Tremor migration patterns and scaling laws resulting from the interaction of deep fault asperities mediated by transient creep

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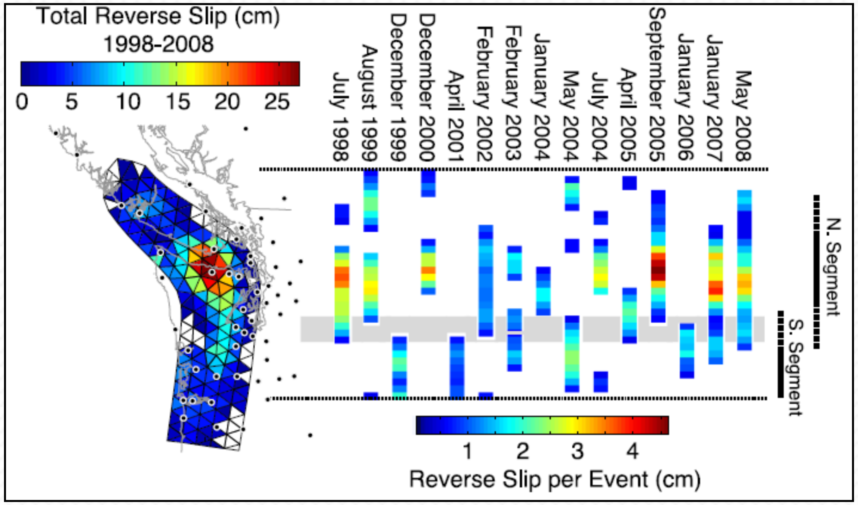
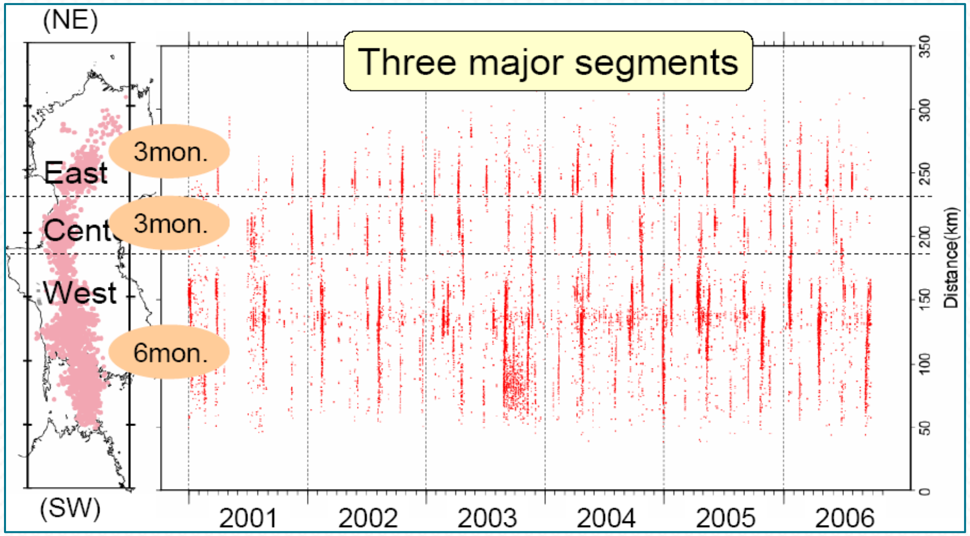
Acknowledgments: **H. Houston and B. Delbridge** (U. Washington), K. Ariyoshi (JAMSTEC), A. Rubin (Princeton), H. Perfettini (IRD)

Spatio-temporal patterns: segmentation and interactions

GPS-inferred slip during slow slip events in Cascadia (Schmidt and Gao, 2010)

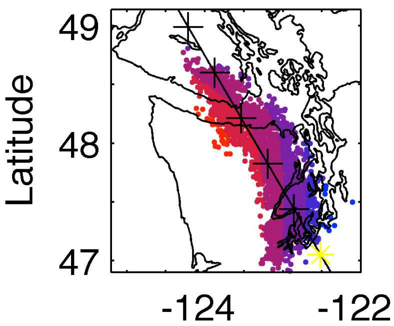


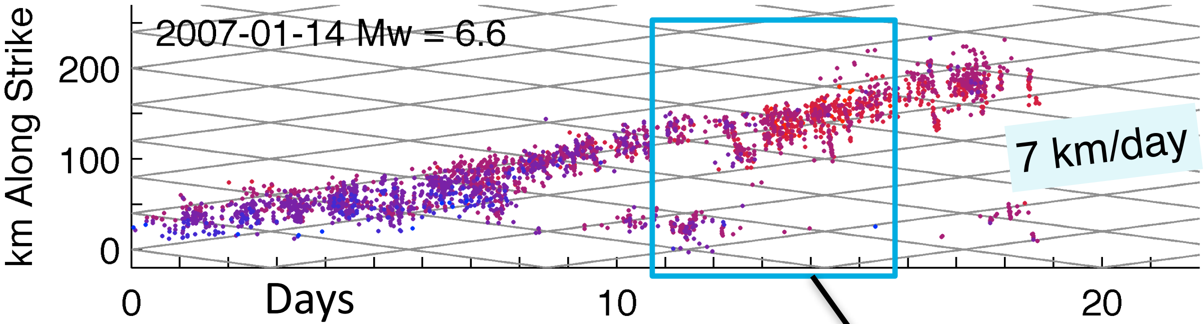
Tremor activity in Shikoku, Japan (Obara et al)

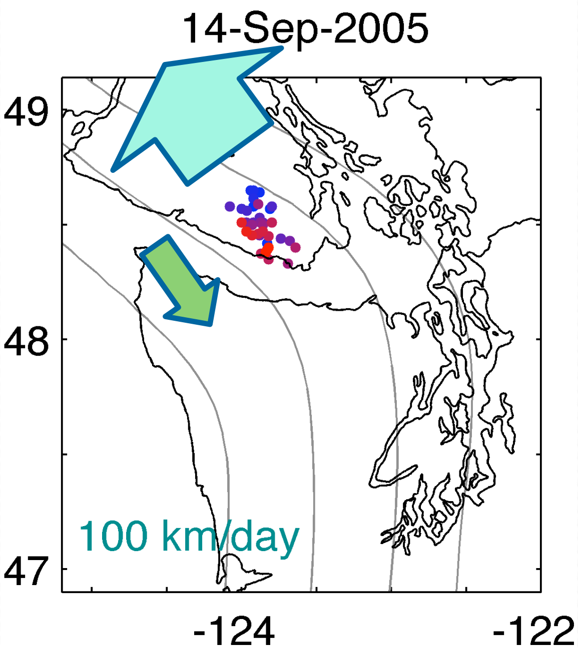


What can we learn about the dynamics of large earthquakes from observations of tectonic tremor? (e.g. the role of fault heterogeneities)

Tremor migration and rapid tremor reversals

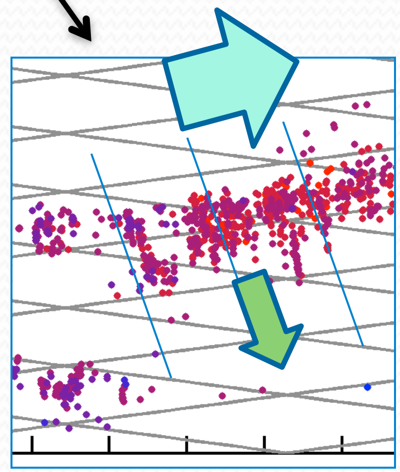






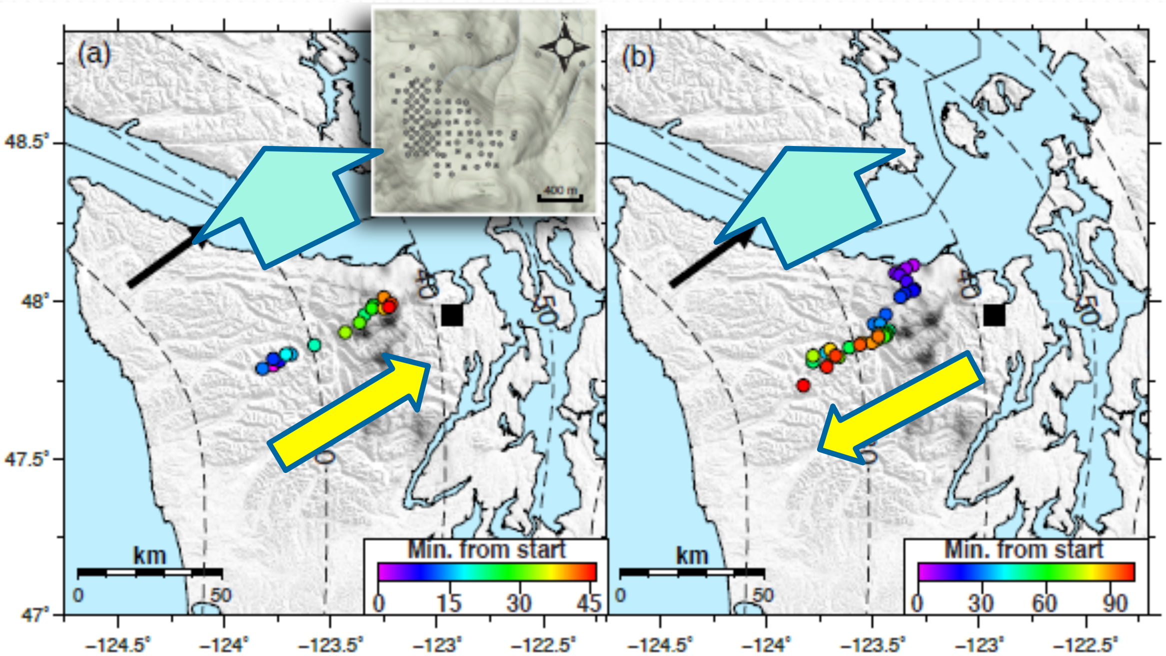
Tremor migrates slowly along strike (~10 km/day) tracking the front of the slow slip event

Episodic tremor swarms propagate backwards, faster (~ 100 km/day)

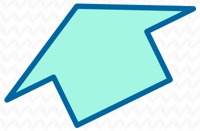


Houston et al (2010)

Tremor swarm streaks along dip



Ghosh et al (2010)



Long term migration ~ 10 km/day

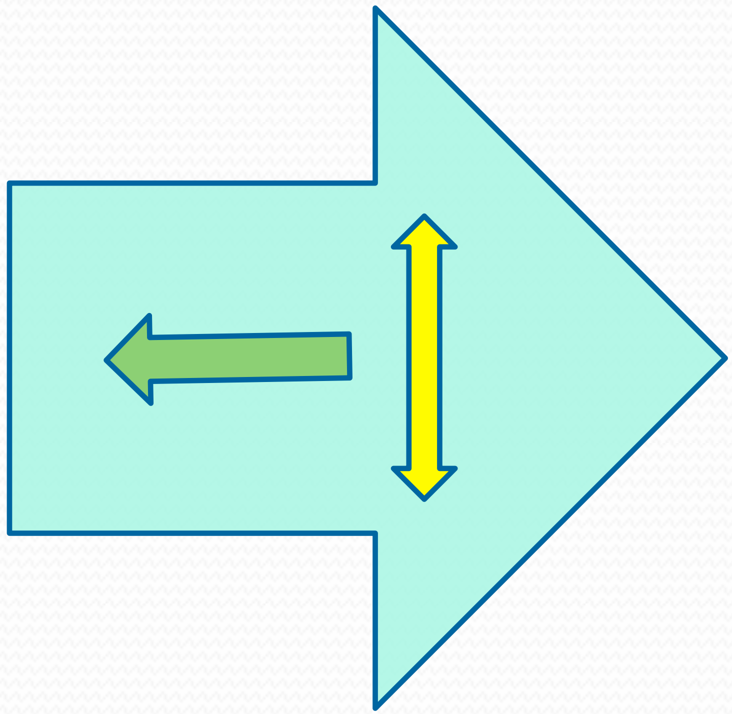
Fast up/down-dip migration swarms ~ 50 km/hr
= 100 times faster

