Interaction of Earthquake Characteristics and Fault Mechanics at Various Scales from Observation-Driven Simulations

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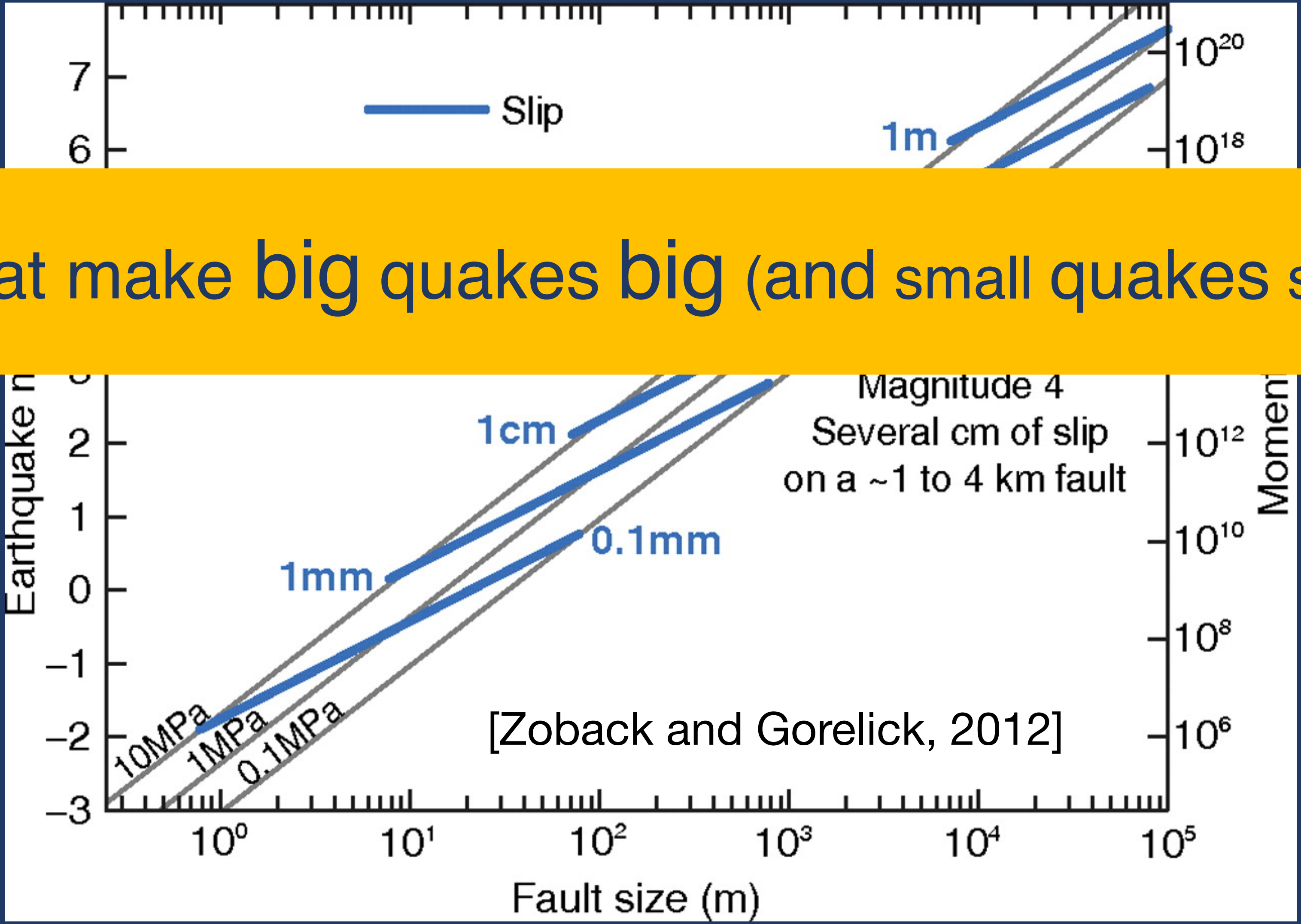
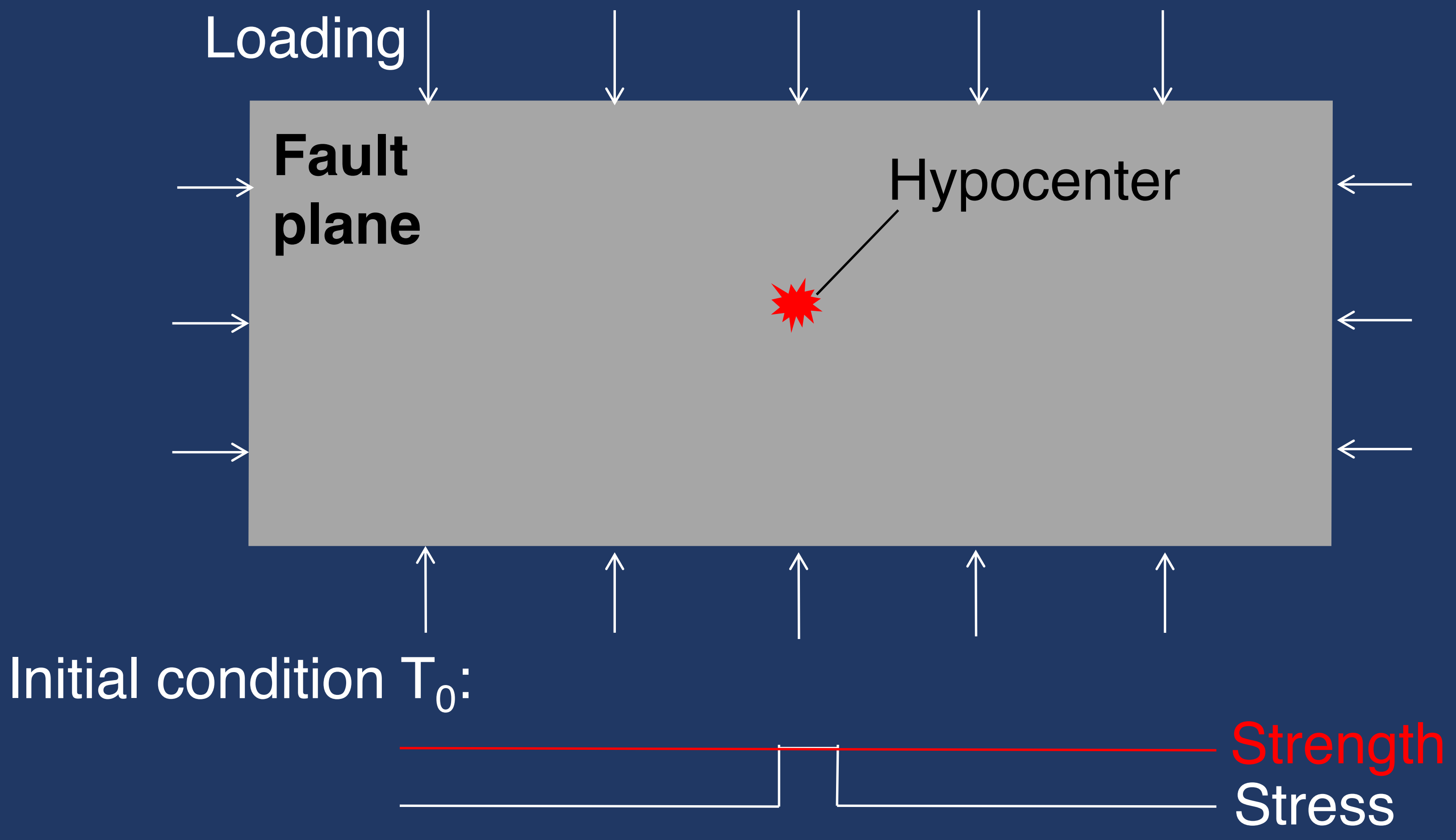
Earthquake source observations encompass various spatial-temporal scales



What make big quakes big (and small quakes small)?

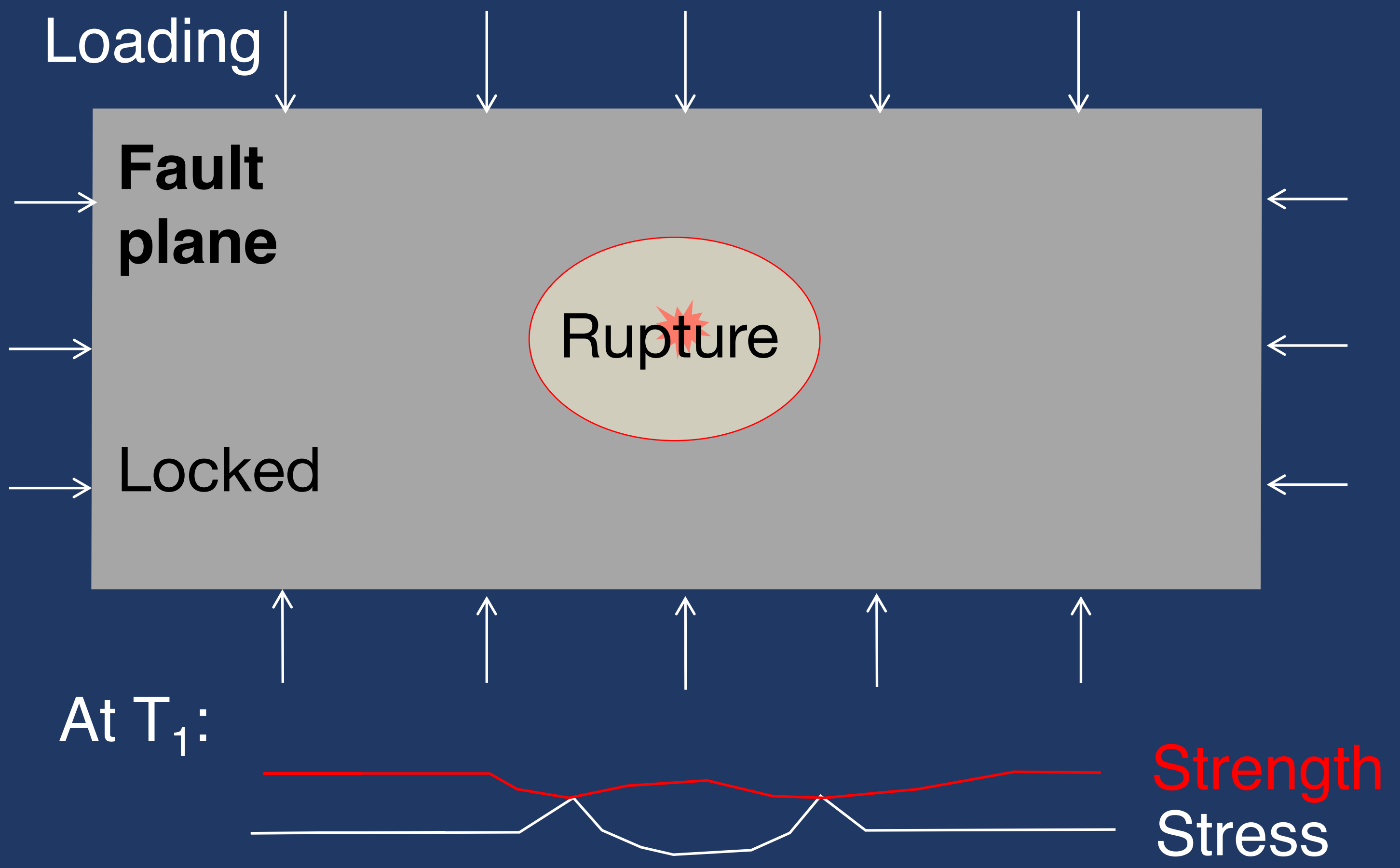
[Zoback and Gorelick, 2012]

How do earthquakes start, grow and arrest?



