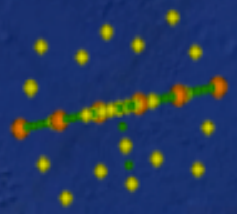
Constraints on Flow Dynamics within the Oceanic Asthenosphere from an Ocean-bottom Seismograph Array in the Central Pacific



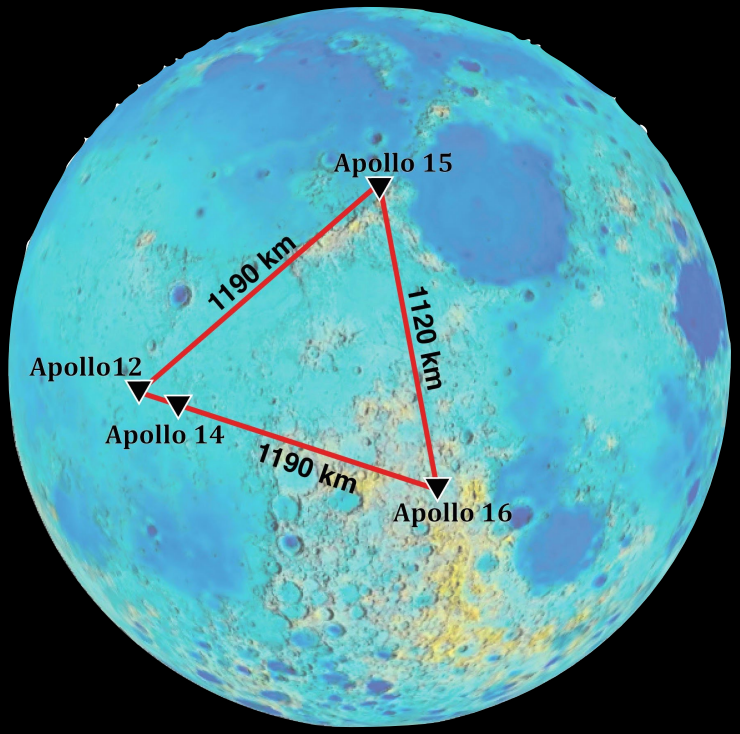
林佩瑩 Pei-Ying Patty Lin

Taiwan Ocean Research Institute

NCU, Zhongli, Taiwan, Dec. 2016

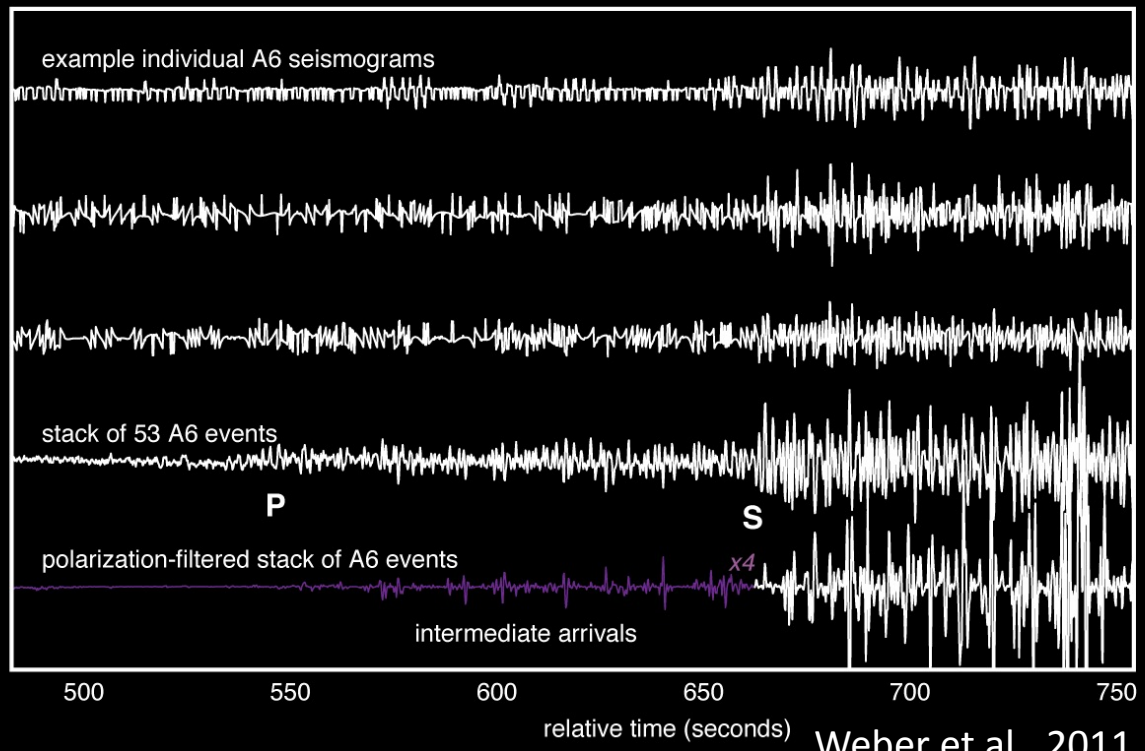
OBS data is the noisiest seismic record?

Apollo Passive Seismic Experiment (APSE)



Ans:

NOPE!



Weber et al., 2011

Team members

- **Lamont-Doherty Earth Observatory of Columbia University**

Pei-Ying Patty Lin

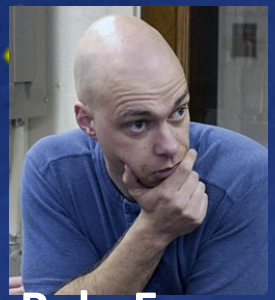
James Gaherty

Ge Jin

- **Woods Hole Oceanographic Institution**

John Collins

Daniel Lizarralde


Rob. Evans

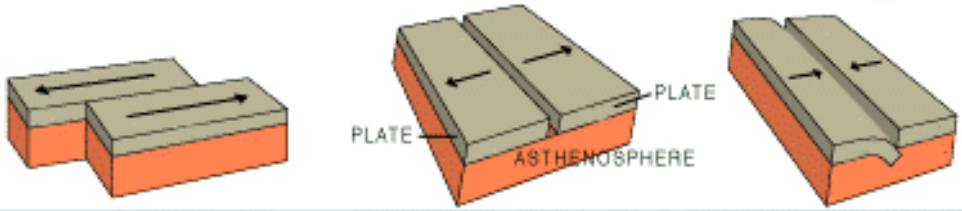
Hannah Mark

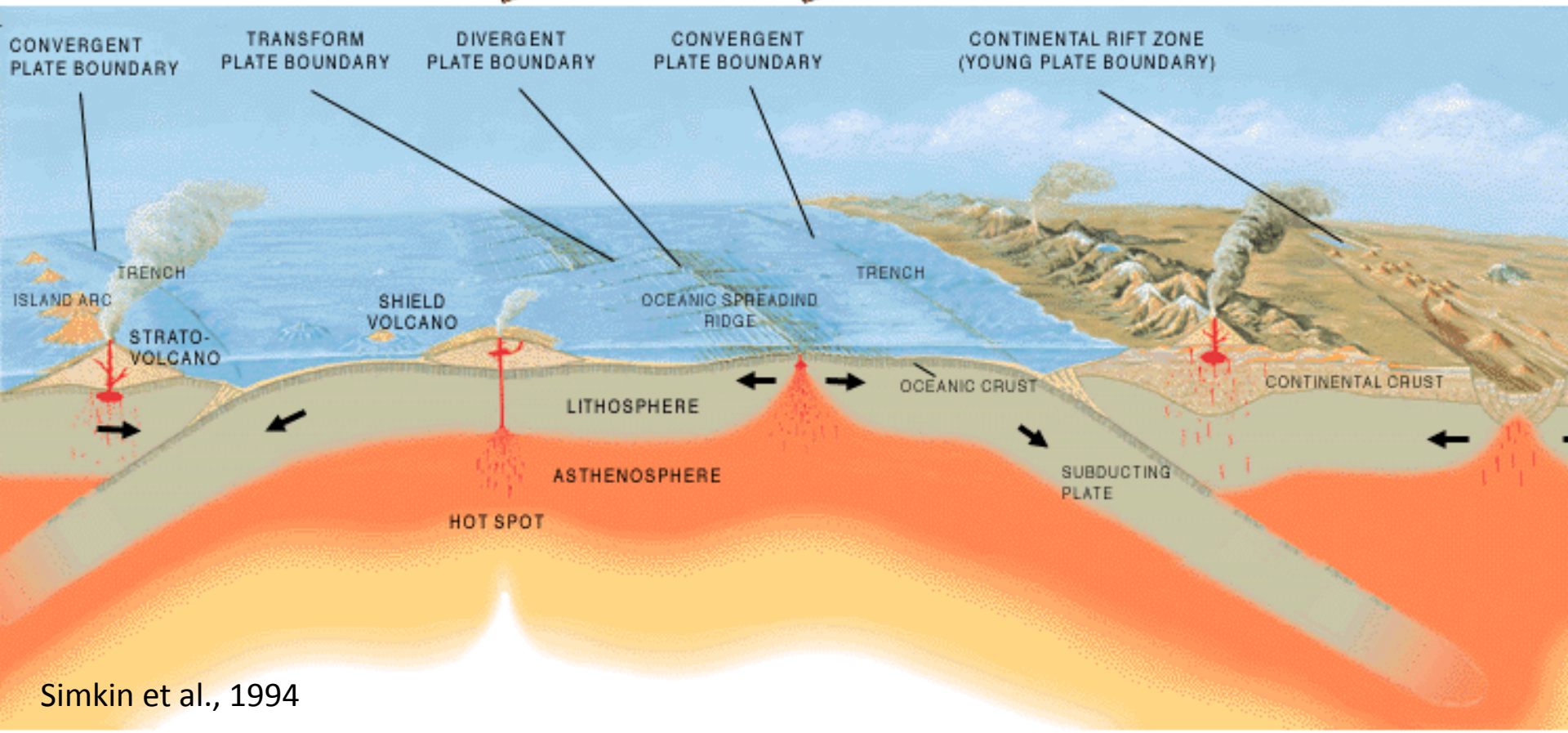
Emily Sarafian

- **Brown University**

Greg Hirth

What is a plate?

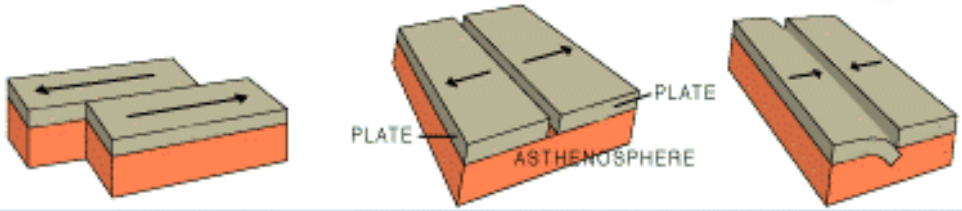


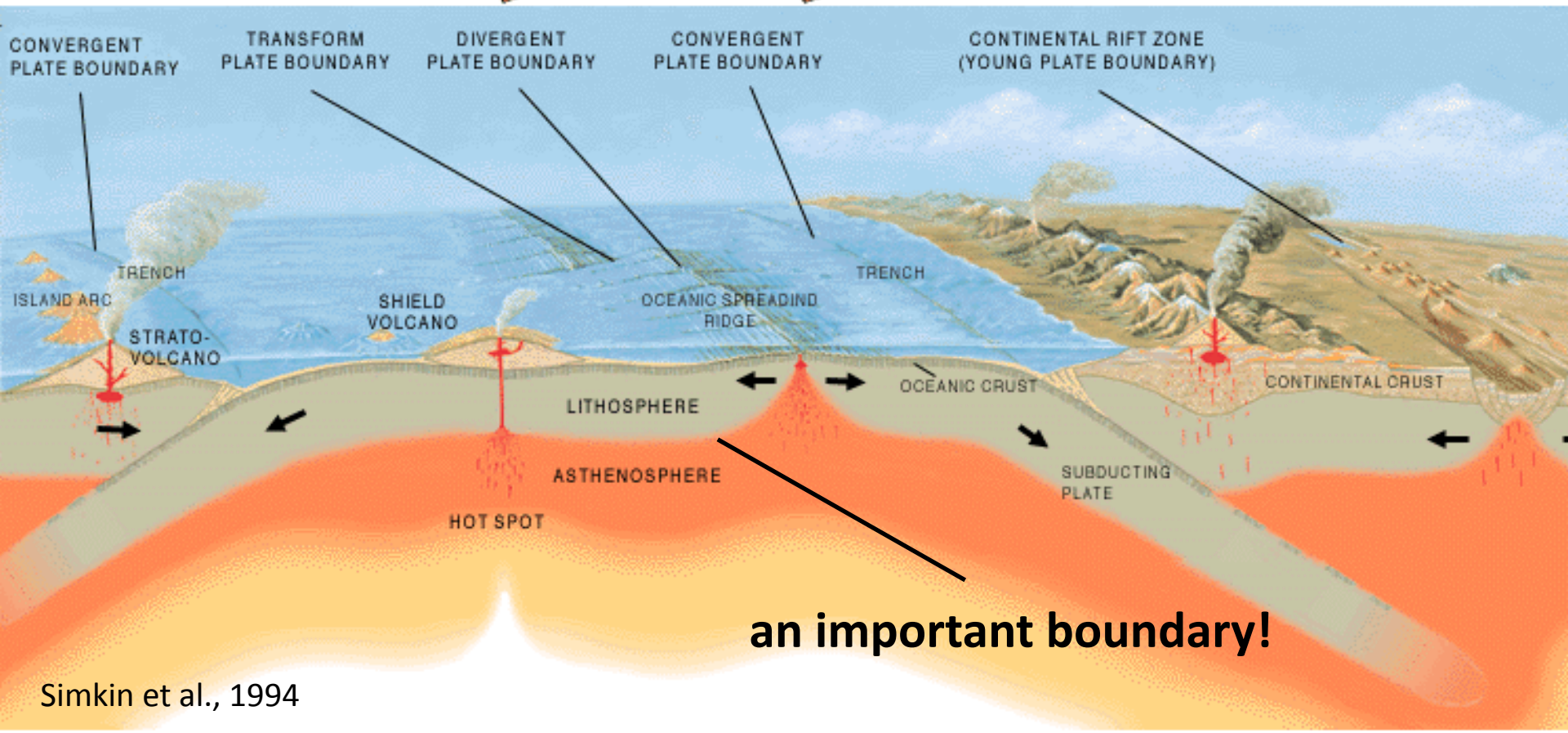


Simkin et al., 1994

Geoscientists focus on plate boundary interactions (for good reasons!)

What is a plate?

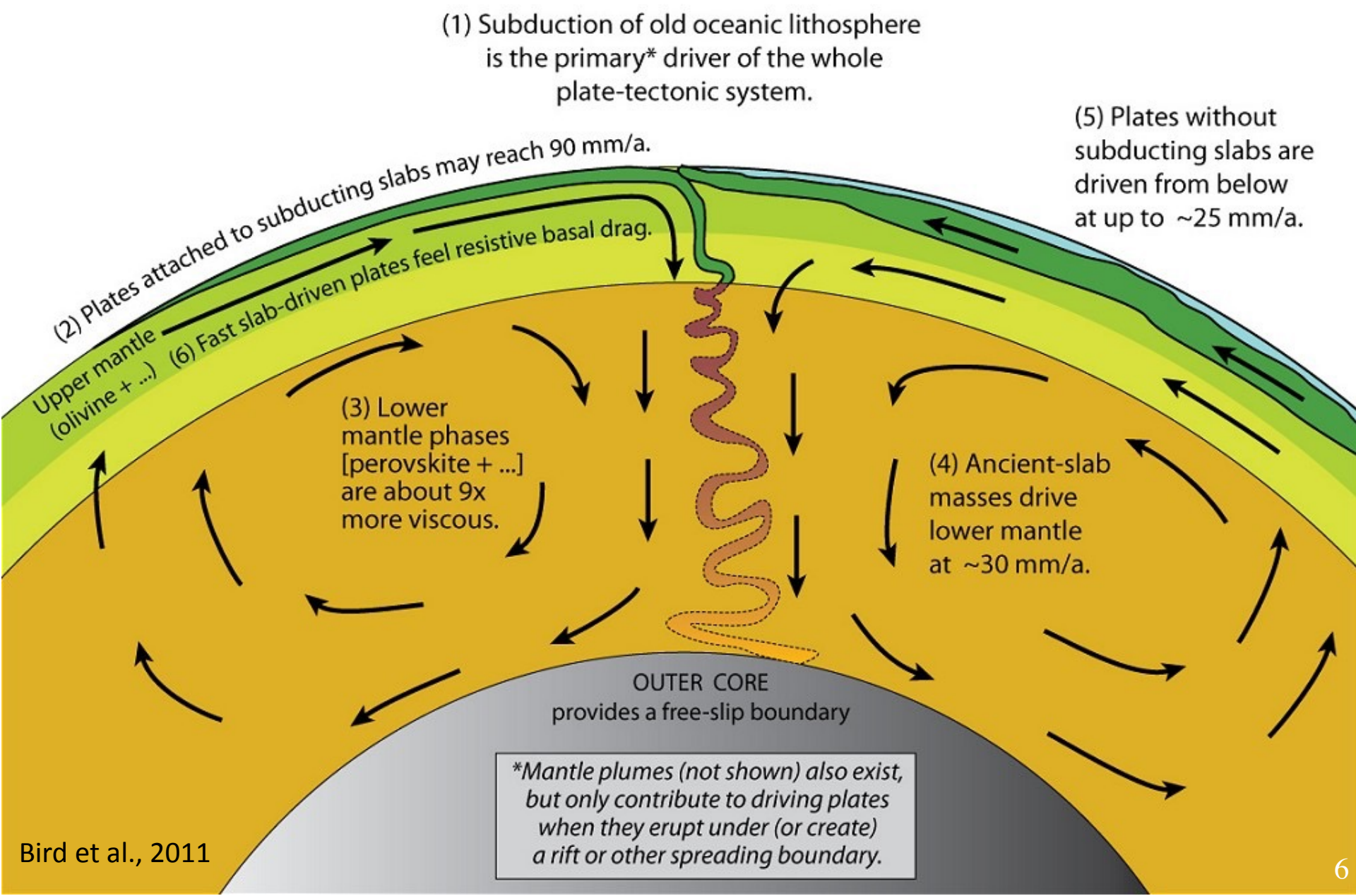




Simkin et al., 1994

Geoscientists focus on plate boundary interactions (for good reasons!)
but rheology of plate controls much of these interactions

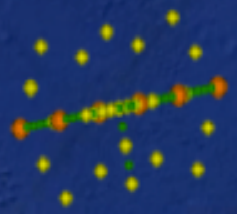
And how does it interact with underlying mantle?



Bird et al., 2011

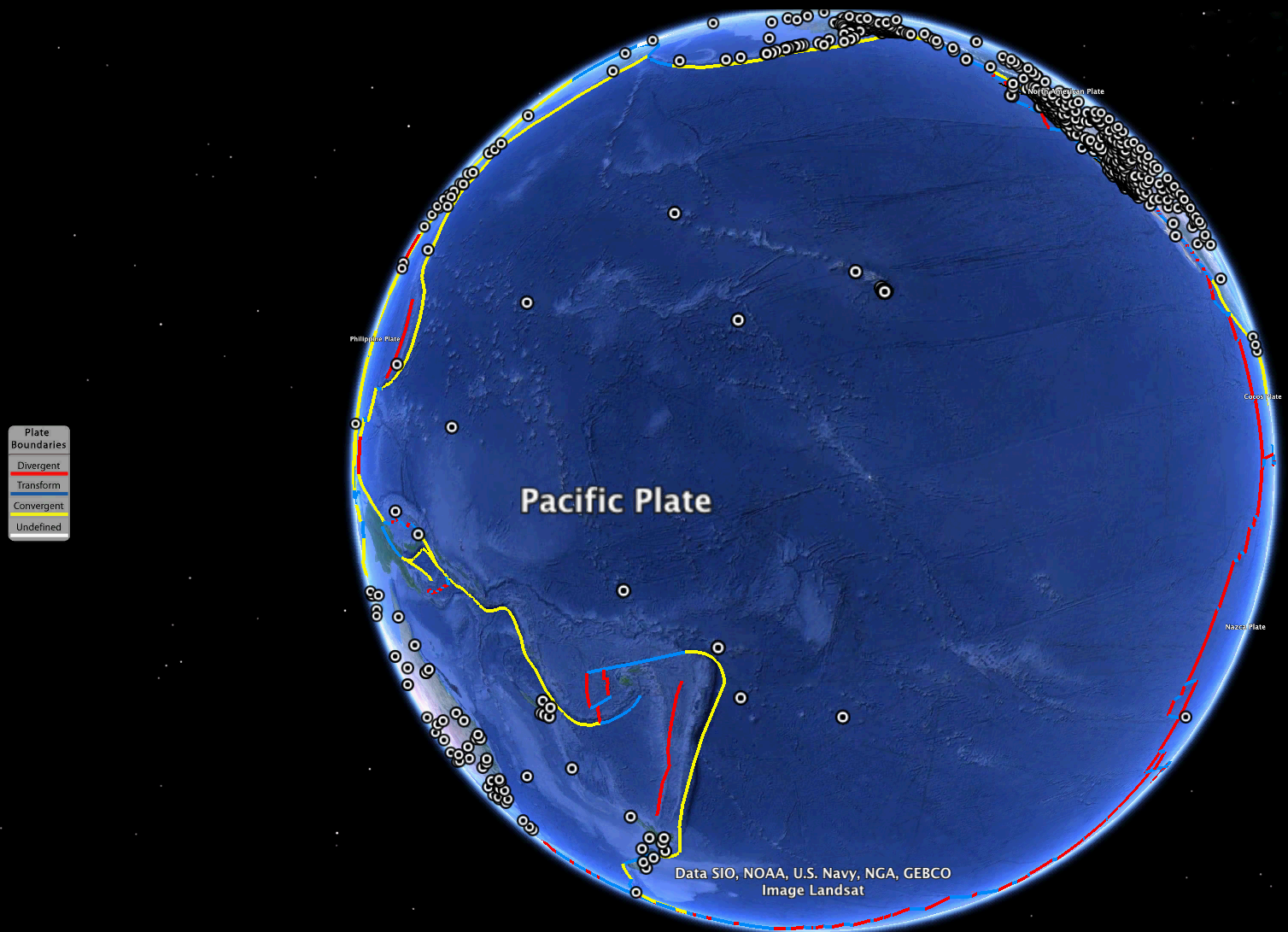
Motivation

- Observations of detailed oceanic upper-mantle structure are limited due to spatial sampling – excellent global coverage, but little at scale for understanding detailed lithosphere/asthenosphere processes



Seismic observations in the Pacific Basin

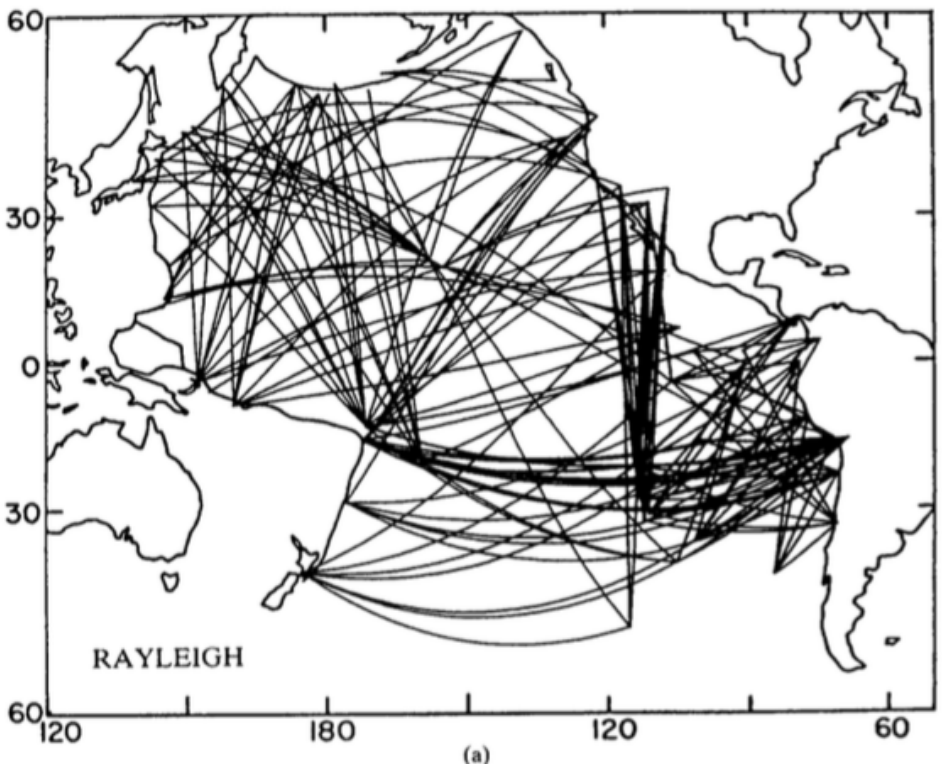
- **Using global dataset** (Smith et al., 2004; Maggi et al., 2006; Visser et al., 2008; Ekström, 2011; Yuan & Beghein, 2013; French et al., 2013; etc.)

