Interseismic Deformation in Models with Stress Dependent Fault Creep

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UNIVERSITY OF MICHIGAN
GEOLOGICAL SCIENCES

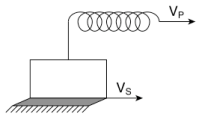
introductory statements:

- most earthquake cycle models with stress-dependent fault slip are motivated by understanding earthquakes (fast or slow)
- many geodetically motivated postseismic models with stress-driven postseismic fault creep
- geodetically motivated interseismic fault creep models almost always kinematic

fault- or shear-zone rheologies:

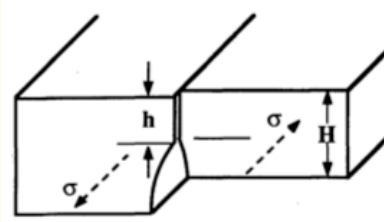
- linear viscous
- nonlinear viscous (with or without grain size dependence)
- rate-dependent friction (**RD friction**; aka, velocity strengthening friction, hot friction)
- rate- and state-dependent friction (**RS friction**; can be velocity strengthening or weakening)

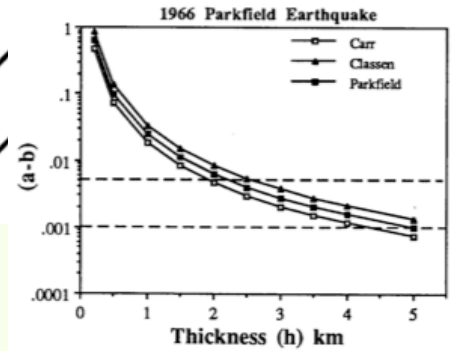
Postseismic fault creep models – spring & slider models

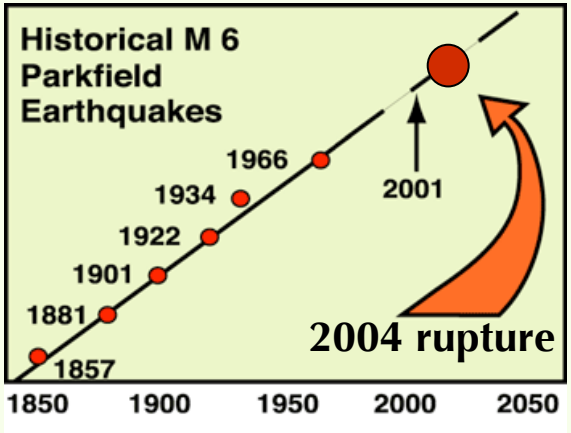


RD friction

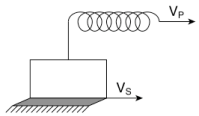
Marone et al., 1991







Postseismic fault creep models – spring & slider models



RD friction

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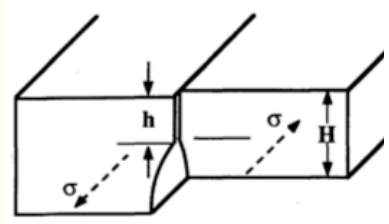
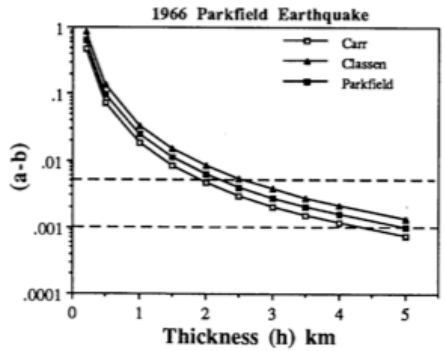
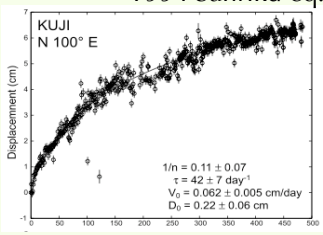


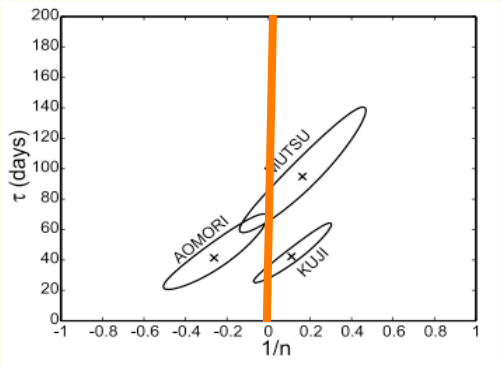


NL viscous

Montési, 2004

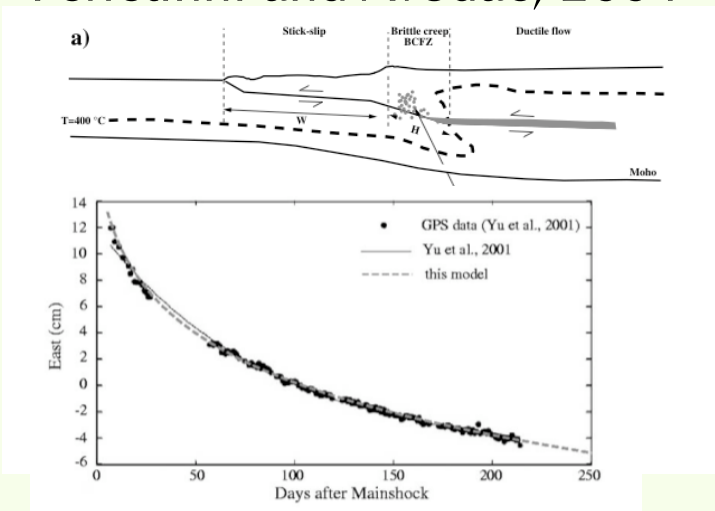
1994 Sanriku eq.





