The seismic consequences of being a leaky fault

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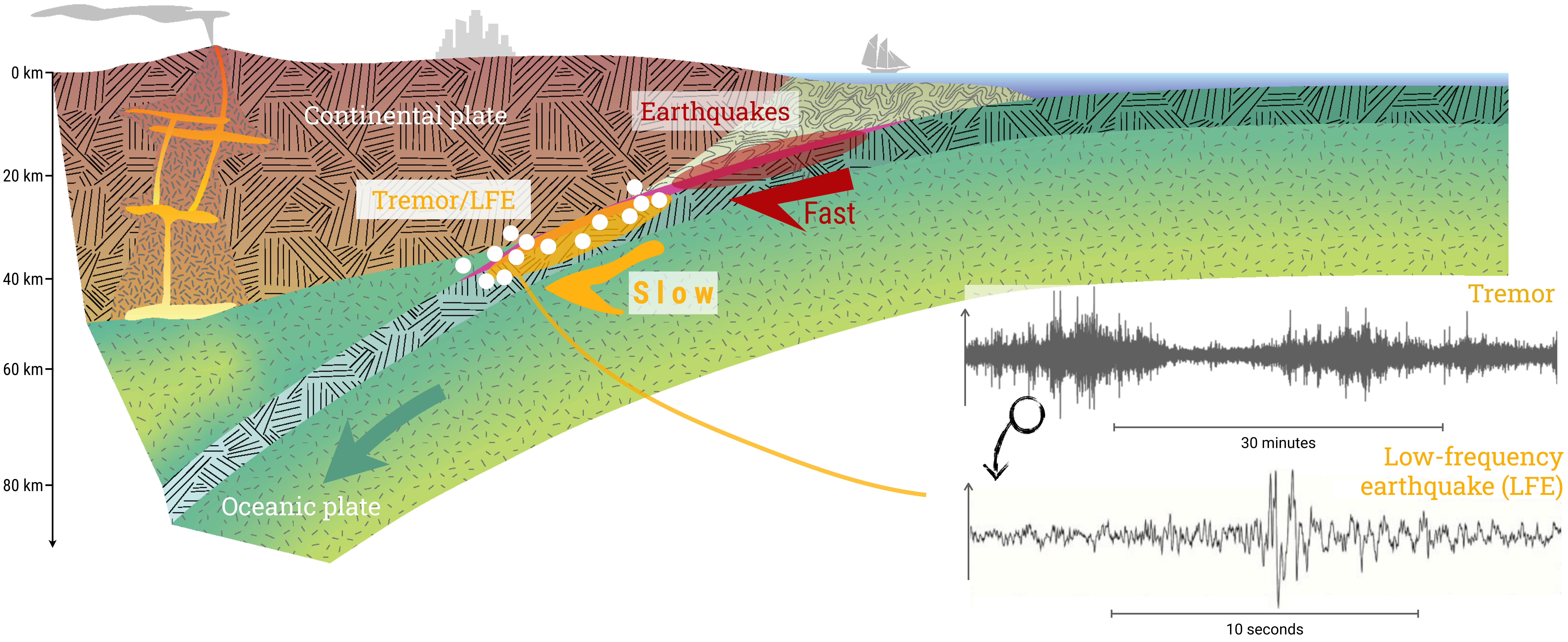
Tremor indicates a fast stress release process on (near) the plate interface



Tremor activity is “synchronized”

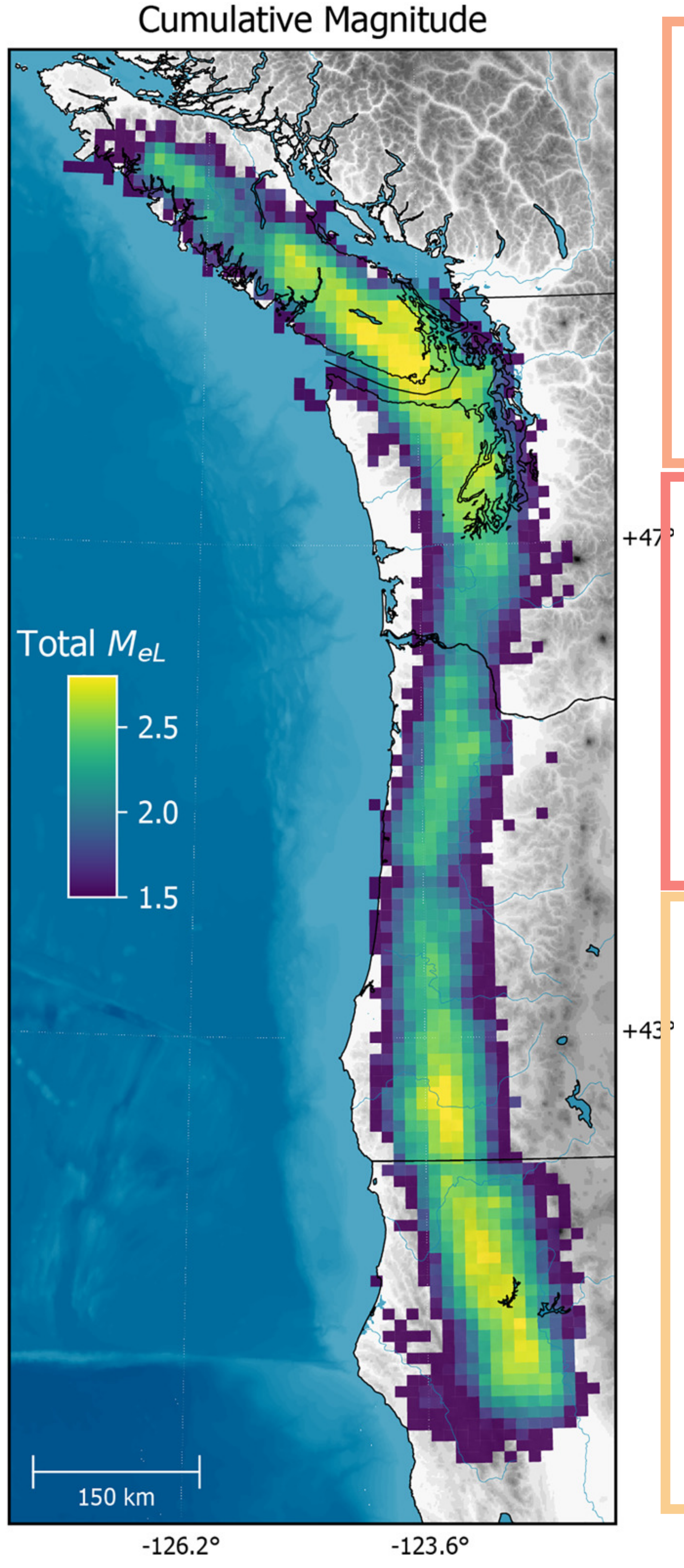
i.e. Large portions of the fault activate at the same time

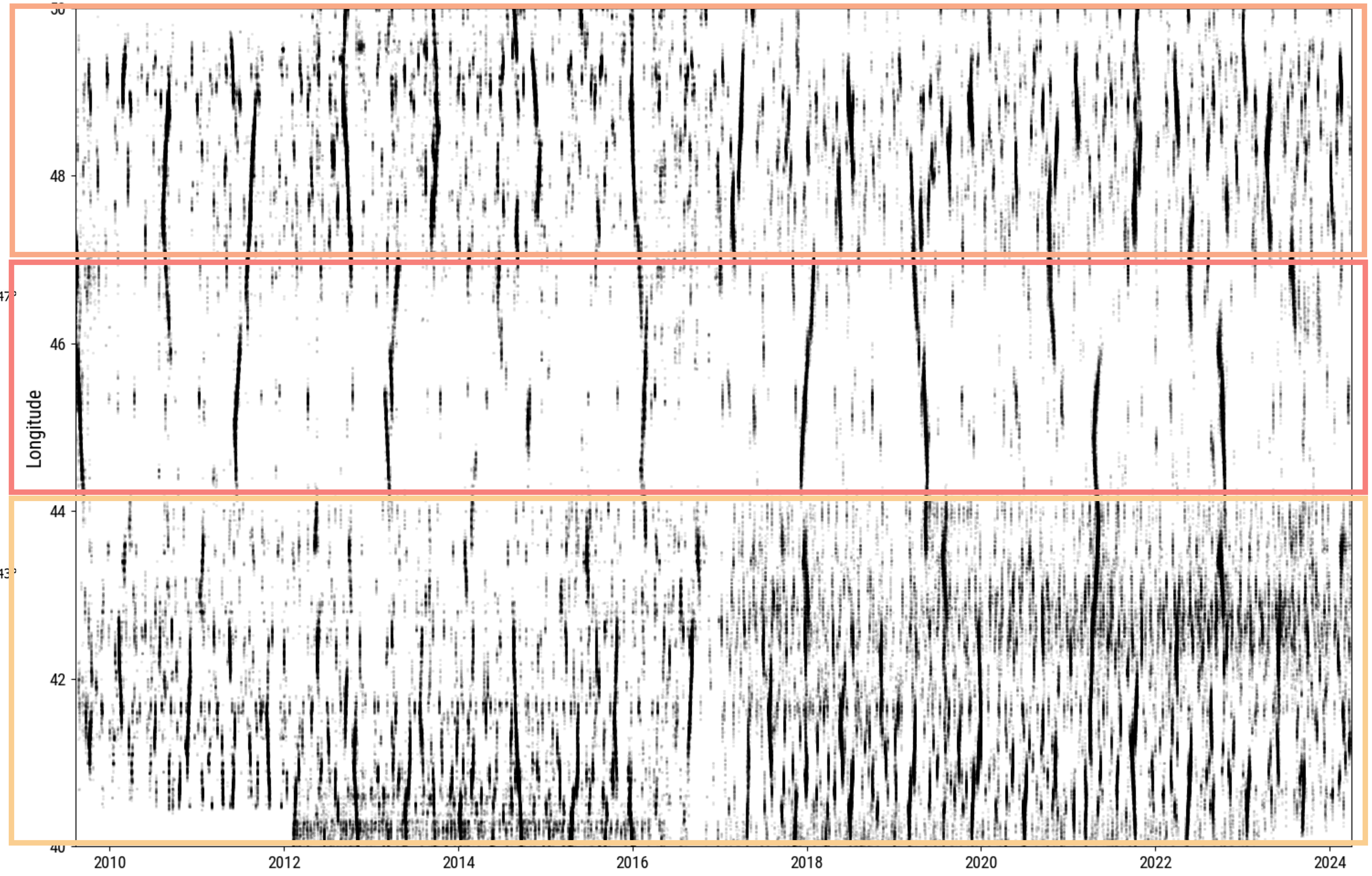
➡ Characteristic sizes

➡ Periodicity

Segmentation of tectonic tremor in the Cascadia subduction zone

Adapted from Wech et al. (2021, 2008 etc)





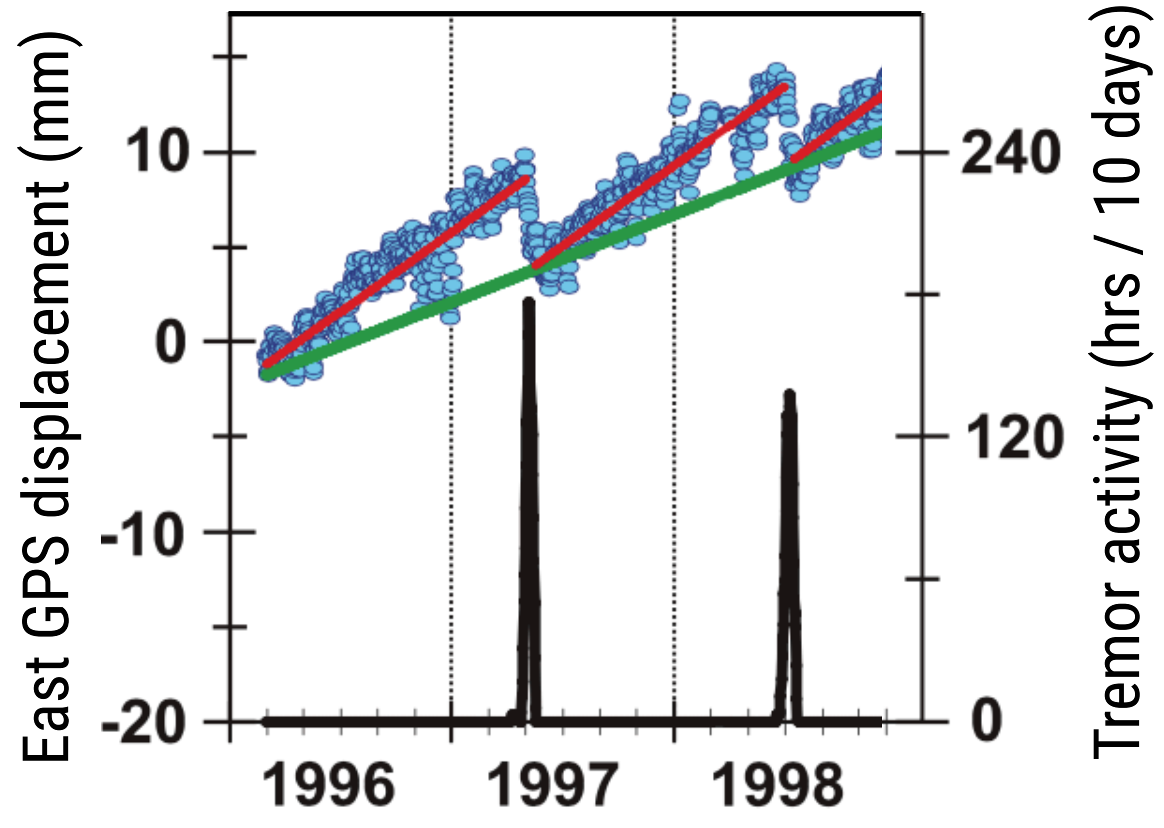
Quasi-periodic activity, long-period (~14 mo) recurrence. Intermediate scale synchronization.

Quasi-periodic activity, long-period (19 mo) recurrence Large-scale synchronization

Temporally clustered activity, ~9 mo recurrence scale Shorter-scale synchronization

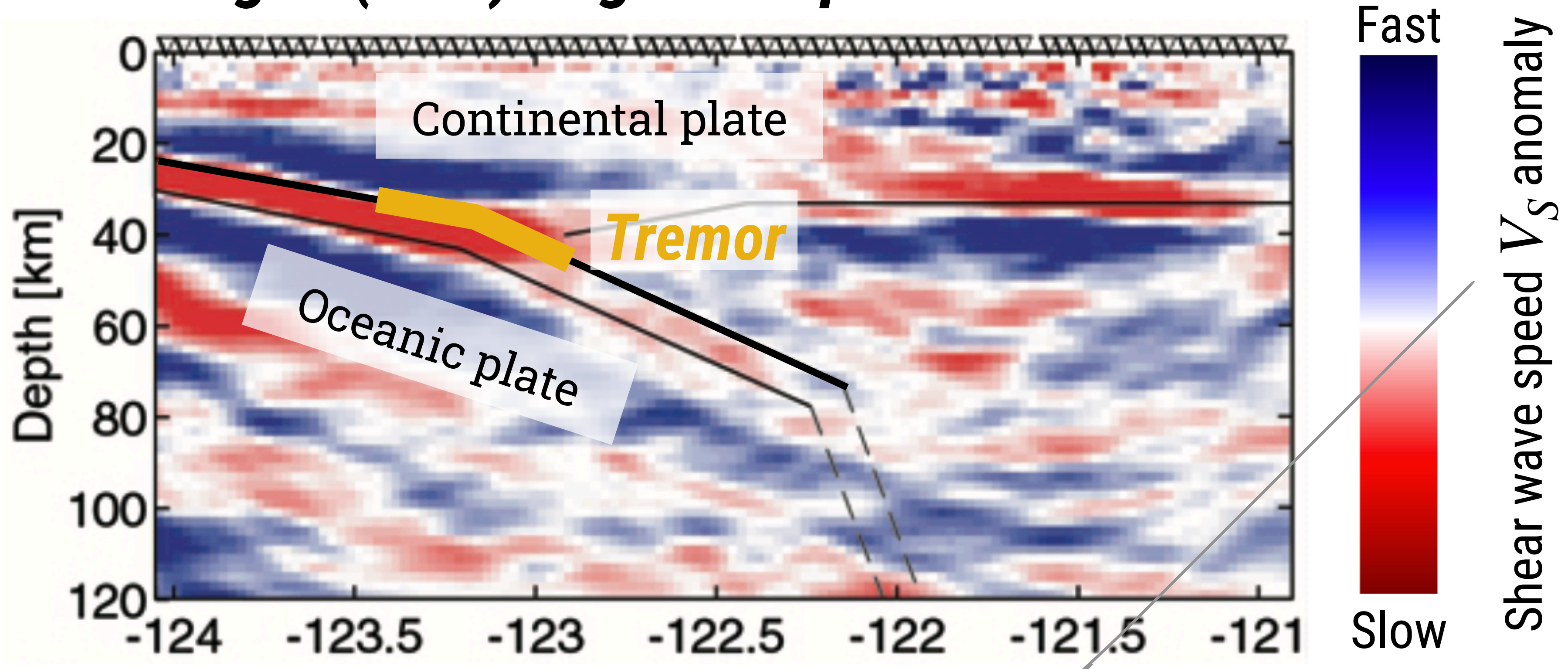
Tremor is generated as the fault slips slowly, in a high fluid pressure environment

Tremor and slip under Vancouver Island



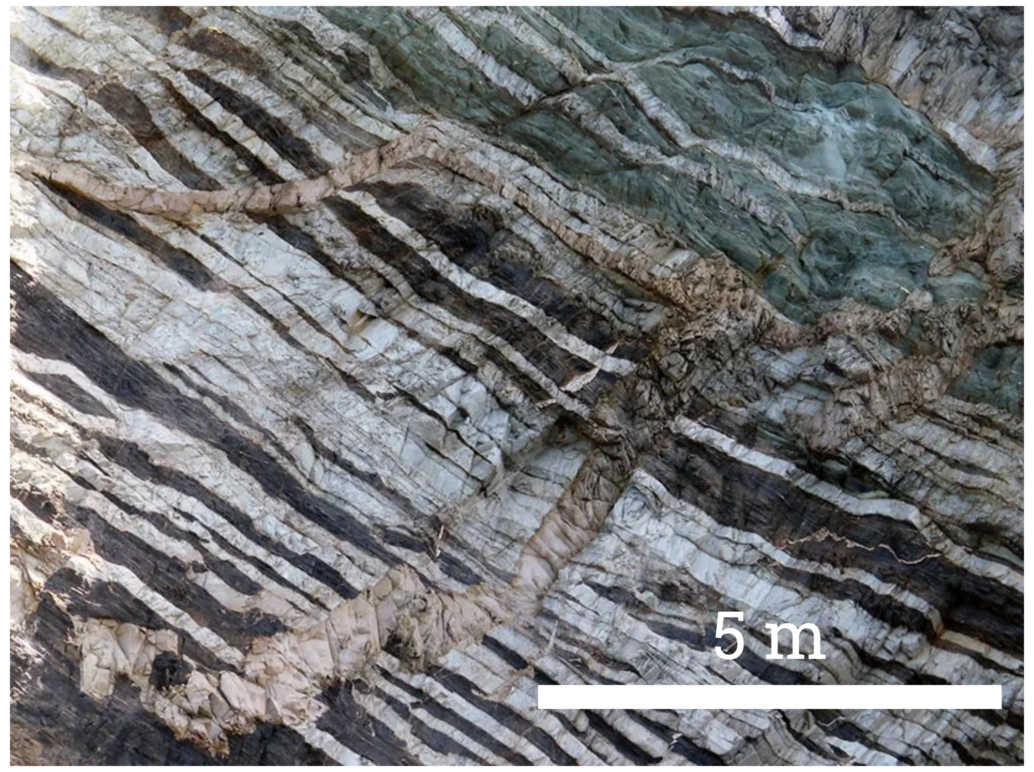
Modified from Rogers & Dragert (2003)

Low velocity zone in tremor source region, in Oregon (USA): high fluid pressure?



Adapted from Rondenay et al. (2001)

Veining and hydrofracturing (CA, USA)



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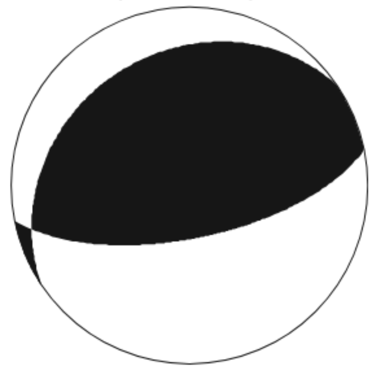
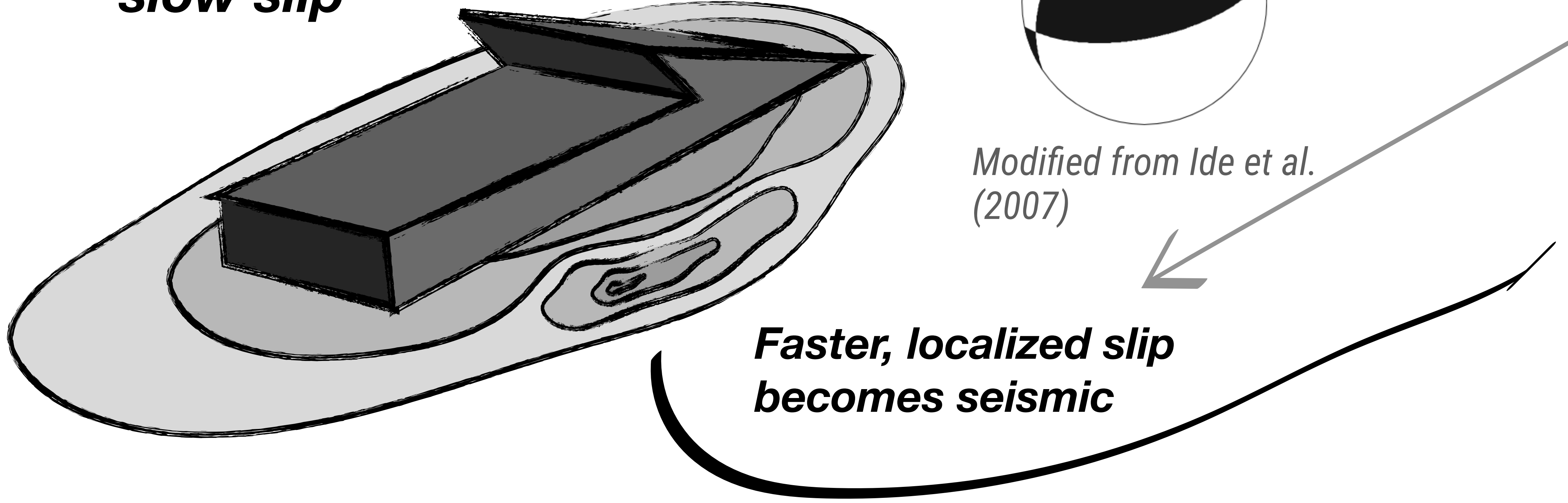
LFE focal mechanism (Nankai, Japan)



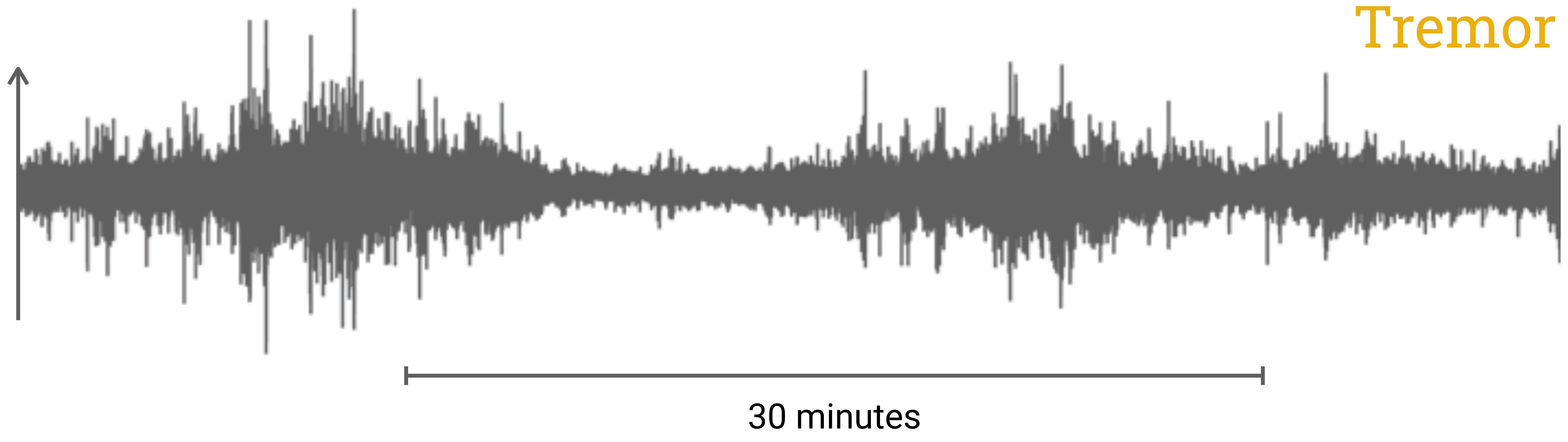
Modified from Ide et al. (2007)

Geodetically-detected slow slip



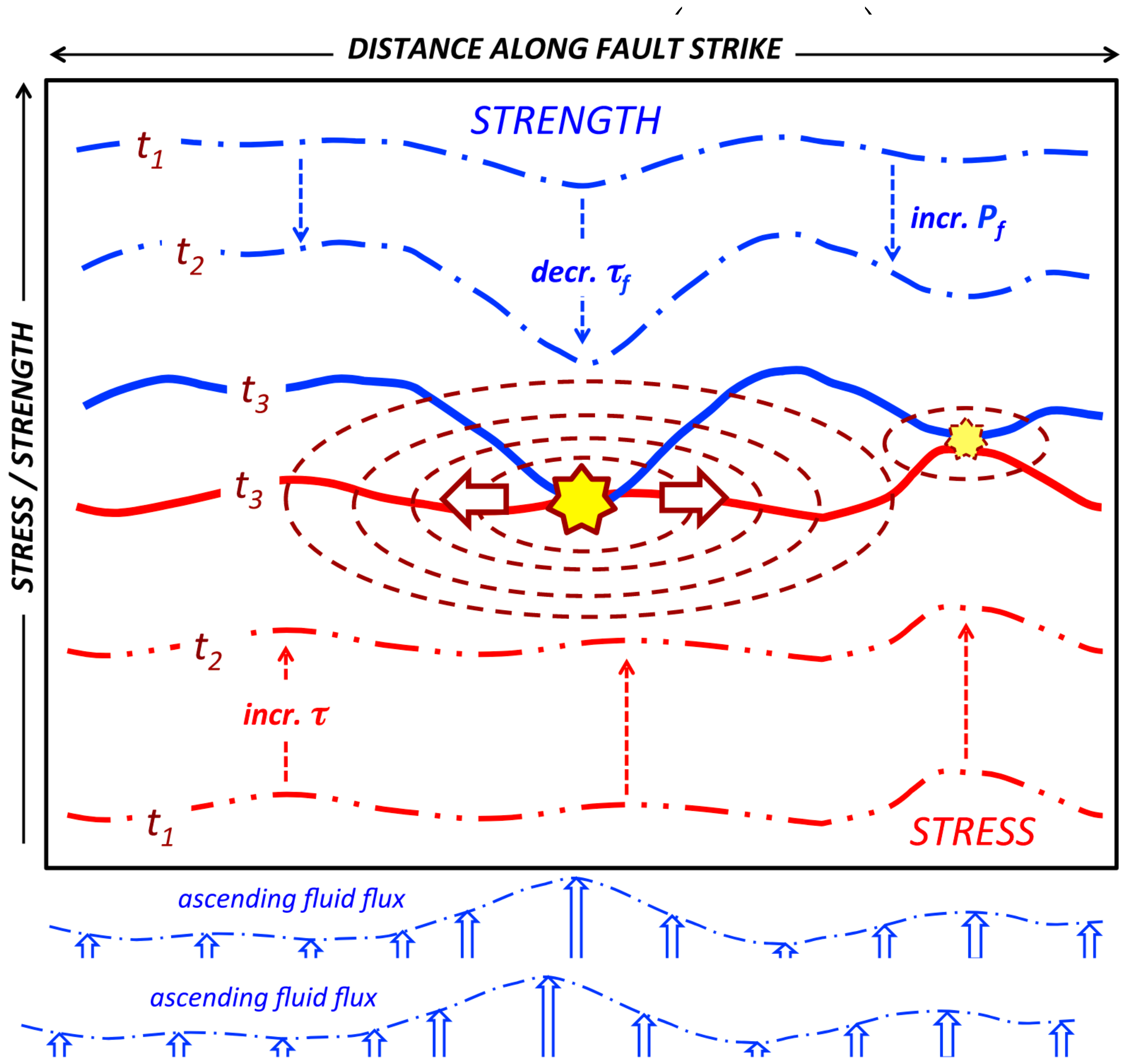
Faster, localized slip becomes seismic

Strong, fast (?) fluid pressure transients



A fault-valve mechanism

Hydraulic and ***solid*** stresses load the fault simultaneously

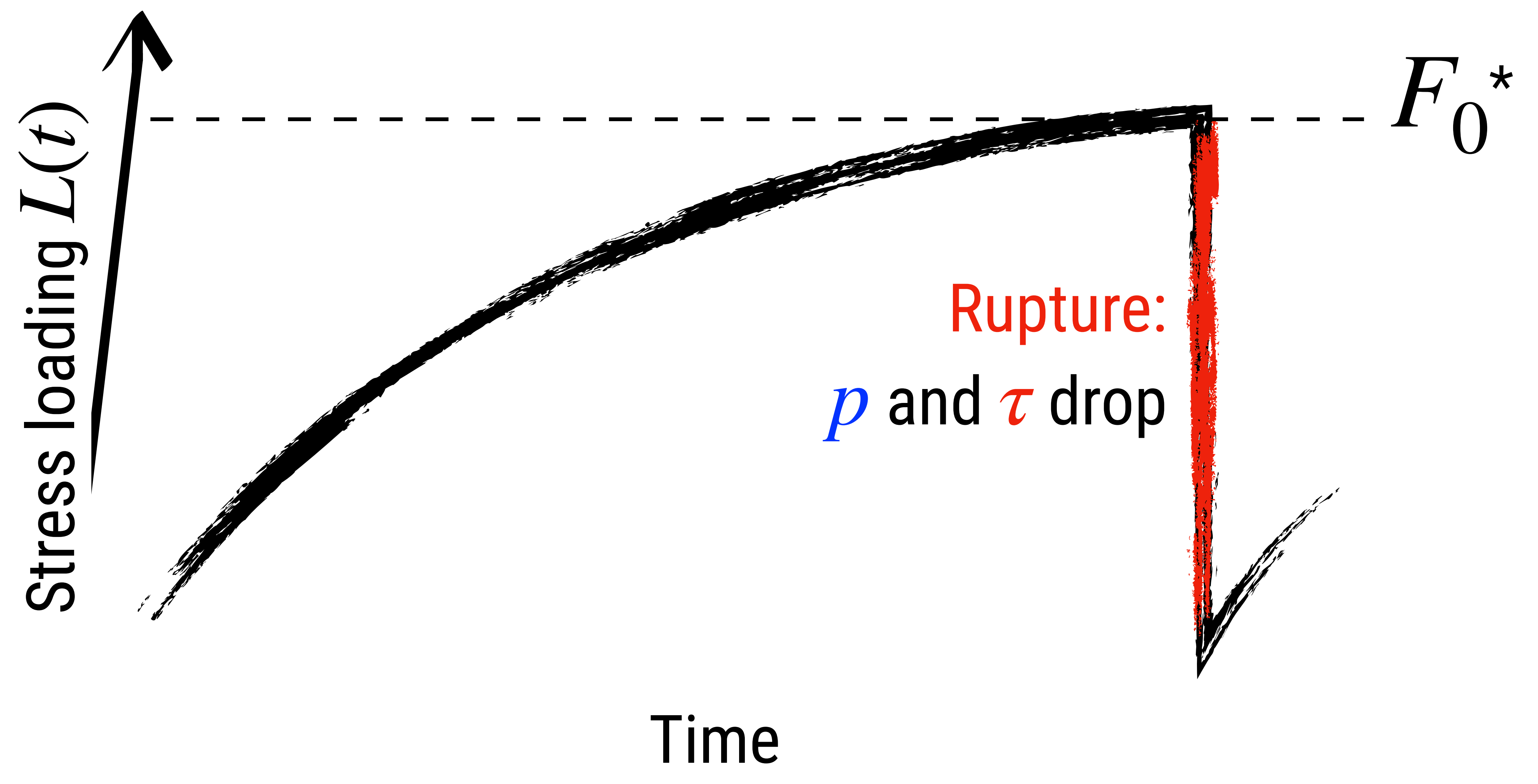


Hydraulic loading

Solid stress loading

Stress to failure: $F = \mu\sigma_n - \left(\boxed{\mu p(t)} - \tau(t)\right)$

Stress loading: $L(t) = \boxed{\mu p(t)} + \tau(t)$



$^*F_0$: Residual fault strength after failure

($F_0 = \mu\sigma_n$ for full stress drop)