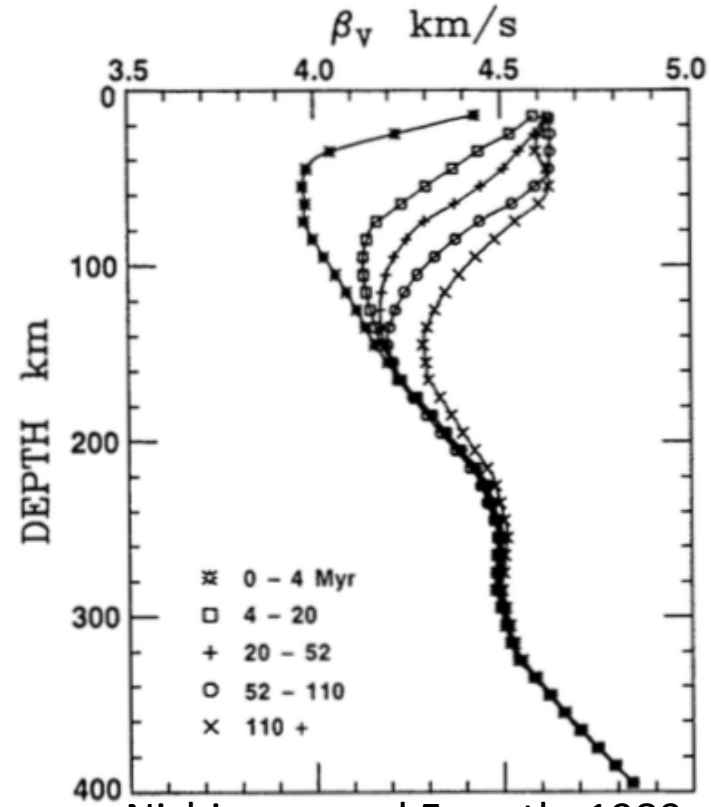


Google earth

Seismic observations in the Pacific Basin

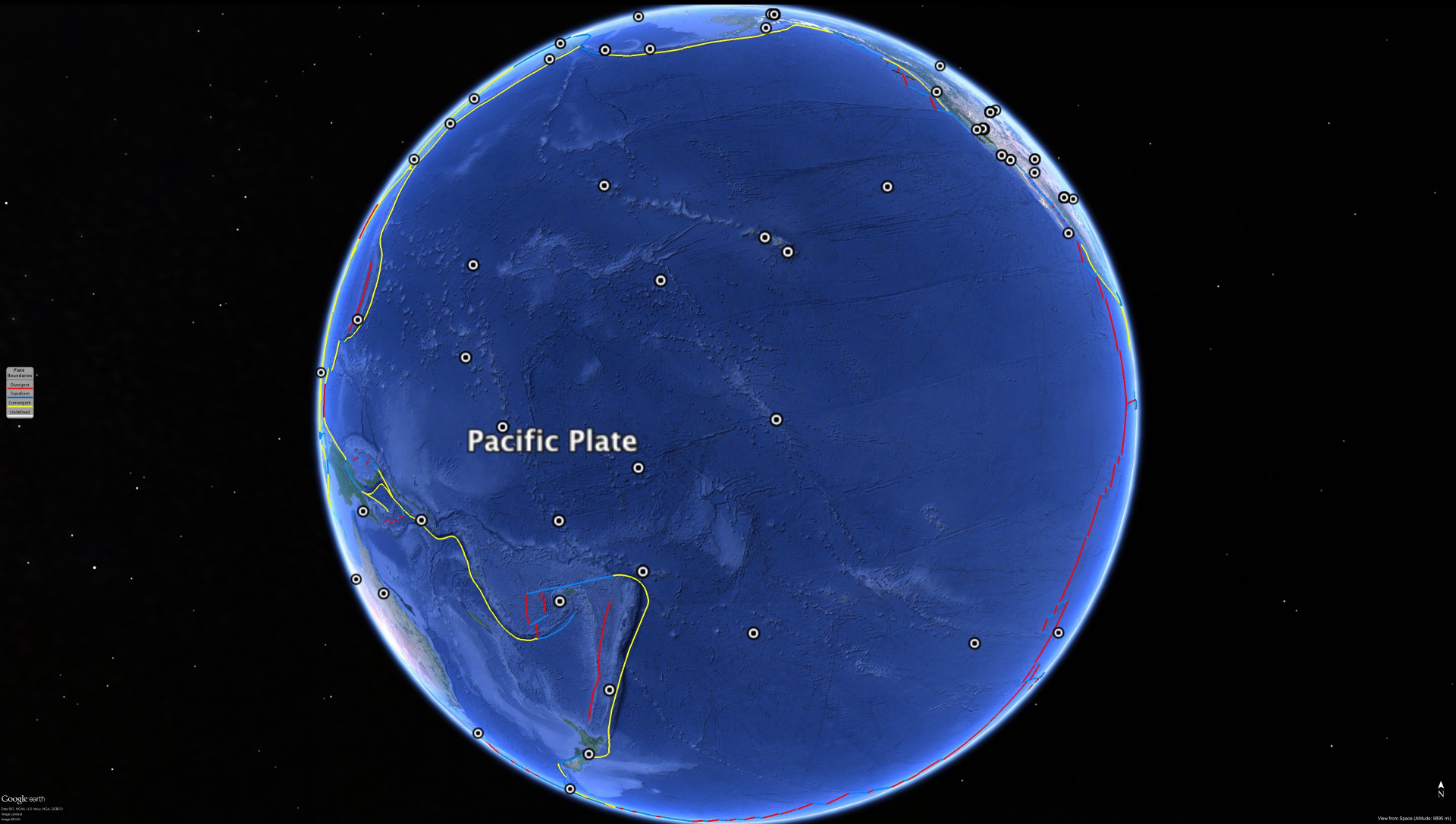
- Using global dataset (Smith et al., 2004; Maggi et al., 2006; Visser et al., 2008; Ekström, 2011; Yuan & Beghein, 2013; etc.)
- Underside Reflections (Schmerr, 2012; Rychert et al, 2012; etc.)
- **Limited stations in ocean basins** (Nishimura & Forsyth, 1989; Montagner, 2002; Olugboji et al, 2013; etc.)





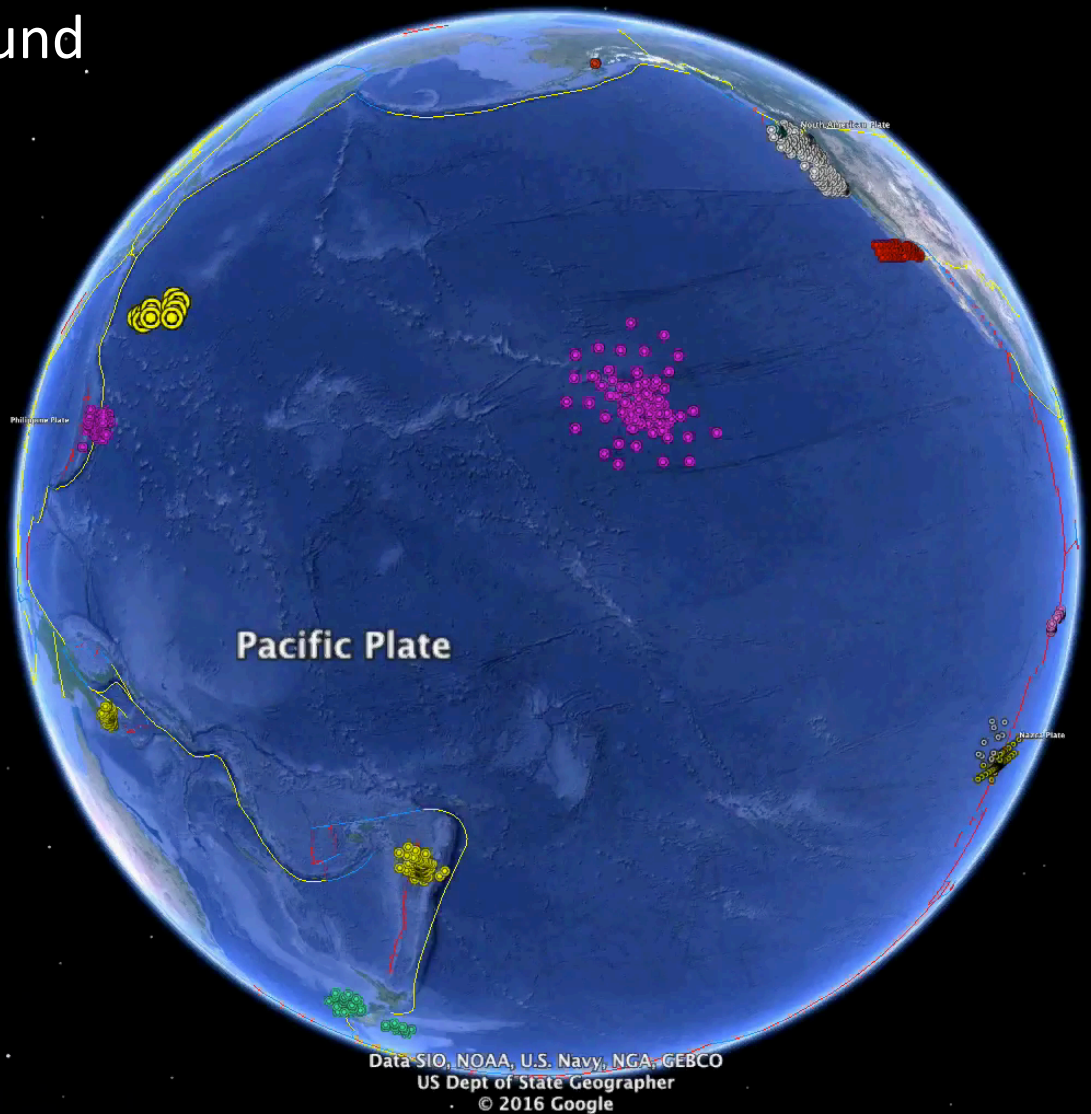
Nishimura and Forsyth, 1989

Limited stations in the Pacific Ocean Basin



OBS deployments in the Pacific Ocean Basin

- **Ocean Bottom Seismograph Deployments**
  OBSs usually are deployed at the area with interesting tectonic background



Motivation

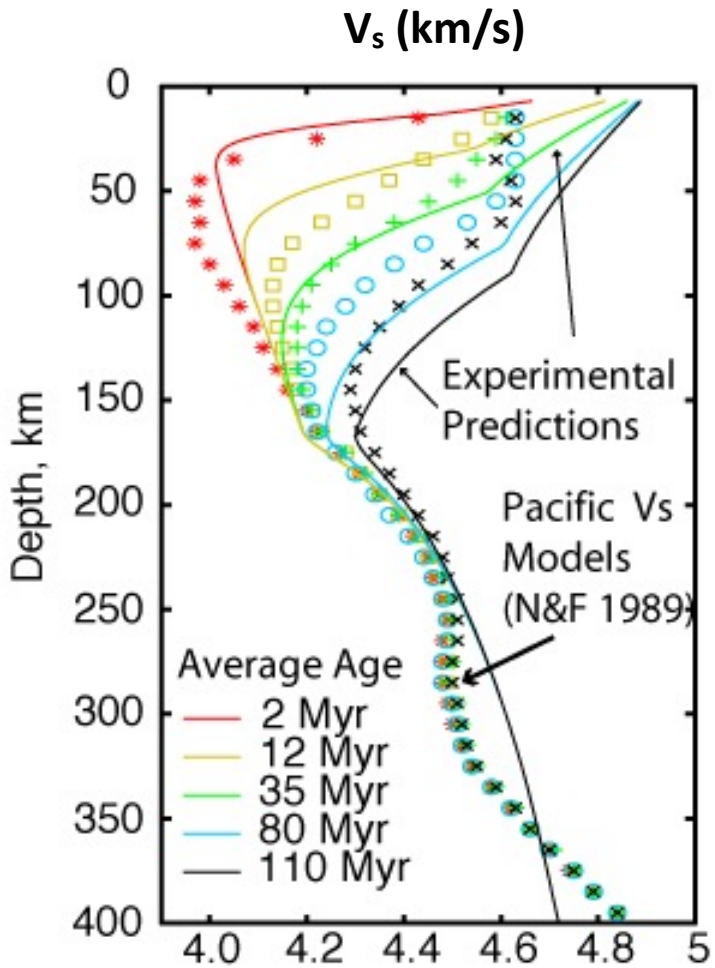
- Observations of detailed oceanic upper-mantle structure are limited due to spatial sampling – excellent global coverage, but little at scale for understanding detailed lithosphere/asthenosphere processes

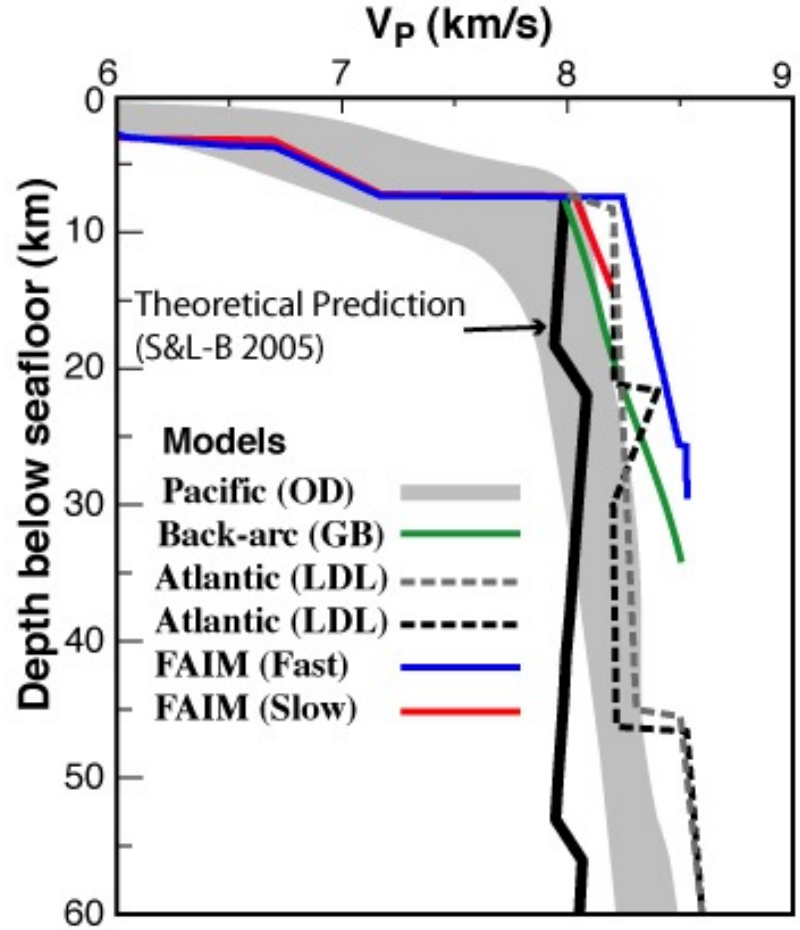
- **Seismic observations from the ocean basins are inconsistent with the theoretical models of oceanic upper mantle structure**

Seismic observations in ocean basins

The previous seismic observations are **NOT** consistent with laboratory measurements such as the

- depth of low velocity zone (LVZ)
- Velocity gradient in lid





Faul and Jackson, 2005

Motivation

- Observations of detailed oceanic upper-mantle structure are limited due to spatial sampling – excellent global coverage, but little at scale for understanding detailed lithosphere/asthenosphere processes

- Seismic observations from the ocean basins are inconsistent with the theoretical models of oceanic upper mantle structure

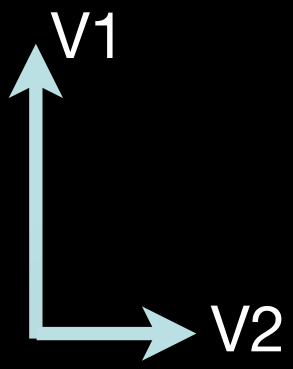
- **Variation and strength in anisotropy is important for explaining the velocity gradient with depth and the nature of lithosphere-asthenosphere boundary (LAB)**

What is seismic anisotropy?

http://www.webmineral.com/

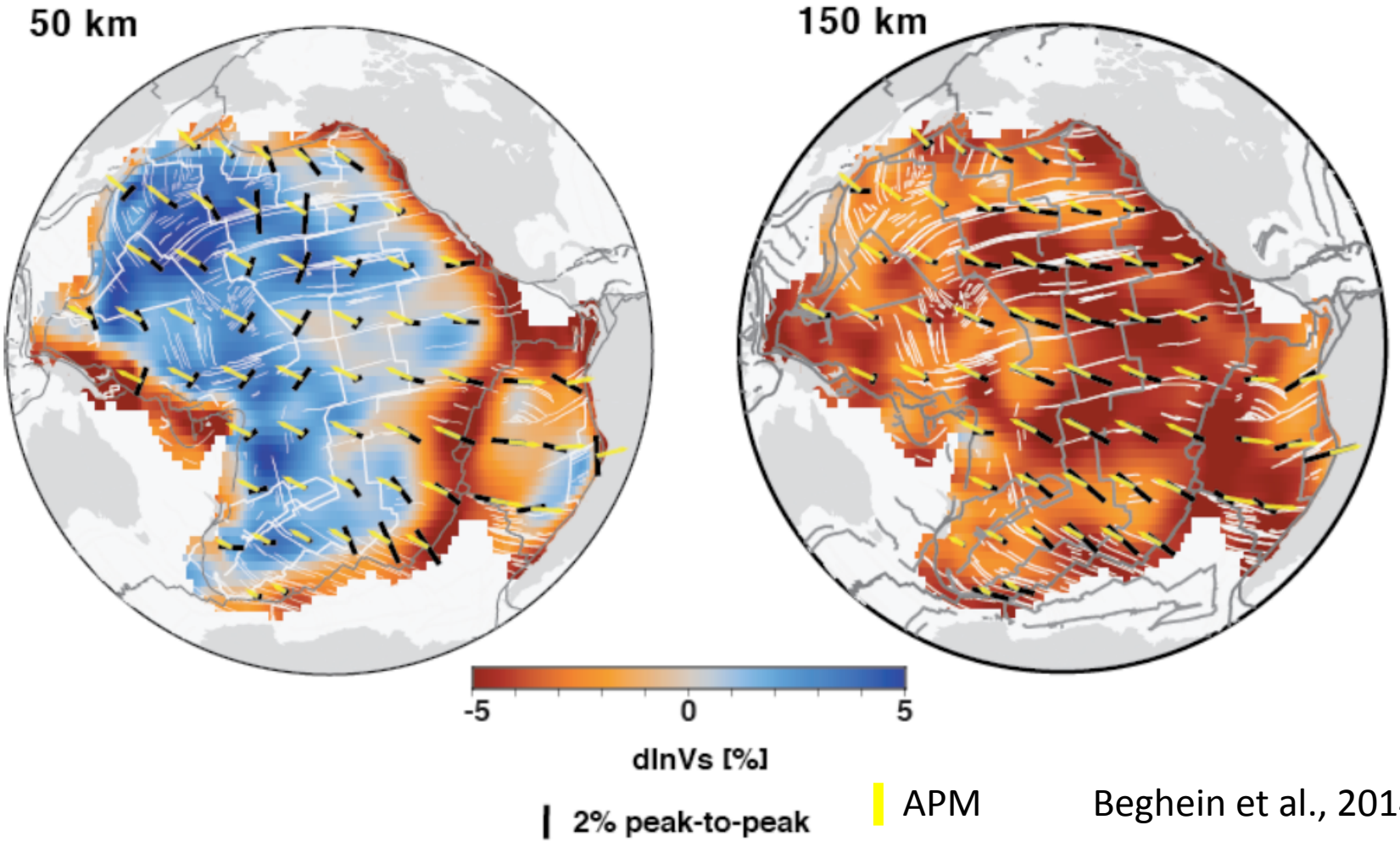
Olivine: highly anisotropic
dominant upper mantle constituent

The **speed** at which a seismic wave propagates depends on its **direction** (of propagation or of polarization)



Seismic anisotropy in oceanic upper mantle

Seismic anisotropy as indicator of flow-induced mantle fabric



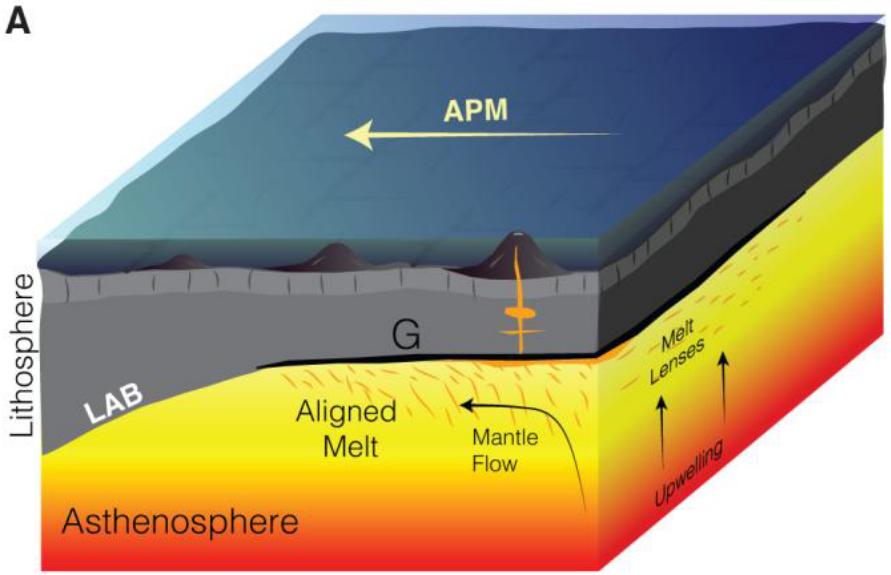
Beghein et al., 2014

- Azimuthal anisotropy is strongest in the asthenosphere
- Fast direction mainly consistent with apparent plate motion.

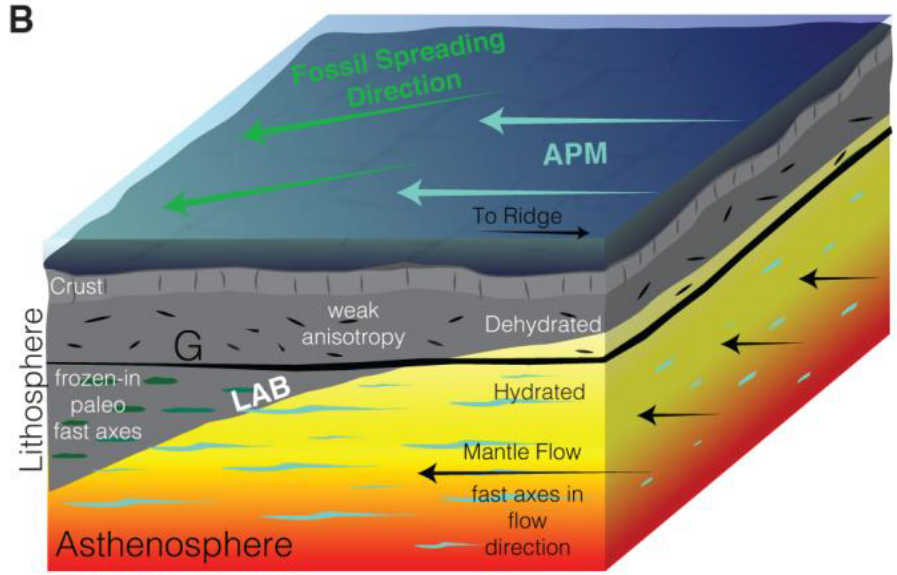
Seismic anisotropy in oceanic upper mantle

Lithosphere-Asthenosphere Transition

Melt



Dissolved H_2O



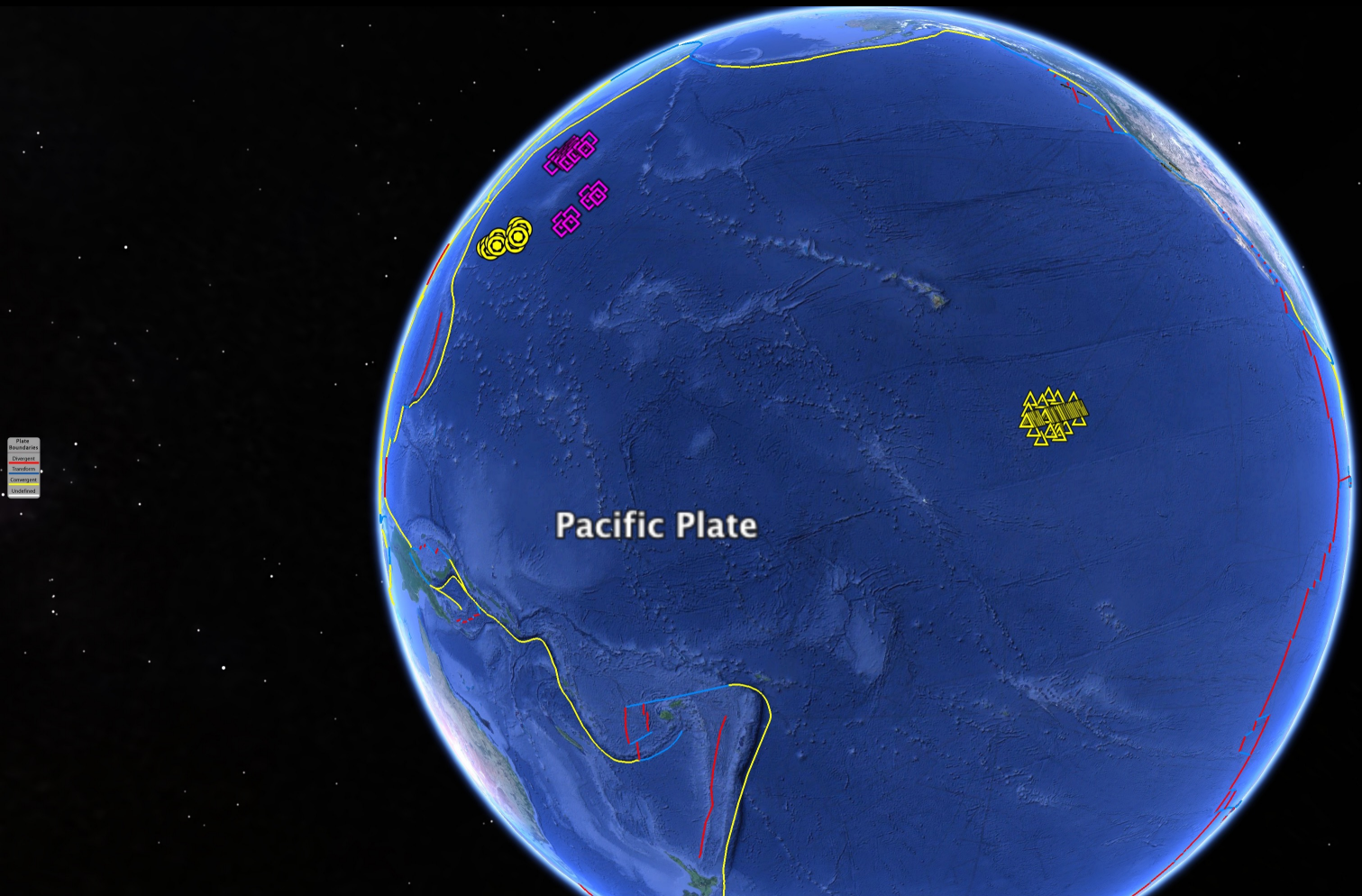
Beghein et al., 2014

- Model A shows melt in uppermost asthenosphere to help lubricate and facilitate plate motion
- Model B shows a hydrated asthenosphere. Olivine aligns with the present-day APM in the hydrated asthenosphere.