A hierarchy of tremor migration patterns

- Long term migration
- Rapid tremor reversals
- Streaks along dip

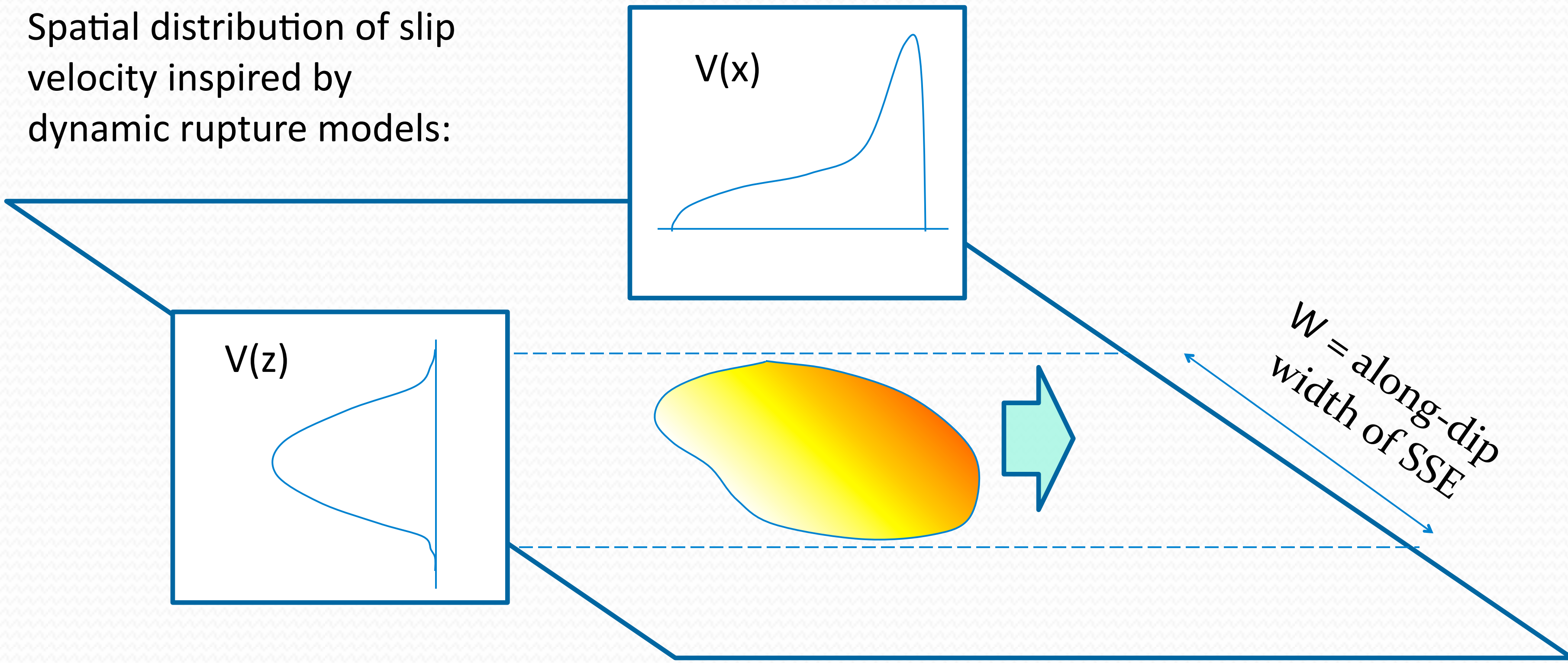
Tremor migration speed

10 km/day
100 km/day
1000 km/day

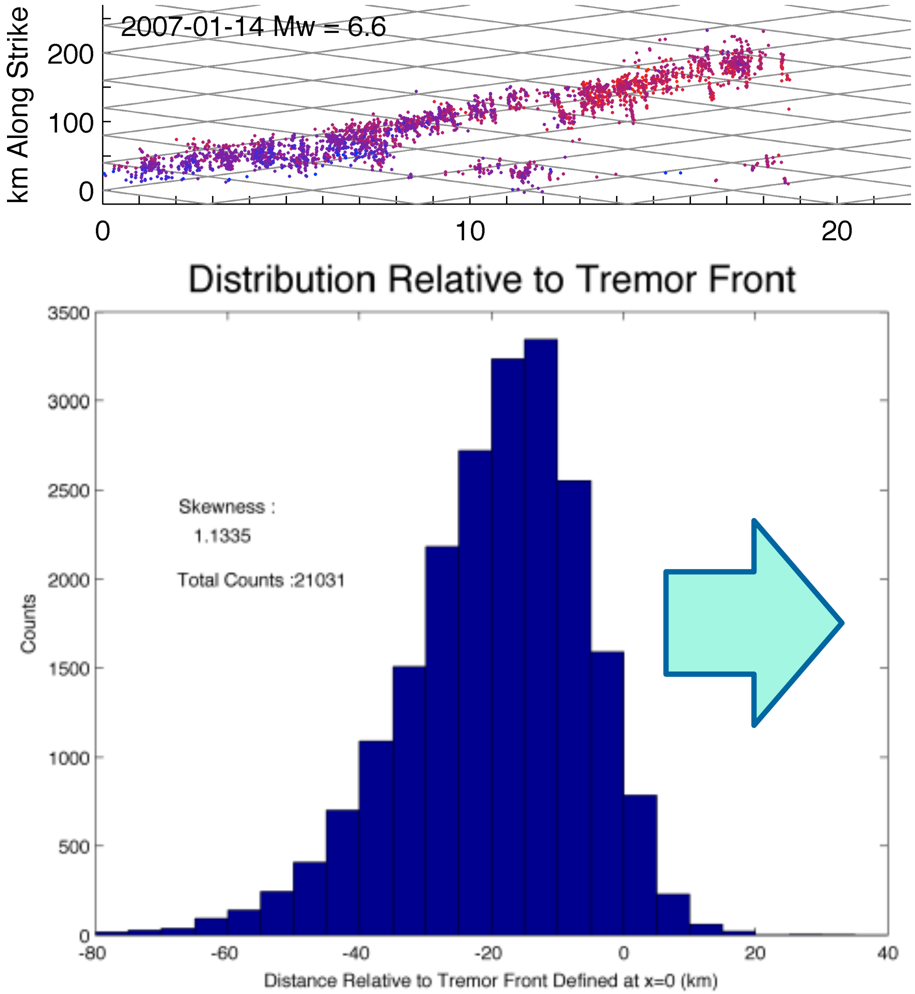


On the (expected) shape of a slow slip pulse

Spatial distribution of slip velocity inspired by dynamic rupture models:

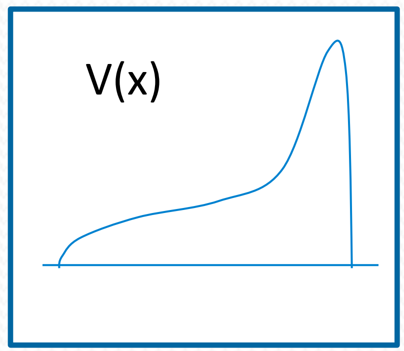


Relationships between tremor and slow slip



Houston et al (2010)

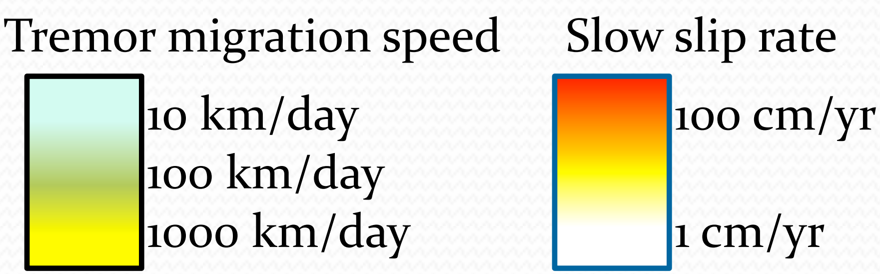
The along-strike distribution of tremors relative to the main front position is similar to the expected distribution of slip velocity in a slow slip pulse

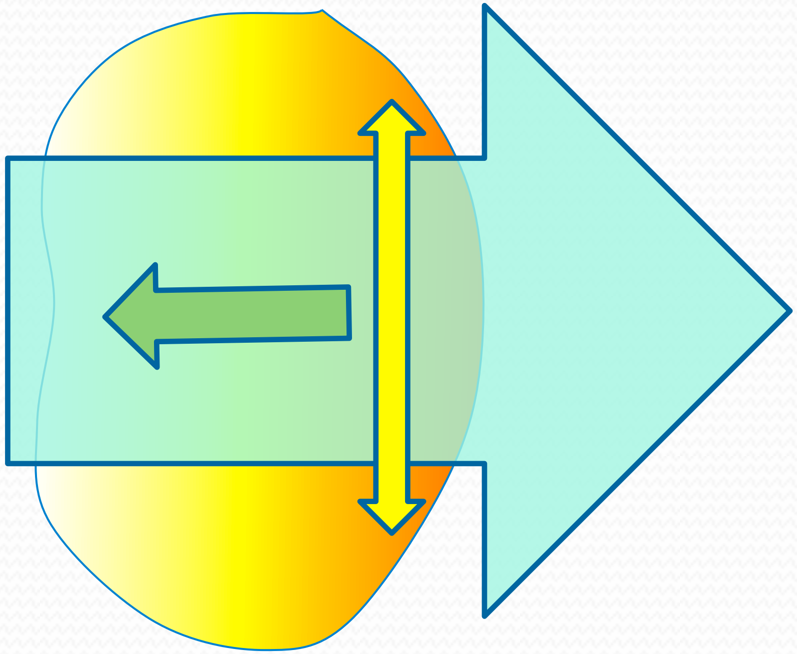


→ **Tremor rate correlates with slow slip rate**

A hierarchy of tremor migration patterns and their relation to slow slip

- Long term migration driven by slow slip front
- Rapid tremor reversals back into the slow slip pulse
- Streaks along the leading edge of the slow slip front



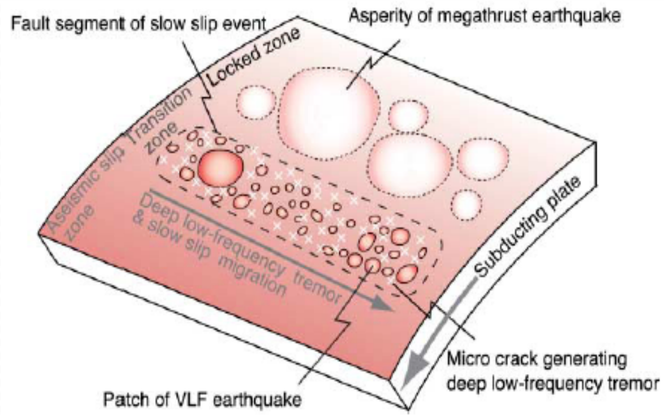


→ Tremor migration speed correlates with slow slip rate

An emerging view of slow slip and tremor mechanisms

Essential ingredients:

- **Quasi-static elasticity**
- **Deep frictional stability transition (~brittle-ductile)**
- **Fault heterogeneities ("asperities") embedded in a creeping fault**



Ito et al (2007)

Specific ingredients for illustrative numerical simulations:

- Rate-and-state friction
- Overpressurized fluids
- Dilatant fault gouge material

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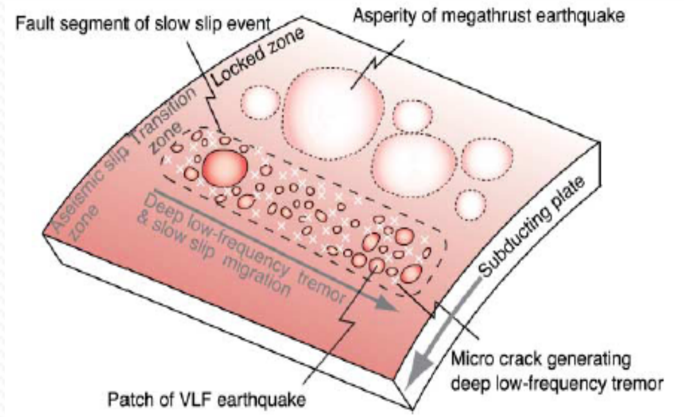

