Earthquake rupture processes revealed by **dense** array analyses

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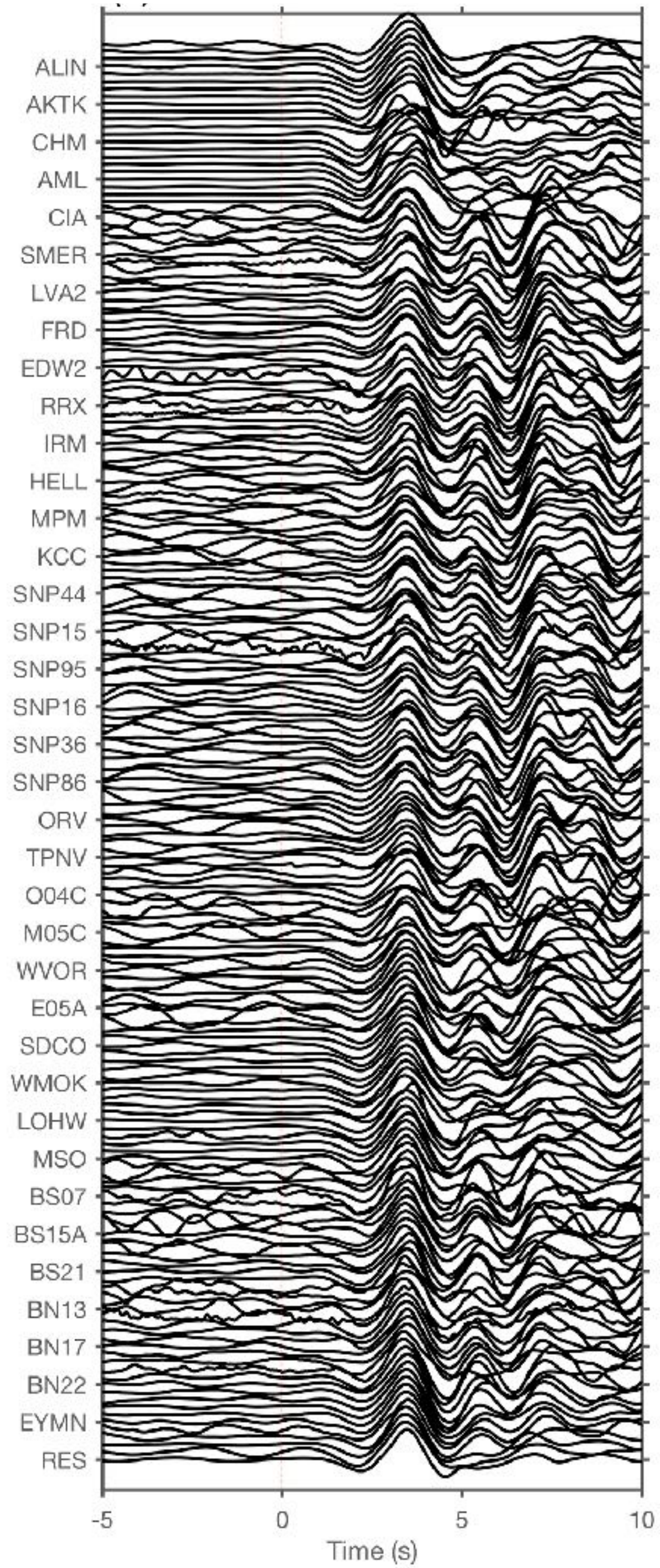
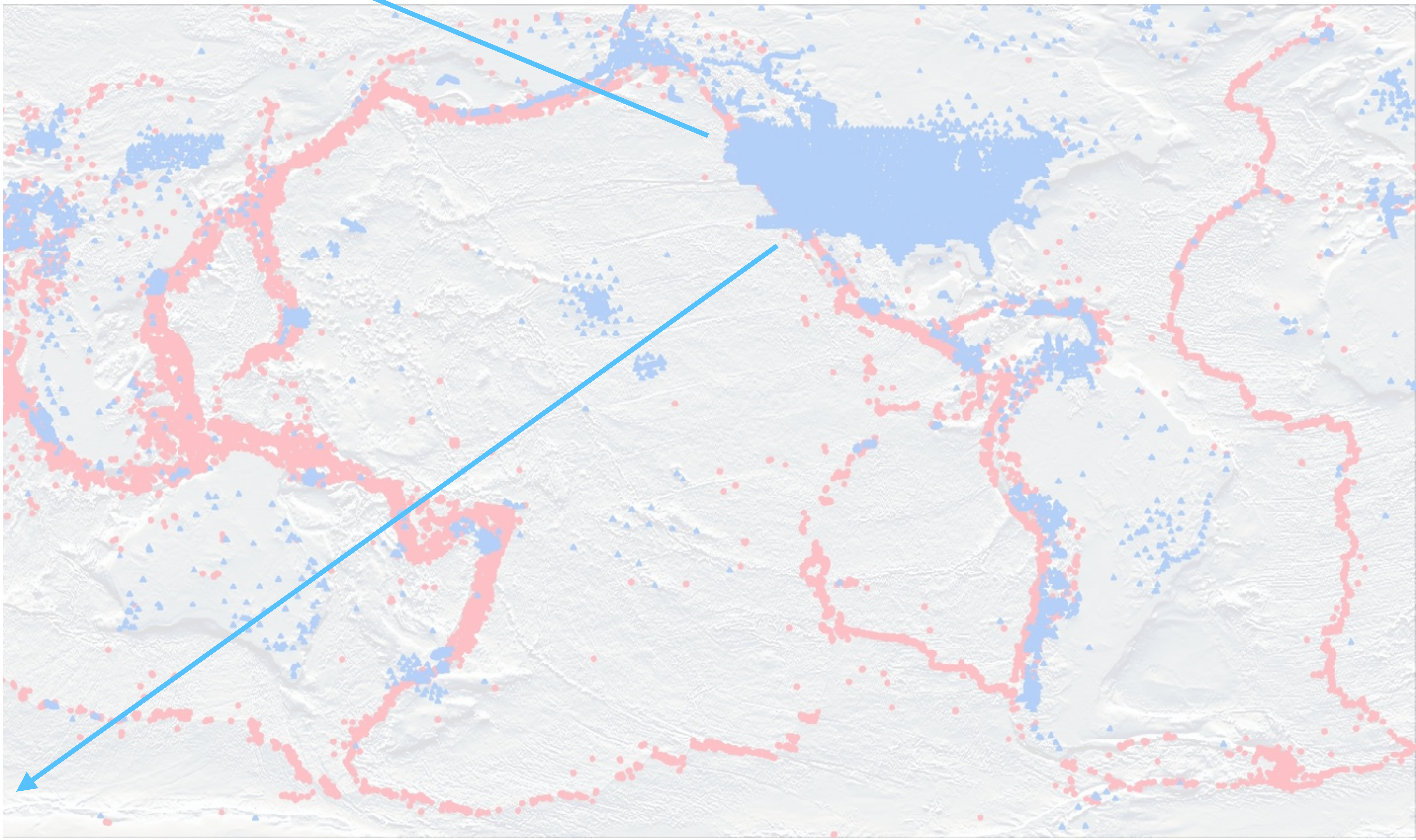
Over a quadrillion times energy difference!

Study Earthquakes with Arrays

Data credit: FDSN and GCMT

Coherent wavefield of large aperture Arrays

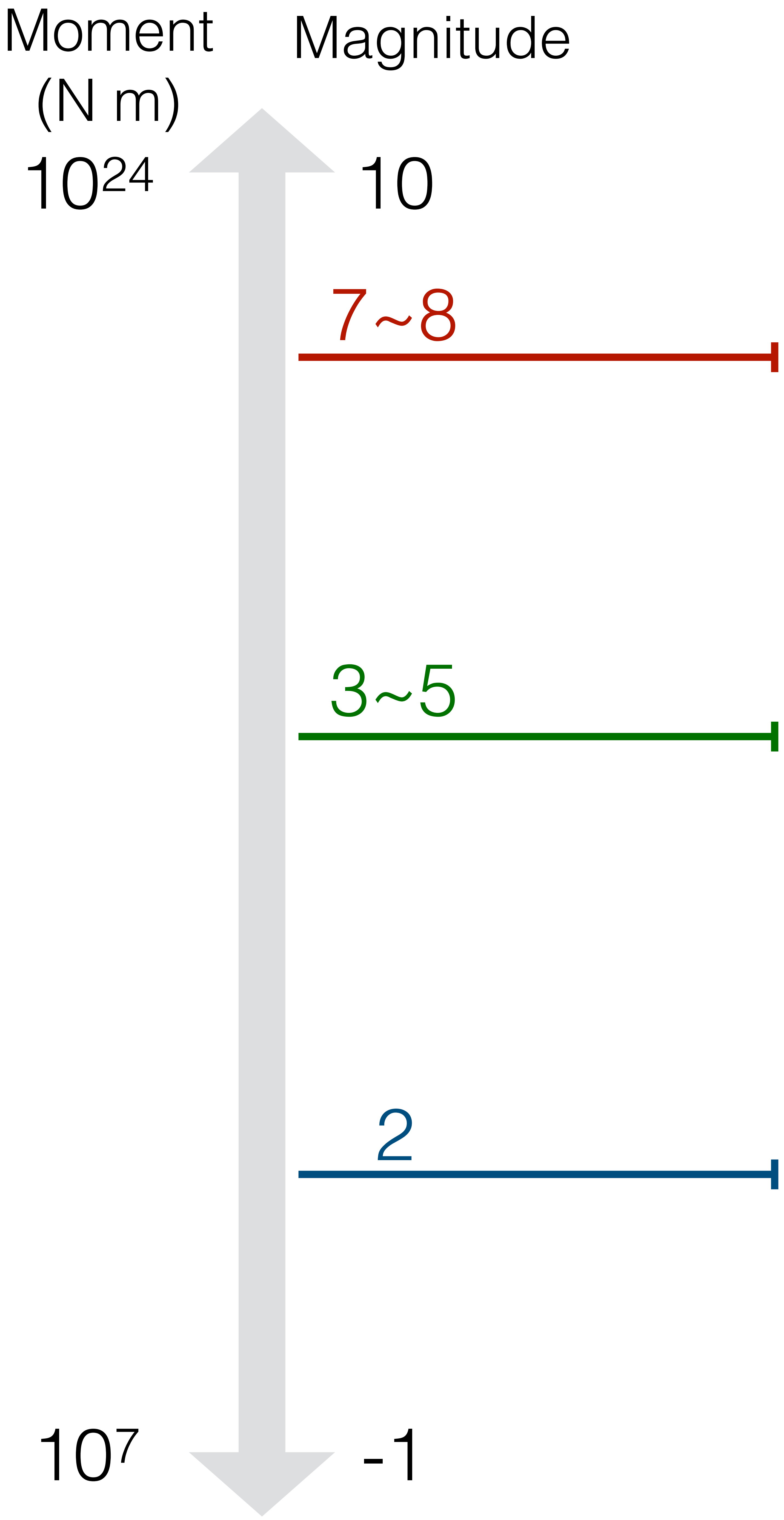




Fan & Shearer, 2017, *JGR*

Data credit: FDSN and GCMT

How earthquake processes evolve along faults?



Global Arrays

Local near-instantaneous **dynamic triggering** of large earthquakes

Continental Arrays

Using surface waves of large aperture arrays to detect and locate non-earthquake (**glacial-quakes, landslides, submarine landslides**) events

Nodal Arrays

Investigating **microearthquake finite source** attributes with IRIS Community Wavefield Demonstration Experiment in Oklahoma

Moment (N m)

Magnitude

10^{24} 10

How earthquake processes evolve along faults?

7~8

Global Arrays

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3~5

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2

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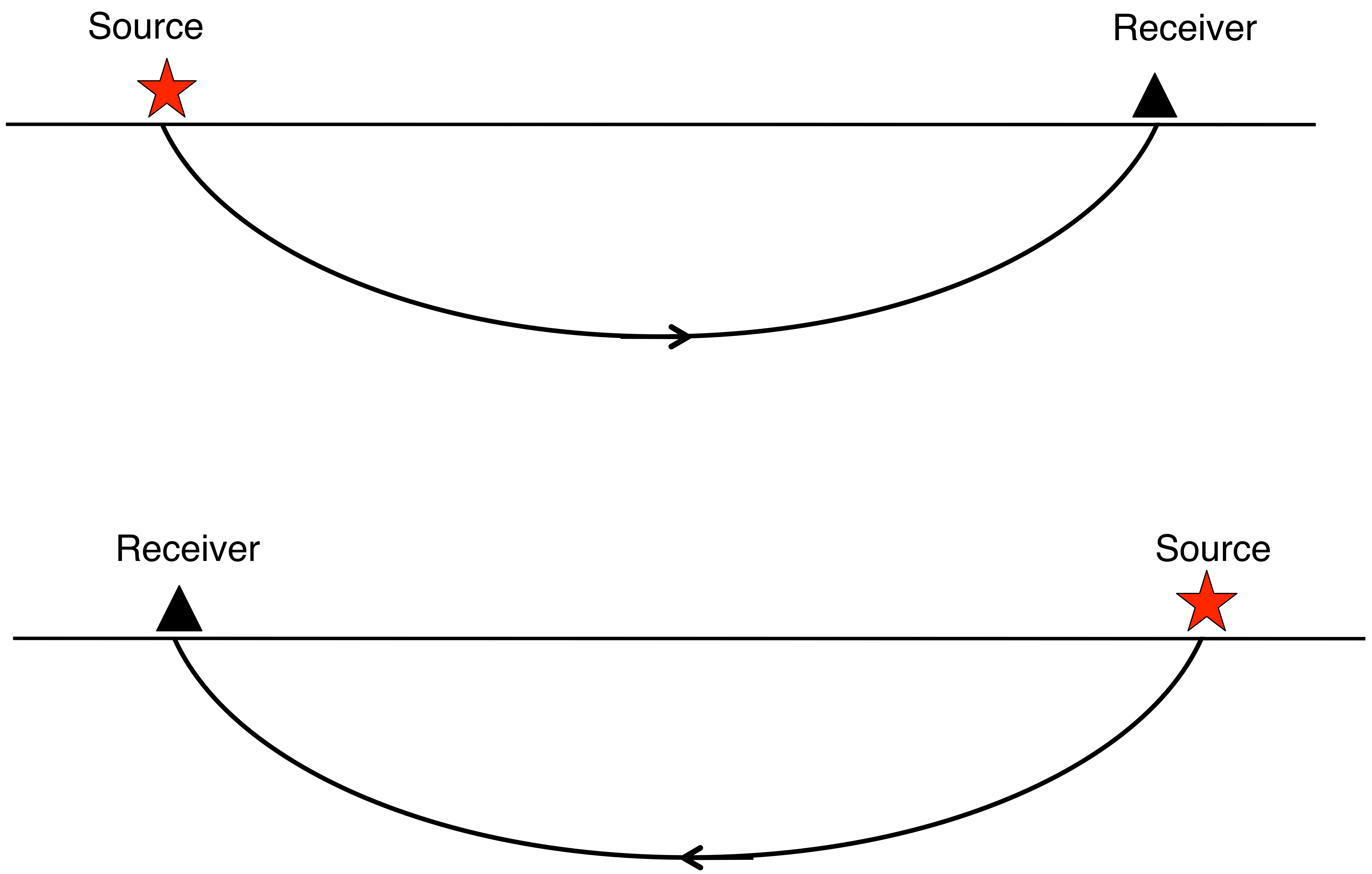
10^{7} -1

Back-projection

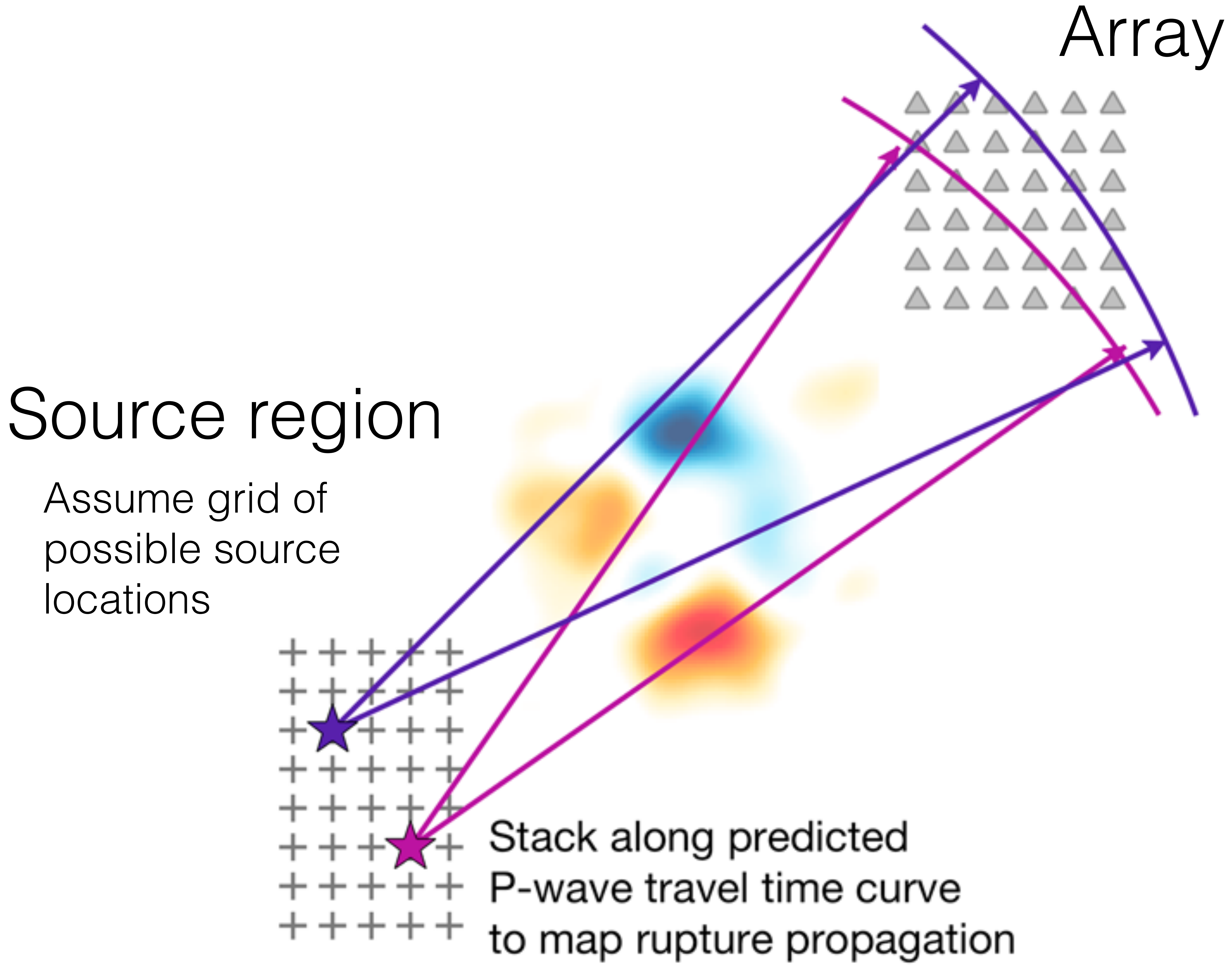


Both have same ray path and travel time

Fan & Shearer, *JGR*, 2017

Back-projection

Both have same ray path and travel time



Fan & Shearer, *JGR*, 2017

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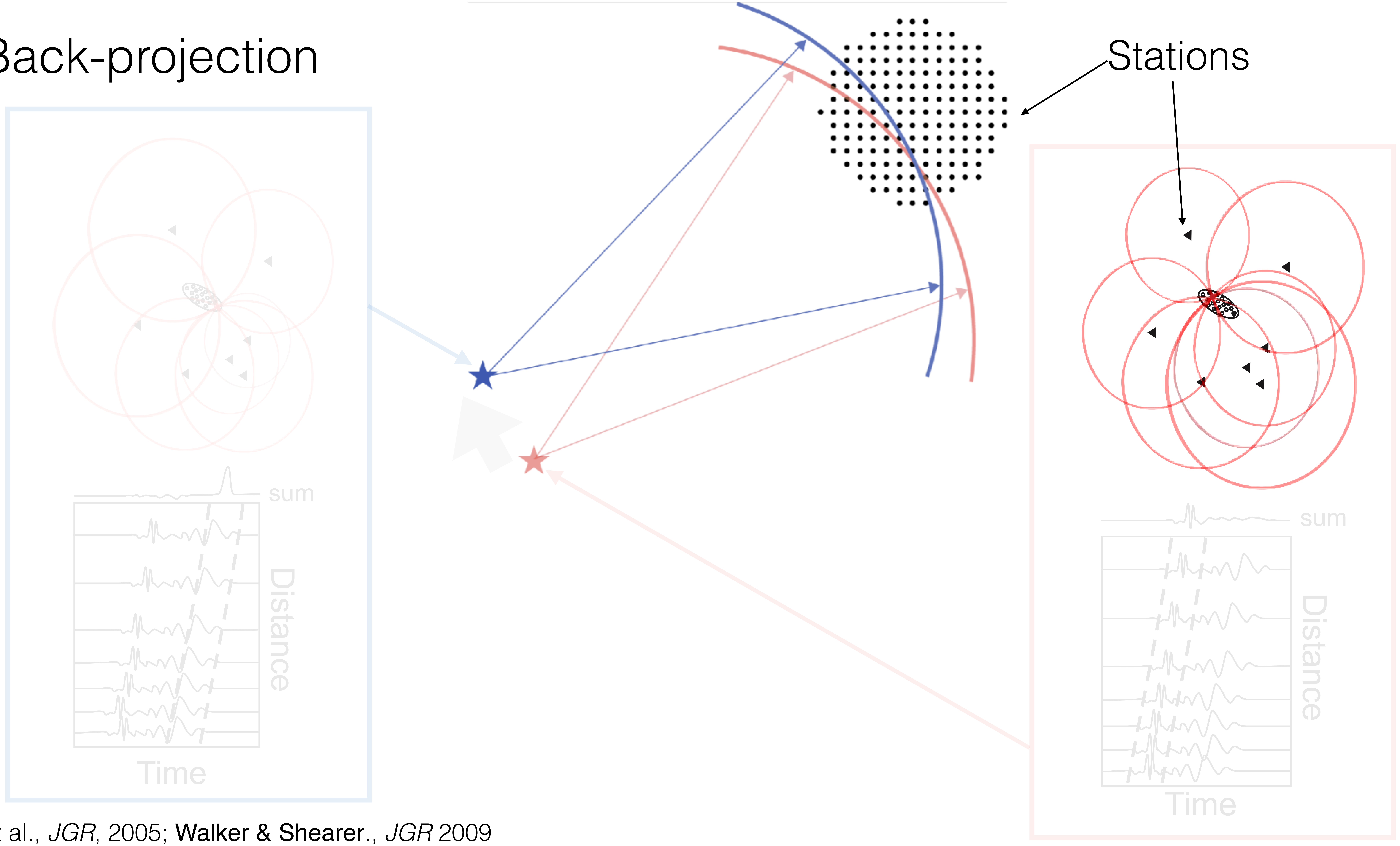
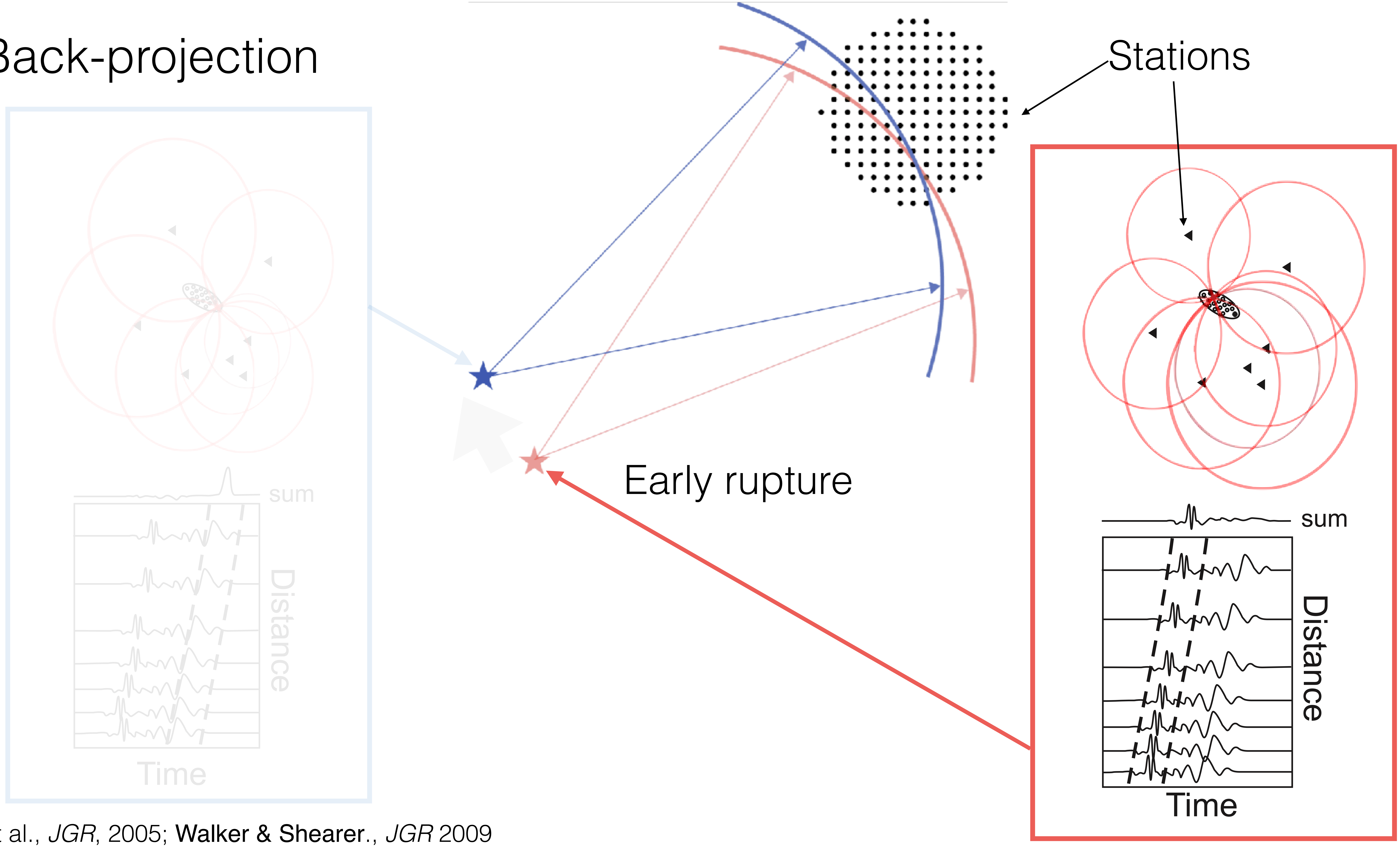


