Estimating Crustal Velocity Structure in Alaska from Acoustic-to-Seismic Coupling from the 2022 Hunga Eruption, Tonga

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Cleared for release

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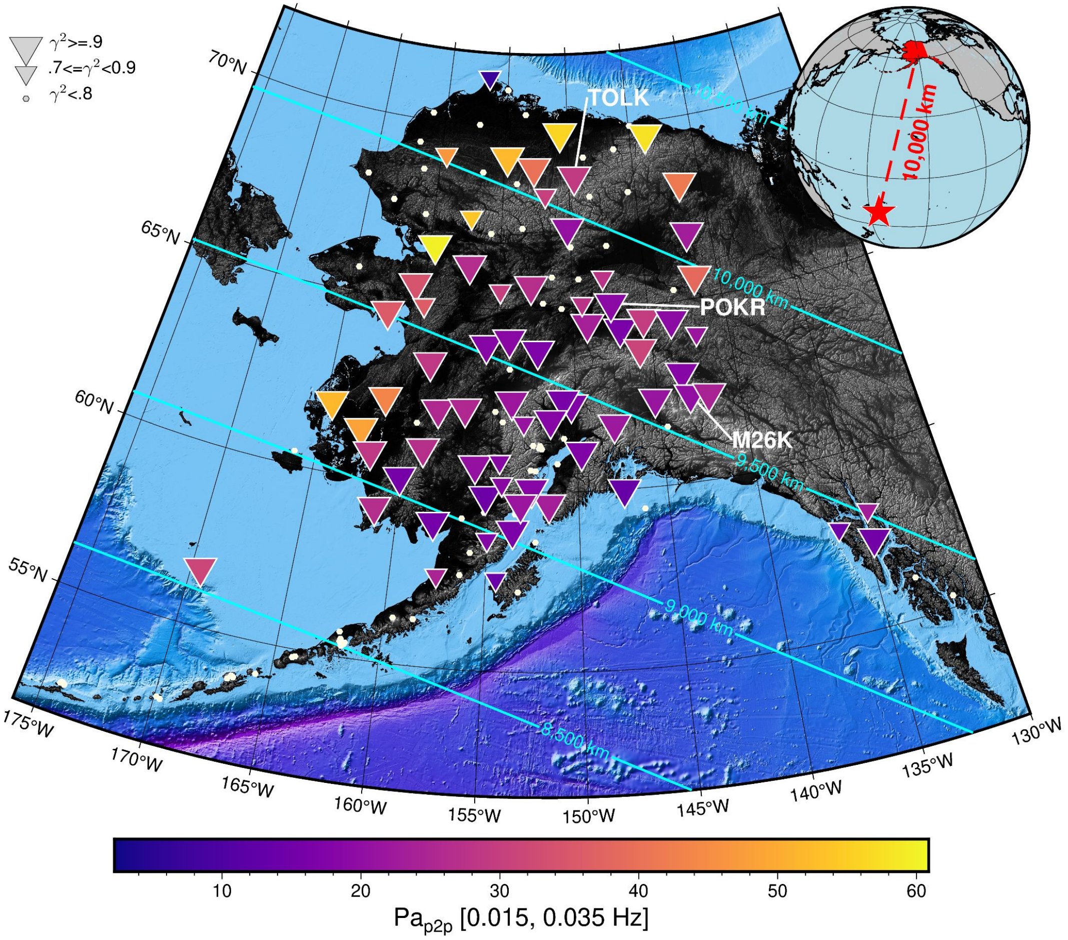
Motivation

Use the once-in-a-lifetime source from the Hunga, Tonga eruption to examine crustal structure using acoustic-seismic coupling at deeper depths than is typically possible

Tonga Geological Survey

Hunga, Tonga Infrasound in Alaska

- 150 stations equipped with colocated, broadband:
  - seismic (BH?)
  - infrasound (BDF)
  - barometer (BDO)
- Large pressure amplitudes (> 60.0 Pa) at huge offsets!



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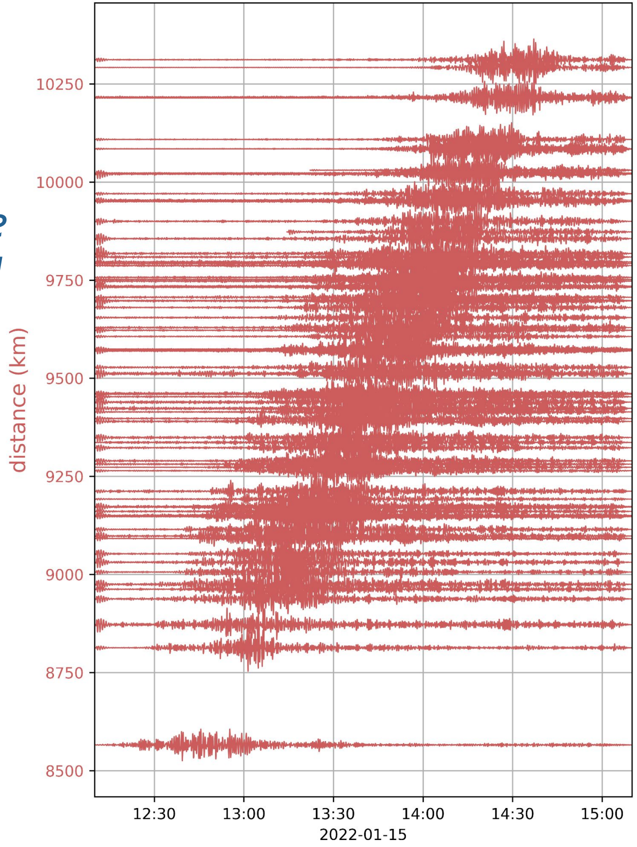
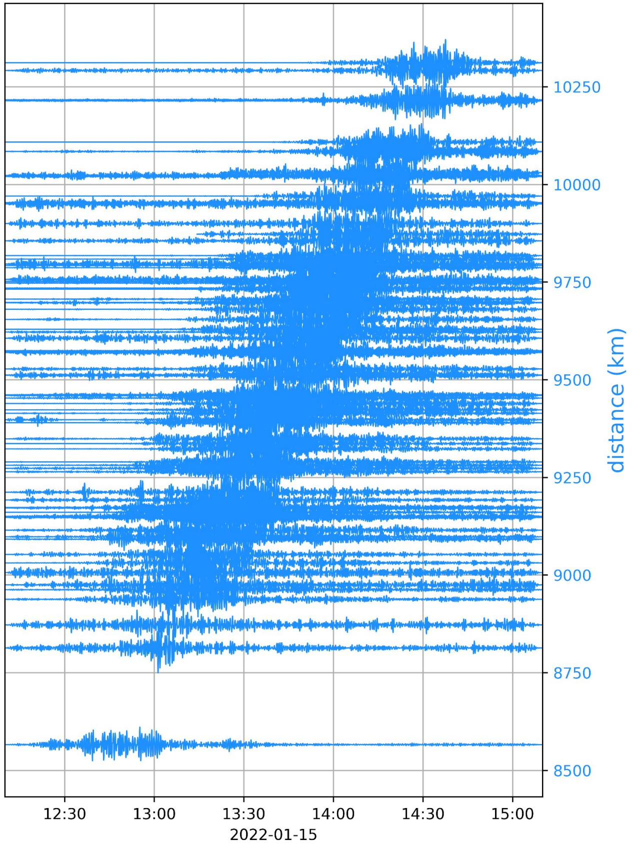
Pressure-to-Seismic Coupling

"A correlation has often been observed to exist between changes in the magnitude of the long-period seismic and atmospheric pressure fields"
— Sorrels, 1971



Infrasound (BDF)



Seismic (BHZ)

