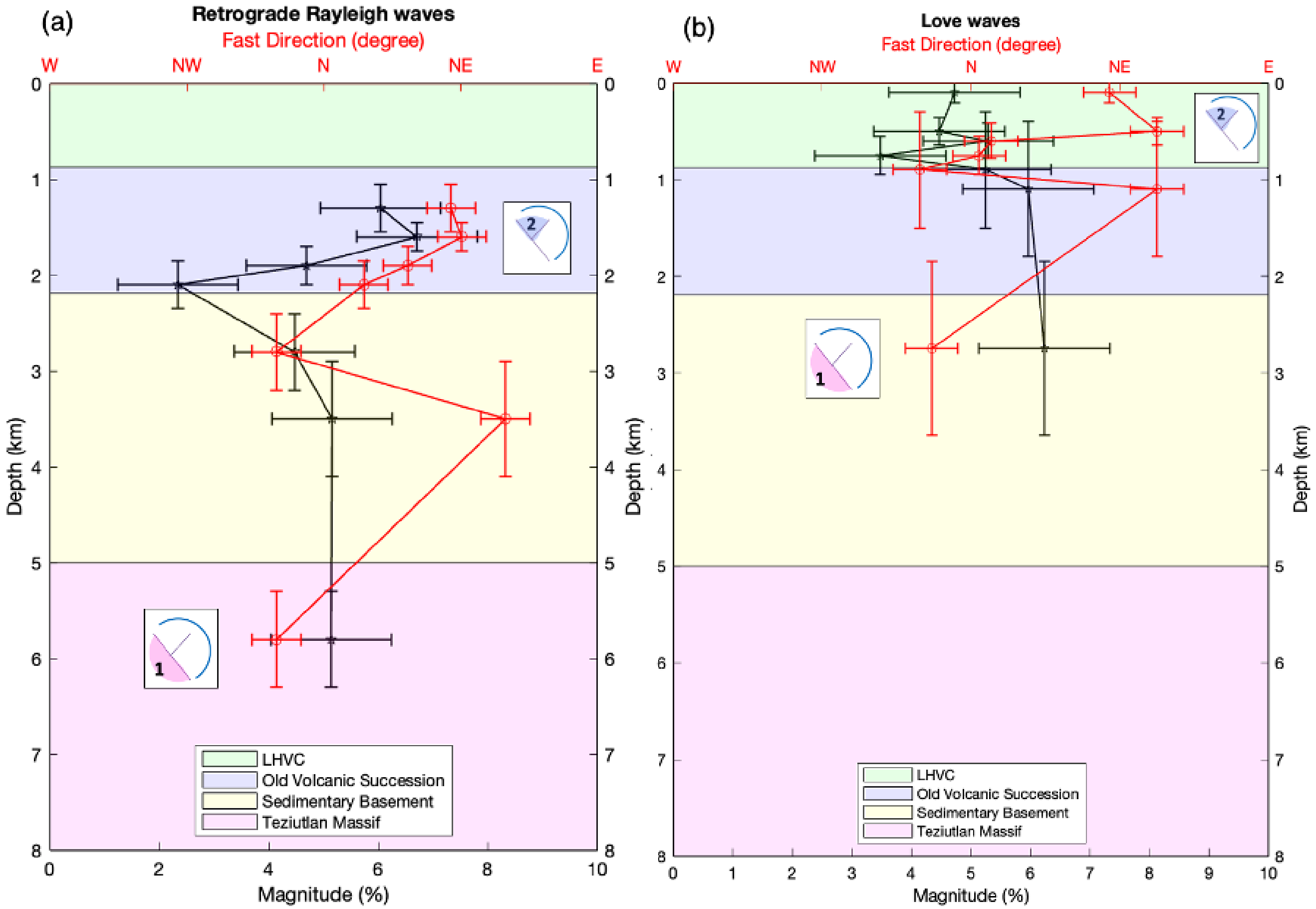
Observe interaction of synthetic Rayleigh waves with subsurface faults.

Outline

- Why?
  - Outline the purpose of this presentation.
- Numerical Modelling
  - Background on the model used for generating surface waves.
- Rayleigh Wave Propagation
  - Examples of synthetic Rayleigh waves.
- 3C Beamforming
  - How we know it is Rayleigh waves and velocity analysis.
- Interpretations so far…
- What's next?
- Overall summary

Why?

- Faults are fundamental in geothermal fields. Why? -> hydrothermal flow
- Rayleigh waves have been shown to interact with (sub) vertical faults at depth.



Problems:

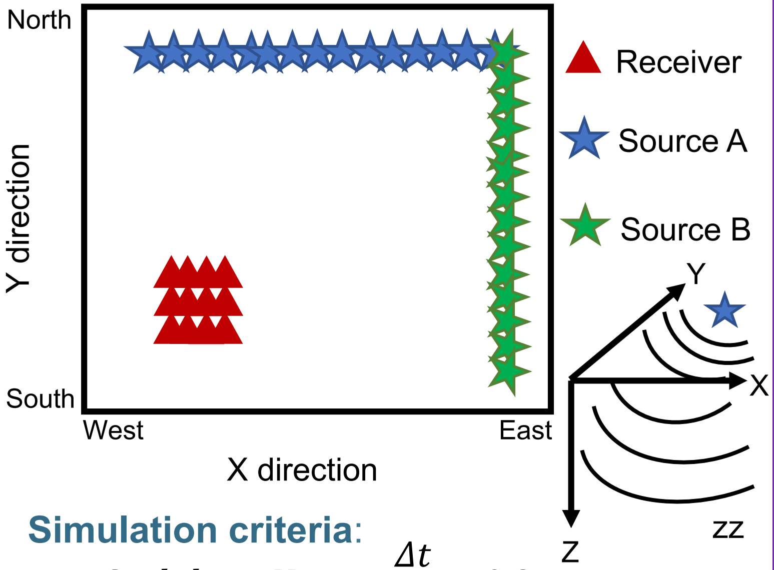
- This is based on Rayleigh wave velocity variation assumptions when interacting with faults.

Figure 1: Fast directions and magnitude of apparent anisotropy of (a) Retrograde Rayleigh waves and (b) Love waves at varying depths, in the Los Humeros Geothermal Field Mexico. (Kennedy et al., 2022)

Numerical Modelling

Outline of Methodology

Receiver Station Layout

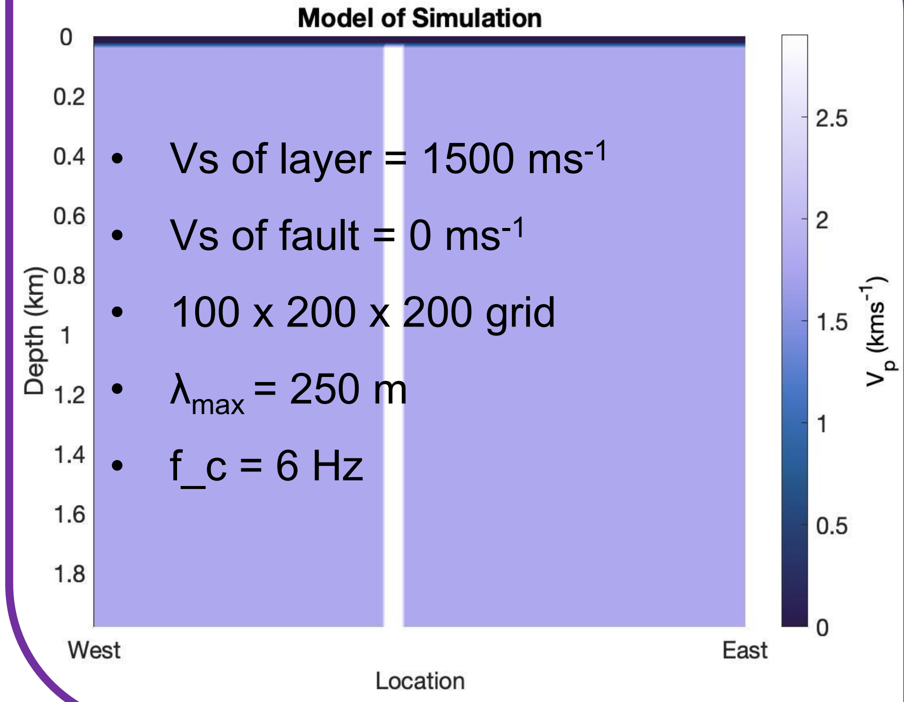


Simulation criteria:

$$Stability: V_{max} \times \frac{\Delta t}{\Delta x} \leq 0.8$$

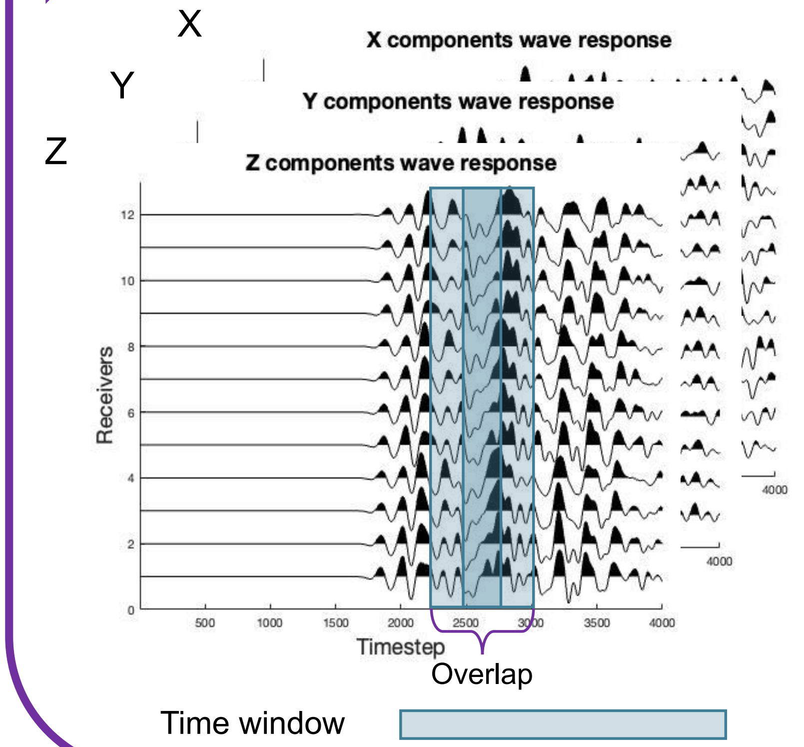
$$Dispersion: \lambda_{max} = \frac{V_{min}}{f_{max}} \geq 10 \times \Delta x$$

1 Slice (0.2 km y-direction) of 3D Model with a "water"-filled fault of 56 m width

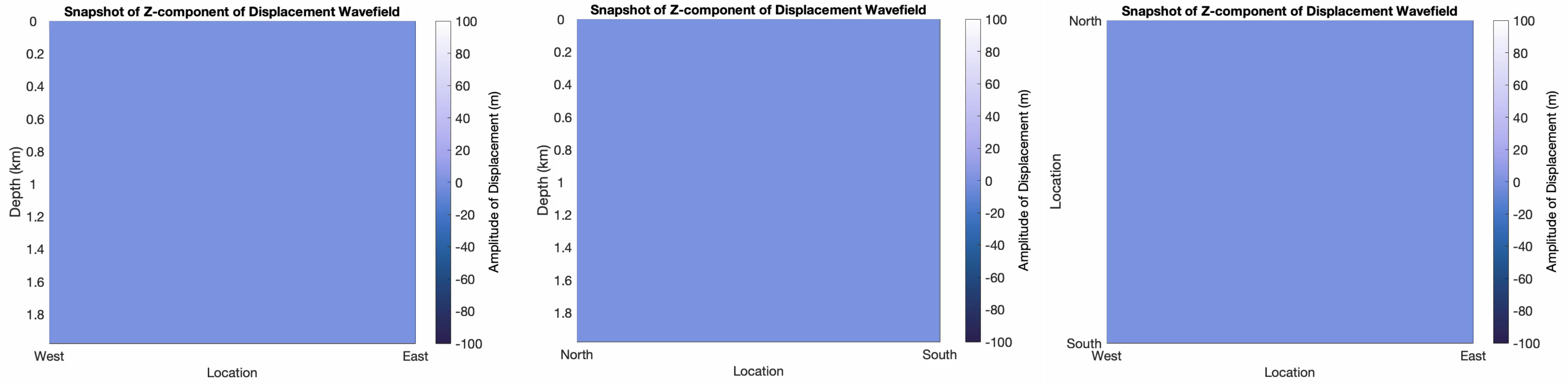


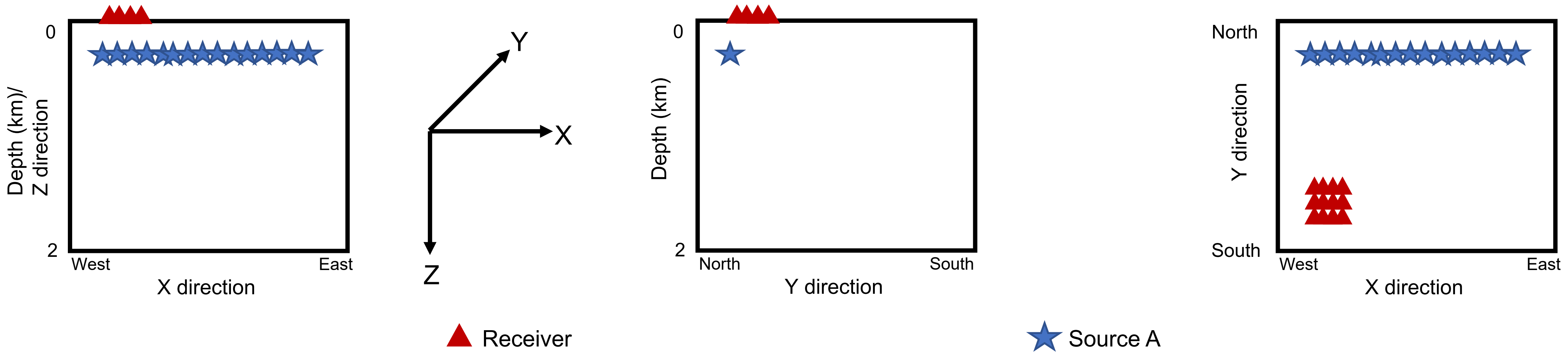
- Vs of layer = 1500 ms^{-1}
- Vs of fault = 0 ms^{-1}
- 100 x 200 x 200 grid
- λ_{max} = 250 m
- f_c = 6 Hz