Ishii et al., *JGR*, 2005; Walker & Shearer., *JGR* 2009

Back-projection



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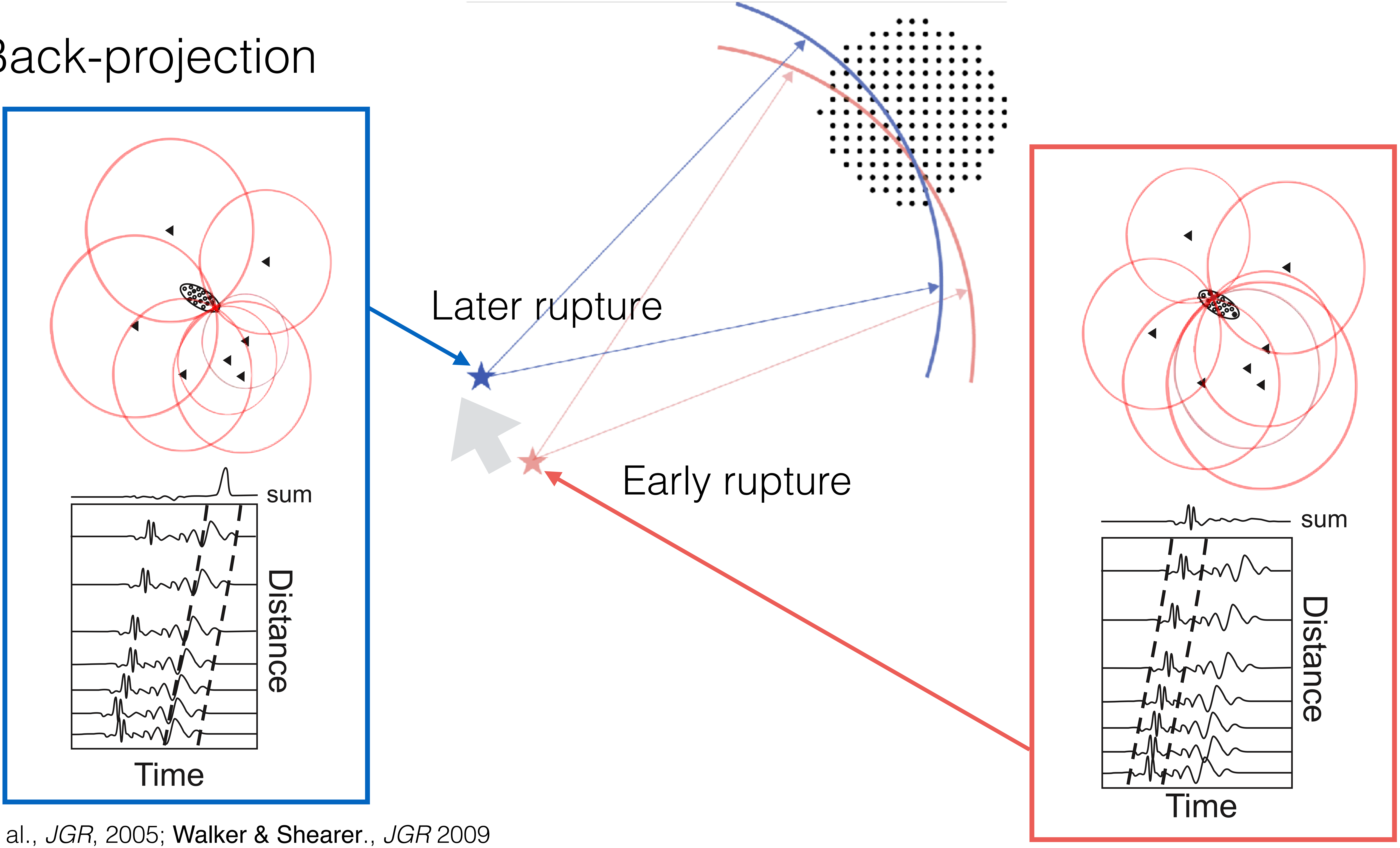
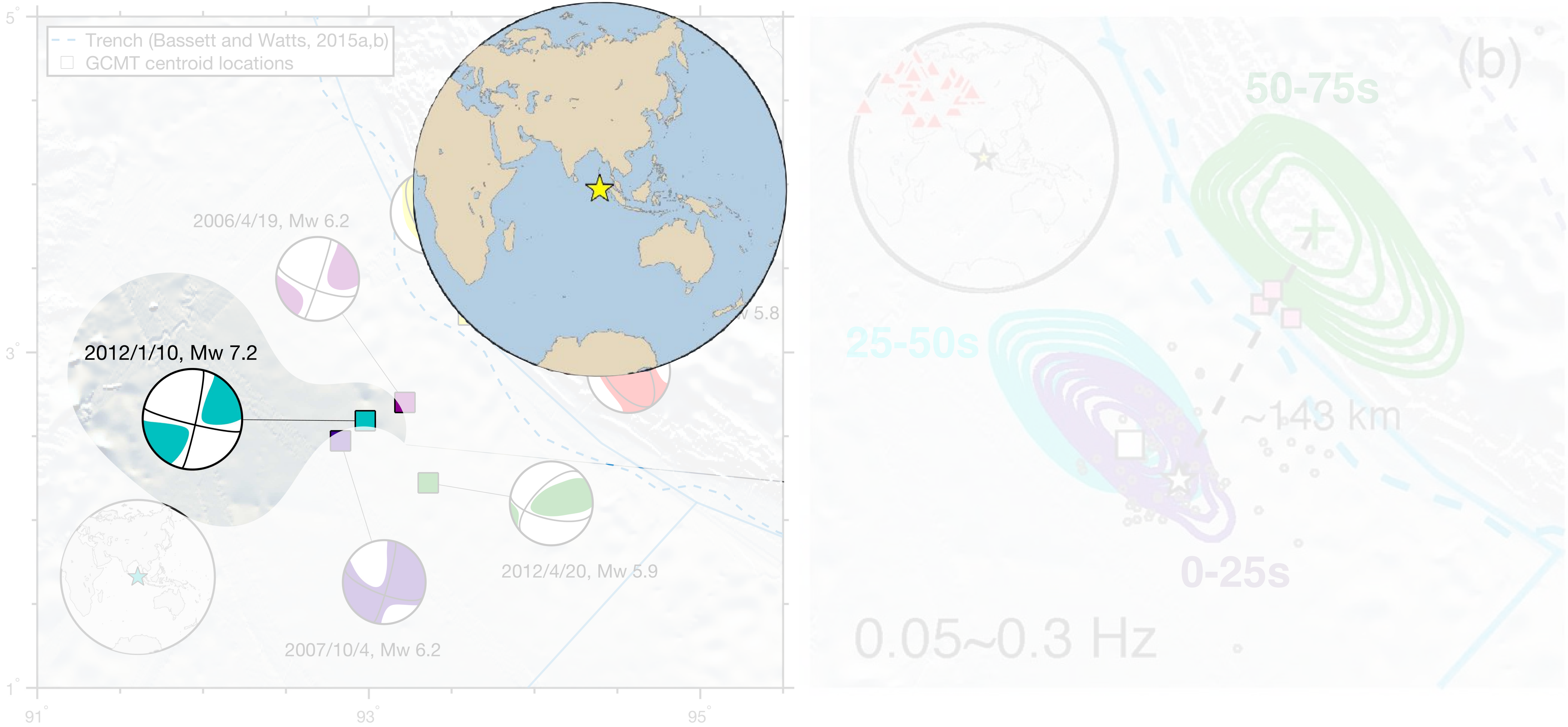


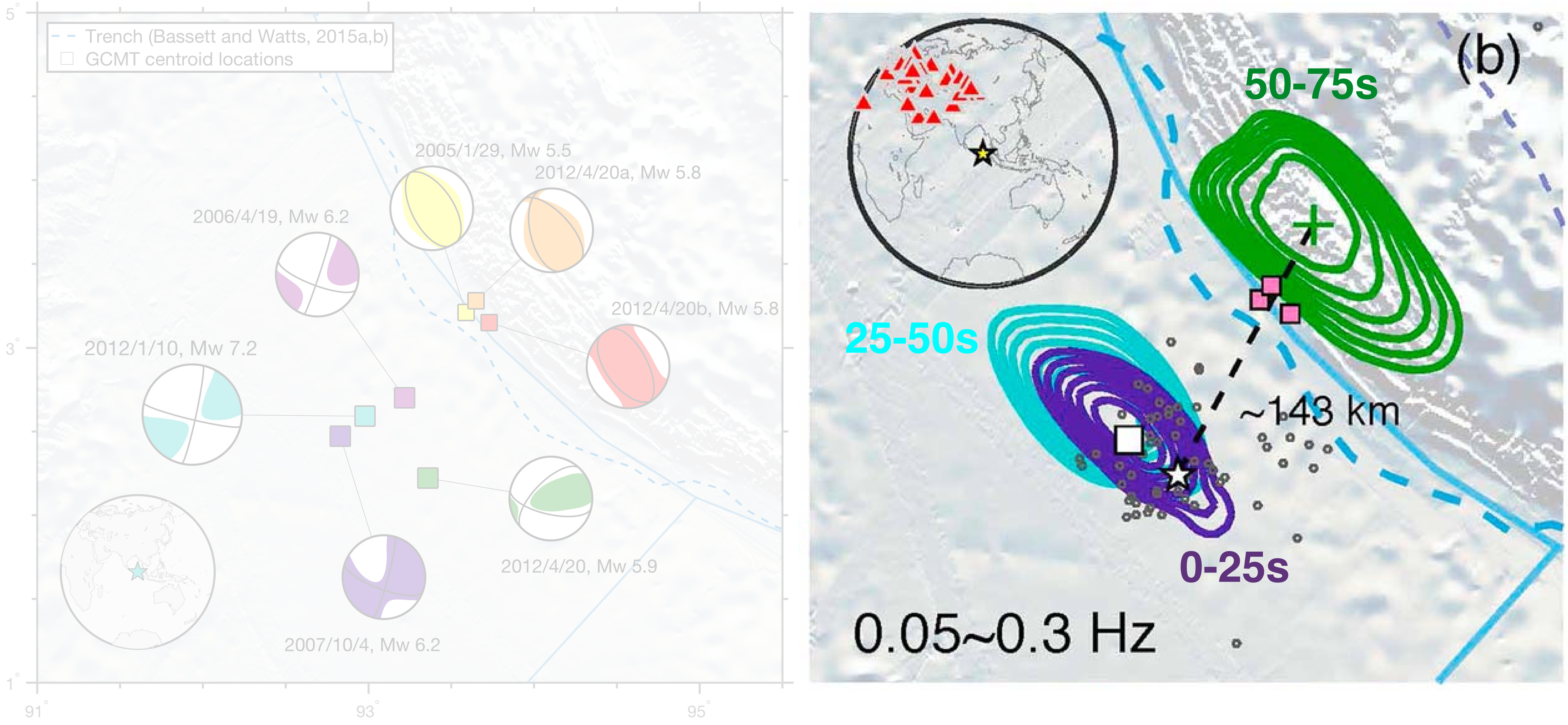
Ishii et al., *JGR*, 2005; Walker & Shearer., *JGR* 2009

Fault interactions and triggering in Sumatra



Fan & Shearer, *GRL*, 2016; Fan & Shearer, *JGR*, 2018

Fault interactions and triggering in Sumatra
(Not mainshock water phase artifacts!)



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Fault interactions and triggering in Sumatra
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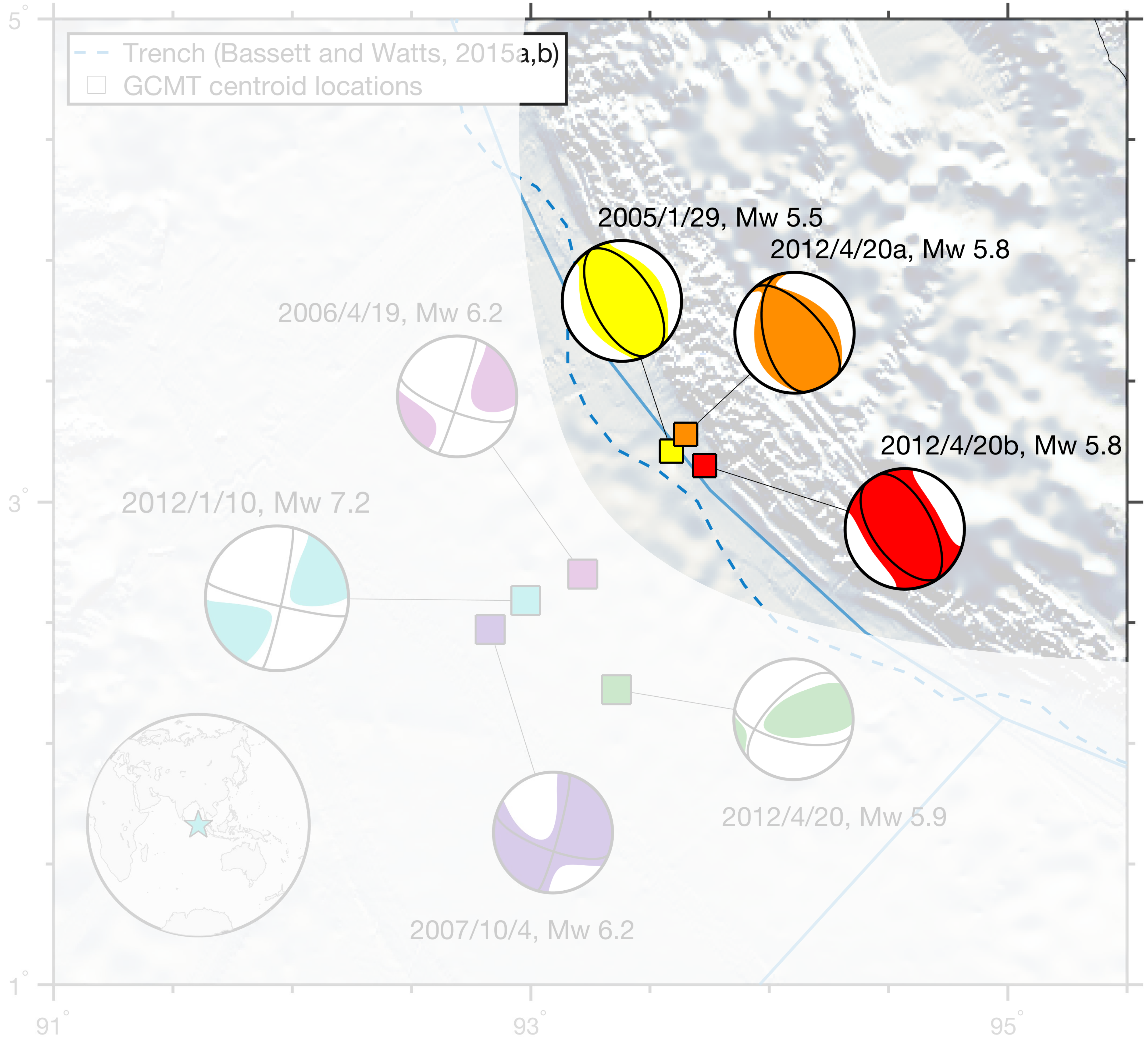
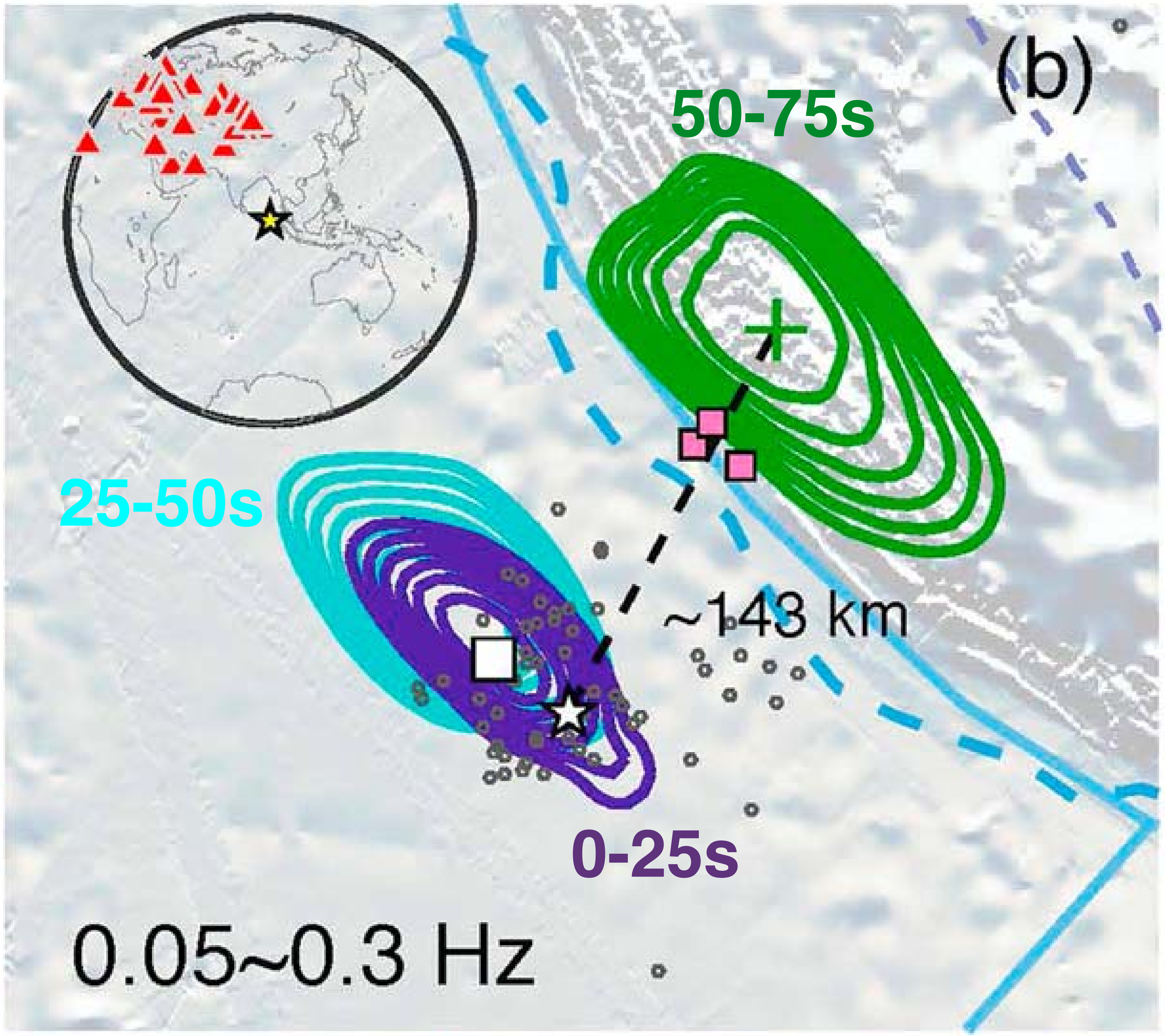




Fan & Shearer, *GRL*, 2016; Fan & Shearer, *JGR*, 2018

How common is this type of triggering?

