20,000 Leagues Under the Sea

With a Fleet of Seismic Robots

Frederik J Simons

Princeton University



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Guust Nolet



Introduction – I

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- These affect the propagation velocity of **seismic waves**
- They cause anomalies in the **gravitational field**
- They are manifest as **surface and subsurface topography**

Introduction – II

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we must study all three (physical) observables:

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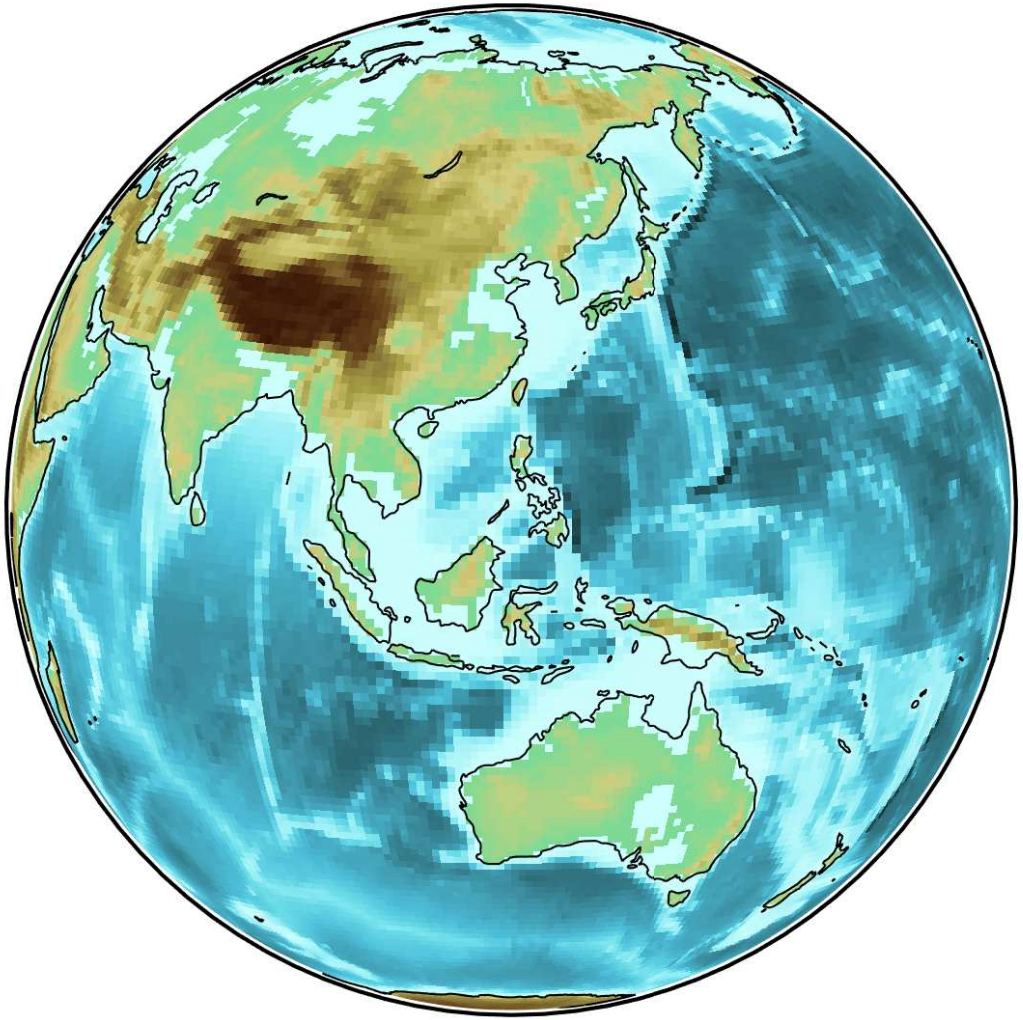
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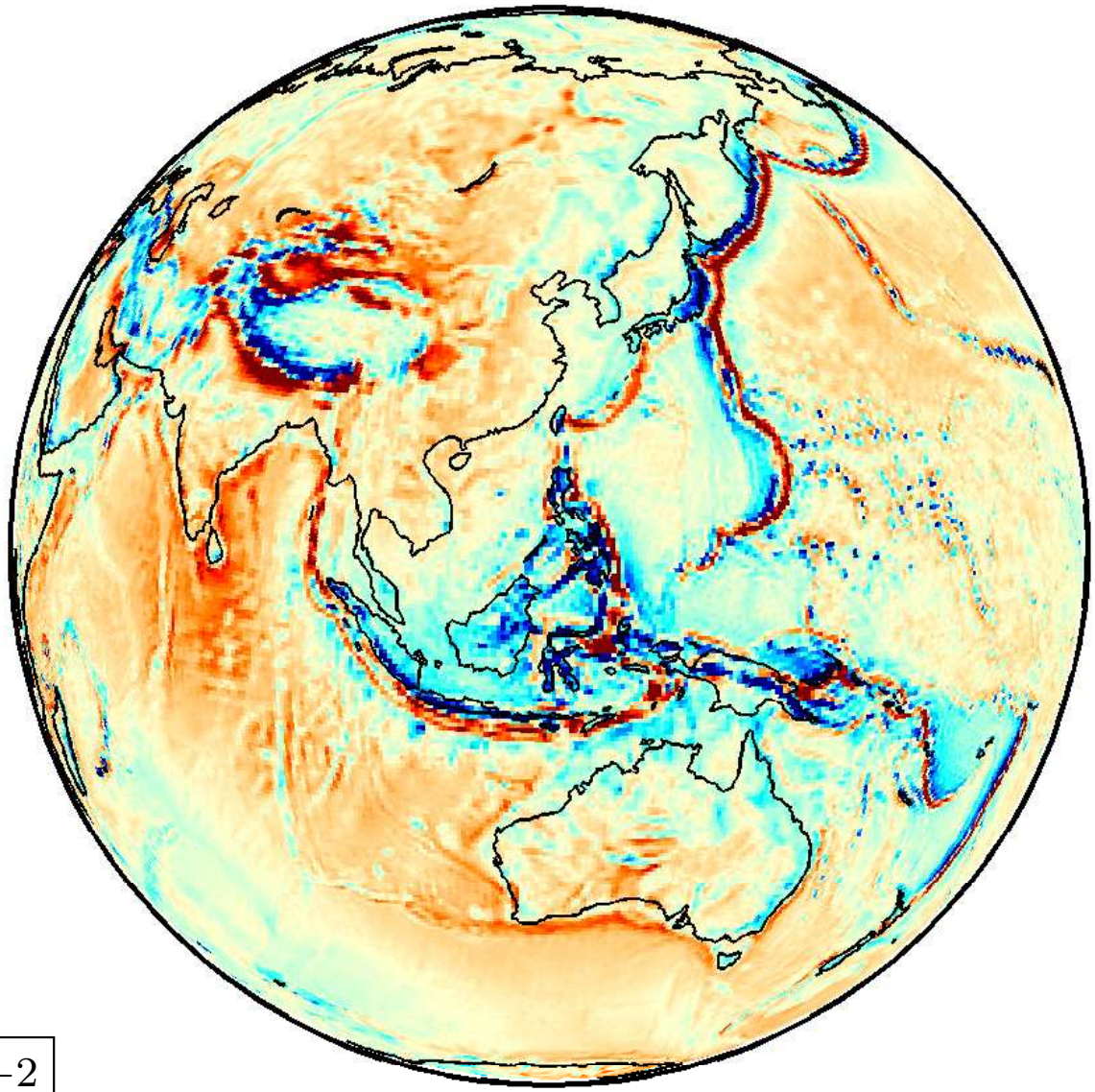
as well as how they **correlate**, at any and all **scales**.

Topography



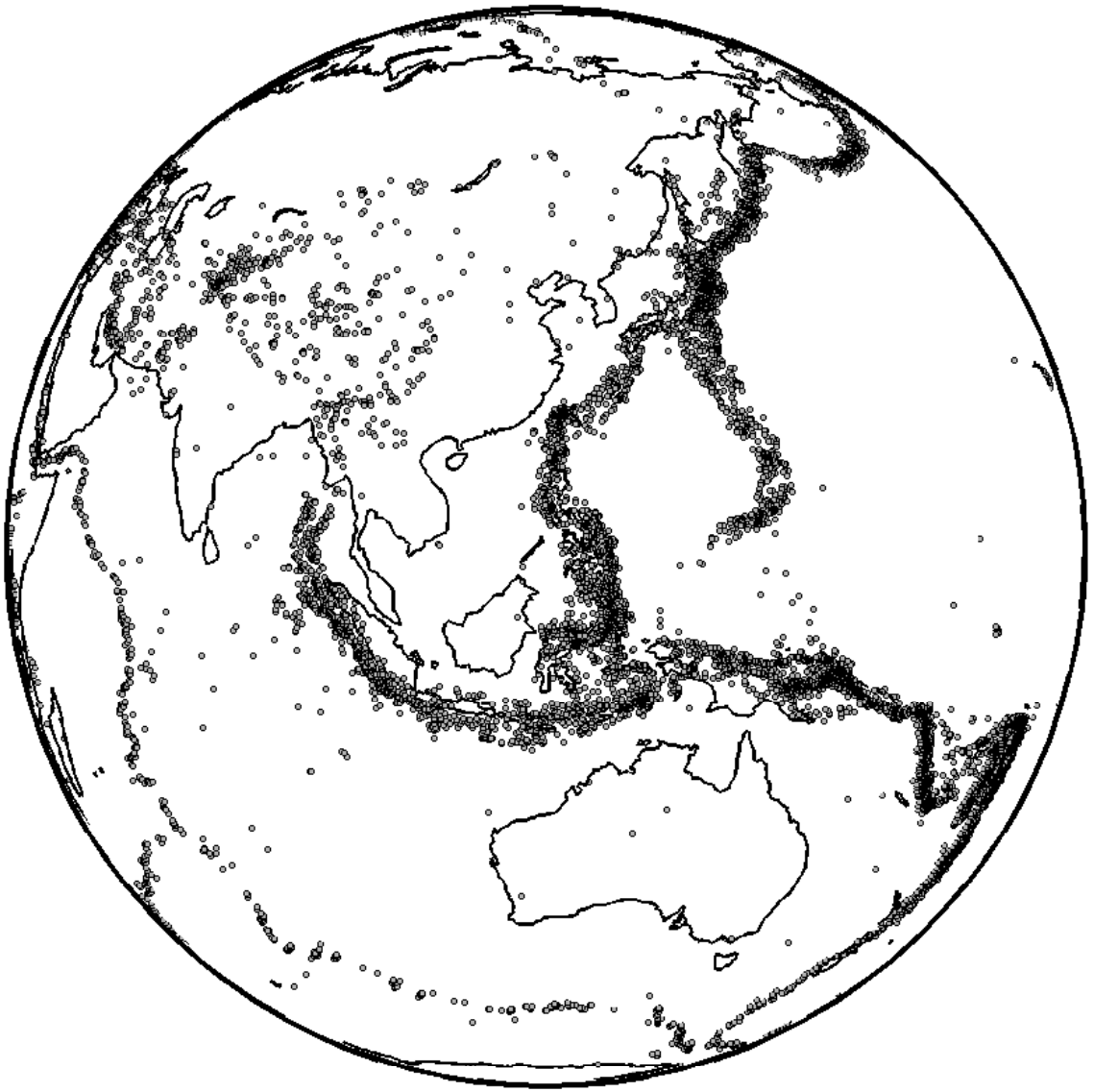
$R \approx 6371\,\text{km}$

Gravity



$g \approx 9.81\ \text{m/s}^{-2}$

Seismicity



$N \approx 2/\text{day}$

Chemistry $\rightarrow$ Physics $\rightarrow$ Geophysics

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Temperature / Pressure

(*how hot is it deep down there?*)

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Composition / Phase changes

(*what is it made of, and how?*)

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Seismic wave speeds

(*how fast do earthquake waves travel?*)

Measuring seismic wave speeds

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Earthquakes / Sources

(*energy release at a point in time and space*)

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Forward modeling
(*ray theory, finite-frequency, full-waveform modeling*)

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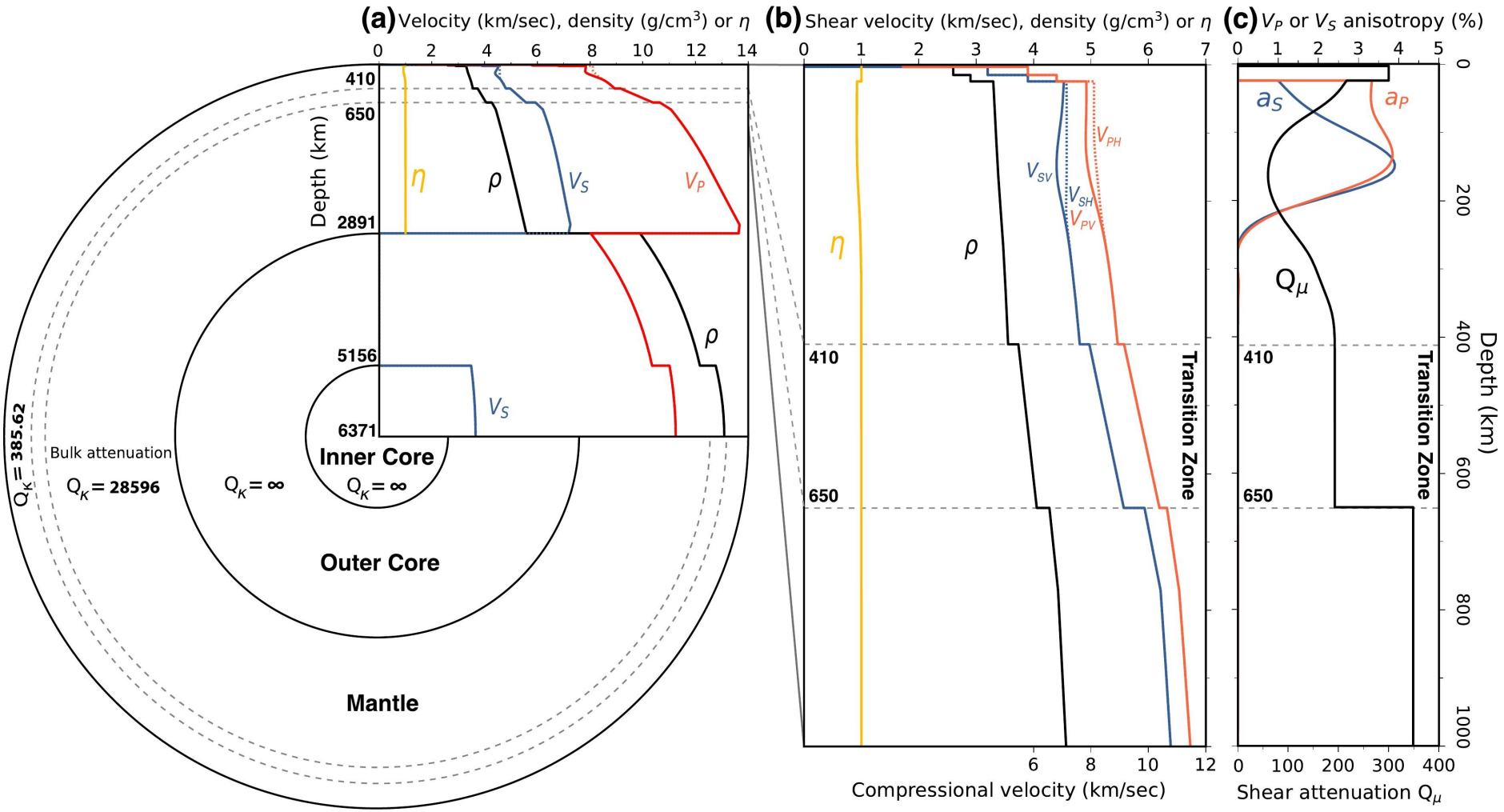
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Forward modeling
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Inverse modeling
(*seismic tomography, three-dimensional structure*)

Reference model



Forward modeling using SPECFEM3D_GLOBE



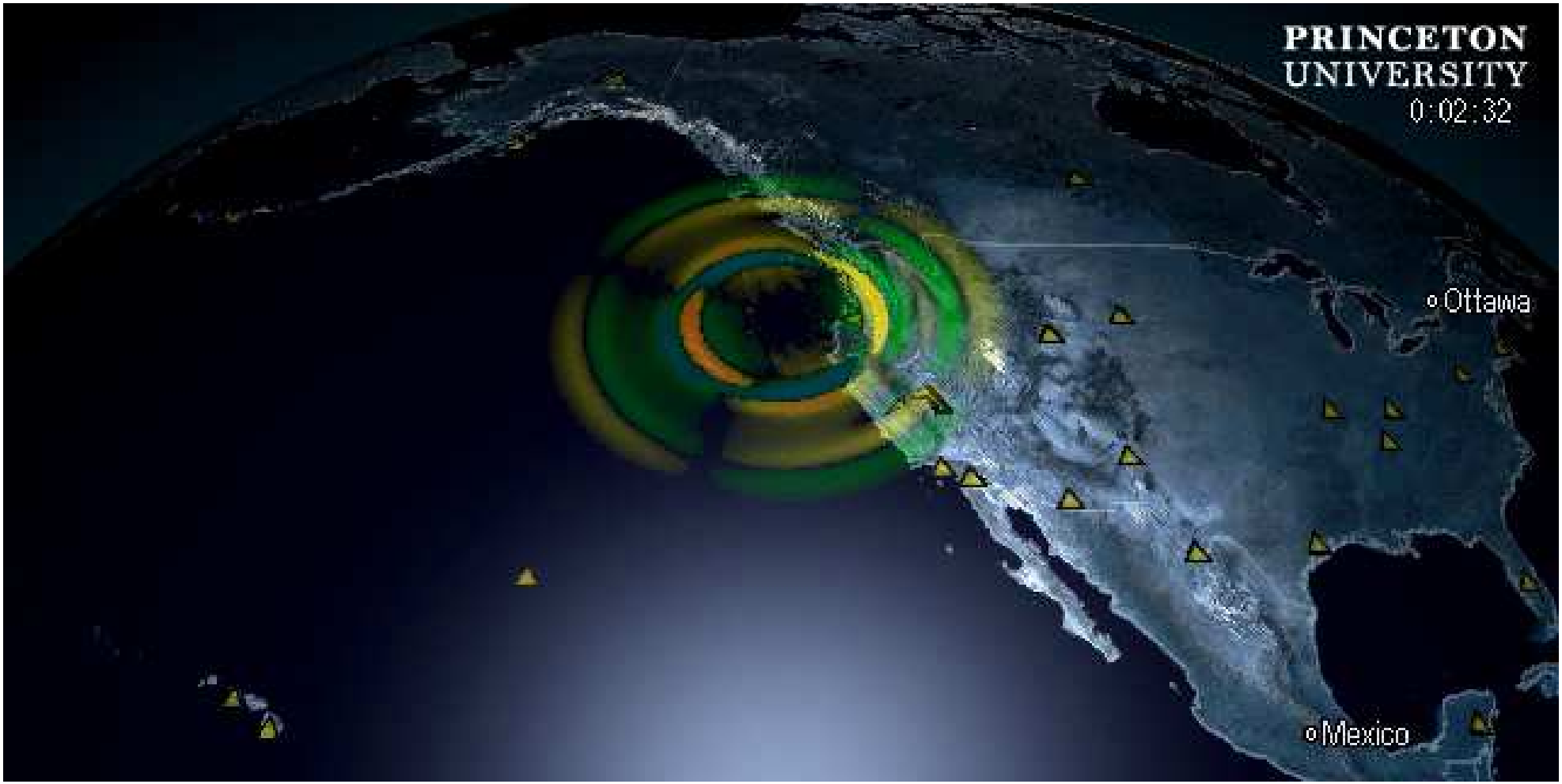
Forward modeling using SPECFEM3D_GLOBE



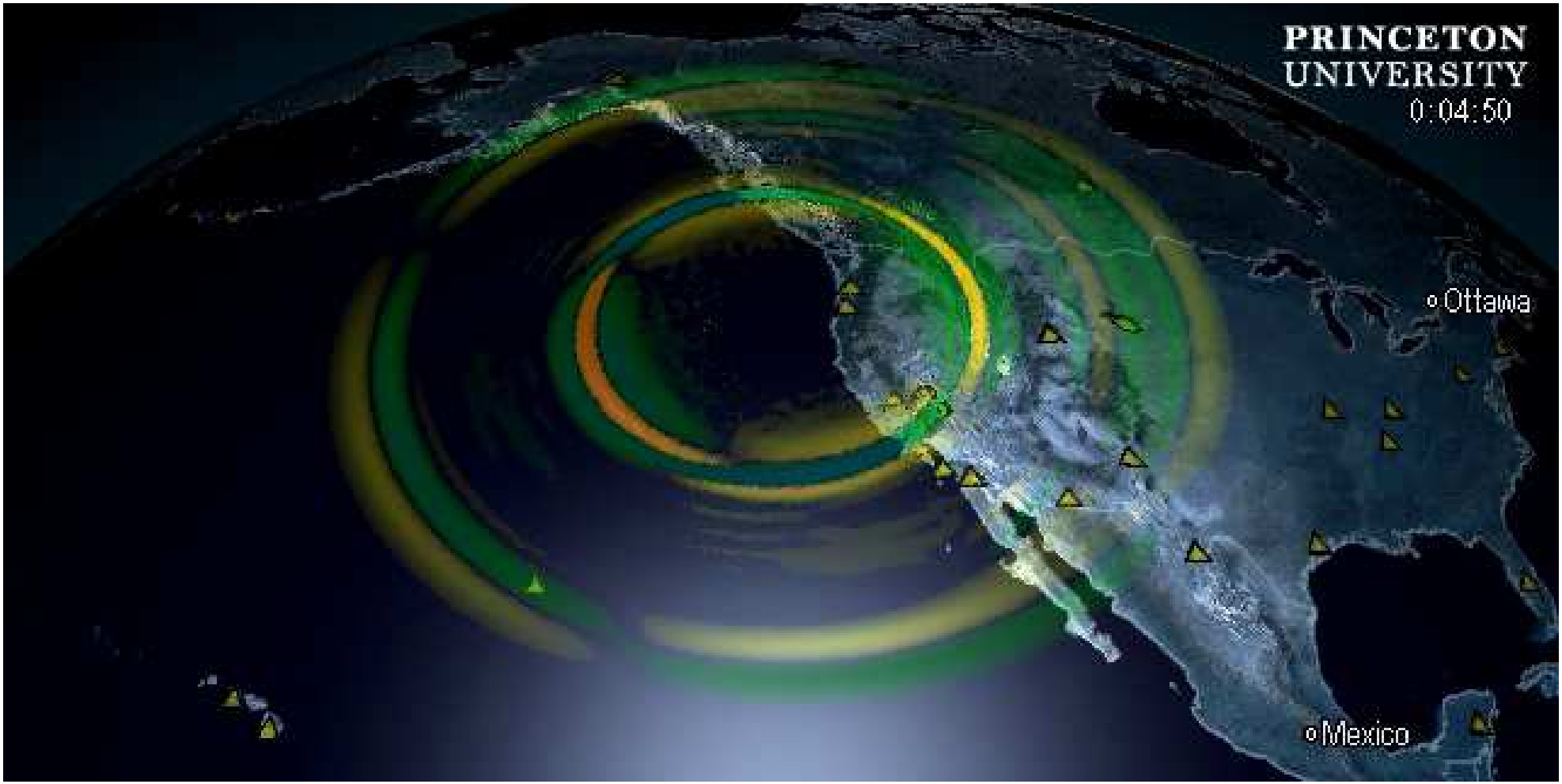
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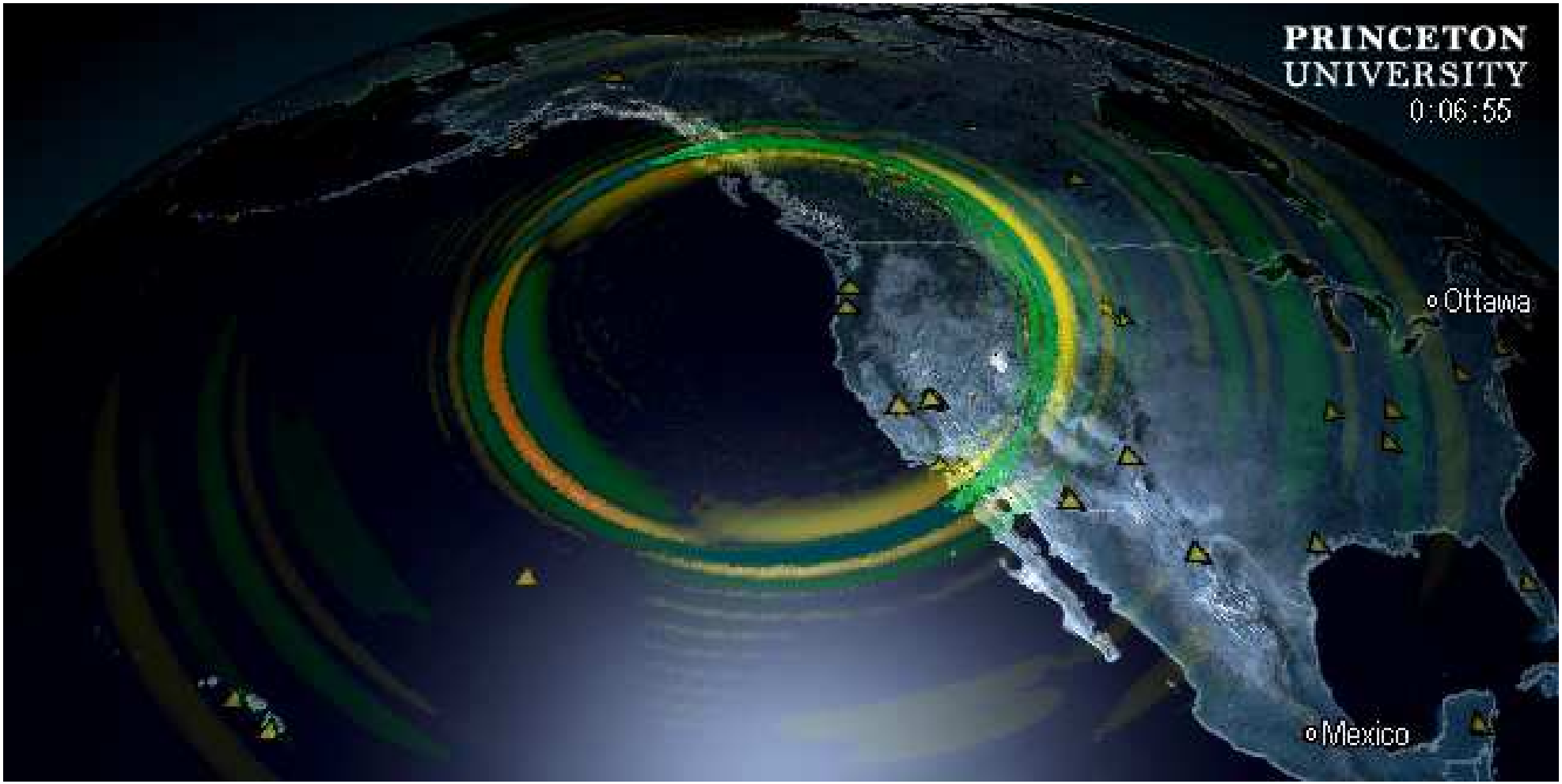
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Forward modeling using SPECFEM3D_GLOBE



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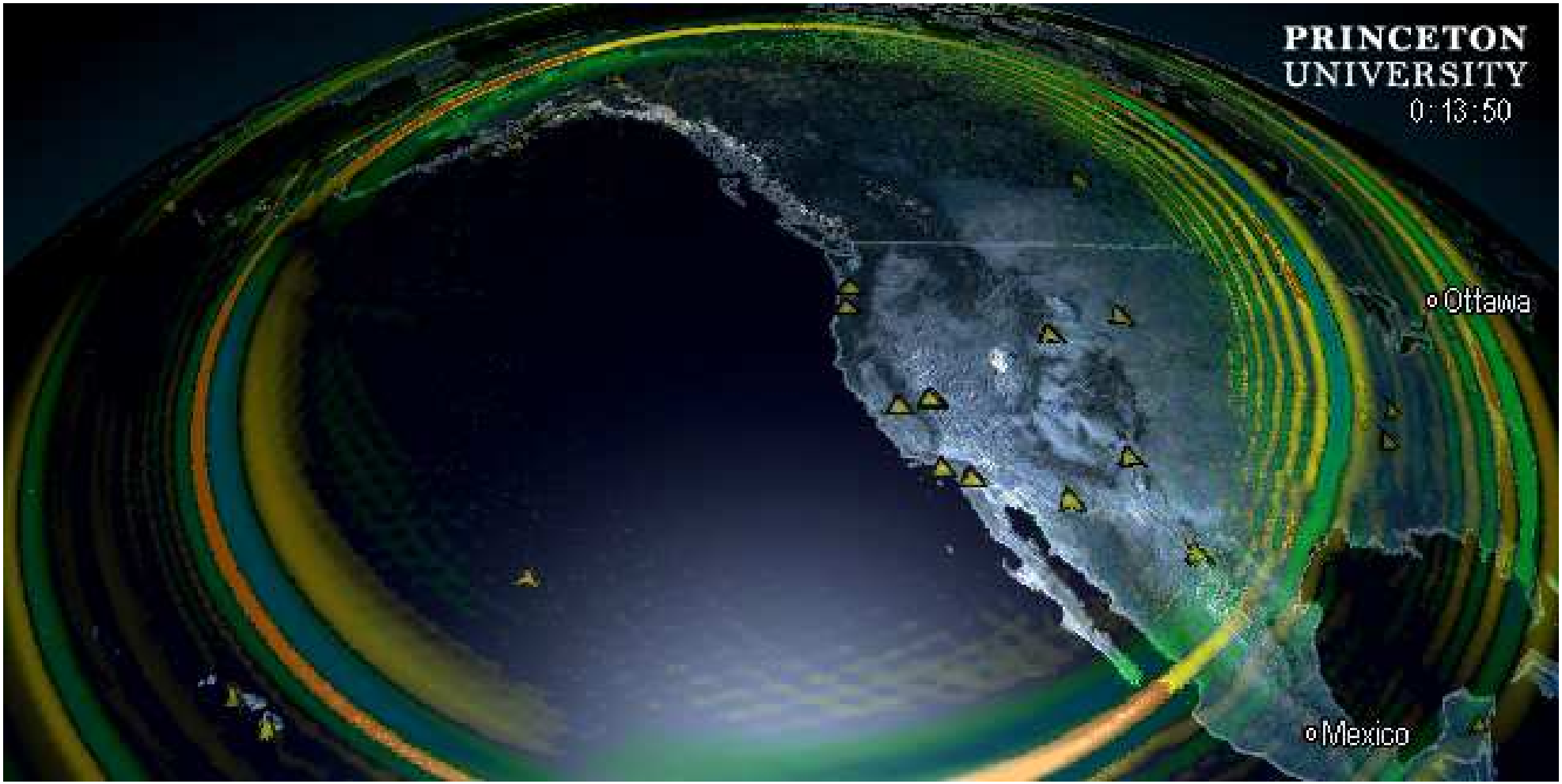
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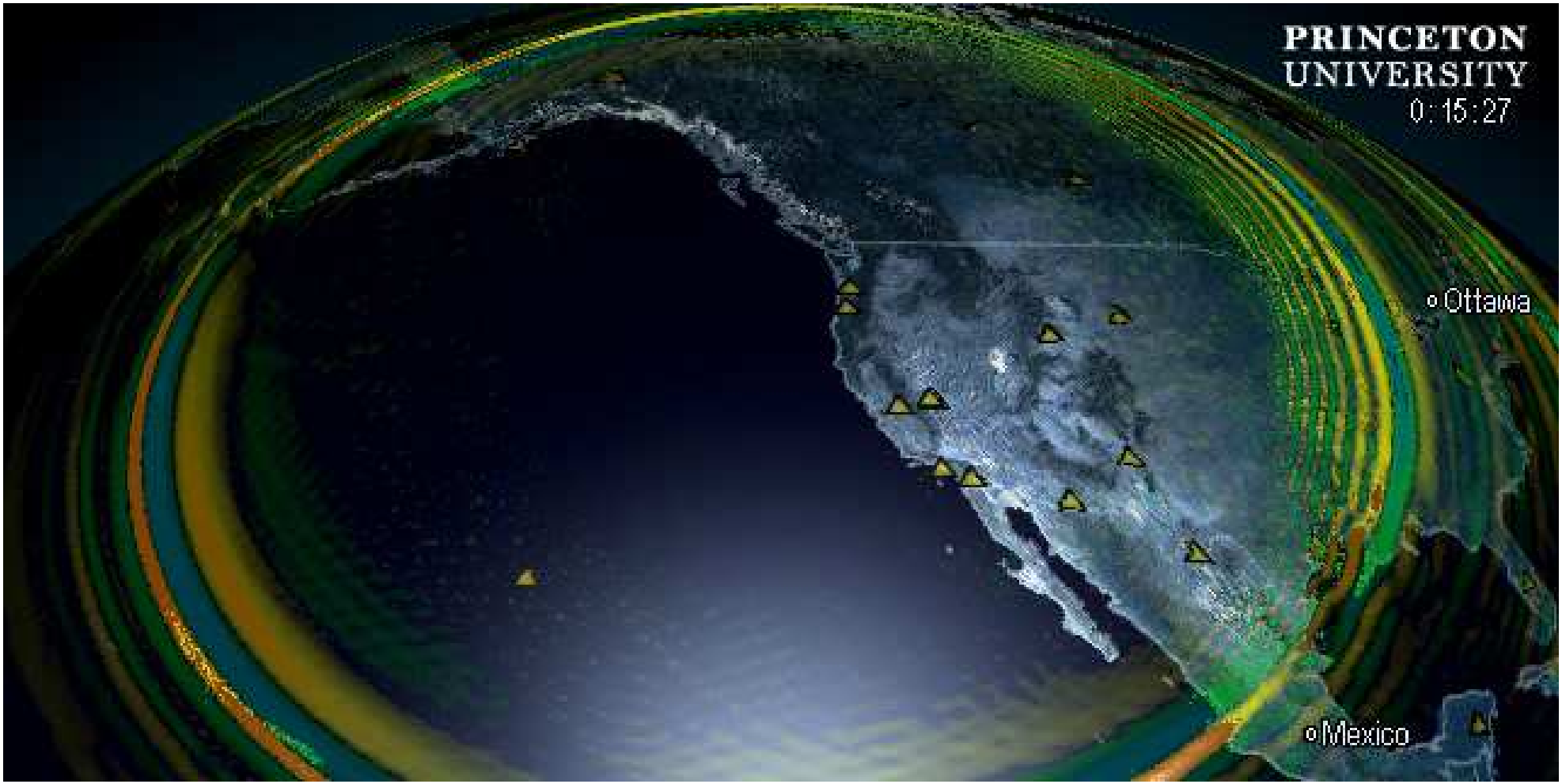
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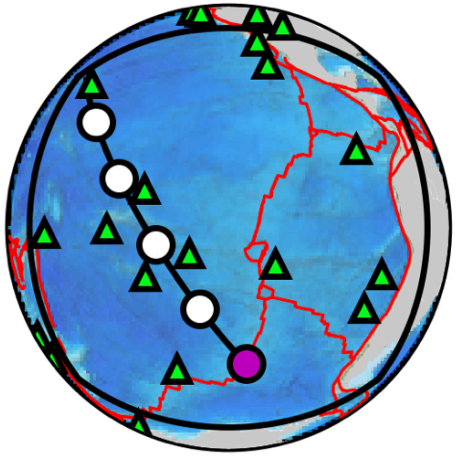
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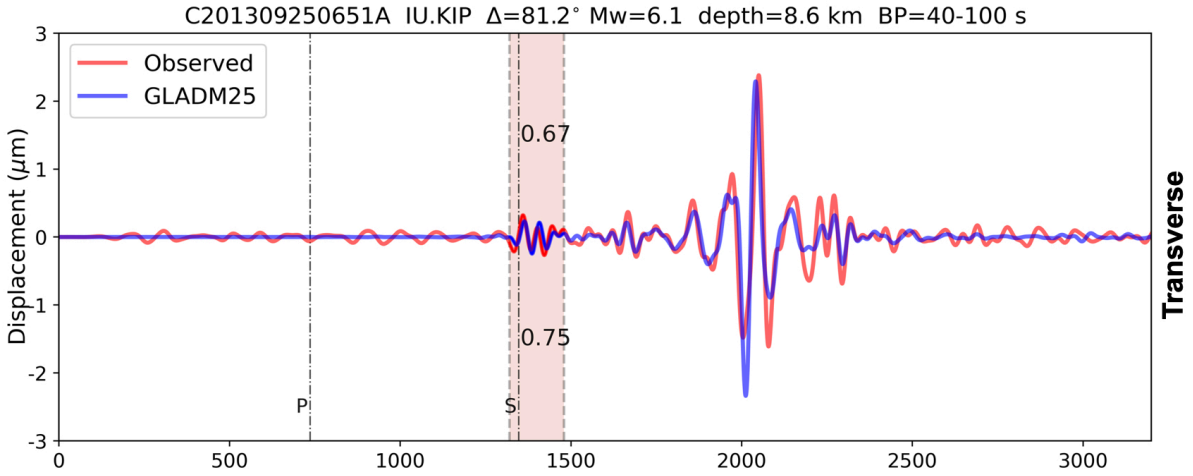


