‘UA POU, MARQUESAS ISLANDS, OLD ORCA RECOVERY CRUISE, NOVEMBER 2020

Tilt and Compliance Removal: Community Tools Enabling Science

HELEN JANISZEWSKI UNIVERSITY OF HAWAIʻI AT MĀNOA

JOSH RUSSELL SYRACUSE UNIVERSITY

MSROC EARLY CAREER WORKSHOP, AGU 2023

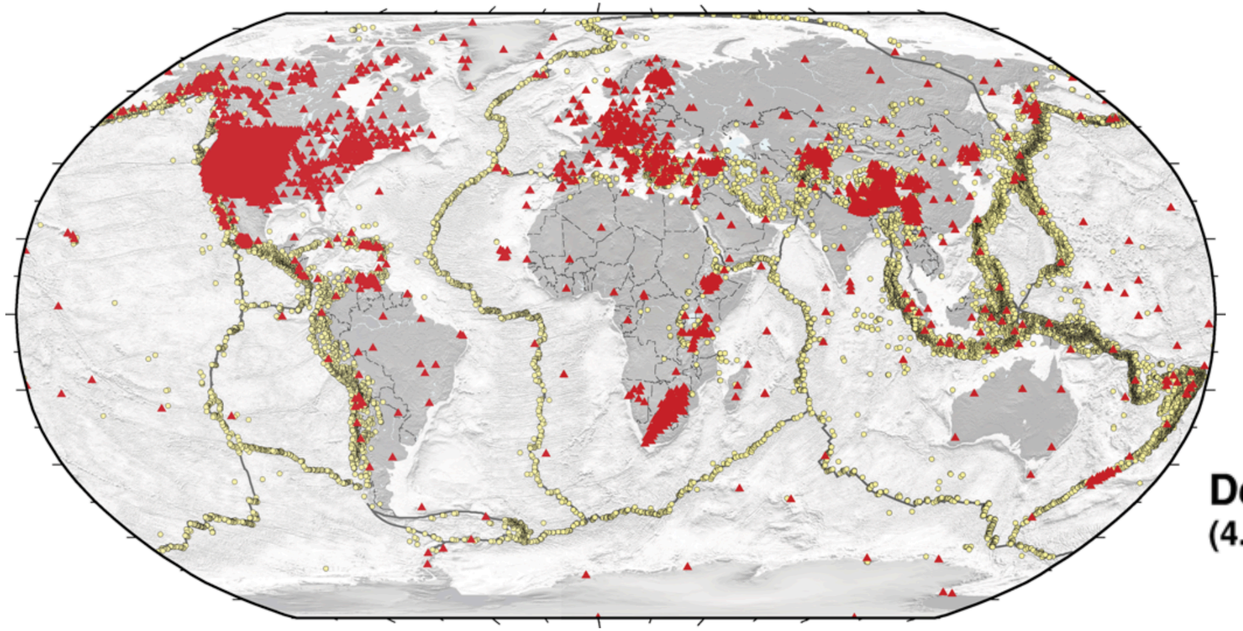
earth SCIENCES
SCHOOL OF OCEAN AND EARTH SCIENCE AND TECHNOLOGY
UNIVERSITY OF HAWAIʻI AT MĀNOA

Syracuse University

NSF

OBSIC

WHY OCEAN-BOTTOM SEISMOLOGY?

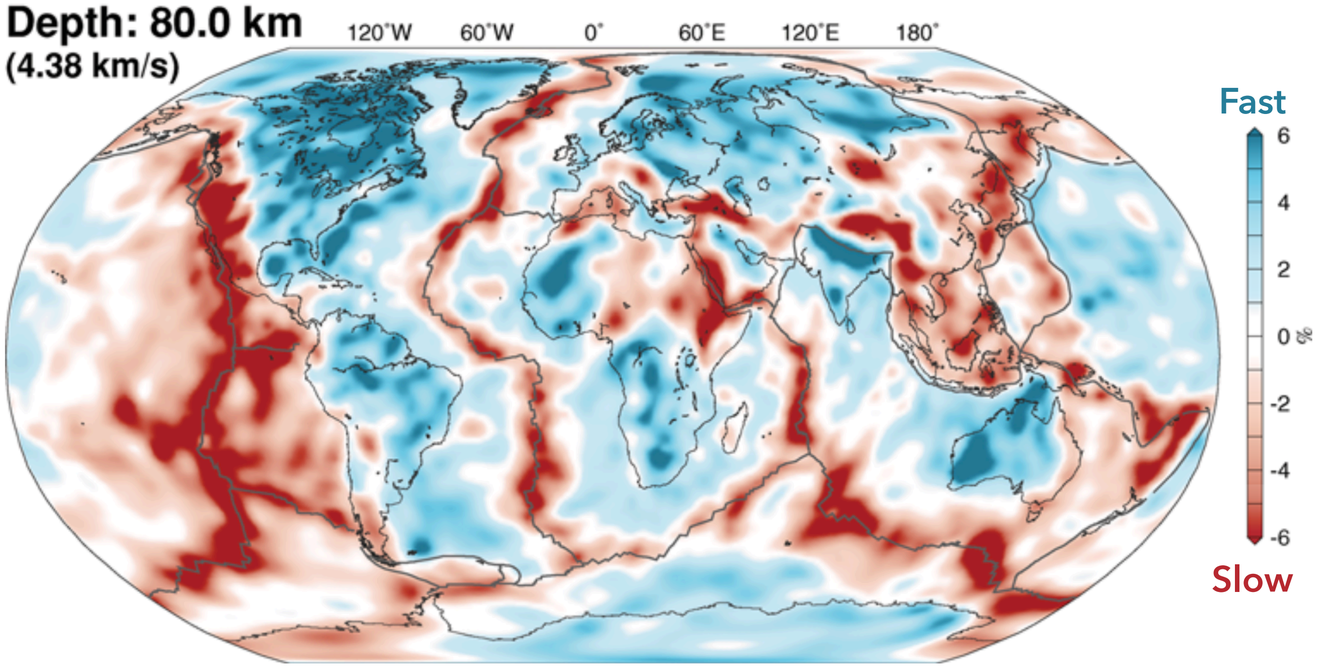


Seismometers

Earthquakes

~70% of Earth's lithosphere is oceanic, yet historically poor sampling of the ocean basins

Global models have only coarse lateral resolution and limited ability to resolve the oceanic lithosphere



Schaeffer & Lebedev (2013) GJI

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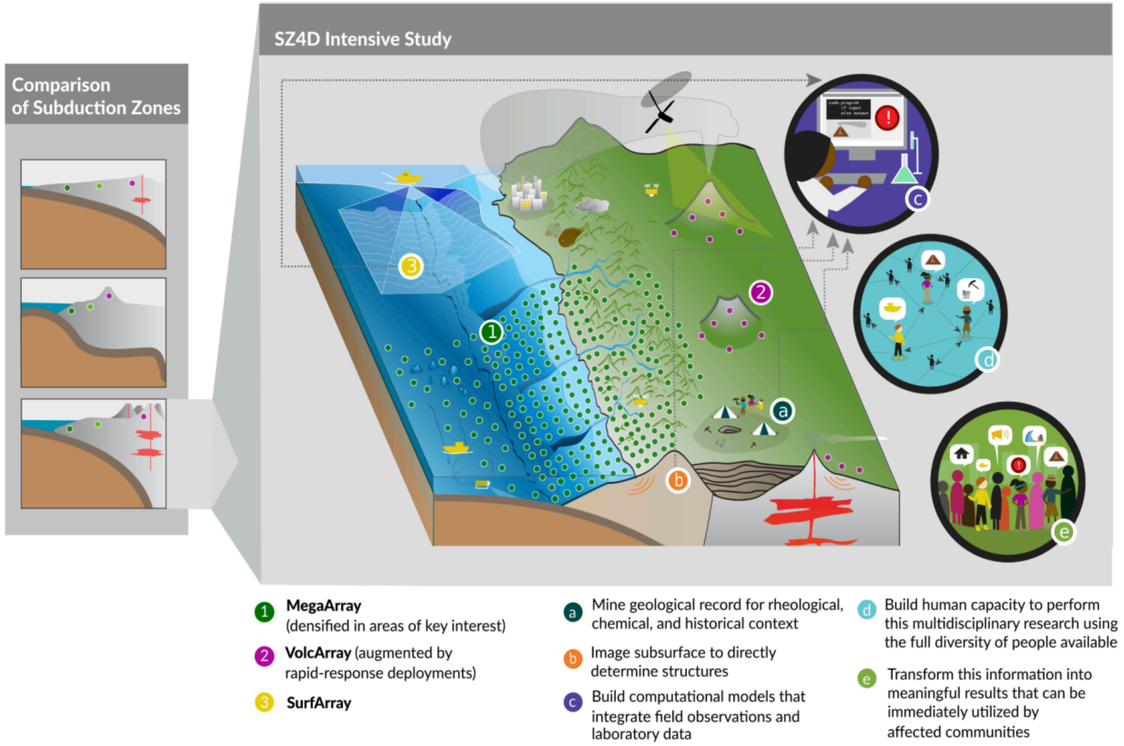
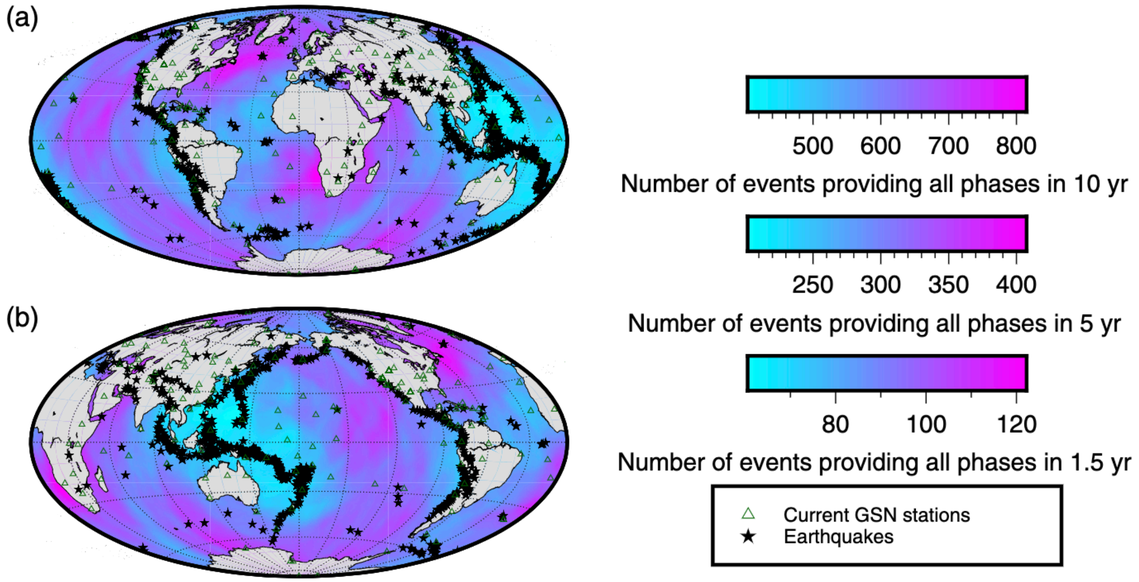
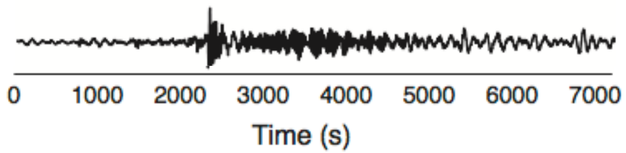


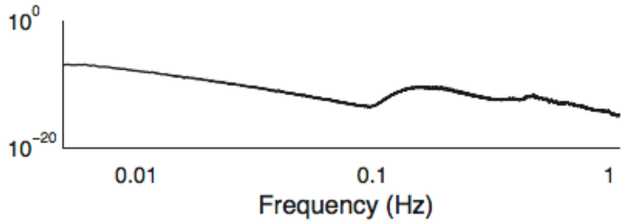
Draft SZ4D Implementation Plan



Kohler et al., 2020

TIMESERIES AND SPECTRA





$$G_{xy}(f) = \frac{1}{n_d}\sum_{i=1}^{n_d} X_i^*(f)Y_i(f)$$

$$\gamma_{xy}^2(f) = \frac{|G_{xy}(f)|^2}{G_{xx}(f)G_{yy}(f)}$$

$$A_{xy}(f) = \frac{|G_{xy}(f)|}{G_{xx}(f)}$$

$$\phi_{xy}(f) = \arctan\left[\frac{Q_{xy}(f)}{C_{xy}(f)}\right]$$

Cross/Auto Spectra
Power Spectra
What is the power/ amplitude of the time series at a given frequency?

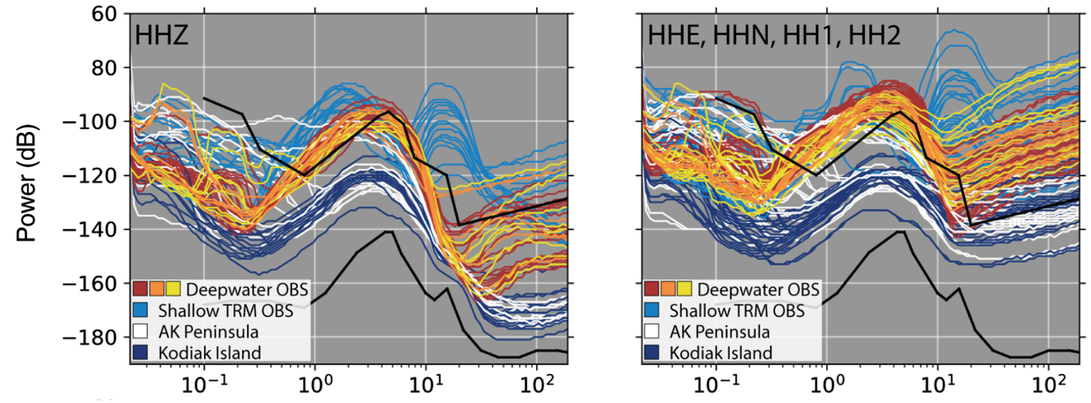
Coherence
At a given frequency, how "coherent" are two signals? How much of y can I predict, if I know x?

Admittance
Gain factor of the *transfer function*. If I want to relate the x and y components, what constant do I multiply as a function of frequency?

Phase
If the signals are coherent, what's the cycle separation between x and y?

Bell et al. ,2015

OBS NOISE BASICS



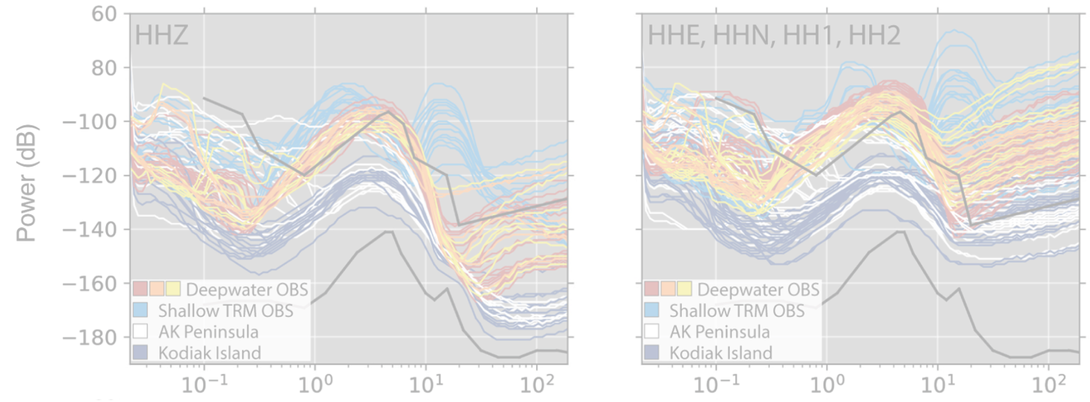
Barcheck et al., 2020

OBS data are relatively noisy, in part due to compliance and tilt noise.

Compliance Noise = Coherent **Pressure** energy observed on **Vertical** channel

Tilt Noise = Coherent **Horizontal** energy observed on **Vertical** channel

OBS NOISE BASICS



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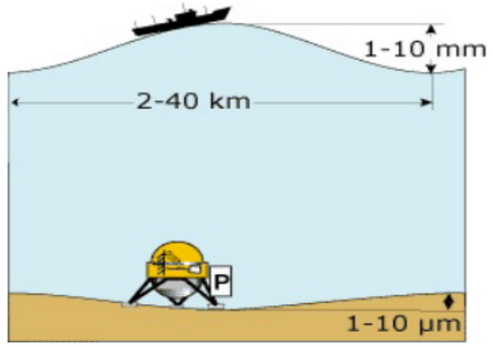
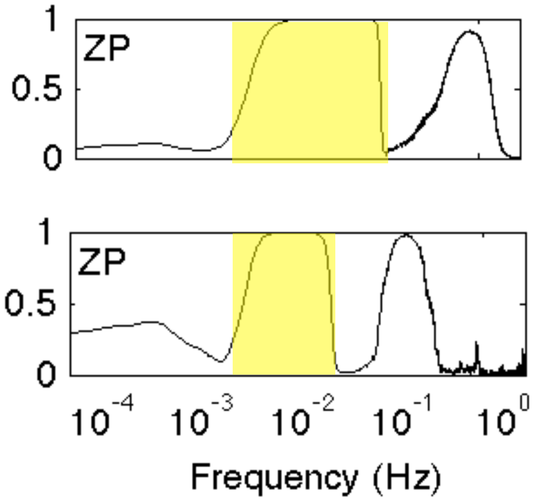


Crawford et al., 1999

Pressure-Vertical Coherence



Infragravity waves induce compliance noise, which has a frequency-depth dependence.