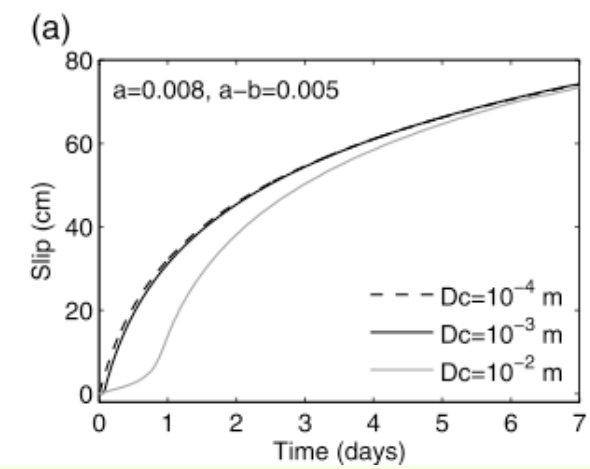
RD friction

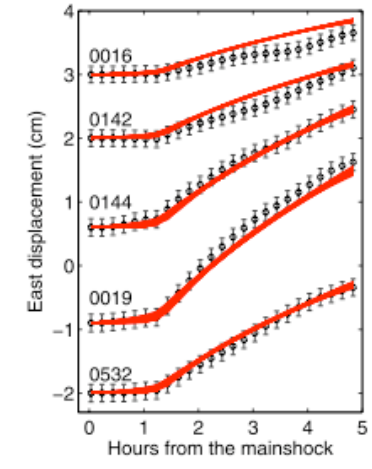
Perfetinni and Avouac, 2004



RS friction

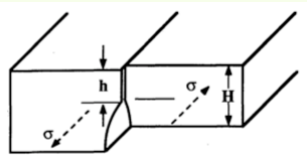
Fukuda et al., 2009

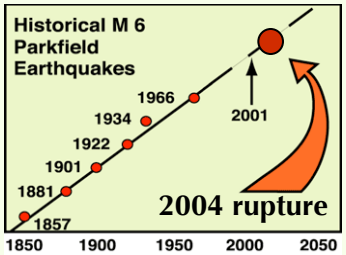




Postseismic fault creep models – 3D models I

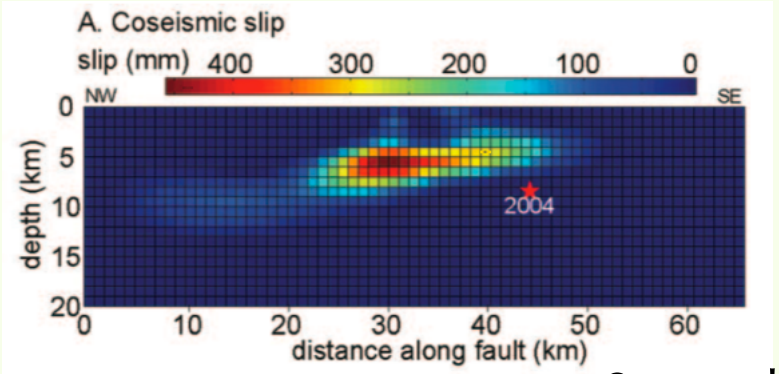
Marone et al., 1991



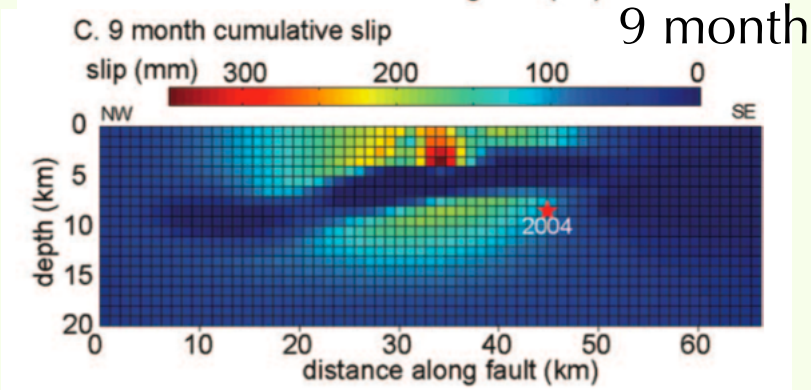


RS friction

Johnson et al., 2006

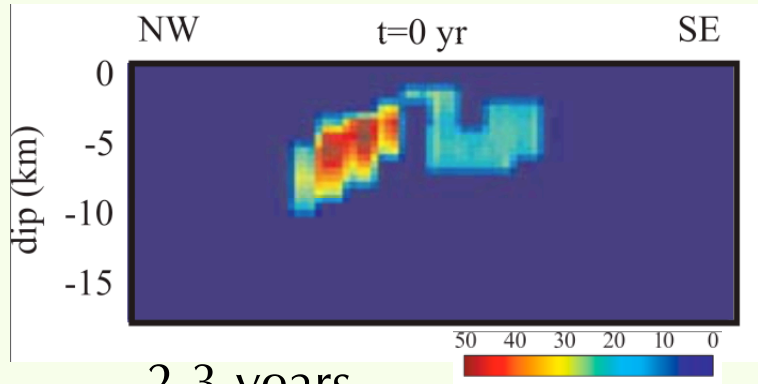


9 months

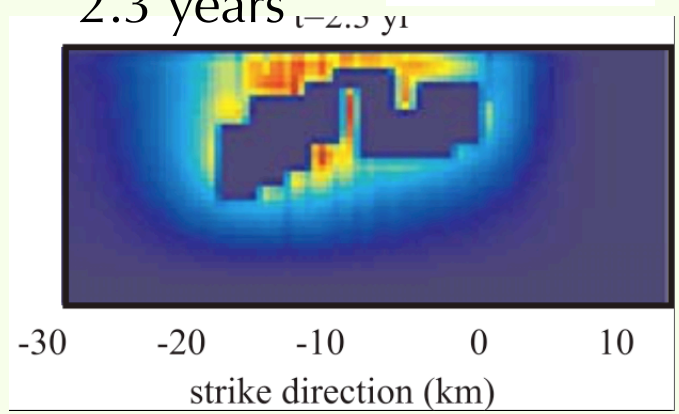


RD friction

Barbot et al, 2009

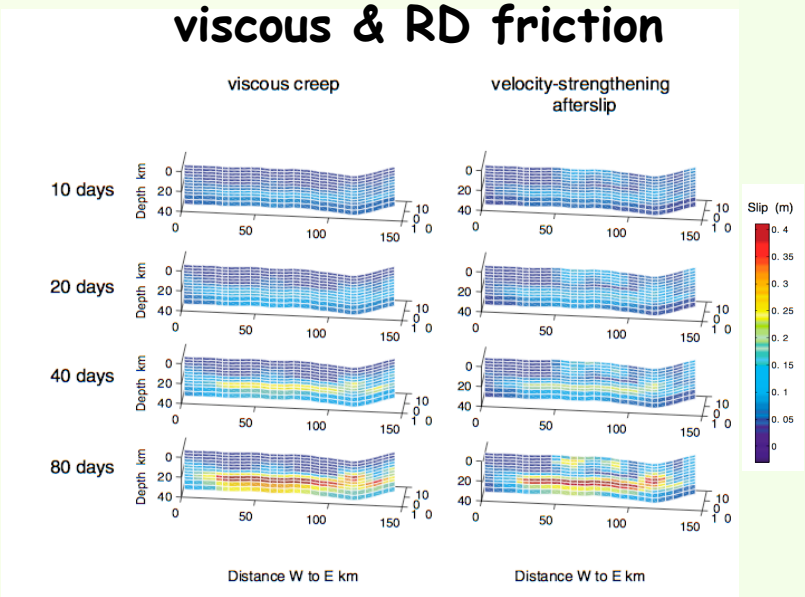


2.3 years

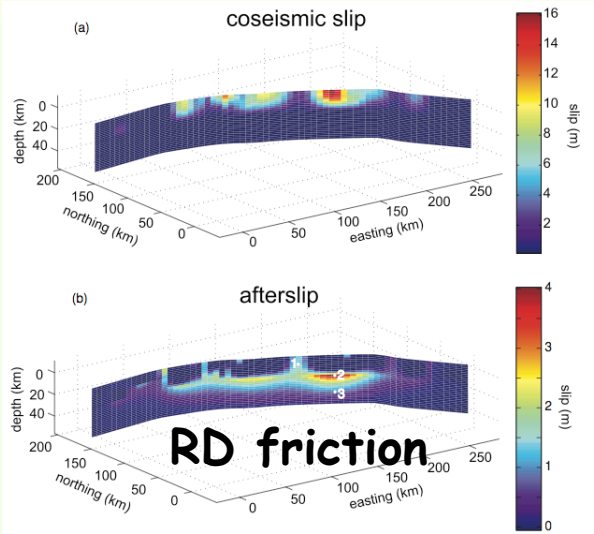


Postseismic fault creep models – 3D models II

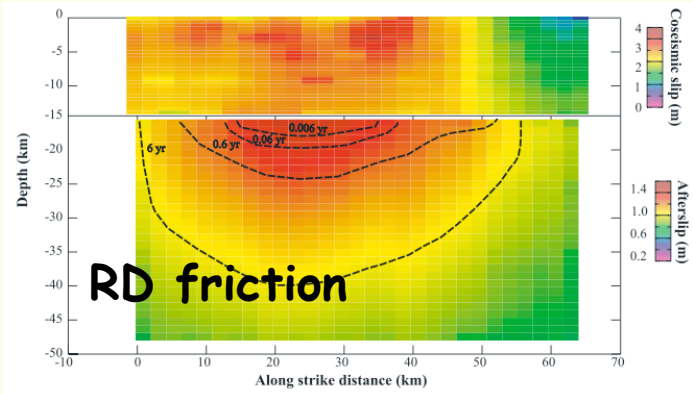
Hearn et al., 2002 (& 2009)



