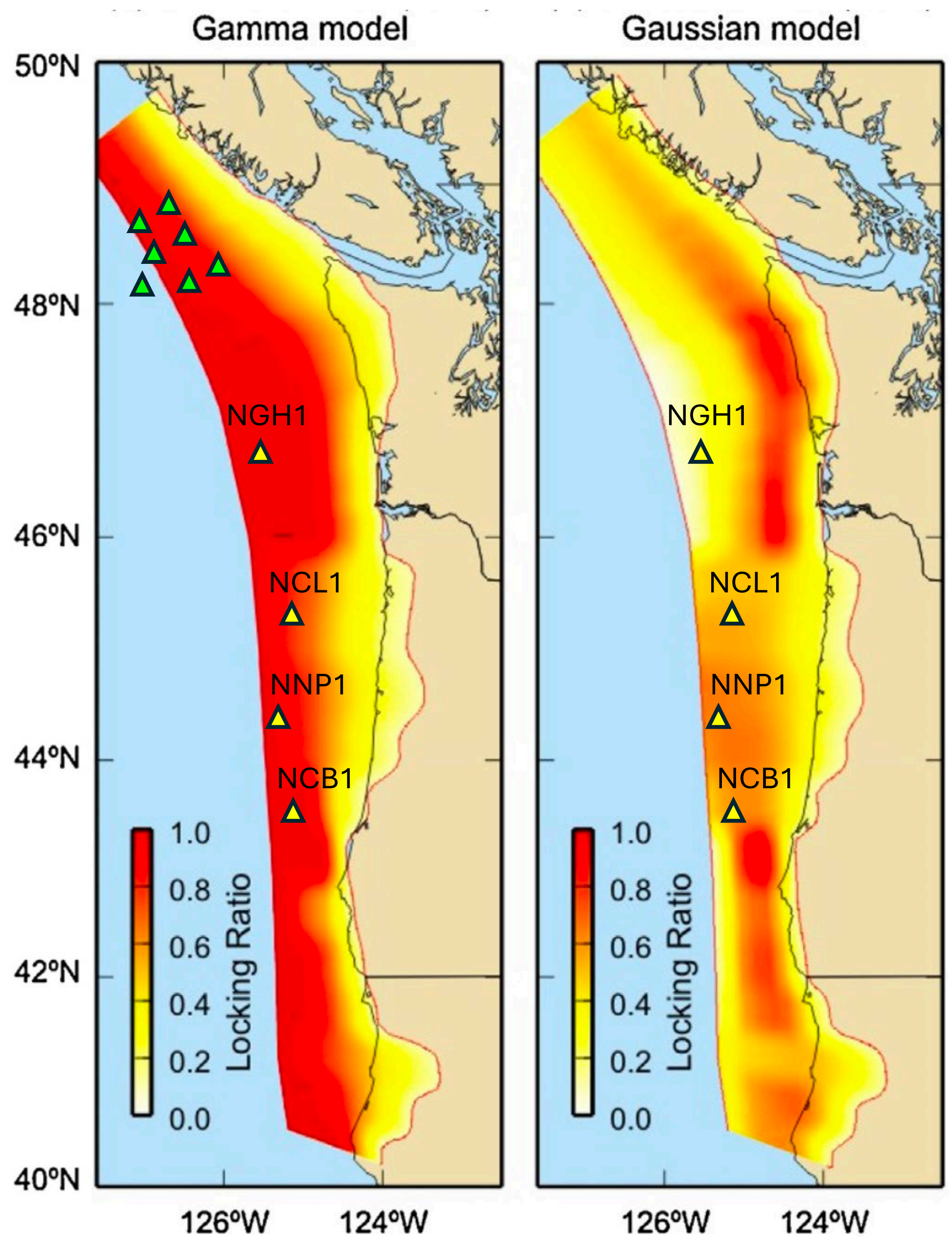
Deep-sea Borehole Observations Reveal Strain Accumulation due to Megathrust Locking: Cascadia and Beyond

Tianhaozhe Sun[1,2], Earl Davis[1]

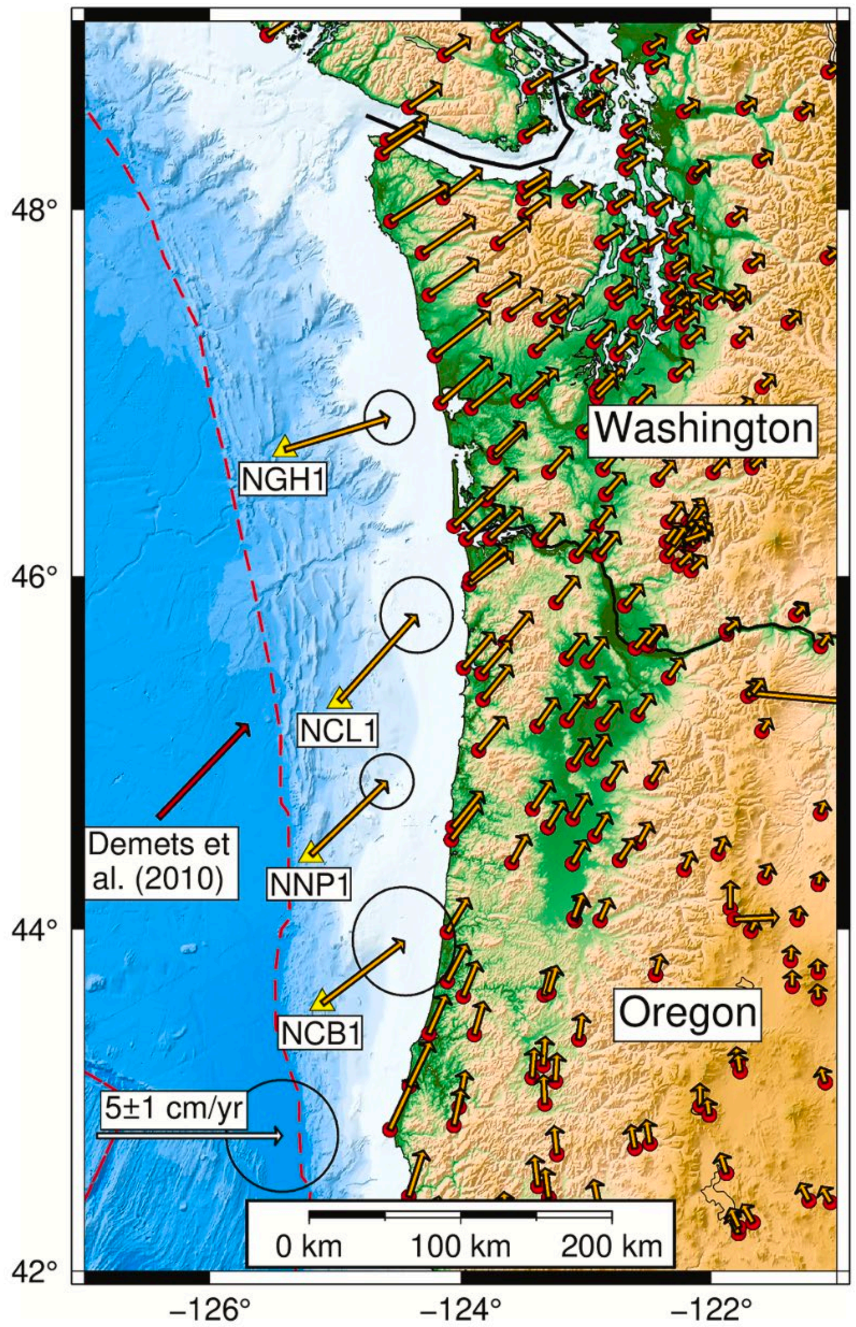
1. Pacific Geoscience Centre, Geological Survey of Canada
2. School of Earth and Ocean Sciences, University of Victoria

CRESCENT Topical Workshop: Offshore Observations, October 27, 2025, Seattle, WA

See Jesse Hutchinson's talk soon

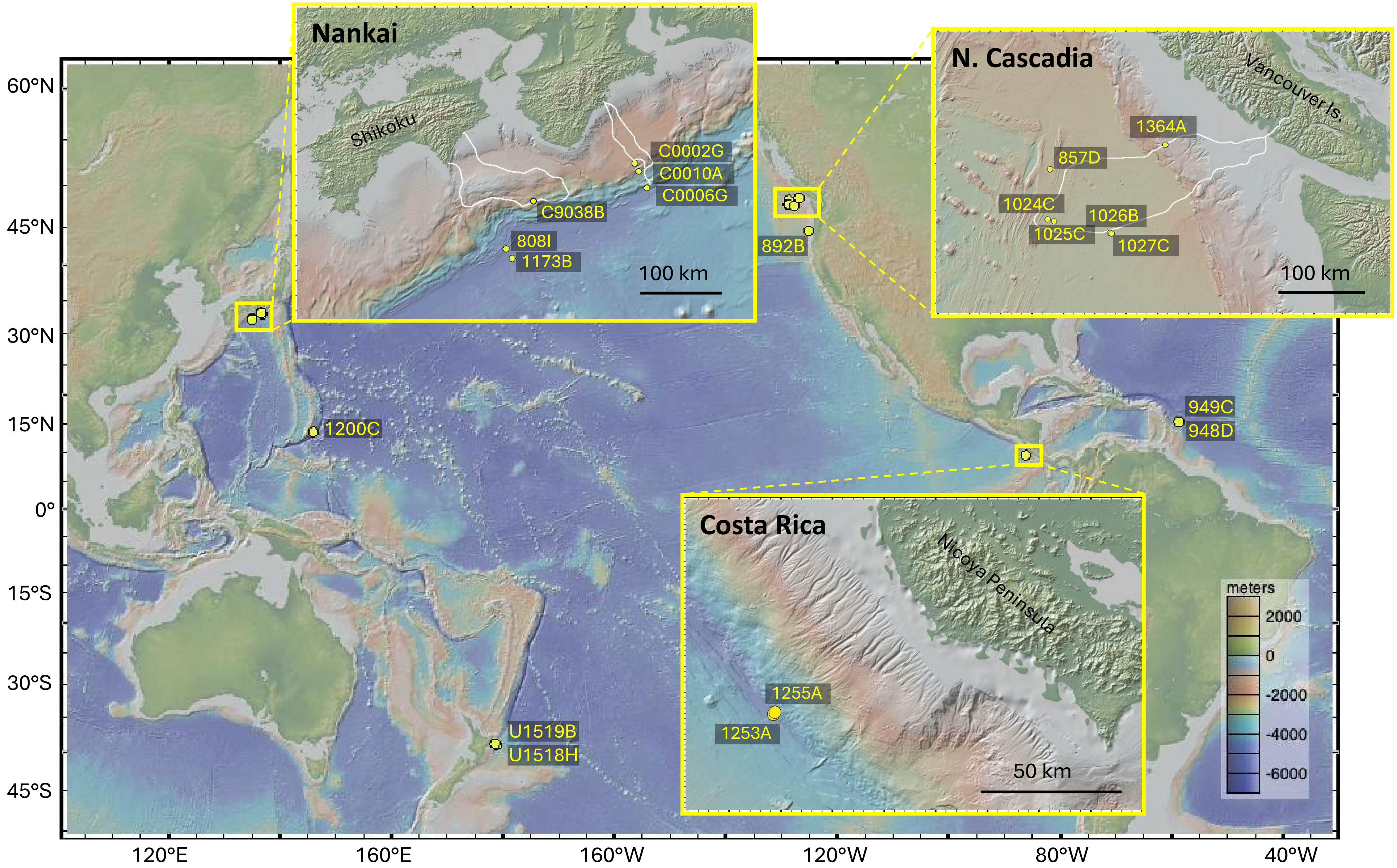


Schmalzle et al. (2014), Figure: Wang and Tréhu (2016)