Compliance Noise = Coherent **Pressure** energy observed on **Vertical** channel

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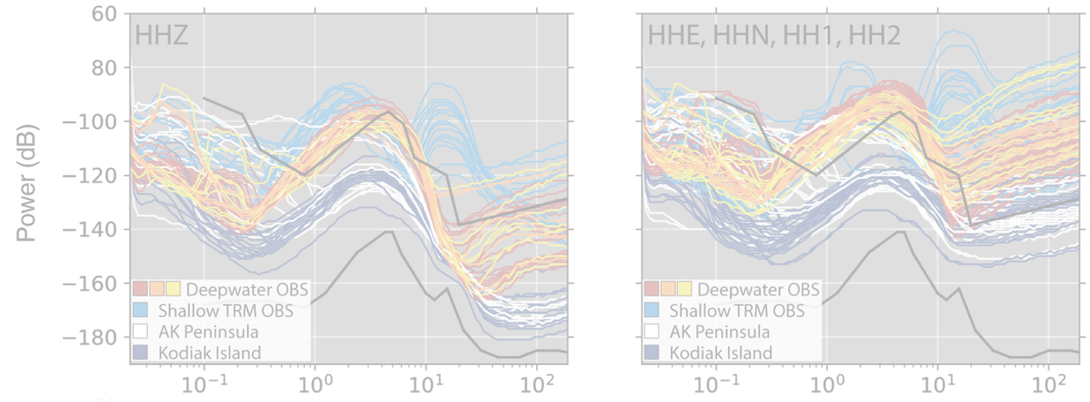
OBS NOISE BASICS



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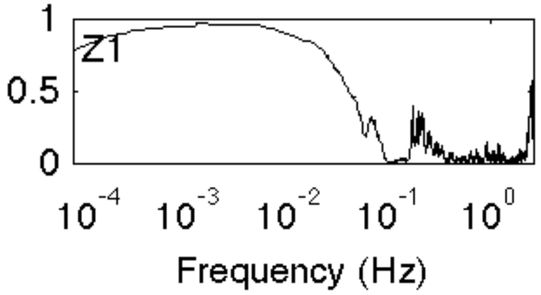
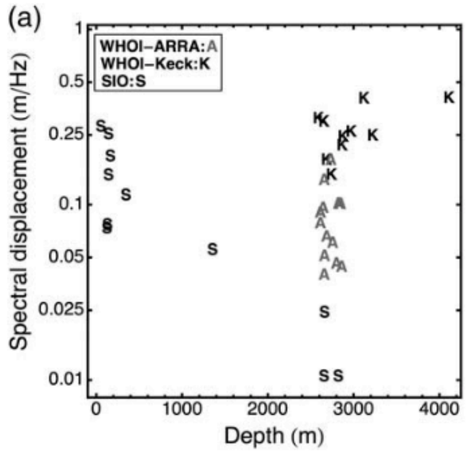
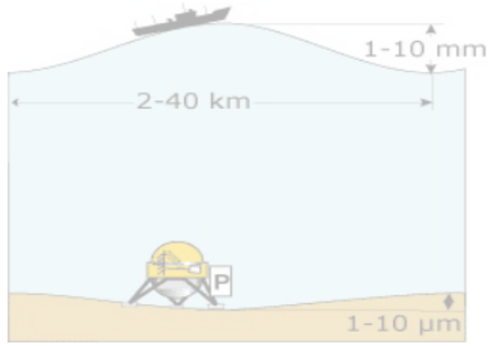




Bottom currents cause tilt noise, which may vary with water depth and instrument design.



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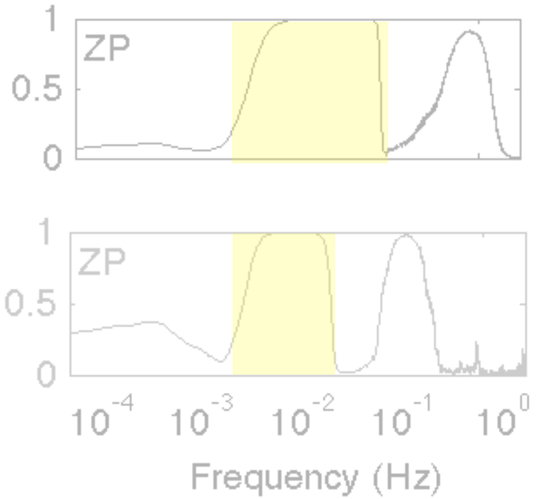

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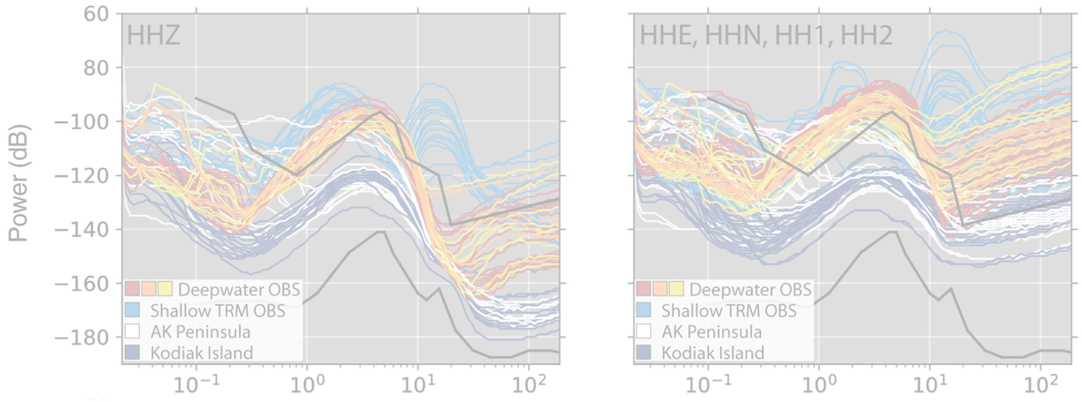

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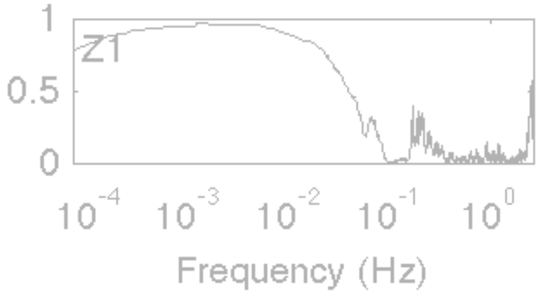

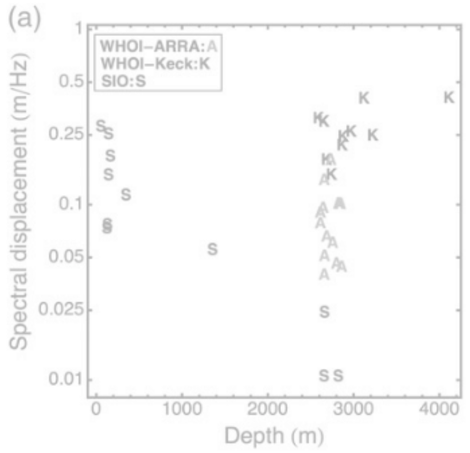

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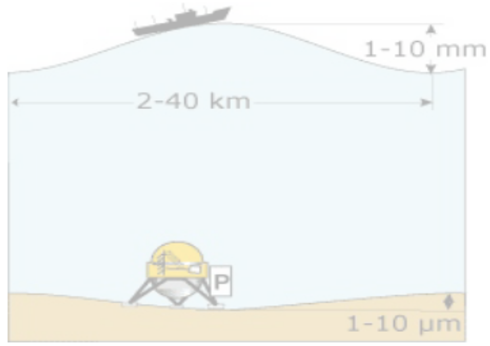

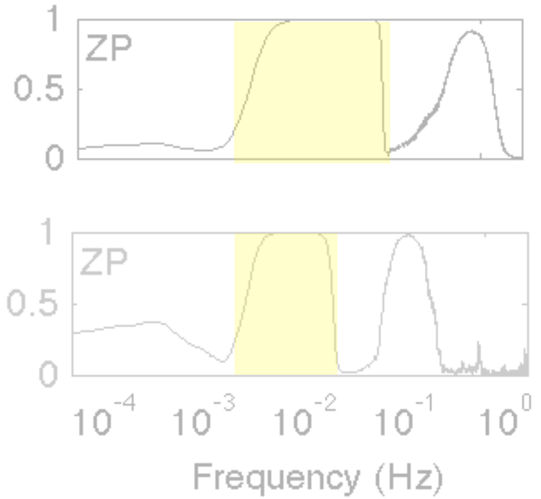

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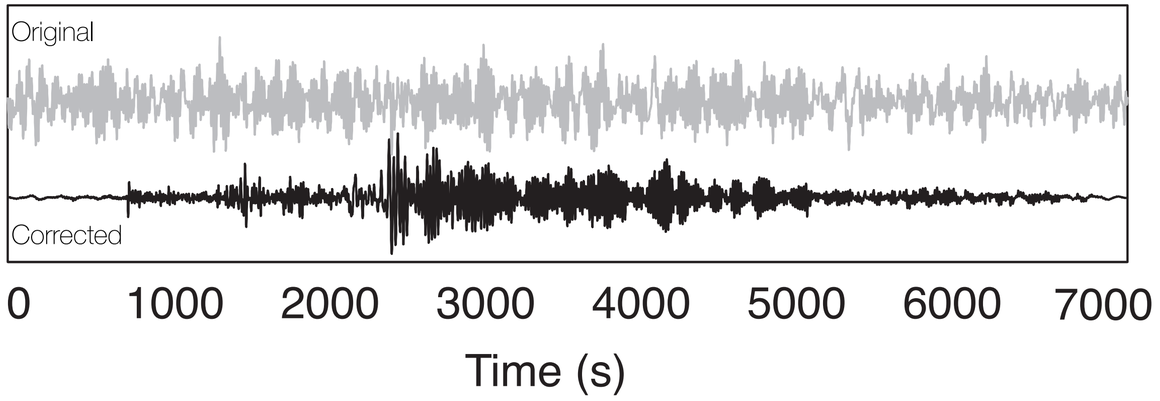


Tilt and compliance noise can be removed from vertical components, improving data quality.

ATaCR Manual

Automated Tilt and Compliance Removal

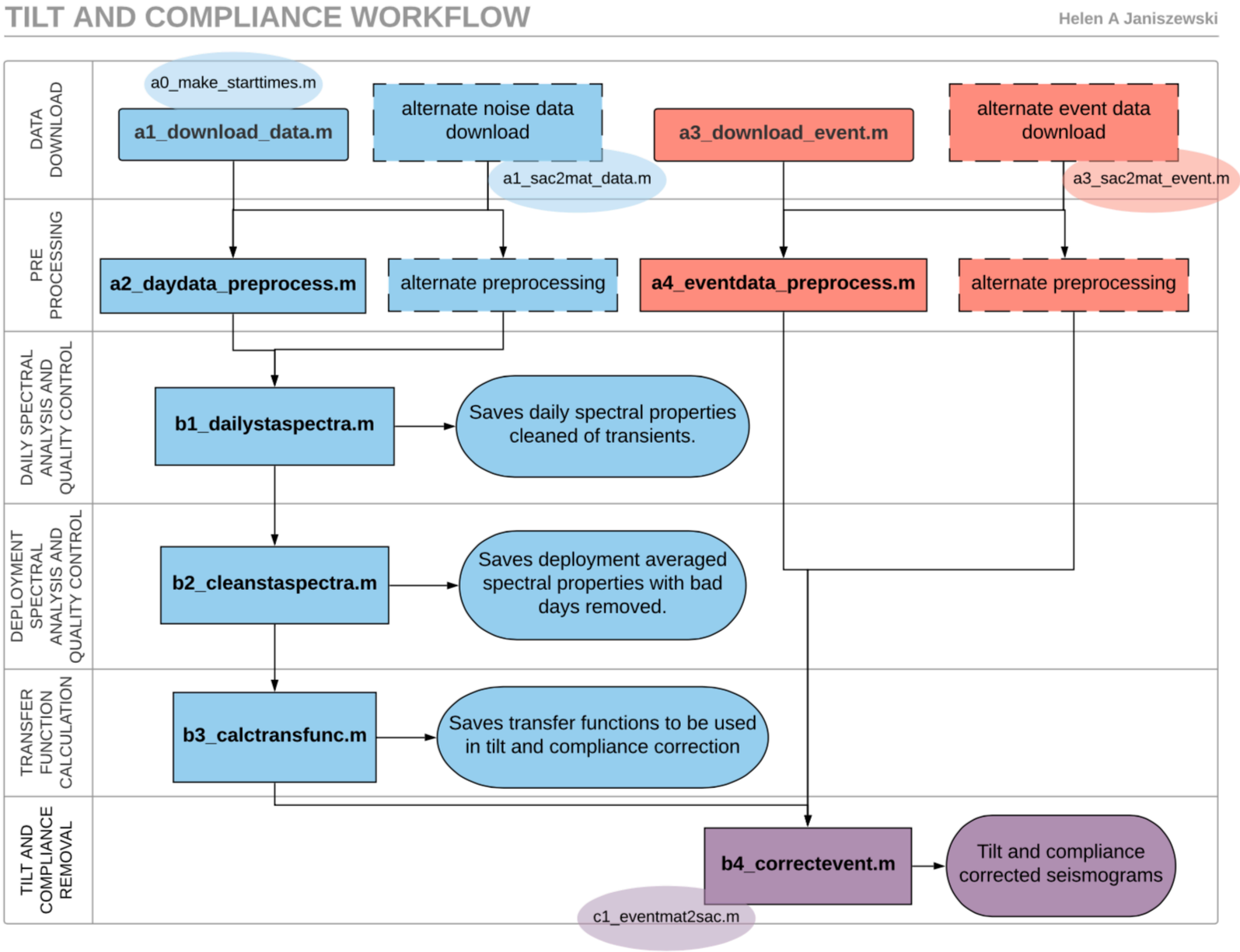
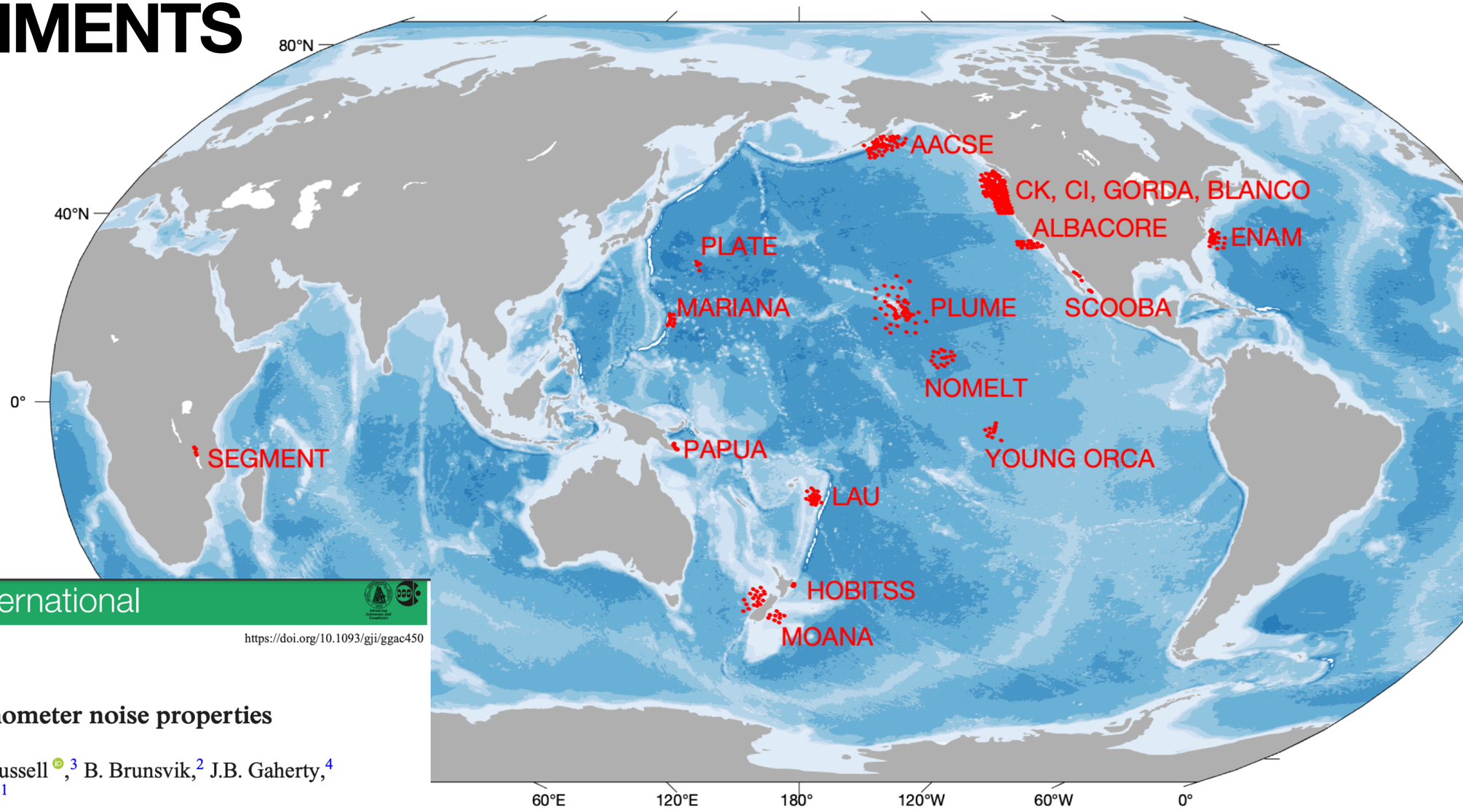


Figure 1: Flowchart for using the **ATaCR** Package.