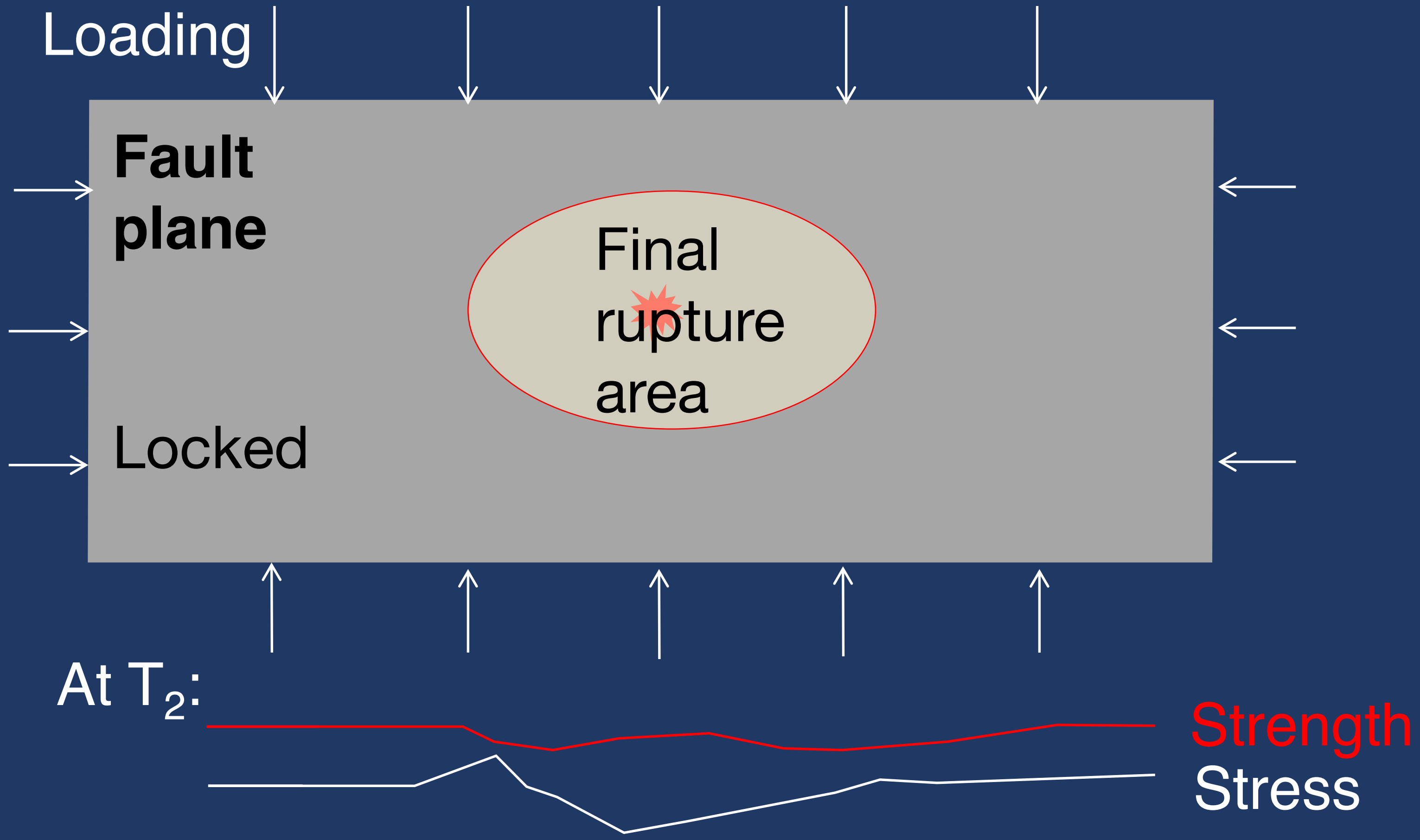
An earthquake occurs when shear stress on the fault overcomes frictional strength.

How do earthquakes start, grow and arrest?



Fault stress and strength vary spatially and temporally due to the sliding velocity, fault geometry, material heterogeneity, fluid, etc.

How do earthquakes start, grow and arrest?



Earthquake rupture stops when fault stress can not overcome frictional strength anymore.

We use earthquake simulations to understand source physics

- **Dynamic rupture simulations** solve the kinematic rupture process of an earthquake by considering the short-term interaction between fault stress and frictional strength.

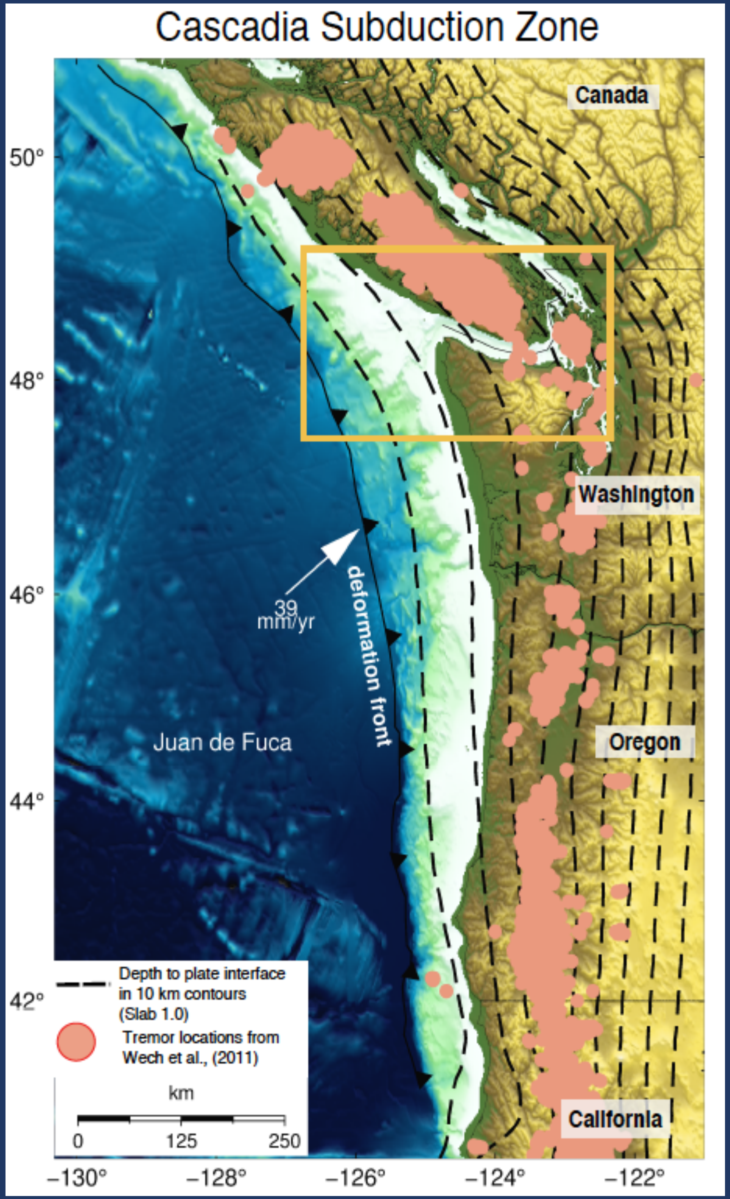
- **Earthquake cycle simulations** solve both the aseismic slip during the interseismic period and the earthquake rupture process when a fault is subjected to slow tectonic loading.

