The Potential of Large-N Passive Seismology to Image Meter Scale Variations in Reservoir Heterogeneity

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Aquifer Heterogeneity

- Shallow and deep geothermal resources require reliable aquifer characterization and for prediction ahead of drilling
- For deep geothermal 2D and 3D seismic reflection surveying can be justified as part of exploration programs, as evidenced from European experience
- For shallow geothermal and for monitoring passive seismic methods may afford benefits in both logistics and cost
- ***Does large-N seismology offer a scalable solution to imaging and monitoring for shallow geothermal?***

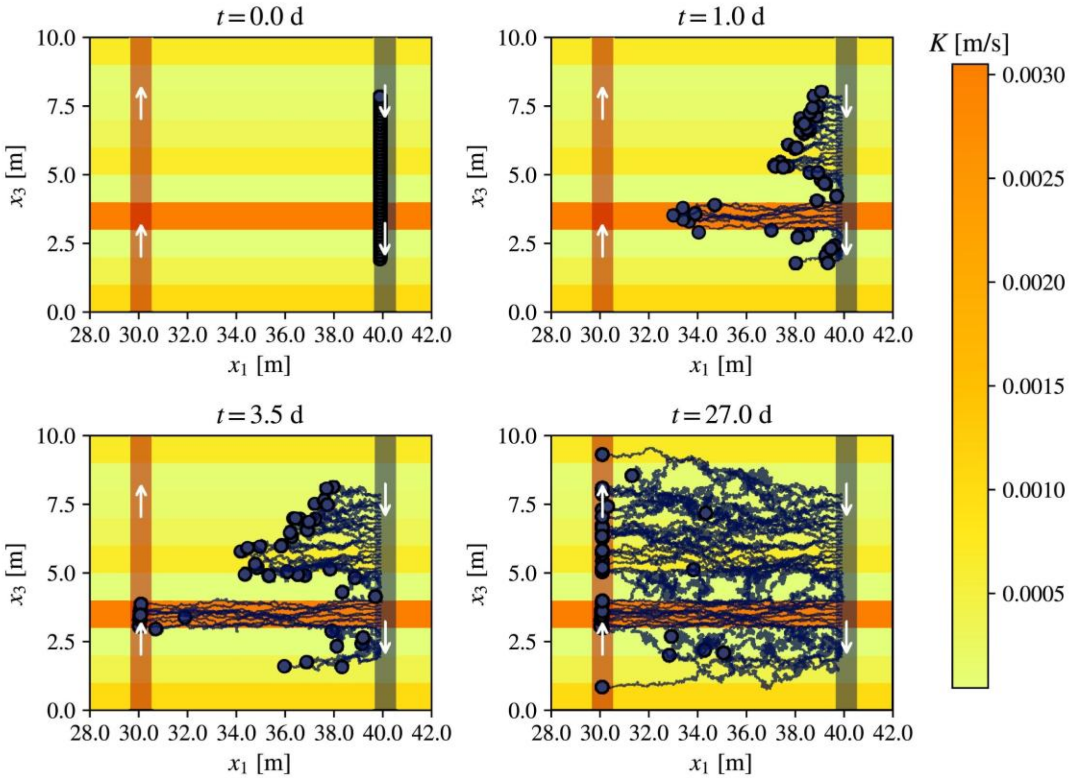


Image from Di Dato et al., 2022

Phenomena of seismic waves

- We can indirectly recover information about the Earth's properties by utilizing a variety of physical phenomena associated with seismic waves.
- In active source methods we are primarily concerned with reflections, however, ambient noise analysis utilizes a diffuse wavefield that is a function of multiple phenomena.
- Potential advantages of ambient noise over active source include – reduced costs, continuous monitoring, lower environmental impact.