15 YEARS
18 EXPERIMENTS
551 OBS



Geophysical Journal International

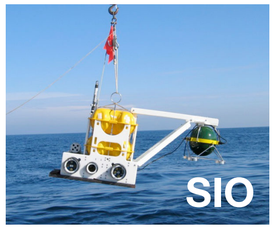
Geophys. J. Int. (2023) **233,** 297–315
Advance Access publication 2022 November 25
GJI Seismology

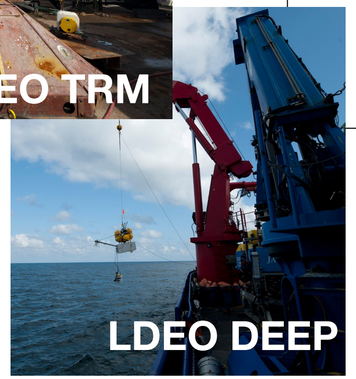
https://doi.org/10.1093/gji/ggac450

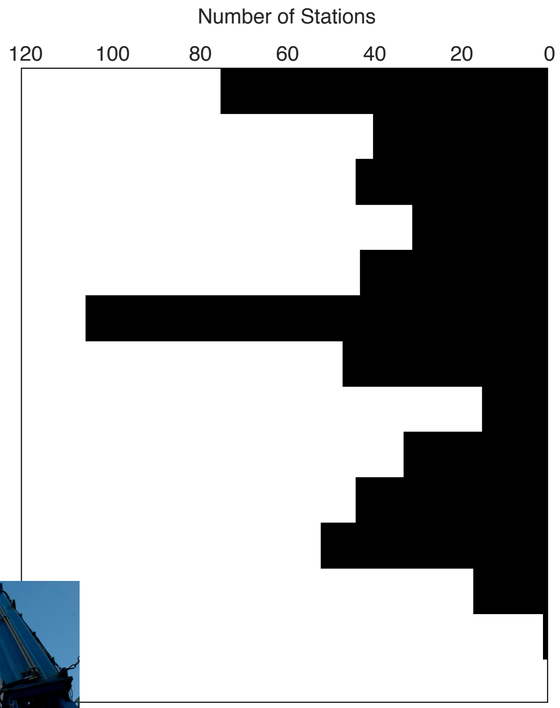
Broad-band ocean bottom seismometer noise properties

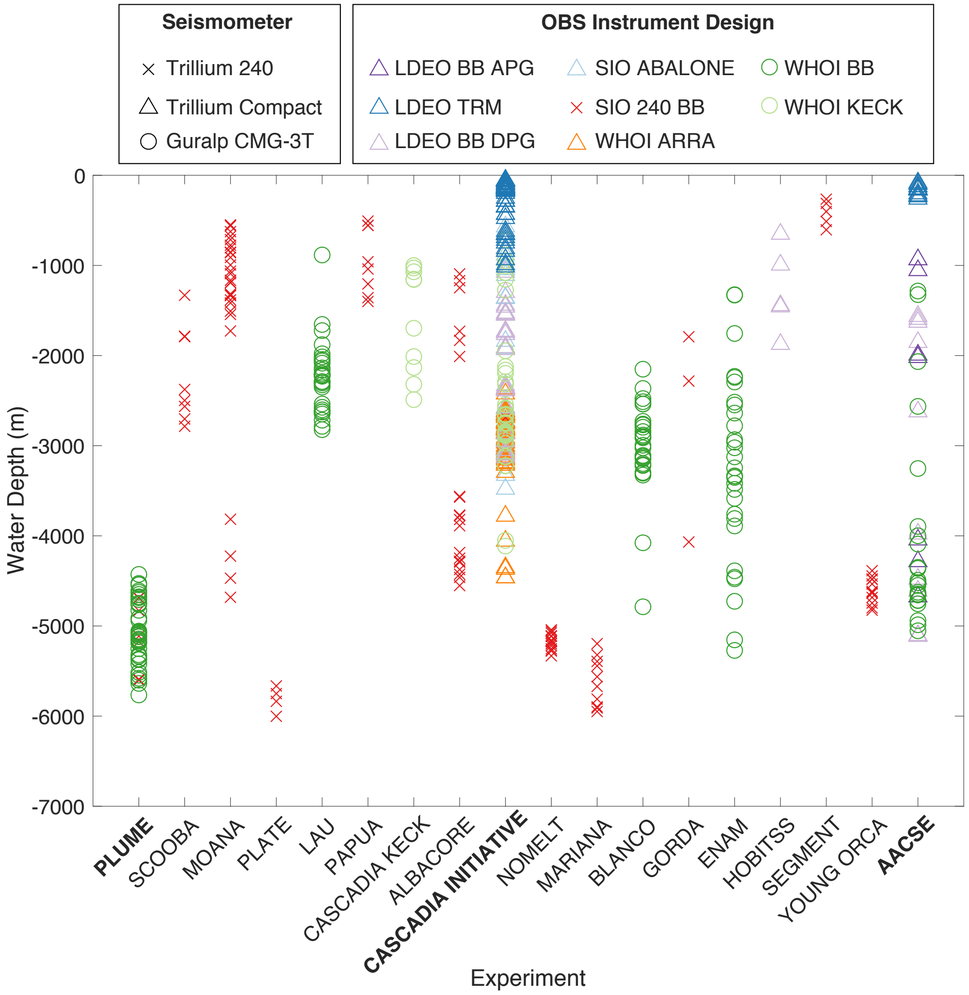
Helen A. Janiszewski [1], Z. Eilon,[2] J.B. Russell [3], B. Brunsvik,[2] J.B. Gaherty,[4] S.G. Mosher,[5] W.B. Hawley[6] and S. Coats[1]

15 YEARS
18 EXPERIMENTS
551 OBS
~50 - 6000 M
3 SEISMOMETERS
8 OBS DESIGNS



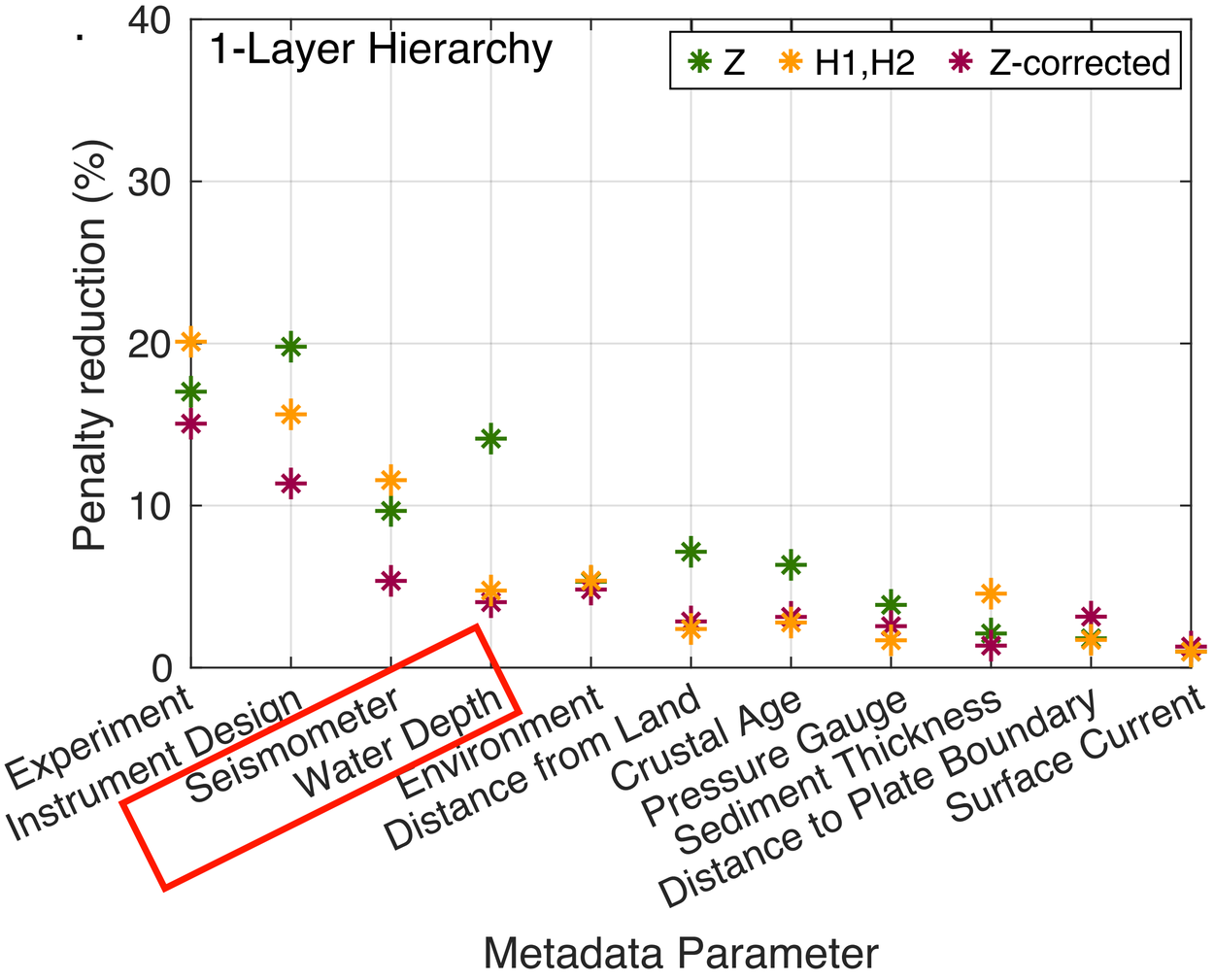






OBSIC

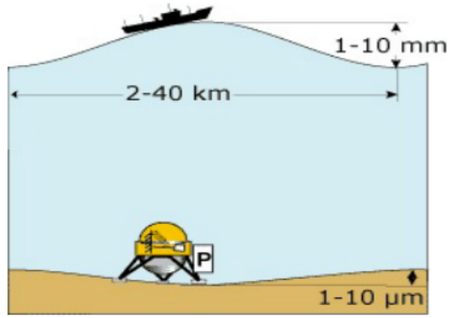
SEISMOMETER AND WATER DEPTH



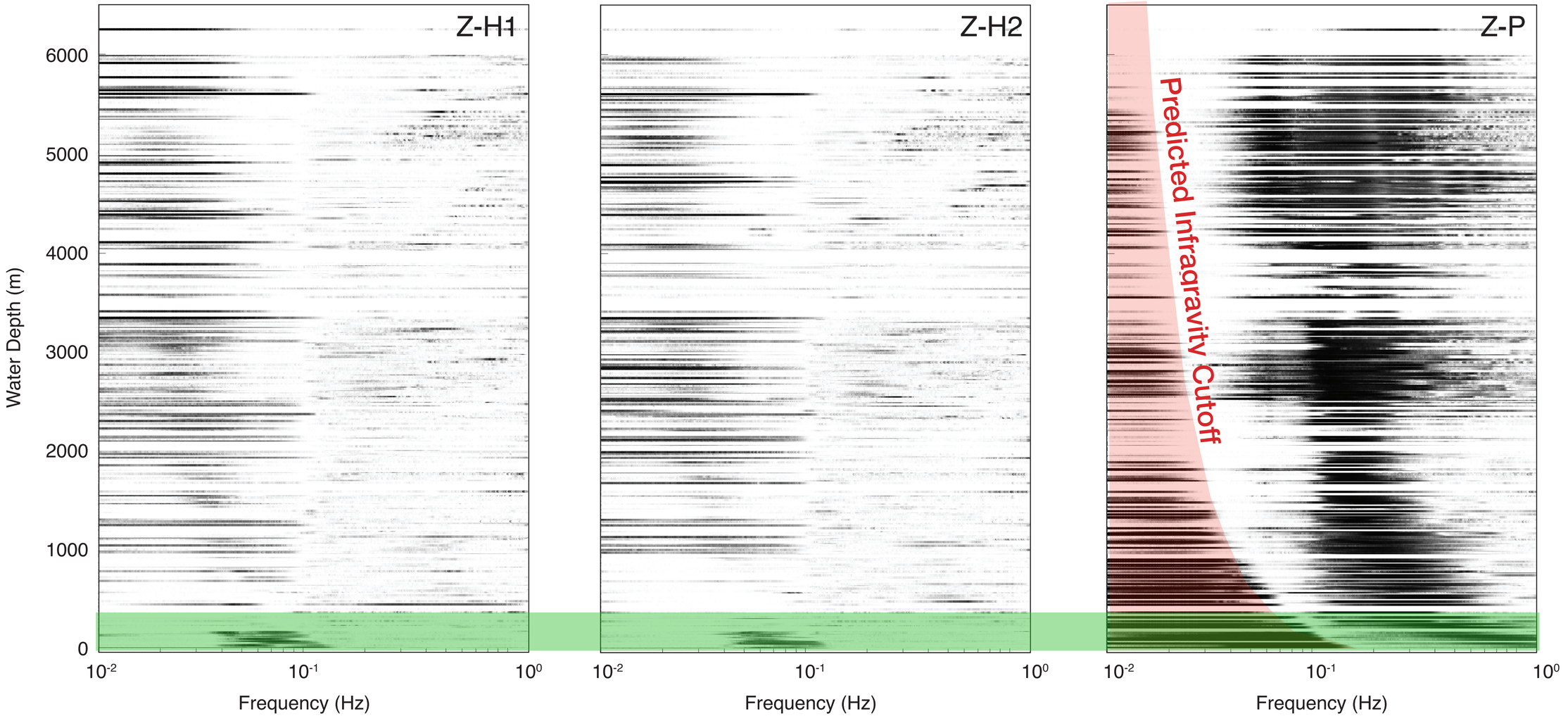
Seismometer and water depth offer the next two sets of most similar groupings.

Less direct covariance with other parameters yields more interpretable results.

COHERENCES, WATER DEPTH, COMPLIANCE



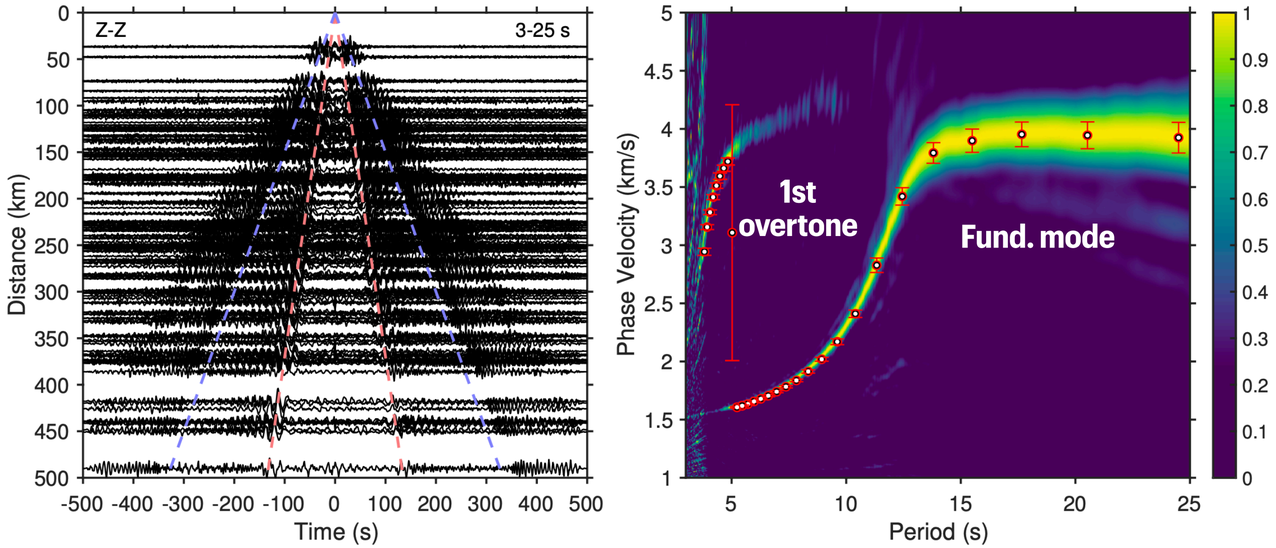
Crawford et al., 1999



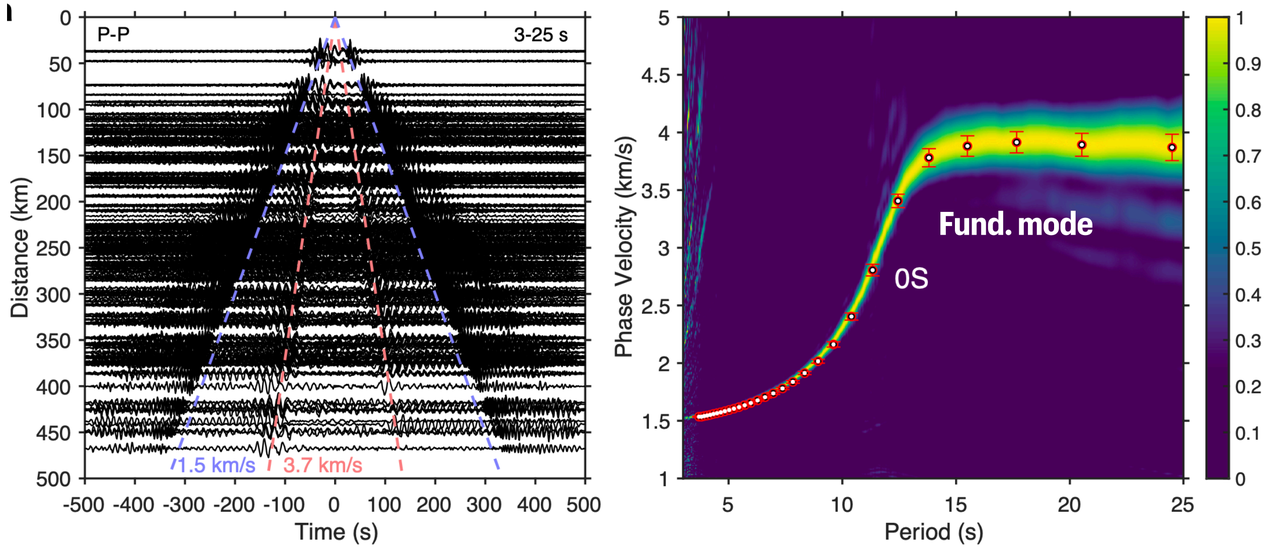
ATACR-ENABLED SCIENCE

COMPLIANCE CORRECTIONS APPLIED TO AMBIENT NOISE

Vertical



Pressure



Example from the Young ORCA experiment

Vertical component

– Fundamental mode Rayl. (5–25 s)
  – Short periods = water column
  – Longer periods = solid earth
– 1st overtone Rayl. (3–?)
  – Solid earth!