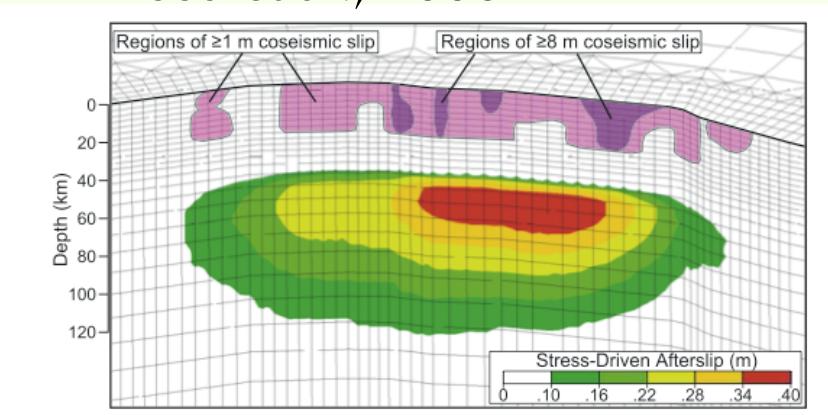
Johnson et al., 2009



Perfettini & Avouac, 2007

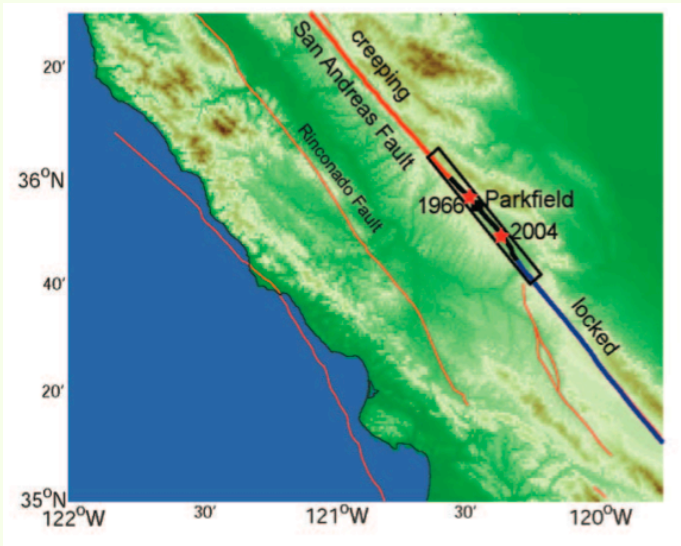


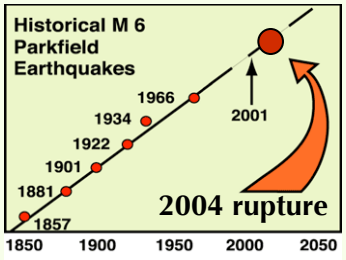
Freed et al., 2006



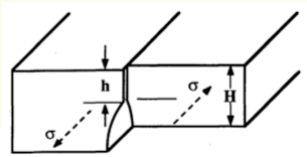
***frictionless* (i.e., rheology free)**

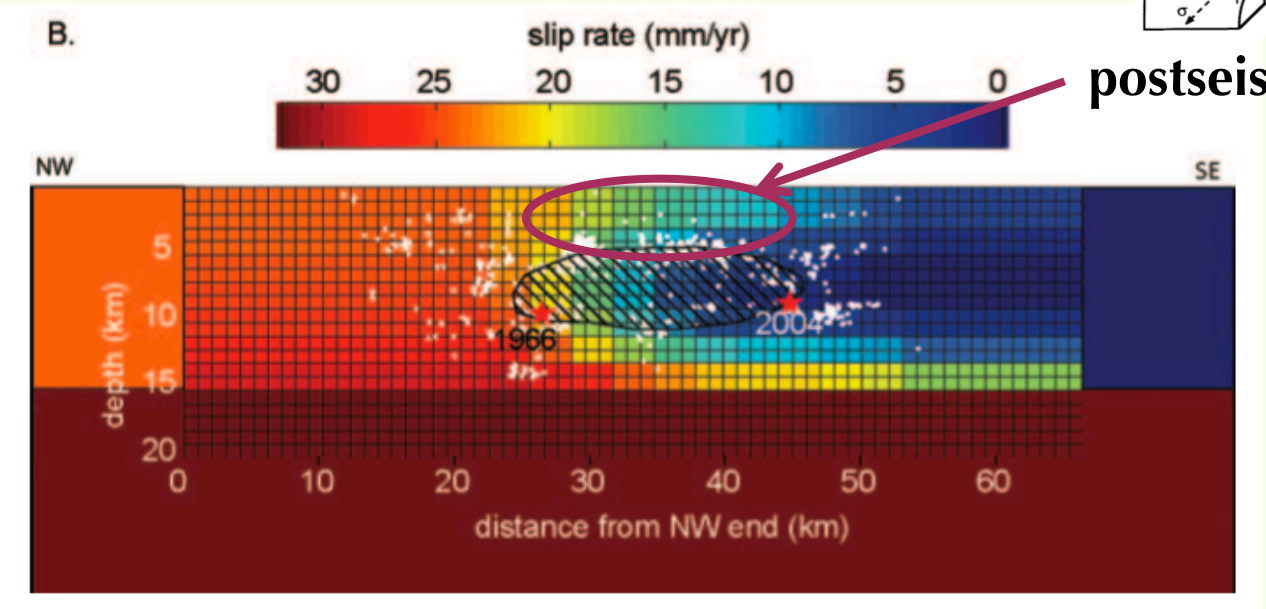
interseismic fault creep – **steady**:





Marone et al., 1991





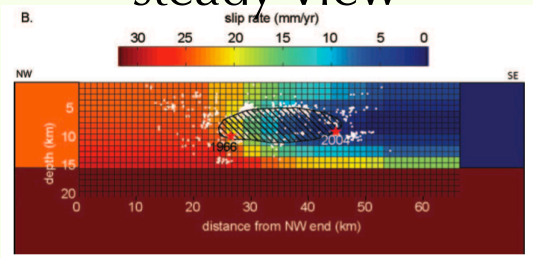
postseismic slip

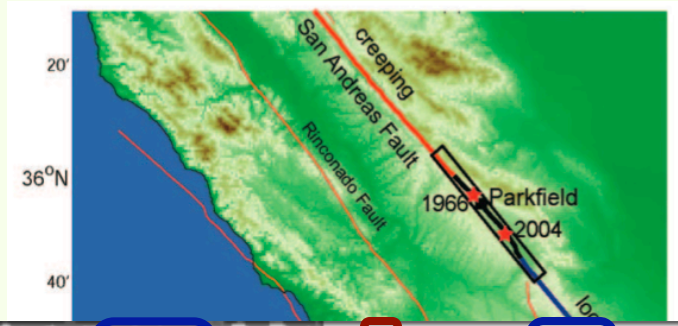
Johnson et al., 2006, after Murray et al., 2001

