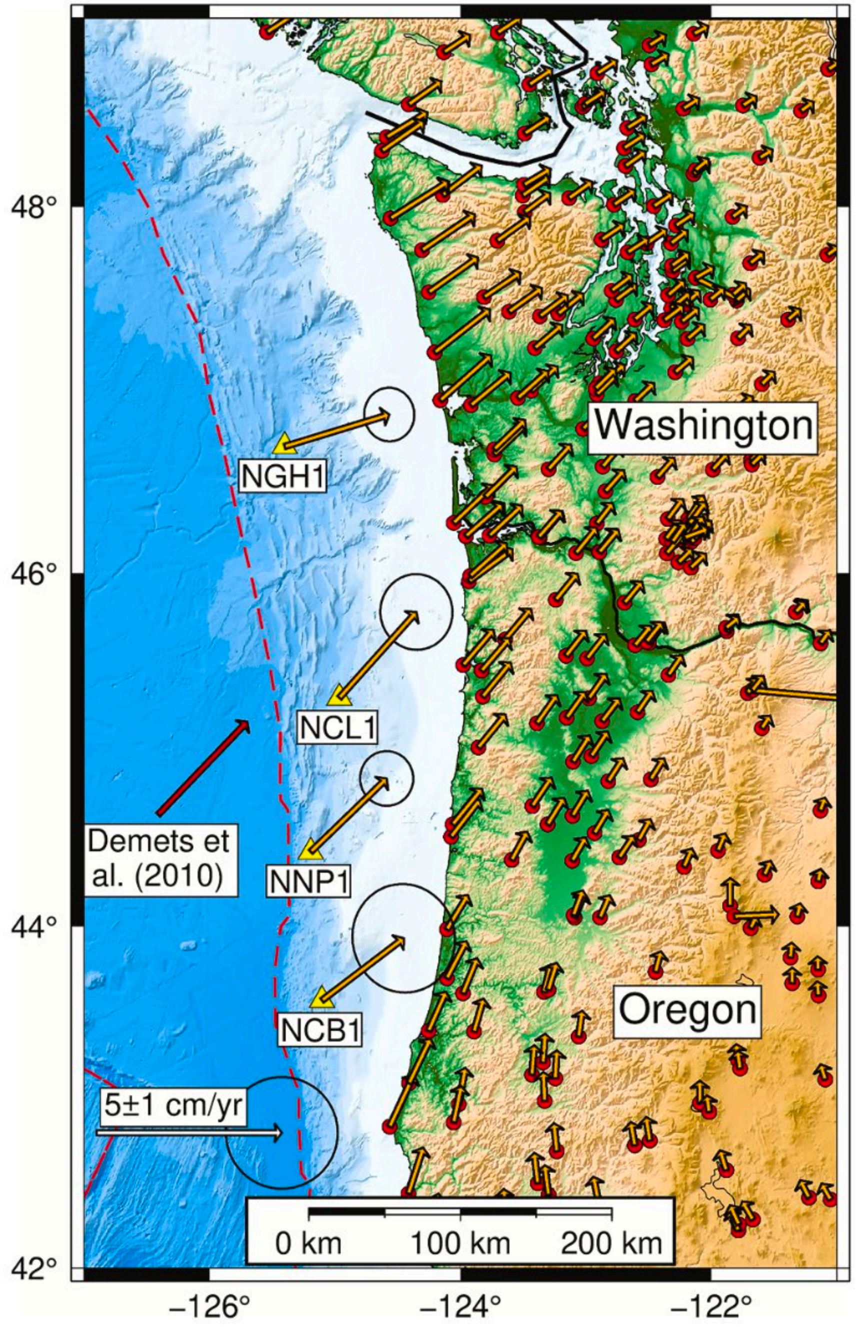


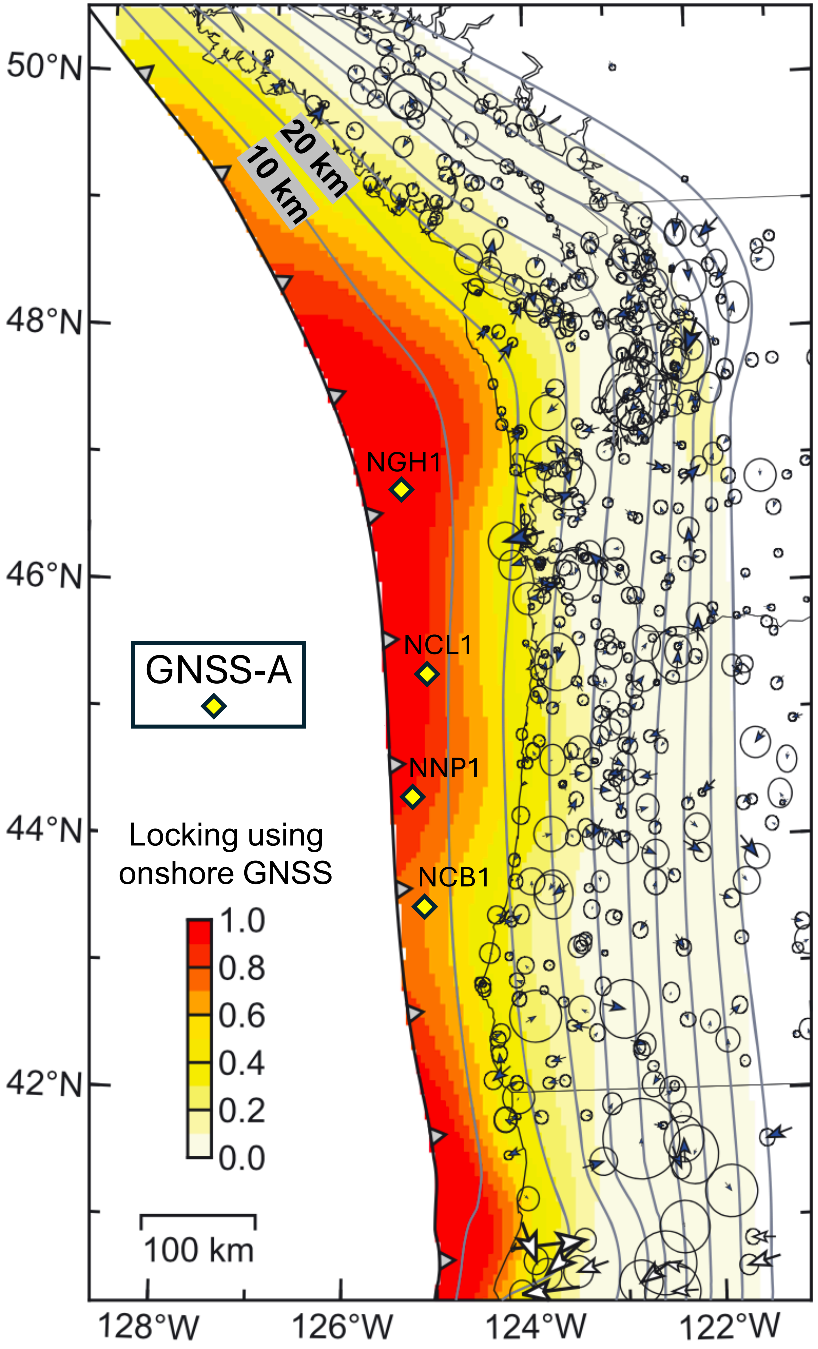
DeSanto et al. (2025)

Investigating "Variability" in Shallow Megathrust Slip: Cascadia in a Global Context

Tianhaozhe Sun[1,2], Kelin Wang[1,2], Earl Davis[1], Keir Becker[3], Heinrich Villinger[4], Martin Heesemann[5], Fumiaki Tomita[6], Takeshi Iinuma[7], Ryota Hino[6], and more

1. Geological Survey of Canada
2. University of Victoria, Canada
3. University of Miami, USA
4. University of Bremen, Germany
5. Ocean Networks Canada
6. Tohoku University, Japan
7. Japan Agency for Marine-Earth Science and Technology

CRESCENT Annual Meeting, October 28-29, 2025, Seattle, WA



Li et al. (2018)

Investigating "Variability" in Shallow Megathrust Slip: Cascadia in a Global Context

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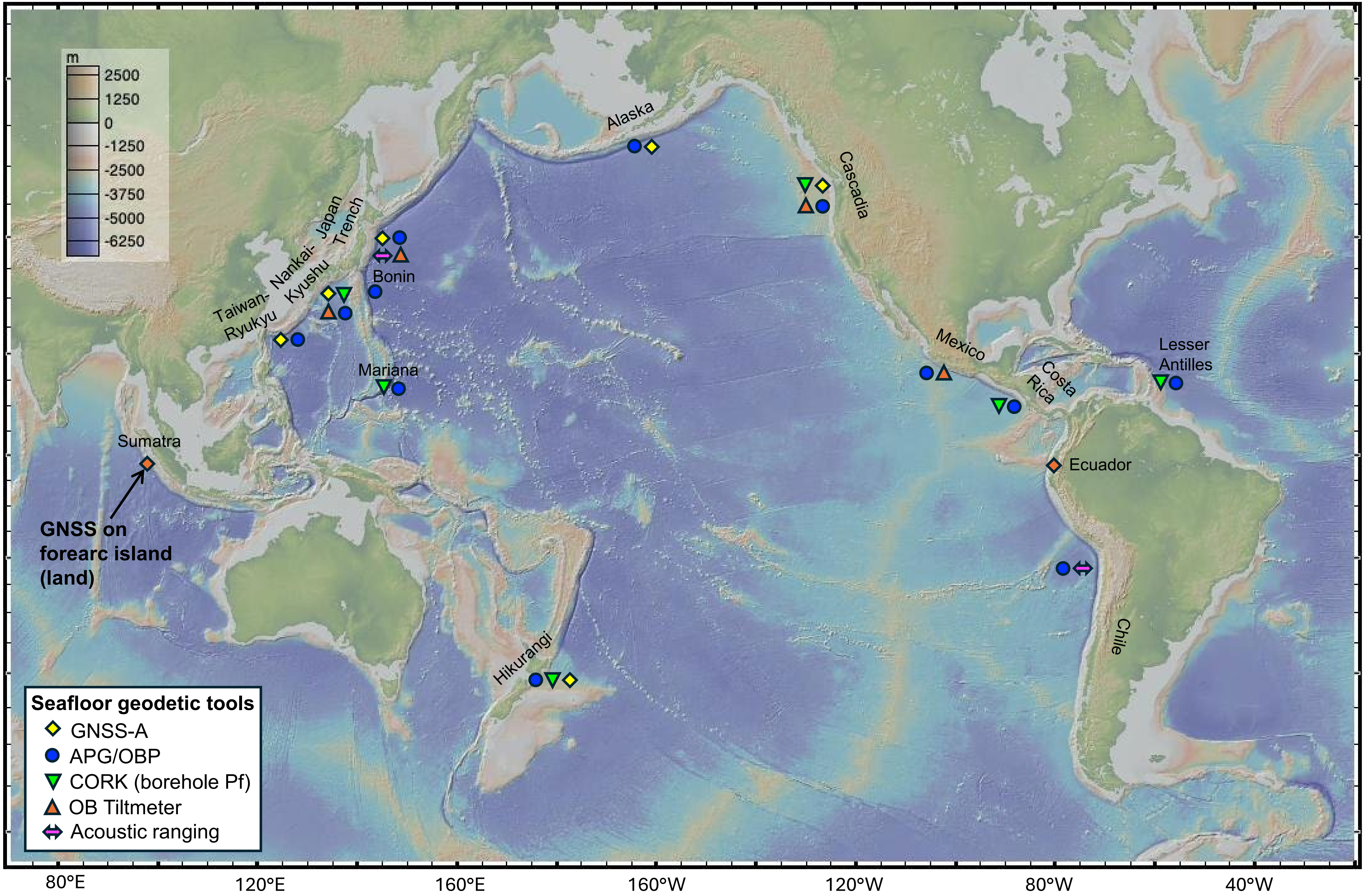

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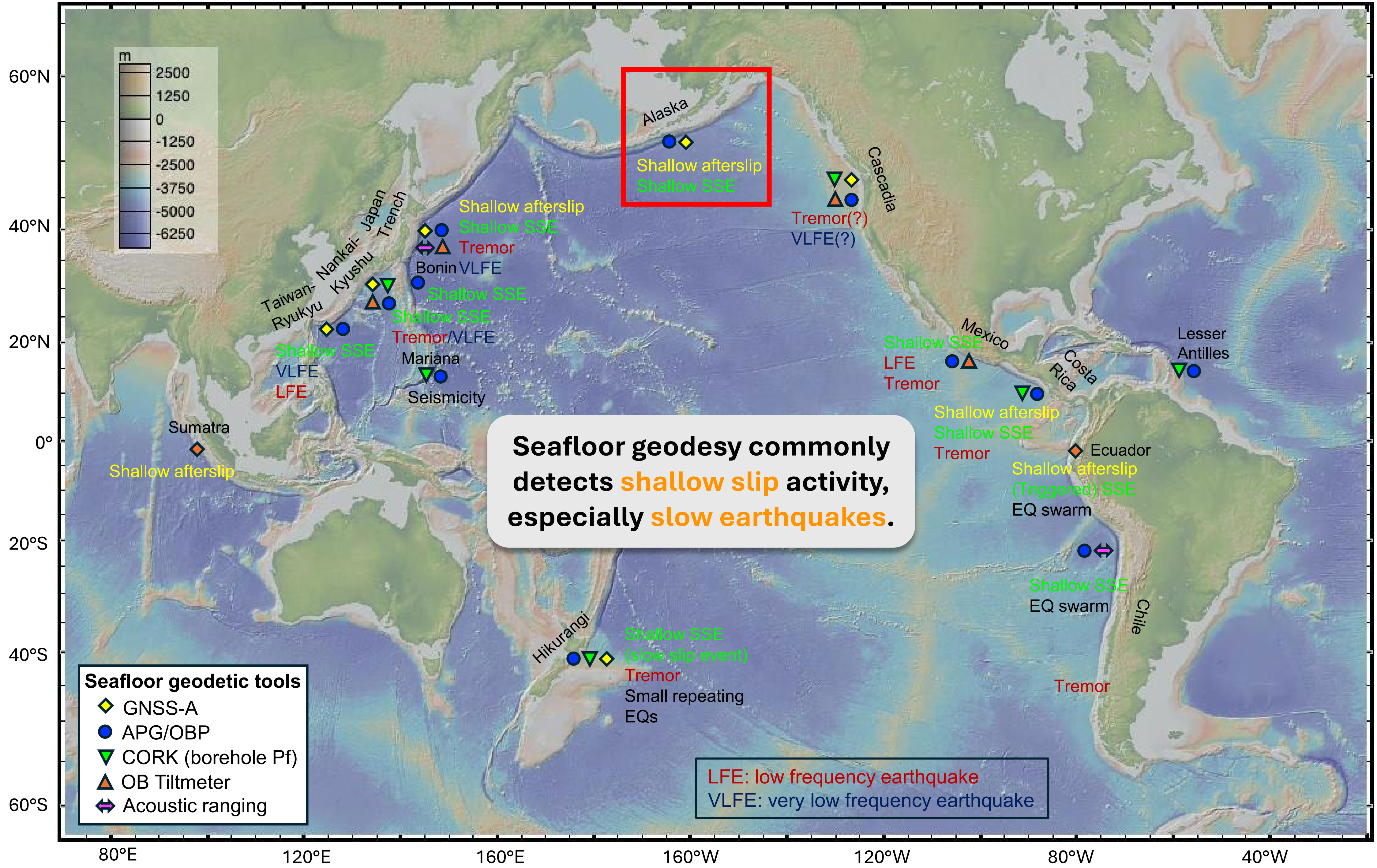
Alaska
Cascadia
Japan Trench
Nankai-Kyushu
Taiwan-Ryukyu
Bonin
Mariana
Mexico
Costa Rica
Lesser Antilles
Sumatra
Ecuador
Chile
Hikurangi
GNSS on forearc island (land)
Seafloor geodetic tools
GNSS-A
APG/OBP
CORK (borehole Pf)
OB Tiltmeter
Acoustic ranging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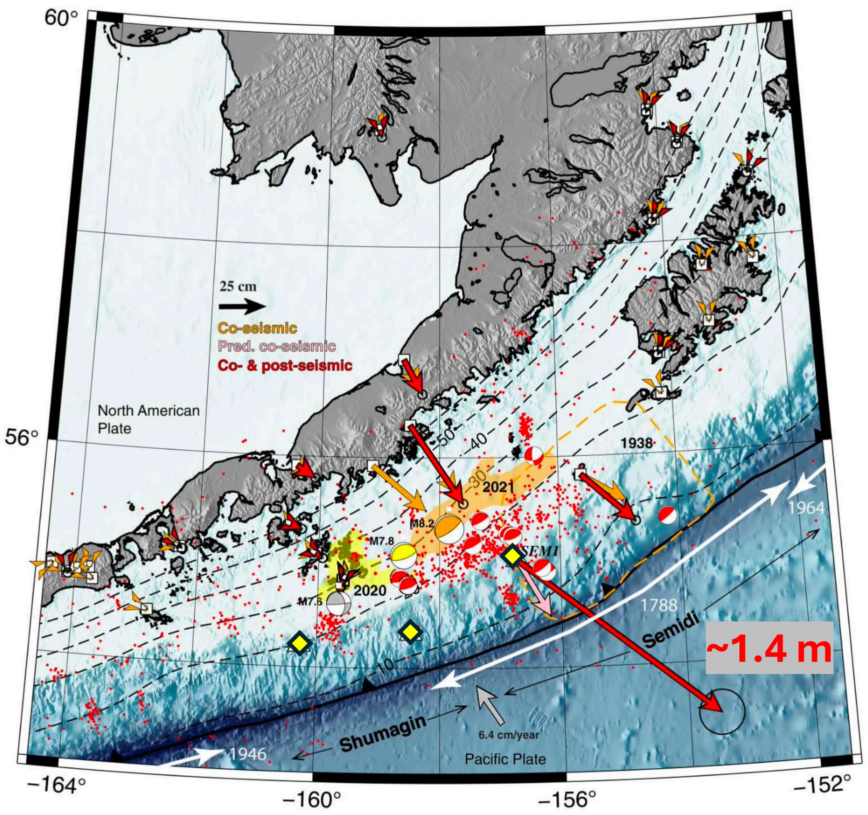
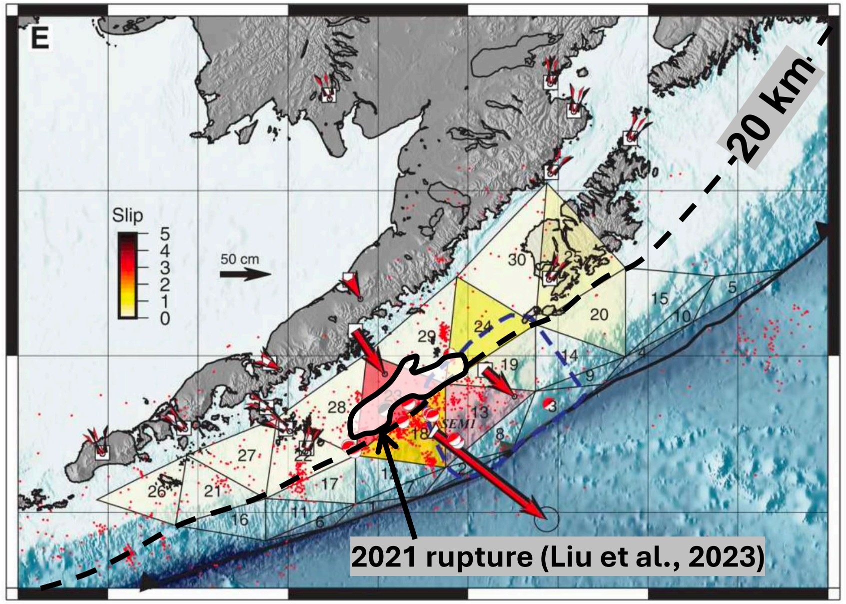
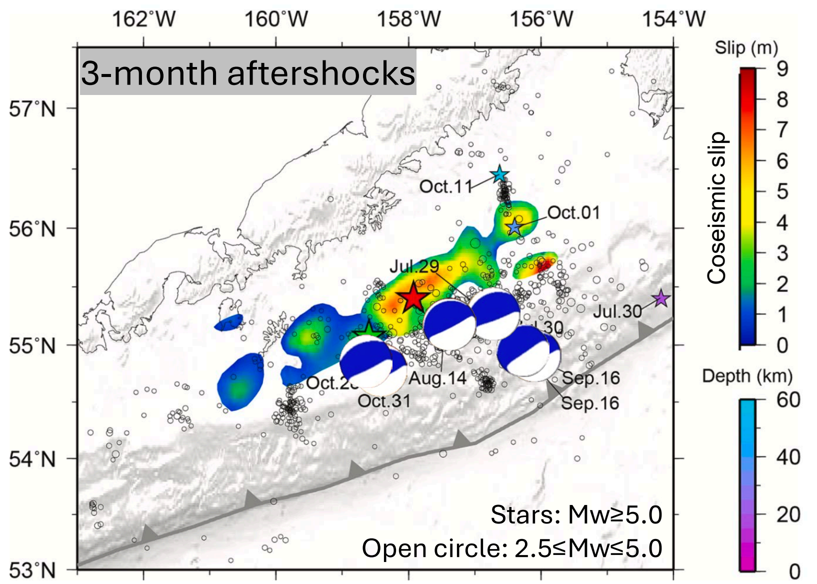
120°E
160°E
160°W
120°W
80°W
40°W
Alaska
Shallow afterslip
Shallow SSE
Cascadia
Tremor(?)
VLFE(?)
Japan Trench
Shallow afterslip
Shallow SSE
Tremor
Bonin VLFE
Nankai-Kyushu
Shallow SSE
Shallow SSE
Tremor/VLFE
Taiwan-Ryukyu
Shallow SSE
VLFE
LFE
Mariana
Seismicity
Sumatra
Shallow afterslip
Mexico
Shallow SSE
LFE
Tremor
Costa Rica
Shallow afterslip
Shallow SSE
Tremor
Lesser Antilles
Ecuador
Shallow afterslip
(Triggered) SSE
EQ swarm
Shallow SSE
EQ swarm
Chile
Tremor
Hikurangi
Shallow SSE
(slow slip event)
Tremor
Small repeating EQs
Seafloor geodesy commonly detects shallow slip activity, especially slow earthquakes.
Seafloor geodetic tools
GNSS-A
APG/OBP
CORK (borehole Pf)
OB Tiltmeter
Acoustic ranging
LFE: low frequency earthquake
VLFE: very low frequency earthquake