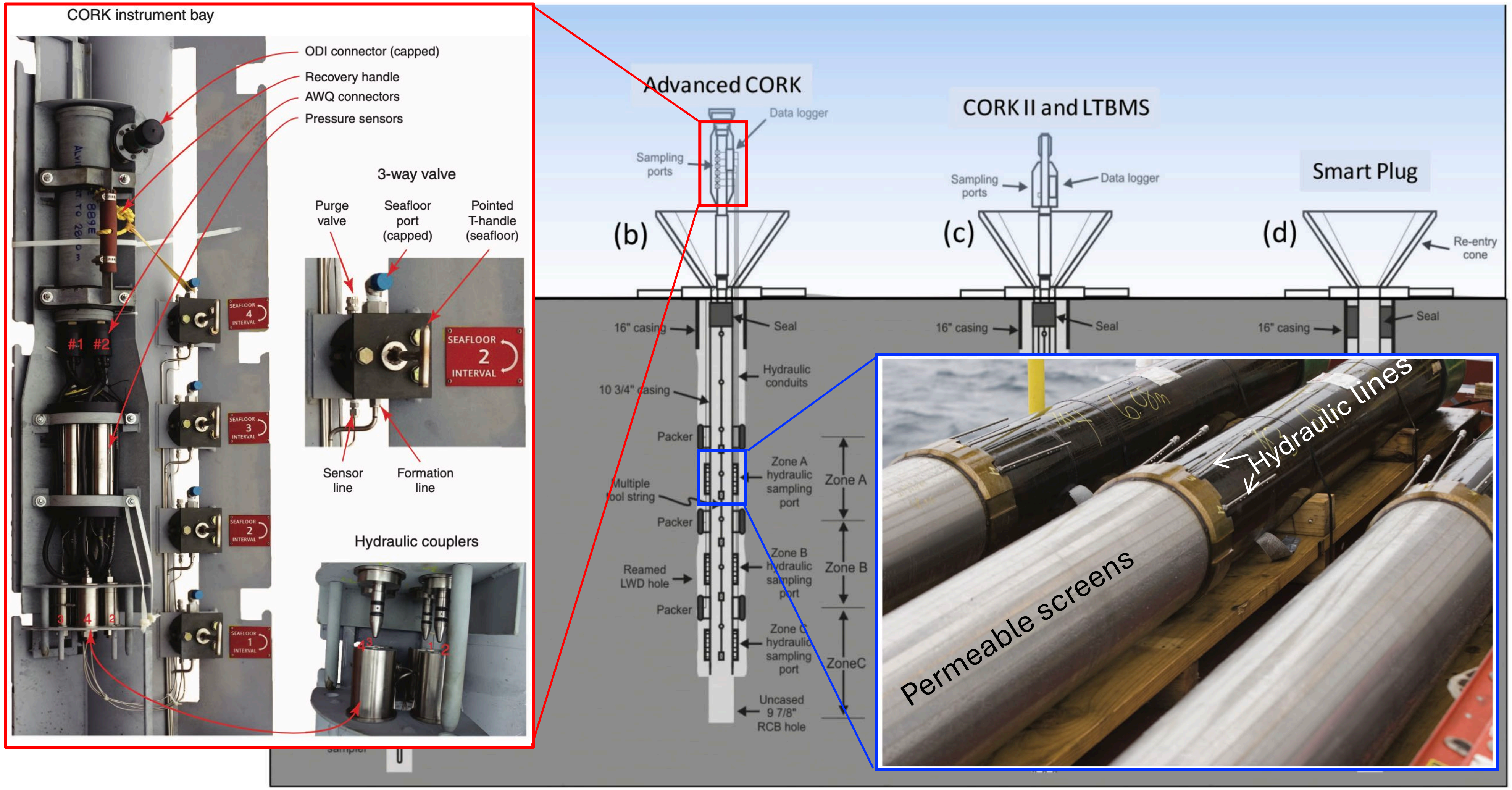
DeSanto et al. (2025)

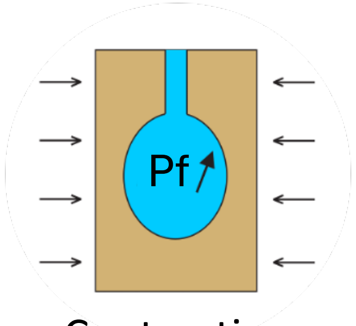
20 deep-sea borehole fluid pressure observatories at subduction zones worldwide



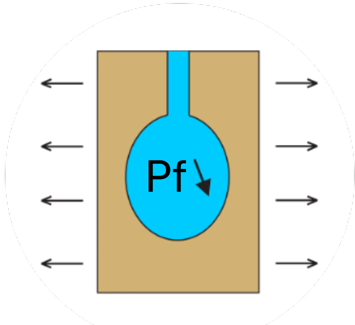
Davis, Sun et al. (2025, Canadian Journal of Earth Sciences, Review)

CORK (Circulation Obviation Retrofit Kit) and LTBMS (Long-Term Borehole Monitoring System) configurations





Contraction
→ Pf increase



Dilatation
→ Pf decrease

Examples:

Juan de Fuca plate:
- 847D, 1027C

Lesser Antilles:
- 949C, 948D

Cascadia:
- 1364A

Nankai (off Muroto):
- 1173B, 808I

Nankai (off Kii):
- C0002G, C0006G,
- C0010A

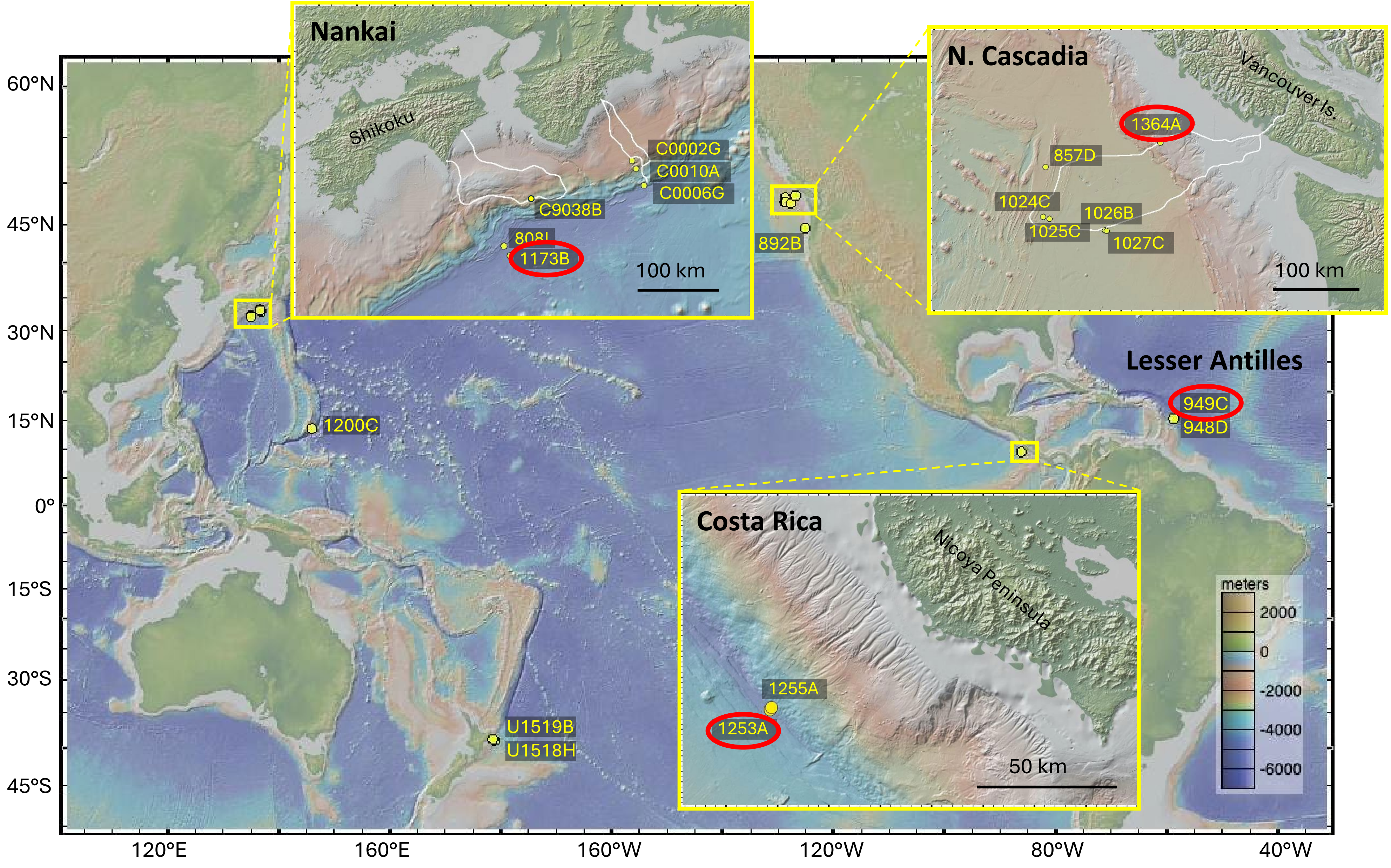
Costa Rica:
- 1253A, 1255A

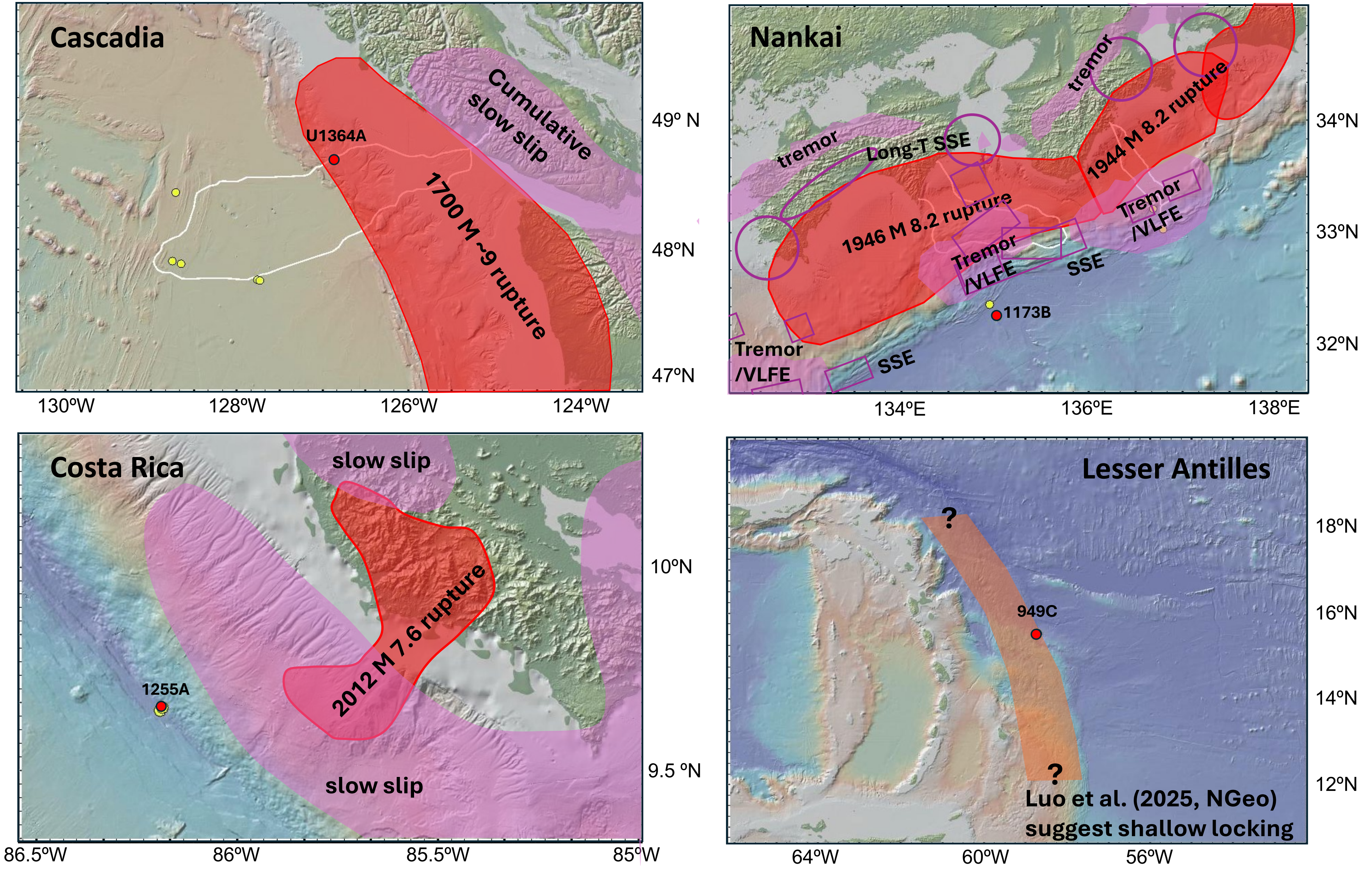
Nankai (off Kii):
- C0010A

(before 2010)

See McKenzie Carlson's talk soon

4 boreholes in sufficiently low-permeability environments to detect tectonic loading signals





References:

Cascadia:

Wang et al. (2013)

Bartlow (2020)

Nankai:

Takemura et al. (2023)

Baba et al. (2002)

Yamashita et al. (2015)