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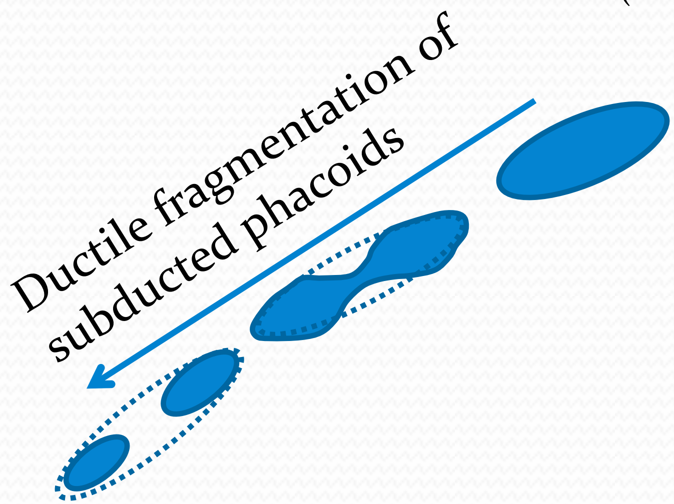

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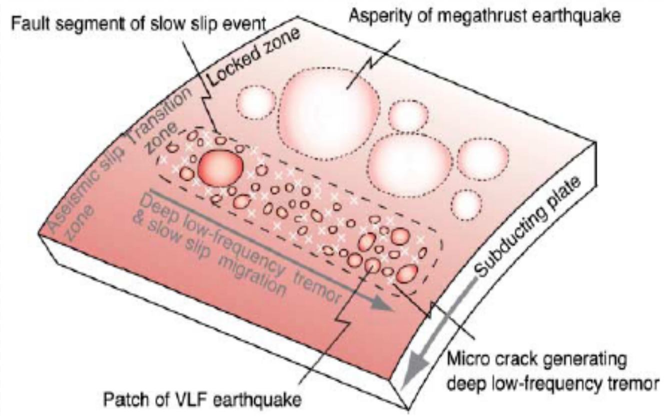

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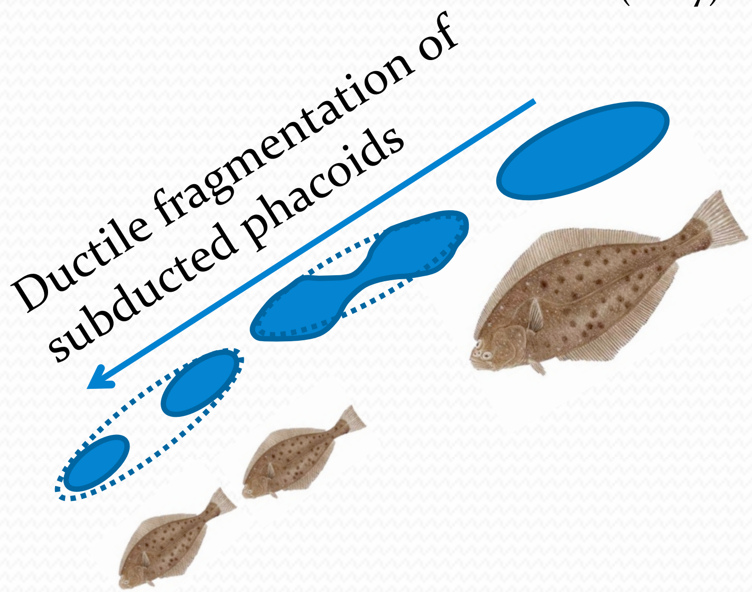
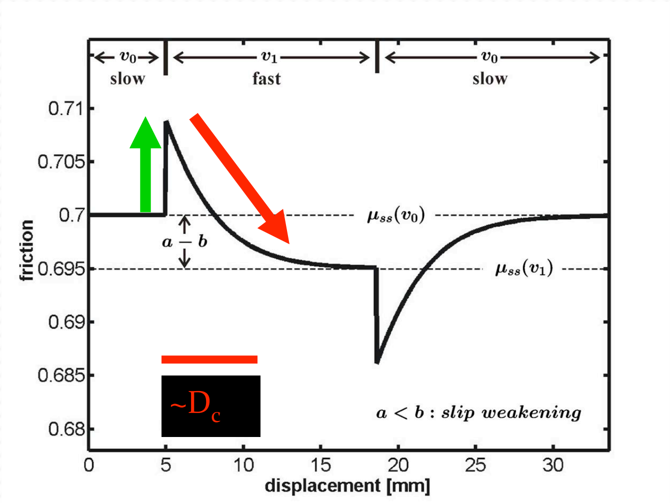


Typical evolution of friction in velocity step experiments



Rate-and-state friction

- Phenomenological friction law introduced by Dieterich and Ruina in the early 1980s
- Essential components:
  - non-linear viscosity
  - evolution effect
- Stability of slip depends on the sign of (a-b):
  - a-b>0 : velocity strengthening, stable
  - a-b<0 : velocity weakening, unstable
- Nucleation style depends on a/b
- Open questions:
  - Appropriate state evolution law ?
  - Experiments at high P and T ?
  - Effect of fluids ?

Rate-and-state dependent friction coefficient:

$$\frac{\tau}{\sigma} = f^* + a \ln \frac{V}{V^*} + b \ln \frac{V^* \theta}{D_c}$$

State evolution law:

$$\dot{\theta} = 1 - \frac{V\theta}{D_c}.$$

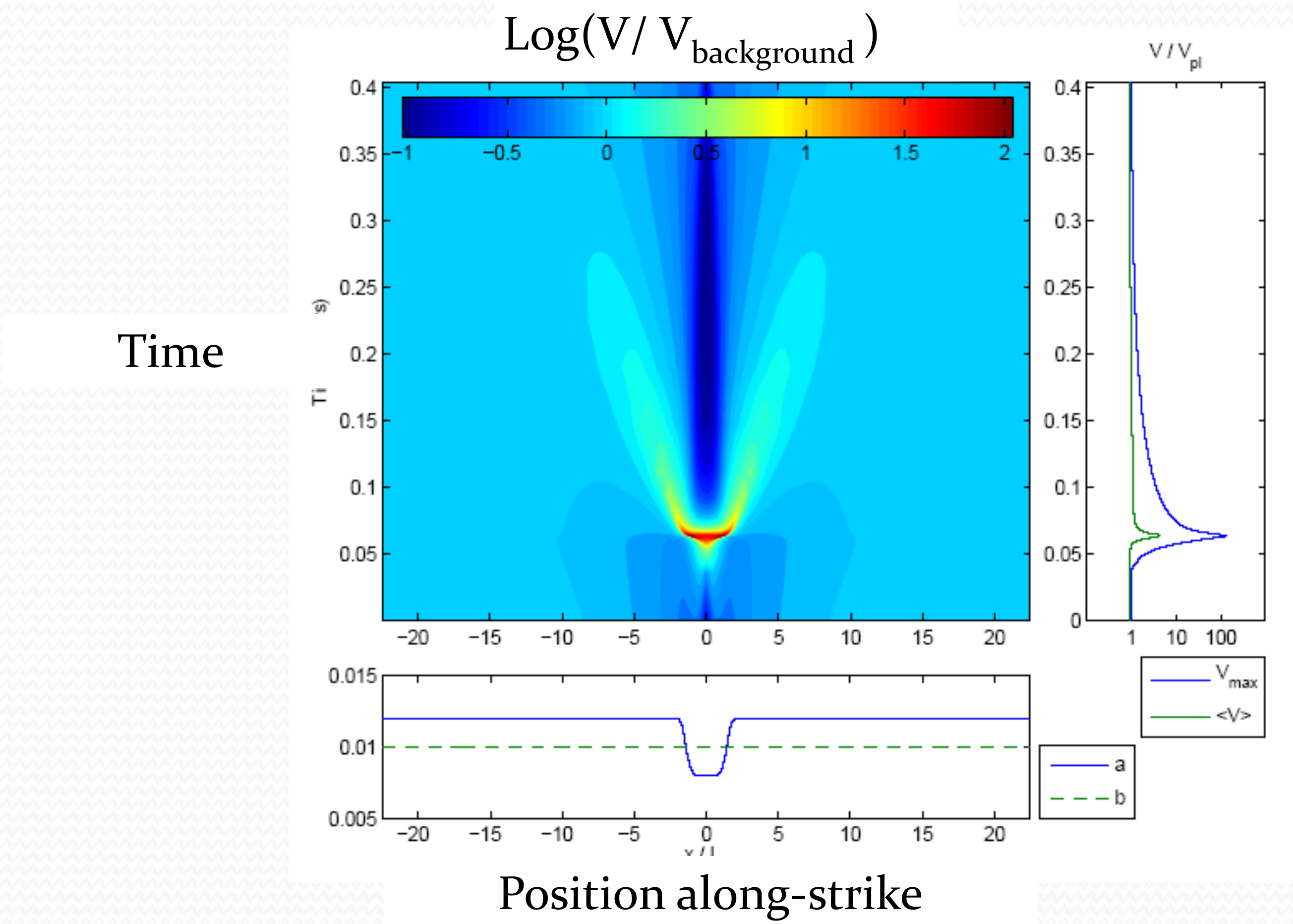
"Aging" law

or

$$\dot{\theta} = -\frac{V\theta}{D_c} \ln \frac{V\theta}{D_c}$$

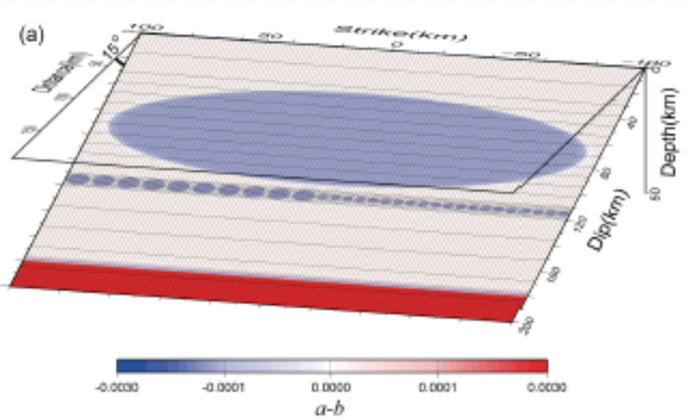
"Slip" law

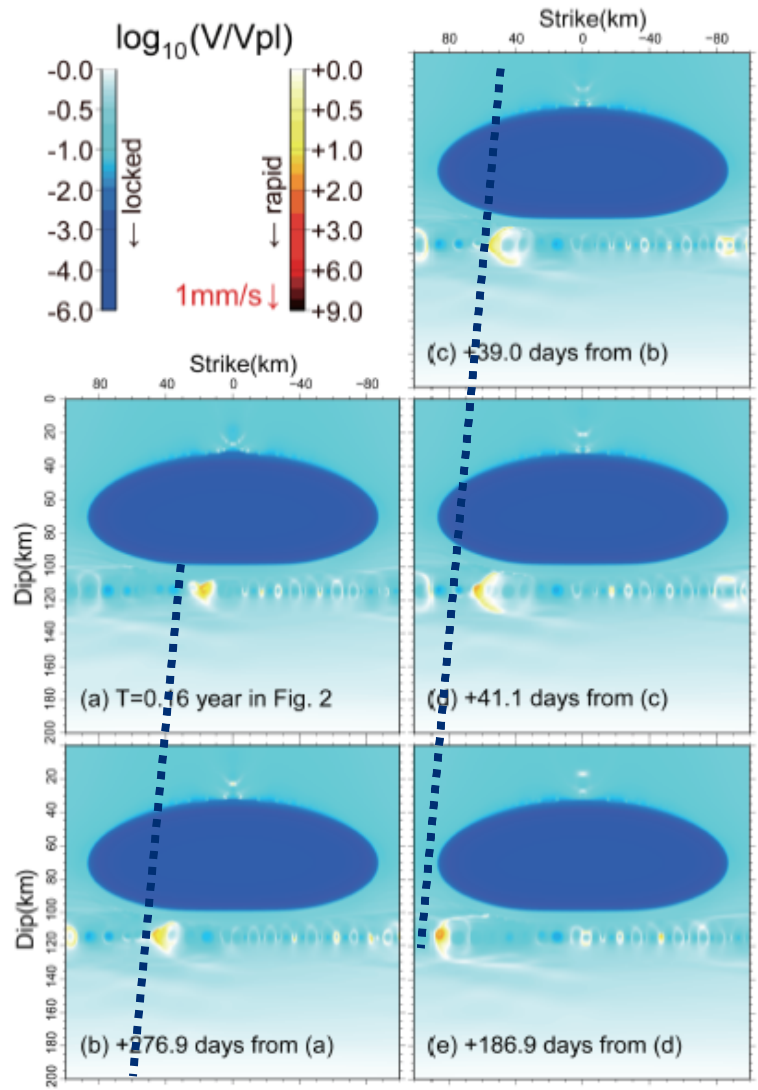
An isolated brittle asperity (v-weakening) within a creeping fault (v-strengthening).