Local near-instantaneous dynamic triggering of large earthquakes

Fan & Shearer, *Science*, 2016

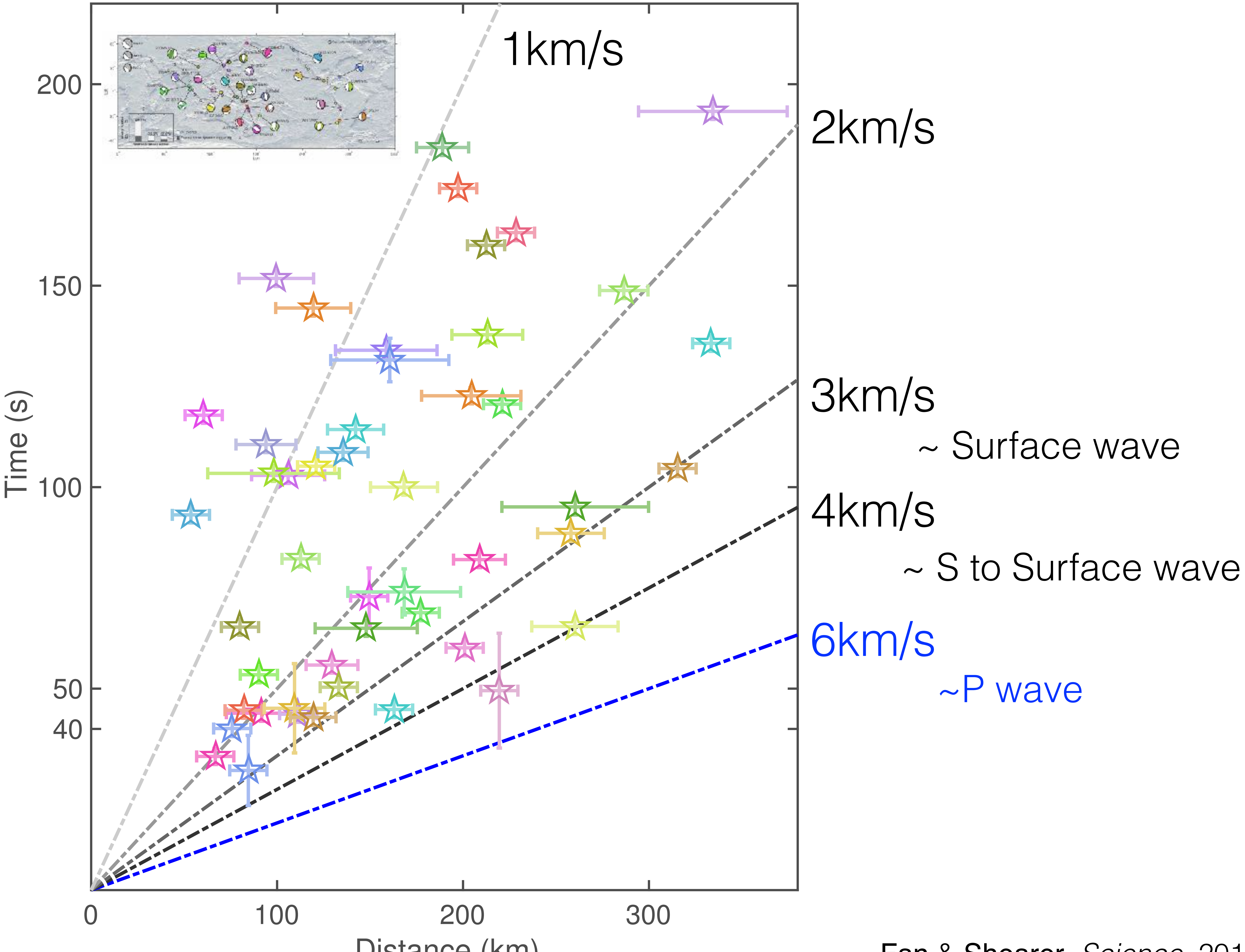
Local near-instantaneous dynamic triggering of large earthquakes

Fan & Shearer, *Science*, 2016

Local near-instantaneous dynamic triggering of large earthquakes

Fan & Shearer, *Science*, 2016

Distance vs time of the triggered early aftershocks



Fan & Shearer, *Science*, 2016

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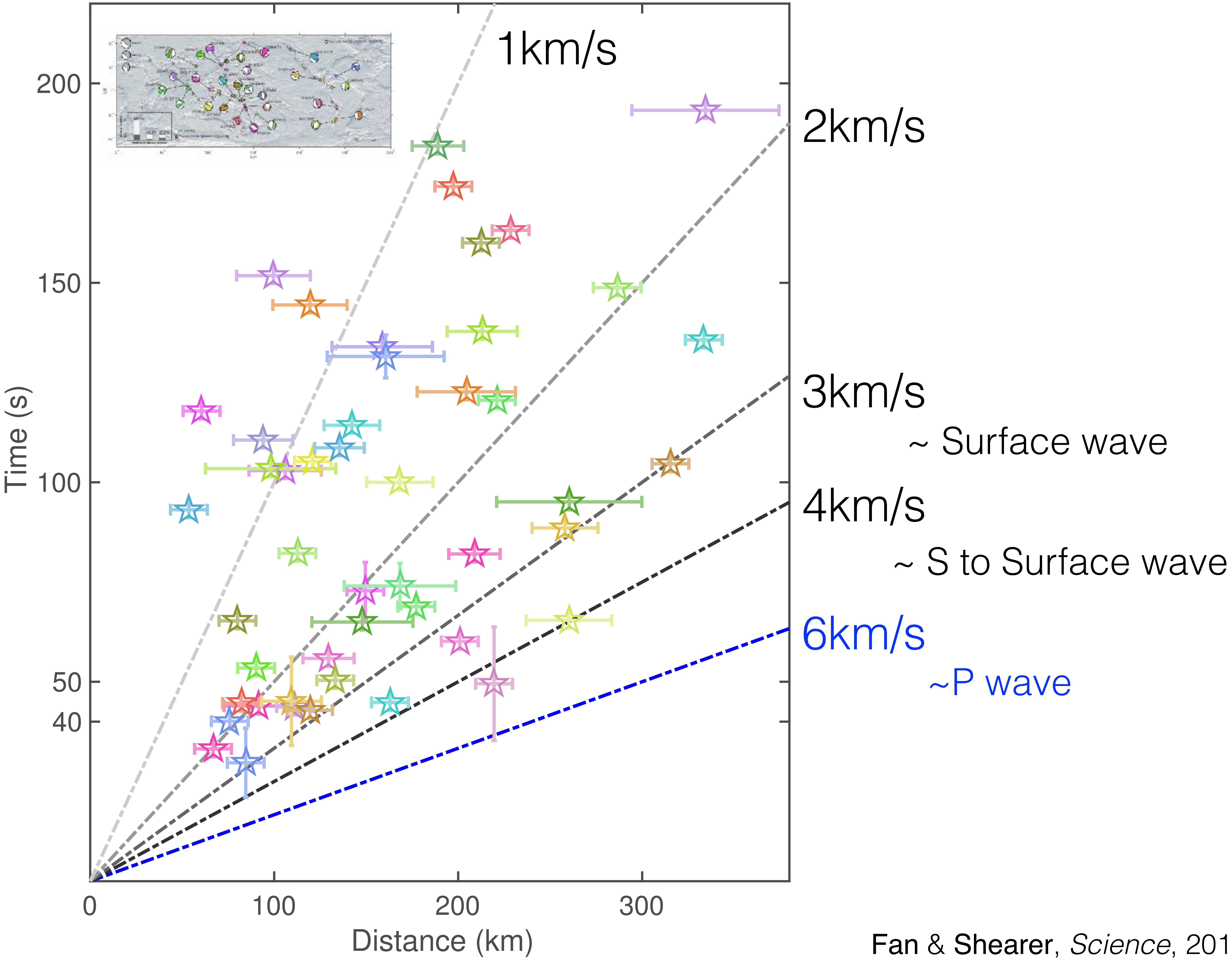
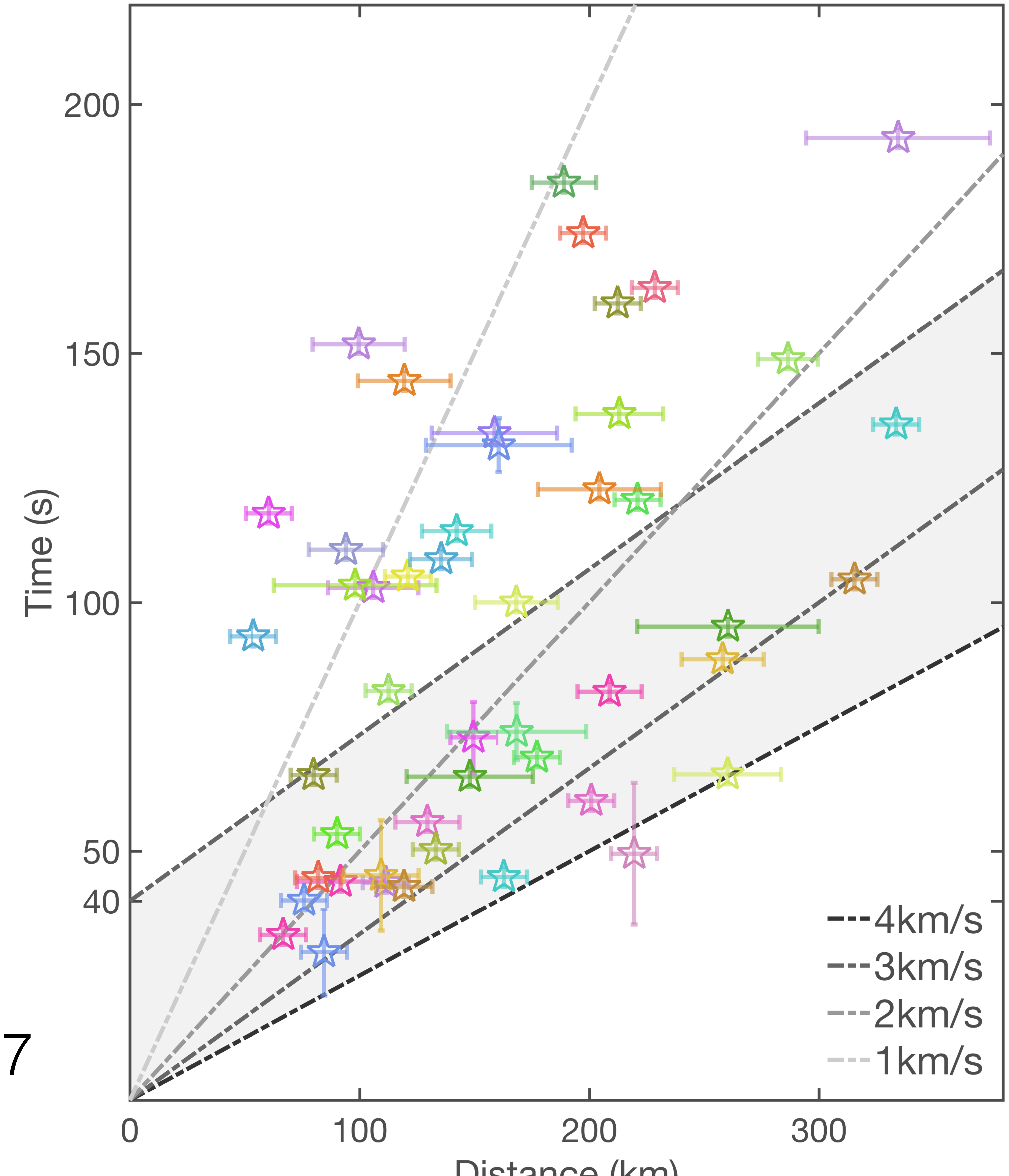


- Why aftershocks?
- Why dynamic?

Fan & Shearer, *Science*, 2016

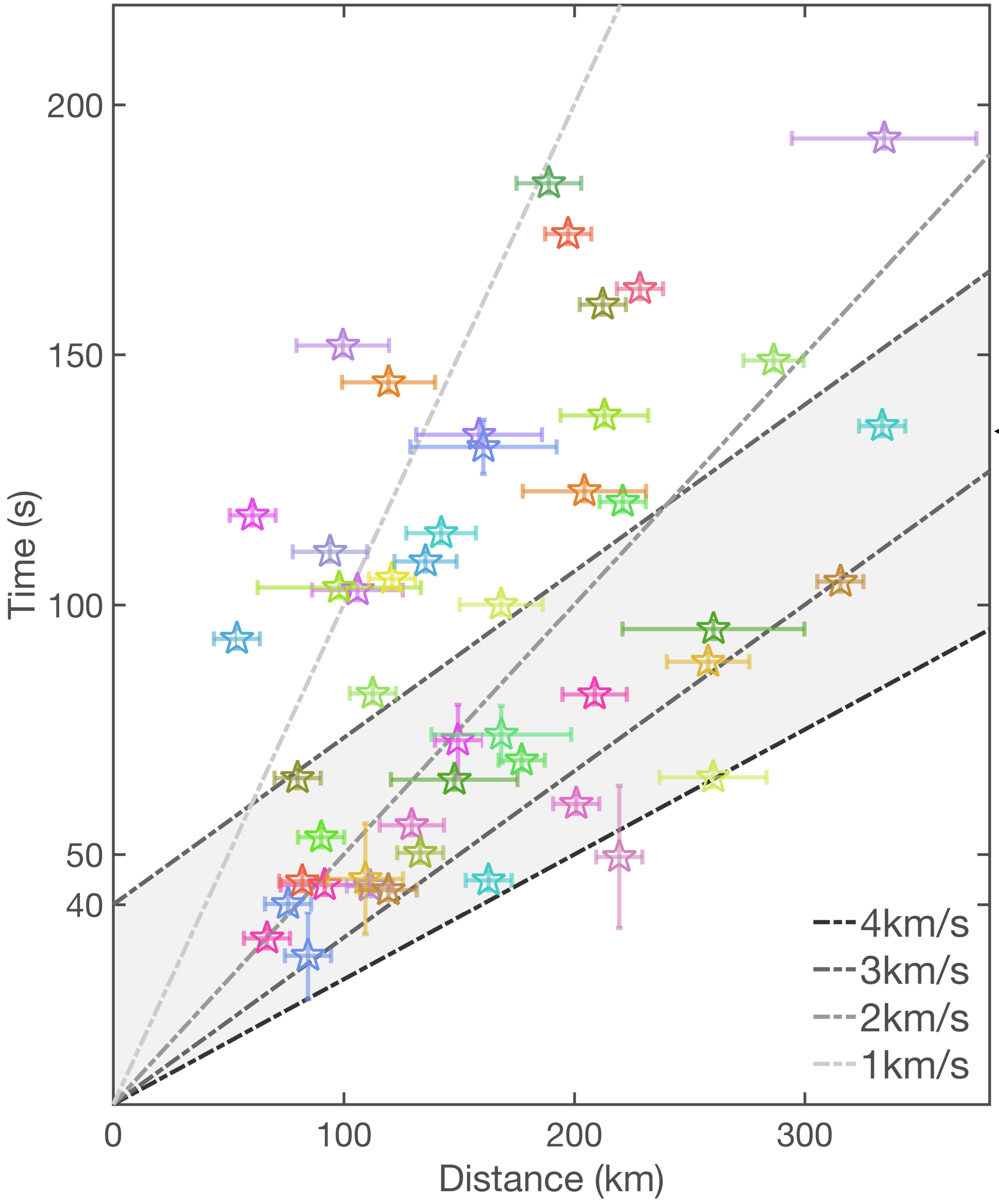
Distance vs time of the triggered early aftershocks



~40s high amplitude seismic waves from M7 earthquakes

Fan & Shearer, *Science*, 2016

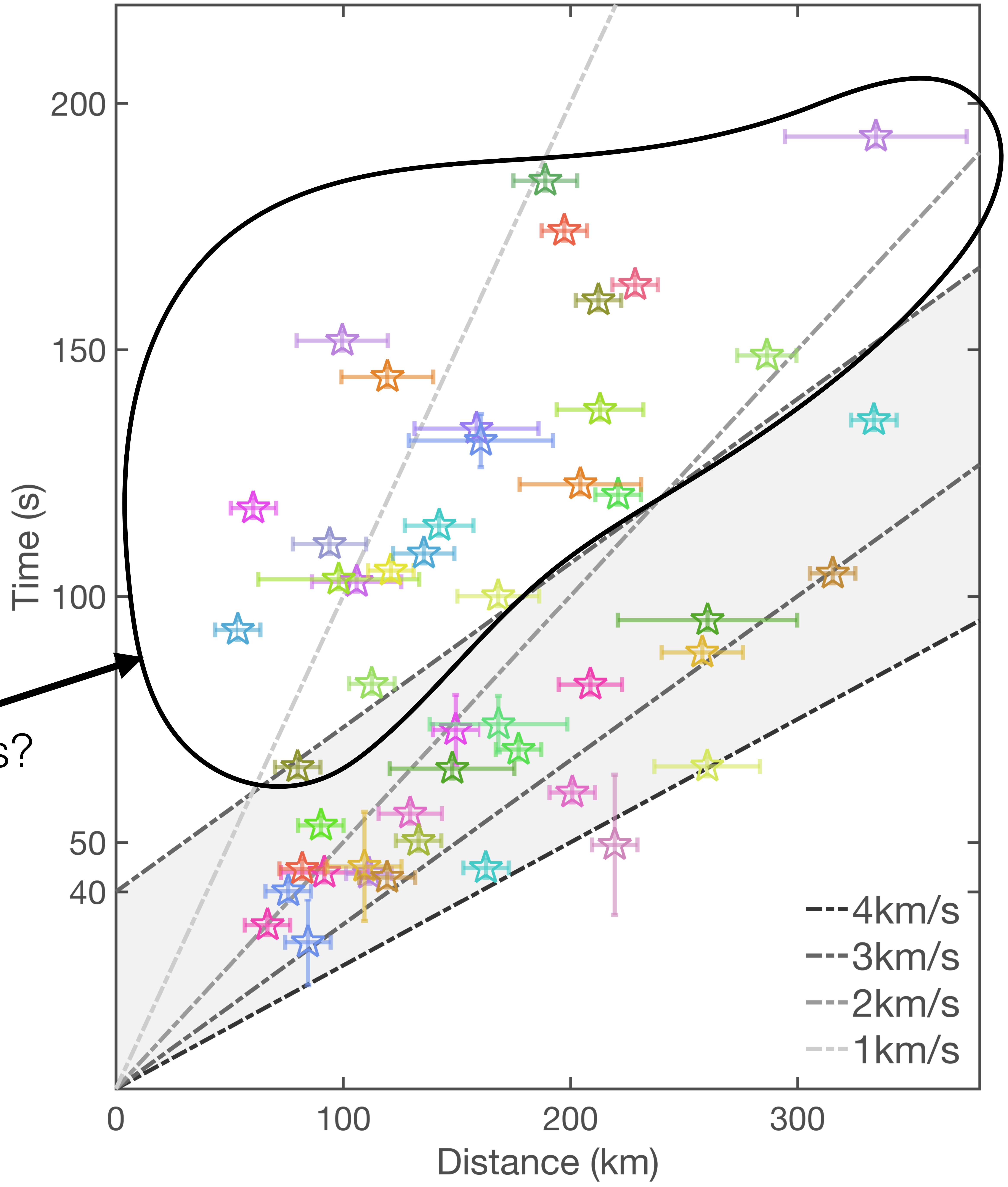
Distance vs time of the triggered early aftershocks



Receiver faults failed immediately

Fan & Shearer, *Science*, 2016

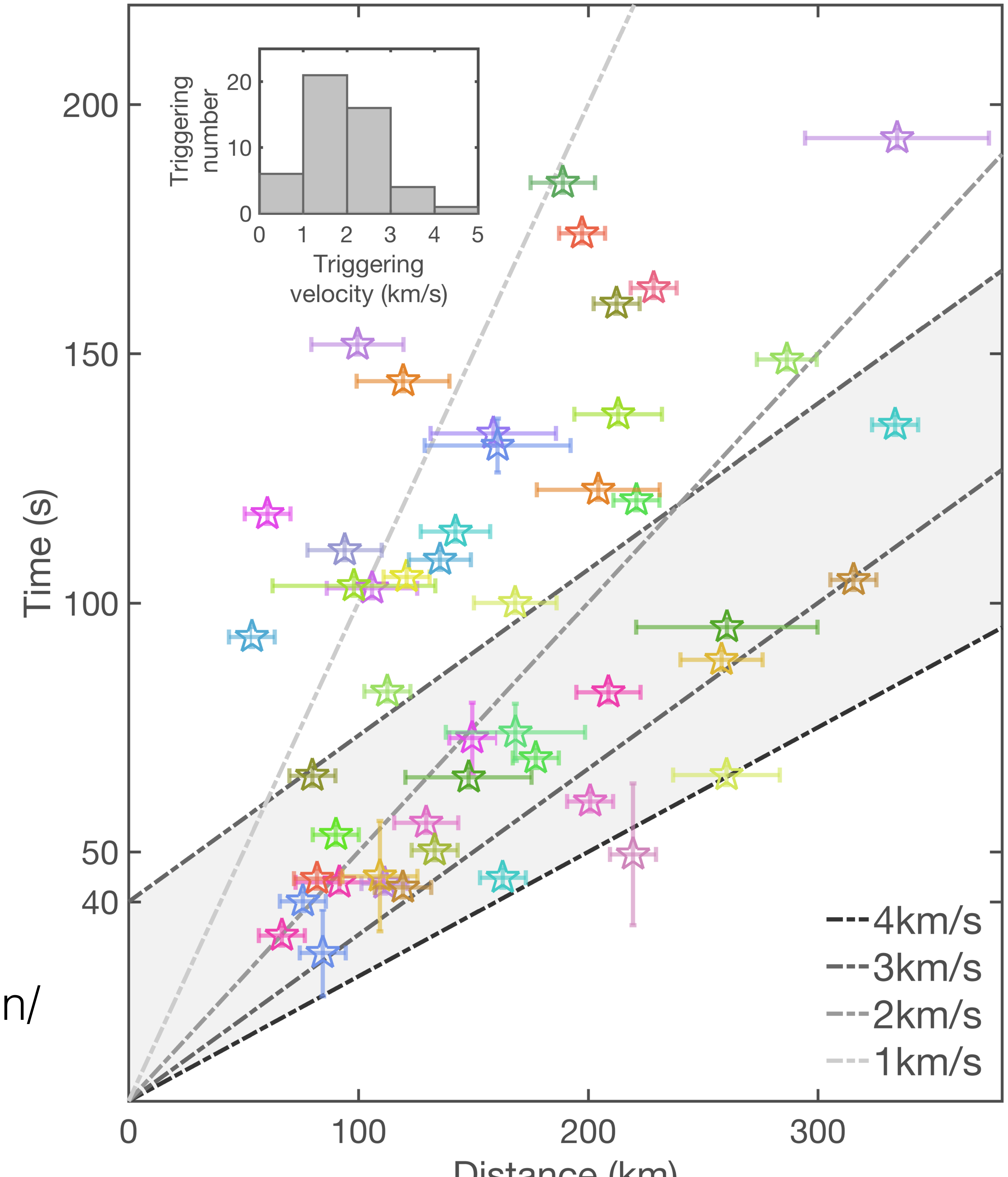
Distance vs time of the triggered early aftershocks



- Aftershocks of aftershocks?
- Nucleation stage?
- Hydraulic response?
- Non-linear frictional properties?

Fan & Shearer, *Science*, 2016

Distance vs time of the triggered early aftershocks



- Any preferred tectonic setting?
- How about long term strain/ stress field?

Fan & Shearer, *Science*, 2016

Global Arrays:

Large earthquakes (M > 7) with **all type of focal-mechanisms** commonly **dynamically trigger** early aftershocks on **nearby faults** as far as 300 km within tens of seconds.

Moment (N m)

Magnitude

How earthquake processes evolve along faults?