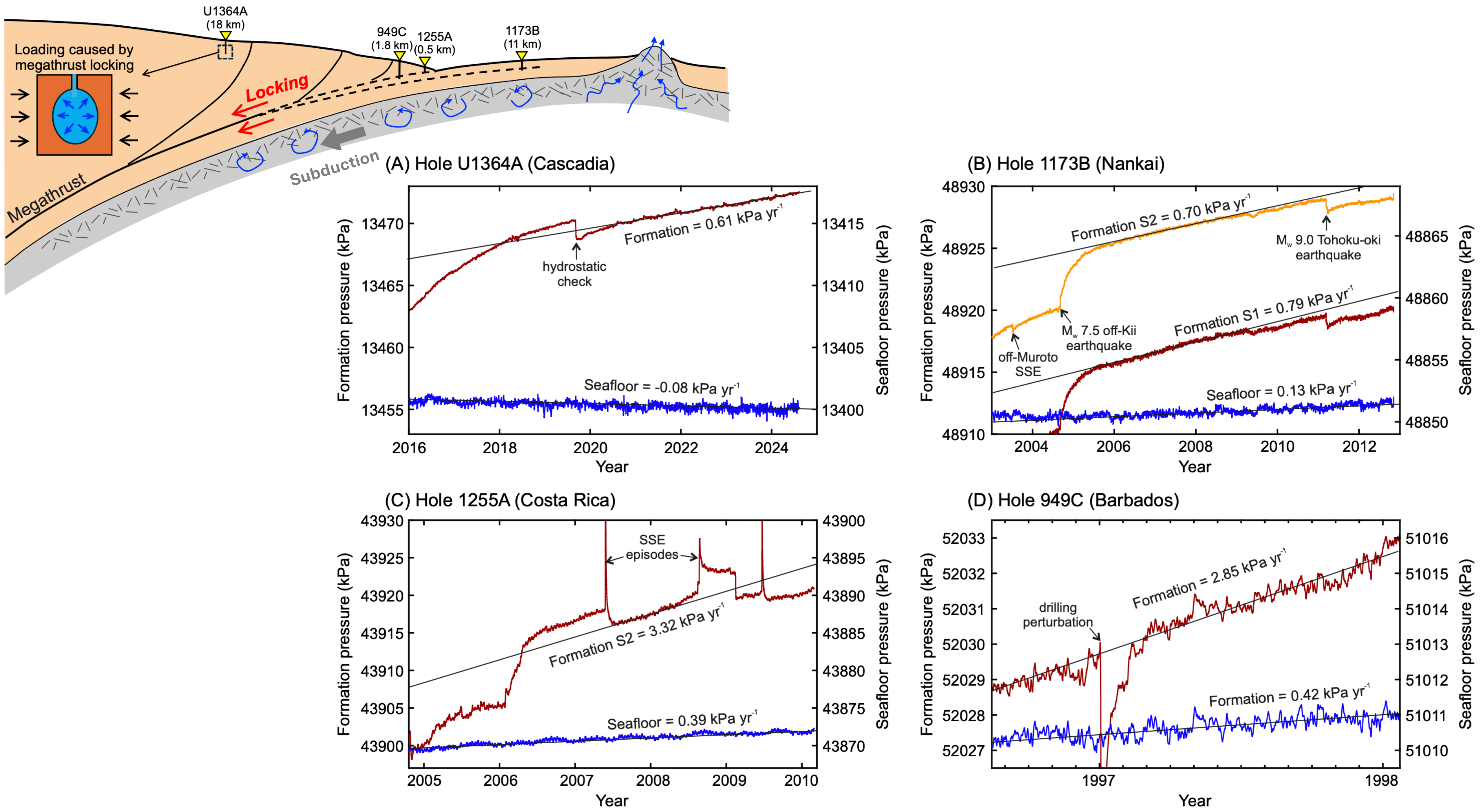
Costa Rica:

Yue et al. (2013)

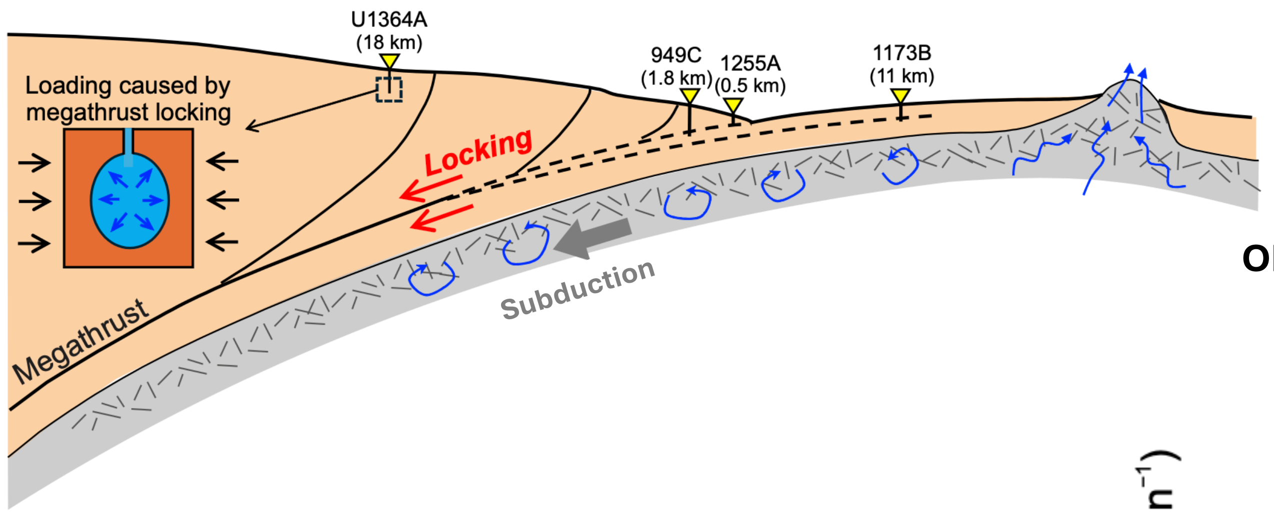
Dixon et al. (2015)

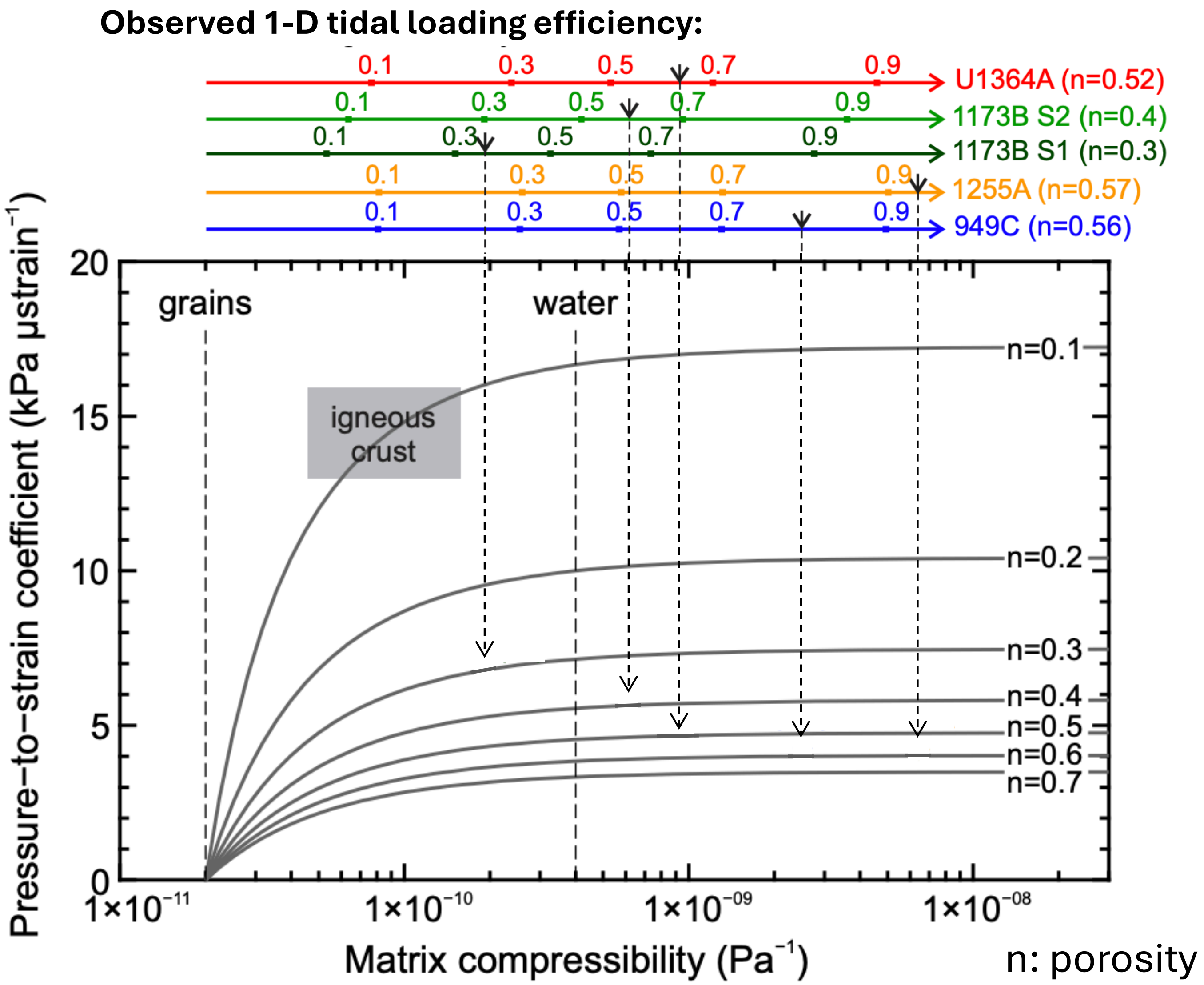
Lesser Antilles:

Luo et al. (2025)



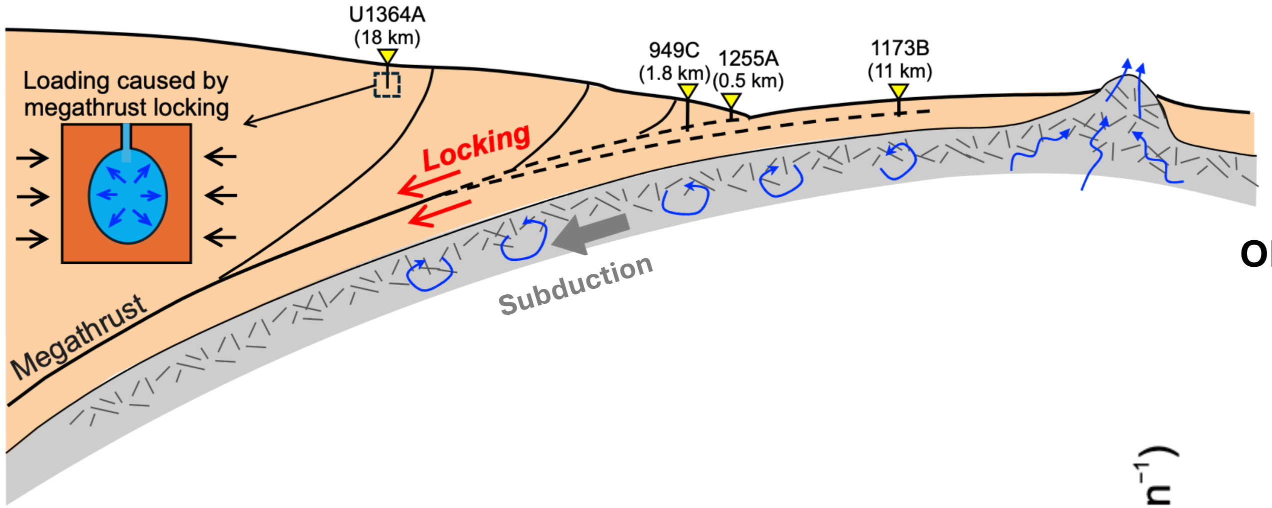
U1364A
(18 km)
949C
(1.8 km)
1255A
(0.5 km)
1173B
(11 km)
Loading caused by megathrust locking
Locking
Subduction
Megathrust
(A) Hole U1364A (Cascadia)
Formation = 0.61 kPa yr-1
hydrostatic check
Seafloor = -0.08 kPa yr-1
Formation pressure (kPa)
Seafloor pressure (kPa)
Year
(B) Hole 1173B (Nankai)
Formation S2 = 0.70 kPa yr-1
Mw 9.0 Tohoku-oki earthquake
Mw 7.5 off-Kii earthquake
off-Muroto SSE
Formation S1 = 0.79 kPa yr-1
Seafloor = 0.13 kPa yr-1
(C) Hole 1255A (Costa Rica)
SSE episodes
Formation S2 = 3.32 kPa yr-1
Seafloor = 0.39 kPa yr-1
(D) Hole 949C (Barbados)
drilling perturbation
Formation = 2.85 kPa yr-1
Formation = 0.42 kPa yr-1





Site-specific **pressure-to-strain (Pf-to-ε) coefficient** derived from:

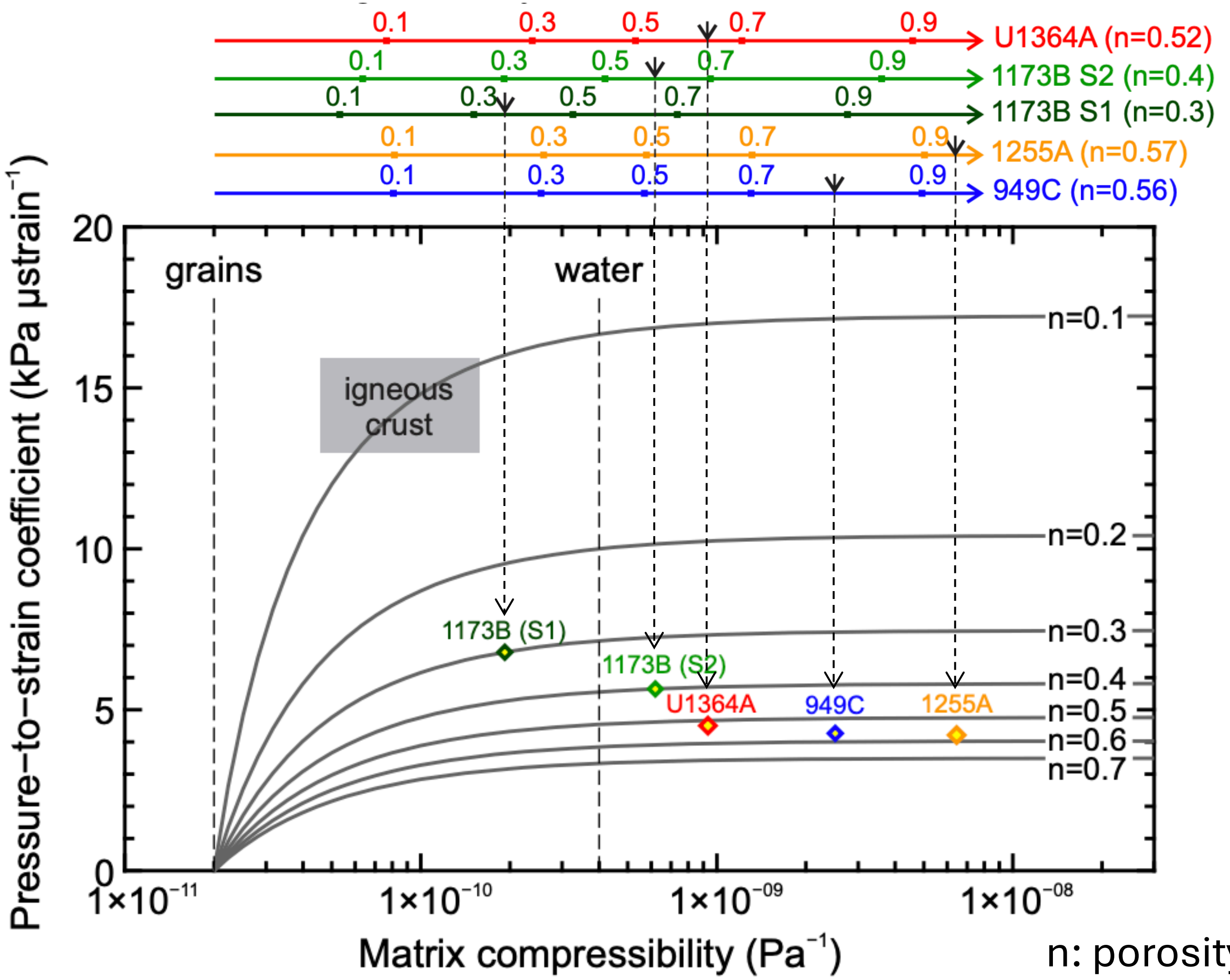
- Sediment porosity of the surrounding formation (via logging)
- 1-D tidal loading efficiency



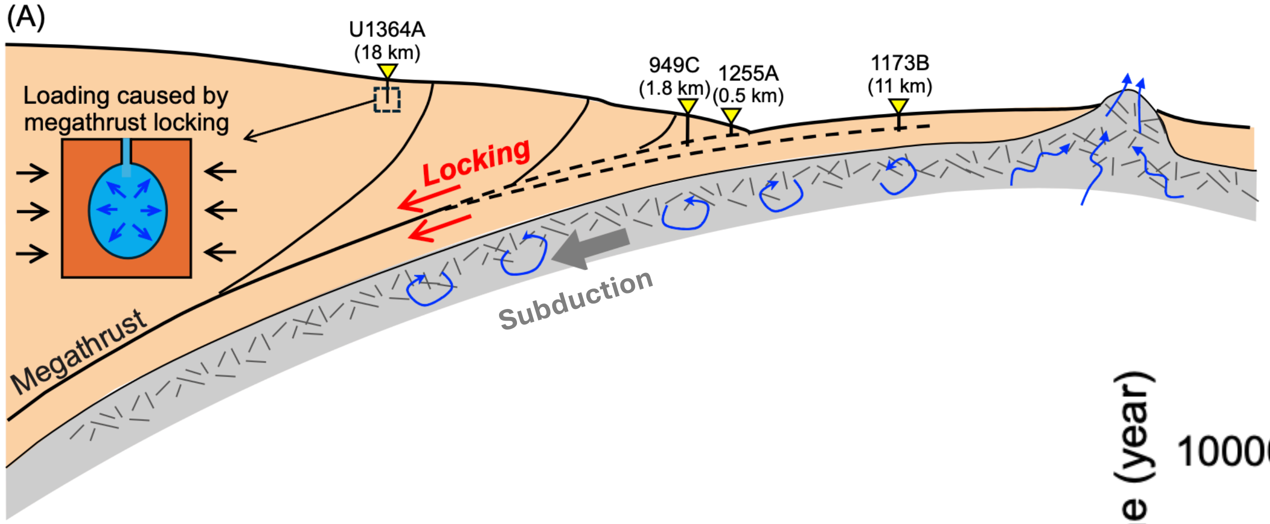
Site	Corrected Pf trend (kPa yr^{-1})	Pf-to-ε coefficient (kPa/10^{-6})
U1364A (Cascadia)	0.66	4.51
1255A (Costa Rica)	2.89	4.21
1173B (S1)	0.66	6.79
1173B (S2) (Nankai)	0.57	5.65
949C (Barbodos)	2.43	4.26

within 4% difference

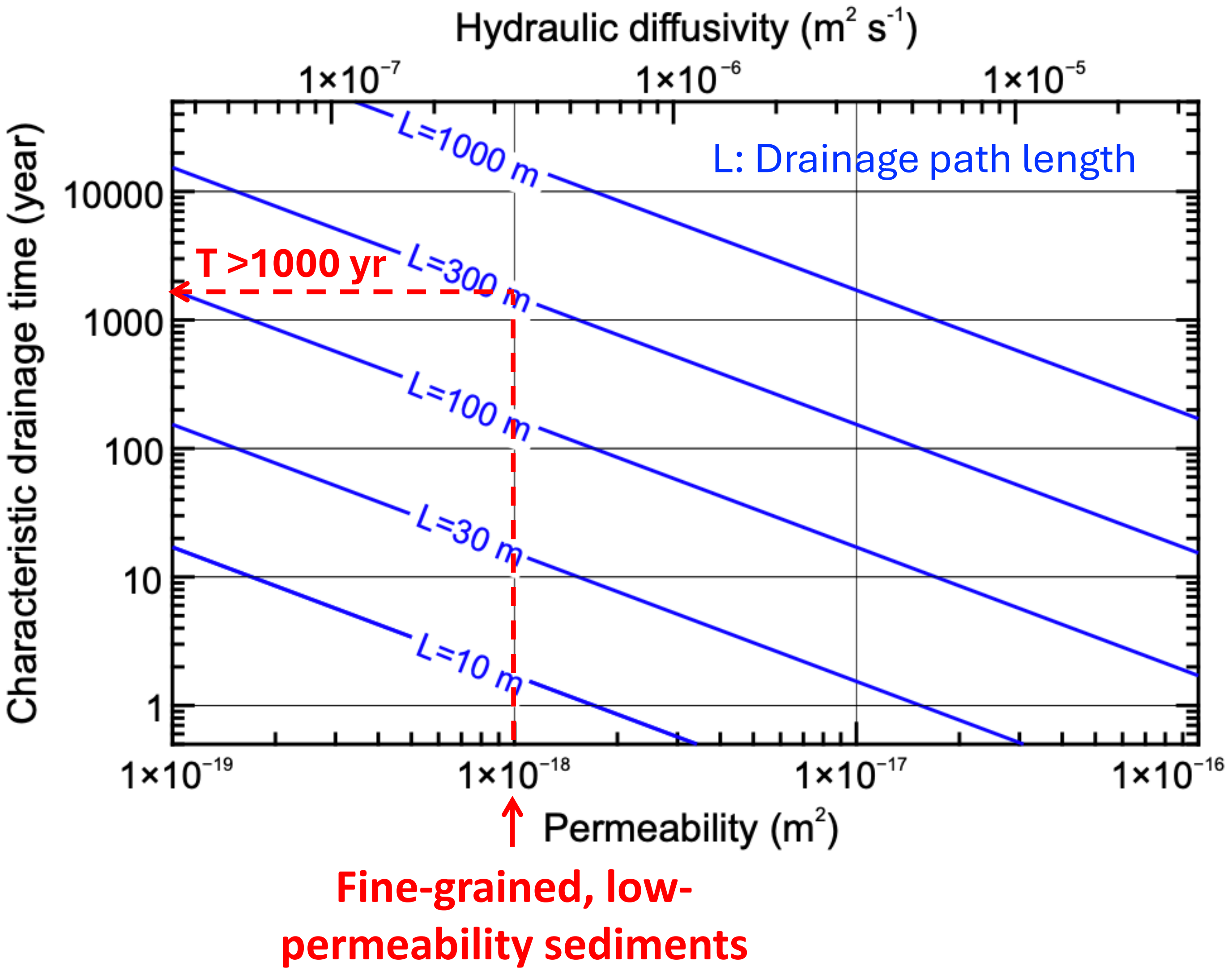
Observed 1-D tidal loading efficiency:



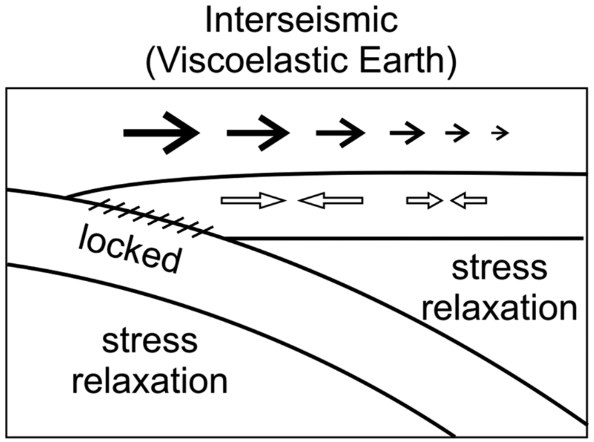
n: porosity



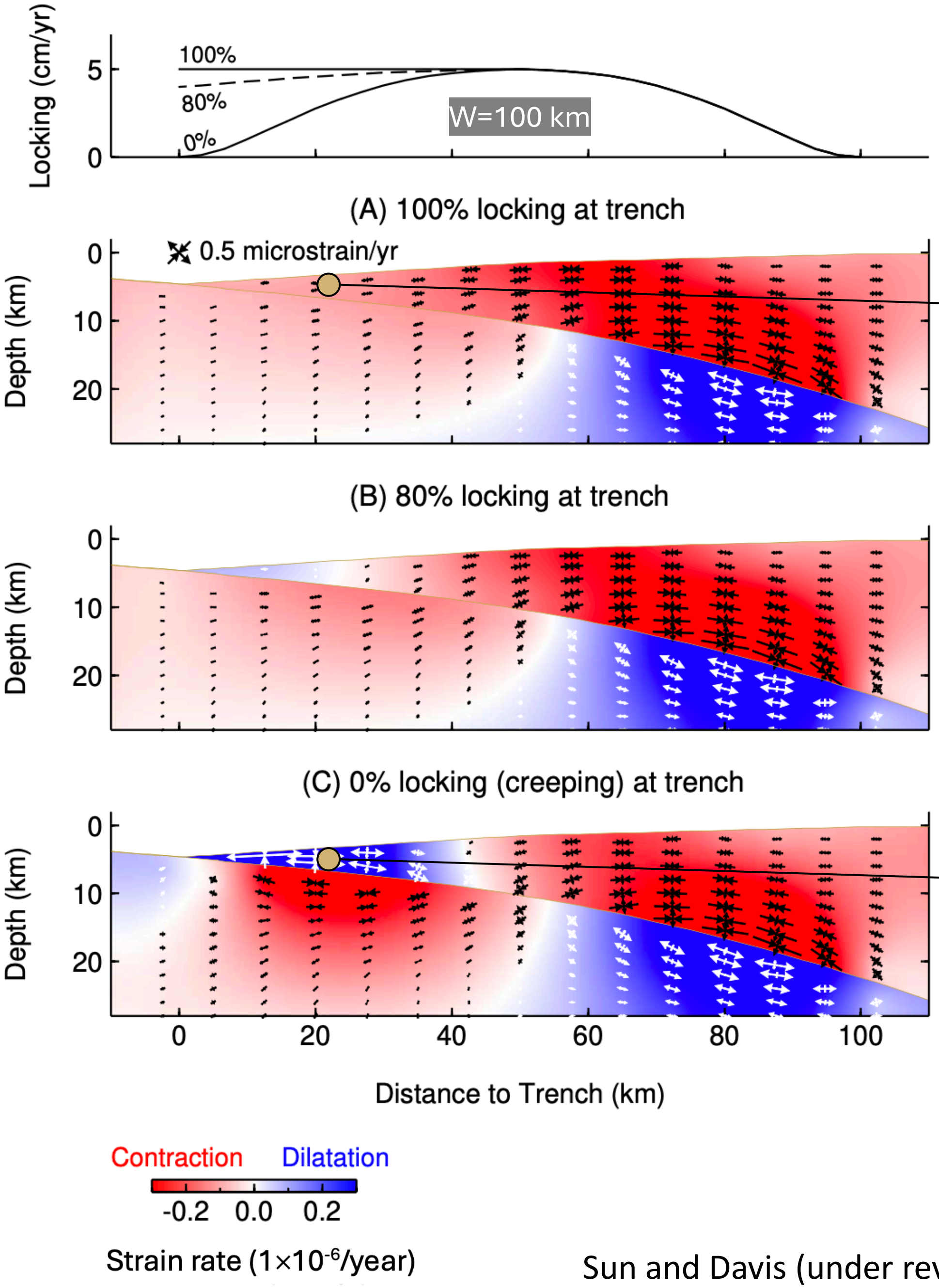
Site	Corrected Pf trend (kPa yr^{-1})	**Pf-to-ε coefficient** (kPa/10^{-6})	Derived strain rate (10^{-6} yr^{-1})
U1364A (Cascadia)	0.66	4.51	0.146
1255A (Costa Rica)	2.89	4.21	0.686
1173B (S1)	0.66	6.79	0.097
1173B (S2) (Nankai)	0.57	5.65	0.101
949C (Barbodos)	2.43	4.26	0.570