Monday, November 1, 2010

Computer simulations of deep tremor swarms





Tremor swarms result from a cascade of triggering between brittle asperities **mediated by creep transients**:

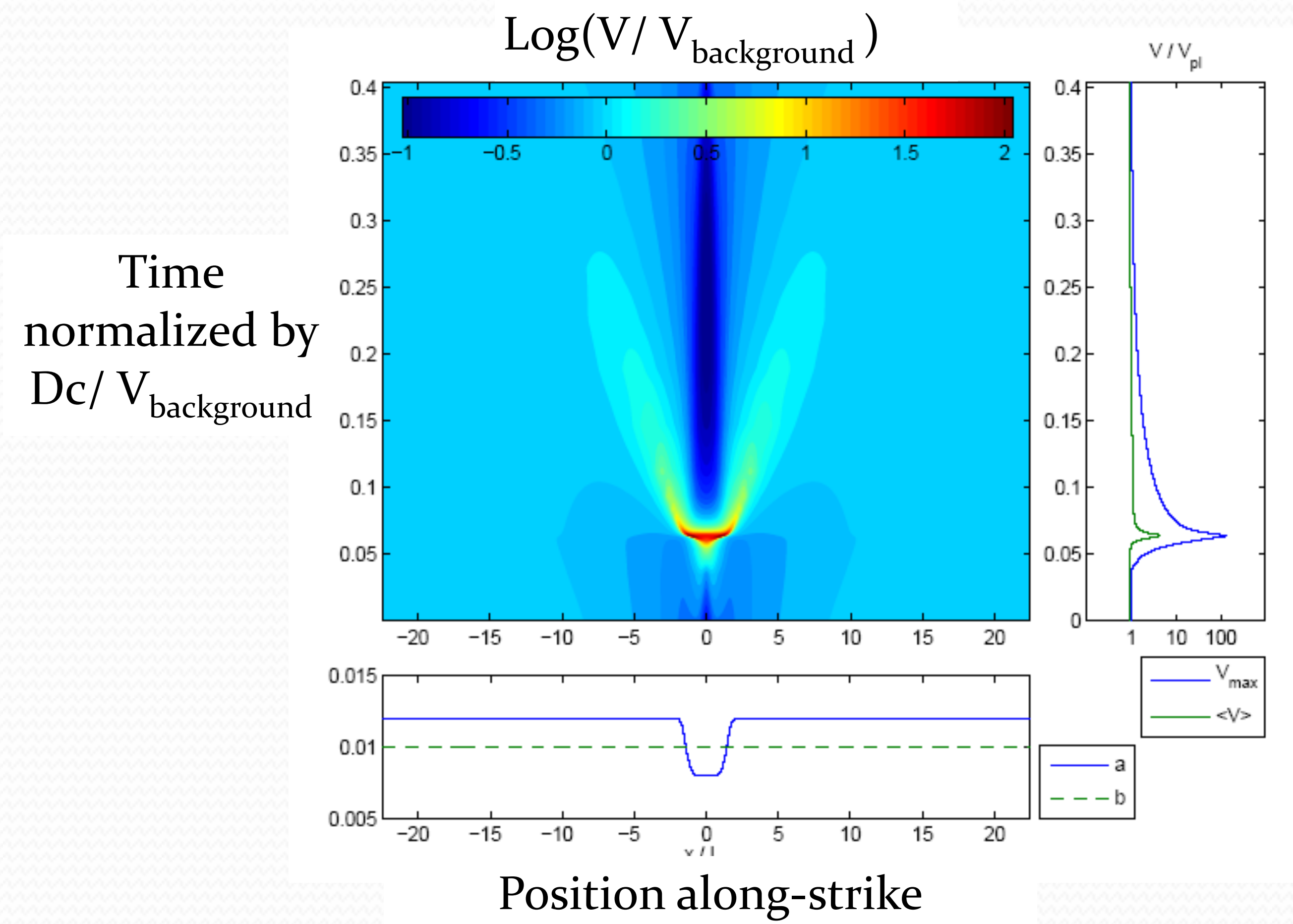
Asperity failure

→ propagating creep perturbation

→ loading and failure of next asperity

Quasi-dynamic 3D simulations in collaboration with K. Ariyoshi (Earth Simulator, JAMSTEC, Japan)

An isolated brittle asperity (v-weakening) within a creeping fault (v-strengthening).



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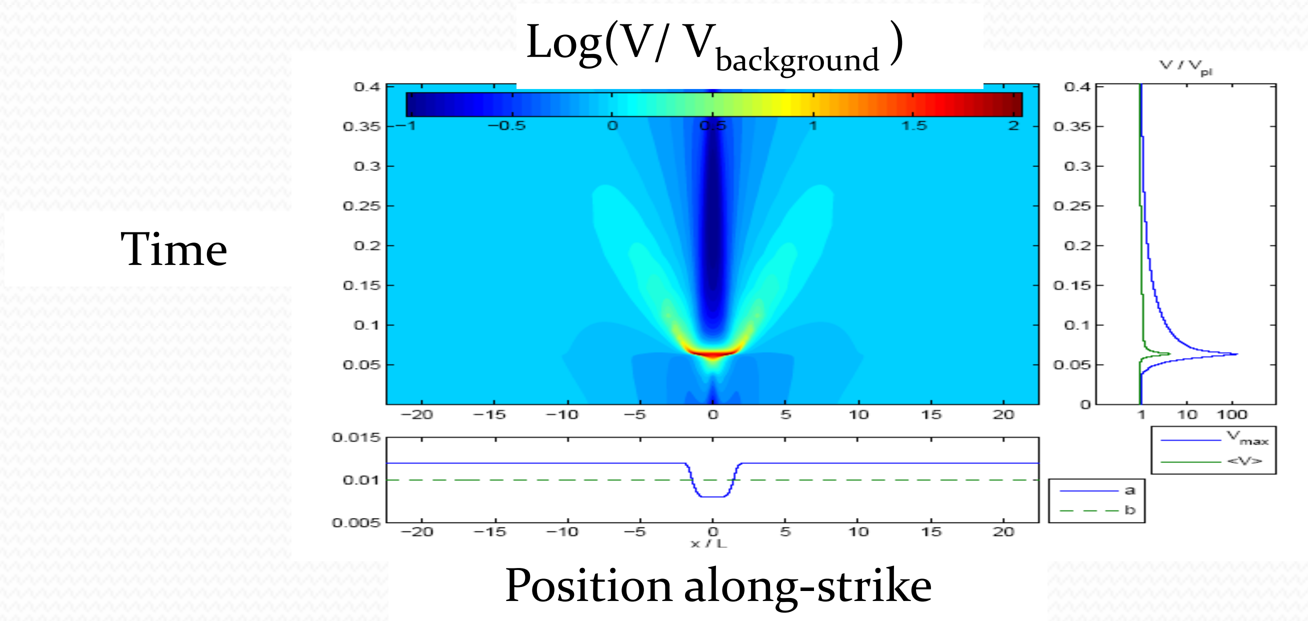
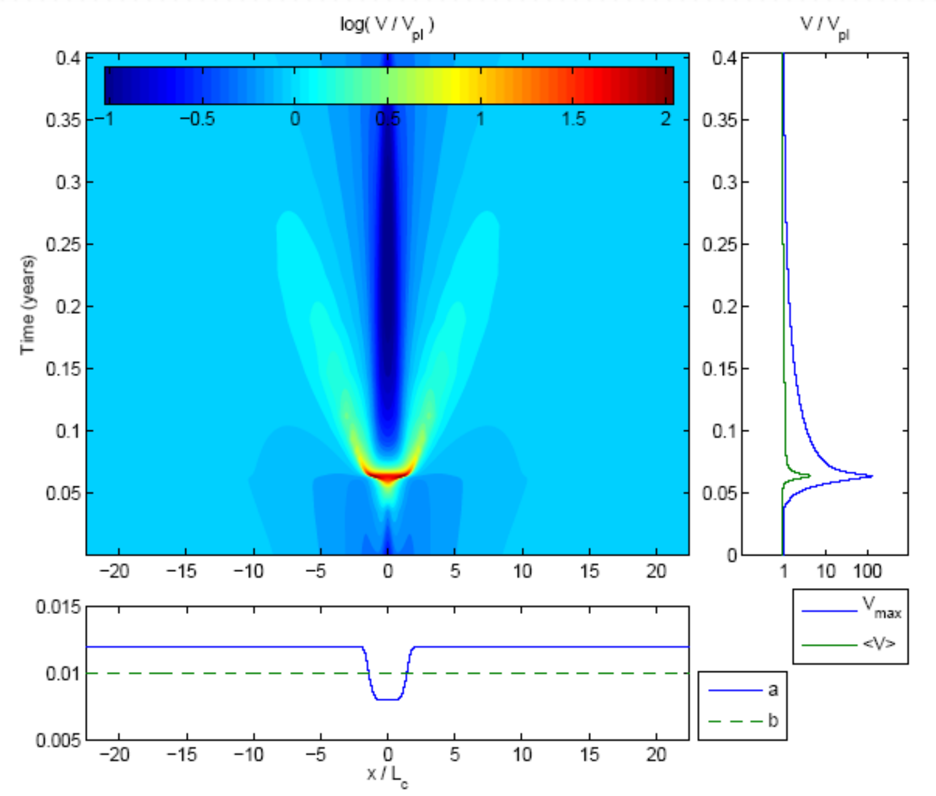
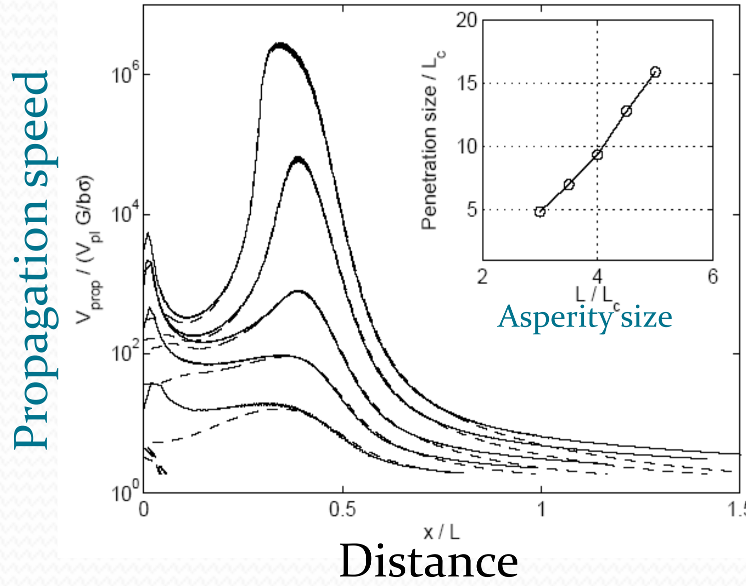


Faster $V_{background}$ implies faster propagation speed of post-seismic creep

Interaction between a brittle asperity and the surrounding creep





Relation between propagation speed, strength drop and slip velocity:

$$V_{prop} \propto \frac{G}{b\sigma} \frac{V_{\max}}{\ln(V_{\max}\theta_i/D_c)}$$

Ampuero and Rubin (2008)

Relation between tremor migration speed and background slip rate

- Relation between migration speed, strength drop and slip velocity of creep:

$$V_{prop} \propto \frac{G}{b\sigma} \frac{V_{\max}}{\ln(V_{\max}\theta_i/D_c)}$$ = shear modulus × peak slip rate / strength drop