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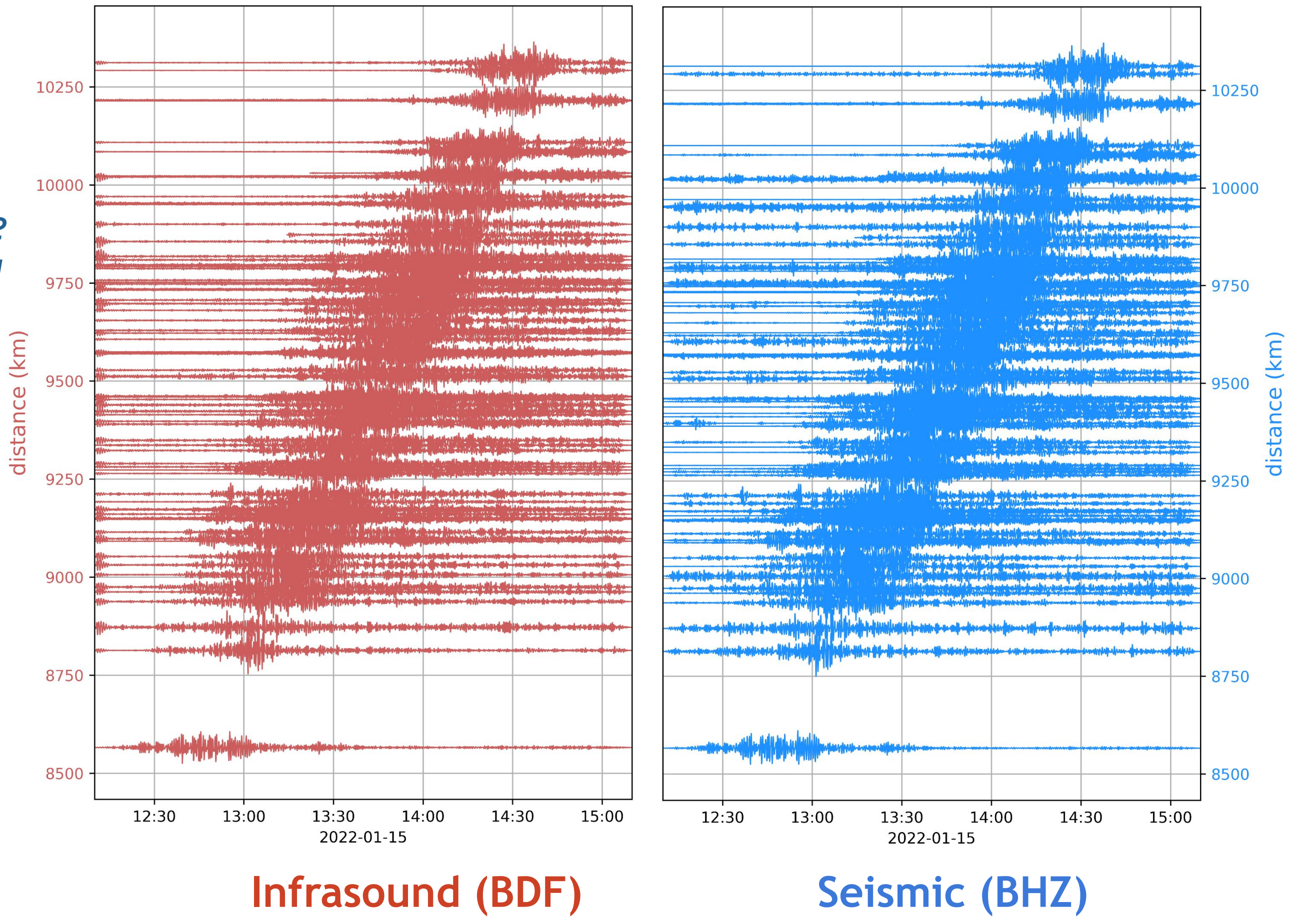

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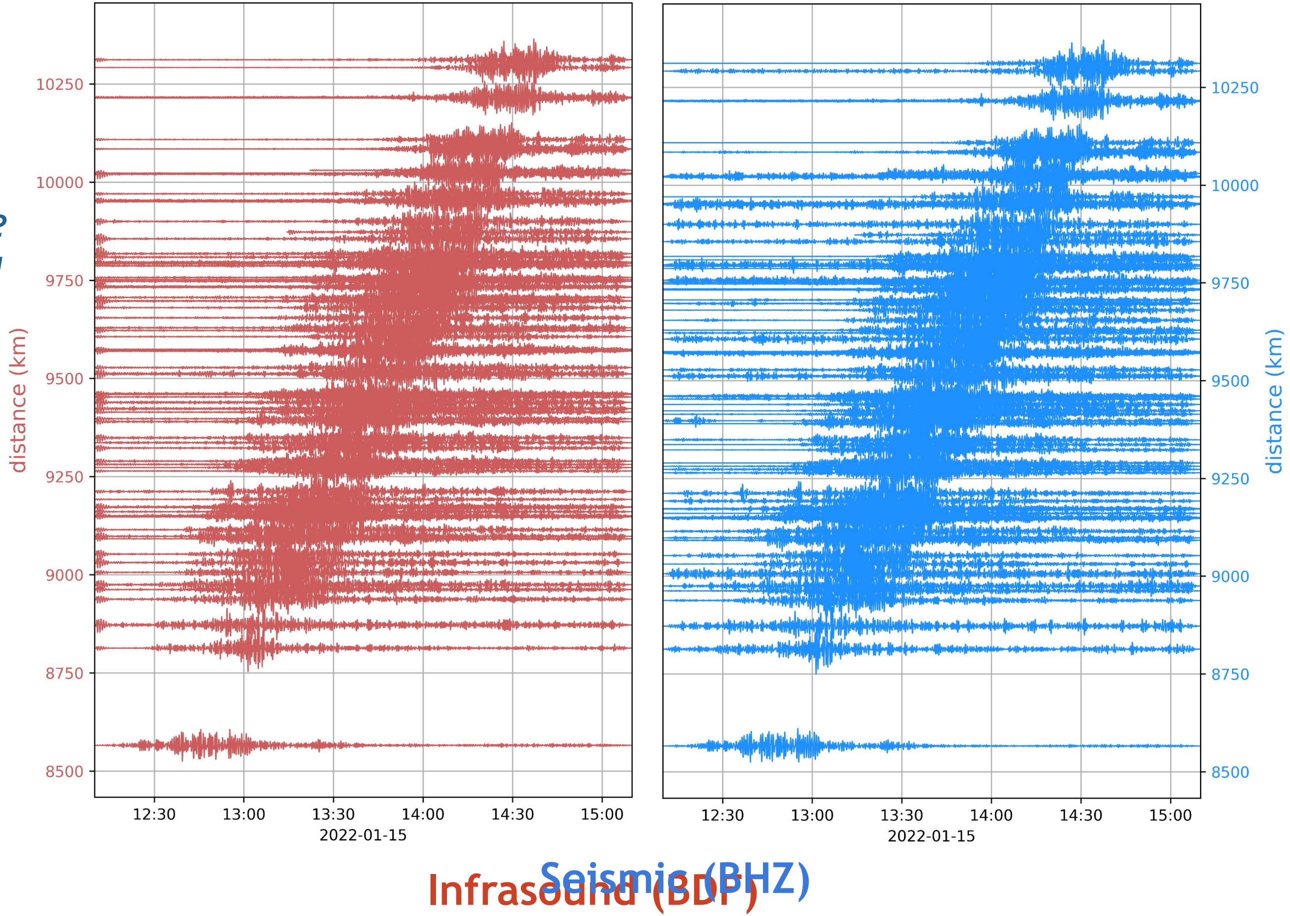

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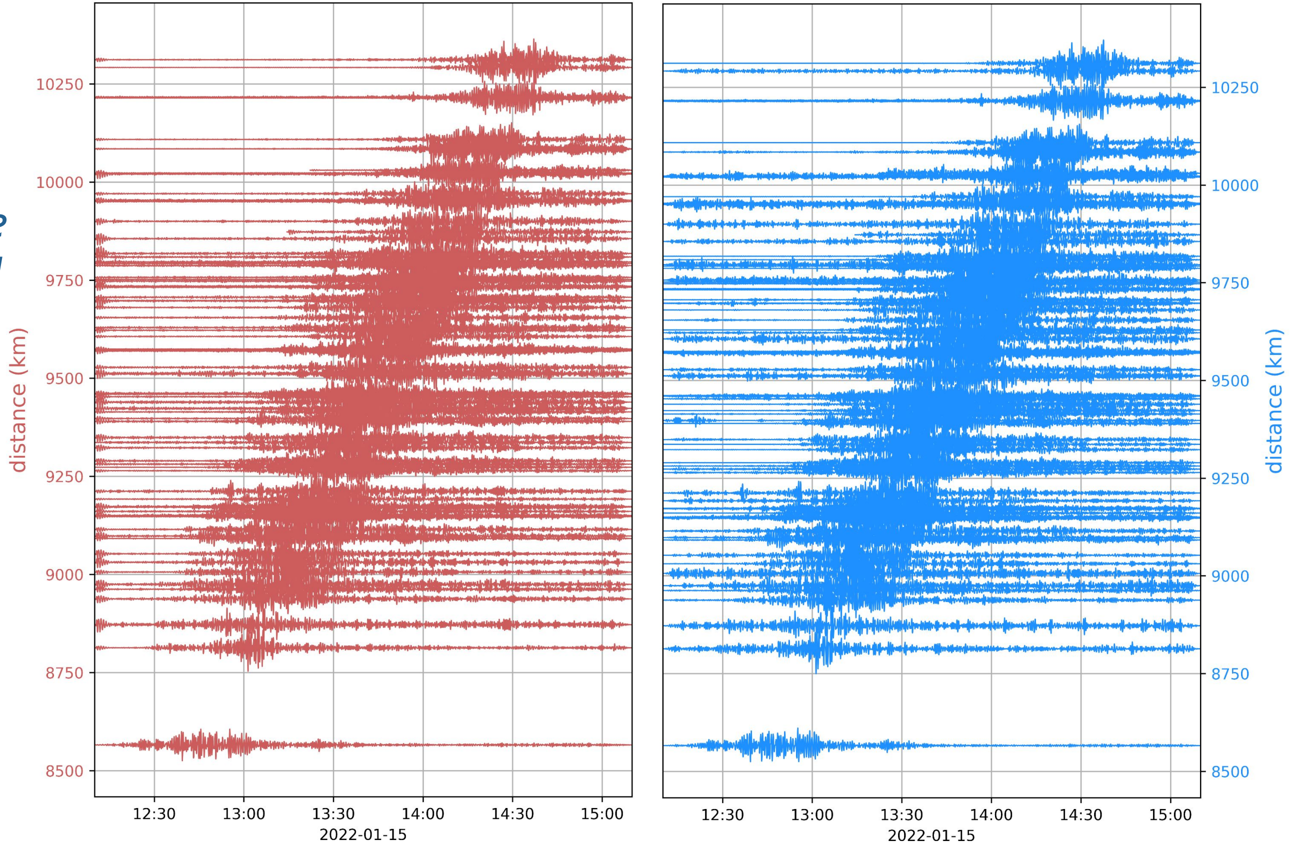

Seismic (BHZ) Infrasound (BDF)