Forward modeling using SPECFEM3D_GLOBE

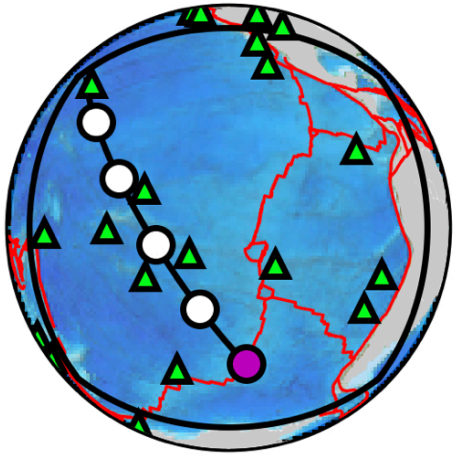


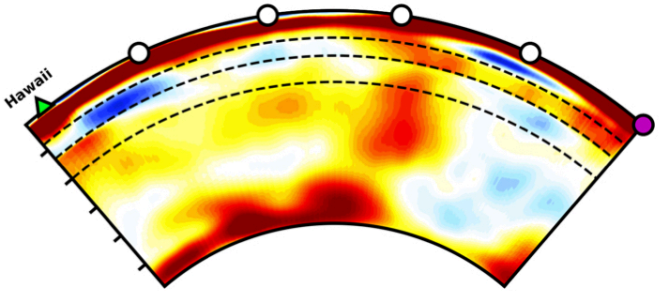
Observations vs Reference synthetics

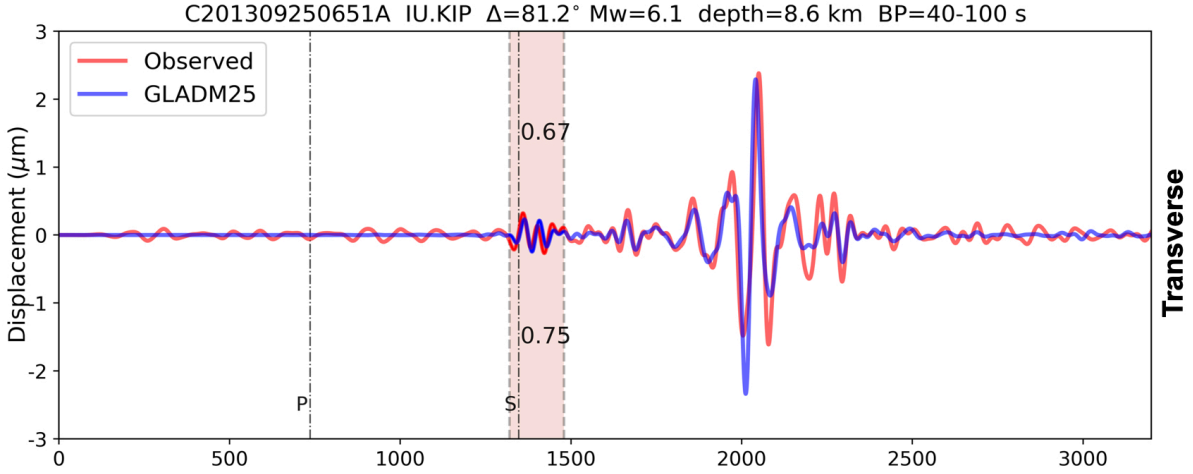


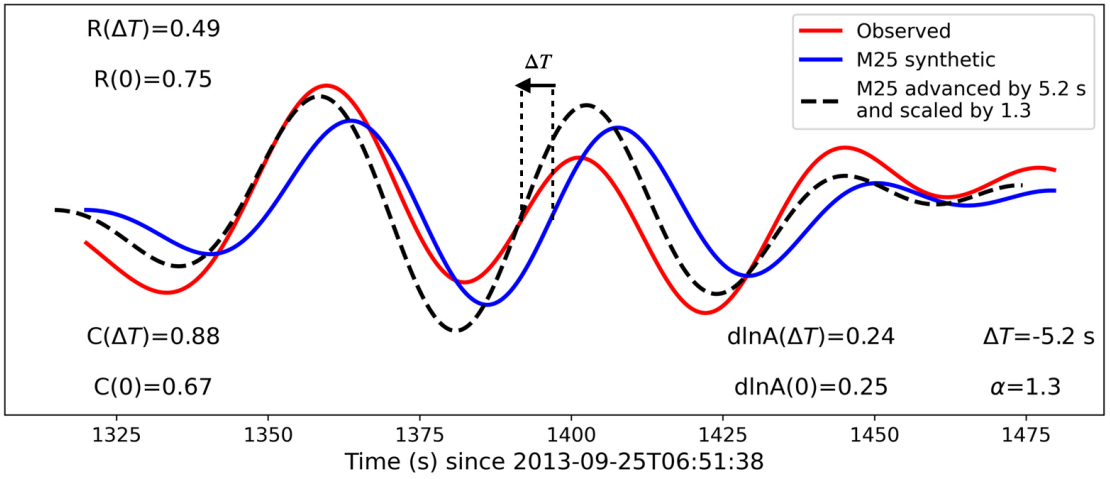


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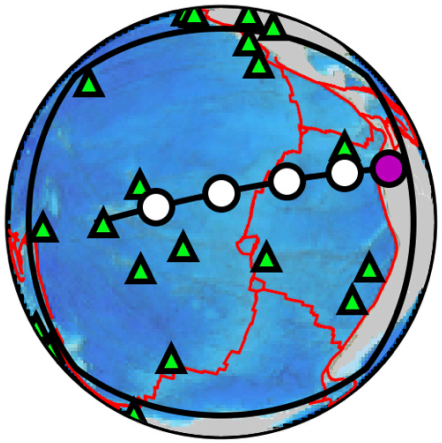


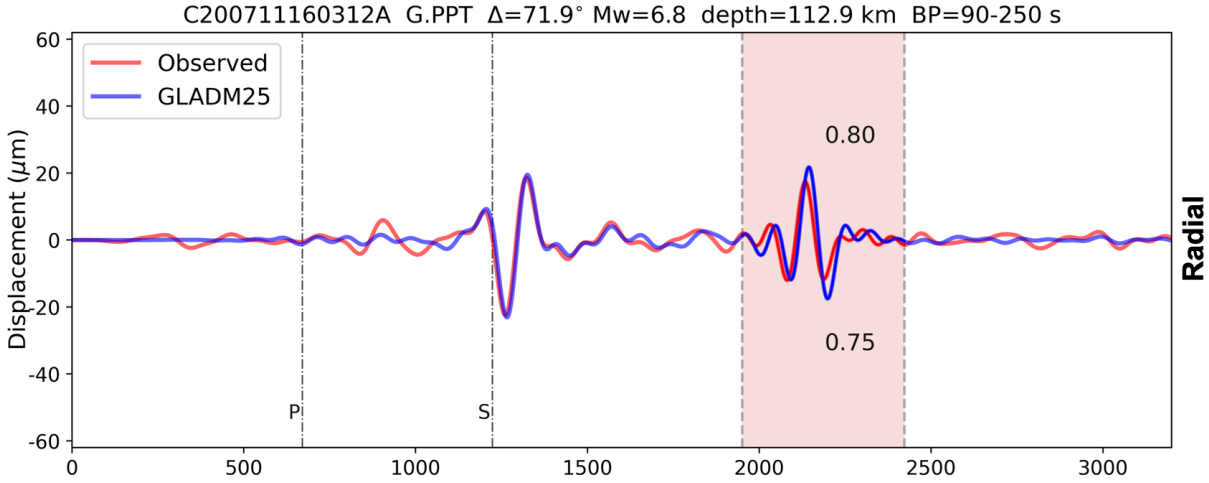




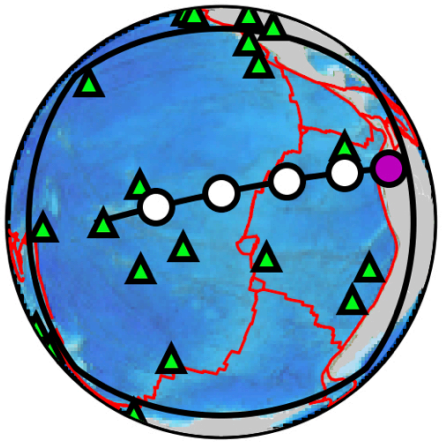


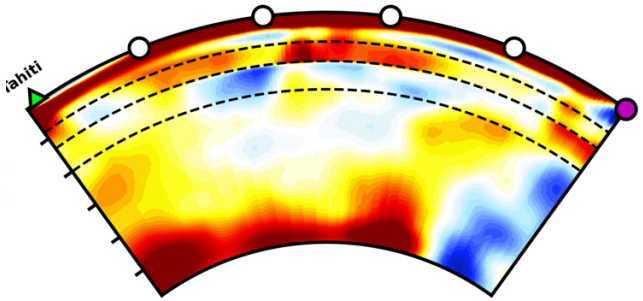
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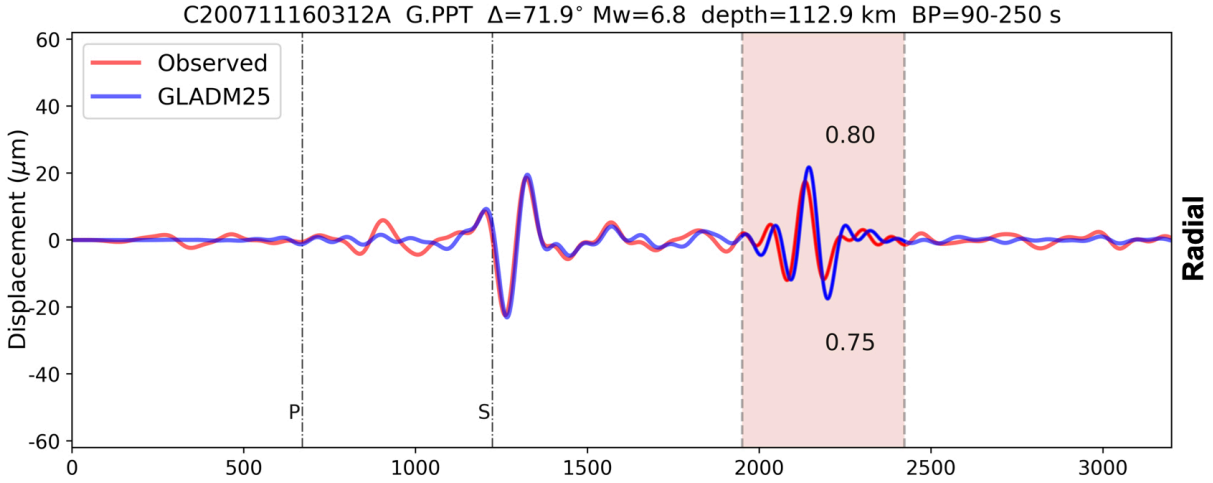


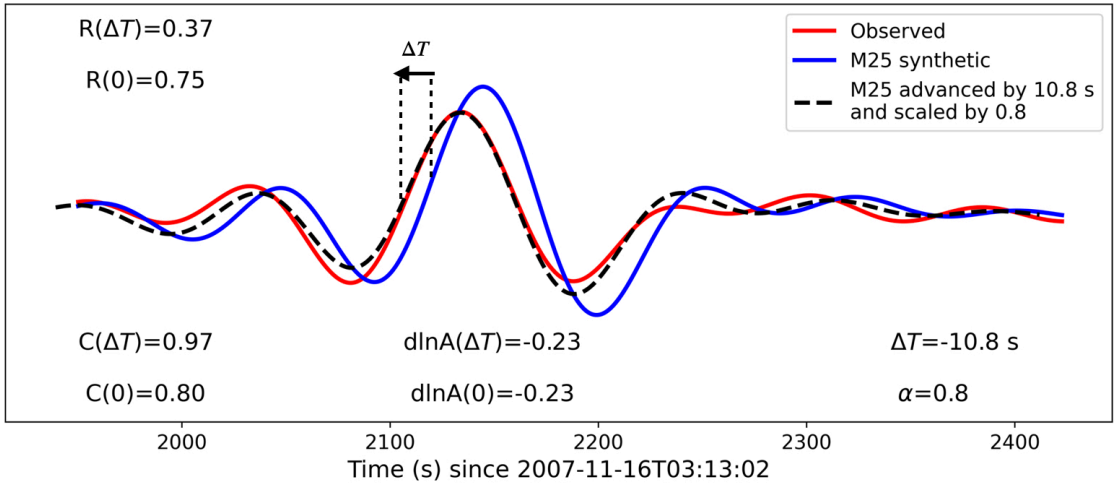


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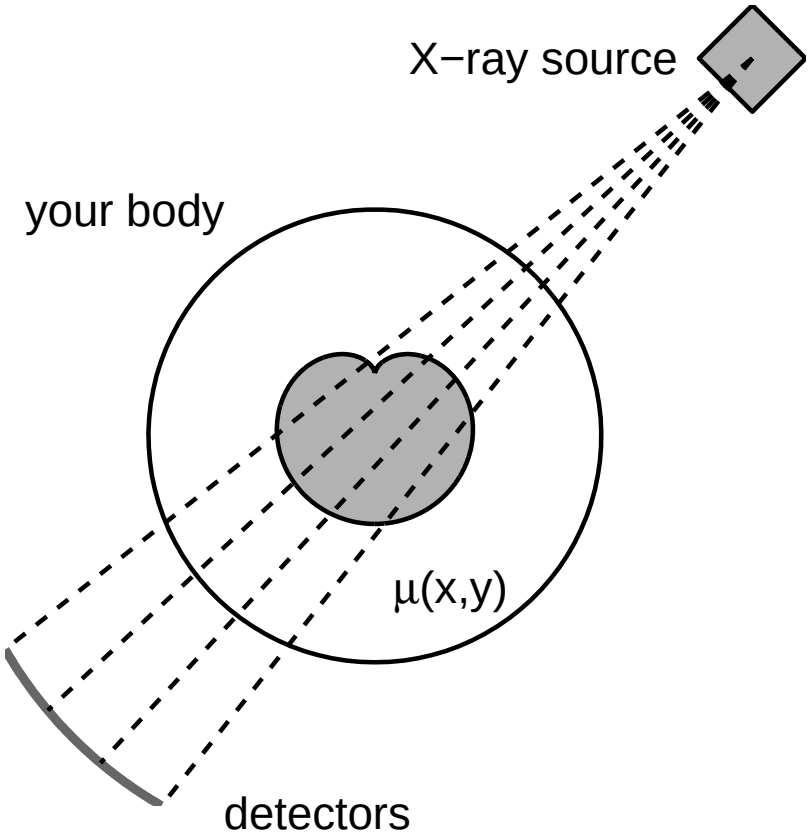




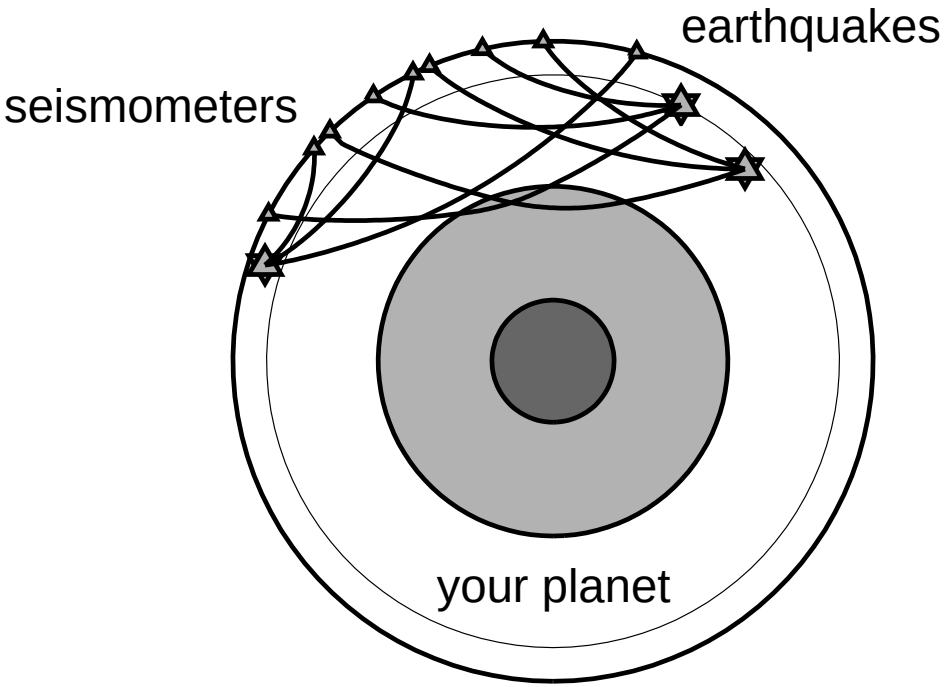


Inverse Modeling: Tomography

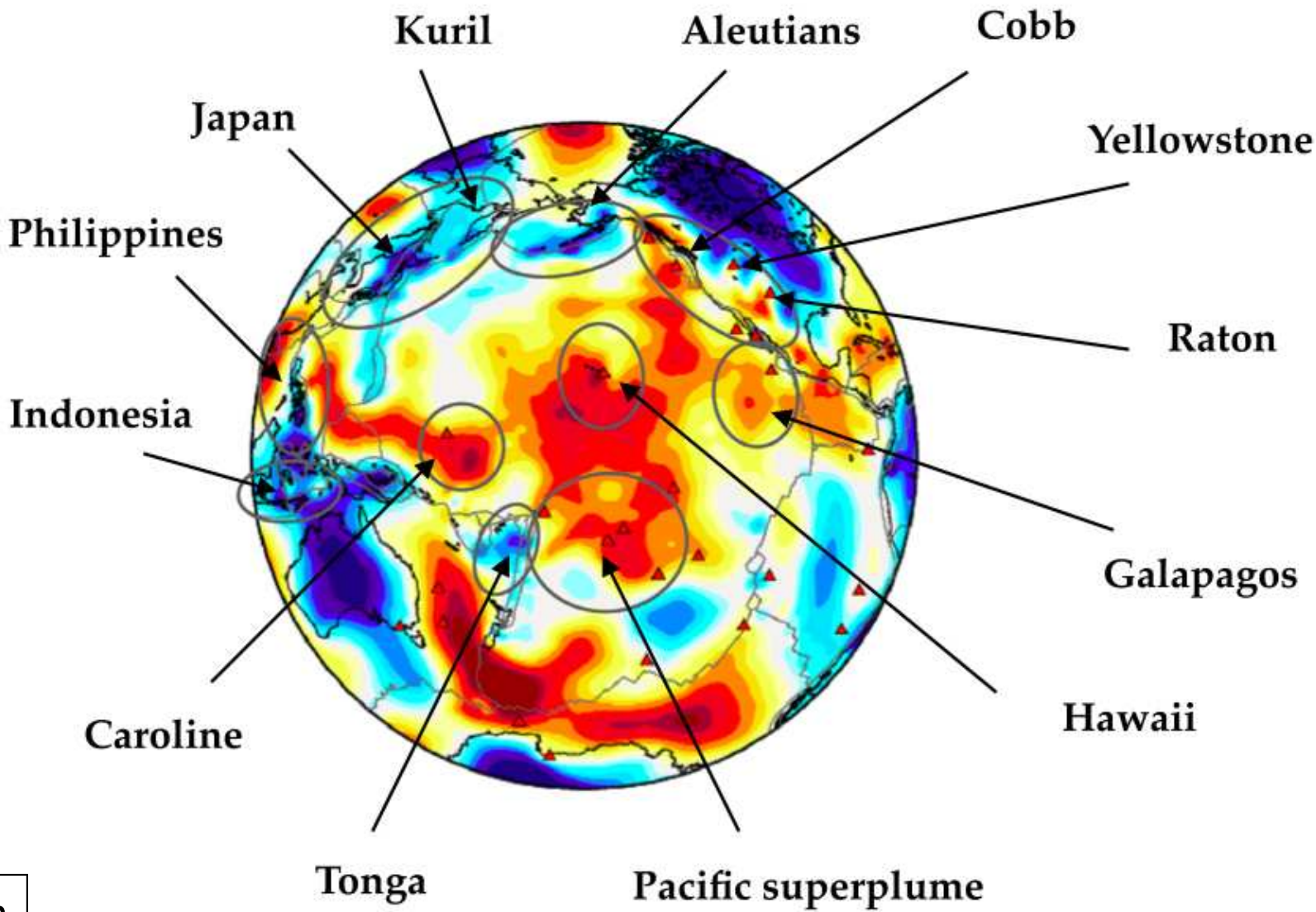
X-rays



elastic waves

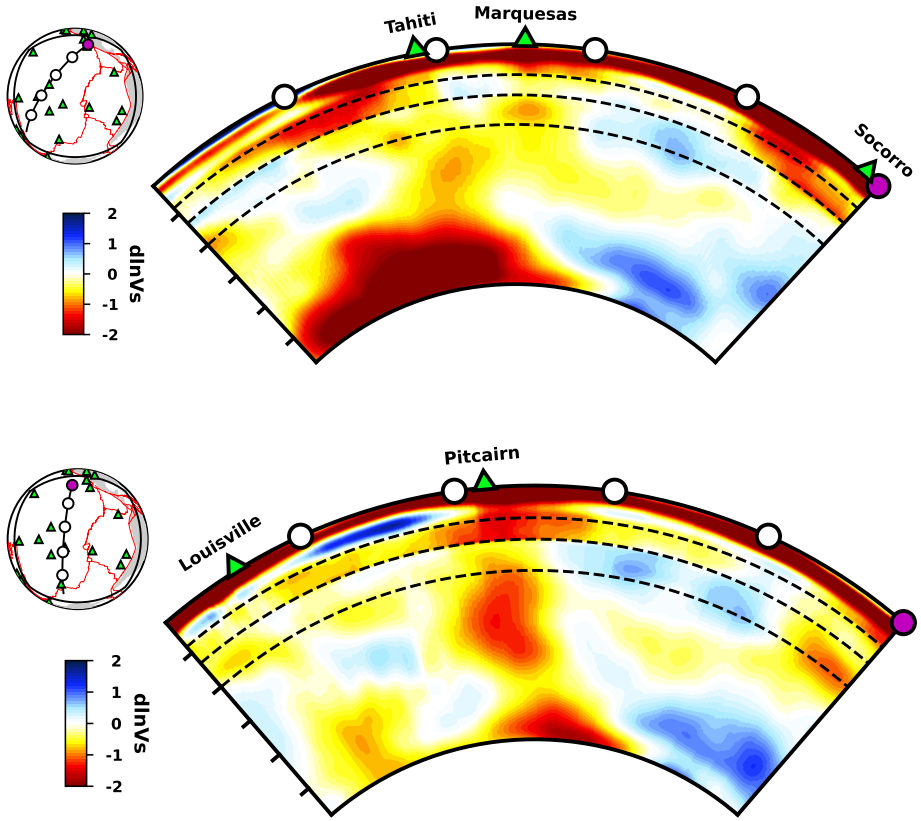


The Mantle: *Plumes — I*



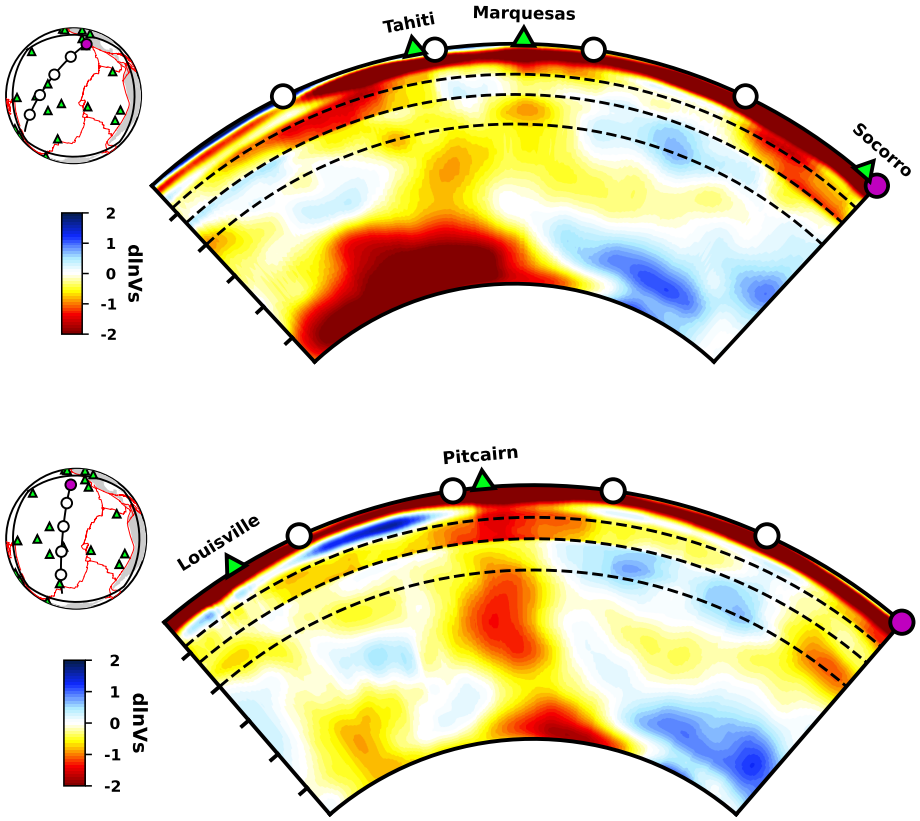
Bozdağ et al., *GJI*, 2016

The Mantle: *Plumes — II*

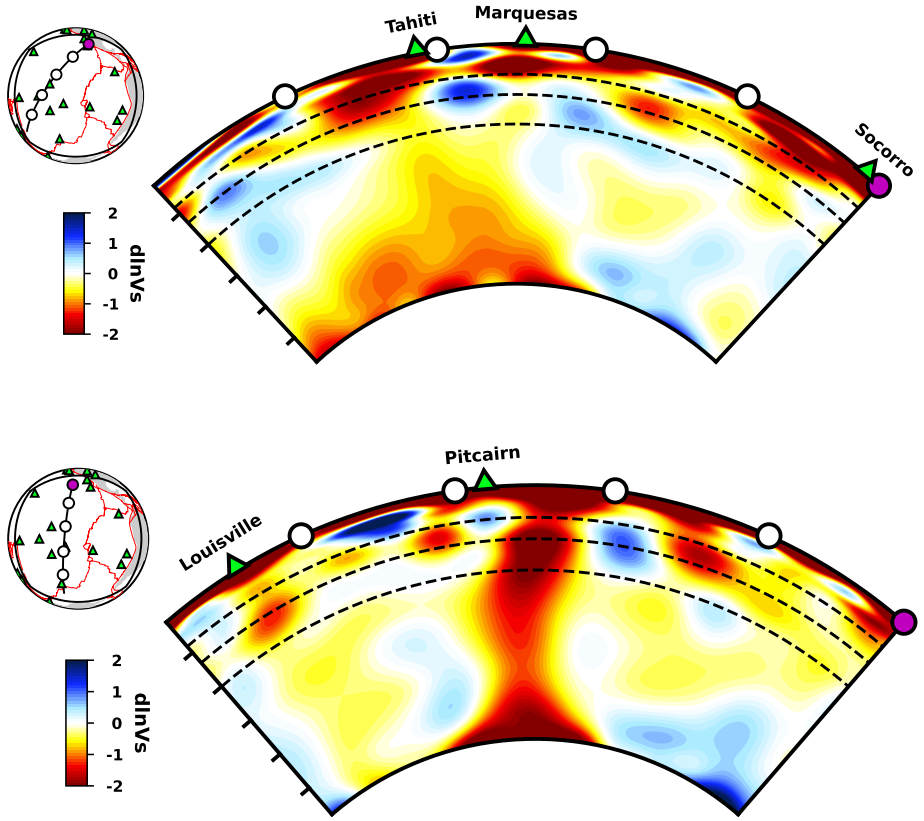


GLAD-M25

The Mantle: *Plumes — II*

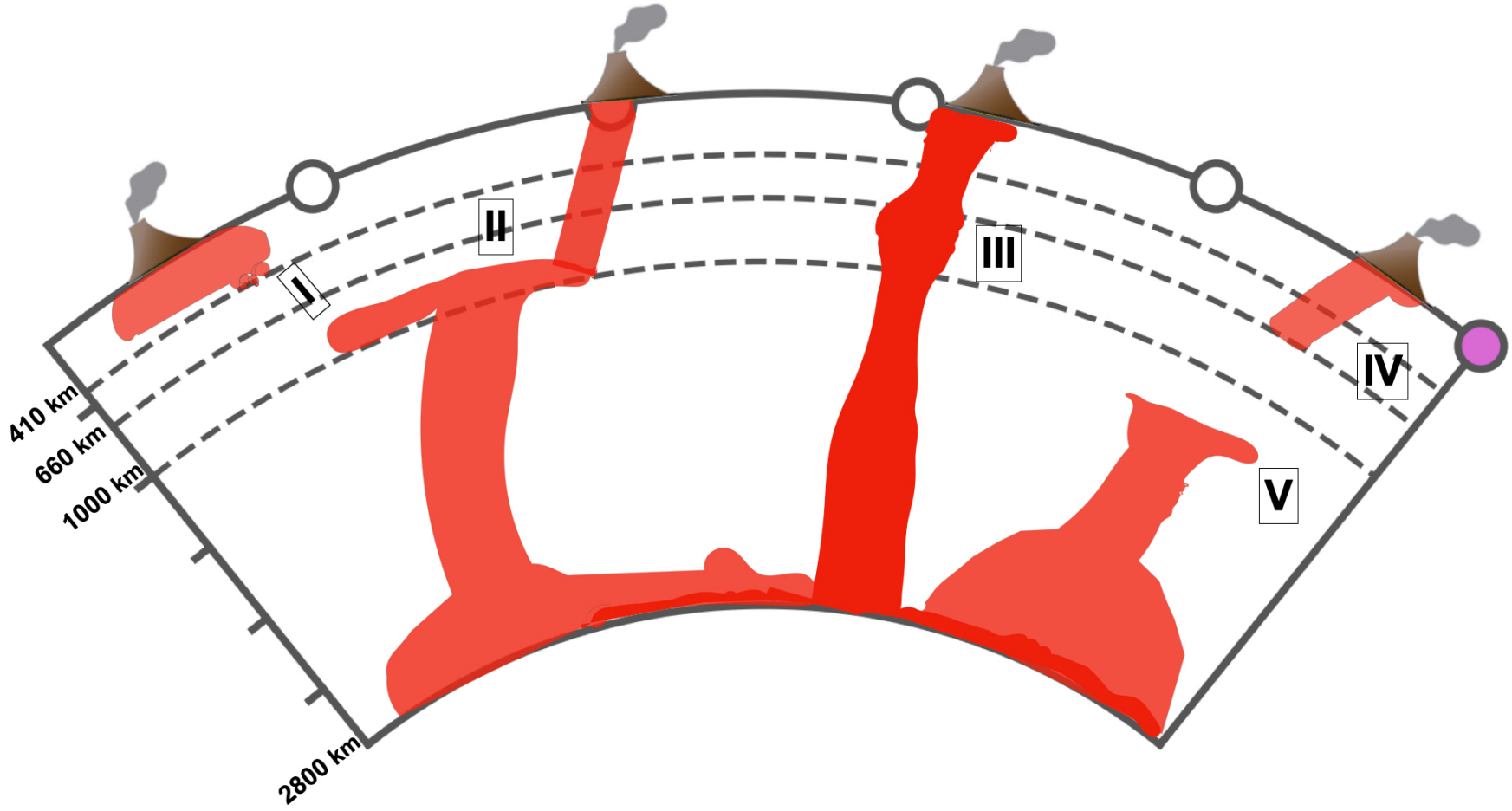


GLAD-M25



SEMUCB-WM1

The Mantle: *Plumes — II*



Wamba, Simons & Irving, *GJI*, 2025

(Part of) The Problem

Never enough earthquakes...

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Definitely not enough seismometers!

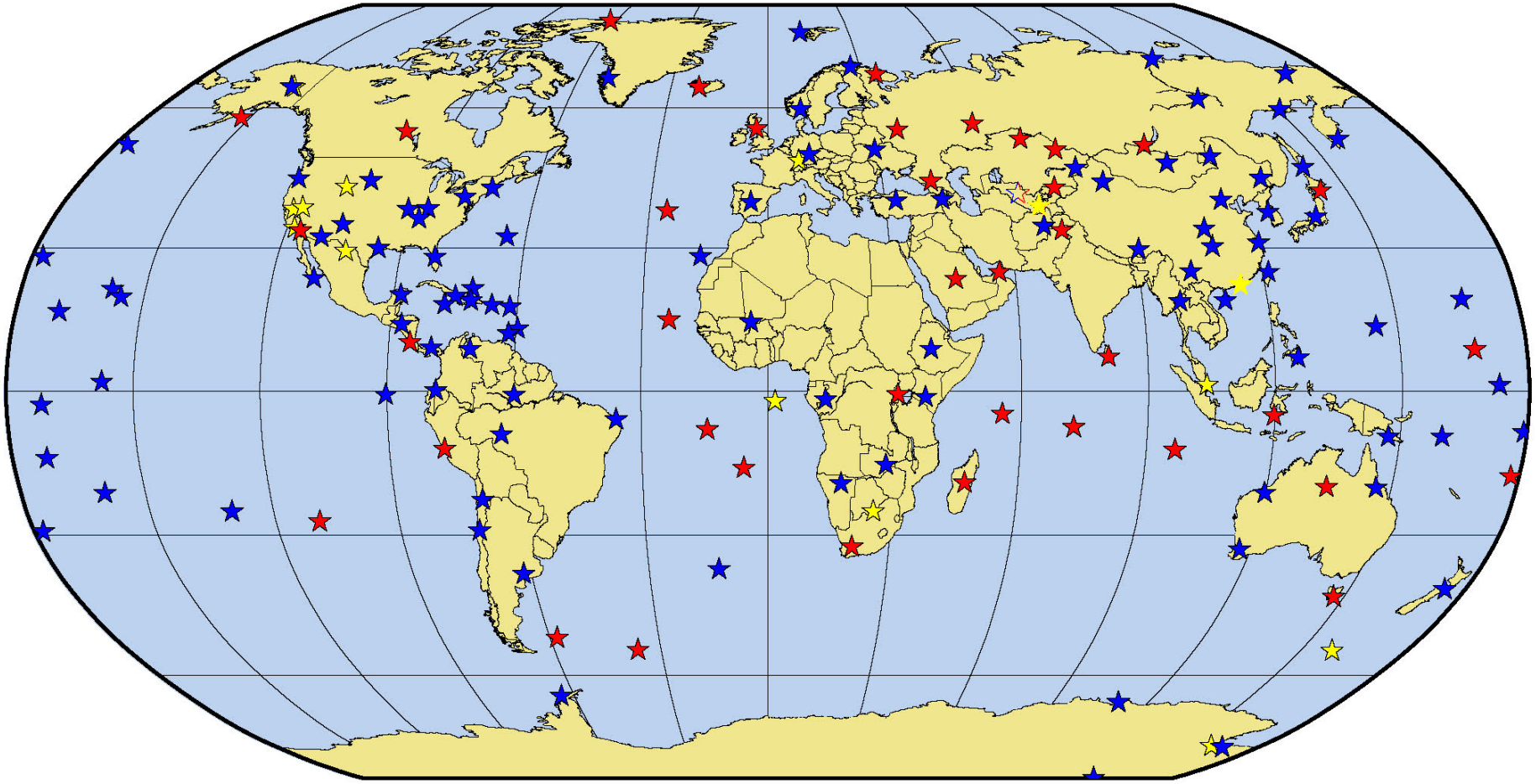
(Part of) The Problem

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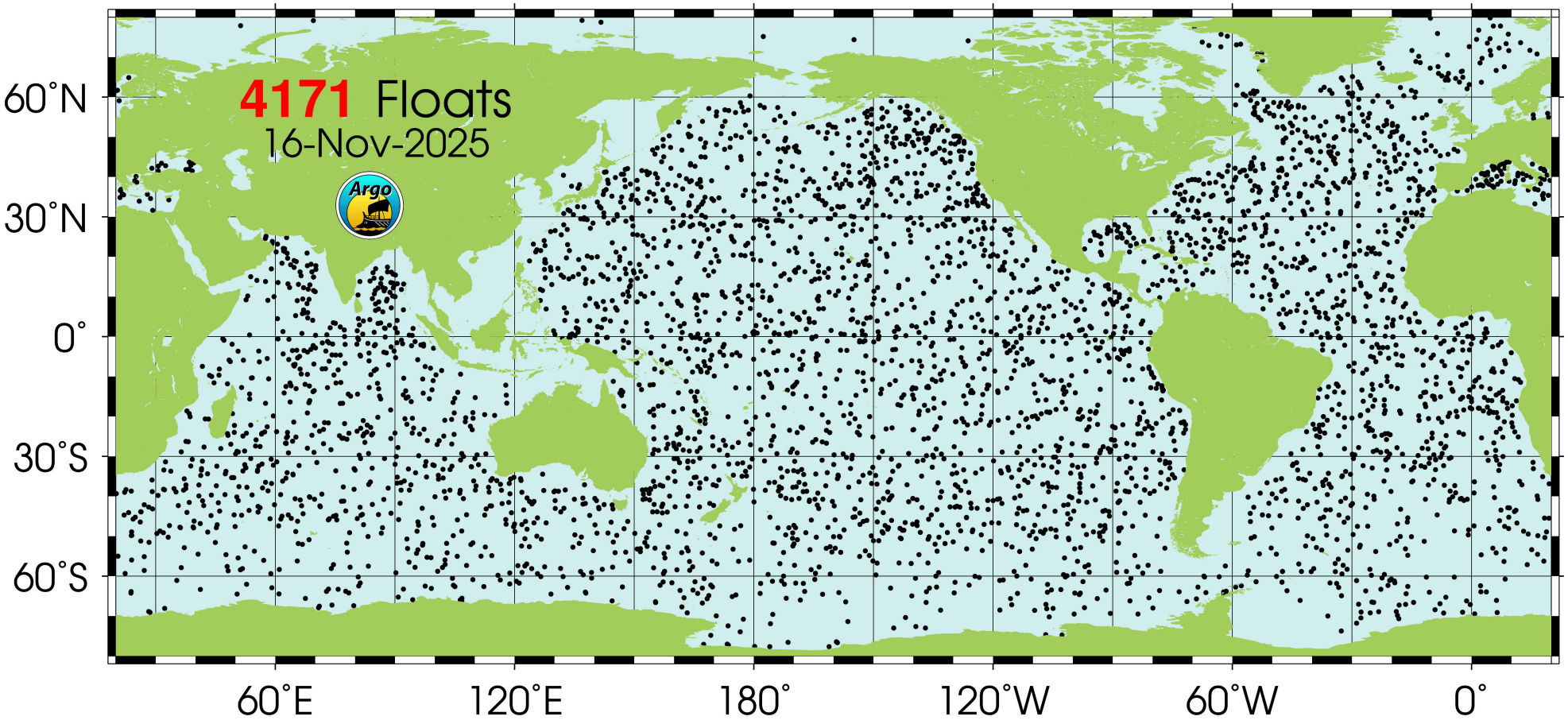
Definitely not enough seismometers!