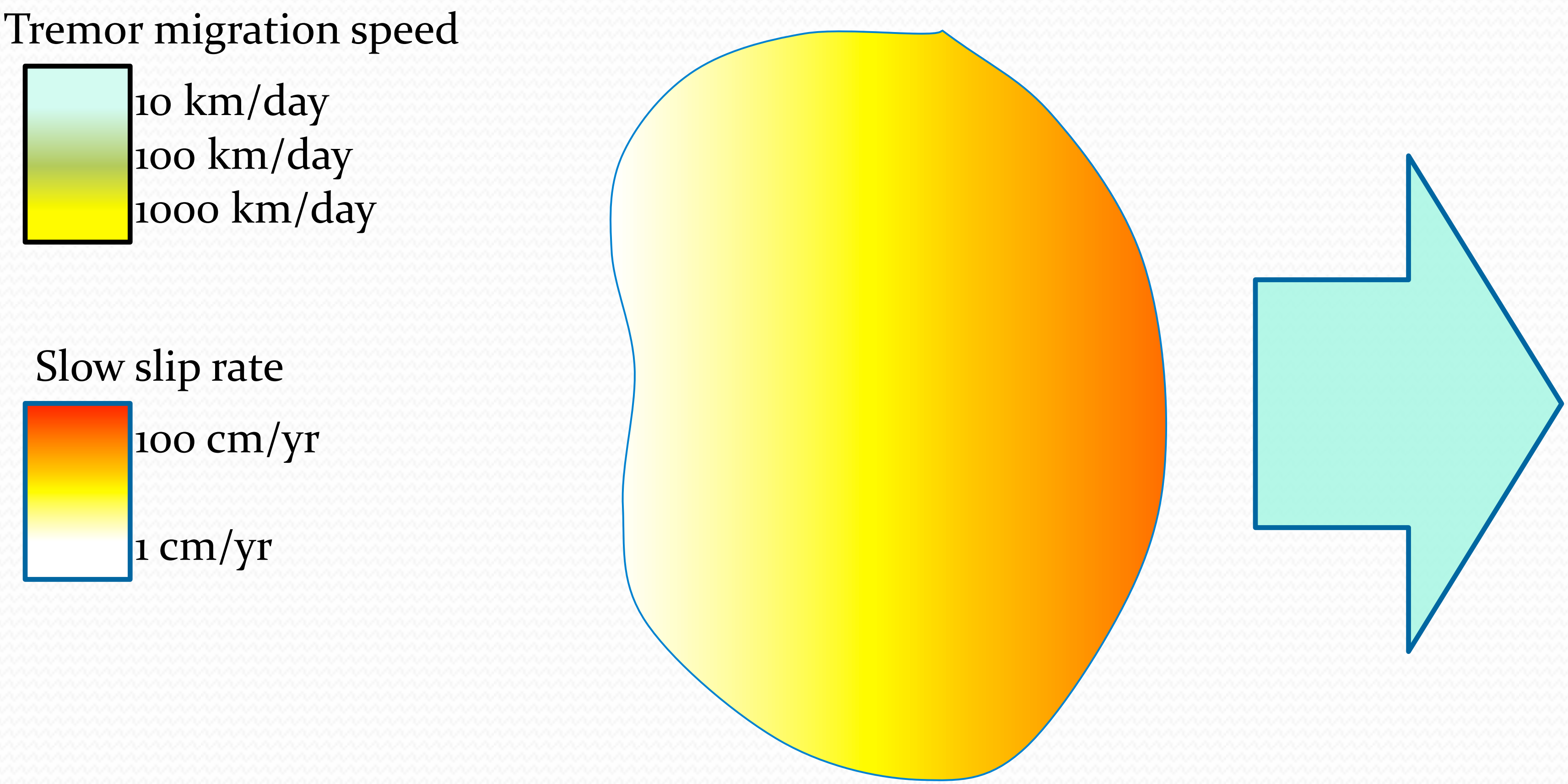
- Relation between peak and background slip rate:

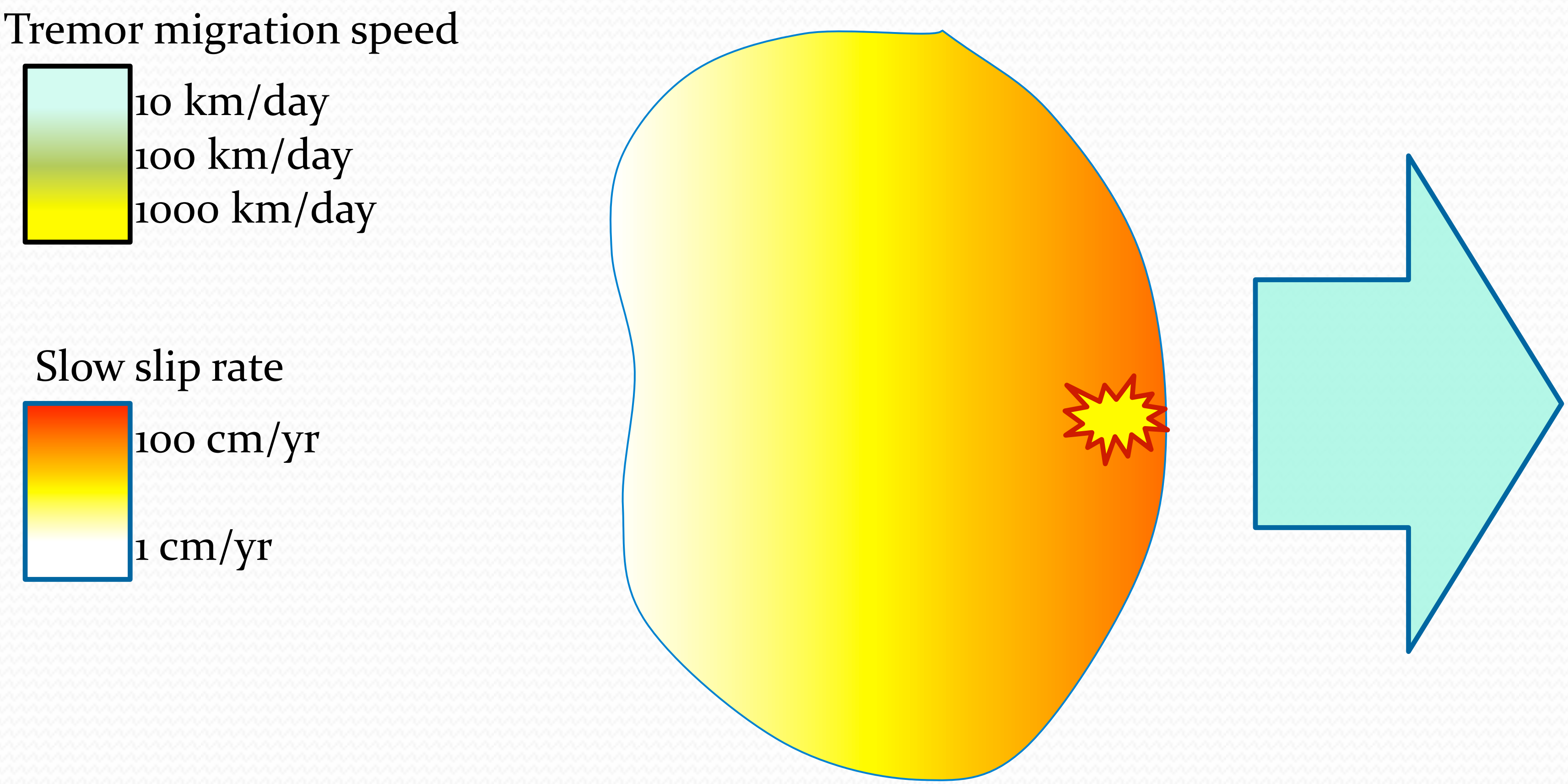
$$V_{max} \sim \exp(\Delta\tau/a\sigma)\, V_{background}$$

- $V_{background}$ is the slip rate imposed by the slow slip pulse

→ **V_{prop} is proportional to $V_{background}$**

Tremor migration assisted by transient creep


Tremor migration speed
10 km/day
100 km/day
1000 km/day
Slow slip rate
100 cm/yr
1 cm/yr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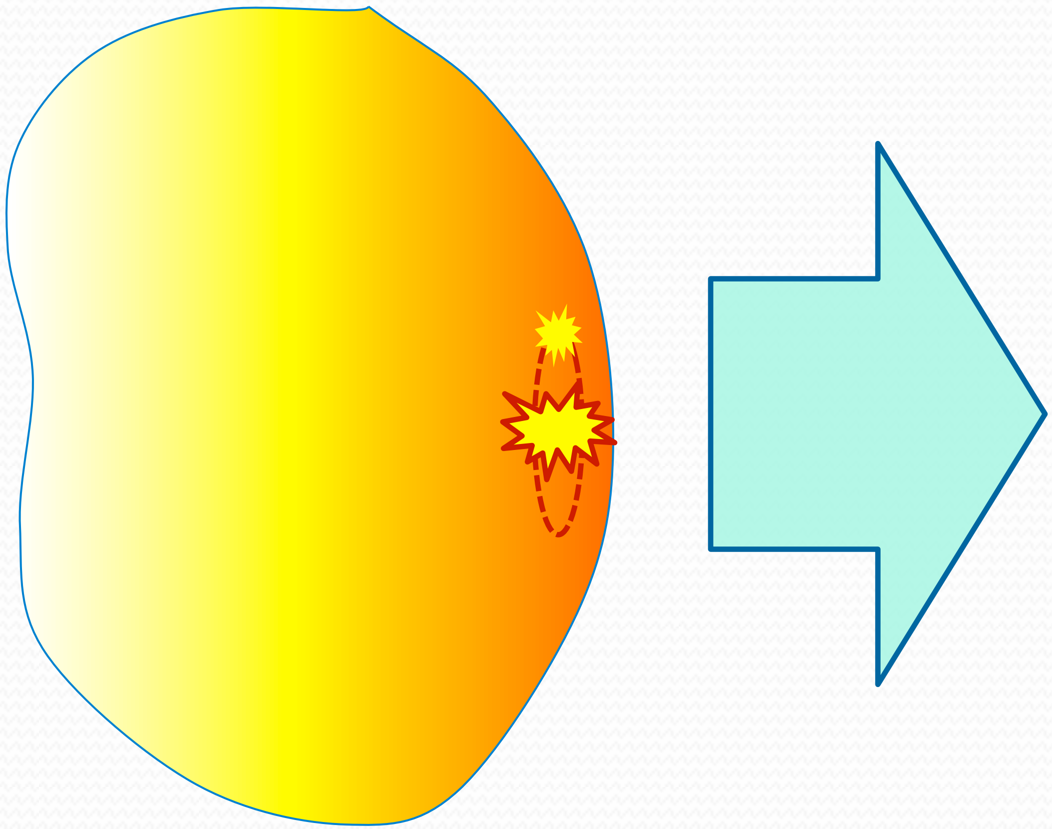