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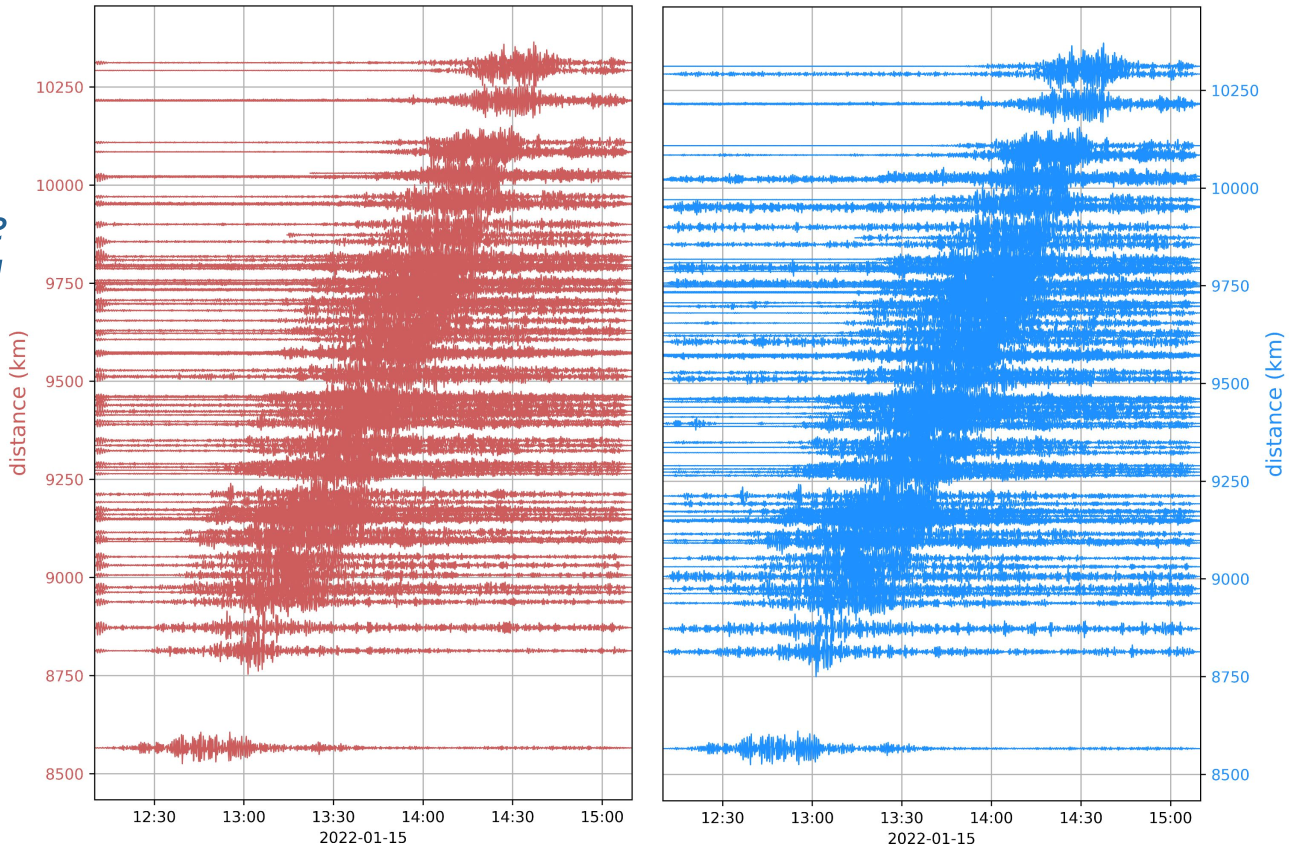

Seismic (BHZ) Infrasound (BDF)

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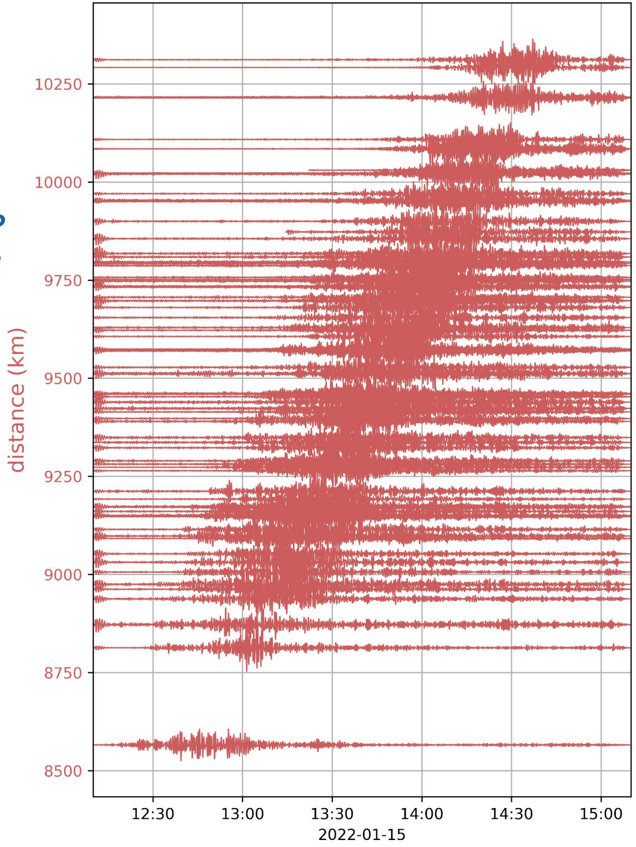

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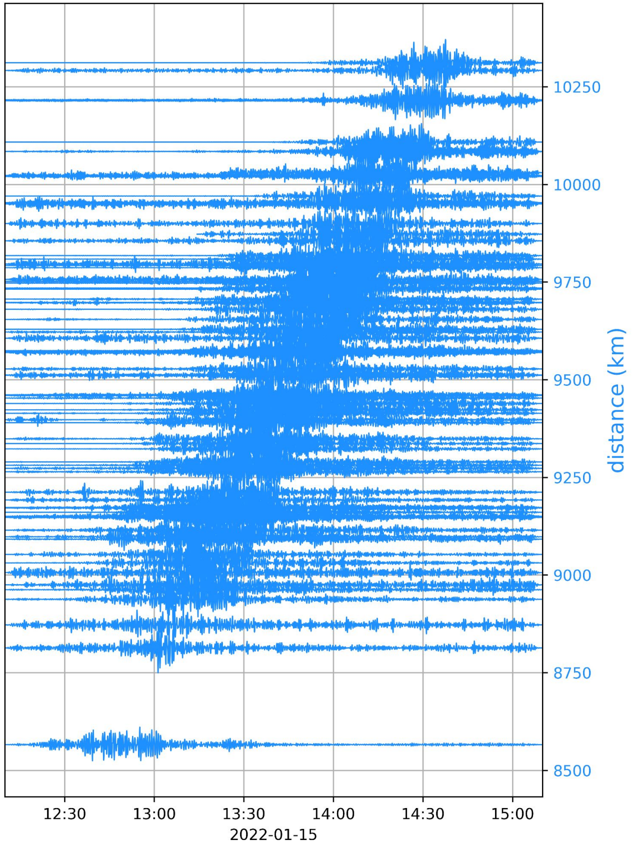
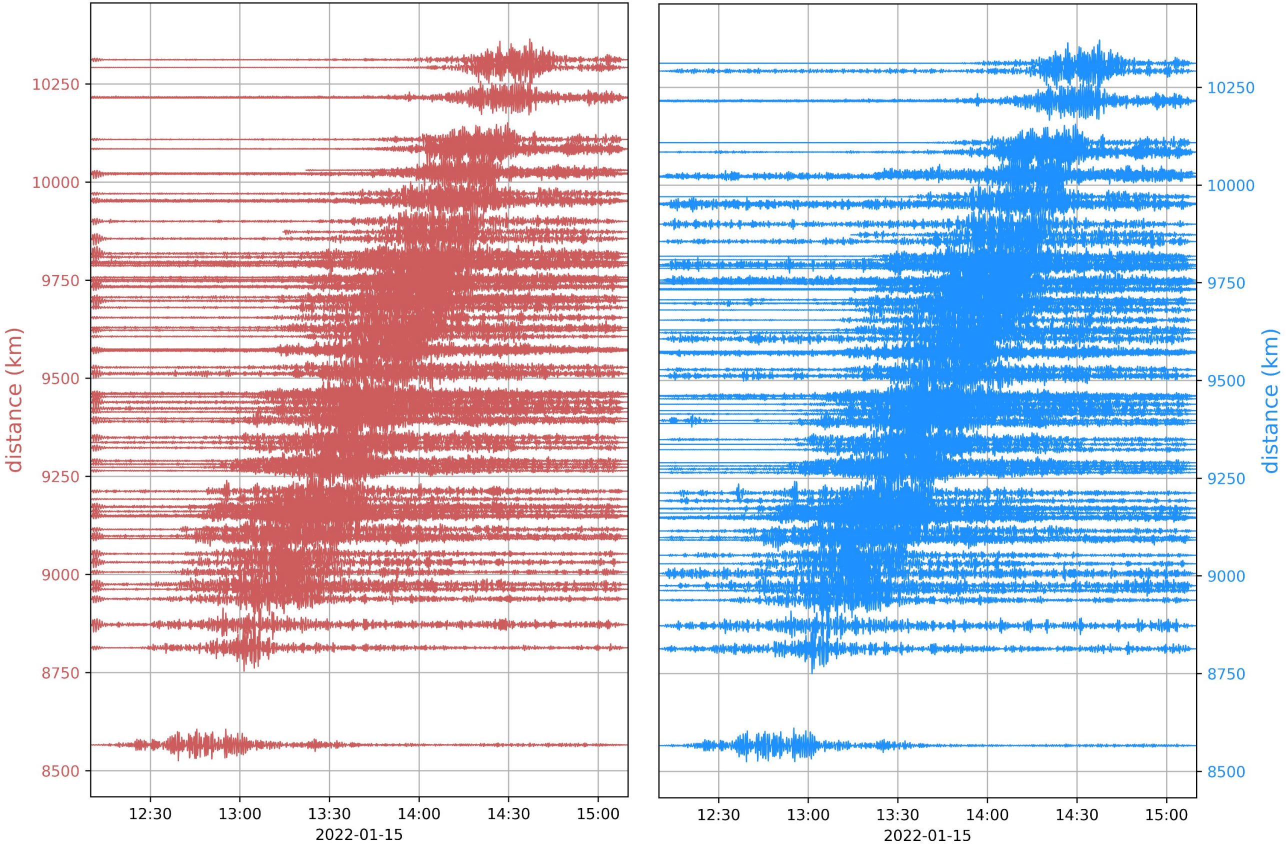