Fuzzy images, especially of plumes.

Seismology and the World's oceans



Oceanography and the World's oceans



Can we build *anything* resembling ARGO for seismology?

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To record *teleseismic* earthquakes

suitable for *mantle* tomography?

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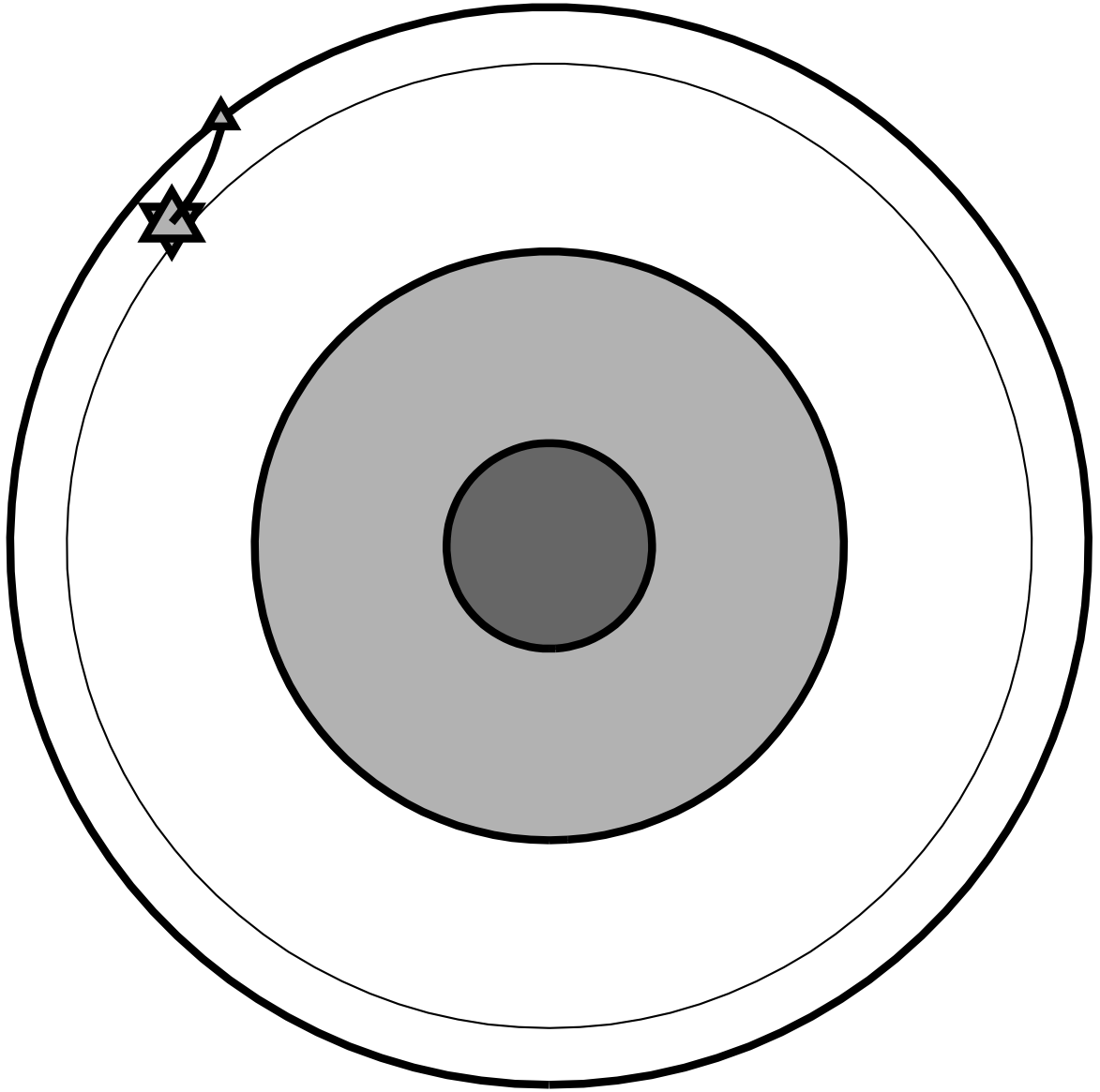
To record *teleseismic* earthquakes

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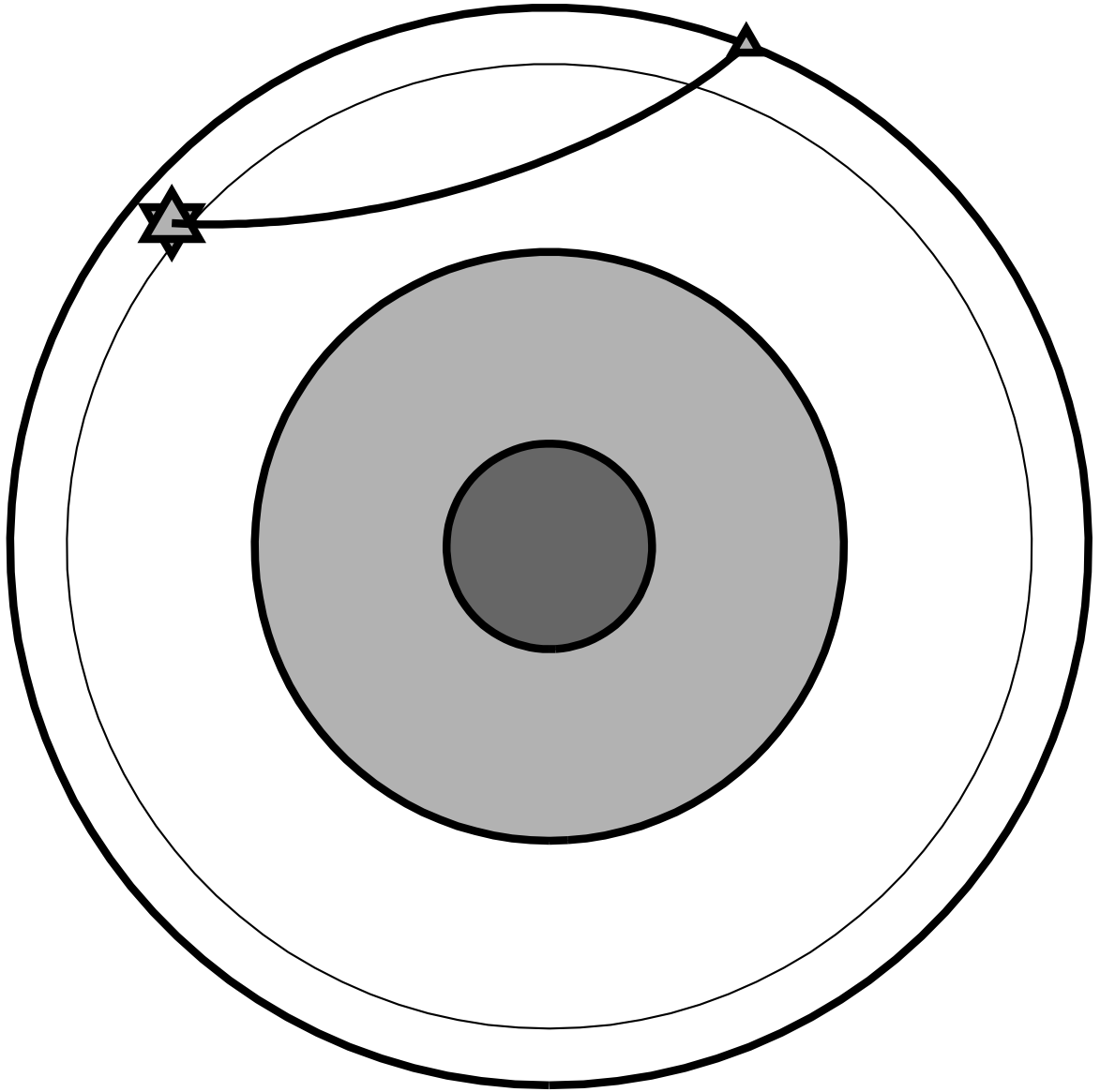
MERMAID = Mobile Earthquake Recording

in Marine Areas by Independent Divers

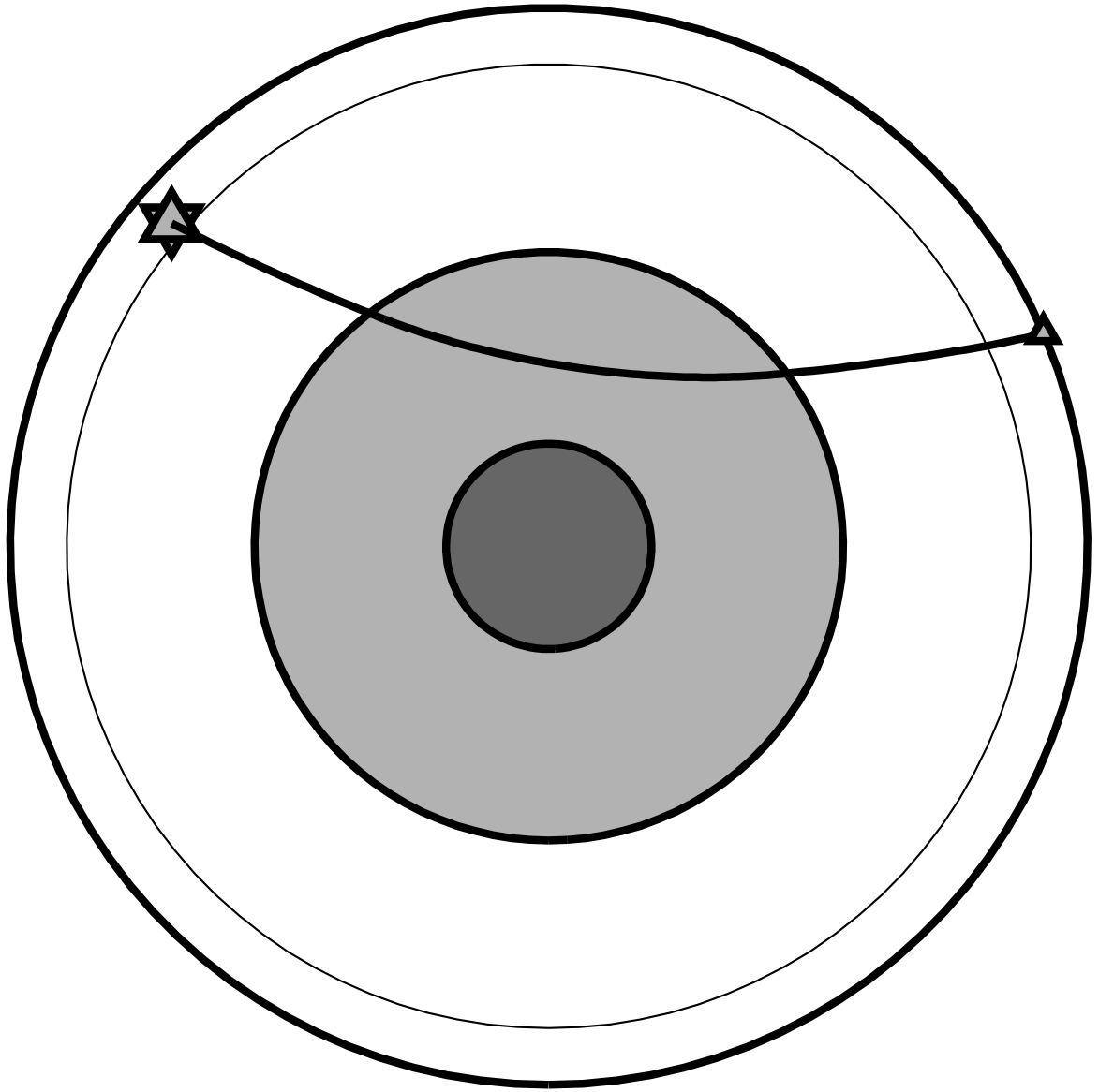
Local phases



Teleseismic phases

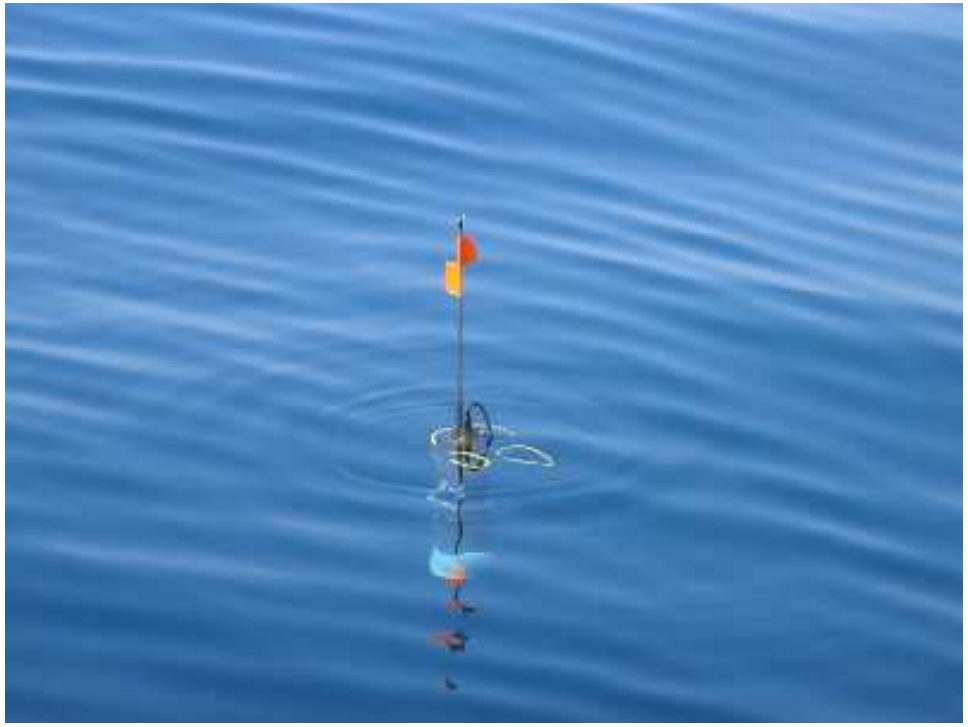


Core phases

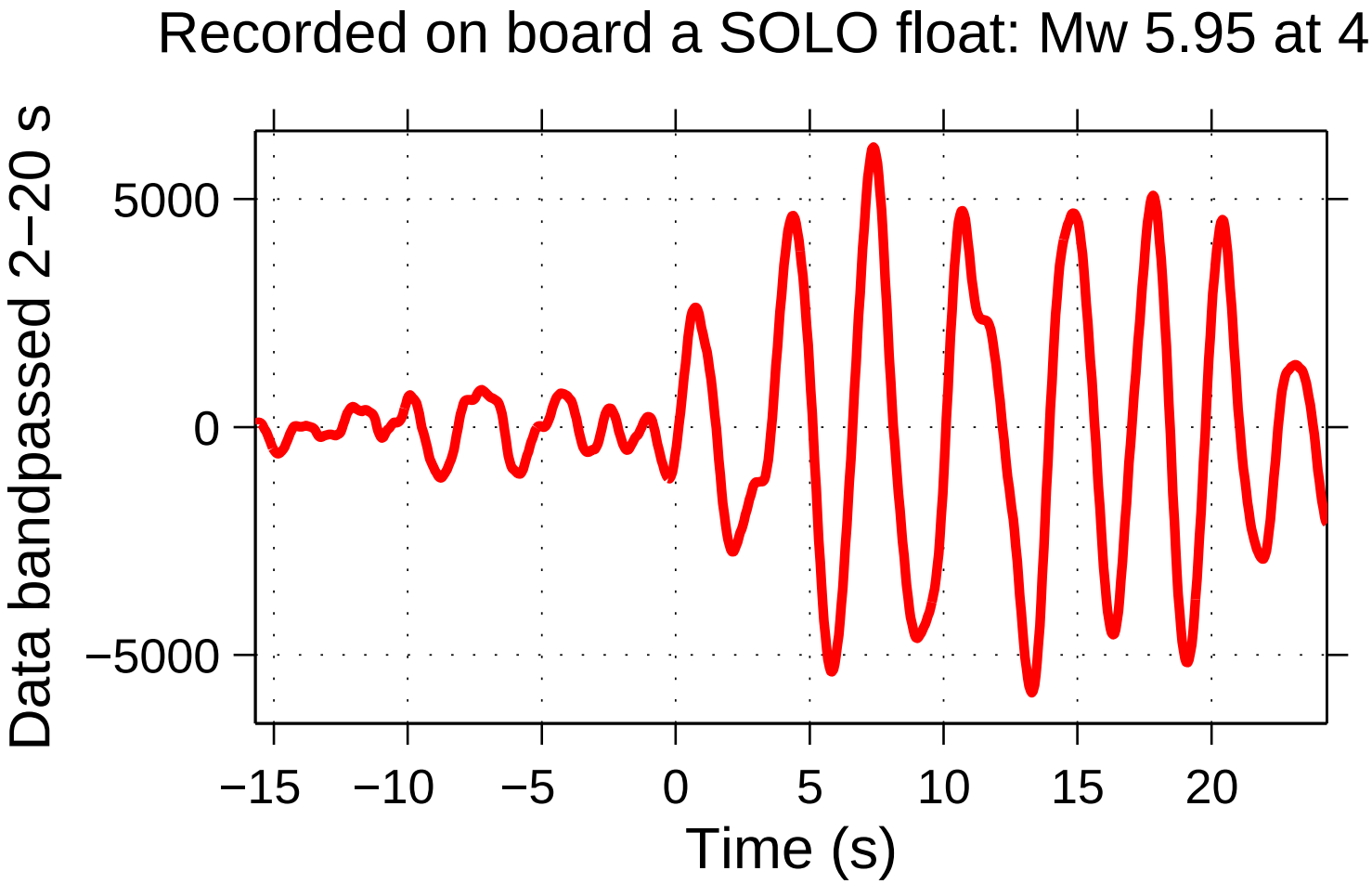


MERMAID I

(2003–2012)



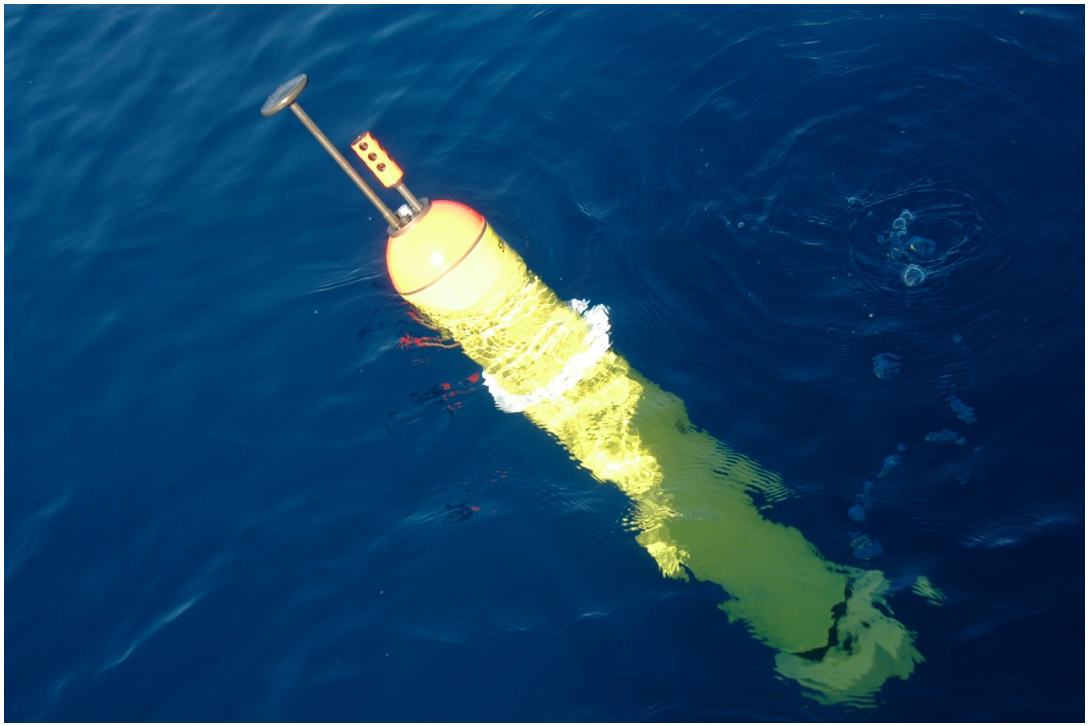
MERMAID-001: *One* teleseismic event

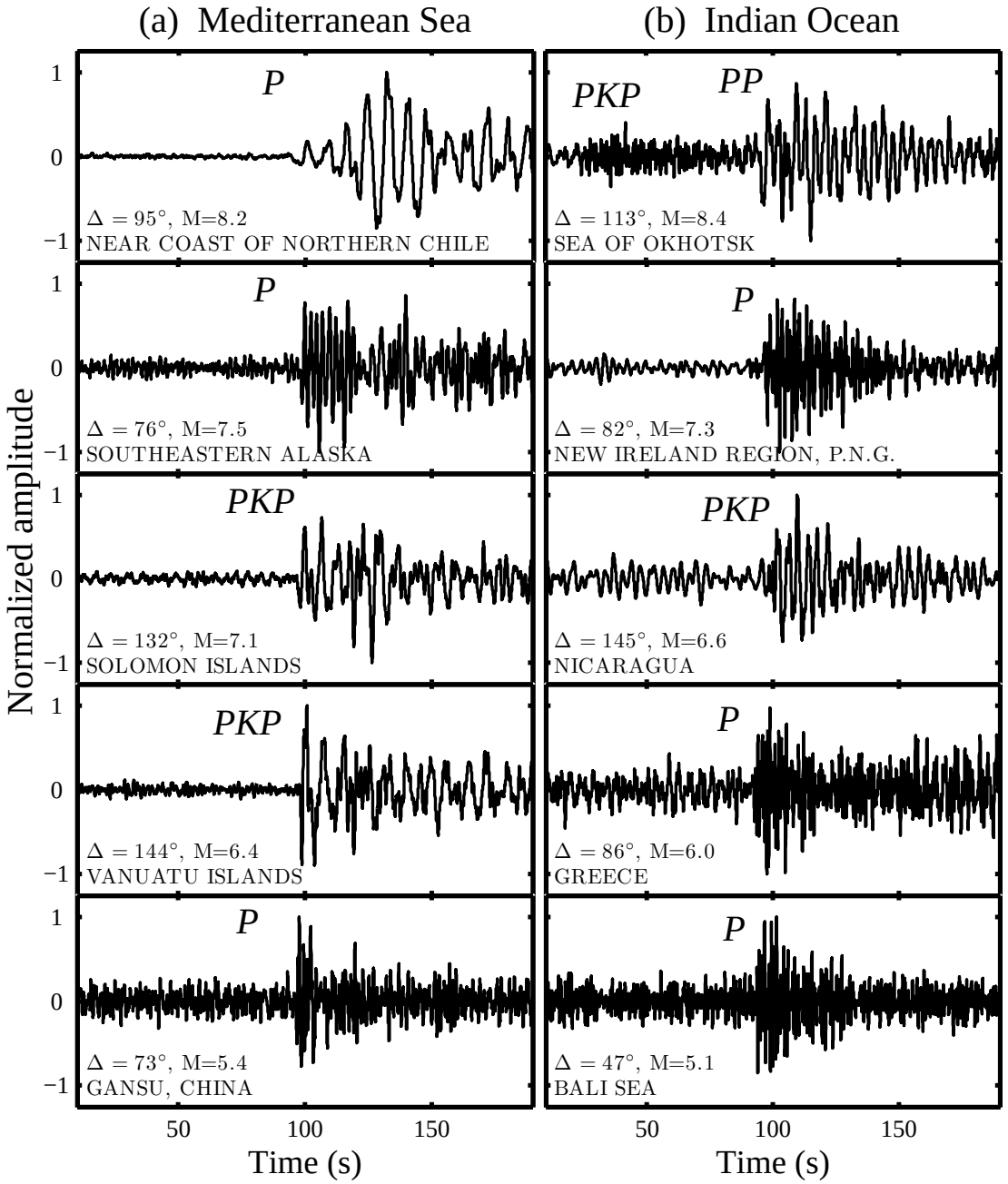


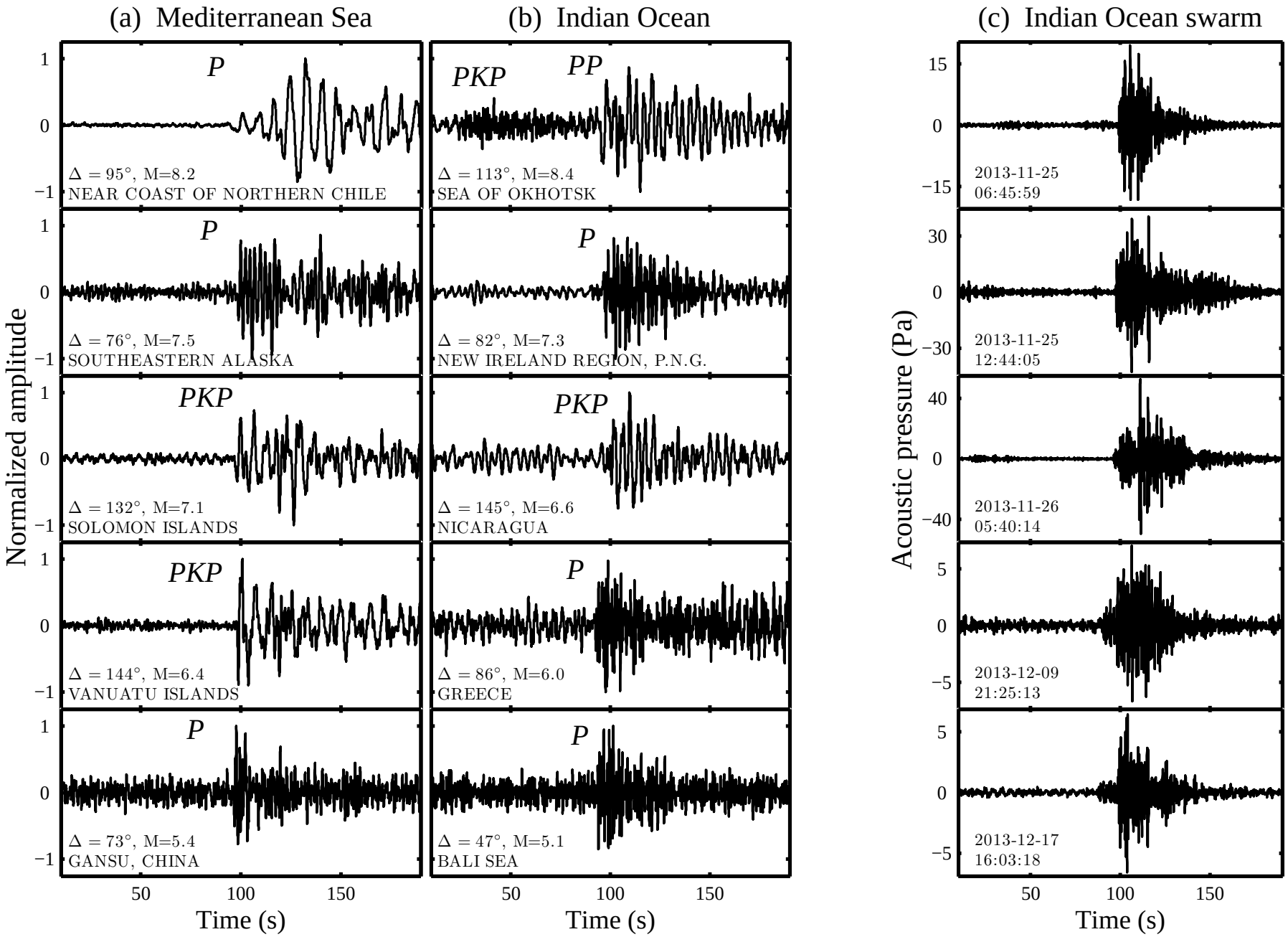
Simons et al., *EOS*, 2006

MERMAID II

(2012–2016)

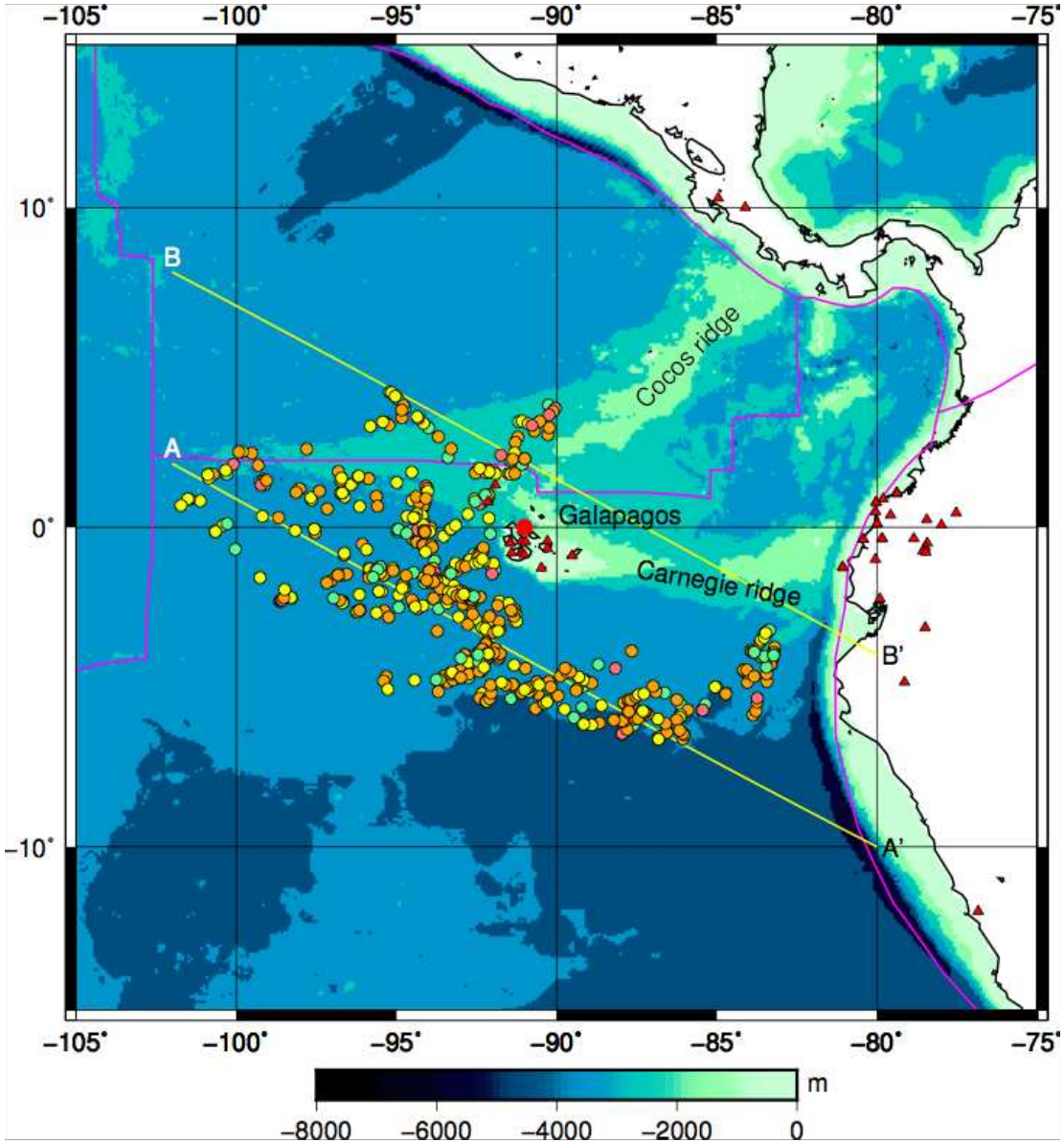



(a) Mediterranean Sea
(b) Indian Ocean
Normalized amplitude
P
PKP
PP
Δ = 95°, M=8.2
NEAR COAST OF NORTHERN CHILE
Δ = 113°, M=8.4
SEA OF OKHOTSK
Δ = 76°, M=7.5
SOUTHEASTERN ALASKA
Δ = 82°, M=7.3
NEW IRELAND REGION, P.N.G.
Δ = 132°, M=7.1
SOLOMON ISLANDS
Δ = 145°, M=6.6
NICARAGUA
Δ = 144°, M=6.4
VANUATU ISLANDS
Δ = 86°, M=6.0
GREECE
Δ = 73°, M=5.4
GANSU, CHINA
Δ = 47°, M=5.1
BALI SEA
1
0
−1
50
100
150
Time (s)



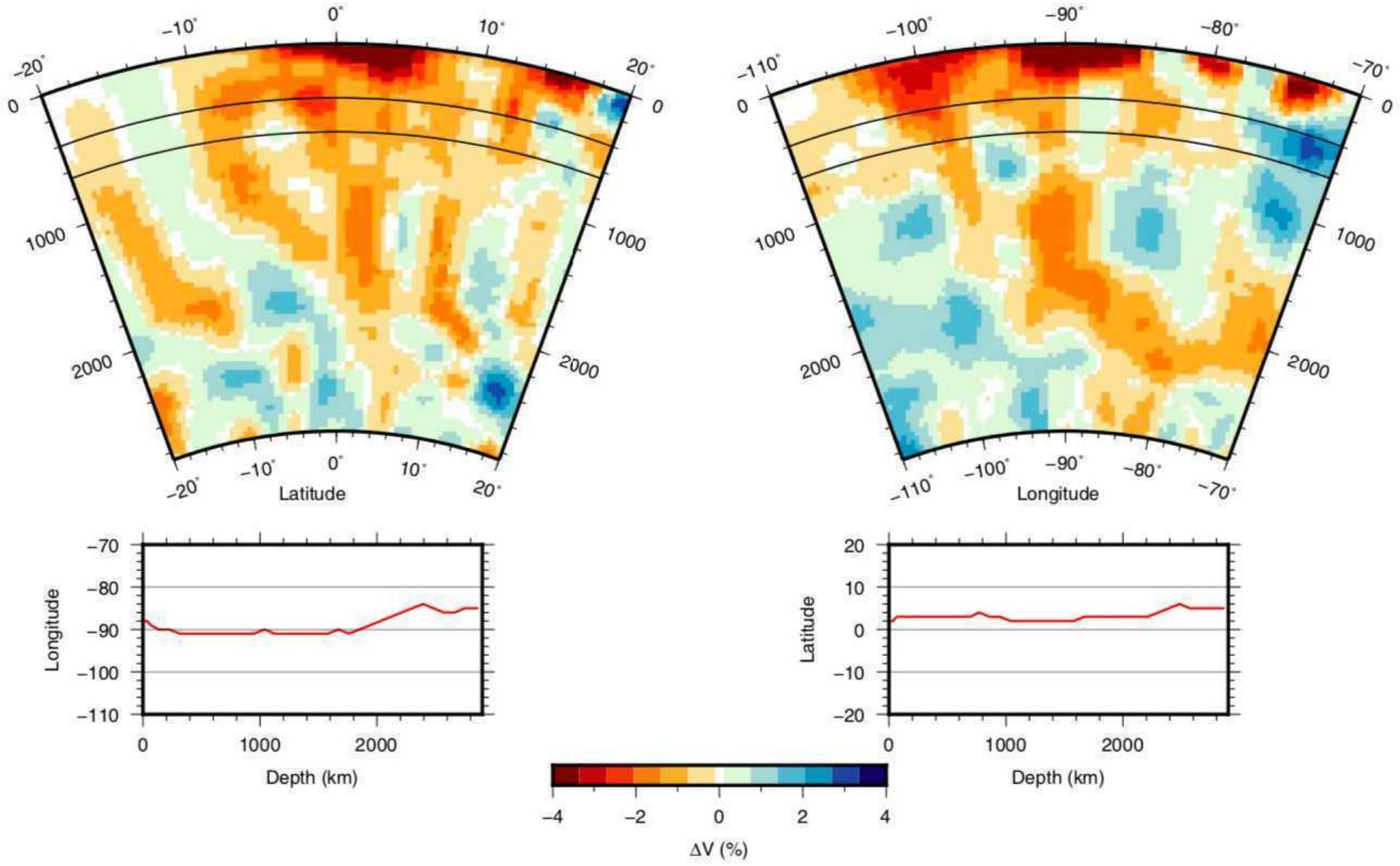
Sukhovich et al., *Nature Comm.*, 2015

11 little MERMAIDs, 2 short years



Nolet et al., *Scientif. Rep.*, 2019

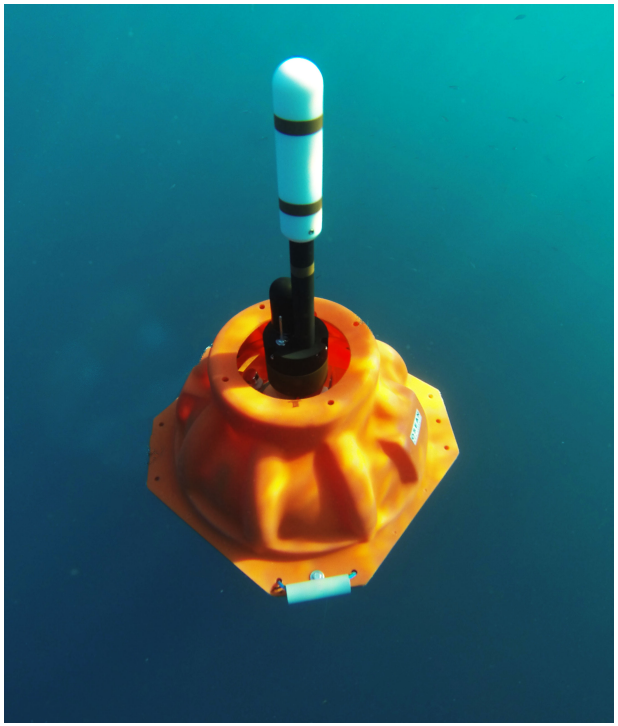
Resolving the Galápagos plume (?)