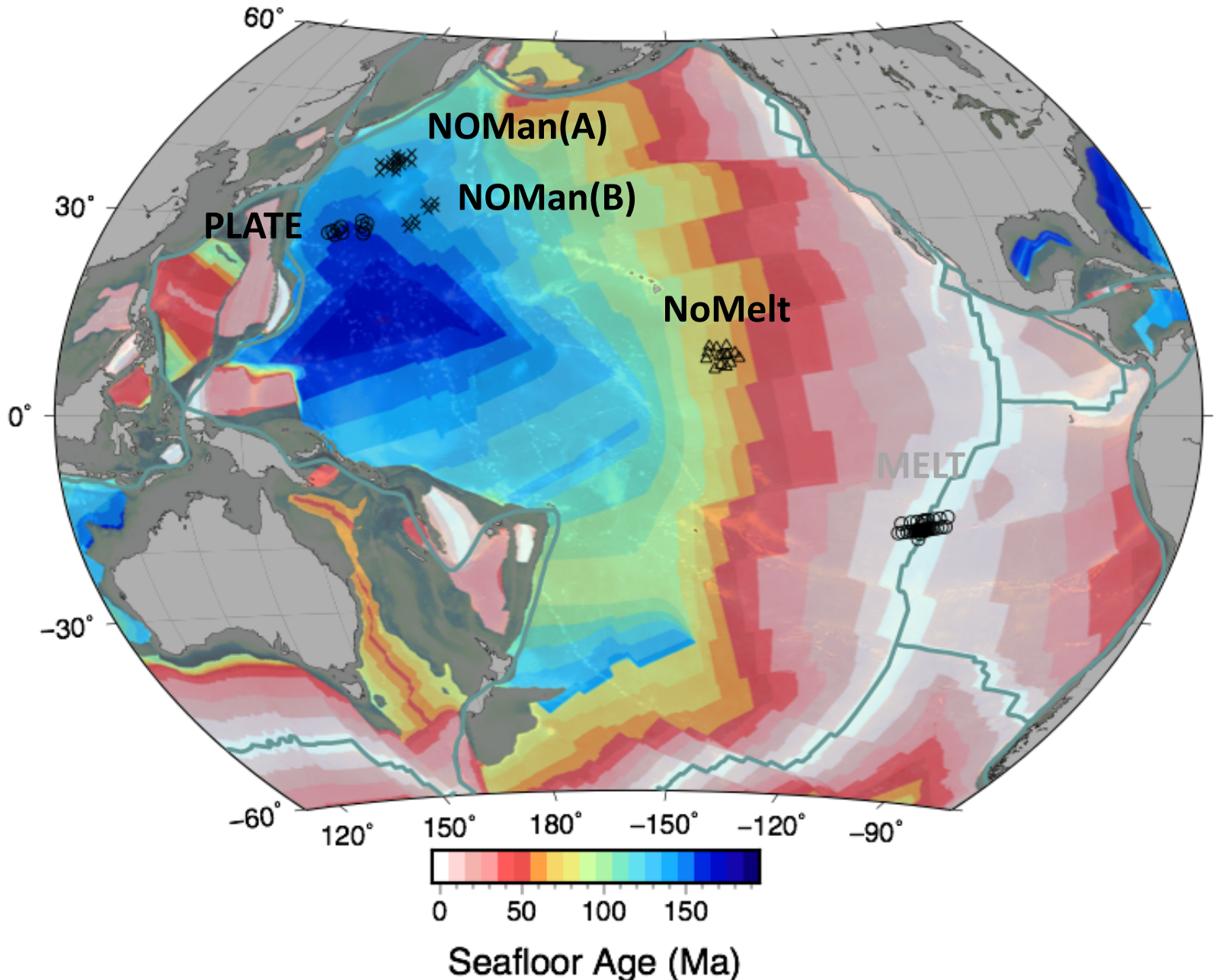
OBS deployments in the Pacific Ocean Basin

3 OBS projects → 1 main objective

- To understand structure and dynamics of the "NORMAL" Oceanic Lithosphere/Asthenosphere system



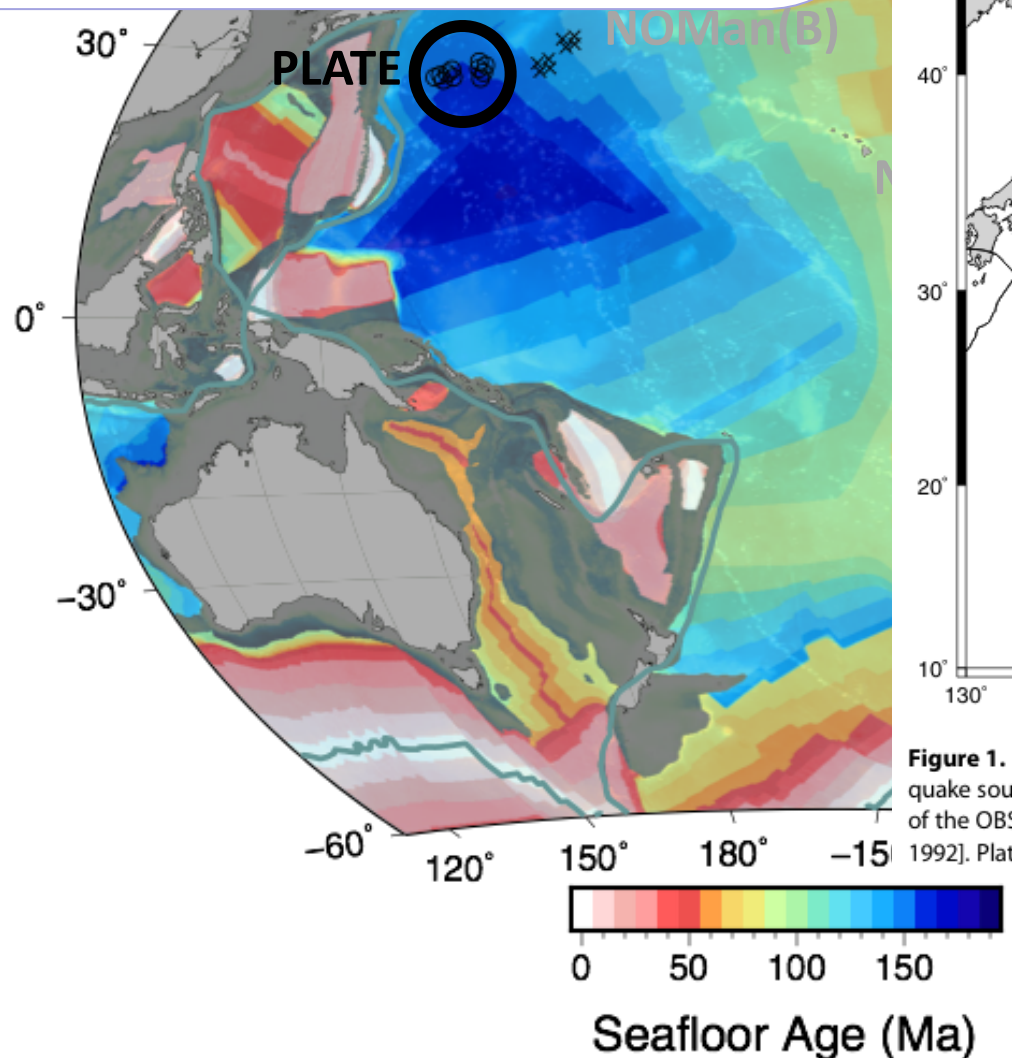
OBS deployments in the Pacific Ocean Basin



OBS deployments in the Pacific Ocean Basin

Pacific Lithosphere Anisotropy and Thickness Experiment

2009-2010



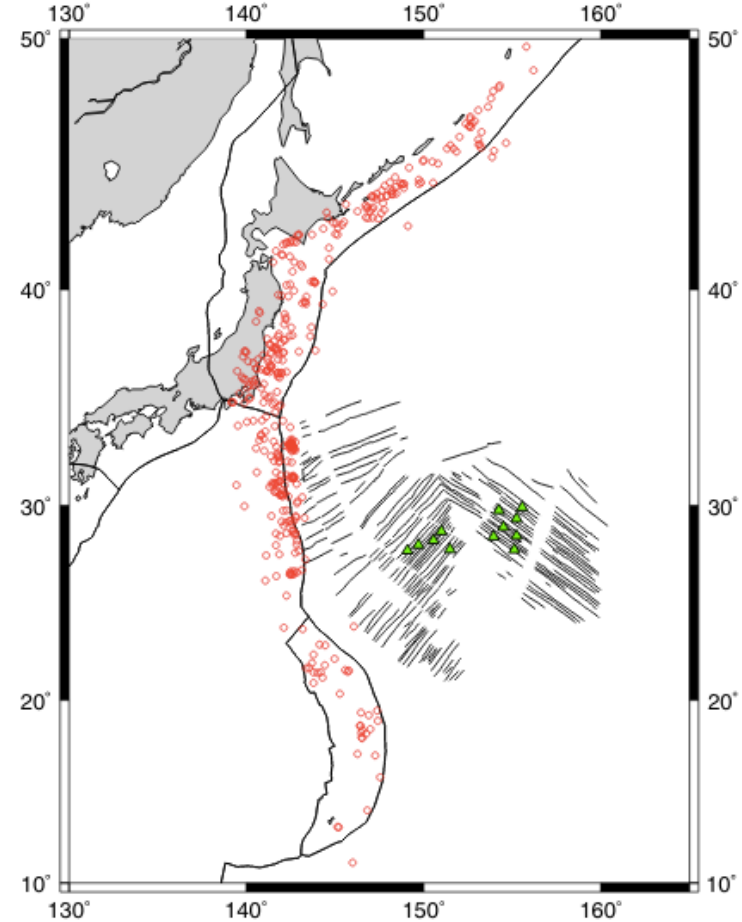
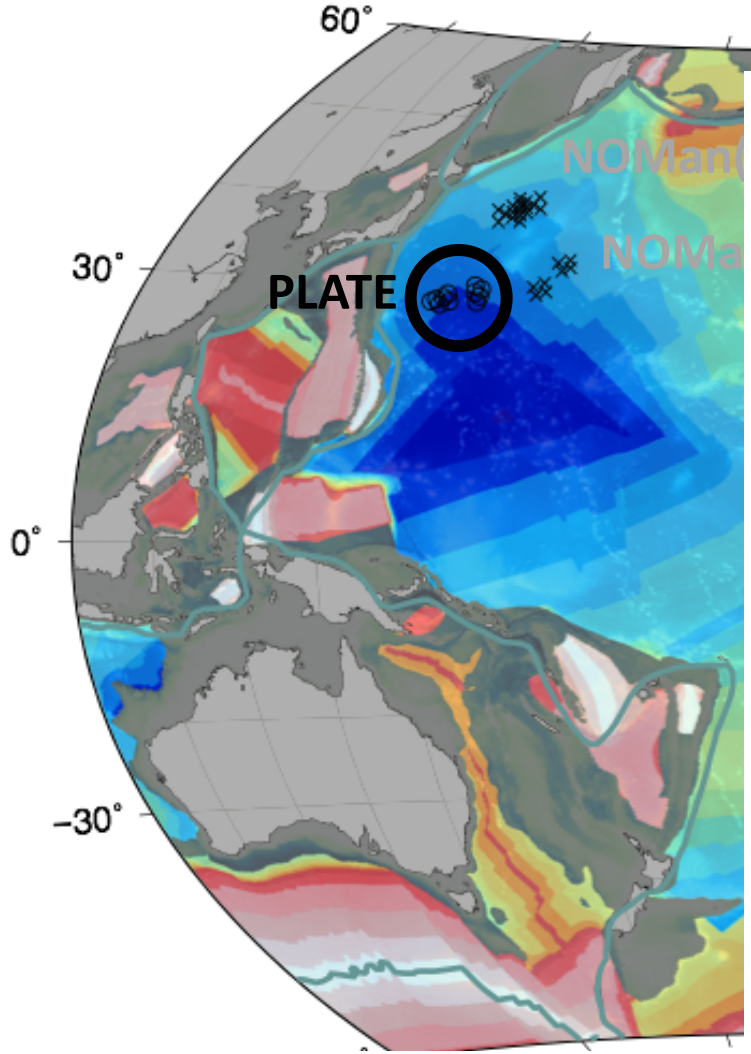


Figure 1. OBS deployment sites (green triangles) and locations of earthquake sources (red circles). Mesozoic magnetic anomalies in the vicinity of the OBS are shown as parallel black lines [after *Nakanishi et al.*, 1989, 1992]. Plate boundaries from *Bird* [2002].

Shintaku et al., 2015

OBS deployments in the Pacific Ocean Basin



Pn anisotropy

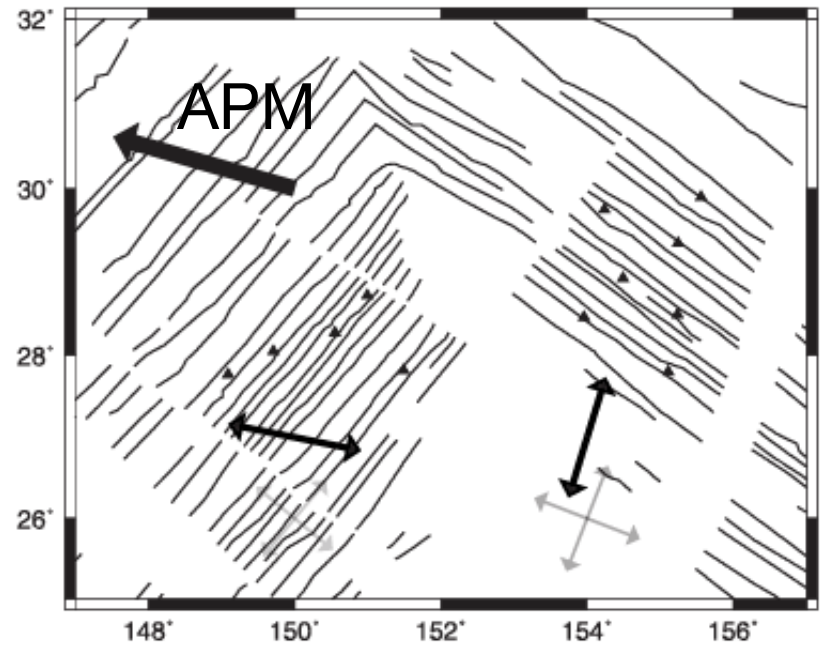


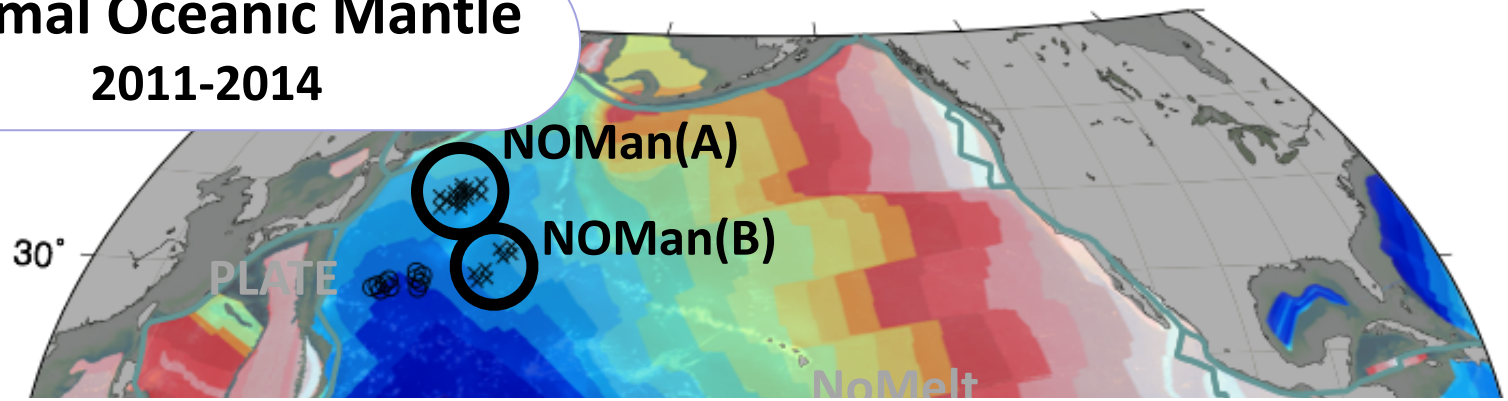
Figure 8. Relative magnitudes and fast directions of the 2θ and 4θ components for the western and eastern arrays are shown by length and orientation of the two-headed and four-headed arrows. Bold arrow is the absolute plate motion direction in the no-net-rotation coordinate system [Argus, 1992].

The difference in anisotropy on the two limbs indicates that fossil anisotropy in the lithosphere is more important than the absolute plate motion in controlling Pn velocity

Shintaku et al., 2015

OBS deployments in the Pacific Ocean Basin

Normal Oceanic Mantle
2011-2014



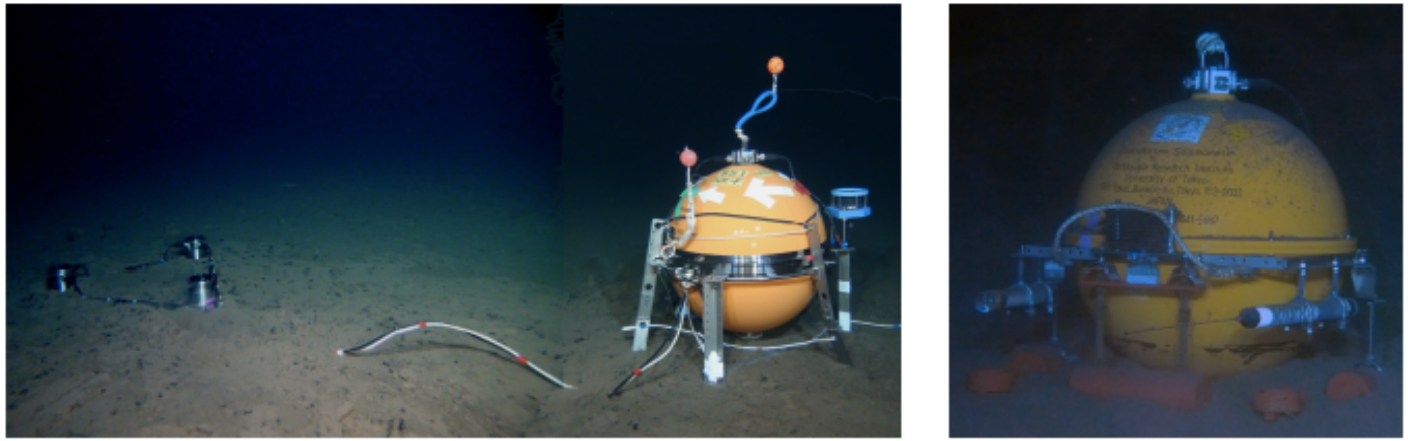
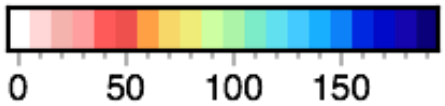


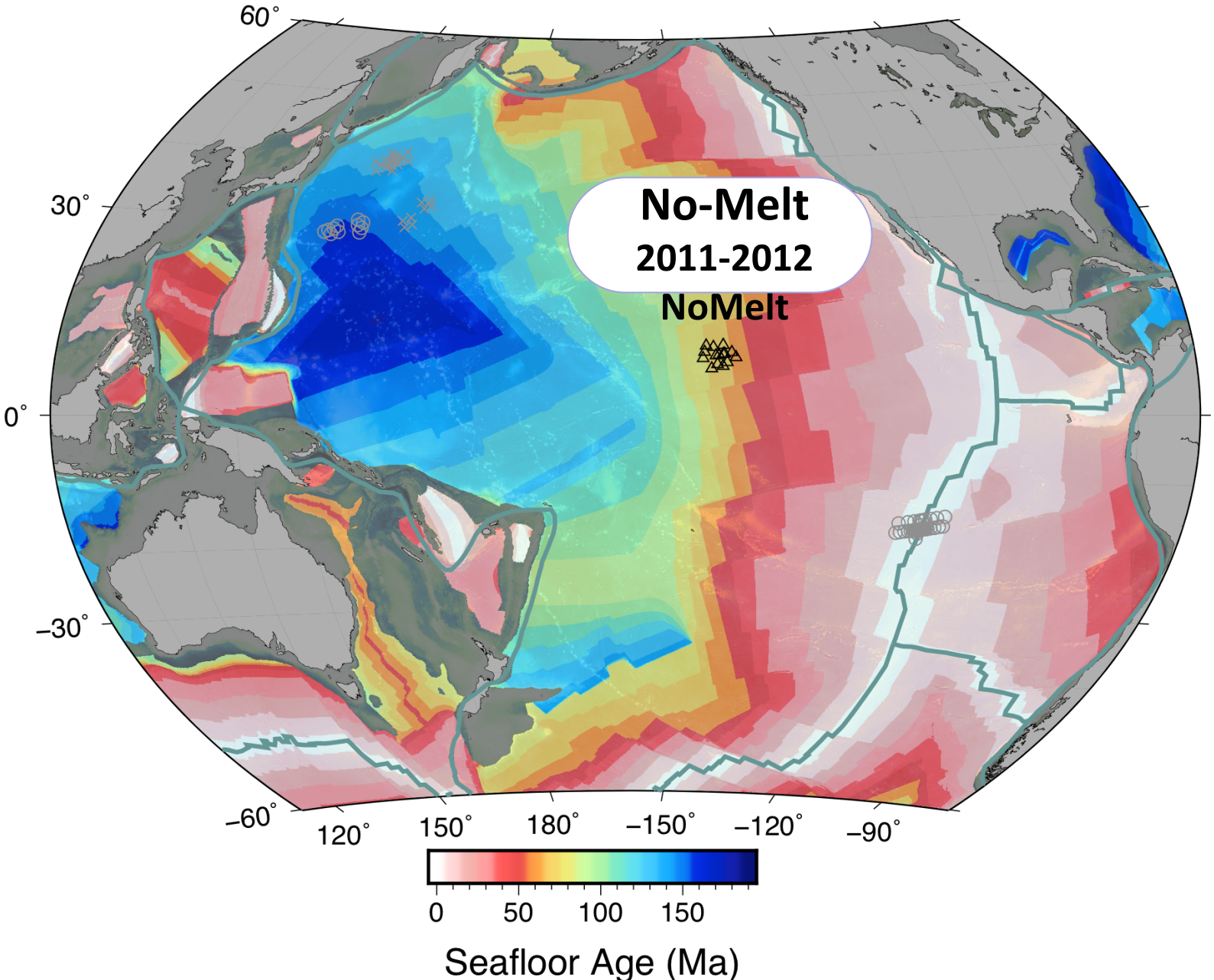
Figure 2. The BBOBS-NX (left, NM15) soon after the deployment ROV operation in Aug. 2012. The BBOBS (right, NM19) was rescued by the ROV, after 3 years-long stay at the seafloor from the deployment in Nov. 2011.

NOMan Team, 2015



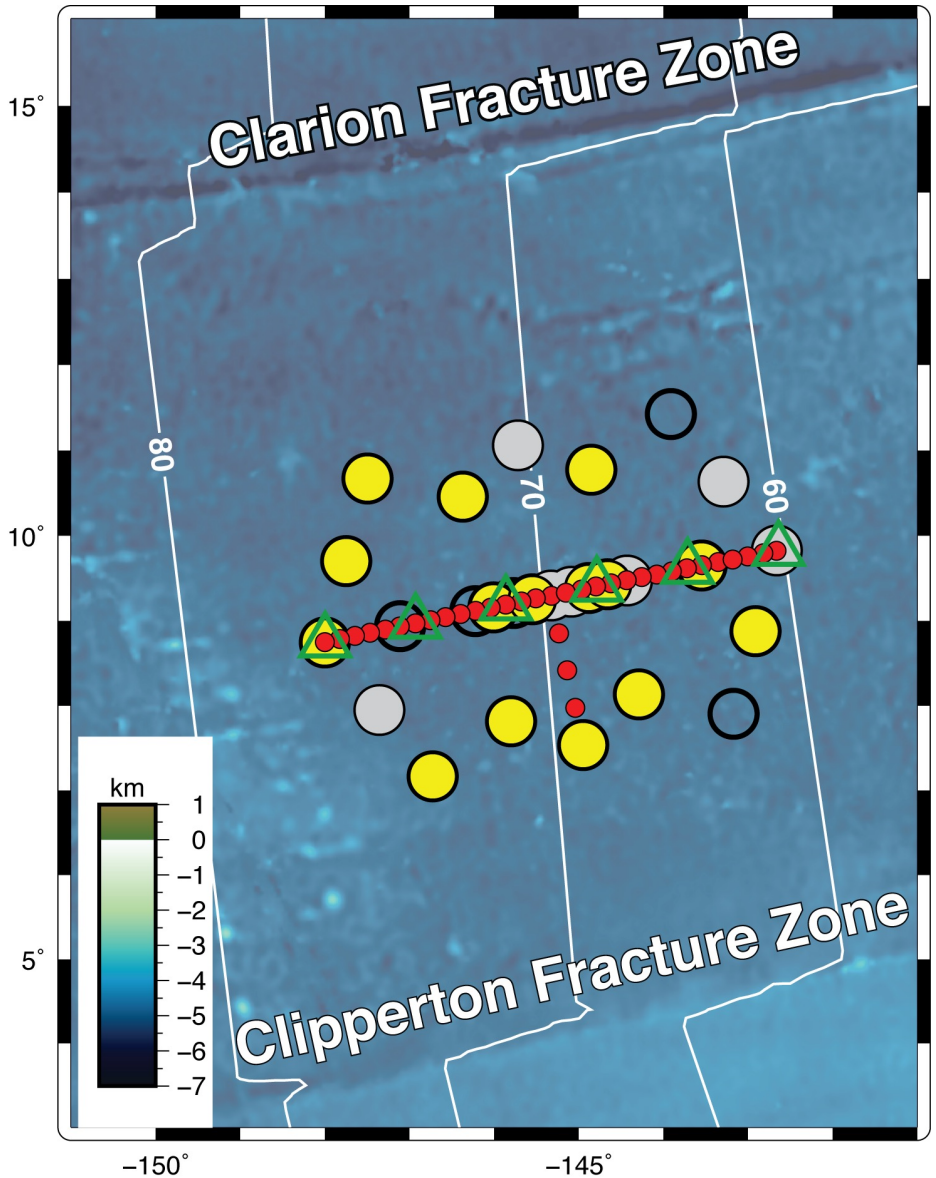
Seafloor Age (Ma)

NoMelt


No-Melt
2011-2012
NoMelt
60°
30°
0°
−30°
−60°
120°
150°
180°
−150°
−120°
−90°
0
50
100
150
Seafloor Age (Ma)

NoMelt

Characterize the stable oceanic lithosphere-asthenosphere system at



- Minimal evidence of post-ridge volcanism
- 70 Ma average seafloor age
- 600x400 km study region