10^{24} — 10

7~8 — **Global Arrays**

Tsunami earthquake and **splay faults**

3~5 — **Continental Arrays**

Using surface waves of large aperture arrays to detect and locate non-earthquake (**glacial-quakes, landslides, submarine landslides**) events

2 — **Nodal Arrays**

Investigating **microearthquake finite source** attributes with IRIS Community Wavefield Demonstration Experiment in Oklahoma

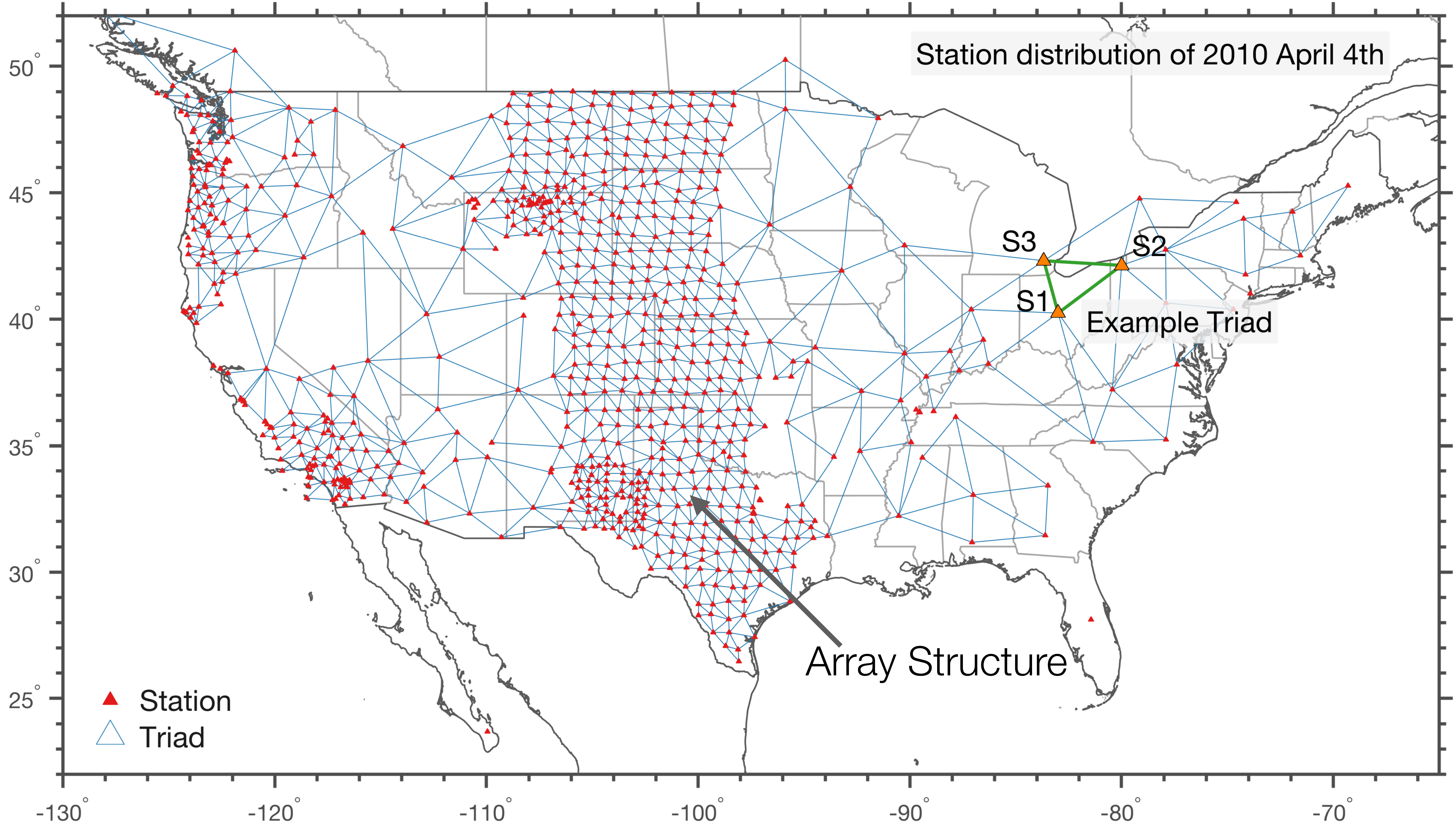
10^{7} — -1

Using surface waves recorded by a large mesh of three-element arrays to detect and locate disparate seismic sources

Goal:

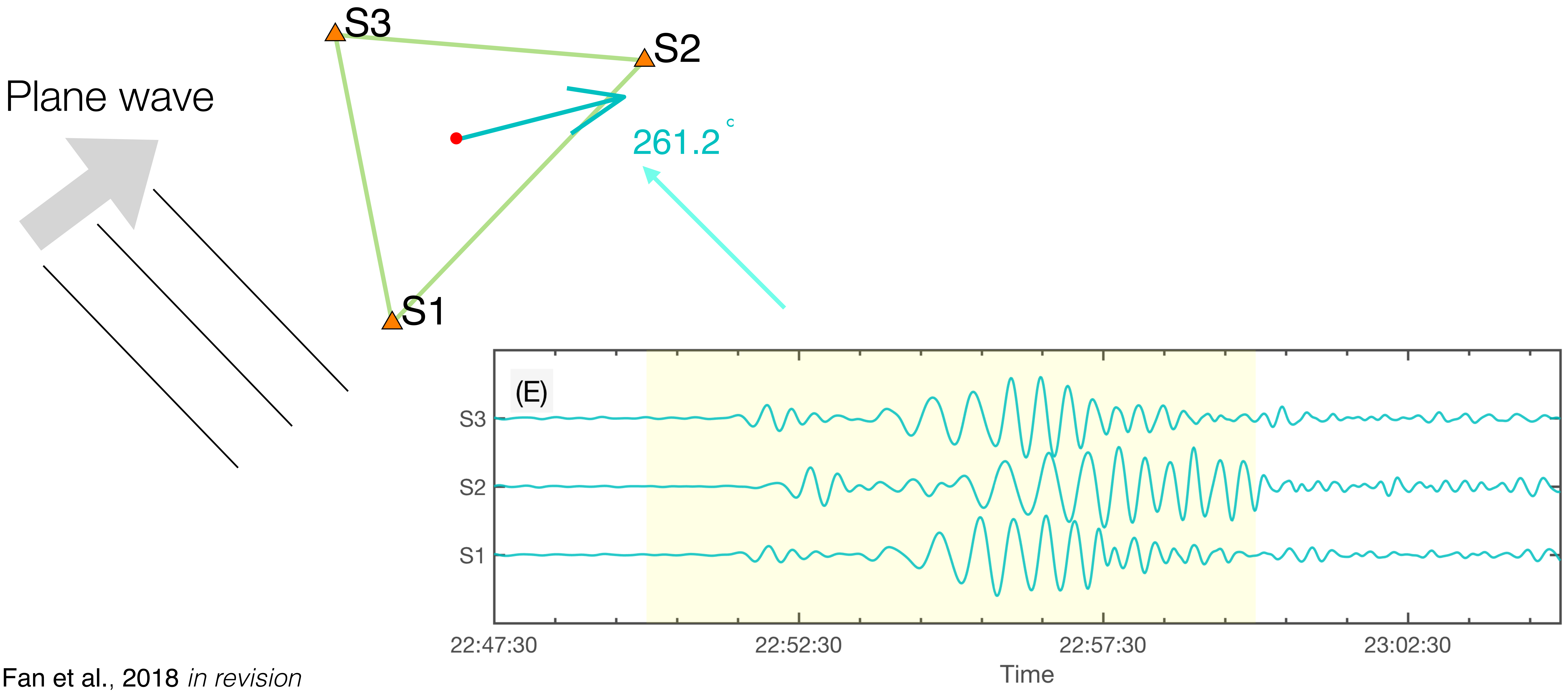
The unknown unknowns.

What are in the observed seismic wavefield?



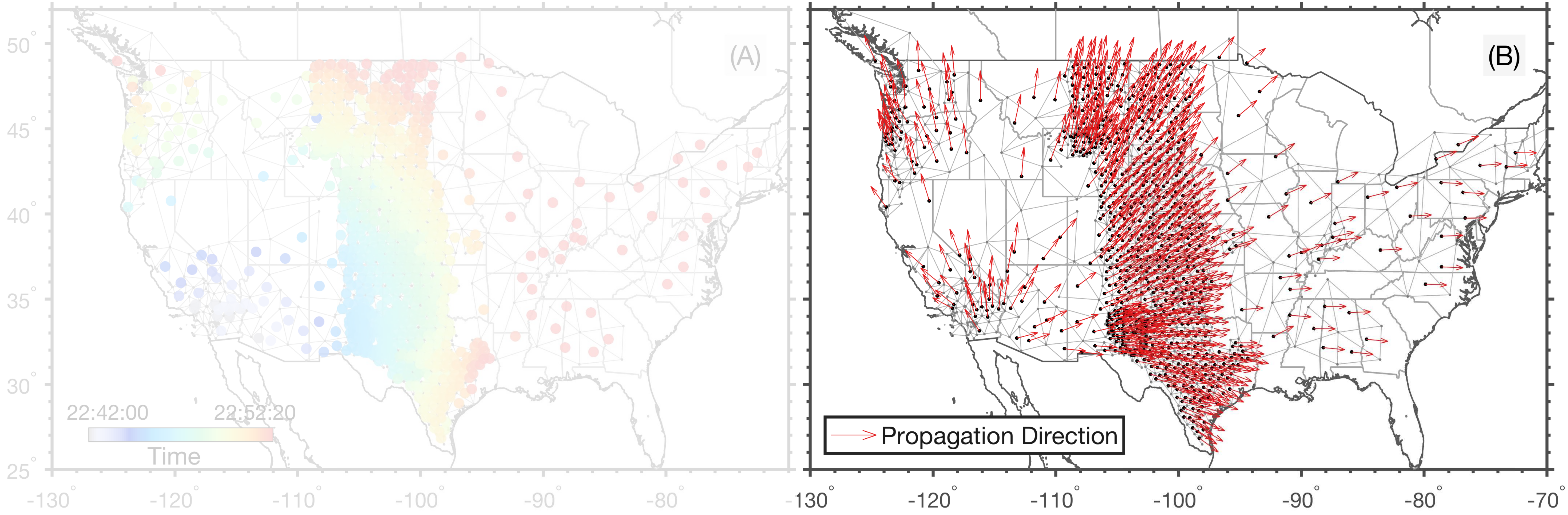
Fan et al., 2018 *in revision*

Direction of highly coherent local surface waves (period: 20 to 50 s)



Fan et al., 2018 *in revision*

Resolve seismic sources with wavefield



Fan et al., 2018 *in revision*

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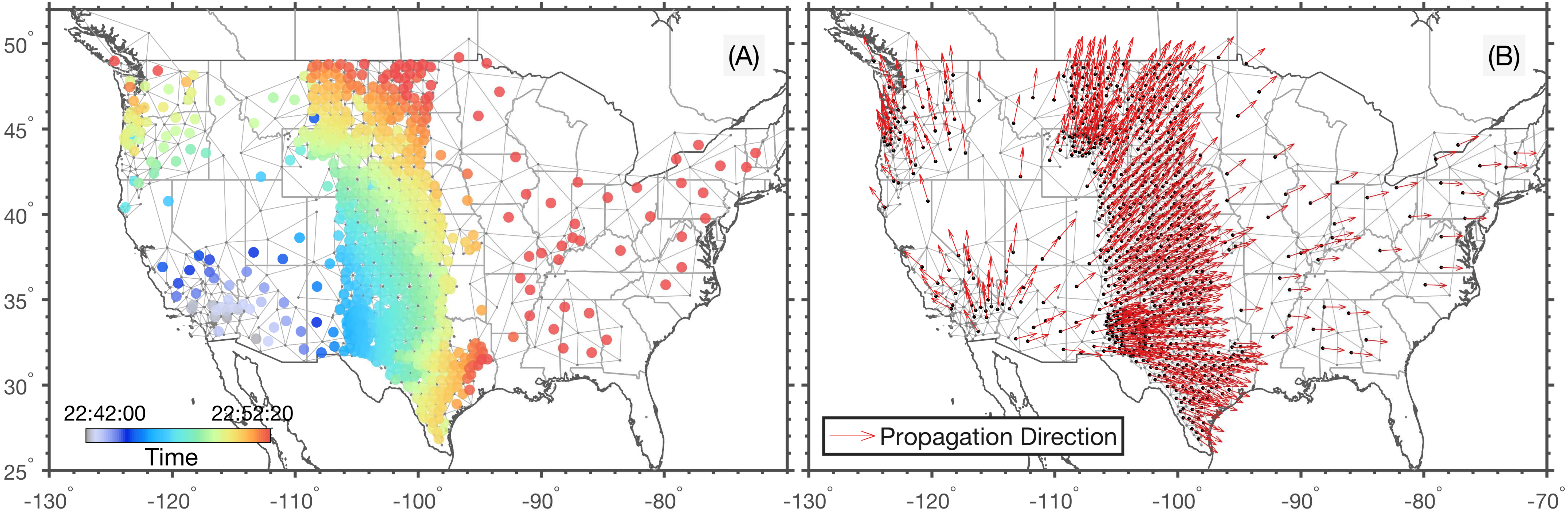
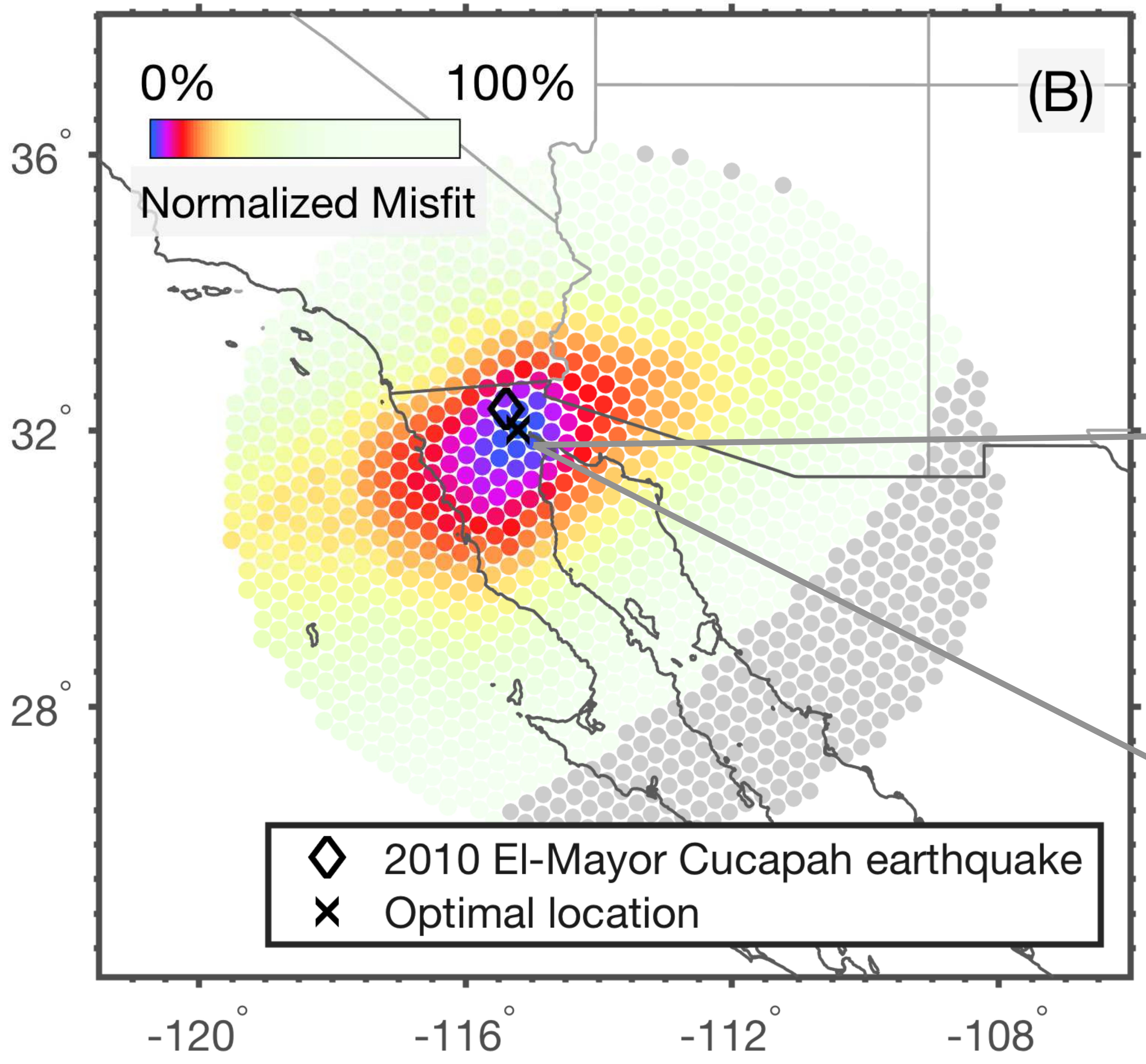
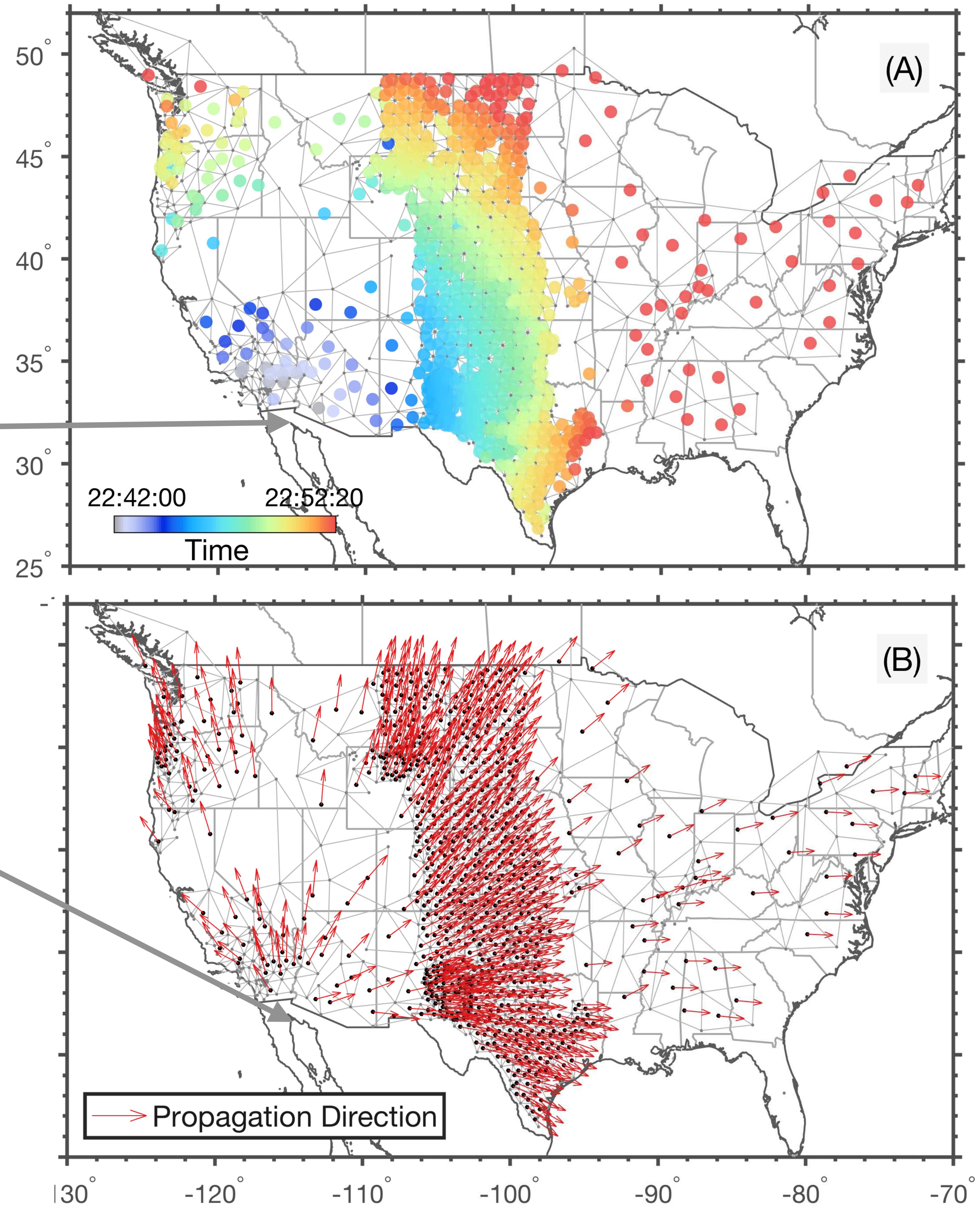