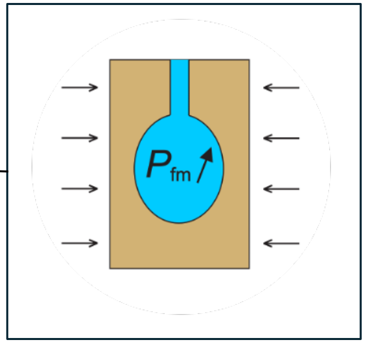


Viscoelastic model

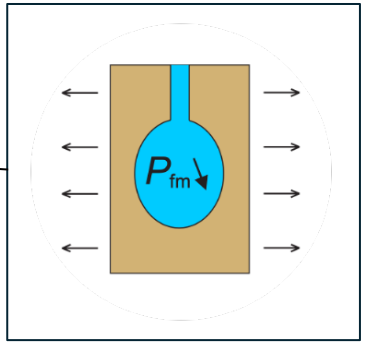


(Li et al., 2018)





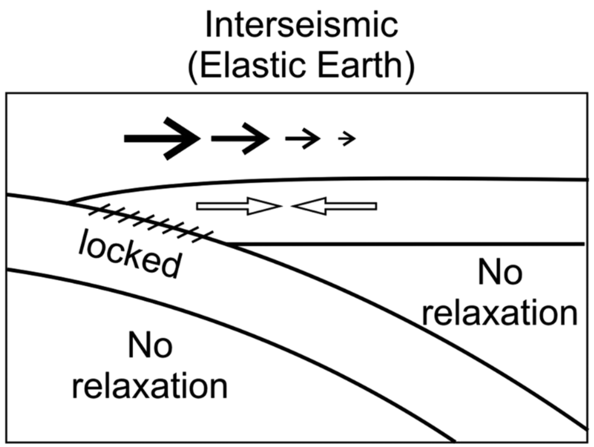
Contraction
→ Pf increase



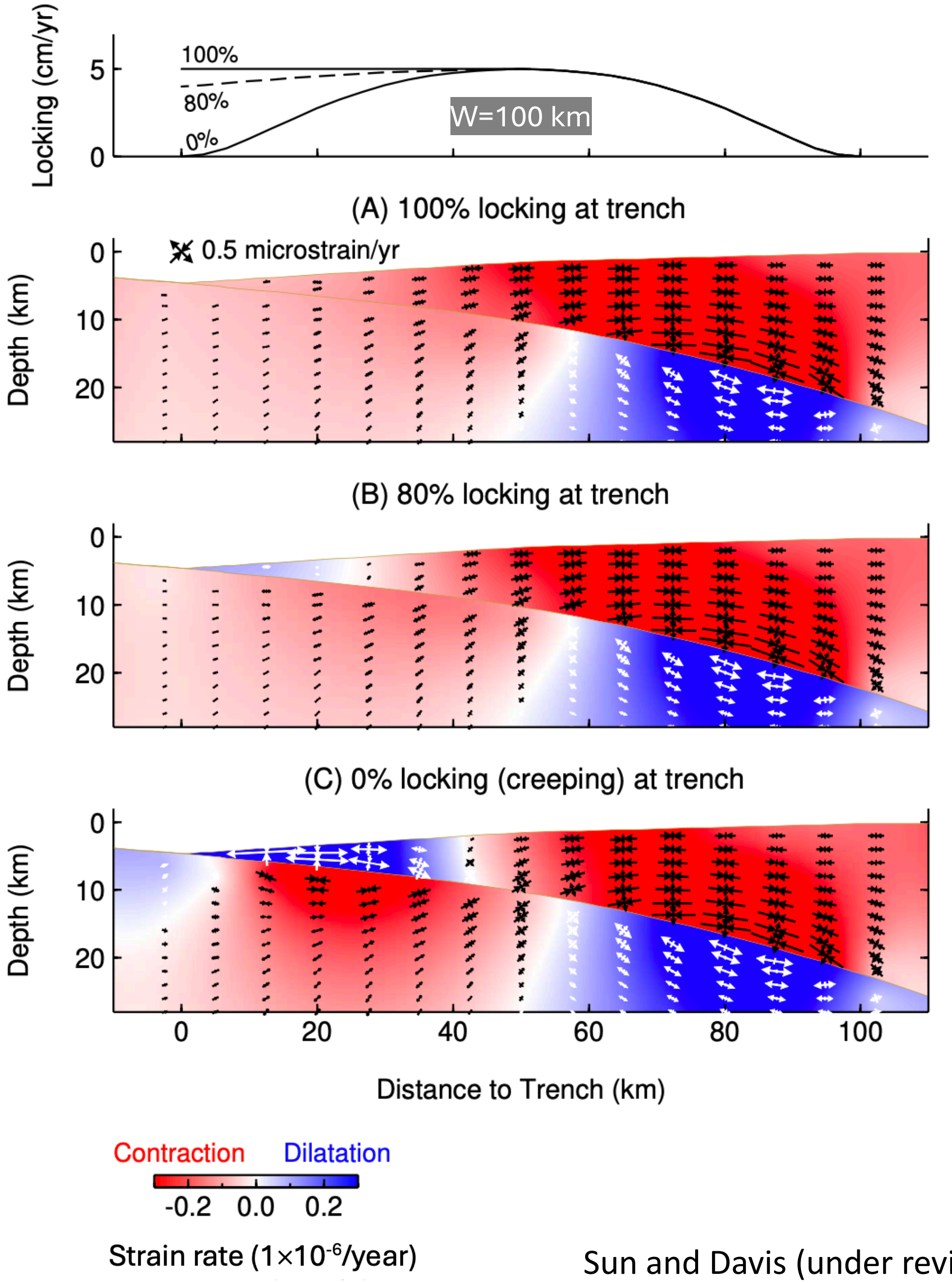
Dilatation
→ Pf decrease

Sun and Davis (under review)

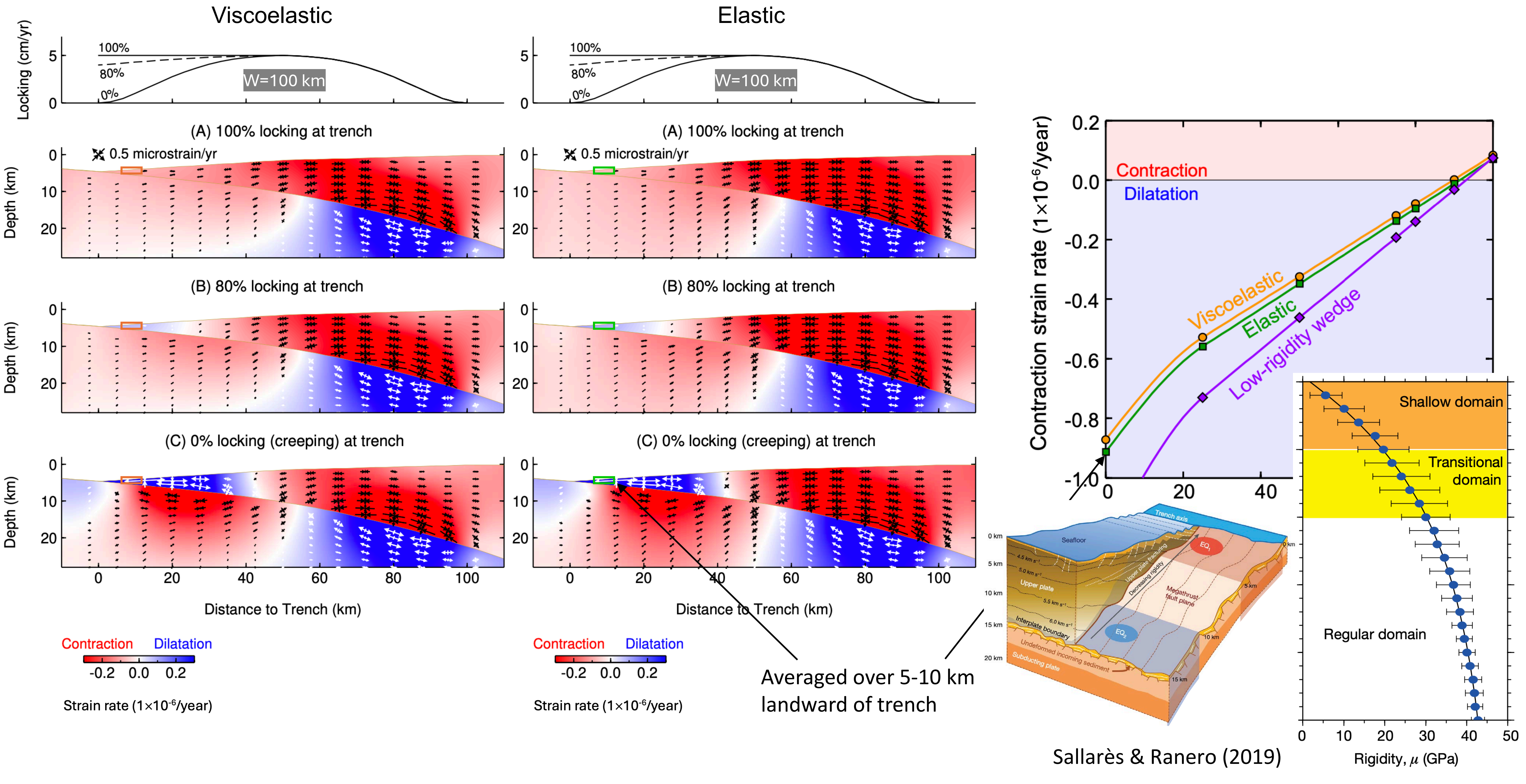
Elastic model



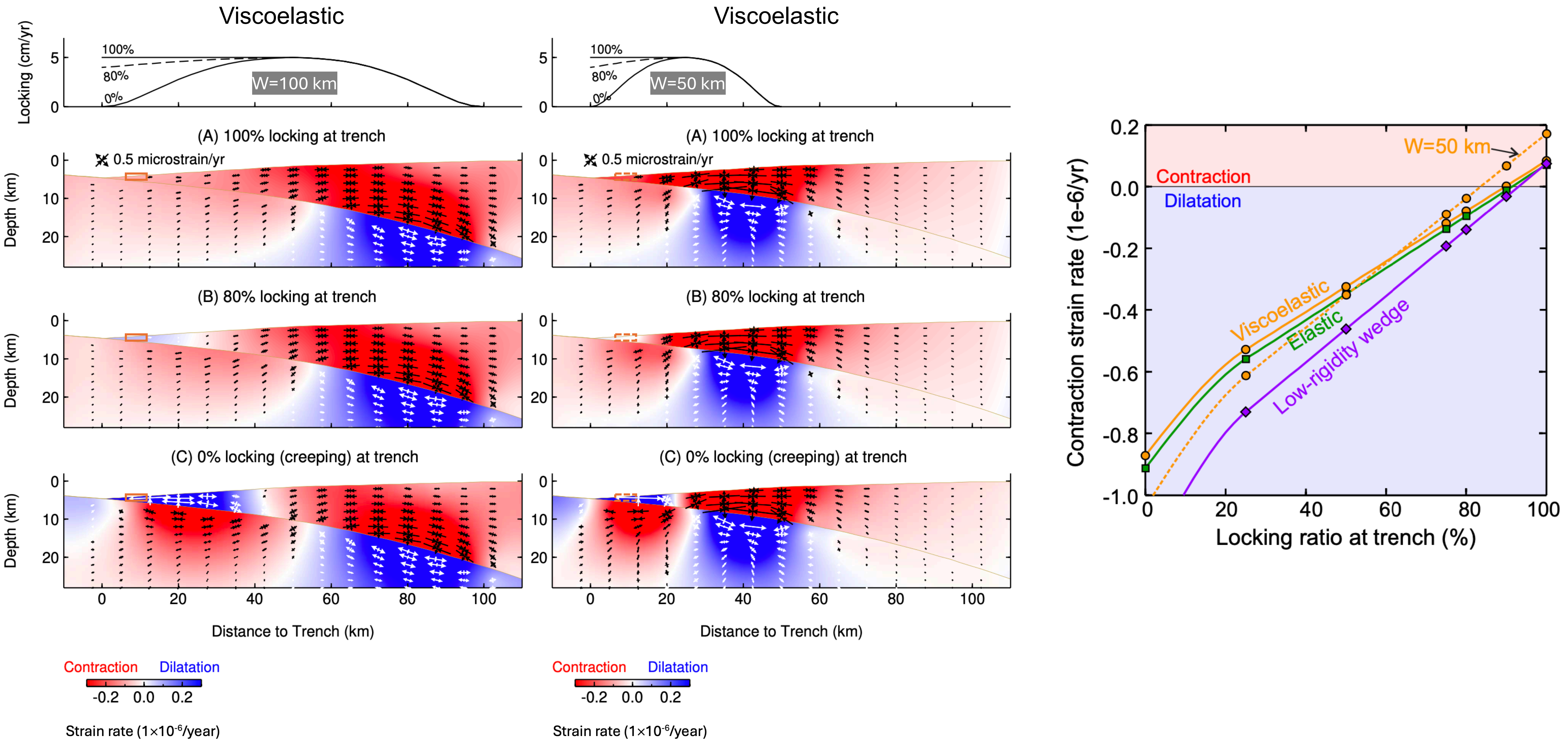
(Li et al., 2018)