Shallow afterslip following the 2021 Mw 8.2 Chignik earthquake recorded by GNSS-A



Brooks et al. (2023)



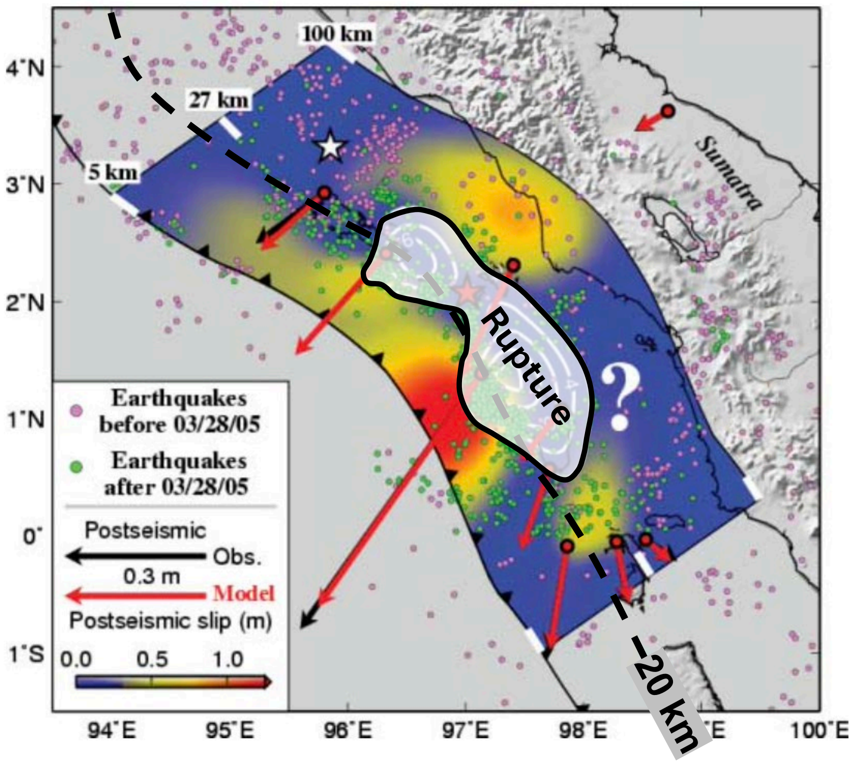


Liu et al. (2023)

- Large cumulative co- and post-seismic (2.5-month) displacement of GNSS-A station **SEM1**
- ~1-3 m slip up-dip of the Chignik rupture, shallower than 20 km
- Many aftershocks (low-angle thrust faulting) updip of the rupture

Shallow afterslip documented by GNSS stations on forearc islands or land areas

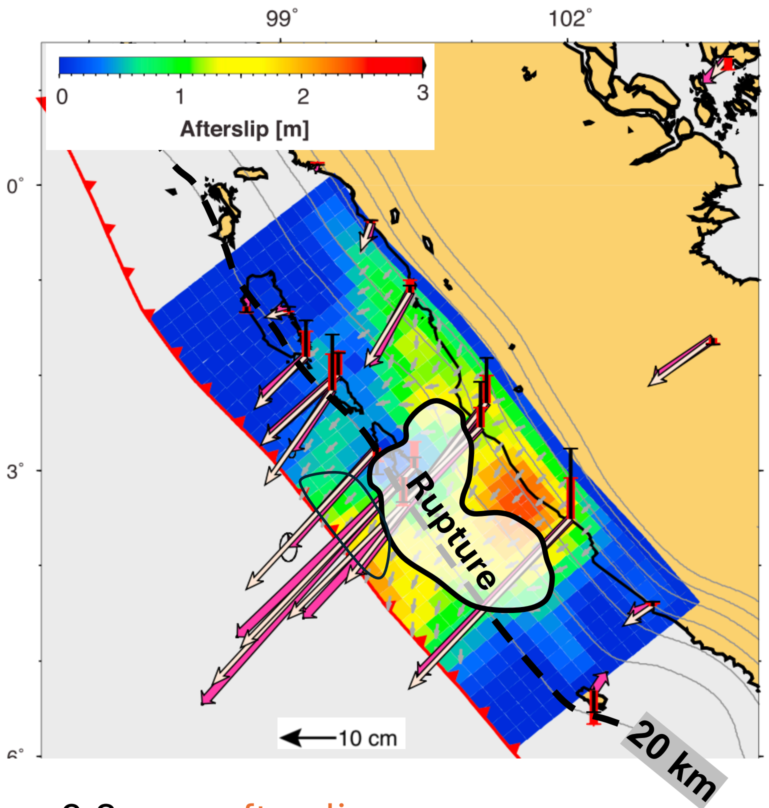
2005 Mw 8.6 Nias



9-month afterslip

Hsu et al. (2006)

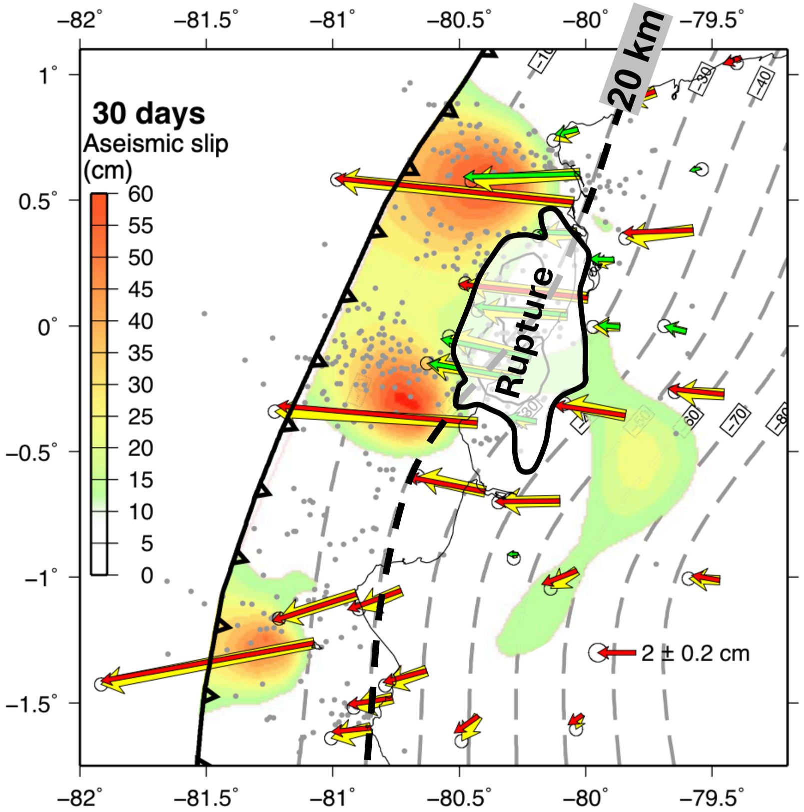
2007 Mw 8.4 Bengkulu



6.3-year afterslip

Tsang et al. (2016)

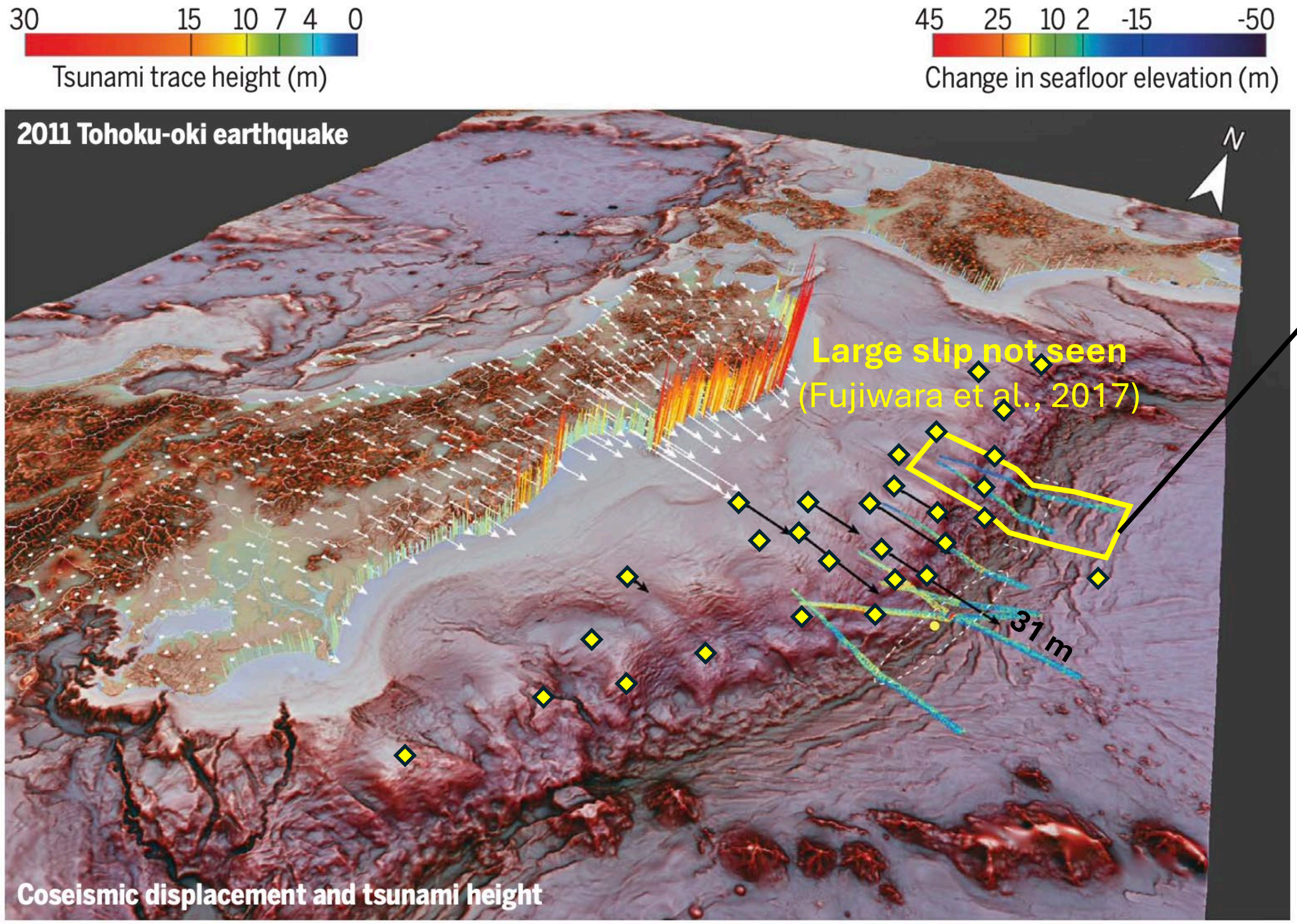
2016 Mw 7.8 Ecuador

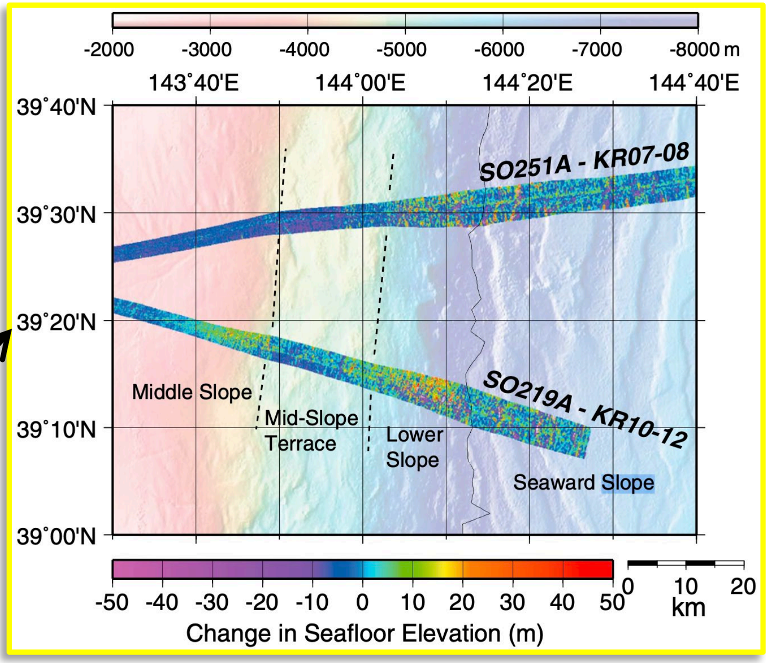


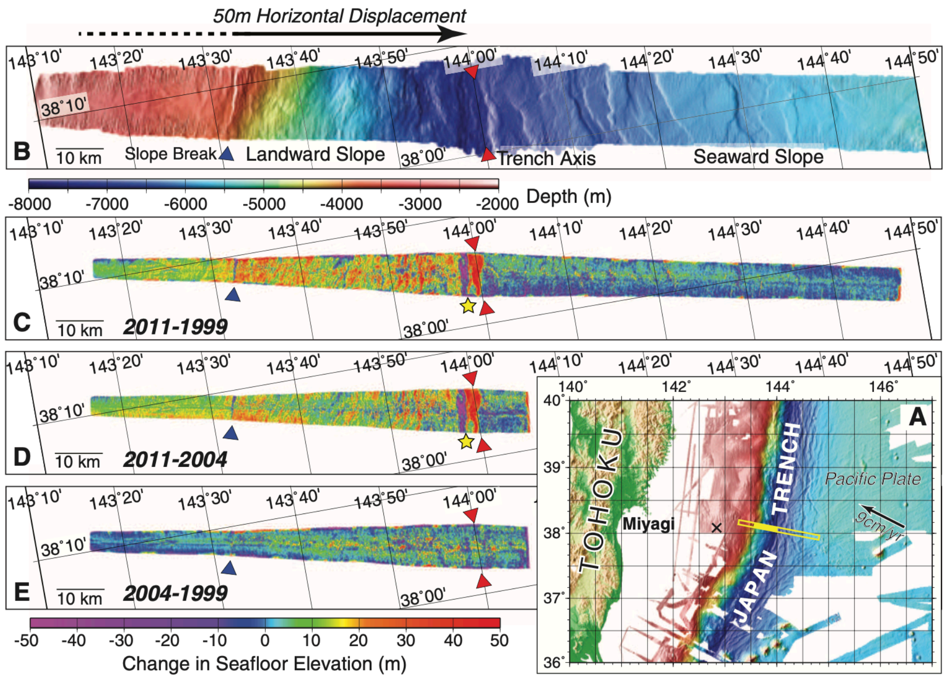
1-month afterslip and triggered SSE

Rolandone et al. (2018)