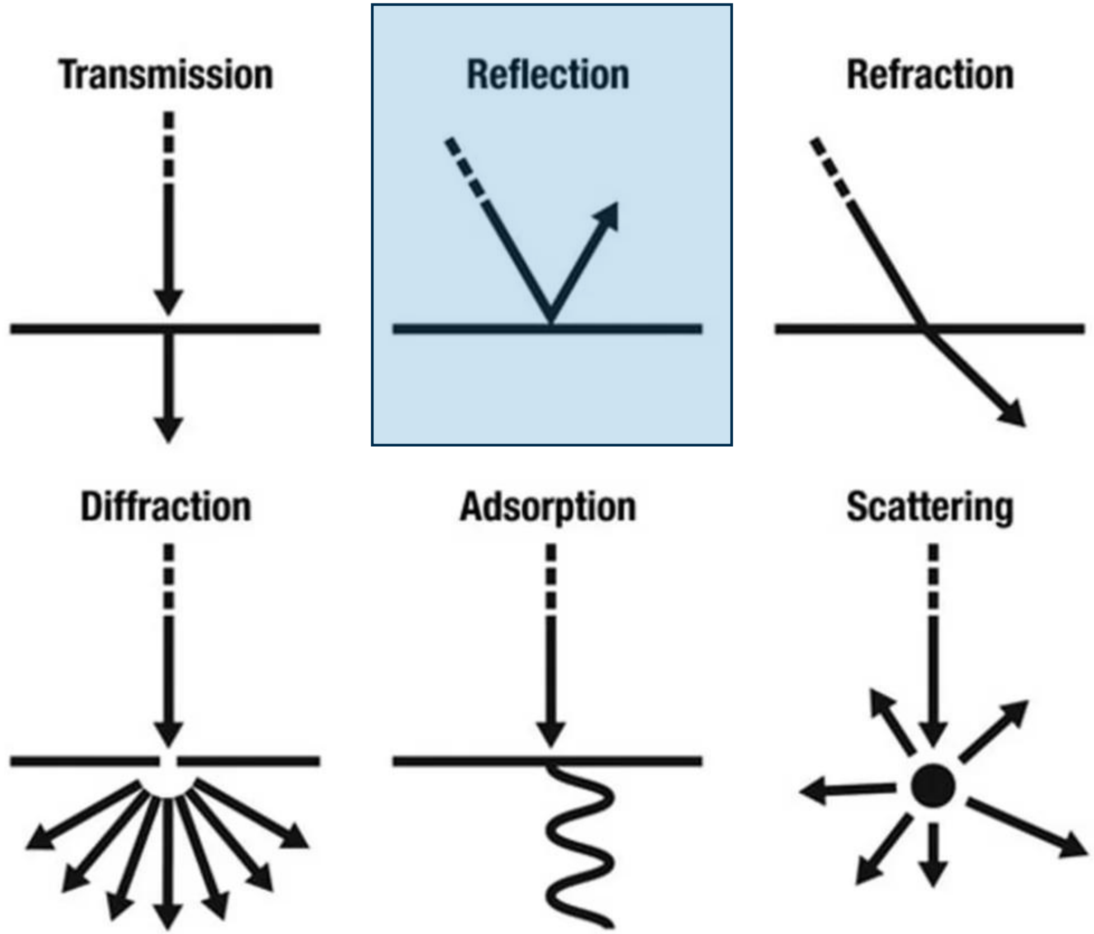
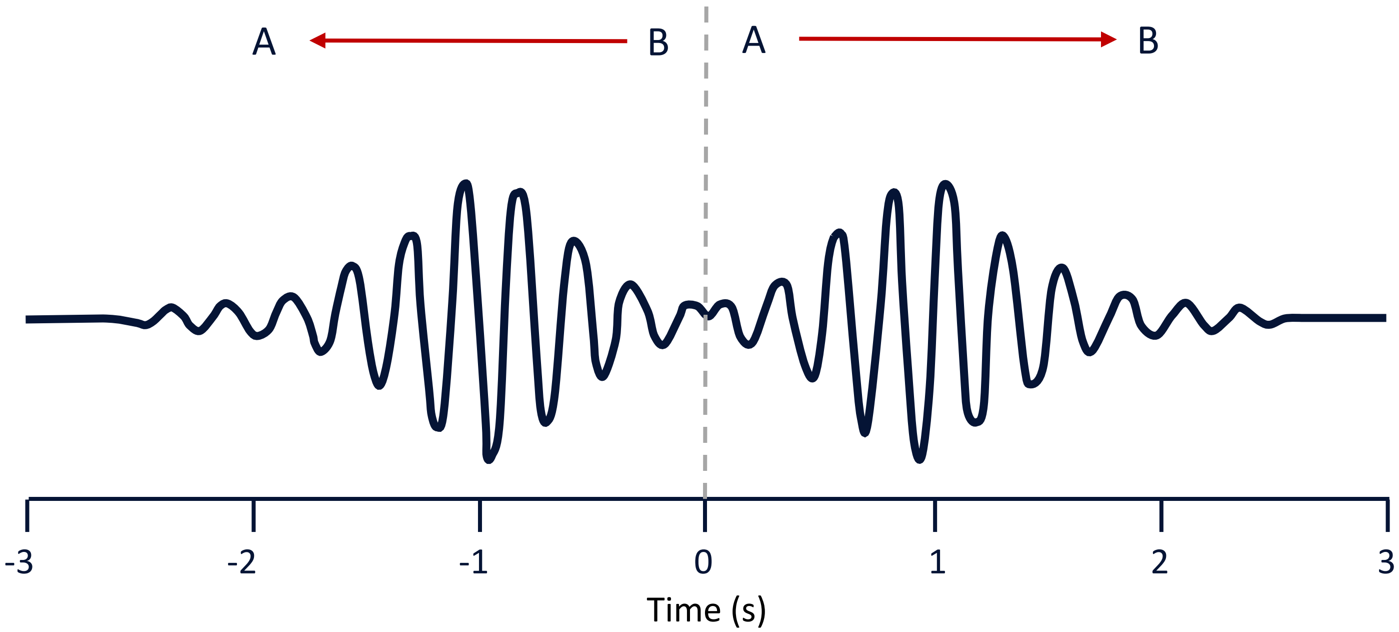
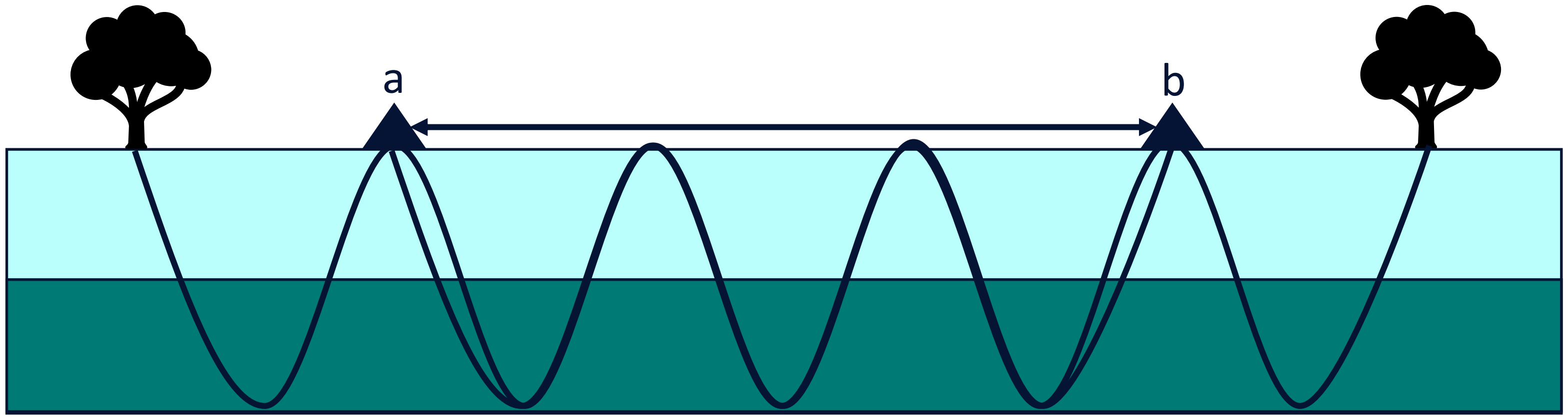


Image originally from Physics Weekly

Cross Correlation (CCF)

- Cross correlation of long time series between two receivers is an approximation for the Earth's Green Function.
- Green function describes how the Earth responds to an impulse at point A, recorded at point B, and vice versa





$$G(a,b,t) \approx u(a,t) \otimes u(b,t)$$

Survey

Survey Location

- RAF Leeming is a living and working community with a range of land-use and building types covering ~6km^2
- Within urban settings anthropogenic activities represent the main sources of seismic energy, typically >1 Hz

Aims

- Evaluate the use of single component receivers (referred to here in as nodes) for ambient noise analysis
- Demonstrate the acquisition of geophysical data at a 'complex site'.