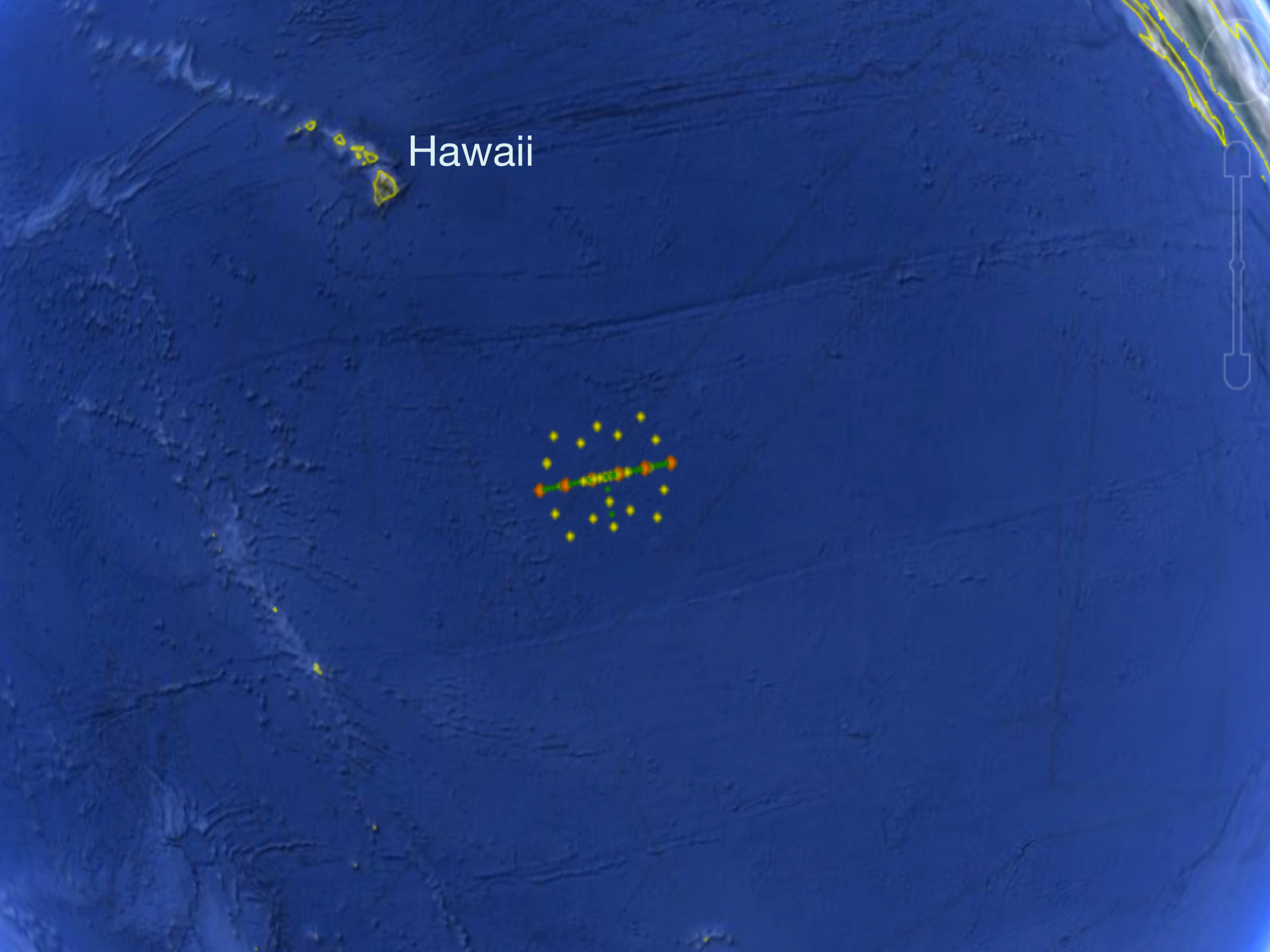
- a single co-located multi-tool experiment

● Short-period OBS array

△ Magnetotelluric MT array

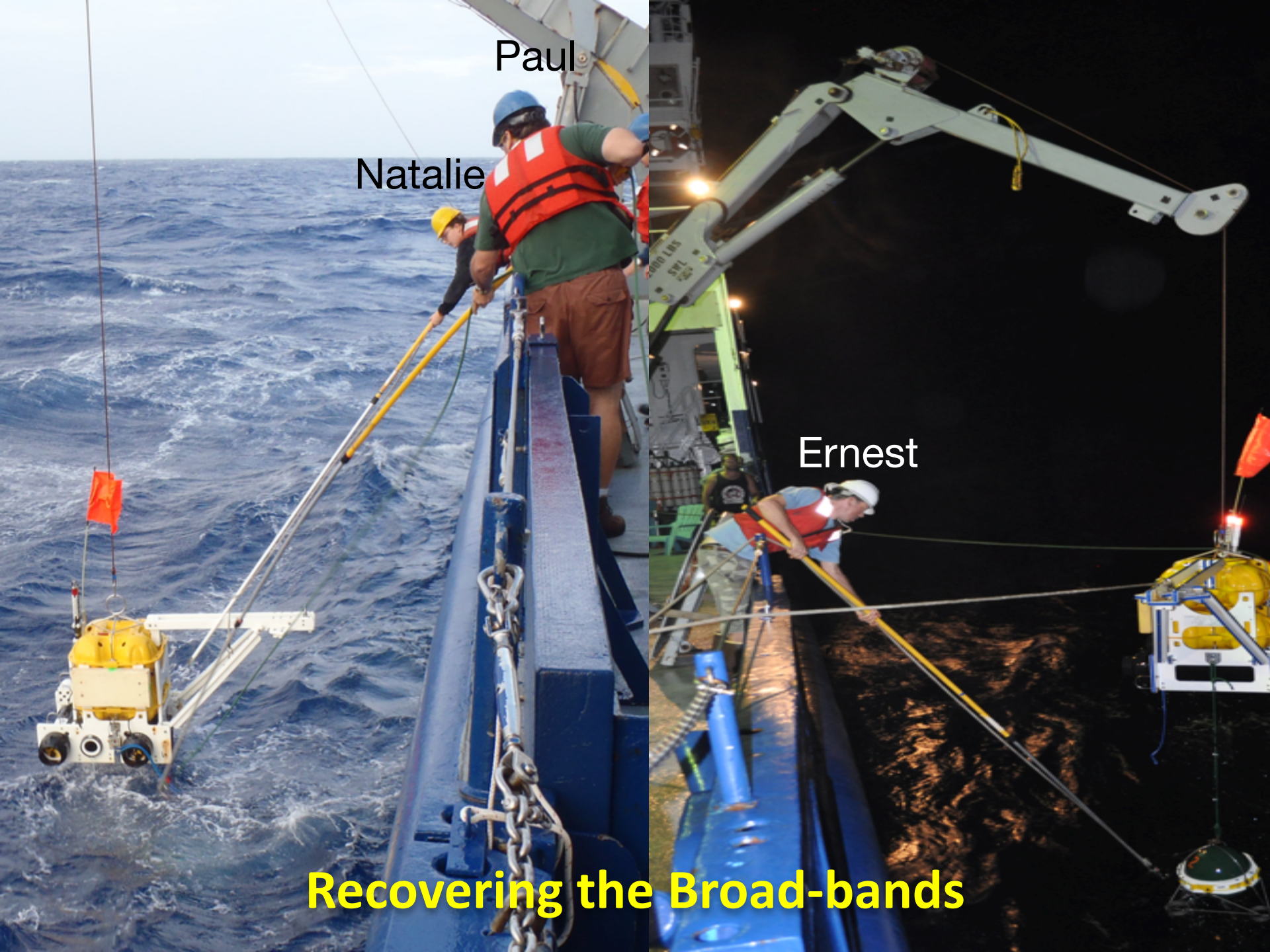
○ Broad-band OBS array

- ○ * 5 missing
- ● * 6 low S/N
- ● * 16 high S/N


Hawaii

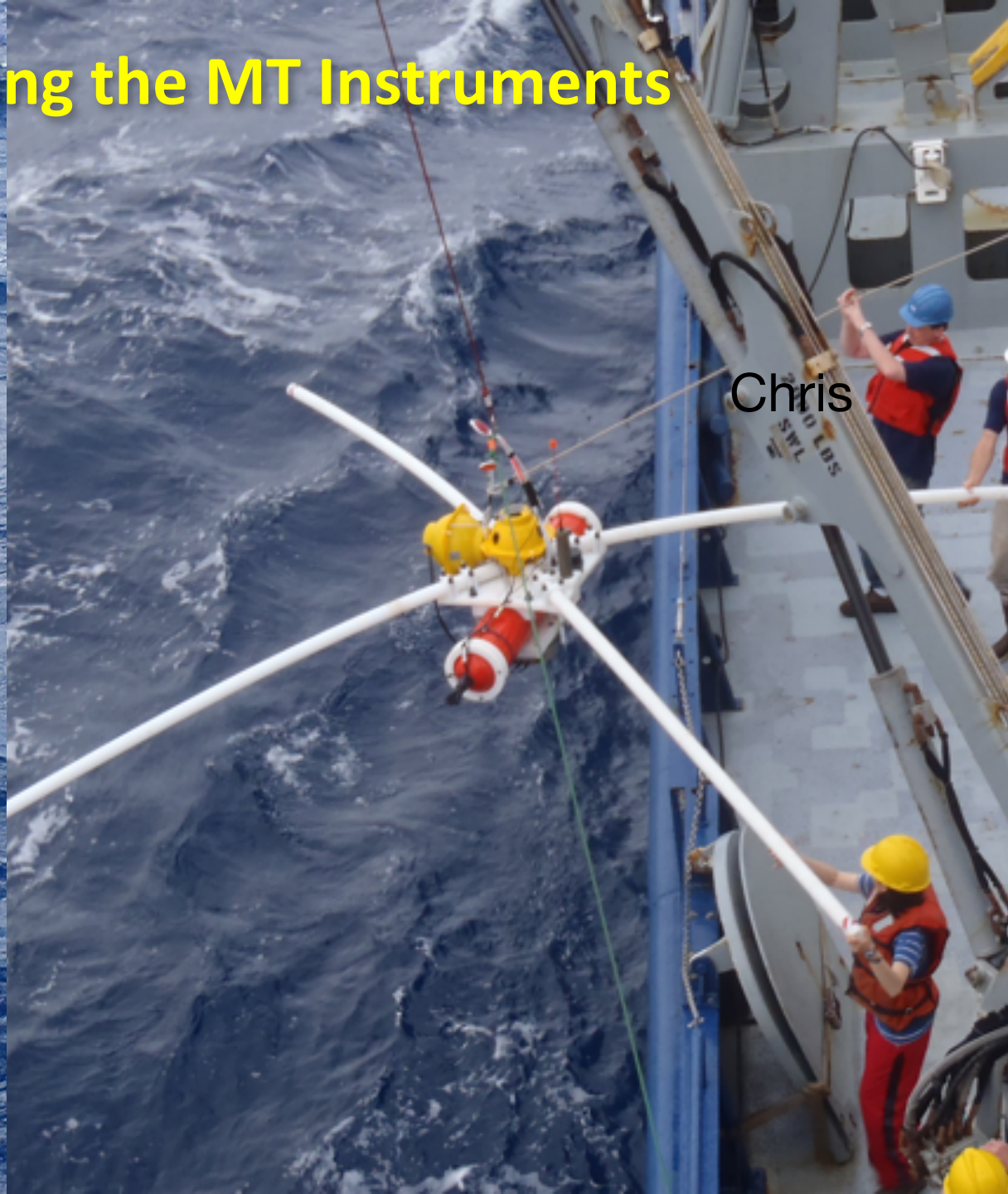
R/V Melville
MELVILLE
Retired in September 2014

365 23 59 59
Day of Year
Hour
Minute
Second
GMT Time
Recovery Cruise

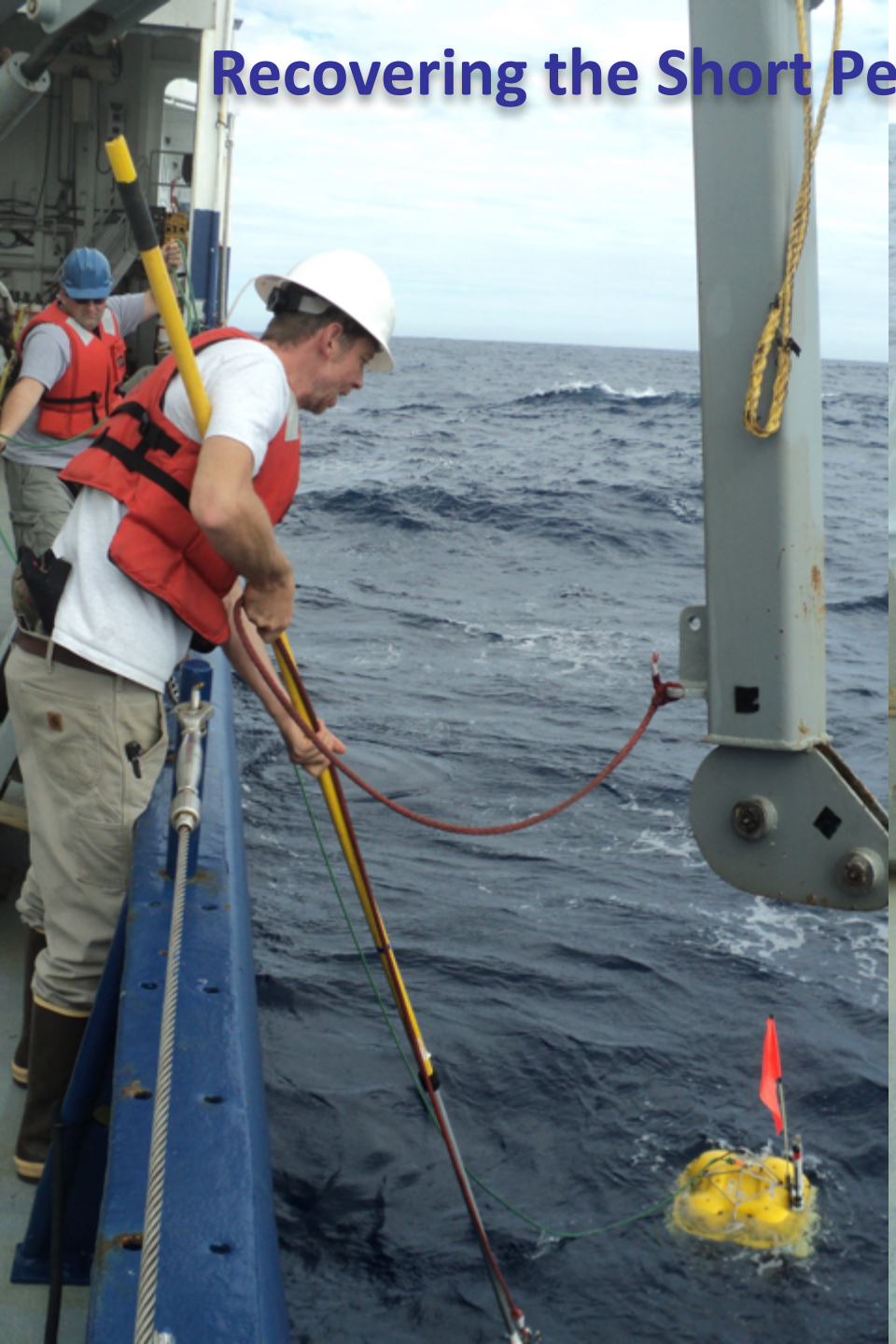


Recovering the Broad-bands

Recovering the MT Instruments



Recovering the Short Periods

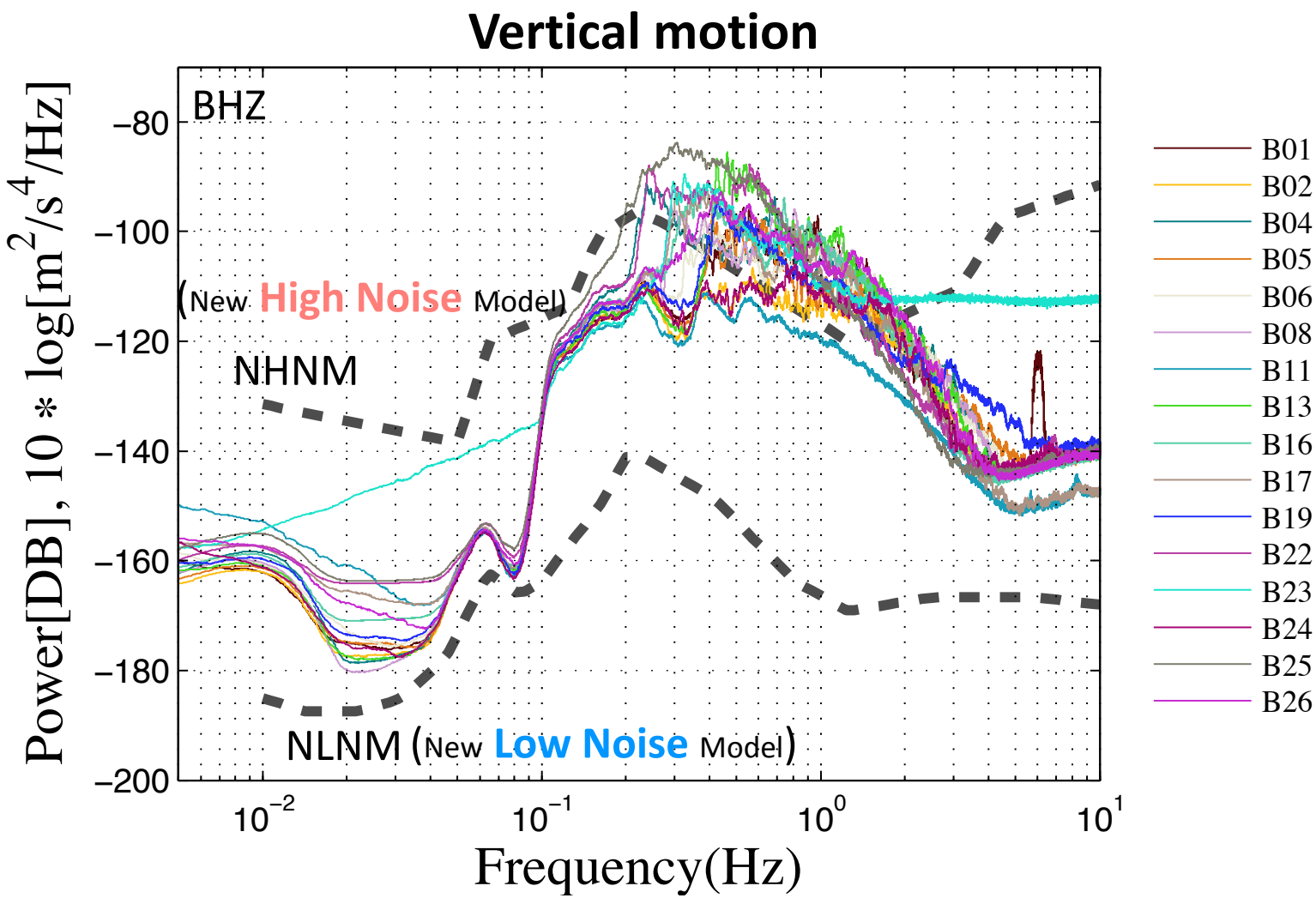


Captain
vodacom

Heading Home

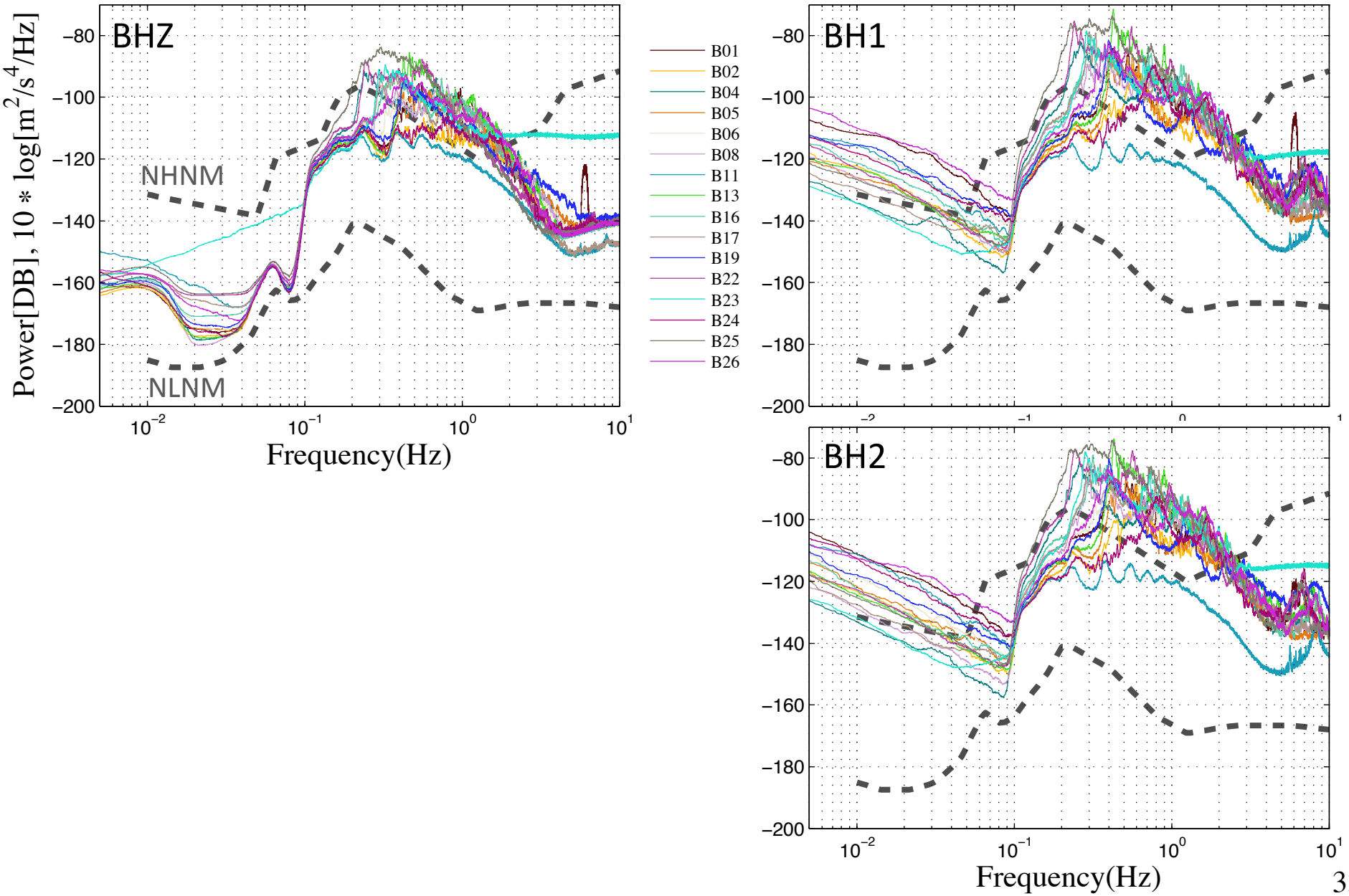
OBS Data Quality (PSD)

PSD: Power Spectrum Density

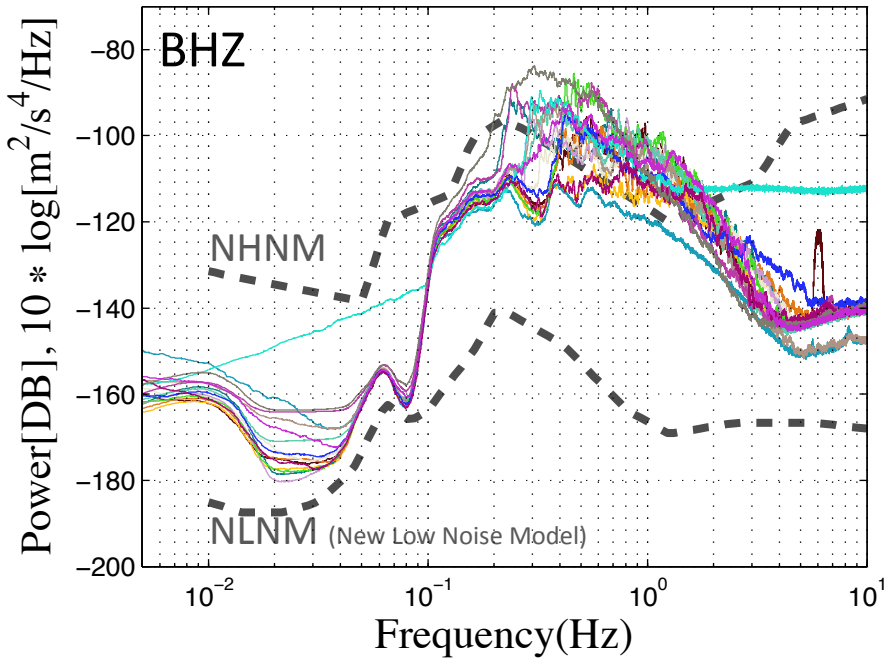


OBS Data Quality (PSD)