The 2011 Mw 9.0 Tohoku-oki trench-breaching rupture





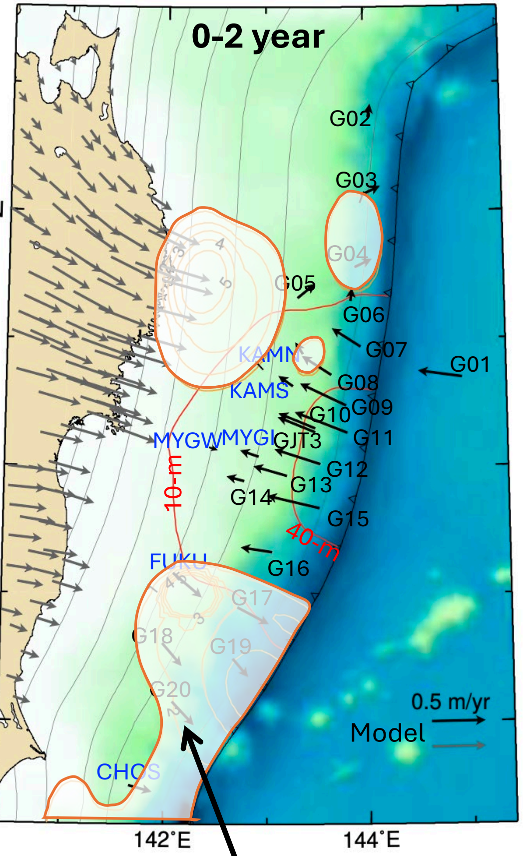


Kodaira et al. (2021)

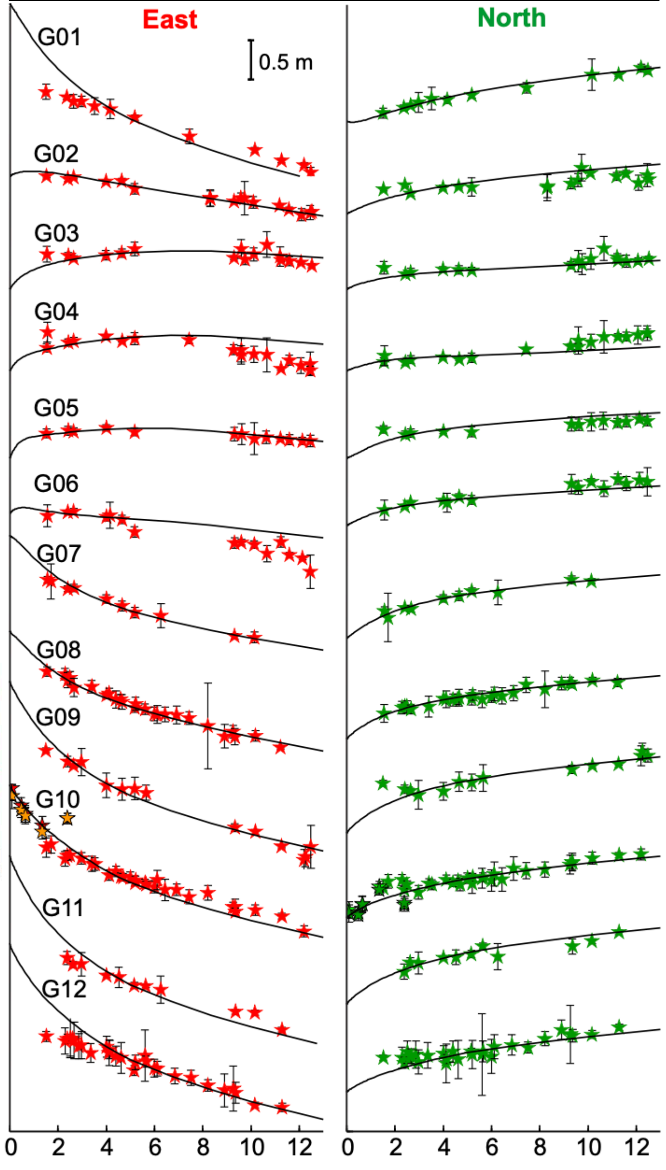
Seafloor GNSS-A: Sato et al. (2011), Kido et al. (2011)

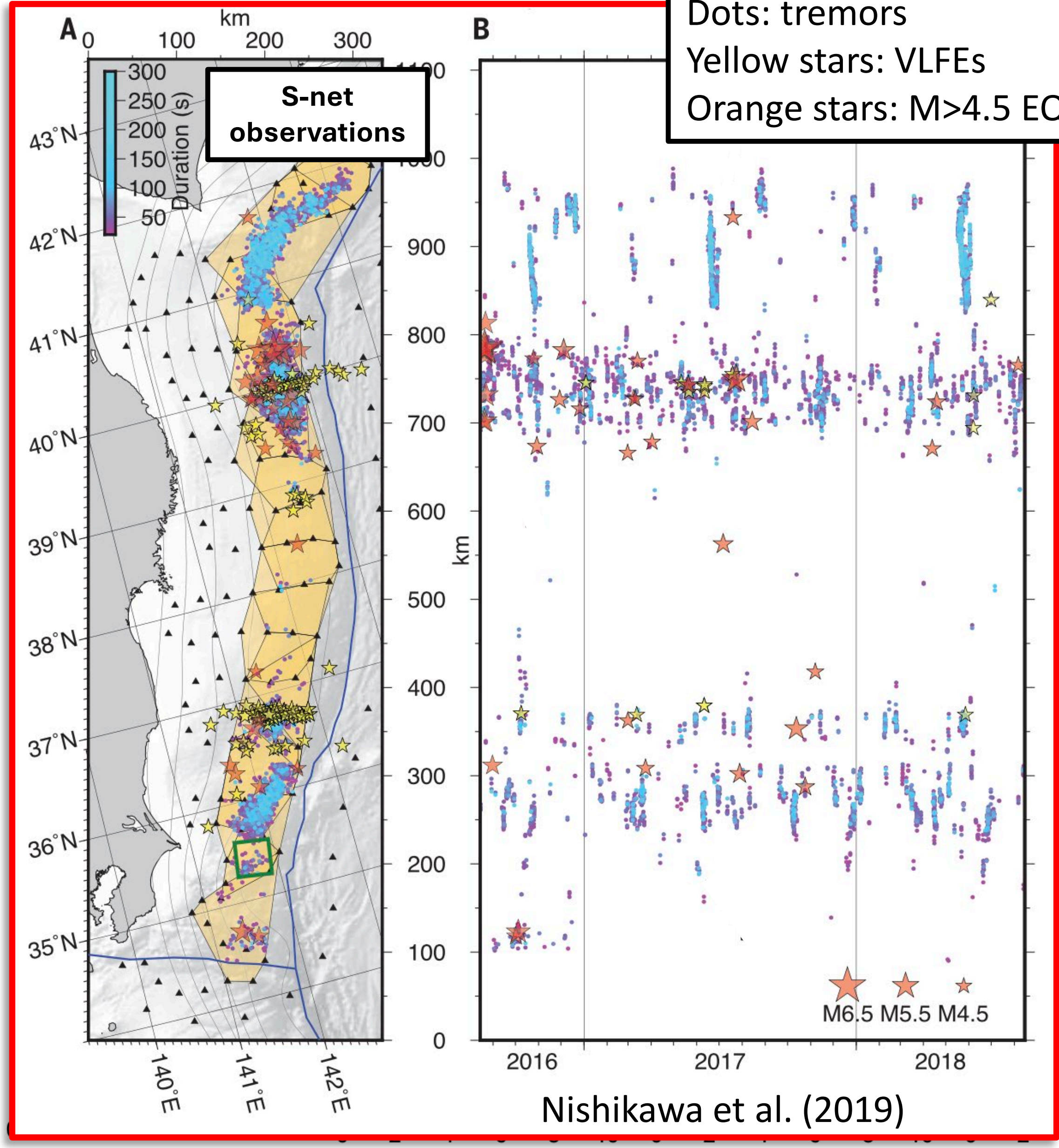
Differential bathymetry: Fujiwara et al. (2011)

Tohoku University GNSS-A sites



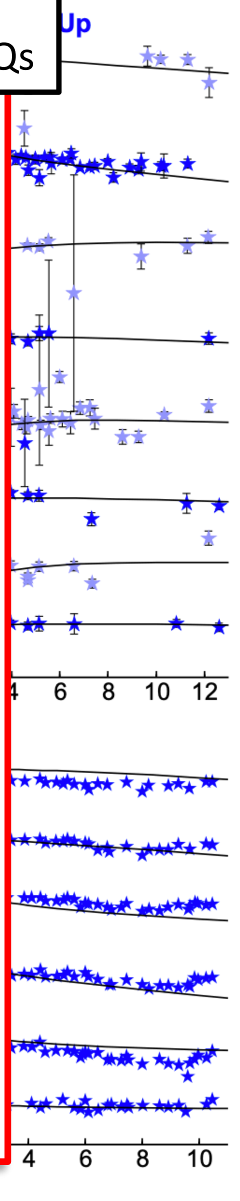
Large shallow afterslip outside of the Tohoku-oki rupture





Dots: tremors
Yellow stars: VLFEs
Orange stars: M>4.5 EQs

Nishikawa et al. (2019)

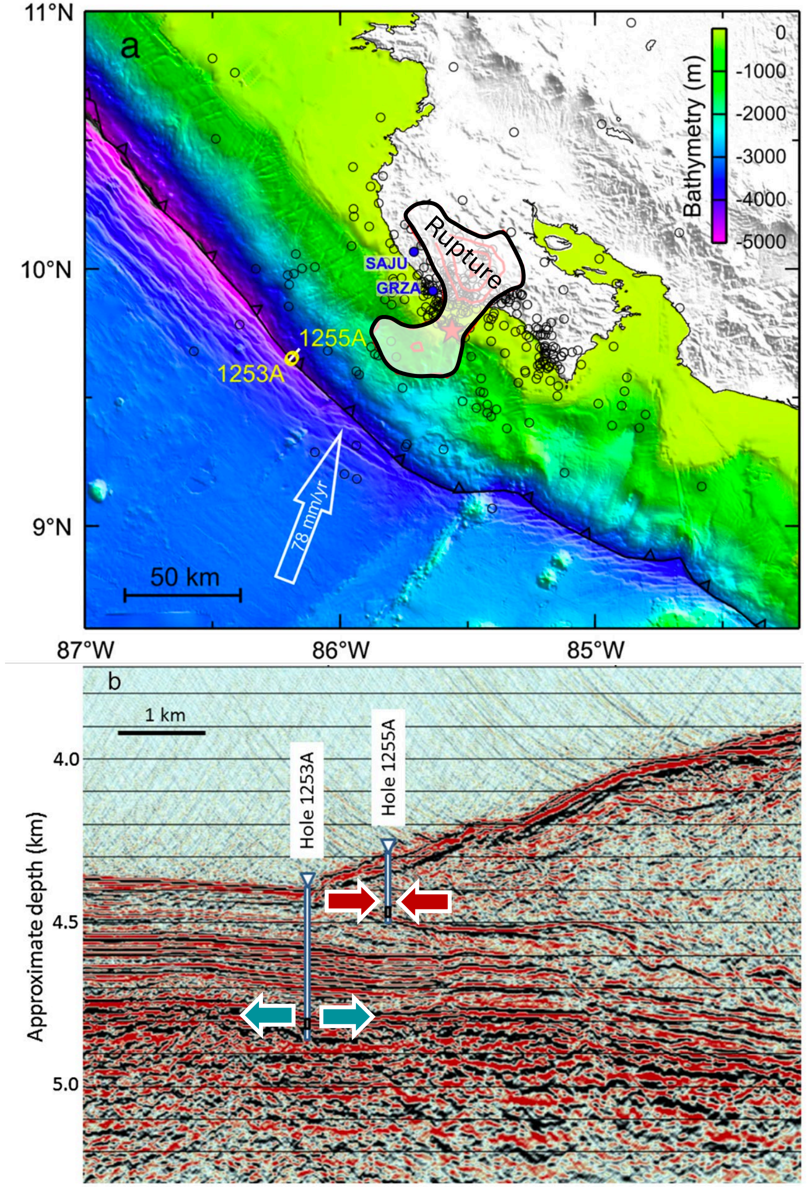


Black lines: Viscoelastic deformation model

Japan Coast Guard GNSS-A sites

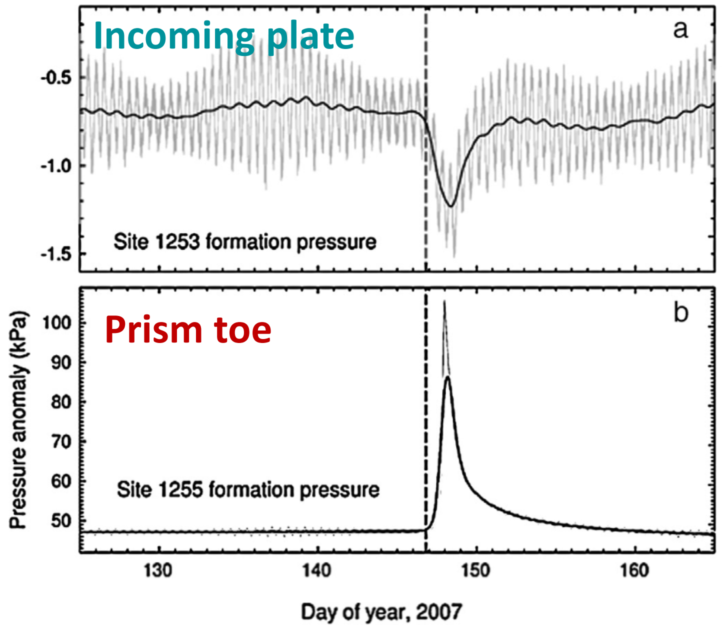
Tomita, Sun et al. (in preparation)
Sun and Wang (2015)

Costa Rica: recurring SSEs before the 2012 Mw 7.6 Nicoya earthquake recorded by deep-sea CORKs

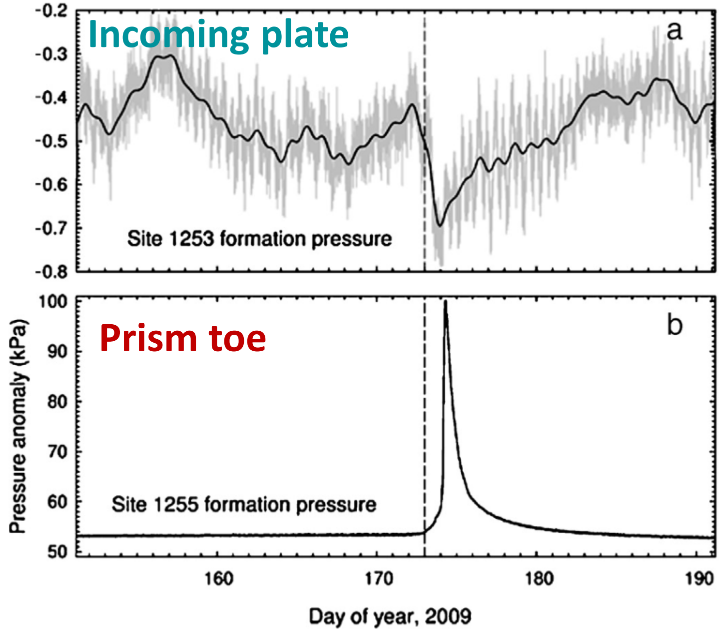


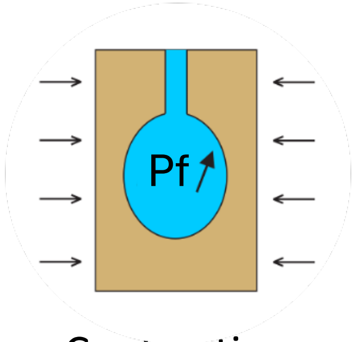
Davis et al. (2015), Sun et al. (2017)