Fan et al., 2018 *in revision*

2010 Mw 7.2 El-Mayor earthquake



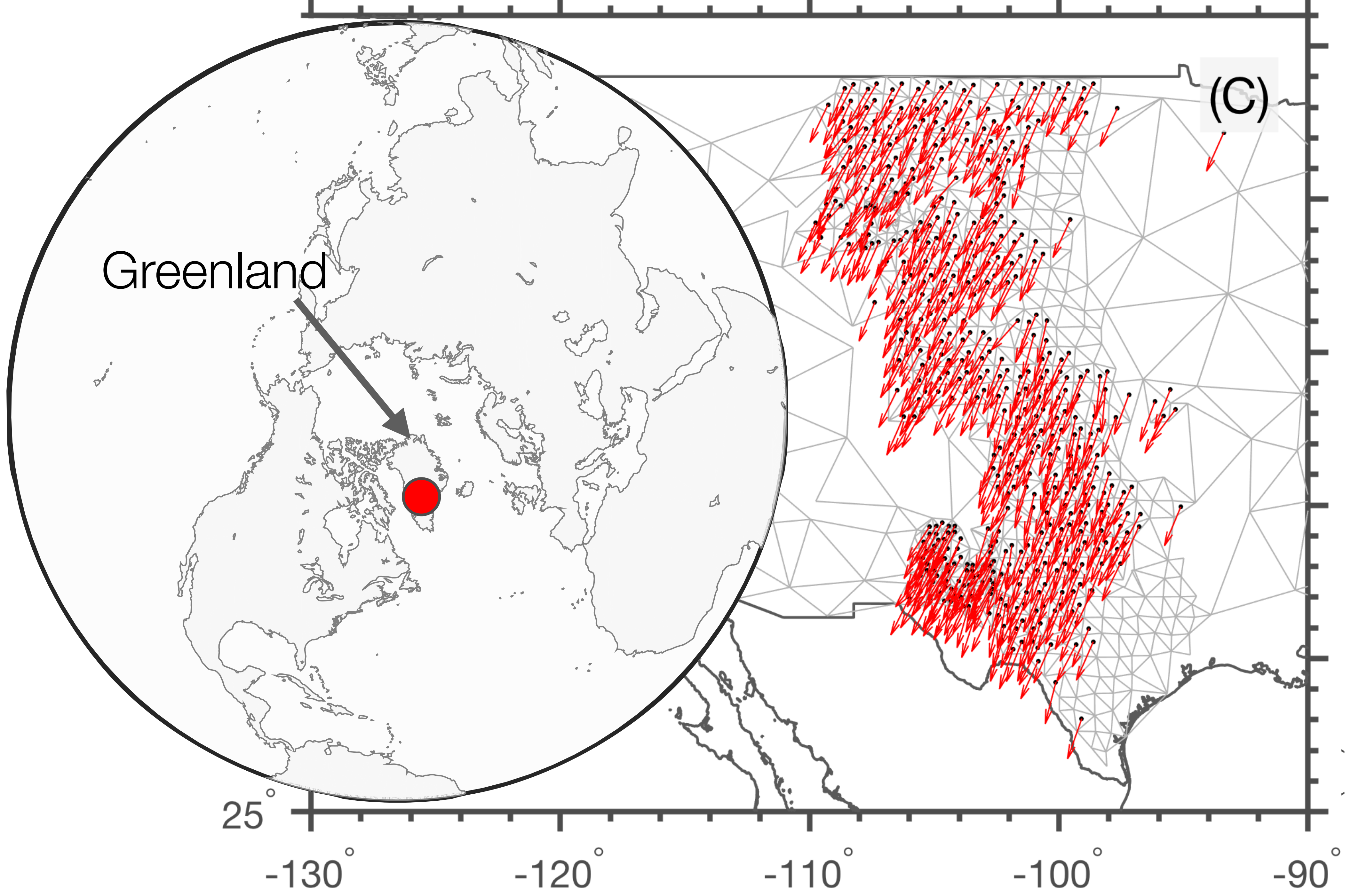


Fan et al., 2018 *in revision*

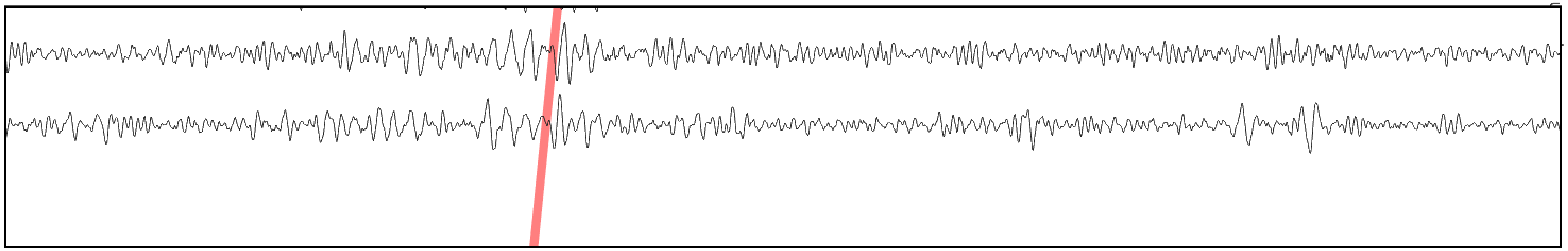
Glacial quakes

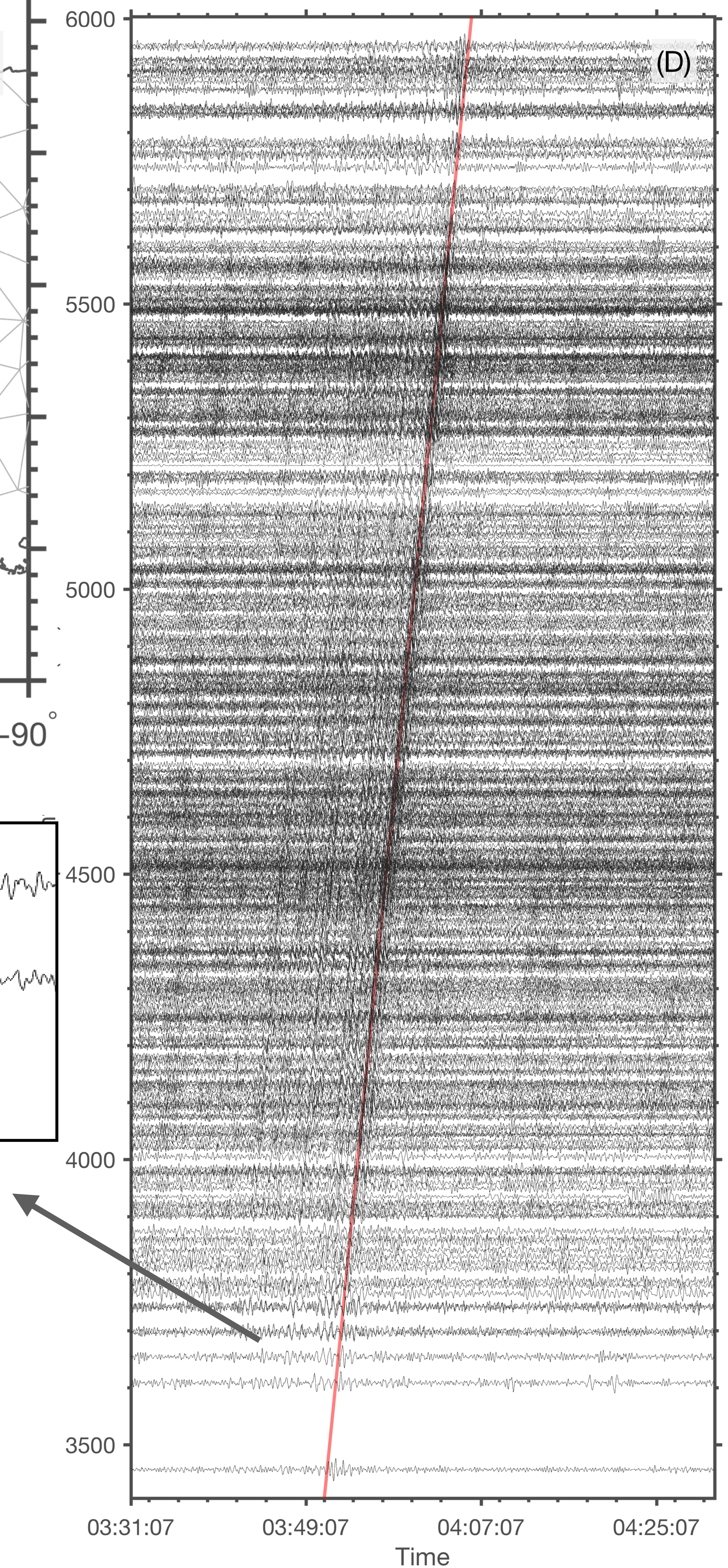
Fan et al., 2018 *in revision*

Glacial quakes



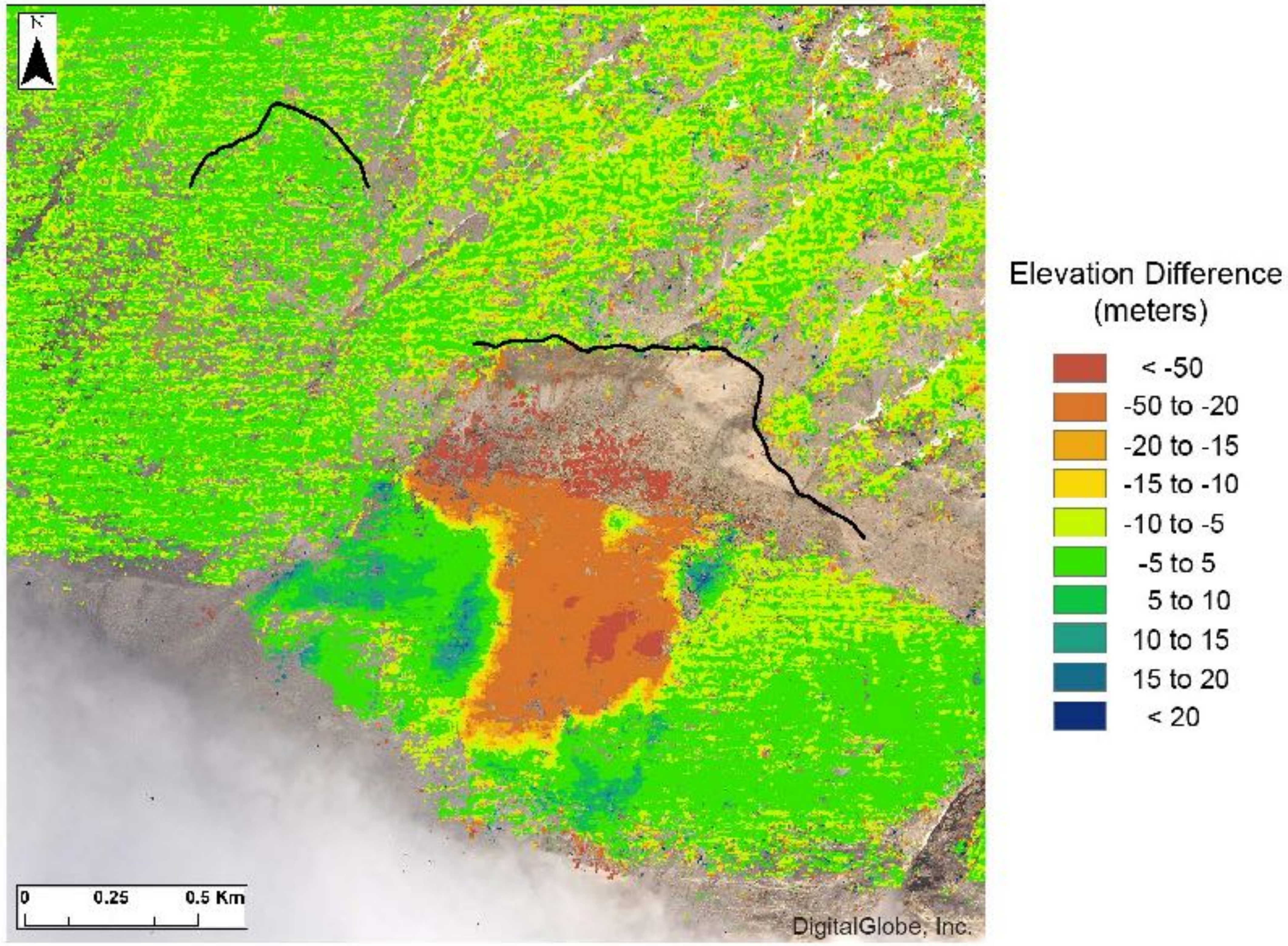
Noisy data





Fan et al., 2018 *in revision*

Nuugaatsiaq Landslide (~Ms 4.8)



Elevation difference between
6/5/17 and 6/22/17

Bessette-Kirton et al., 2017 *USGS*; Fan et al., 2018 *in revision*

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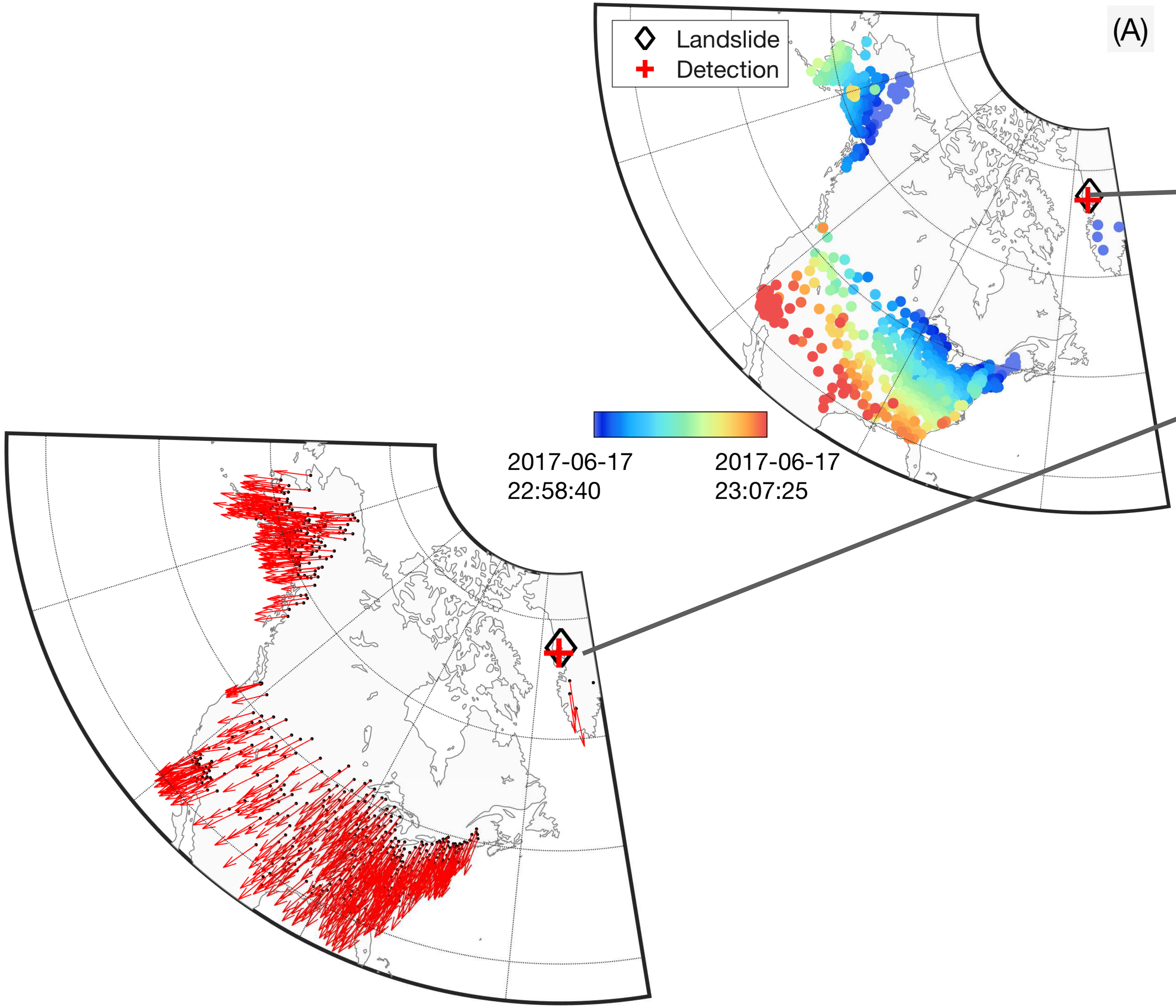

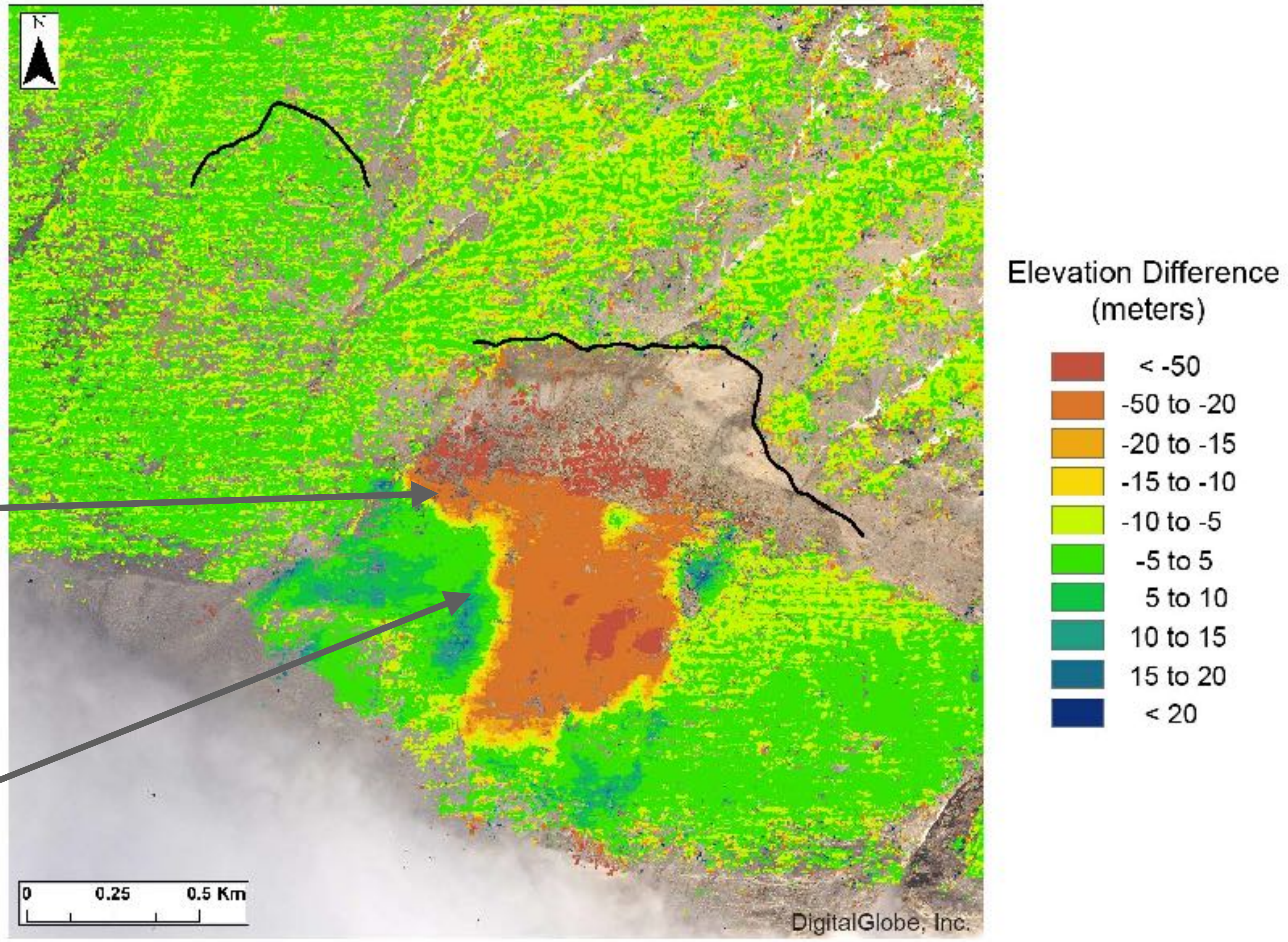

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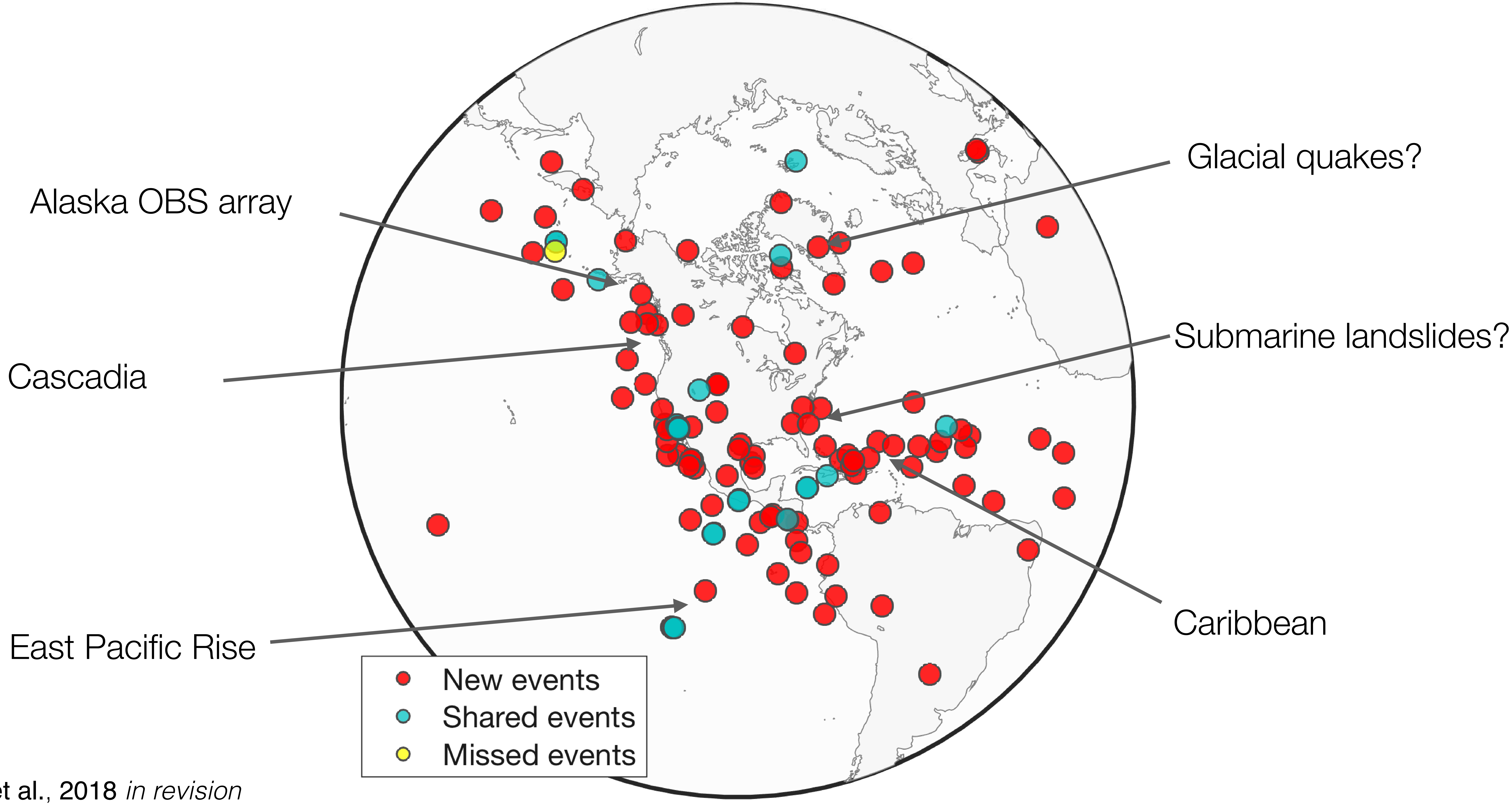
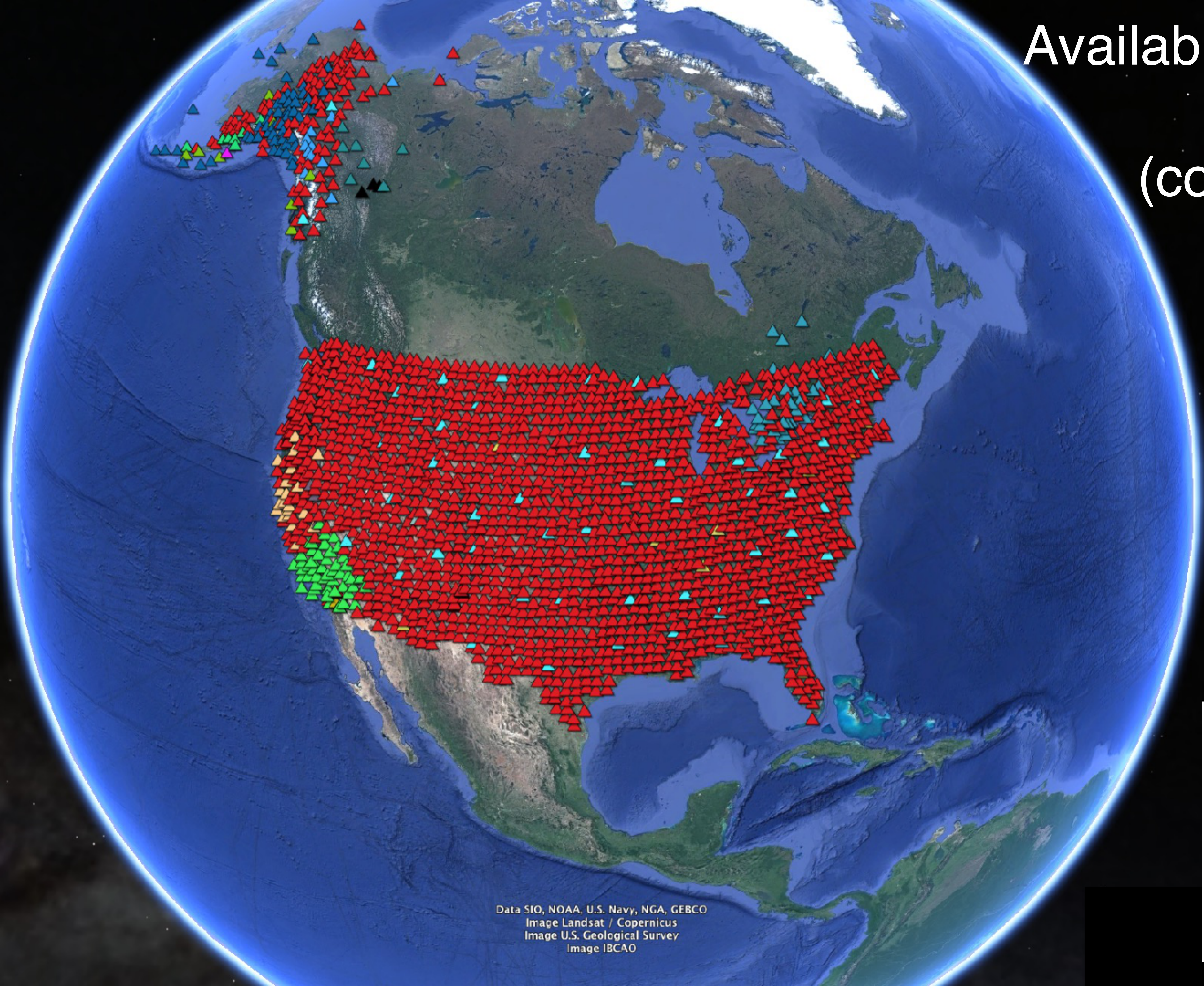
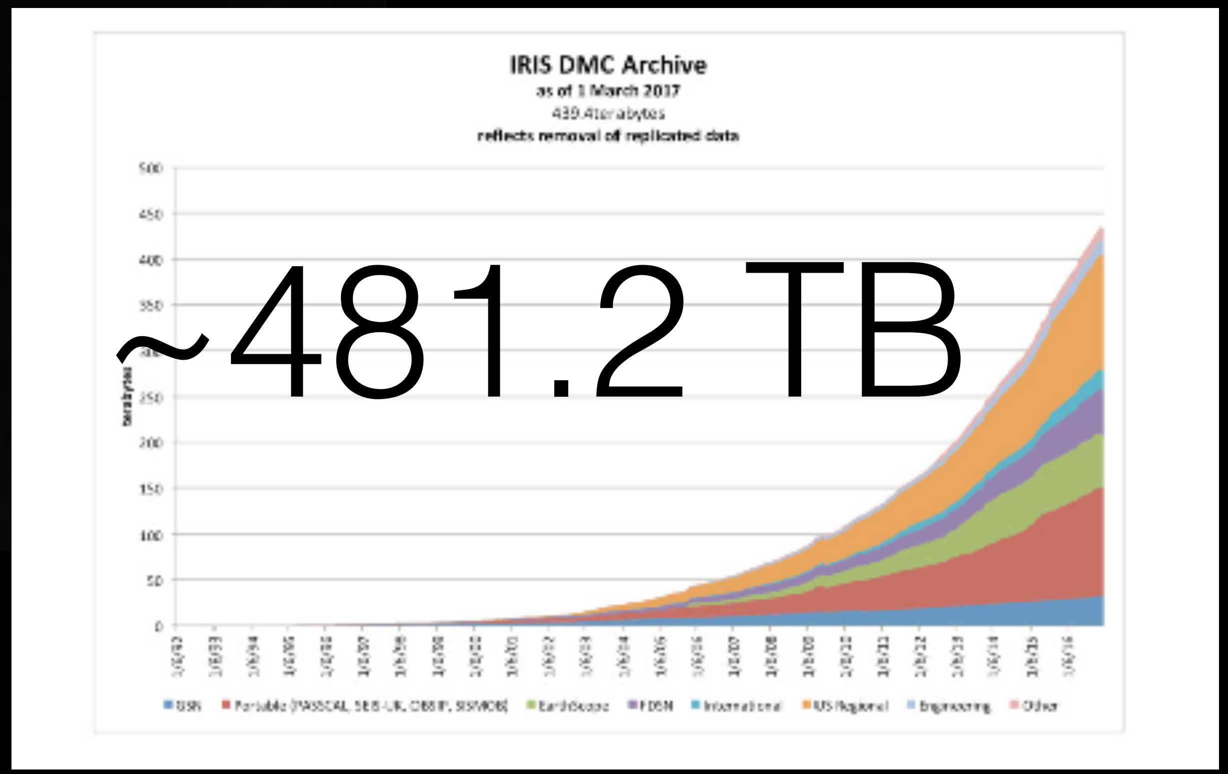
Opportunities