Pressure component

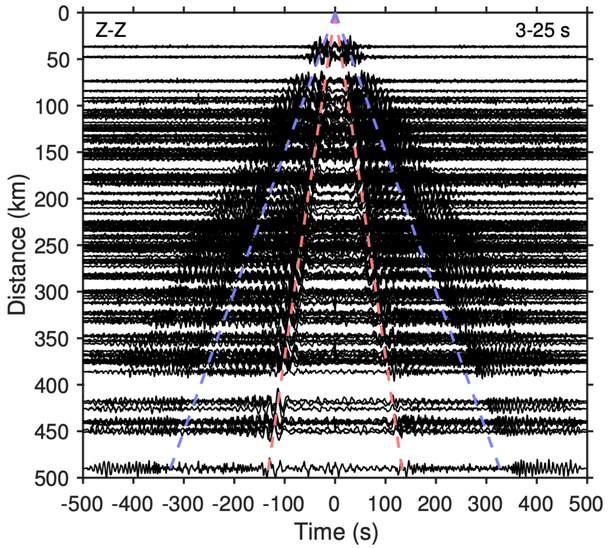
– Fundamental mode Rayl. (5–25 s)
  – Short periods = water column
  – Longer periods = solid earth

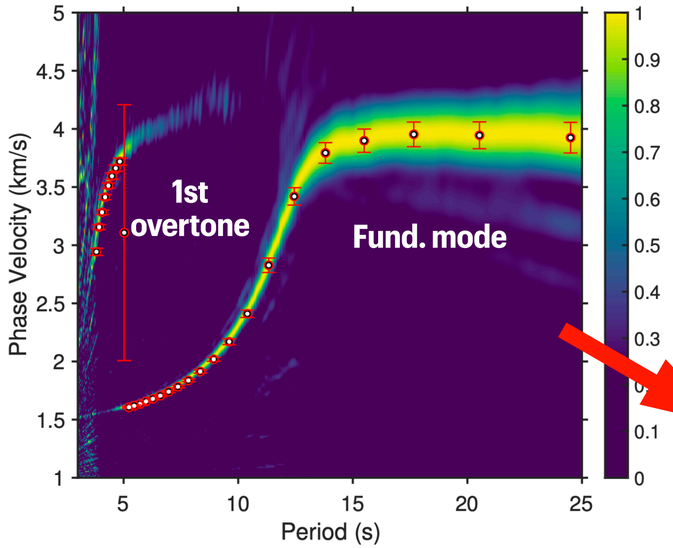
Fundamental mode Rayleigh waves coherent on both Pressure and Vertical

Russell et al. (in prep)

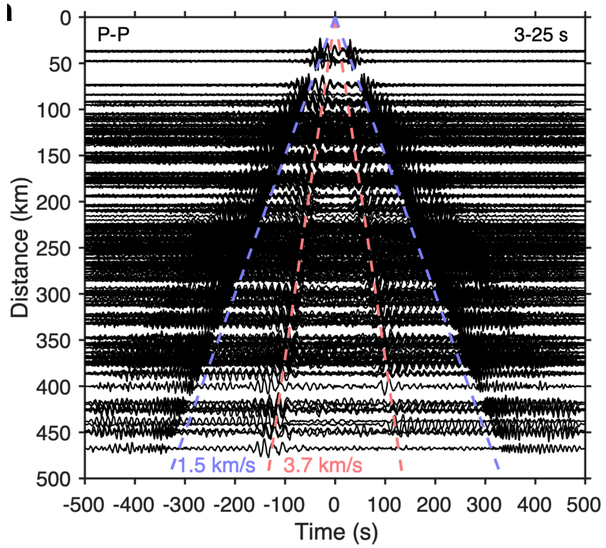
COMPLIANCE CORRECTIONS APPLIED TO AMBIENT NOISE

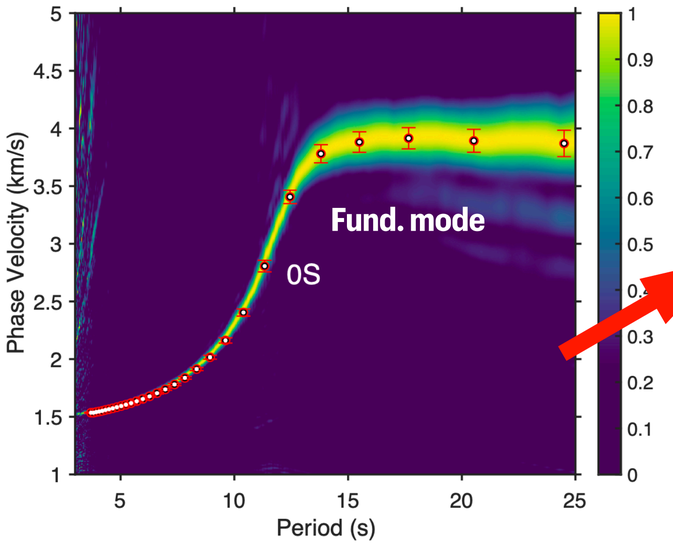
Vertical





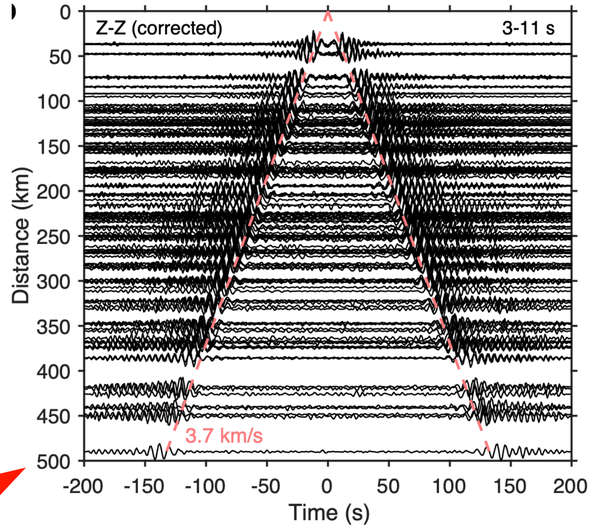
Pressure

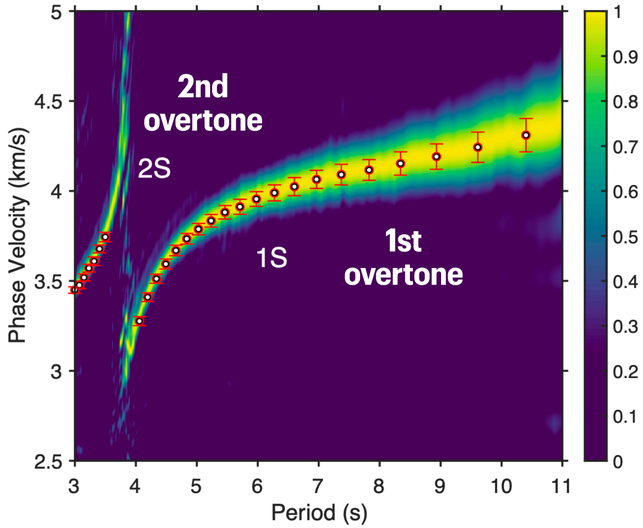




Daily "compliance" corrections **suppress fundamental mode Rayleigh wave** sensitive to the water column, **isolating overtones in solid Earth** (Bowden et al., 2016)

Compliance-corrected Vertical





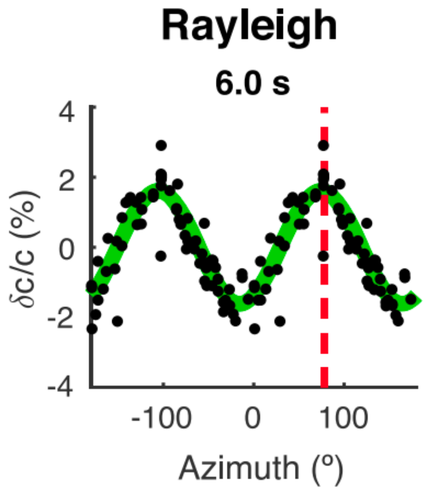
Russell et al. (in prep)

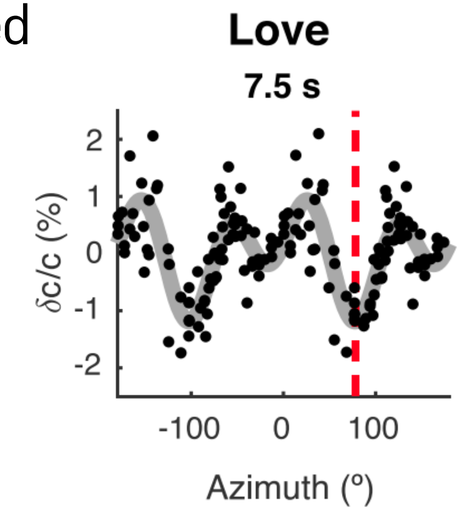
THE POWER OF OVERTONE RAYLEIGH WAVES: CHARACTERIZING THE OCEANIC LITHOSPHERE

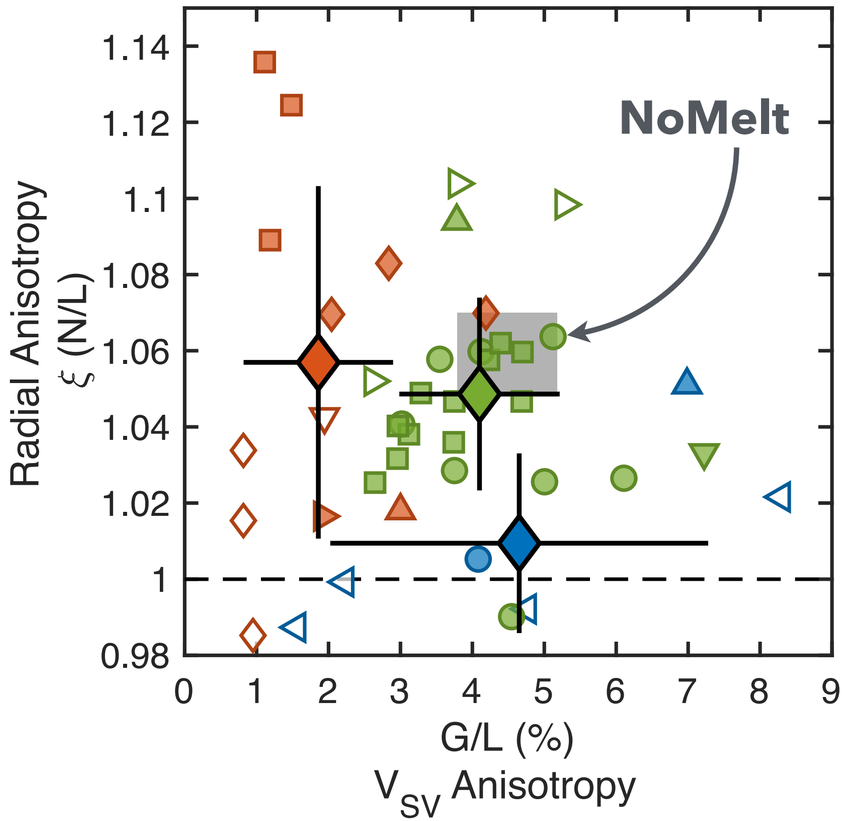
In-situ characterization of oceanic lithosphere petrofabrics

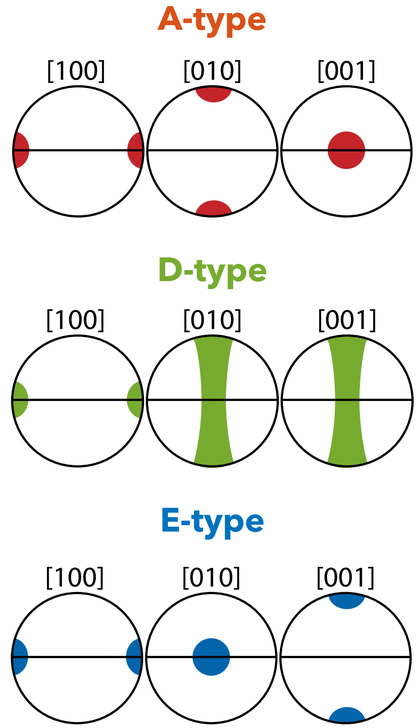
Direct comparisons with laboratory deformed olivine samples indicate **D-type LPO**

Near-ridge deformation dominated by dislocation-assisted **grain boundary sliding** processes implying **grain-size dependent deformation**







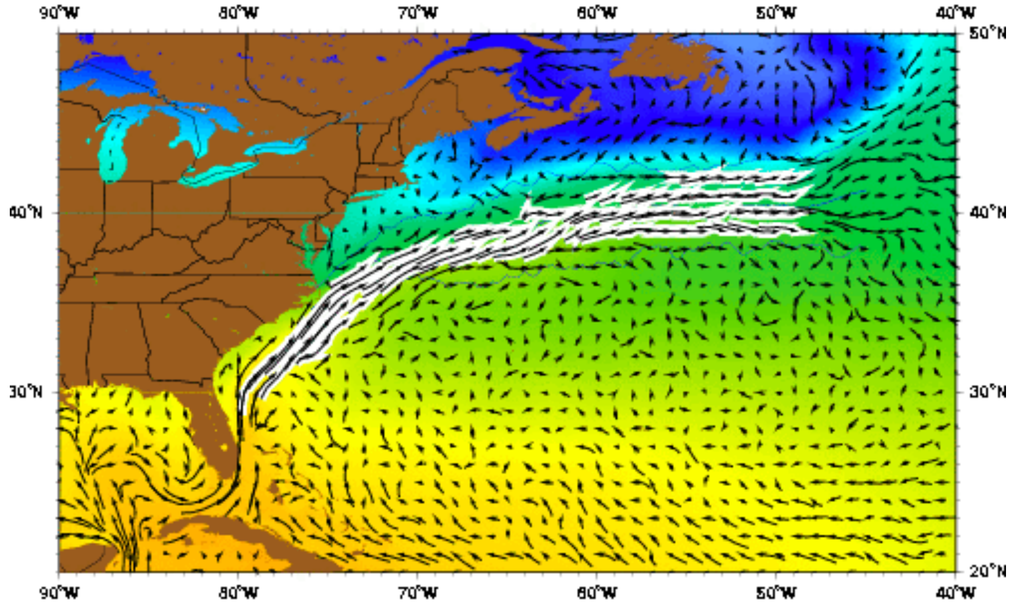


Russell et al (2022)

TILT CORRECTIONS APPLIED TO AMBIENT NOISE

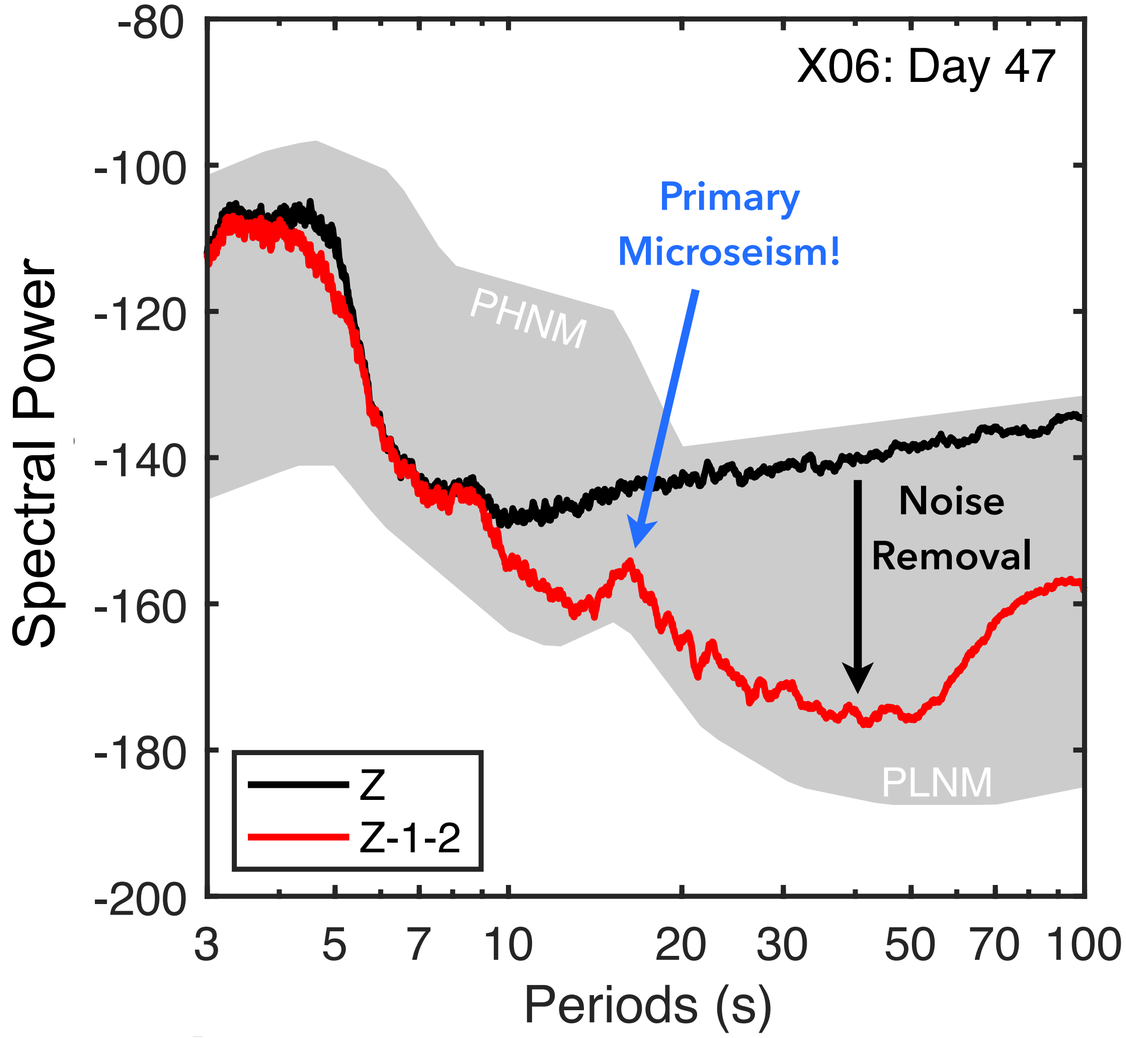
At the ENAM experiment, removing tilt noise prior to ambient-noise correlations **improved SNR of primary microseism by a factor of ~2 on average** and up to a factor of ~10 in some cases

Strong Gulf Stream currents



https://oceancurrents.rsmas.miami.edu/atlantic/gulf-stream.html

ENAM Experiment



Russell & Gaherty (2021)