Overview

1. Megathrust earthquakes: Northern Cascadia dynamic rupture scenarios
2. Small to moderate earthquakes: Earthquake cycle models with damaged fault zones

Observations ⇄ Simulations
(seismic, geology and geodetic)

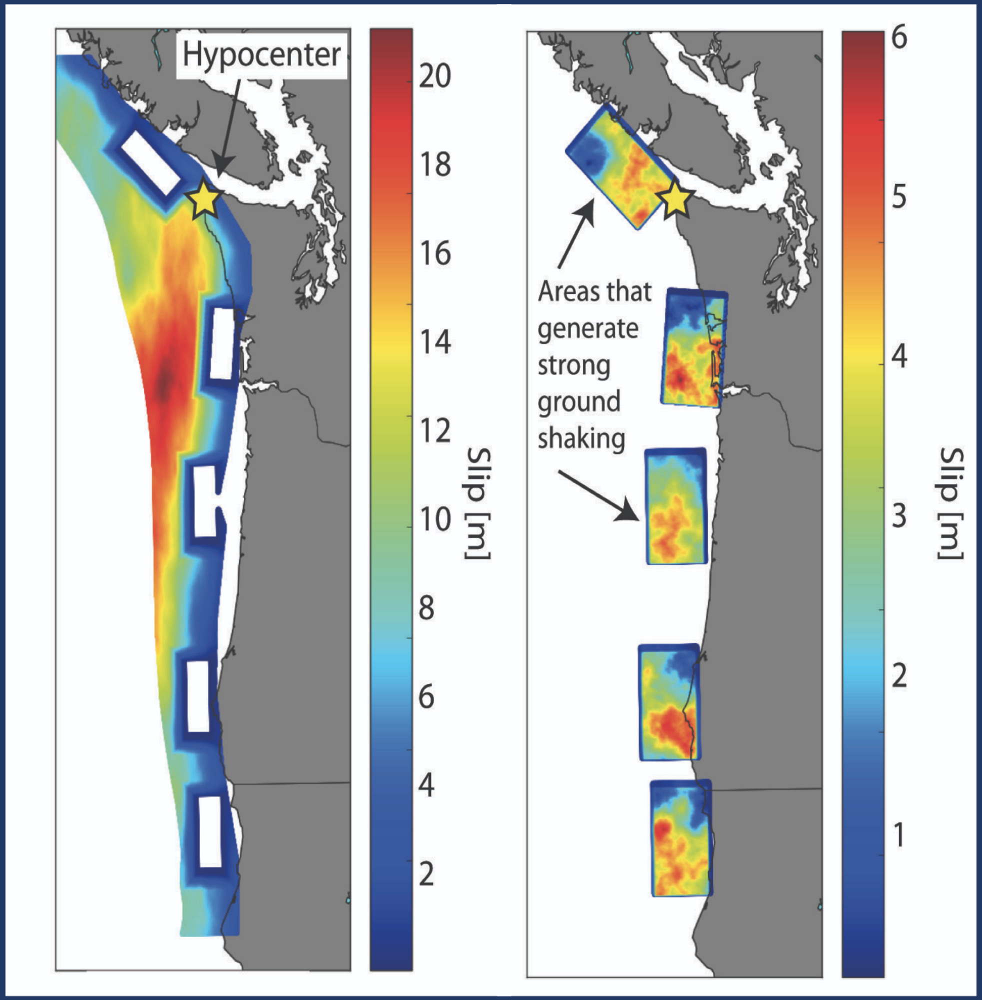
I: Cascadia M9 earthquake



Little is known about the characteristics of Cascadia M9 earthquake, but a variety of observations are available:

- Plate geometry and velocity structure
- Historical earthquakes and tsunamis
- Locking depth (~12-20km)
- Episodic tremor and slip (ETS) region (~30-40km)
- A gap between the locked region and the ETS region

I: Recent results from kinematic rupture simulations

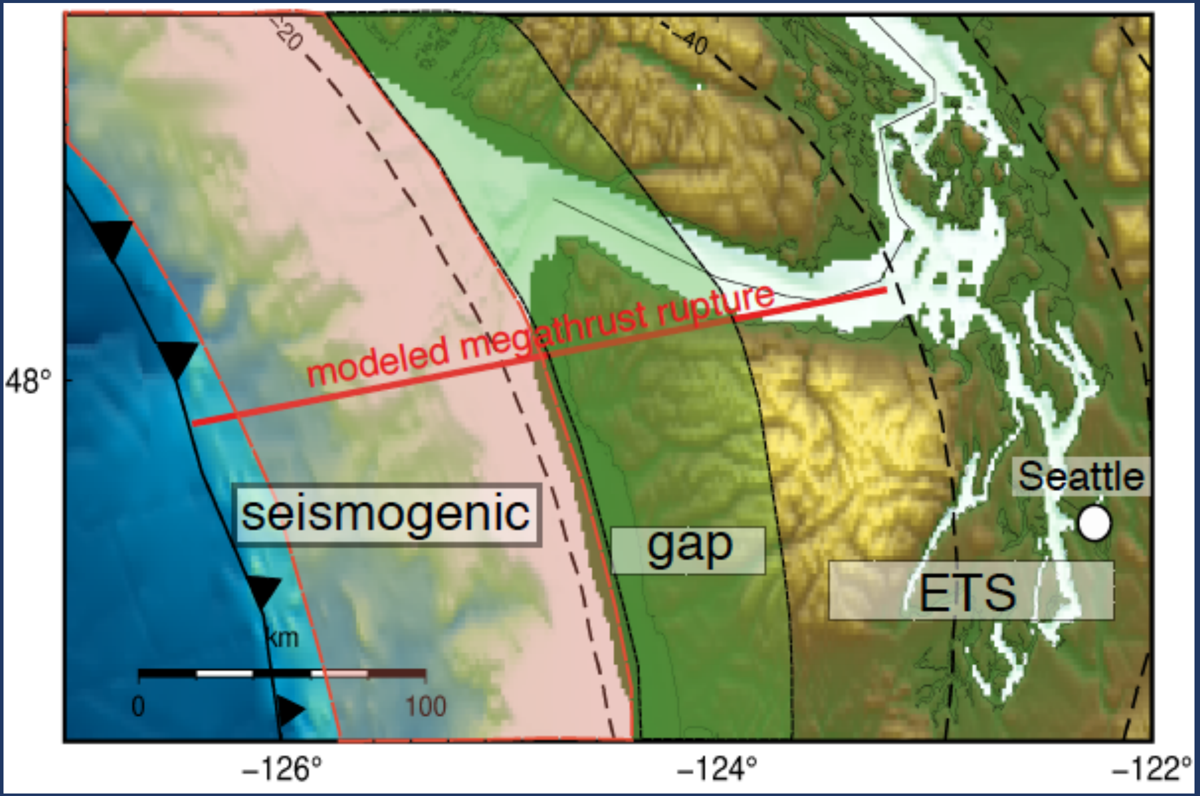


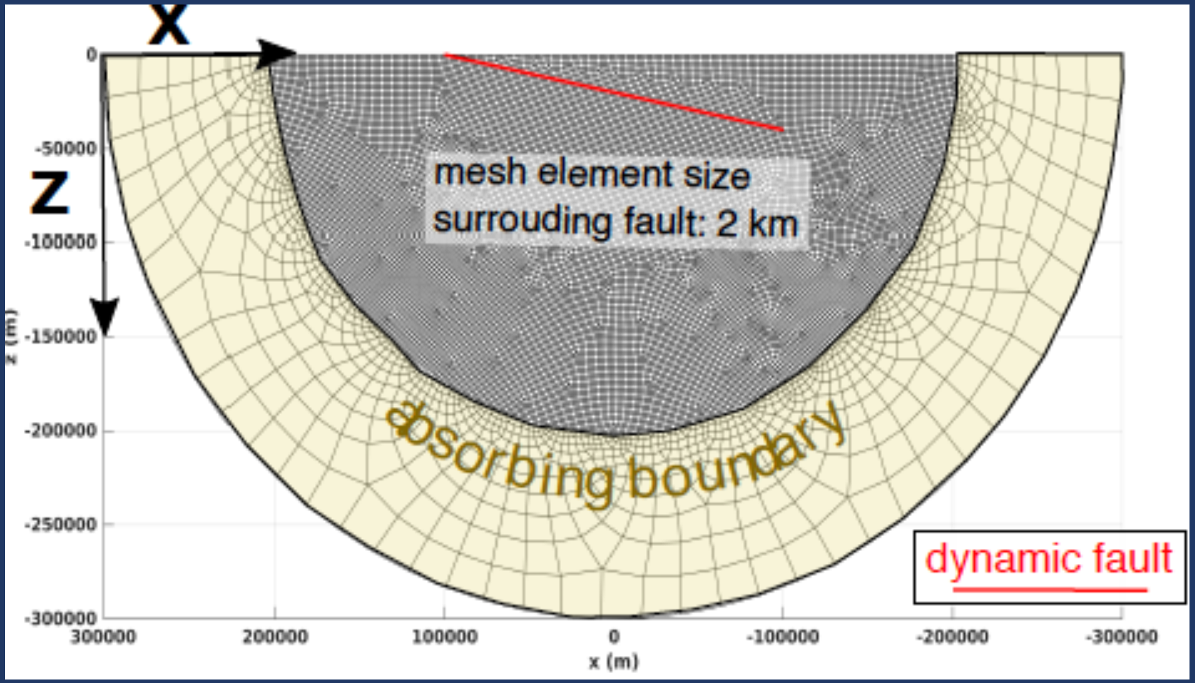
[Frankel et al., 2018; Wirth et al., 2018]

- Ground motions are generated from short rise-time multiple sub-events superimposed on a long rise-time slip distribution.
- Shaking intensity depends on the slip distribution, down-dip rupture limit, hypocenter and subevent locations.
- Extending the down-dip rupture limit to the top of the ETS region results in a ~2-3x increase in PGA for Seattle.

I: 2D Northern Cascadia dynamic rupture

Can we produce more constraints on slip distribution and down-dip rupture extent by incorporating the existing observations in dynamic rupture simulation?