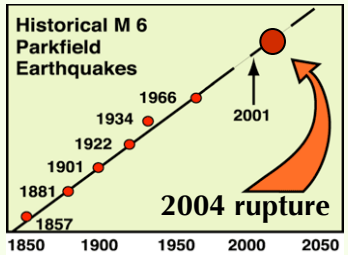
kinematic

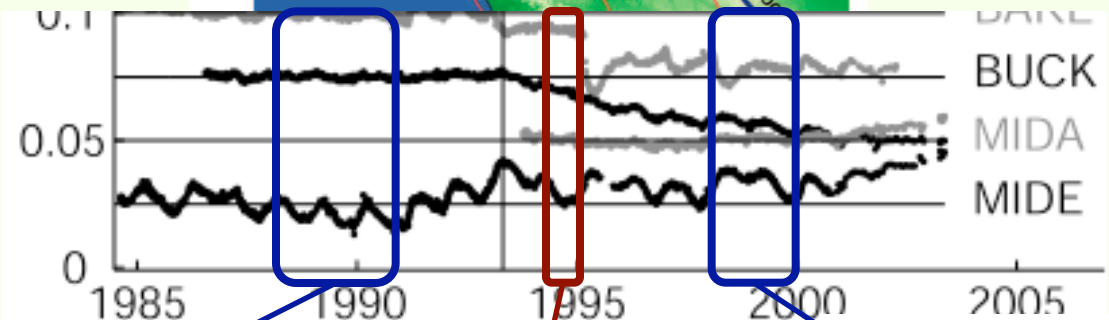
interseismic fault creep – **not always steady**:

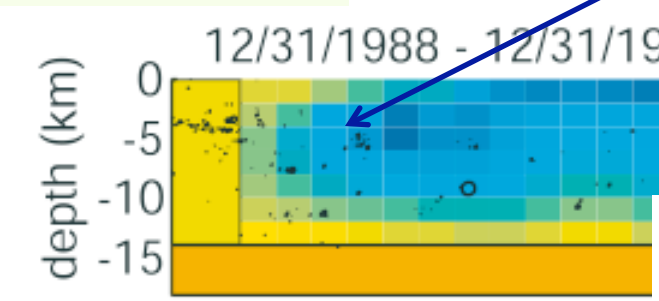
steady view

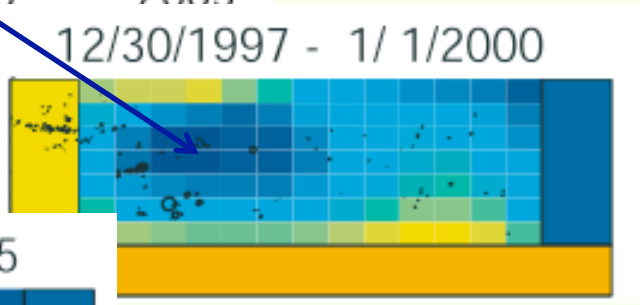


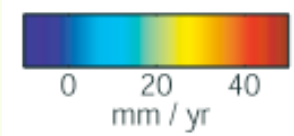


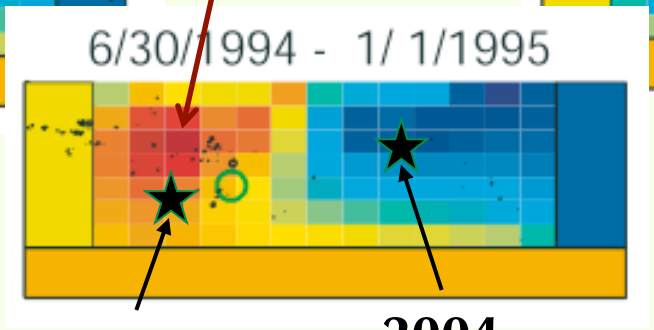












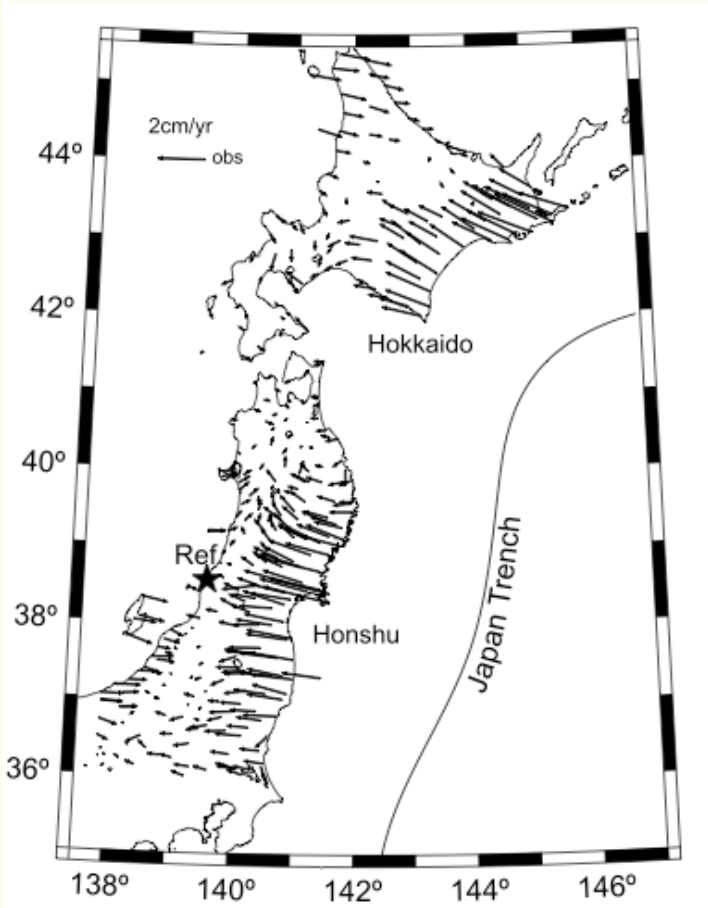
1966 **2004**

Murray & Segall, 2005

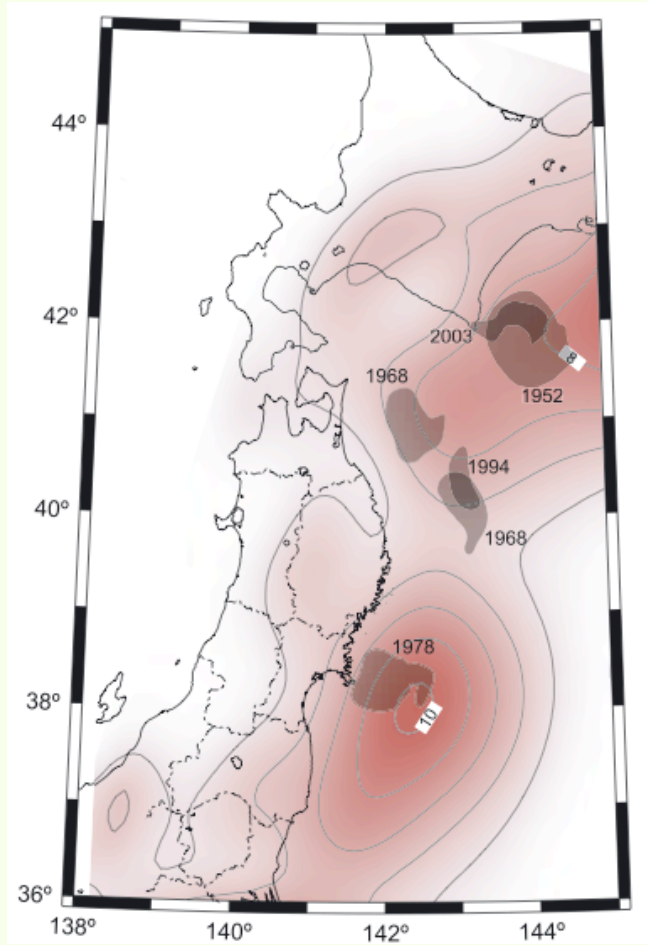
kinematic

geodetic view of interseismic megathrust mechanics – **steady**:

GPS observations of inerseismic deformation



inferred regions of the megathrust that are "locked"



back-slip model (Savage, 1983)