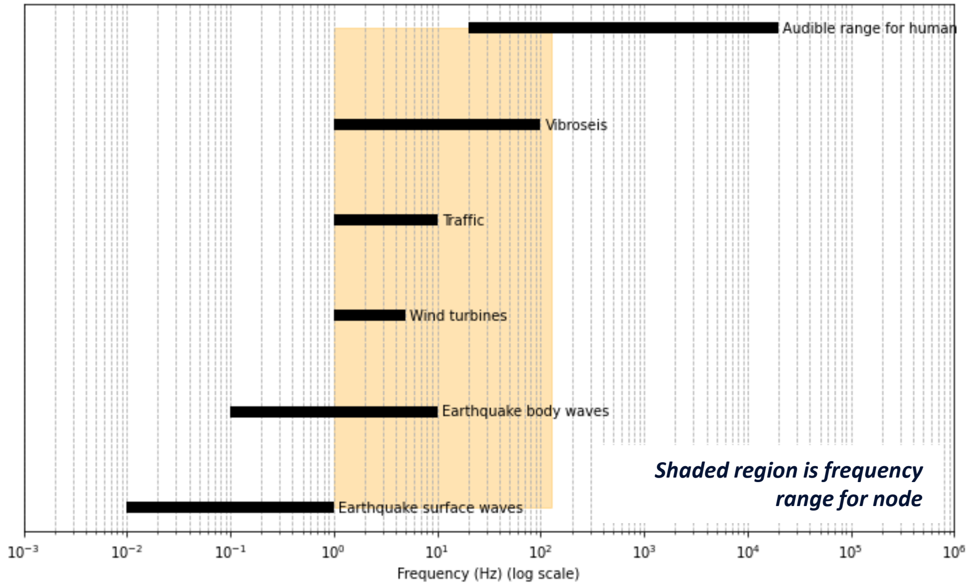
Deployment

- 3271 receivers deployed over 12 days covering an area of ~5km^2 during July and August 2022.
- Total recording period was 28 days
- Deployment restrict to soft ground (e.g. grass or soil areas)
- Up to 10 people per day either working in teams of 3 or 4
- All receivers were buried flush with ground level leaving top of node just visible.
- The total data volume of raw trace data is >17Tb

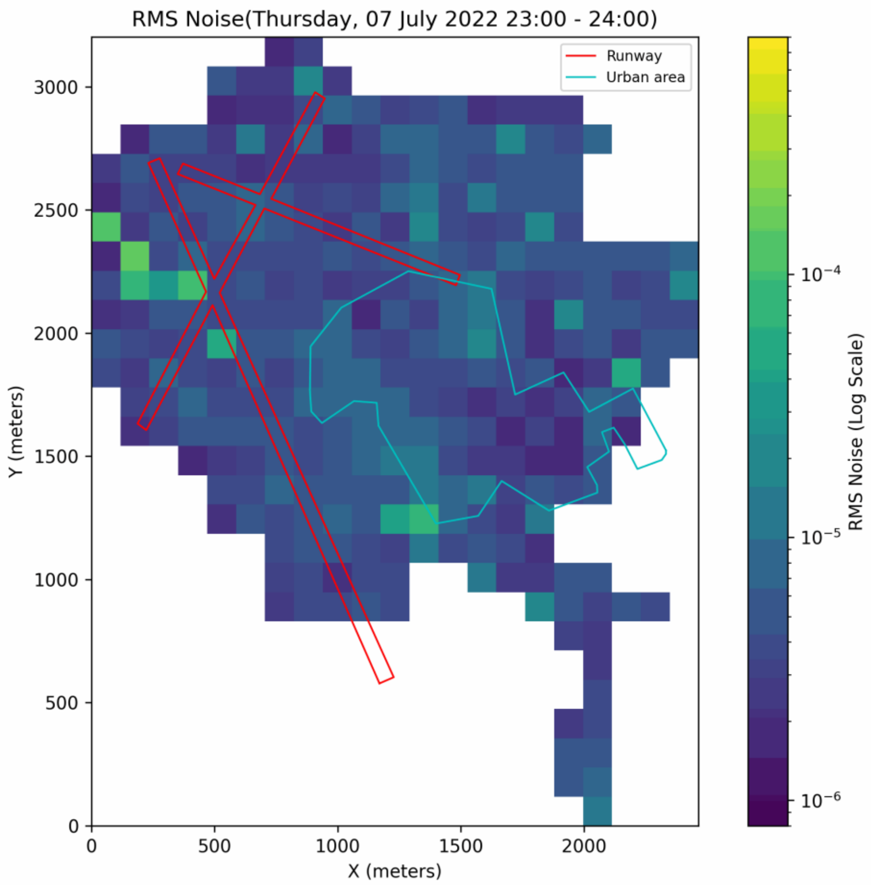
Ambient Noise Field

- The dominant seismic waves recovered in our CCFs are surface waves and as the receivers are single component they are most likely Rayleigh waves.