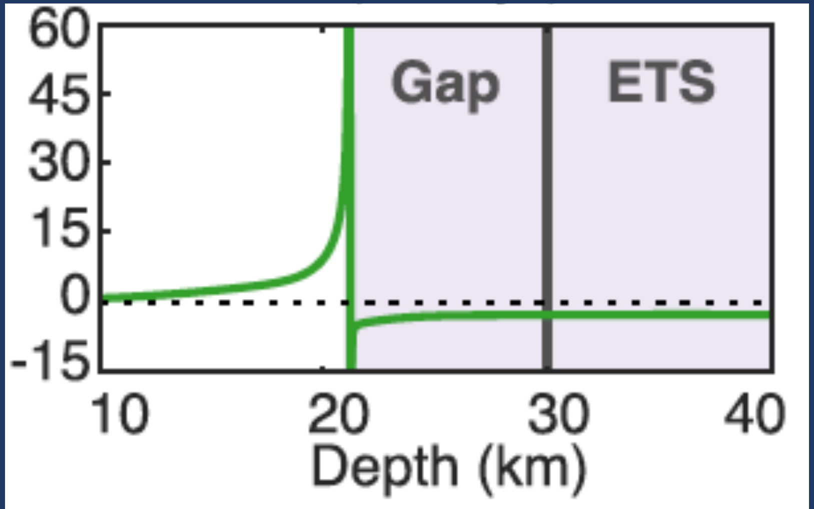


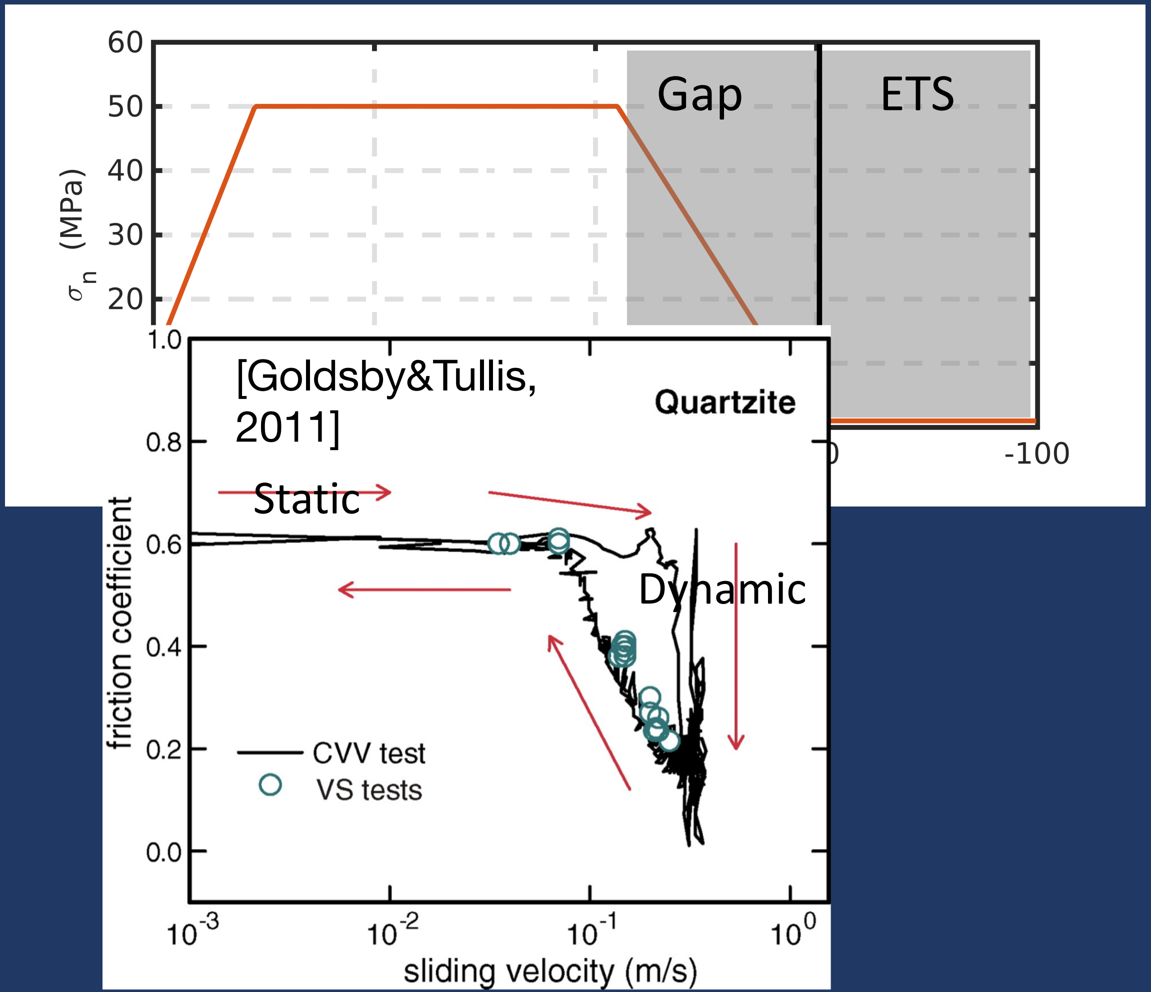
I: 2D Northern Cascadia dynamic rupture

Shear stress accumulation
= stress rate ✖ recurrence interval

Shear strength
= normal stress ✖ friction coefficient

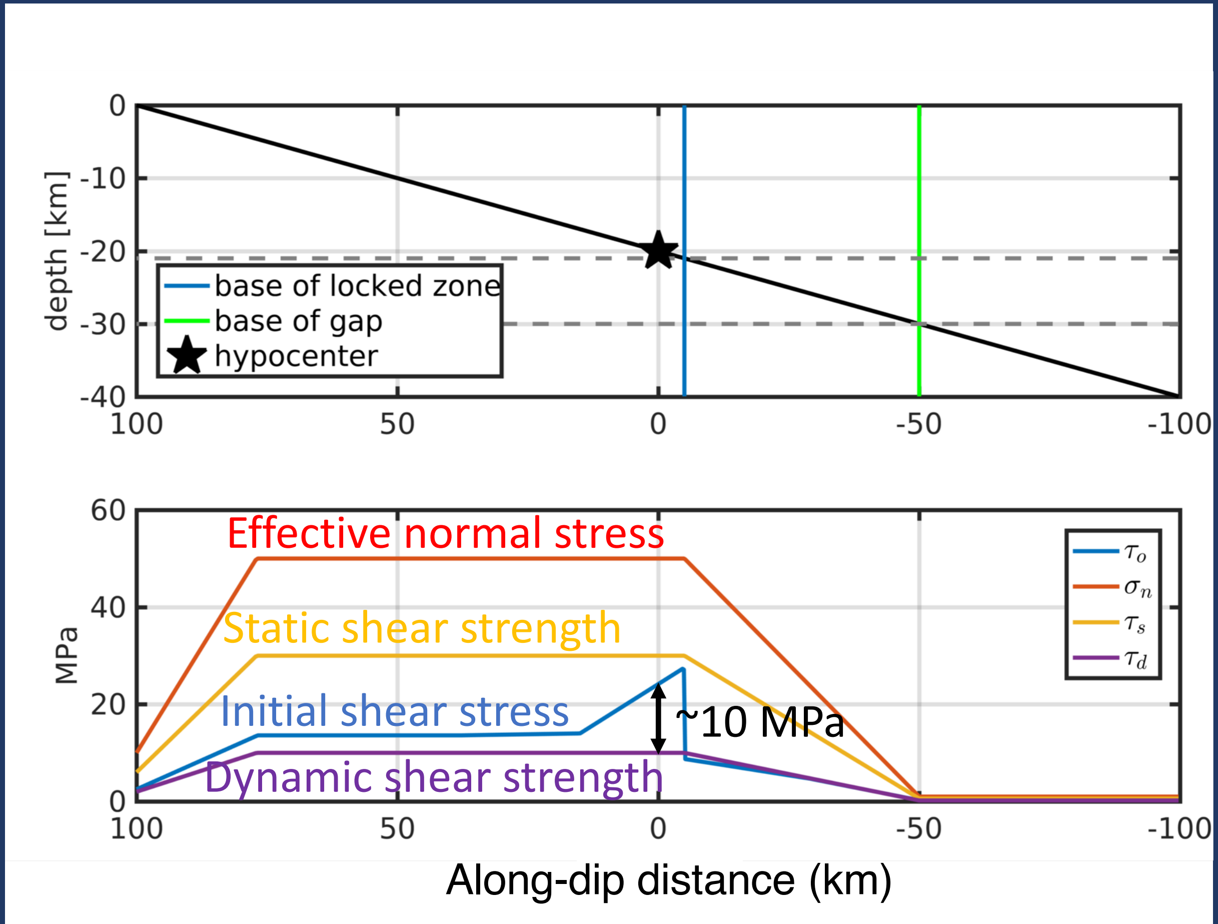
Stress rate (kPa/yr) inverted from GPS and tide gauge/leveling deformation rates [Bruhat&Segall, 2017]