Infrasound (BDF)

Pressure-to-Seismic Coupling

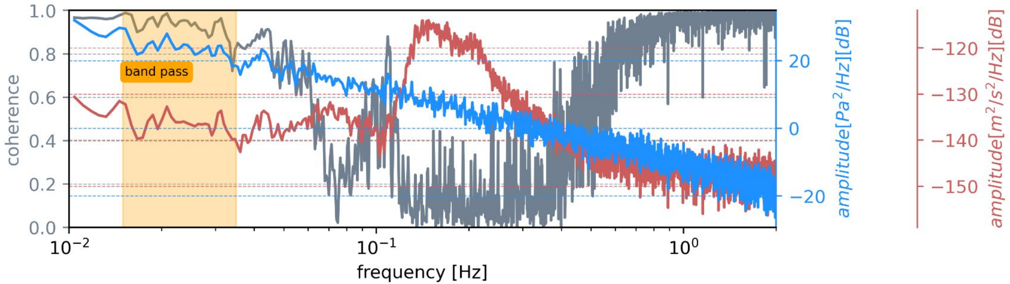
"...colocated data allow us to identify the frequency range of strong coupling between the atmosphere and the solid Earth and provide us information on how the solid Earth responds to surface pressure changes."
—Tanimoto and Wang, 2018

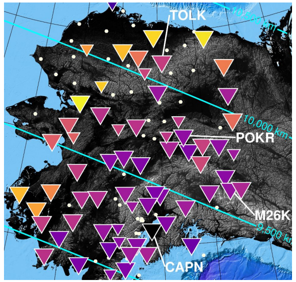


Seismic (BHZ)

Infrasound (BDF)

Data Selection





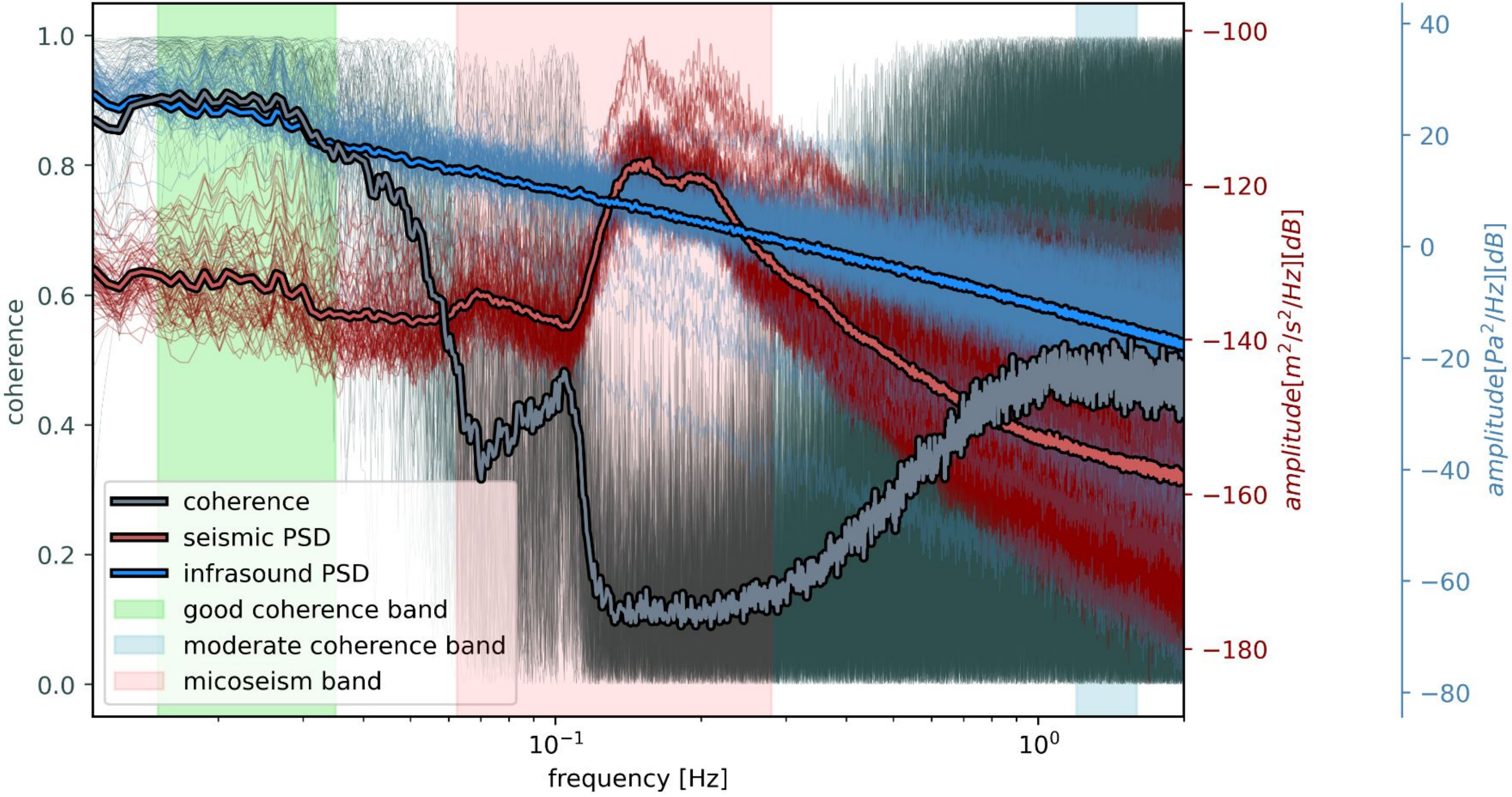
We choose bands with good coherence (> 0.8) between the seismic and pressure:

The magnitude squared coherence between the pressure and vertical seismic is:

$$\gamma^2 = \frac{\overline{G_{PS}}^2}{\overline{G_{PP}}\,\overline{G_{SS}}}$$

Where G_{PS} is the cross spectral density of the pressure and seismic, and G_{PP} and G_{SS} are the autospectral densities

Network Coherence



Broadband infrasound and seismic

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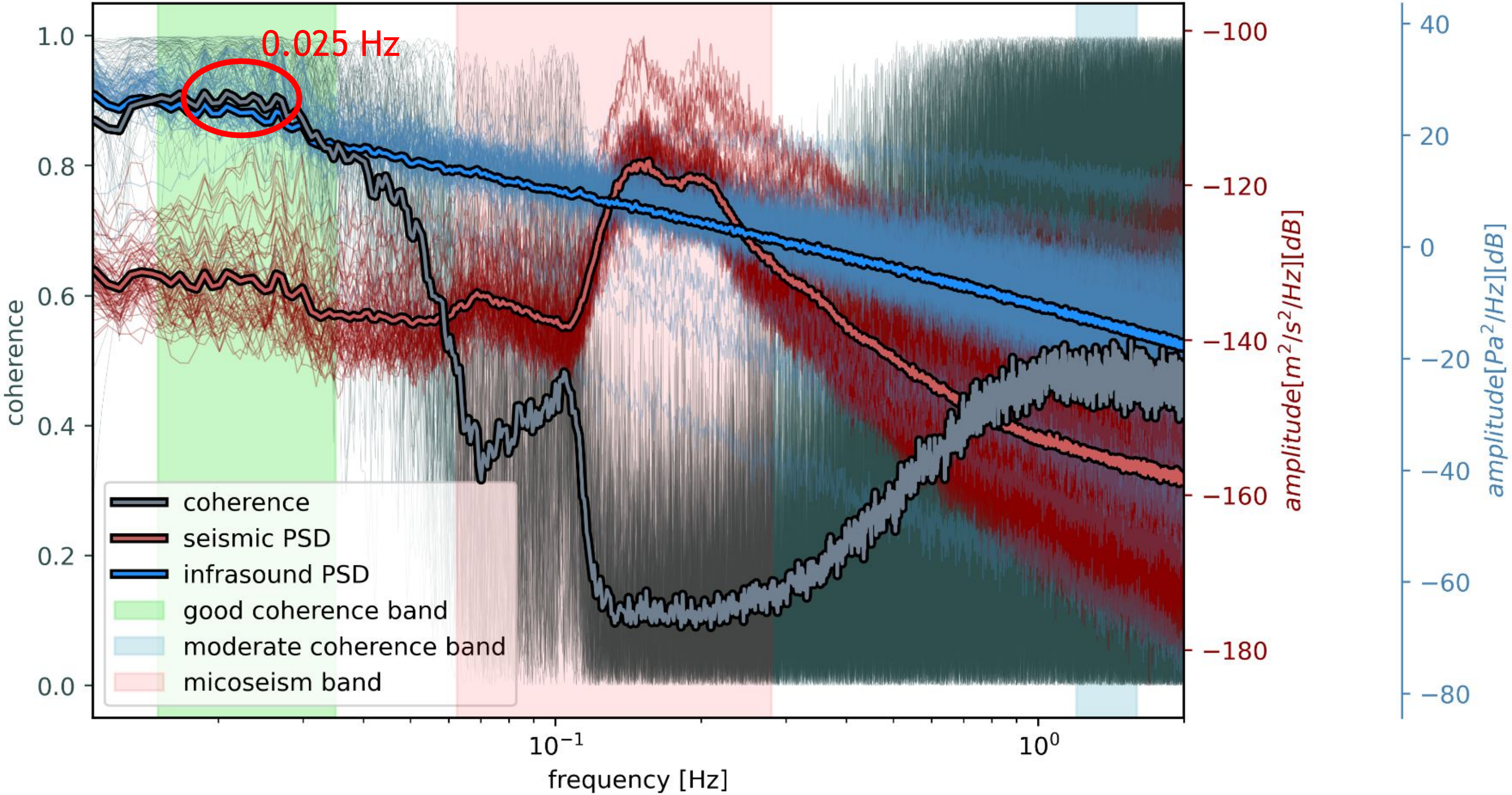
Network Coherence