May 2007 SSE

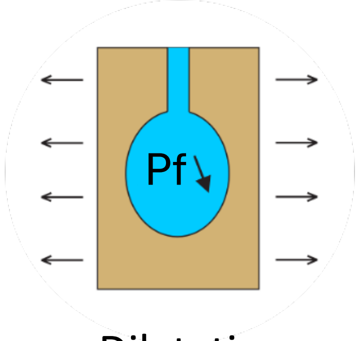


June 2009 SSE



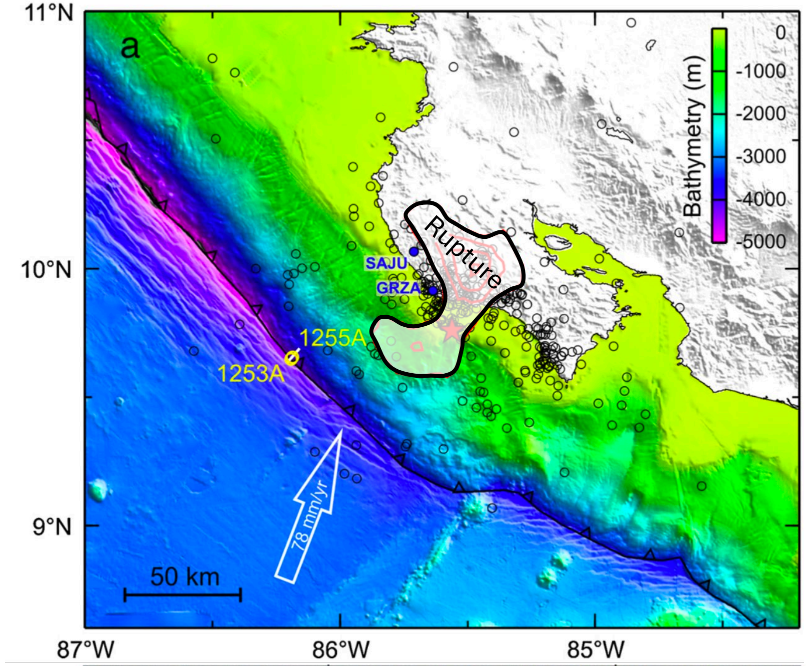


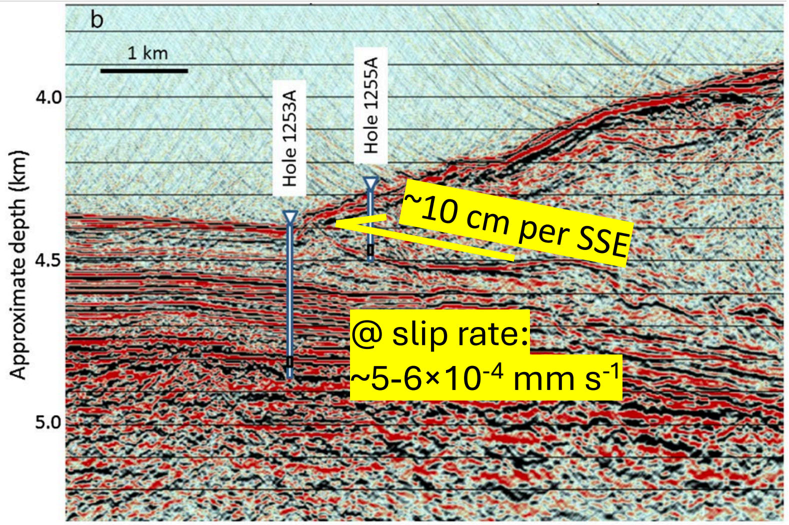
Contraction
>> Pf increase

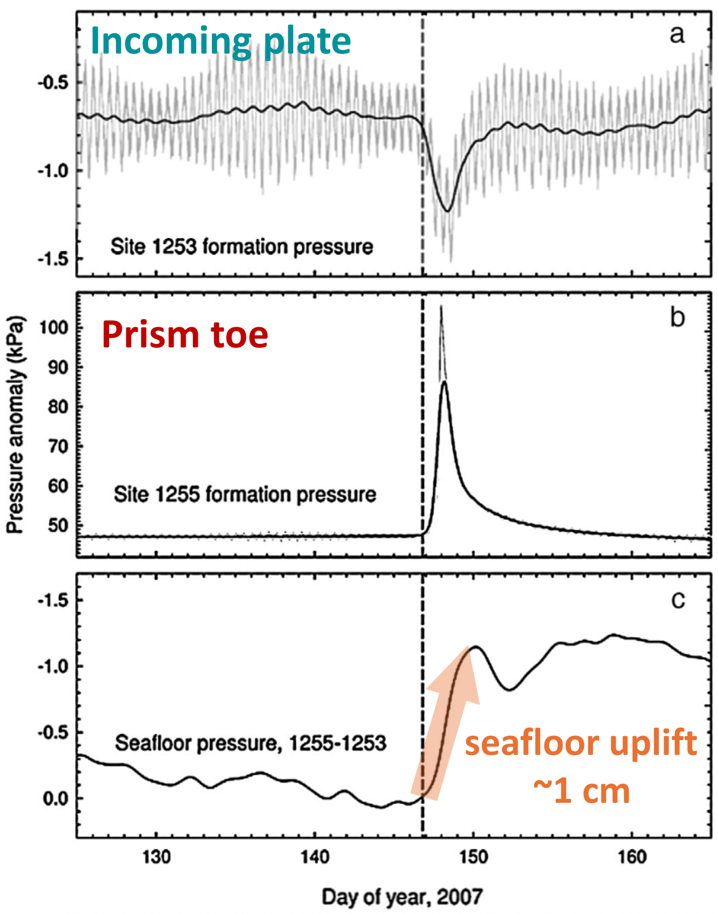


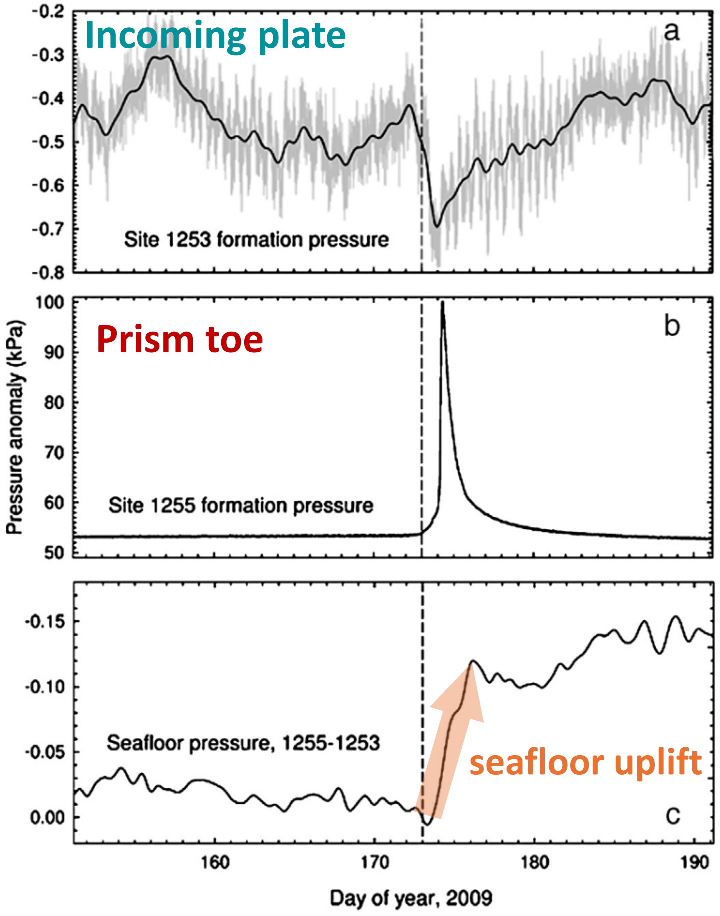
Dilatation
>> Pf decrease

Costa Rica: recurring SSEs **before** the 2012 Mw 7.6 Nicoya earthquake recorded by deep-sea CORKs



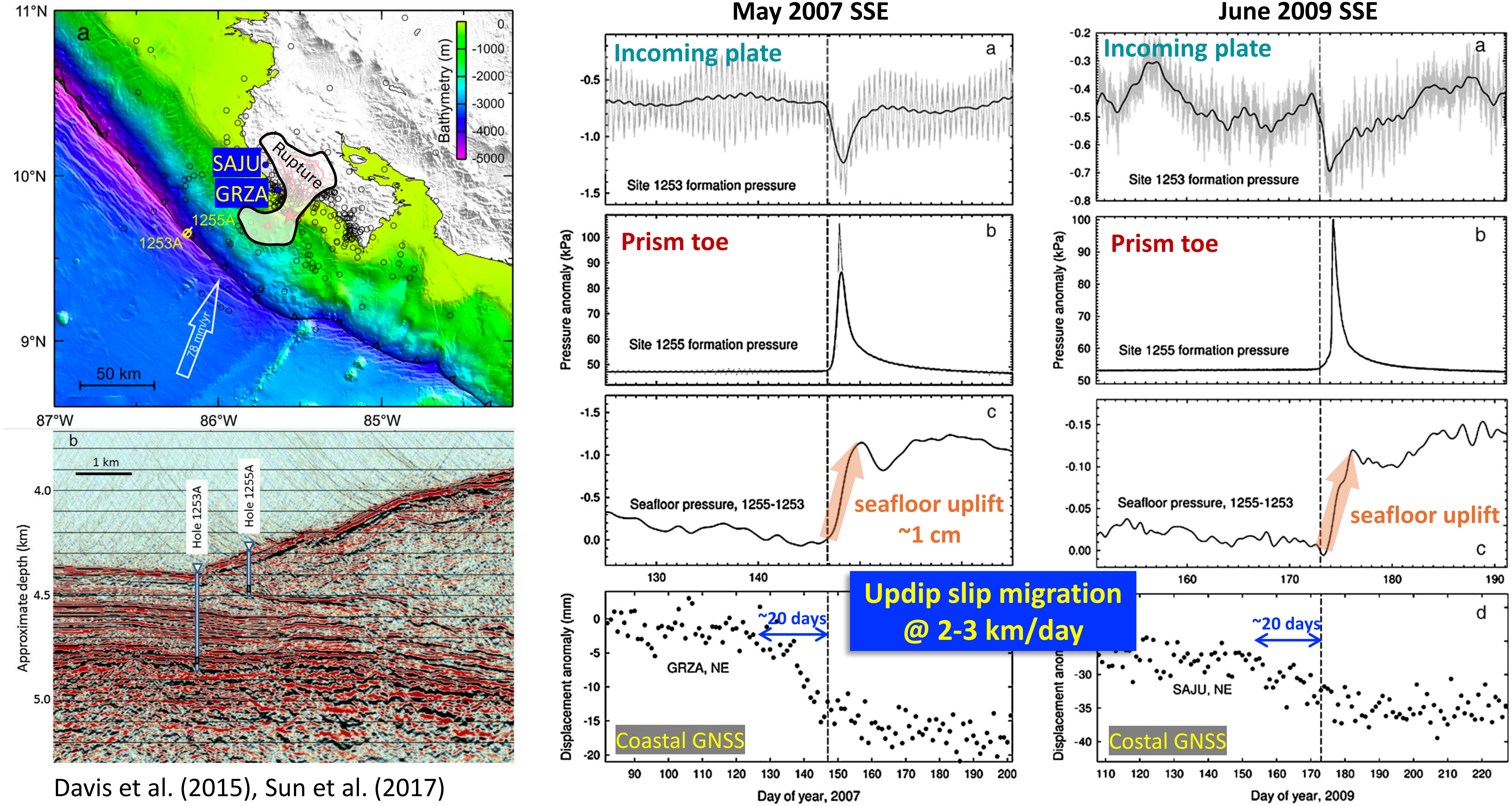






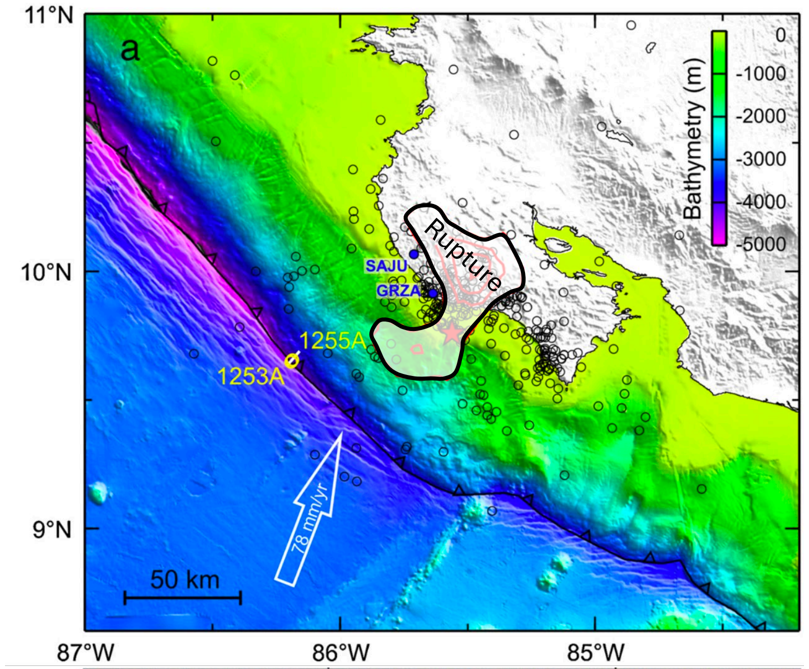
Davis et al. (2015), Sun et al. (2017)

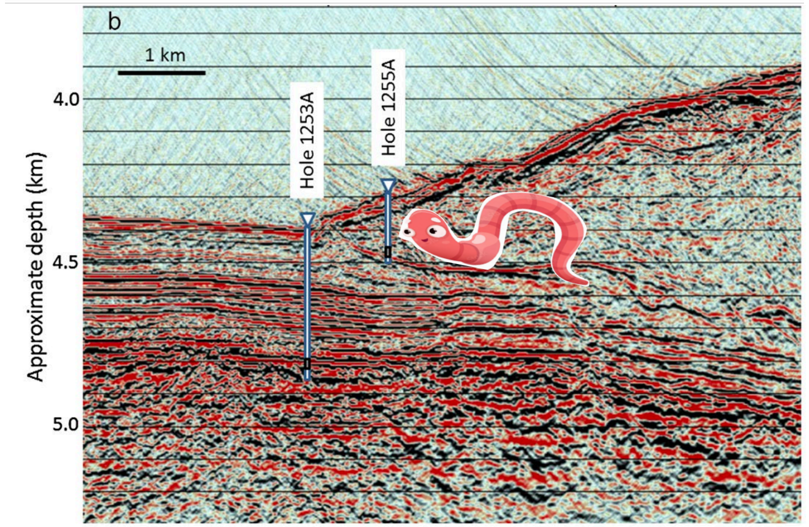
Costa Rica: recurring SSEs before the 2012 Mw 7.6 Nicoya earthquake recorded by deep-sea CORKs



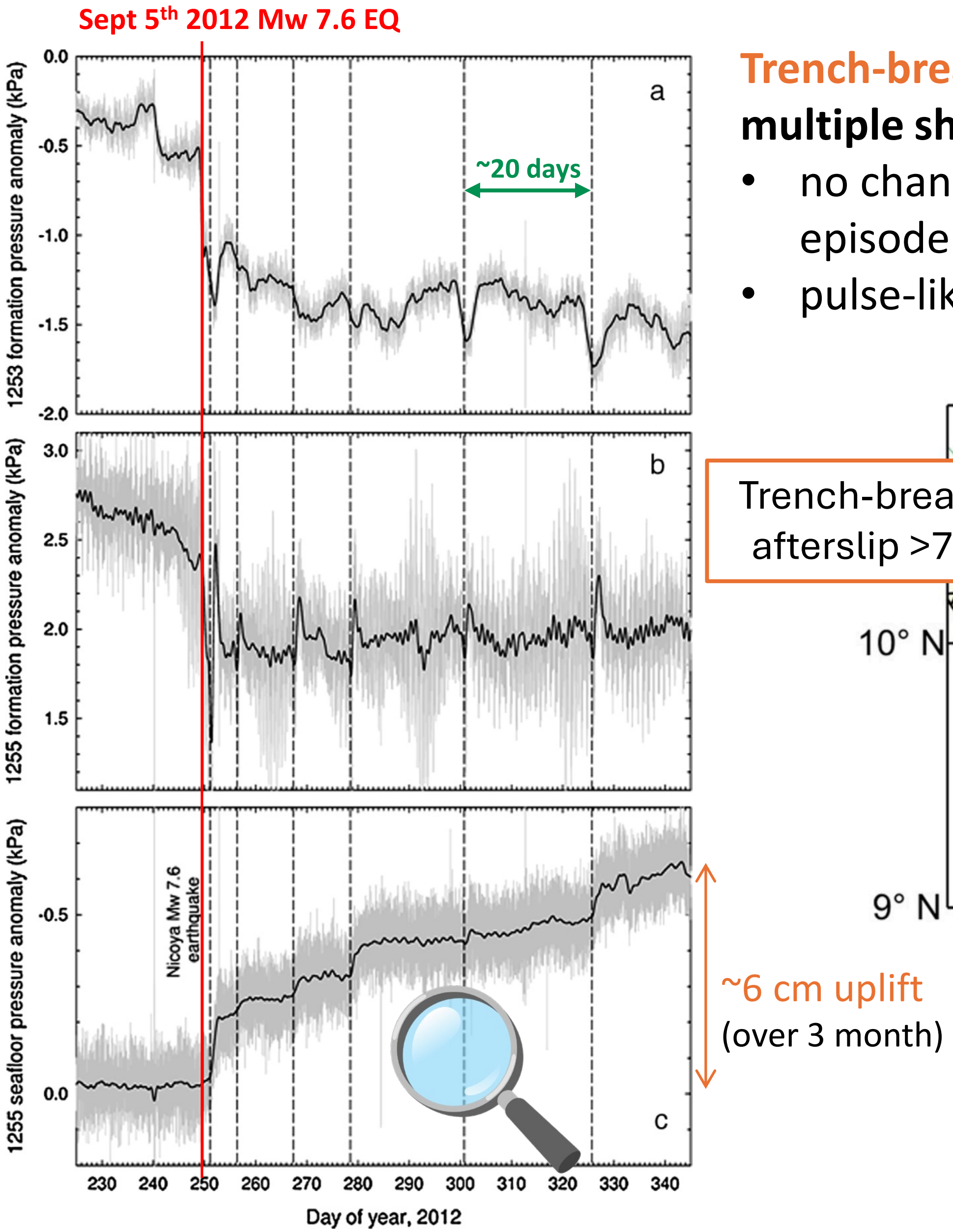
Davis et al. (2015), Sun et al. (2017)