Wave Response

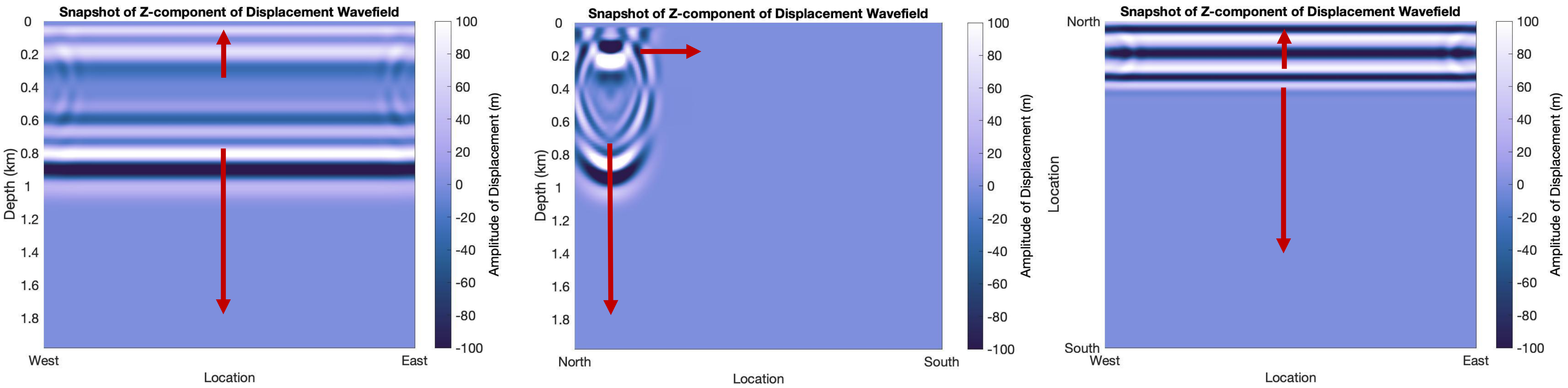


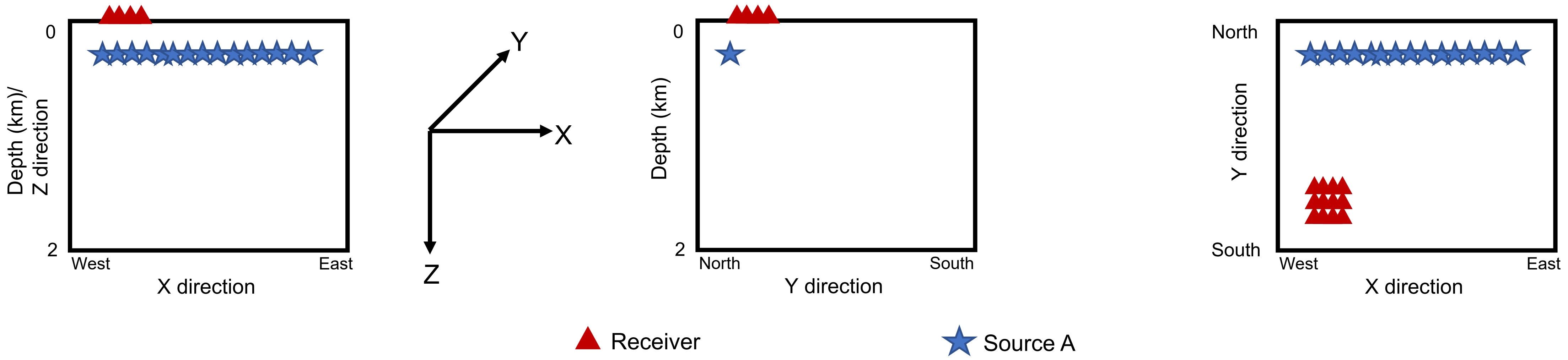
Rayleigh Wave Propagation



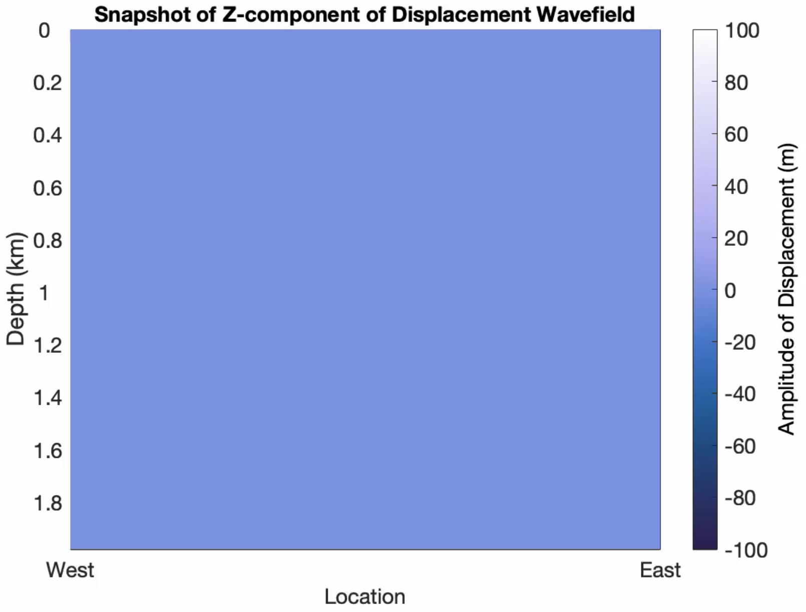


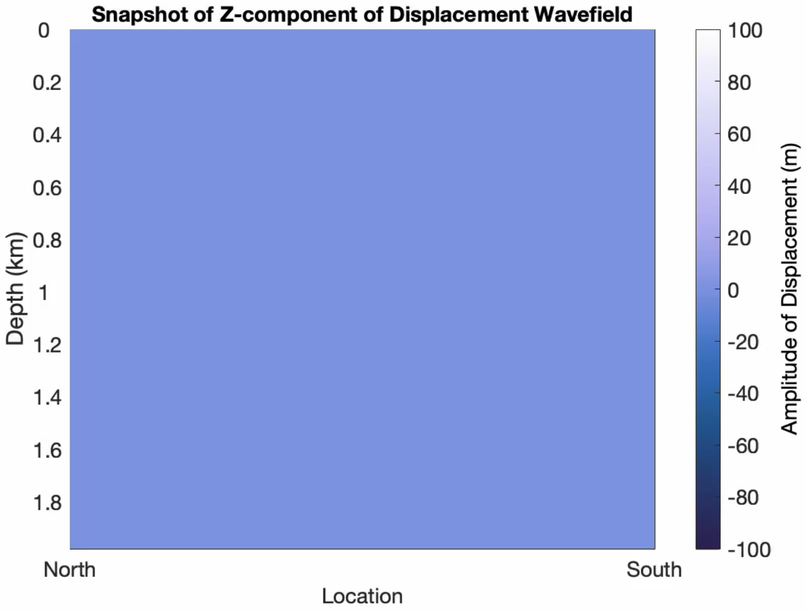
Homogeneous model

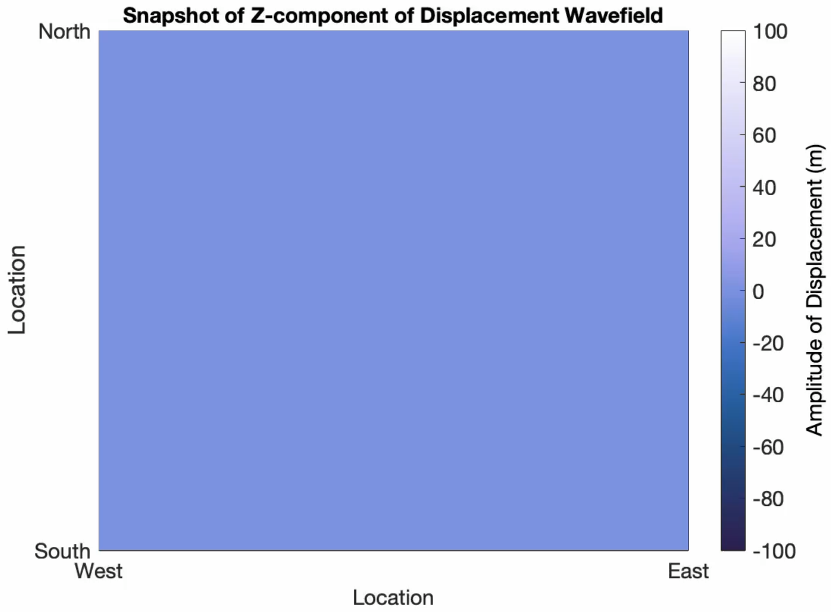


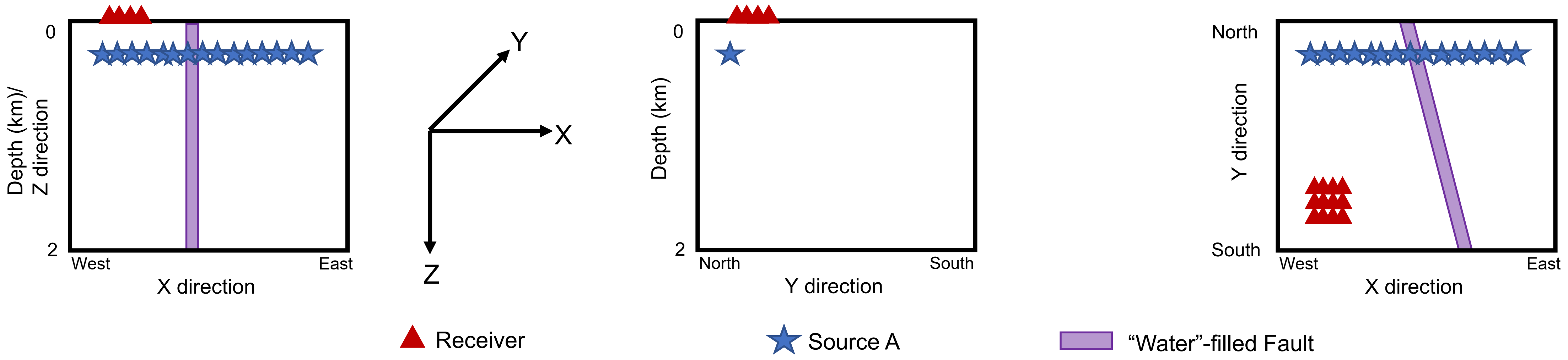


Homogeneous model

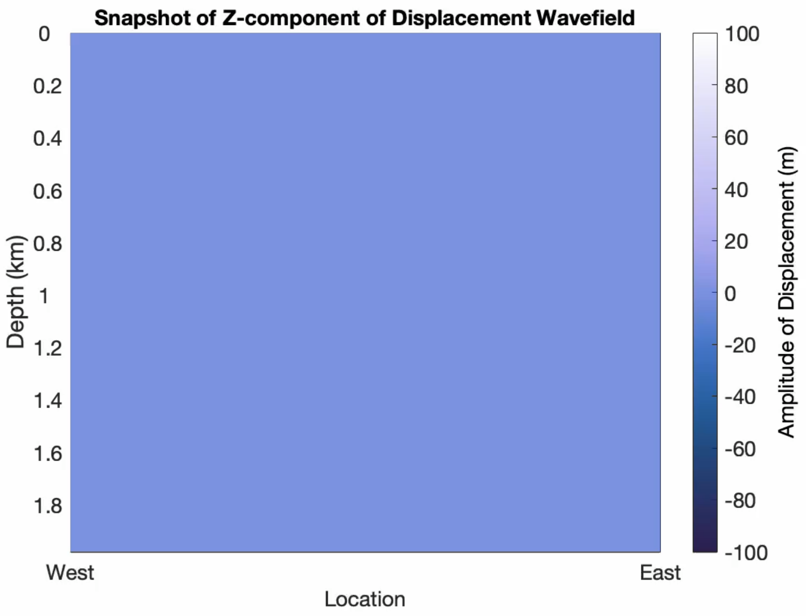


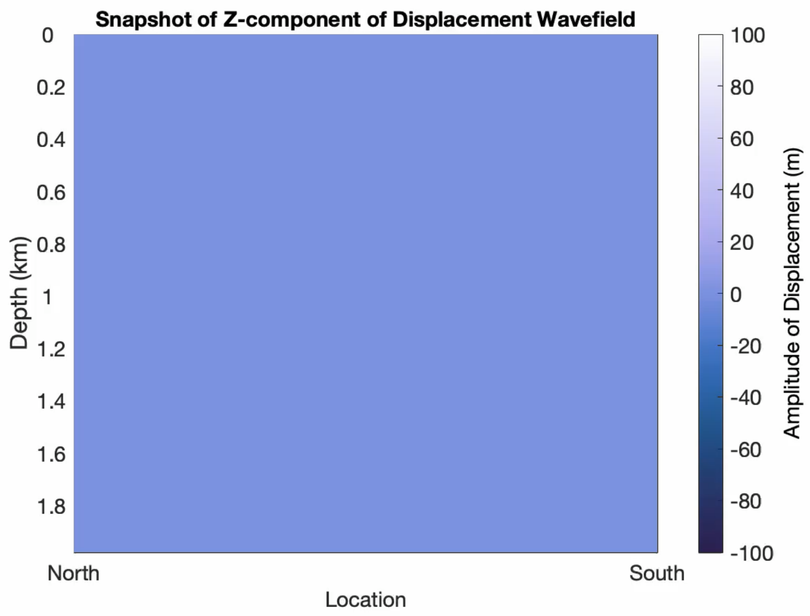