Broadband infrasound and seismic

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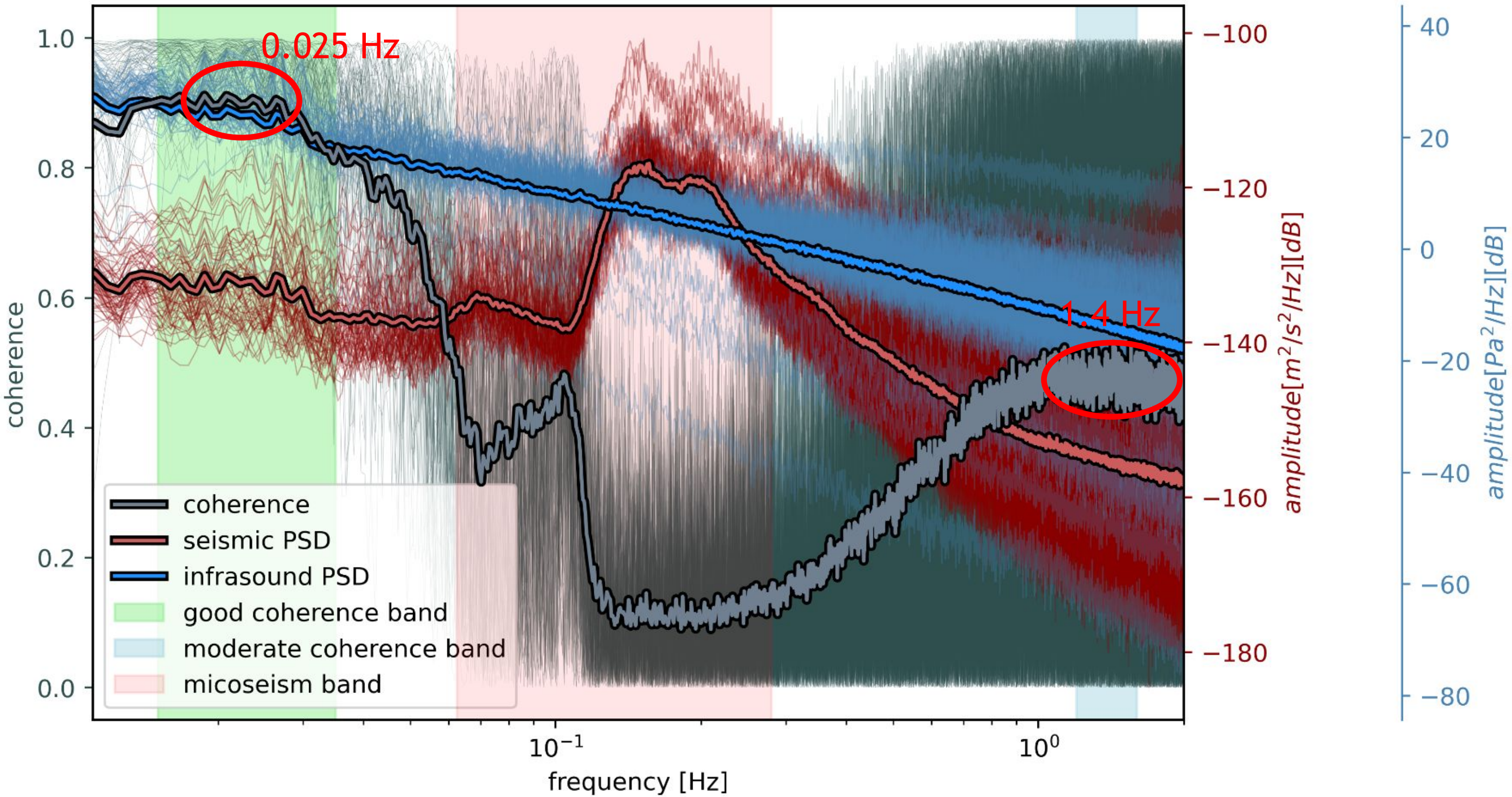


Broadband infrasound and seismic

Coupling Calculation

Coupling spectra is simply the ratio of seismic amplitudes to infrasound amplitudes:

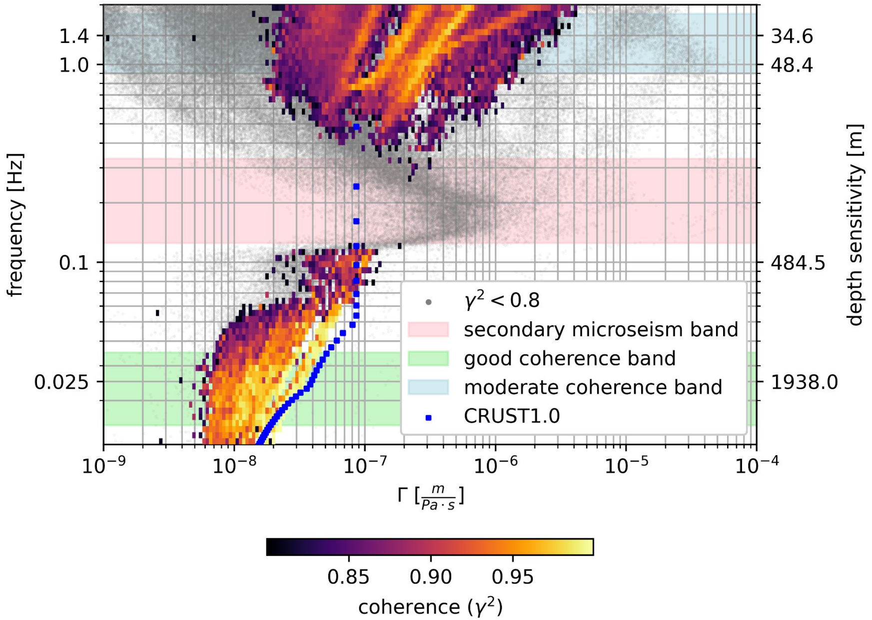
$$\Gamma(f) = \sqrt{\frac{PSD_s(f)}{PSD_p(f)}},$$

Where PSD_s and PSD_p are the seismic and pressure power spectral densities, respectively.

Also, a rule of thumb for the depth sensitivity of coupling to material parameters is give by;

$$h = 0.15 \cdot c \cdot T$$

Where *h* is depth, *T* is period, and *c* is the pressure source speed. (Tanimoto and Wang, 2019)



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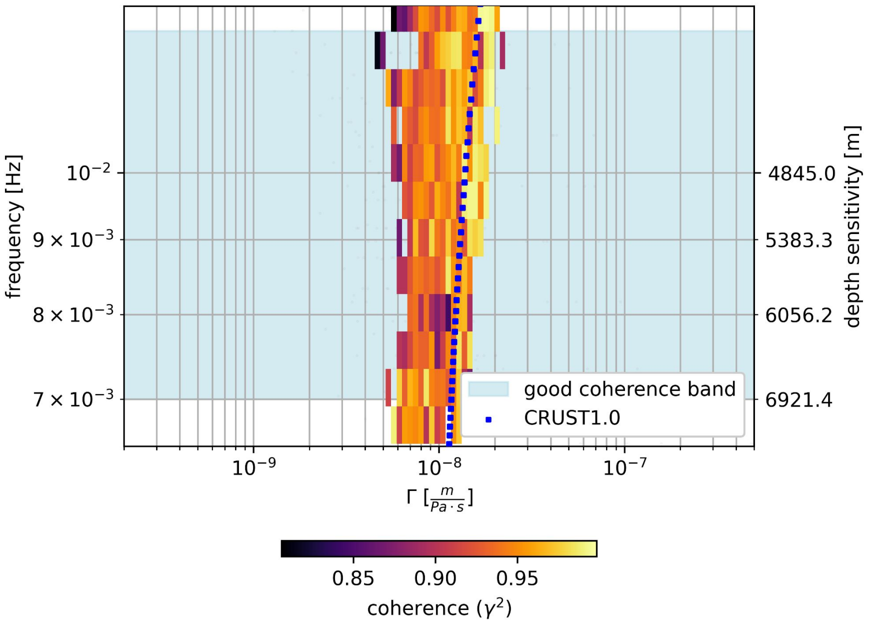