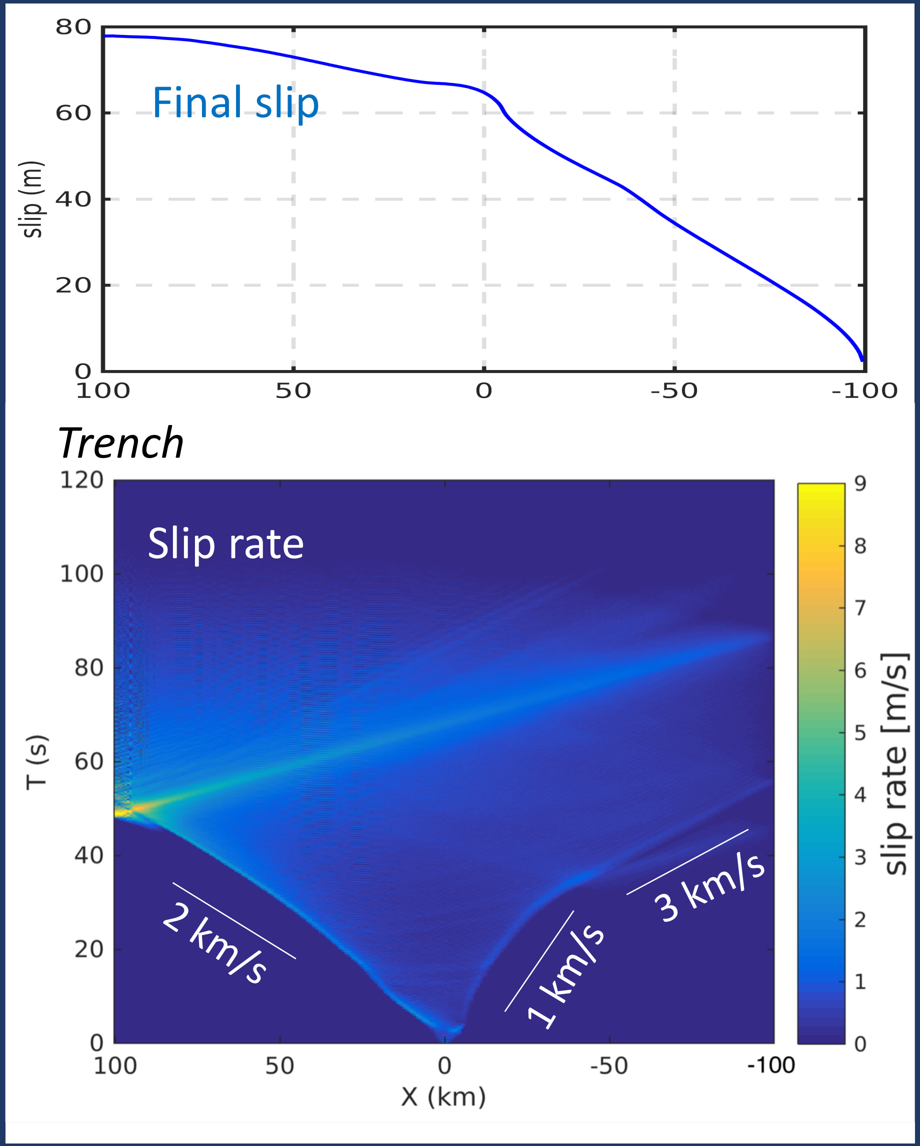




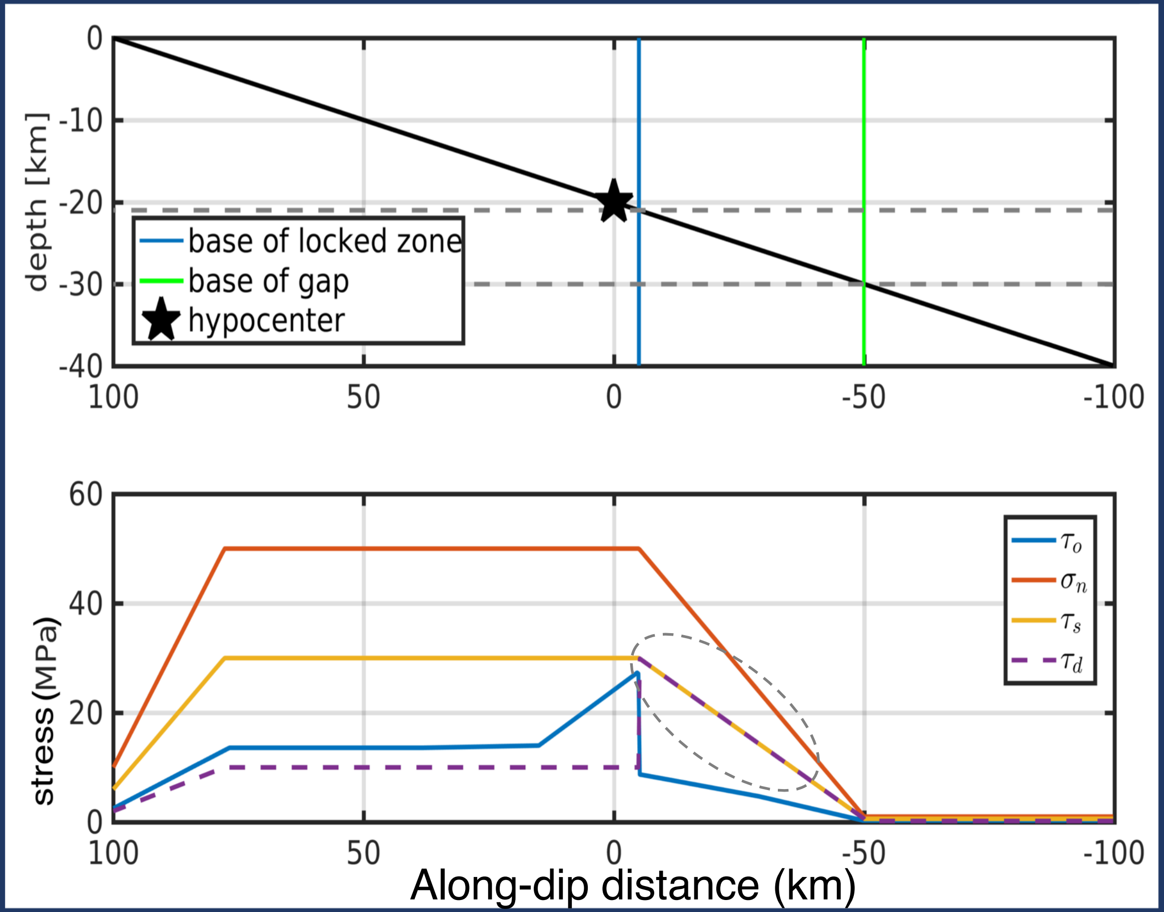
Given a recurrence interval of 500yr, the average shear stress accumulation right above the gap is ~10 Mpa.

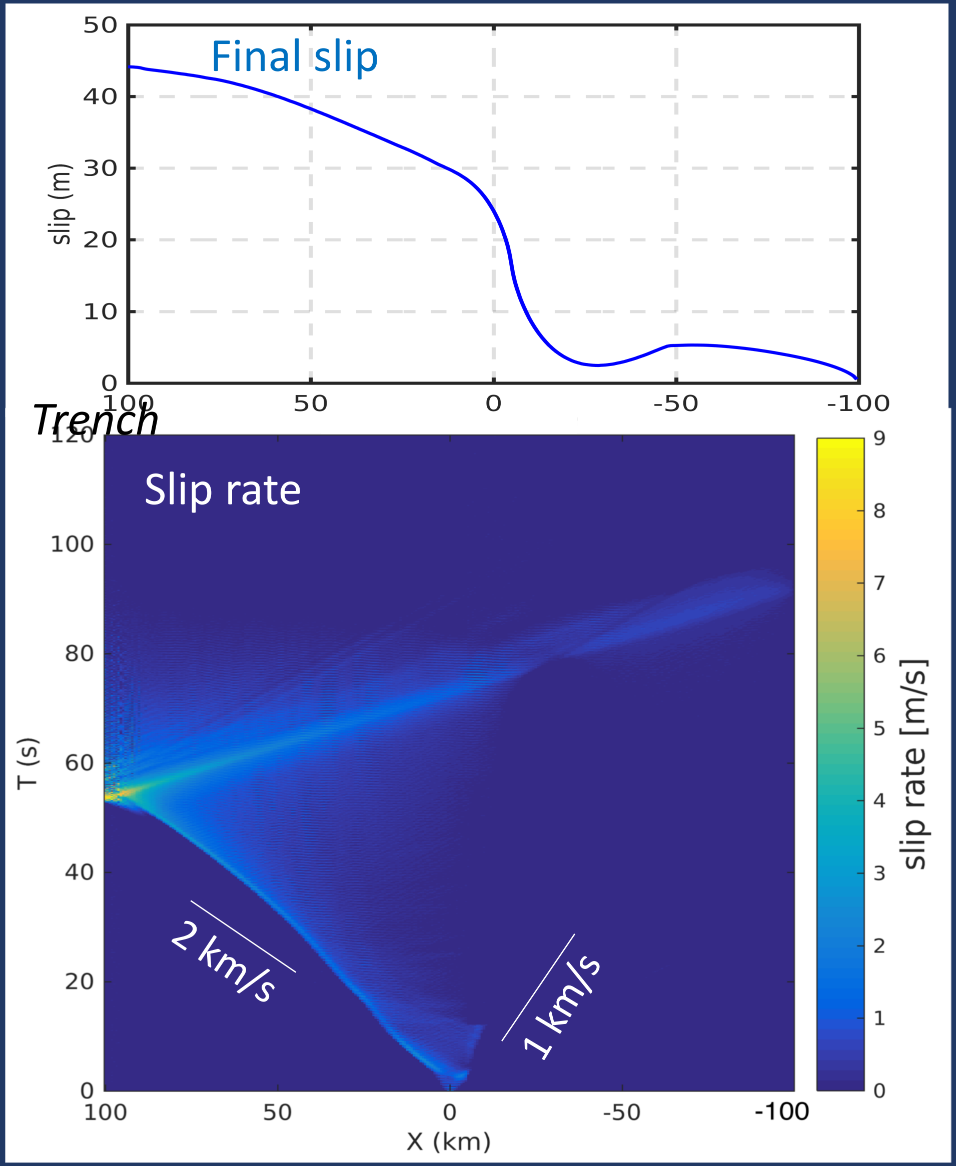
Model 1: Sharp shear stress gradient at the base of locked zone and dynamic weakening in the gap





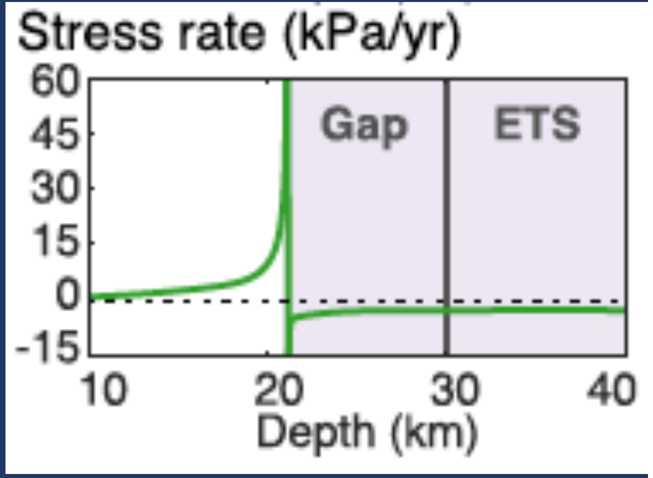
Model 2: Model 1 + Slip-neutral friction in the gap

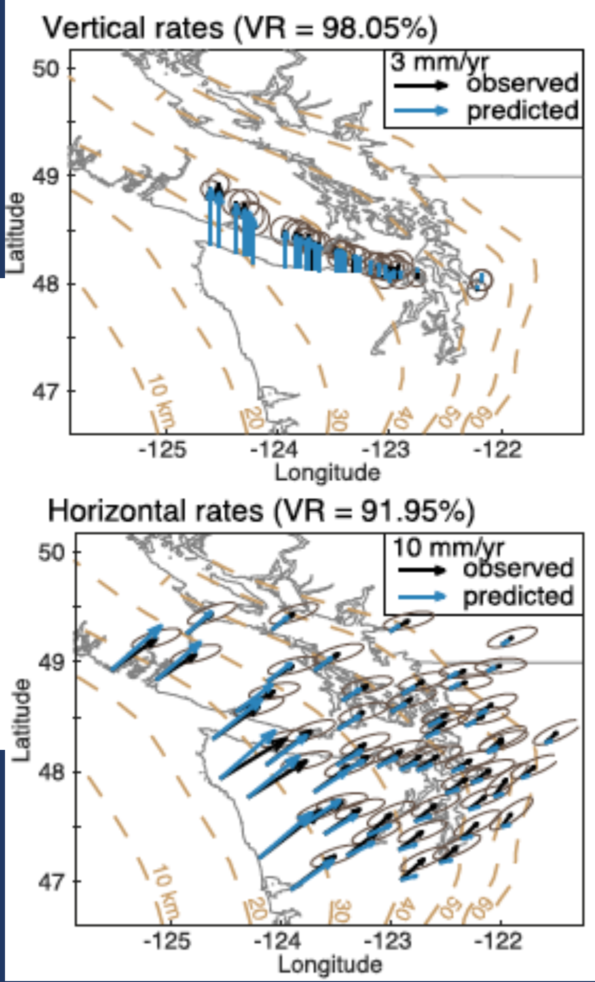




Summary I: It is the gap region that determines whether down-dip rupture can propagate to the ETS zone in Northern Cascadia.