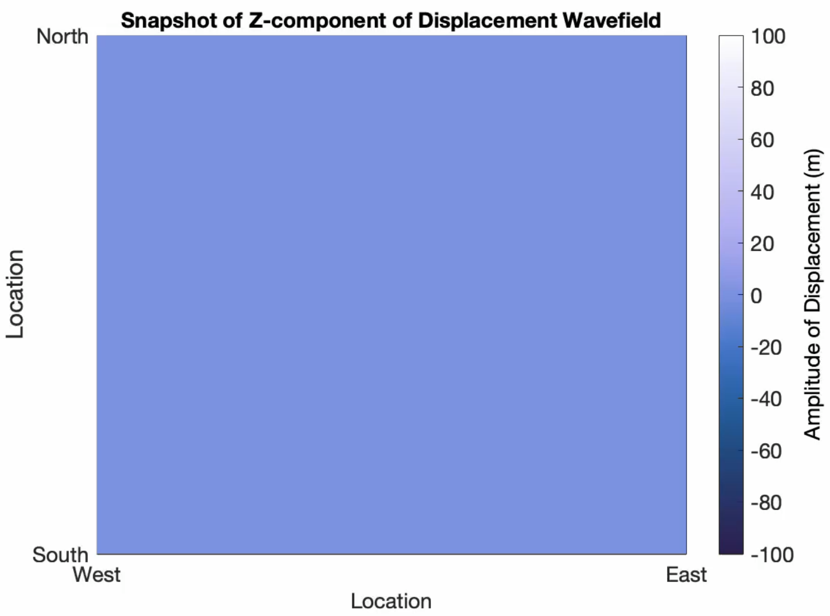


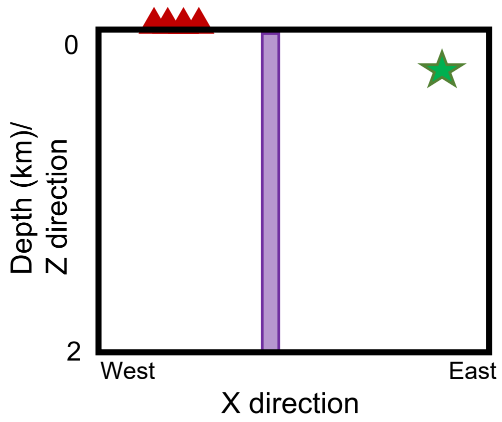


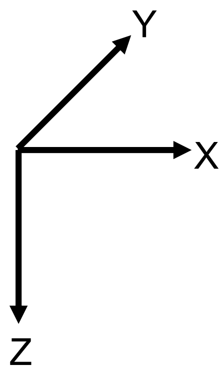
Heterogeneous model

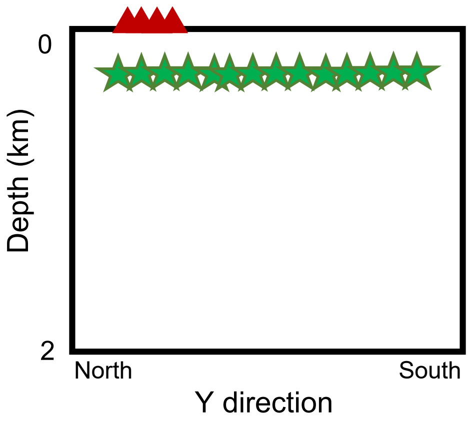


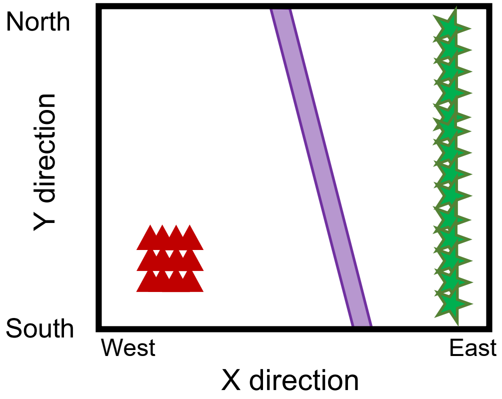












Receiver

Source B

"Water"-filled Fault

Heterogeneous model

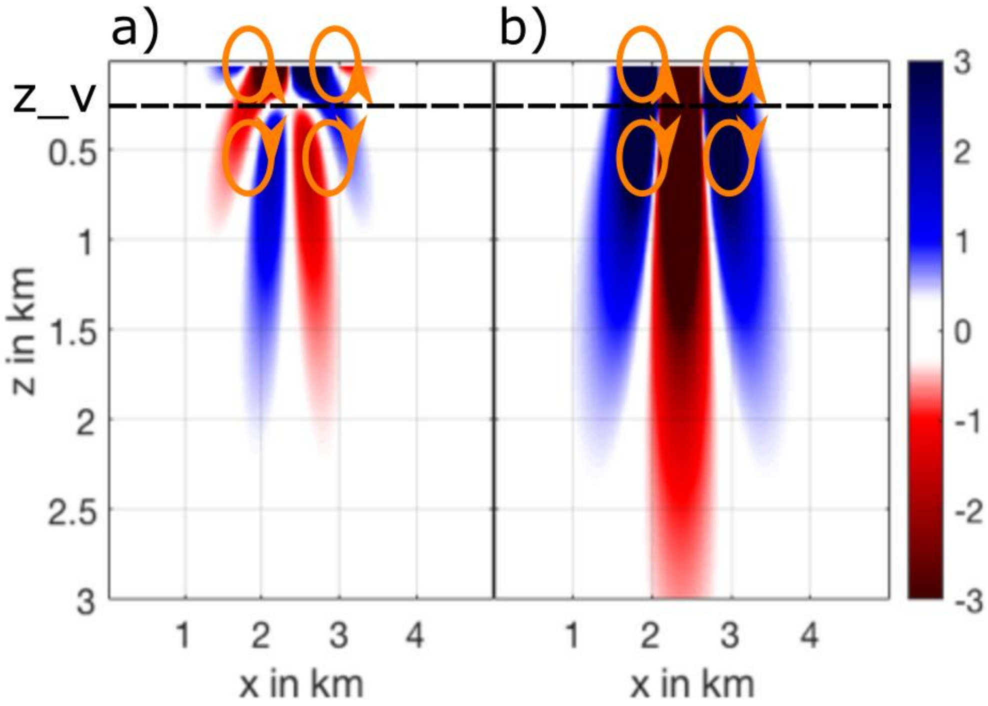
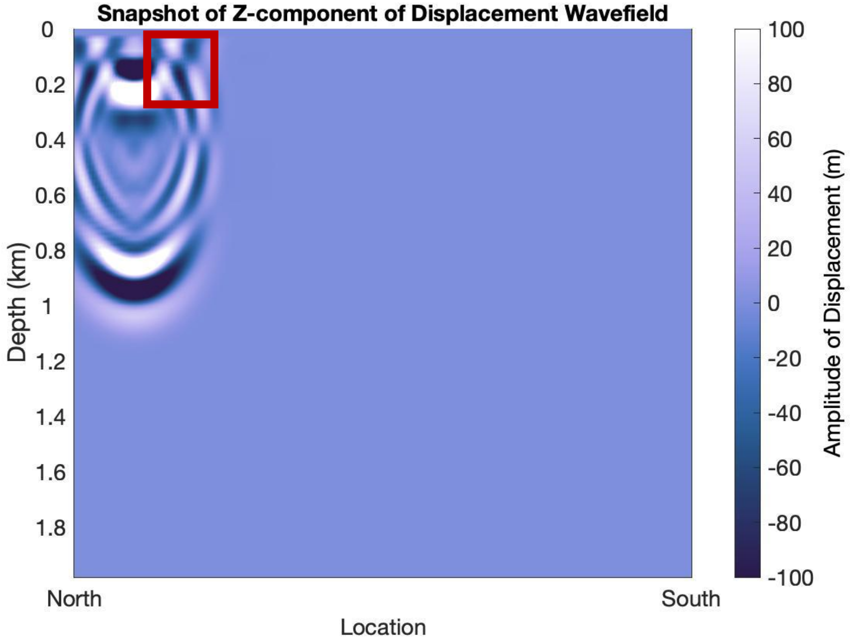
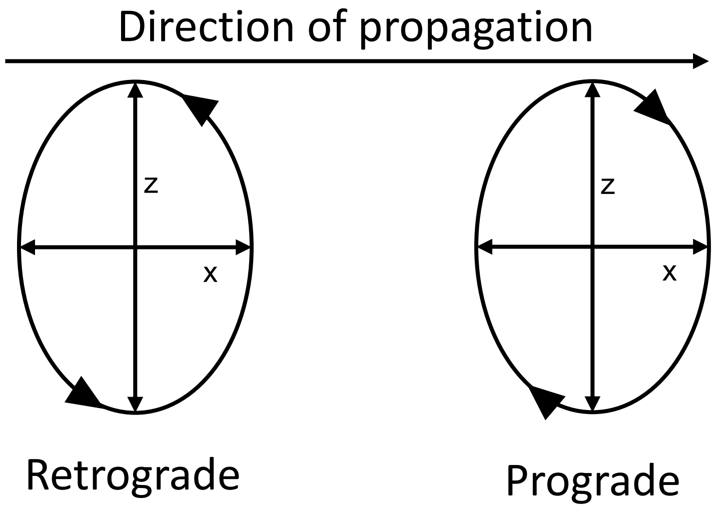