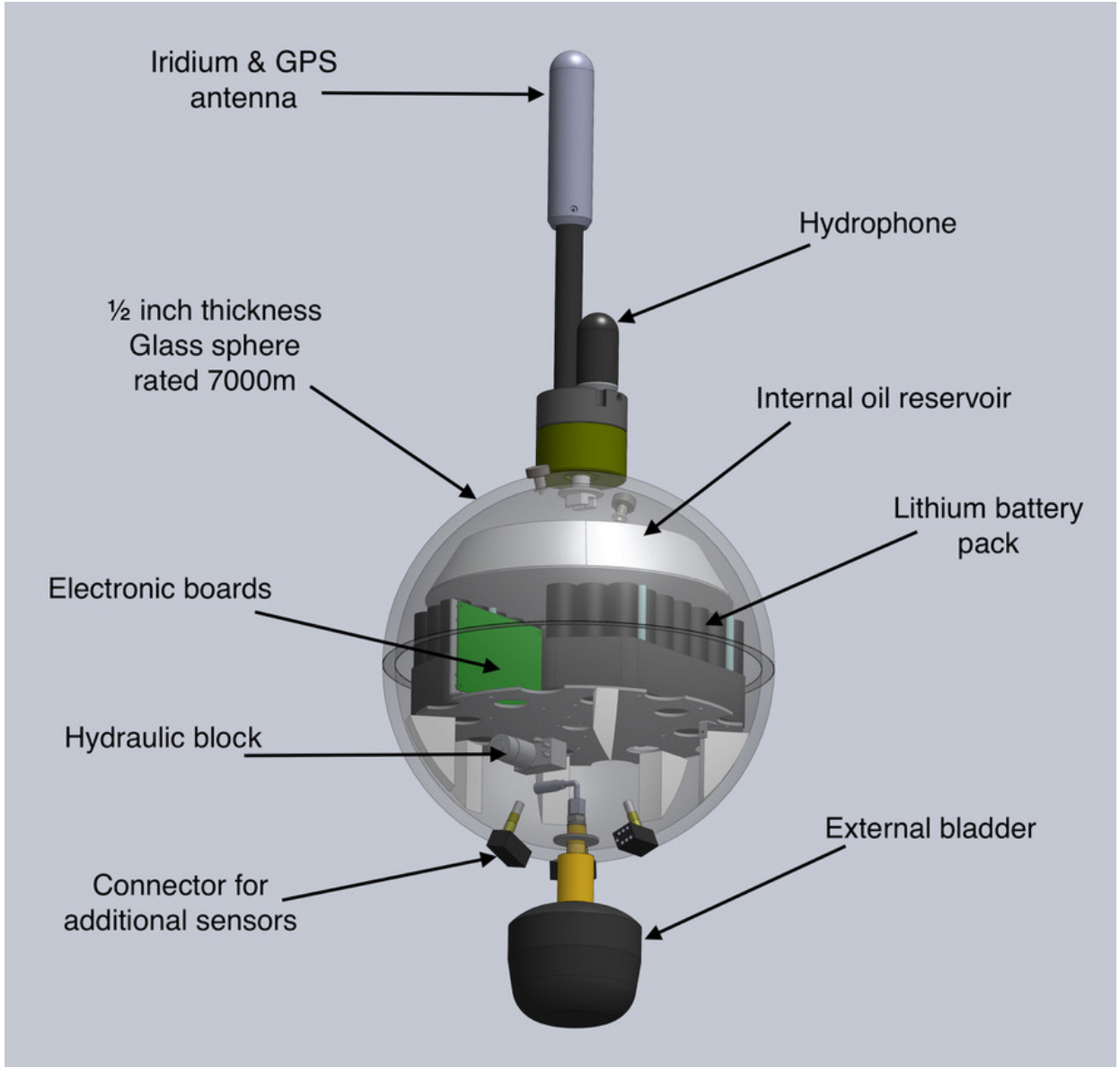
Nolet et al., *Scientif. Rep.*, 2019

MERMAID III

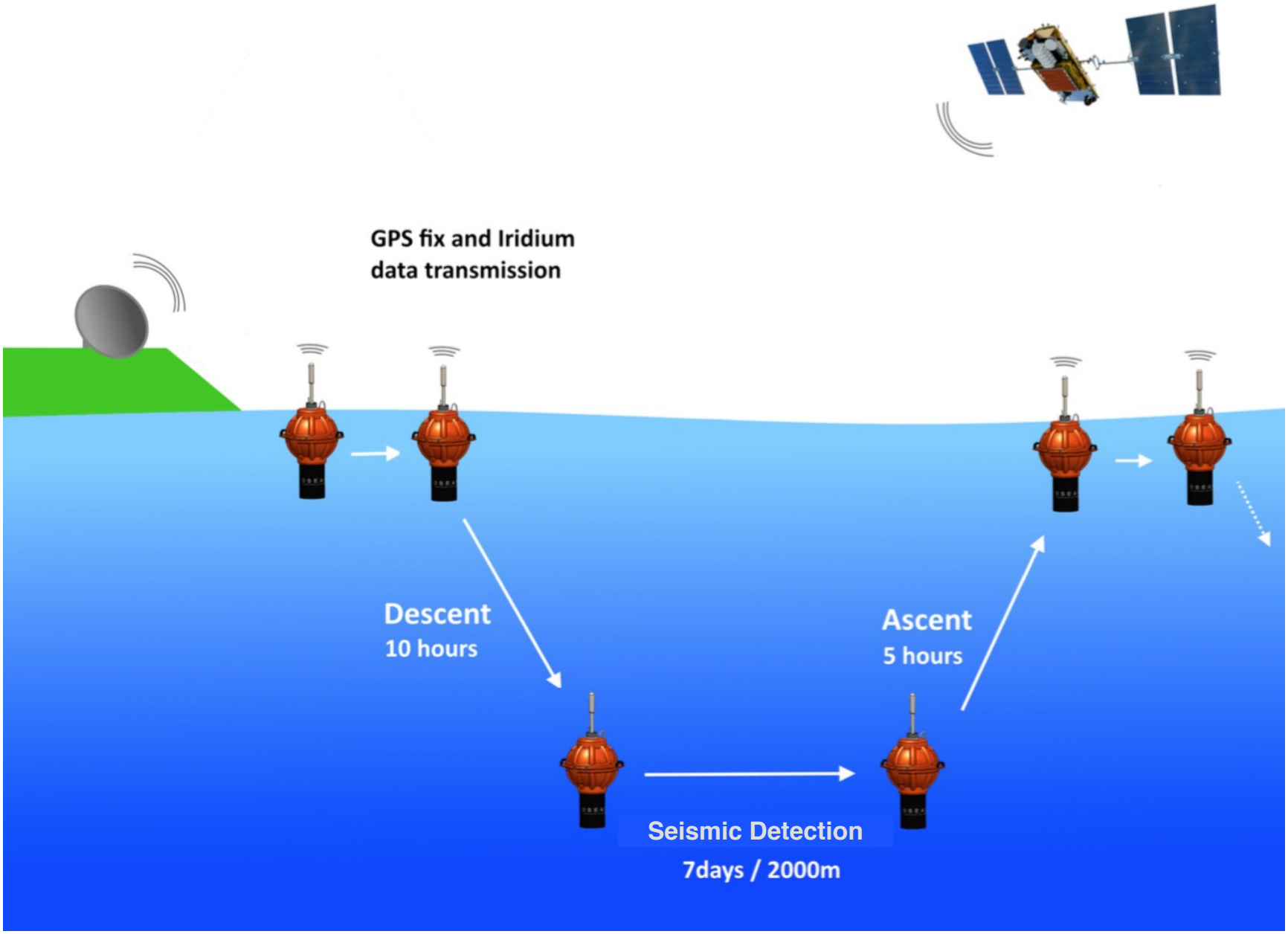
(2016–present)



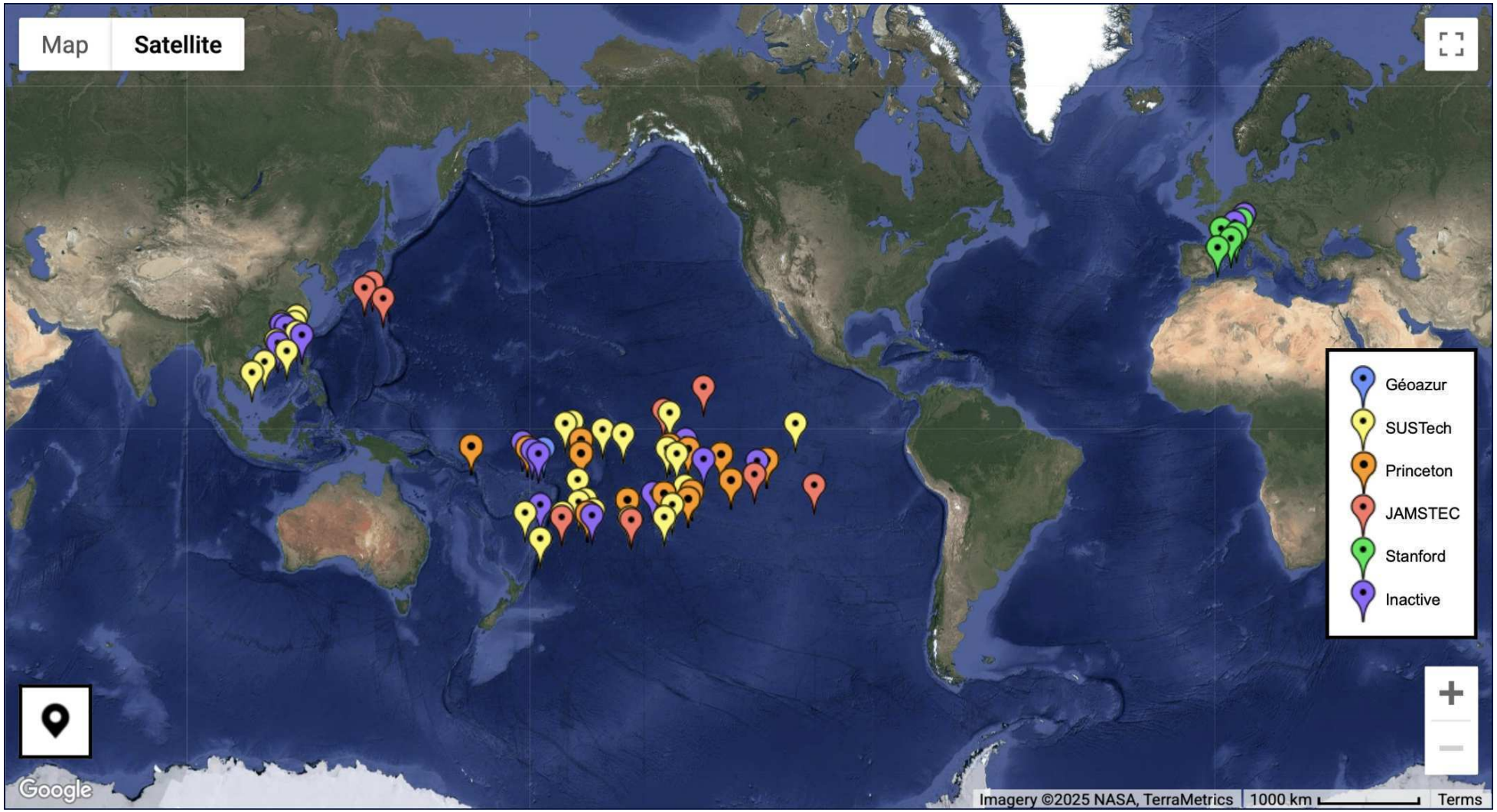
Five years of autonomy, one year of data buffer



Hello & Nolet, *Encycl. Solid Eart Geophys.*, 2020

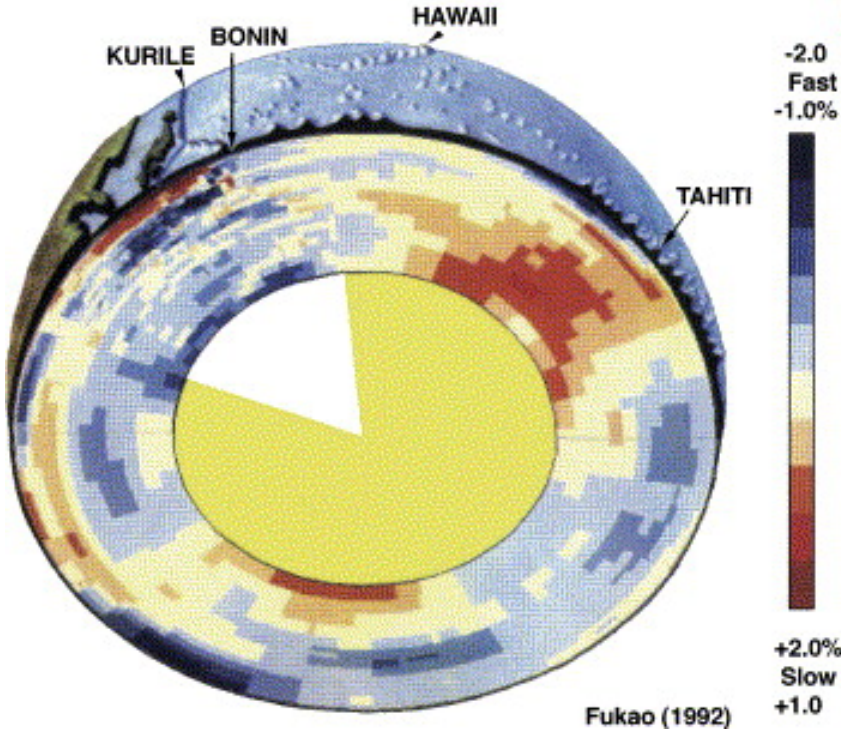

GPS fix and Iridium
data transmission
Descent
10 hours
Ascent
5 hours
Seismic Detection
7days / 2000m

Where is MERMAID?

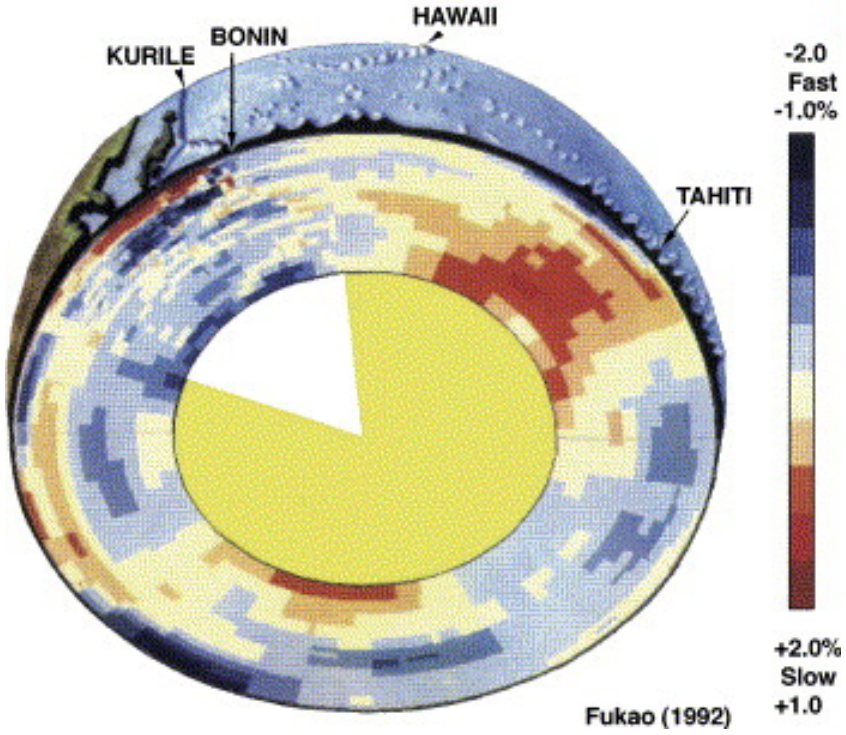


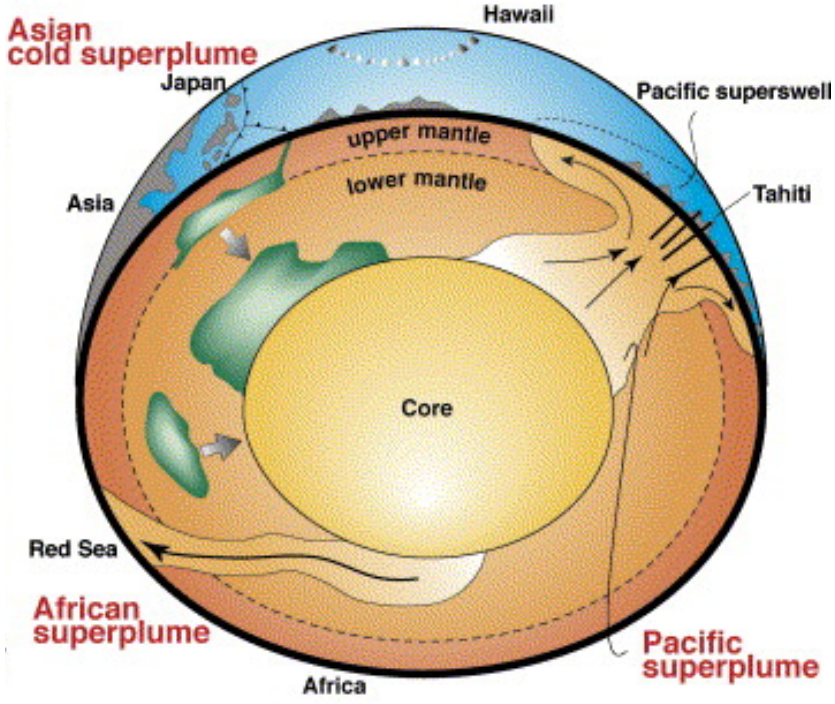





HAWAII
BONIN
KURILE
TAHITI
-2.0
Fast
-1.0%
+2.0%
Slow
+1.0
Fukao (1992)