Continuous monitoring of deformation rates

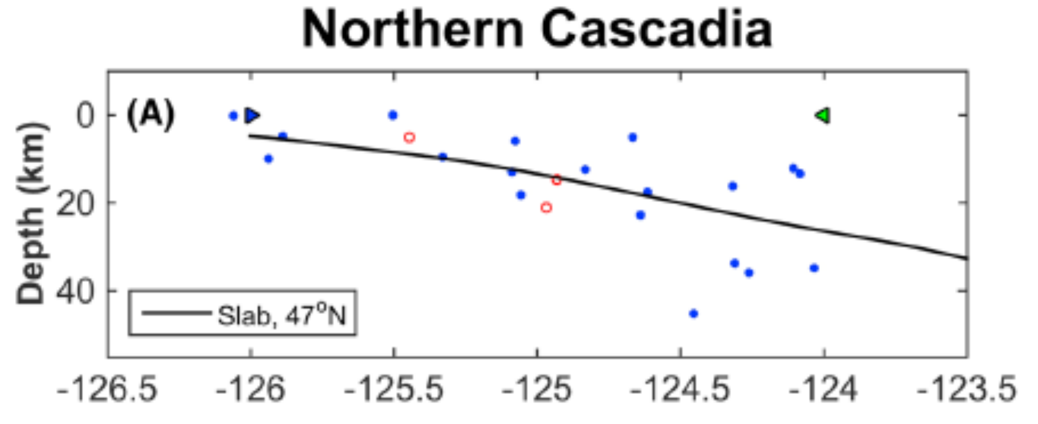




[Bruhat&Segall, 2017]

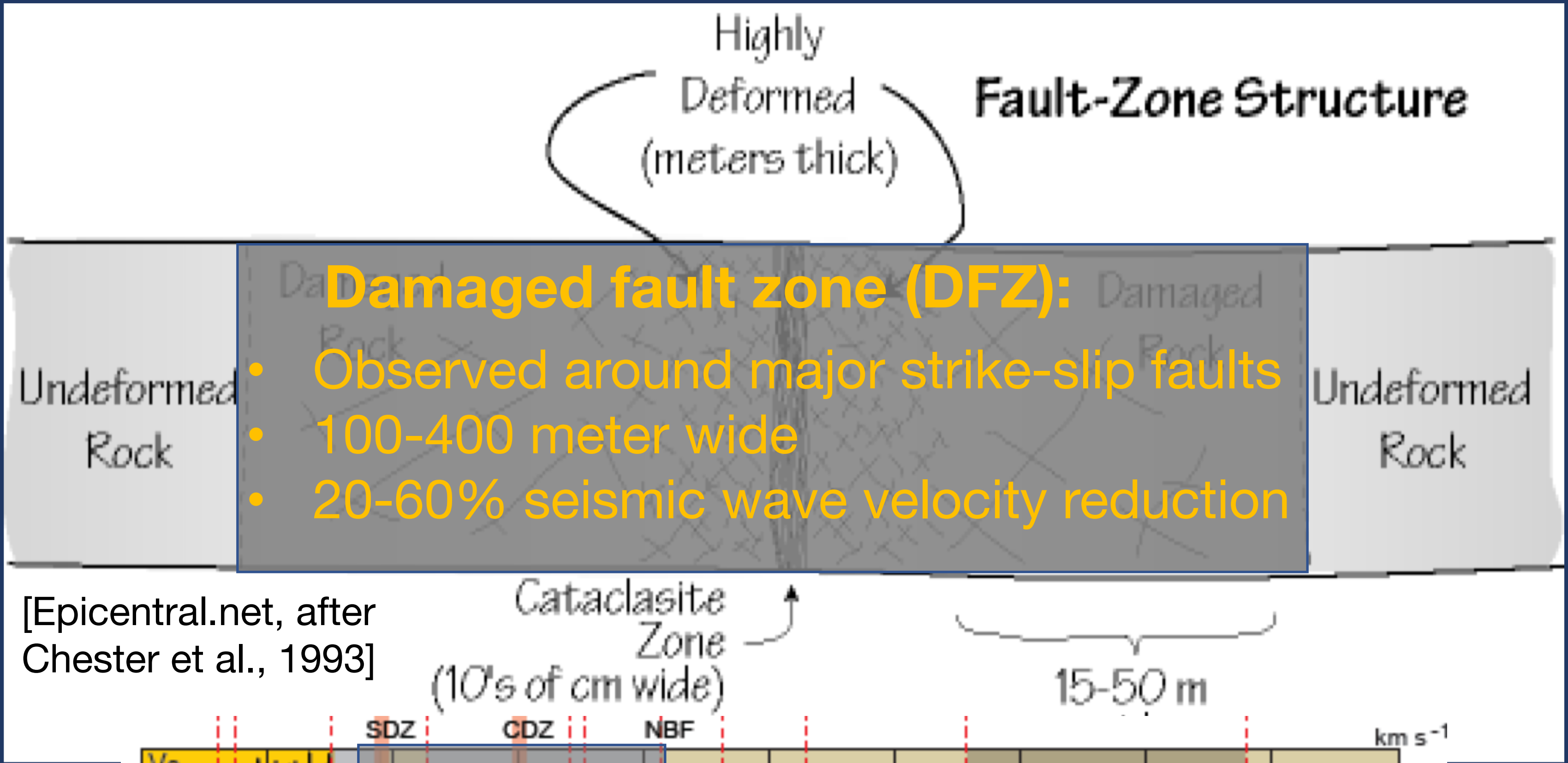
Continuous monitoring of seismicity on plate interface

Earthquakes detected from 4-yr Cascadia Initiative OBS data



[Stone et al., 2018]

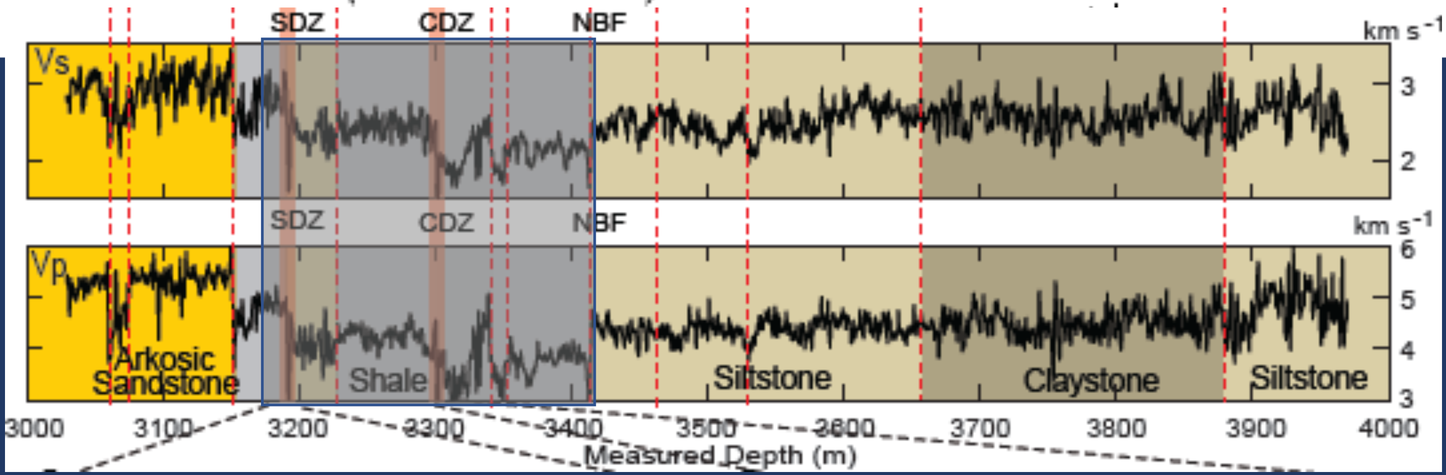
II: Earthquakes occur in damaged fault zones



Damaged fault zone (DFZ):

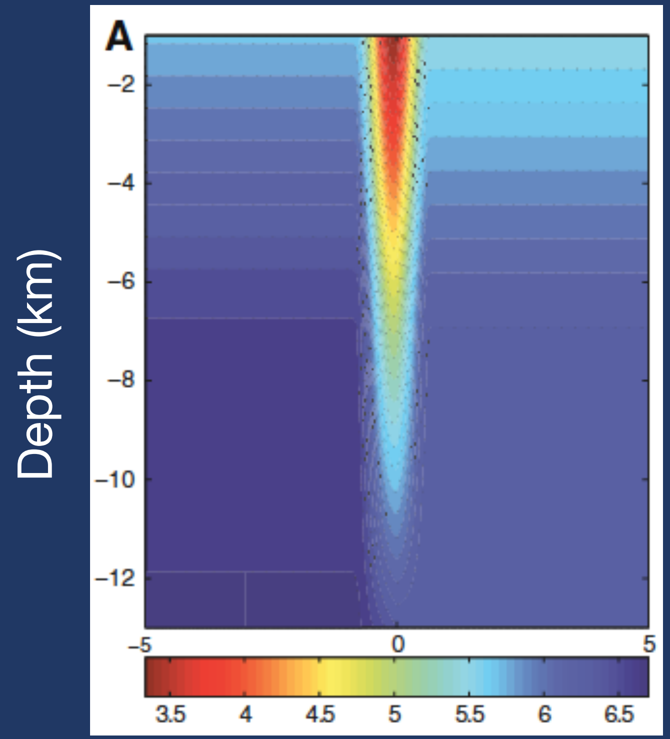
- Observed around major strike-slip faults
- 100-400 meter wide
- 20-60% seismic wave velocity reduction