Theoretical range of frequencies for selected sources

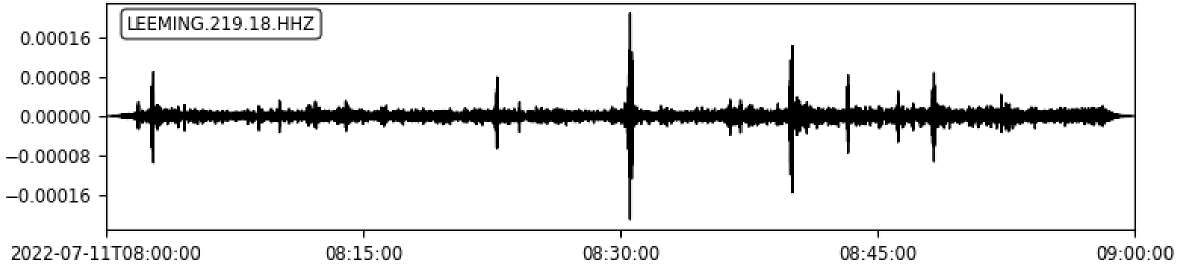


Animation of hourly RMS noise



From trace to CCF

1 Hour of raw data from two nodes (140 m apart)



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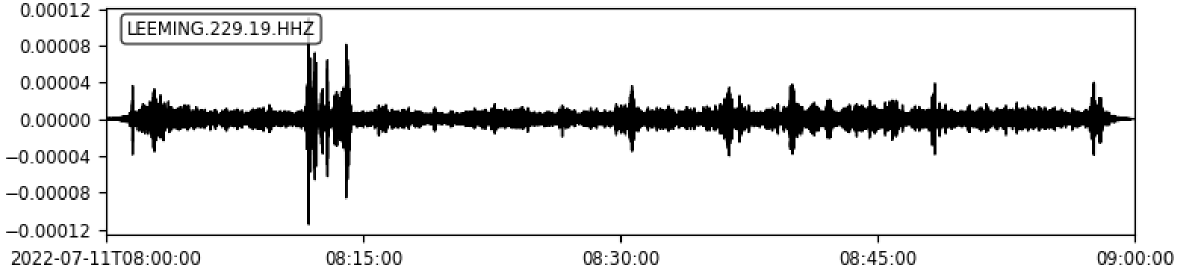
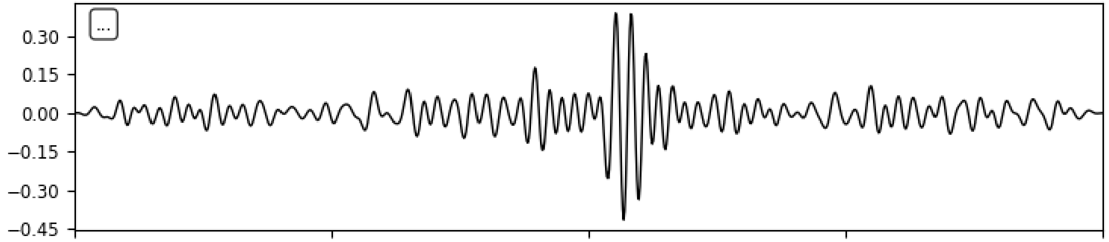


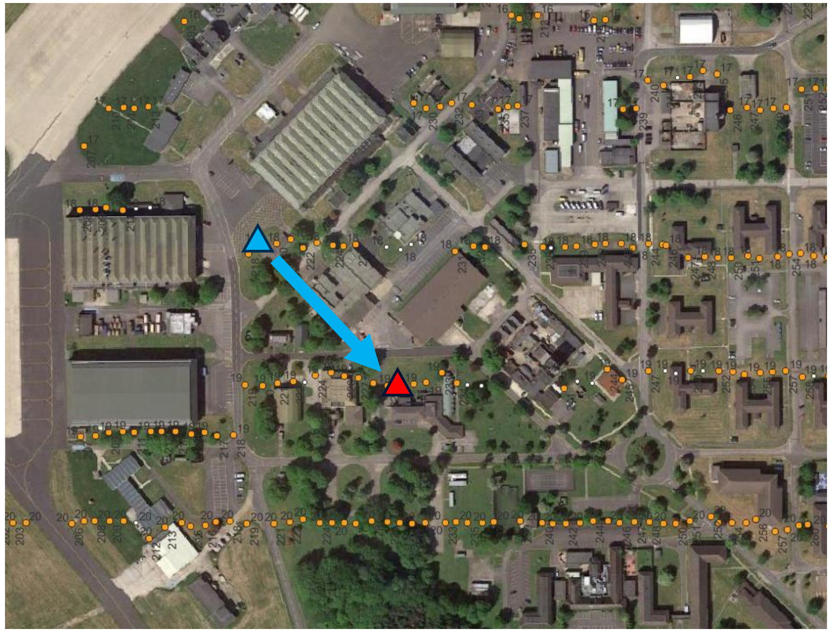
Cross Correlation Function (CCF)

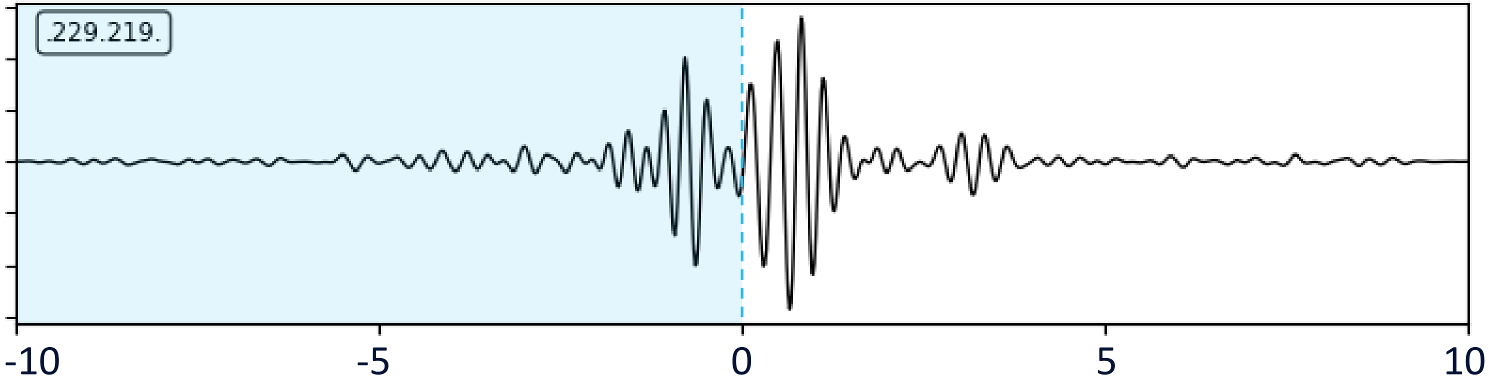
2022-07-11T08:59:50 - 2022-07-11T09:00:10