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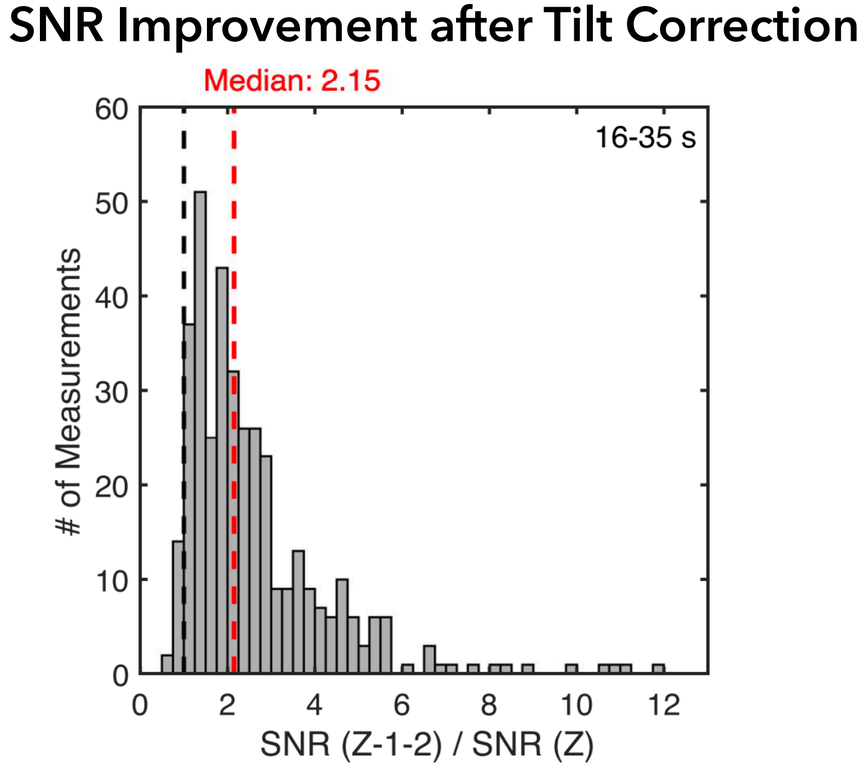
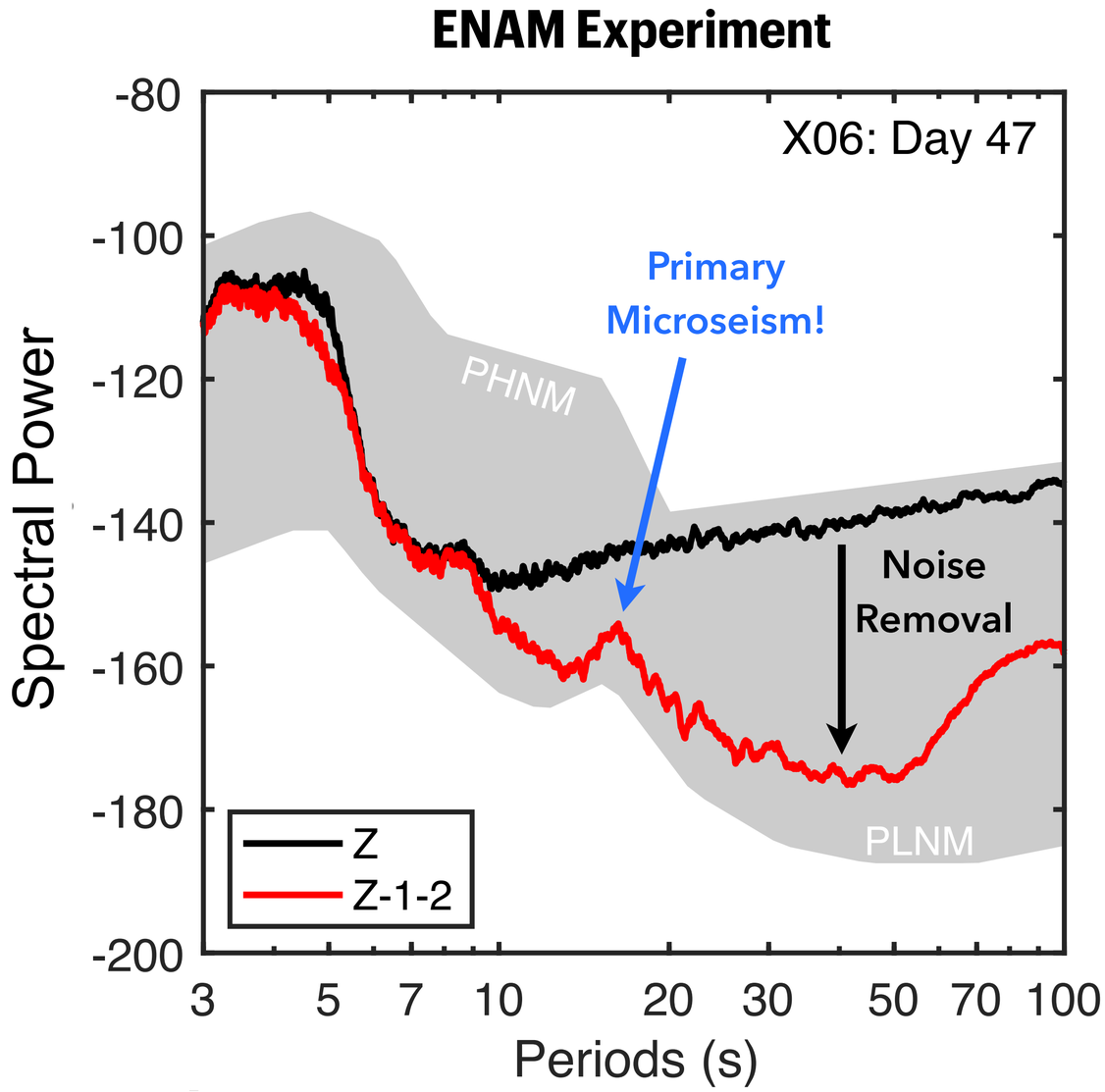
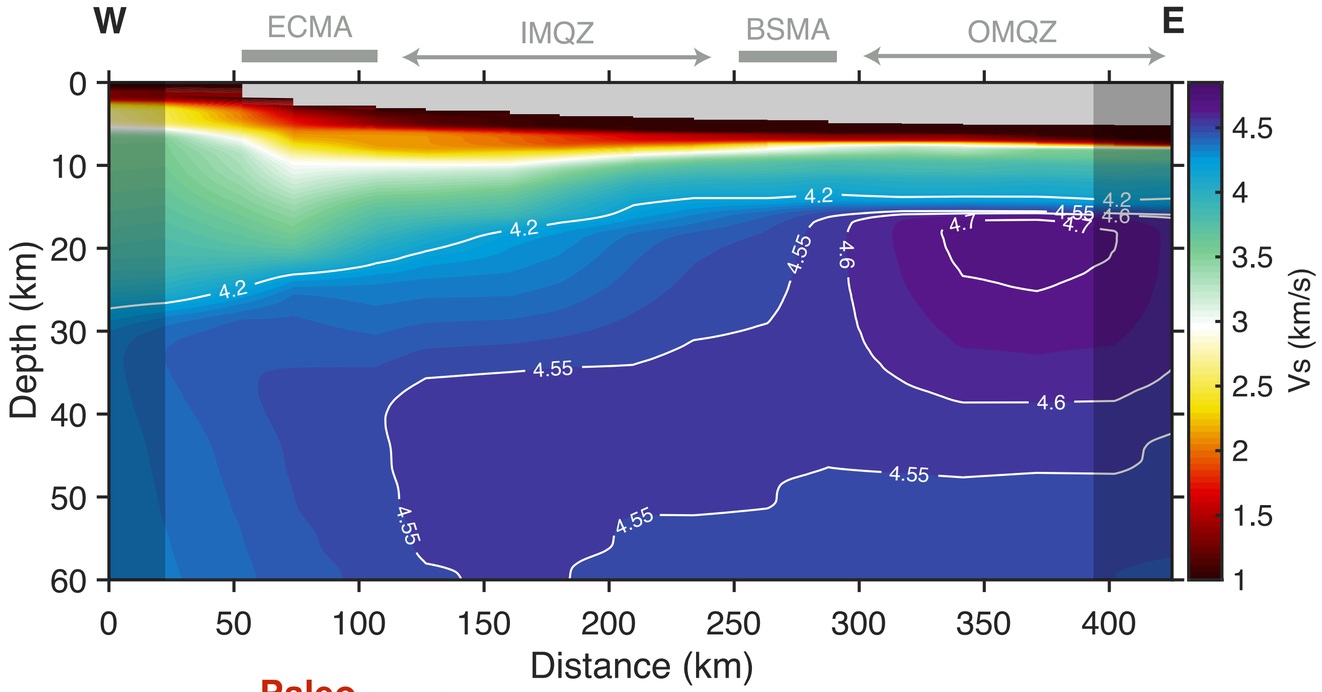
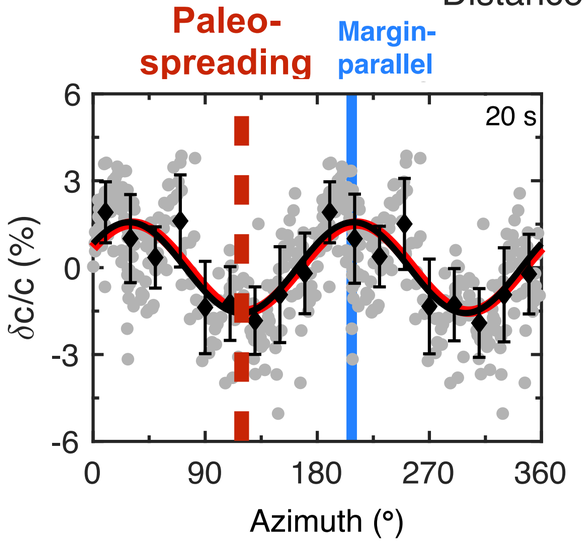


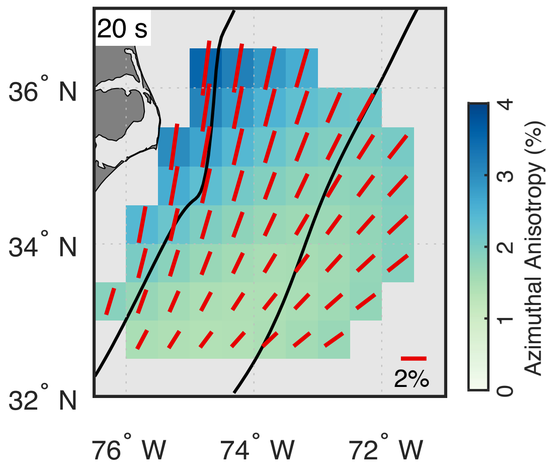


Russell & Gaherty (2021)

DENOISED OBS RECORDS IMPROVE IMAGING CAPABILITIES

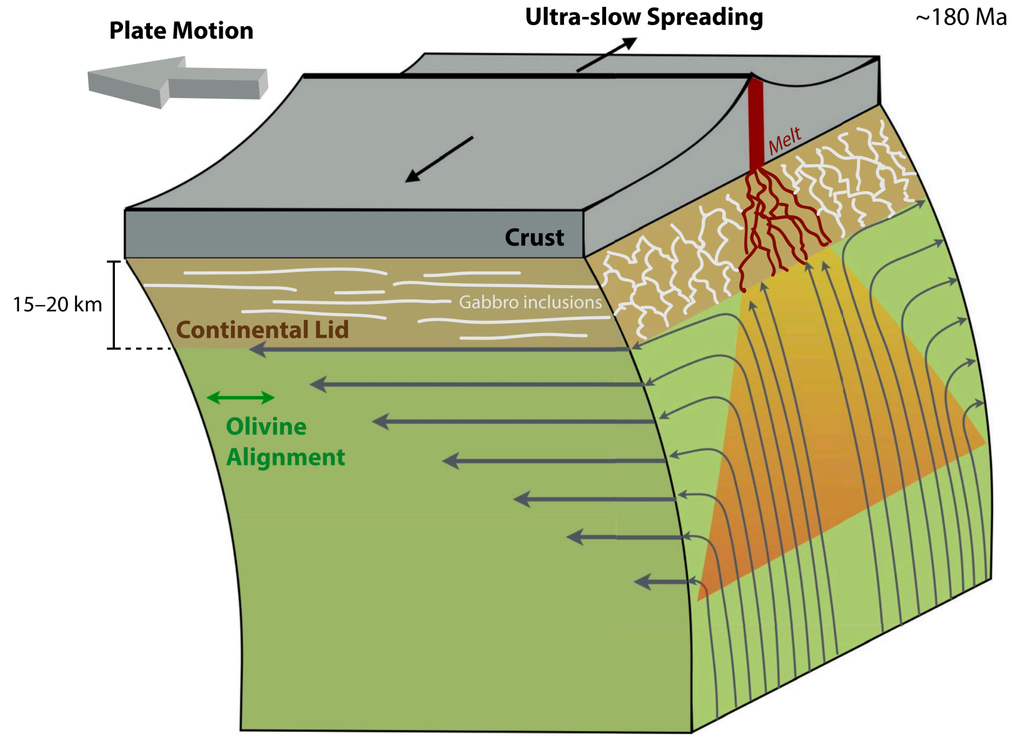






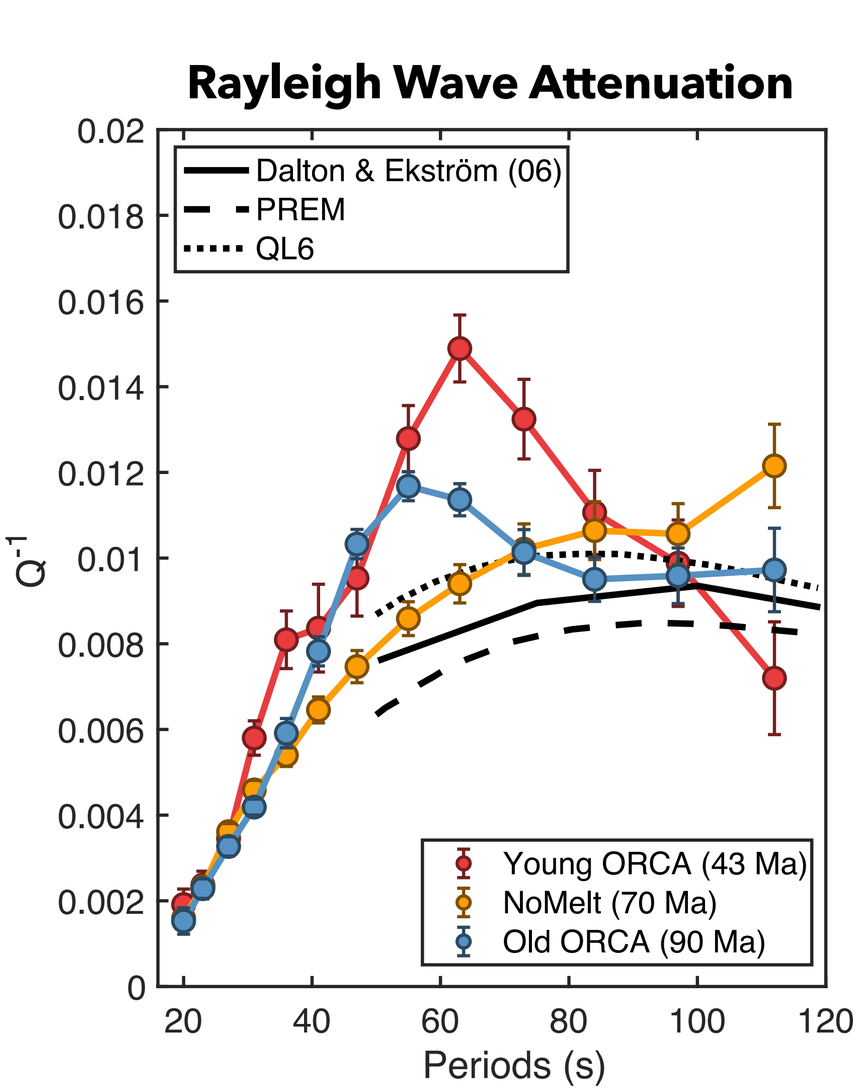
Constraints on timing and mantle dynamics during breakup of Pangea ~170 Ma

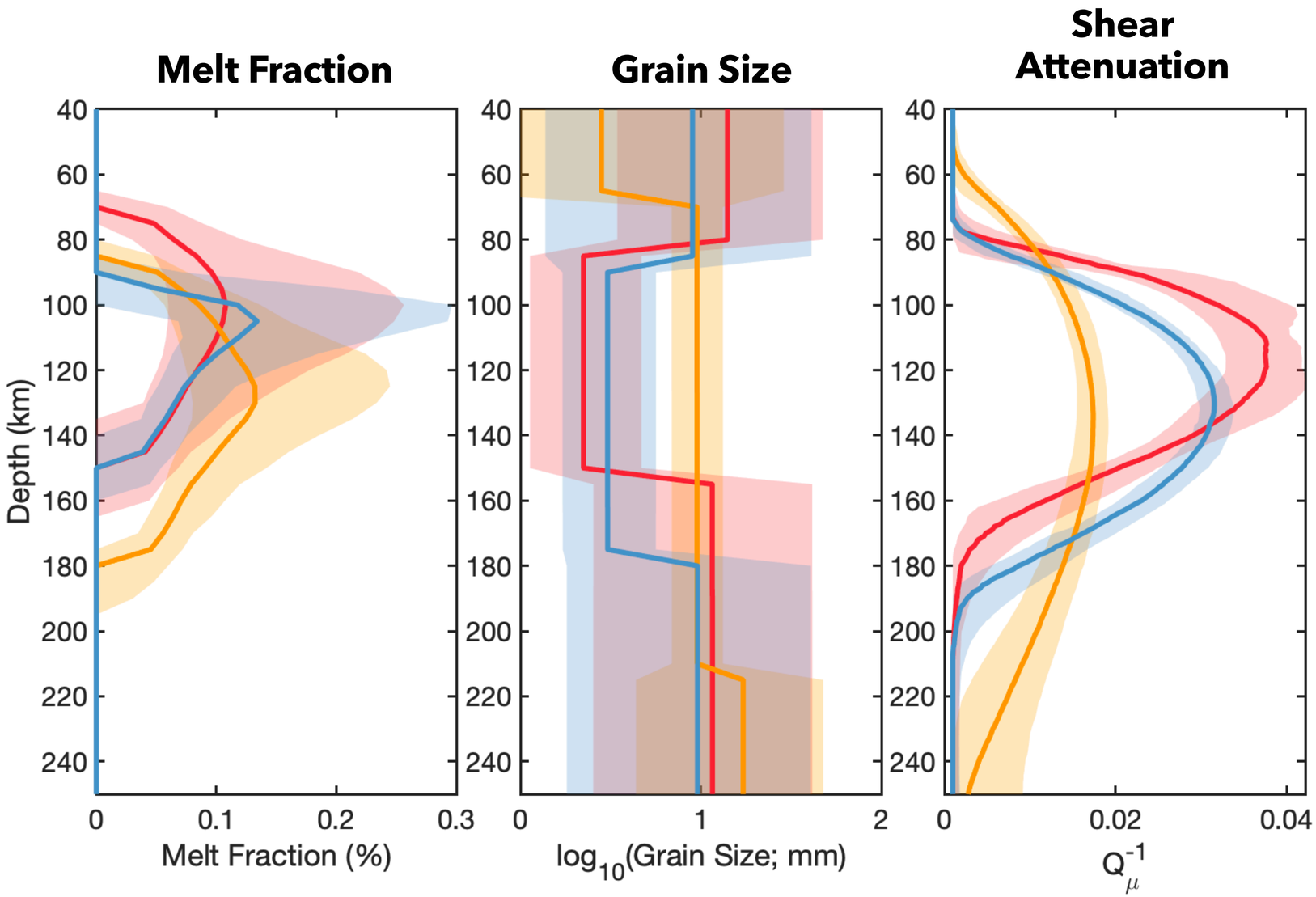
Plate-motion modified corner-flow during ultra-slow spreading