Figure 2: A retrograde Rayleigh wave propagating in the x-direction. a) xsnap and b) zsnap. If you combine both of these, you get the particle motion of the wave (in orange).

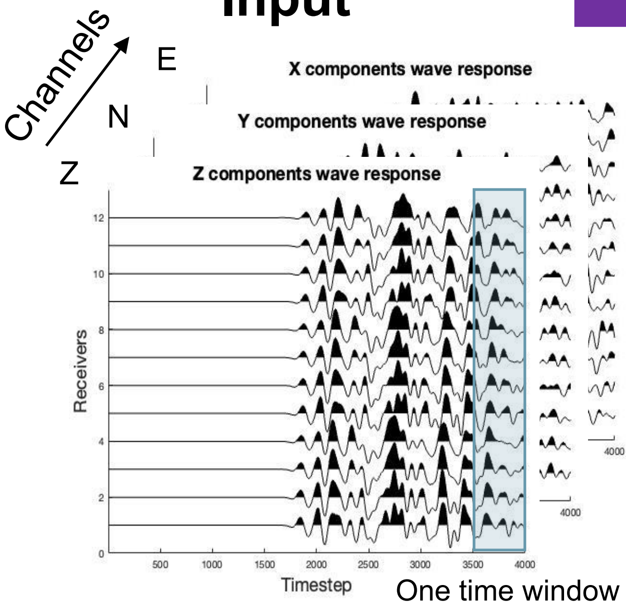


- Typically Retrograde Rayleigh (outlined box) waves are shown at the surface.
- Prograde Rayleigh waves only tend to form due to a geologic change (e.g. sedimentary layer or fault) which reverses the particle motion.



3C Beamforming

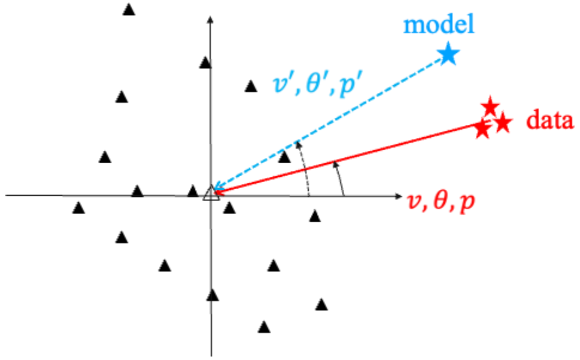
Input



Three-component synthetic noise data

3C Beamforming

after Riahi et al. (2013)

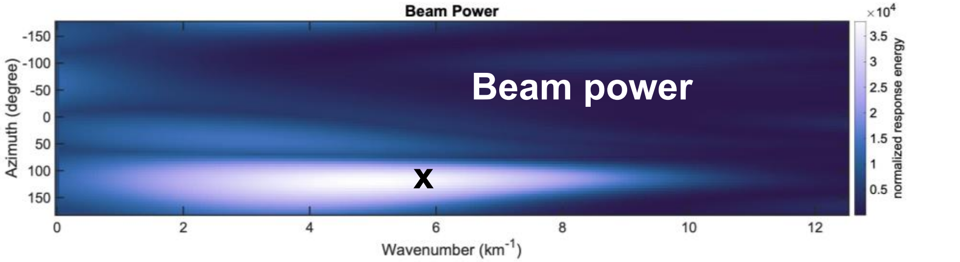


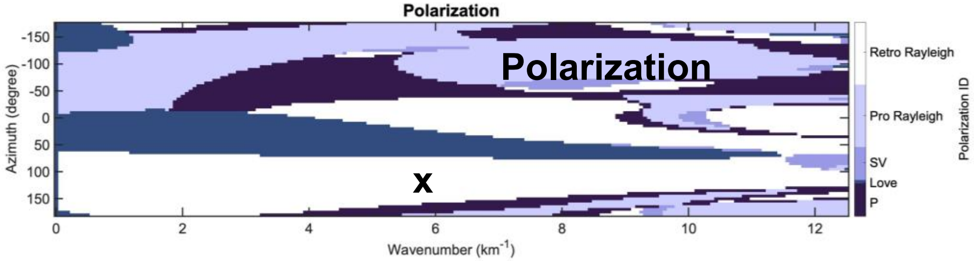
Grid search

- velocities (v')
- azimuths (θ')
- polarisations (p')