A fault-valve mechanism

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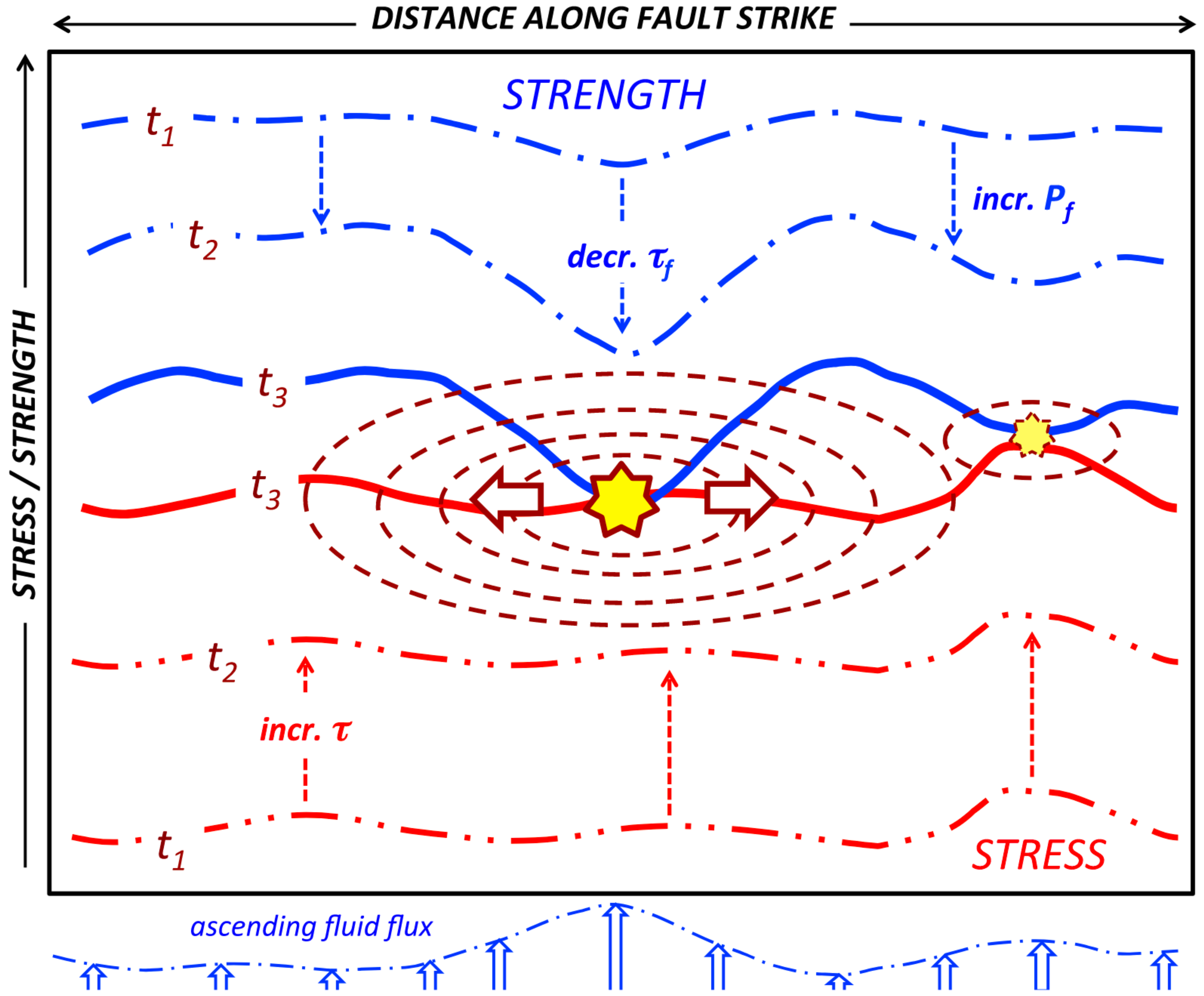
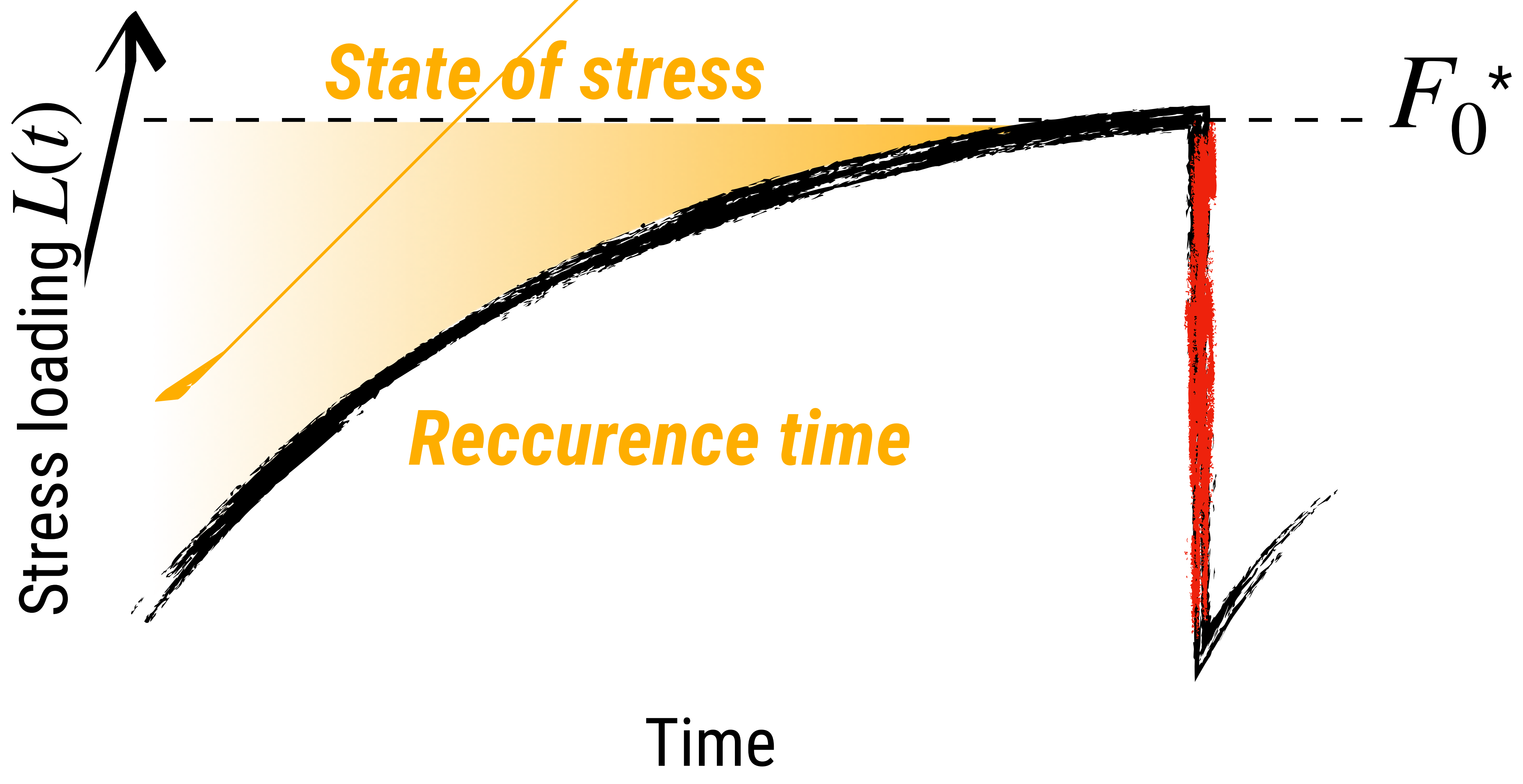


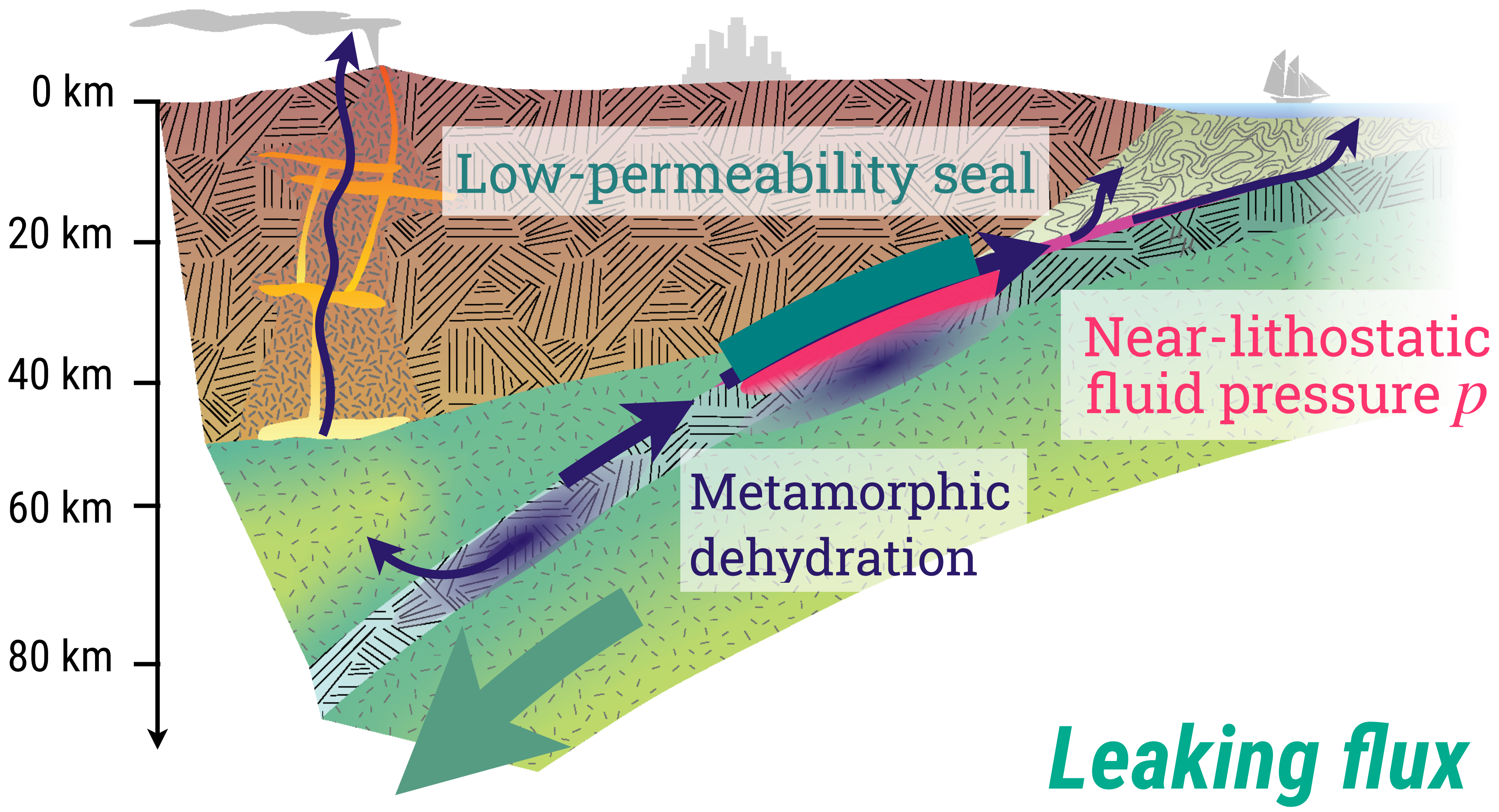
The dynamics of stress accumulation has fundamental consequences on the seismic cycle



$^*F_0$: ***Solid***+***Hydraulic*** strength

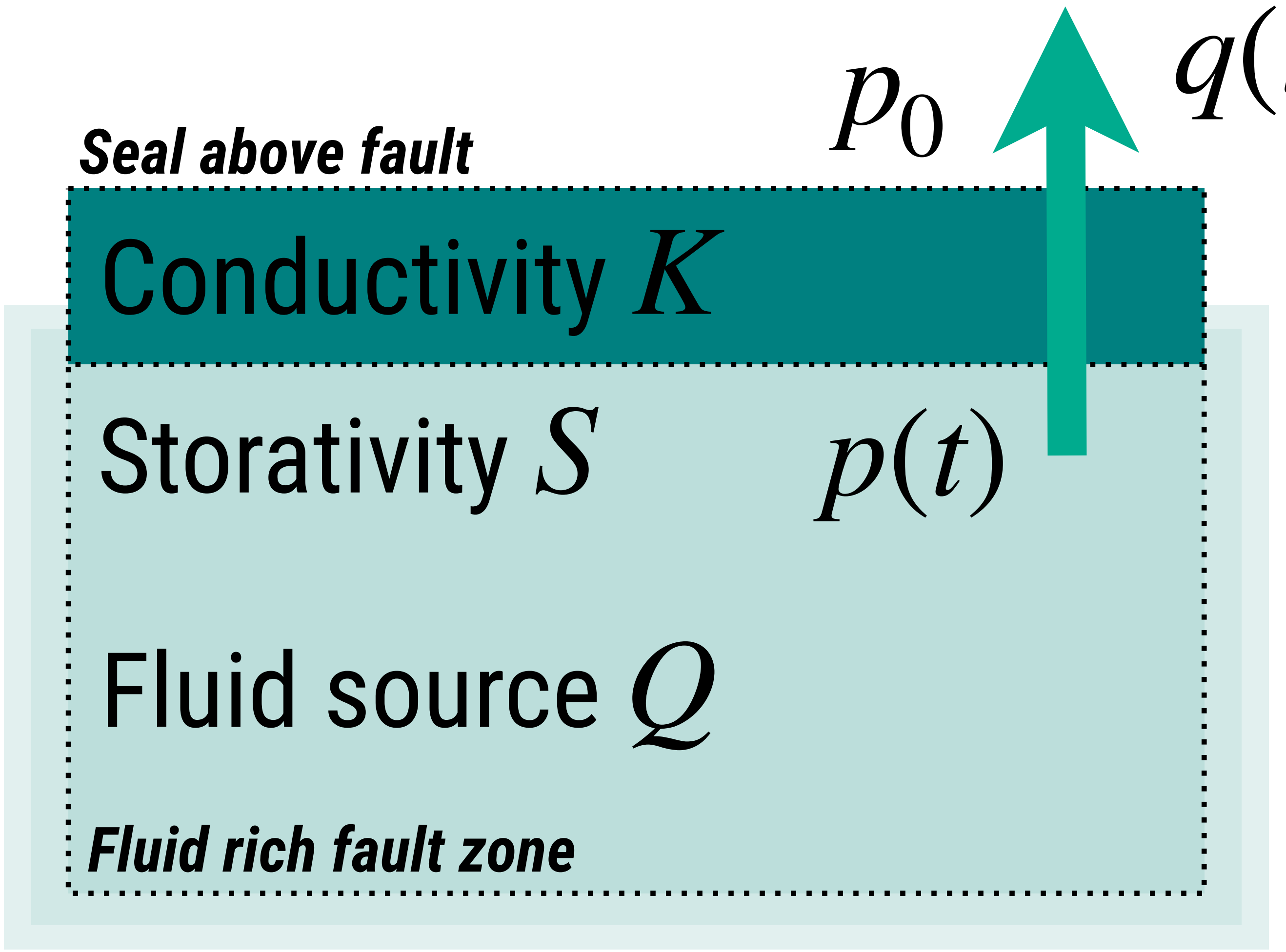
Stresses leak out of the fault

Hydraulic stresses leak out of the fault due to ***(low) permeability seals***



Leaking flux

$$q(t) = K\left(p(t) - p_0\right)$$



Pressure increase through fluid storage

$$\dot{p} = Q/S$$

Hydraulic stress loading:

$$\dot{p}(t) = \boxed{\frac{Q}{S}} - \boxed{\frac{K}{S}p(t)} + \text{cst}$$

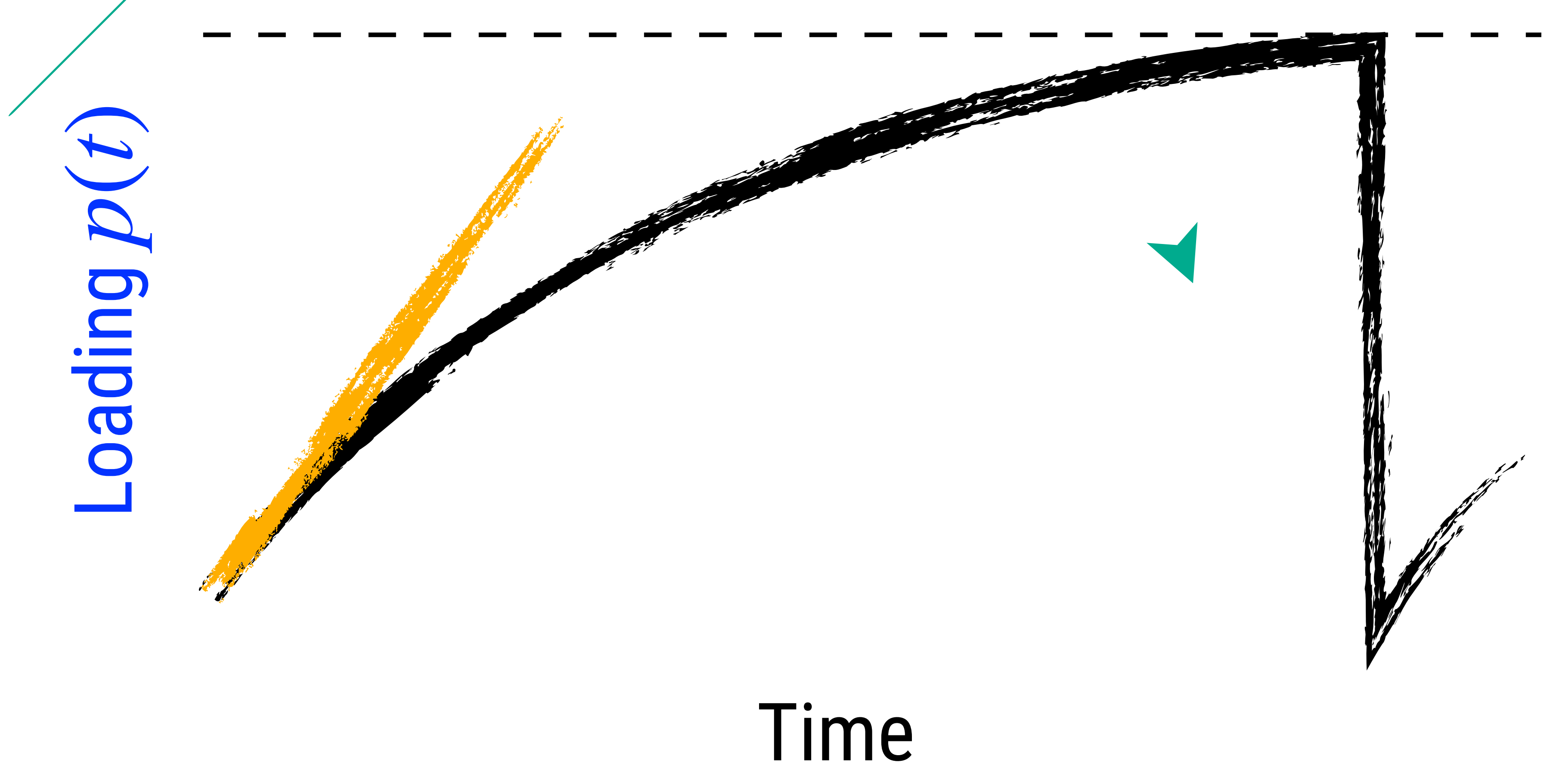
Elastic fluid storage

Q : dehydration flux

S : storativity

Permeability leak

K : seal conductivity



Stresses leak out of the fault

Hydraulic and ***solid*** stresses both leak out of the fault producing a concave loading curve in time

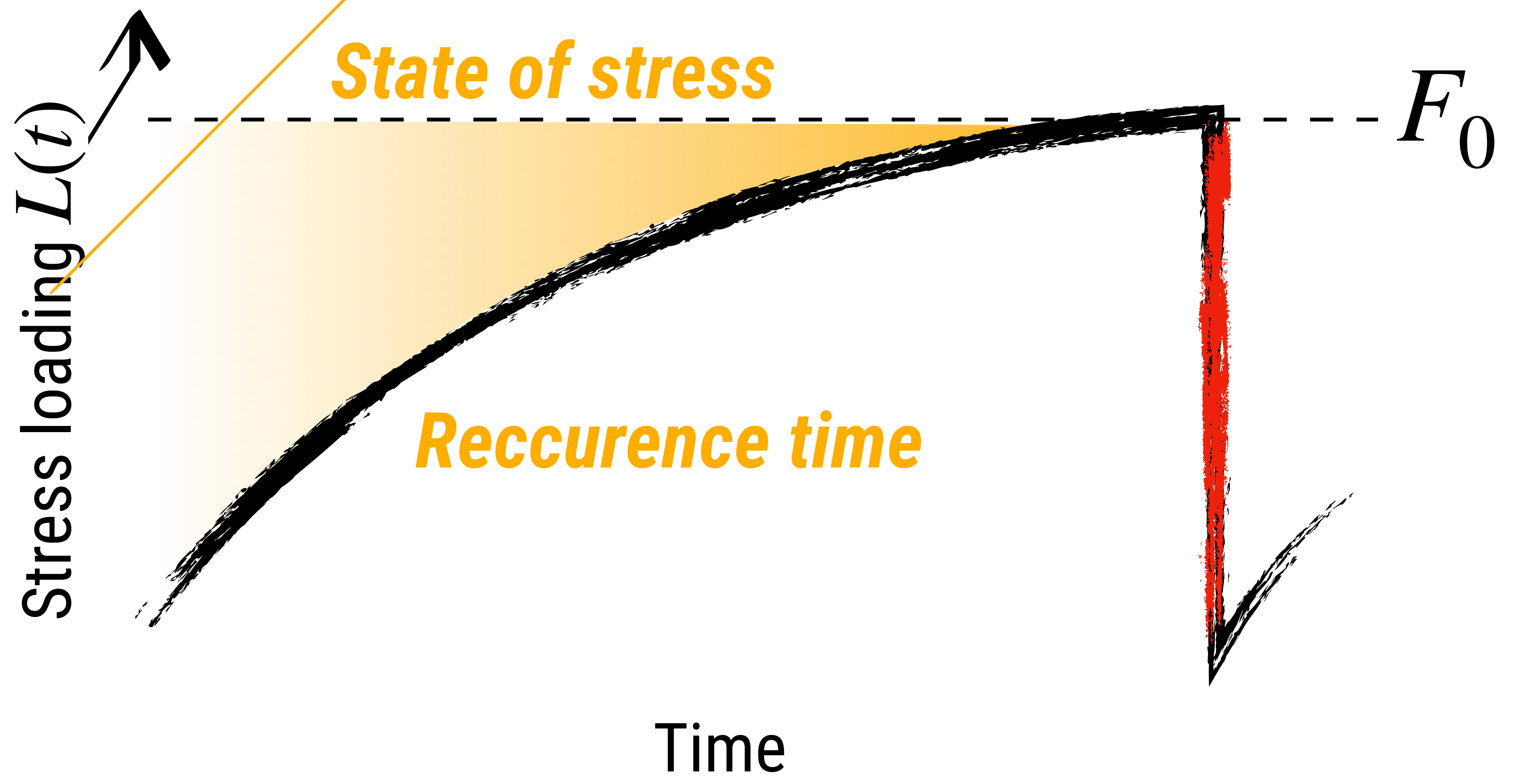
Stress loading: $L(t) = \boxed{\mu p(t)} + \tau(t)$

Hydraulic loading: $\dot{p}(t) = \frac{Q}{S} - \frac{K}{S}p(t)$

Solid loading: $\dot{\tau}(t) = GV - \frac{G}{\eta_s}\tau(t)$

➡ ***Leakage competes with steady loading in shaping the recurrence***

➡ ***The curvature makes the stress sit near failure for a long share of the cycle***

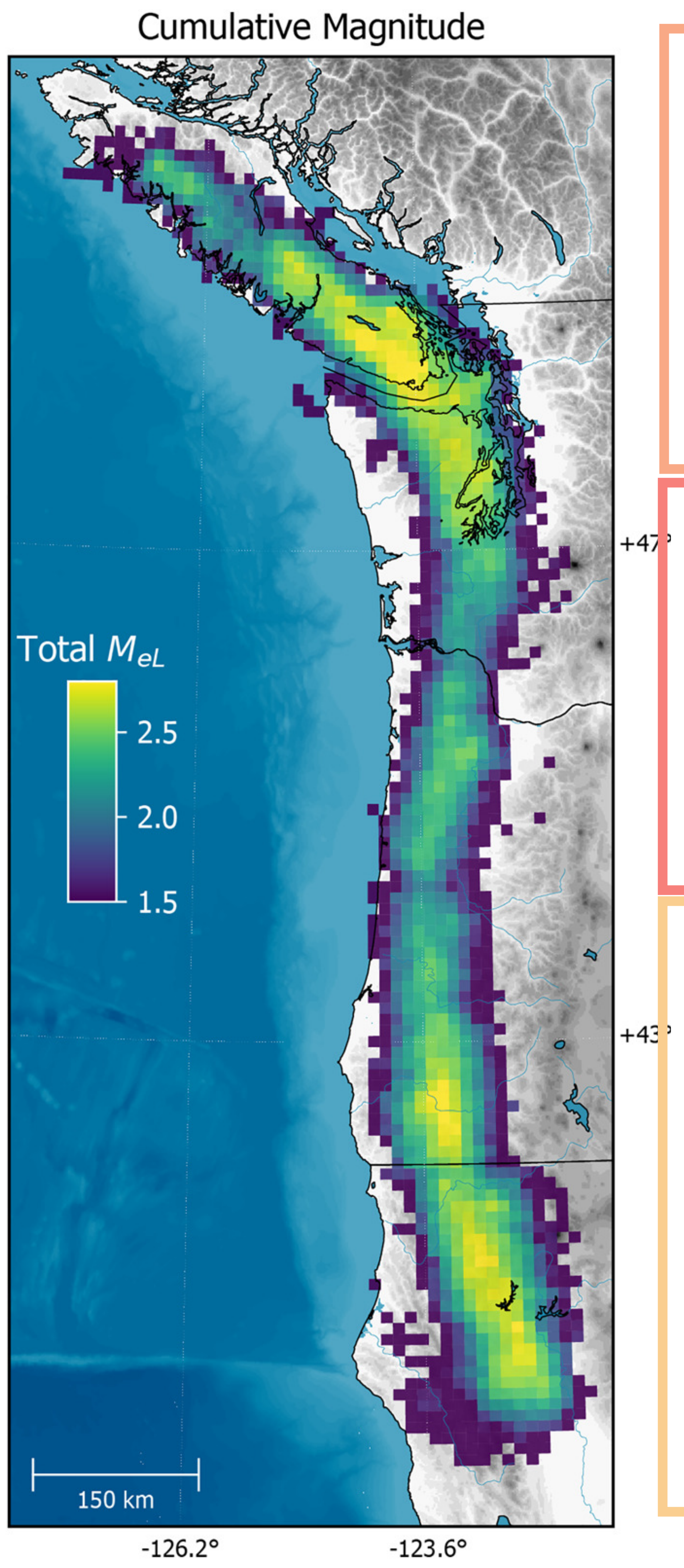


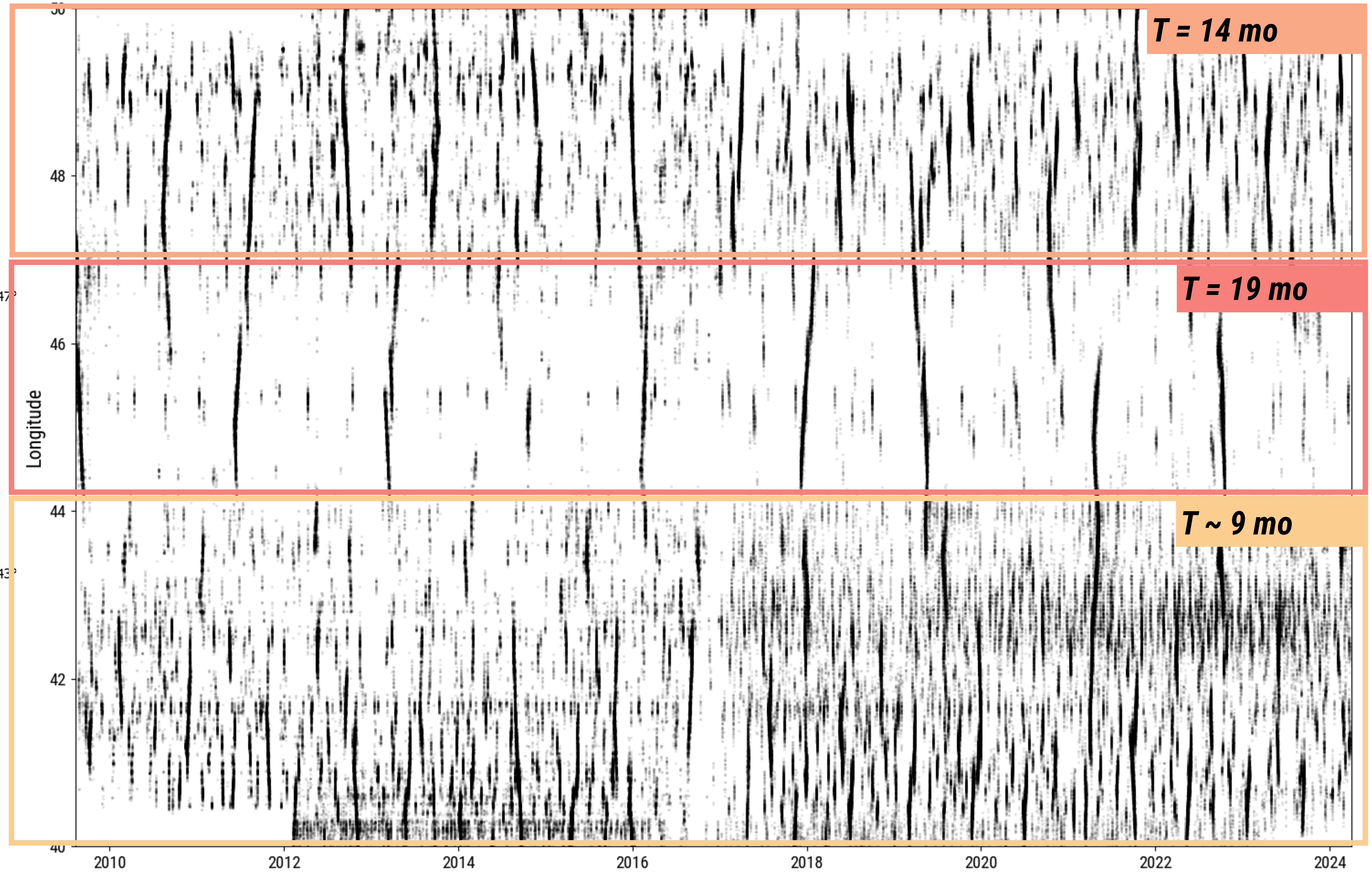
The seismic consequences of being a leaky fault

1. Sources and sinks control recurrence
2. Tremor synchronization
3. Sensitivity to transients

Segmentation of ETS recurrence along-strike

Adapted from Wech et al. (2021, 2008 etc)