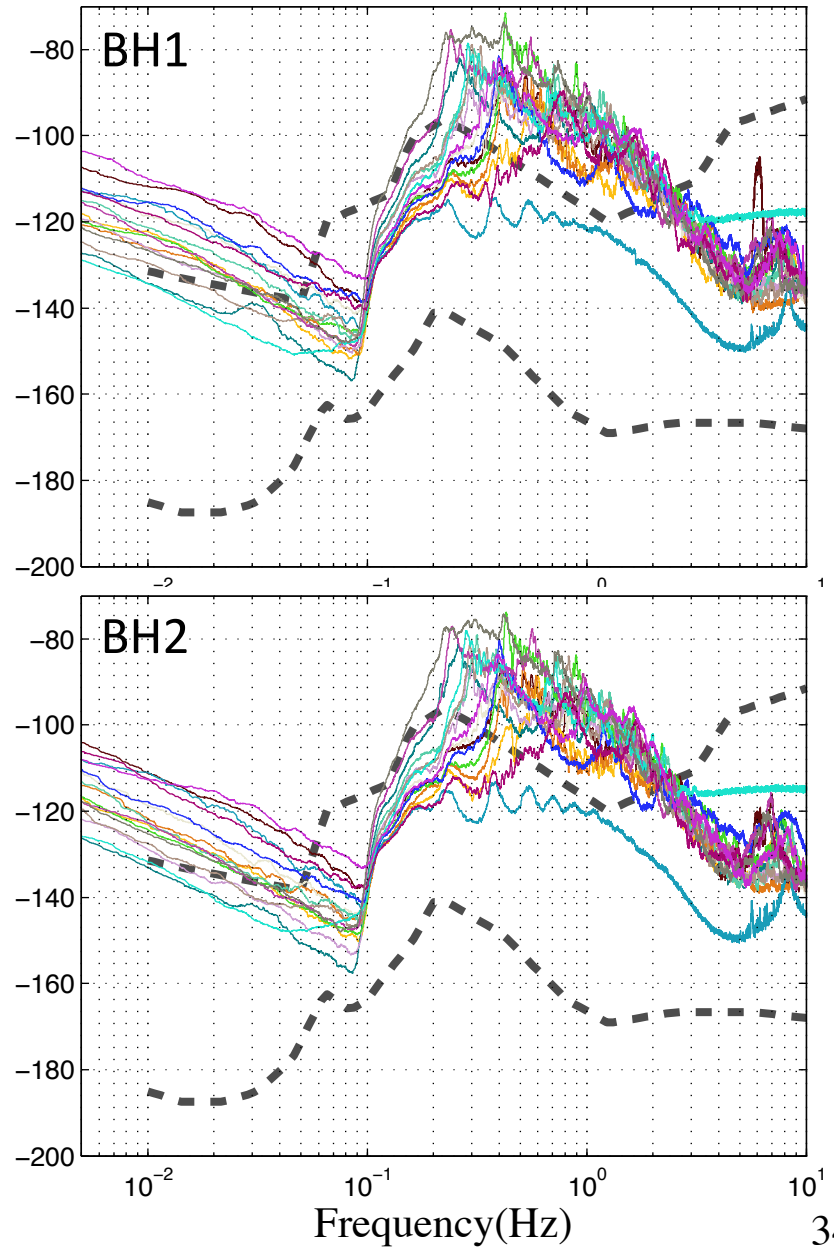
2 horizontal motions



OBS data trouble - Noise in OBS Data



(1) Tilt noise

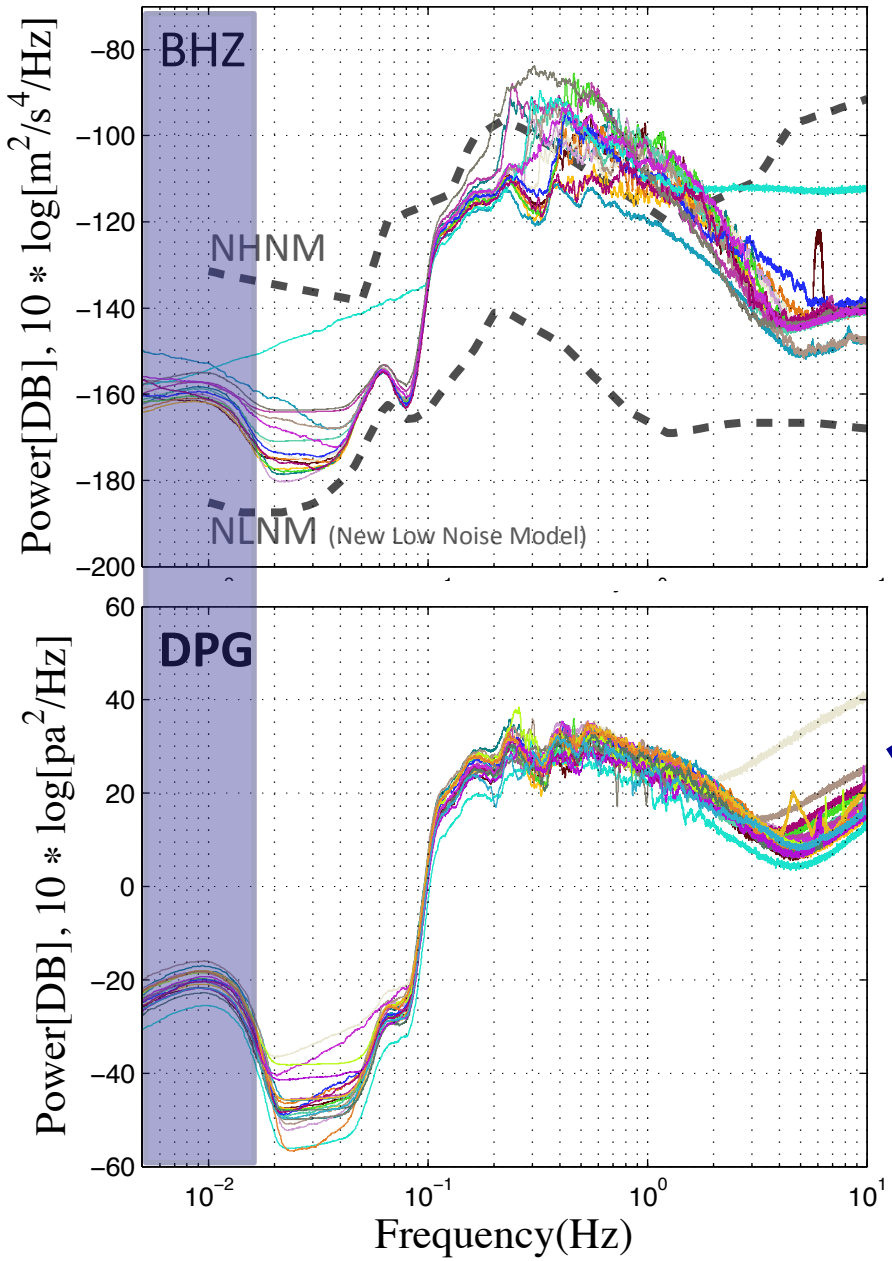


OBS vertical data are contaminated by

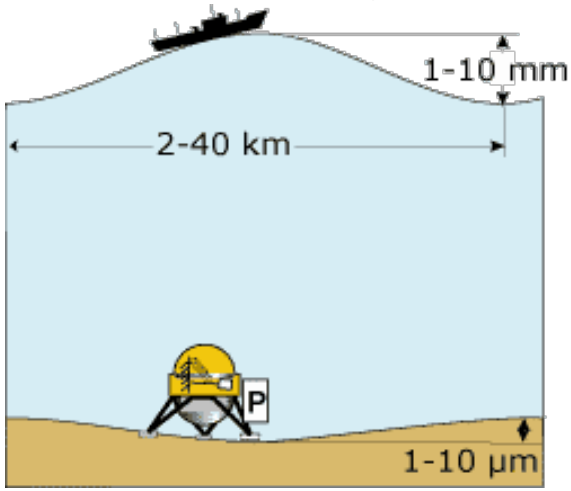
(1) Tilt noise --

induced by bottom currents that leaks from horizontal components.

OBS data trouble - Noise in OBS Data



Seafloor compliance

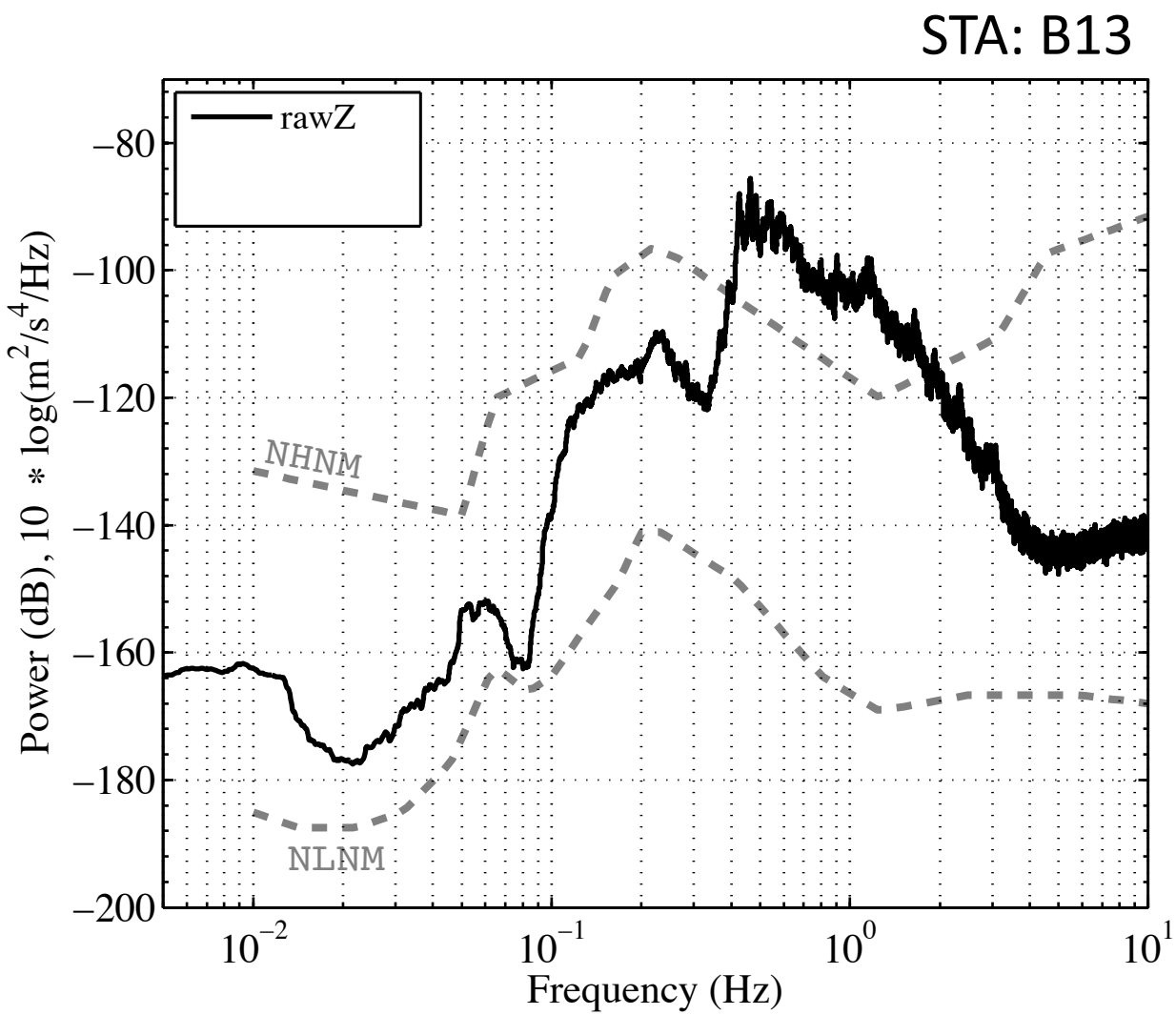


Courtesy of Wayne Crawford

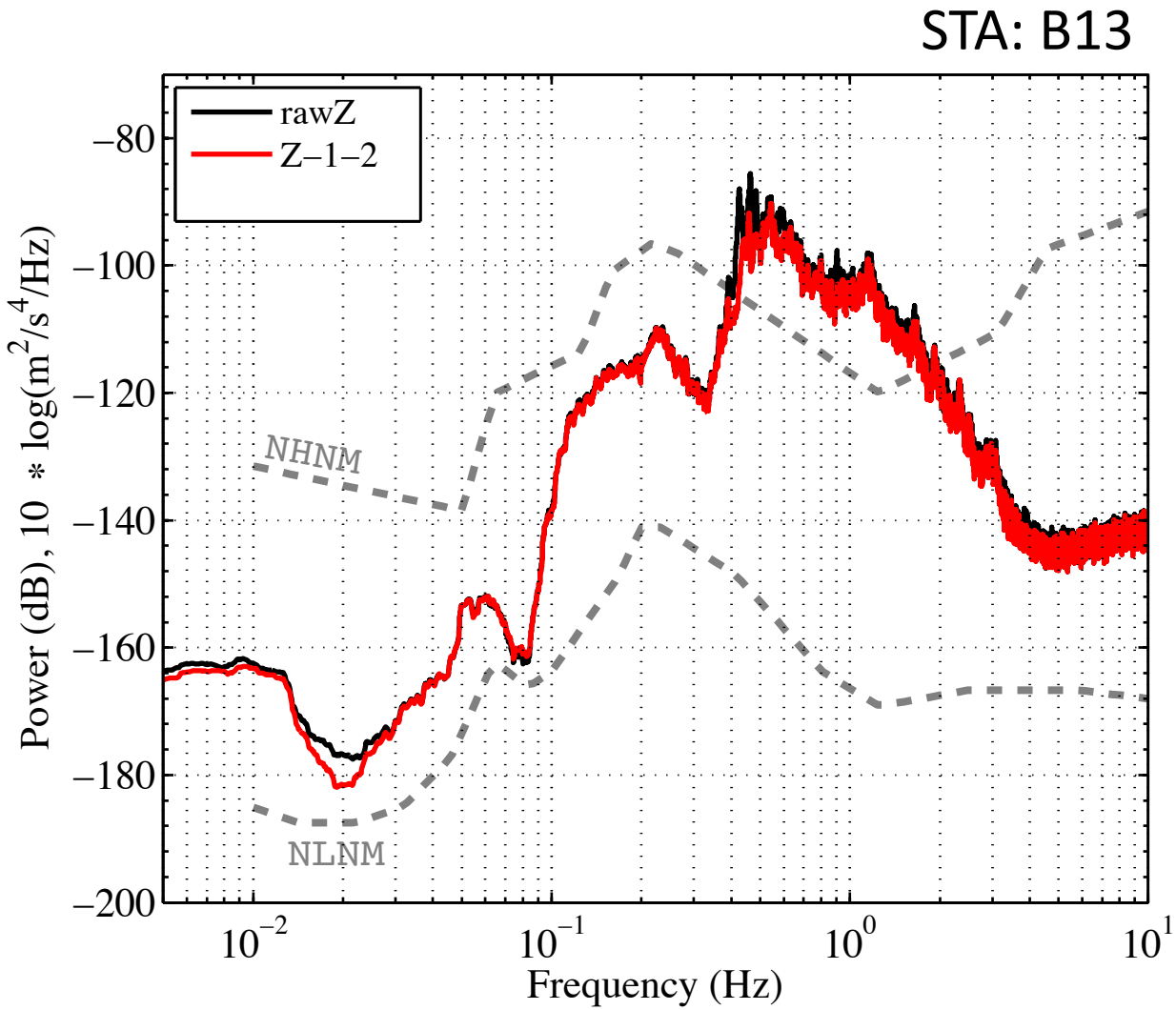
(2) Compliance noise

OBS vertical data are contaminated by (2) Compliance noise -- induced by infragravity waves that are also recorded on bottom-pressure data.

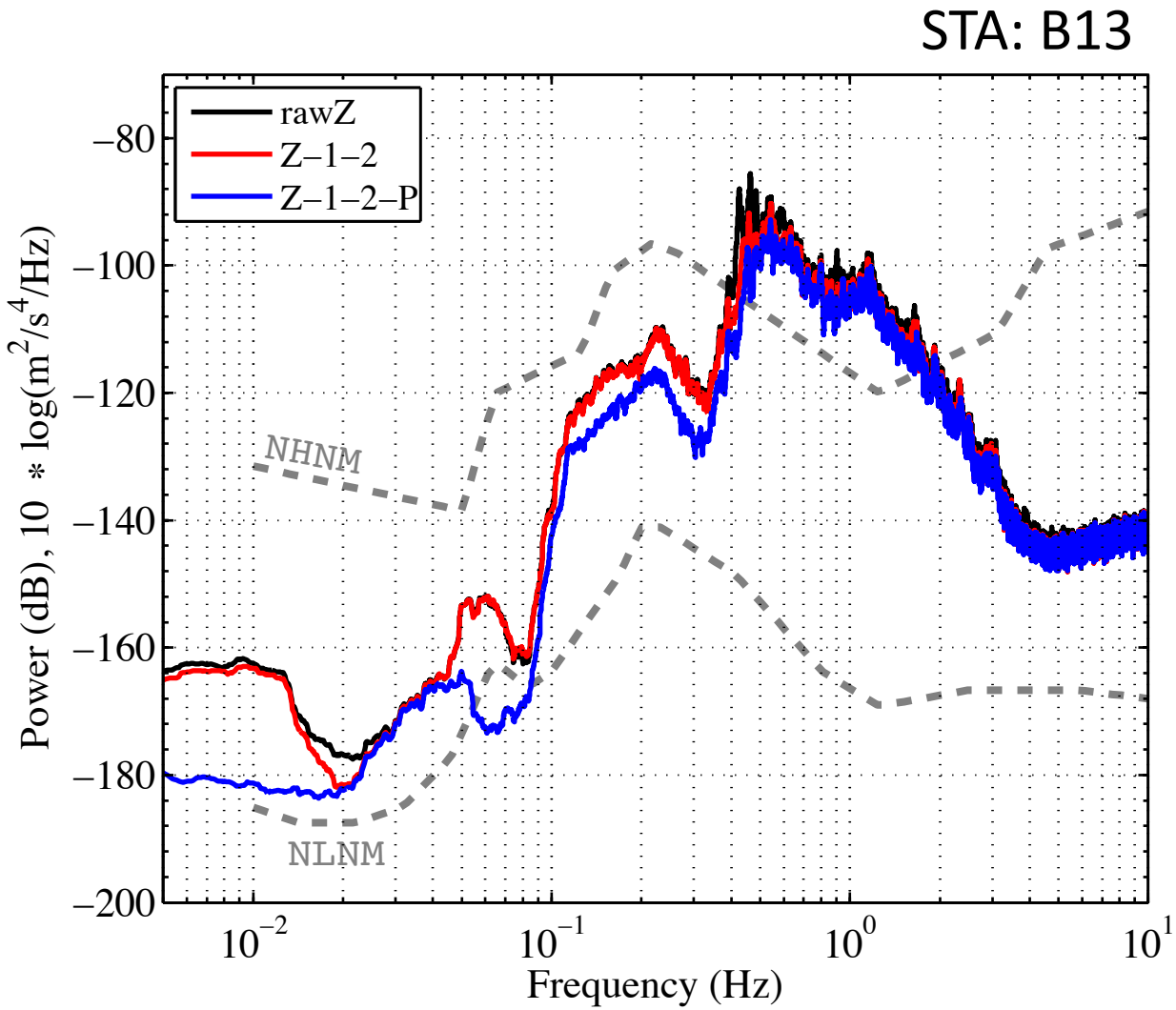
Noise Correction for OBS Data



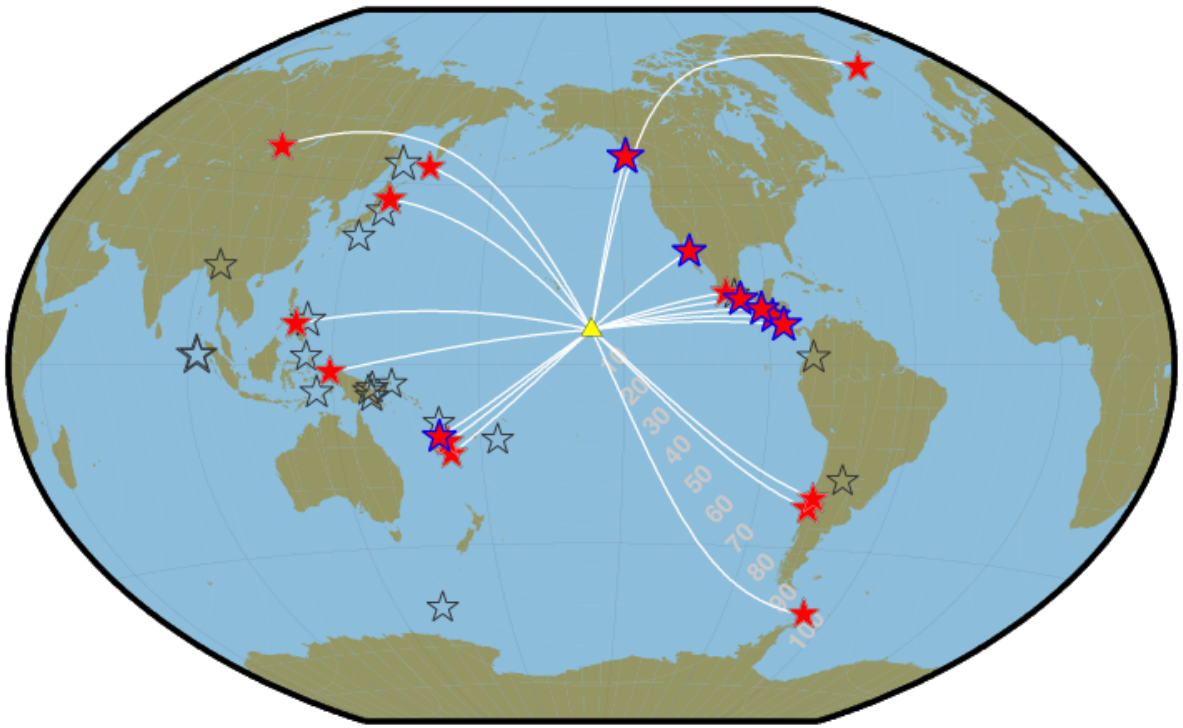
Noise Correction for OBS Data



Noise Correction for OBS Data



Teleseismic Events Recorded by NoMelt



★ events with high quality Rayleigh waves

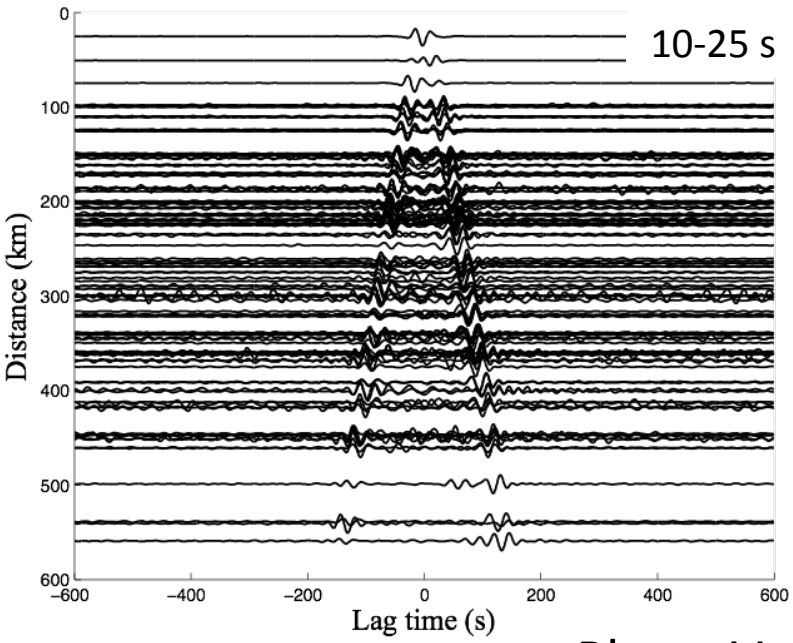
Objectives

Using surface-wave dispersion to characterize Vs structure & its seismic anisotropy in upper 300 km beneath the array

Phase Velocity Measurements

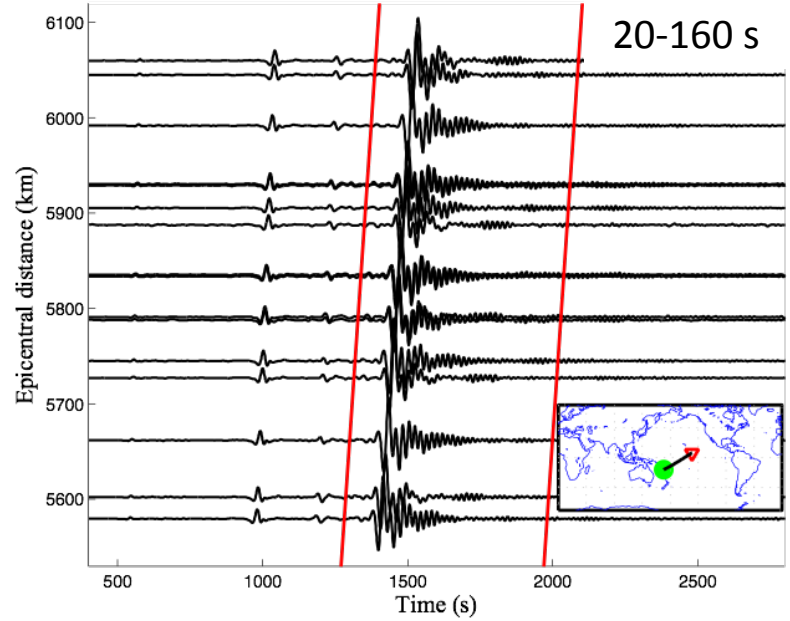
Ambient Noise Data

Cross-correlation Waveforms

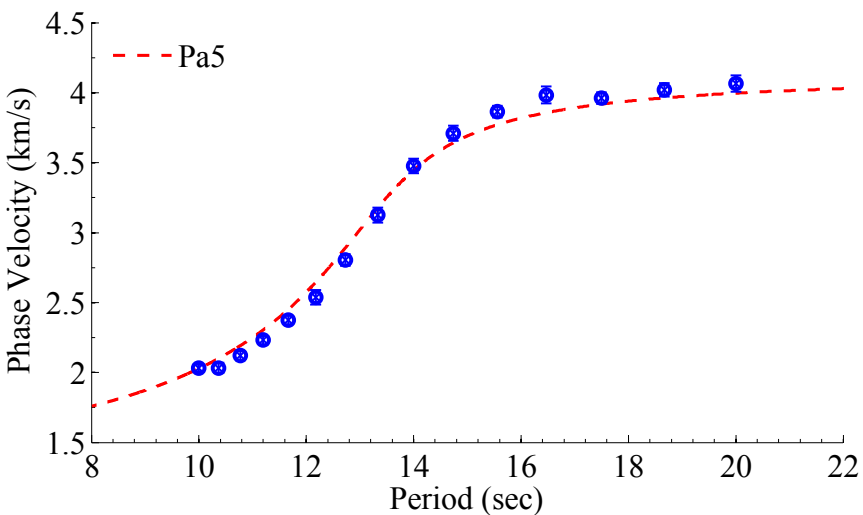


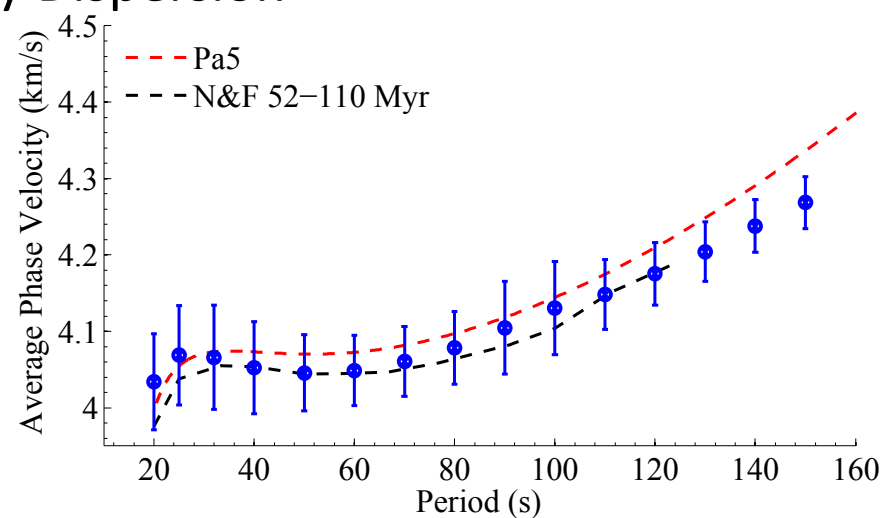
Earthquake-generated Data

Event: March 9th, 2012 Depth: 16.0 (km) Mag: 6.7



Phase Velocity Dispersion



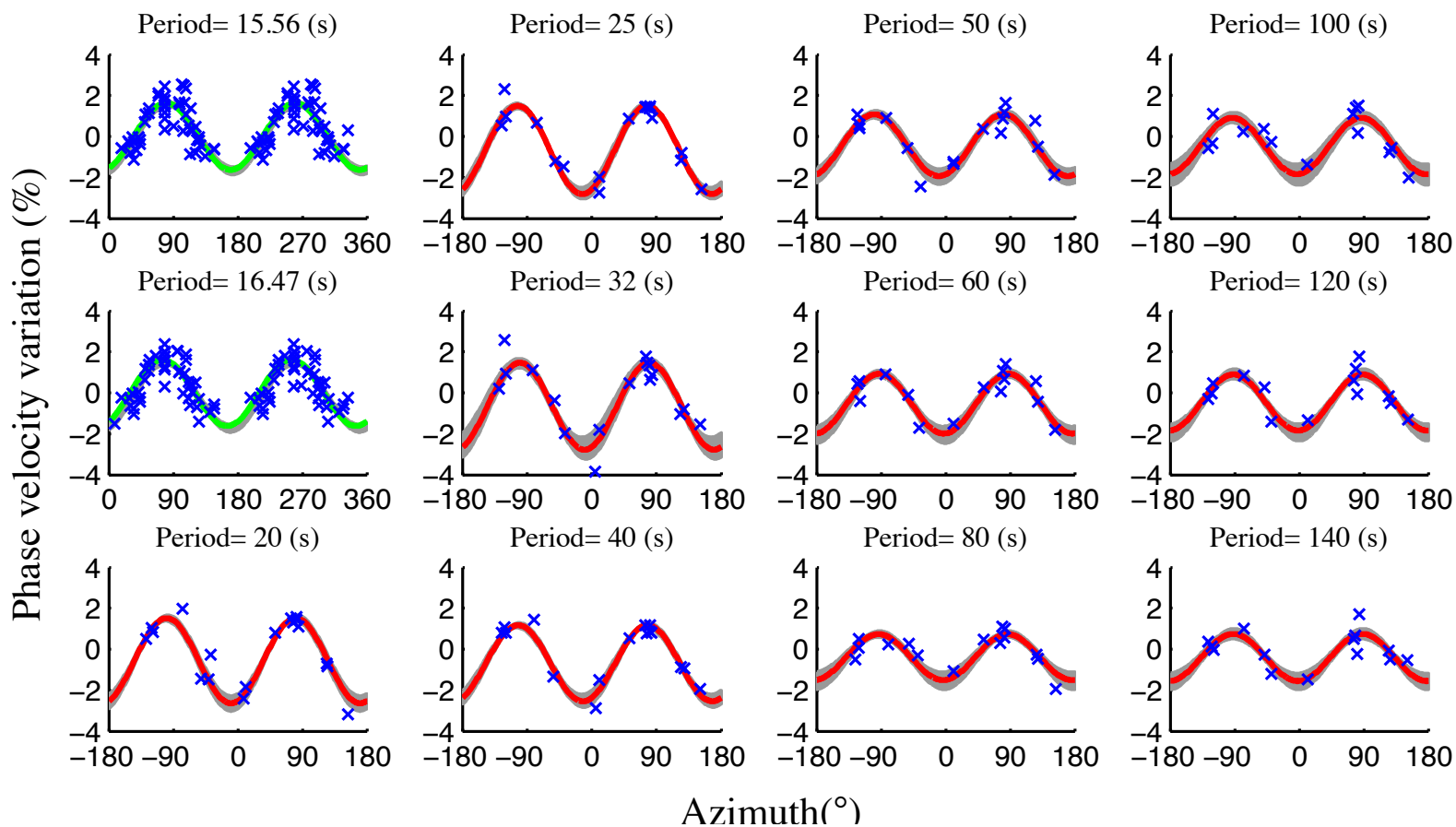


Azimuthal Phase Velocity Variations

Phase velocity measurements = Isotropic term + Anisotropic term (Variation as function of azimuth)

$$C(\theta_{azi}) = C_{iso} + C_{iso} \times \boxed{\frac{A_{peak-to-peak}}{2} \times \cos(2(\theta_{azi} - \psi_{fast-dir}))}$$