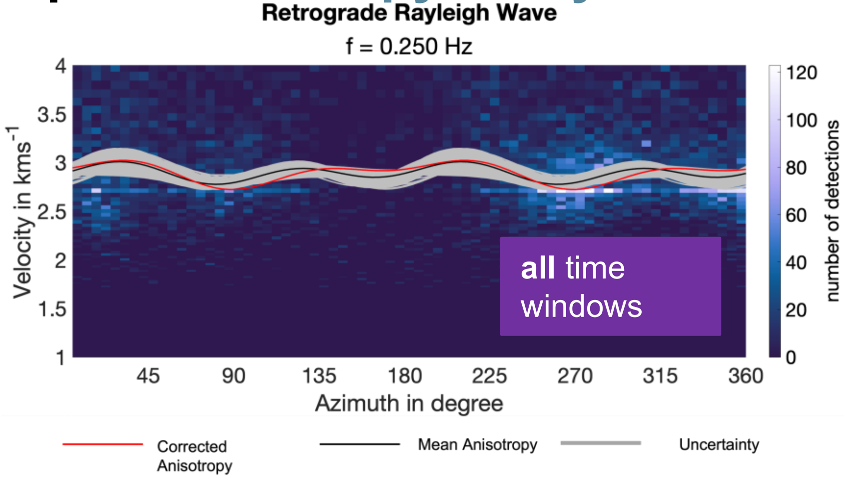
one frequency, **one** time window

Wave characteristics





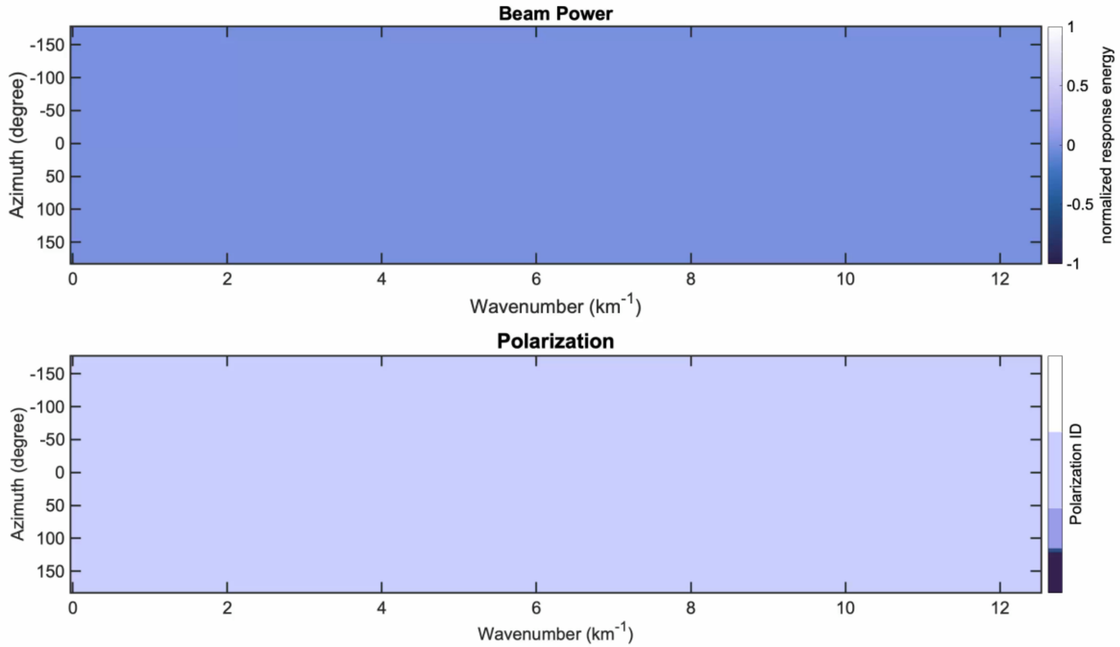
Output: Anisotropy Analysis

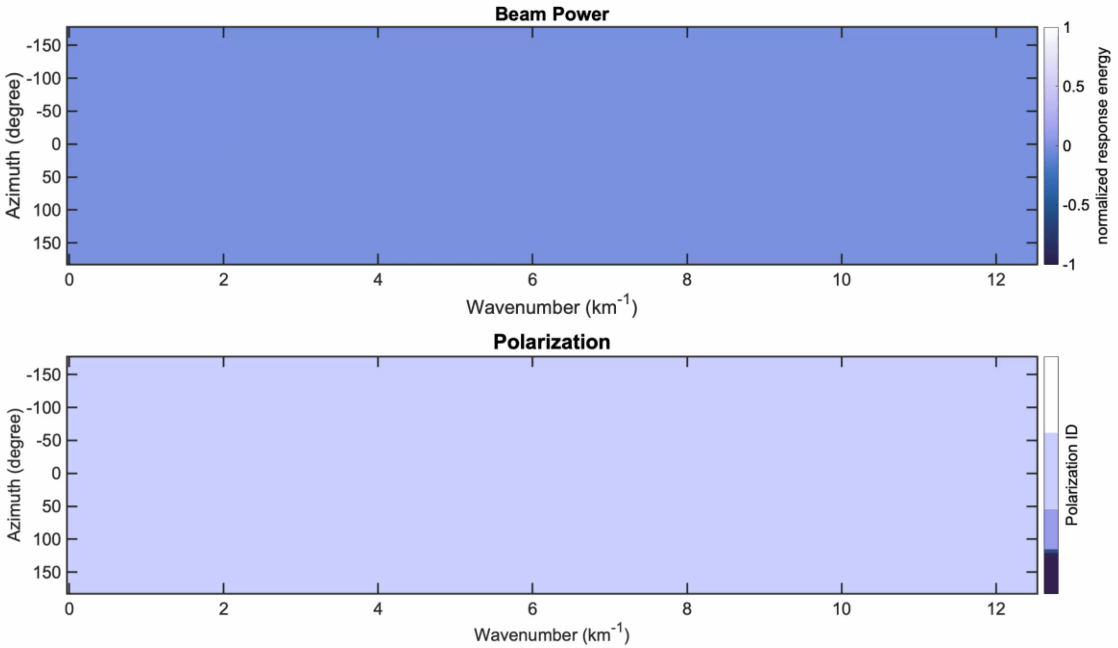


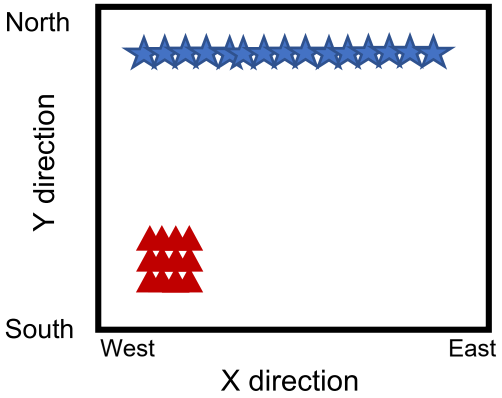
Anisotropy Curve

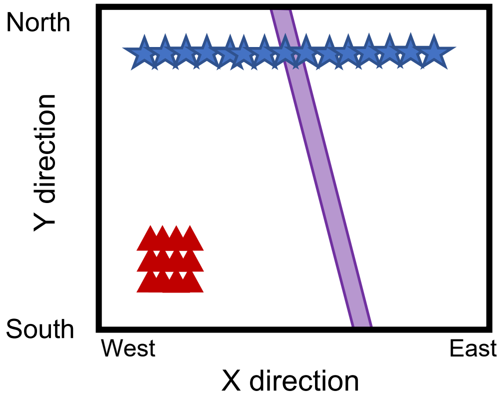
$$v(\theta) = a_0 + a_1 \cos(2\theta) + a_2 \sin(2\theta) + a_3 \cos(4\theta) + a_4 \sin(4\theta)$$

(Kennedy et al., 2022)