~freq (Hz)	1.2-1.6	0.015 - 0.035	0.007 - 0.0125
~depth (km)	0.035	2.0	5.0

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Relating Coupling to Elastic Parameters

$$\Gamma(f) = \sqrt{\frac{PSD_s(f)}{PSD_p(f)}} = \frac{c(\lambda + 2\mu)}{2\mu(\lambda + \mu)}$$

Where c is sound speed and λ and μ are the first Lame' parameter and rigidity, respectively (Sorrels, 1971)

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$$\bar{\mu} = \frac{\lambda + \mu}{\lambda + 2\mu}\mu$$

Estimating Near-Surface Rigidity from Low-Frequency Noise Using Collocated Pressure and Horizontal Seismic Data

Jiong Wang[*1] and Toshiro Tanimoto[1]

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$$\bar{\mu} = \frac{c}{2\Gamma(f)}$$

$$V_s = \sqrt{\frac{\bar{\mu}}{\rho_{mod}}}$$

where ϱ_{mod} is a depth-averaged density estimate from CRUST1.0

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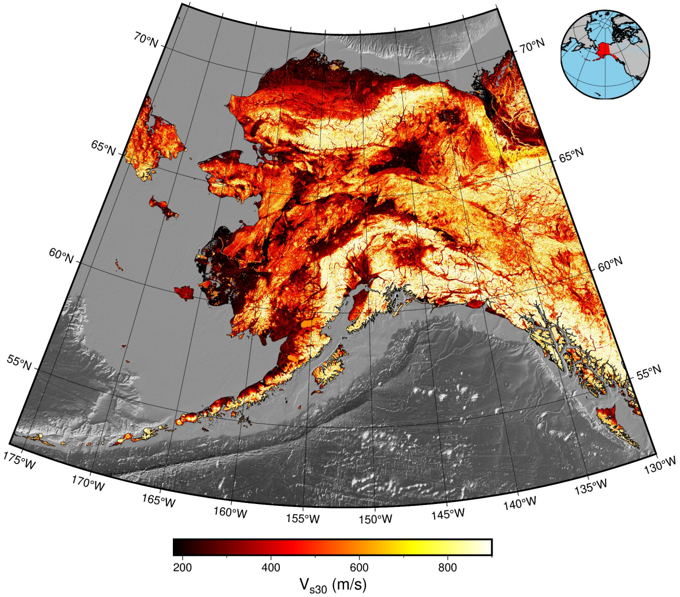
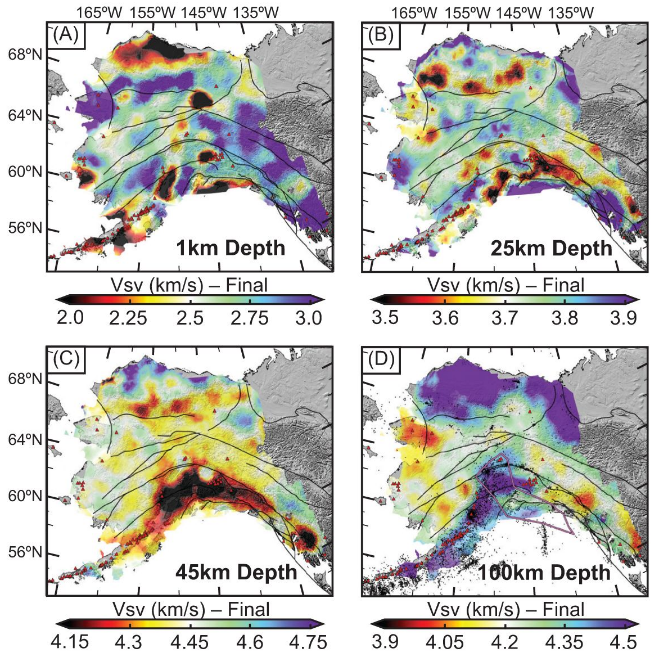
Compare to existing models:





1.4 Hz (35 m)

Model: USGS proxy V_{S30} **(Allen and Wald, 2007)**

0.025 Hz (2.0 km) and 0.00975 Hz (5.0 km)

Model: tomographic (**Berg, *et al.*, 2020**)

Depth-averaged to appropriate depth

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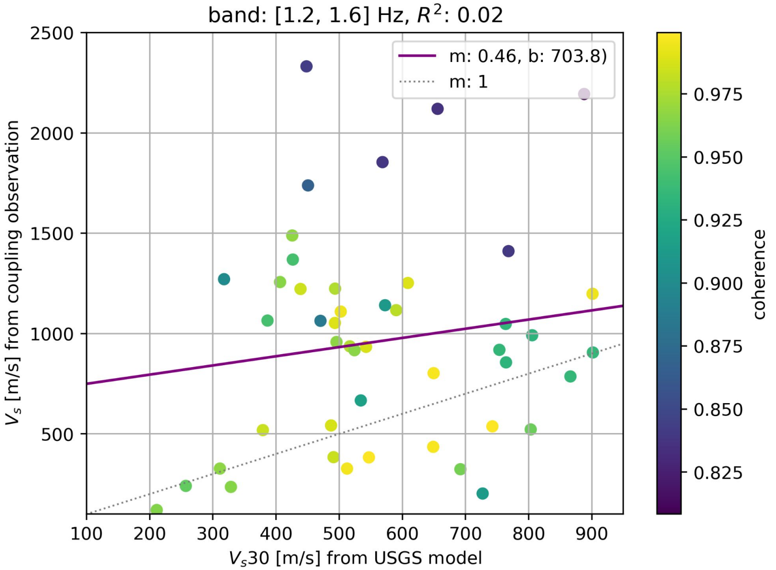
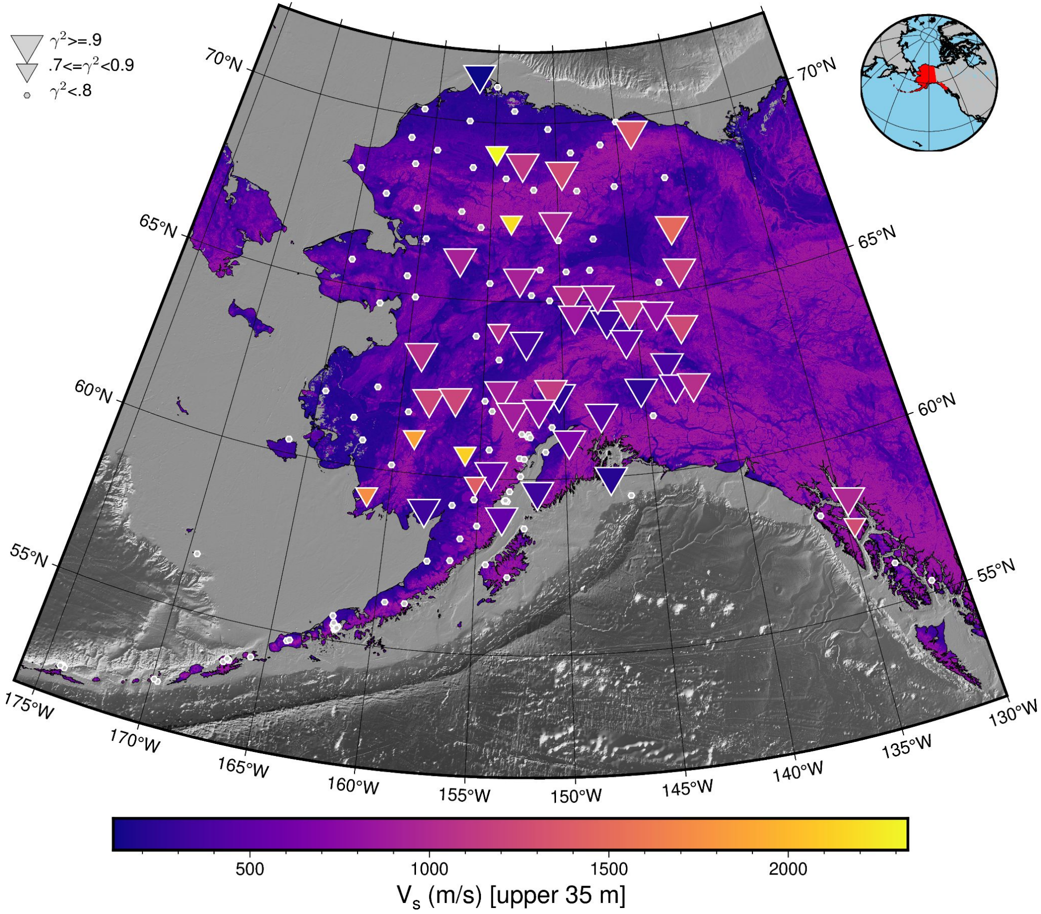
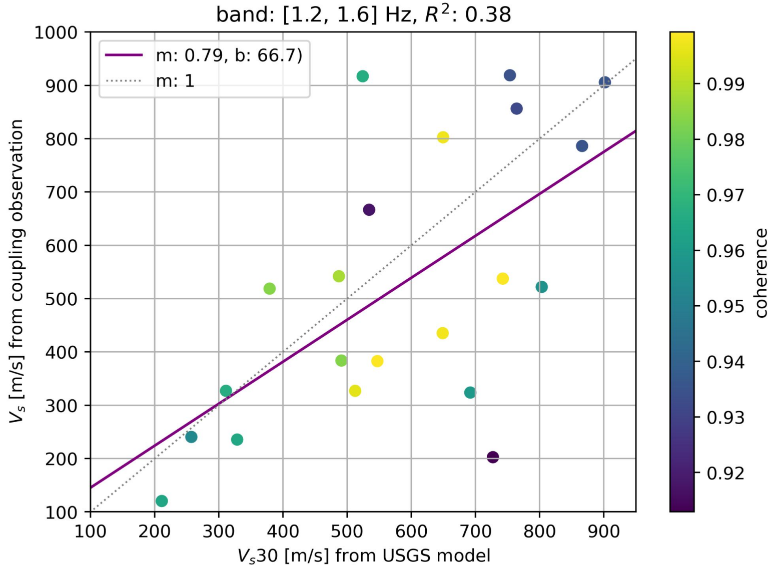
Results: Mean V_s for Upper 35 m (~1.4 Hz)