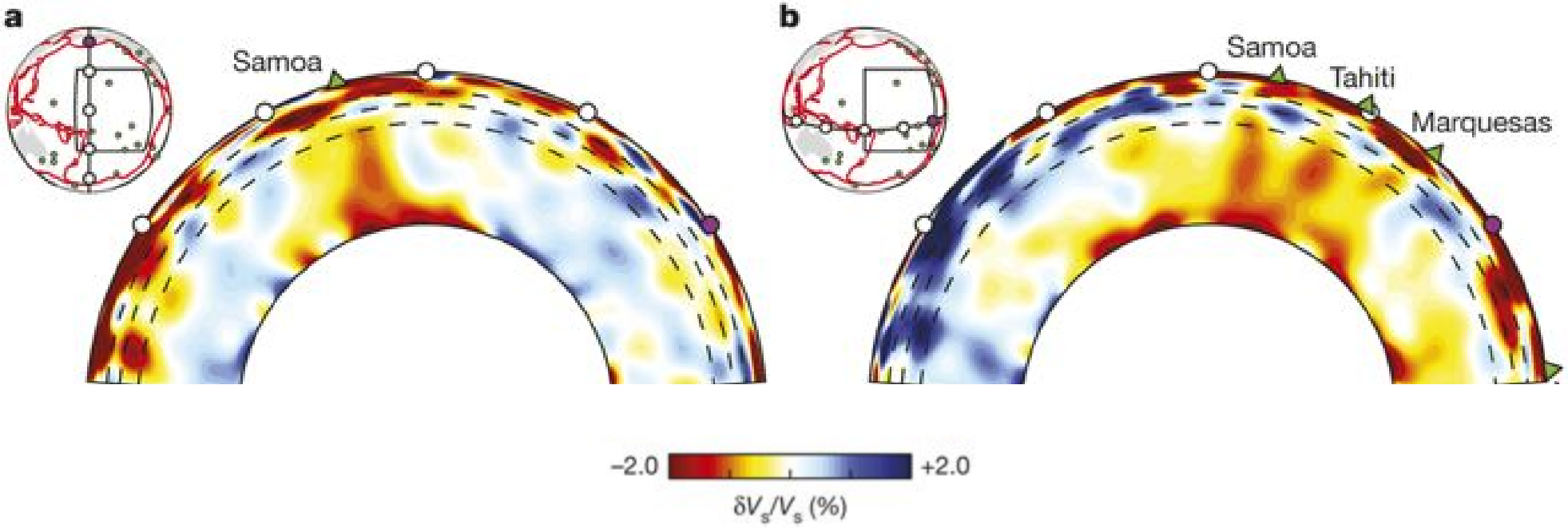






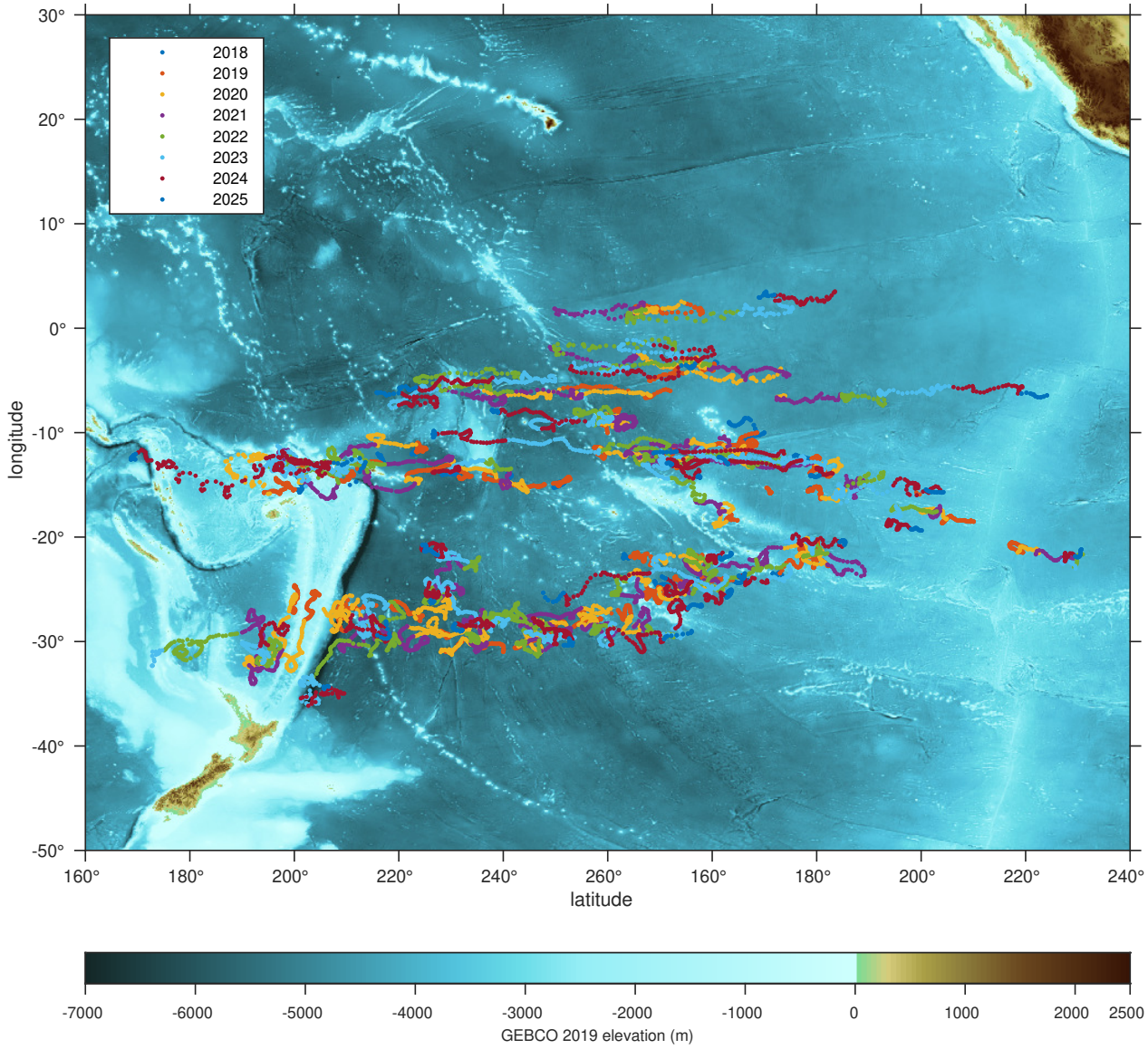
Maruyama, *Gondwana Res.*, 2007

The Mantle: *Plumes — III*



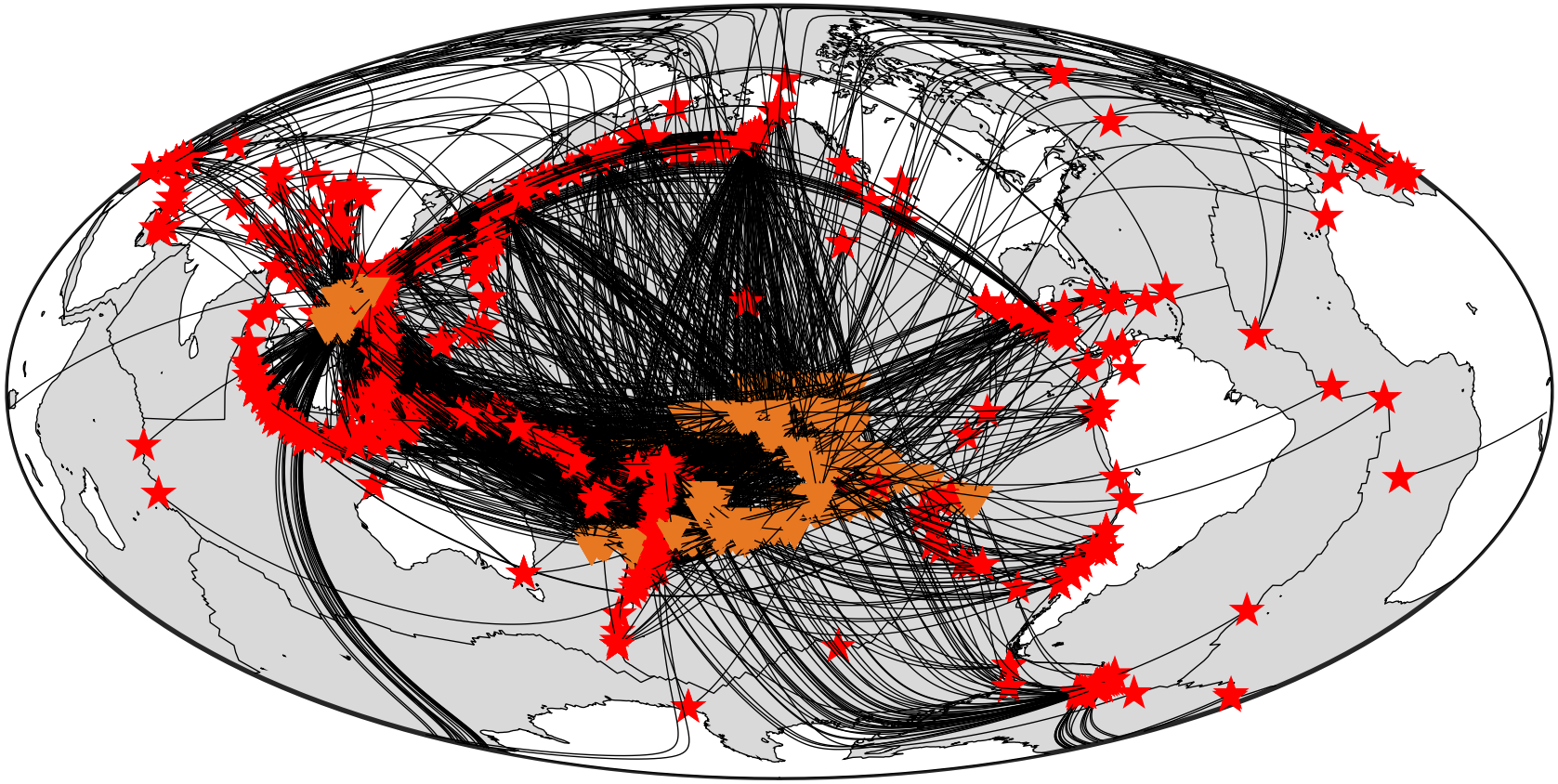
French, *Nature*, 2015

Seven years and counting



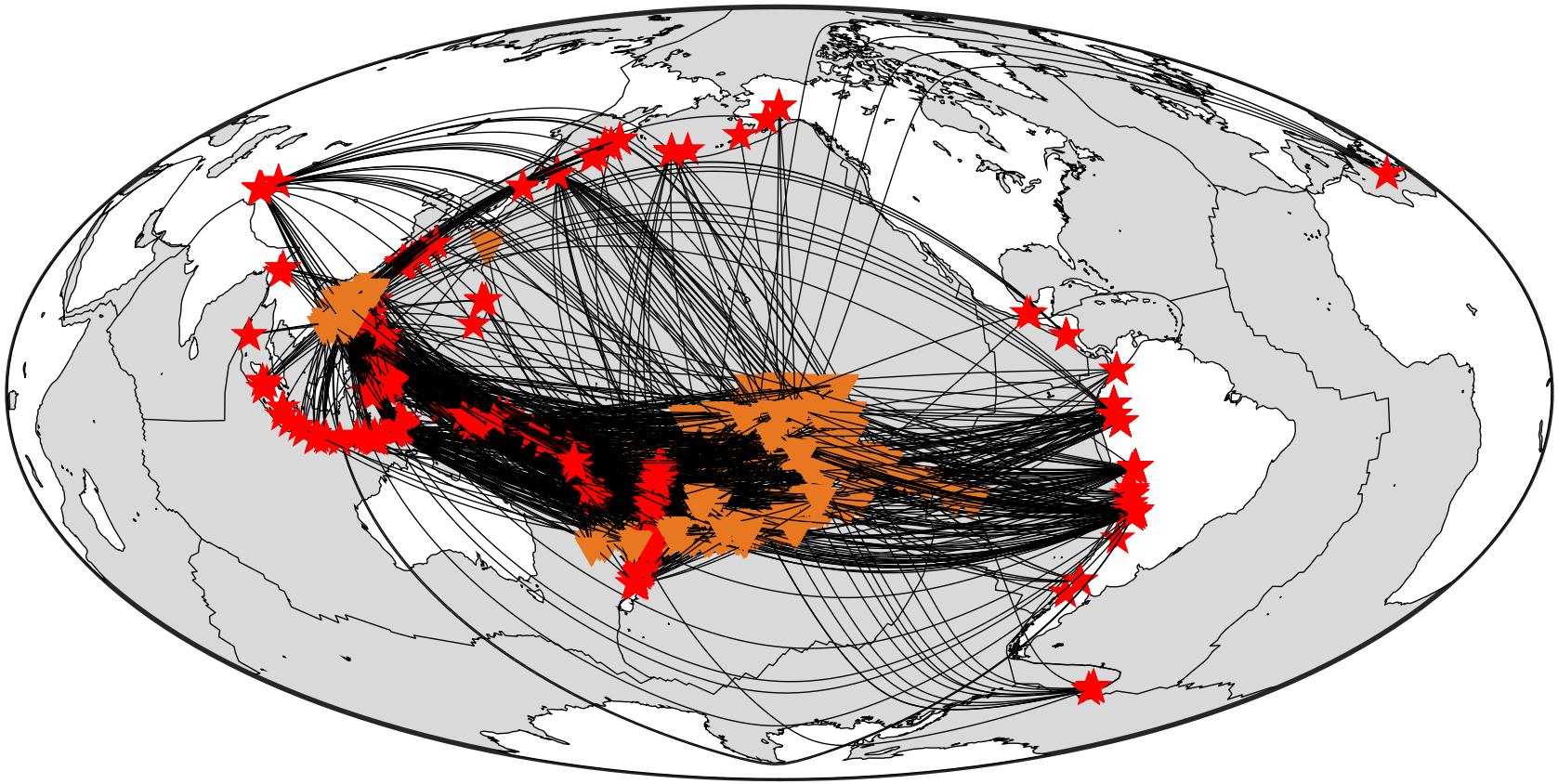
Shallow earthquakes

Event Depth $\leq$ 70 km
5813 Paths, 2118 Earthquakes, 61 MERMAIDs



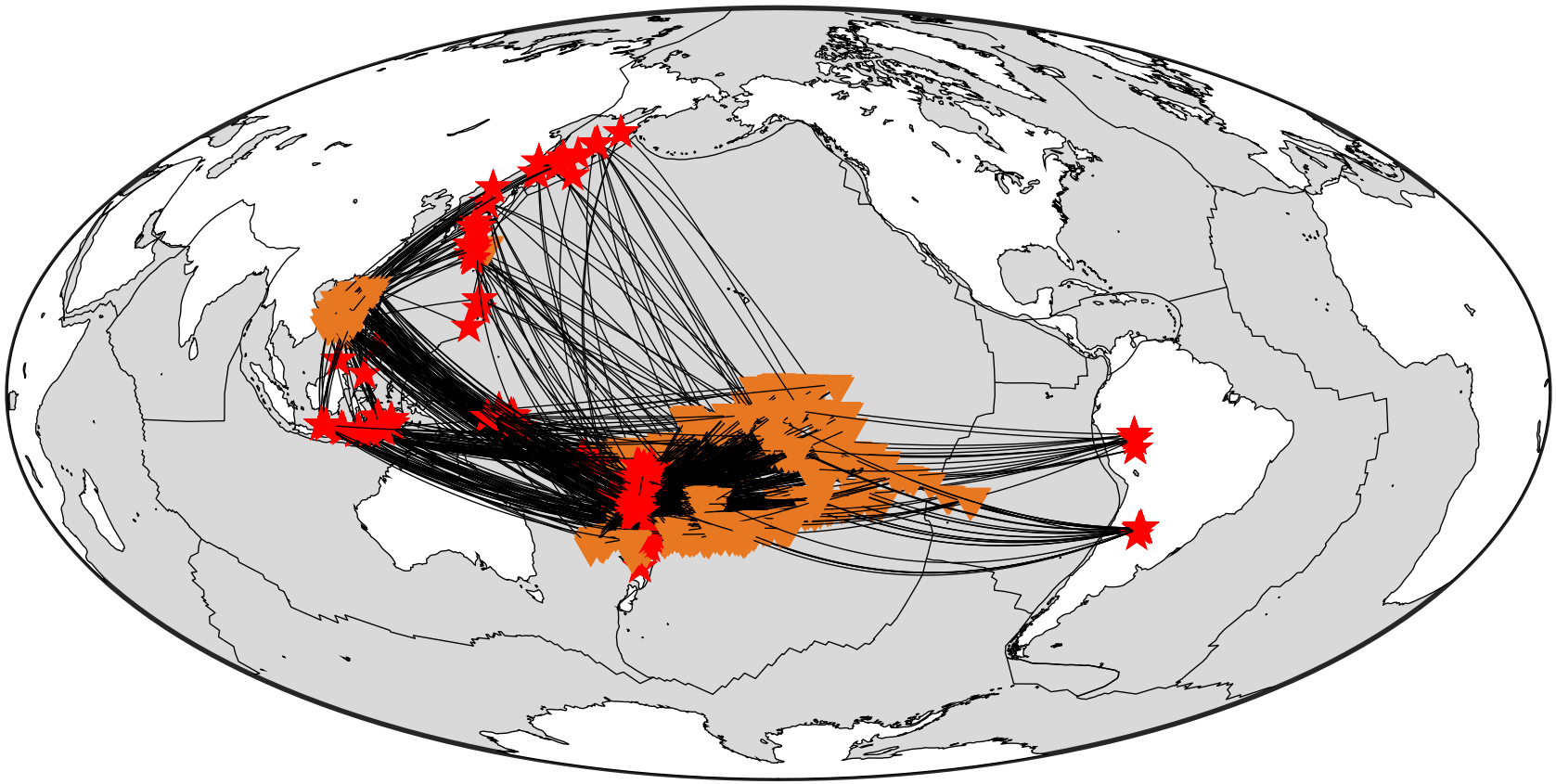
Intermediate earthquakes

70 km $<$ Event Depth $\leq$ 300 km
2239 Paths, 583 Earthquakes, 61 MERMAIDs

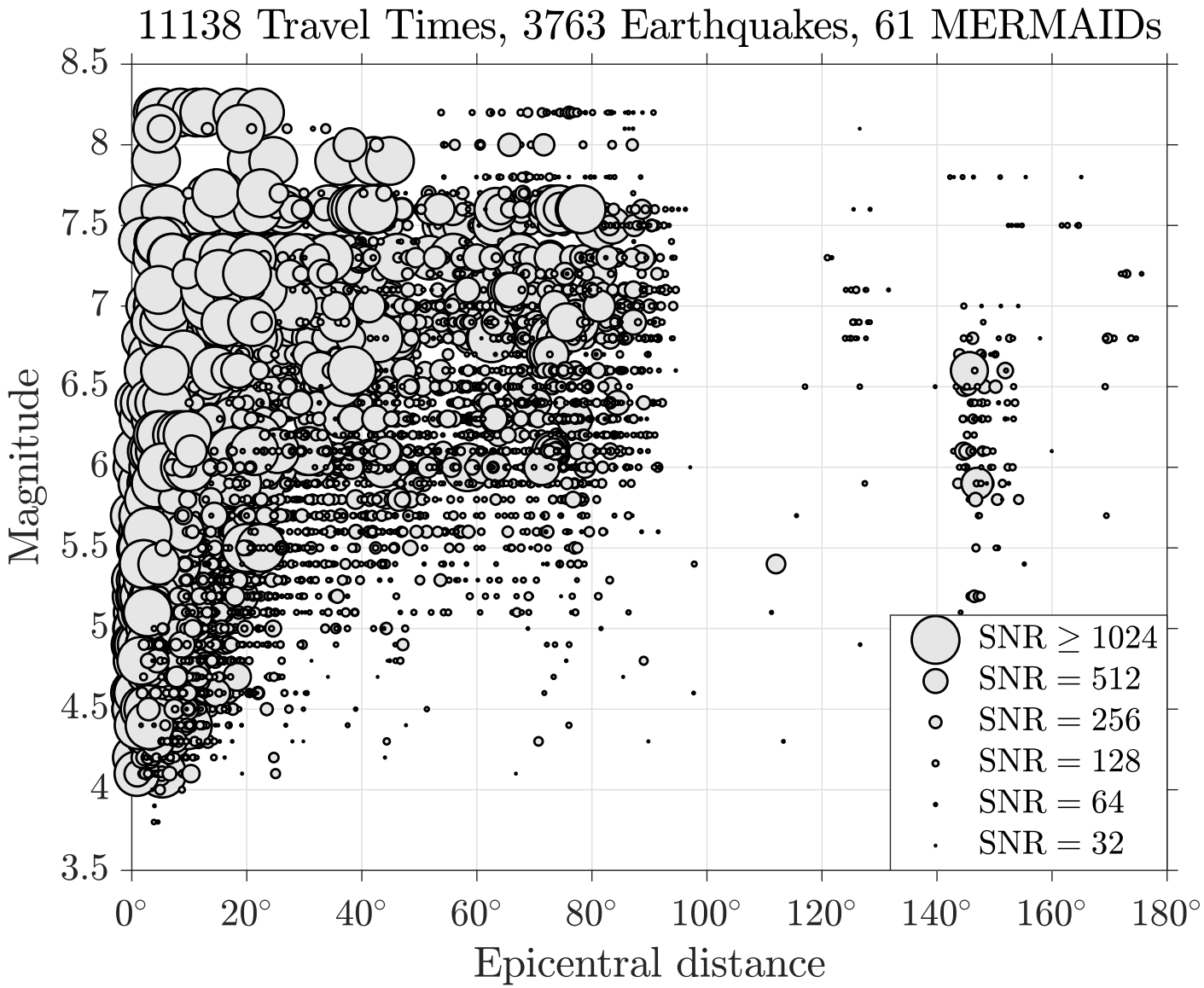


Deep earthquakes

Event Depth > 300 km
3086 Paths, 1065 Earthquakes, 61 MERMAIDs

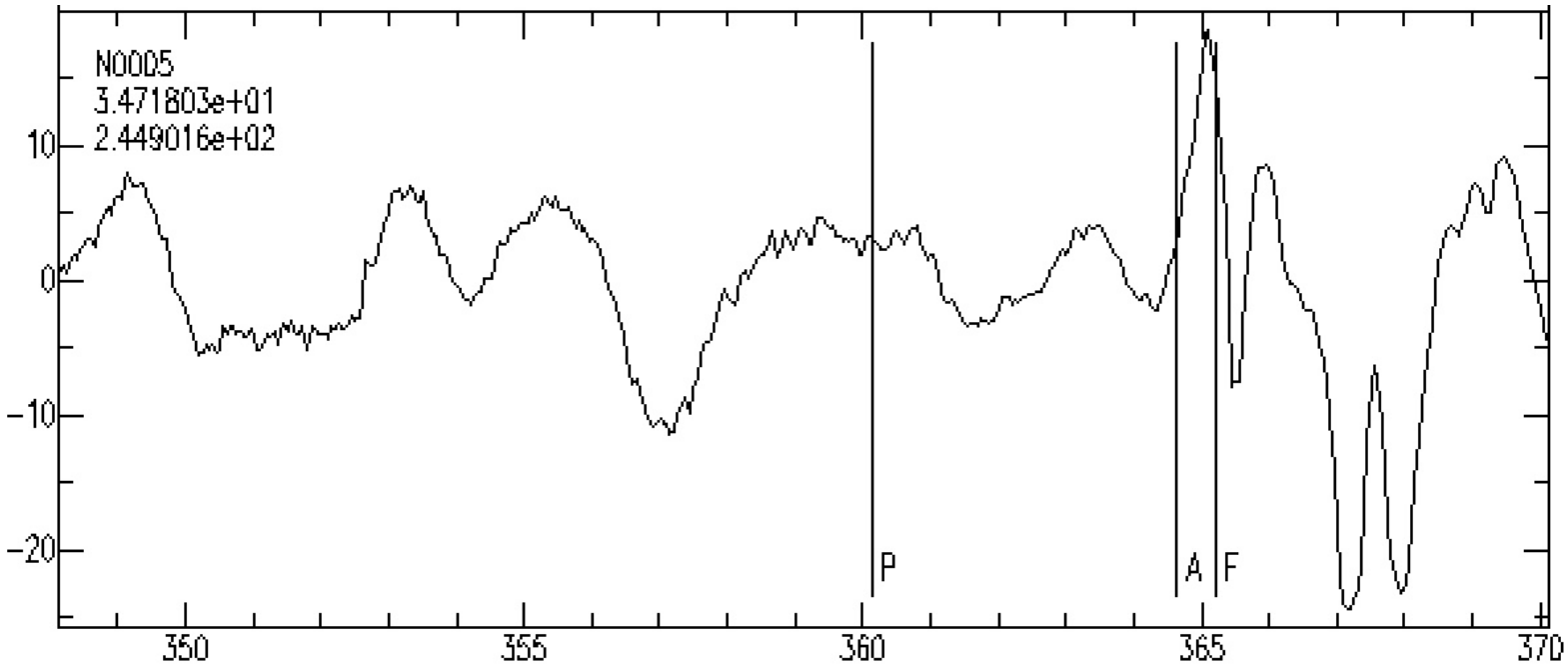


A Unique New Dataset



Looptijdtomografie

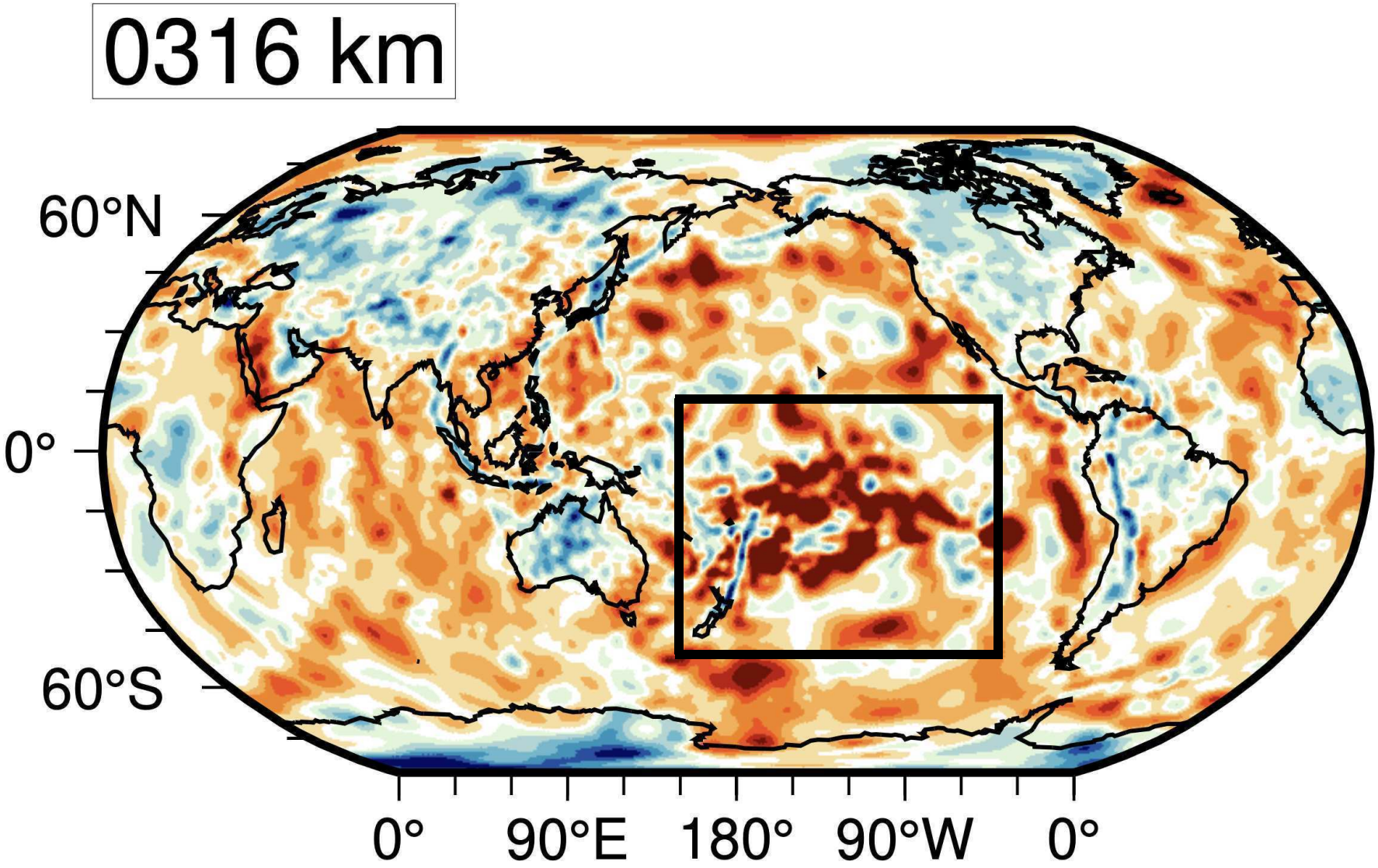
11,165,138 Arrival Times



5,534 *short* MERMAID records

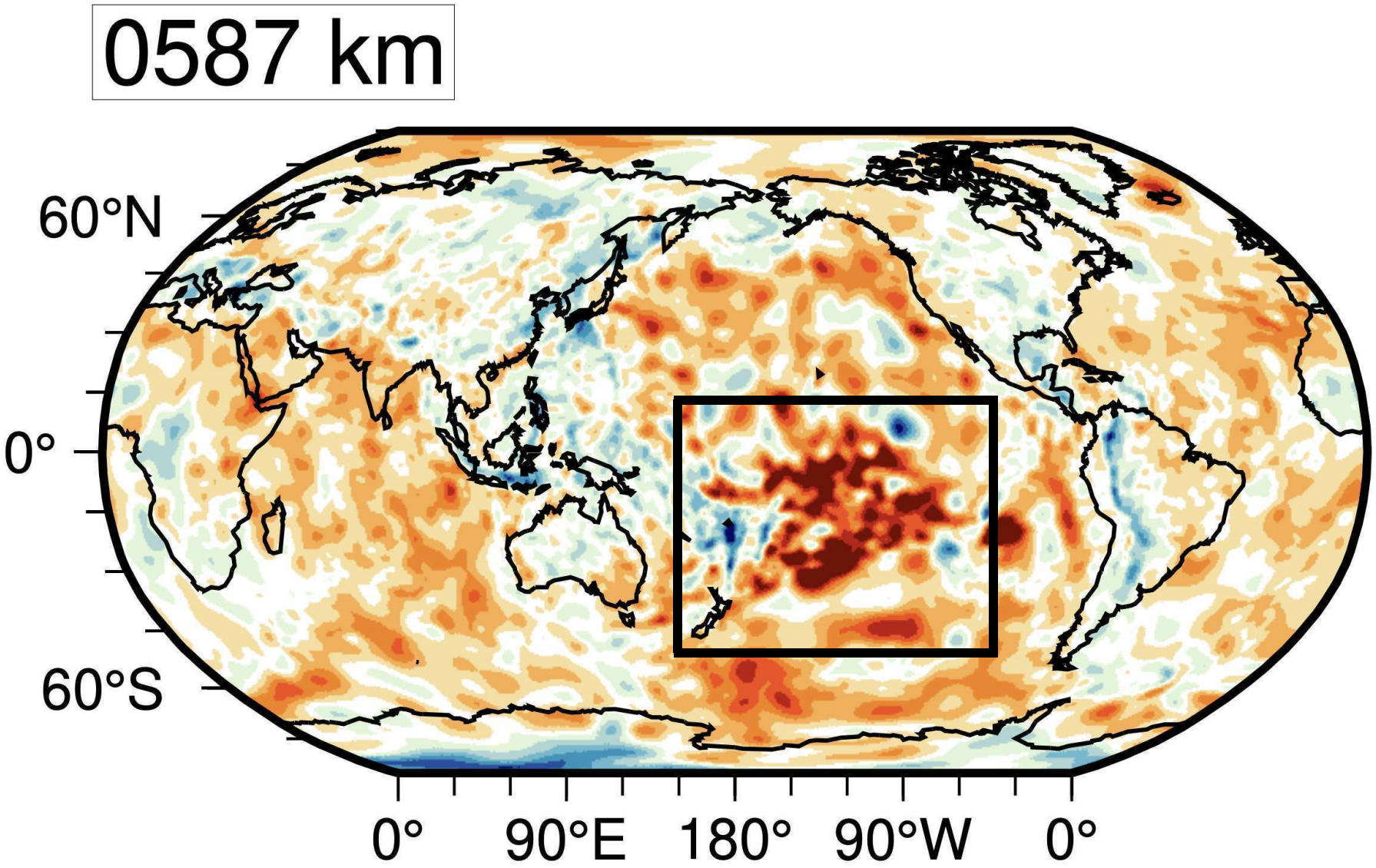
Nolet et al., *Seismica*, 2025

A new global seismic wave speed model



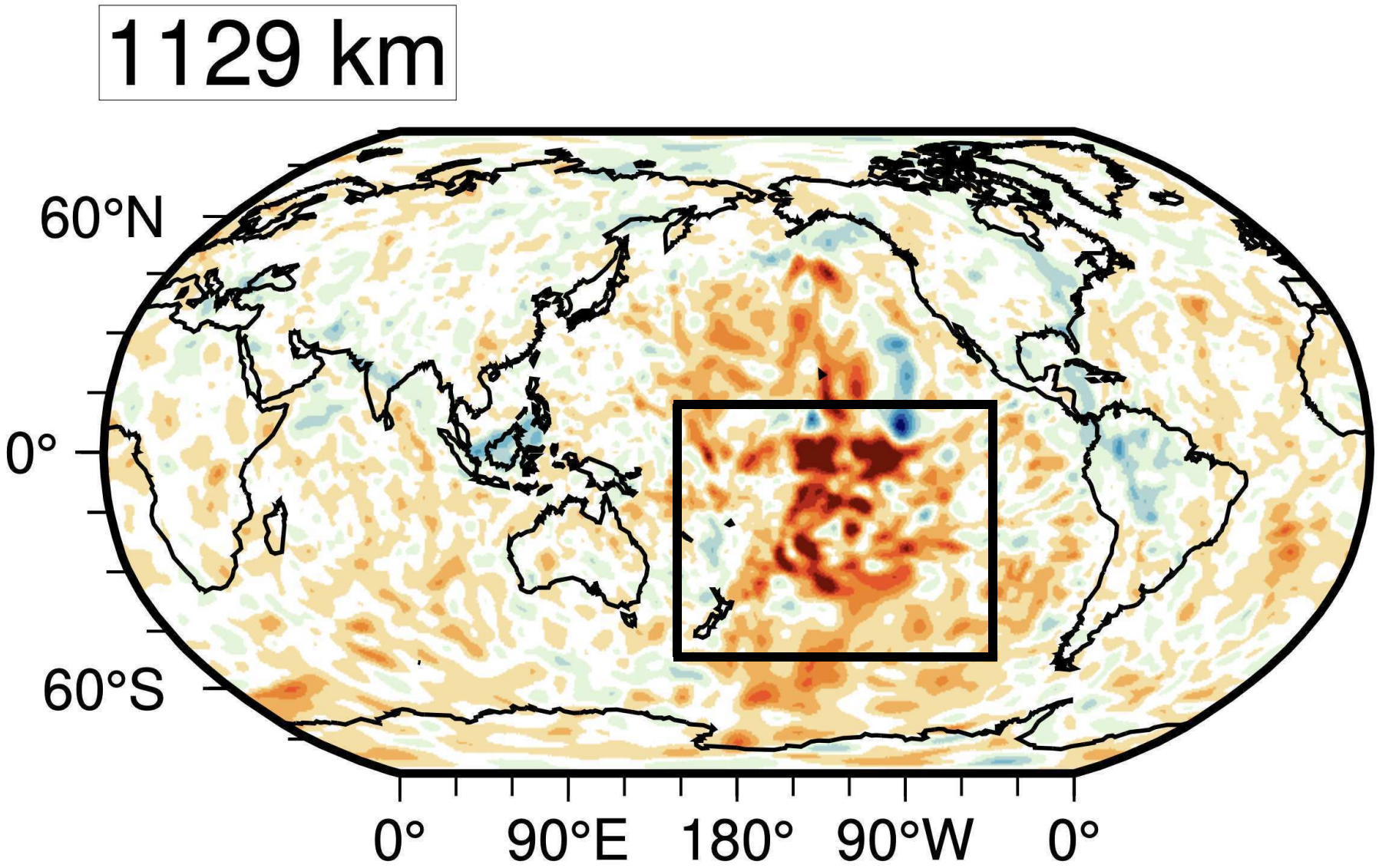
Nolet et al., *in review*

A new global seismic wave speed model



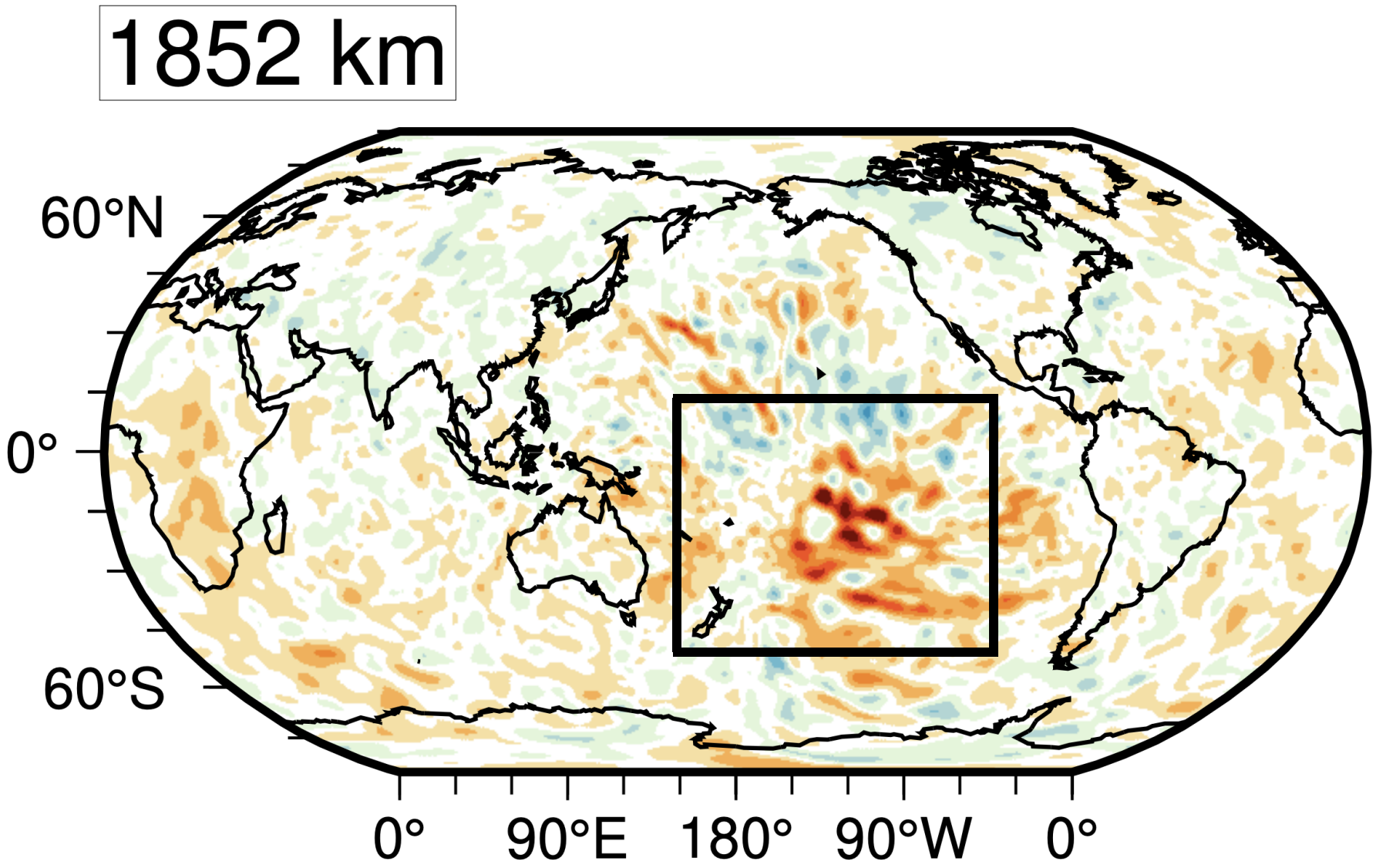
Nolet et al., *in review*

A new global seismic wave speed model



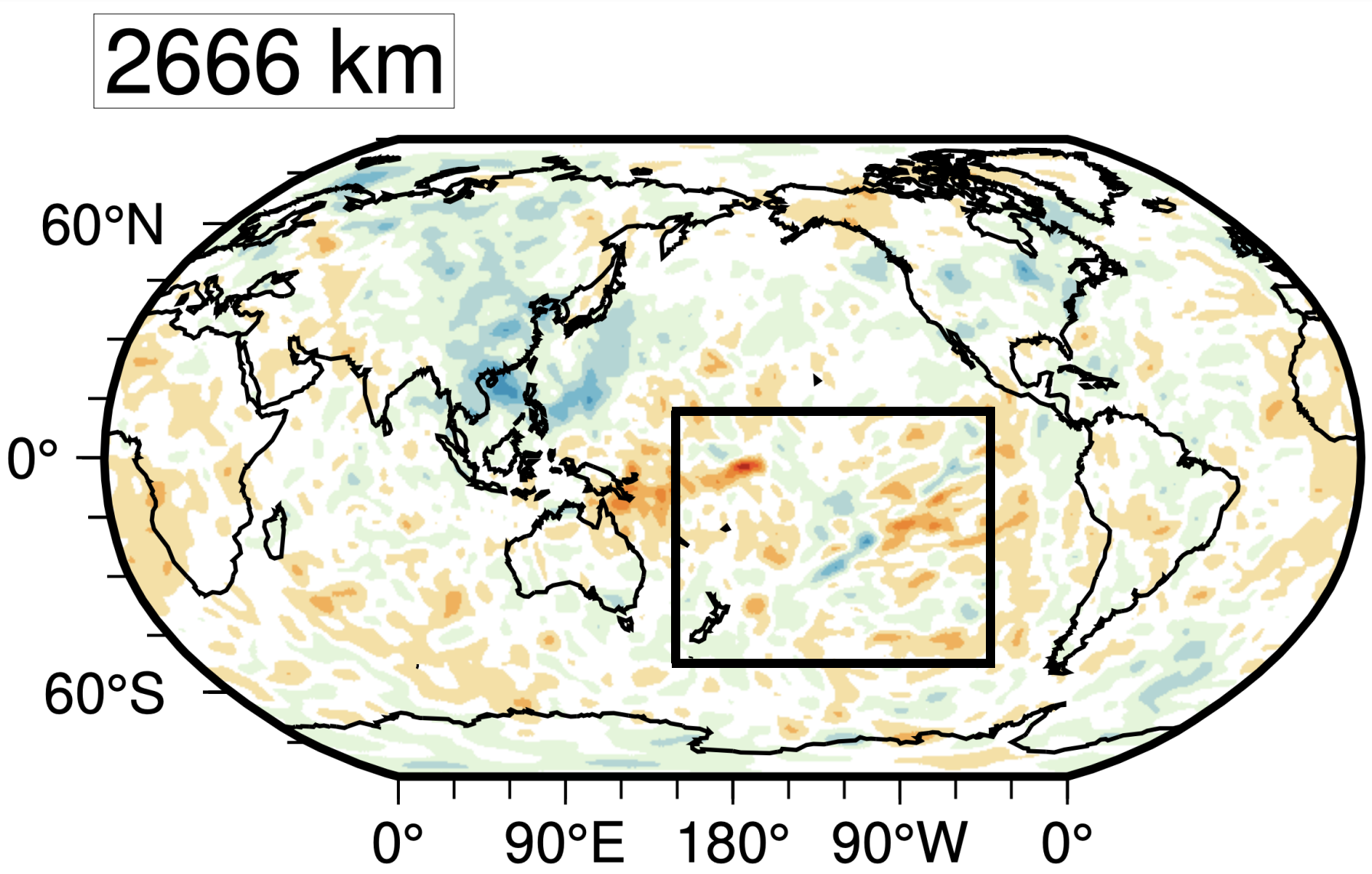
Nolet et al., *in review*

A new global seismic wave speed model



Nolet et al., *in review*

A new global seismic wave speed model

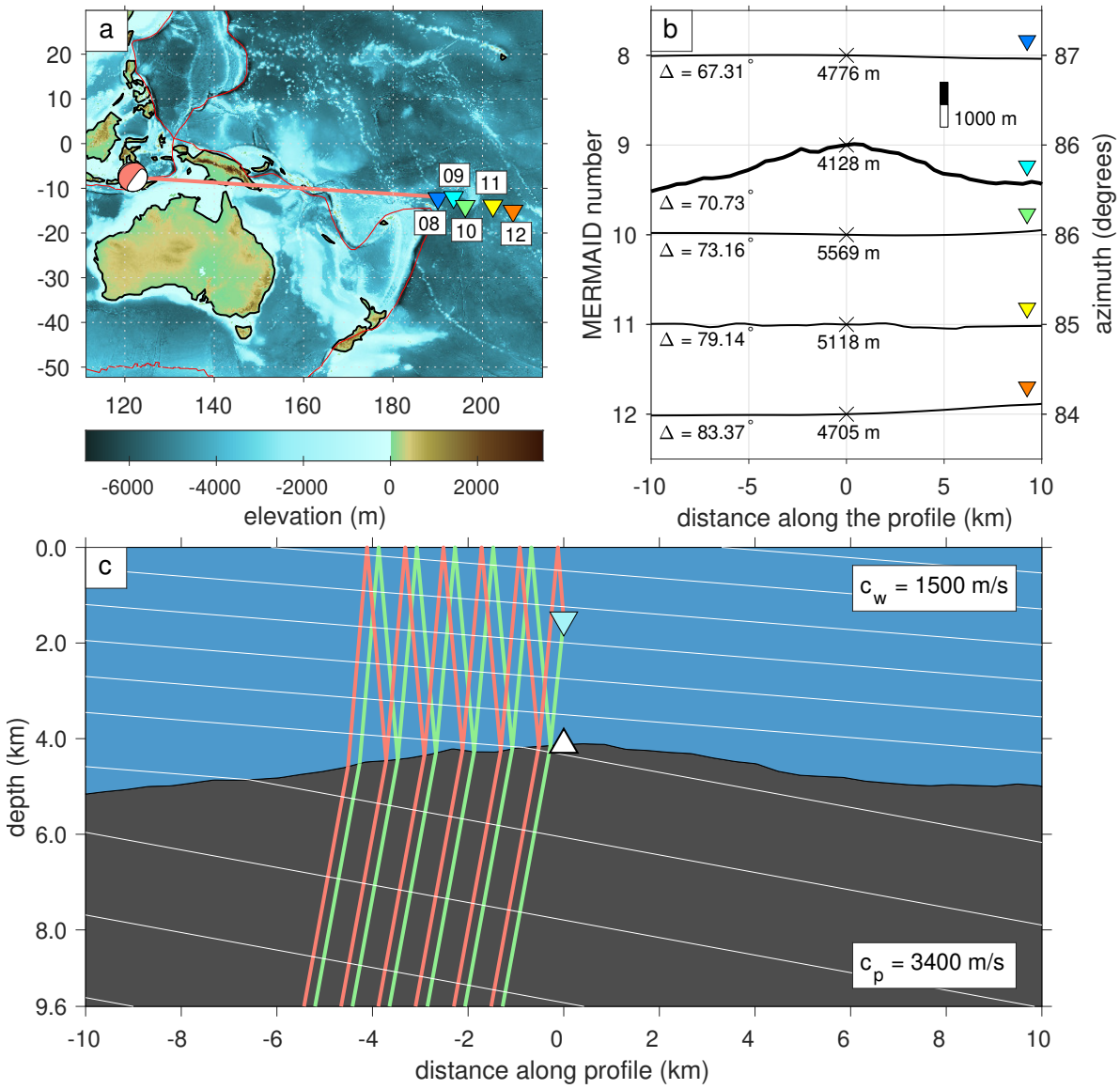


Nolet et al., *in review*

Those were travel times*. Next stop:*

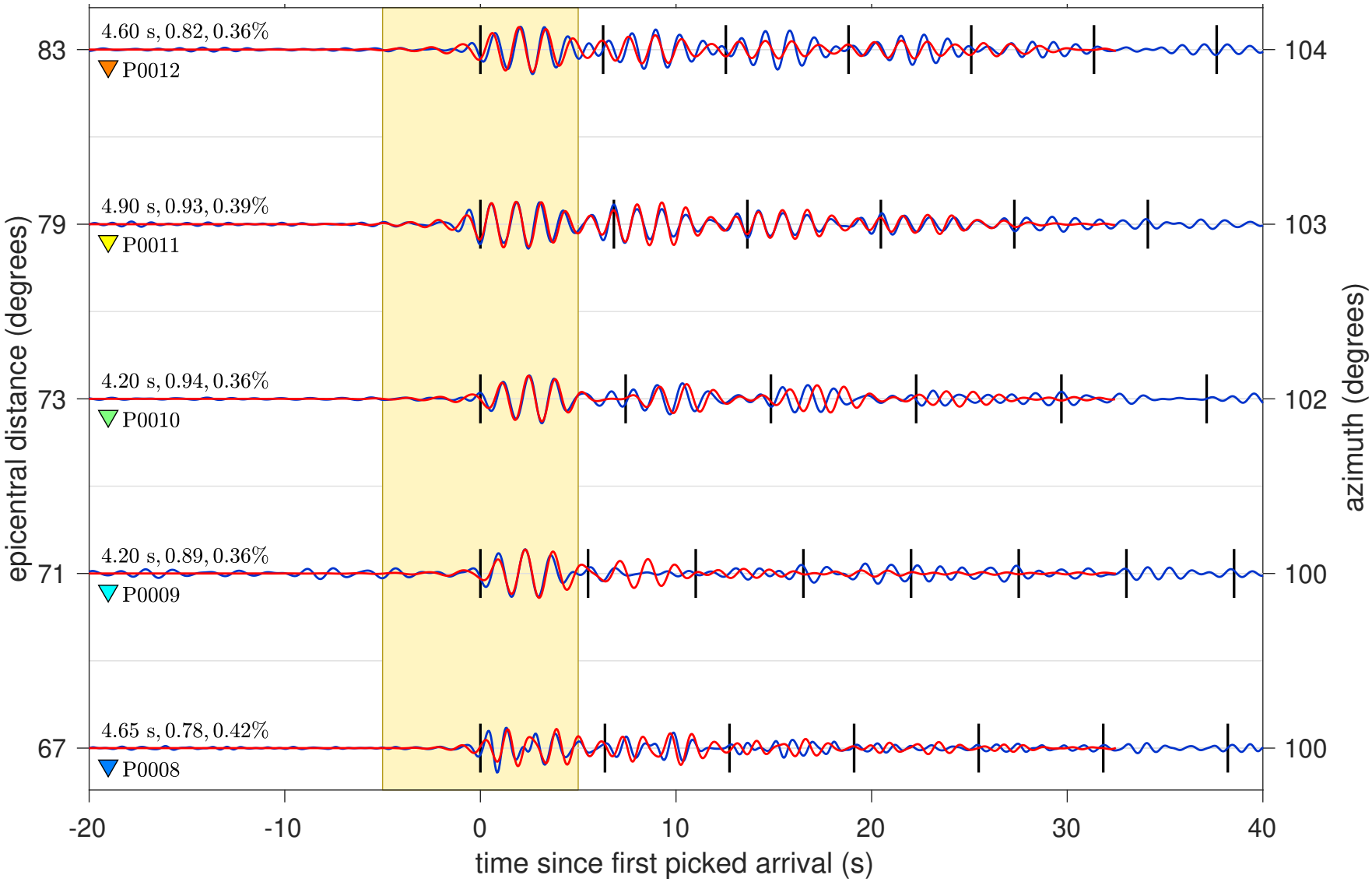
Modeling MERMAID Waveforms

Waveform Modeling Scheme



Pipatprathanporn & Simons, *GJI*, 2024

Waveform Modeling Scheme



Pipatprathanporn & Simons, *GJI*, 2024

Theme 1: Earthquakes

Theme 1: Earthquakes

Polynesian plume tomography...