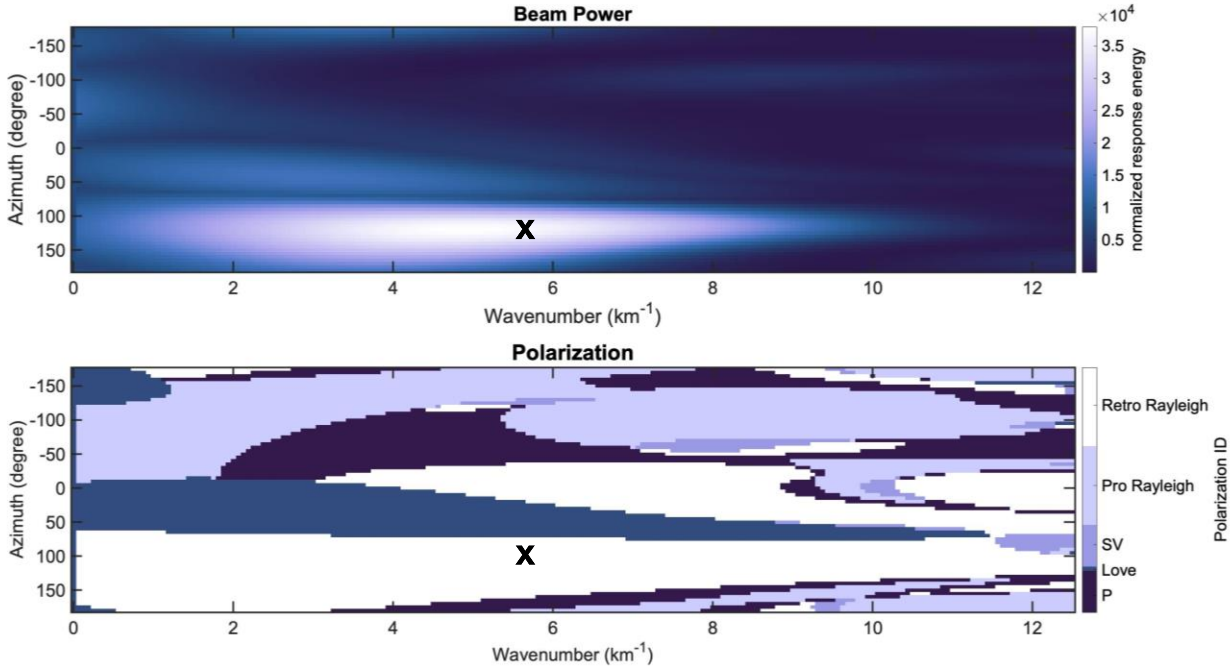


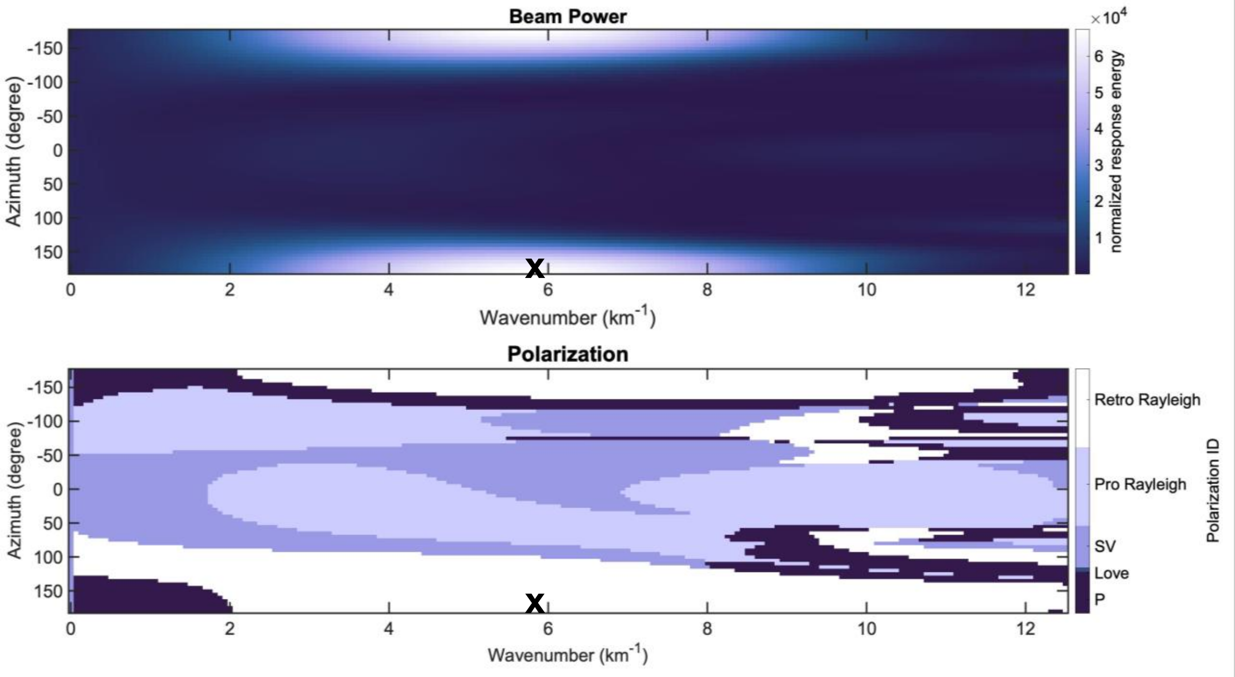




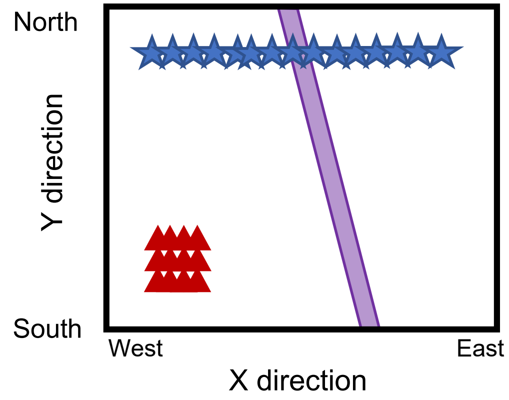
▲ Receiver ★ Source A "Water"-filled Fault

Interpretation so far…



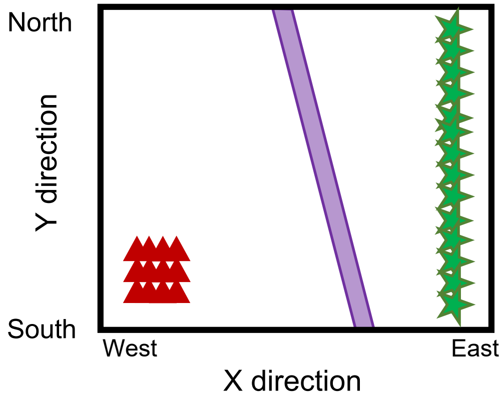


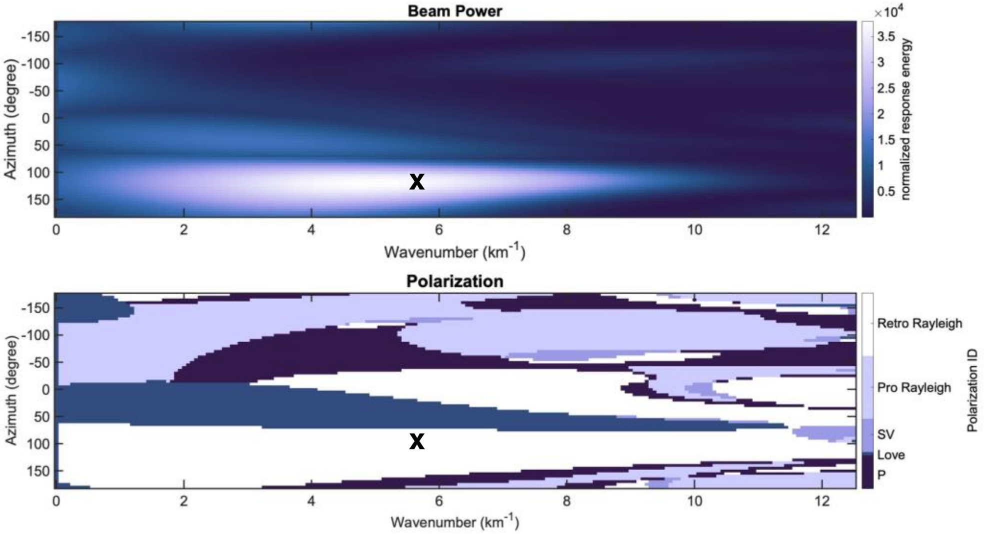
One time window, one frequency



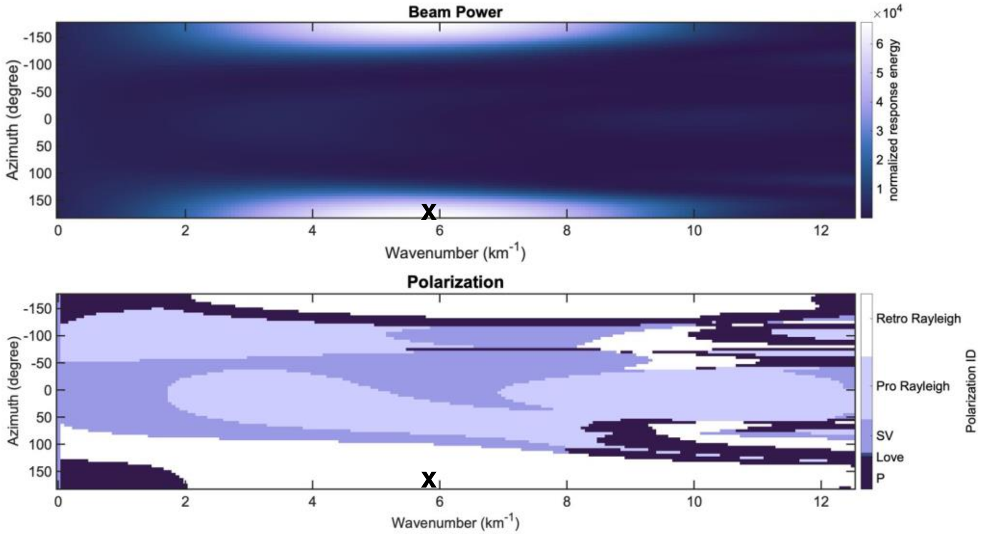
The velocity of maximum normalised energy Retrograde Rayleigh wave = 1.684 kms^{-1}

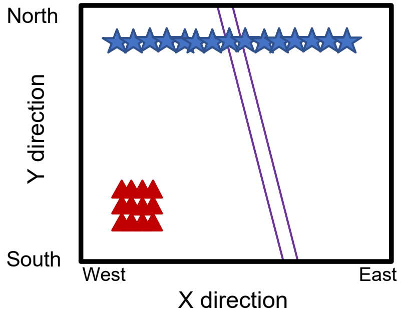
The velocity of maximum normalised energy Retrograde Rayleigh wave = 1.333 kms^{-1}



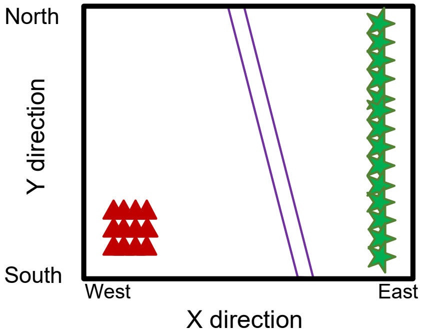


One time window, one frequency





The number of time windows (out of 15) Rayleigh waves were found.	Source A	Source B
No fault	9	3
Fault	6	8