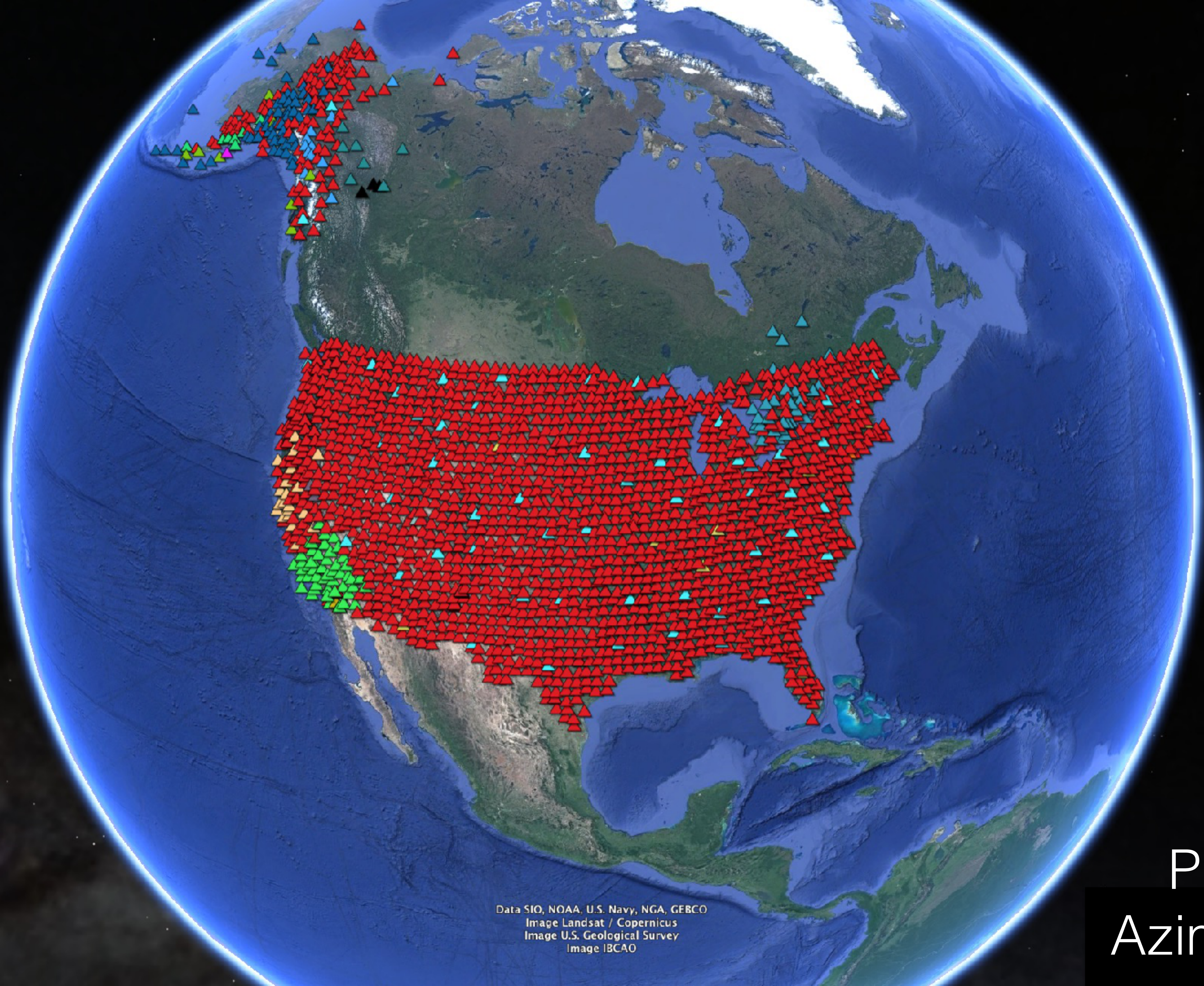


Fan et al., 2018 *in revision*

Available data is the key for new findings (computers as well)







Now:
TA Archive,
Data transfer

HPC with
Large Dataset

Future:
Preserve Legacy,
Azimuthal Coverage

Continental Arrays

Exotic slip events may occur more often than we thought.

Moment (N m) Magnitude

How earthquake processes evolve along faults?

10^{24} 10

7~8

Global Arrays

Tsunami earthquake and **splay faults**

3~5

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Using surface waves of large aperture arrays to detect and locate non-earthquake (**glacial-quakes, landslides, submarine landslides**) events

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Nodal Arrays

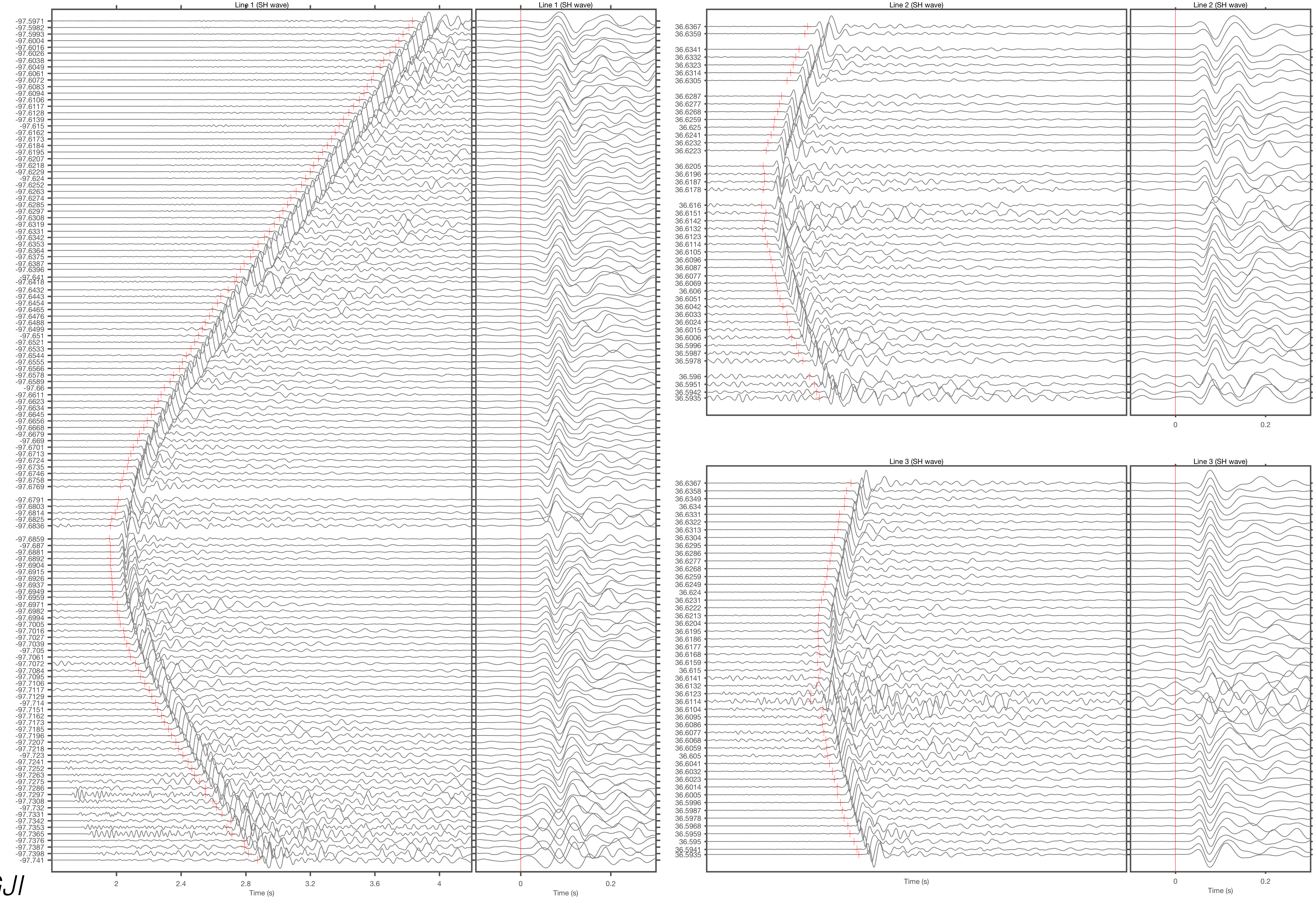
Investigating **microearthquake finite source** attributes with IRIS Community Wavefield Demonstration Experiment in Oklahoma

10^{7} -1

IRIS Community **Wavefield** Demonstration Experiment in Oklahoma

Fan & McGuire, 2018, *GJI*

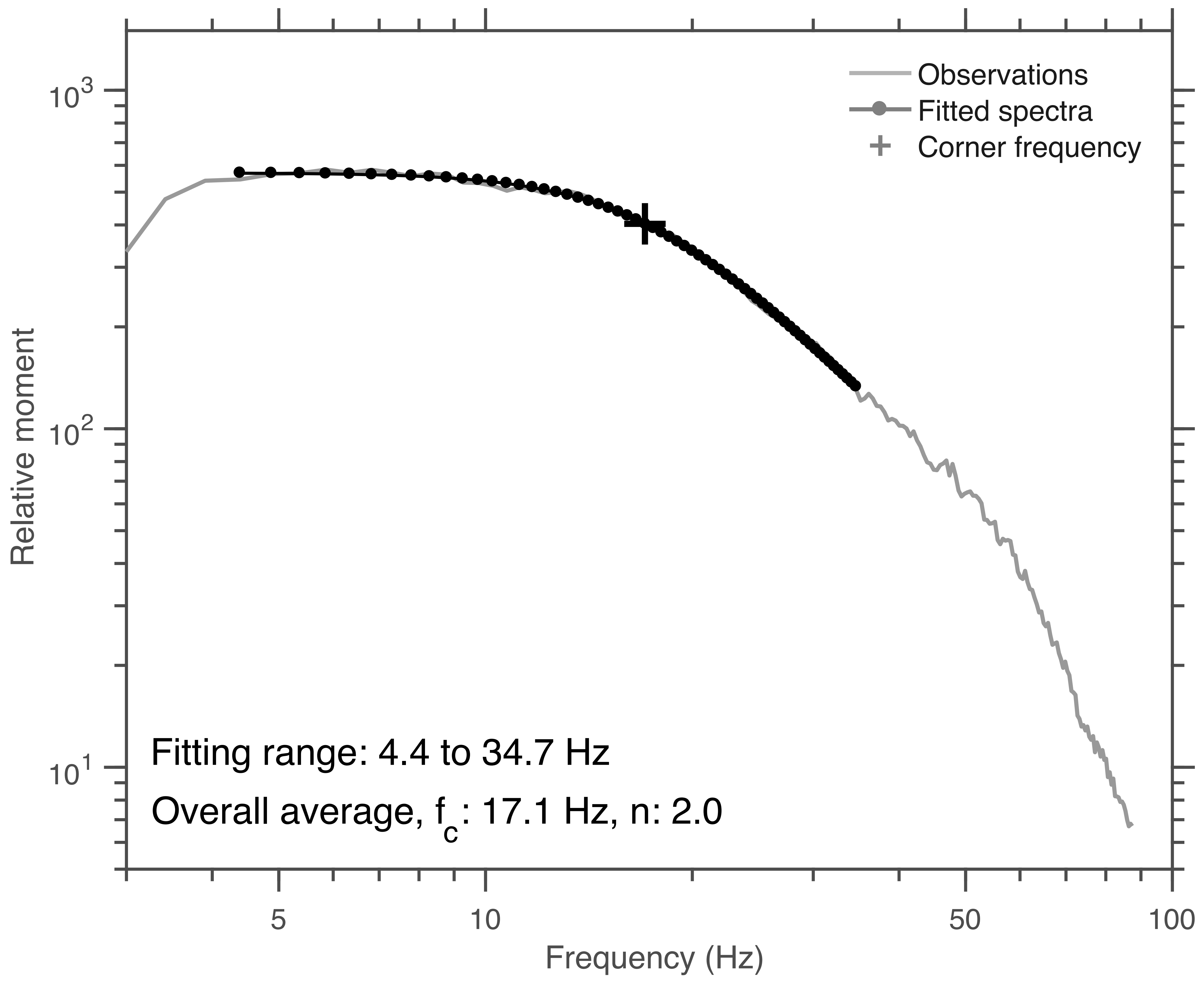
SH waves



Fan & McGuire, 2018, *GJI*

Pre-wavefield time.....

Observations → Corner frequency → Rupture area → Stress-drop



Assume a simple dynamic rupture model(s)

$$\Delta\sigma = \frac{7}{16}\left(\frac{f_c}{\kappa\beta}\right)^3 M_0$$

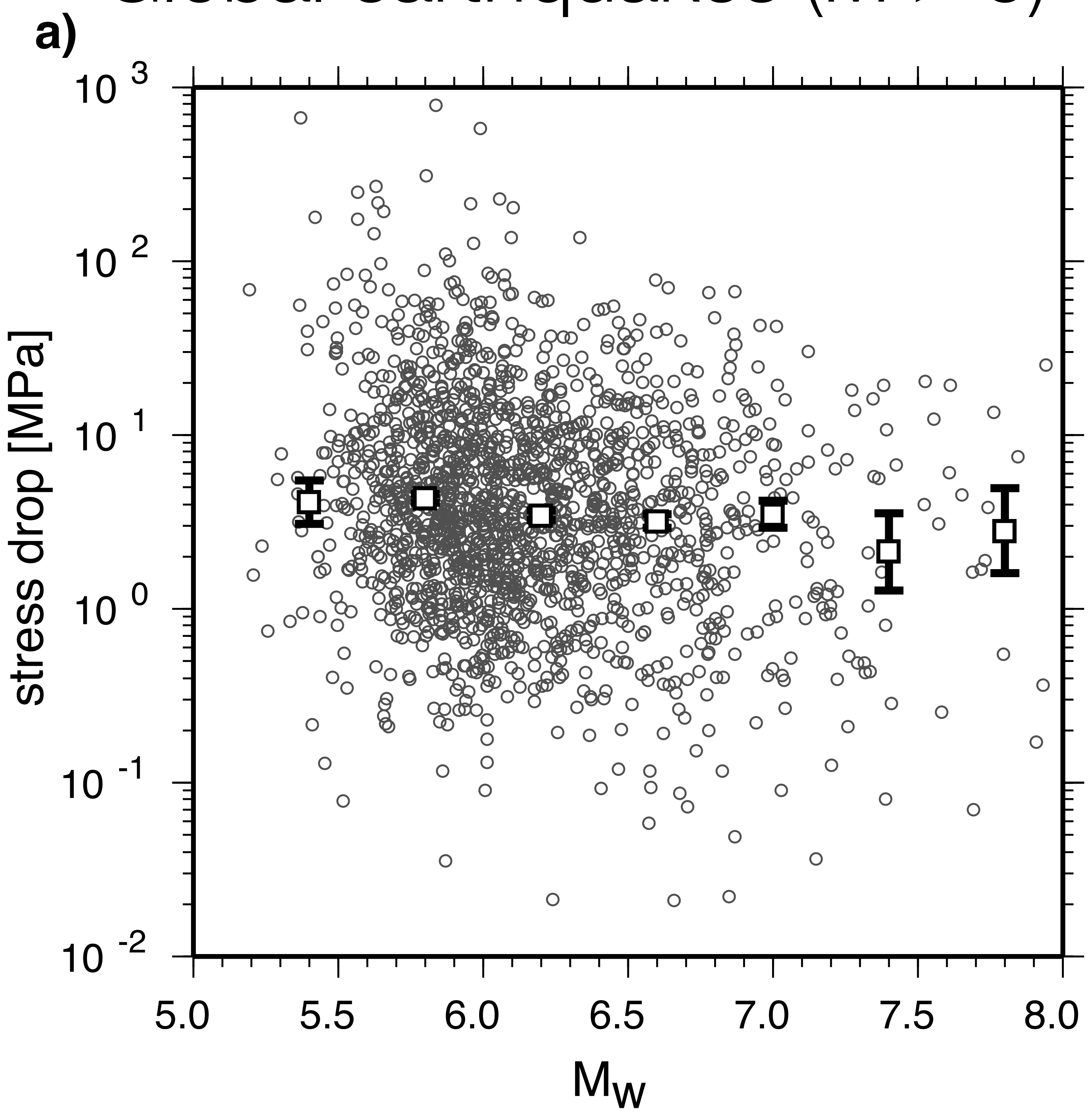
Brune model

Fan & McGuire, 2018, *GJI*

Earthquake stress-drops inform rupture dynamics and earthquake physics, but having factor of 1000 difference for a given magnitude!

Global earthquakes (M > 5)

Stress-drop



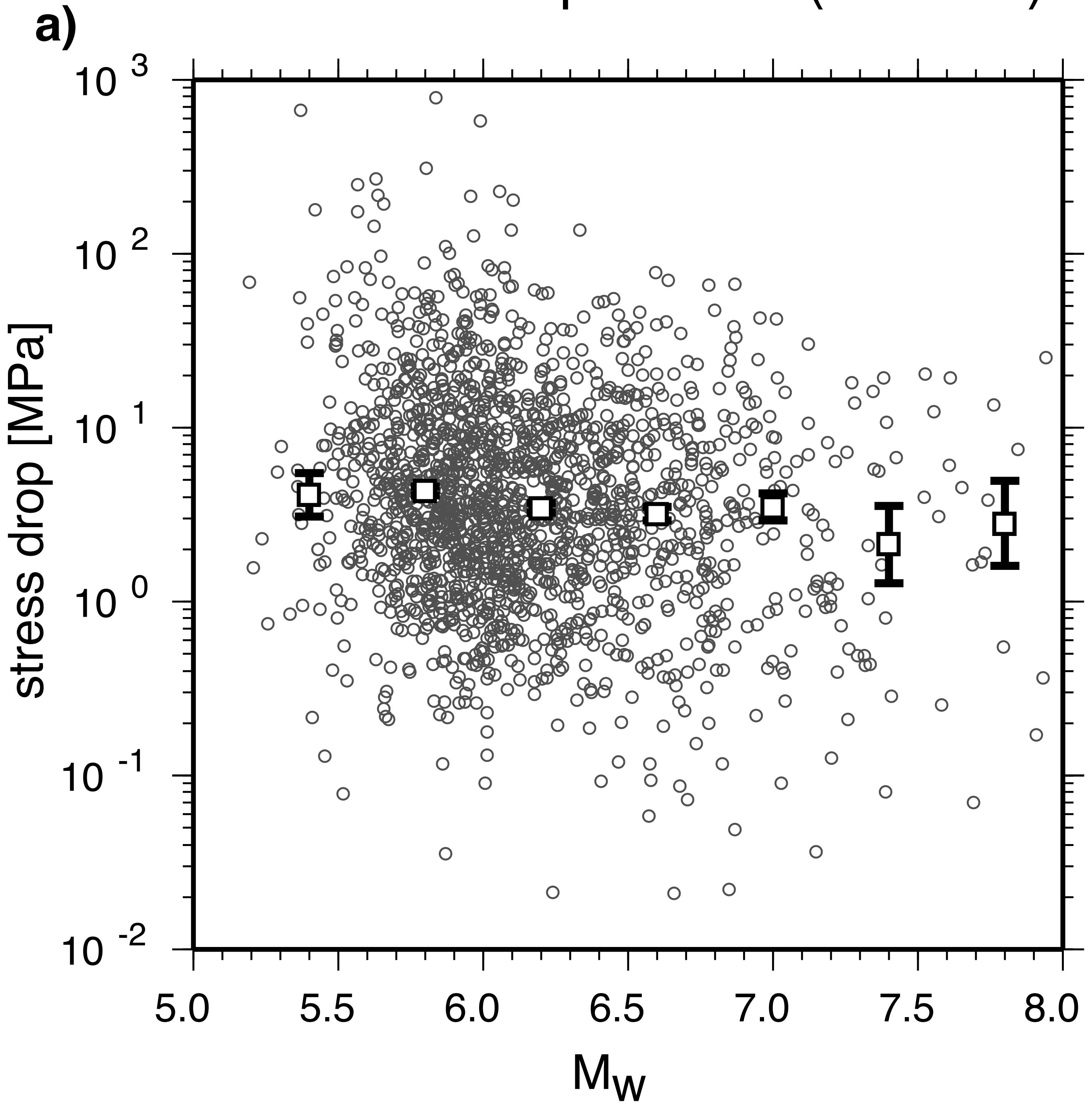
Magnitude

Parkfield earthquakes (M < 3)

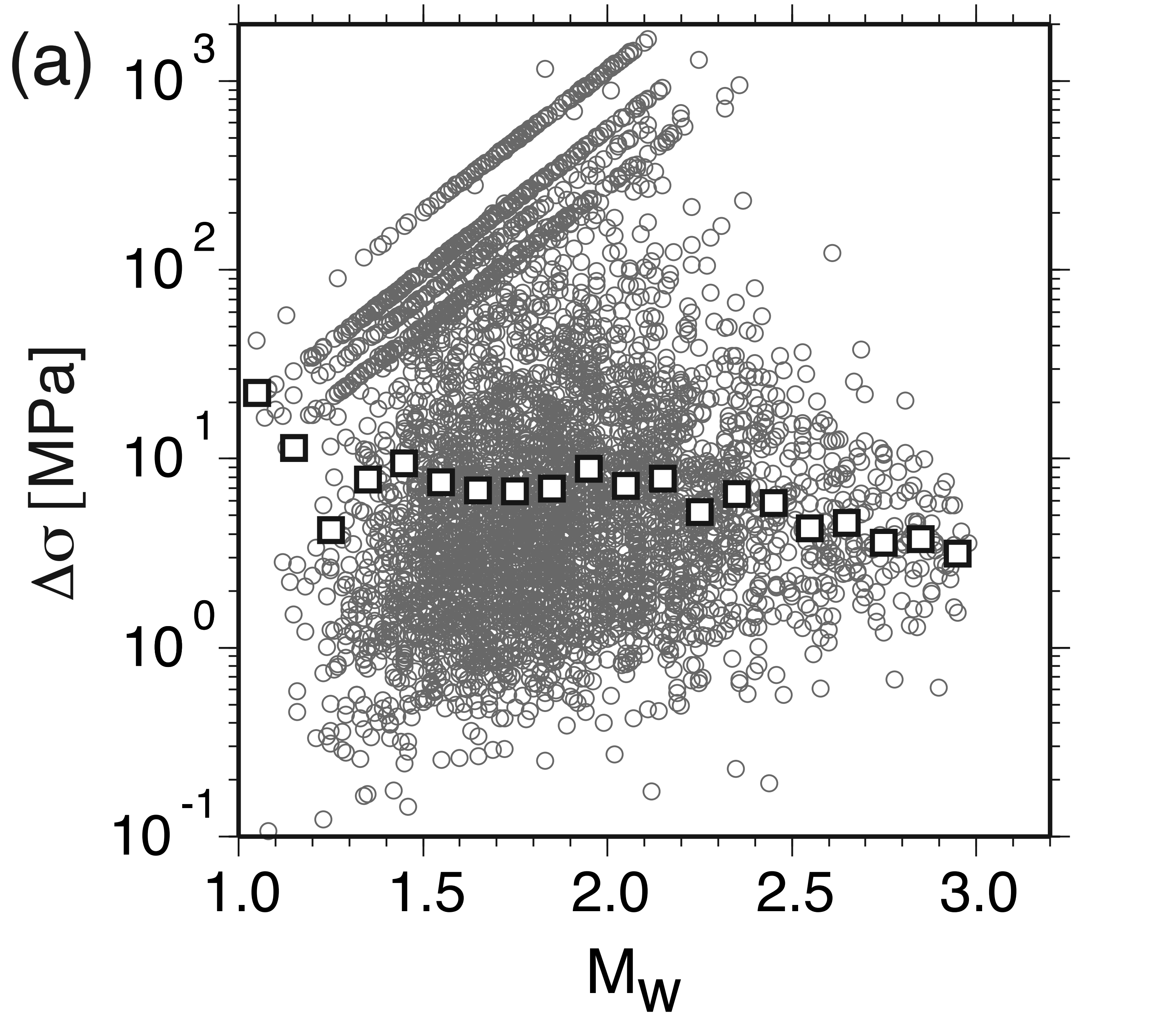
Allmann & Shearer, 2007, 2009, *JGR*

Earthquake stress-drops inform rupture dynamics and earthquake physics, but having factor of 1000 difference for a given magnitude!