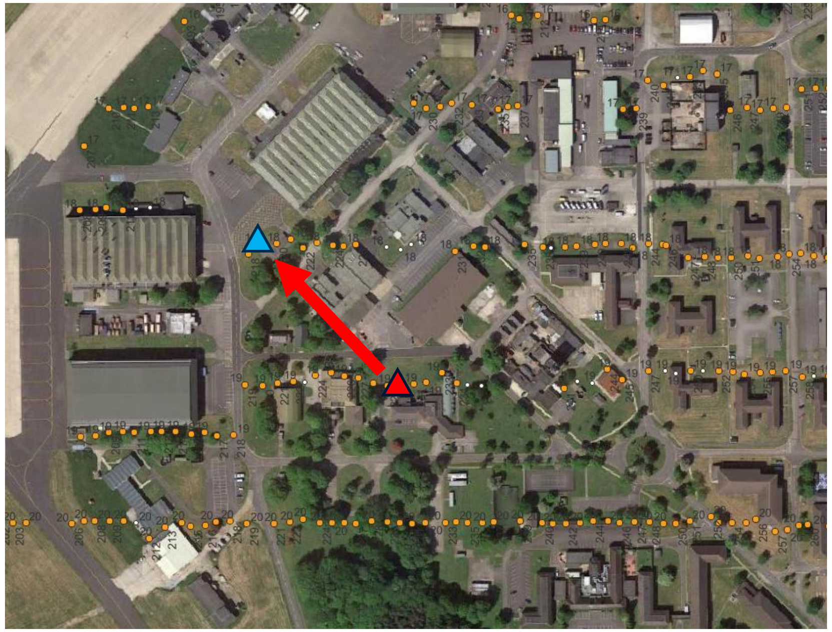
From trace to CCF

Stacked CCF
~680 hourly CCFs stacked

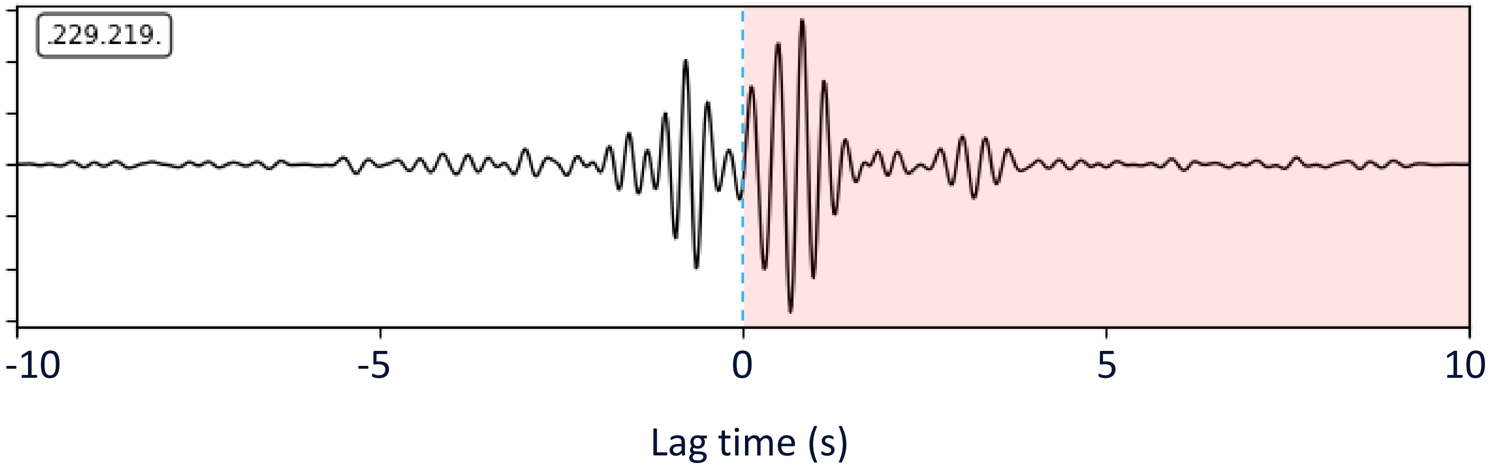




From trace to CCF



Stacked CCF
~680 hourly CCFs stacked



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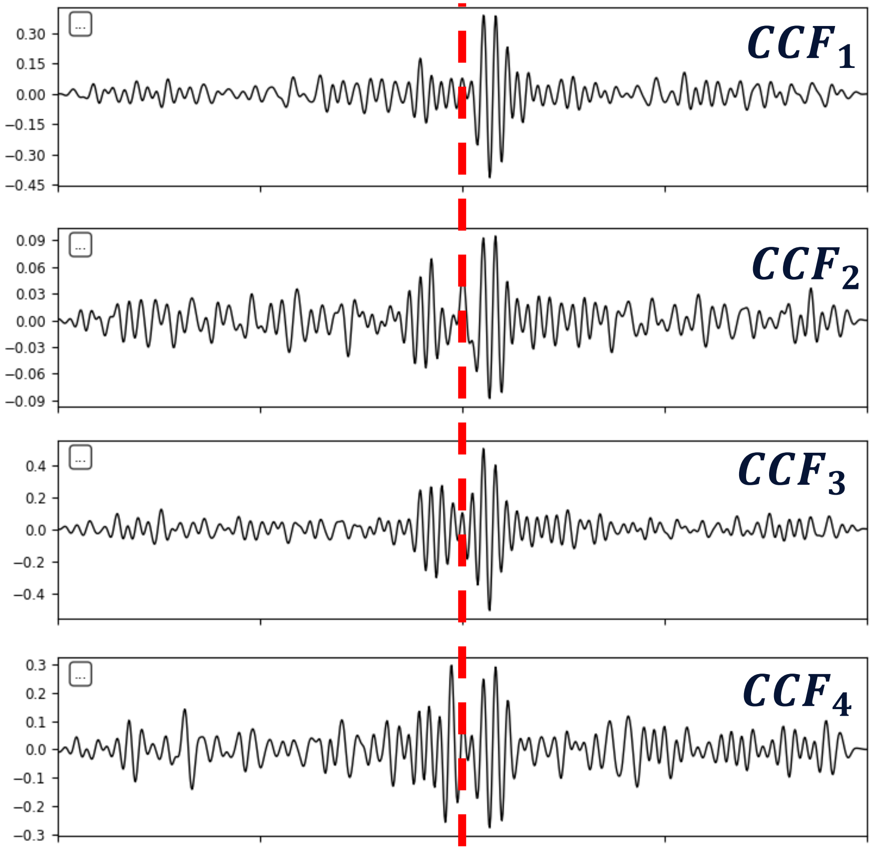
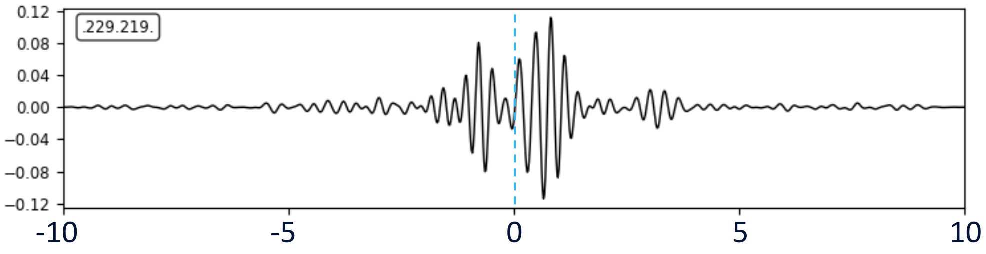
Stacked CCFs