Suwa et al., 2006

kinematic

geodetic view of interseismic megathrust mechanics – **steady**:

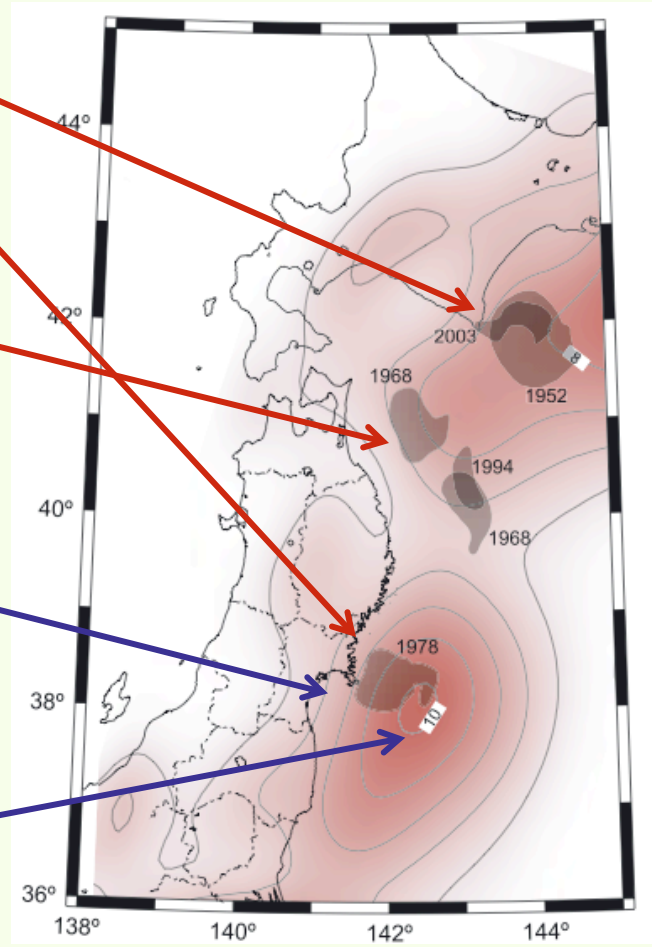
inferred regions of the megathrust that are "locked"

earthquakes where plate is "locked"

earthquakes where plate not fully "locked"

"locked" regions are smooth and much bigger than "asperities"
(back-slip models forced to be smooth)

maximum back-slip larger than plate convergence rate

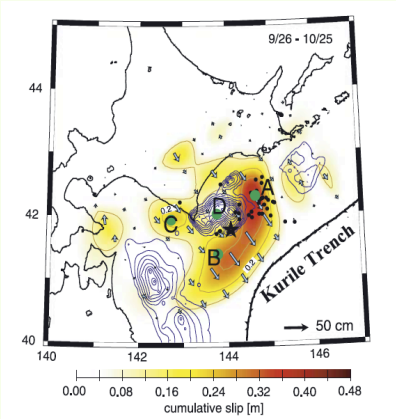


Suwa et al., 2006

What is missing? **fault rheology**

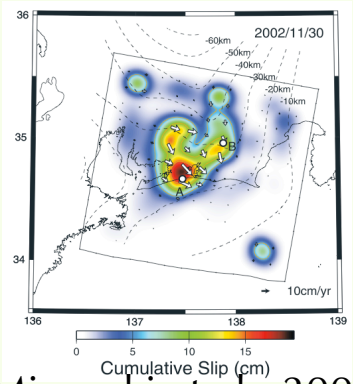
geodetic view of interseismic megathrust mechanics – **far from steady**:

wide-spread postseismic fault creep



Miyazaki et al, 2004

slow slip events (i.e., "spontaneous" transient creep)

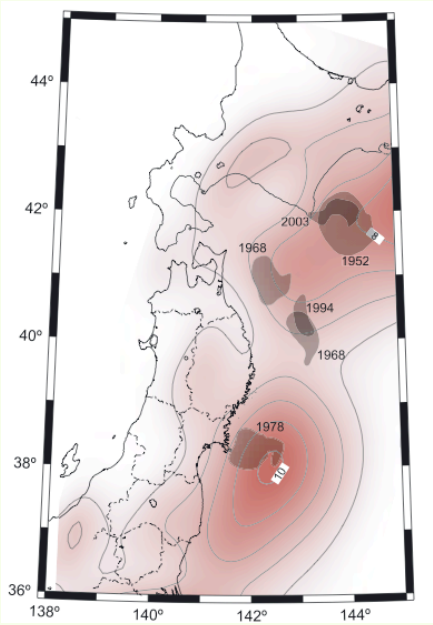


Miyazaki et al., 2006

maybe:

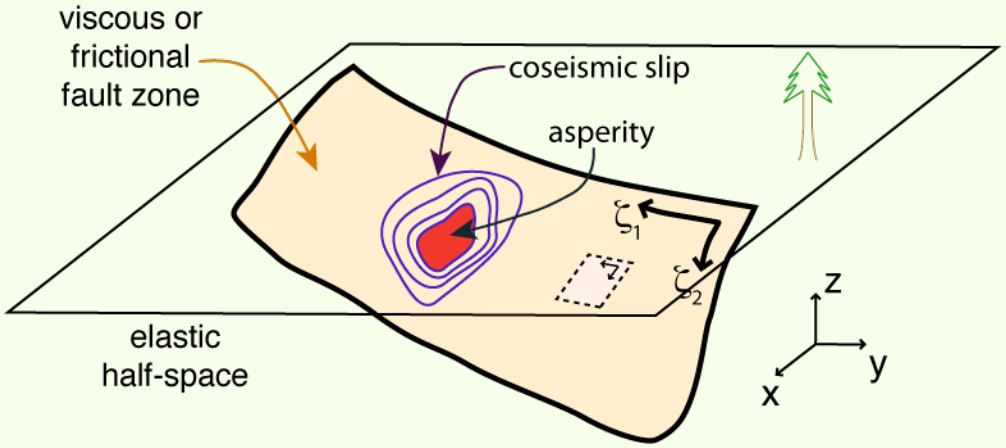
transient interseismic creep causes regions to appear partially coupled
(e.g., Wang & Dixon)

we are missing lots of small "asperities" in this figure (e.g., Suwa et a., 2006)



Suwa et al., 2006

Interseismic Fault Creep Model

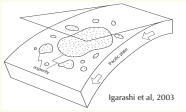


- 3D, non-planar fault in elastic half-space (Okada, 1992)
- **driven by slip on extension of fault**
- both dip- and strike-slip
- multiple asperities
- irregular earthquake sequences
- **heterogeneous fault-zone rheology**
- friction, viscous, non-linear viscous
- **spin-up model over multiple ruptures**

"asperities" = regions with ONLY coseismic slip

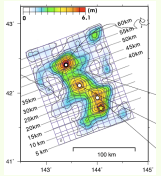
impose coseismic slip (both in and out of asperities), **solve for interseismic creep**