Segmentation of ETS recurrence along-strike

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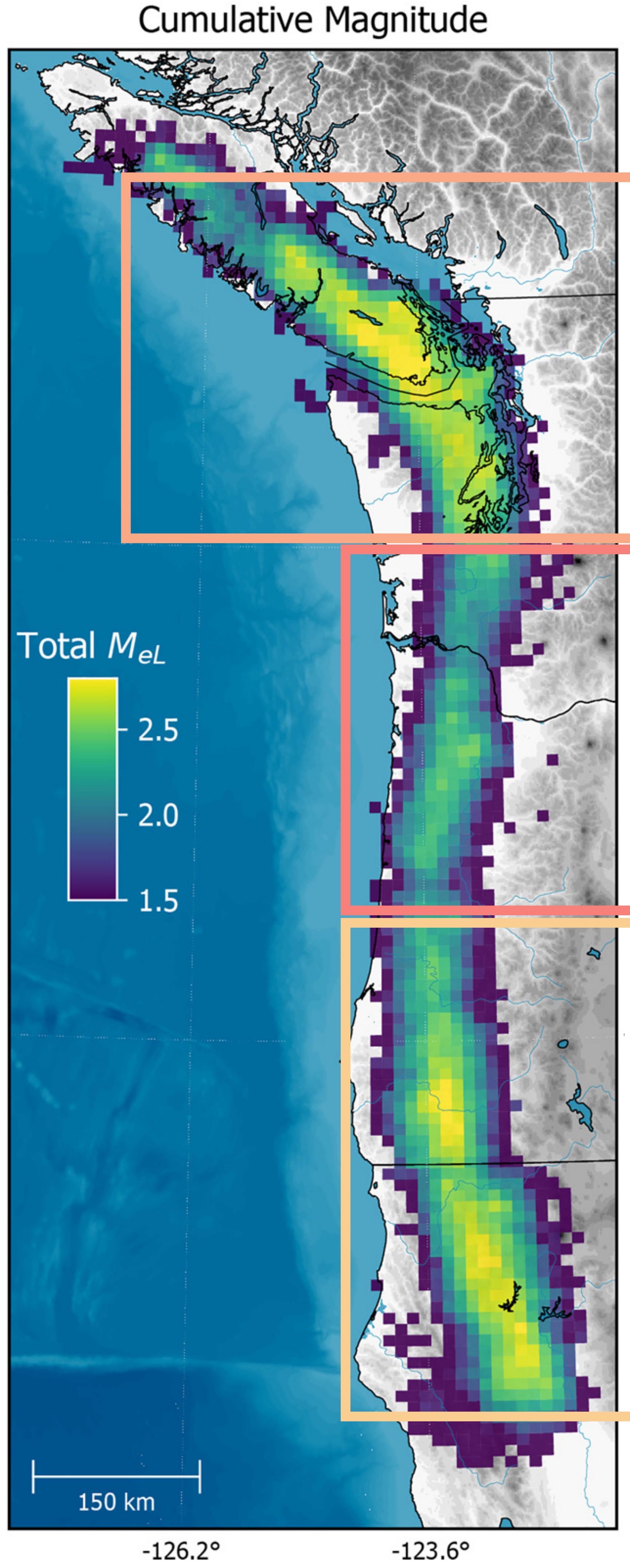
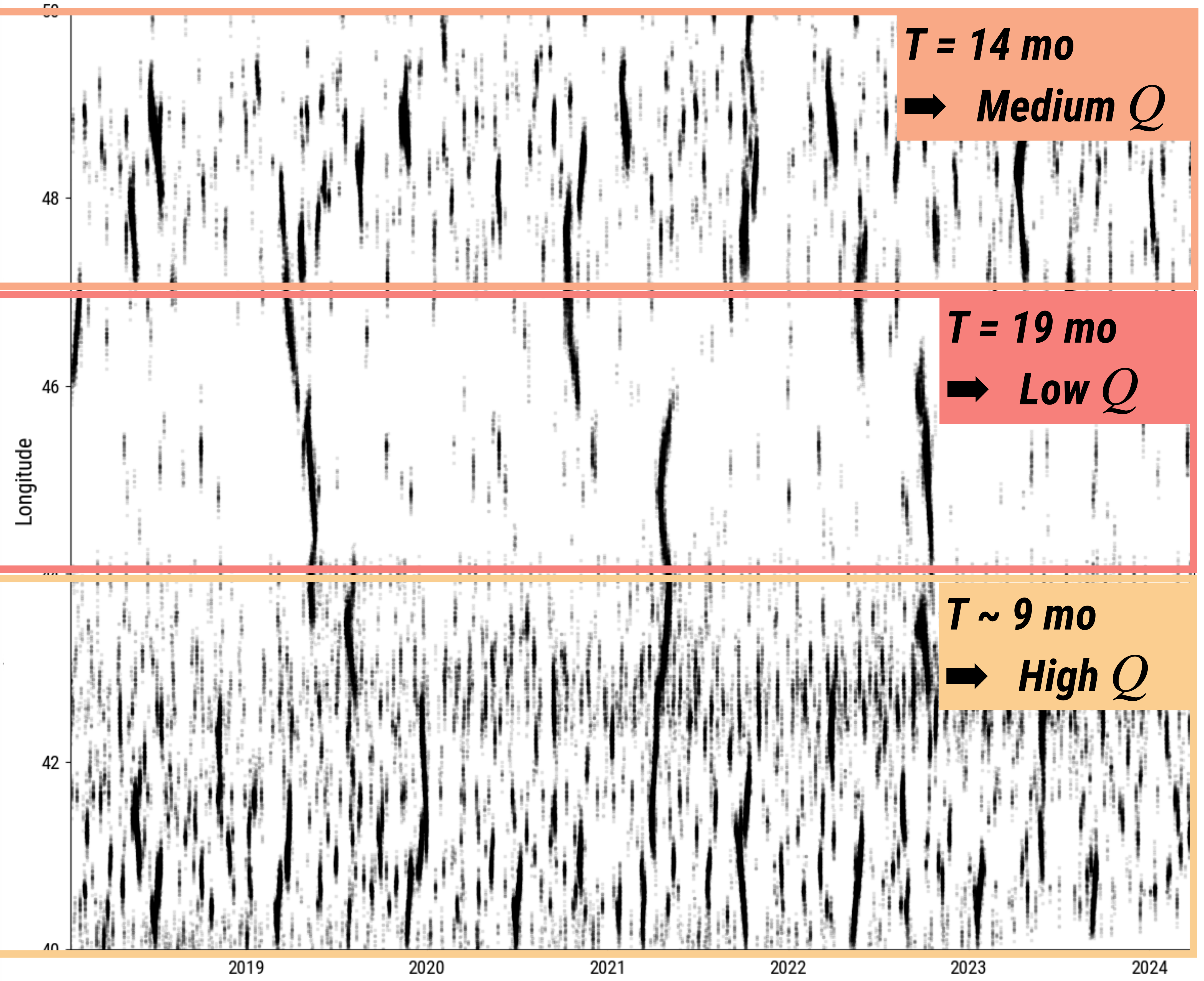
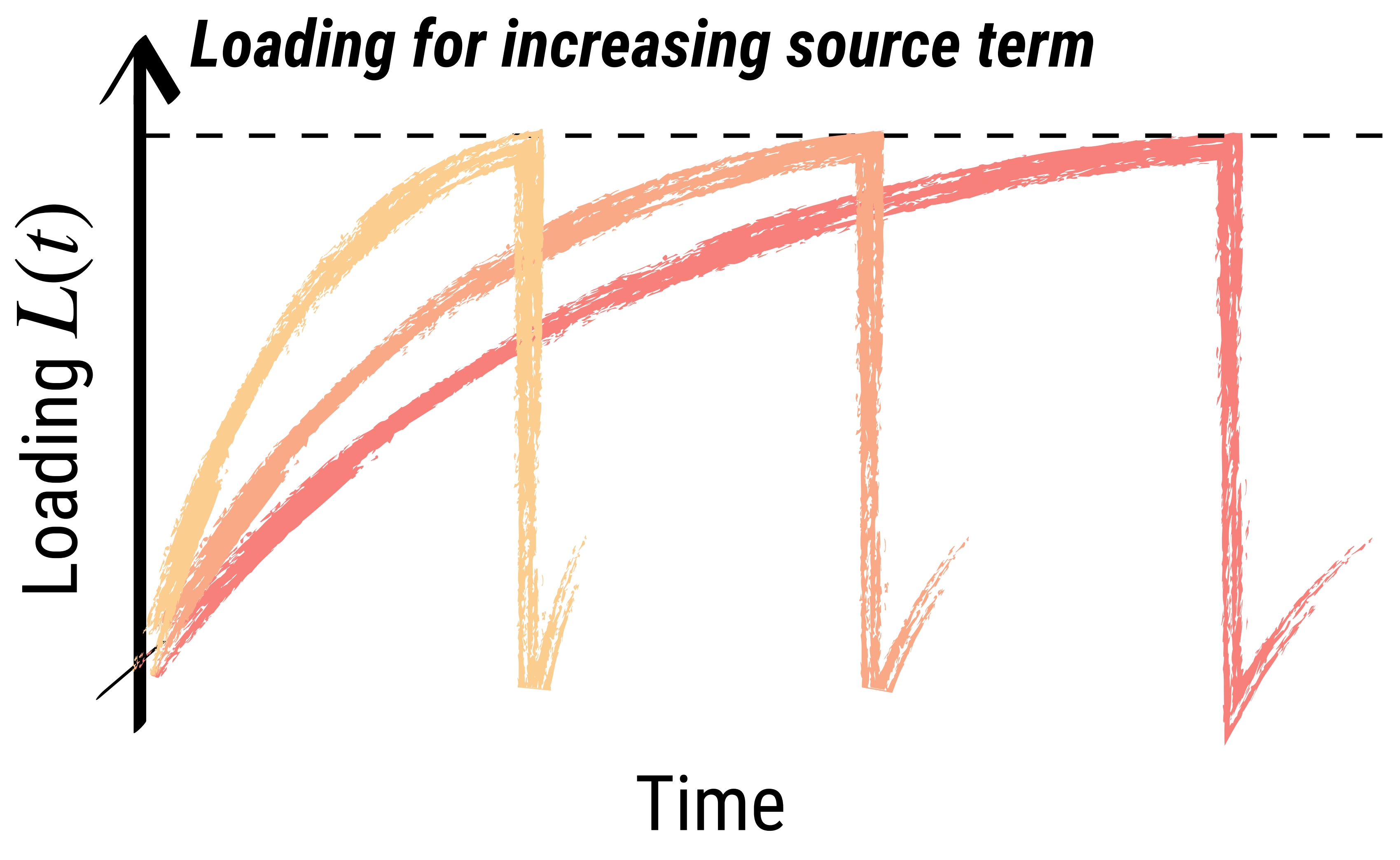
➡ ***Lower source flux Q produces longer loading, thus longer recurrence times***

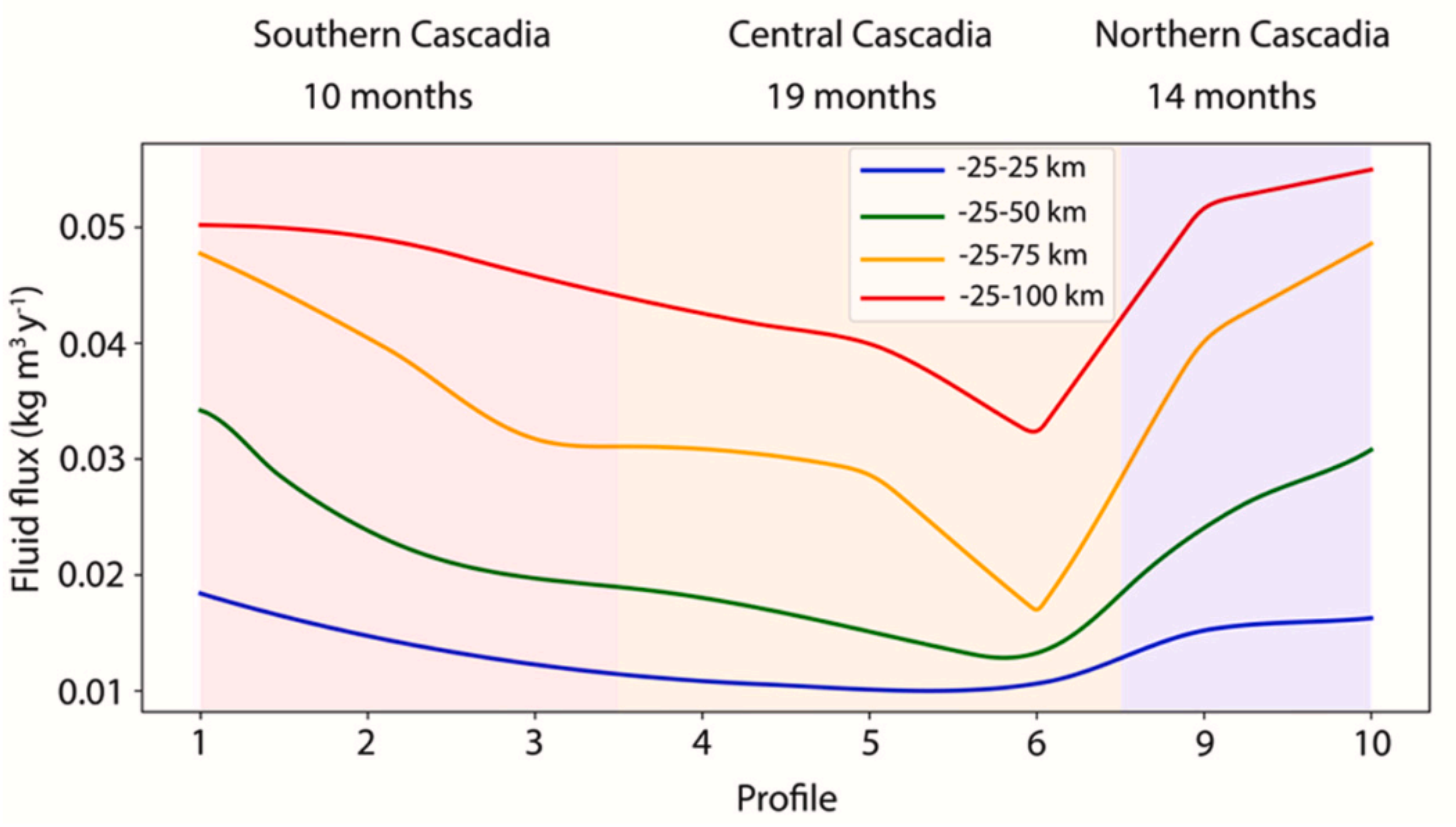






Fluid flux in Cascadia subduction zone

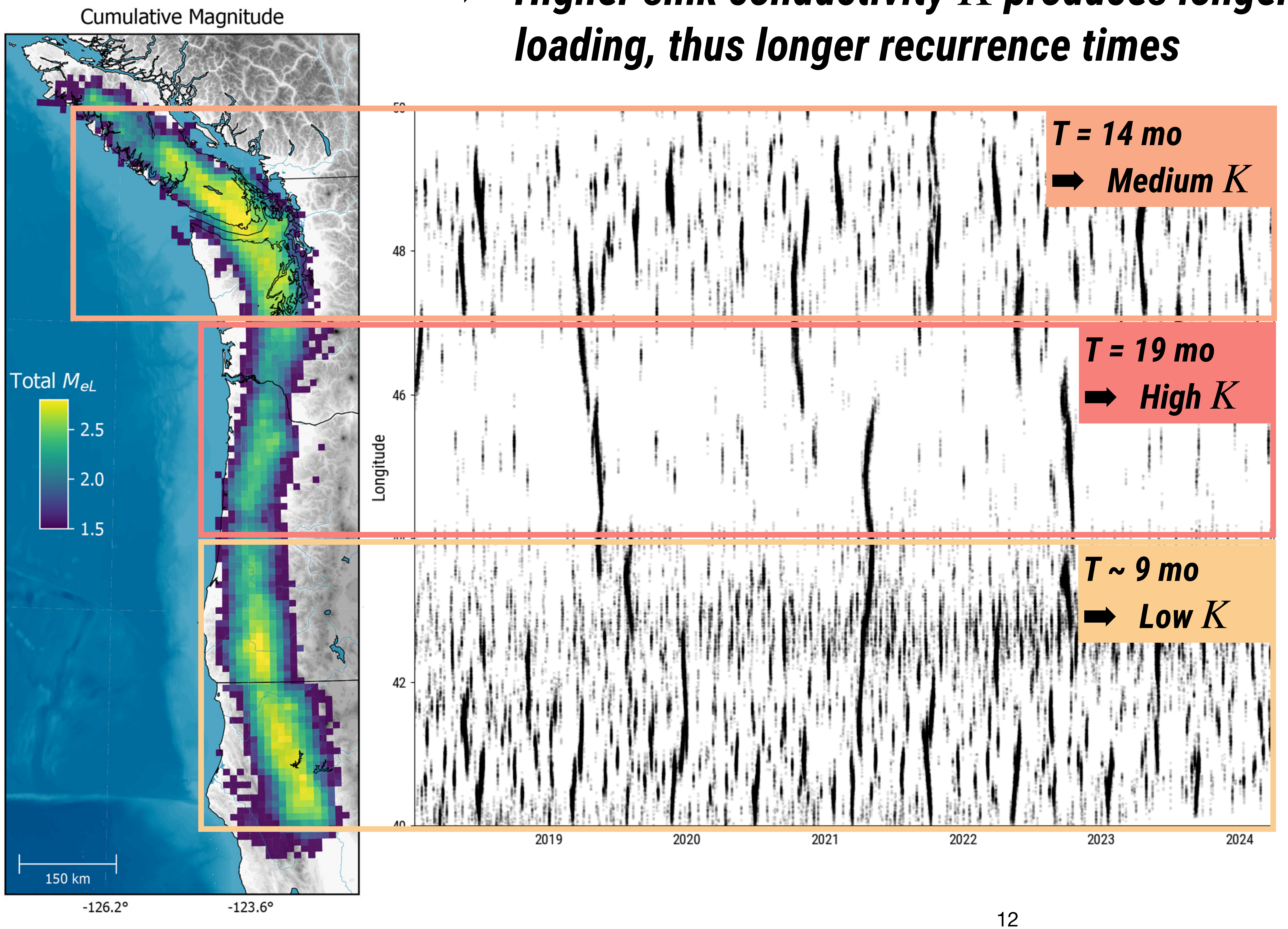
Modeling results from McLellan et al (2022)

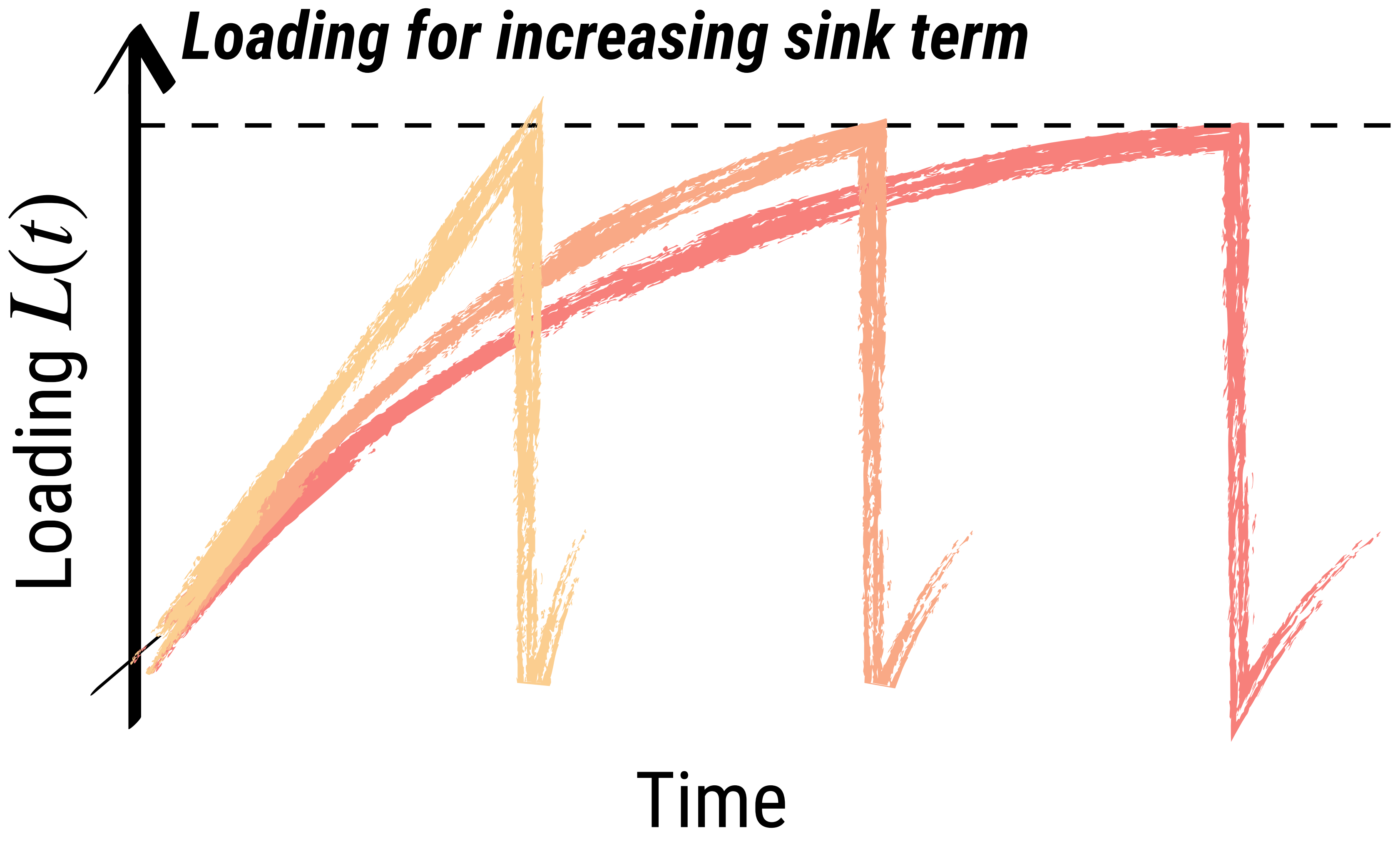


Segmentation of ETS recurrence along-strike

Adapted from Wech et al. (2021, 2008 etc)

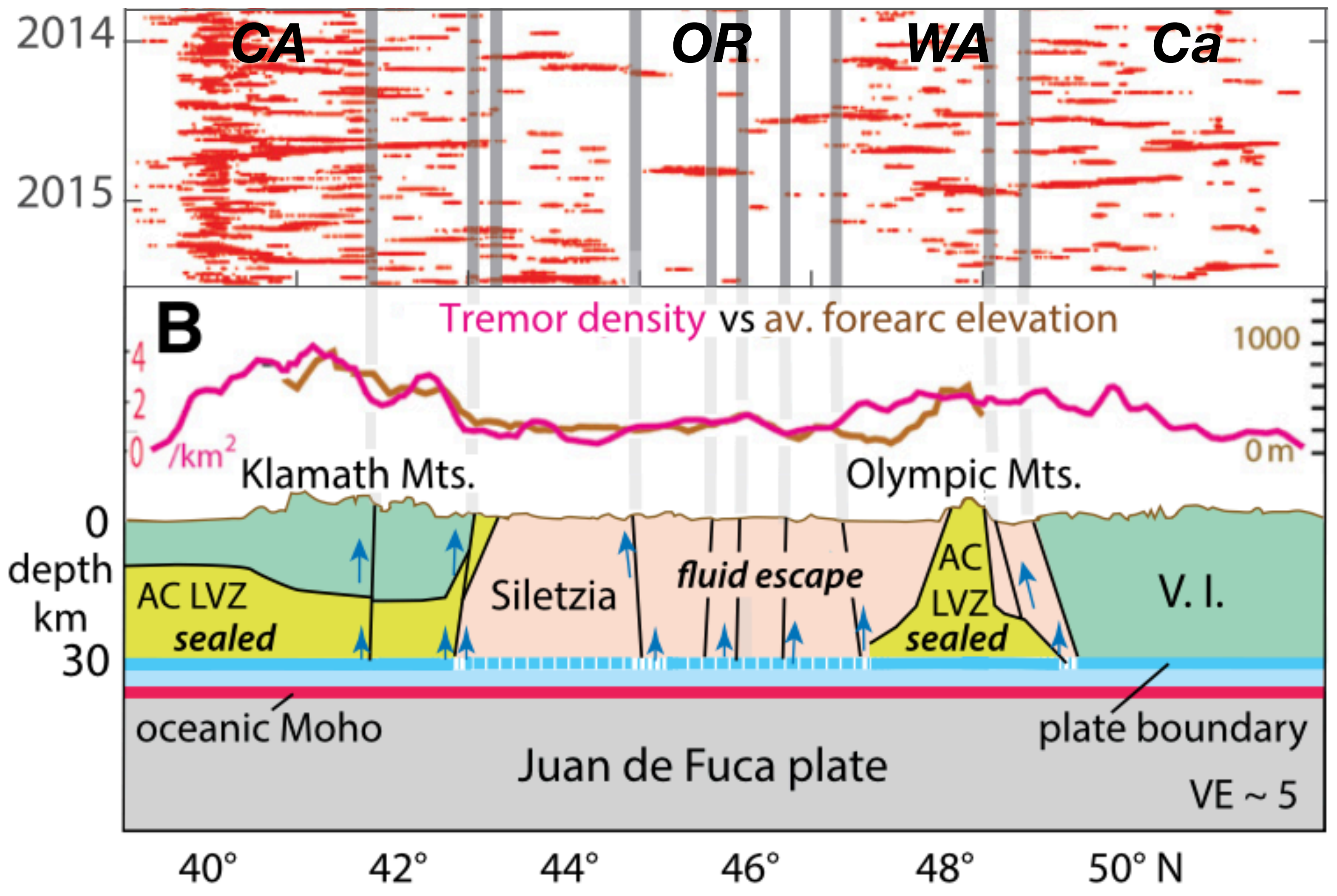
➡ ***Higher sink conductivity K produces longer loading, thus longer recurrence times***





Large crustal faults and tremor distribution in Cascadia

Wells et al (2017)



The seismic consequences of being a leaky fault

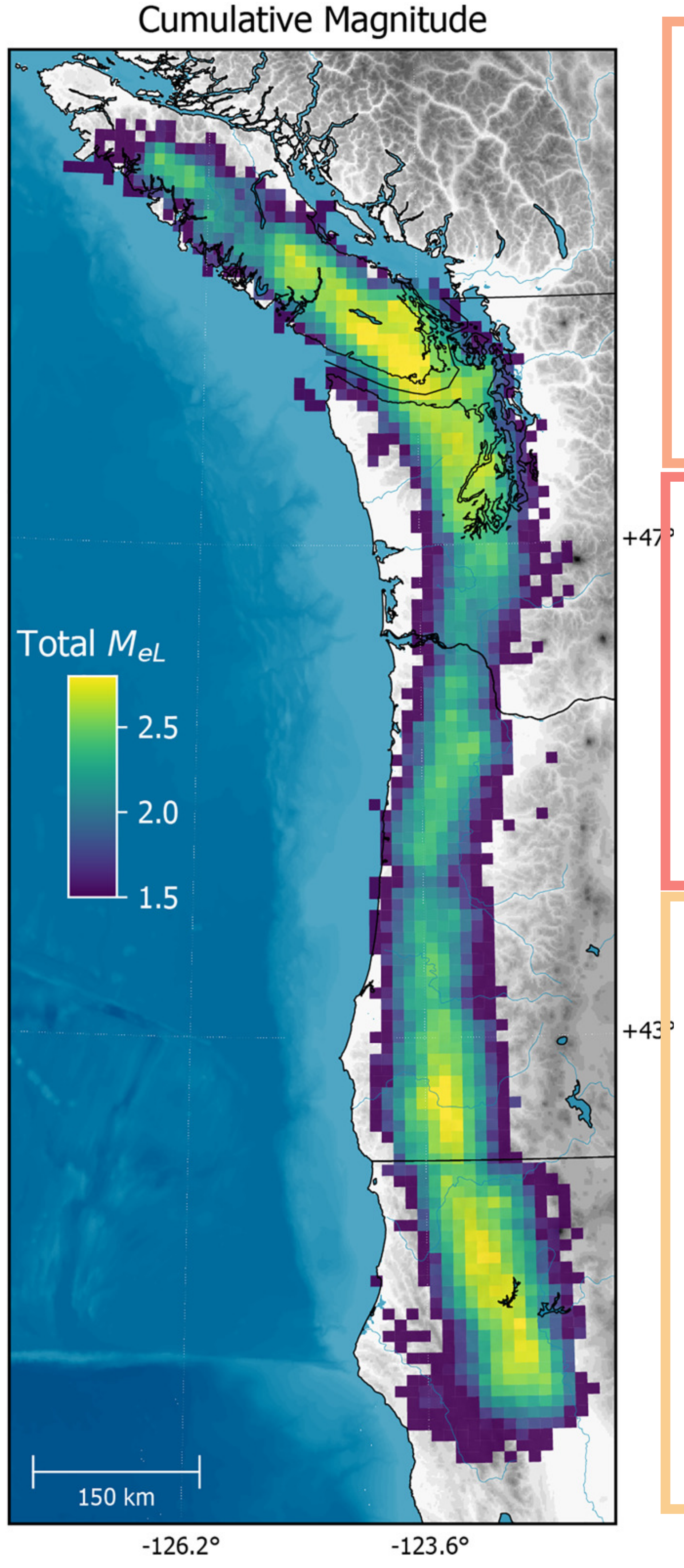
1. Sources and sinks control recurrence
2. **Tremor synchronization**
3. Sources and sinks control recurrence

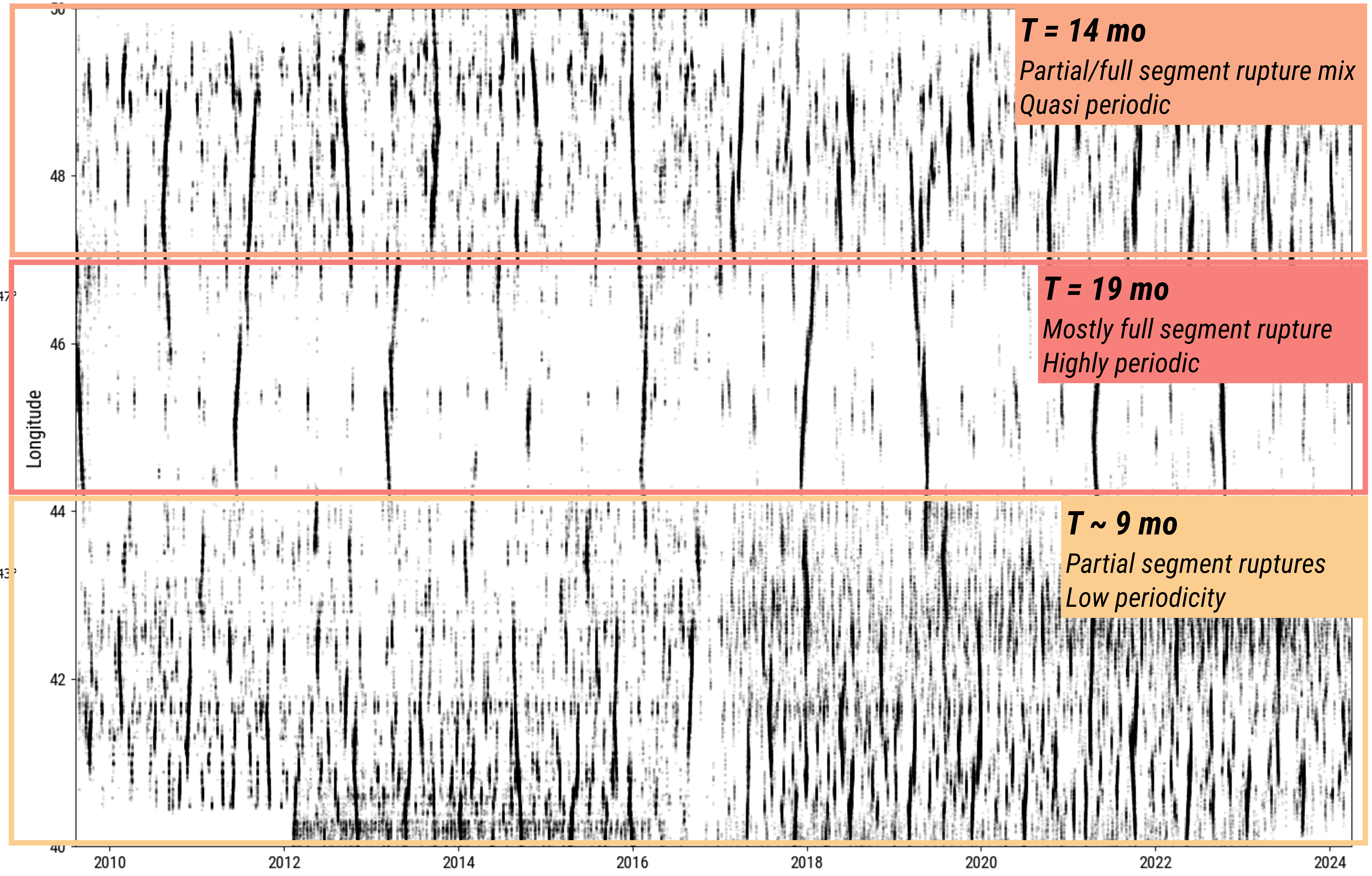
Segmentation of ETS "synchronization" along-strike

i.e. Large portions of the fault activate at the same time

➡ Characteristic sizes
➡ Periodicity

Adapted from Wech et al. (2021, 2008 etc)