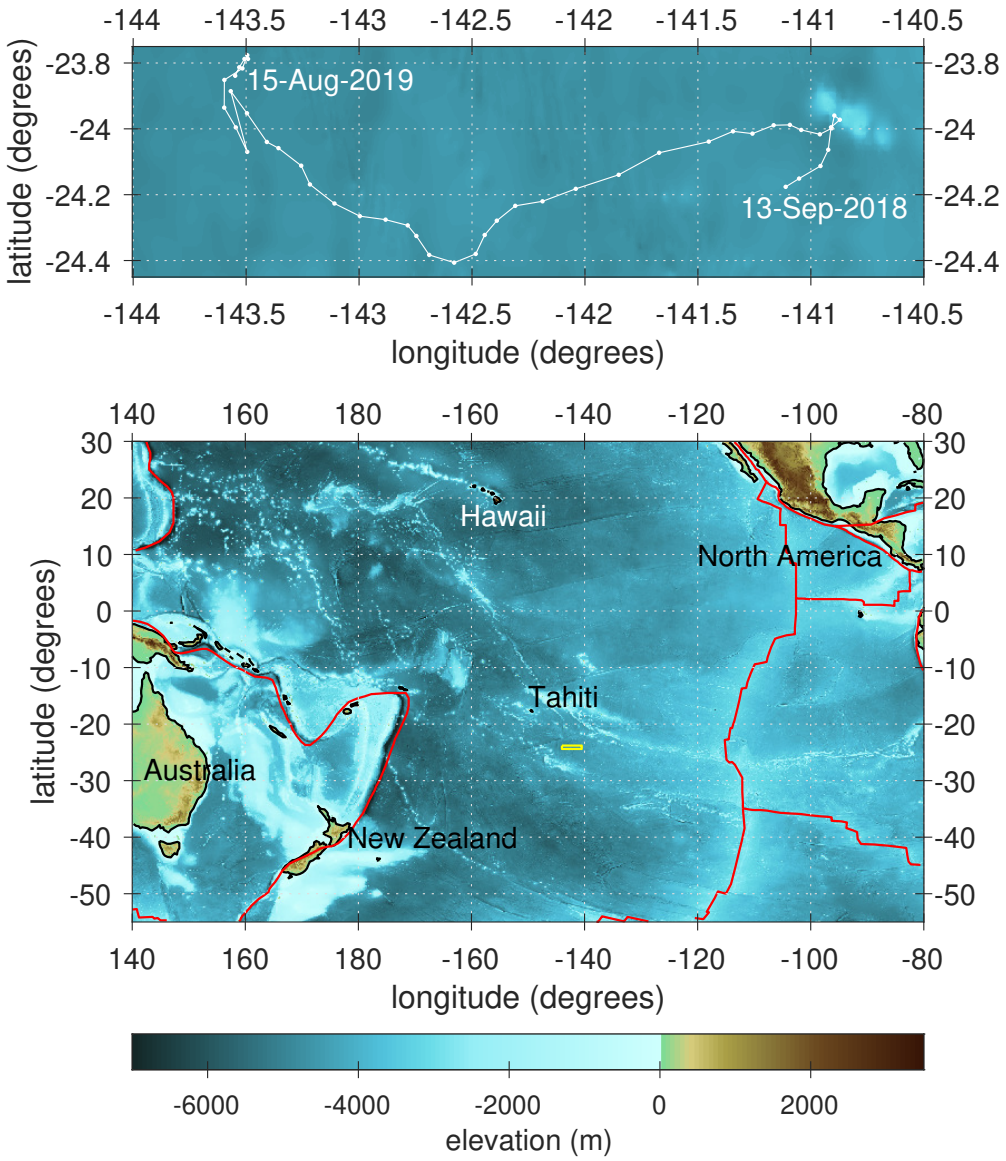
Theme 1: Earthquakes

Polynesian plume tomography...

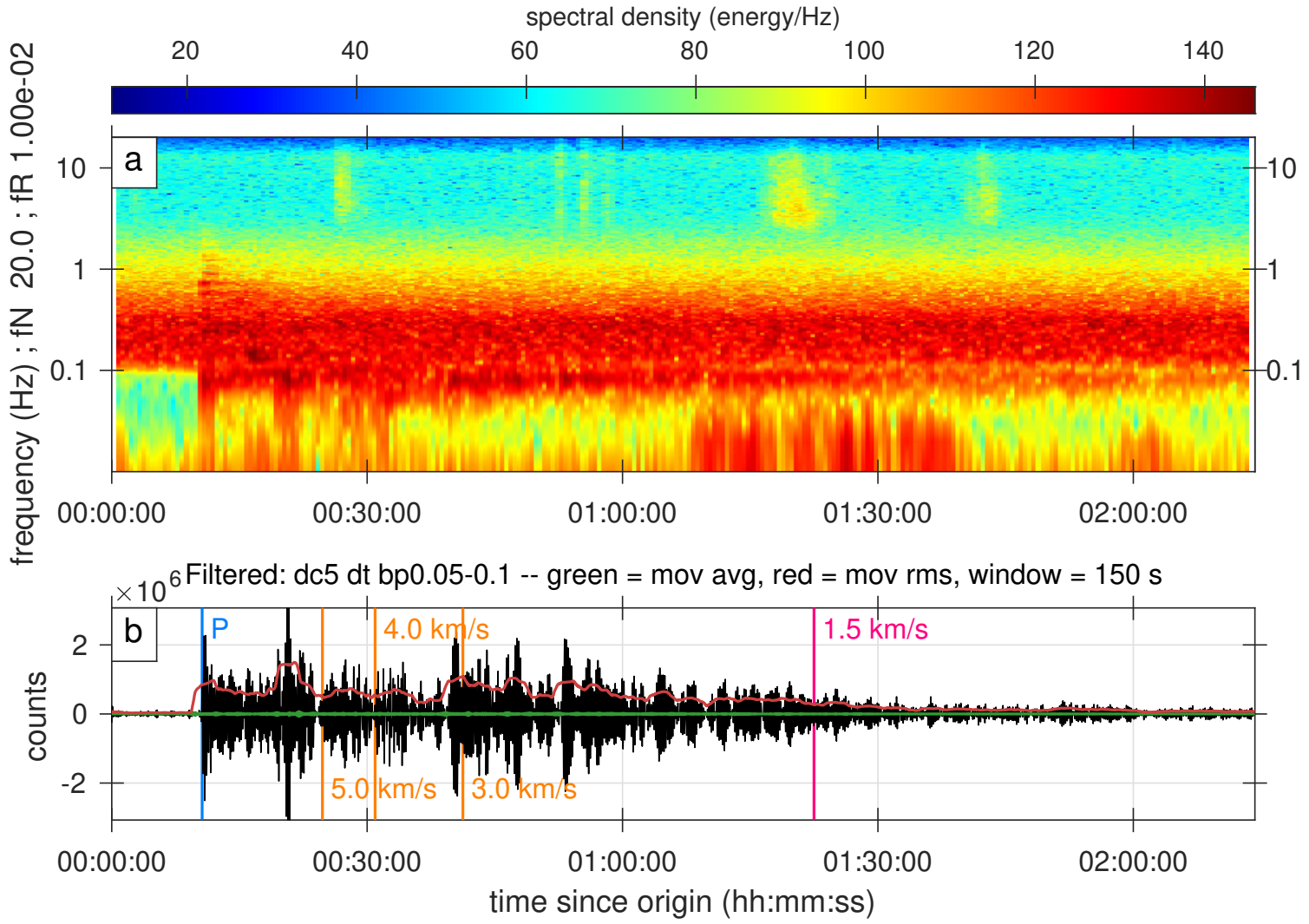
Stay tuned for more!

Ocean noise & Microseisms

A Most Unusual Recovery

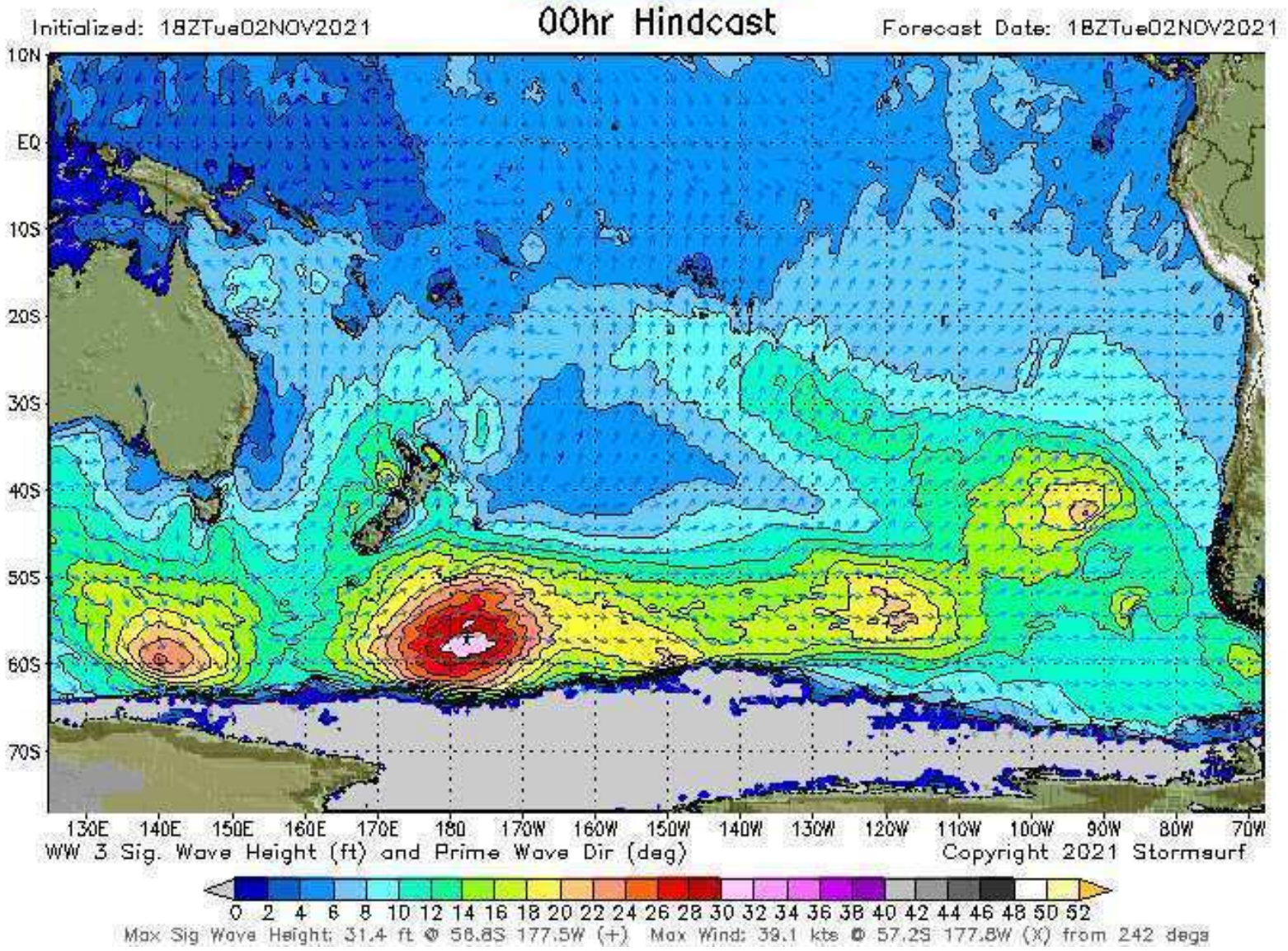


Loooong Records

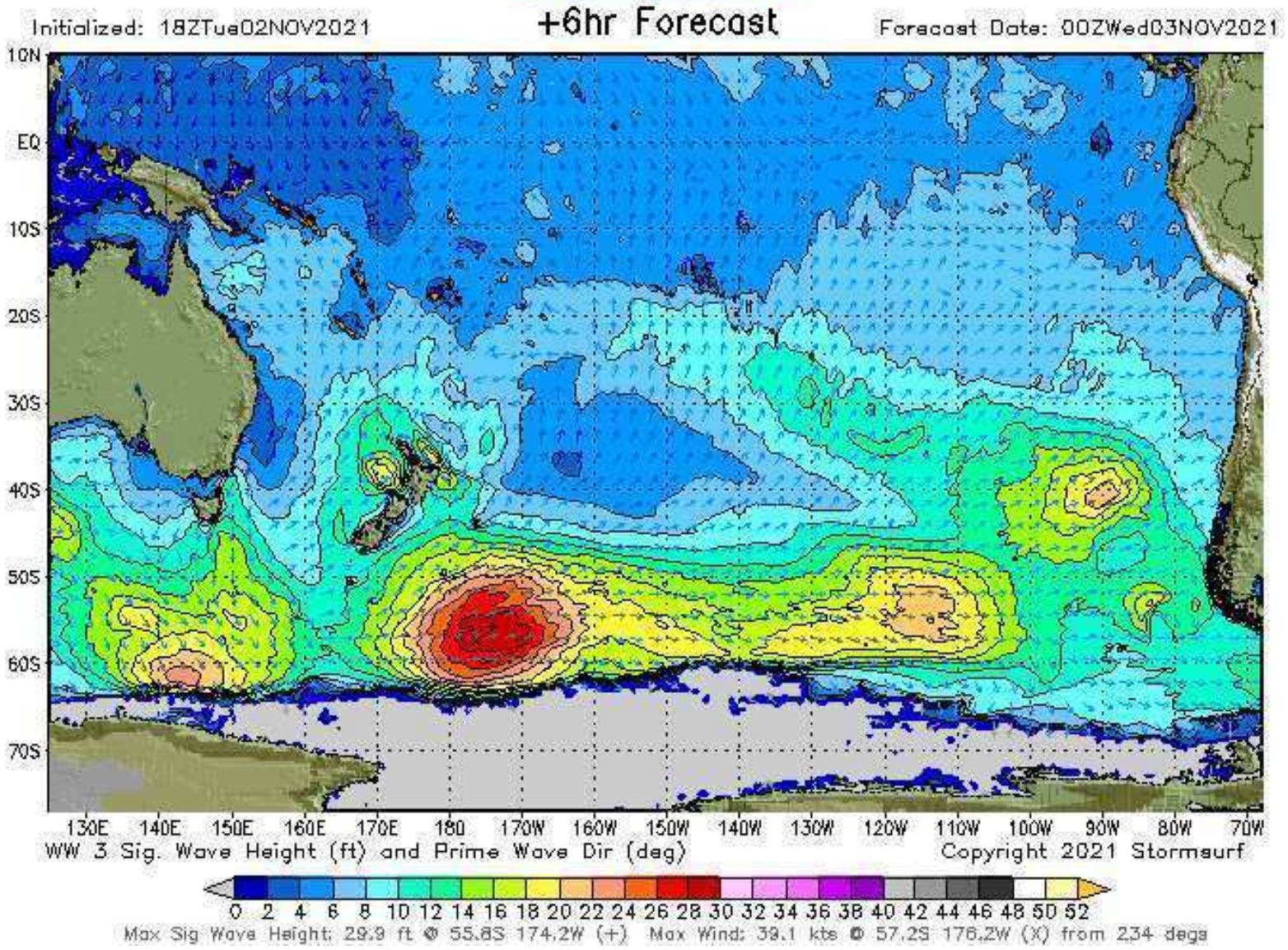


Meanwhile, at the ocean **surface**...

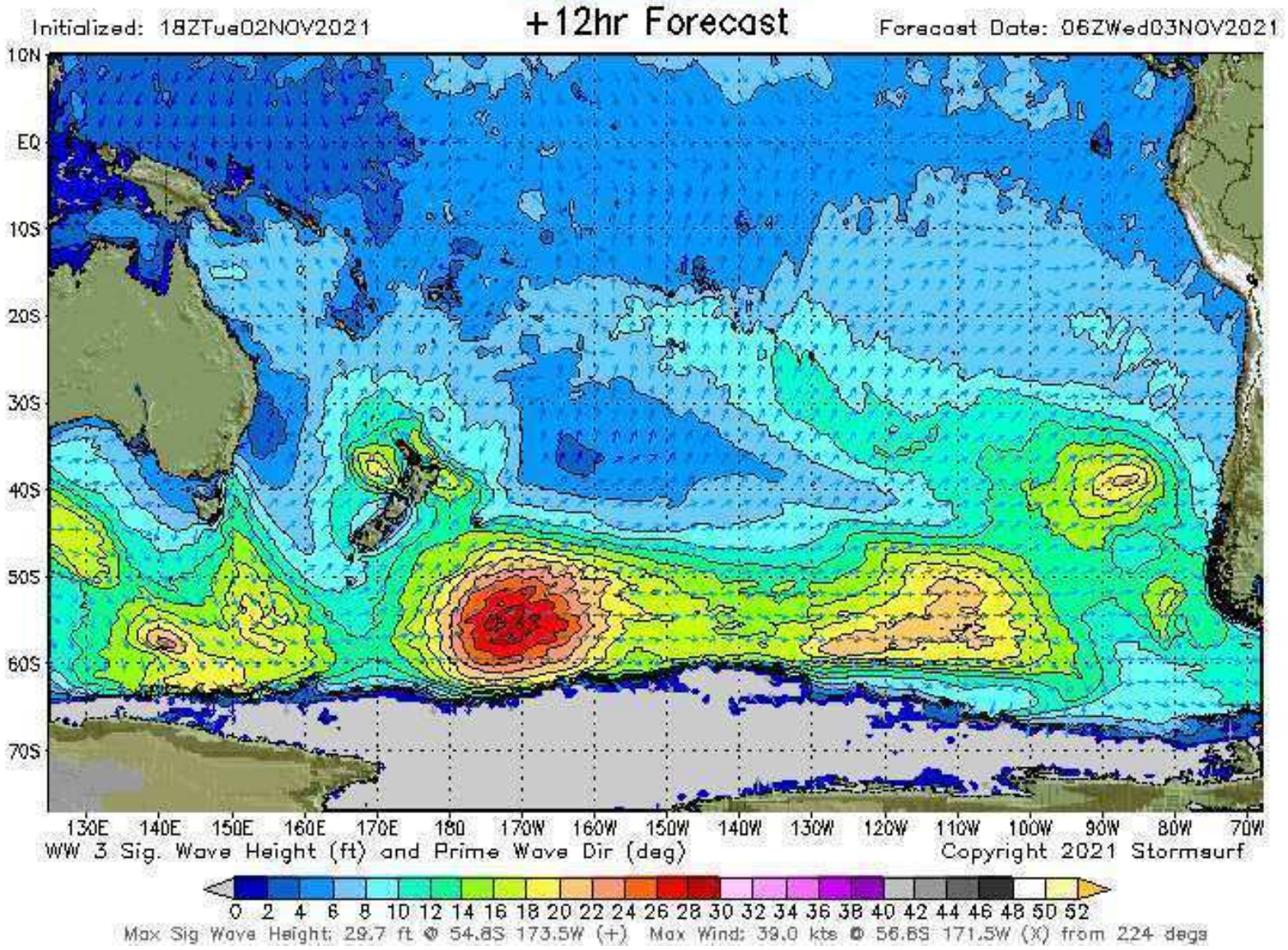
Ocean Waves


Initialized: 18ZTue02NOV2021
00hr Hindcast
Forecast Date: 18ZTue02NOV2021
10N
EQ
10S
20S
30S
40S
50S
60S
70S
130E 140E 150E 160E 170E 180 170W 160W 150W 140W 130W 120W 110W 100W 90W 80W 70W
WW 3 Sig. Wave Height (ft) and Prime Wave Dir (deg)
Copyright 2021 Stormsurf
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34 36 38 40 42 44 46 48 50 52
Max Sig Wave Height: 31.4 ft @ 56.8S 177.5W (+) Max Wind: 39.1 kts @ 57.2S 177.8W (X) from 242 degs

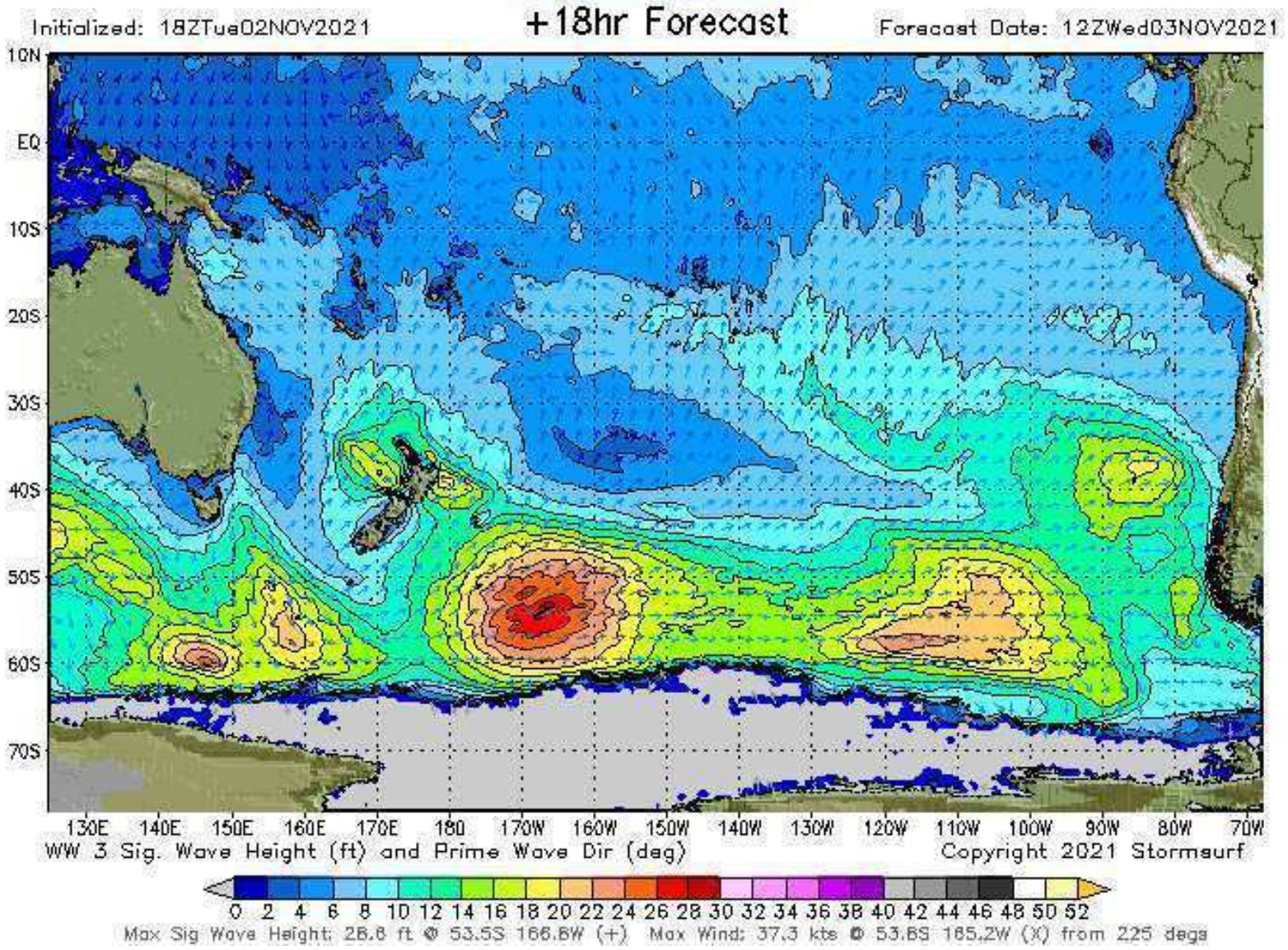
Ocean Waves


Initialized: 18ZTue02NOV2021
+6hr Forecast
Forecast Date: 00ZWed03NOV2021
10N
EQ
10S
20S
30S
40S
50S
60S
70S
130E 140E 150E 160E 170E 180 170W 160W 150W 140W 130W 120W 110W 100W 90W 80W 70W
WW 3 Sig. Wave Height (ft) and Prime Wave Dir (deg)
Copyright 2021 Stormsurf
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34 36 38 40 42 44 46 48 50 52
Max Sig Wave Height: 29.9 ft @ 55.8S 174.2W (+) Max Wind: 39.1 kts @ 57.2S 176.2W (X) from 234 degs

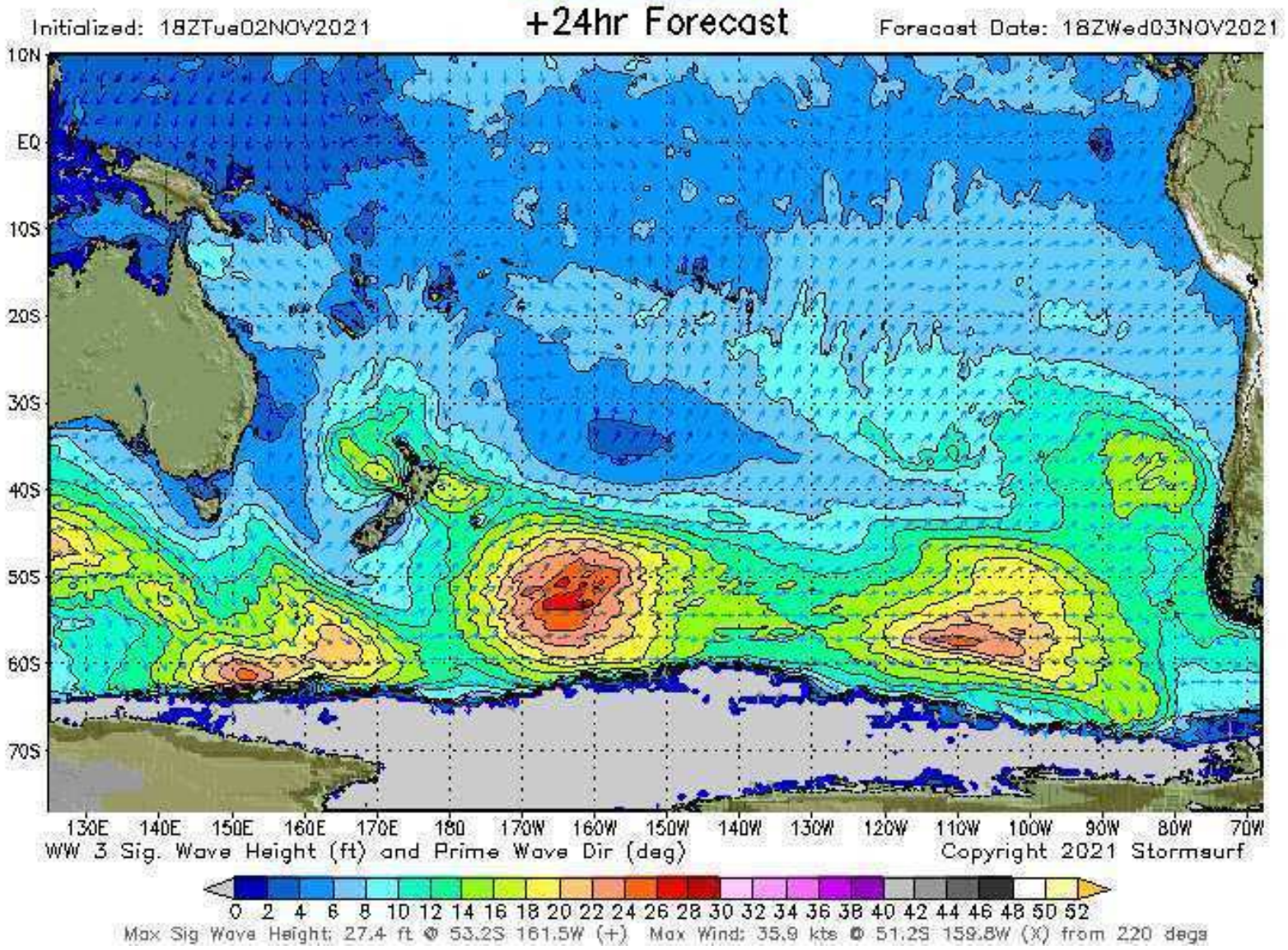
Ocean Waves


Initialized: 18ZTue02NOV2021
+12hr Forecast
Forecast Date: 06ZWed03NOV2021
10N
EQ
10S
20S
30S
40S
50S
60S
70S
130E 140E 150E 160E 170E 180 170W 160W 150W 140W 130W 120W 110W 100W 90W 80W 70W
WW 3 Sig. Wave Height (ft) and Prime Wave Dir (deg)
Copyright 2021 Stormsurf
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34 36 38 40 42 44 46 48 50 52
Max Sig Wave Height: 29.7 ft @ 54.8S 173.5W (+) Max Wind: 39.0 kts @ 56.6S 171.5W (X) from 224 degs

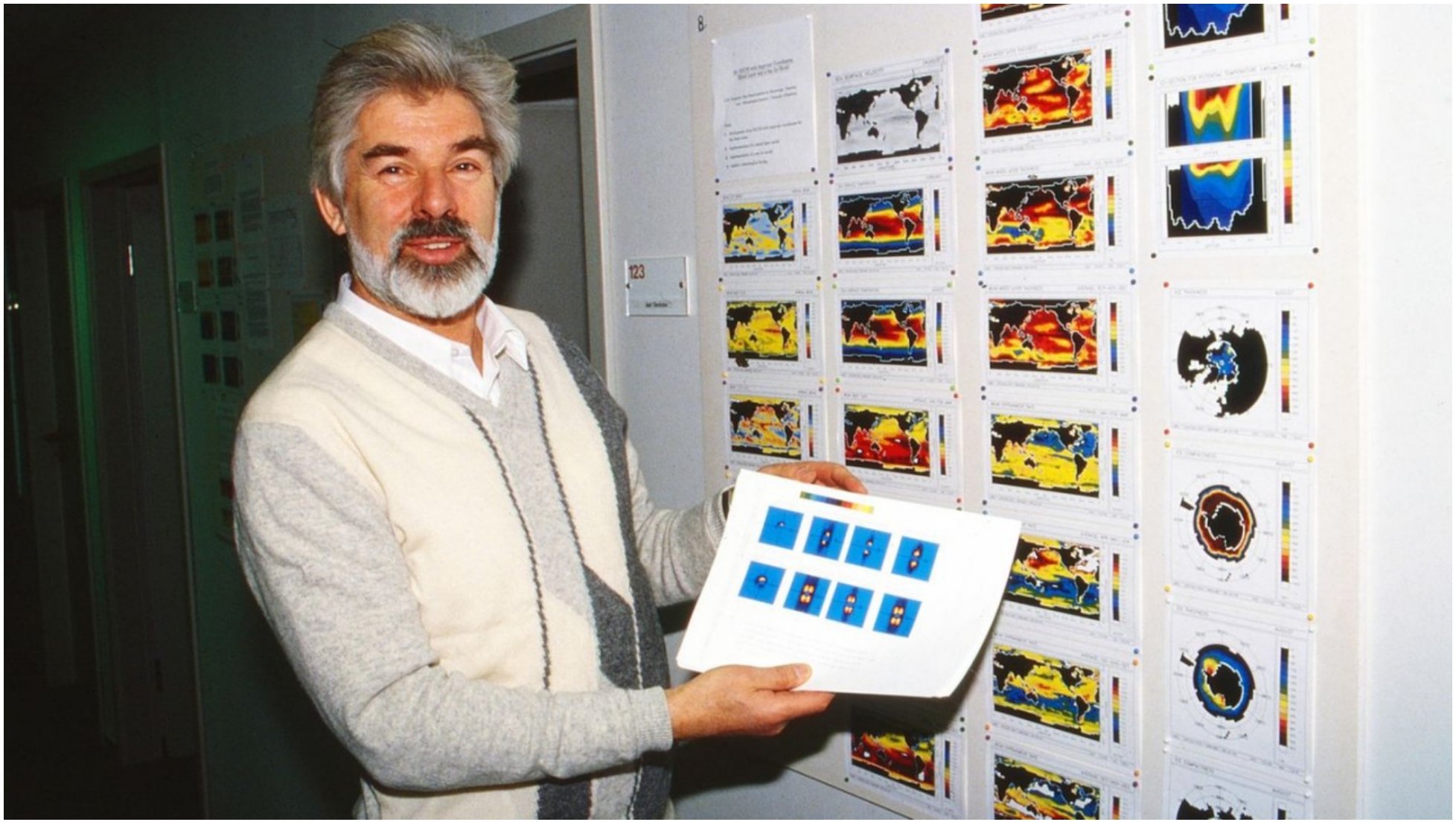
Ocean Waves


Initialized: 18ZTue02NOV2021
+18hr Forecast
Forecast Date: 12ZWed03NOV2021
10N
EQ
10S
20S
30S
40S
50S
60S
70S
130E 140E 150E 160E 170E 180 170W 160W 150W 140W 130W 120W 110W 100W 90W 80W 70W
WW 3 Sig. Wave Height (ft) and Prime Wave Dir (deg)
Copyright 2021 Stormsurf
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34 36 38 40 42 44 46 48 50 52
Max Sig Wave Height: 28.8 ft @ 53.5S 166.8W (+) Max Wind: 37.3 kts @ 53.8S 165.2W (X) from 225 degs

Ocean Waves

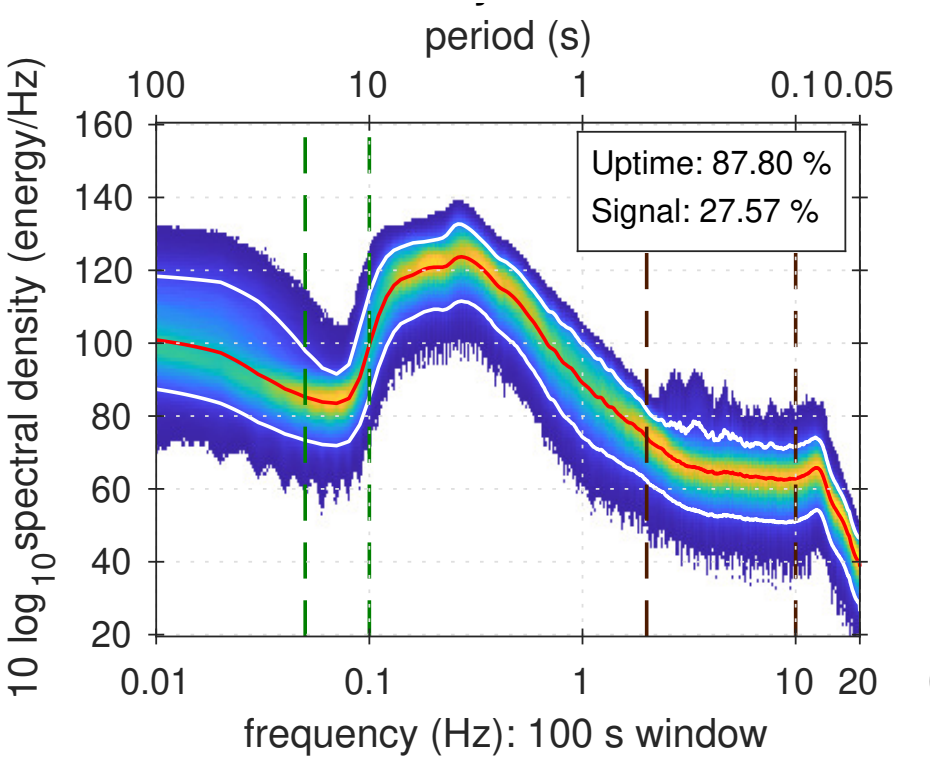

Initialized: 18ZTue02NOV2021
+24hr Forecast
Forecast Date: 18ZWed03NOV2021
10N
EQ
10S
20S
30S
40S
50S
60S
70S
130E 140E 150E 160E 170E 180 170W 160W 150W 140W 130W 120W 110W 100W 90W 80W 70W
WW 3 Sig. Wave Height (ft) and Prime Wave Dir (deg)
Copyright 2021 Stormsurf
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34 36 38 40 42 44 46 48 50 52
Max Sig Wave Height: 27.4 ft @ 53.2S 161.5W (+) Max Wind: 35.9 kts @ 51.2S 159.8W (X) from 220 degs