Variation as function of azimuth



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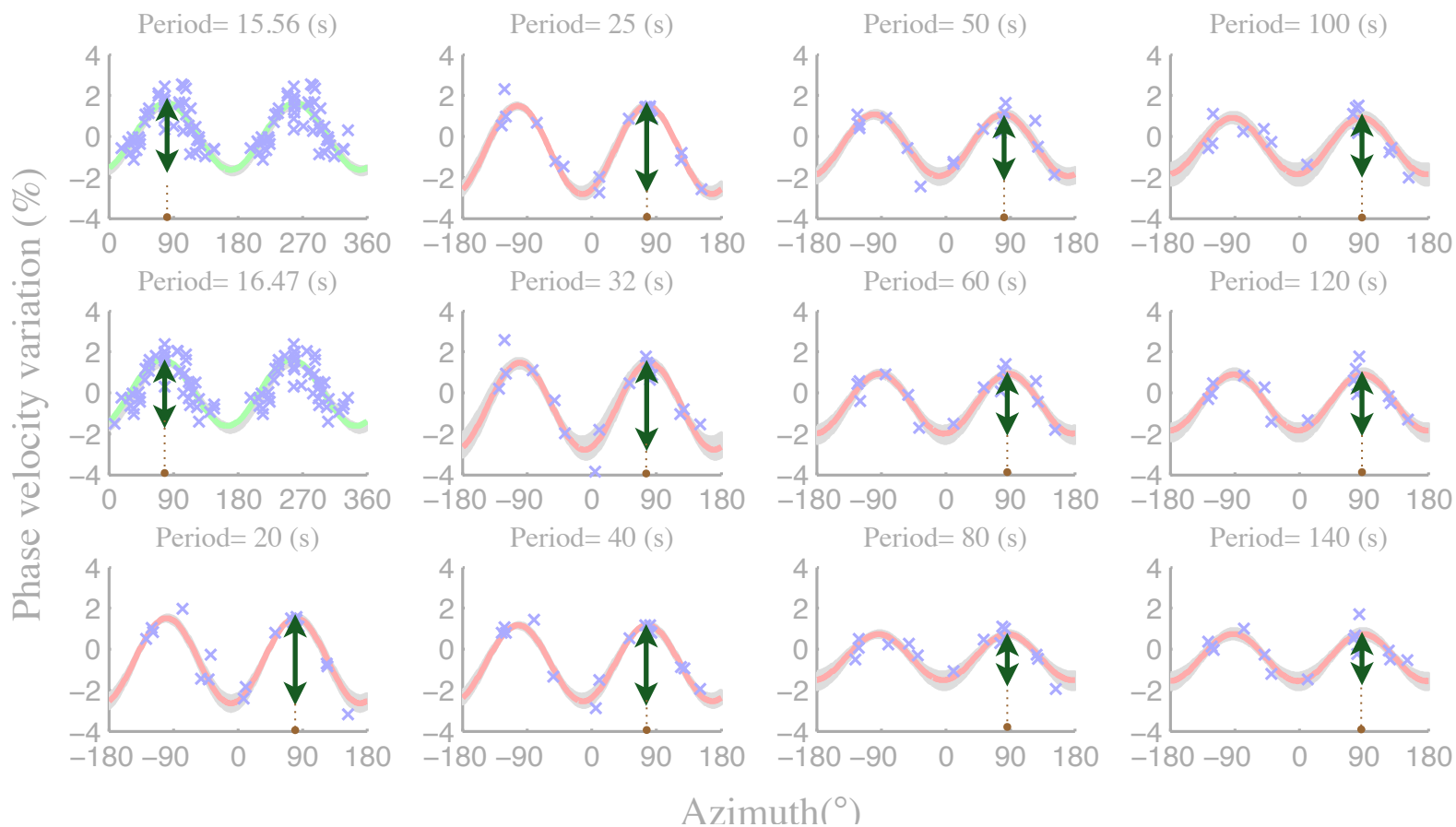
Variation as function of azimuth

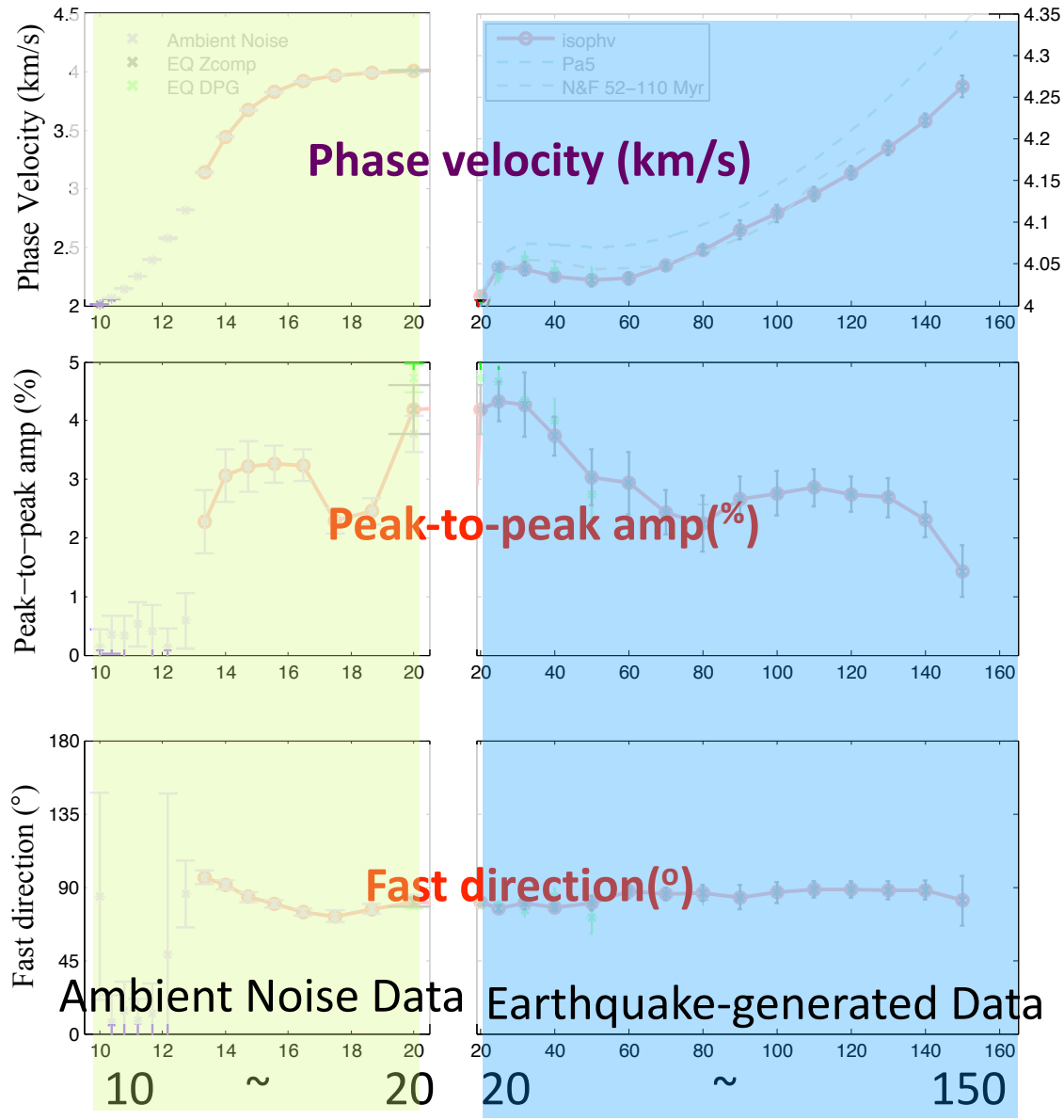


Phase Velocity & Azimuthal Anisotropy

Isotropic term

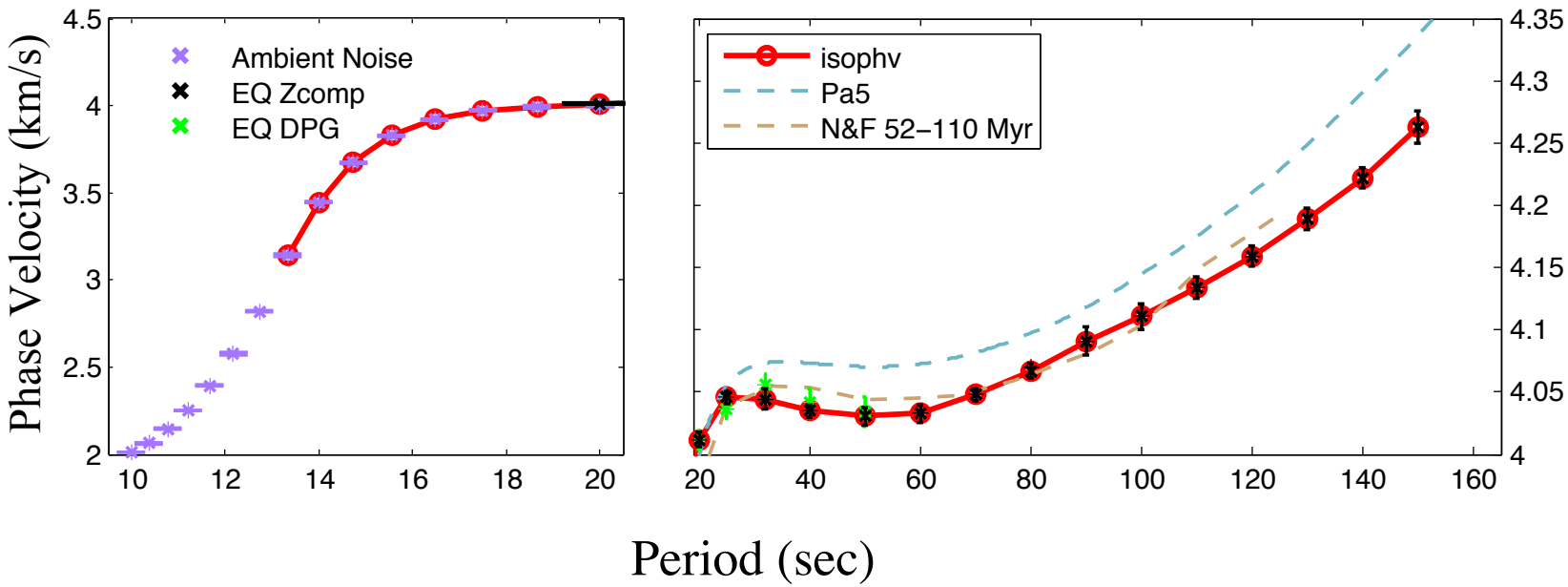
+

Anisotropic term



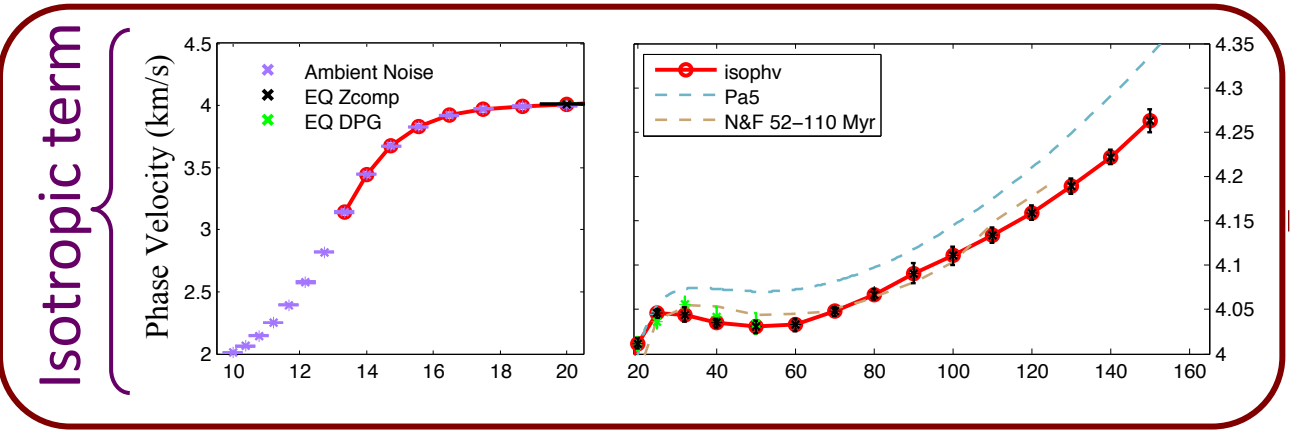
Phase Velocity & Azimuthal Anisotropy

Isotropic term

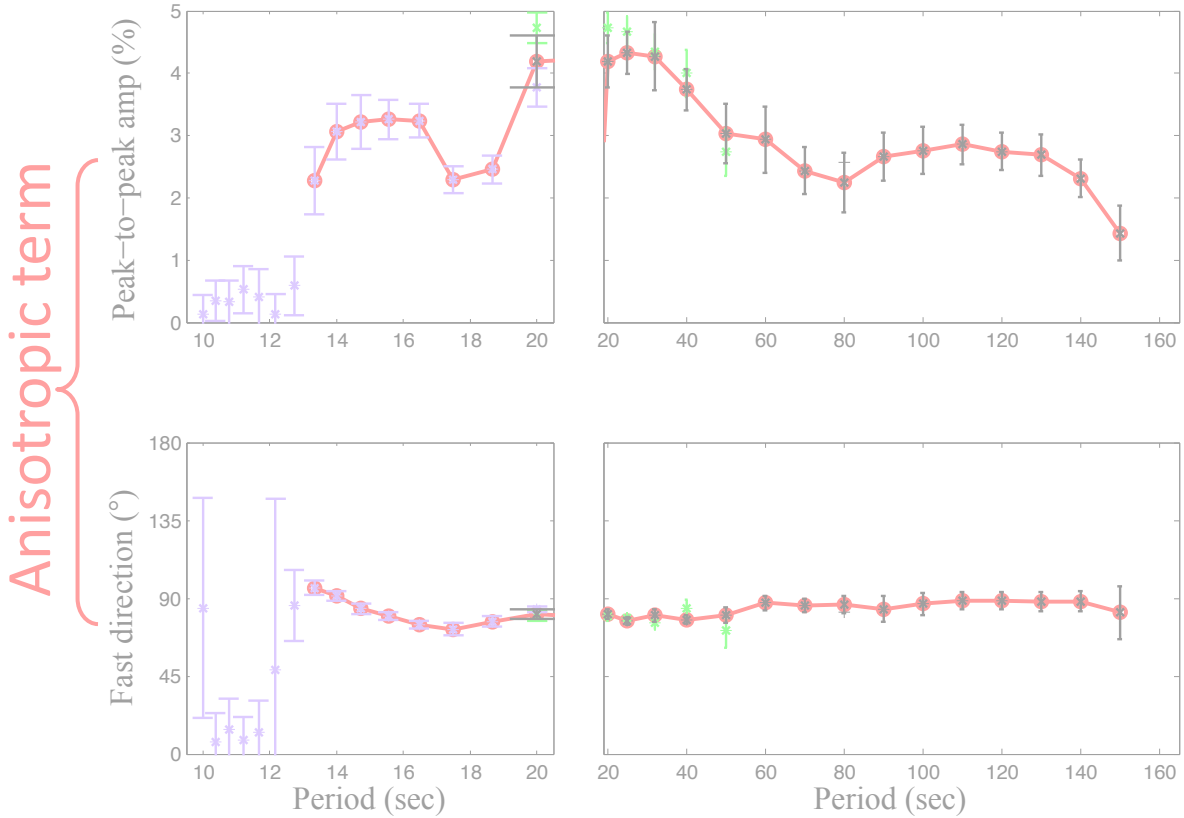


- No strong lateral variation
- Consistent results from different data types
- Rollover in velocity