Global earthquakes (M > 5)



Parkfield earthquakes (M < 3)



Allmann & Shearer, 2007, 2009, *JGR*

Estimating rupture area is the key

After

Before

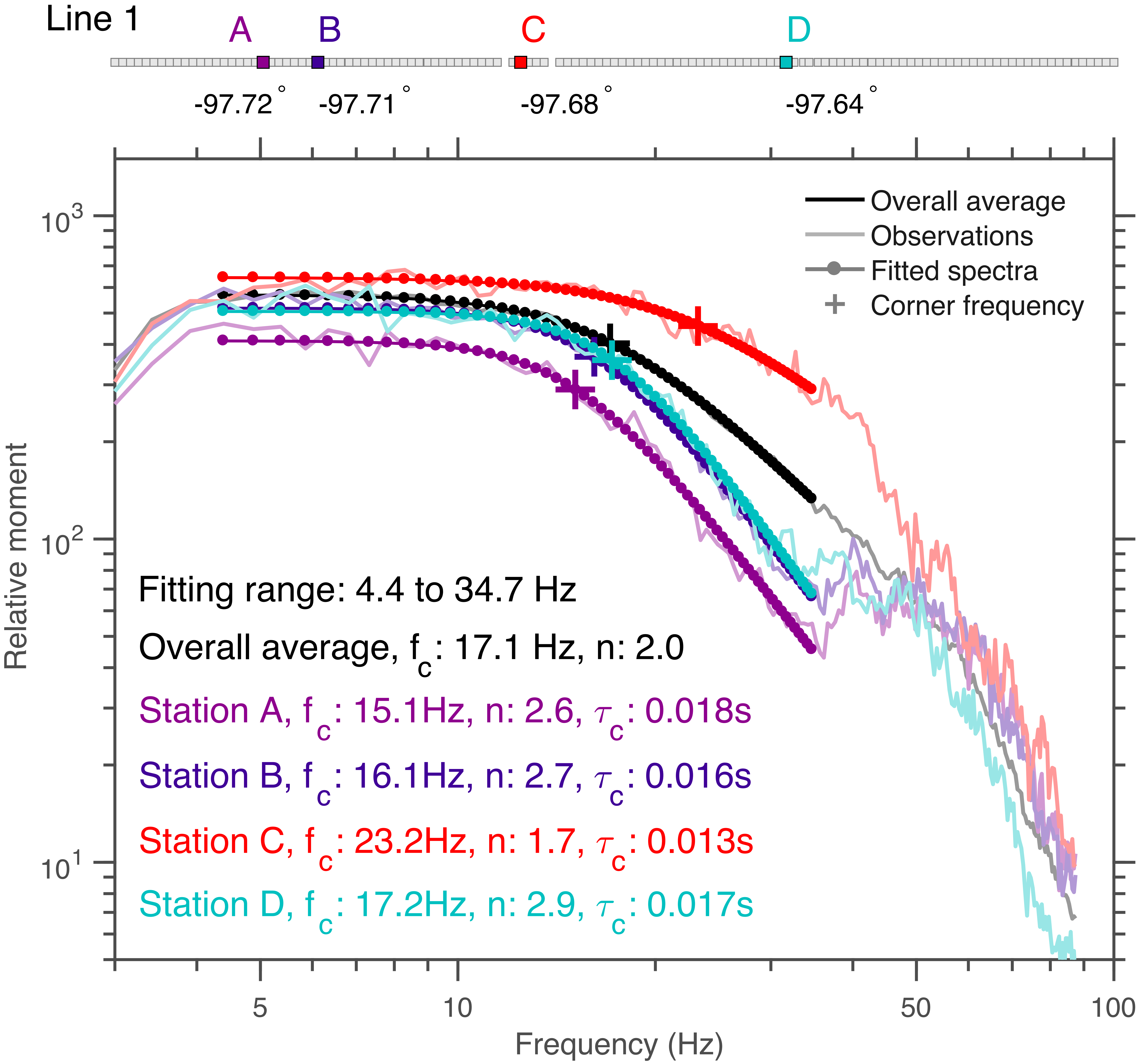
$$\Delta\sigma = \frac{\int_S (\sigma(t_2) - \sigma(t_1))dS}{A}$$

Stress-drop

Rupture area

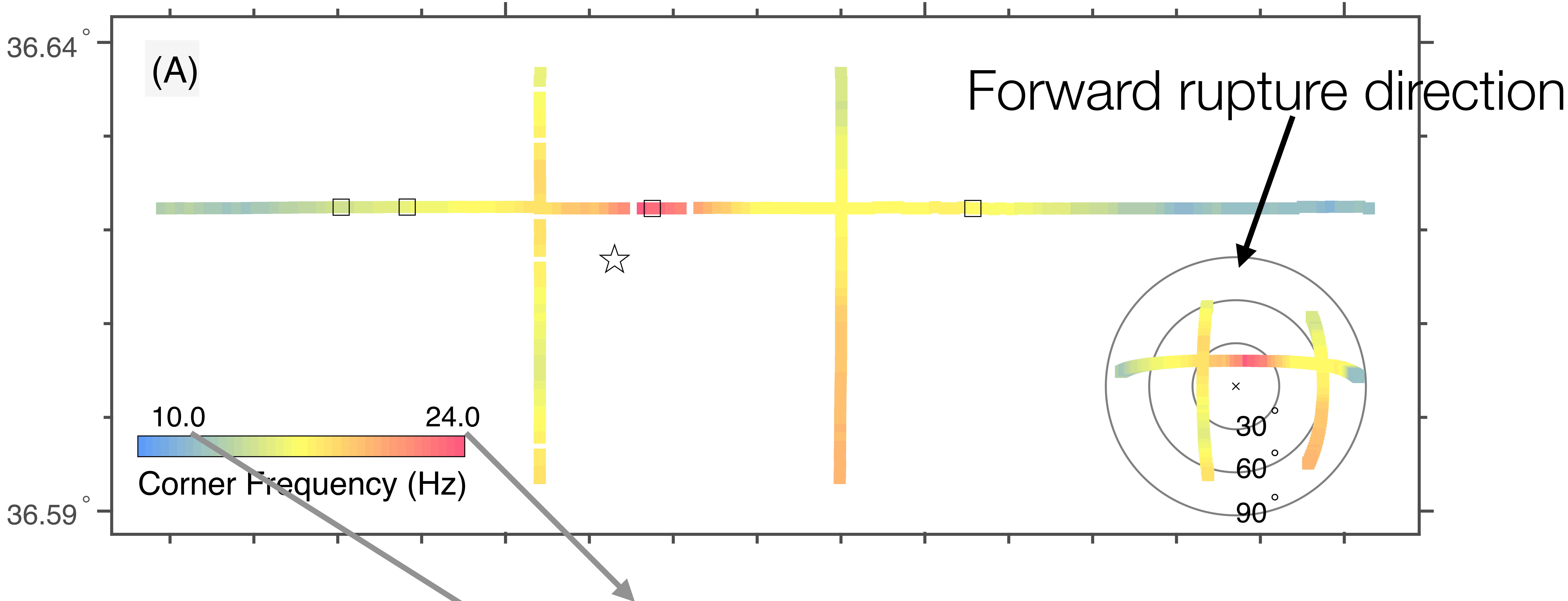
Brune model $$\Delta\sigma = \frac{7}{16}\left(\frac{f_c}{\kappa\beta}\right)^3 M_0$$

Wavefield: Physical meaning of corner frequency



Fan & McGuire, 2018, *GJI*

Physical meaning of corner frequency

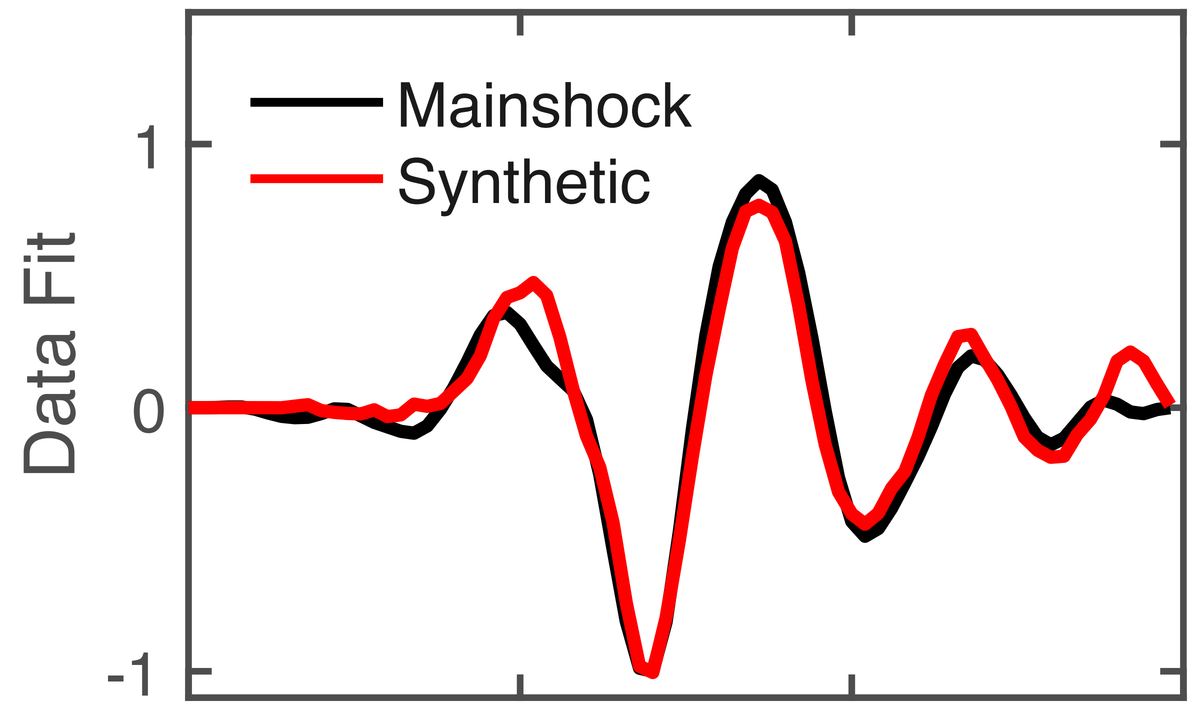


$$\frac{24^3}{10^3} \simeq 14$$

Fan & McGuire, 2018, *GJI*

Directly estimate microearthquake finite source attributes with nodal array by second moments

Empirical Green's function (EGF) deconvolution to get apparent source time functions (ASTF)



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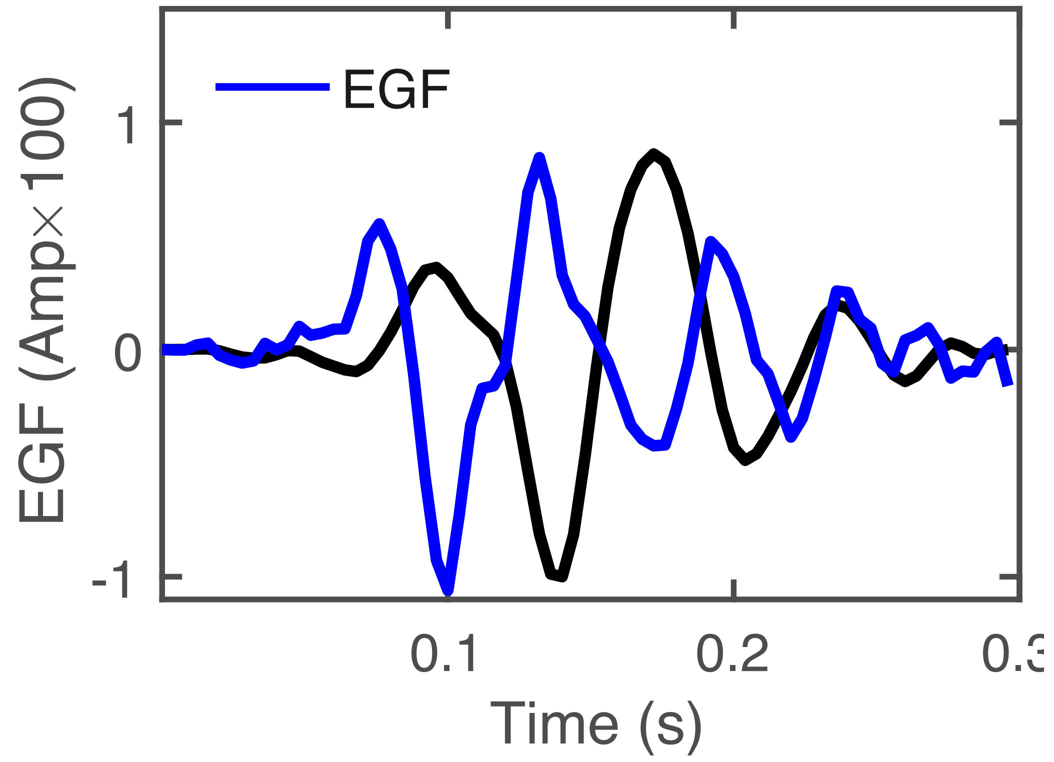

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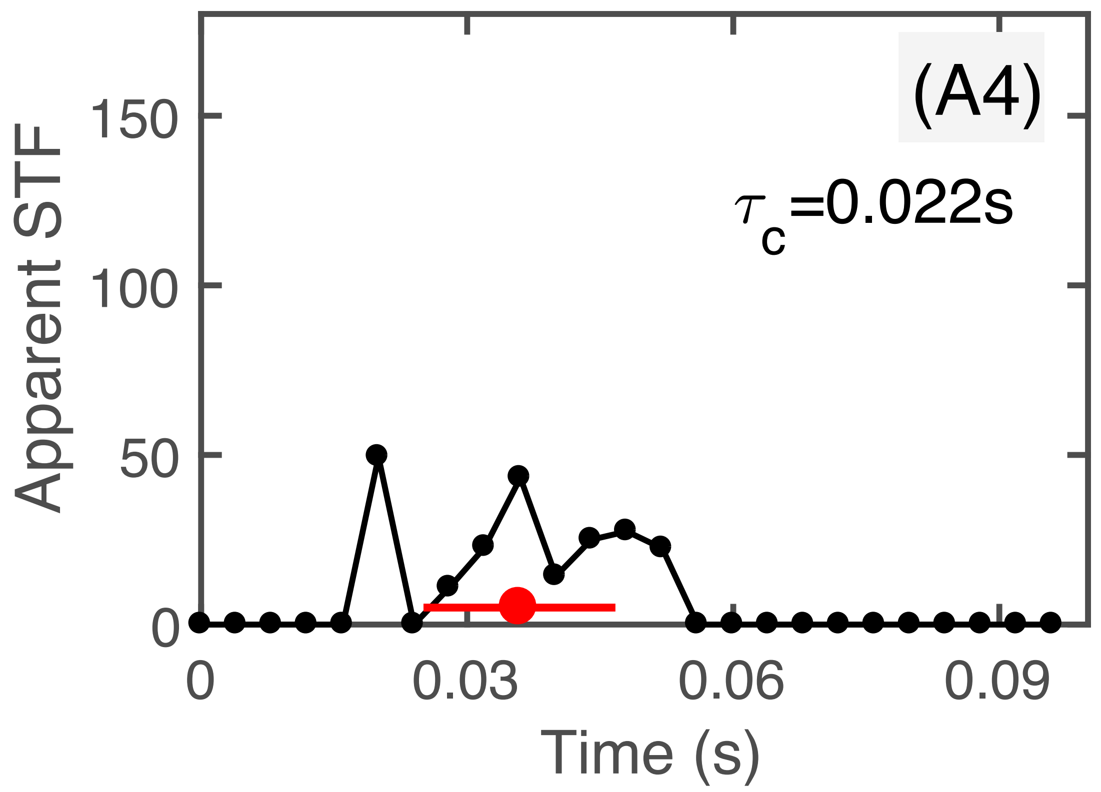