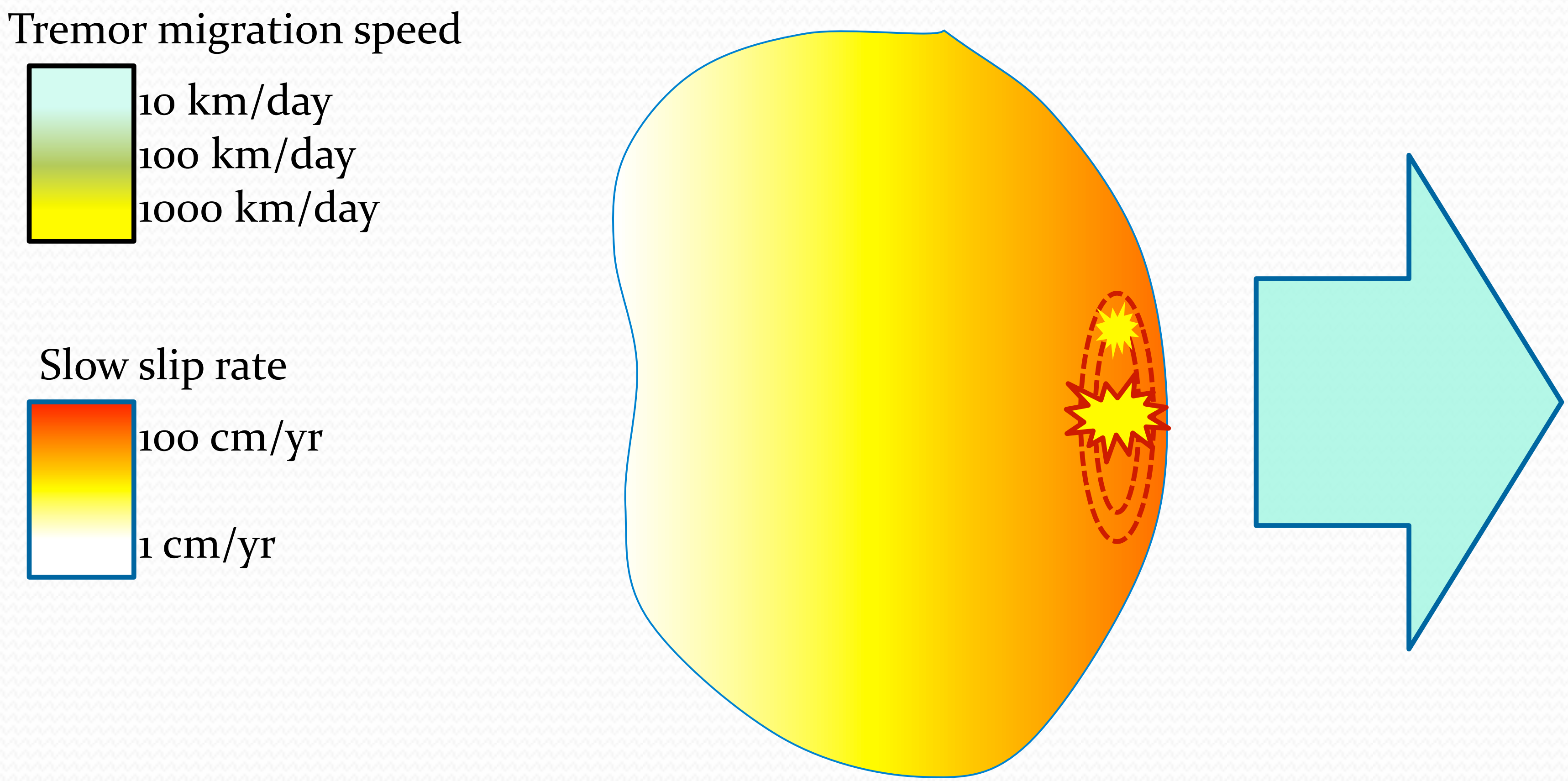
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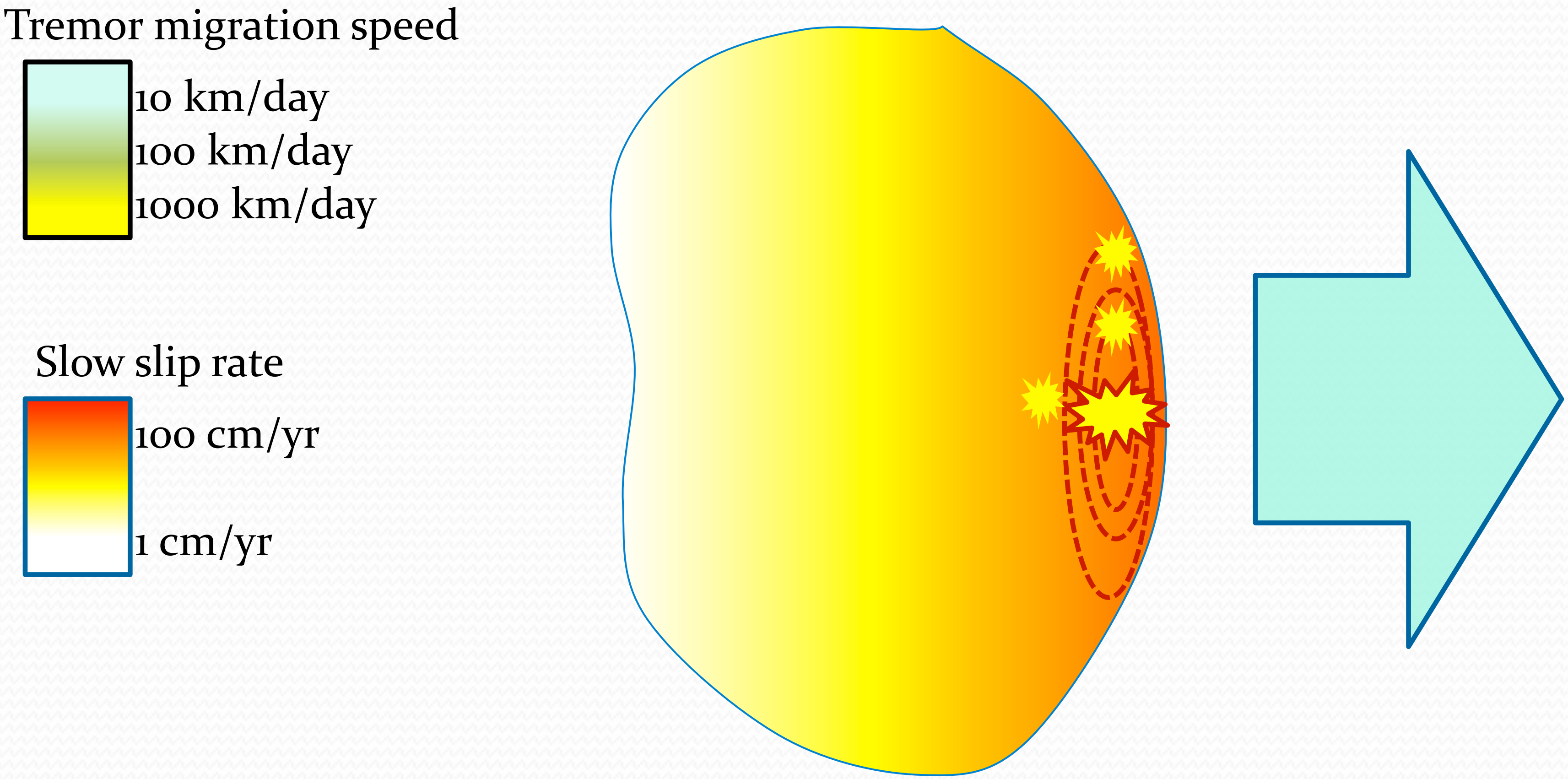
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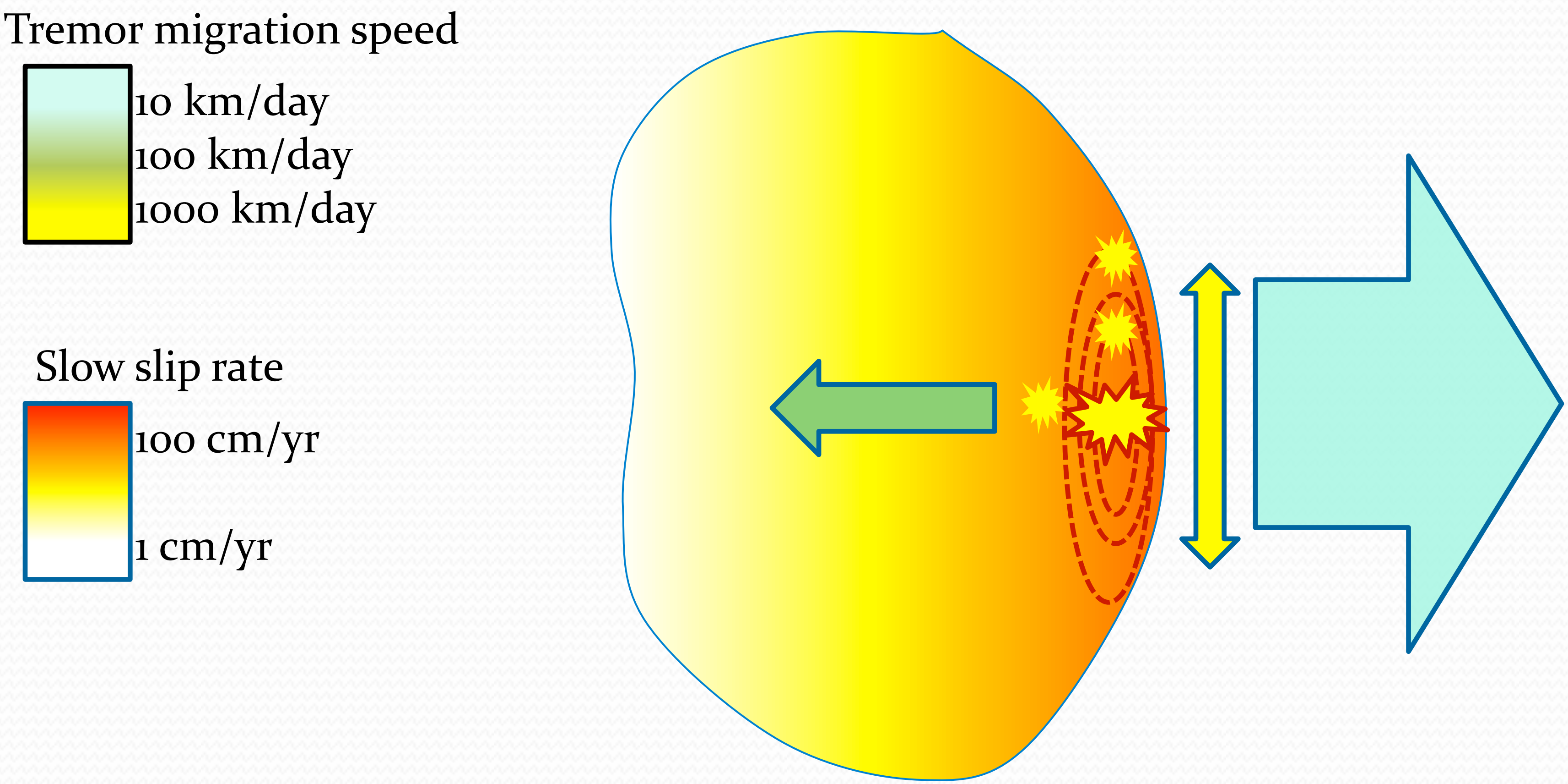
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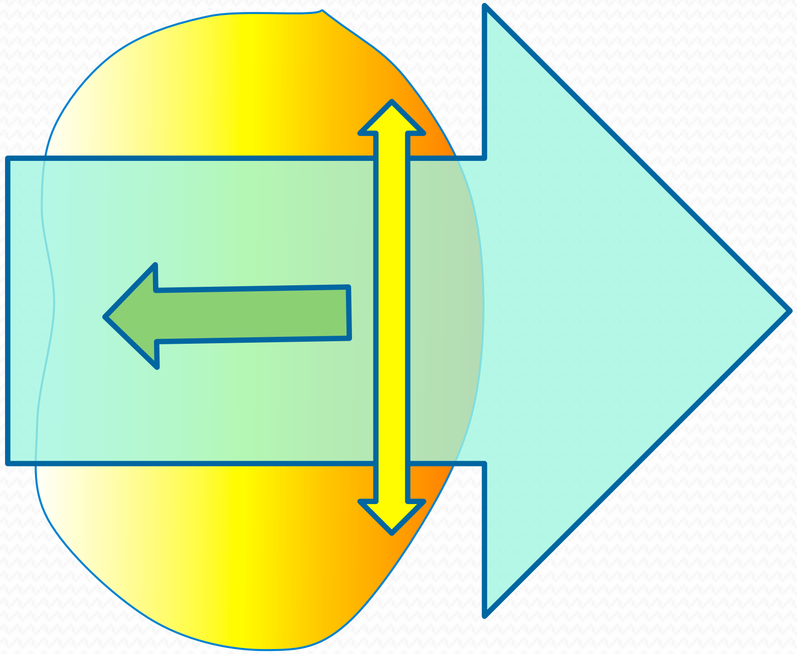