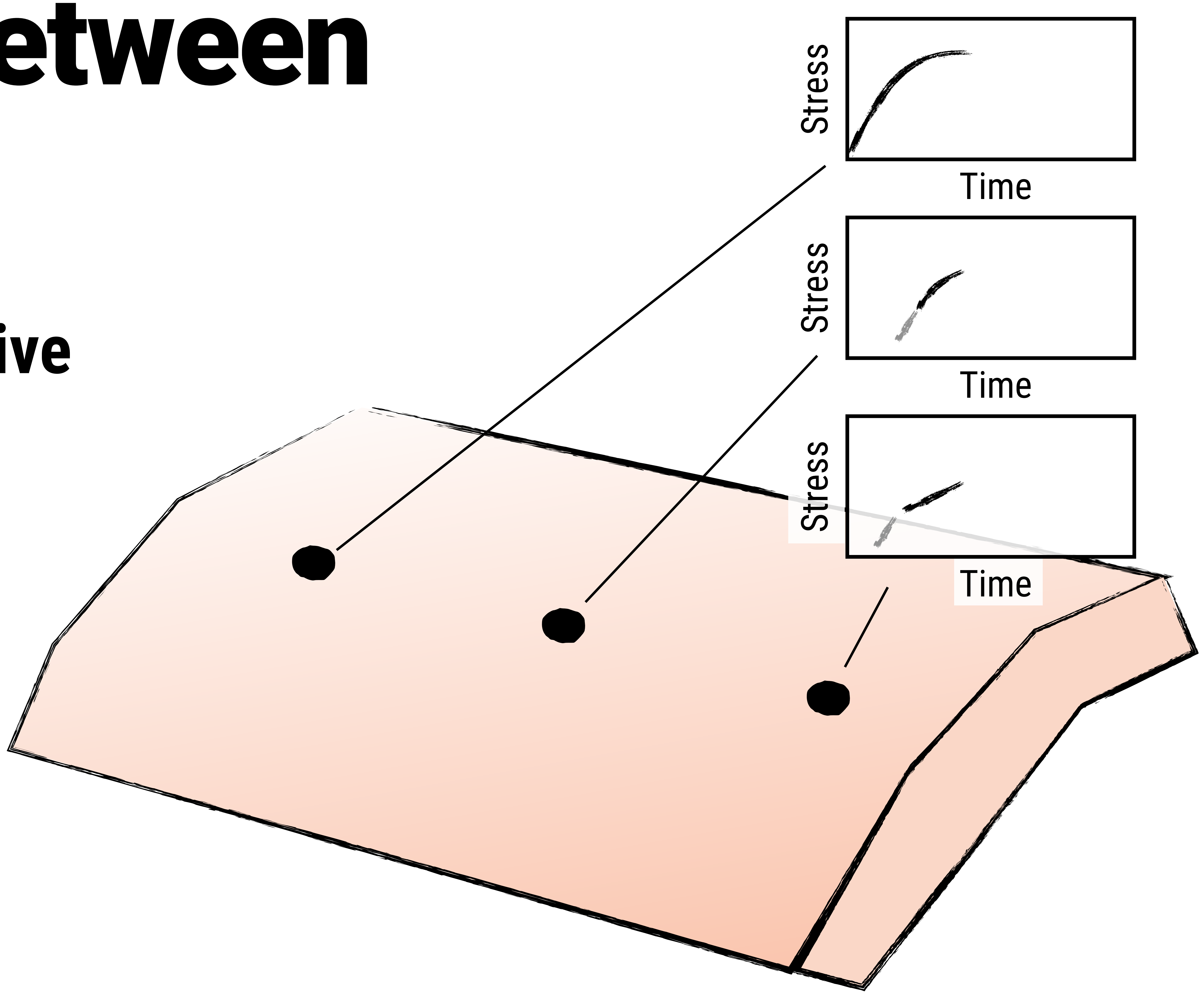




Synchronization emerges from interactions between fault segments

➡ Synchronization through **constructive stress interactions:** failure brings neighbors closer to fail

➡ Synchronization in time/space translates into **regularity of recurrence**



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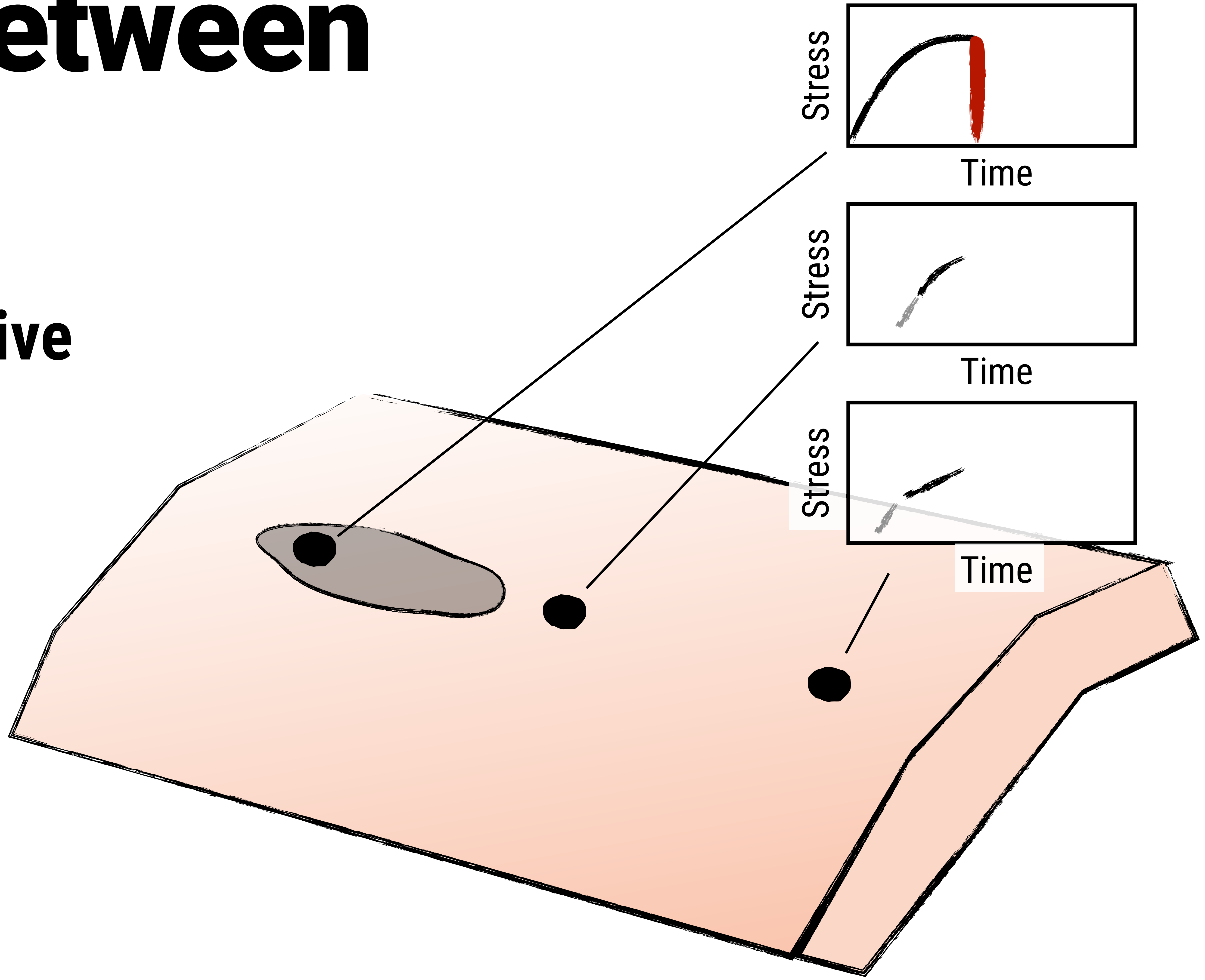

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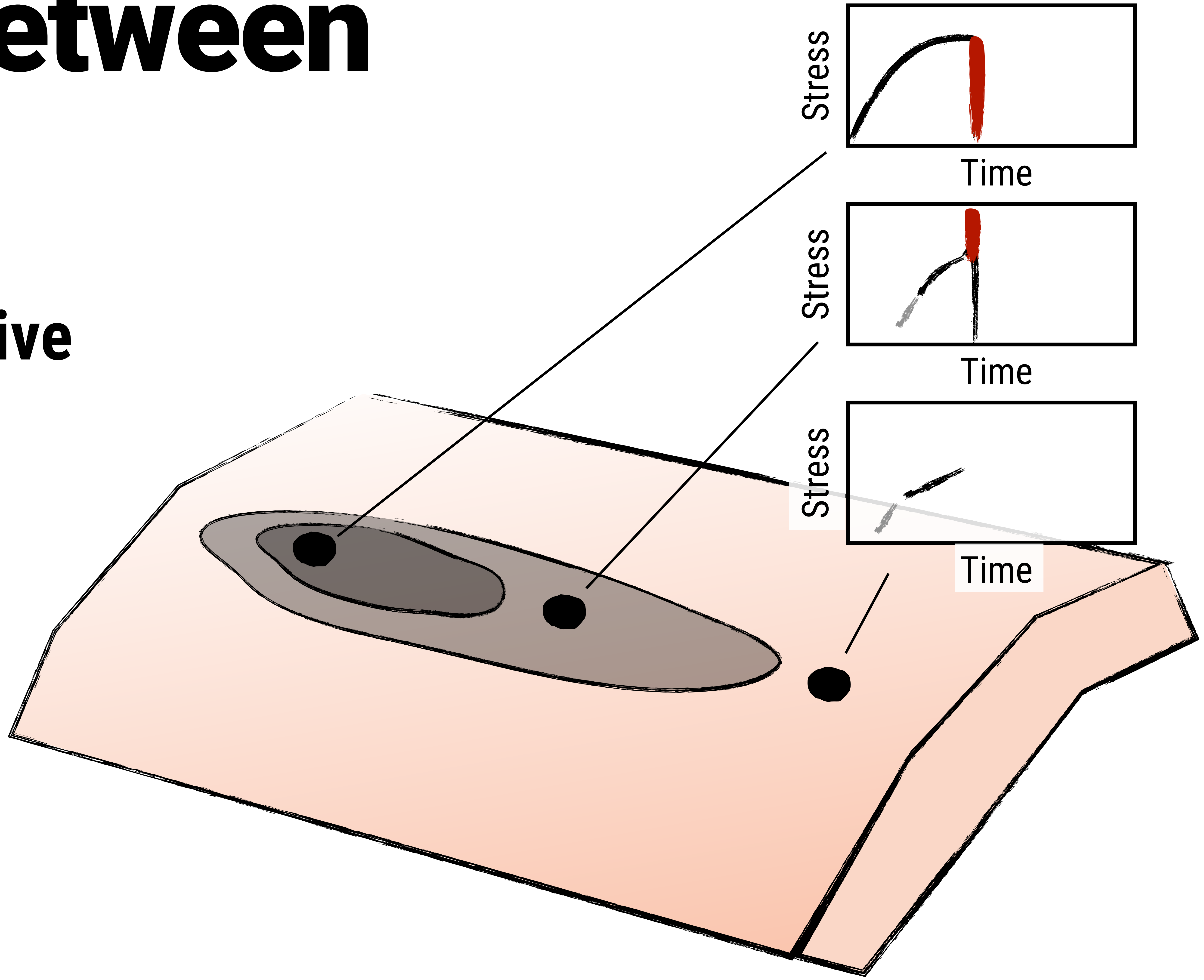

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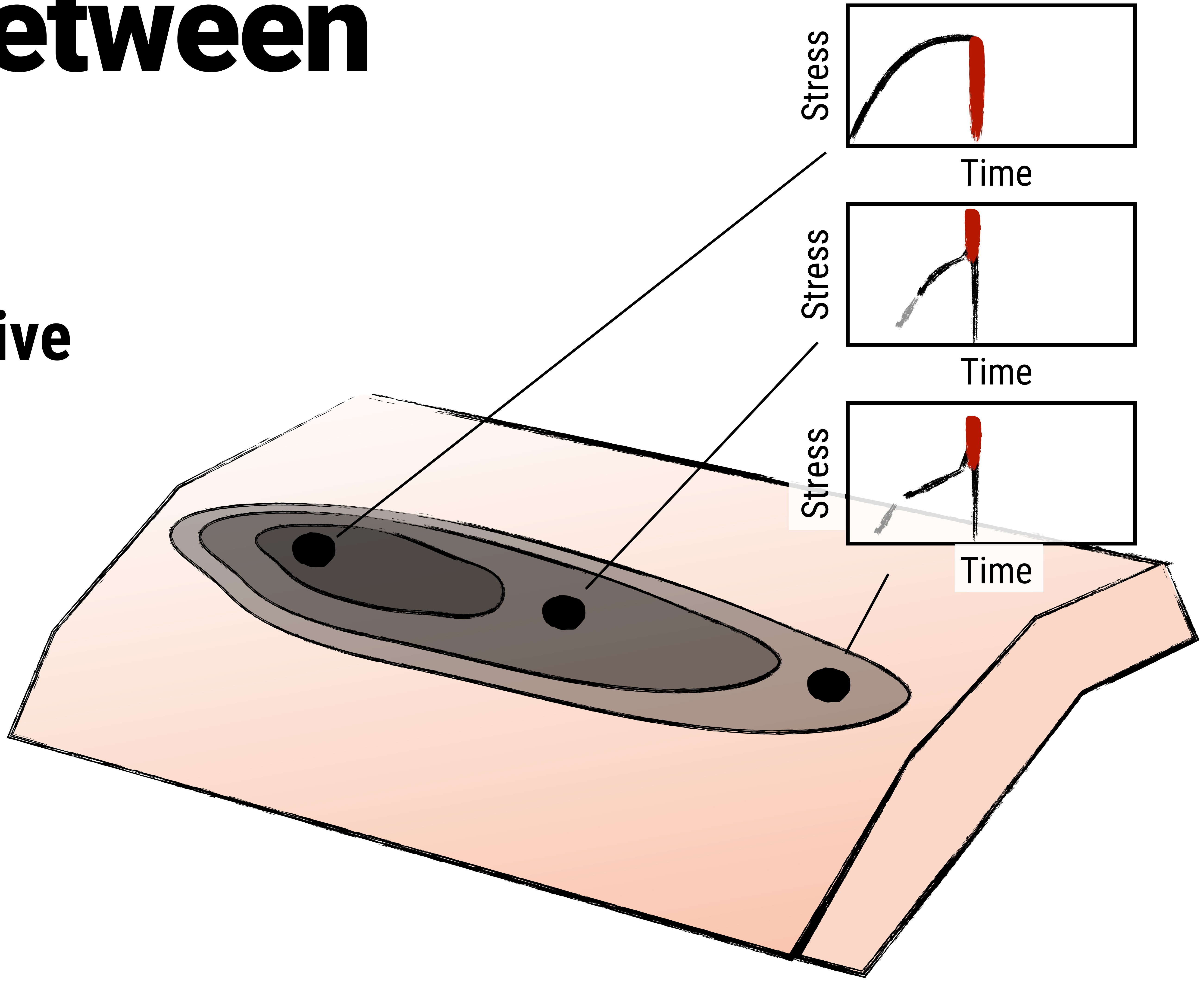

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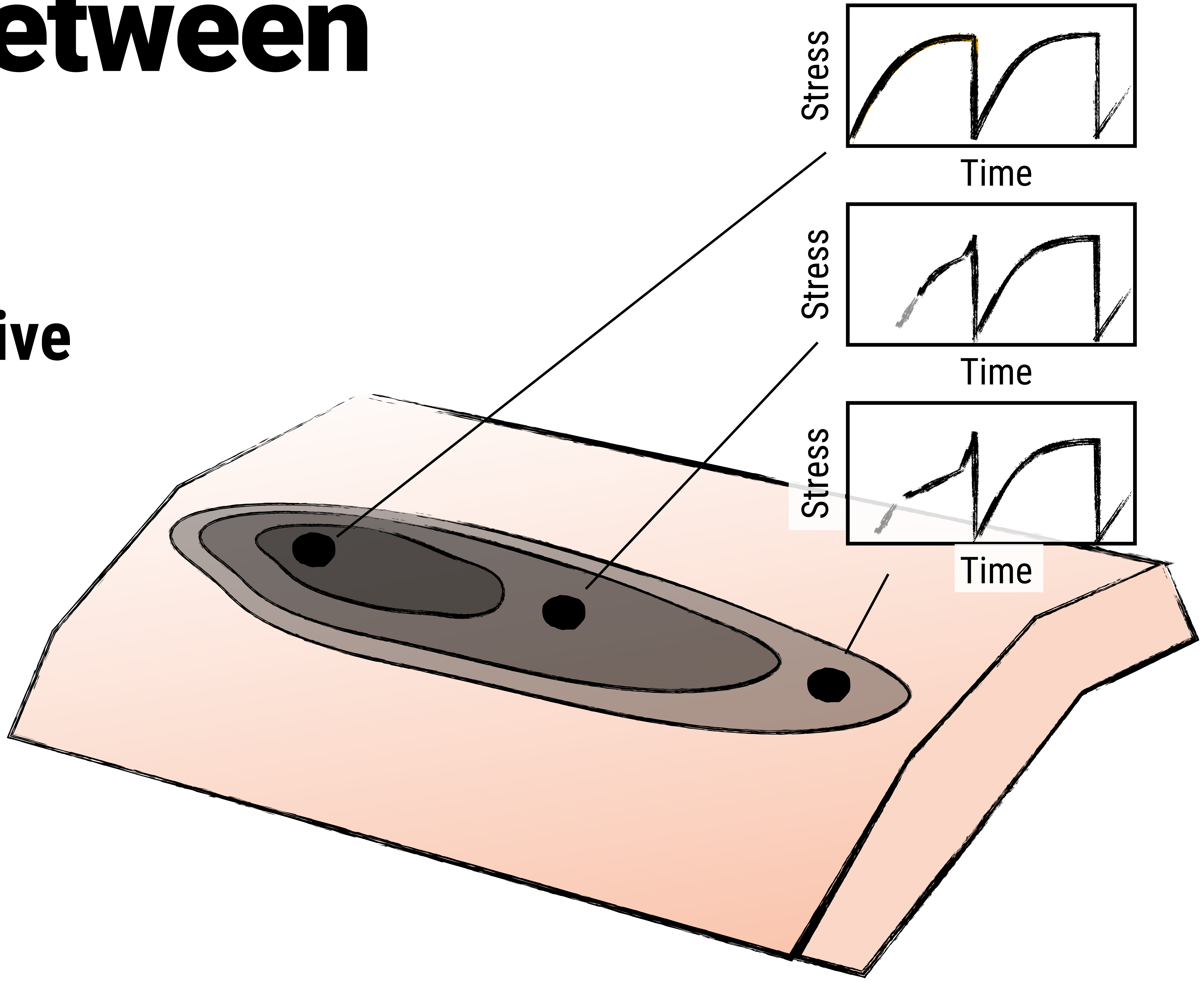
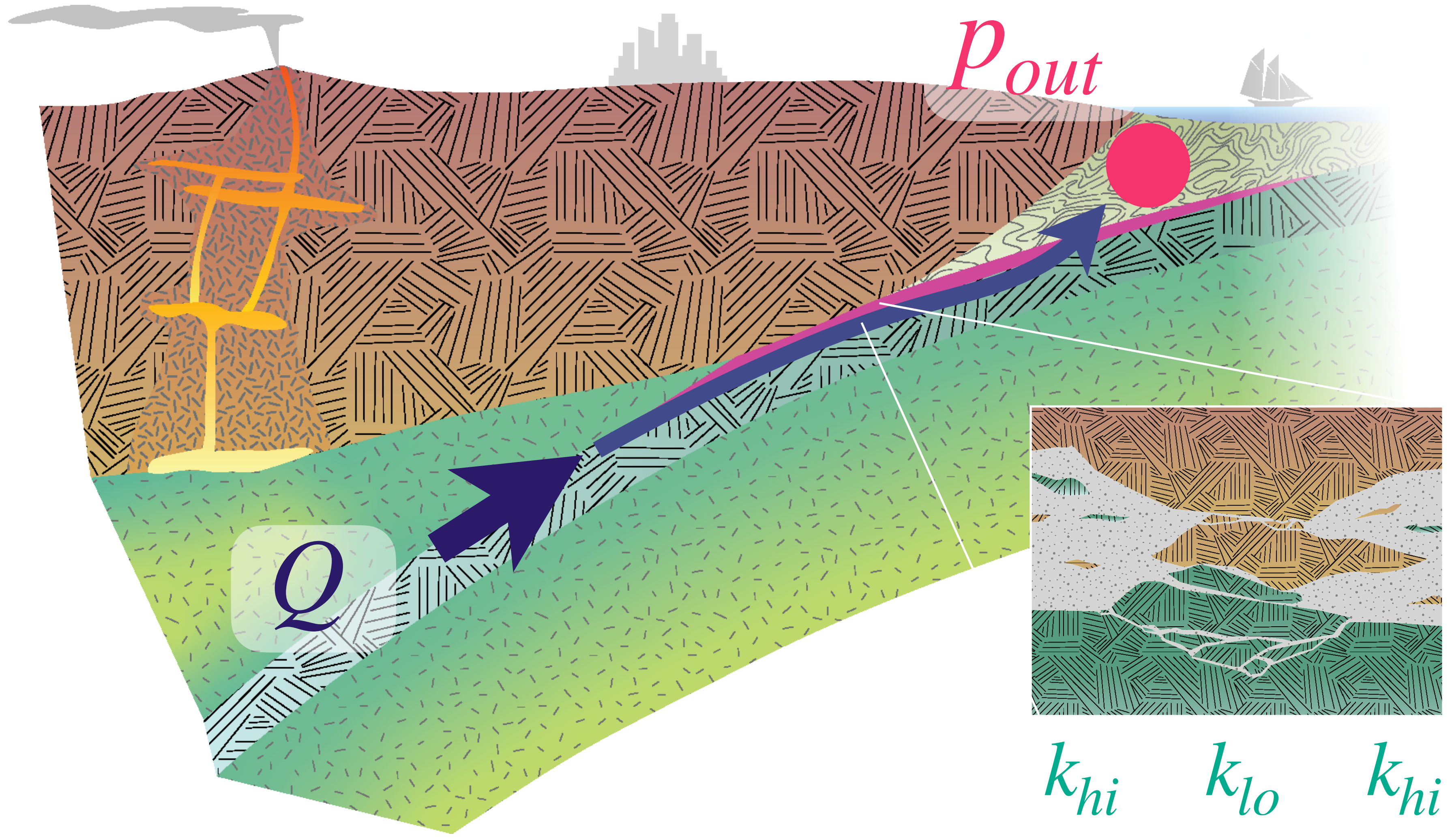
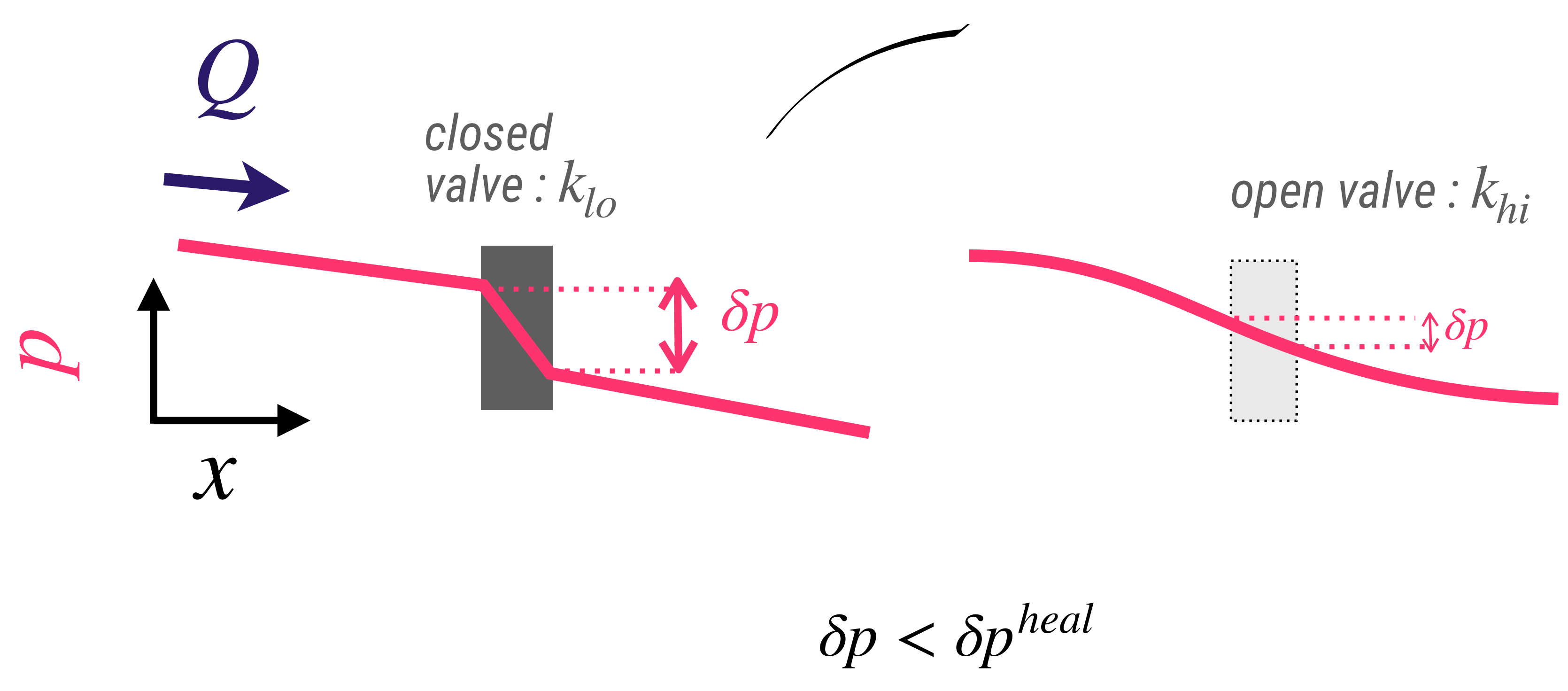


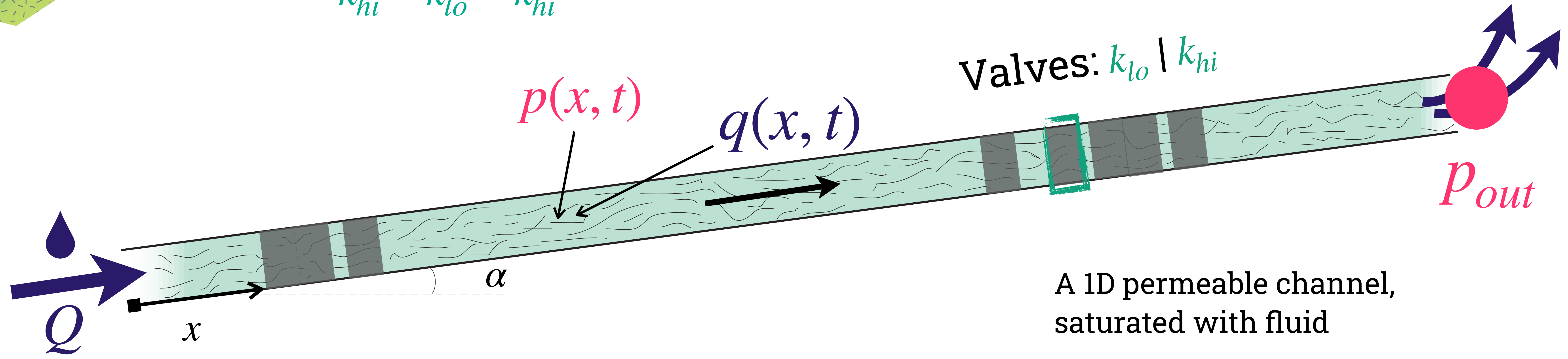
Modeling interactions in a purely hydraulically loaded fault

Modeling results from Farge et al. (2021, 2023)



Valve mechanism





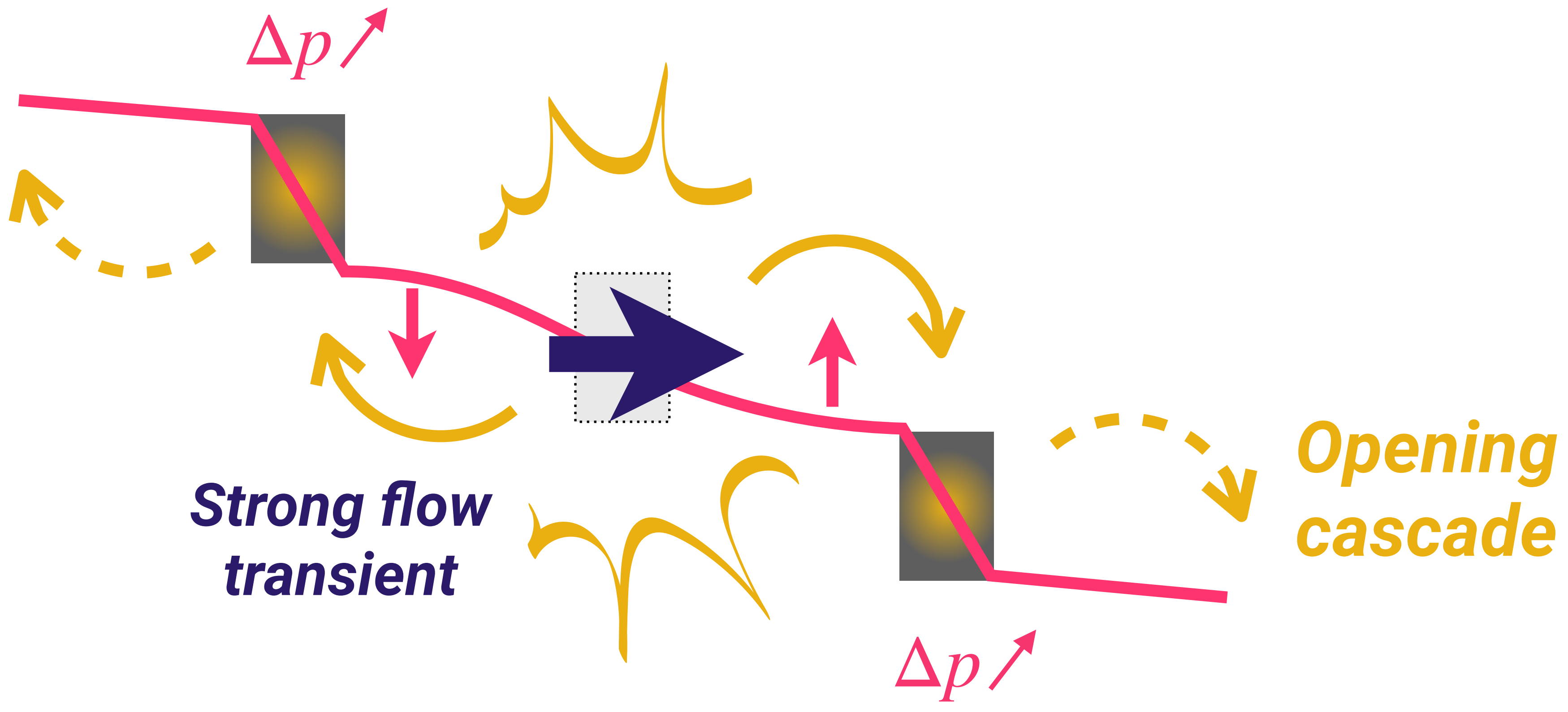
A 1D permeable channel, saturated with fluid