[Epicentral.net, after Chester et al., 1993]



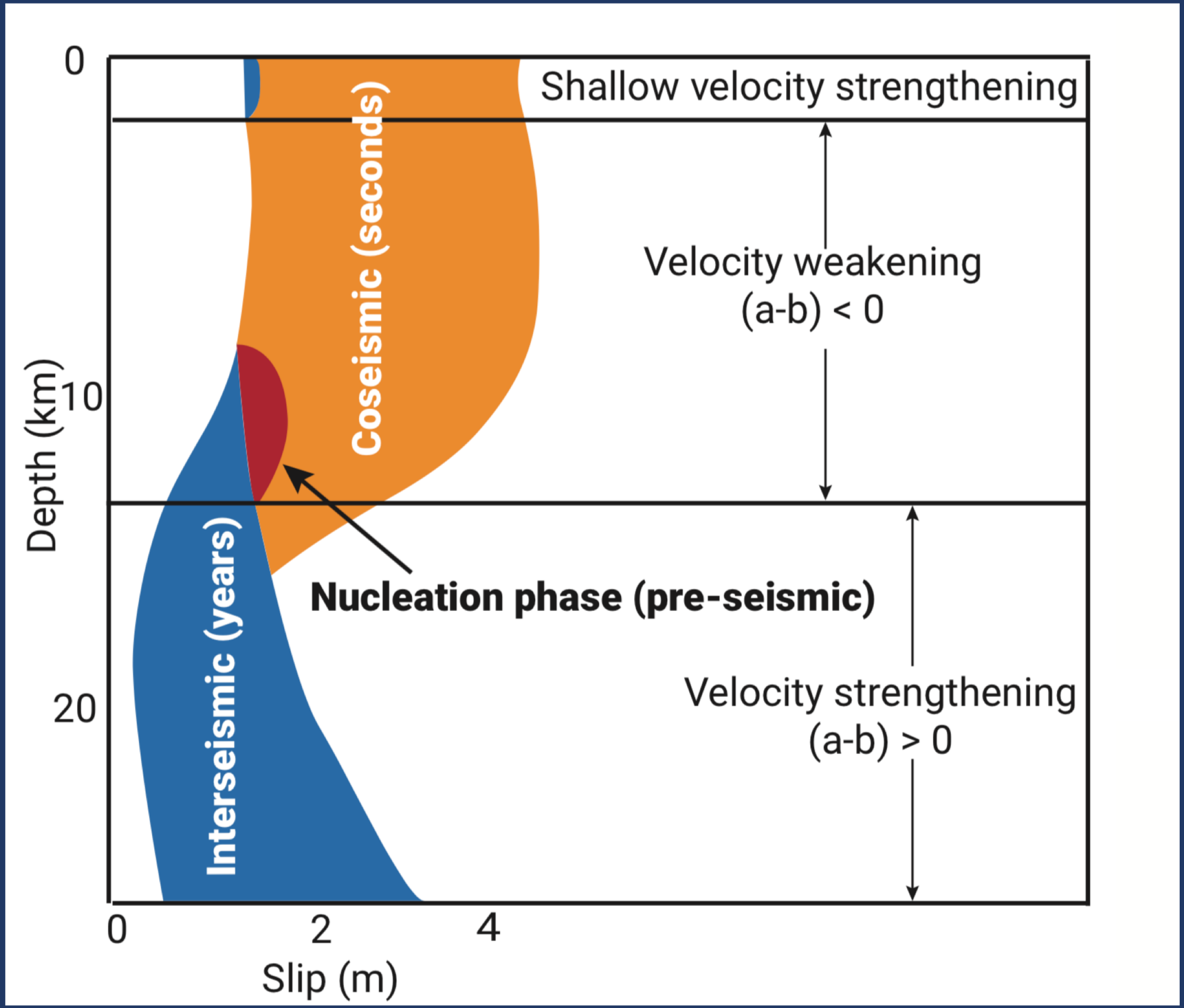
[SAFOD borehole data from Zoback et al., 2011]

II: DFZ structure varies along depth

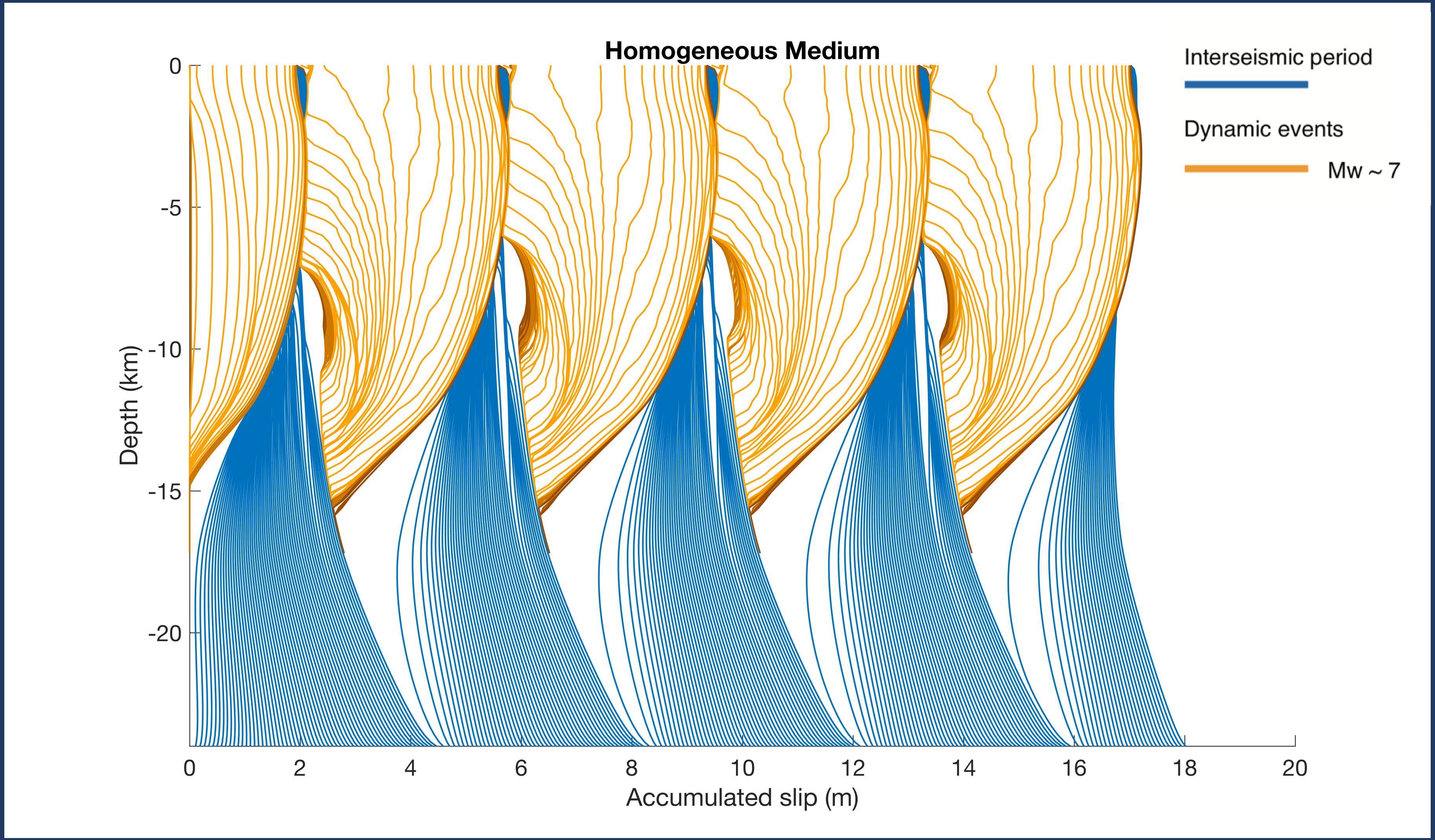


P wave velocity (km/s)

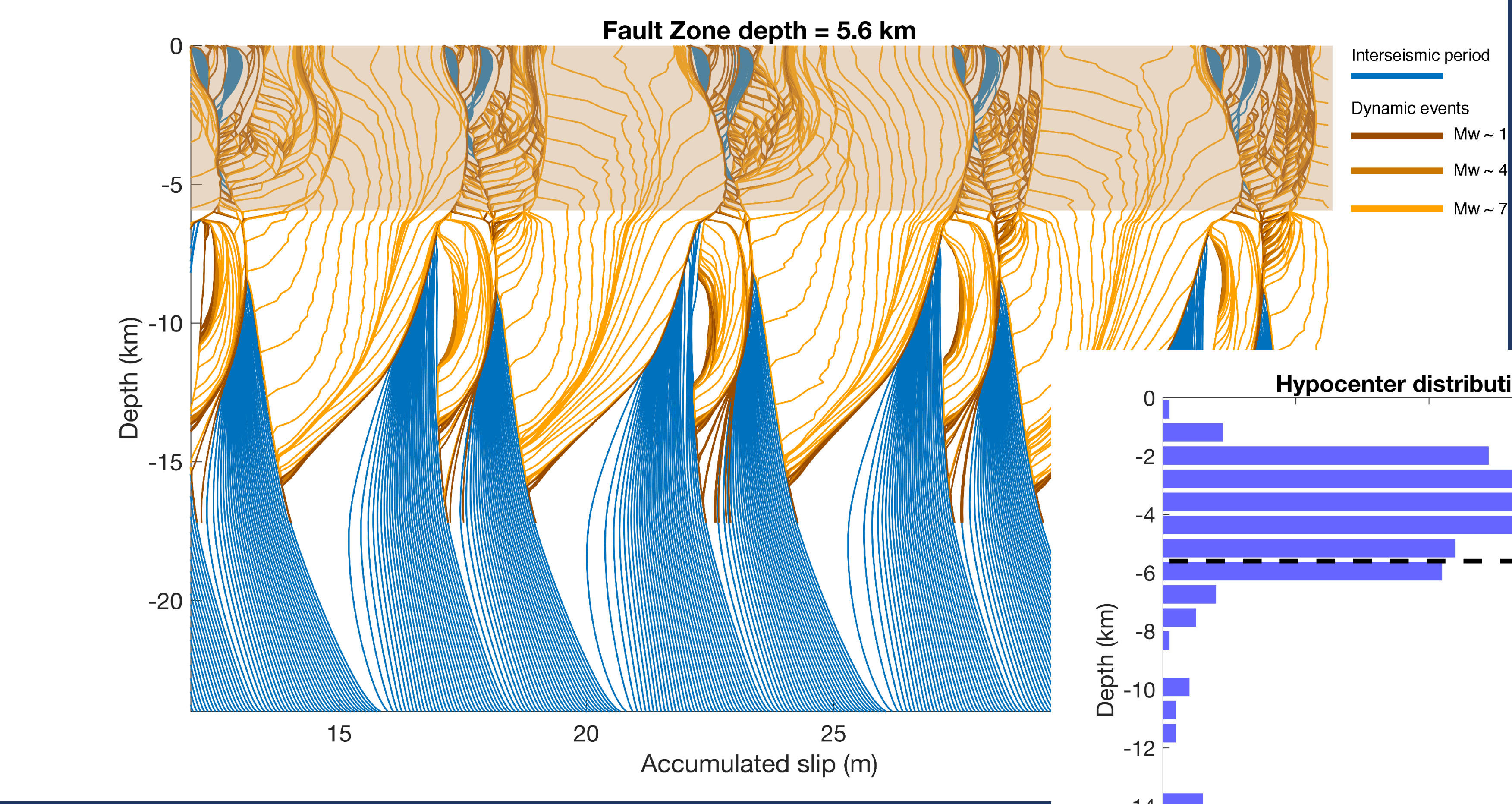
[Cochran et al., 2009]