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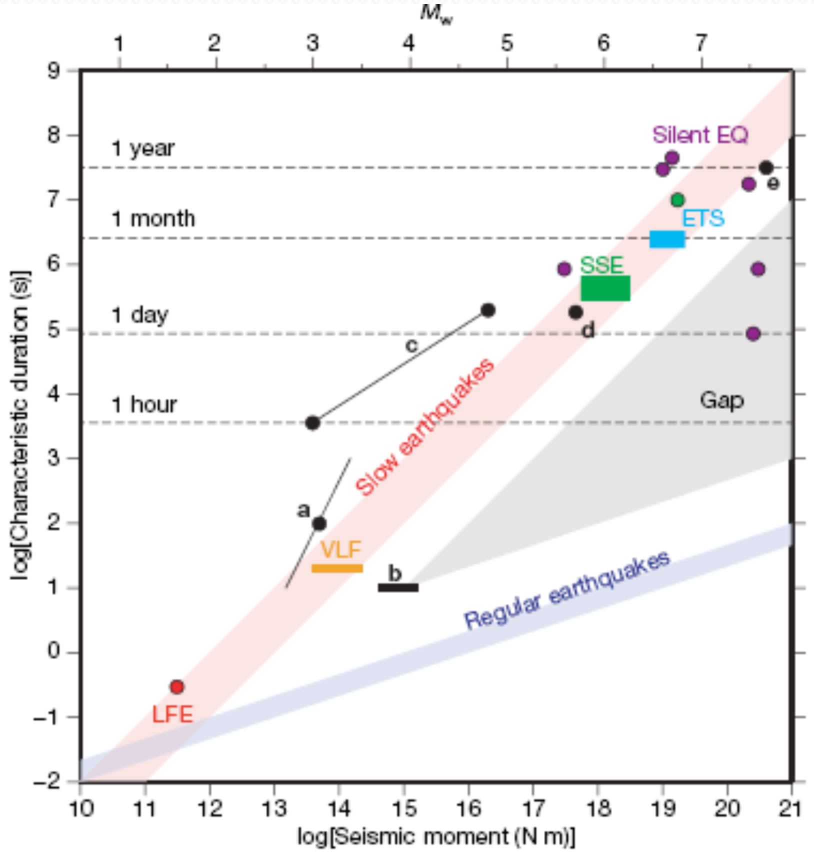
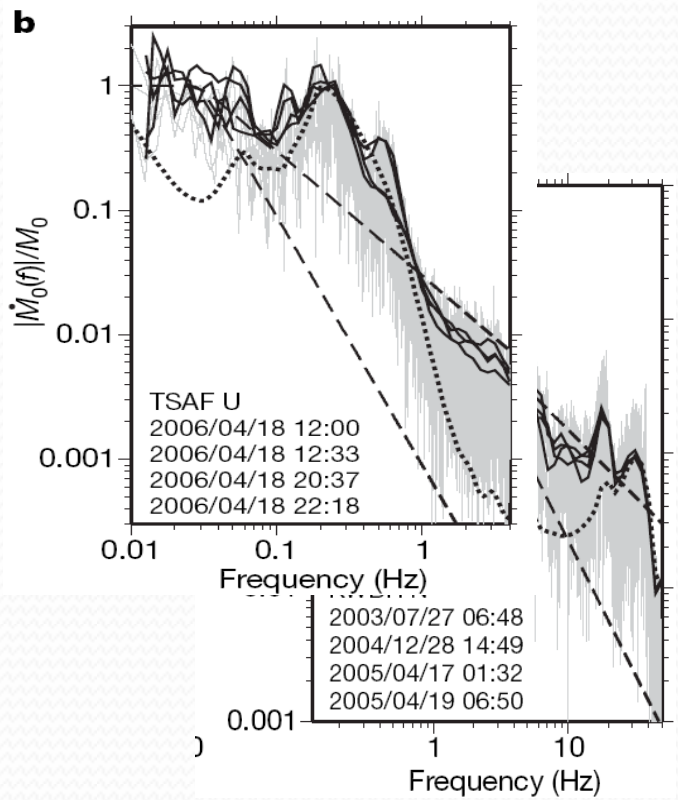
→ Tremor migration speed correlates with slow slip rate

On scaling laws



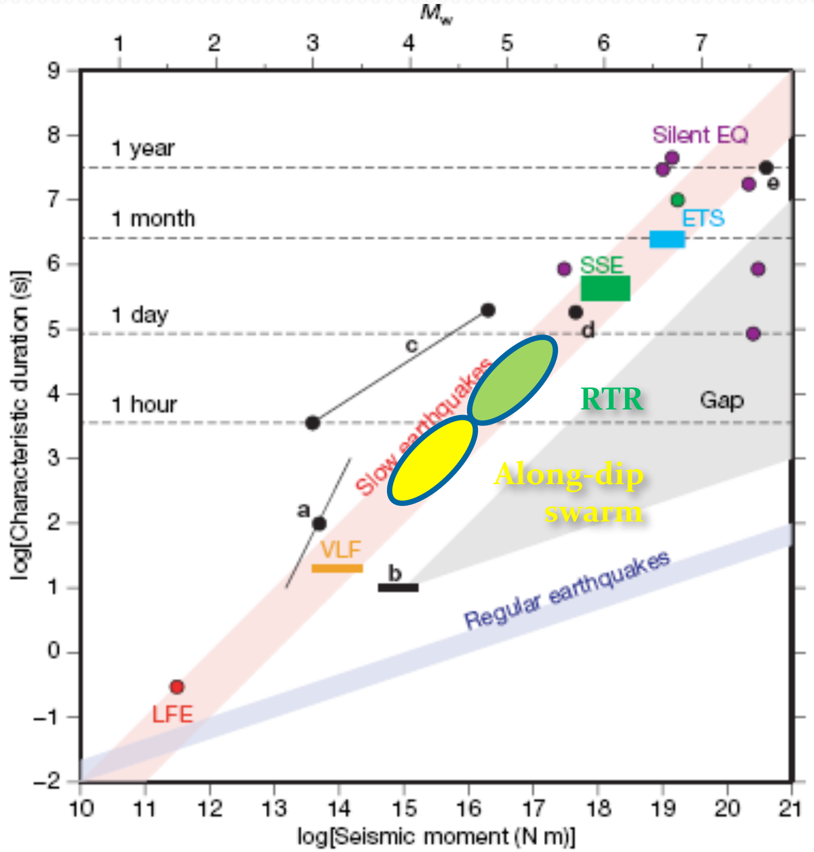


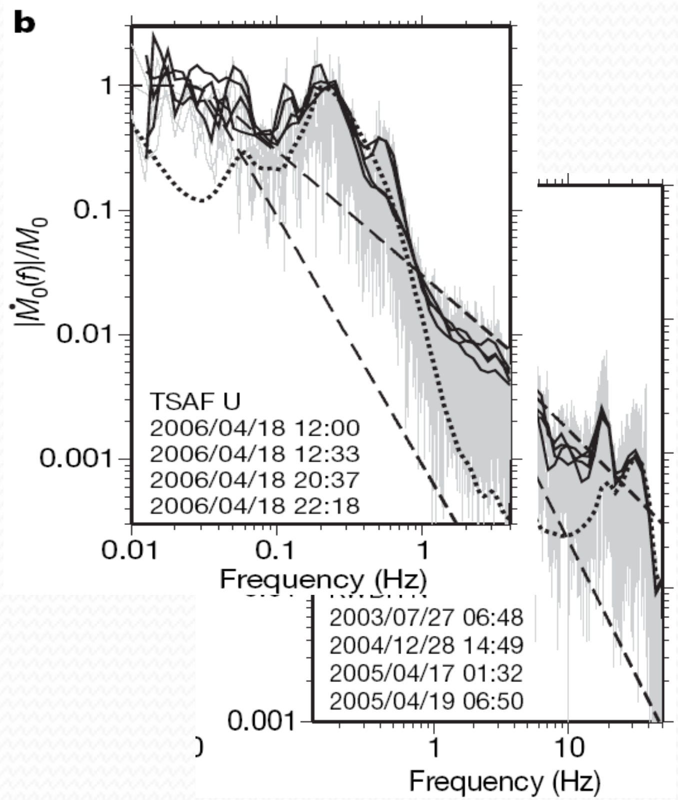
Slow earthquakes and tremor have anomalous moment-duration scaling:

$$M_0 = (10^{12} \sim 10^{13})\,T$$

Tremor spectra falls of as 1/f

On scaling laws





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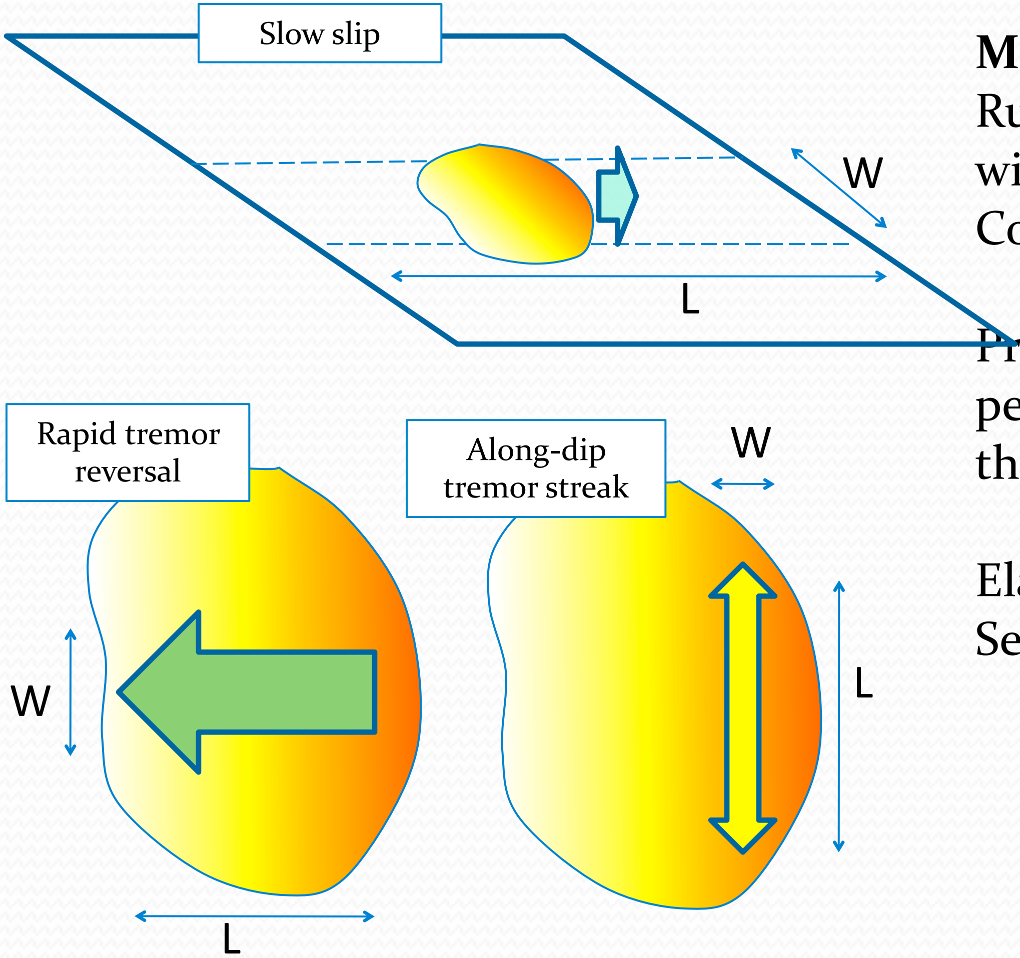

Observations (Ide et al, 2007):

- Anomalous moment-duration scaling:
- Tremor spectra falls of as 1/f

$$M_0 = (10^{12} \sim 10^{13})\, T$$

Model:

Rupture on a very elongated source area:
width W << length L
Constant rupture speed

$$V_r = L/T$$

Produces 1/f spectrum at intermediate periods between the duration Vr/L and the rise time.

Elasticity implies
Seismic moment : $D \approx W \, \Delta\tau / \mu$

$$M_0 = \mu \, L \, W \, D$$

$$M_0 \approx \Delta\tau \, W^2 \, V_r \, T$$

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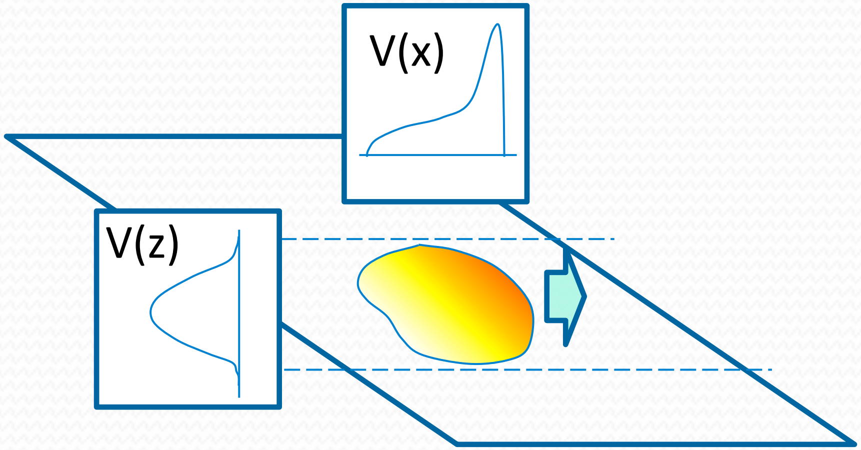
On scaling laws

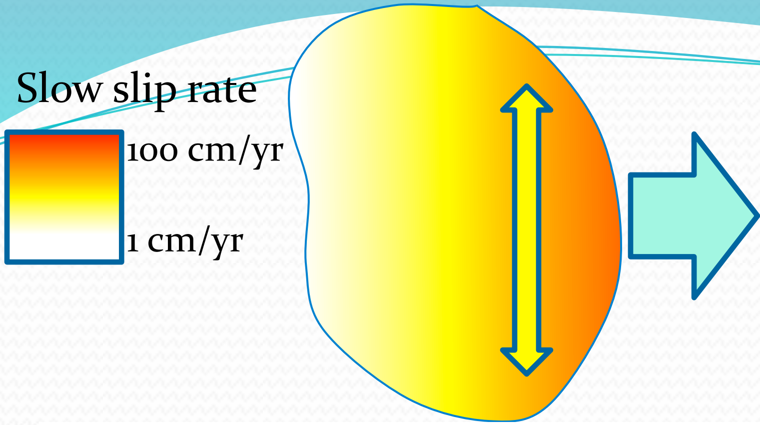


If similar stress drop for SSE, RTR and tremor streaks (not a necessary assumption):

→ **$W^2 V_r \approx$ constant**

Consistent with length scales observed in Cascadia?