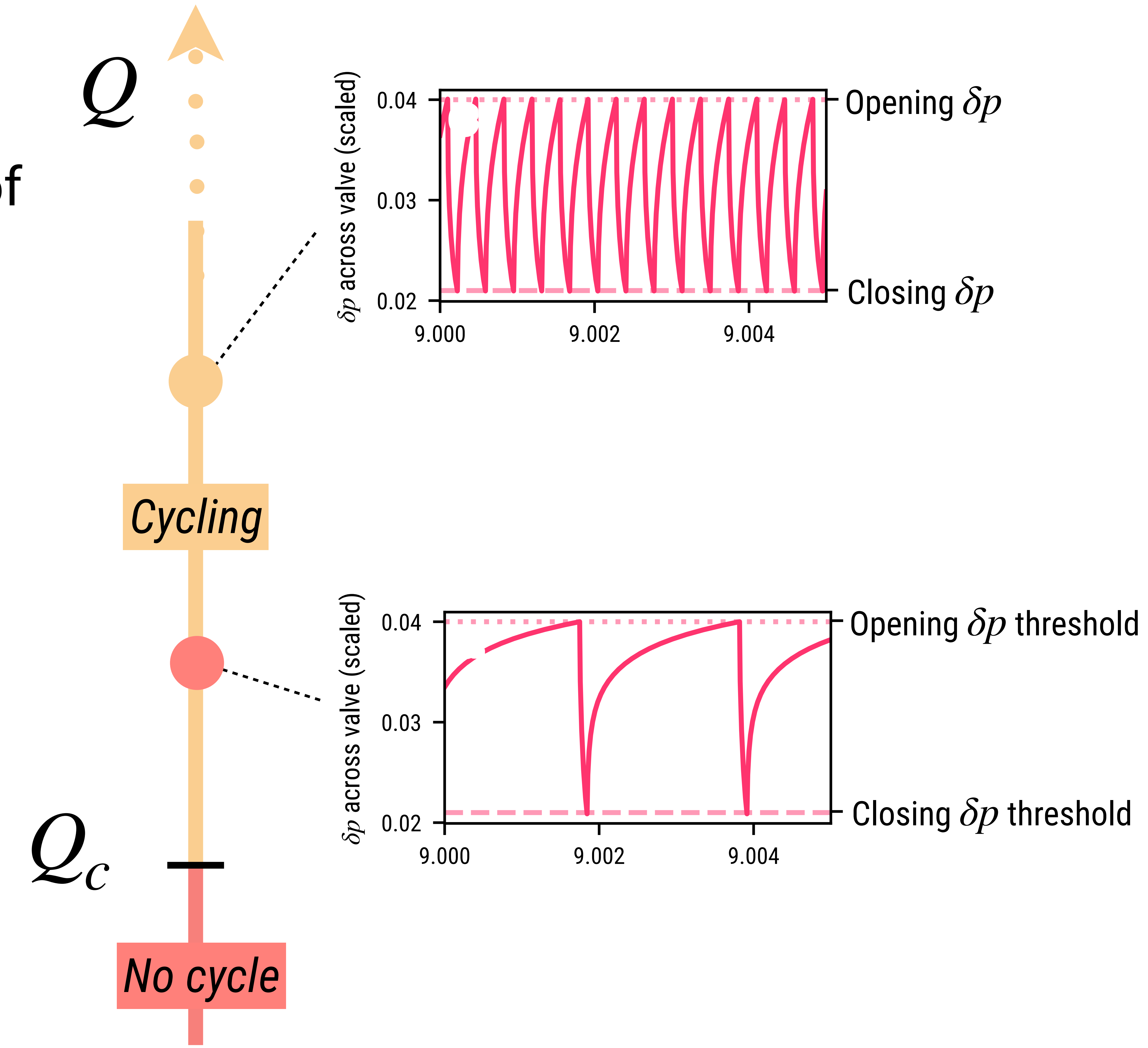
The proximity to rupture controls sensitivity to interactions

The source **source flux** Q shapes the cycle of a fault element:

➡ How **close to threshold** it is on average

➡ How **sensitive** to neighboring activity





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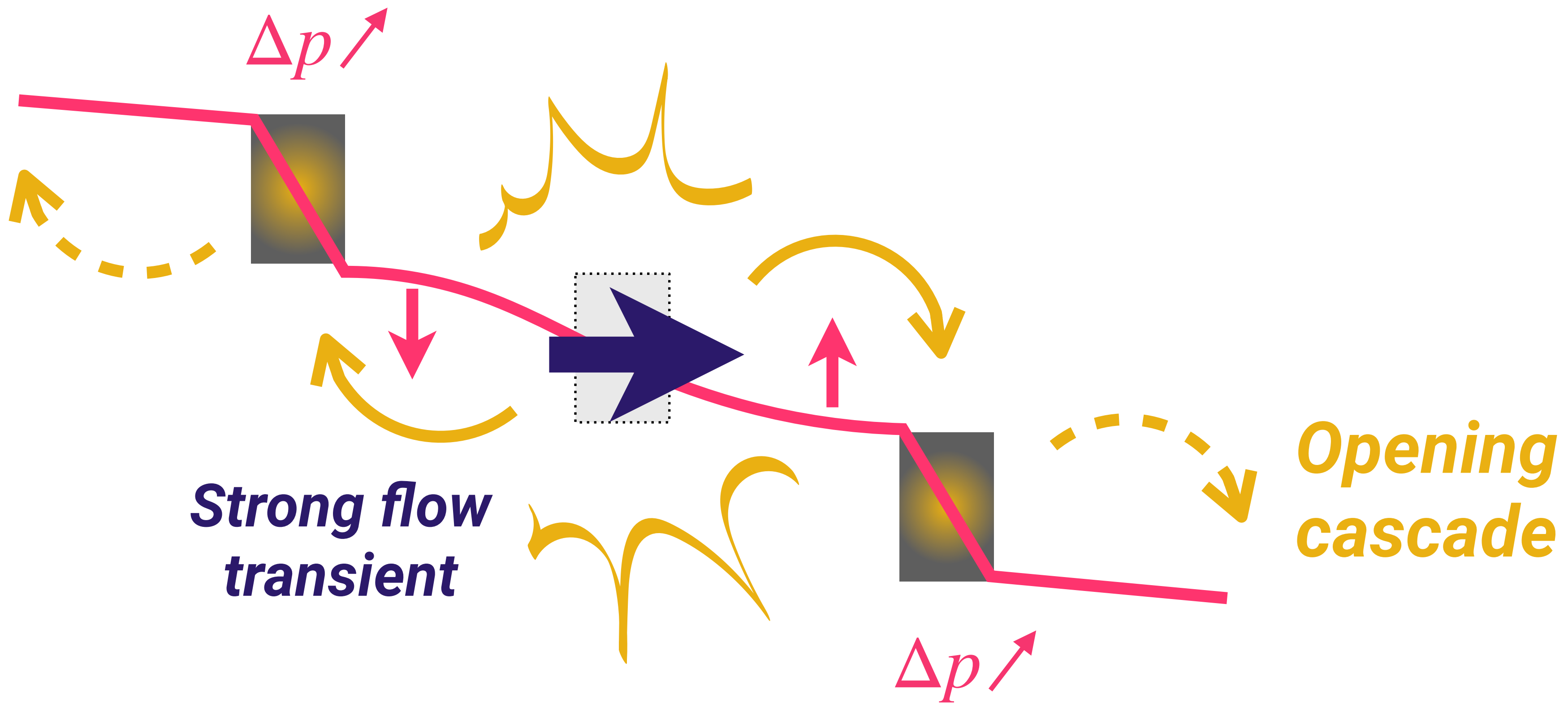
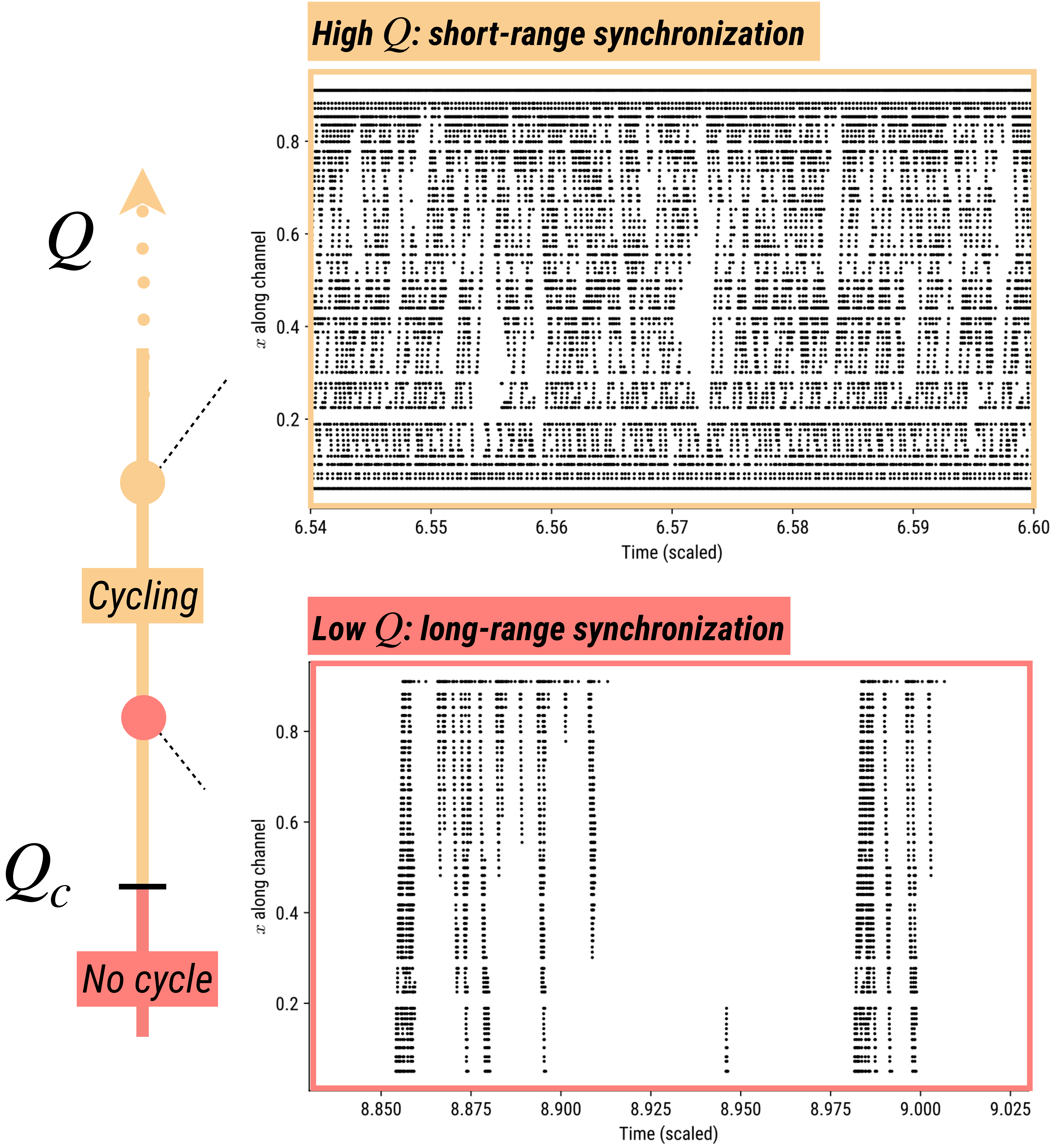
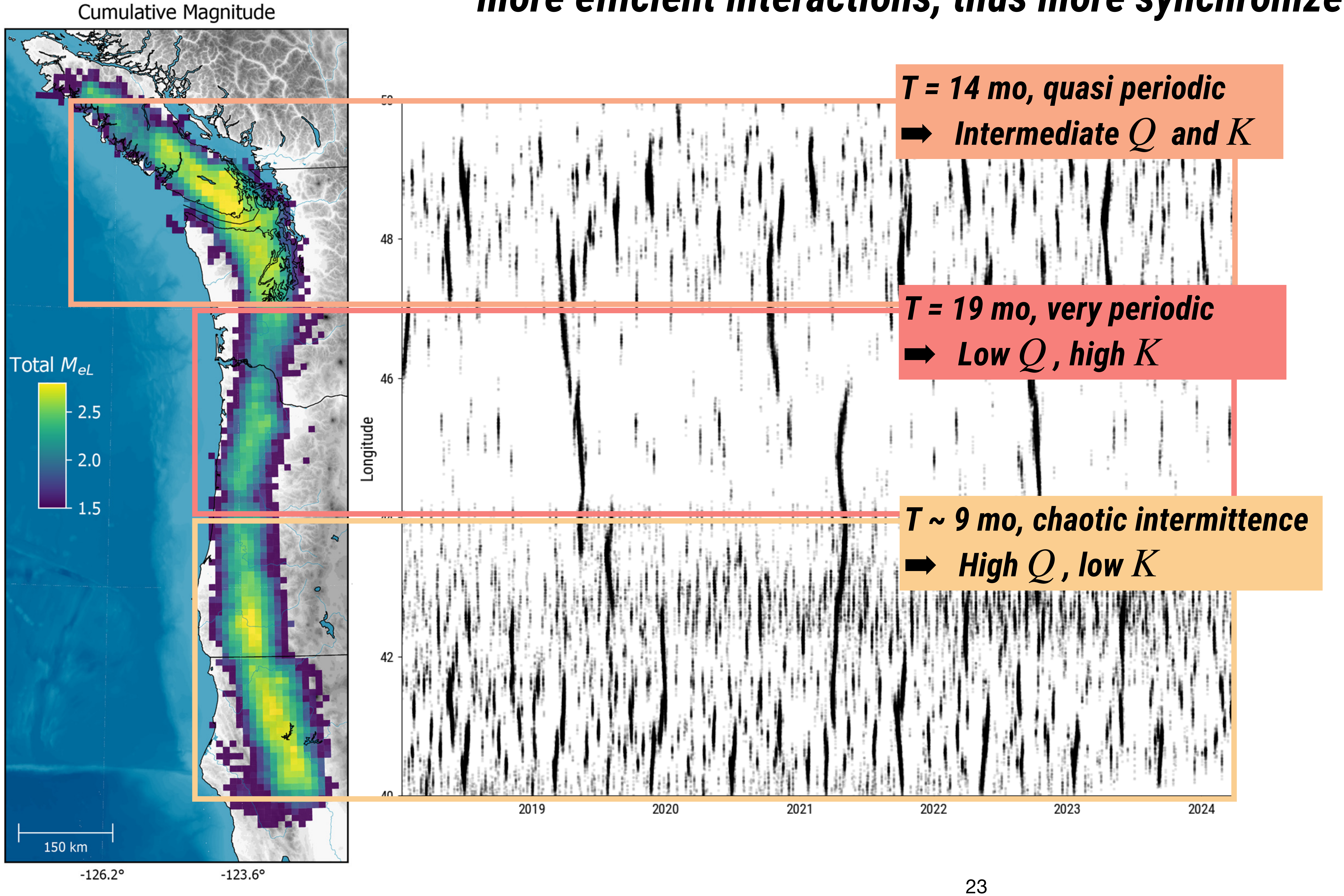


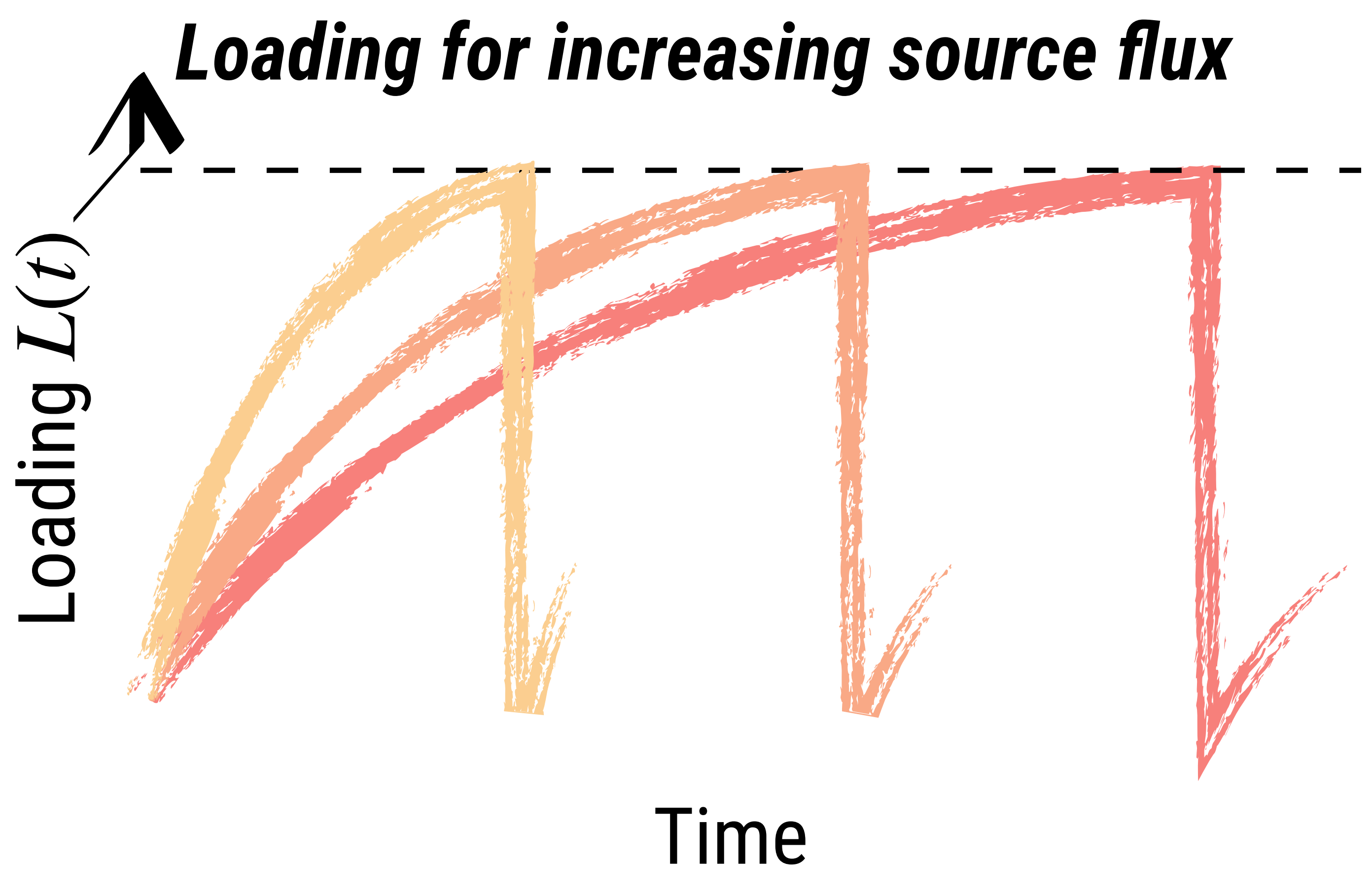


Segmentation of ETS synchronization along-strike

➡ ***Lower source flux Q / higher sink conductivity K produces more efficient interactions, thus more synchronized activity***

Adapted from Wech et al. (2021, 2008 etc)





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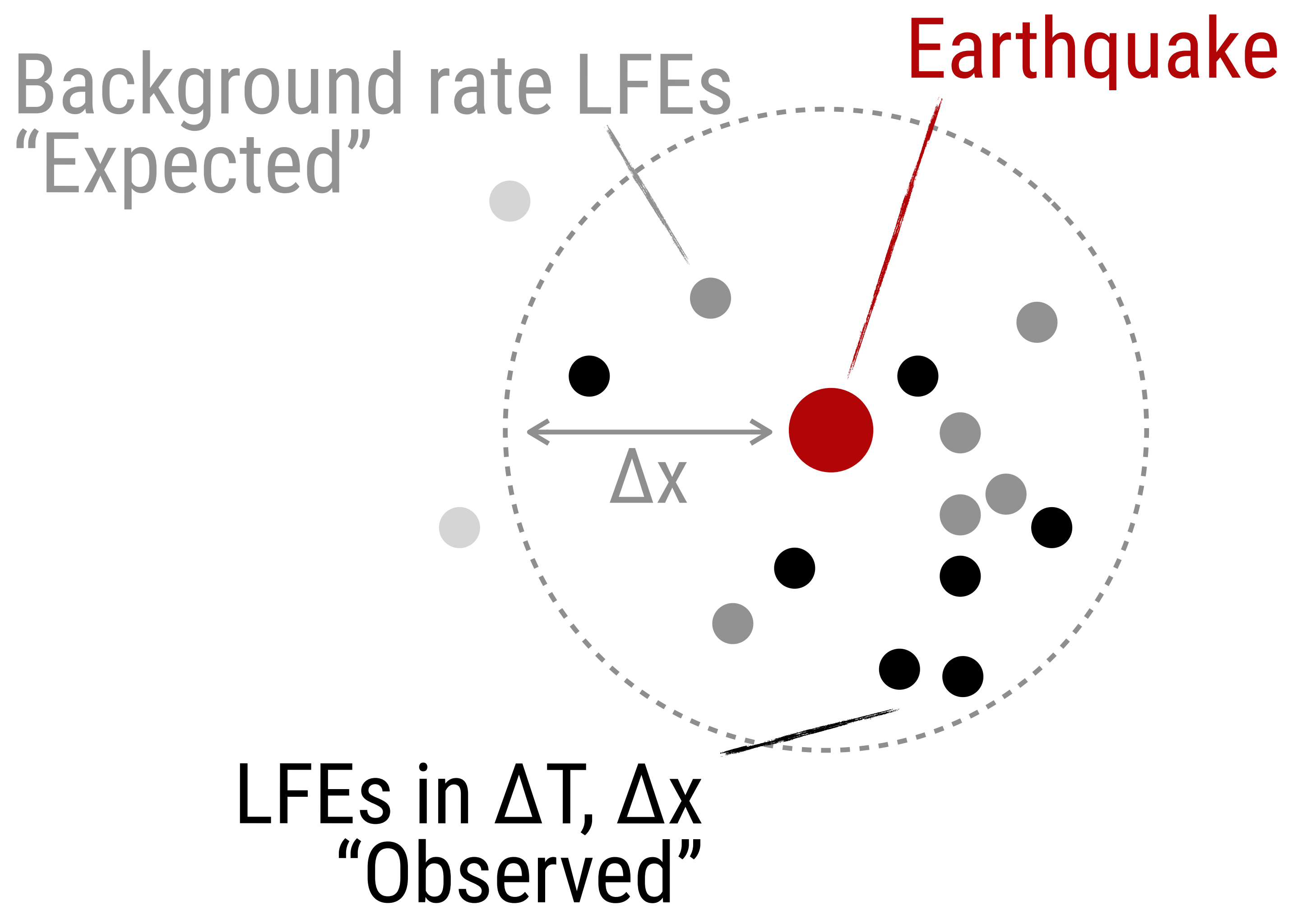
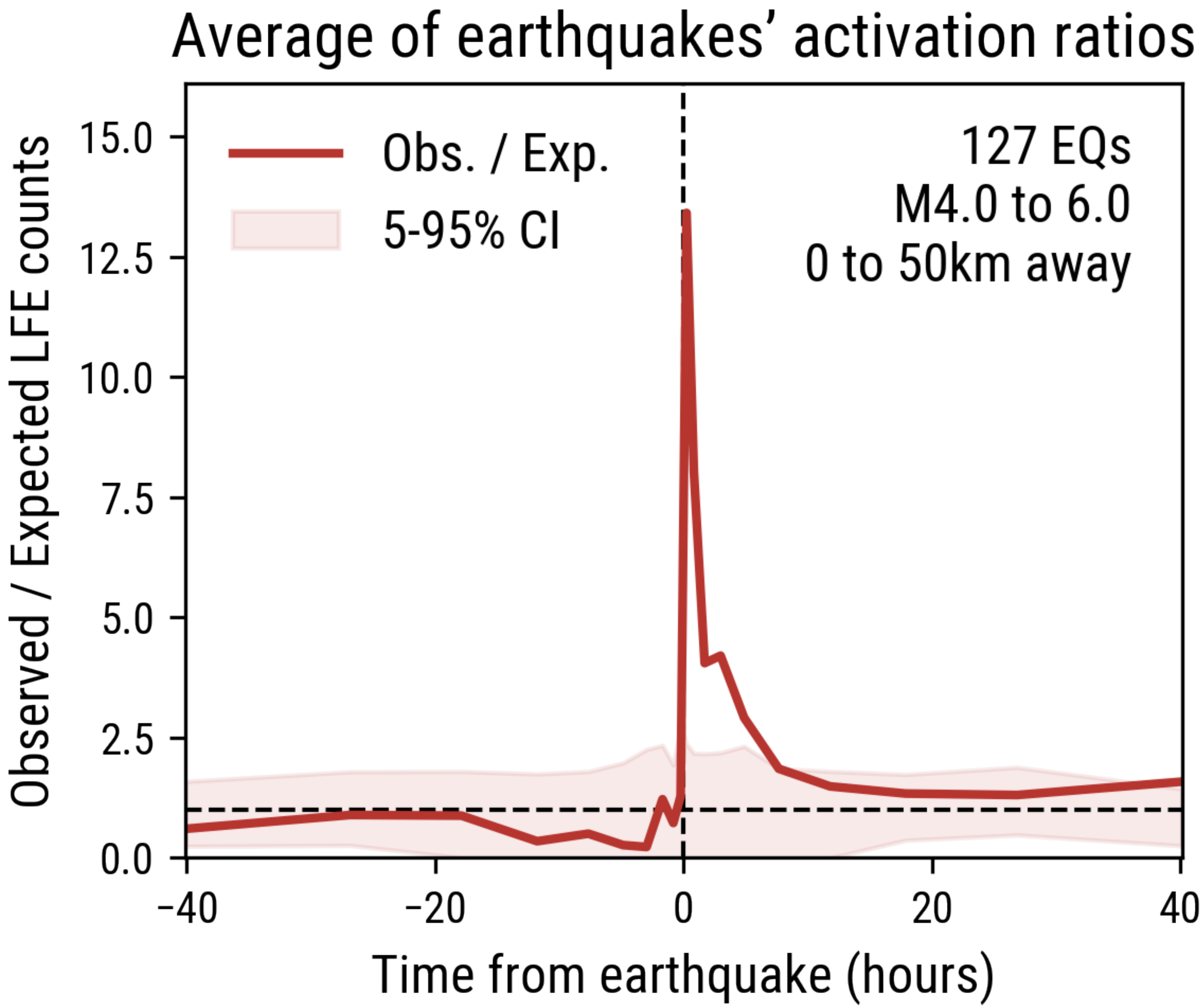
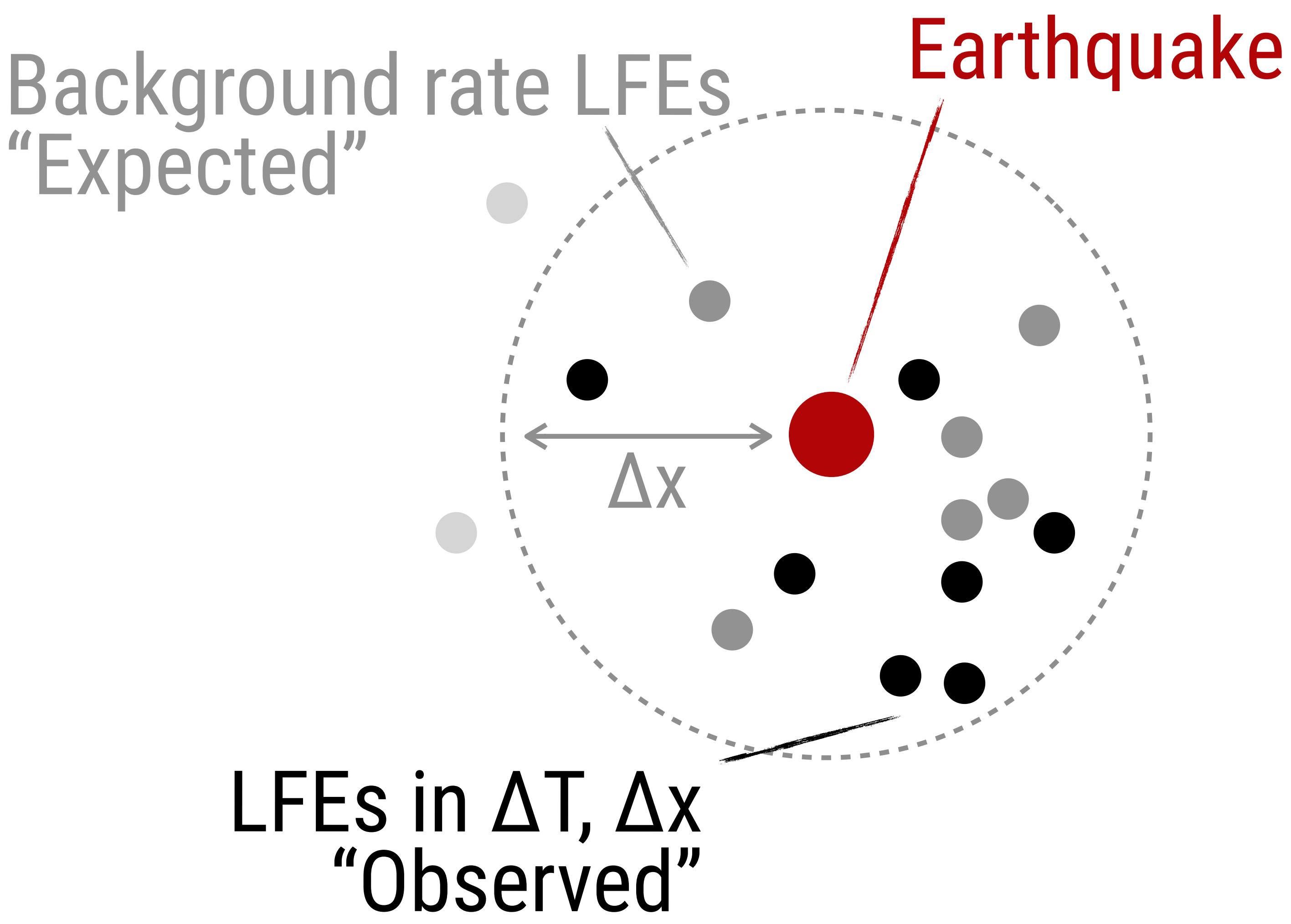
Earthquakes trigger tremor