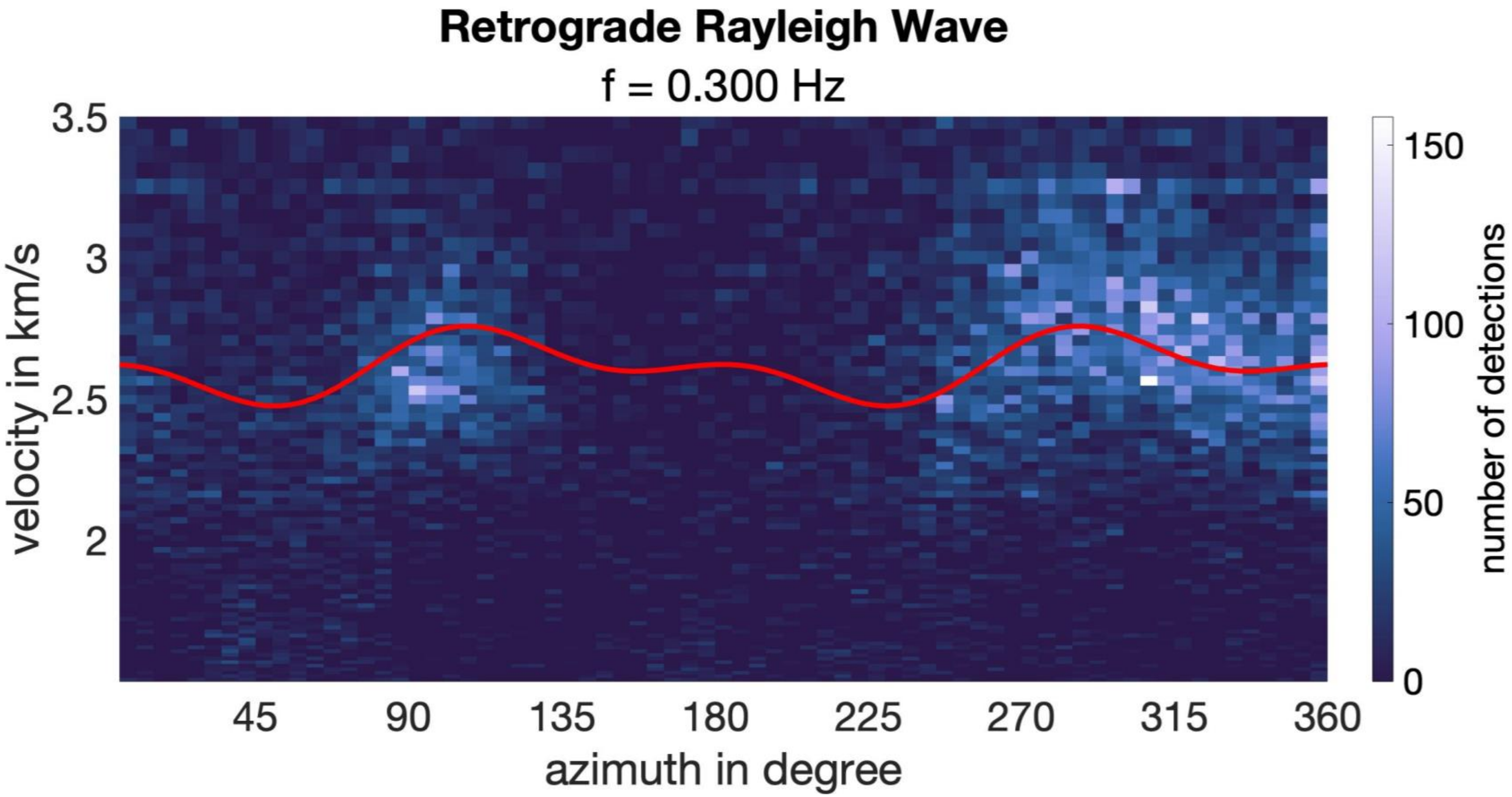


(above is based on Rayleigh waves corresponding to maximum normalised response energy)

- Fault created Rayleigh waves, but it was not the only cause.
- Rayleigh wave particle motion direction changed with the presence of the fault.

What’s next?

- Further synthetic wave type analysis for all wave arrival times/azimuth.
- Creating a synthetic anisotropy curve similar to real data below.



- Continuing this for faults of different geological situations.

Overall summary:

- Numerical modelling can be used to generate Rayleigh waves.
- Rayleigh waves travel faster when travelling along the “water-filled” fault.
- 3C beamforming can help depict wave types, propagation velocity and direction.

Any questions?

Further reading/future talks:

Kennedy, H., Löer, K., and Gilligan, A.: Constraints on fracture distribution in the Los Humeros geothermal field from beamforming of ambient seismic noise, Solid Earth, 13, 1843–1858, https://doi.org/10.5194/se-13-1843-2022, 2022.

- EGU23 Vienna: TS2.1-EGU23-5756, https://doi.org/10.5194/egusphere-egu23-5756
- EGC 1 Aberdeen: Day 3-Fault and Fracture Characterisation for the Energy Transition, https://www.energygeoscienceconf.org/technical-programme/
- PGRiP 2023 Aberdeen/Edinburgh: https://pgrip2023.wordpress.com/

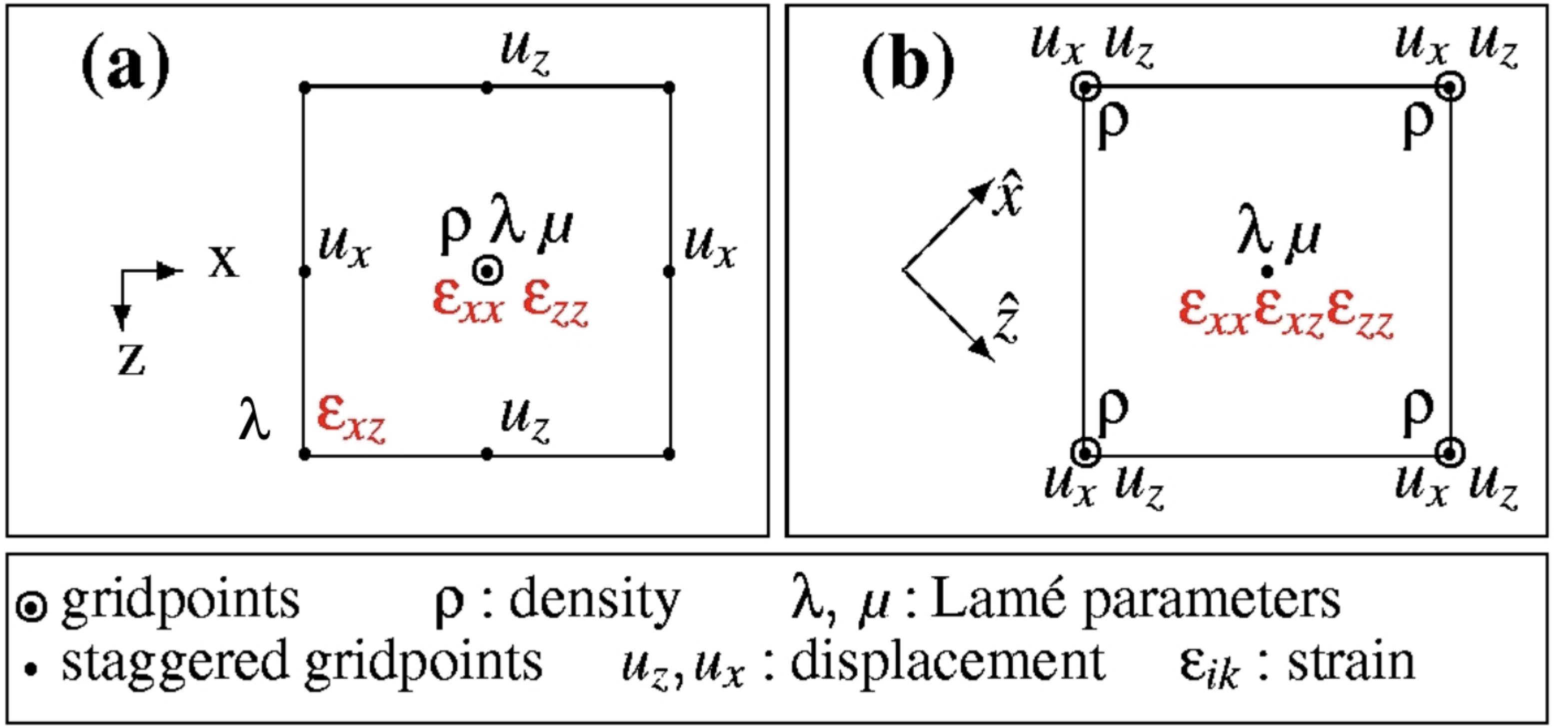
References:

Kennedy, H., Löer, K., and Gilligan, A.: Constraints on fracture distribution in the Los Humeros geothermal field from beamforming of ambient seismic noise, Solid Earth, 13, 1843–1858, https://doi.org/10.5194/se-13-1843-2022, 2022.

Nima Riahi, Götz Bokelmann, Paola Sala, and Erik H Saenger. Time-lapse analysis of am- bient surface wave anisotropy: A three-component array study above an underground gas storage. Journal of Geophysical Research: Solid Earth, 118(10):5339–5351, 2013.

Erik H Saenger, Norbert Gold, and Serge A Shapiro. Modeling the propagation of elastic waves using a modified finite-difference grid. Wave motion, 31(1):77–92, 2000.

- RSD FD Scheme:



(a) Standard Staggered Grid
(b) Rotated Staggered Grid
Saenger et al. (2000)

- Stability and dispersion criteria:

In place to create stability in the model (due to amplitude increasing exponentially with every timestep). Numerical dispersion (frequency-dependent velocity-based errors) is also an issue.