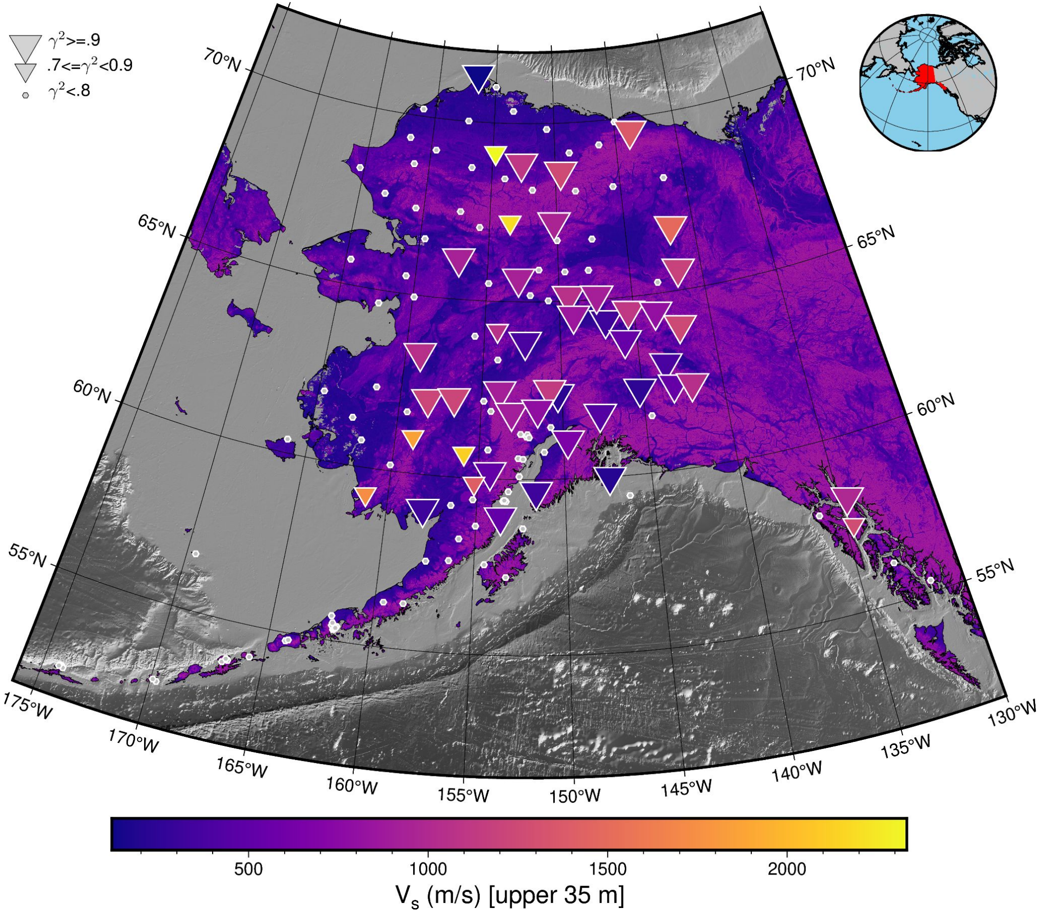




Background model from USGS global proxy V_{S30}

Results: Mean V_s for Upper 35 m (~1.4 Hz)





Background model from USGS global proxy V_{S30}

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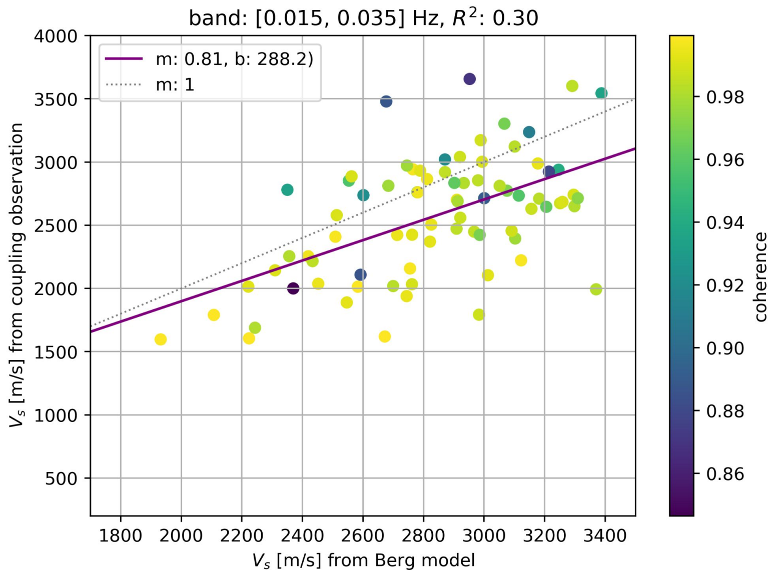
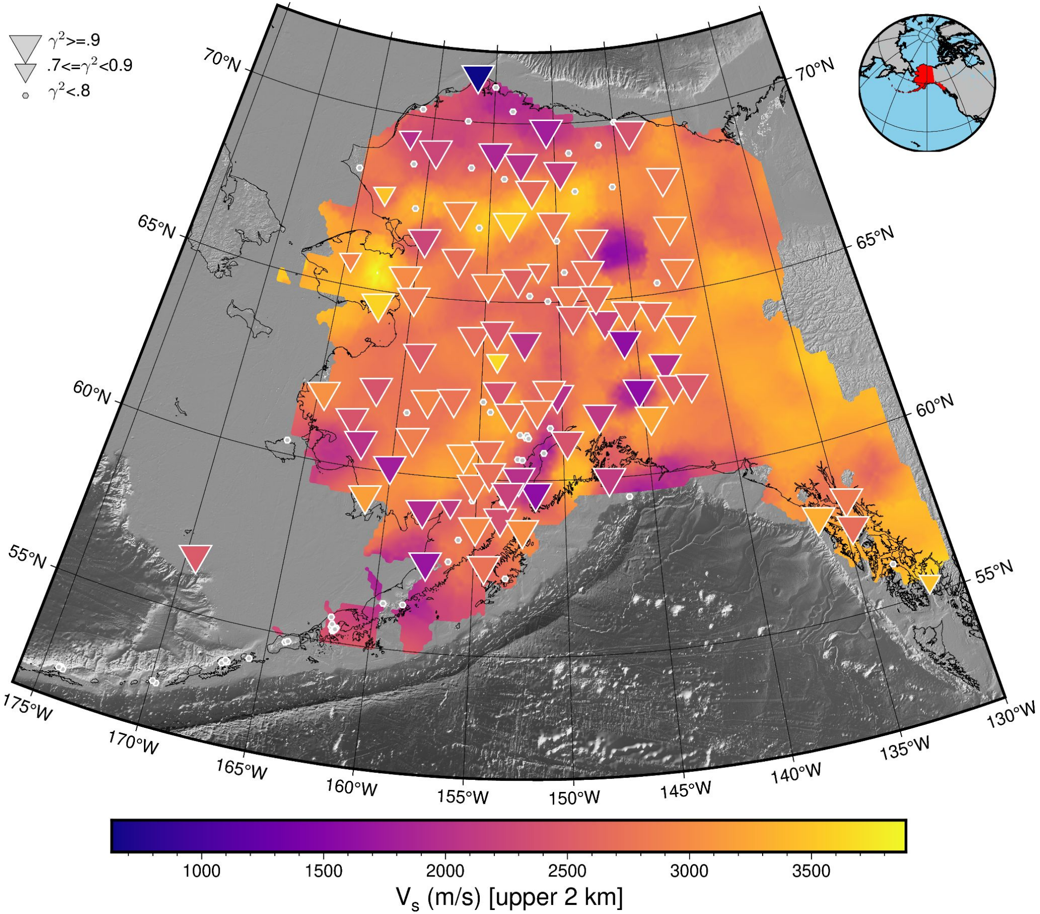
Results: Mean V_s for Upper 2.0 km (~0.025 Hz)





Background tomographic model from Berg, *et al.*, 2020 (depth averages)