Nonlinear interaction of ocean waves

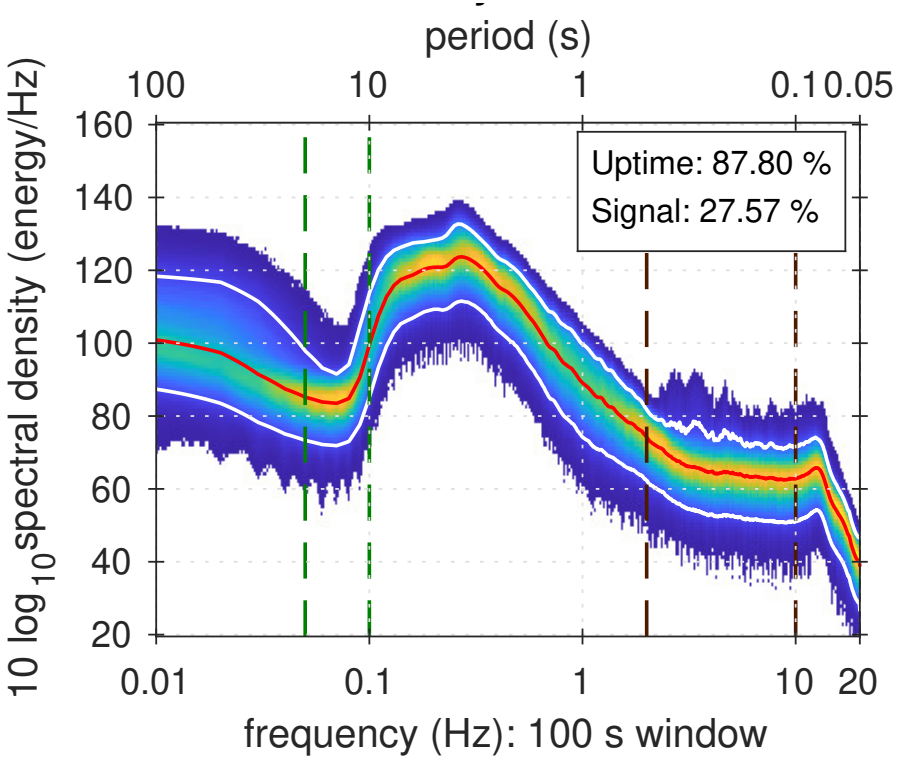


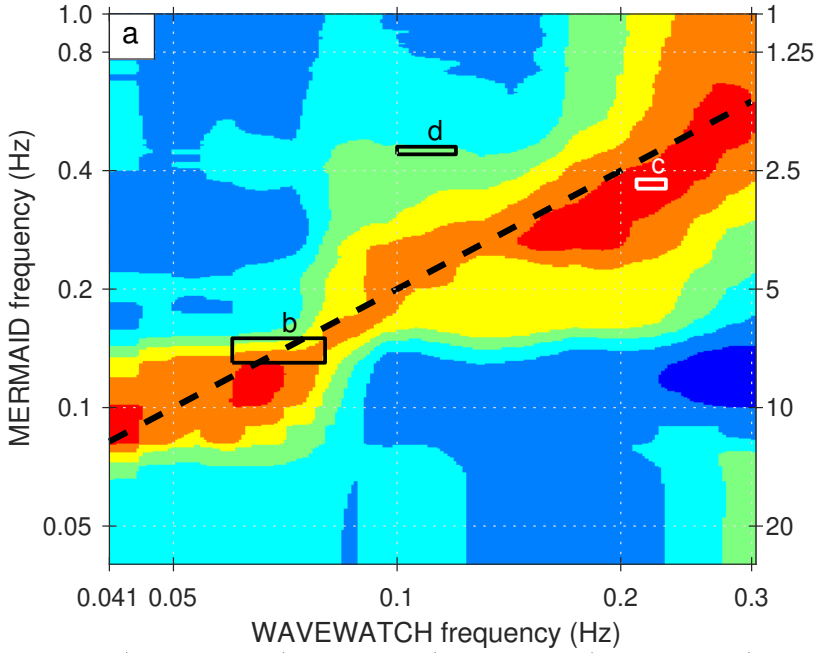
Klaus Hasselman, *Nobel Prize*, 2021

MERMAID, an Environmental Sensor

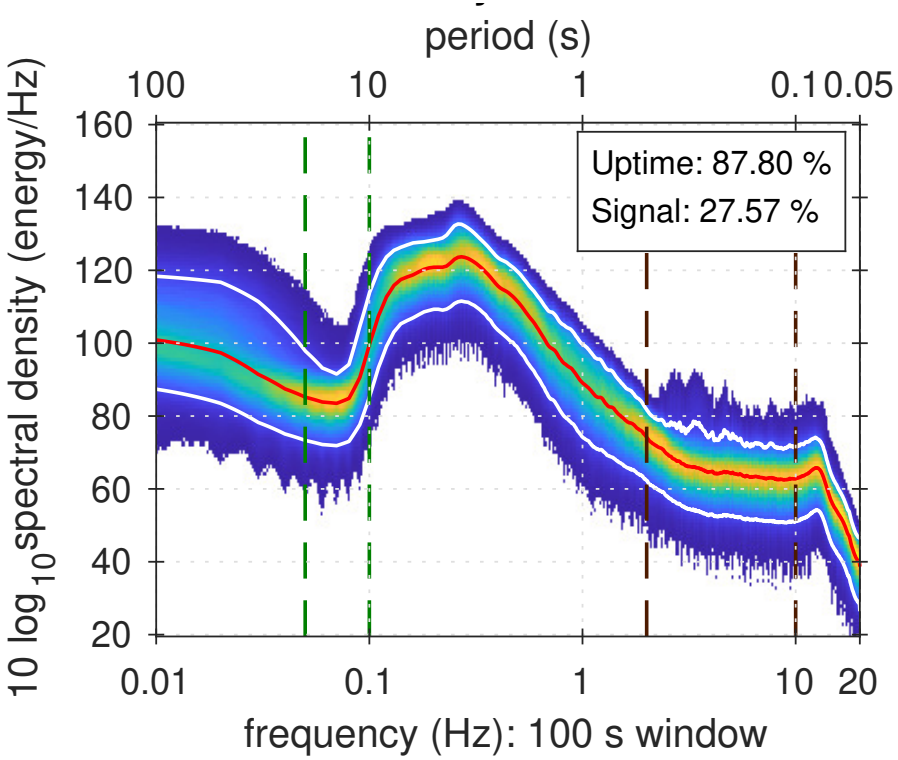


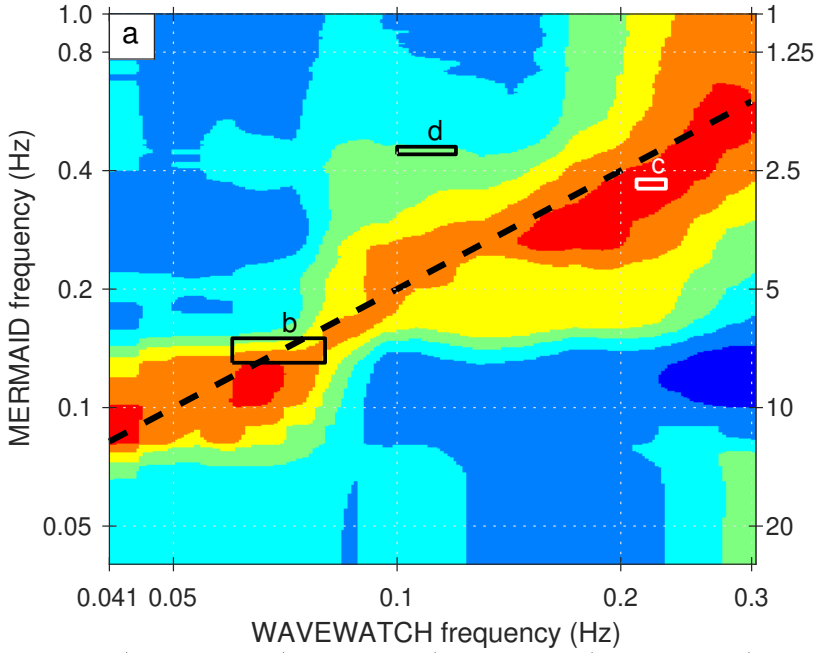
MERMAID, an Environmental Sensor

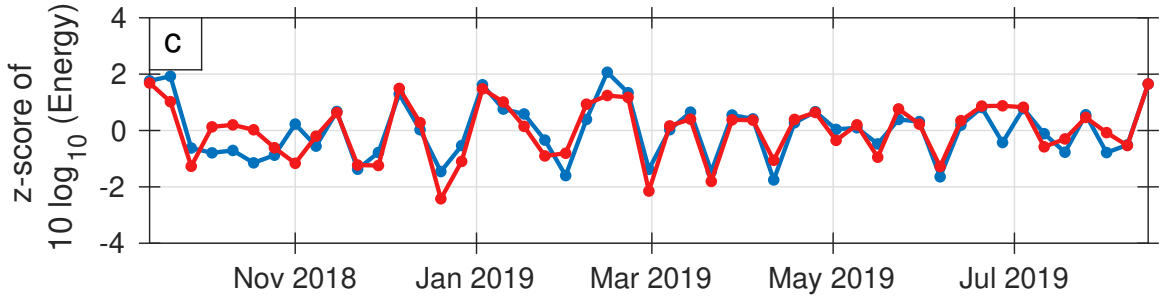




MERMAID, an Environmental Sensor







Pipatprathanporn & Simons, 2022

Theme 2: Microseisms

Theme 2: Microseisms

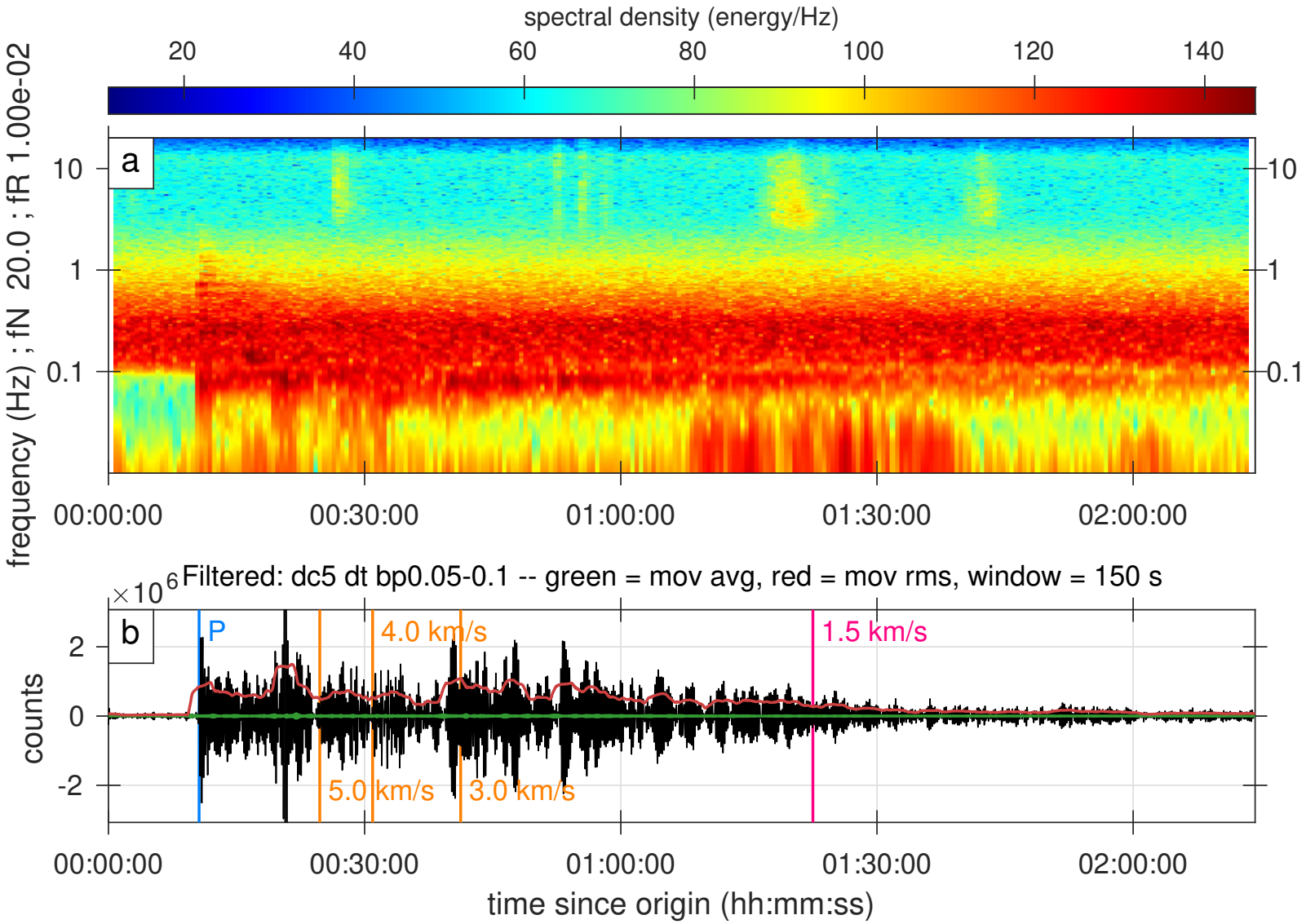
MERMAID observes the secondary-microseism generating process in situ.

Theme 2: Microseisms

MERMAID observes the secondary-microseism generating process in situ*.*

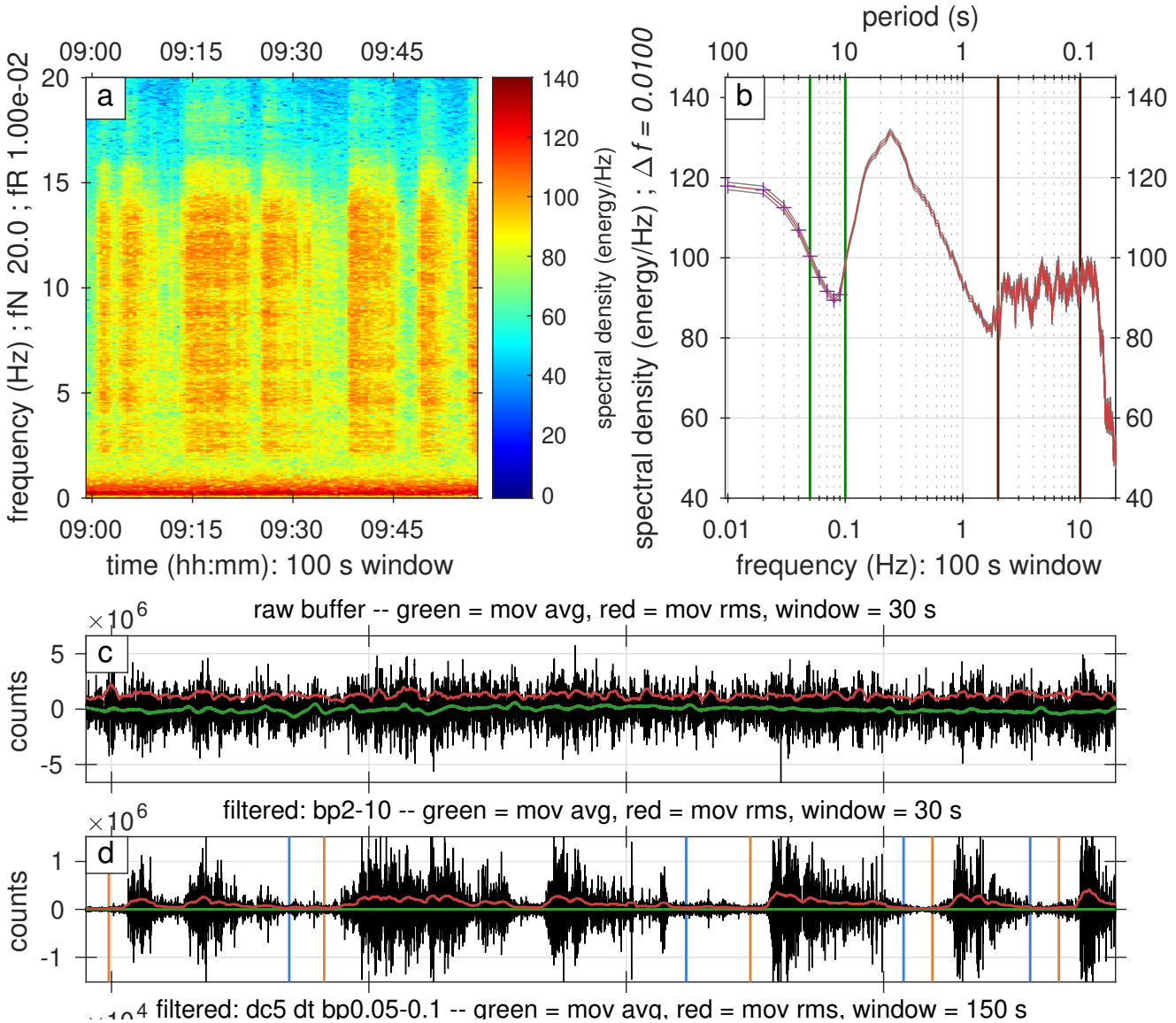
The secondary microseism is of the Rayleigh-wave variety.

Back to the long records — I

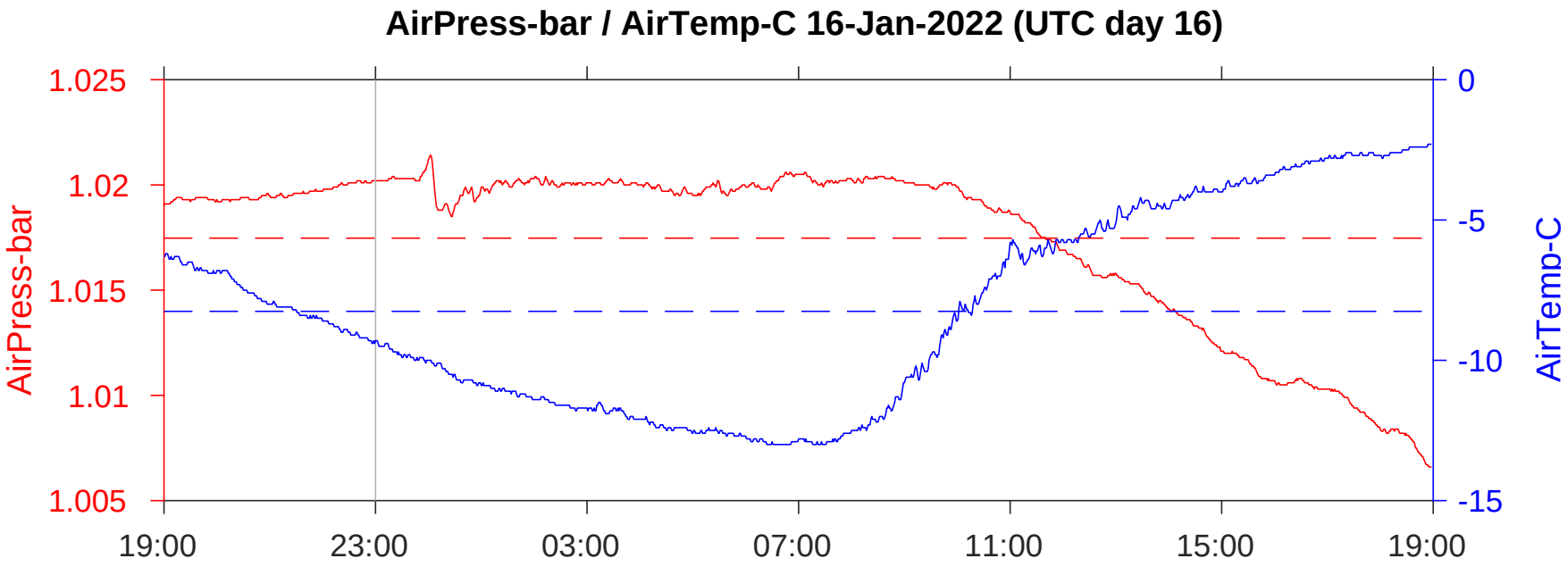


Pipatprathanporn & Simons, 2022

Back to the long records — II



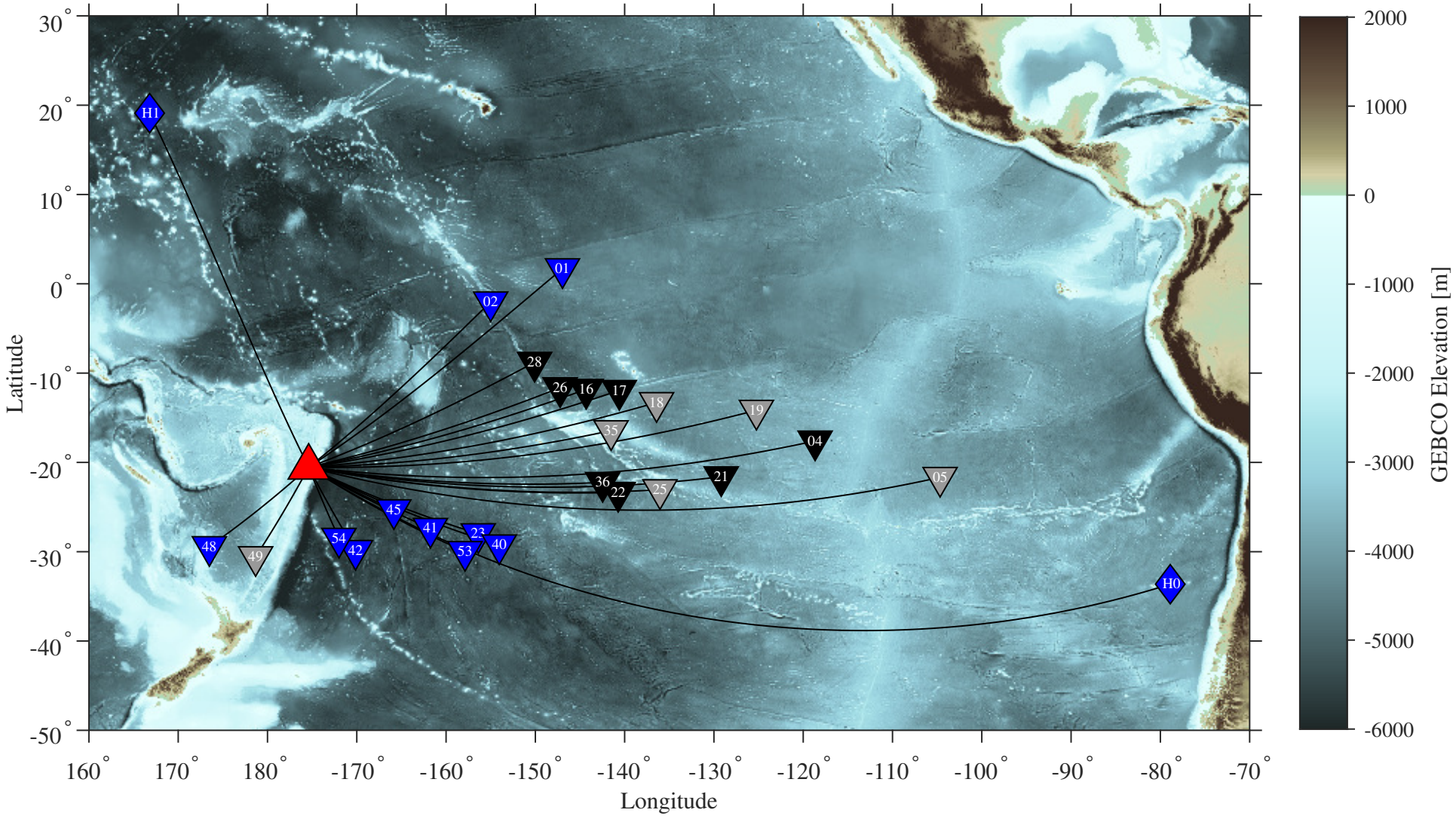
Hunga-Tonga: Guyotweather!



Hunga-Tonga $\leftrightarrow$ Guyot 12,353 km (the short way)

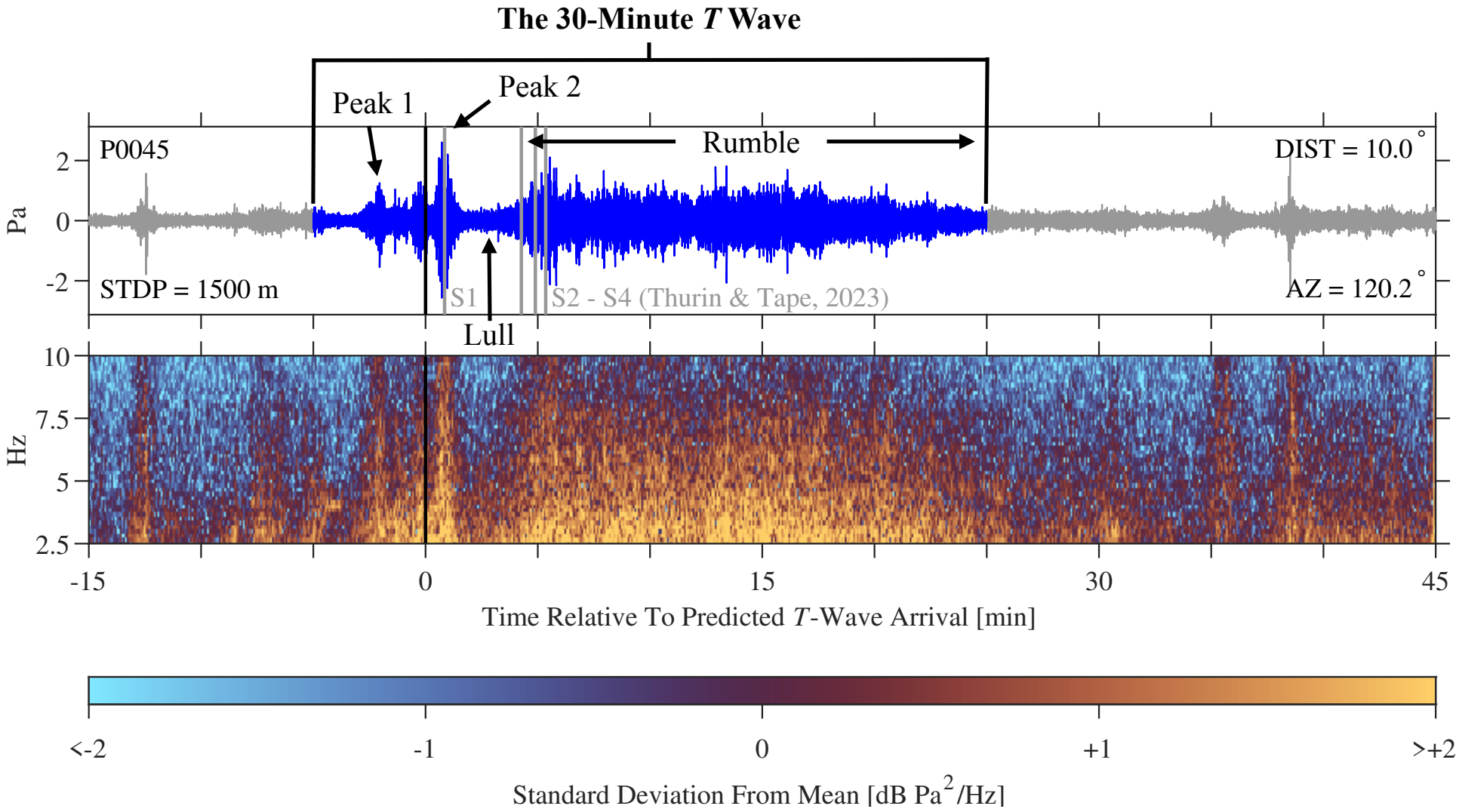
Hunga-Tonga $\leftrightarrow$ Guyot 27,677 km (the long way)

Hunga-Tonga: 24 MERMAIDs were listening!



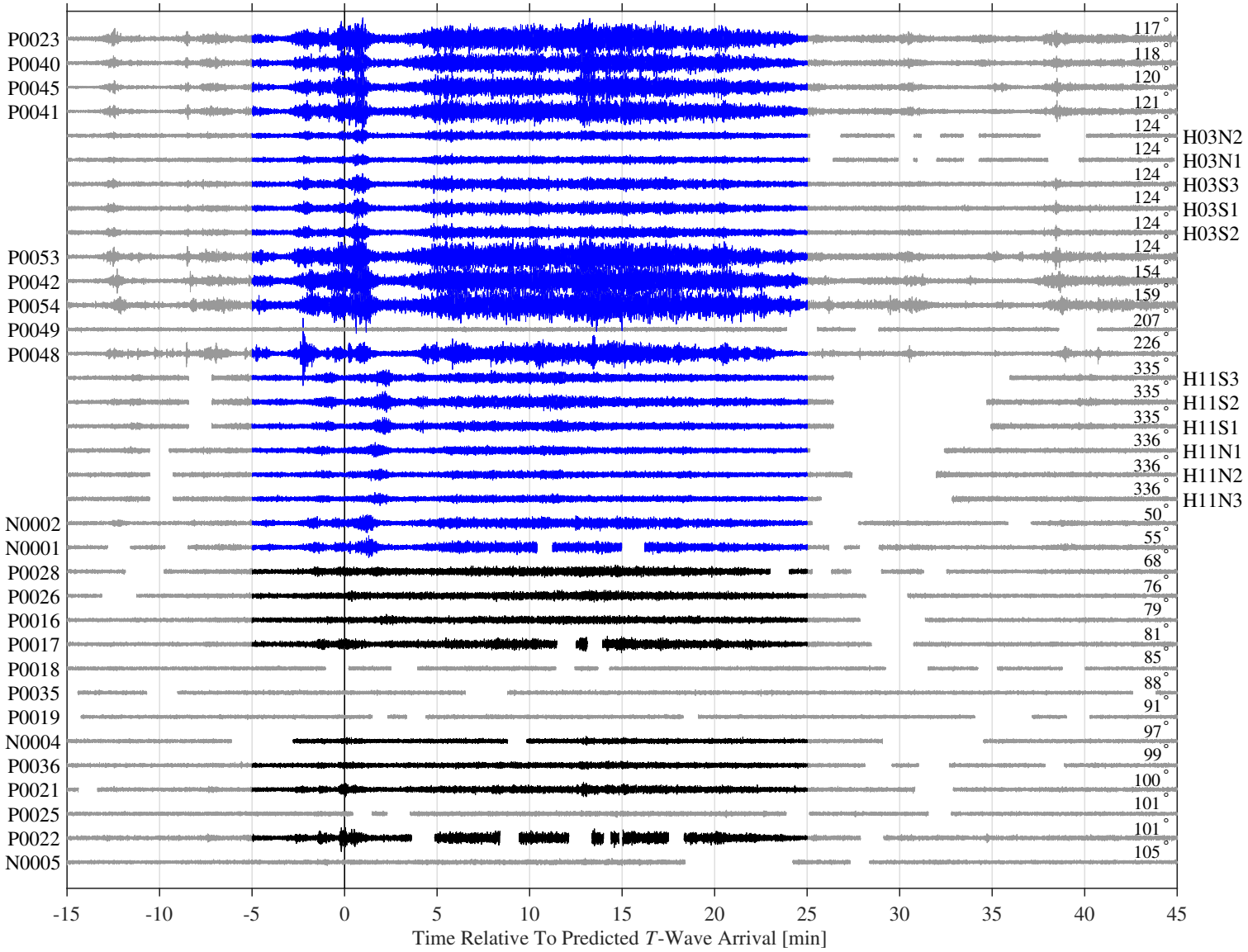
Simon, Simons, Irving et al., *JGR*, 2025

Hunga-Tonga: As heard by MERMAID



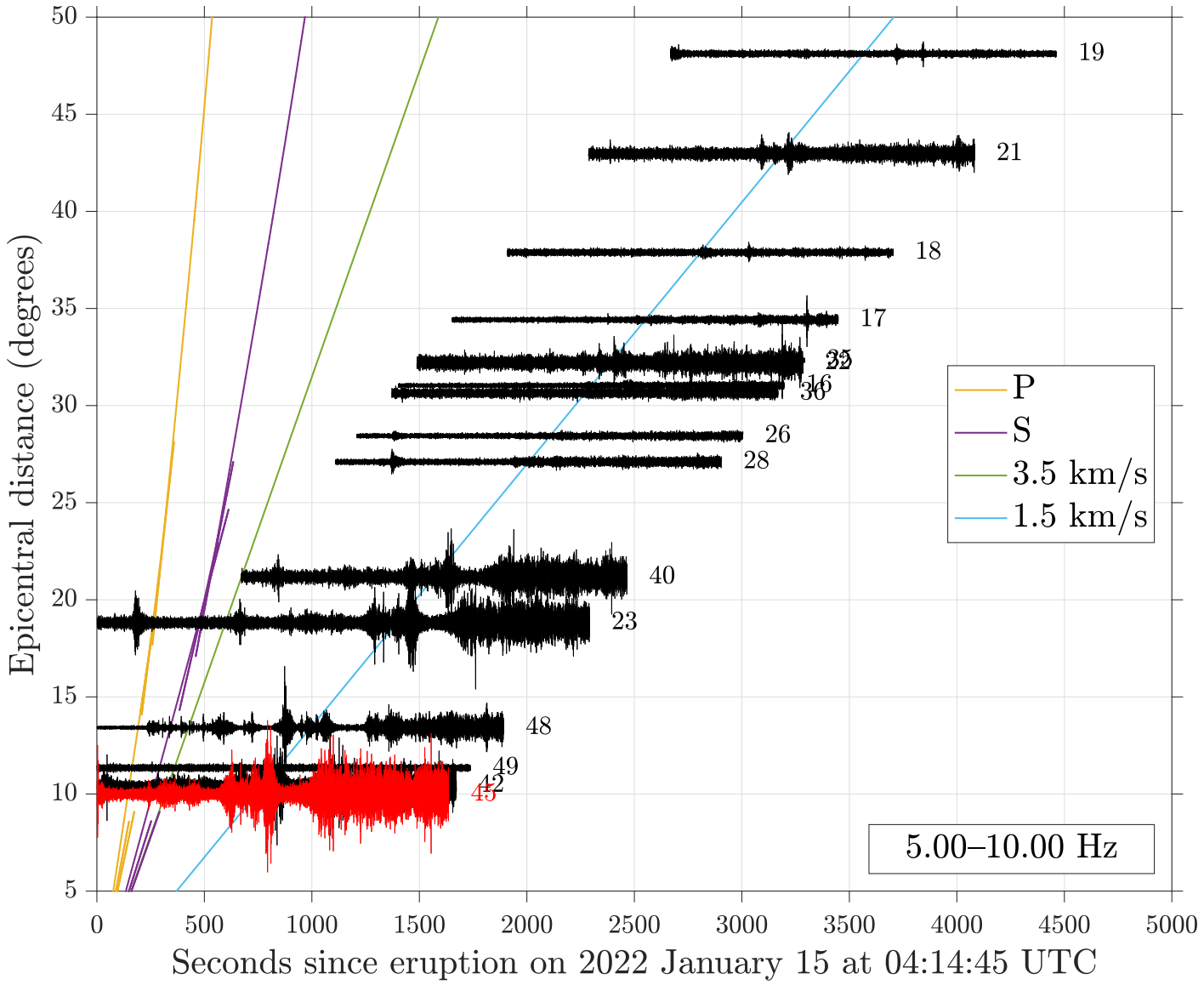
Simon, Simons, Irving et al., *JGR*, 2025