Phenome	W (km)	Vr (km/
SSE	50	10
RTR	15?	100
streaks	5?	1000



$$M_0 \approx \Delta\tau \, W^2 \, V_r \, T$$

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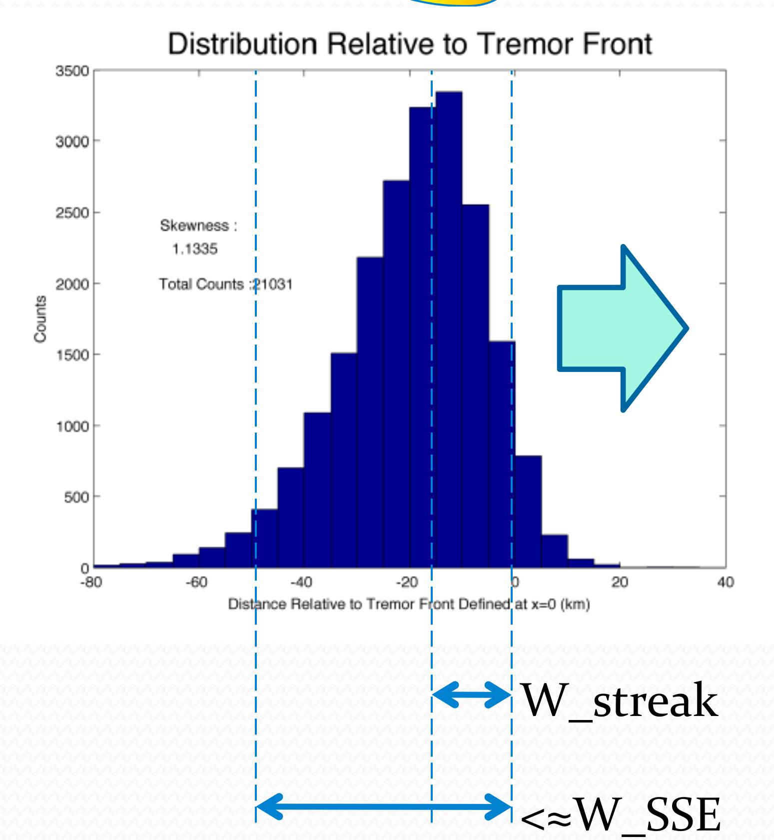

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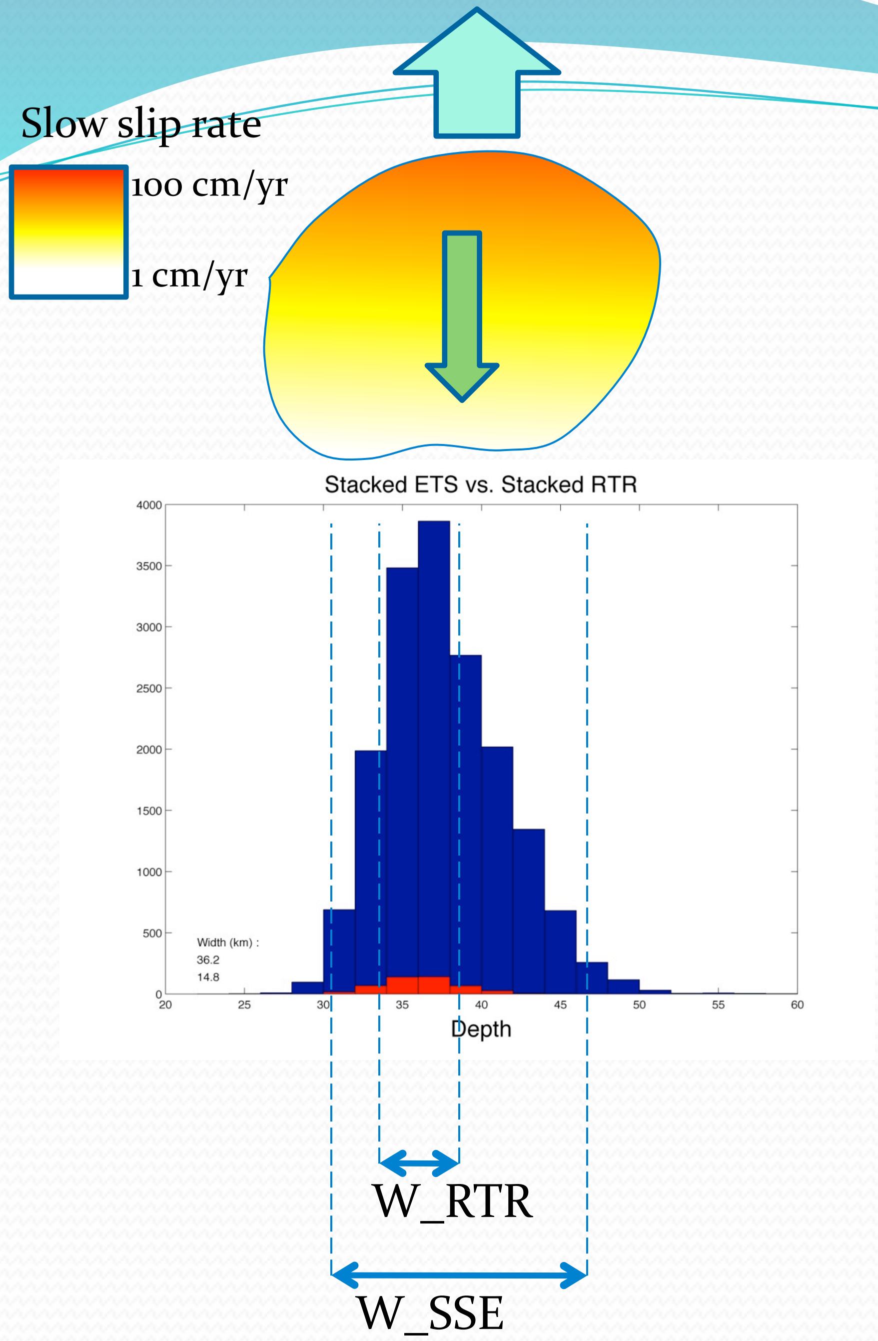

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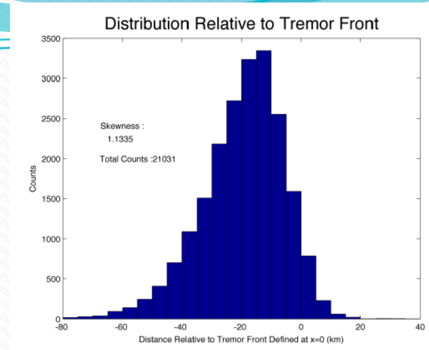
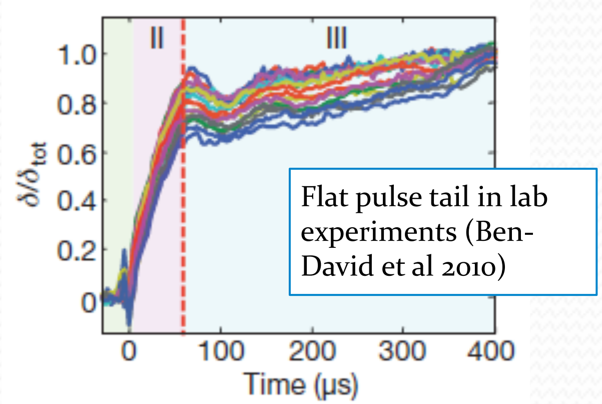
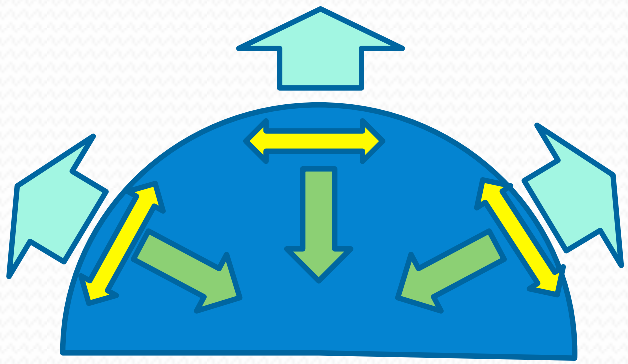
Some open questions

- Model suggests *RTRs should slow down* as they propagate into the tail of the slow slip pulse. Is the pulse tail flatter than we think?
- Streaks are not vertical but parallel to convergence rate: competition between dynamic effects and persistent structural features?
- Model predictions during nucleation of SSE (~circular expansion stage):
  - RTR in radial direction
  - Fast swarms in azimuthal direction
- Other recent models :
  - A. Rubin designed ad hoc friction law. Is that the "mesoscopic" equivalent response of a heterogeneous fault (asperities+creep)?
  - J. Dieterich finds RTRs without creep. Speed controlled by stressing vs healing rates behind the

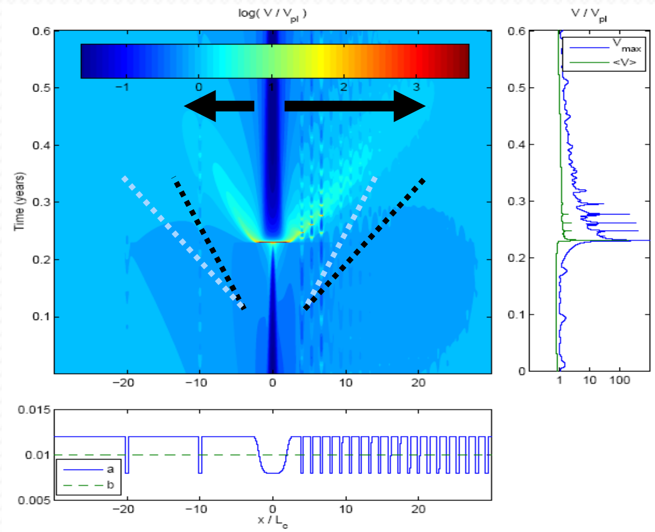






Conclusions

- Slow slip and tremor phenomena provide an opportunity to observe, in slow motion (high resolution), the dynamics of heterogeneous faults.
- A rich hierarchy of spatio-temporal patterns has been observed in Japan and Cascadia that can be unified by a model of interaction between brittle asperities mediated by propagative creep transients
- The model explains also empirical scaling laws for slow earthquakes
- Some predictions of the model, with implications for earthquake precursors, remain to be tested: if tremors are natural creepmeters during earthquake nucleation, can changes of tremor migration patterns indicate the approach of large megathrust earthquakes?



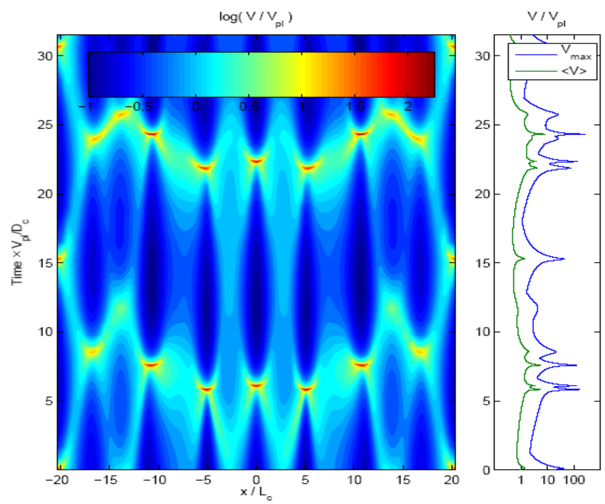


Figure 14: Slow earthquake cycles on a velocity-weakening fault strip, with $W/\pi L_c = 1.3$, $L/W = 10$ and $a/b = 0.8$.