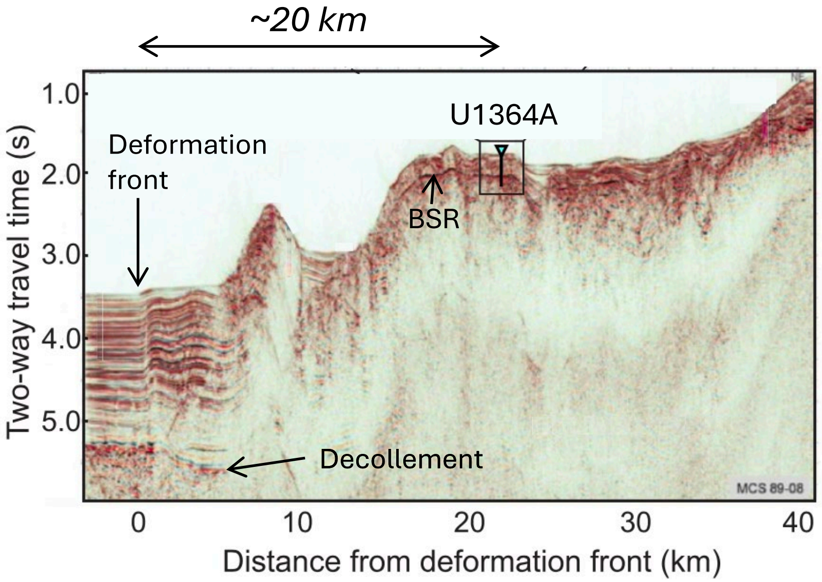
Sun and Davis (under review)

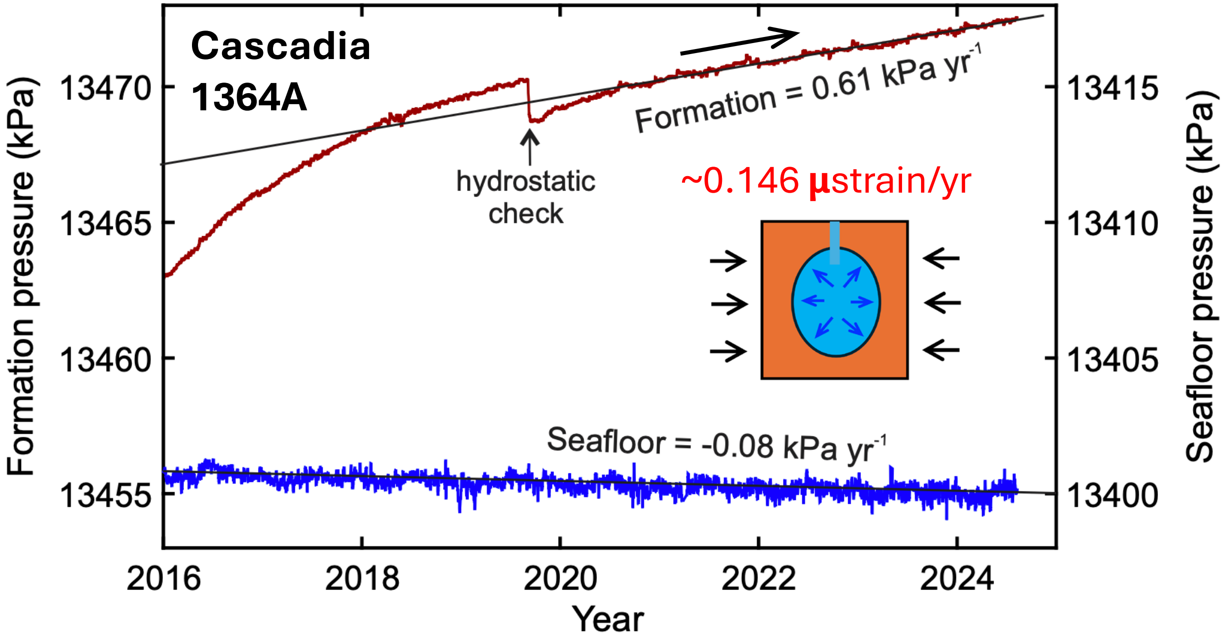


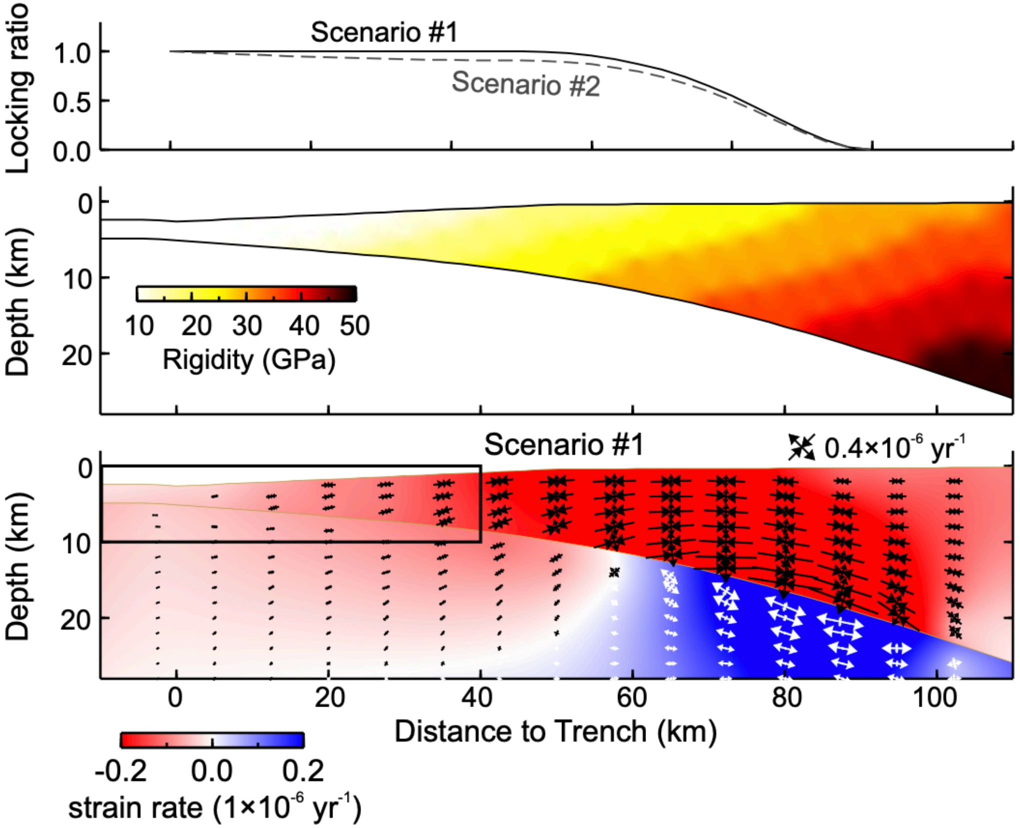
Viscoelastic
Elastic
Locking (cm/yr)
100%
80%
0%
W=100 km
(A) 100% locking at trench
0.5 microstrain/yr
(B) 80% locking at trench
(C) 0% locking (creeping) at trench
Depth (km)
Distance to Trench (km)
Contraction
Dilatation
-0.2 0.0 0.2
Strain rate (1×10⁻⁶/year)
Contraction strain rate (1×10⁻⁶/year)
Viscoelastic
Elastic
Low-rigidity wedge
Averaged over 5-10 km landward of trench
Seafloor
Trench axis
Upper plate
Interplate boundary
Undeformed incoming sediment
Subducting plate
Megathrust fault plane
Shallow domain
Transitional domain
Regular domain
Rigidity, μ (GPa)
Sallarès & Ranero (2019)

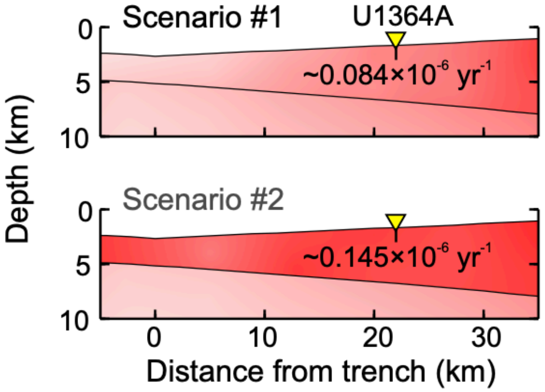


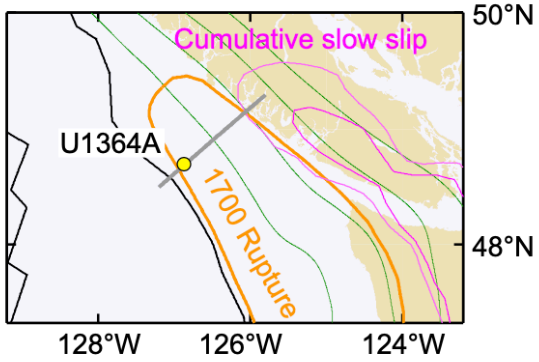
Viscoelastic
Viscoelastic
Locking (cm/yr)
100%
80%
0%
W=100 km
W=50 km
(A) 100% locking at trench
(B) 80% locking at trench
(C) 0% locking (creeping) at trench
0.5 microstrain/yr
Depth (km)
Distance to Trench (km)
Contraction
Dilatation
Strain rate (1×10⁻⁶/year)
Contraction strain rate (1e-6/yr)
Locking ratio at trench (%)
W=50 km
Viscoelastic
Elastic
Low-rigidity wedge