Hunga-Tonga: Record section



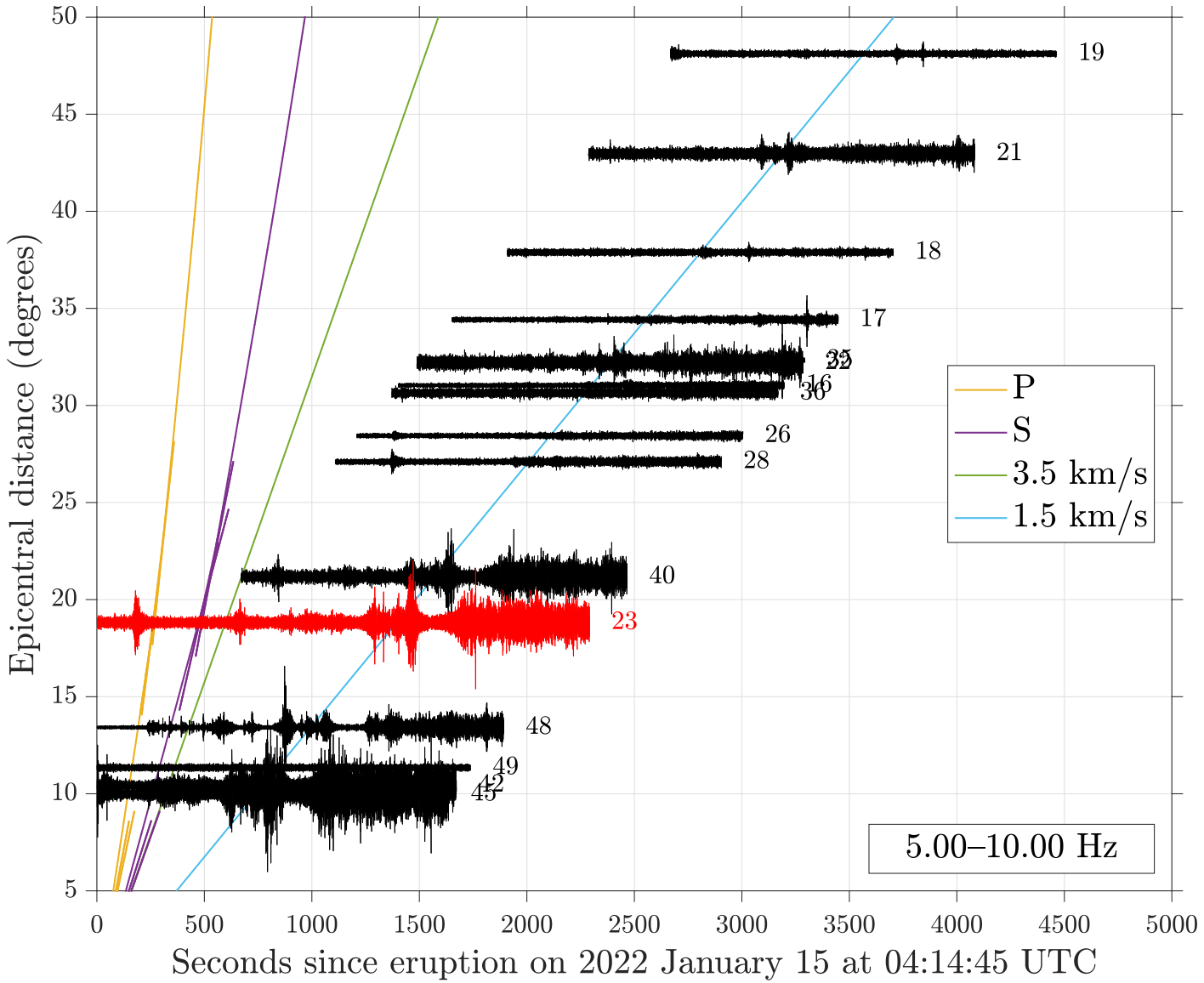
Simon, Simons, Irving et al., *JGR*, 2025

Hunga-Tonga: MERMAID 45



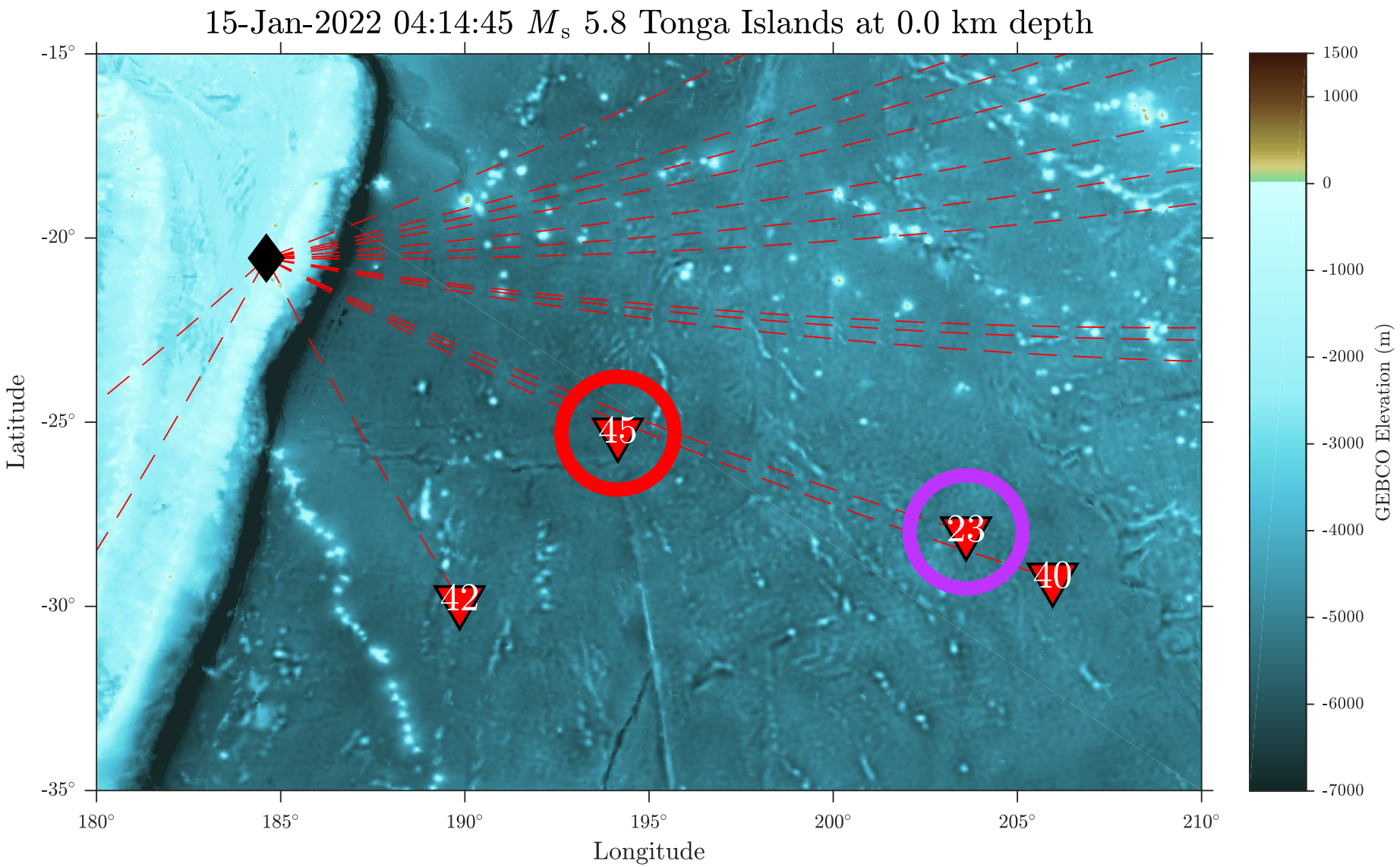
Simon, Simons, Irving et al., *JGR*, 2025

Hunga-Tonga: MERMAID 23



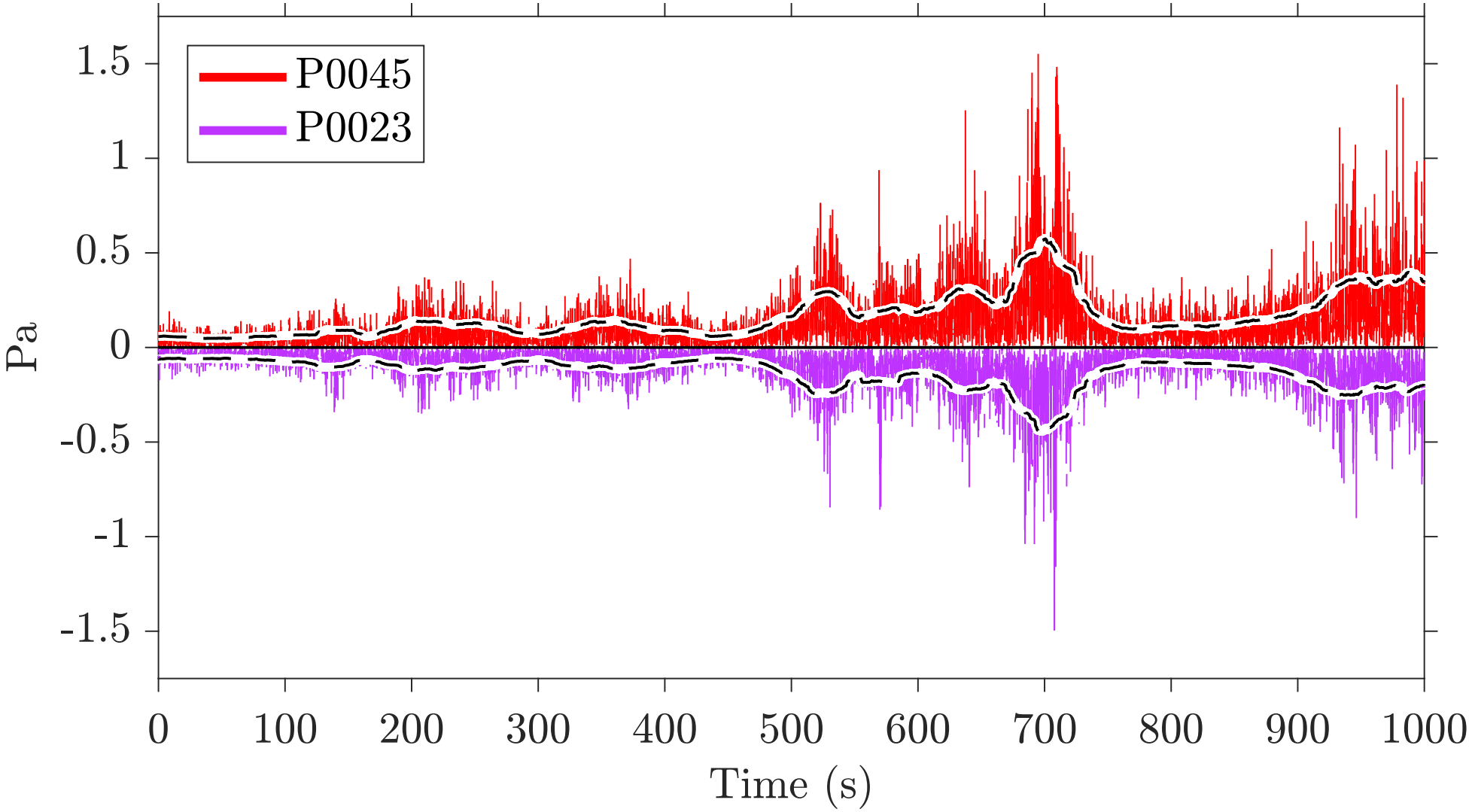
Simon, Simons, Irving et al., *JGR*, 2025

Hunga-Tonga: MERMAID 45 vs 23



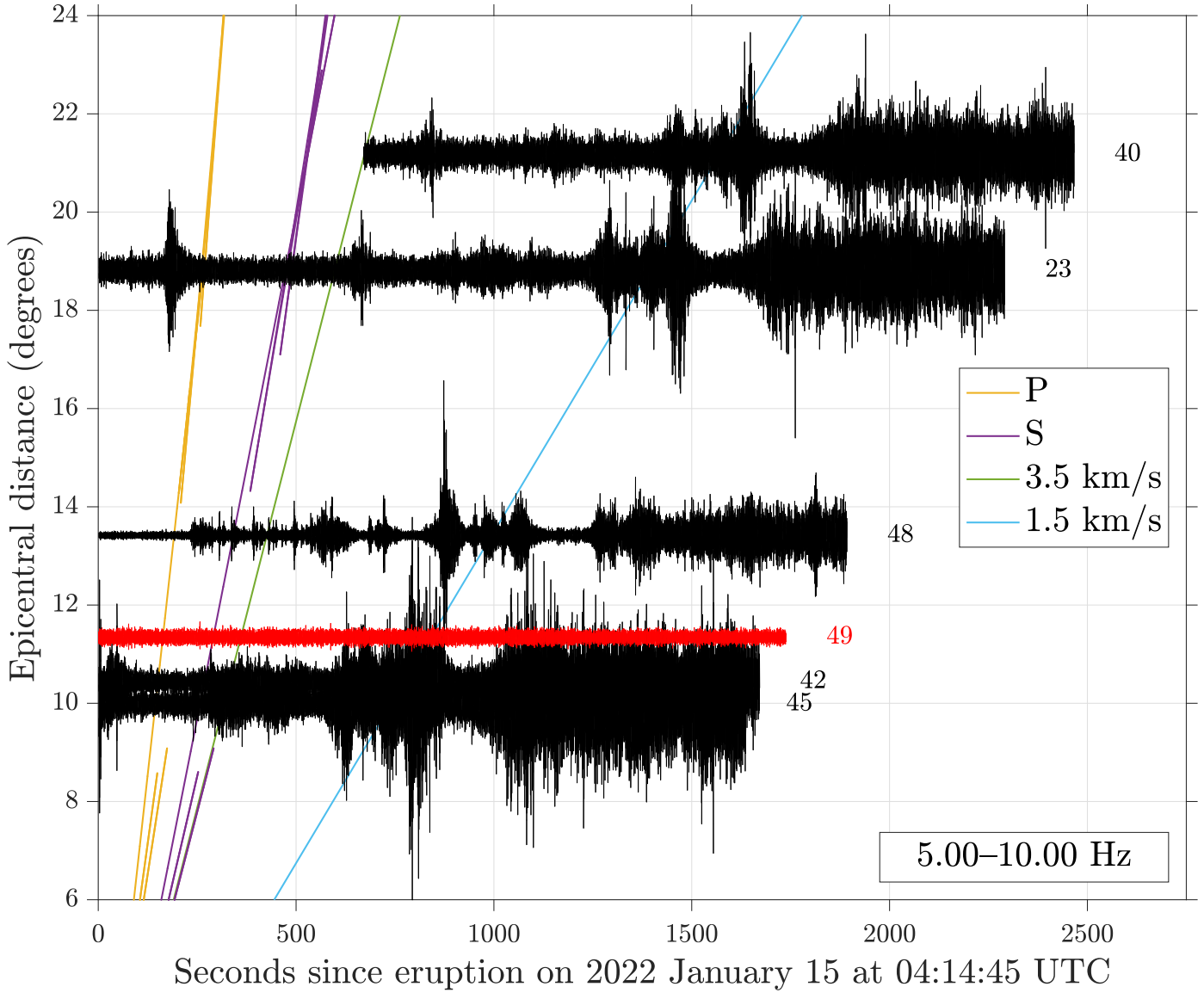
Simon, Simons, Irving et al., *JGR*, 2025

Hunga-Tonga: MERMAID 45 vs 23



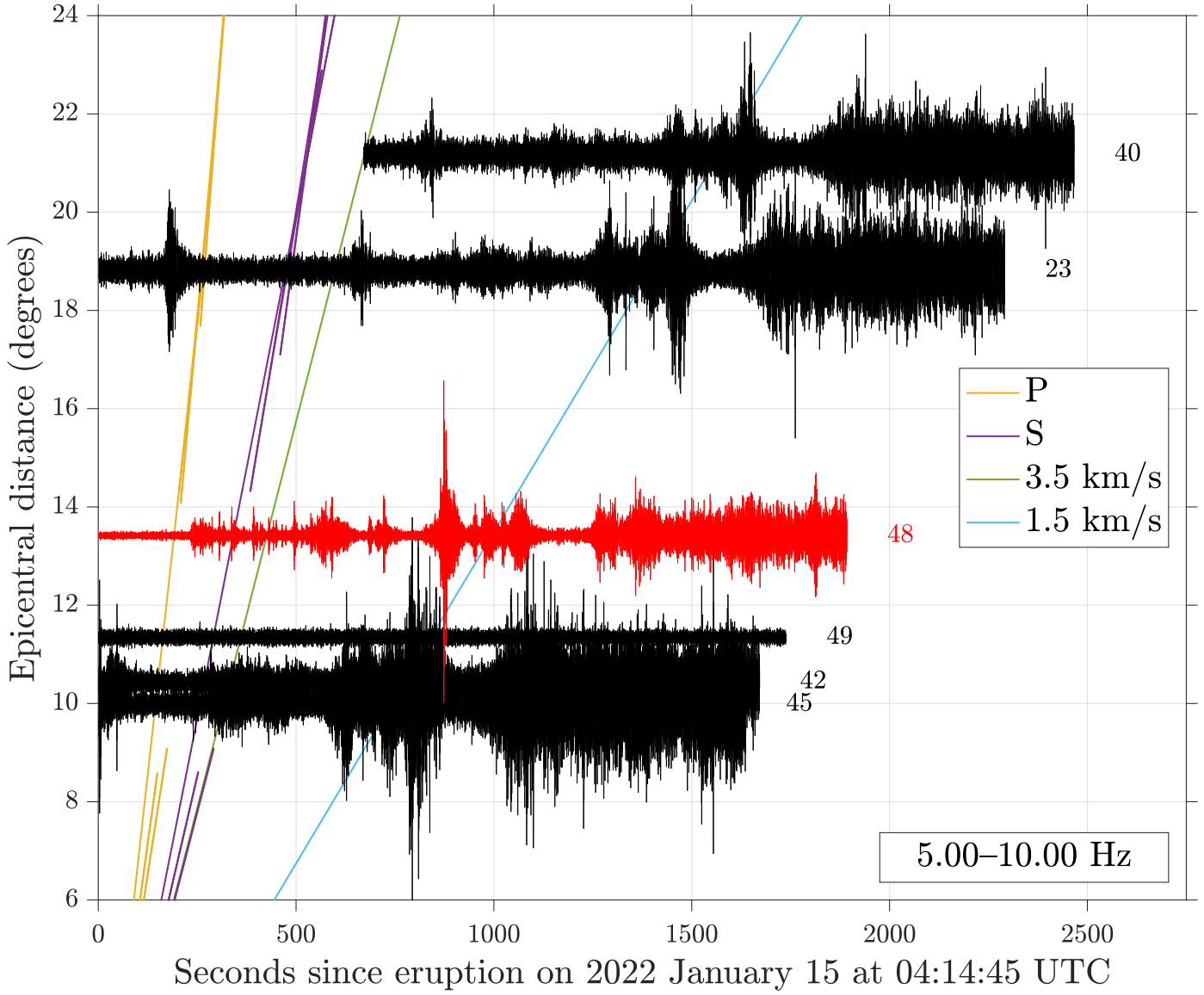
Simon, Simons, Irving et al., *JGR*, 2025

Hunga-Tonga: MERMAID 49



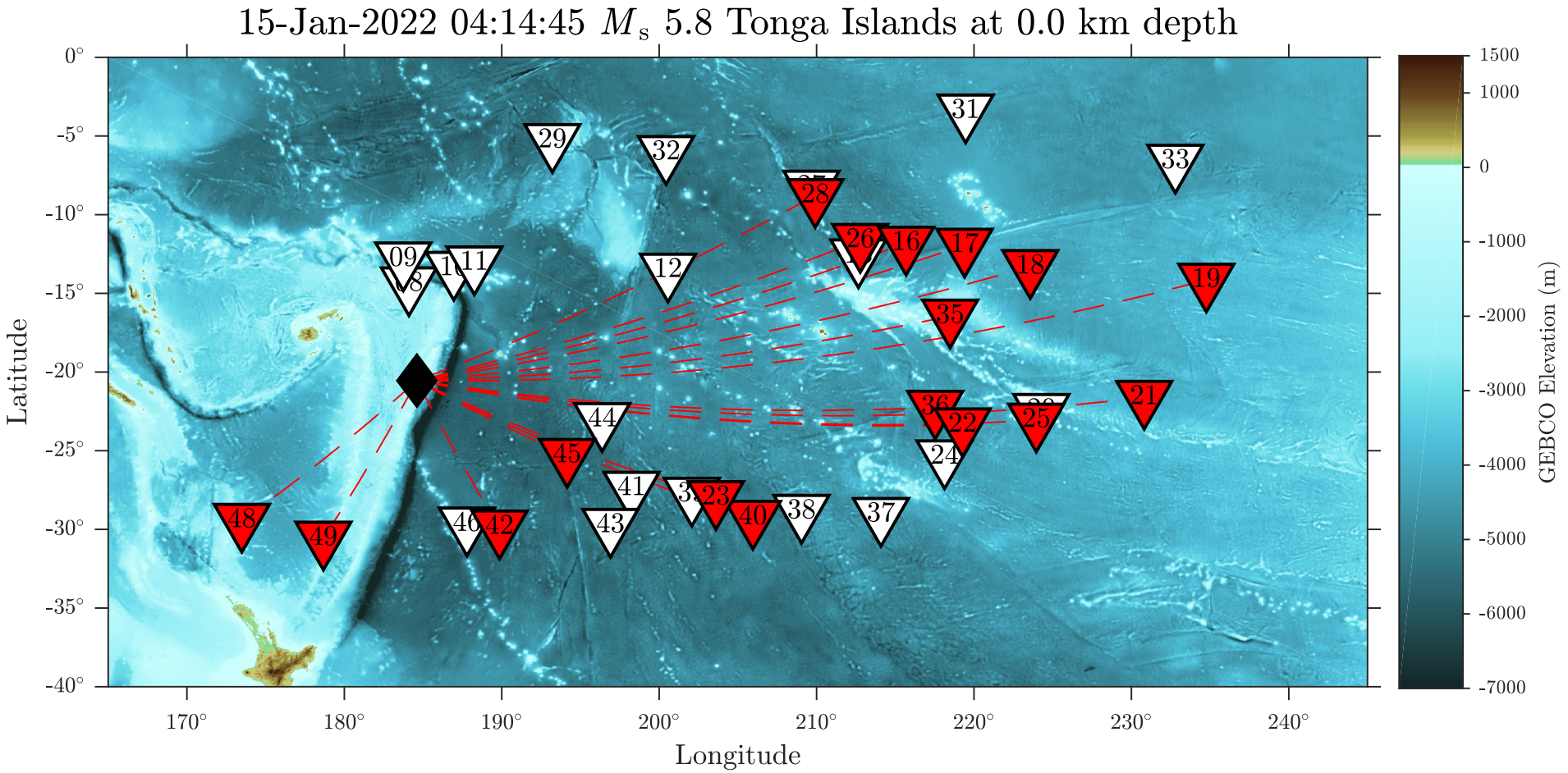
Simon, Simons, Irving et al., *JGR*, 2025

Hunga-Tonga: MERMAID 48



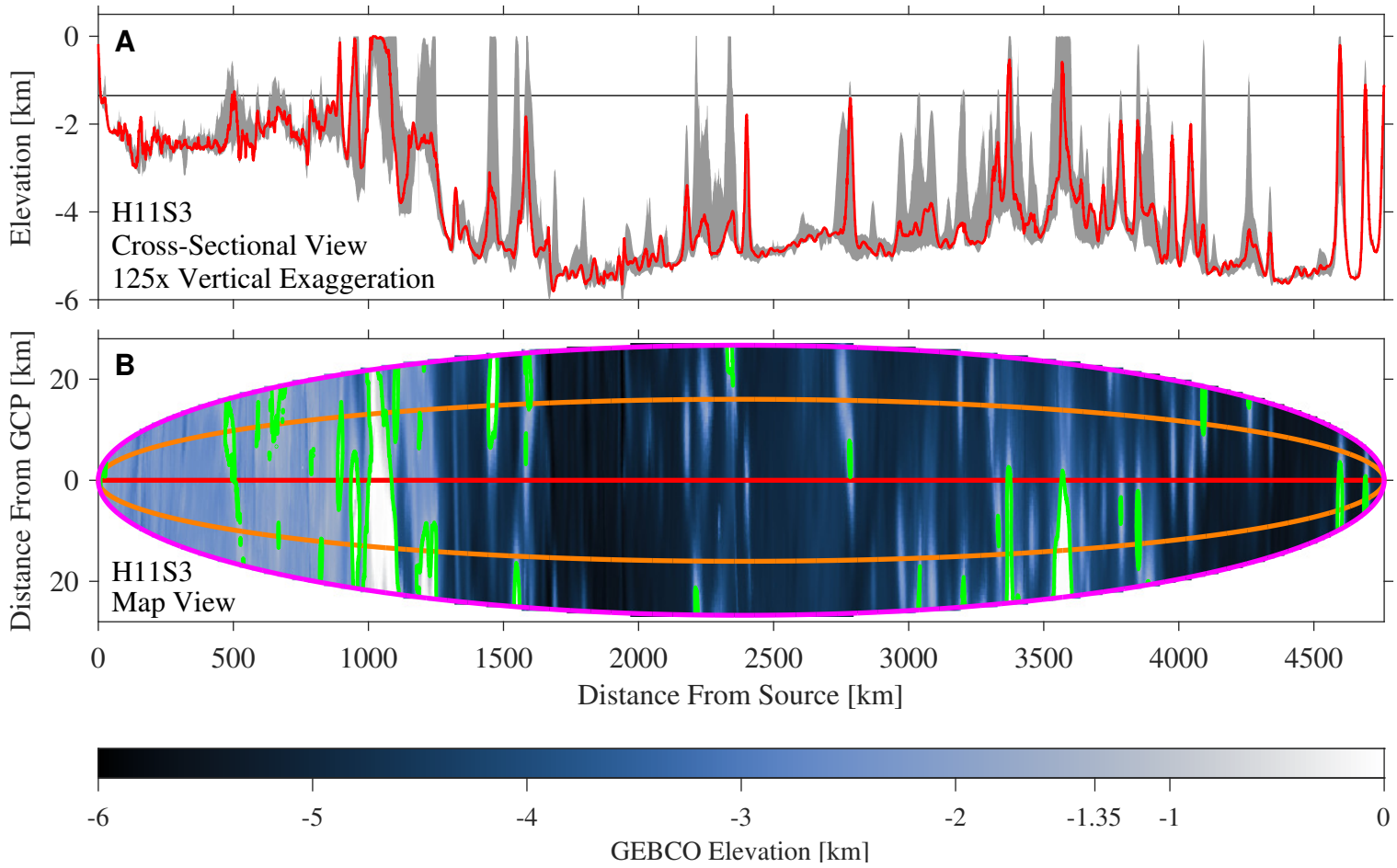
Simon, Simons, Irving et al., *JGR*, 2025

What explains signal character and strength?



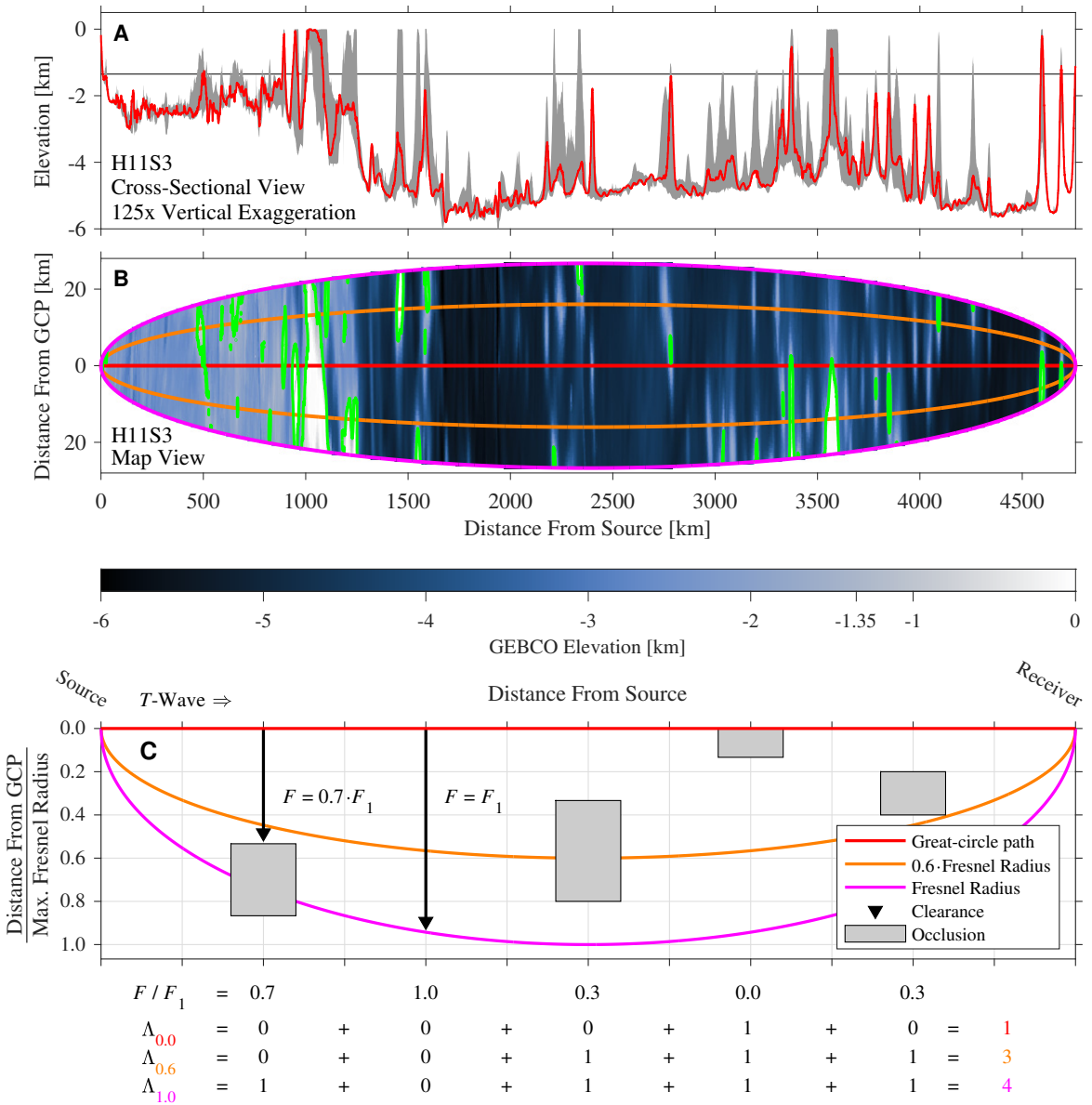
Simon, Simons, Irving et al., *JGR*, 2025

Ocean-bottom interactions



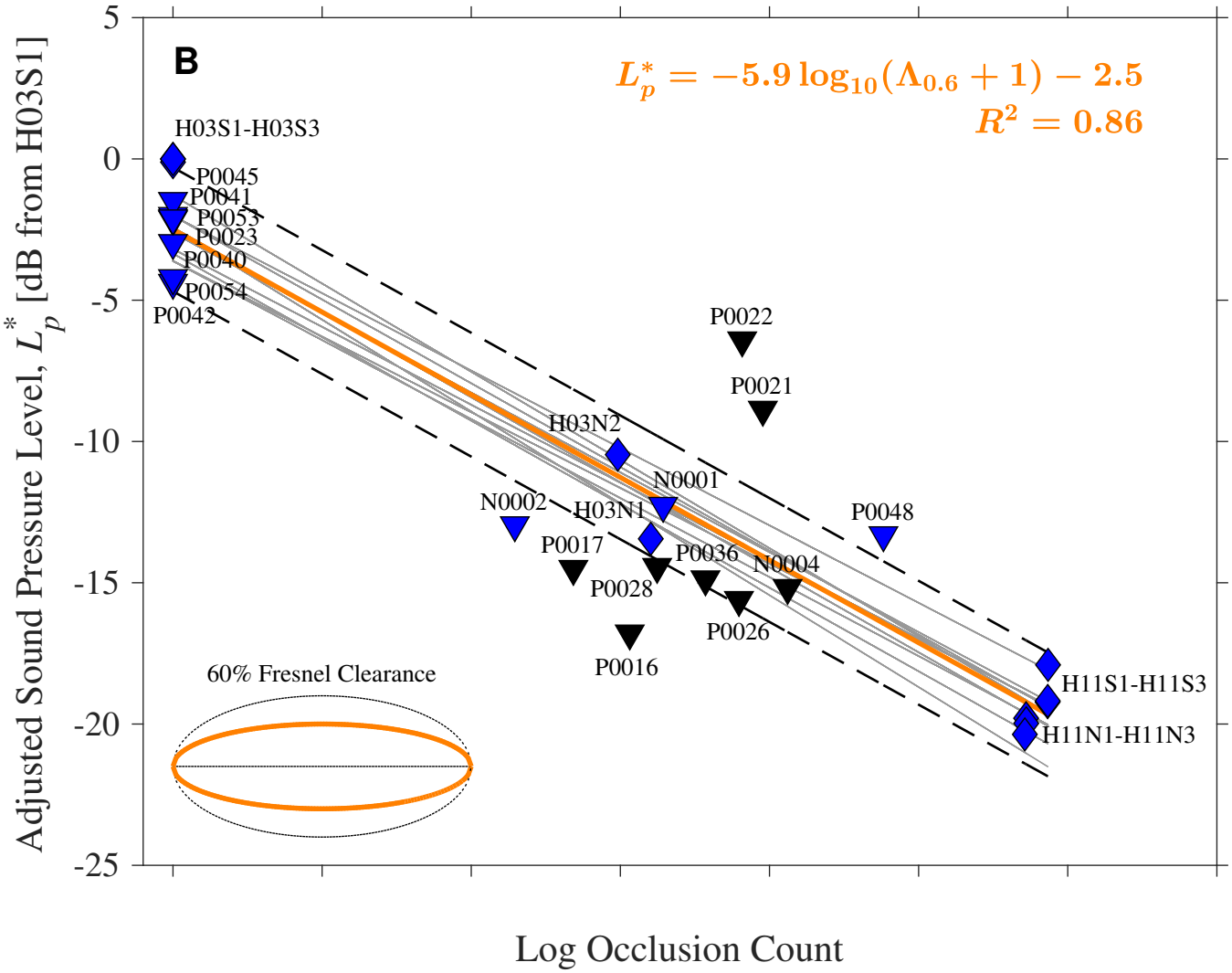
Simon, Simons, Irving et al., *JGR*, 2025

Ocean-bottom interactions



Simon, Simons, Irving et al., *JGR*, 2025

Hunga-Tonga: Ocean-floor interactions



Simon, Simons, Irving et al., *JGR*, 2025

Theme 3: Volcanoes

Theme 3: Volcanoes

MERMAID hears a lot of random *volcanic activity...*

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Heard signal influenced by path effects.

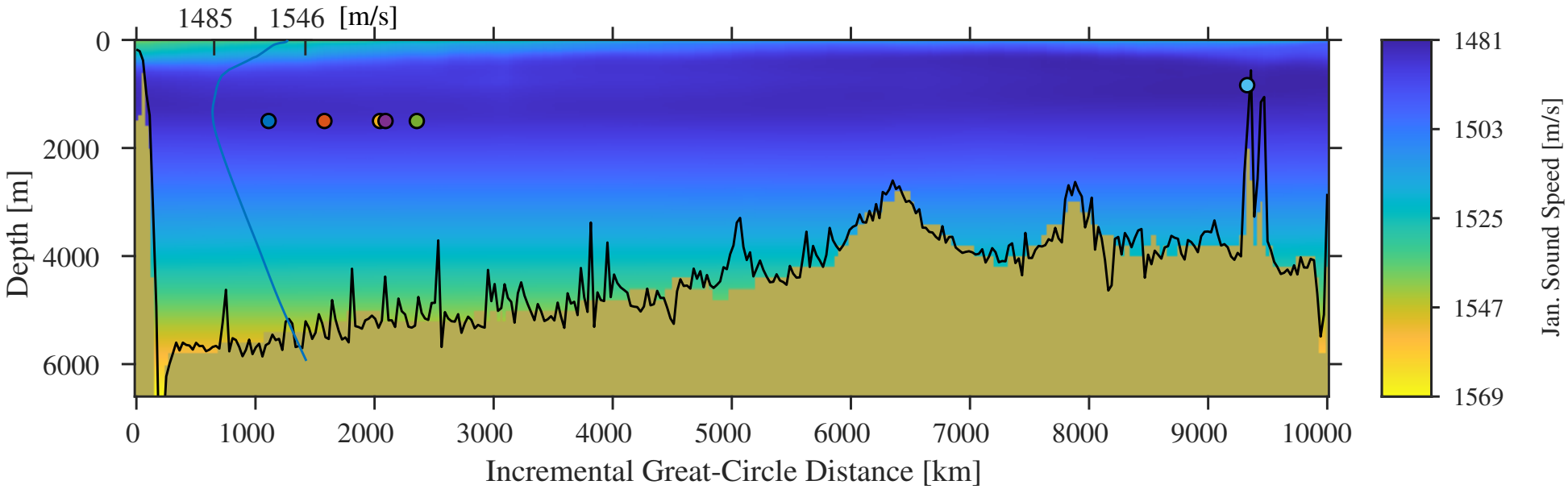
MERMAID IV

(2023–present)





Active and passive thermometry



Coming to an ocean near You