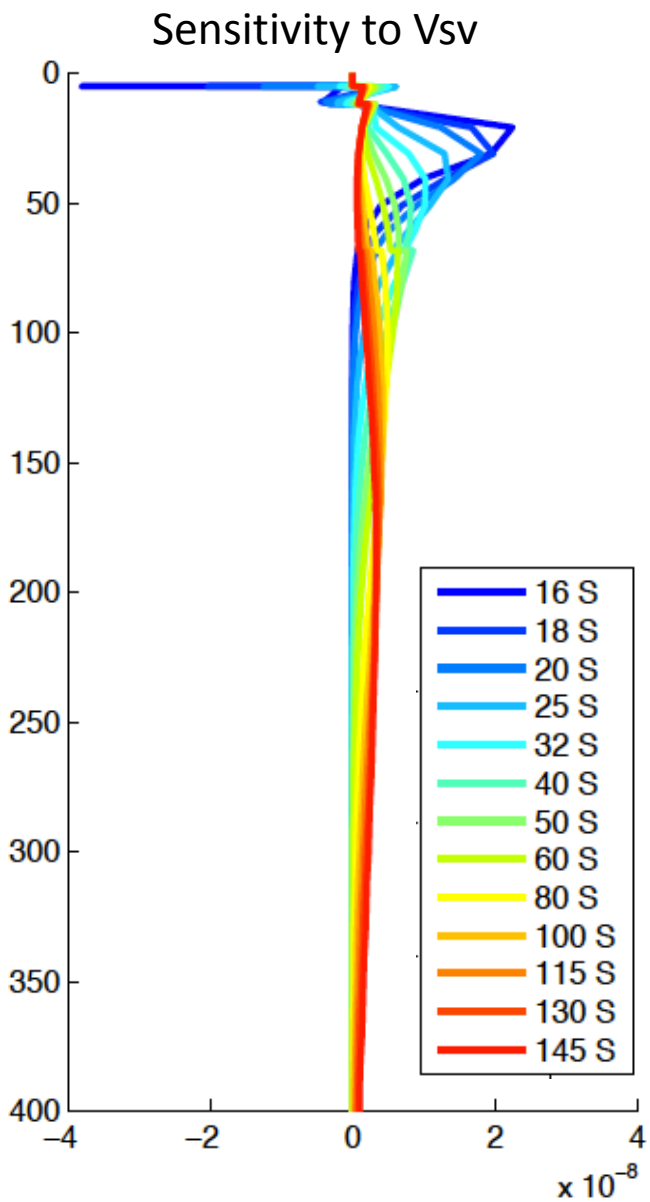
Phase Velocity & Azimuthal Anisotropy

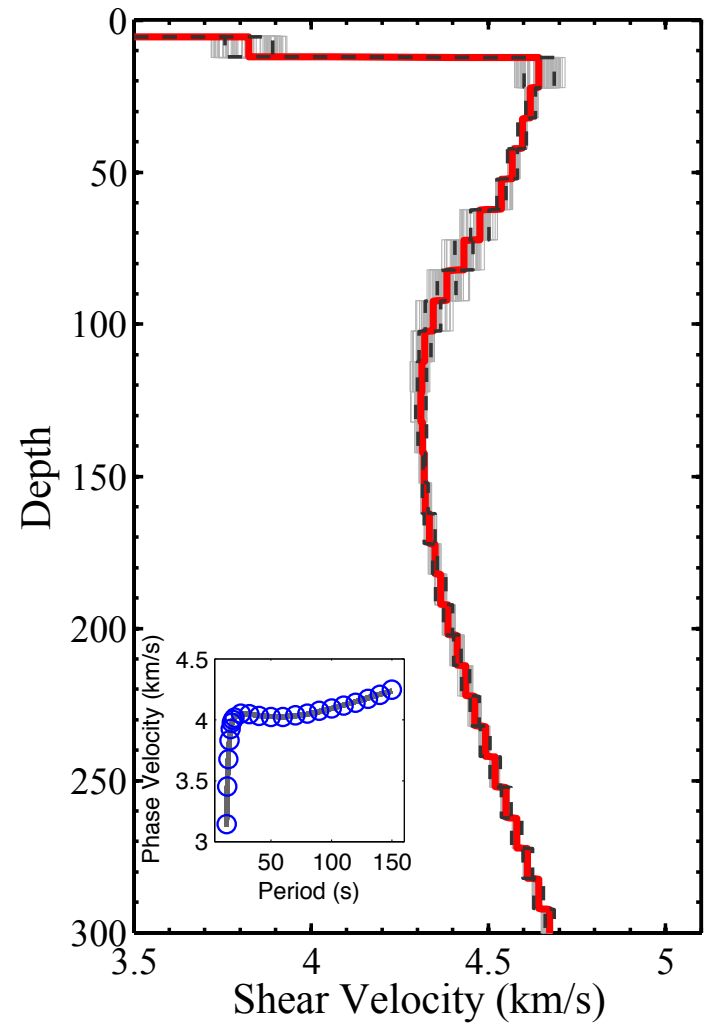


1D shear wave speed model

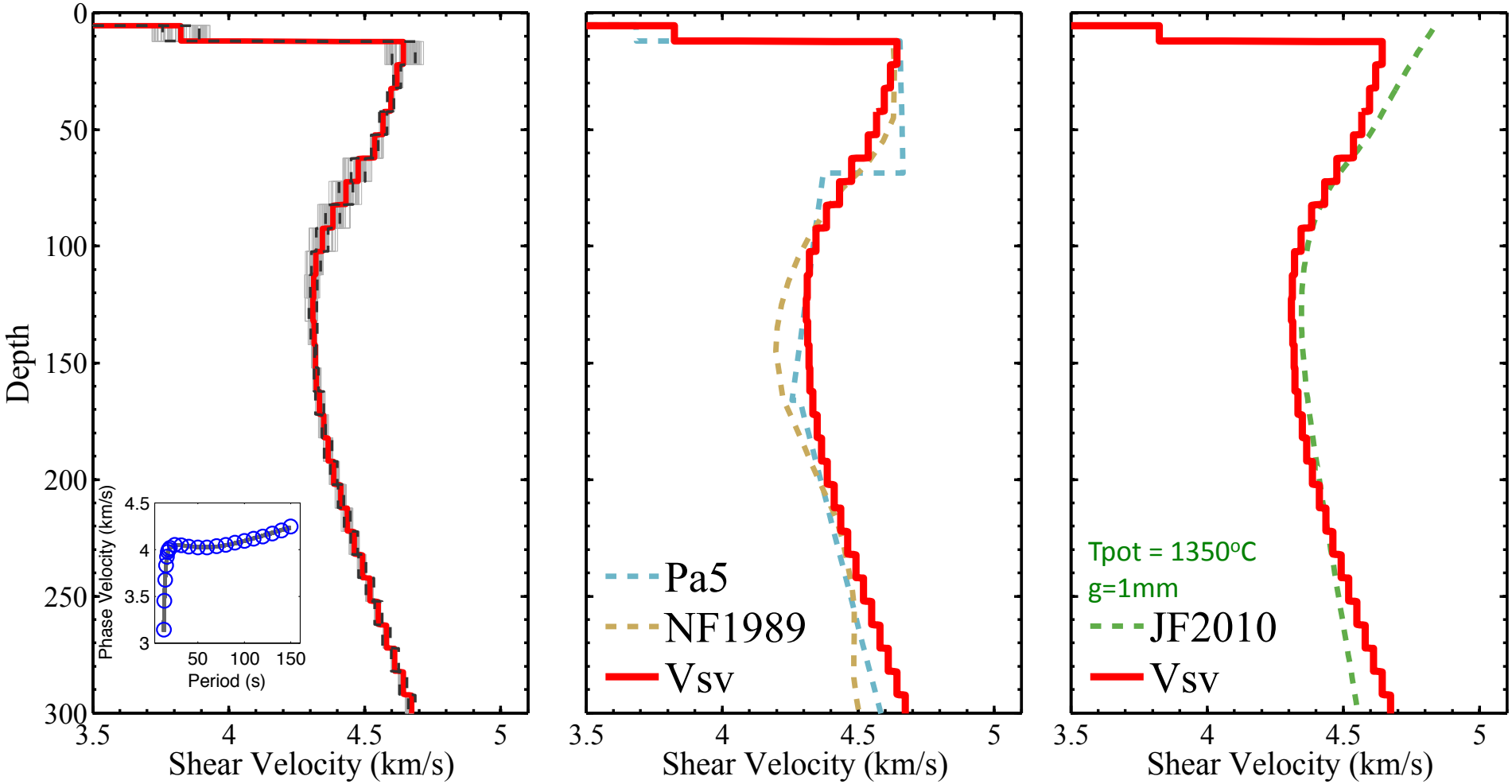


1D Shear Wave Speed Model



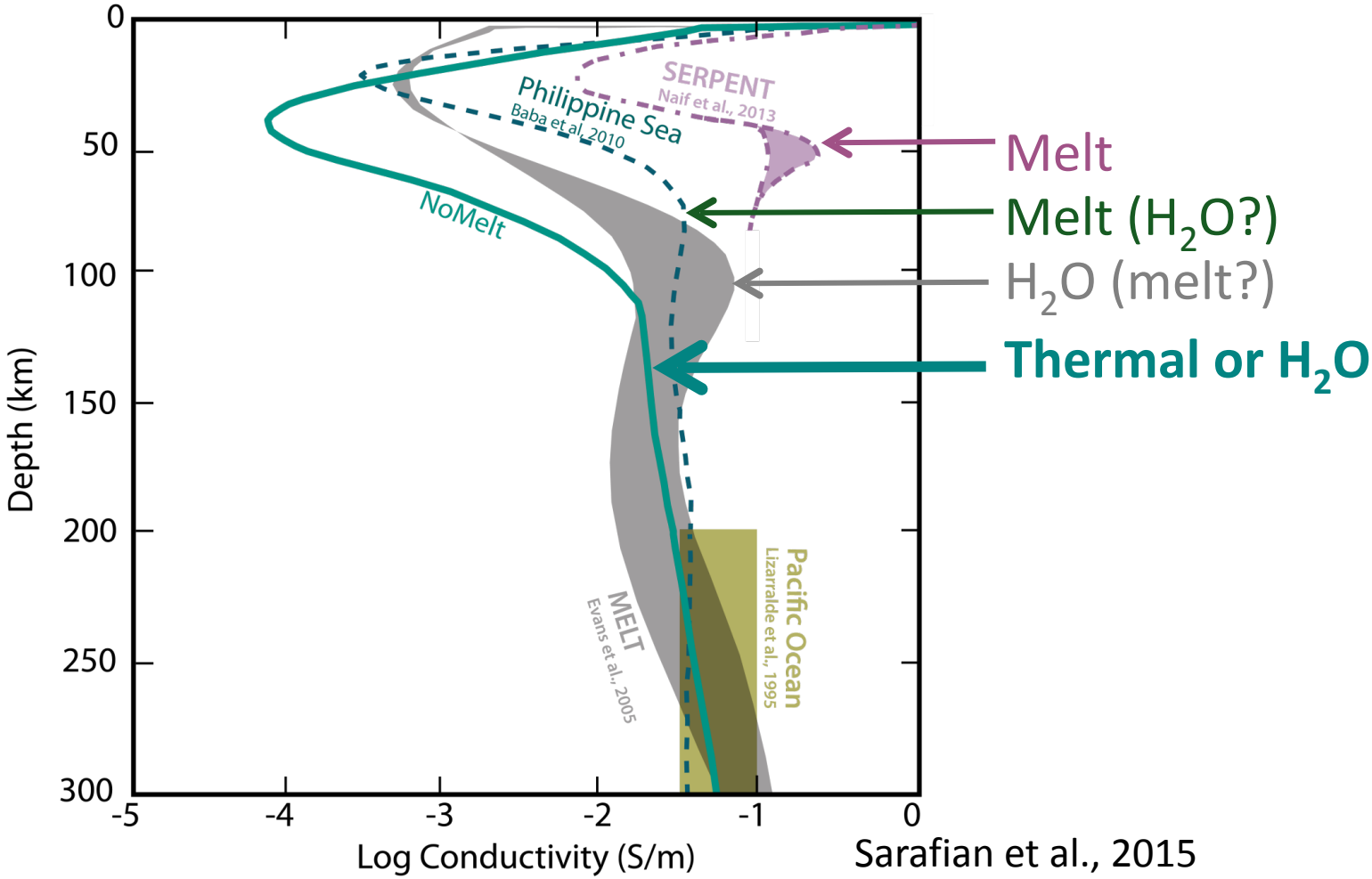


1D Shear Wave Speed Model



- Thin high Vs lid
- Shallow LVZ
- No or little need for melt

Constraints from Electrical Conductivity



Sarafian et al., 2015

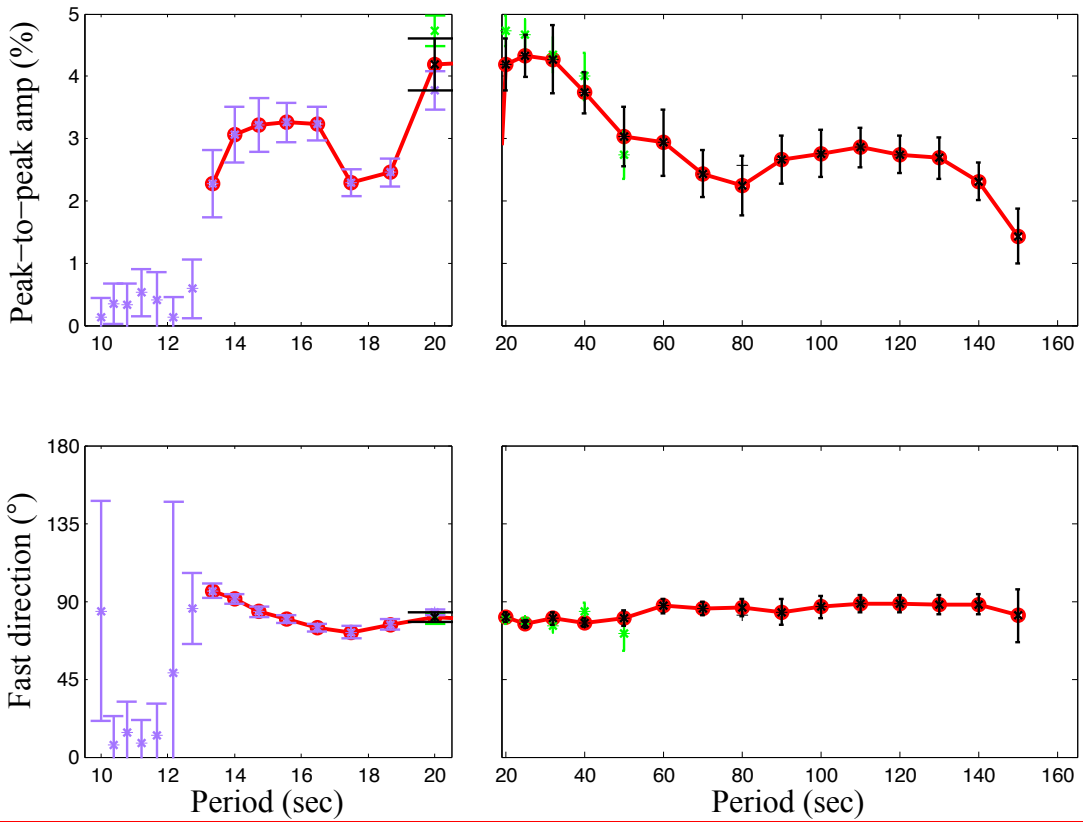
- Dry lid (80 km thick) overlying damp asthenosphere
  - H2O content of 5-400 ppm, depending on choice of lab data
- inferred temperature and watercontent **do not** result in melting conditions

Phase Velocity & Azimuthal Anisotropy

Isotropic term

- No strong lateral variation
- Consistent results from different data types
- Rollover in velocity

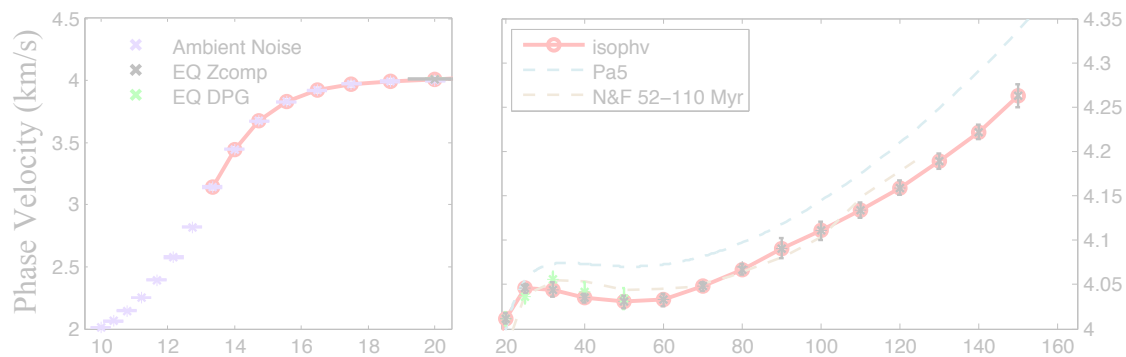
Anisotropic term



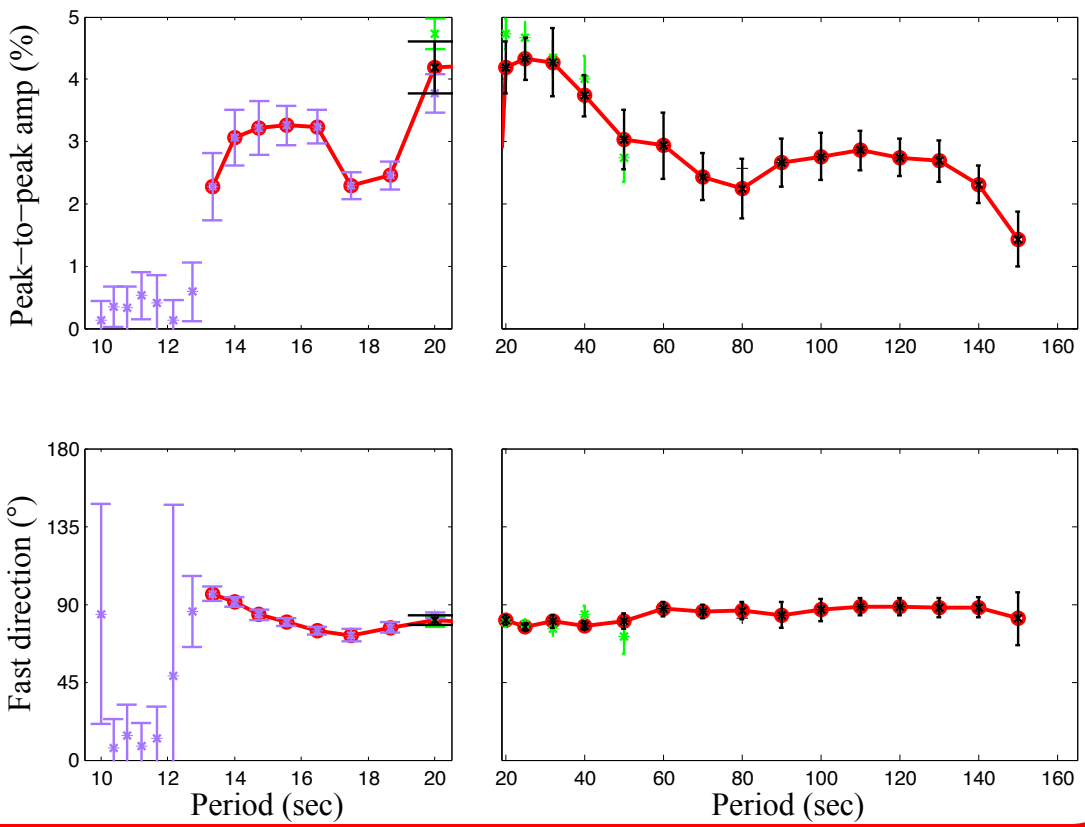
- Strongest anisotropy in the shorter period with fast direction ~78°
- Weaker anisotropy at intermediate periods
- Strengthening and rotating towards a more EW direction at the longest periods

Phase Velocity & Azimuthal Anisotropy

Isotropic term

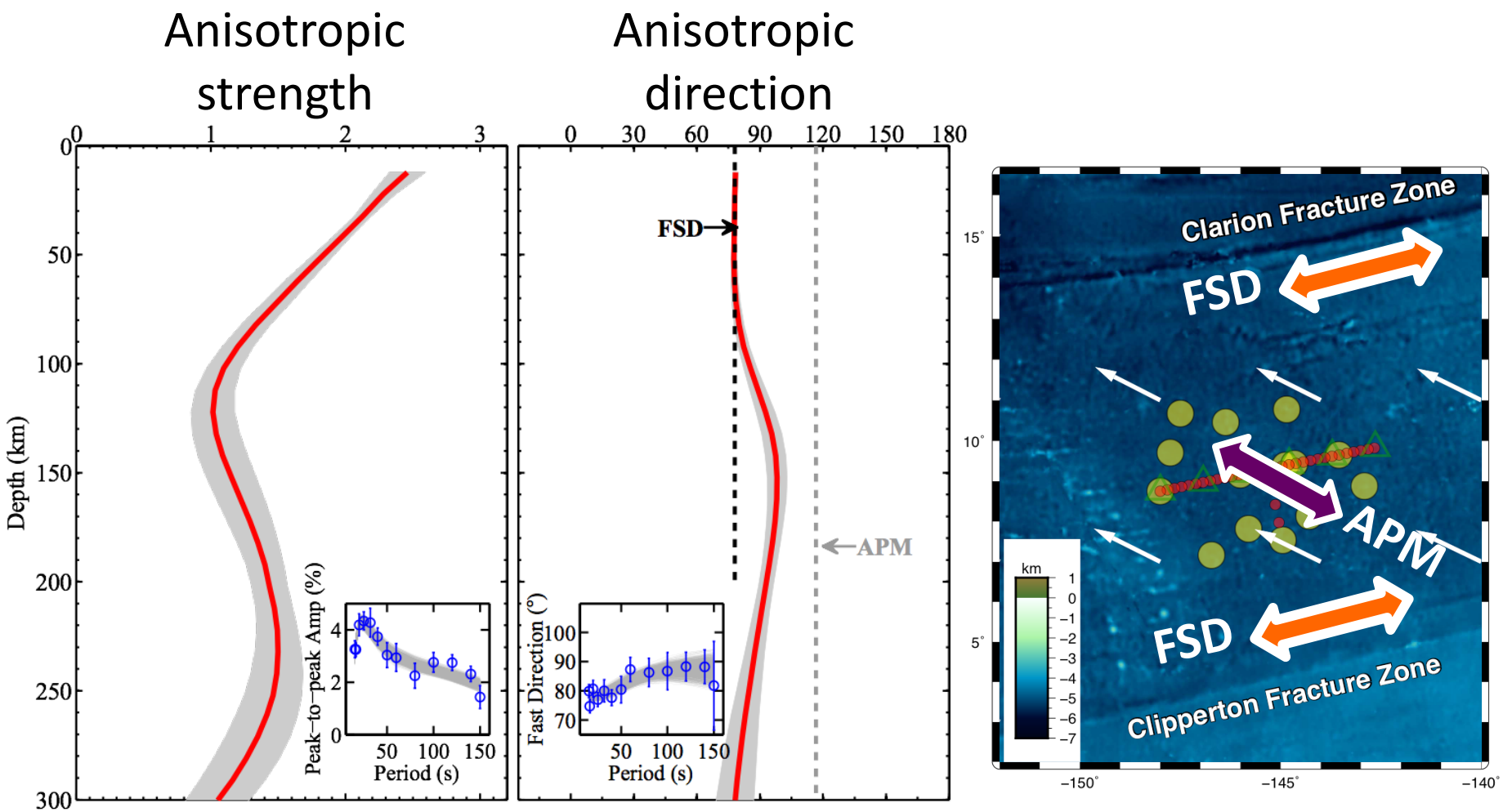


Anisotropic term



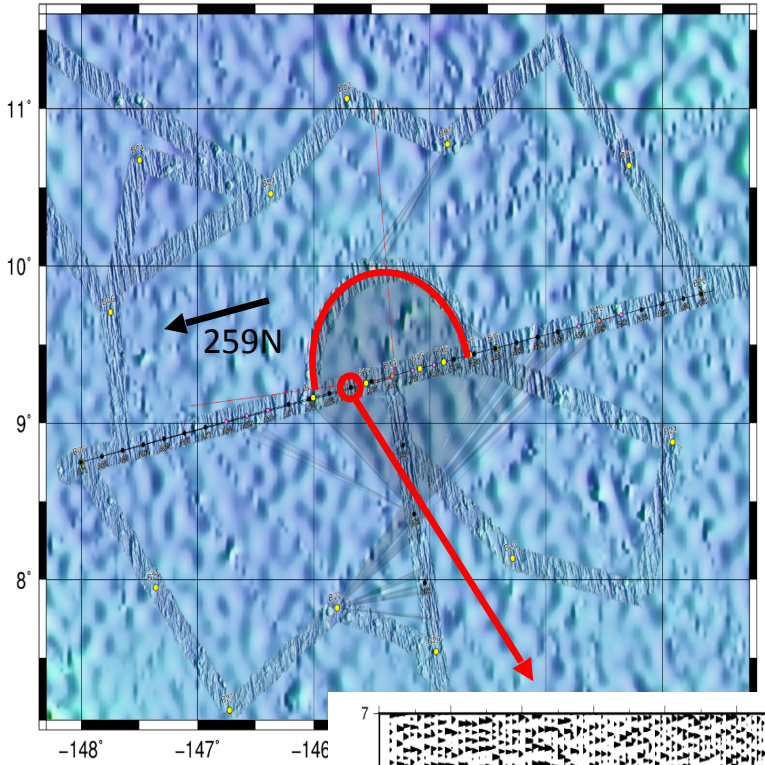
1D azimuthally anisotropic model

1D Azimuthally Anisotropic Model

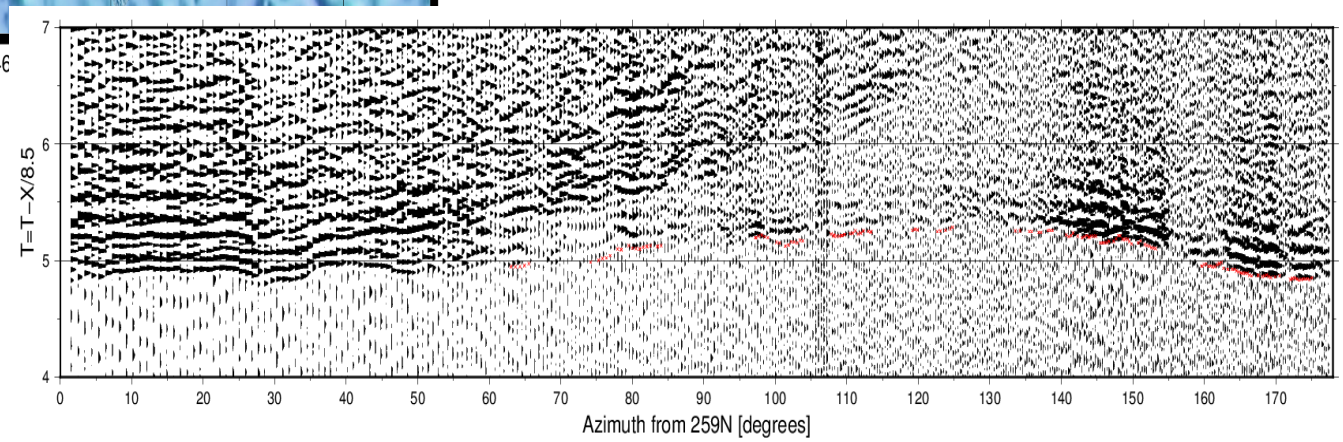


- Strongest at shallow depth & oriented with **F**ossil **S**preading Direction
- Anisotropy in asthenosphere is relatively **WEAK**
- The fast direction does **NOT** correlate with the APM in any depth

Azimuthal Anisotropy from Active Source Data

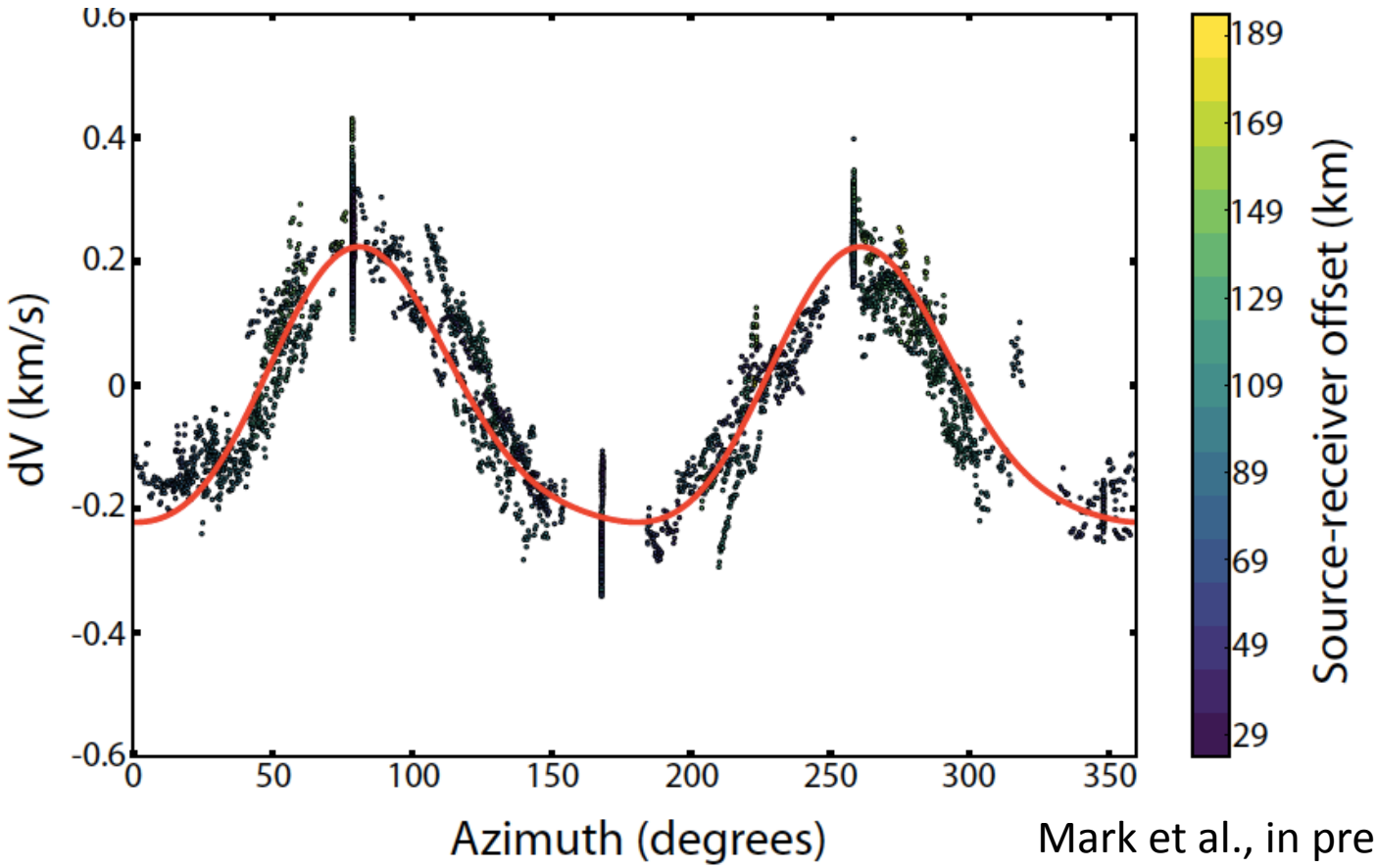


- Active-source data from OBS array constrains azimuthal anisotropy in the uppermost mantle
- Pn (upper mantle reflection) arrivals are recorded by SP-OBS spanning 180 degrees of azimuth



Mark et al., 2014

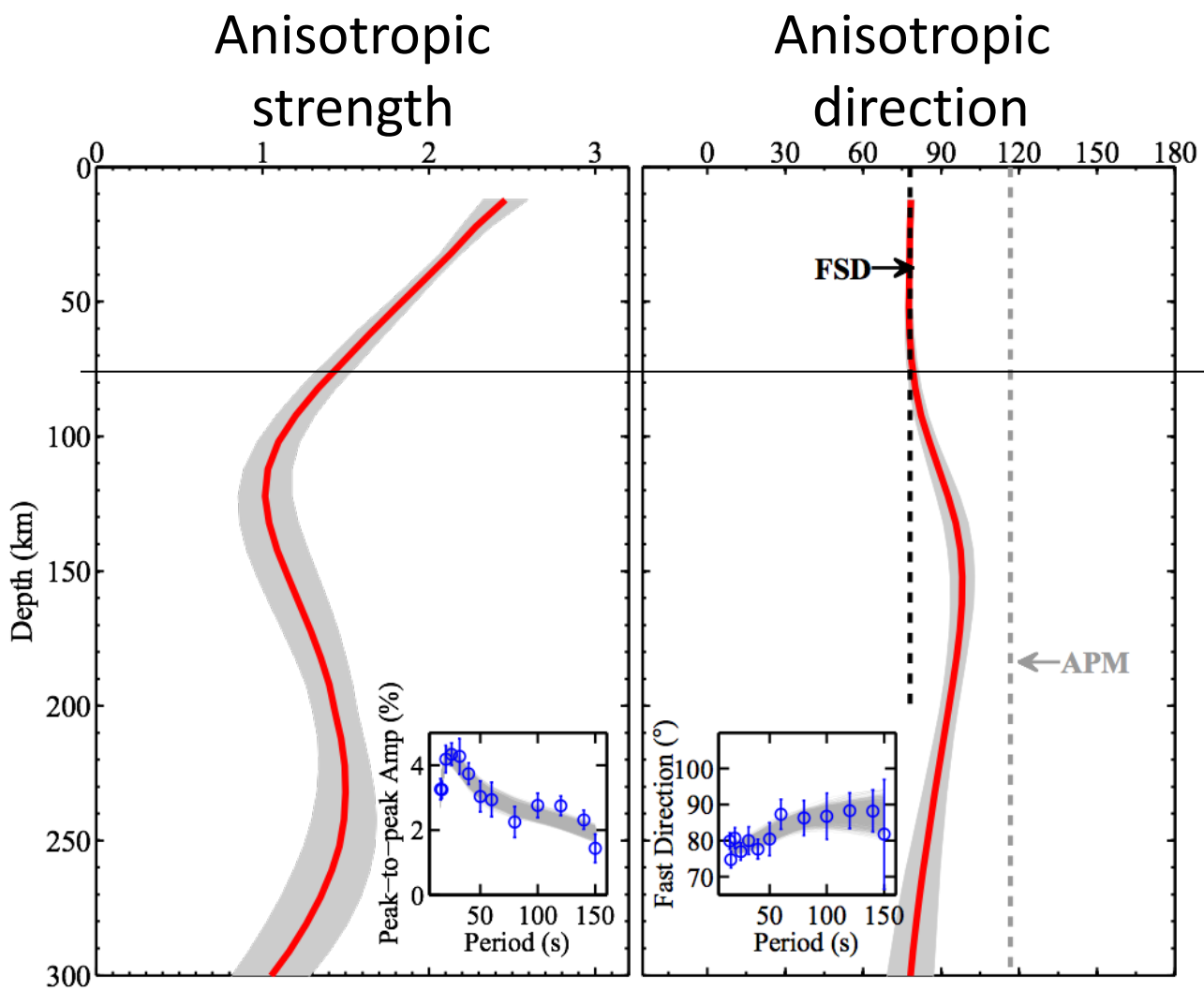
Azimuthal Anisotropy in the Uppermost Mantle



Mark et al., in prep.