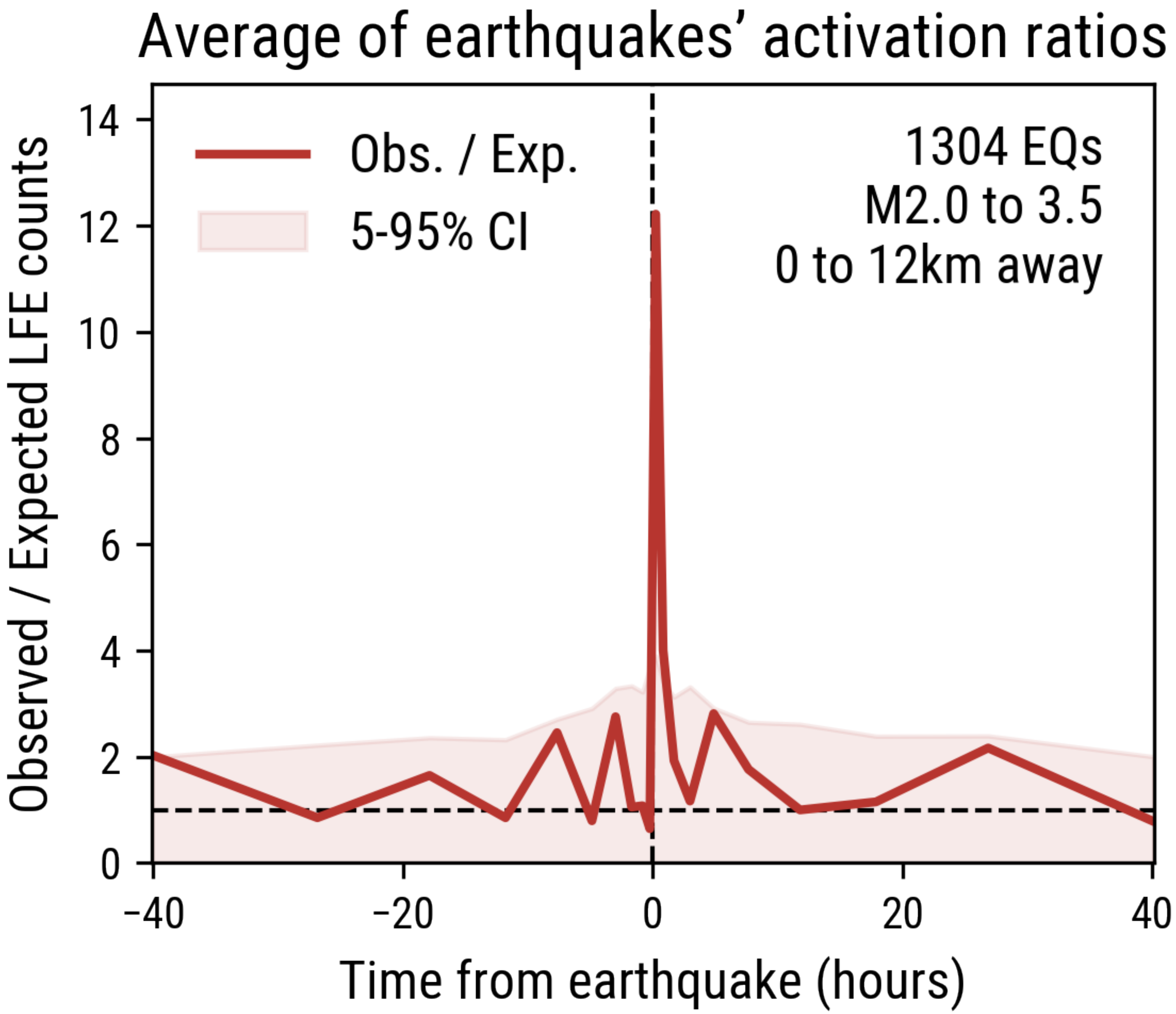


- Large earthquakes known to trigger tremor globally and regionally



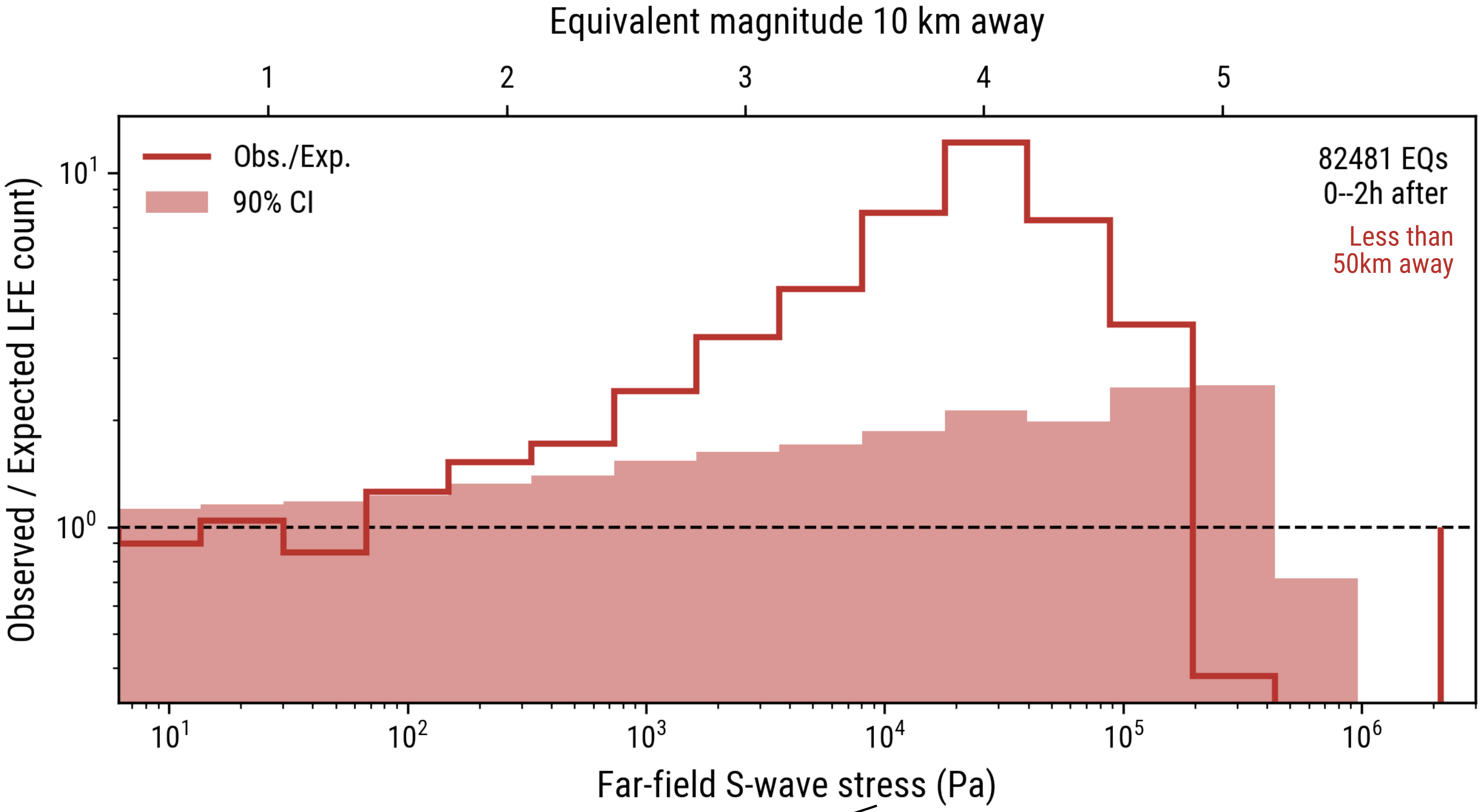
Small Earthquakes trigger tremor



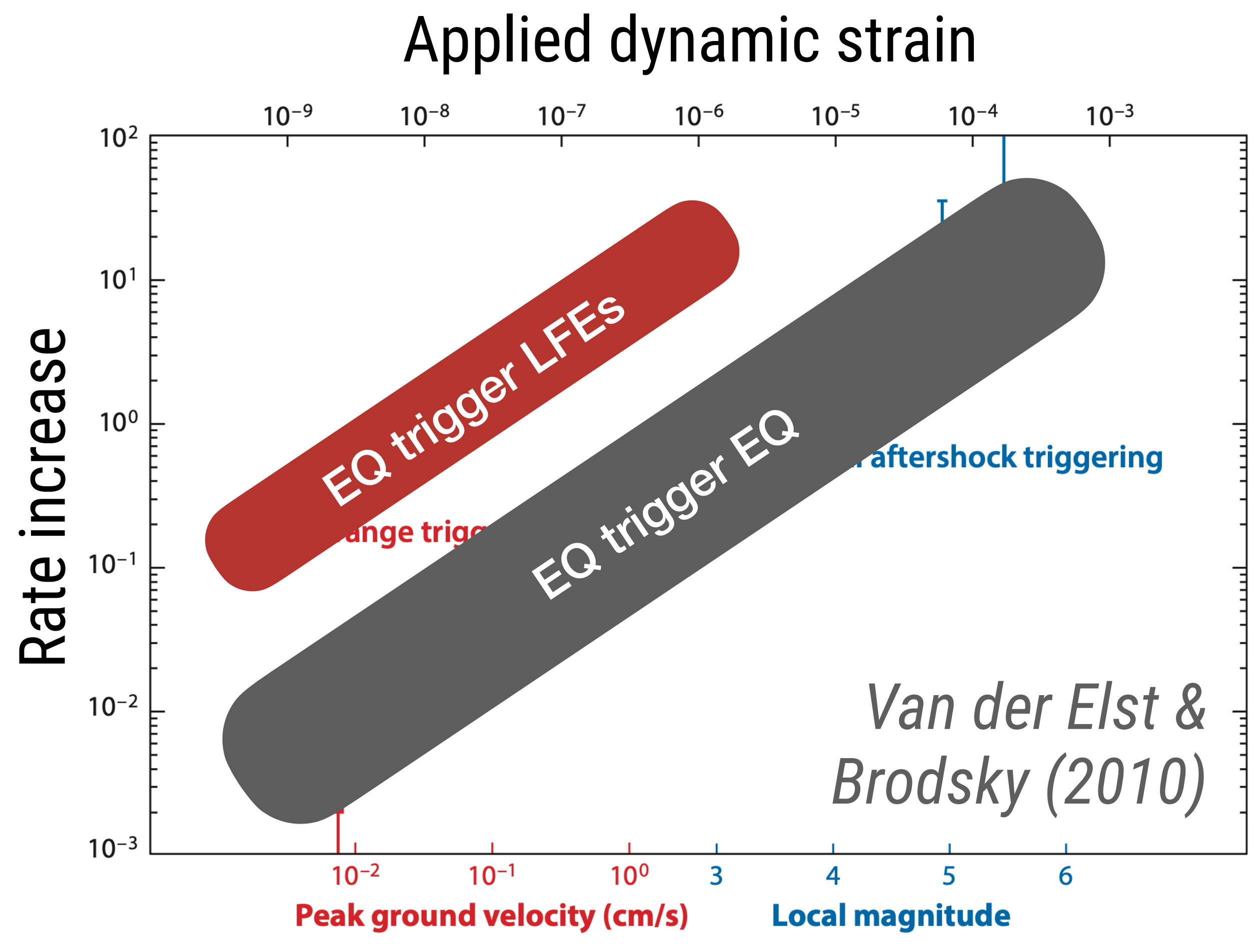


- Large earthquakes known to trigger tremor globally and regionally
- ***Smaller earthquakes trigger tremor locally***

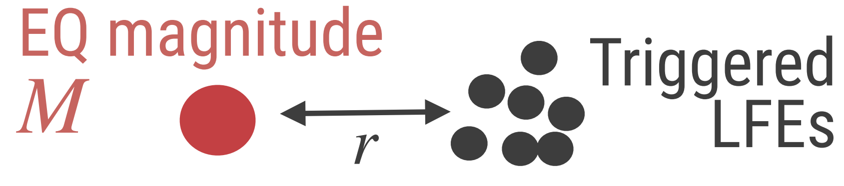
Tremor is extremely* sensitive to dynamic stress



*The same dynamic stress produces ~ **x100 more** triggering of LFEs than EQ*



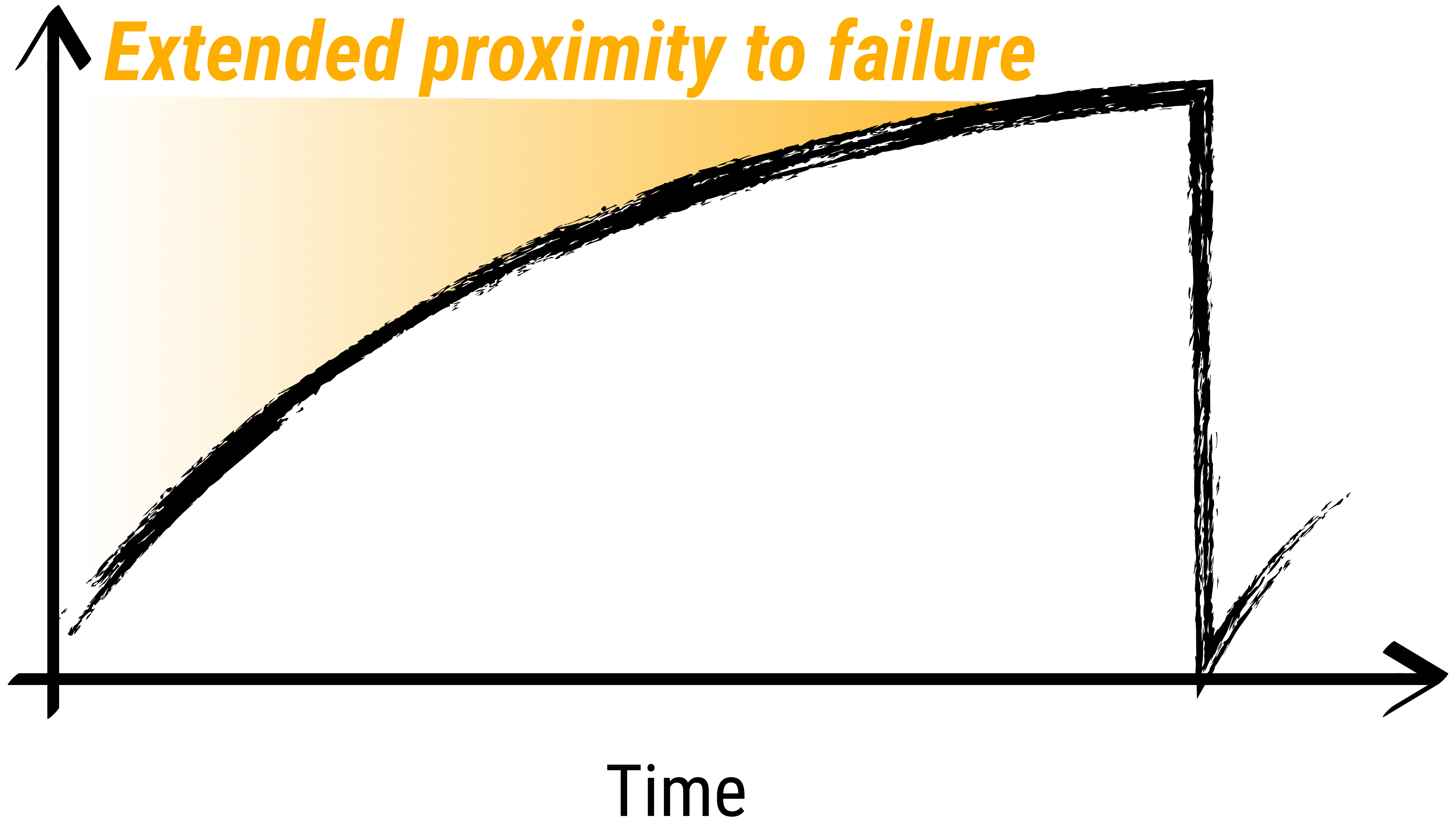
Peak dynamic stress from far-field S-wave



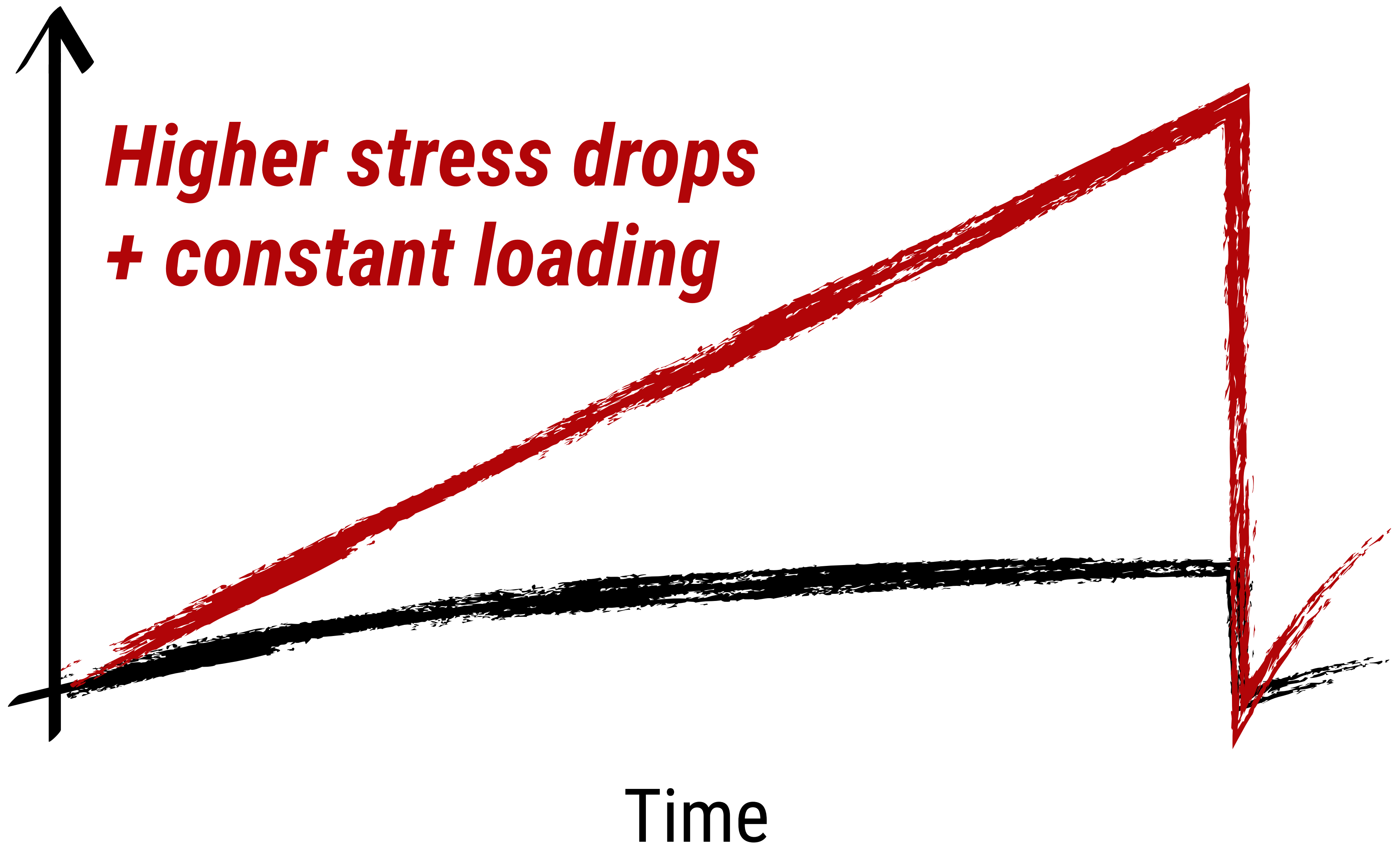
$$\sigma_{max} \propto G \times 10^M / r$$

Tremor is extremely* sensitive to dynamic stress

Tremor / slow-slip loading



Earthquake loading



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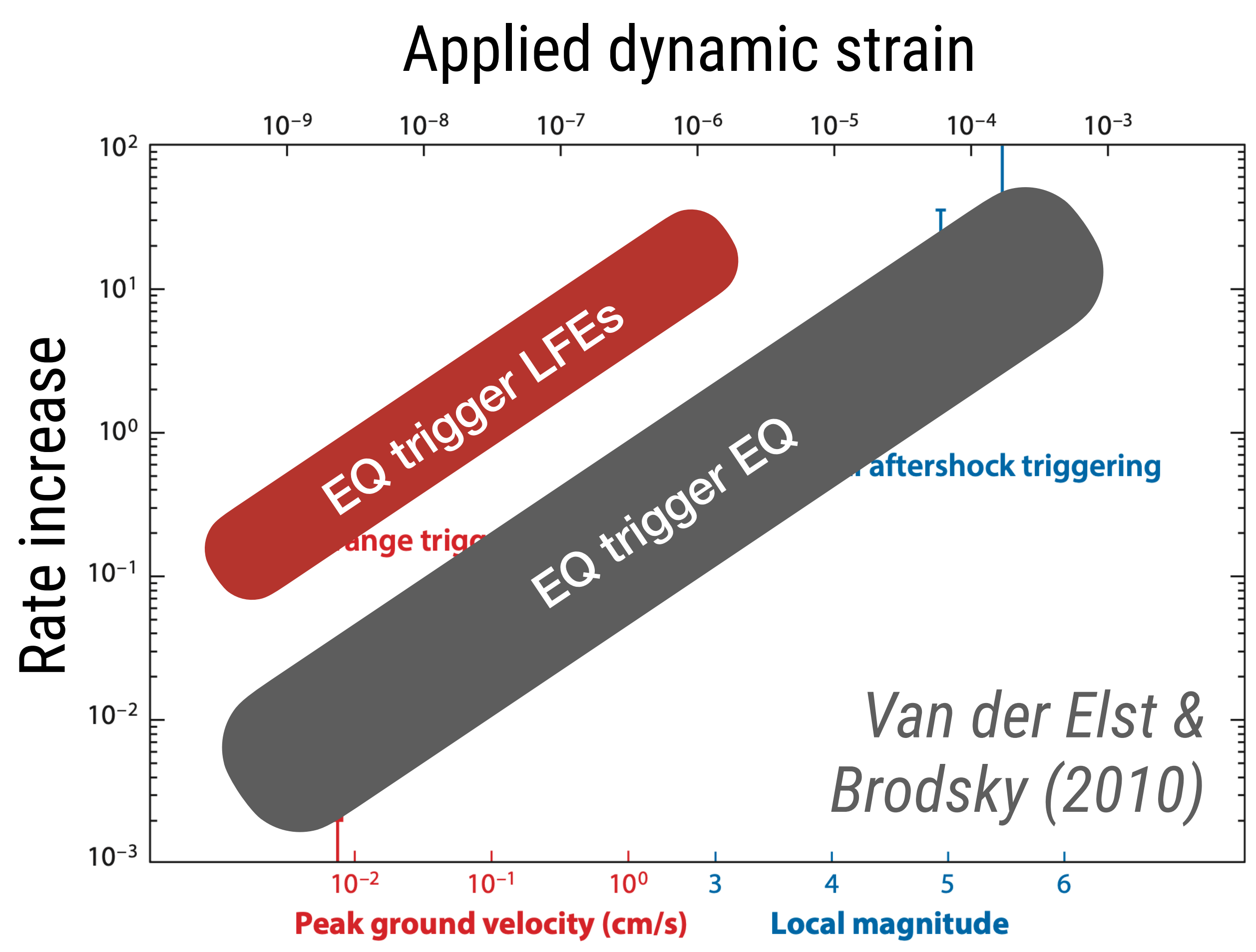

Consequences for tremor synchronization

How far along-strike is the activity correlated, and do earthquakes influence it?

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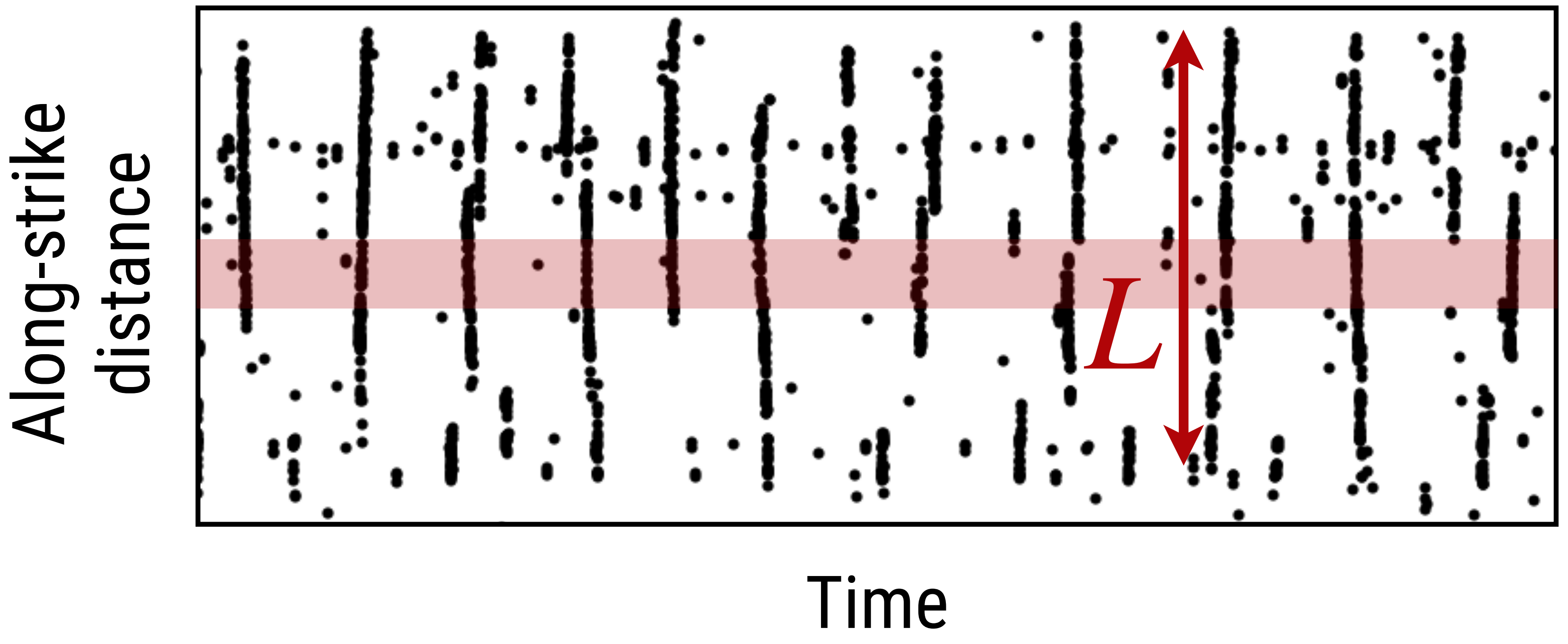
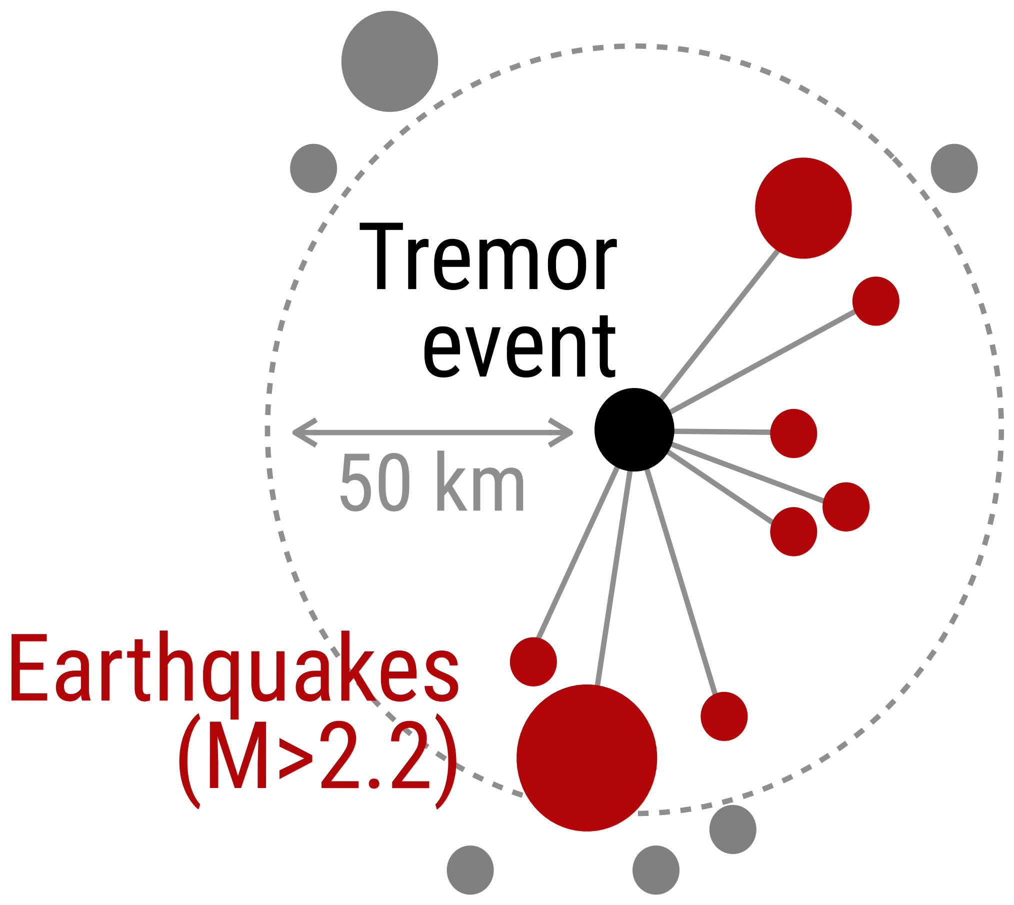
How far along-strike is the activity correlated, and do earthquakes influence it?