Russell & Gaherty (2021)

IMPORTANCE OF ACCURATE OBS AMPLITUDES: SEISMIC ATTENUATION





Russell et al. (in prep)

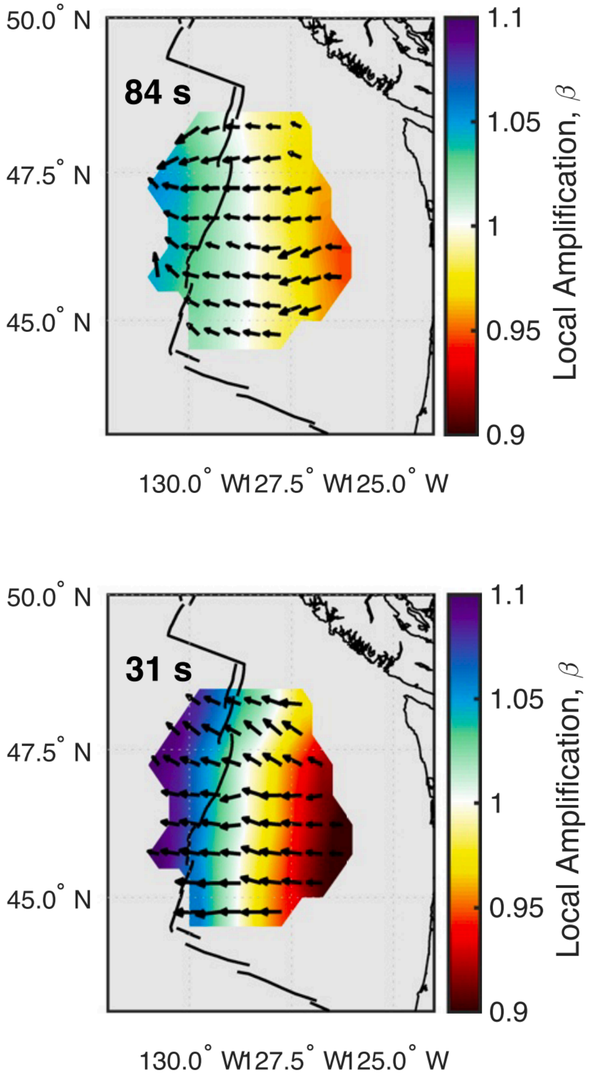
Poster Monday Afternoon: DI13B-0032

LOCAL SITE AMPLIFICATION

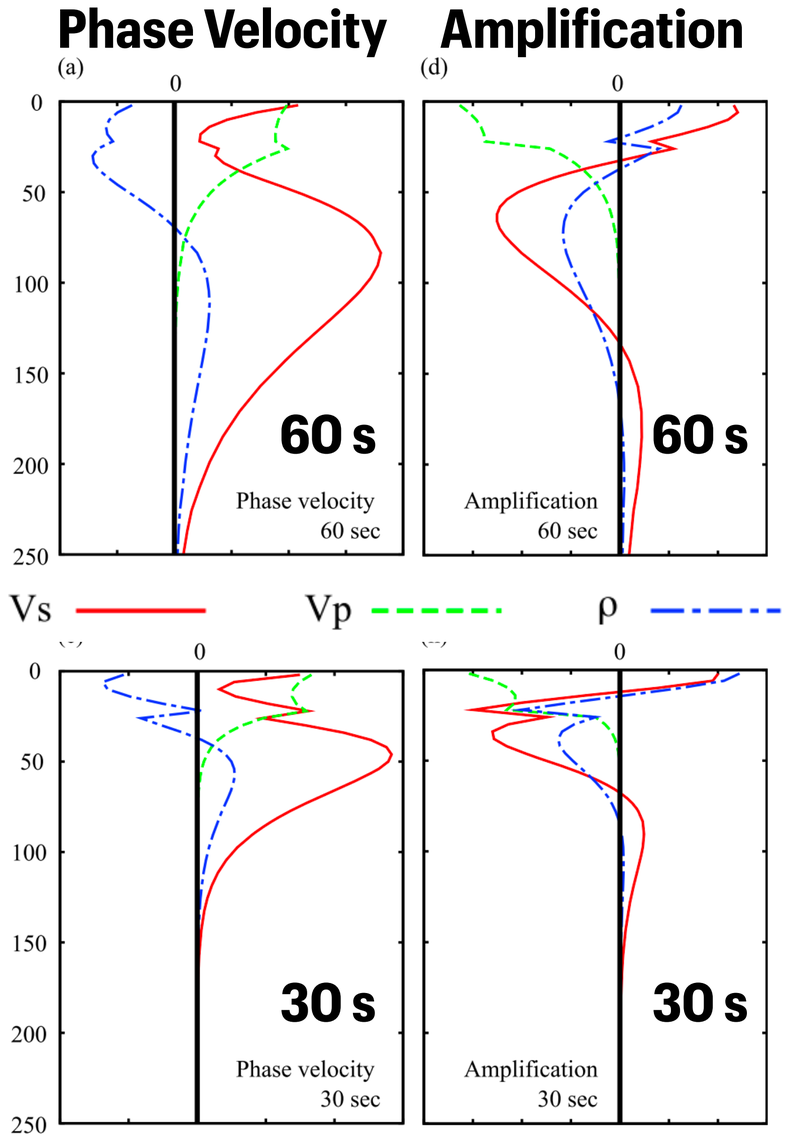
Strong site amplification observed at the Juan de Fuca ridge.

Zero-crossings in Vs sensitivity imply better **sensitivity to discontinuities** compared to phase velocity

Complimentary sensitivity to shallow **Vp/Vs** and **density**
– Organization of melt?
– Shallow cracks?
– Hydrothermal circulation?



Russell & Dalton (2022)



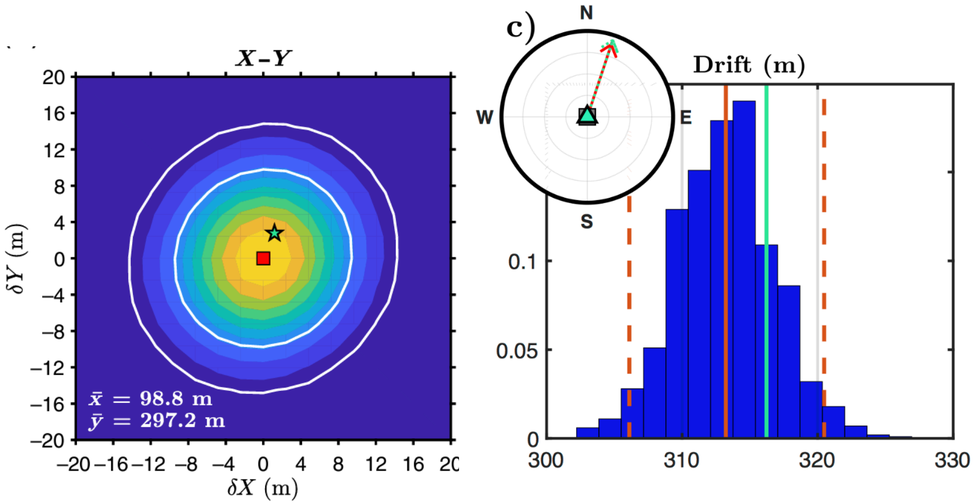
Lin et al. (2012)

OTHER OBS TOOLS

(all on GITHUB)

OBSrange

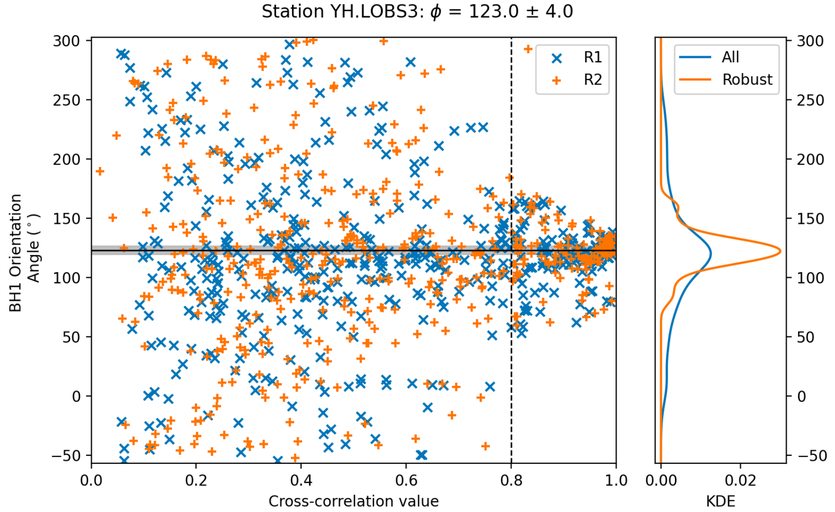
Locating OBS on seafloor



Russell, Eilon, & Mosher (2019)

OrientPy

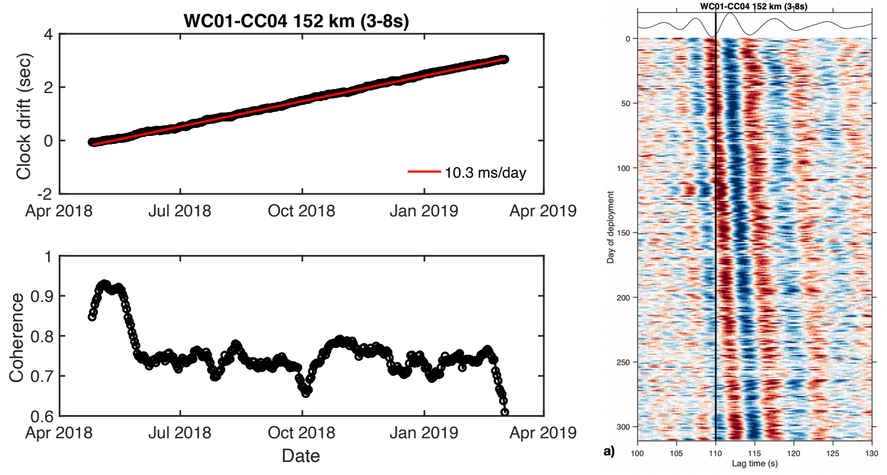
Determining OBS orientations



Pascal Audet, GITHUB

OBSclockdrift

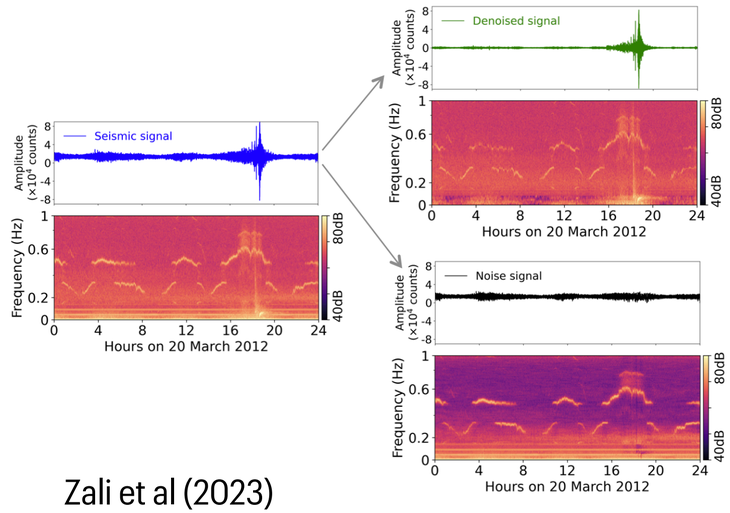
Estimating and correcting clock drift



Josh Russell, GITHUB

NoiseCut

Denoising using Music Information Retrieval Algorithms



Zali et al (2023)

TAKEAWAYS

In the last decade, development of **community-driven tools** have improved the accessibility to OBS data, leading to wider usage and new discoveries
— transformative for the community

Tilt and compliance corrections in particular are useful (and often necessary) for many OBS applications
– Teleseismic surface-wave imaging
– Ambient noise imaging
– Teleseismic body-wave travel-time tomography
– Receiver function imaging

GITHUB LINKS

ATaCR: https://github.com/helenjanisz/ATaCR

ATaCR for Ambient Noise: https://github.com/jbrussell/ATaCR/tree/correct_noise

OBSrange (locating OBS on seafloor): https://github.com/jbrussell/OBSrange

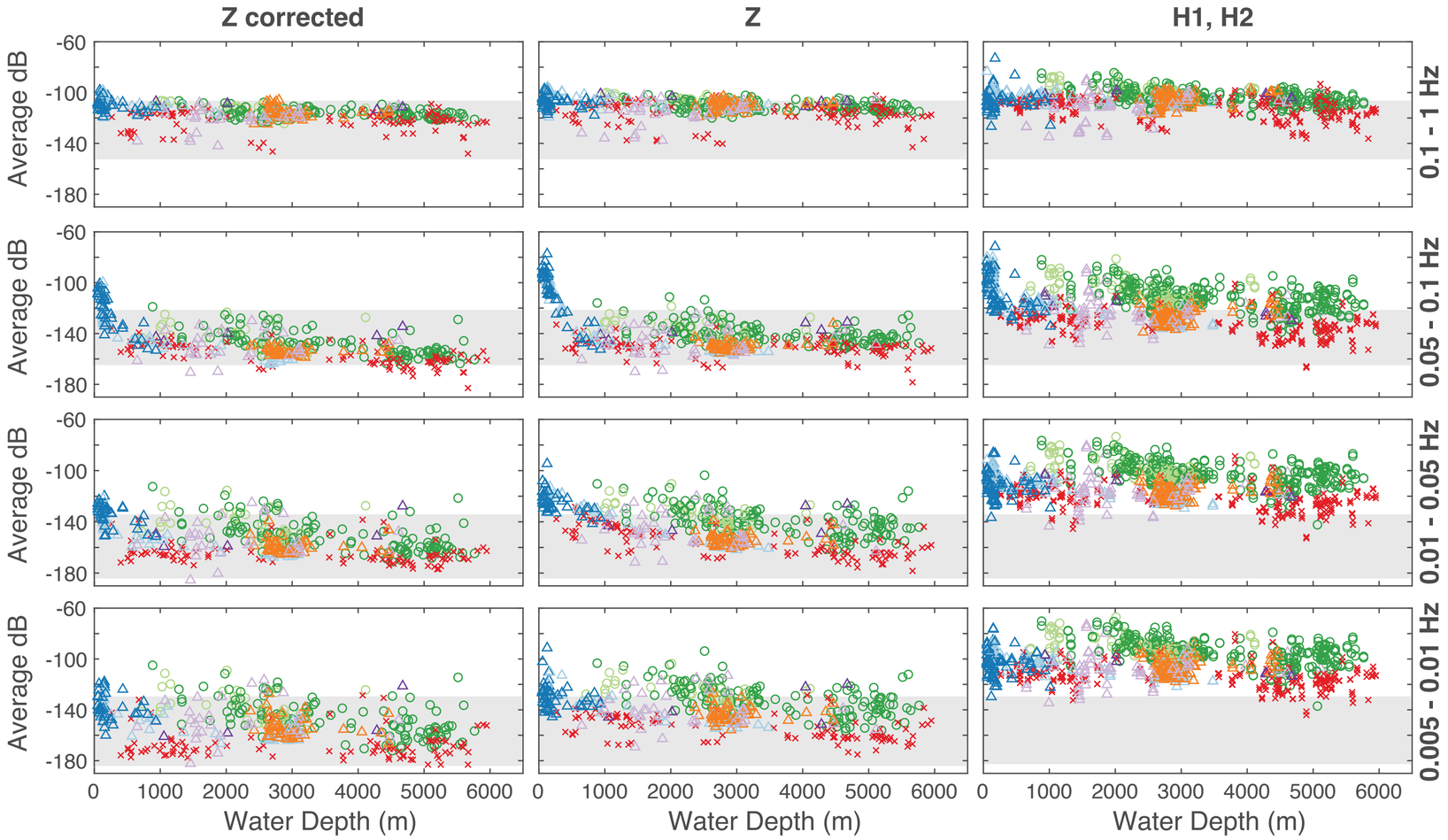
OBStools: https://github.com/nfsi-canada/OBStools