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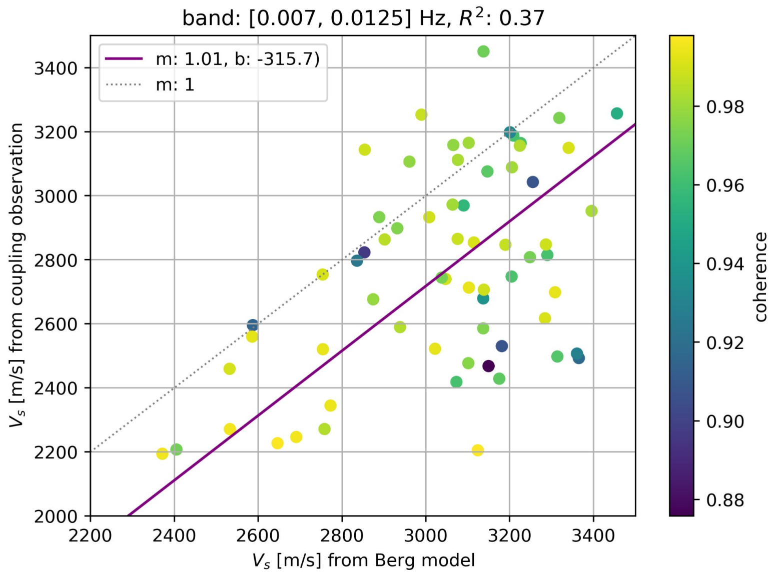
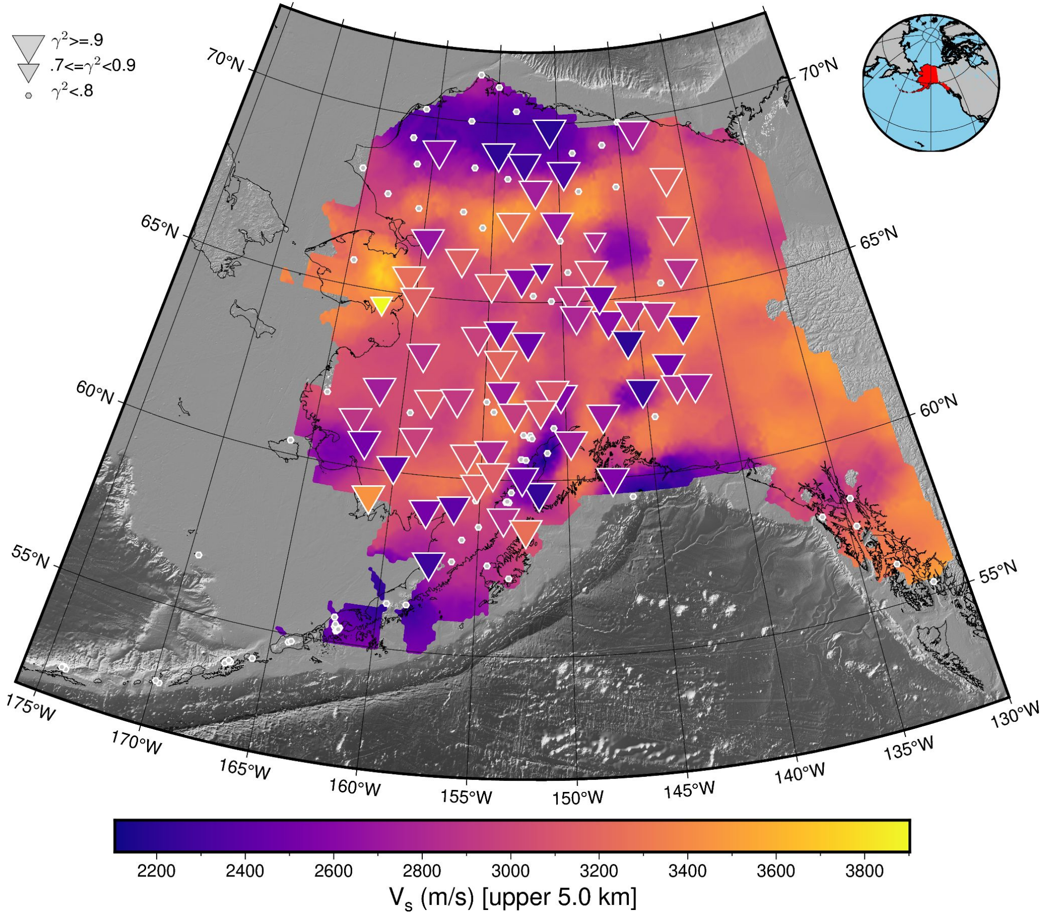
Results: Mean V_S for Upper 5.0 km (~0.00975 Hz)





Background tomographic model from Berg, *et al.*, 2020 (depth averages)

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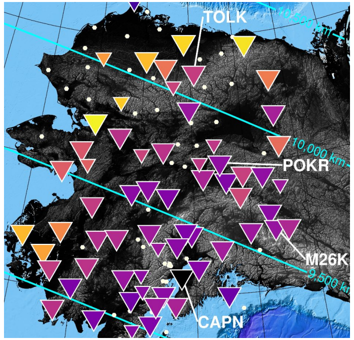
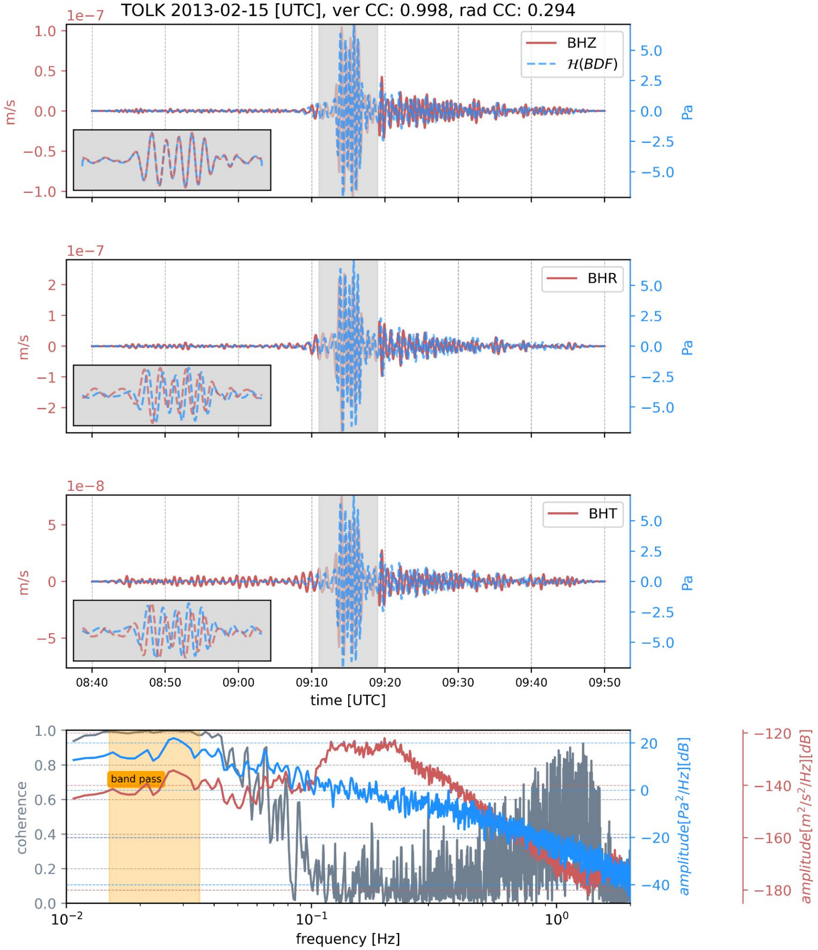
Results: Comparison with 2013 Chelyabinsk Bolide

Photo: Alex Alishevskikh





V_S (m/s) at 2.0 km

	Hunga	Chely	% diff
POKR	2630	2645	0.6
TOLK	2158	2156	0.08

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Conclusions:

- Pressure waves from the Hunga,Tonga eruption produced air-to-ground coupled waves that were beautifully recorded in Alaska
- Microseismic amplitudes generally exceed coupled seismic amplitudes
- Coupling was inversely proportional to the rigidity of the elastic medium, and this was used to estimate bulk V_s
- Successful estimate of mean V_s to depths of:
  - 35 m
  - 2.0 km
  - 5.0 km

Select References:

Busby, R. W., and K. Aderhold (2020). The Alaska transportable array: As built, Seismol. Res. Lett. 91, no. 6, 3017–3027, doi: 10.1785/0220200154.

Berg, E. M., Lin, F.-C., Allam, A., Schulte-Pelkum, V., Ward, K. M., & Shen, W. (2020). Shear velocity model of Alaska via joint inversion of Rayleigh wave ellipticity, phase velocities, and receiver functions across the Alaska transportable Array. Journal of Geophysical Research: Solid Earth, 125

Laske, G., G. Masters, Z. Ma, and M. Pasyanos (2013). Update on CRUST1.0 - A 1-degree global model of Earth’s crust, Geophysical Research Abstracts, 15, Abstract EGU2013-2658.

Sorrells, G. G. (1971) A preliminary investigation into the relationship between long-period seismic noise and local fluctuations in the atmospheric pressure field, Geophys. J. Int., 26, nos. 1/4, 71–82

Tanimoto, T., & Wang, J. (2019). Theory for deriving shallow elasticity structure from colocated seismic and pressure data. Journal of Geophysical Research: Solid Earth, 124, 5811–5835.

Wald and Allen (2007). Topographic Slope as a Proxy for Seismic Site-Conditions (VS30) and Amplification Around the Globe, USGS Open File Report

Wang, J., and T. Tanimoto (2020). Estimating Near-Surface Rigidity from Low-Frequency Noise Using Collocated Pressure and Horizontal Seismic Data, Bull. Seismol. Soc. Am. 110, 1960–1970

Wills, G., Nippress, A., Green, D. N., and Spence, P. J. Site-Specific Variations in Air-to-Ground Coupled Seismic Arrivals from the 2012 October 16 Explosion at Camp Minden, Louisiana, United States. Geophysical Journal International, 231(1):243–255, June 2022

Thank You! Questions or Comments?