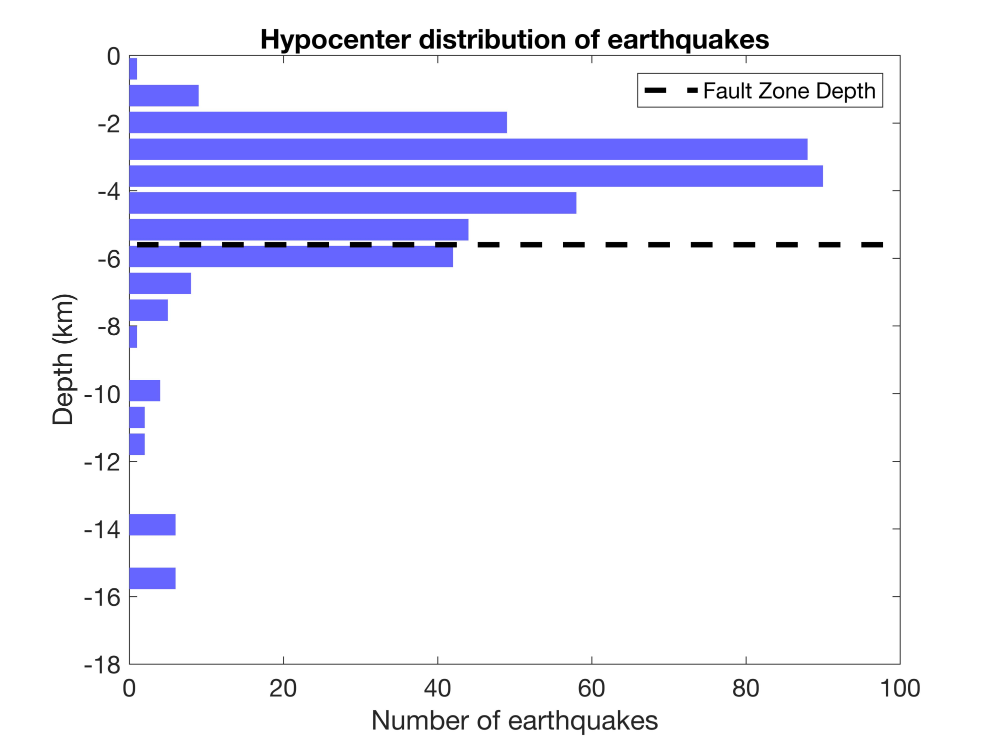


Model 1: Earthquake cycles in a homogeneous medium



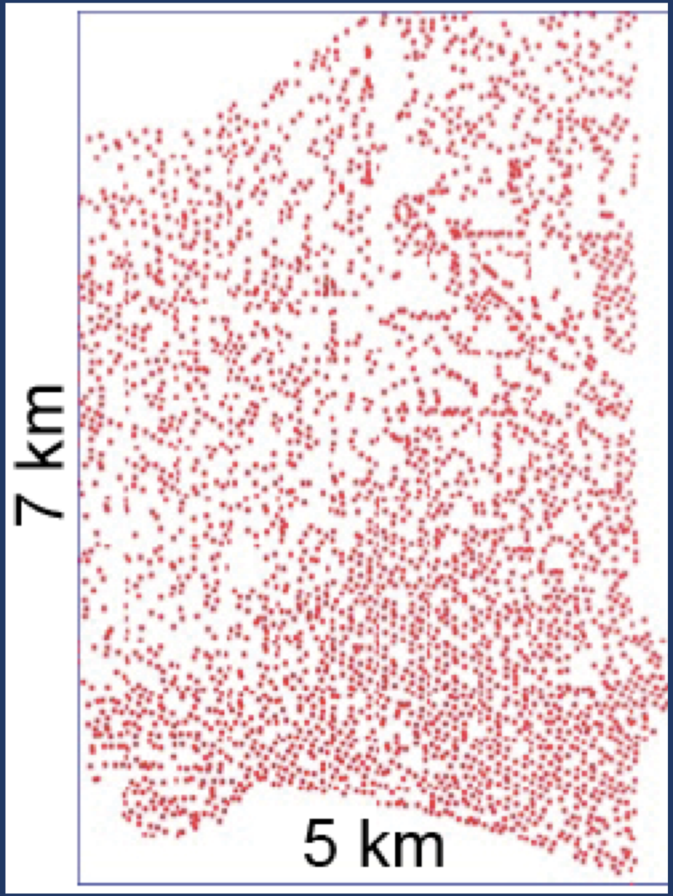
Model 2: Earthquake cycles with a DFZ

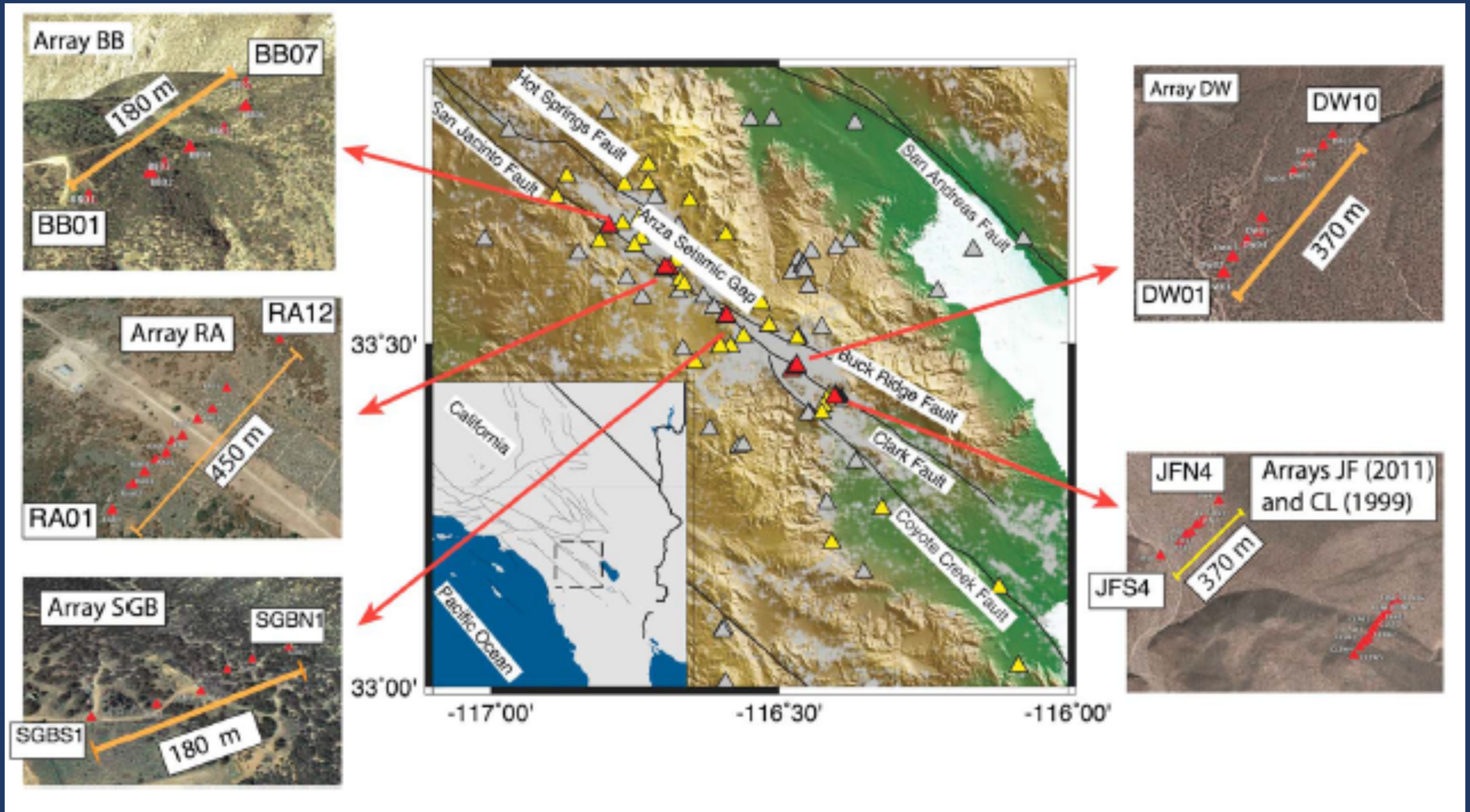




Summary II: Seismicity tends to cluster inside damaged fault zones.

A better understanding of fault zone material heterogeneity using dense arrays





Conclusions

- Northern Cascadia rupture is likely to start near the bottom of locked region due to the concentration of shear stress there. Whether it can propagate to the ETS zone depends on the rheology of the gap region.

- Material heterogeneities like damaged fault zones can cause rupture termination and control seismicity distribution. They generate heterogeneous stress field and earthquakes with a wide range of sizes.