Hourly CCFs



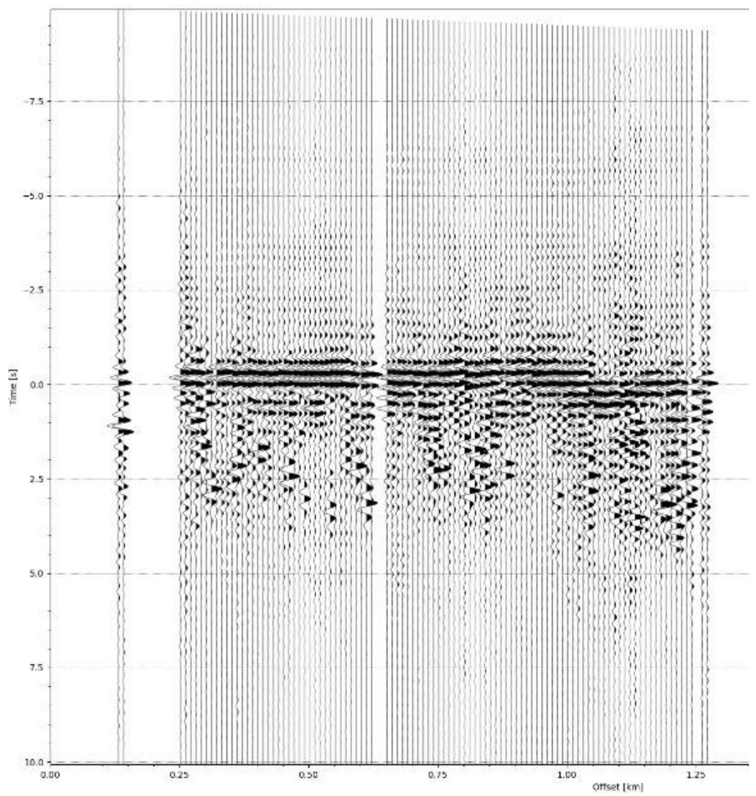
- We use Nth root stacking, that takes the Nth-root of the absolute amplitudes of each individual trace and sums them together (e.g. Yang et al., 2023)

$$Stacked\ CCF(t) = \frac{1}{N}\sum_{i=t}^{N} CCF_i(t)$$



~680 hourly CCFs stacked (t = 1 hours, N = 680)

Virtual Shot Gather

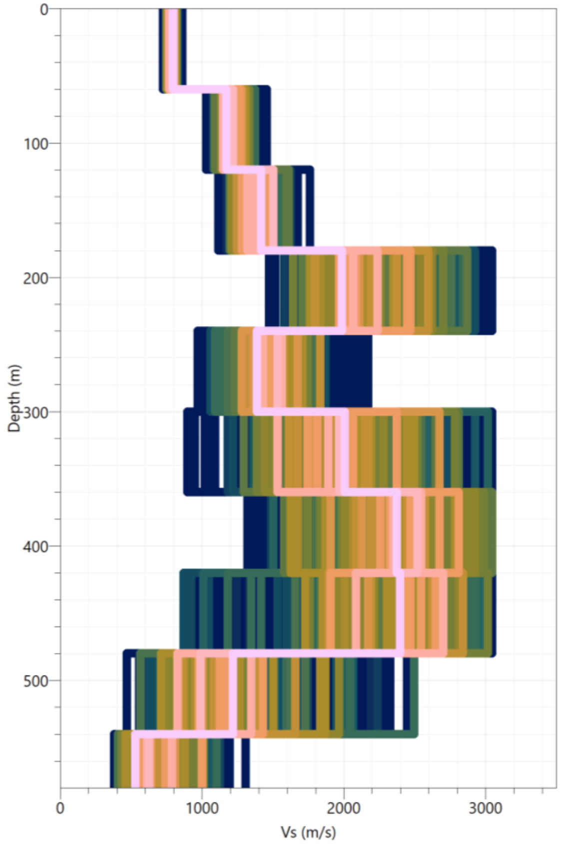


Virtual shot gather

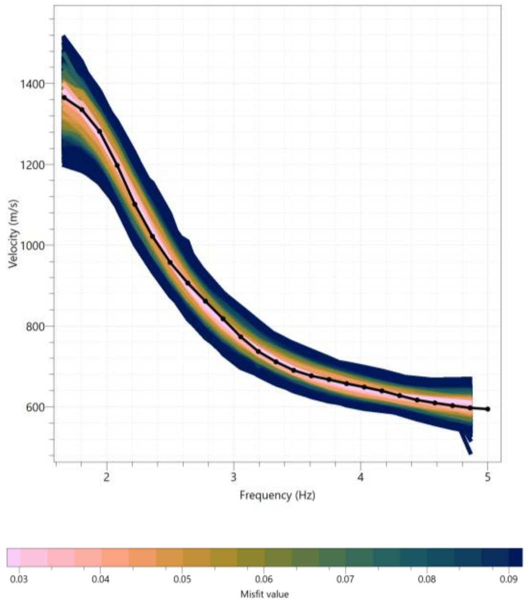
- Combining staked CCFs along a transect we can construct a virtual shot gather.
- A virtual shot gather represents the propagating wavefield that would be measured if a there were an actual shot point.
- Applying a single velocity of correction of 2000m.s^{-1} flattens the gather
- We can use this concept across our dense array to determine the 1D, 2D or 3D velocity structure.