Recorded seismogram

EGF

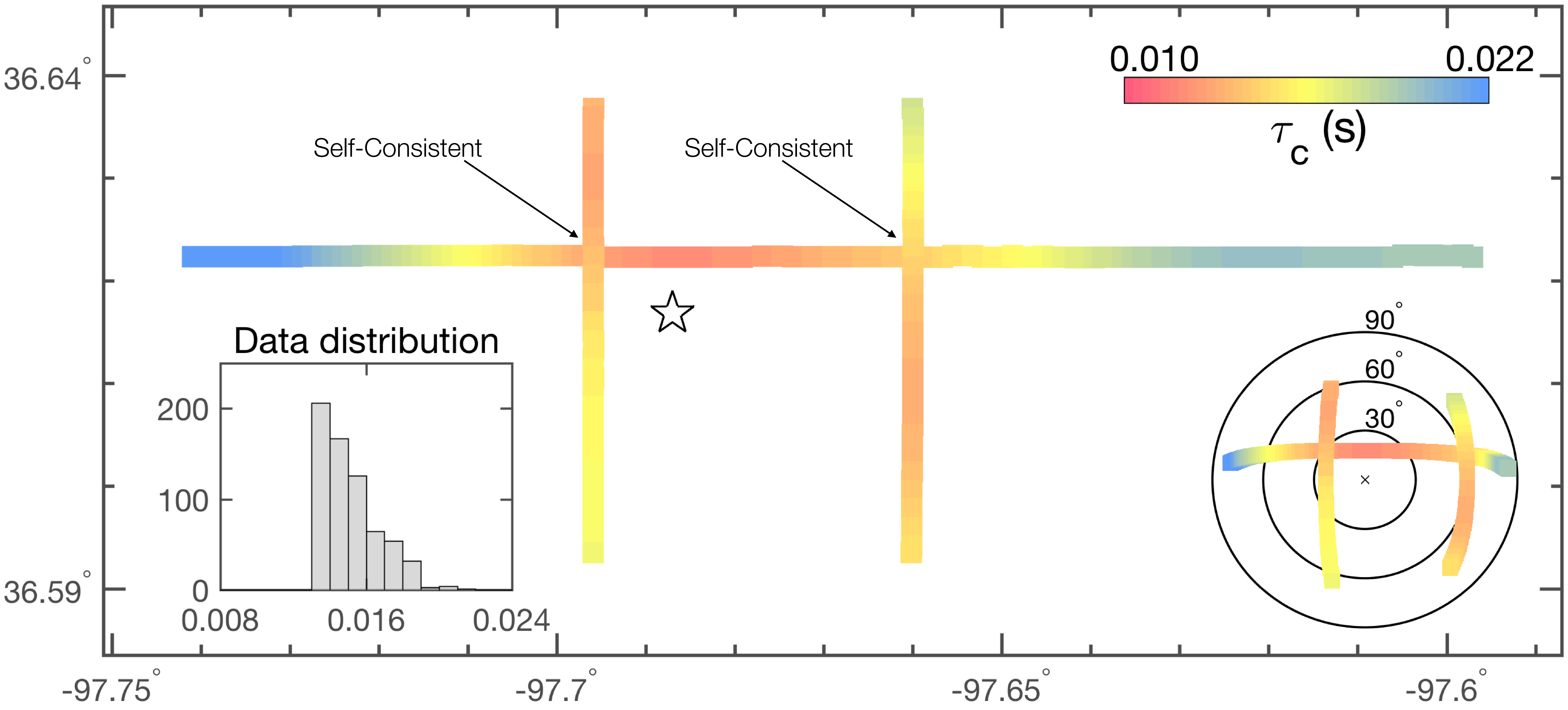
Velocity structure

ASTF

Earthquake source

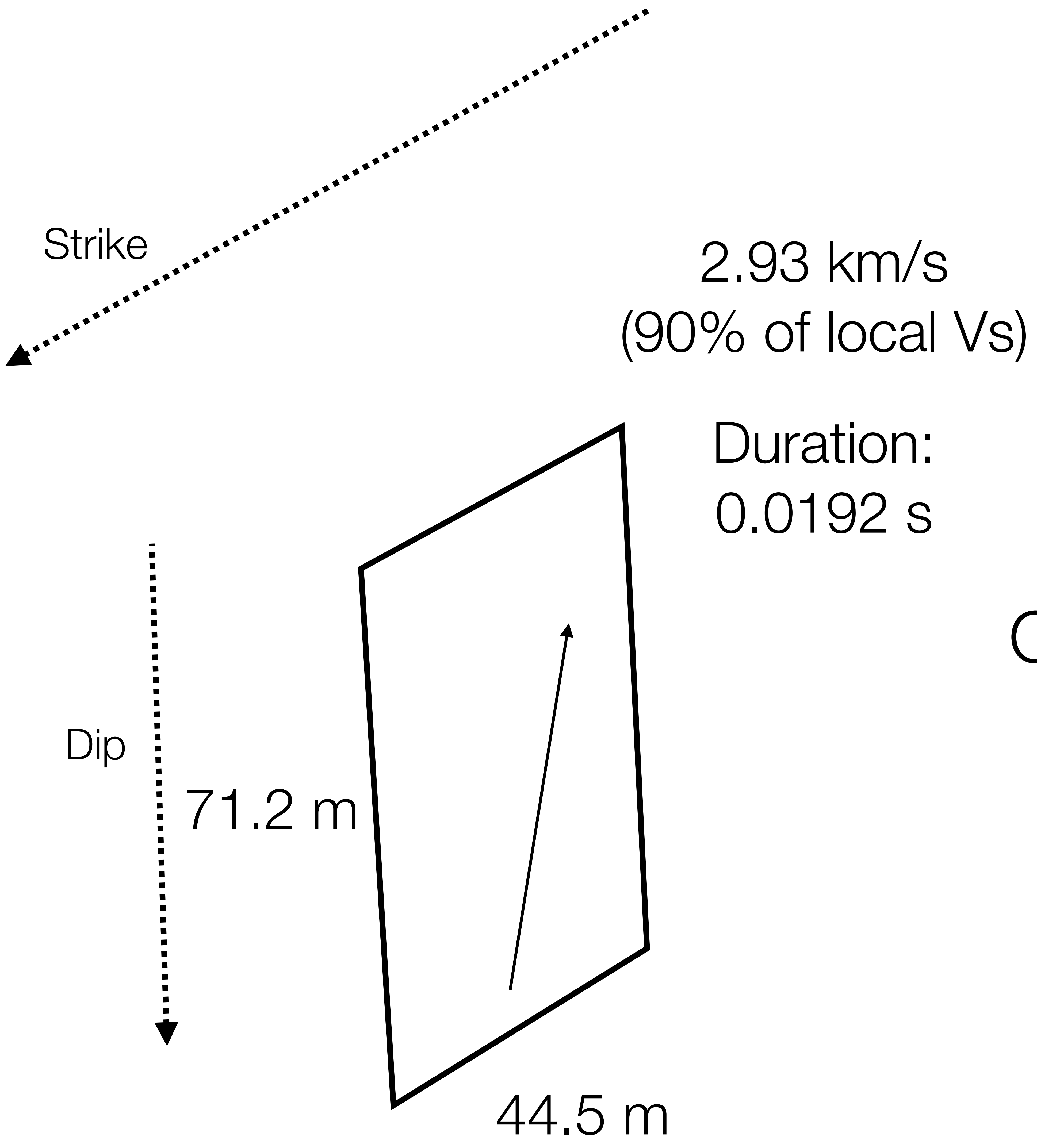
Fan & McGuire, 2018, *GJI*

Physically meaningful pattern of apparent durations



Fan & McGuire, 2018, *GJI*

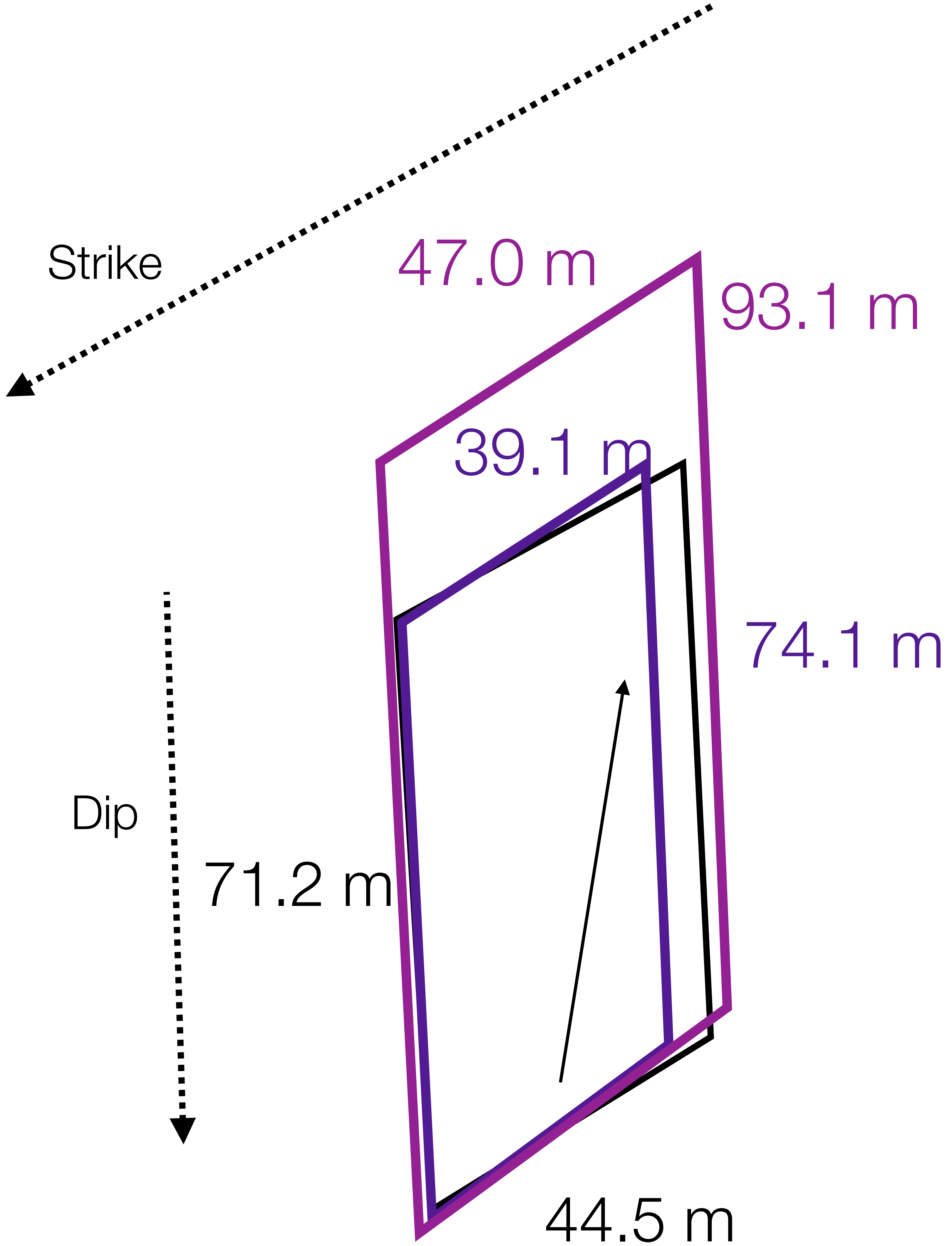
Stress-drop from second moments



Optimal estimation $\Delta\sigma = 7.3\,\mathrm{MPa}$

Fan & McGuire, 2018, *GJI*

Stress-drop uncertainties from **extreme** rupture scenarios permitted by the data



Maximum area $\Delta\sigma = 5.0\,\mathrm{MPa}$

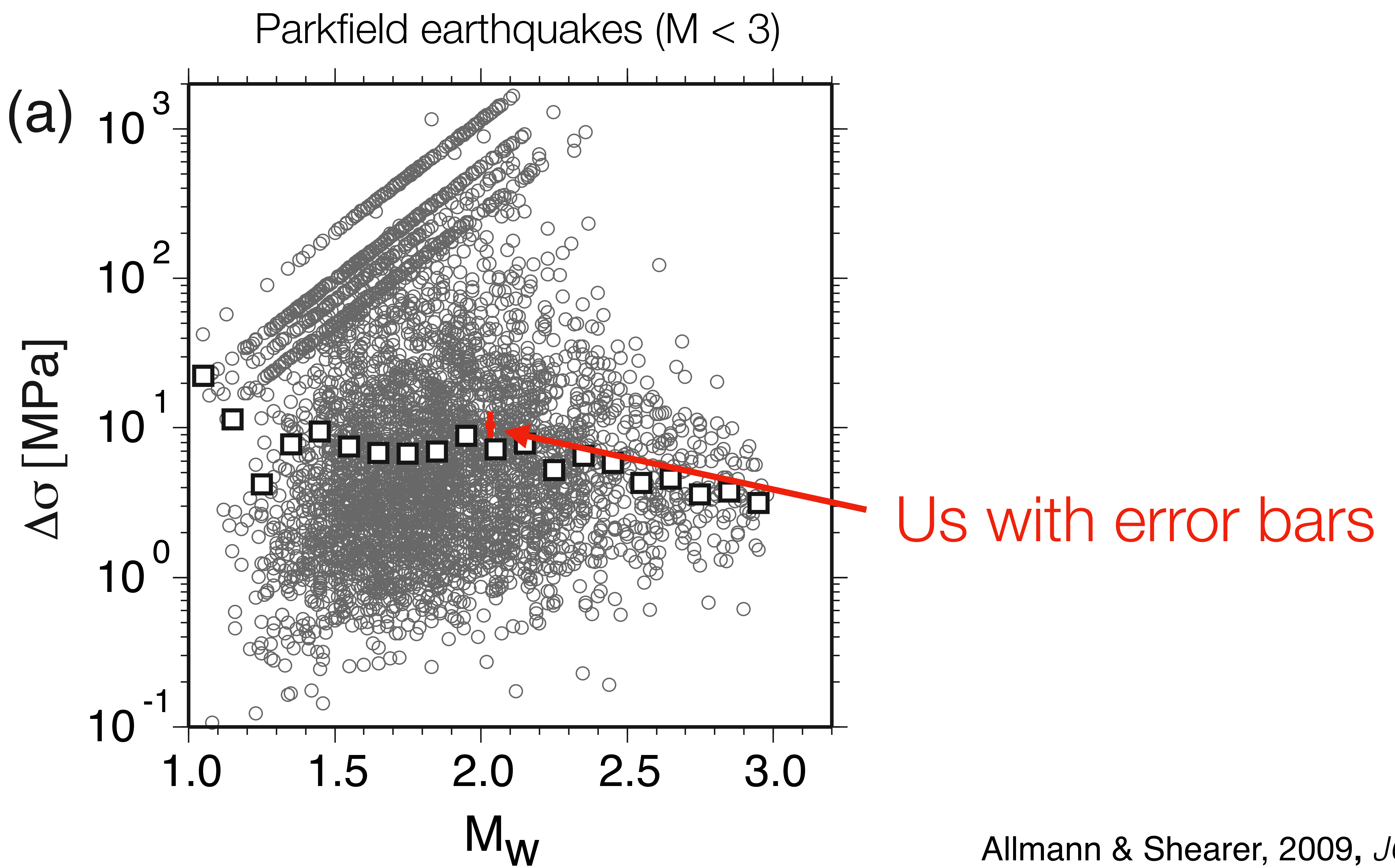
Optimal estimation $\Delta\sigma = 7.3\,\mathrm{MPa}$

Minimum area $\Delta\sigma = 9.1\,\mathrm{MPa}$

Only Factor of 2!

Fan & McGuire, 2018, *GJI*

The concept and methodology has the potential to address the **controversy** on **earthquake stress-drop**



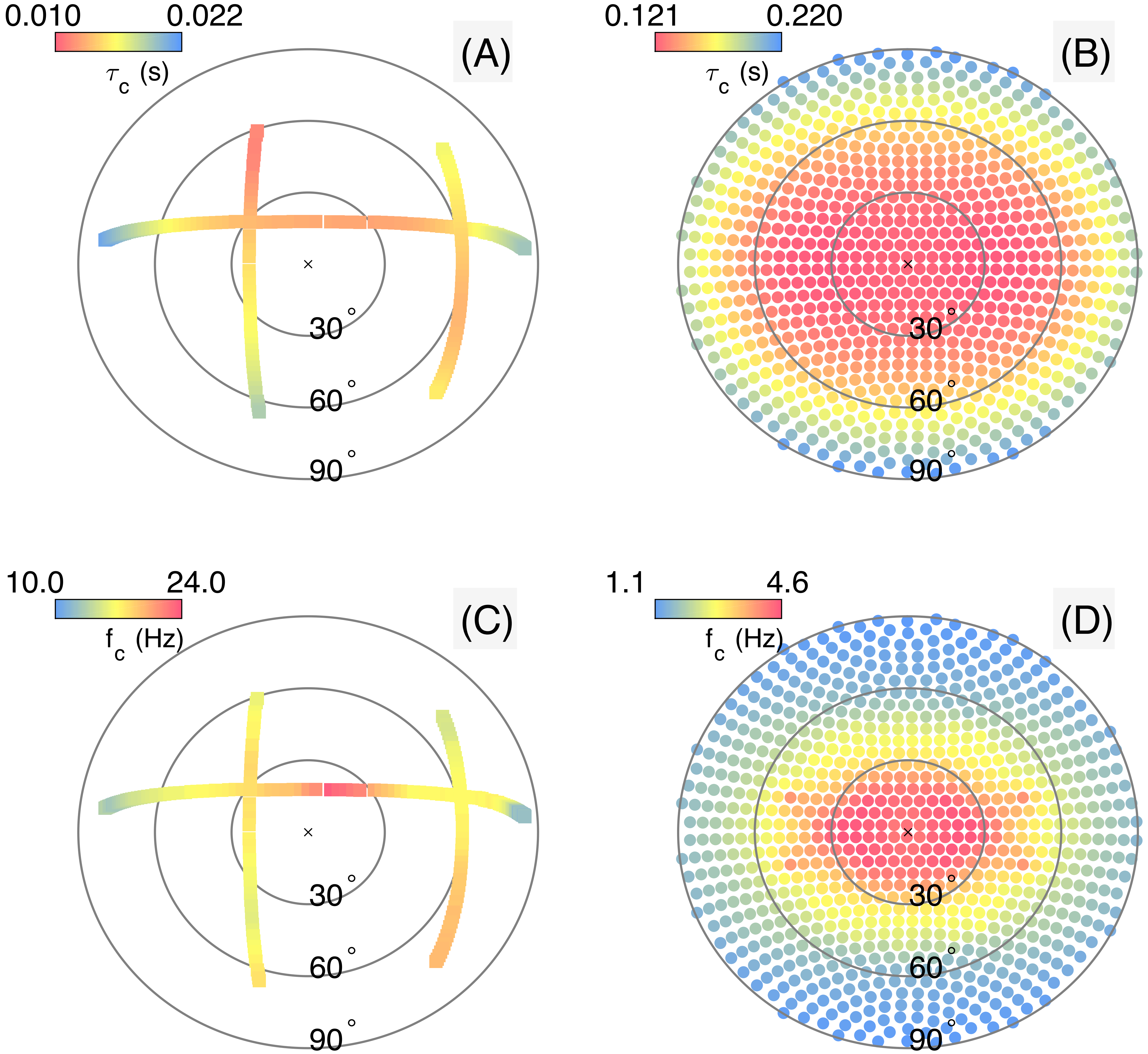
Allmann & Shearer, 2009, *JGR*

Wavefield observations **bridging** models and observations

Observation | Dynamic rupture simulation

Apparent durations

Corner frequencies



Fan & McGuire, 2018, *GJI;* Kaneko & Shearer, 2014, *GJI;* Kaneko & Shearer, 2015, *JGR*

Nodal Arrays:

Small earthquakes can be just as complex as large earthquakes

OPPORTUNITY!

3C nodes has the potential to revolutionize our understanding of both earthquakes and tectonics

HPC & Easy Data Access

Moment (N m) | Magnitude

10^{24} | 10

We observe complexities for small and large earthquakes and exotic slip events

7~8

Global Arrays

Tsunami earthquake and **splay faults**

3~5

Continental Arrays

Using surface waves of large aperture arrays to detect and locate non-earthquake (**glacial-quakes, landslides, submarine landslides**) events

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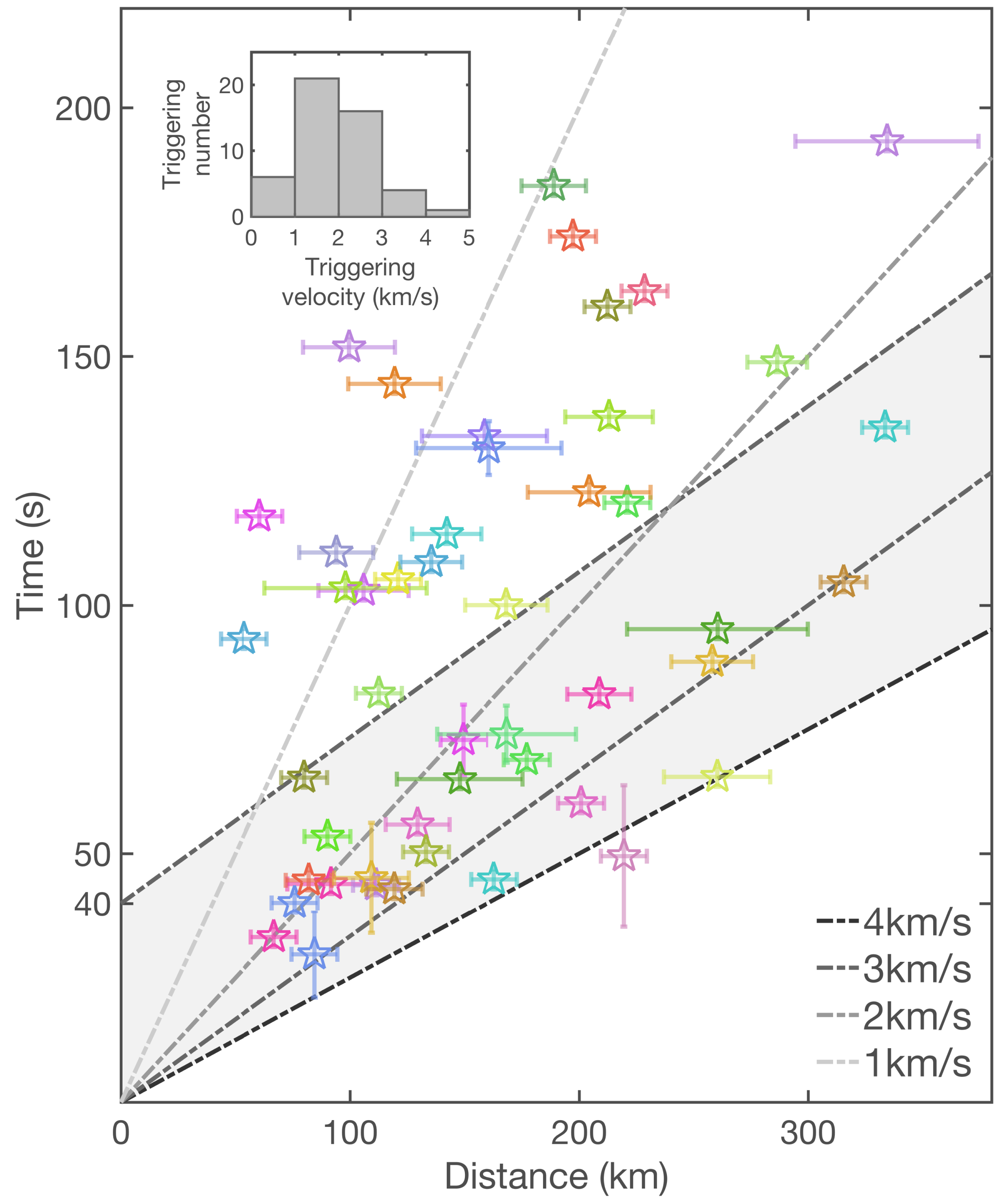
Nodal Arrays

Investigating **microearthquake finite source** attributes with IRIS Community Wavefield Demonstration Experiment in Oklahoma

10^{7} | -1

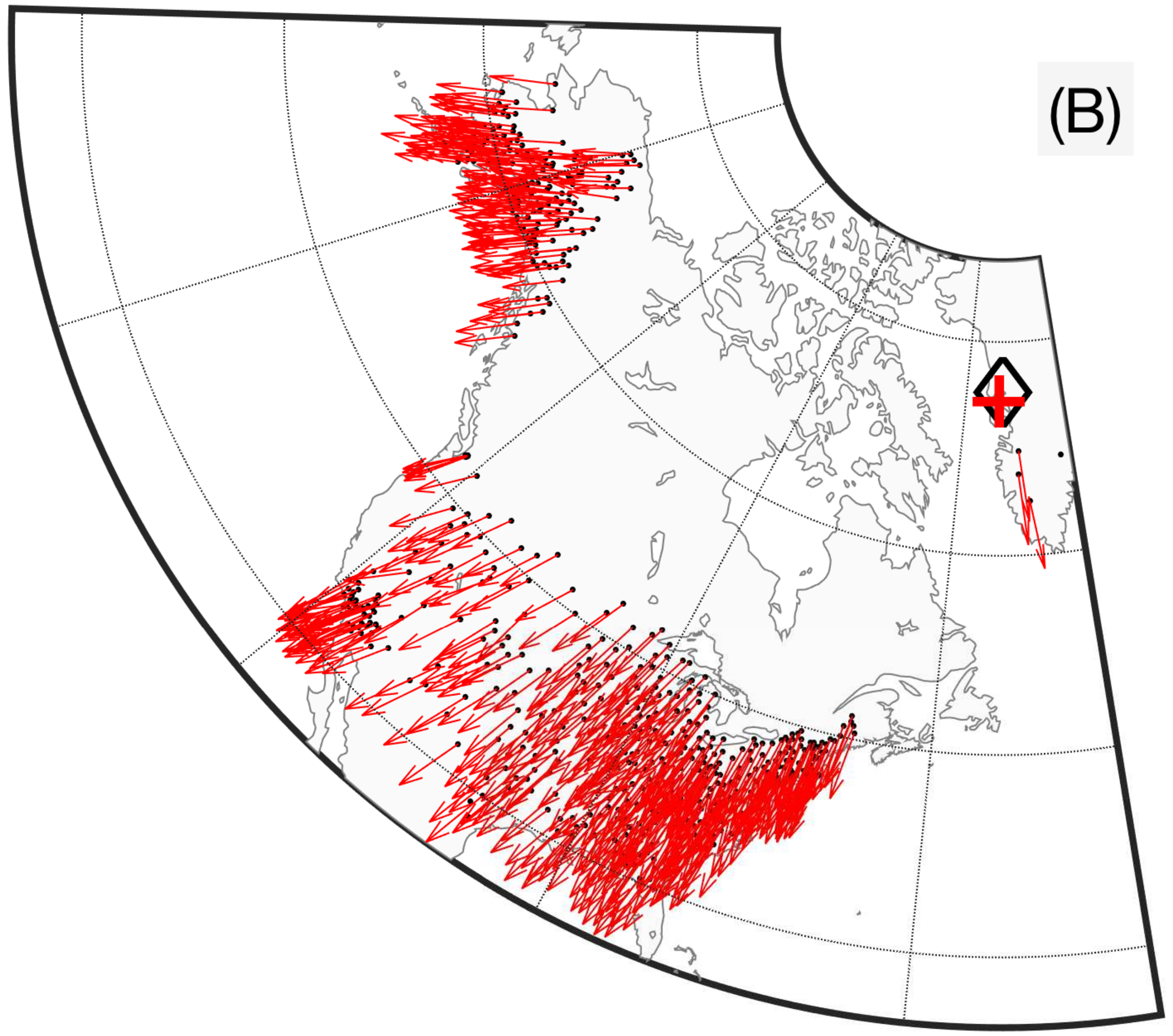
Global Arrays:

Large earthquakes (M > 7) with **all type of focal-mechanisms** commonly **dynamically trigger** early aftershocks.



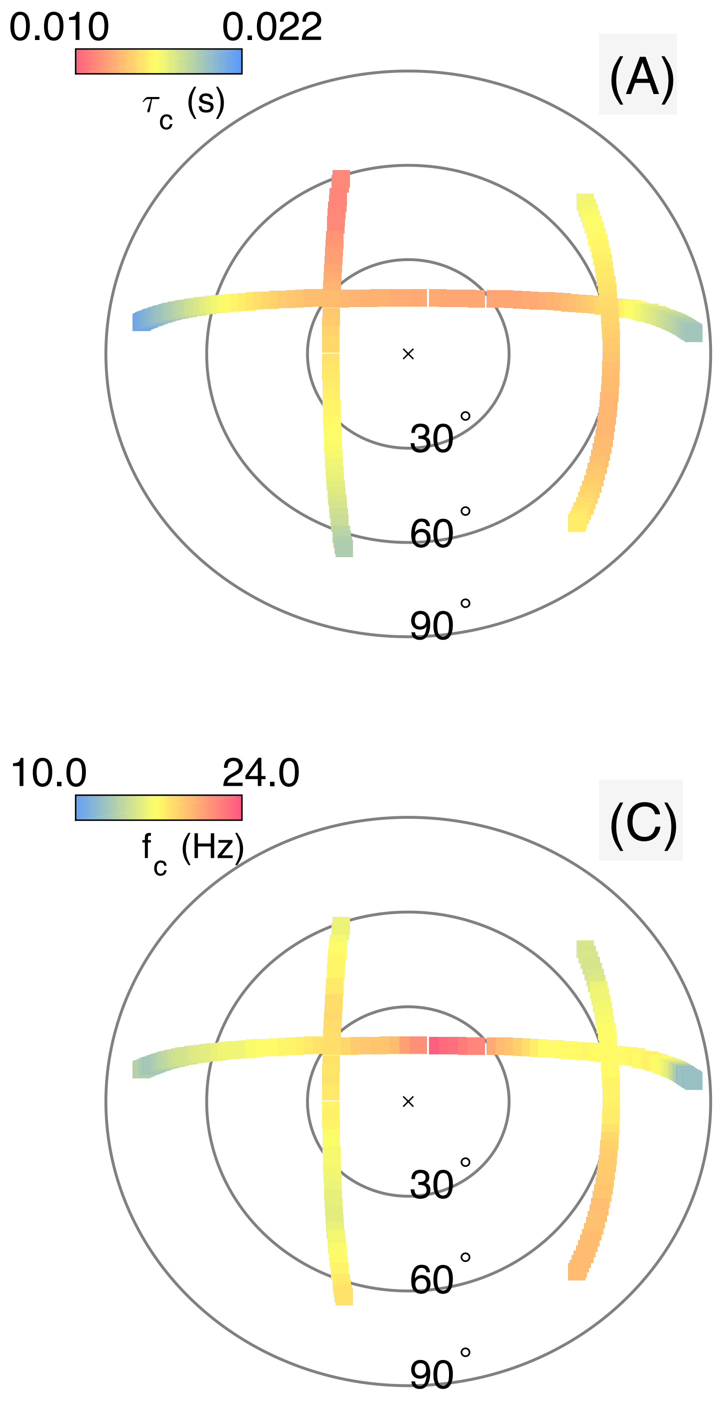
Continental Arrays

Exotic slip events may occur more often than we thought.



Nodal Arrays:

Small earthquakes can be just as complex as large earthquakes



Fan & Shearer, 2016, *Science ;* Fan & McGuire, 2018, *GJI;* Fan et al., 2018, *in revision*