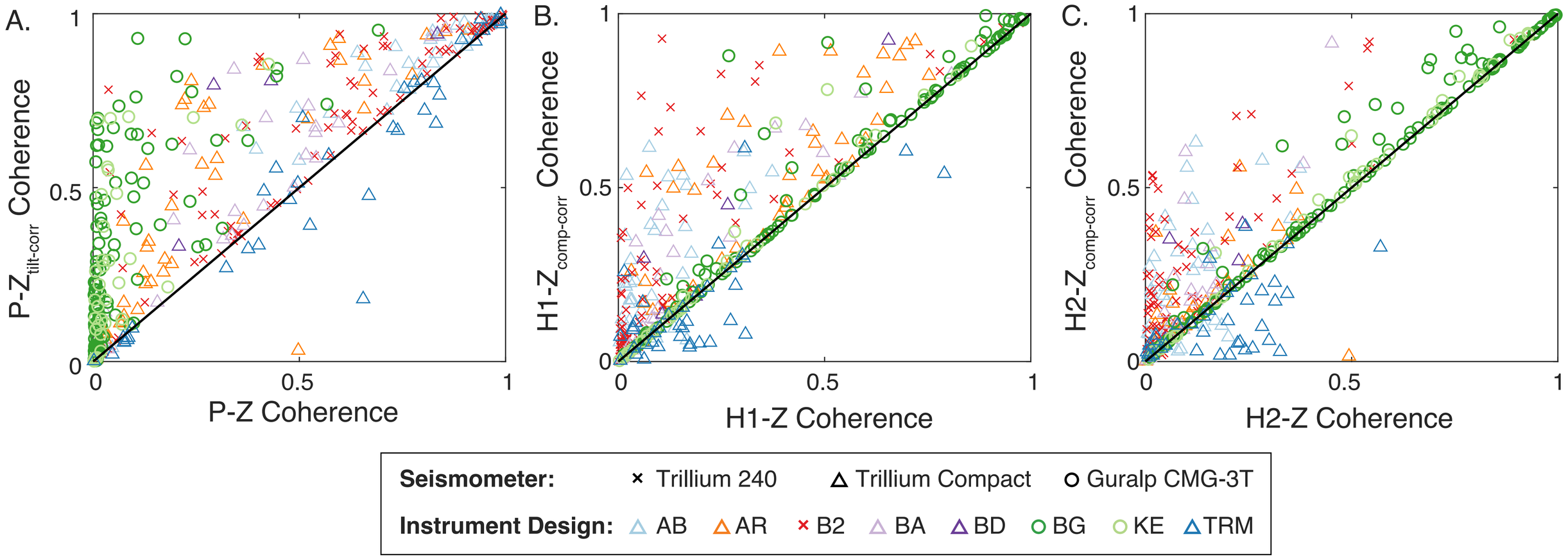
OrientPy (determine OBS orientations): https://github.com/nfsi-canada/OrientPy

OBSclockdrift: https://github.com/jbrussell/OBSclockdrift

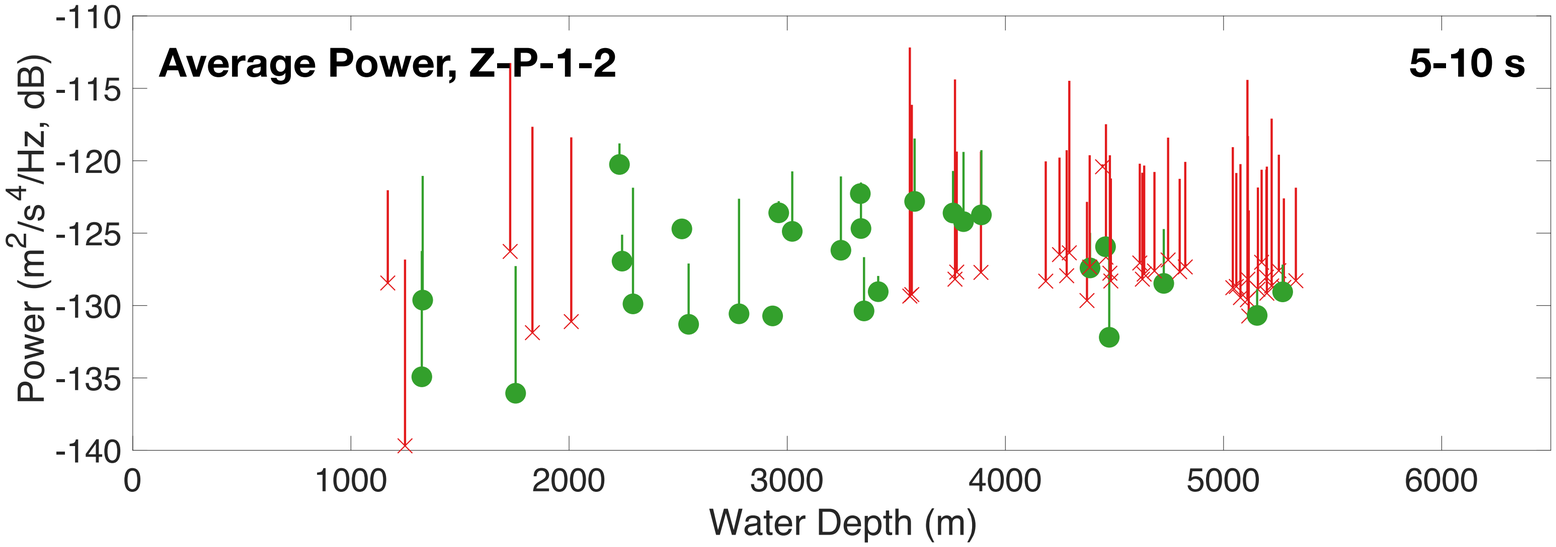
NoiseCut: https://github.com/ZahraZali/NoiseCut

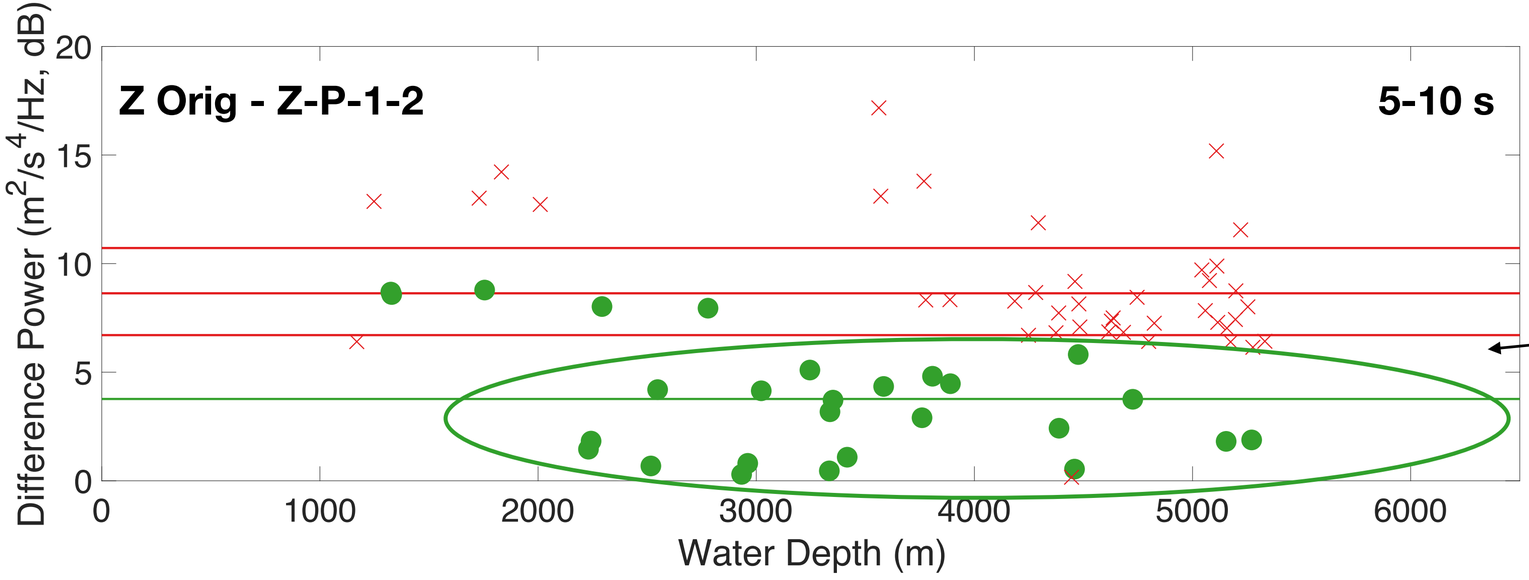
COMMONLY USED FREQUENCY BANDS




A.
B.
C.
P-Z$_{tilt-corr}$ Coherence
H1-Z$_{comp-corr}$ Coherence
H2-Z$_{comp-corr}$ Coherence
P-Z Coherence
H1-Z Coherence
H2-Z Coherence
0
0.5
1
Seismometer:
Trillium 240
Trillium Compact
Guralp CMG-3T
Instrument Design:
AB
AR
B2
BA
BD
BG
KE
TRM

Let's add a few more deployments….