1D Inversion

S-wave velocity depth profile



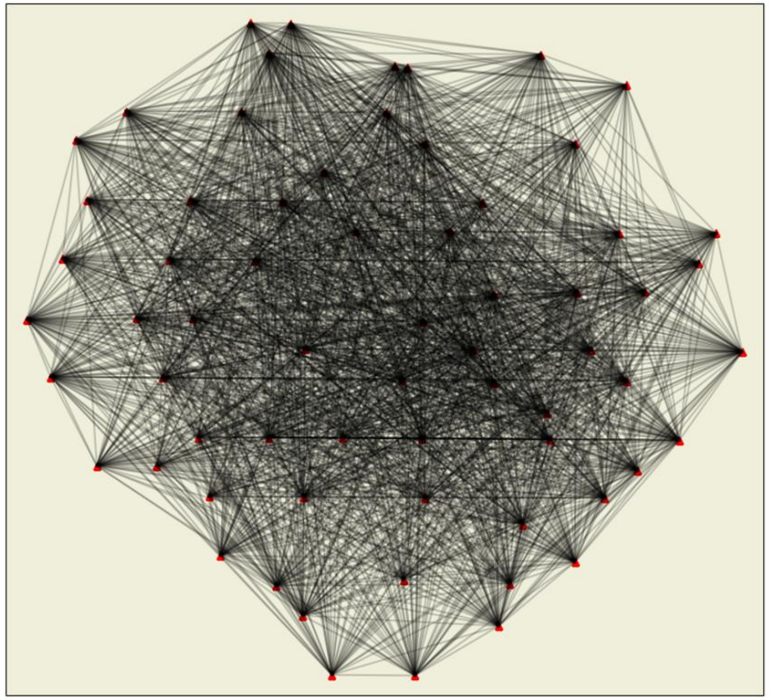
Dispersion curve

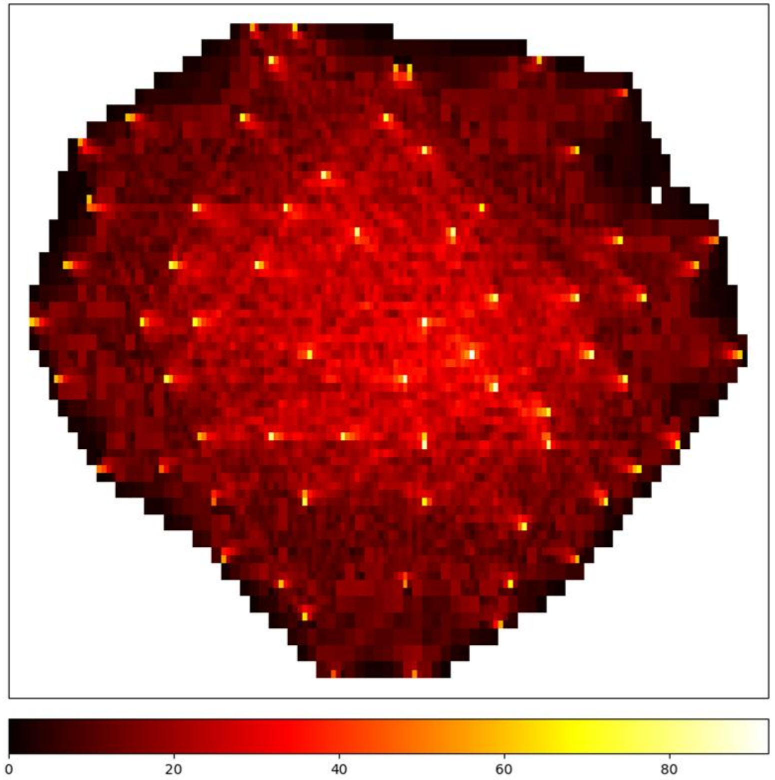


- 1-D shear velocity depth models produced by iteratively inverting a dispersion curve extracted from a CCF with a ~1 km node offset.
- We observe relatively high shear wave velocities in the 200 to 500 m depth range – interpreted due to the shallow Permian evaporites
- Refraction tomography static corrections from reflection are consistent with these interpretations.

Interstation Paths

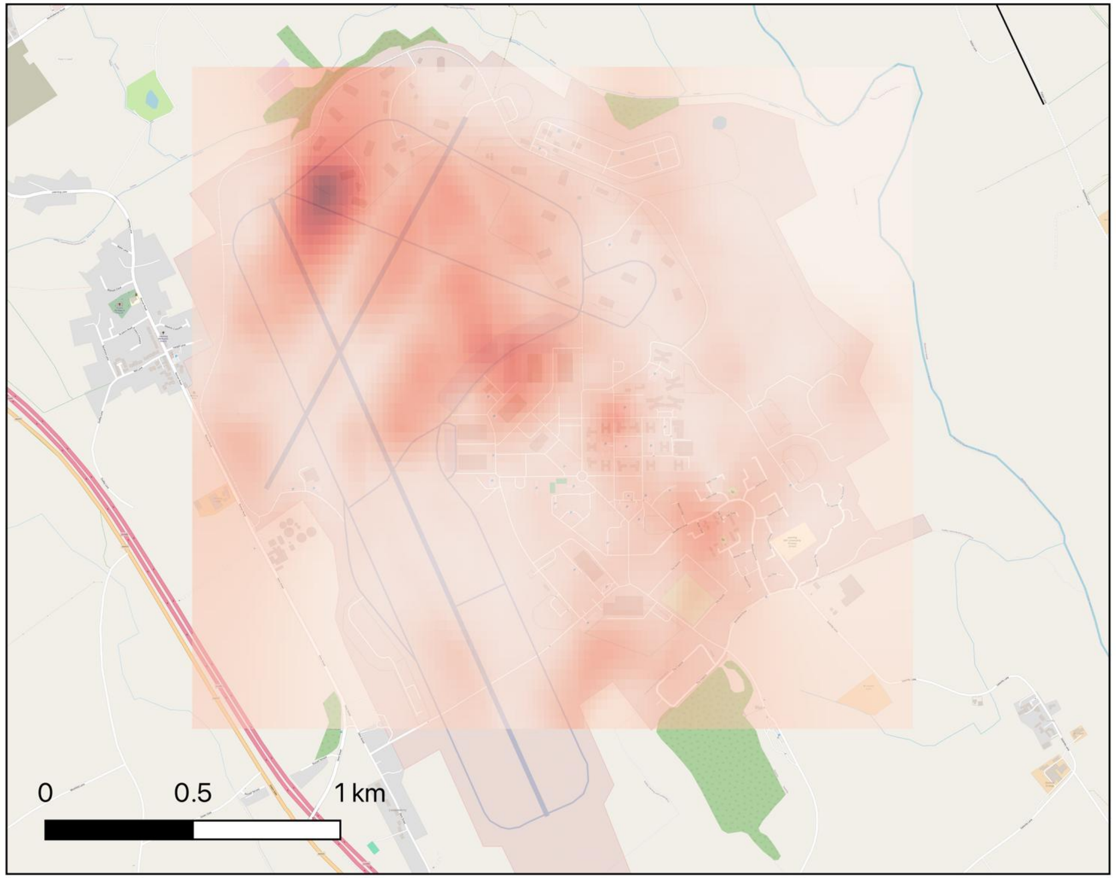
- In the first instance we have developed our processing flow using a subset of stations.
- On the right are 65 nodes from across the site.
- There are 2100 interstation paths for just 65 nodes





Shallow Site Heterogeneity

- The map on the right is group velocity map from 0.2
- The approx. wavelength is 140m, with the map approximates a depth range of 45 to 70 m.
- In current processing we can reproduce spatial variations in group velocity down to ~70m using JUST 65 nodes from across the site.
- In our final processing we anticipate being able to resolve even smaller variations.