1) assume fault geometry, rheology, and asperities

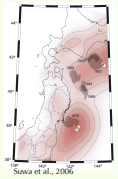


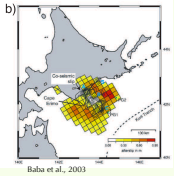
2) impose repeated coseismic slip

Yagi, 2004



3) solve for interseismic and postseismic fault creep

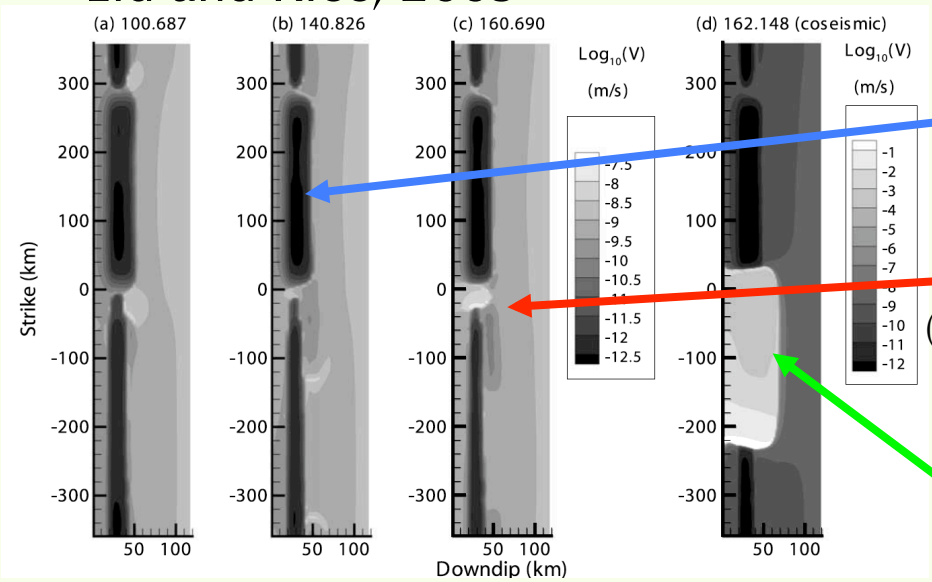




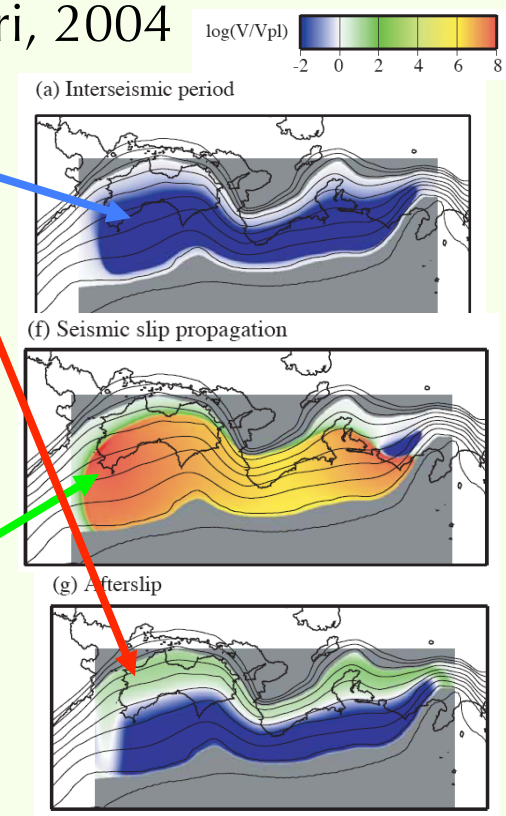
models are spun-up, so that fault tractions at any time are only consequence of the previous earthquakes and <u>fault loading</u>

Hasn't it already been done?

Liu and Rice, 2005



Hori, 2004



"asperities"

aseismic creep
(postseismic, intersesmic)

earthquakes

computationally expensive, difficult to tie to a specific earthquake history

By limiting the problem, computation is decreased dramatically.

tie computations to known eq. histories & constrain rheologies of non-seismic regions of fault from geodetic observations

building an interseismic fault creep model:

$$\tau(\vec{z},t) = \int_{\Lambda} s(\vec{\zeta},t) K(\vec{z};\vec{\zeta}) d\vec{\zeta}$$

traction on the fault

finite fault

slip on the fault

includes the off-fault rheology

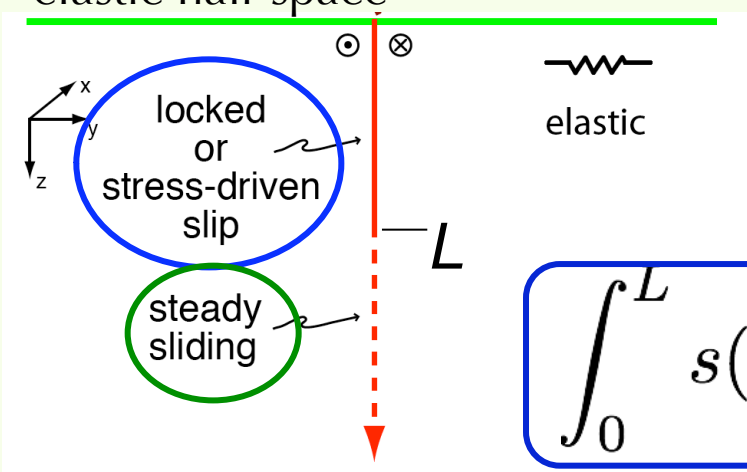
including fault loading:

fault loading rate

$$\tau(\vec{z},t) = \int_{\Lambda} s(\vec{\zeta},t) K(\vec{z};\vec{\zeta}) d\vec{\zeta} + \int_{\Lambda_\infty} t\, V K(\vec{z};\vec{\zeta}) d\vec{\zeta}$$

semi-infinite extension of fault

elastic half-space



$$\boxed{\int_0^L s(\zeta,t) K(z;\zeta) d\zeta} + \boxed{\int_L^\infty t\, V K(z;\zeta) d\zeta}$$

building an interseismic fault creep model:

$$\tau(\vec{z},t) = \int_{\Lambda} s(\vec{\zeta},t) K(\vec{z};\vec{\zeta}) d\vec{\zeta}$$

traction on the fault

finite fault

slip on the fault

includes the off-fault rheology

including fault loading:

$$\tau(\vec{z},t) = \int_{\Lambda} s(\vec{\zeta},t) K(\vec{z};\vec{\zeta}) d\vec{\zeta} + \int_{\Lambda_\infty} t\, V K(\vec{z};\vec{\zeta}) d\vec{\zeta}$$

"back-slip"

$$\tau(\vec{z},t) = \int_{\Lambda} \boxed{\left[s(\vec{\zeta},t) - t\, V \right]} K(\vec{z};\vec{\zeta}) d\vec{\zeta}$$

e.g.; Rice, 1993; Liu and Rice, 2005.

Note: no seismic radiation damping (e.g., Rice, 1993) - there are no seismic waves & no problems with exploding slip velocities in our models…

building an interseismic fault creep model:

$$\tau(\vec{z},t) = \int_\Lambda \left[s(\vec{\zeta},t) - Vt + S_o(\vec{\zeta},t) \right] K(\vec{z};\vec{\zeta}) d\vec{\zeta}$$

traction on fault

interseismic creep on fault

loading (imposed)

earthquakes (imposed)

$$\tau' = \int_\Lambda \left[s' - V't' + S'_o \right] K' d\zeta'$$

use K from finite dislocation solutions, requires fault to be meshed

today we use Okada 1992 to generate K

IE reduced to an algebraic system

fault rheology:

$$\tau' = \int_{\Lambda} \left[s' - V' t' + S'_o \right] K' d\zeta'$$

linear viscous

non-linear viscous

rate-dep (hot) friction

rate-state friction

fault rheology:

$$\tau' = \int_\Lambda \left[s' - V't' + S'_o\right] K' d\zeta'$$

linear viscous

$$v = \tau/\alpha_1 \qquad \alpha_1 = \eta/h$$

non-linear viscous

rate-dep (hot) friction

$$\boxed{v' = \tau'/\alpha'_1}$$

$$\alpha'_1 = \alpha_1 v_T \frac{D}{\mu s_o}$$

rate-state friction

fault rheology:

$$\tau' = \int_\Lambda [s' - V't' + S'_o]\, K' d\zeta'$$

linear viscous

$$v = \tau^n / \alpha_n$$

non-linear viscous
(Montési, 2004)