Costa Rica: pulse-like shallow afterslip after the 2012 Mw 7.6 Nicoya earthquake



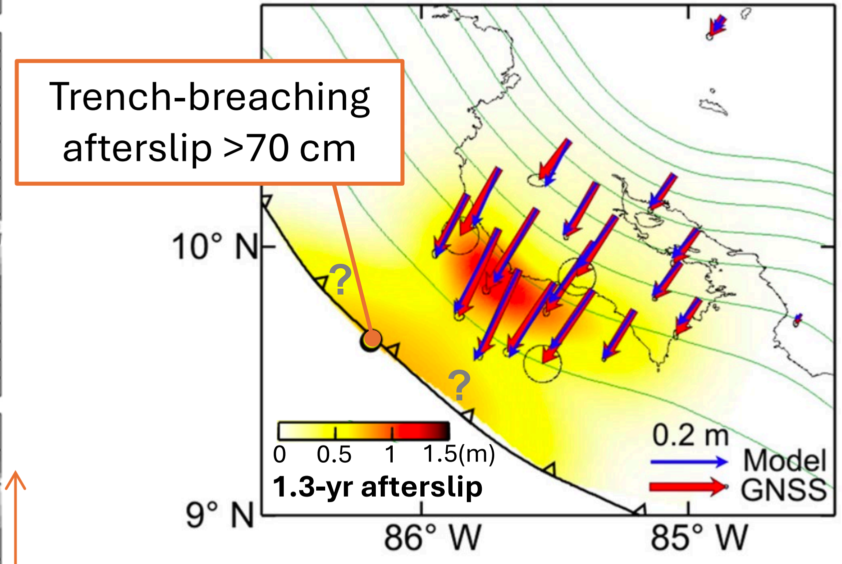


Davis et al. (2015), Sun et al. (2017)

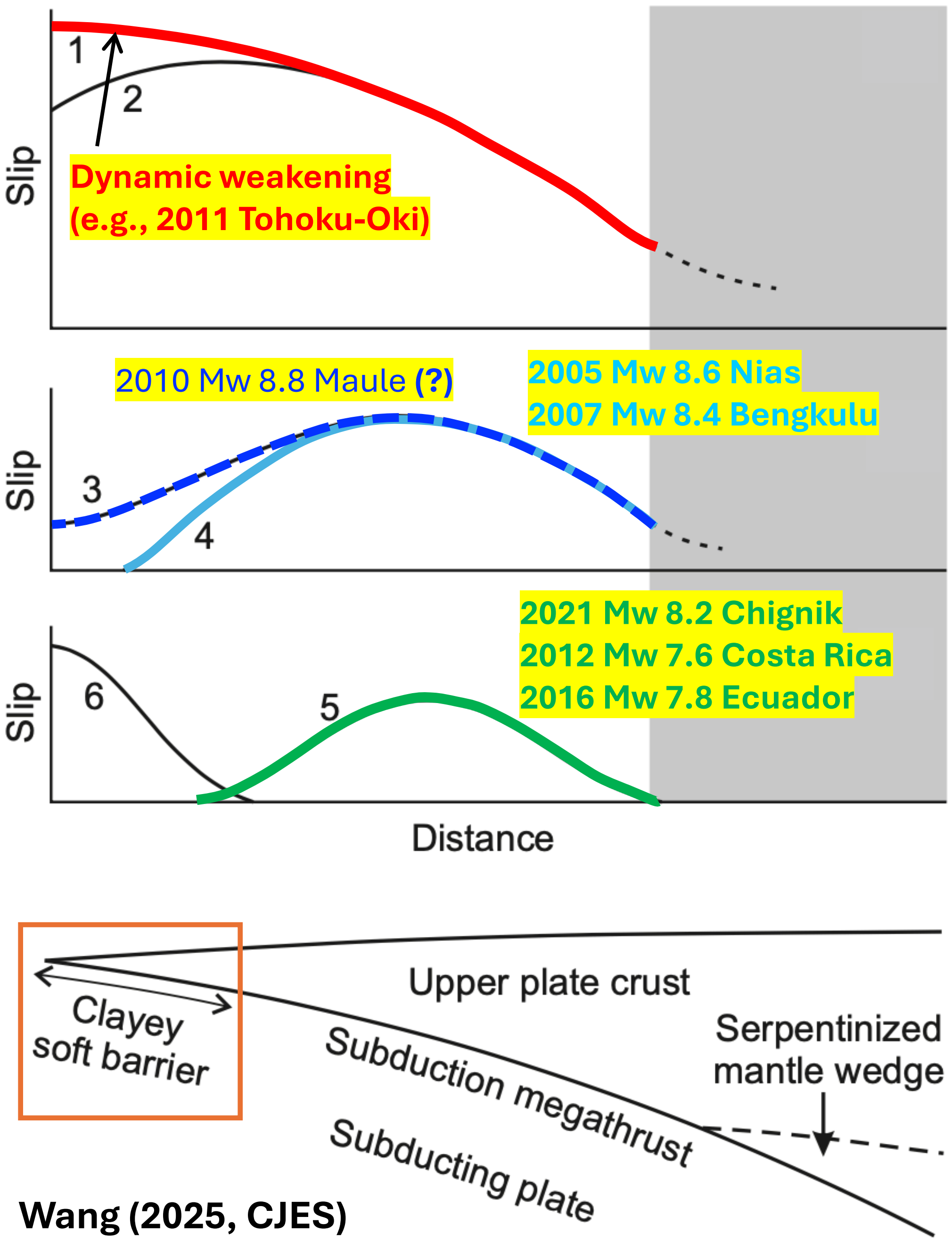


Trench-breaching afterslip in the form of multiple short-interval SSE episodes:

- no change in duration for individual episode
- pulse-like deformation and seafloor uplift



Evidence for **"jerky", pulse-like** shallow afterslip, driven by coseismically increased fault stress



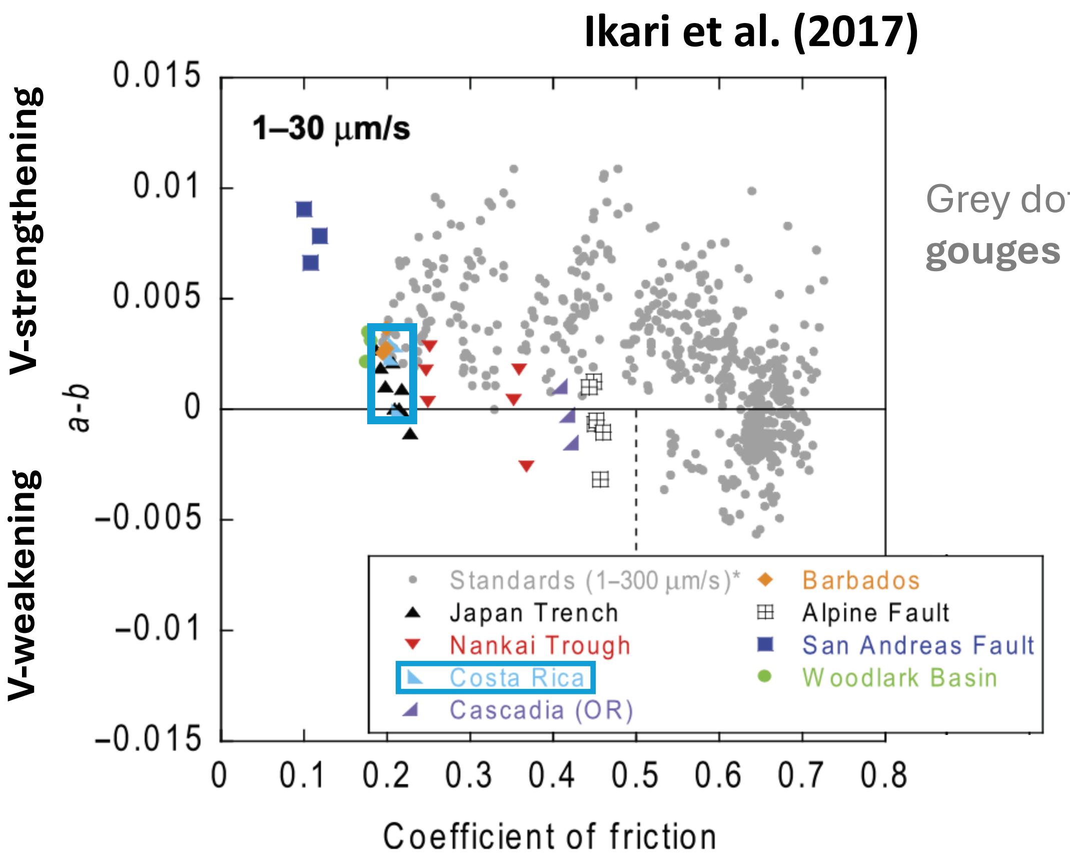
Wang (2025, CJES)

<u>The Emerging Picture:</u>

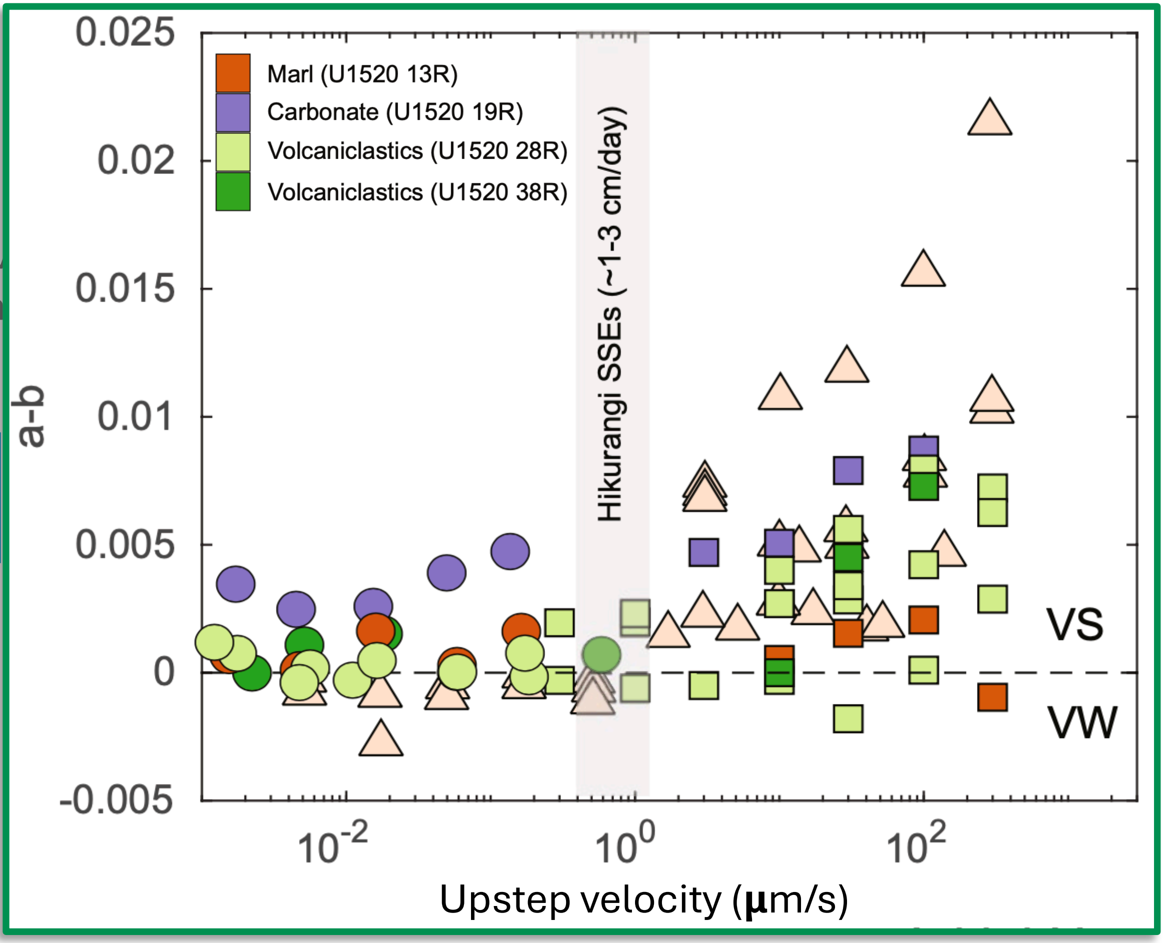
The shallow megathrust tends to host relatively "aseismic" slip, acting as a "soft barrier" to large trench-breaching ruptures.

- V-strengthening/V-neutral frictional properties
- Fault zone roughness and heterogeneities
- Wall-rock properties (consolidation state): a less competent frontal upper plate is less capable of storing elastic strain energy (e.g., Han et al., 2017)
- Fluid-related processes, e.g., dilatancy strengthening, high pore fluid pressure (e.g., Saffer and Wallace, 2015)
- Other mechanisms, e.g., ultra-slow fault healing (e.g., Shreedharan et al., 2023)

V-strengthening/V-neutral frictional properties

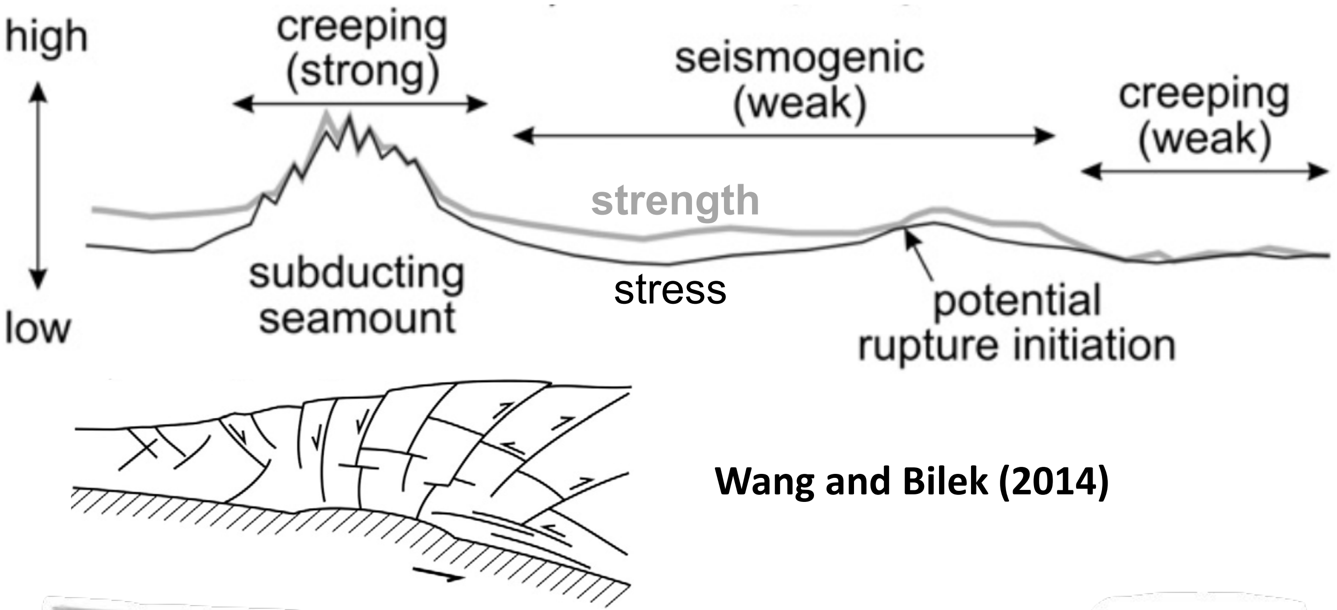


Grey dots: v
gouges (Ika

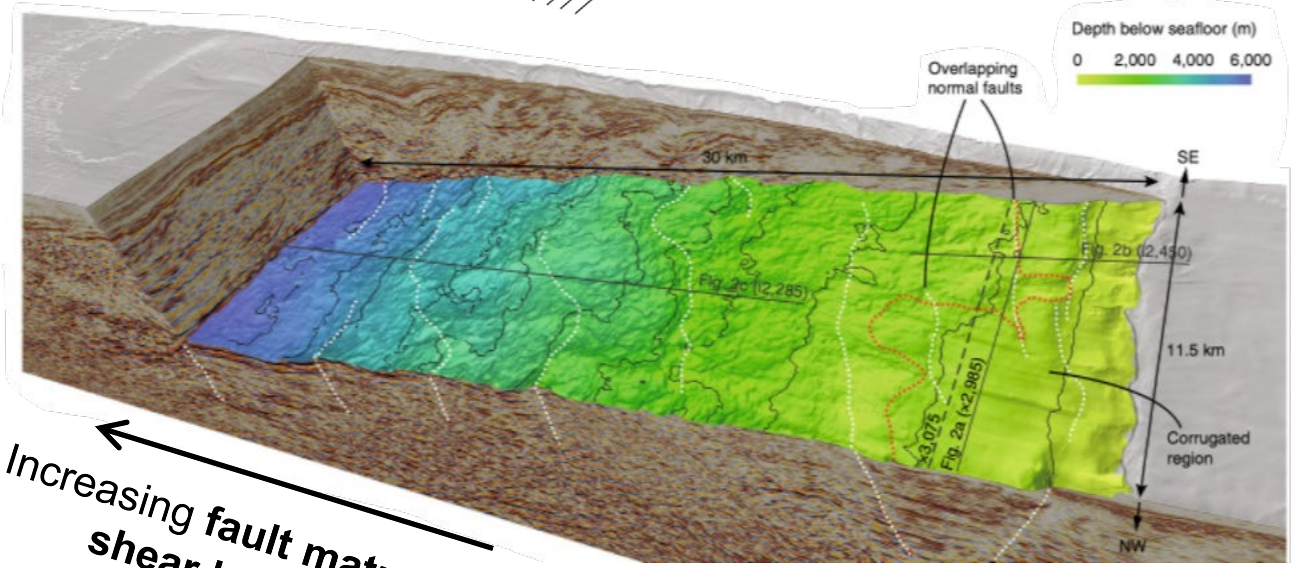


- Natural shallow fault zone samples (rich in weak, phyllosilicate minerals) tend to slide stably to resist seismic sip.
- Within a range of slow rates (near plate rate), mild instability may allow slow slip events.
- Similar observations in more recent studies, e.g., using samples from Northern Hikurangi (Rabinowitz et al., 2018; Shreedharan et al., 2022).