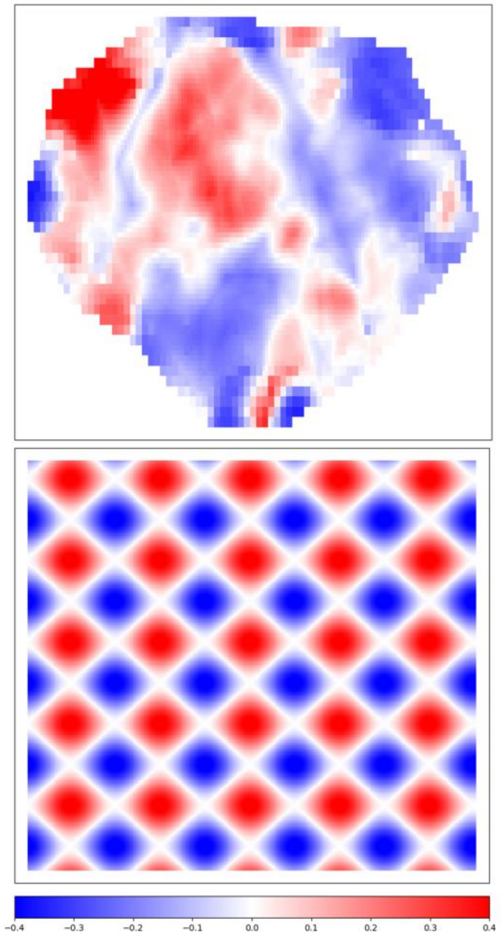


Group velocity map (0.2s)

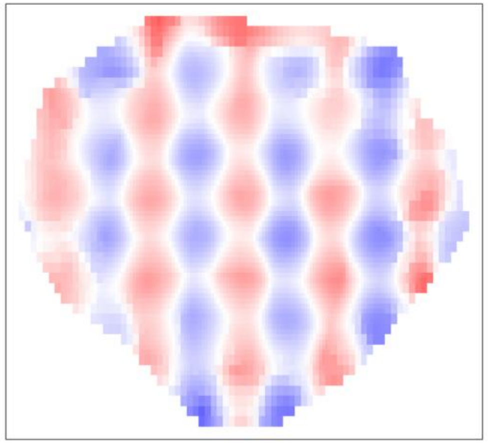
Group Velocities – Reliability Test

Group velocity map, Period = 0.2 s

Synthetic 'checkerboard' model



Recovered 'checkerboard' model



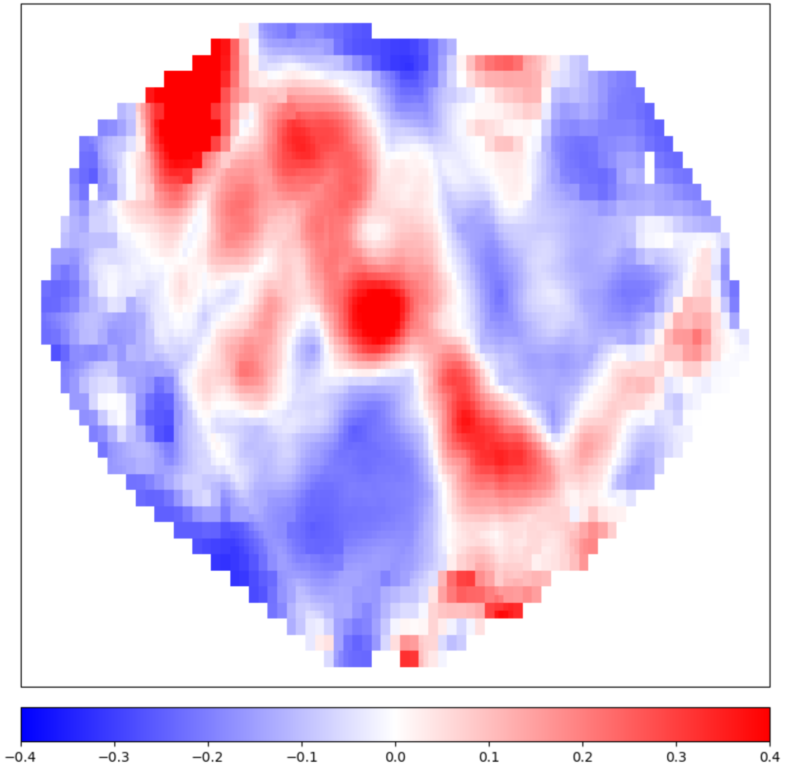
- The resolution is limited by the receiver spacing, the quality of the cross correlation and the recording period

- Checkerboard test uses a subset of 65 nodes
- Minimum station distance of 100m
- The checkboard uses high/lows of 250m
- High confidence in recovered synthetic
- We are currently testing the resolution limits through iterative checkerboard testing

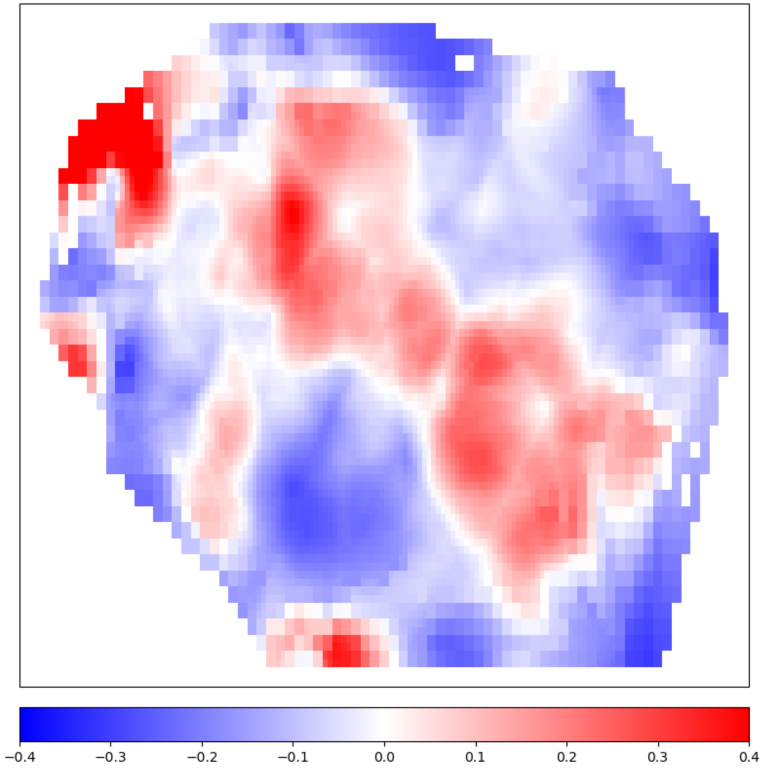
Group Velocities – Replicability Test

- On the right are two independent group velocity maps.
- Constructed using the same processing flow steps but using 65 unique stations in each case.
- While there are differences, the similarity provides confidence in the replicability of the method

0.26 s Group velocity map using red stations



0.26 s Group velocity map using blue stations



Summary

- We have demonstrated the potential for ambient noise tomography to characterize meter scale reservoir heterogeneity.
- The final step of our work will determine shear-wave and body-wave velocity models by inverting the group velocity data
- The next phase of research will investigate use cases for monitoring, where very small relative velocity changes can be detected.
- Large-N affords the potential for imaging and monitoring from the critical zone to depths of kilometers
- Extends the opportunity to image shallow to moderate depth aquifers where active source surveys may not be feasible.

Group velocities for different periods