$$\boxed{v' = (\tau')^n / \alpha'_n}$$

rate-dep (hot) friction

$$\alpha'_n = \alpha_n v_T \left(\frac{D}{\mu s_o} \right)^n$$

rate-state friction

fault rheology:

$$\tau' = \int_\Lambda [s' - V't' + S'_o]\, K' d\zeta'$$

linear viscous

$$v = \mathrm{sgn}\{\tau\}\, 2v_o \sinh\left\{\frac{|\tau| - \sigma_E f_o}{(a-b)\sigma_E}\right\}$$

non-linear viscous

$$v_o = v_T$$
$$\rho_h = f_o/(a-b)$$
$$\alpha'_h = (a-b)\sigma'_E$$

rate-dep (hot) friction
(e.g., Marone et al., 1991,
Linker & Rice, 1997)

rate-state friction

$$v' = 2e^{-\rho_h} \sinh\left\{\frac{\tau'}{\alpha'_h}\right\}$$

sinh for consistency for creep at low τ (Rice & Ben-Zion, 1996)

fault rheology:

$$\tau' = \int_{\Lambda} [s' - V't' + S'_o] \, K' d\zeta'$$

linear viscous

non-linear viscous

rate-dep (hot) friction

rate-state friction
(e.g. Dieterich, 1979; Ruina 1983)

$$f = f_o + a \ln \left\{ \frac{v}{v_o} \right\} + b \ln \left\{ \frac{v_o \theta}{L} \right\}$$

f_o = reference friction

a,b = frictional parameters

v_o = reference slip rate

L = slip length-scale

θ = state parameter

b/a<1 → velocity strengthening

fault rheology:

$$\tau' = \int_\Lambda \left[s' - V't' + S'_o\right] K' d\zeta'$$

linear viscous

$$f = f_o + a \ln\left\{\frac{v}{v_o}\right\} + b \ln\left\{\frac{v_o \theta}{L}\right\}$$

non-linear viscous

$$v_o = v_T$$
$$\rho = f_o / a$$
$$\alpha' = a\sigma'_E$$

rate-dep (hot) friction

$$\gamma = b/a \qquad L' = L/s_o$$

$$v' = 2e^{-\rho} \sinh\left\{\frac{\tau'}{\alpha'}\right\} \left[\frac{\theta'}{L'}\right]^{-\gamma}$$

rate-state friction
(e.g. Dieterich, 1979; Ruina 1983)

$$\frac{\partial \theta'}{\partial t'} = 1 - \frac{\theta' v'}{L'} \qquad \Omega = \frac{\theta' v'}{L'}$$

interseismic fault creep model:

$$\tau' = \int_{\Lambda} \left[s' - V' t' + S'_o \right] K' d\zeta'$$

linear viscous $$v' = \tau' / \alpha'_1$$

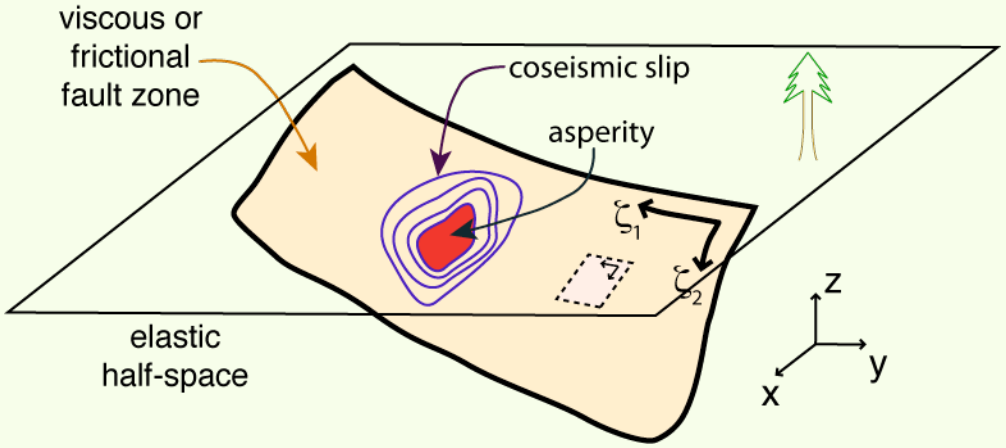
non-linear viscous $$v' = (\tau')^n / \alpha'_n$$

rate-dep (hot) friction $$v' = 2e^{-\rho_h} \sinh \left\{ \frac{\tau'}{\alpha'_h} \right\}$$

rate-state friction $$v' = 2e^{-\rho} \sinh \left\{ \frac{\tau'}{\alpha'} \right\} \left[\frac{\theta'}{L'} \right]^{-\gamma}$$

$$\frac{\partial \theta'}{\partial t'} = 1 - \frac{\theta' v'}{L'}$$

Interseismic Fault Creep Model

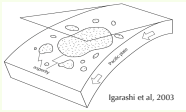


- 3D, non-planar fault in elastic half-space (Okada, 1992)
- use R-K in time, with adaptive time-stepping
- **driven by slip on extension of fault**
- both dip- and strike-slip
- multiple asperities
- irregular earthquake sequences
- **heterogeneous fault-zone rheology**
- friction, viscous, non-linear viscous
- **spin-up model over multiple ruptures**

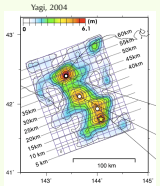
"asperities" = regions with ONLY coseismic slip

impose coseismic slip (both in and out of asperities), **solve for interseismic creep**

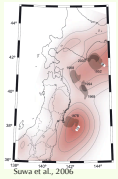
1) assume fault geometry, rheology, and asperities

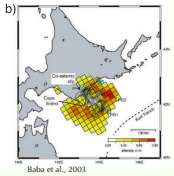


2) impose repeated coseismic slip



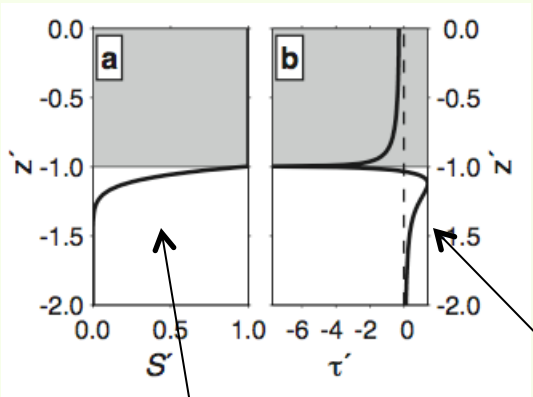
3) solve for interseismic and postseismic fault creep





models are <u>spun-up</u>, so that fault tractions at any time are only consequence of the previous earthquakes and <u>fault loading</u>

2D strike-slip model



2D, strike-slip fault

asperity from surface to z´= -1.0

periodic rupture (every T)

spin-up until interseismic deformation is independent of the initial conditions and is the *same in all seismic cycles* (cycle invariant)