Fault zone roughness and heterogeneities



Wang and Bilek (2014)

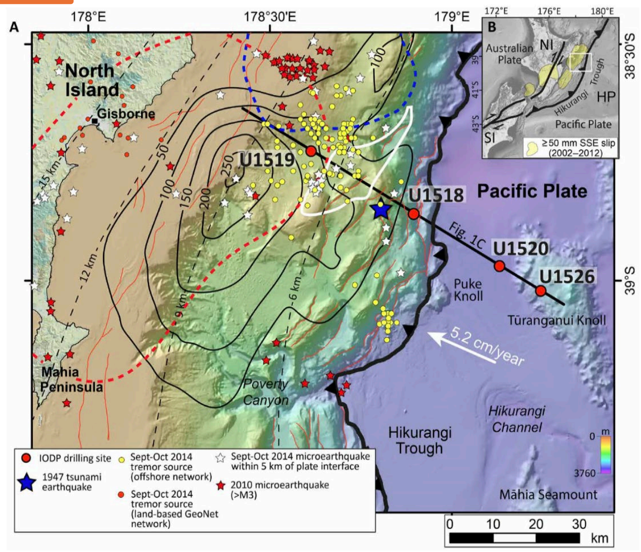


Increasing **fault maturity** and **shear localization**

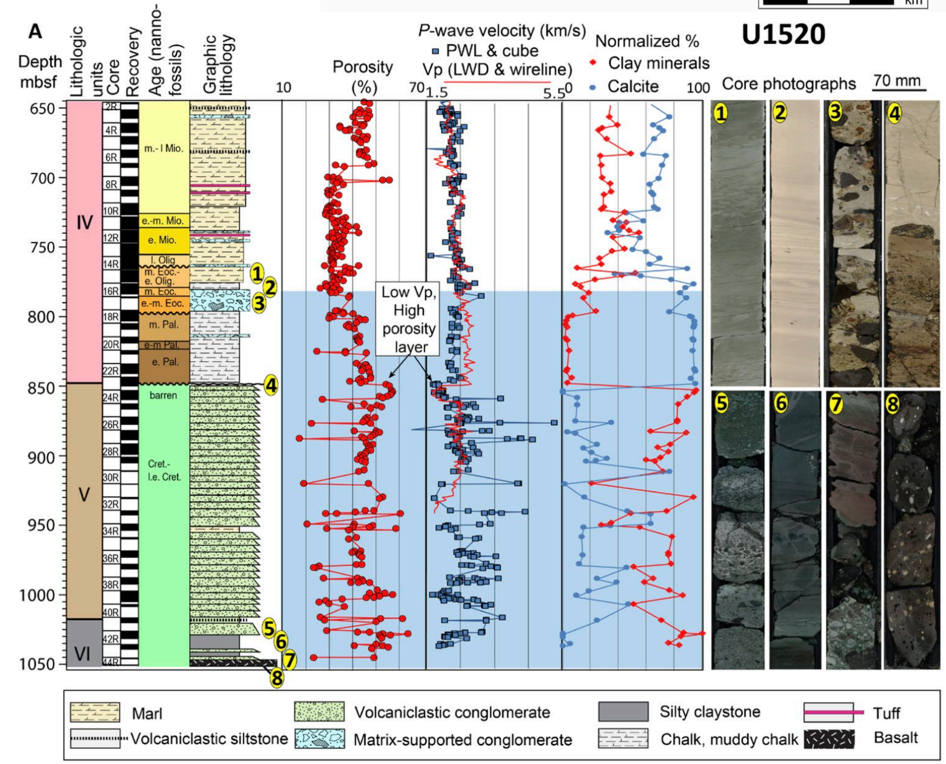
Kirkpatrick et al. (2020)

Lithological heterogeneity

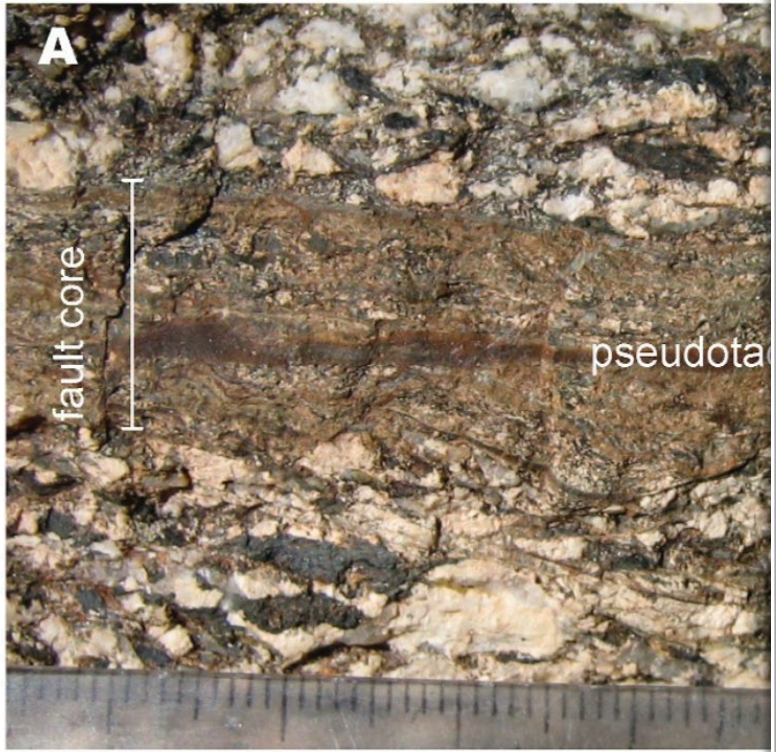
Northern Hikurangi



Barnes et al. (2020)

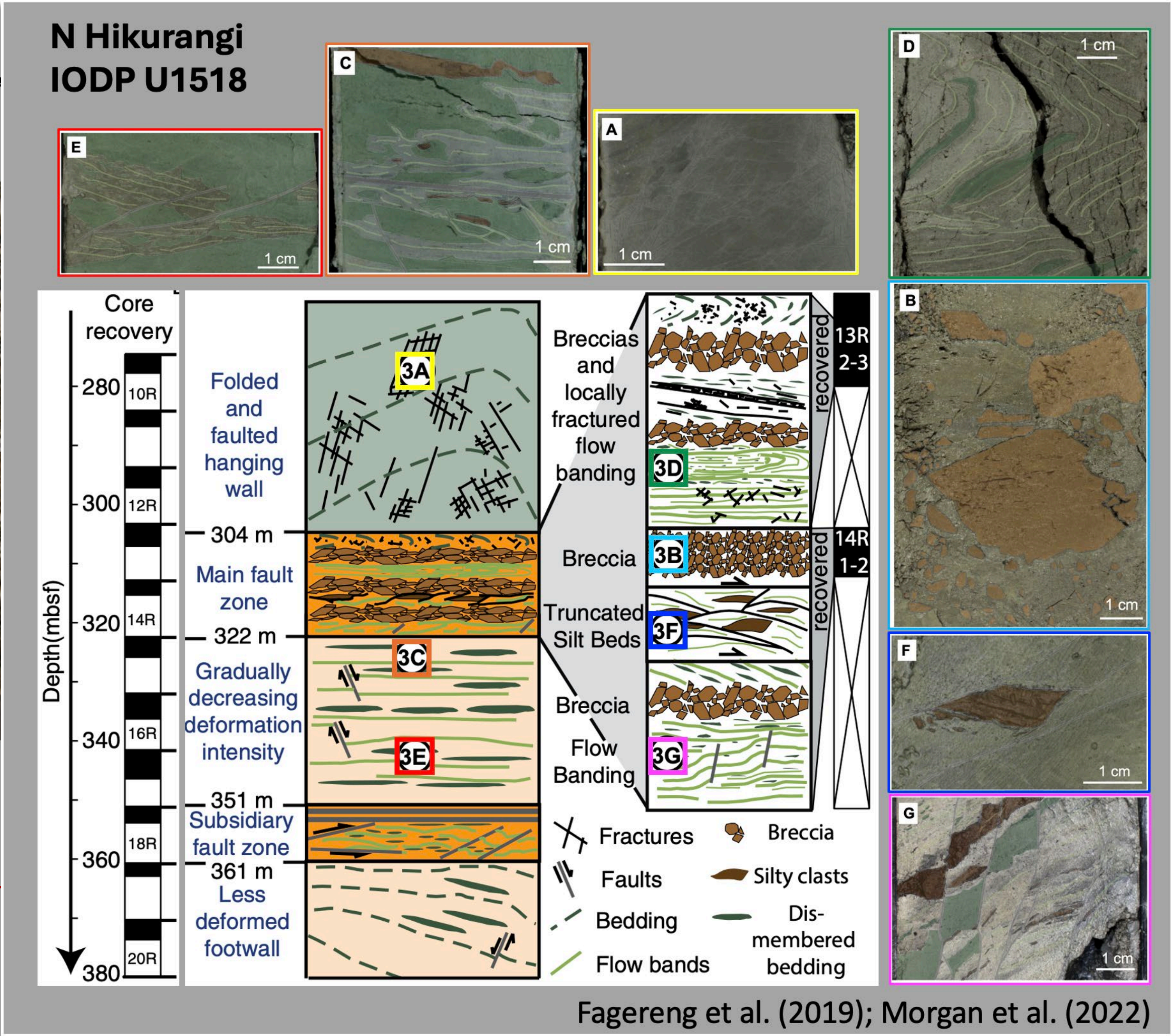


Fault zone heterogeneities cau



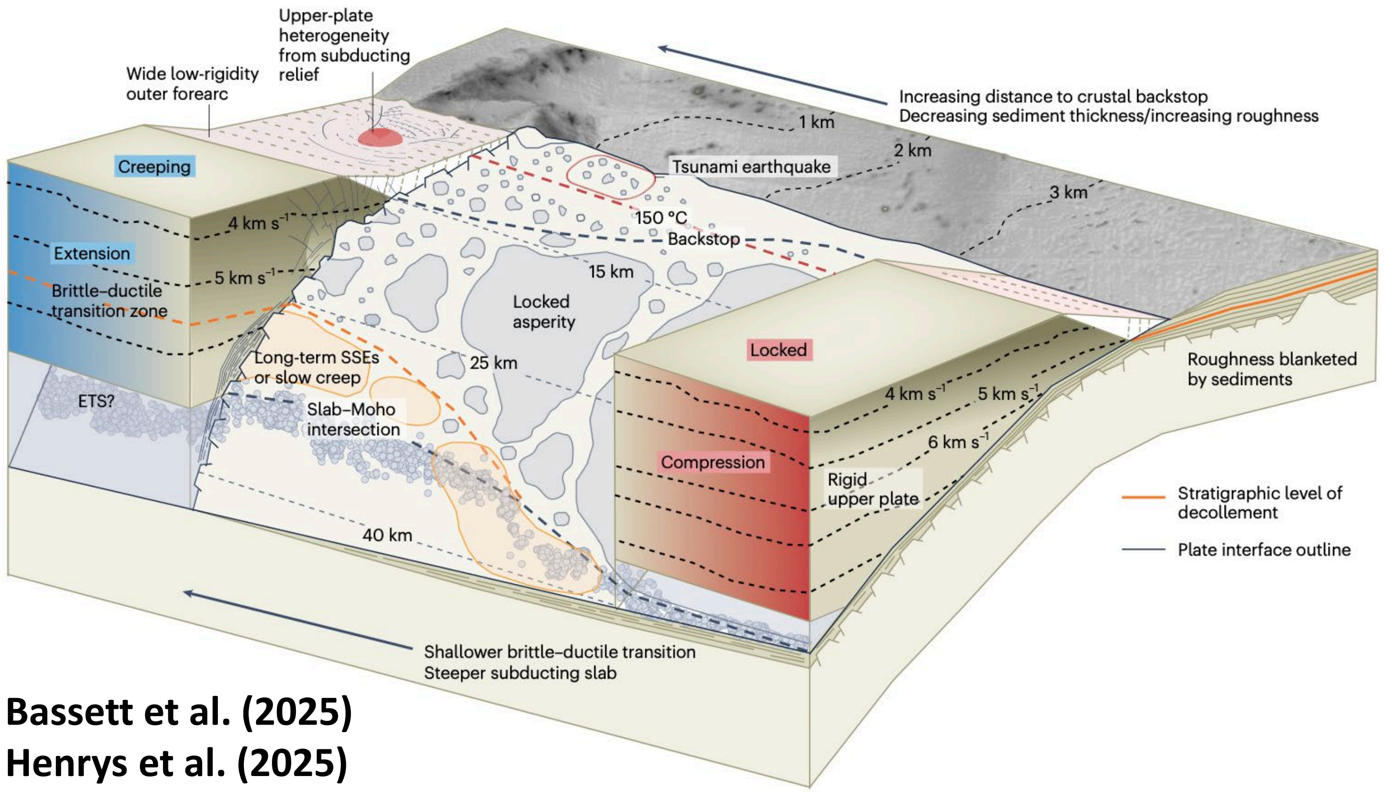
Savage and Rowe (2024)

- Seismic slip layers are typically ~1 m

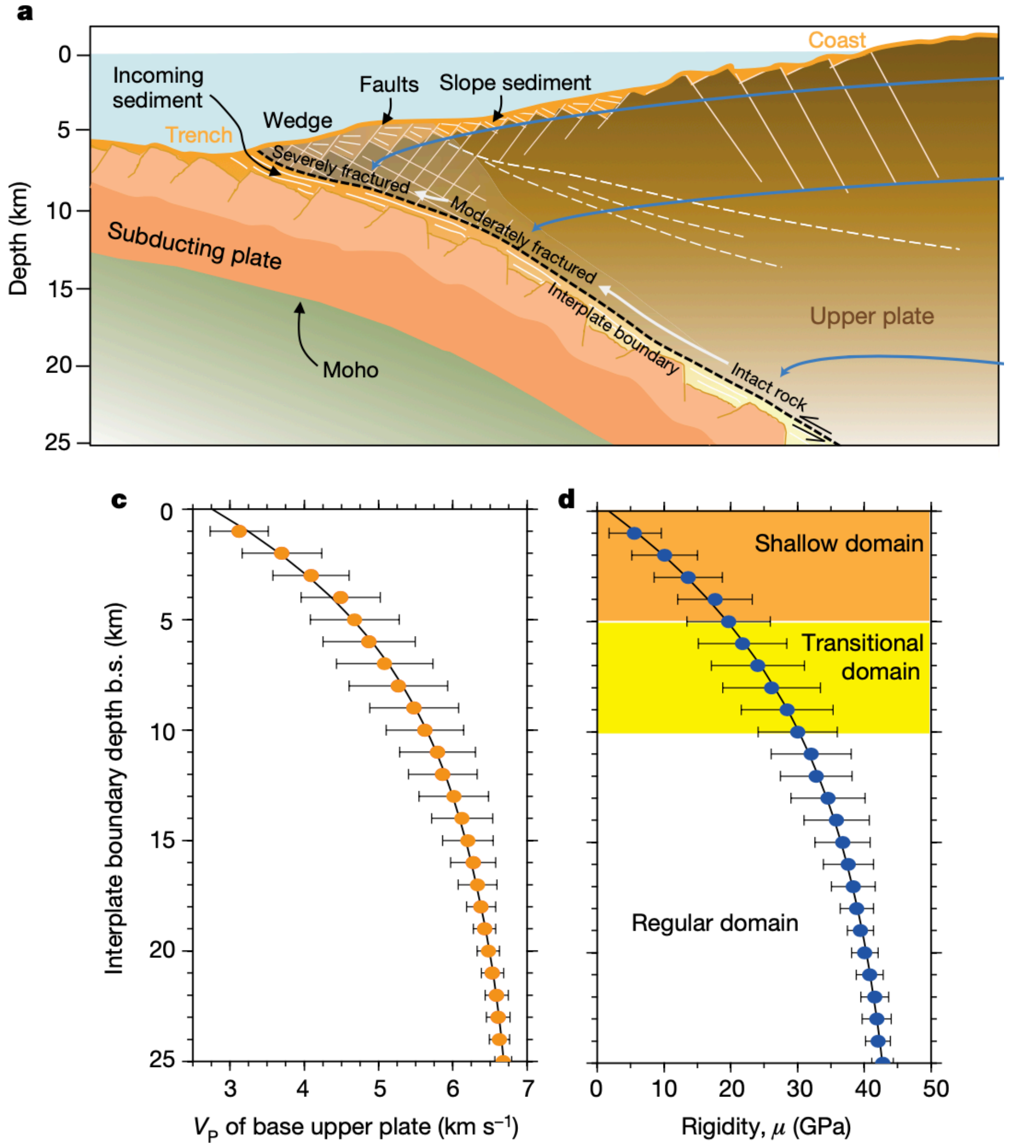


Fagereng et al. (2019); Morgan et al. (2022)