- Upper 10-15 km of the mantle are strongly anisotropic
- Fast directions oriented in fossil spreading direction
- 4θ contribution is small

1D Azimuthally Anisotropic Model



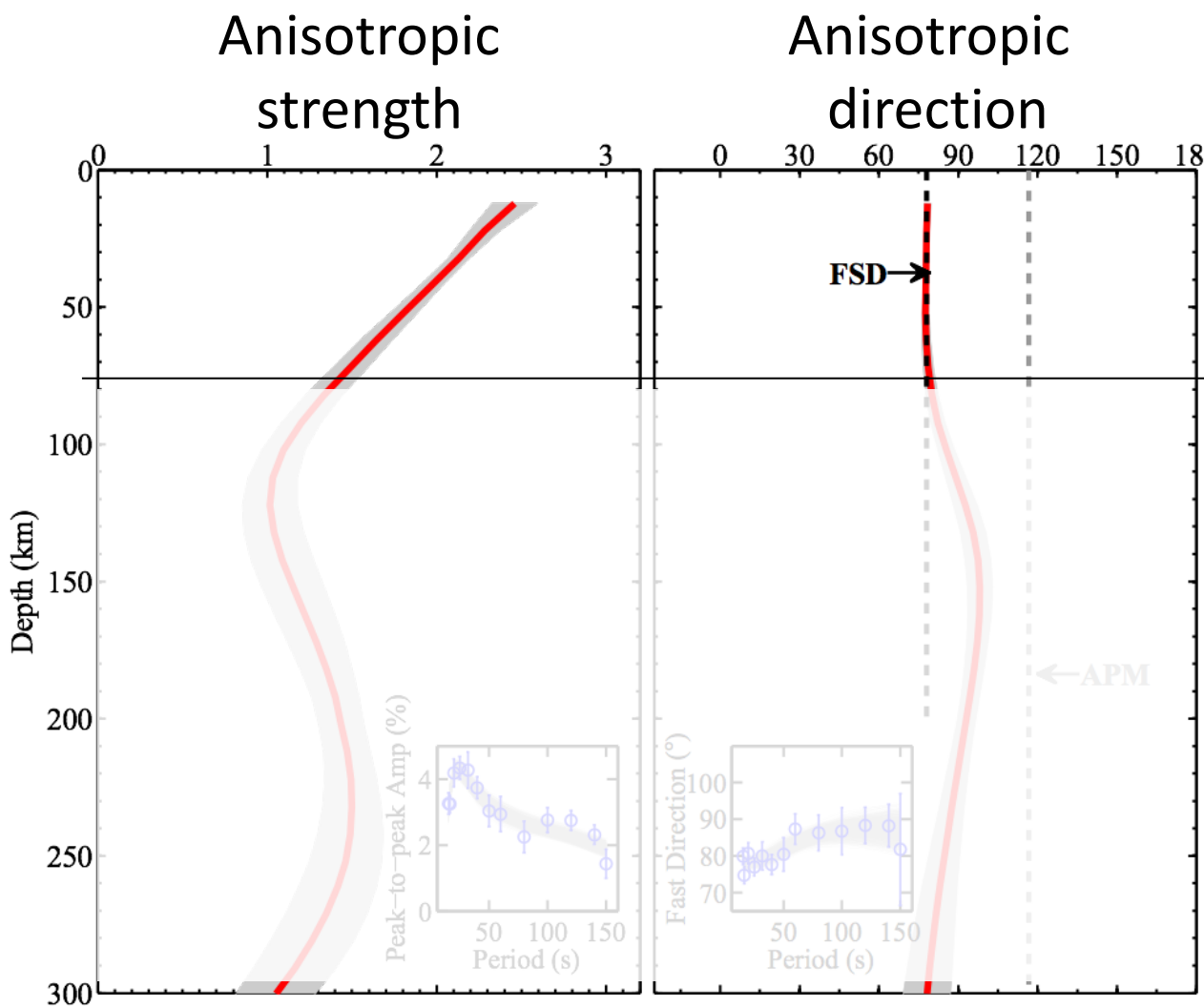
Lithosphere --

- Strongest anisotropy
- Direction is parallel to FSD

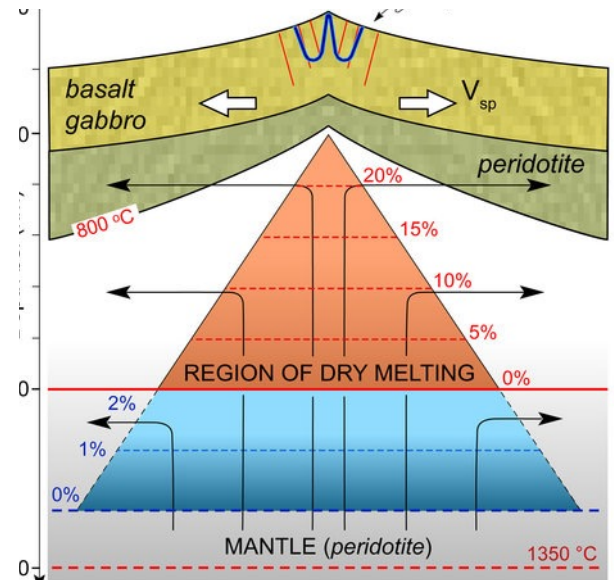
Asthenosphere --

- Relatively weak anisotropy
- Direction does not correlate with APM

Constraints on Mantle Deformation and Flow



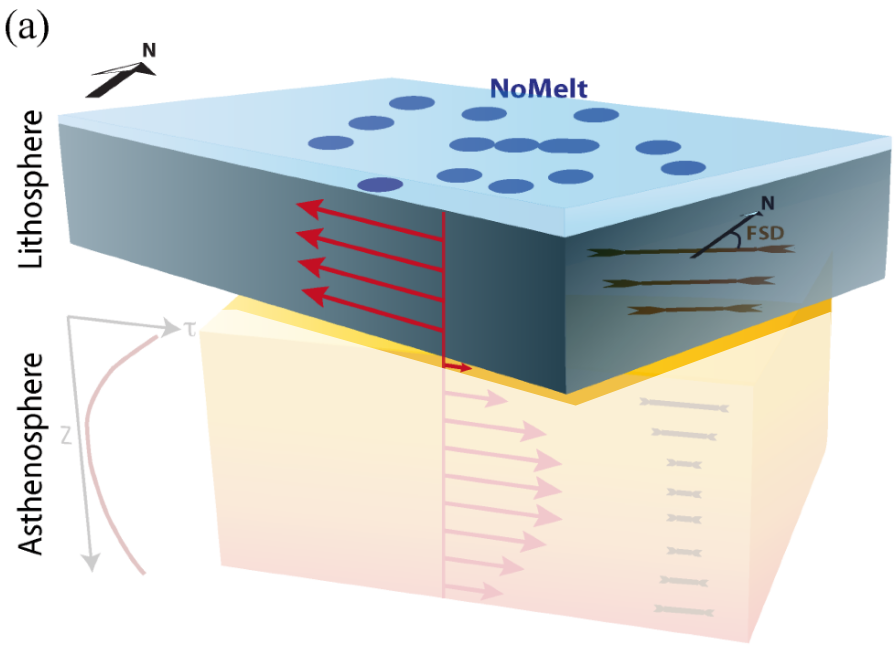
Fossil spreading



Ligi et al., 2013

- Strong corner flow fabric which was formed at mid-ocean ridge.
- Corner flow at the mid-ocean ridge is **DOMINANT** fabric-forming process in the oceanic lithospheric mantle.

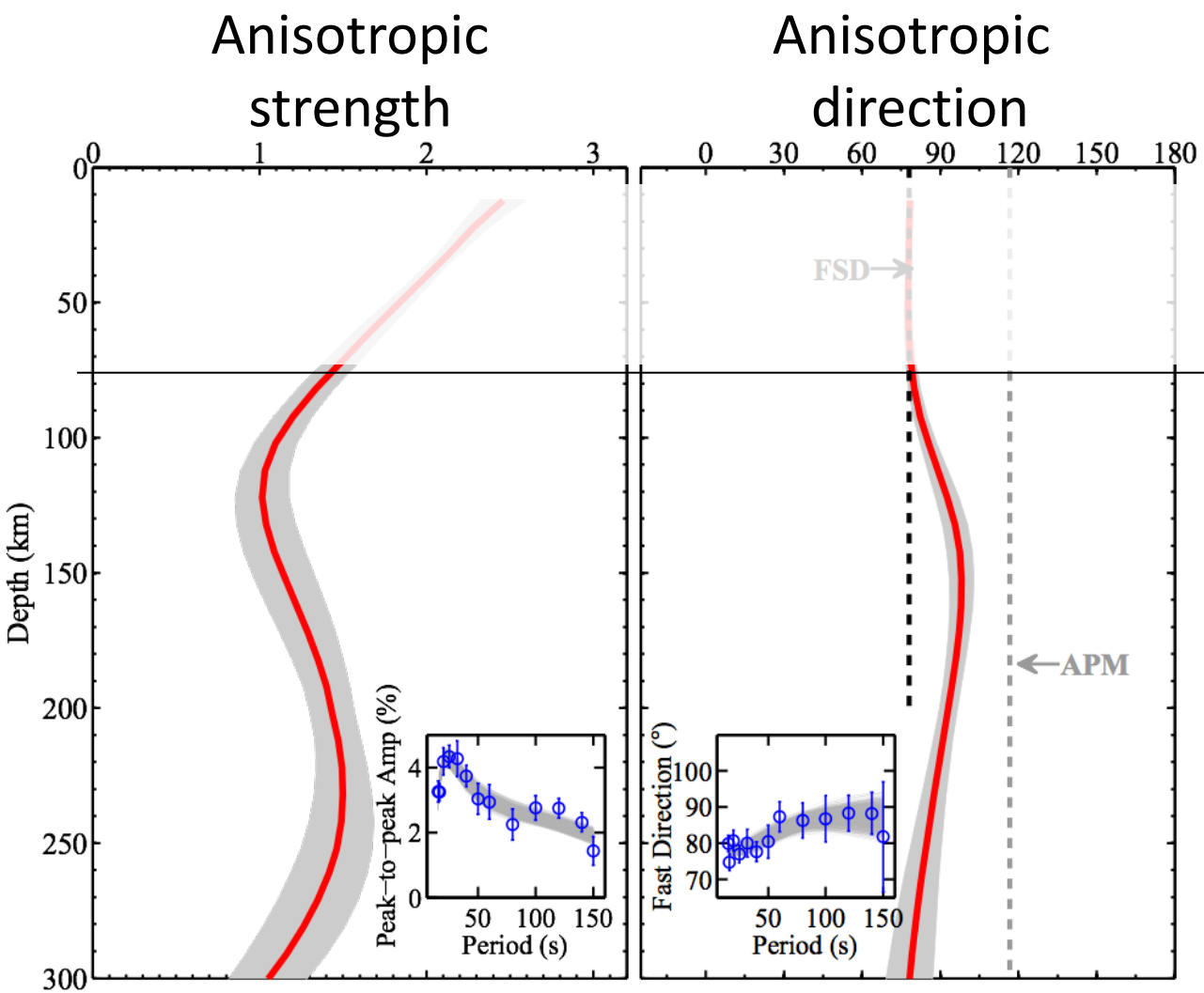
Constraints on Mantle Deformation and Flow



corer flow at mid-ocean ridges

- The lithosphere layer moves in plate velocity in all depth.
- The anisotropy are **frozen fabric** from the shear-strain during corner flow at the ridge axis.
- The strength is largest at top and decreases with depth.

Constraints on Mantle Deformation and Flow



Fossil spreading

~~Effects of melt?~~

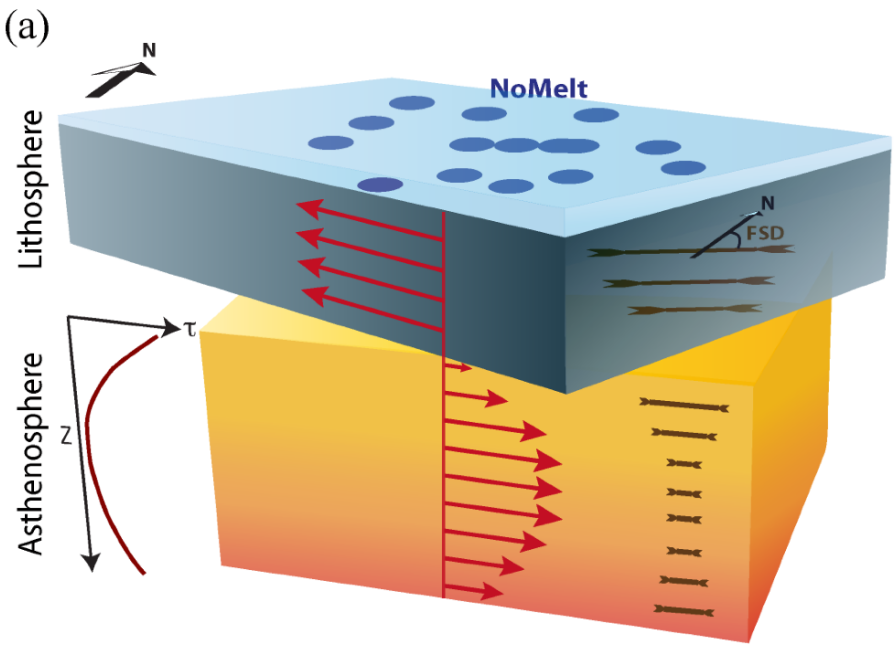
Pressure driven flow?

Buoyancy driven flow?

- No clear APM signals == >

The deformation is induced by dynamic flow within the asthenosphere

Constraints on Mantle Deformation and Flow

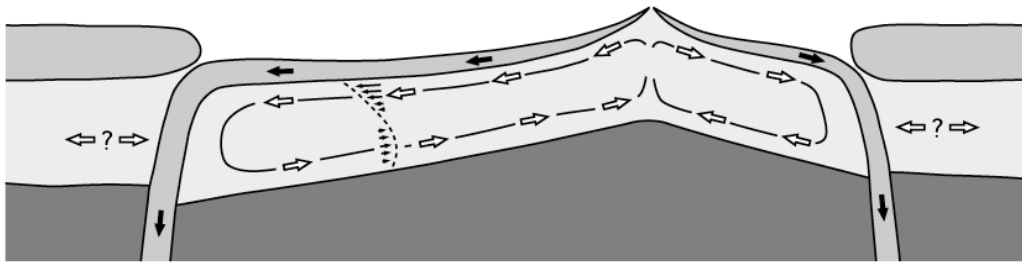


Corner flow (fossil)

Pressure driven flow

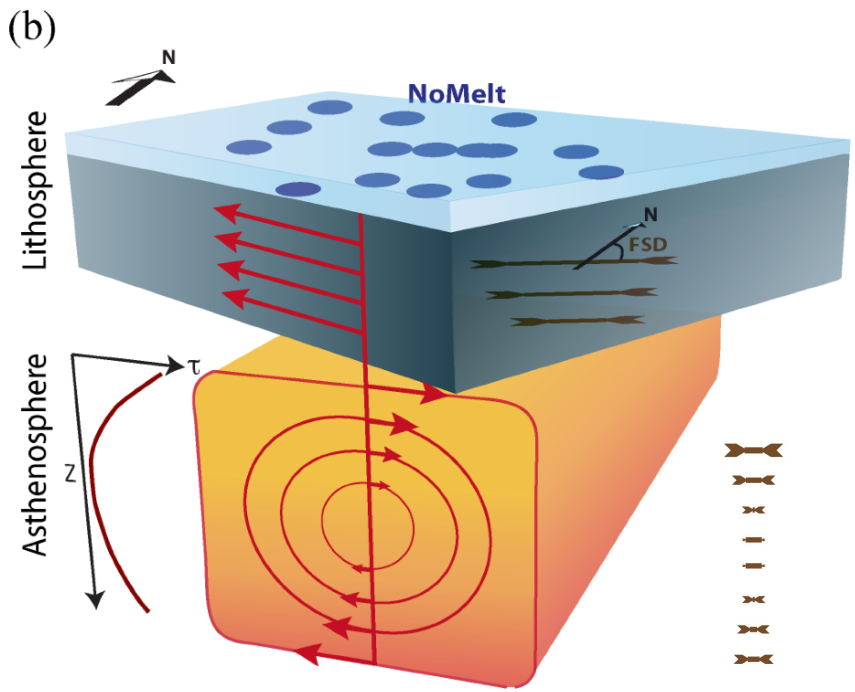
- Return flow from trench or asthenospheric push from ridge
- Large-scale density-driven flow

- Pressure gradients induce a channel flow with a plug-like velocity profile
- Fabric-inducing strain gradients are localized near the top and bottom boundaries of the channel



Nagel et al, *Tectonics*, 2008

Constraints on Mantle Deformation and Flow

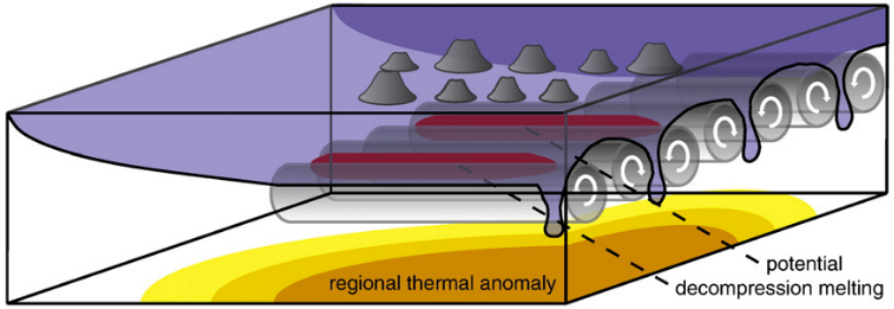


Corner flow (fossil)

Buoyancy driven flow

- Small-scale density-driven flow

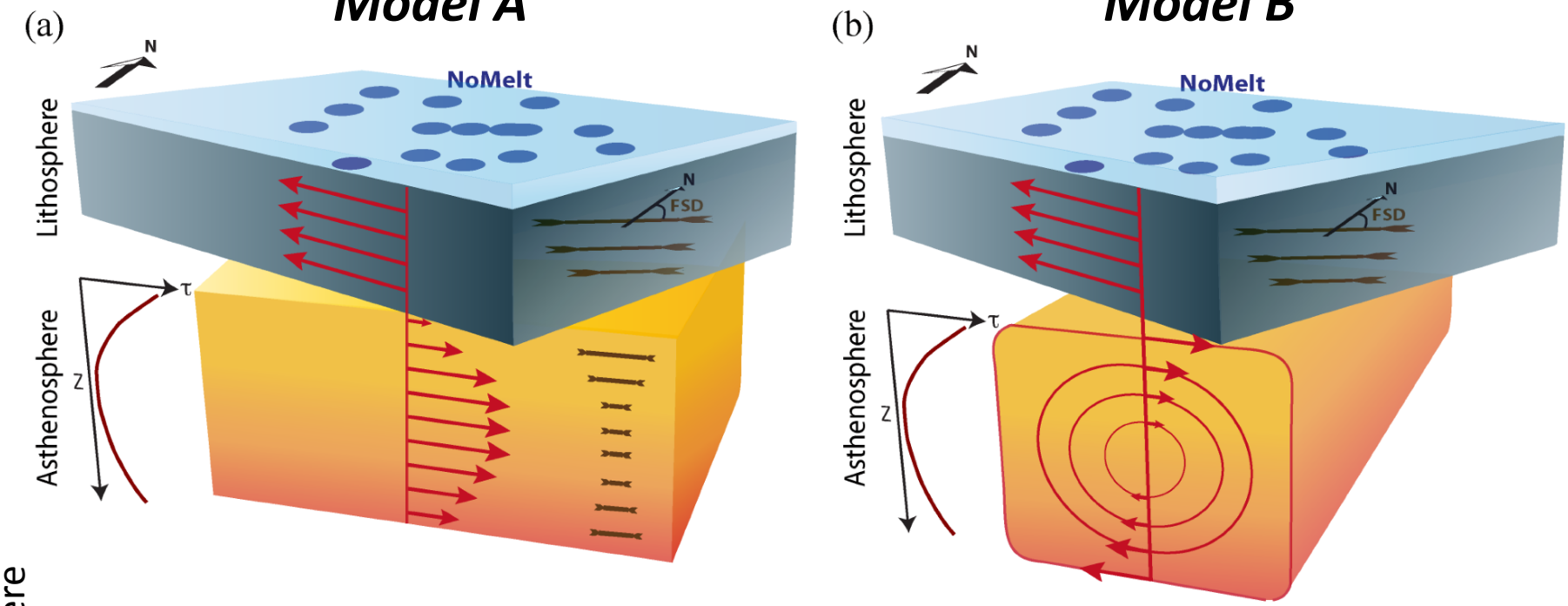
- Density-driven small-scale convection
- Poorly organized horizontal flow in the center of rolls result in weak azimuthal anisotropy



Ballmer et al., *EPSL*, 2010

Azimuthally Anisotropic Model

Model A ***Model B***



Lithosphere

Strong anisotropy are **frozen fabric**
from the shear-strain during corner flow at the ridge axis

Asthenosphere

Pressure driven flow ***Buoyancy driven flow***

Weak asthenosphere channel
Non-linear rheology – localize deformation on the channel margins

Conclusion

- "Normal" oceanic asthenosphere is contains negligible partial melt, with a modest degree of hydration or other volatiles
- Corner-flow at the mid-ocean ridges is the dominant signal of shear deformation in the oceanic upper mantle
- Flow within the asthenosphere is decoupled from the overriding plate
- Asthenospheric flow may be driven by far-field pressure gradients, or near-field internal buoyancy associated with small-scale convection
- Local view provides high-resolution constraints on mantle processes that are missed in large-scale analyses

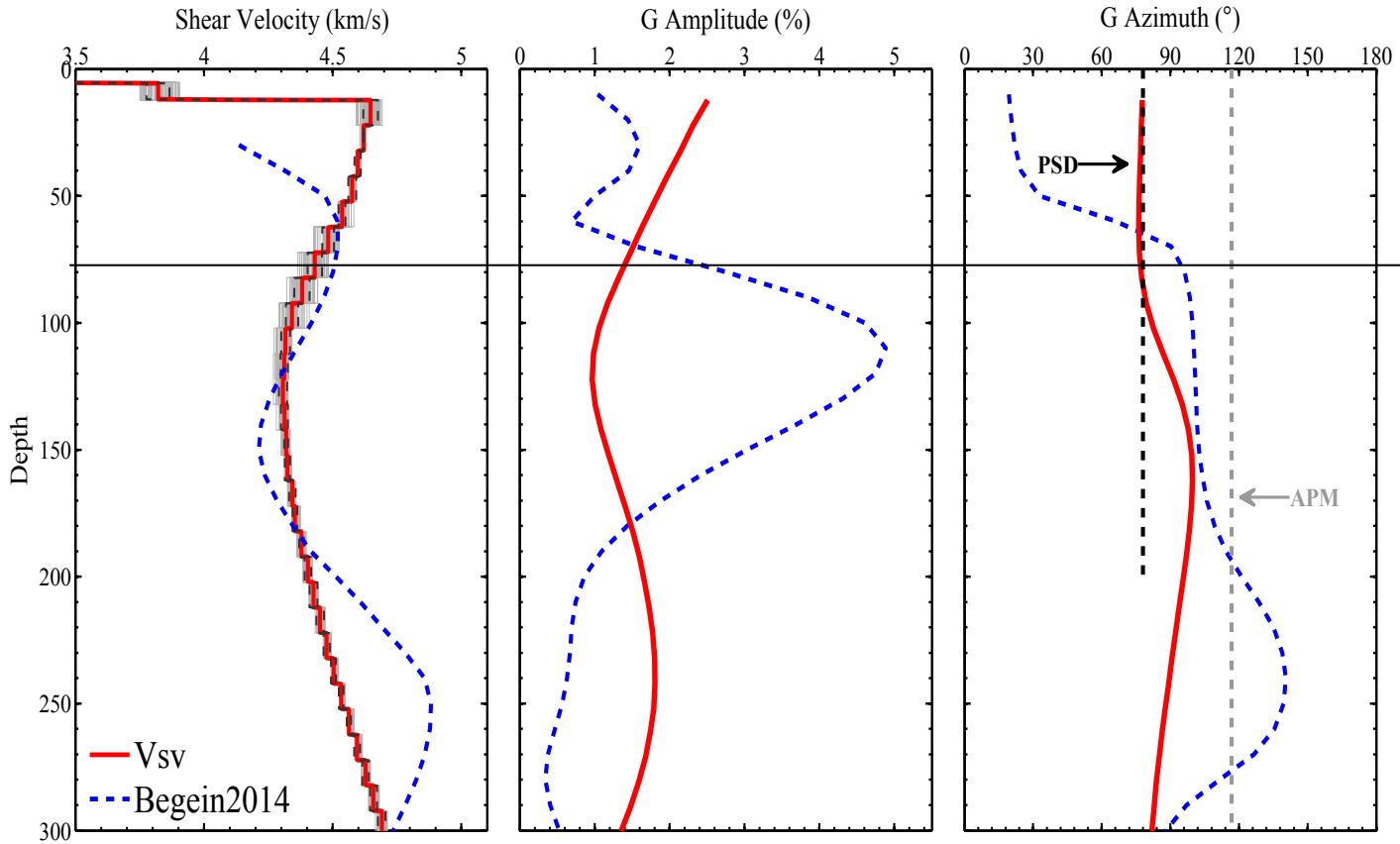
Acknowledgements

- We thank the scientific party, captain, crews, and technical teams of R/V *Marcus G. Langseth* and R/V *Melville* for their work that made this study possible.

- The OBSs deployed are part of the instrument pool supported and maintained by OBSIP. We thank the OBS teams at SIO and WHOI

EXTRA SLIDES

Constraints on Mantle Deformation and Flow



" unusual/unique" seismic observations from our work

Fossil spreading

weak in the asthenosphere
Never really reach AMP

G != 0 in the deeper depth