In 7 tremor zones across the world

1. Measure tremor correlation length



2. Measure number of earthquakes "felt" by tremor



Japan Trench
- Nishikawa et al (2023) tremor
- JMA earthquakes
- 6.5 years, 1000 km

Nankai
- NIED tremor
- JMA earthquakes
- 21 years, 700 km

Cascadia
- PNSN tremor
- ComCat earthquakes
- 15 years, 1,200 km

Alaska
- Wech (2016) tremor
- ComCat earthquakes
- 3 years, 350 km

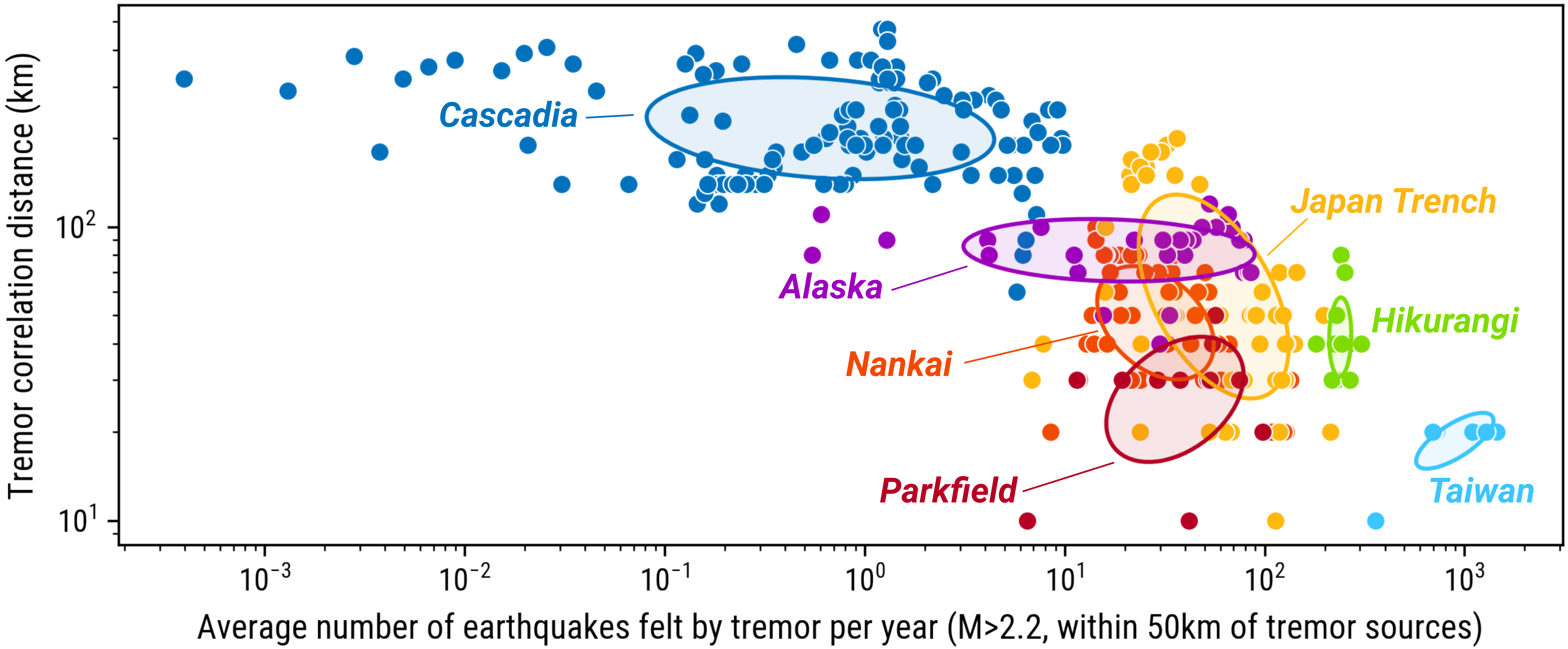
Taiwan
- Ide & Chen (2024) tremor
- CWASN earthquakes
- 11 years, 350 km

Hikurangi
- Todd & Schwartz (2016) tremor
- GeoNet earthquakes
- 7 years, 160 km

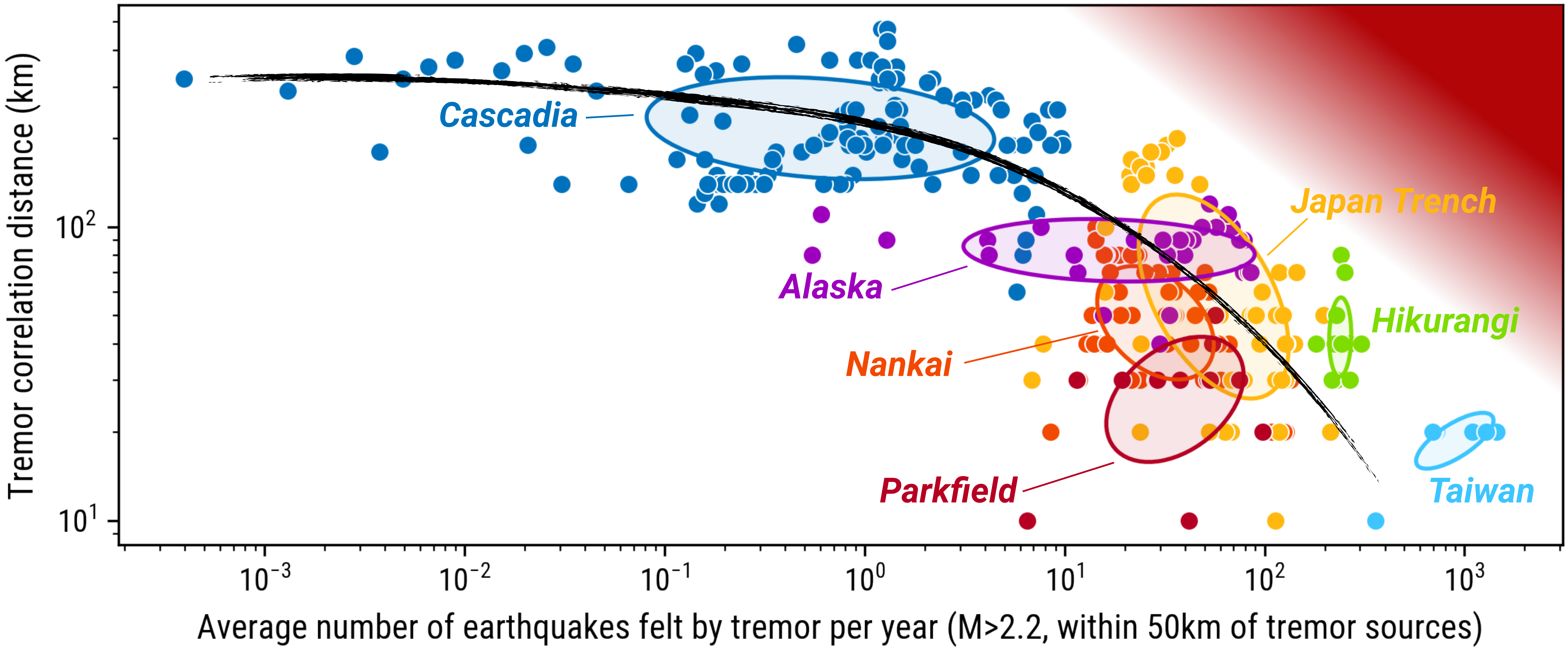
Parkfield
- Shelly (2017) LFEs
- Waldhauser & Schaff (2008) earthquakes
- 17 years, 160 km

Small earthquake activity anti-correlates with **tremor synchronization**

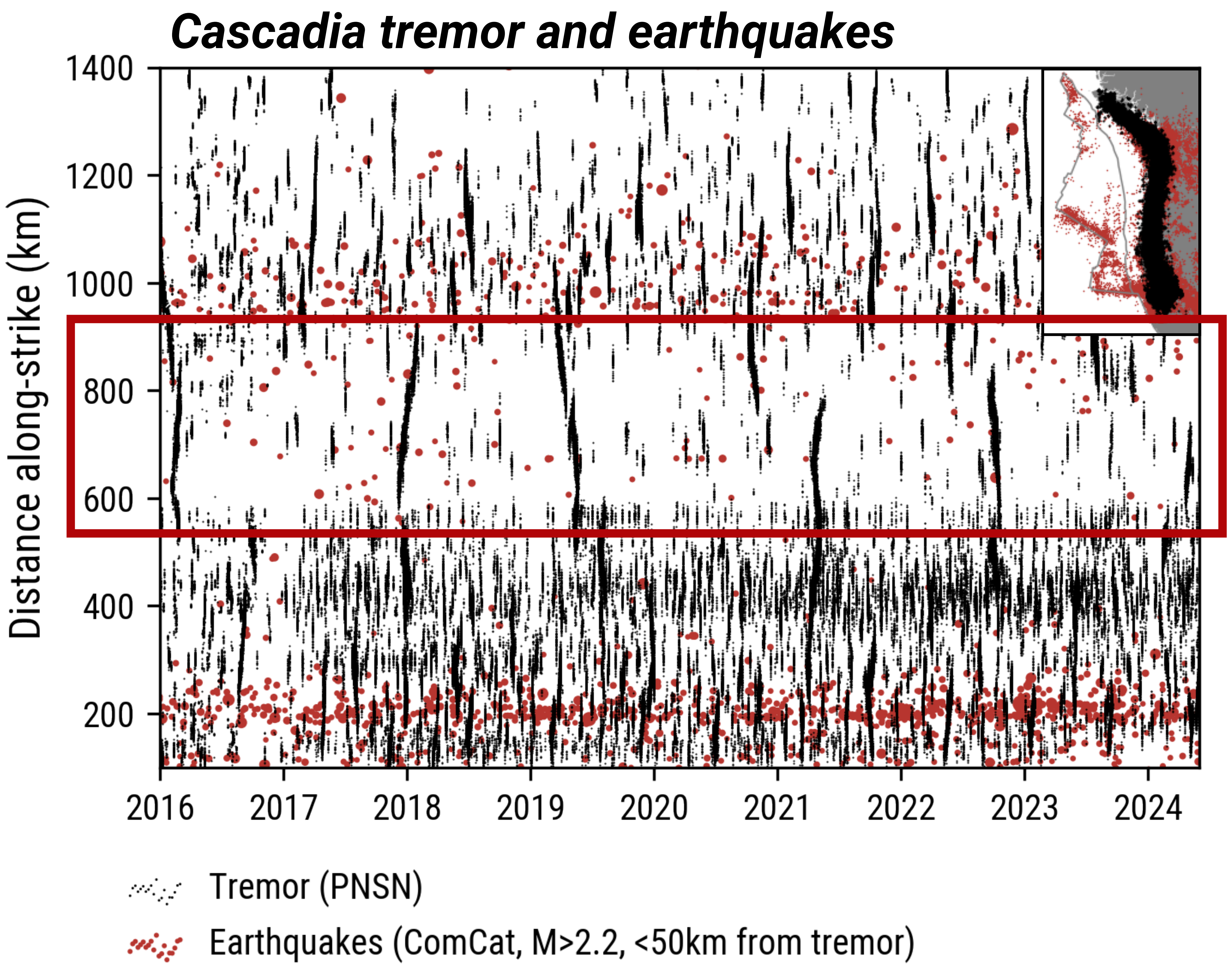
Across regions and along strike

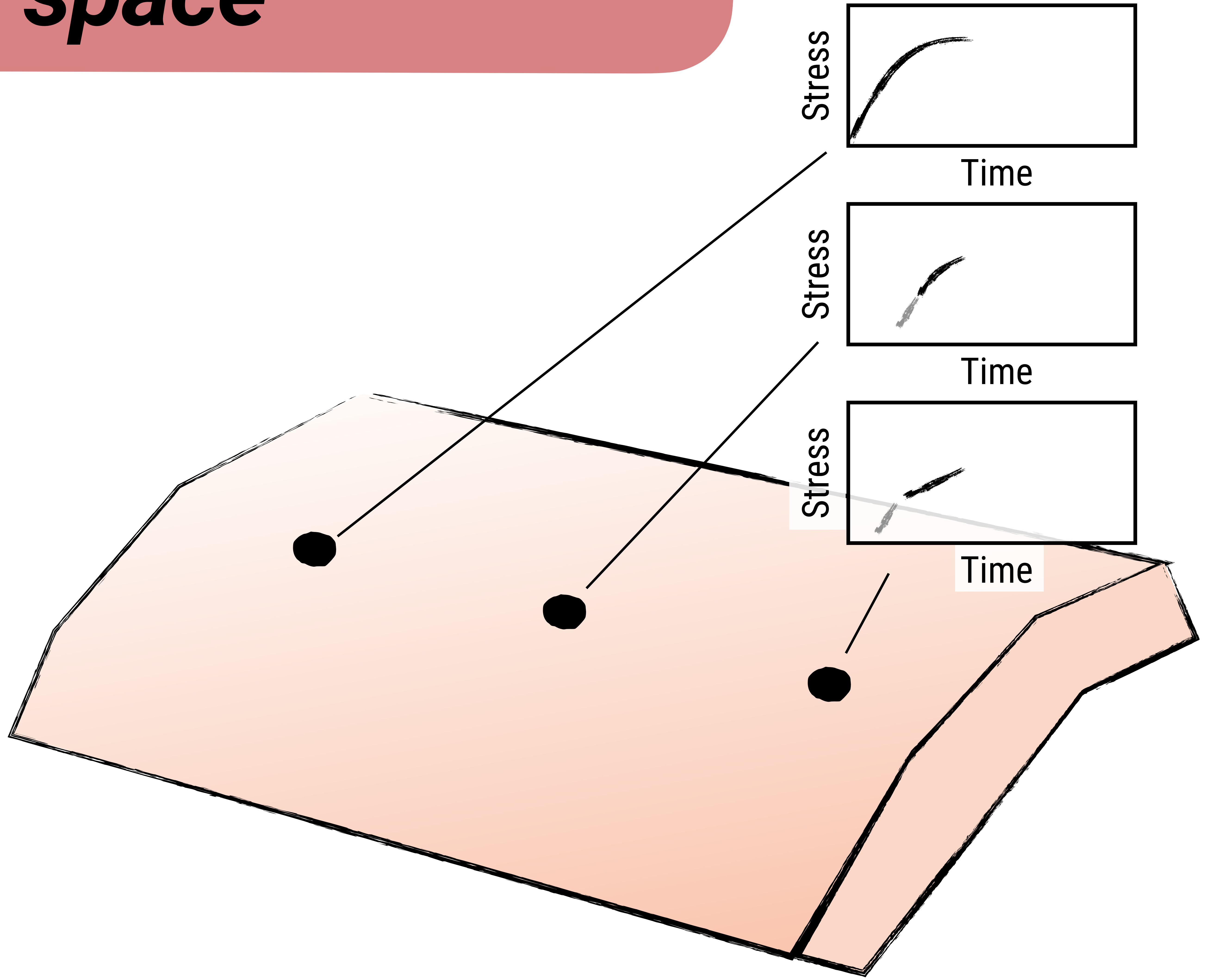


Small Earthquakes Disrupt Tectonic Tremor Synchronization

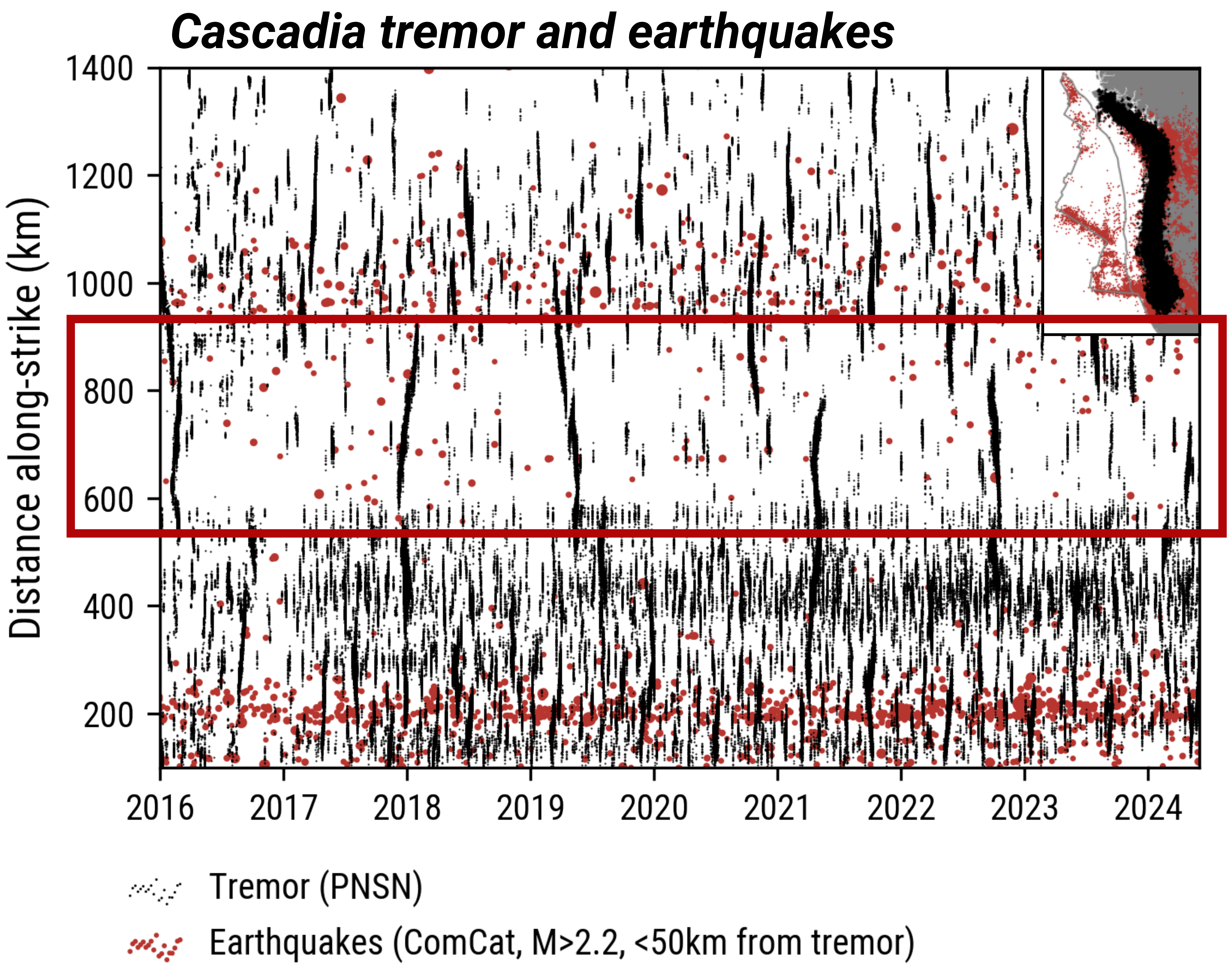


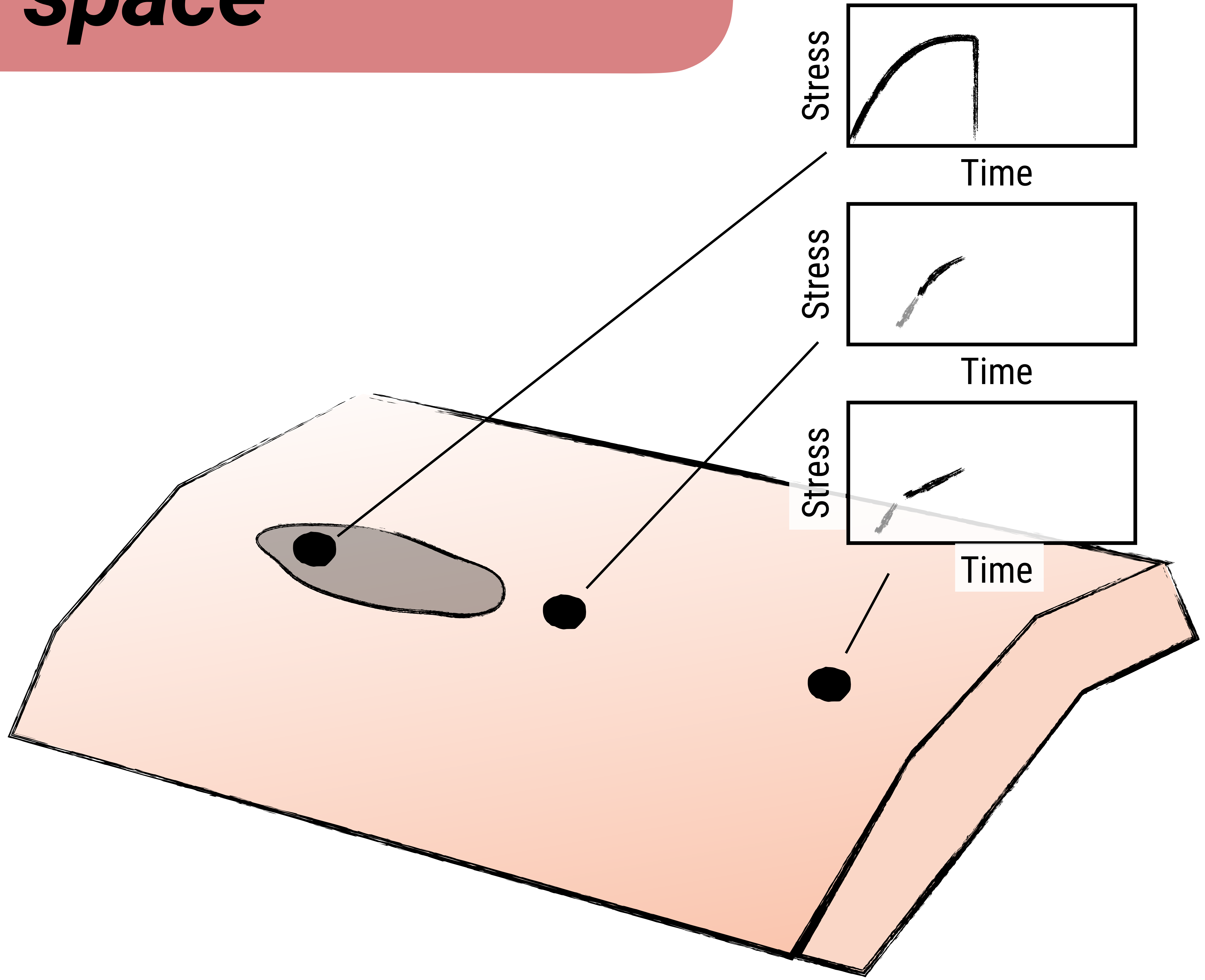
Interactions through rupture synchronize fault activity in time and space



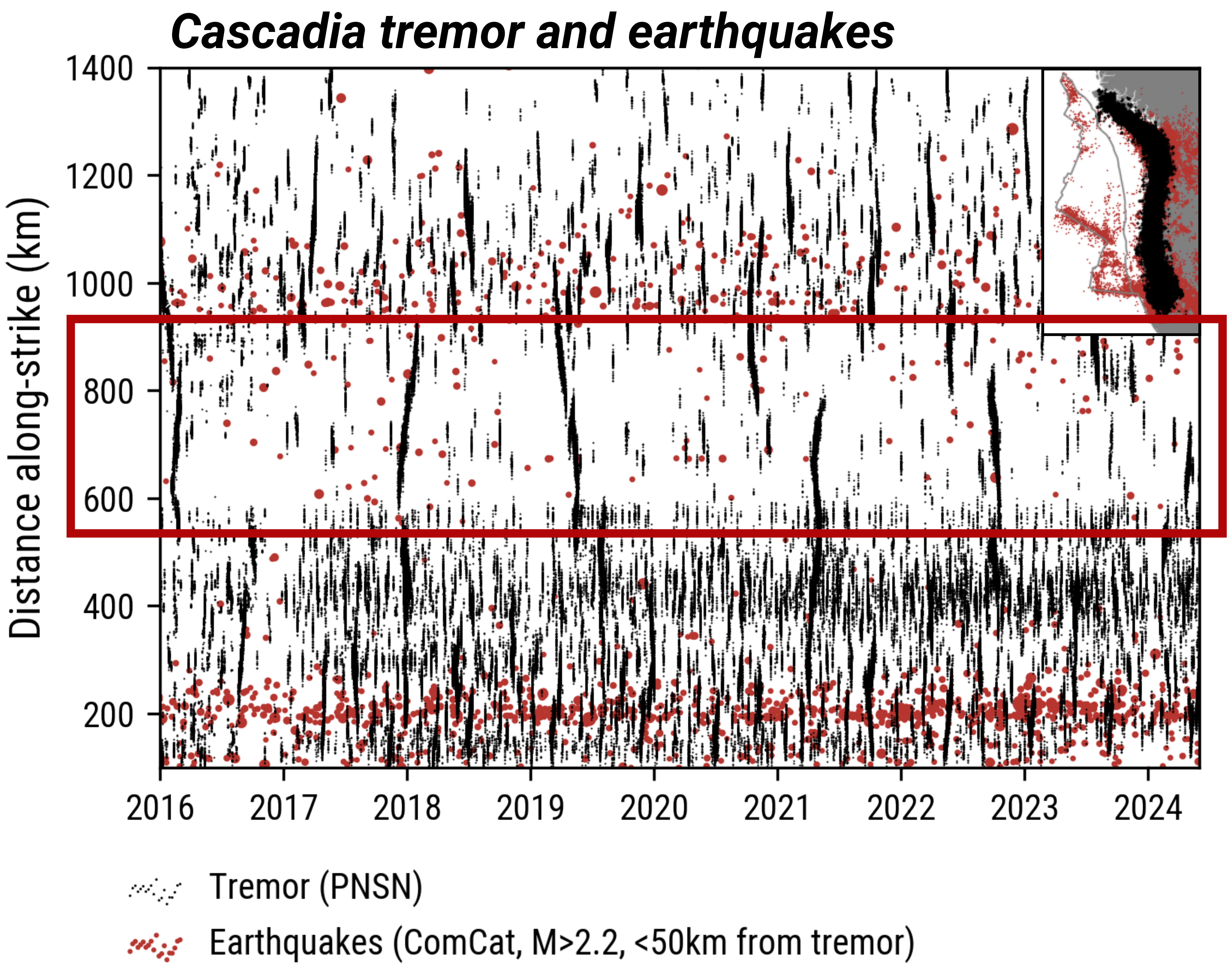


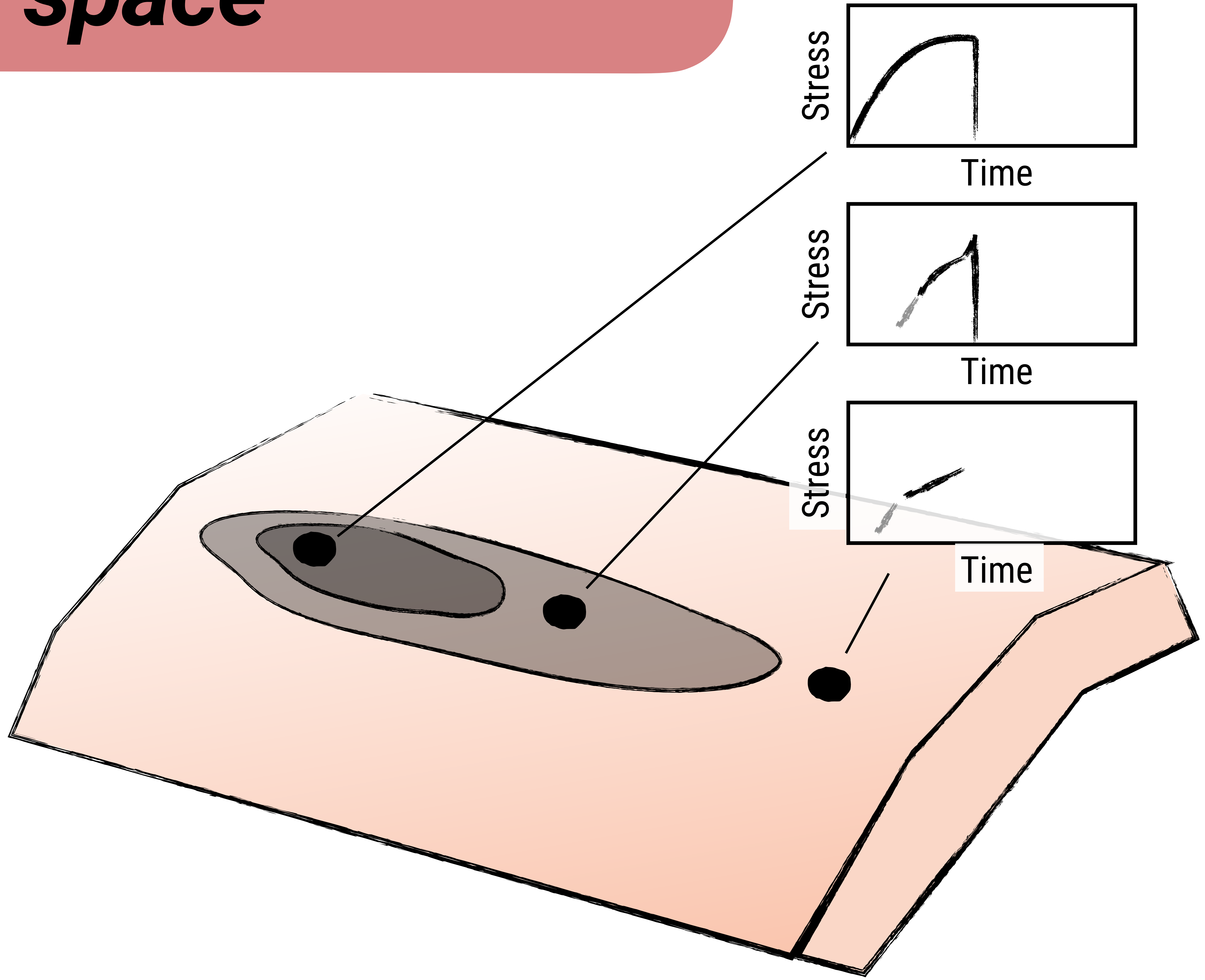
Interactions through rupture synchronize fault activity in time and space



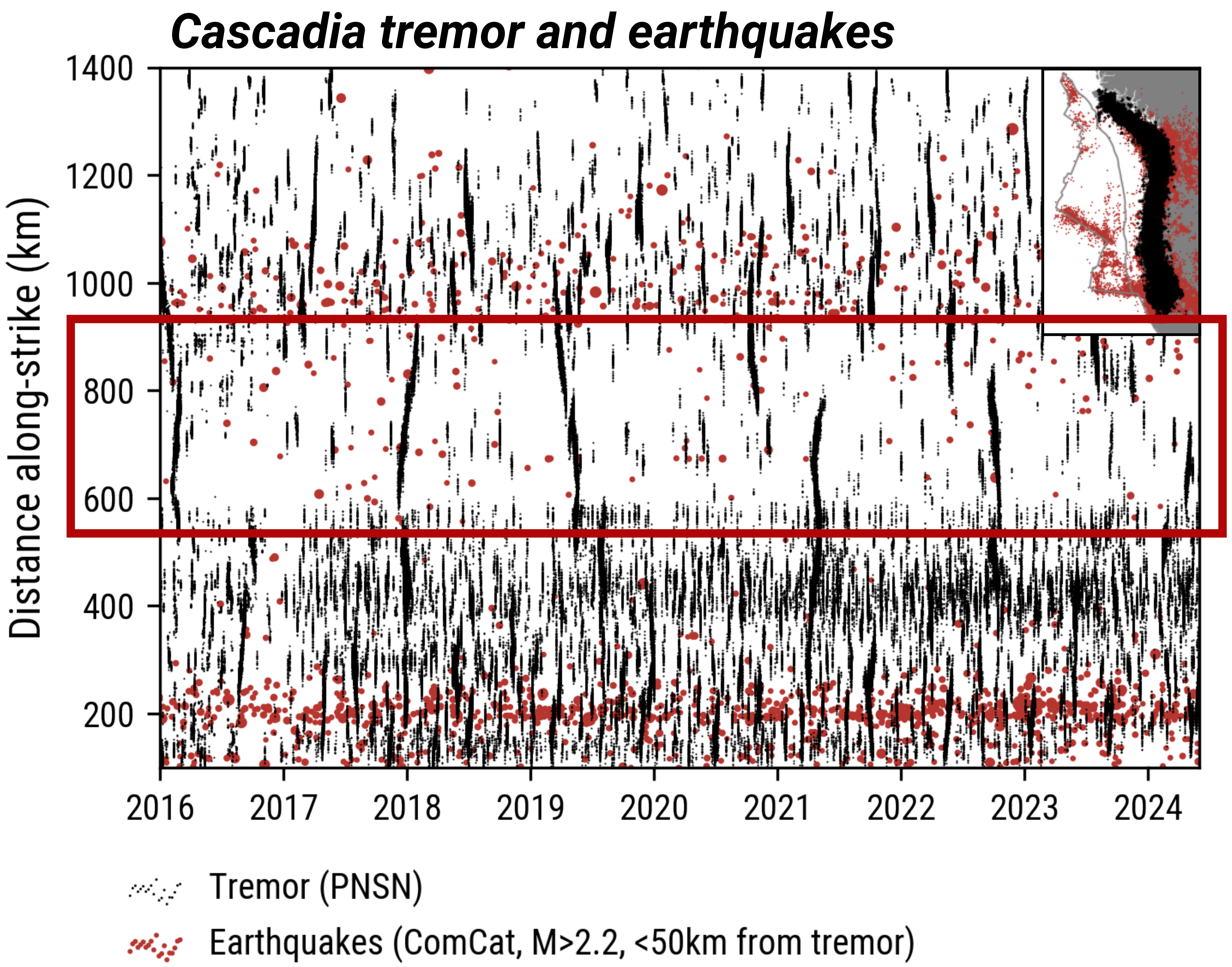


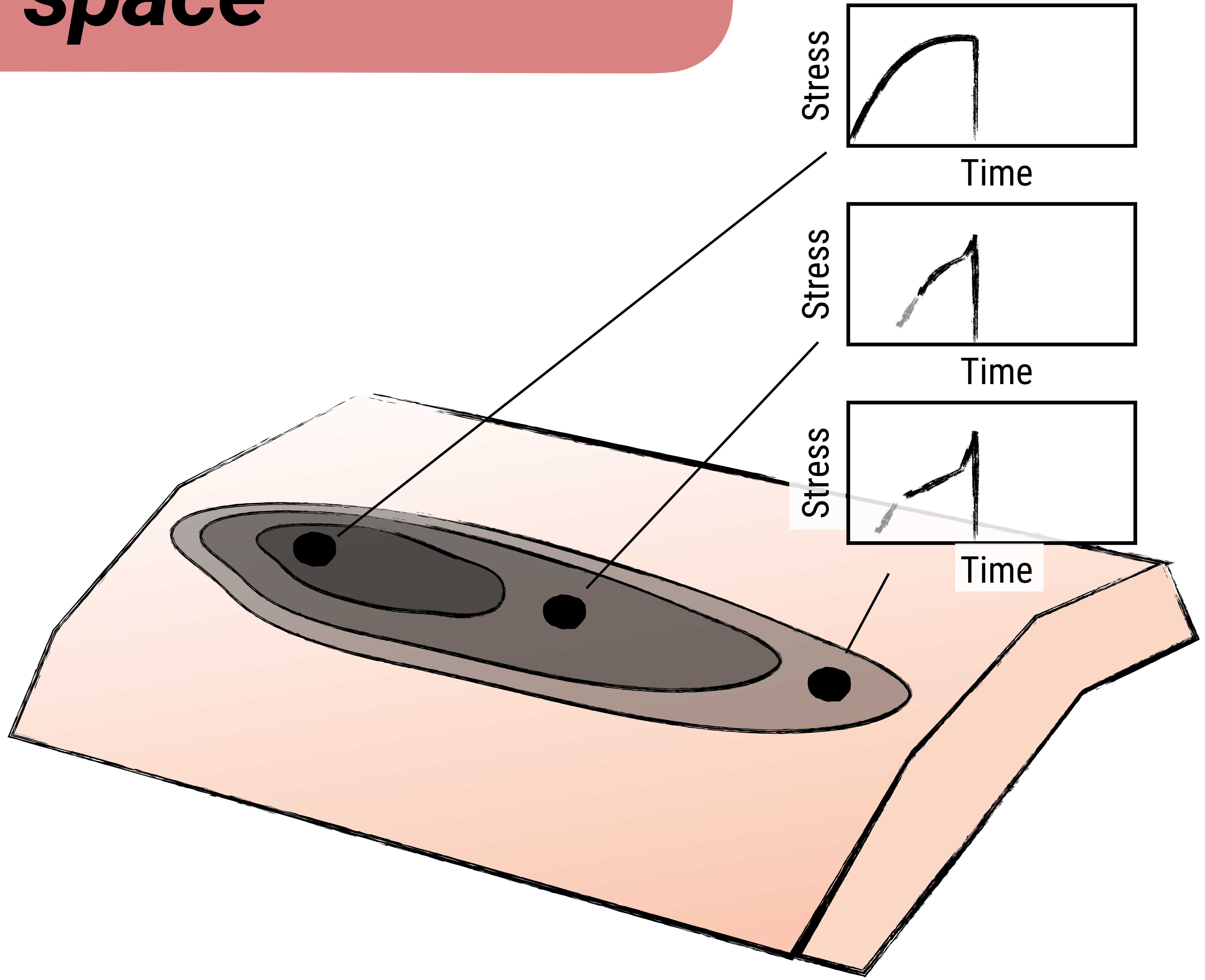
Interactions through rupture synchronize fault activity in time and space