Wall-rock properties (e.g., consolidation state)



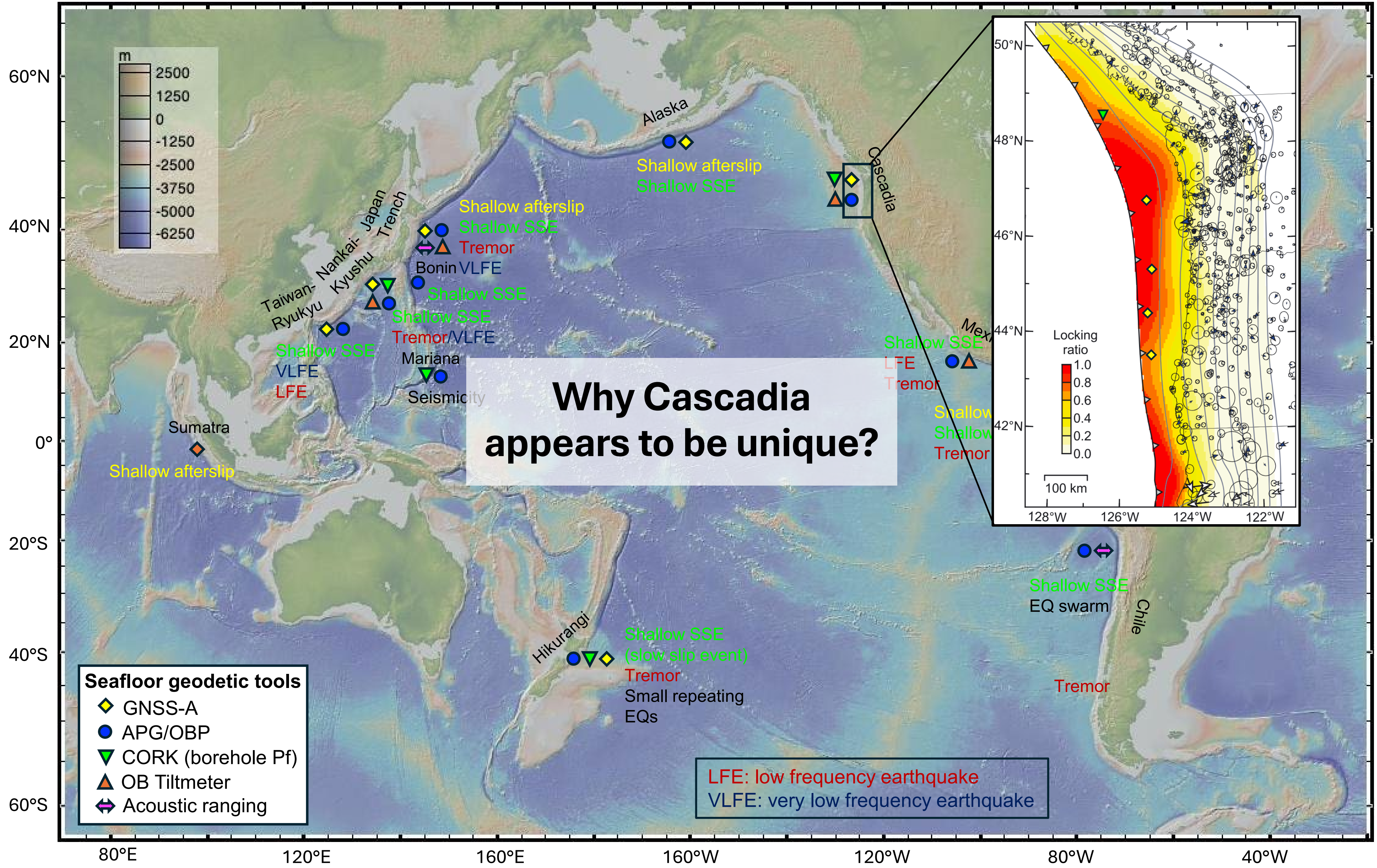
Bassett et al. (2025)
Henrys et al. (2025)



Sallarès and Ranero (2019)

At multiple margins, *e.g.*, ***Hikurangi***, ***Alaska***, and ***Nankai-Kyushu***, mutually related **along-strike variations** in:

- distribution of rigid crustal rocks in the forearc
- roughness of the subducting slab
- upper-plate stress and Pf state
- megathrust locking vs. creeping behaviour


Why Cascadia
appears to be unique?
m
2500
1250
0
-1250
-2500
-3750
-5000
-6250
60°N
40°N
20°N
0°
20°S
40°S
60°S
80°E
120°E
160°E
160°W
120°W
80°W
40°W
Alaska
Shallow afterslip
Shallow SSE
Cascadia
Japan
Trench
Nankai-
Kyushu
Taiwan-
Ryukyu
Shallow afterslip
Shallow SSE
Tremor
Bonin
VLFE
Shallow SSE
Shallow SSE
Tremor/VLFE
Shallow SSE
VLFE
LFE
Mariana
Seismicity
Sumatra
Shallow afterslip
Shallow SSE
LFE
Tremor
Shallow
Shallow
Tremor
Shallow SSE
EQ swarm
Chile
Tremor
Hikurangi
Shallow SSE
(slow slip event)
Tremor
Small repeating
EQs
50°N
48°N
46°N
44°N
42°N
Locking
ratio
1.0
0.8
0.6
0.4
0.2
0.0
100 km
128°W
126°W
124°W
122°W
Seafloor geodetic tools
GNSS-A
APG/OBP
CORK (borehole Pf)
OB Tiltmeter
Acoustic ranging
LFE: low frequency earthquake
VLFE: very low frequency earthquake

Is Cascadia really unique?

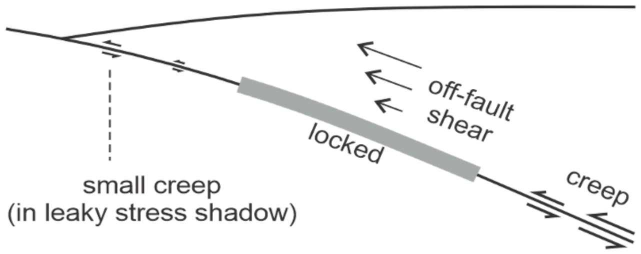
- **The key** is to understand how the shallow slip is moderated by megathrust earthquake cycles

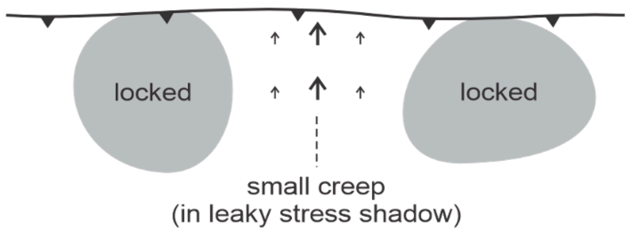
~~Why Cascadia is unique?~~

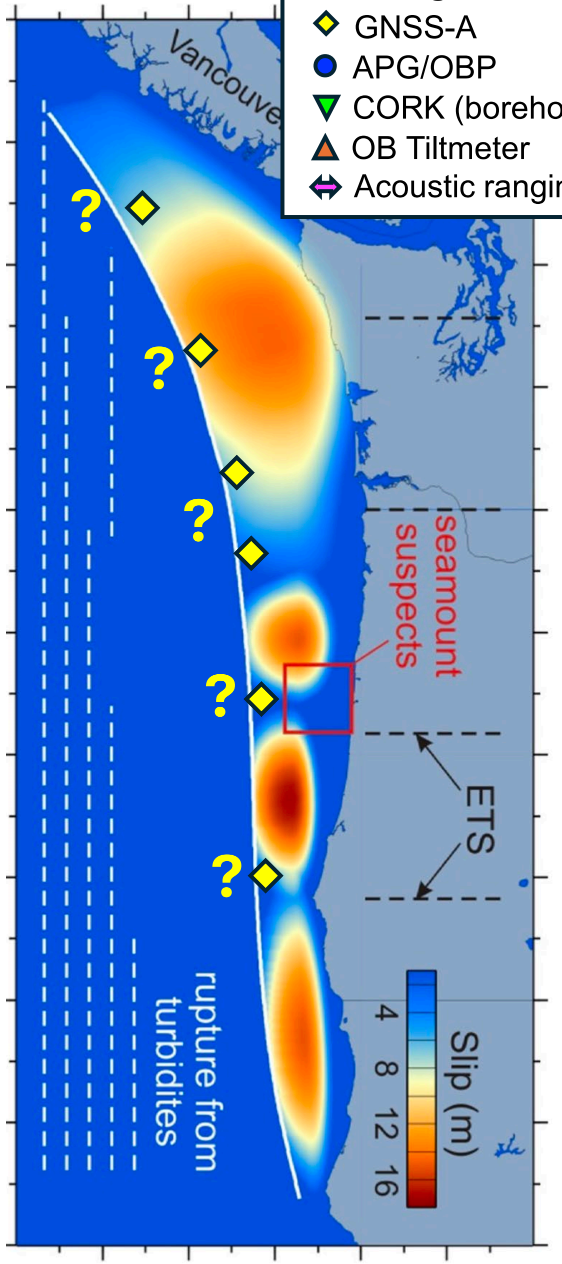
Better questions to ask:

- How the shallow fault creep evolves through the earthquake cycle?
- What condition drives (or shutdowns) shallow creep in the updip stress shadow?

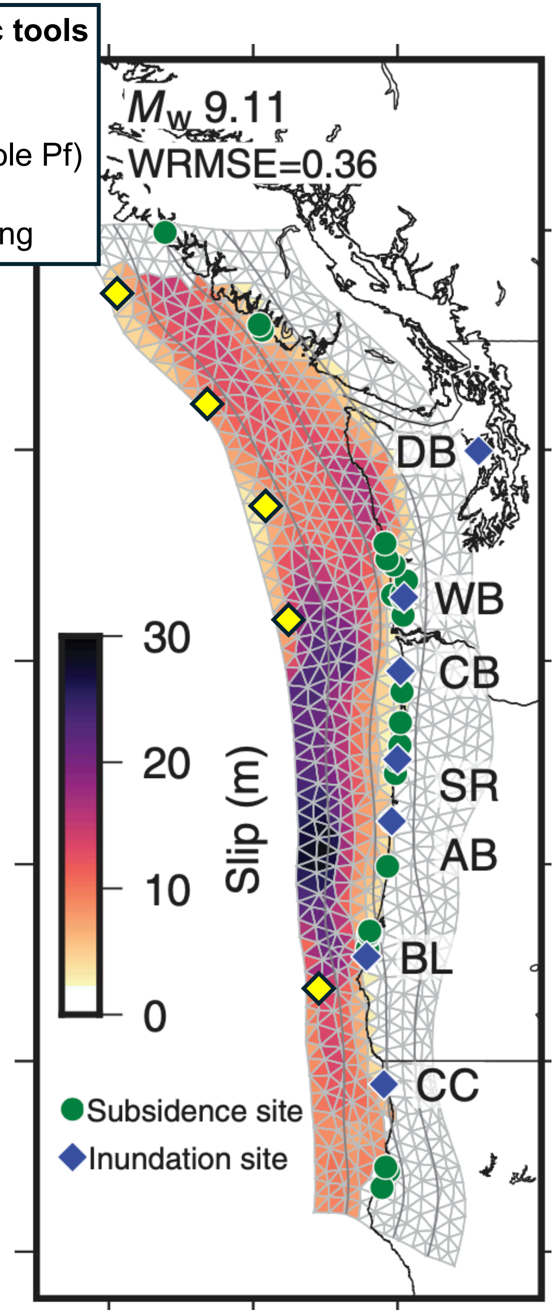
- Recall Kelin Wang's talk yesterday







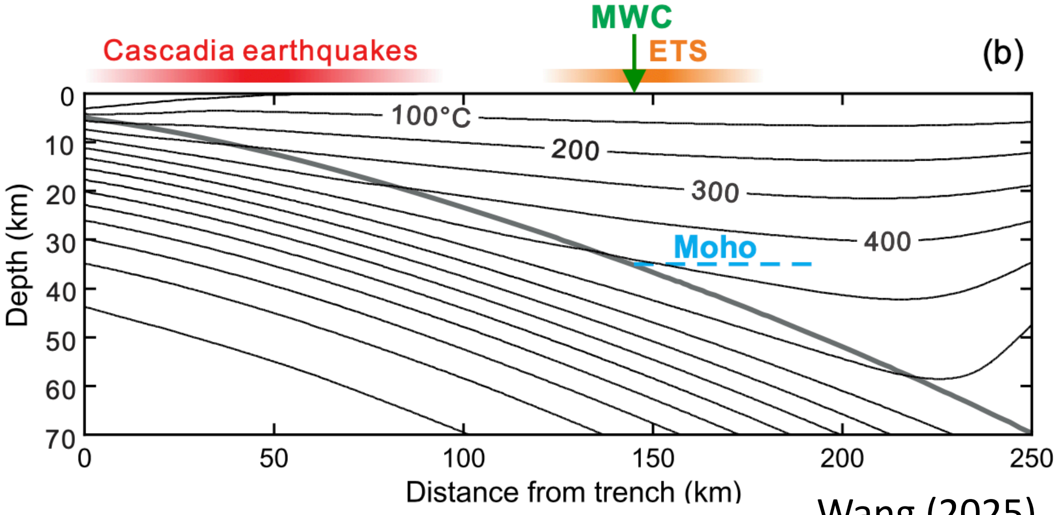
P.-L. Wang et al. (2013)



Small et al. (2025)

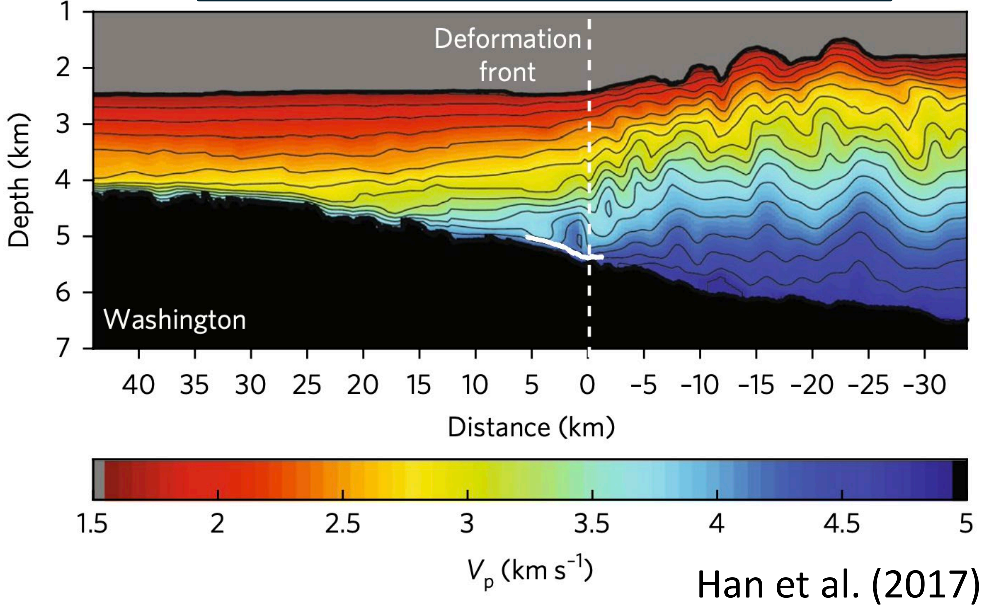
Cascadia is indeed special in many ways:

Warm megathrust even at shallow depths

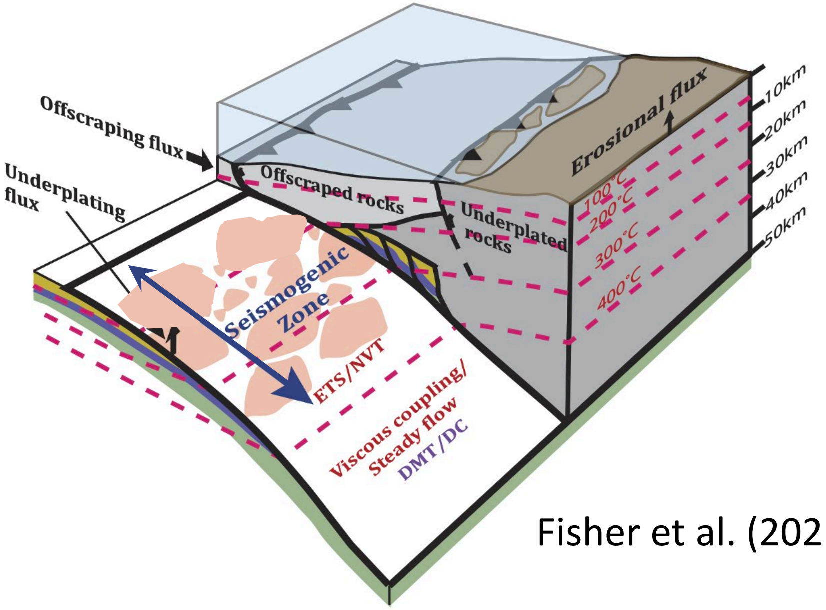


Wang (2025)

Over-consolidated outer wedge



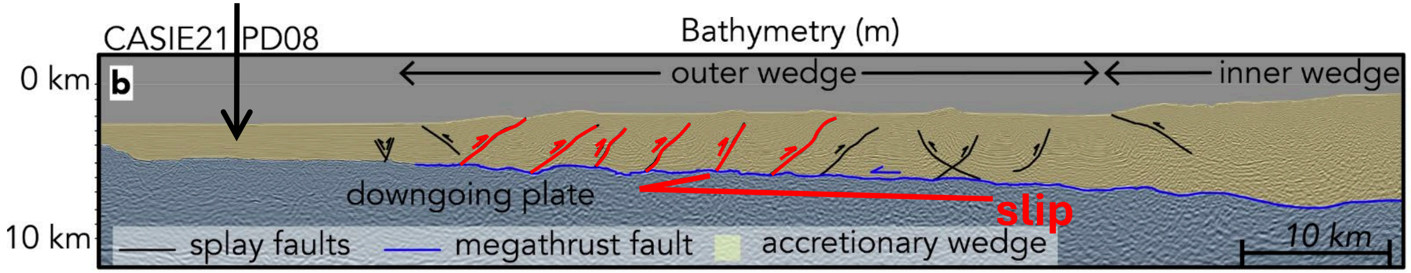
Han et al. (2017)



Fisher et al. (2021)

Extremely low frontal wedge taper

Thick coarse-grained sediments (from Nitinat/Astoria fans)



Coseismic activation of upper-plate thrust faults

Ledeczi et al. (2024)

Summary

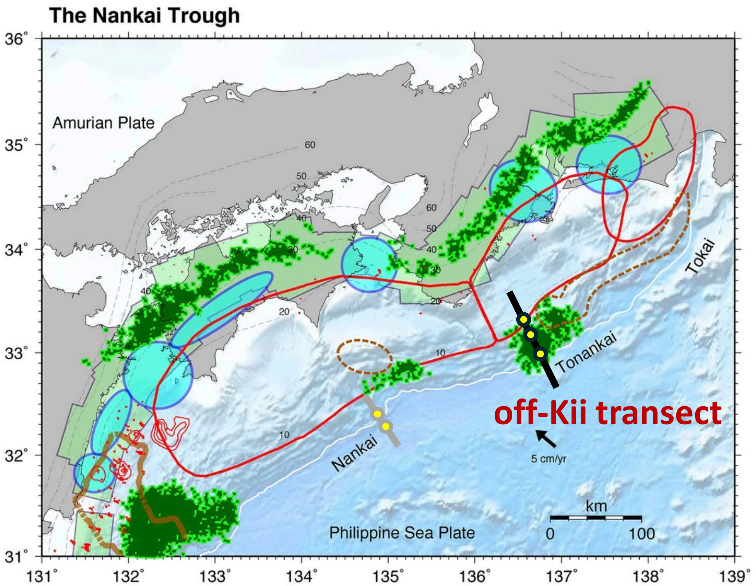
- Worldwide, seafloor geodesy commonly documents shallow “aseismic” slip.
- Shallow megathrust acts as a “soft barrier” to earthquake ruptures, but large trench-breaching rupture can still (occasionally) happen.
- Deep-sea CORK Pf observations reveal jerky, pulse-like shallow creep (afterslip) following the 2012 Costa Rica earthquake. *(My favorite example of shallow SSEs)*
- Fault zone frictional properties and heterogeneities, wall-rock properties and various other factors contribute to the dominance of shallow creep (aseismic slip).
- Cascadia is special but may not be unique; its shallow slip/locking need to be studied in the context of thermo-petrology and megathrust earthquake cycles.
- More seafloor geodetic observations are needed to study the “variability” or “commonality” of shallow megathrust slip.

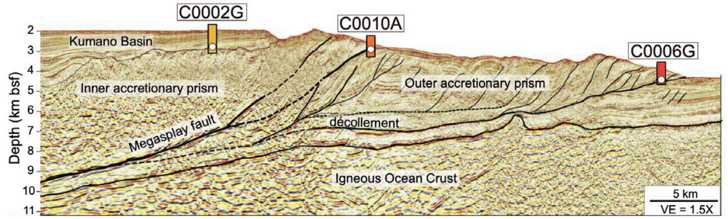
References of shallow slow earthquakes shown in the global map:

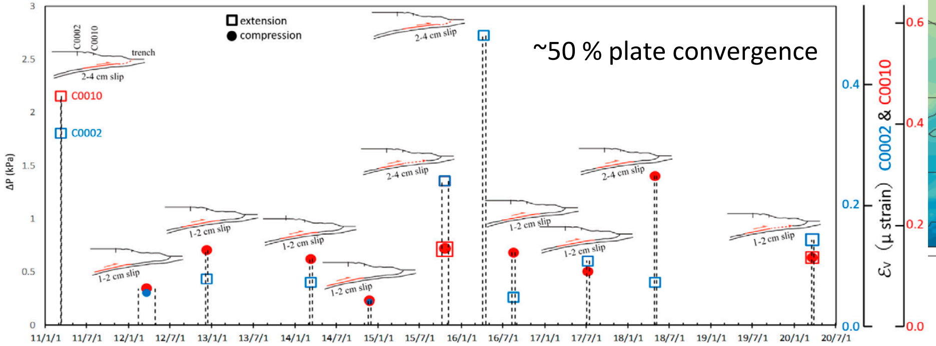
- **Taiwan-Ryukyu**: Chen et al. (2022), Tsang et al. (2025), Nakamura & Kakazu (2017), Ando et al. (2012)
- **Nankai-Kyushu**: Takemura et al. (2023), Yamashita et al. (2015), Araki et al. (2017), Davis et al. (2013), Edgington et al. (2025), Yokota et al. (2020), Ariyoshi et al. (2021)
- **Japan Trench**: Nishikawa et al. (2023), Ito et al. (2013), Sun and Wang (2015)
- **Bonin**: Fukao et al. (2021)
- **Alaska**: Brooks et al. (2023), He et al. (2023)
- **Cascadia**: Krauss et al. (2025), Chaudhuri & Ghosh (2022)
- **Mexico**: Cruz-Atienza et al. (2018, 2025), Chen et al. (2025)
- **Costa Rica**: Dixon et al. (2015), Davis et al. (2015), Sun et al. (2017), Li et al. (2025), Walter et al. (2011)
- **Ecuador**: Rolandone et al. (2018), Collot et al. (2017)
- **Chile**: Azúa et al. (2025), Münchmeyer et al. (2025), Jegen et al. (2024), Soto et al. (2019)
- **Hikurangi**: Wallace et al. (2016), Wallace (2020), Todd et al. (2018), Shaddox et al. (2019), Yarce et al. (2019)
- **Mariana**: Eimer et al. (2020)
- **Sumatra**: Hsu et al. (2006), Tsang et al. (2016)

Backup slides

Transient signals associated with slow and fast earthquakes: The off-Kii transect

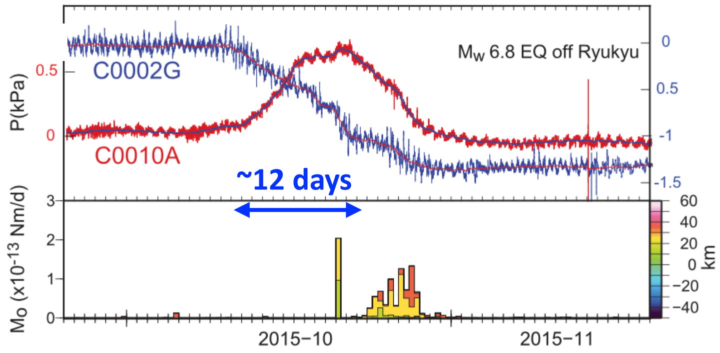


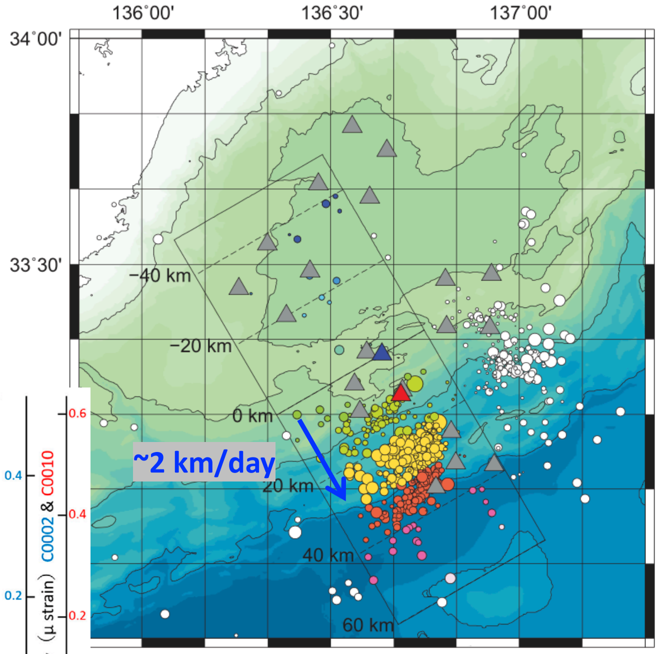




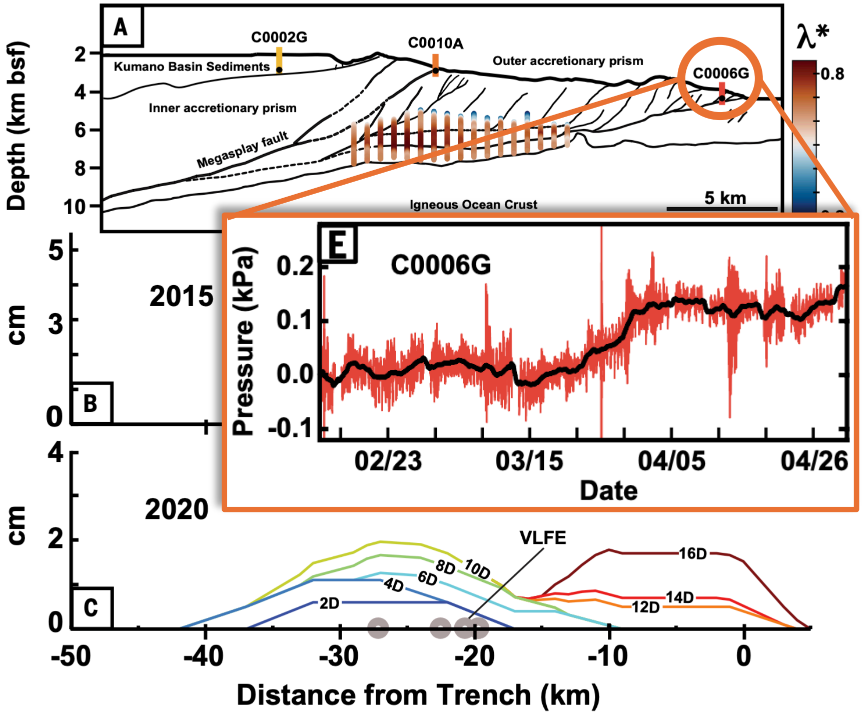
Araki et al. (2017), Ariyoshi et al. (2021)

October 2015 SSE





Araki et al. (2017)

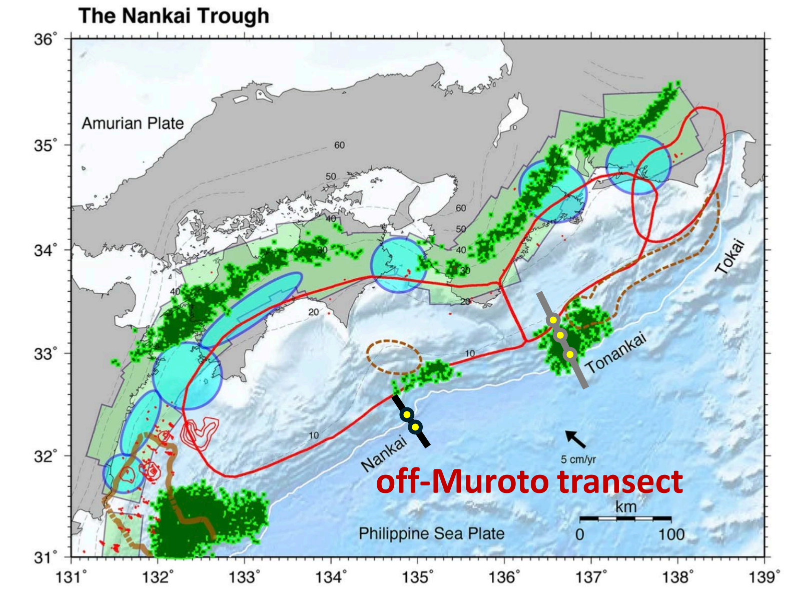


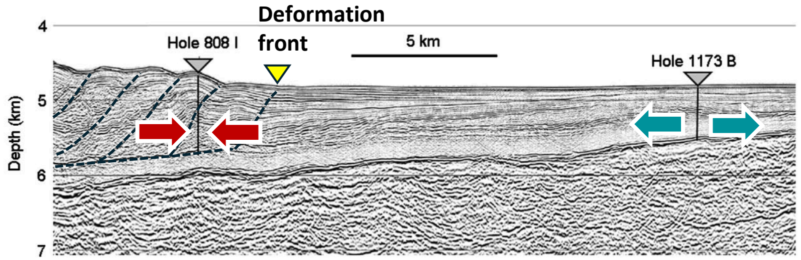
Edgington et al. (2025, Science)

- Updip slip migration over ~2-3 weeks
- Migration speed at 1-2 km/day
- Accompanied by tremors and/or VLFEs

- Slip **possibly** has reached the trench.

Transient signals associated with slow and fast earthquakes: The off-Muroto transect



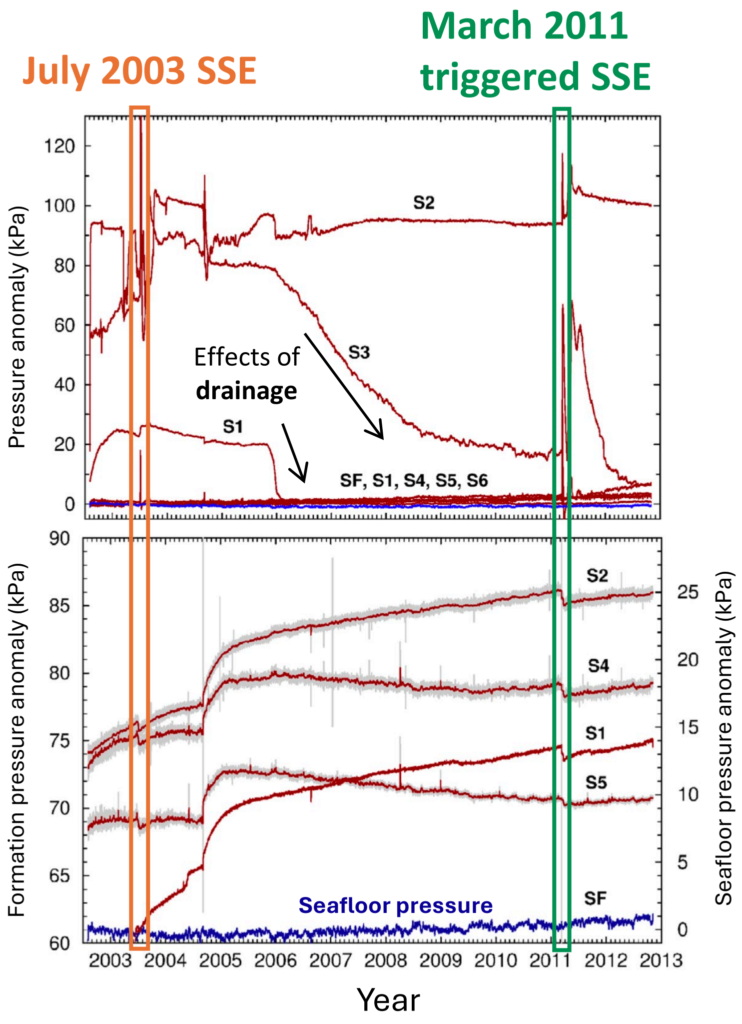


808I:

- Lower slope & trench **turbidites**
- Through the **frontal thrust**
- Reaching decollement

1173B:

- Reaching proto-decollement
- Pf monitoring in lower Shikoku Basin – **hemipelagic mud**



Davis et al. (2013, EPSL)