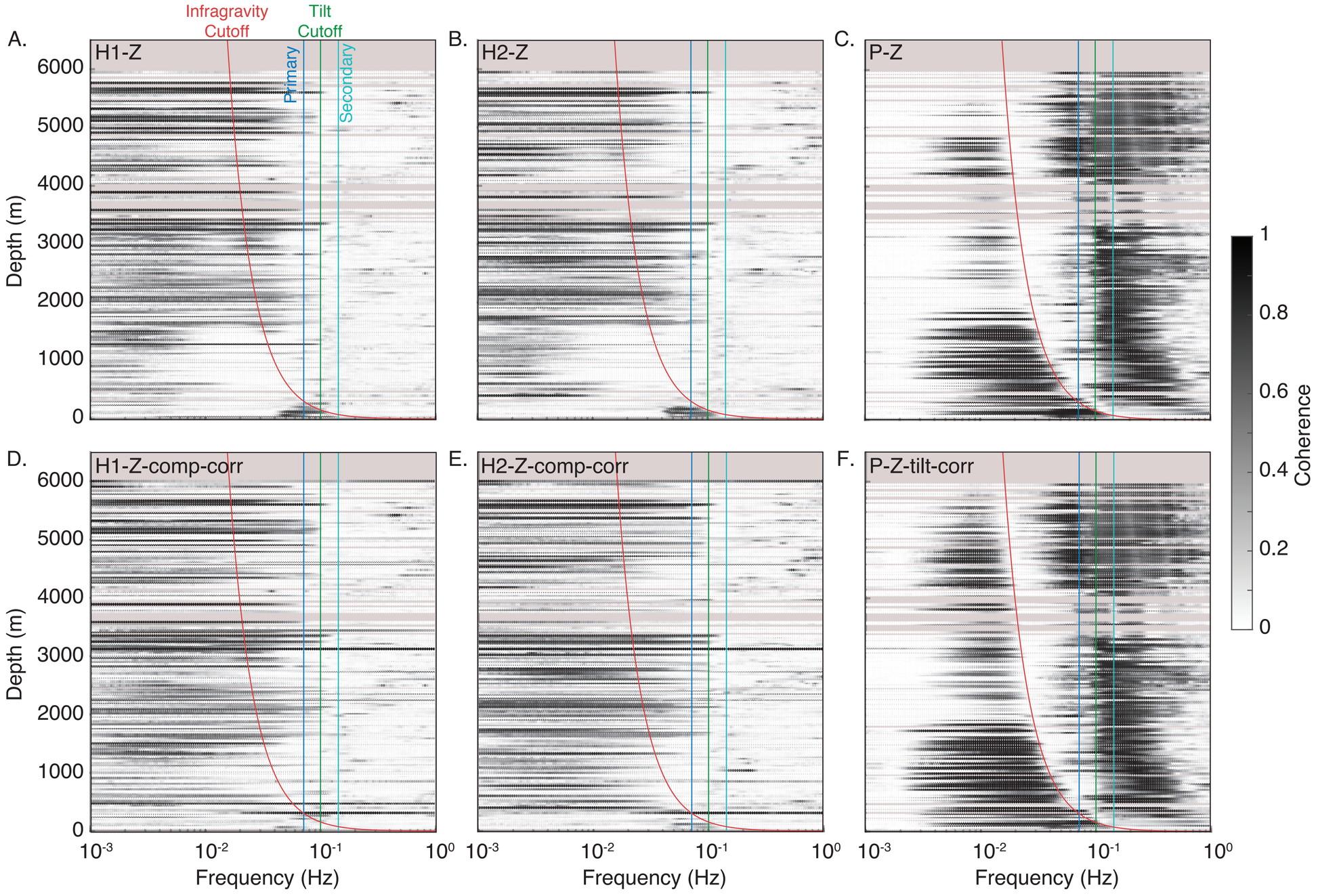


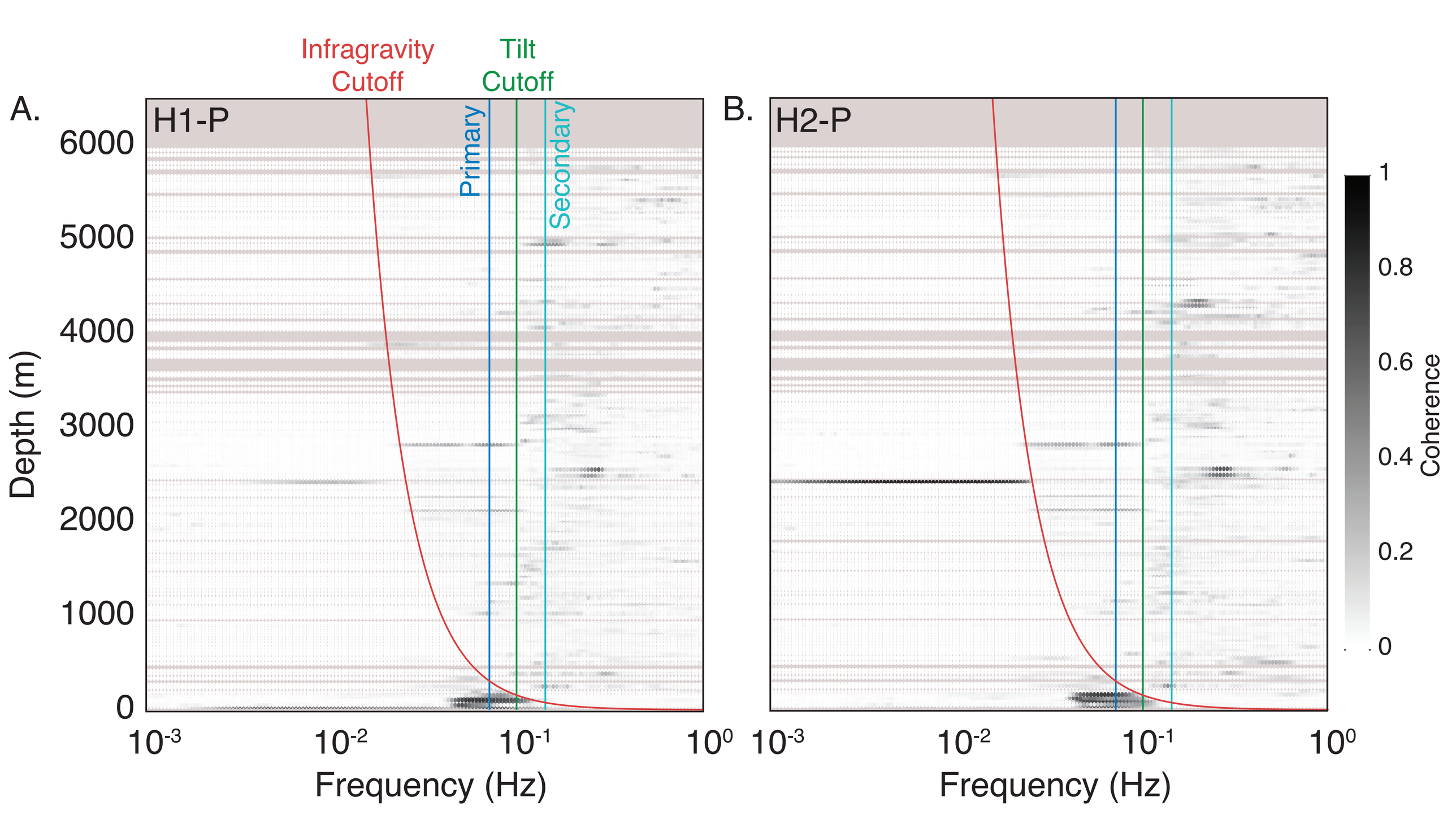


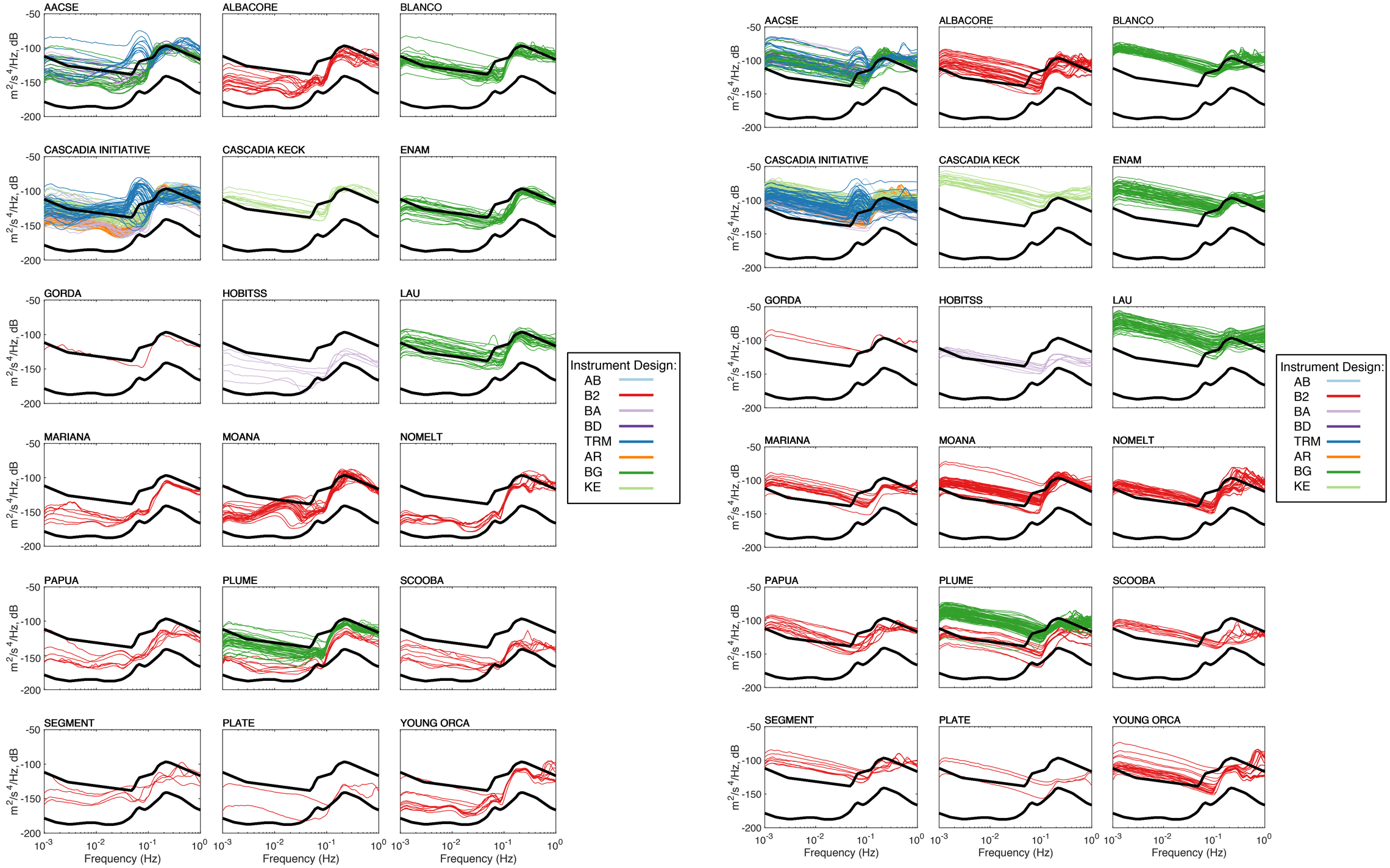
ENAM
ALBACORE
YoungORCA
NoMELT

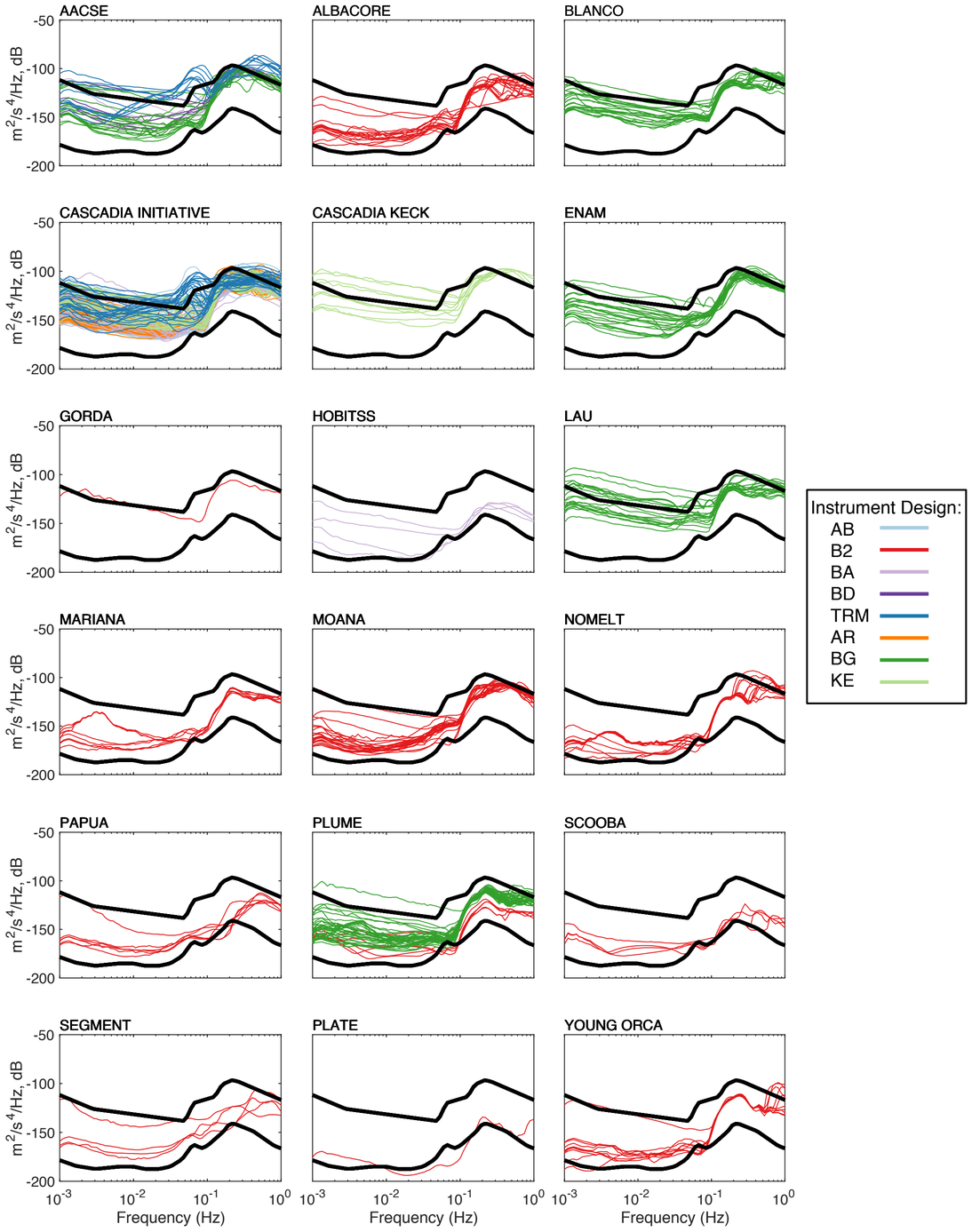
ENAM still looks anomalous relative to other deployments.

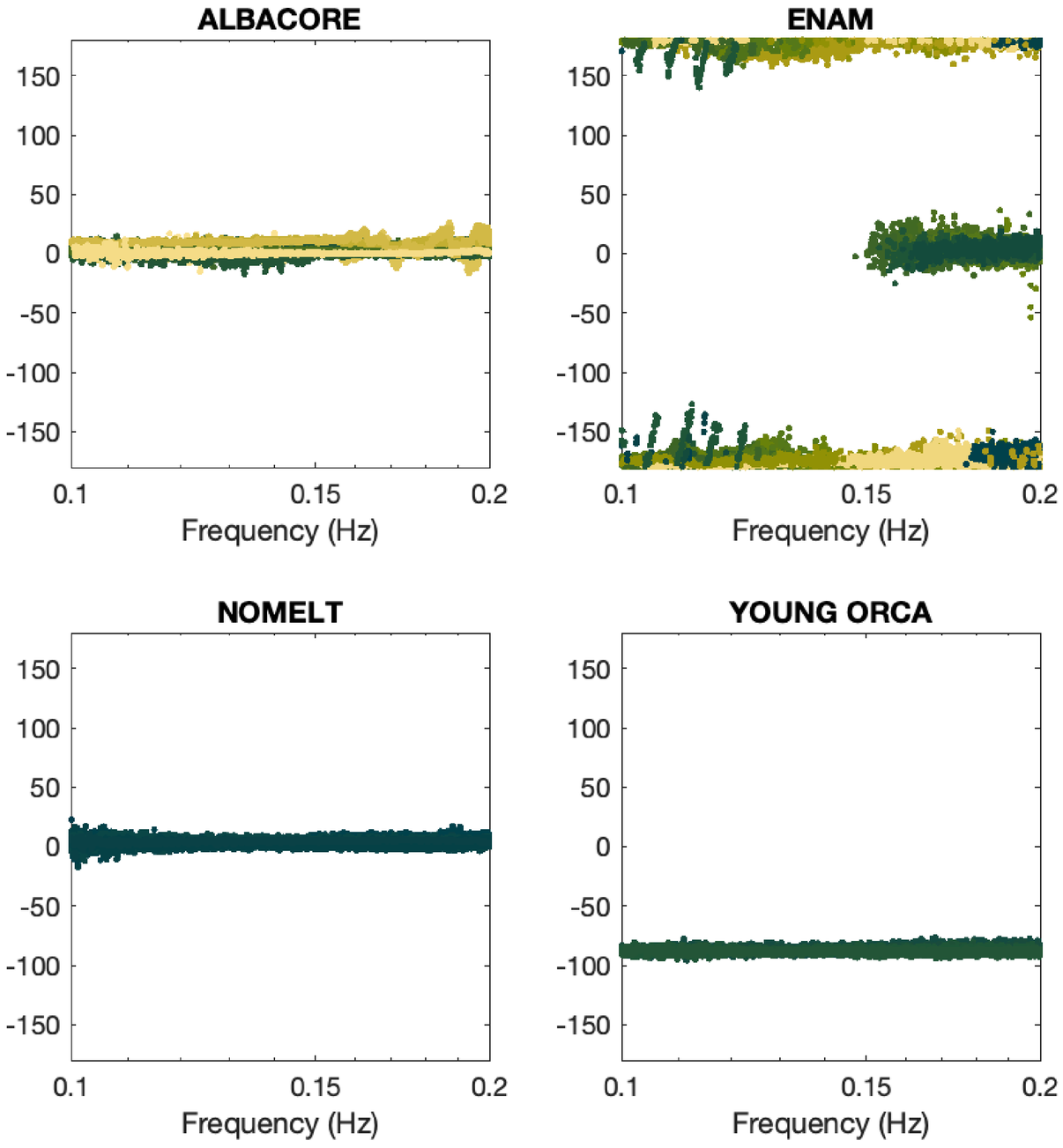
Seismometer	OBS Instrument Design		
× Trillium 240	△ LDEO BB APG	△ SIO ABALONE	○ WHOI BB
△ Trillium Compact	△ LDEO TRM	× SIO 240 BB	○ WHOI KECK
○ Guralp CMG-3T	△ LDEO BB DPG	△ WHOI ARRA	


A.
B.
C.
D.
E.
F.
H1-Z
H2-Z
P-Z
H1-Z-comp-corr
H2-Z-comp-corr
P-Z-tilt-corr
Infragravity Cutoff
Tilt Cutoff
Primary
Secondary
Depth (m)
0
1000
2000
3000
4000
5000
6000
10^{-3}
10^{-2}
10^{-1}
10^{0}
Frequency (Hz)
Coherence
0
0.2
0.4
0.6
0.8
1

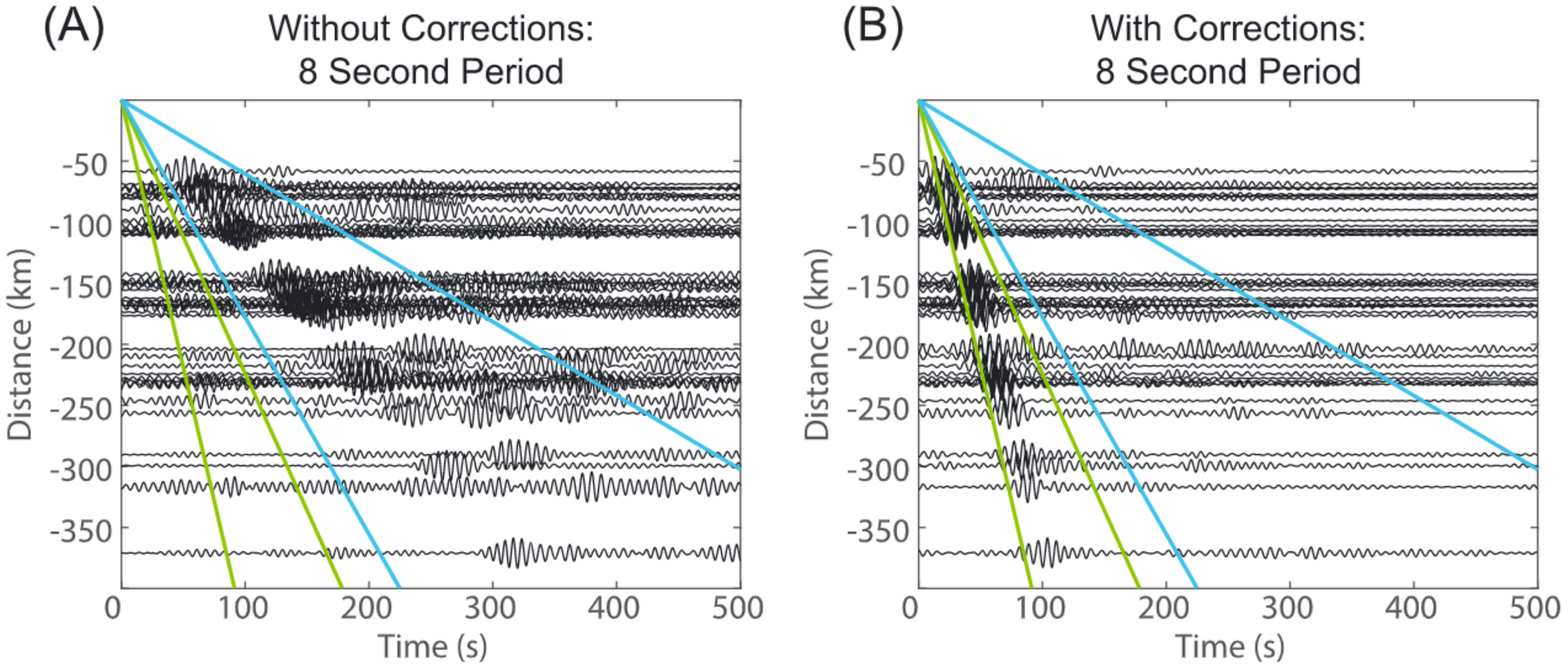

A.
B.
H1-P
H2-P
Infragravity Cutoff
Tilt Cutoff
Primary
Secondary
Depth (m)
6000
5000
4000
3000
2000
1000
0
10^{-3}
10^{-2}
10^{-1}
10^{0}
Frequency (Hz)
Coherence
1
0.8
0.6
0.4
0.2
0


AACSE
ALBACORE
BLANCO
CASCADIA INITIATIVE
CASCADIA KECK
ENAM
GORDA
HOBITSS
LAU
MARIANA
MOANA
NOMELT
PAPUA
PLUME
SCOOBA
SEGMENT
PLATE
YOUNG ORCA
m²/s⁴/Hz, dB
-50
-100
-150
-200
10⁻³
10⁻²
10⁻¹
10⁰
Frequency (Hz)
Instrument Design:
AB
B2
BA
BD
TRM
AR
BG
KE


AACSE
ALBACORE
BLANCO
CASCADIA INITIATIVE
CASCADIA KECK
ENAM
GORDA
HOBITSS
LAU
MARIANA
MOANA
NOMELT
PAPUA
PLUME
SCOOBA
SEGMENT
PLATE
YOUNG ORCA
m²/s⁴/Hz, dB
-50
-100
-150
-200
10⁻³
10⁻²
10⁻¹
10⁰
Frequency (Hz)
Instrument Design:
AB
B2
BA
BD
TRM
AR
BG
KE


ALBACORE
ENAM
NOMELT
YOUNG ORCA
150
100
50
0
-50
-100
-150
0.1
0.15
0.2
Frequency (Hz)

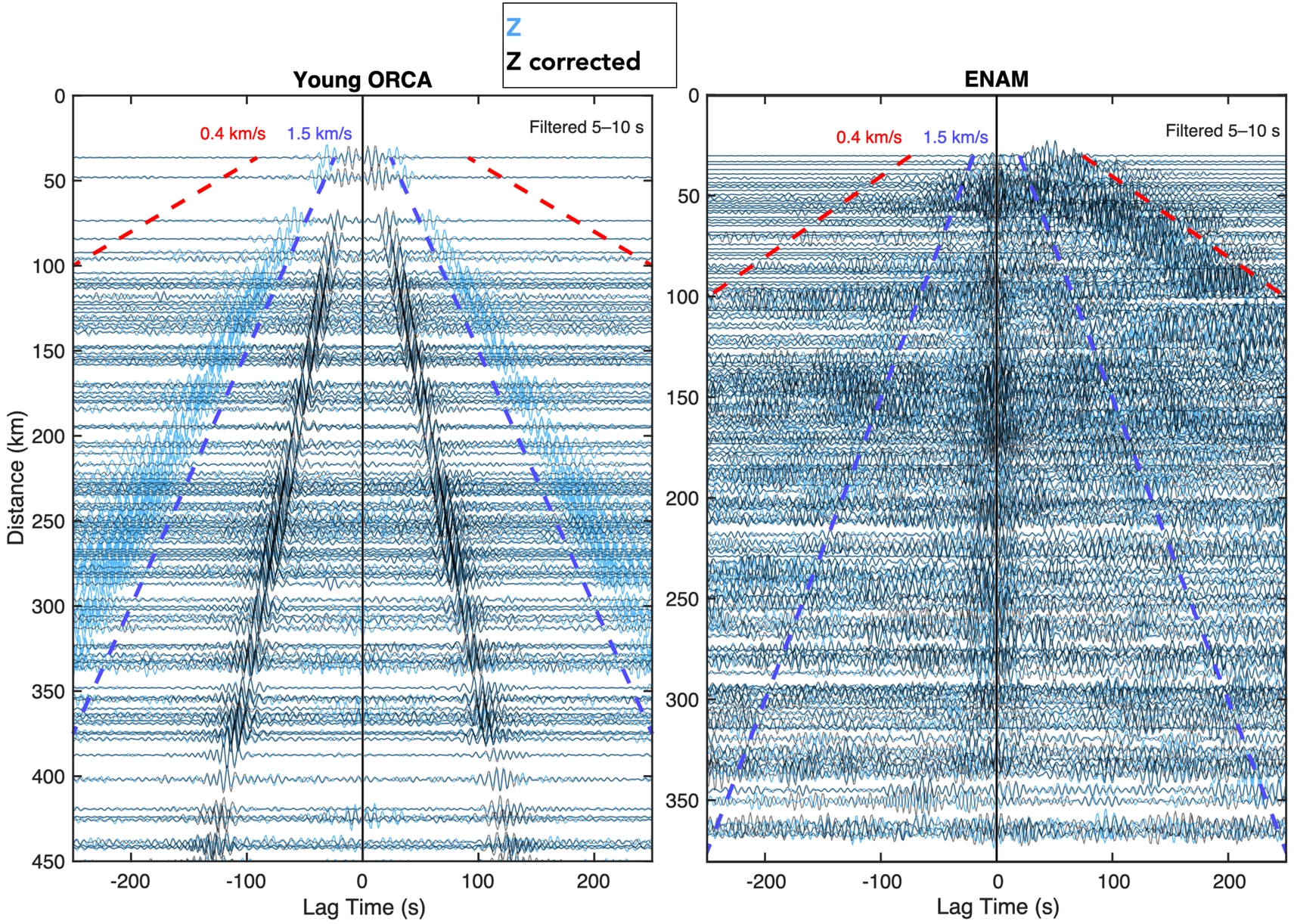
COMPLIANCE CORRECTIONS



Bowden et al., 2016

COMPLIANCE CORRECTIONS APPLIED TO AMBIENT NOISE

Removing tilt and compliance at 5-10 s yields enhanced first overtone signal in some deployments, but not others. **Why?**



COMPLIANCE CORRECTIONS APPLIED TO AMBIENT NOISE

Removing tilt and compliance at 5-10 s yields enhanced first overtone signal in some deployments, but not others. **Why?**

Best guesses: Different noise environment in Atlantic v. Pacific and/or thickly sedimented margin.