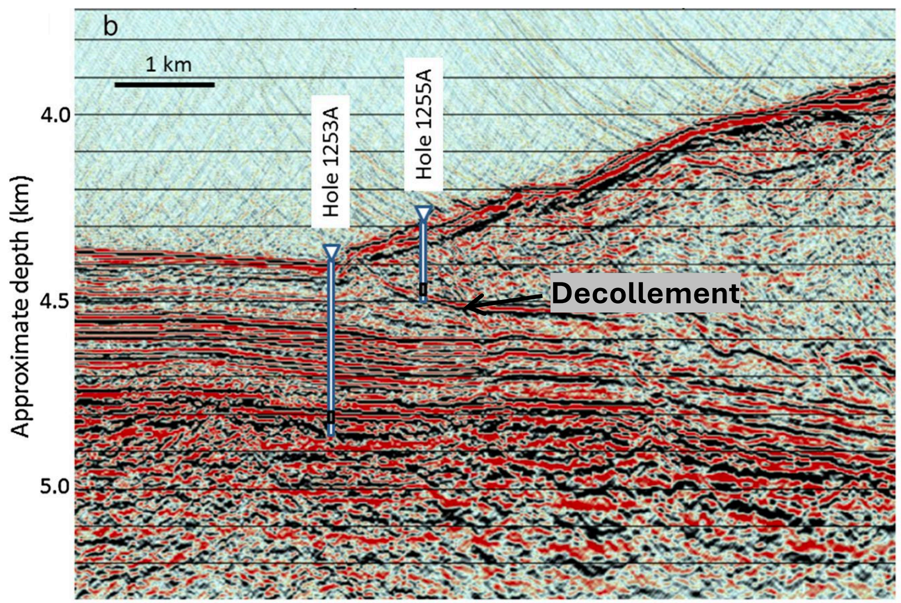


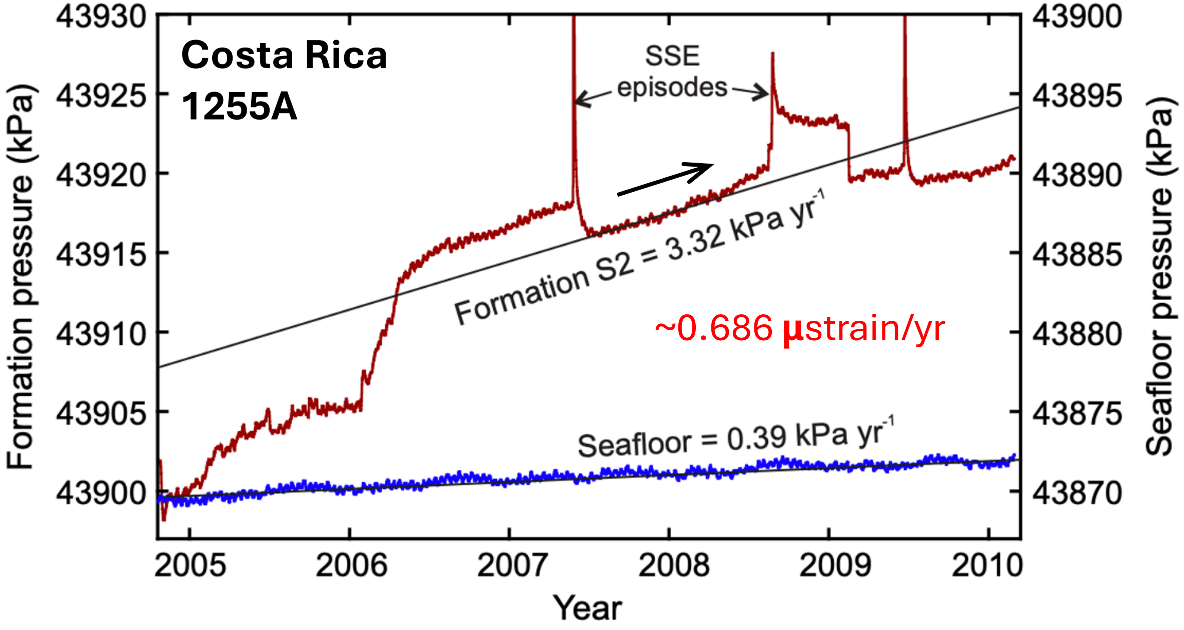


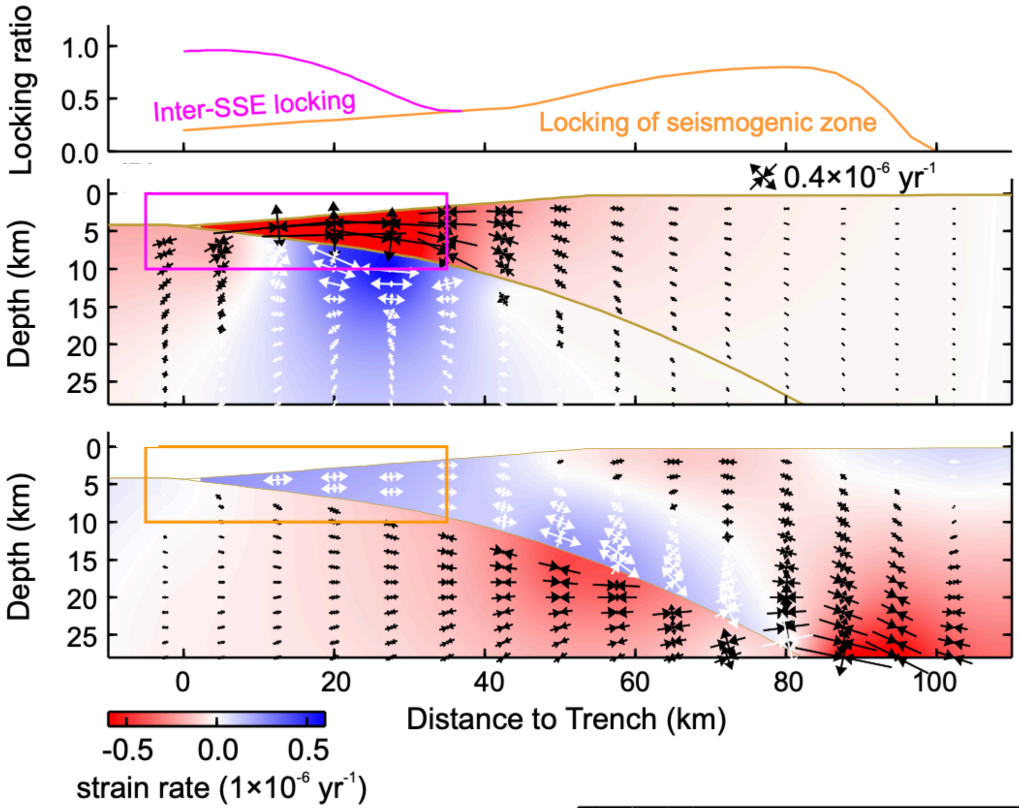


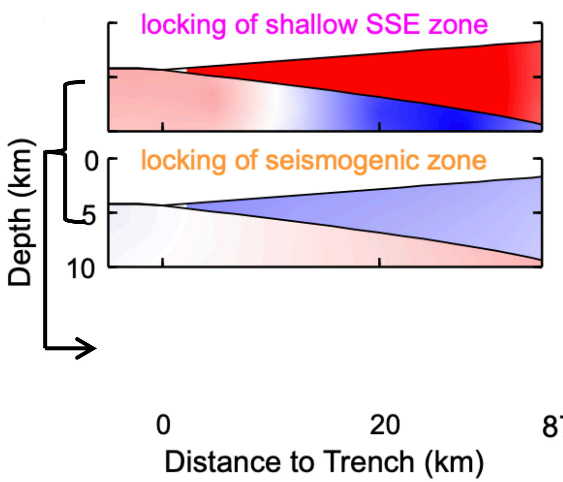
1700 rupture: Wang et al. (2013)
Cumulative slow slip: Bartlow (2020)

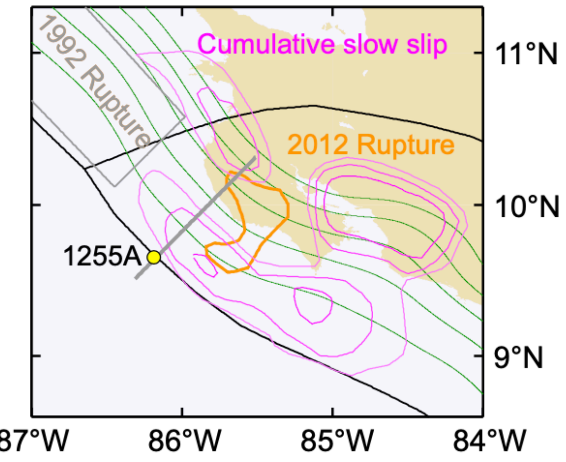
Sun and Davis (under review)







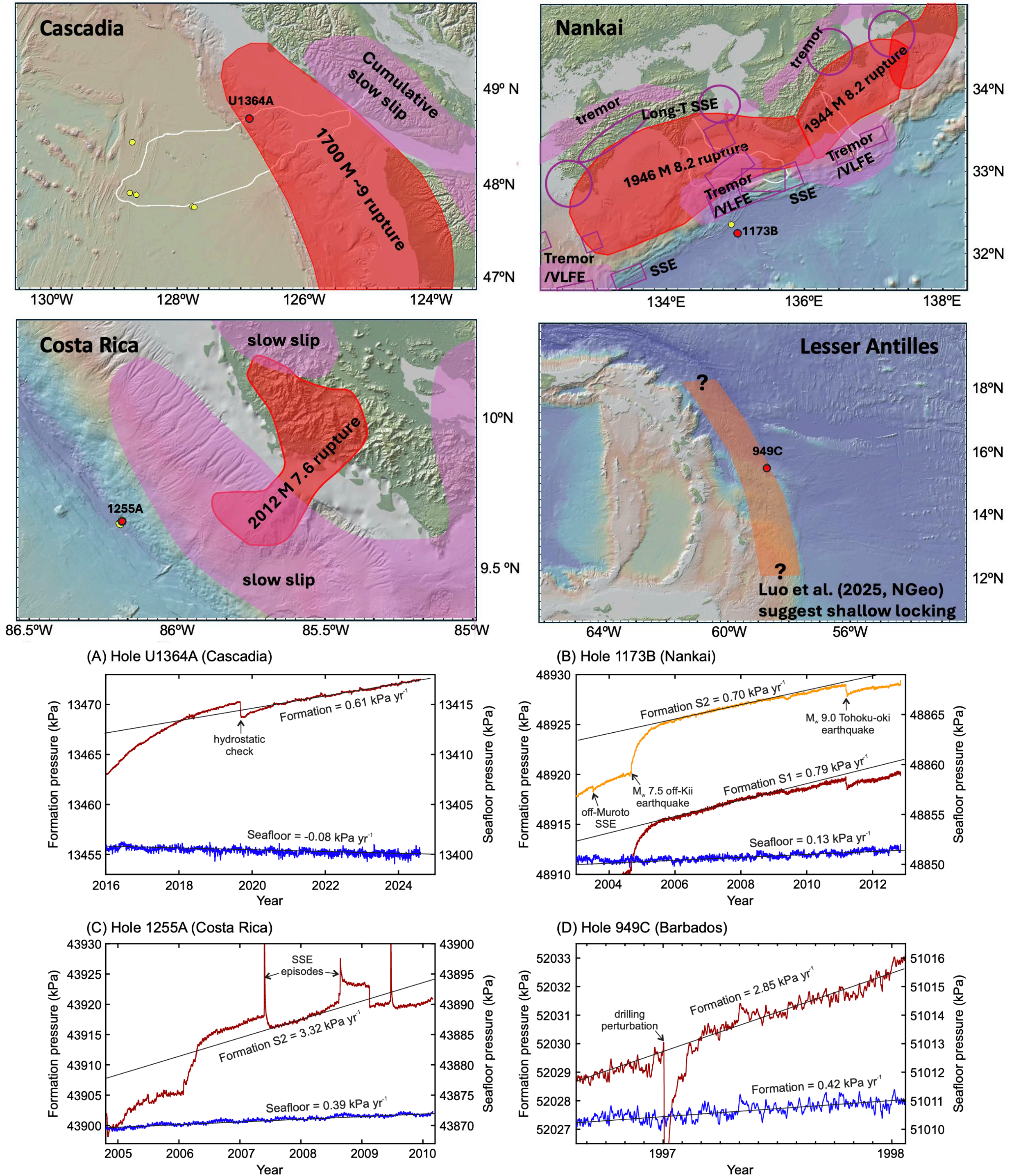




Sun and Davis (under review)

2012 rupture: Yue et al. (2013)

(Projected) cumulative slow slip: Dixon et al. (2015)



Summary

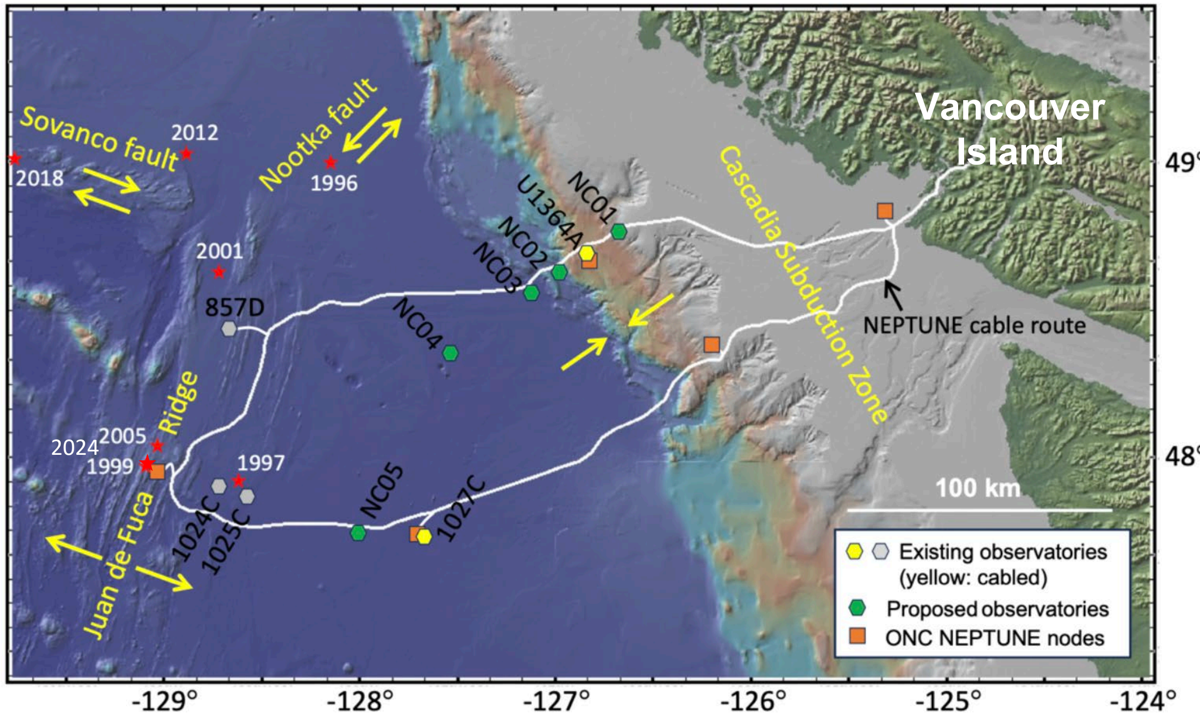
- Deep-sea borehole fluid pressure monitoring established in fine-grained, low-permeability sediments shows secular trend due to megathrust locking

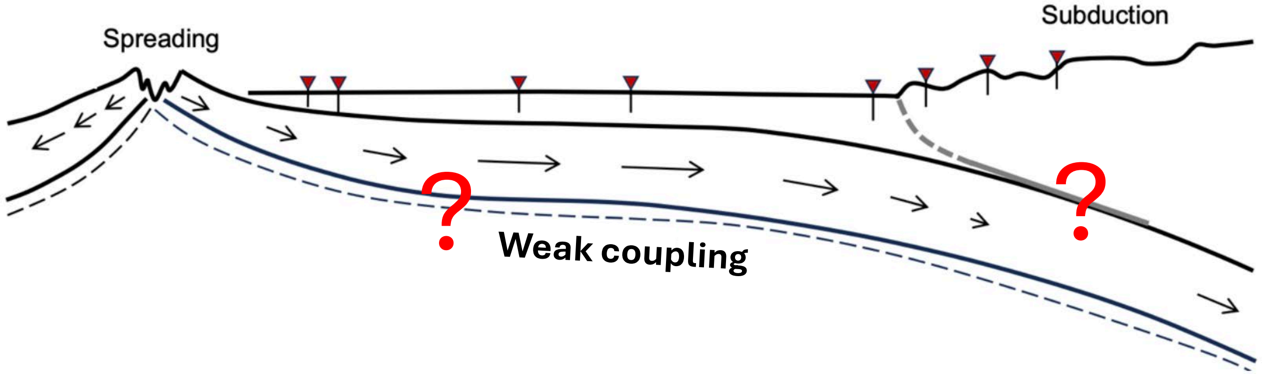
- Borehole Pf observations provide direct evidence for interseismic/inter-SSE strain accumulation, suggesting:
  - Complete shallow megathrust locking at N Cascadia
  - Rapid strain buildup between SSEs at Costa Rica

- At Lesser Antilles, borehole observations support the shallow megathrust locking proposed by Luo et al. (2025, Nature Geoscience).