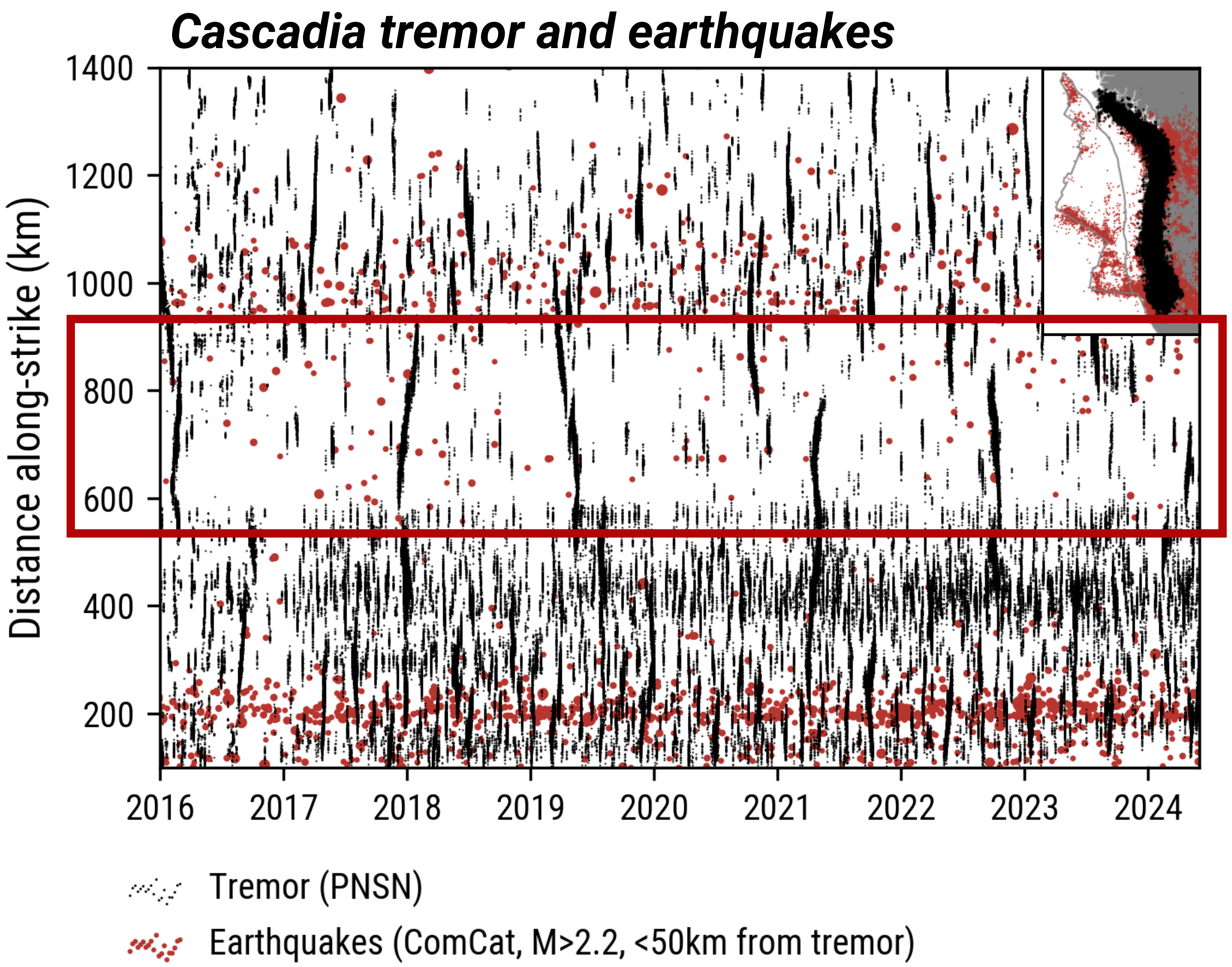


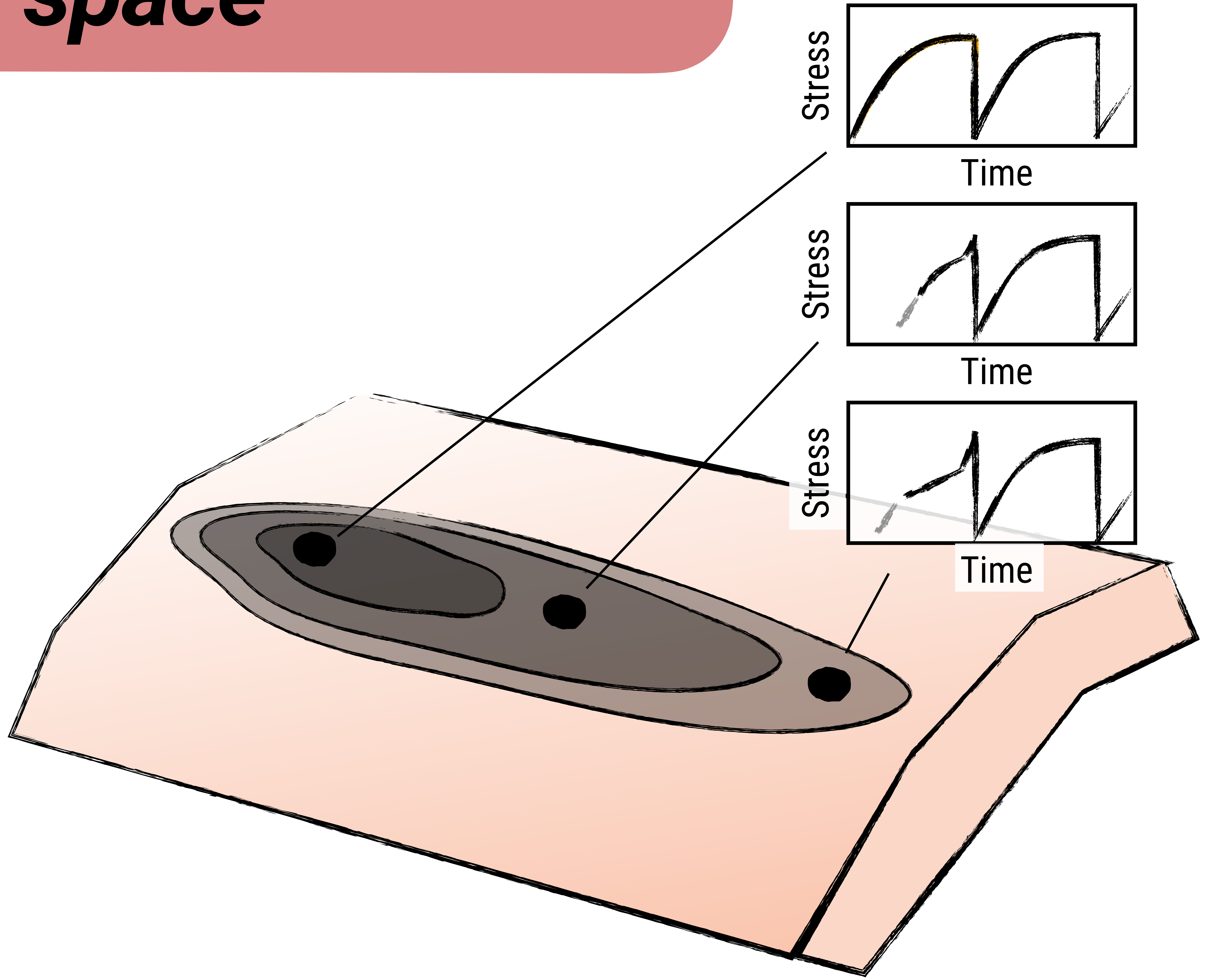
Interactions through rupture synchronize fault activity in time and space



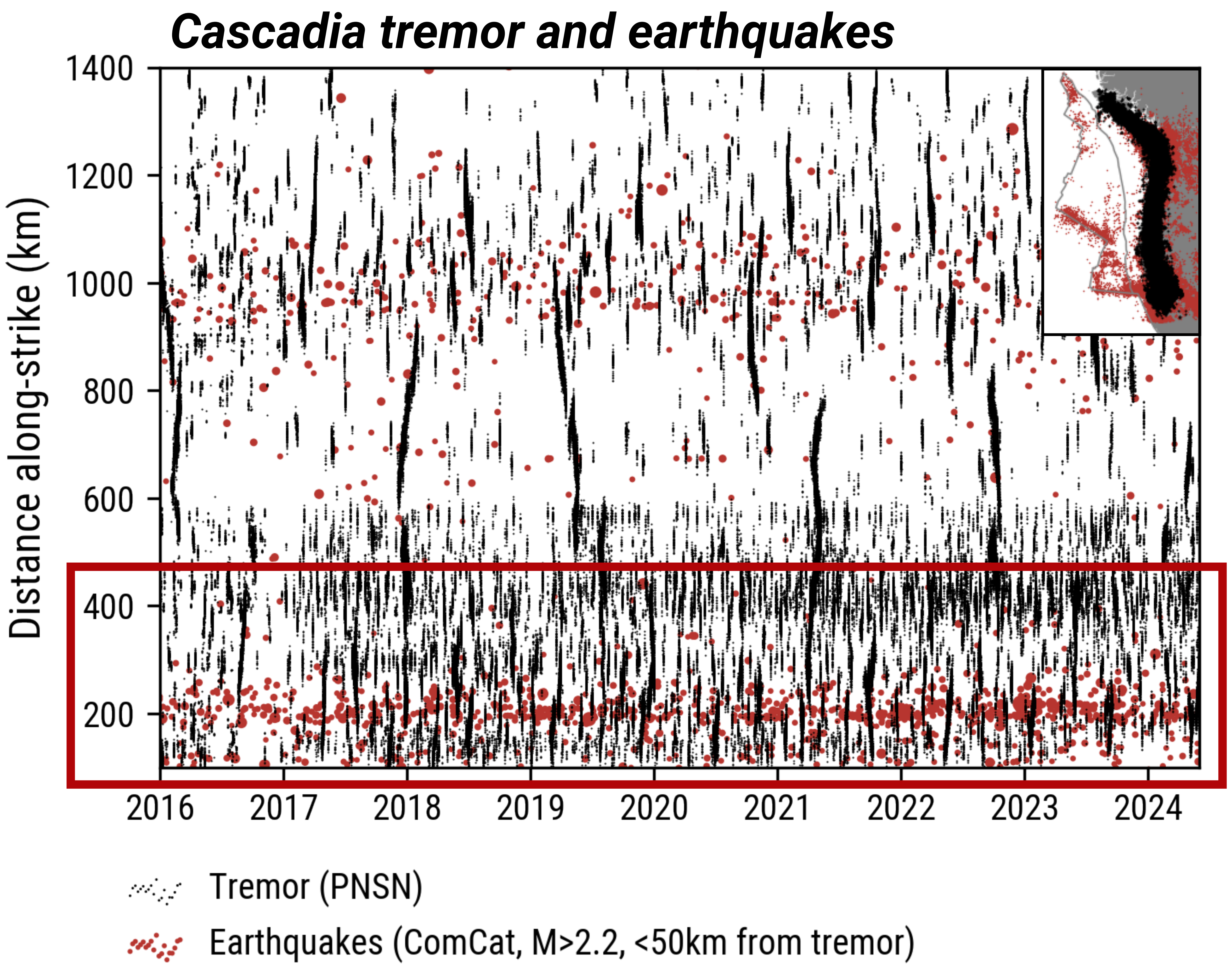


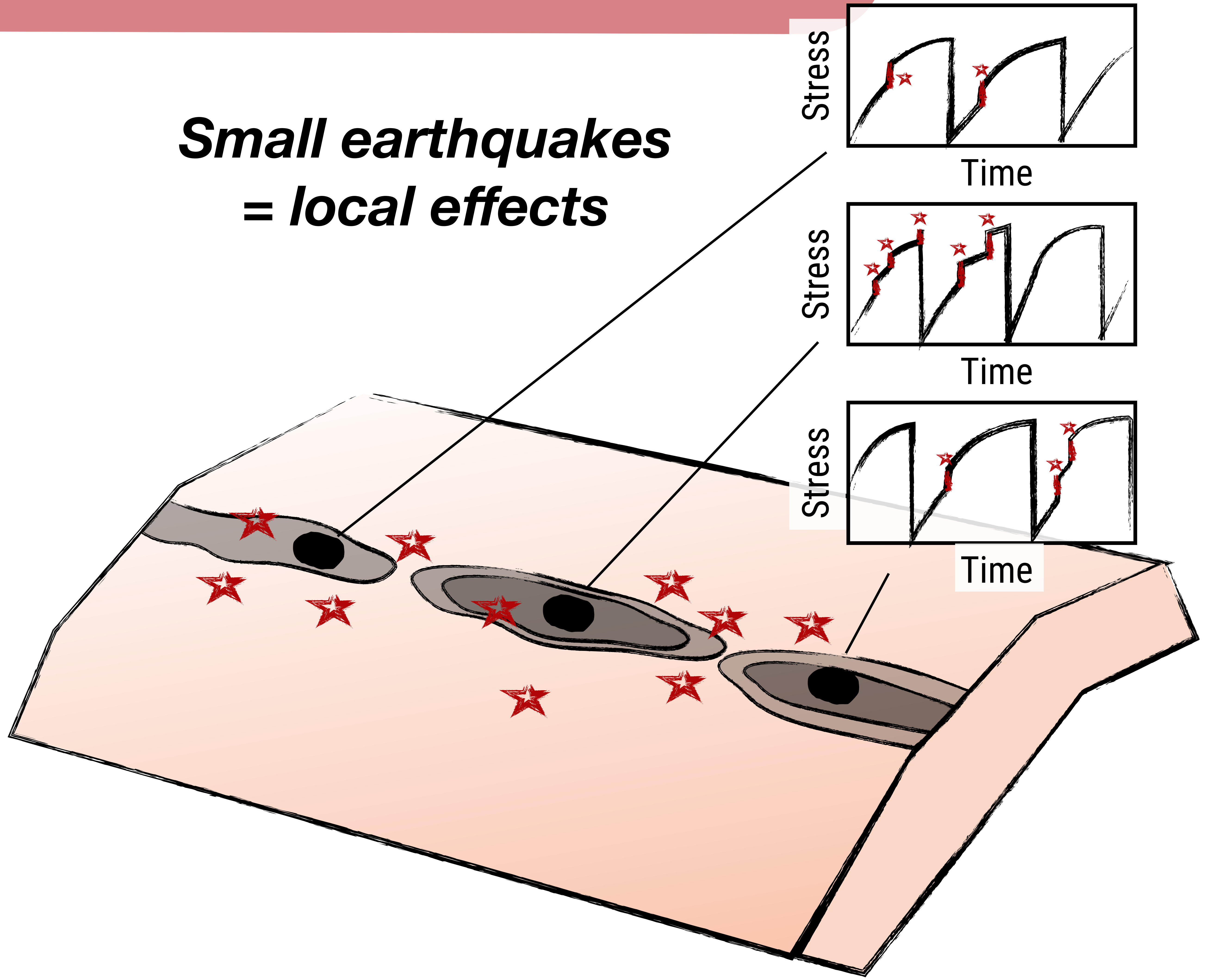
Interactions through rupture synchronize fault activity in time and space





Local earthquakes disturb the synchronization process and inhibit the emergence of large ruptures



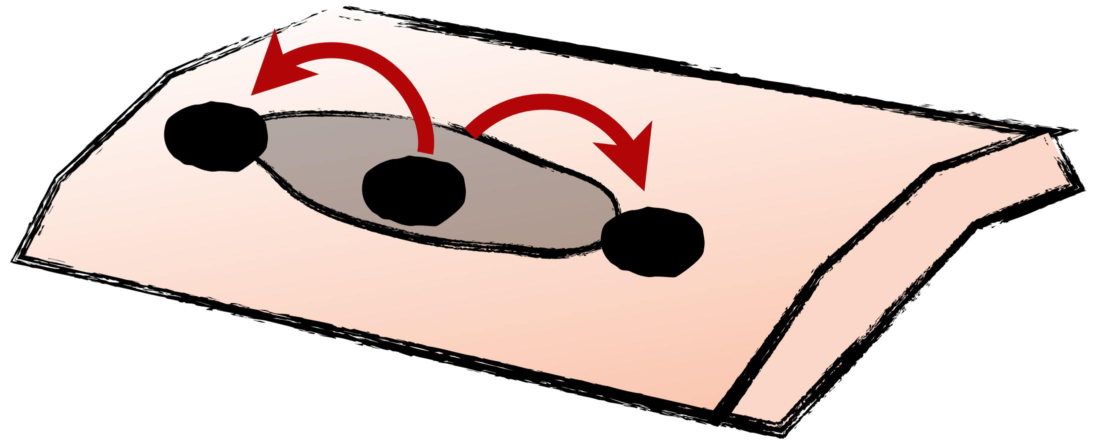


Small earthquakes disrupt ***tectonic tremor synchronization***

➡ Can be modeled!

$$\frac{\mathrm{d}\sigma}{\mathrm{d}t} = V - \alpha\sigma$$

+



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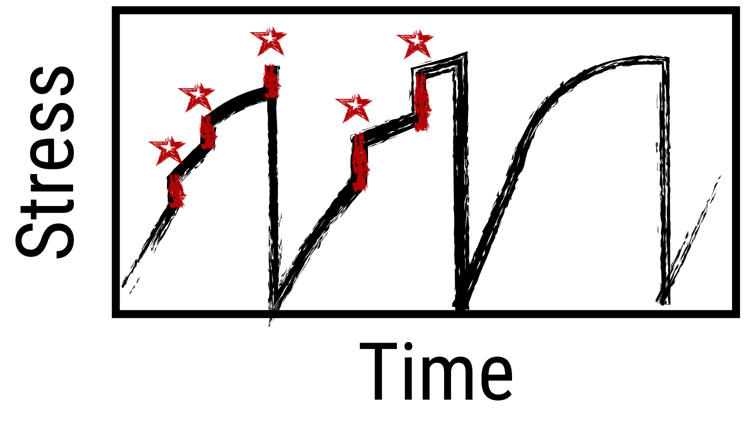
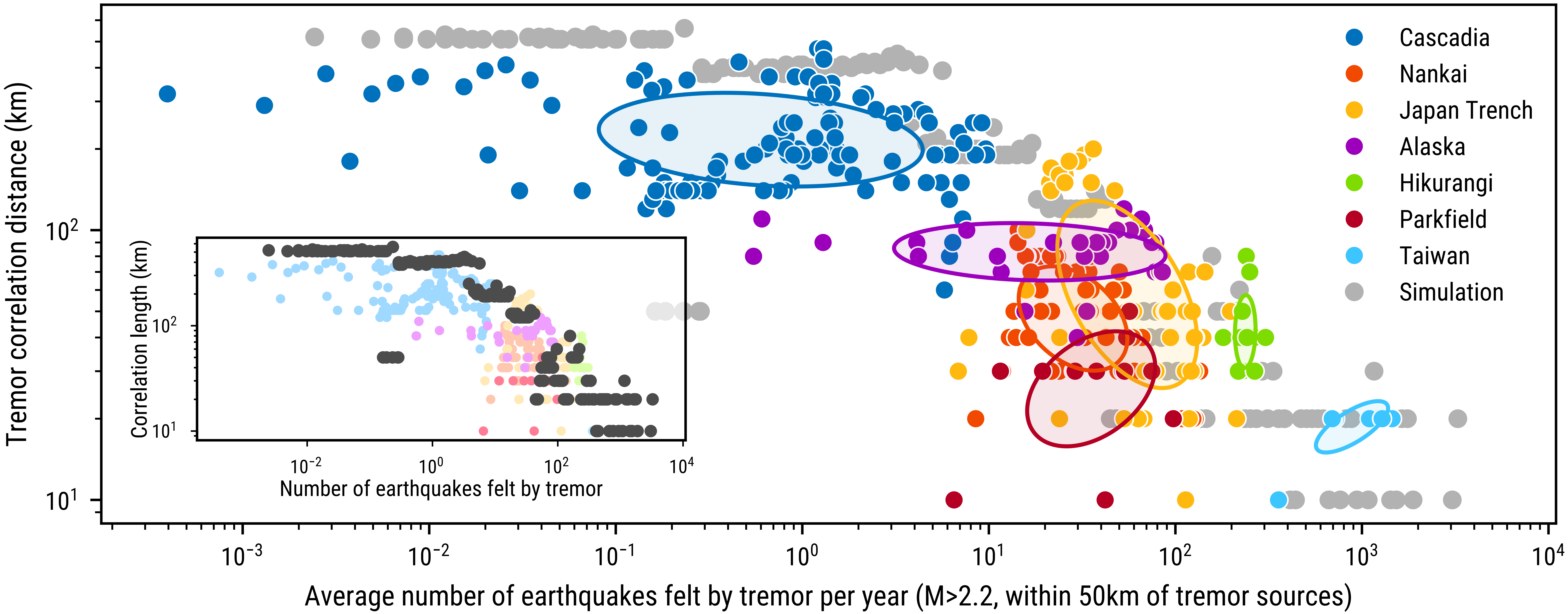
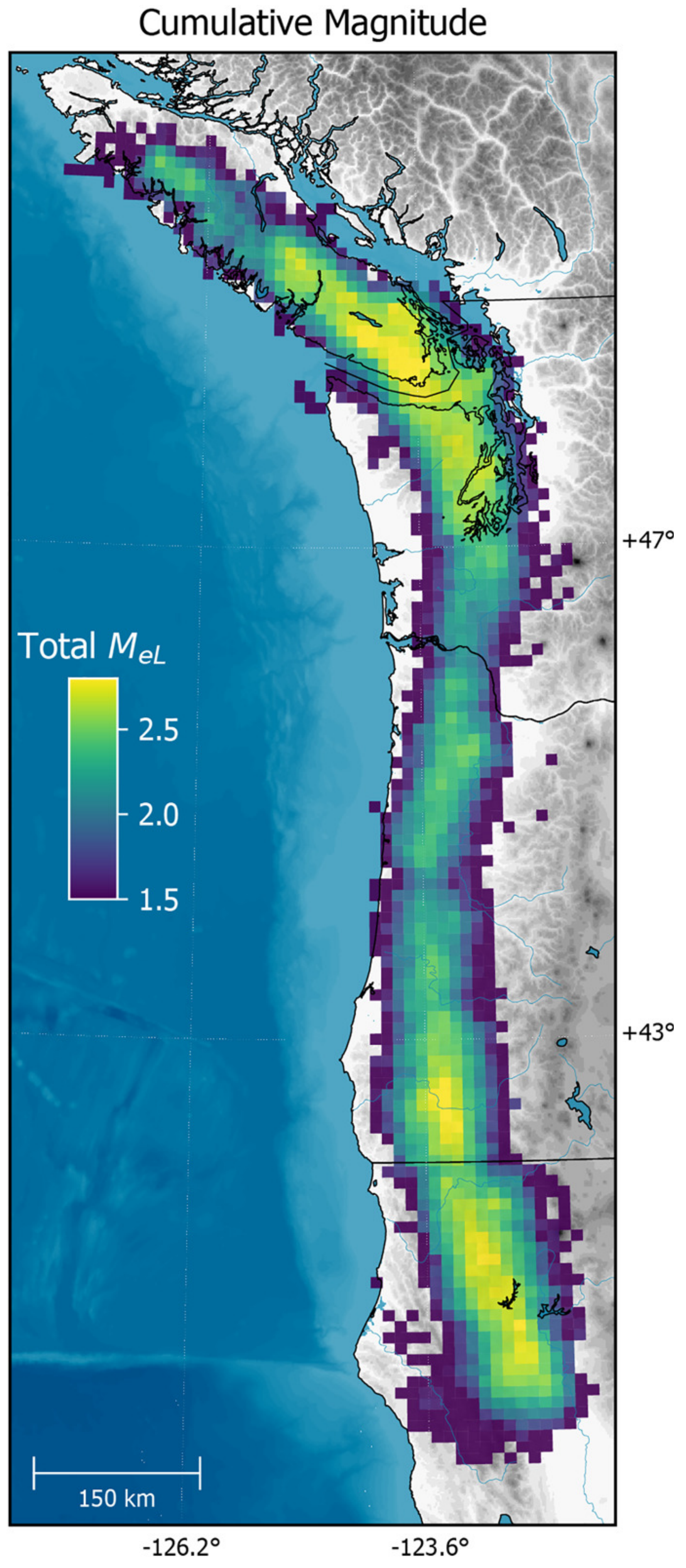


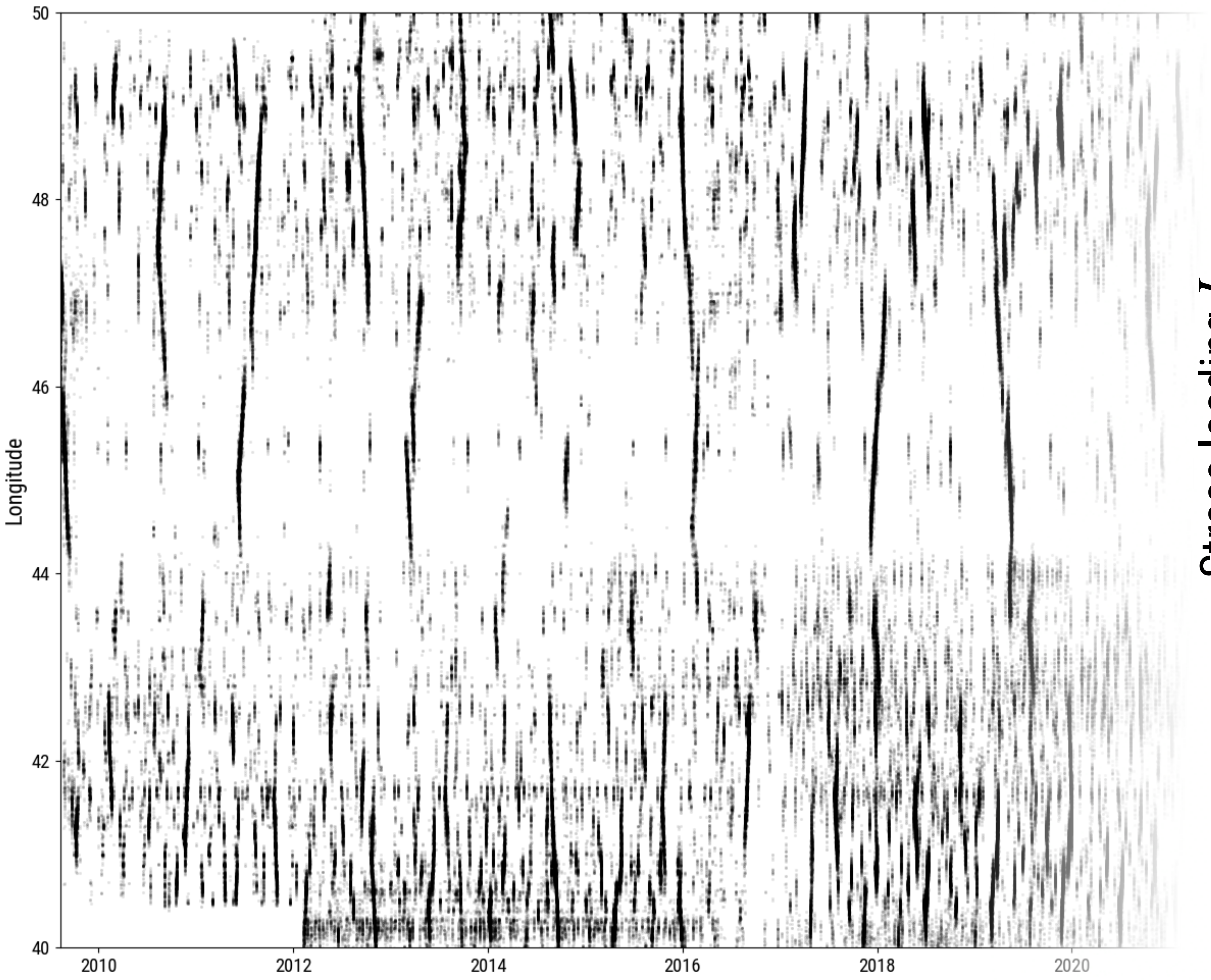
From Farge & Brodsky (2025) – The big impact of small quakes on tremor synchronization (Sci. Adv.)



Conclusion

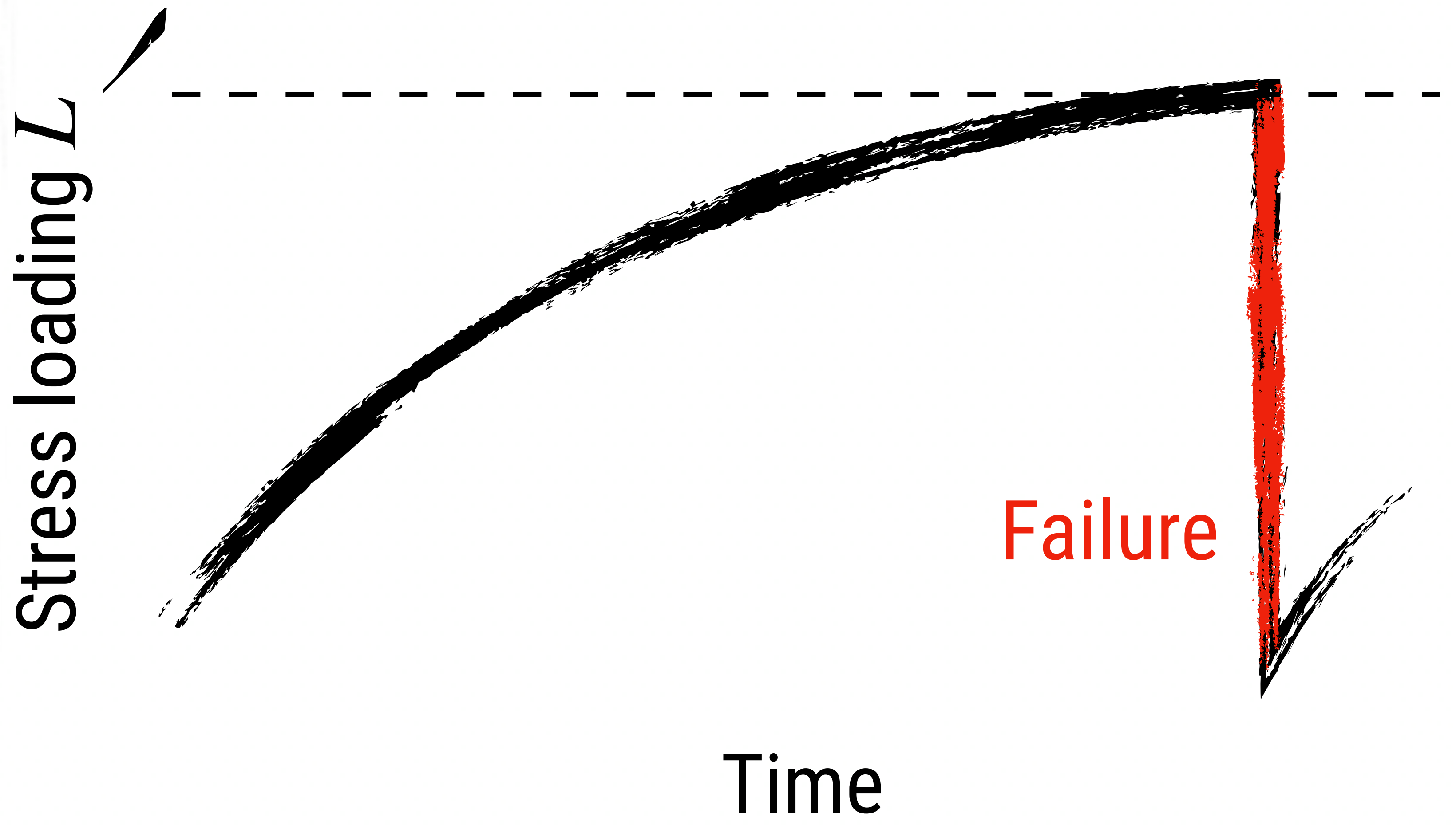
The extraordinary synchronization and sensitivity of tremor and slow slip could emerge from stress leakage





Adapted from Wech et al. (2021, 2008 etc)

Leaky loading



$$\frac{\mathrm{d}\sigma}{\mathrm{d}t} = V - \alpha\sigma$$