- Borehole Pf is sensitive to gradual strain signals of 0.1 μstrain/yr and small slip at cm levels. **Combining this technique with spatially more extensive observations (e.g., GNSS-A network, fiber optical sensing) would be highly promising.**

IODP³ pre-proposal 1107-Pre: Northern Cascadia Borehole Observatories – A Plate-Scale Observatory Network to Study Inter- and Intra-Plate Motion and How Plate Boundaries Communicate



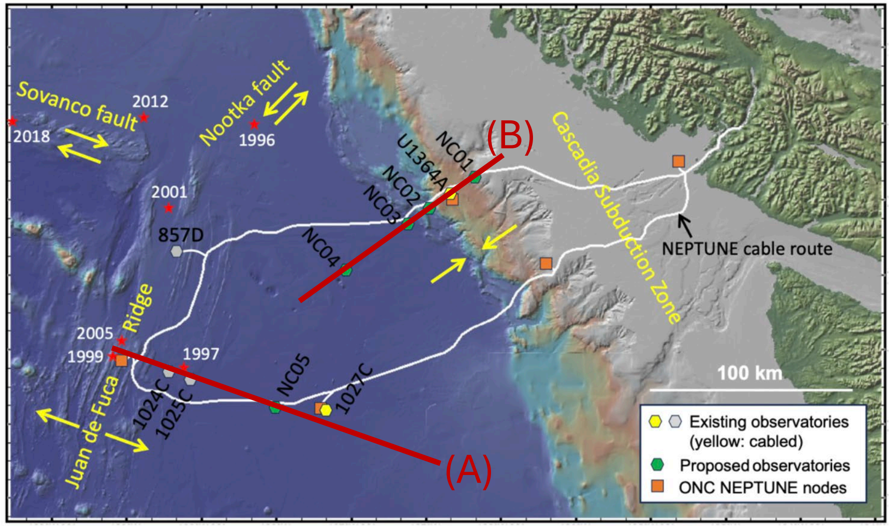


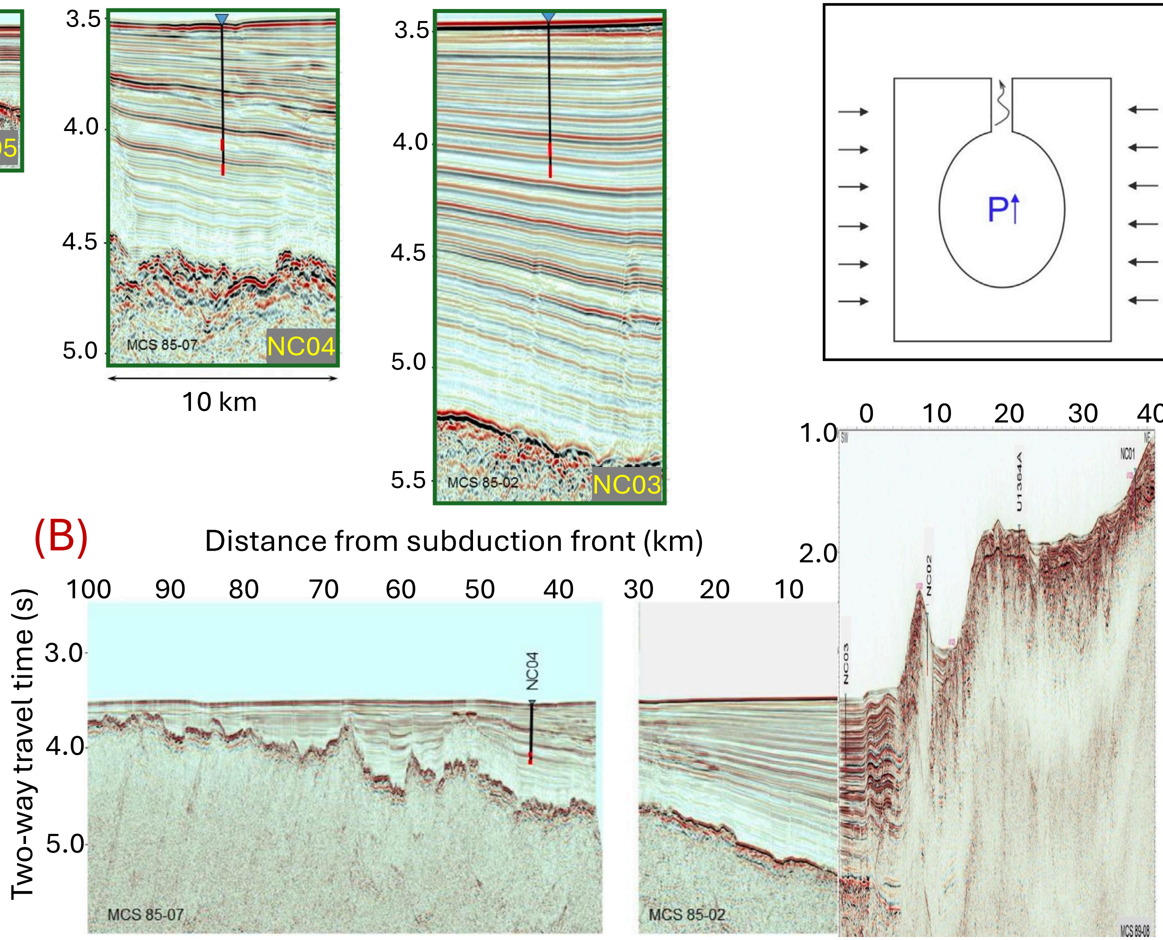
Scientific Objectives:

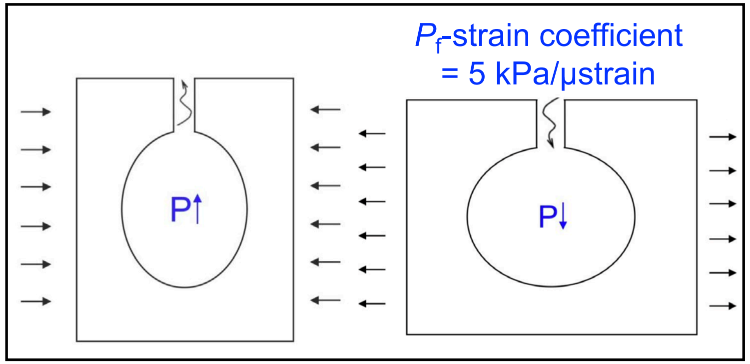
- Defining the locking state of Cascadia subduction zone (CSZ) megathrust
- Studying the interplay between tectonically active plate boundaries and CSZ
- Studying rheology of the lithosphere-asthenosphere system
- Opportunity for real-time observation by connecting with Ocean Networks Canada's NEPTUNE cabled observatory

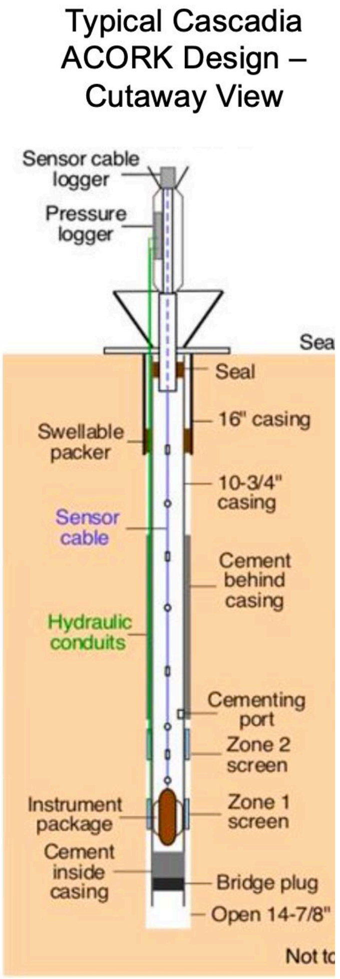
INTERNATIONAL OCEAN DRILLING PROGRAMME

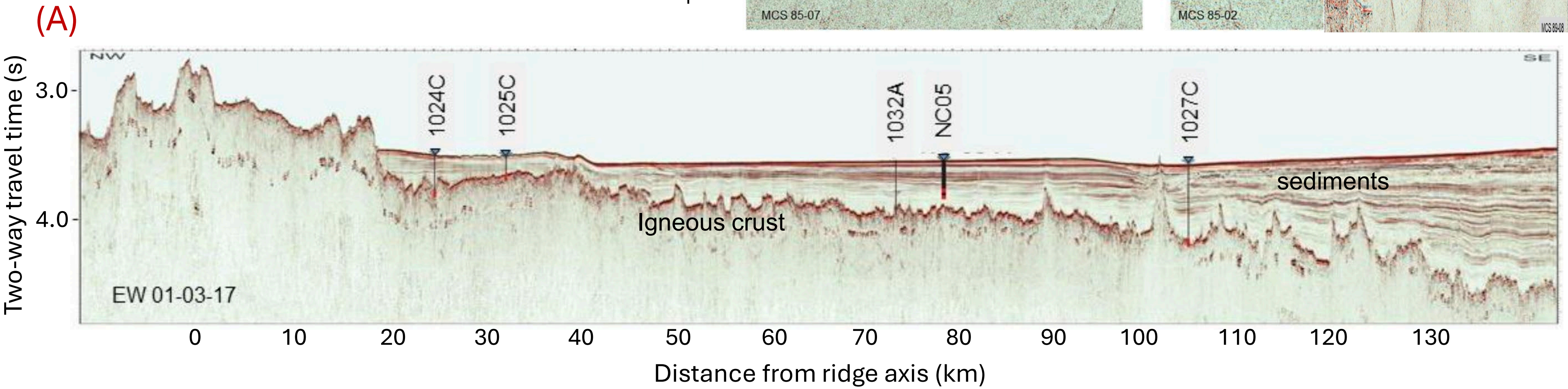
Review result: **Revise to Full**


Sovanco fault
2012
2018
Nootka fault
1996
2001
857D
NC01
U1364A
NC02
NC03
NC04
(B)
Cascadia Subduction Zone
NEPTUNE cable route
2005
1999
Ridge
1997
Juan de Fuca
1024C
1025C
NC05
1027C
100 km
Existing observatories
(yellow: cabled)
Proposed observatories
ONC NEPTUNE nodes
(A)


3.5
4.0
NC05
3.5
4.0
4.5
5.0
MCS 85-07
NC04
10 km
3.5
4.0
4.5
5.0
5.5
MCS 85-02
NC03
(B)
Distance from subduction front (km)
100
90
80
70
60
50
40
30
20
10
0
10
20
30
40
1.0
2.0
Two-way travel time (s)
3.0
4.0
5.0
NC04
MCS 85-07
MCS 85-02
NC03
NC02
U1364A
NC01


P_f-strain coefficient
= 5 kPa/μstrain
P↑
P↓


Typical Cascadia
ACORK Design –
Cutaway View
Sensor cable logger
Pressure logger
Sea
Seal
16" casing
Swellable packer
10-3/4" casing
Sensor cable
Cement behind casing
Hydraulic conduits
Cementing port
Zone 2 screen
Zone 1 screen
Instrument package
Cement inside casing
Bridge plug
Open 14-7/8"


(A)
NW
SE
Two-way travel time (s)
3.0
4.0
1024C
1025C
1032A
NC05
1027C
sediments
Igneous crust
EW 01-03-17
0
10
20
30
40
50
60
70
80
90
100
110
120
130
Distance from ridge axis (km)