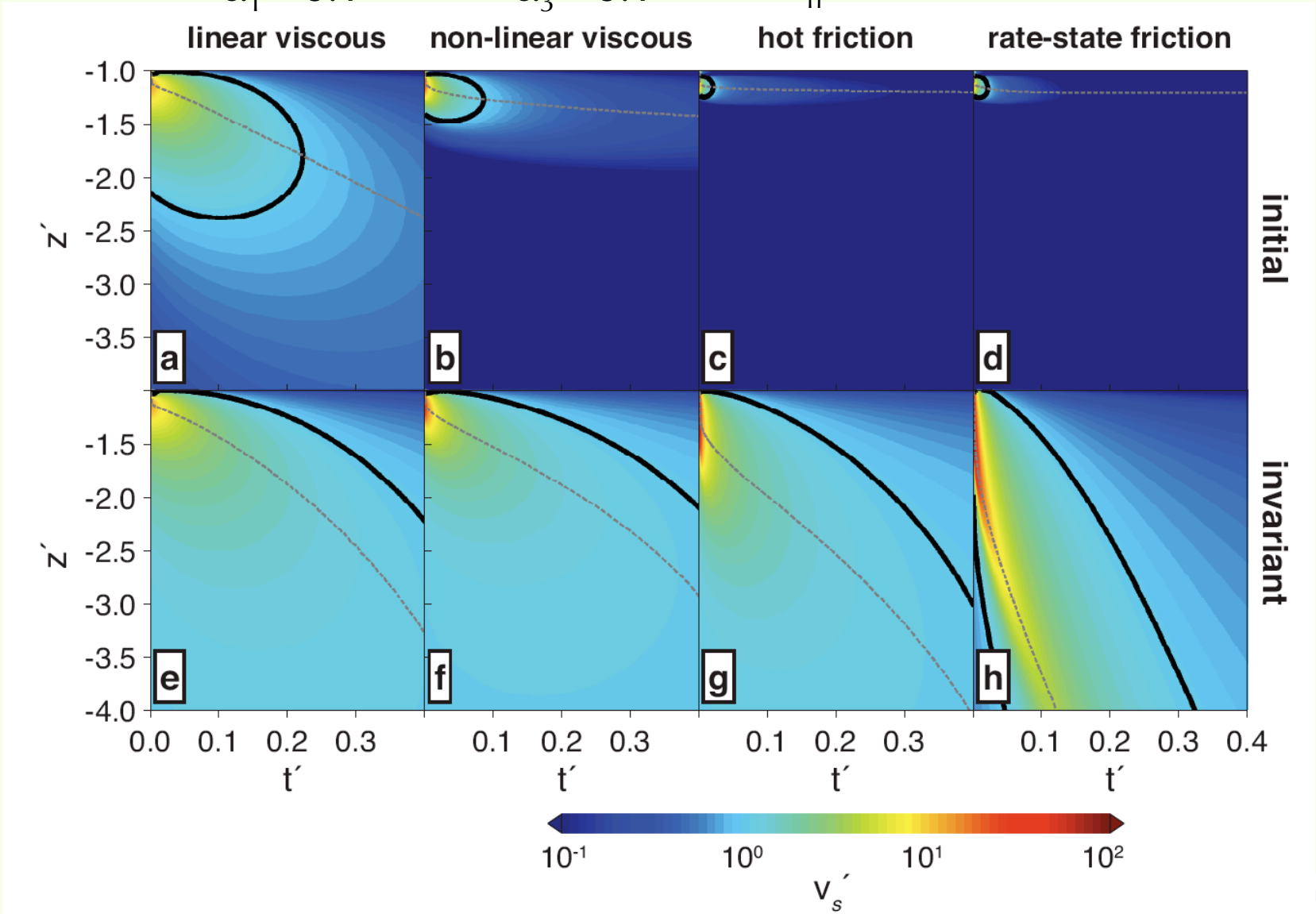
coseismic slip (imposed)

coseismic change in fault traction

2D model – Spin-Up: postseismic creep

$\rho=10$
$\alpha'=0.1$
$\gamma=0.9$
$L'=0.05$

	$n=3$	$\rho_h=10$	
$\alpha_1'=0.1$	$\alpha_3'=0.1$	$\alpha_h'=0.1$	



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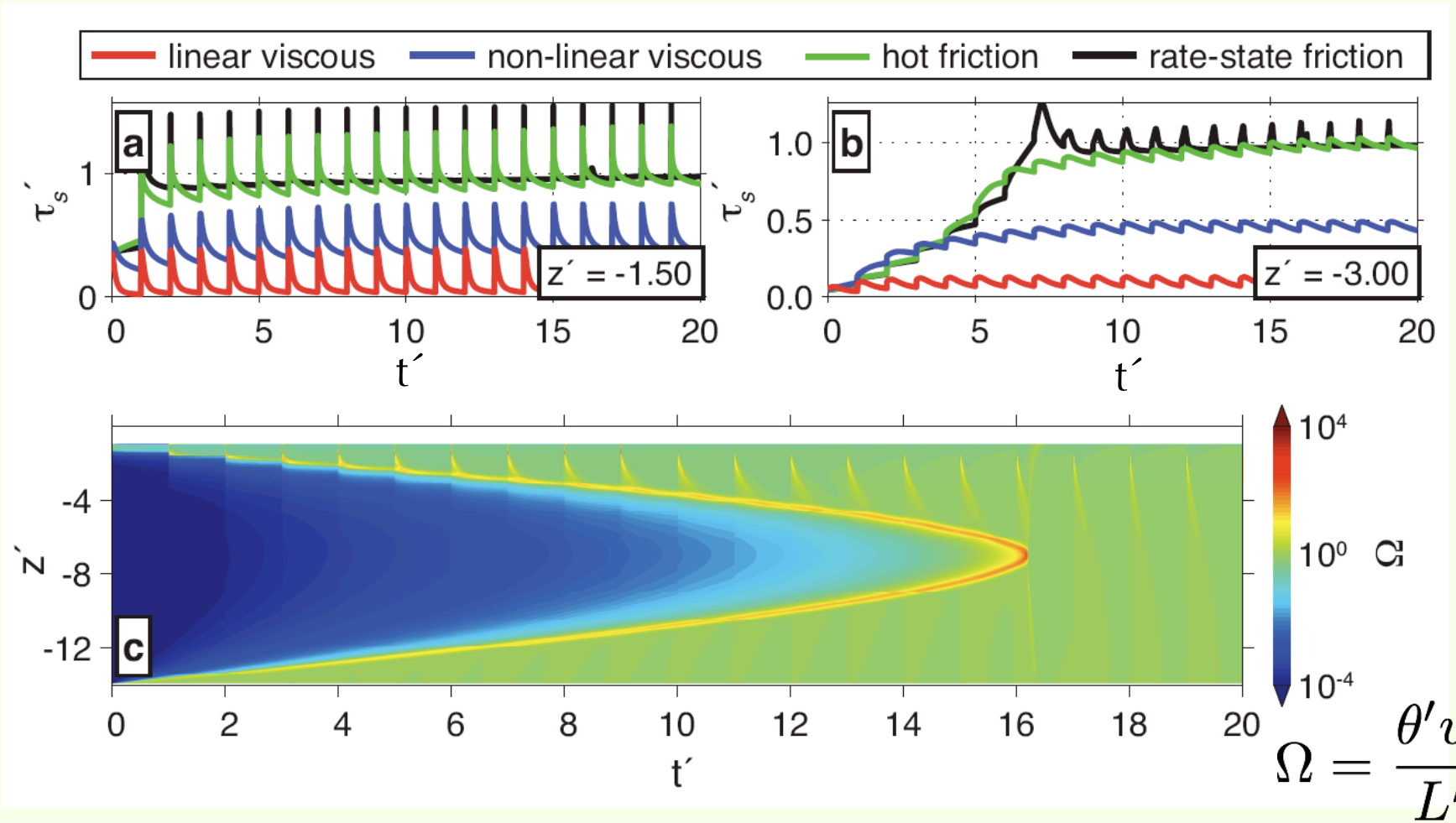
2D model – Spin-Up: tractions outside asperity

$\alpha_1' = 0.1$

$n = 3$
$\alpha_3' = 0.1$

$\rho_h = 10$
$\alpha_h' = 0.1$

$\rho = 10$
$\gamma = 0.9$
$L' = 0.05$
$\alpha' = 0.1$

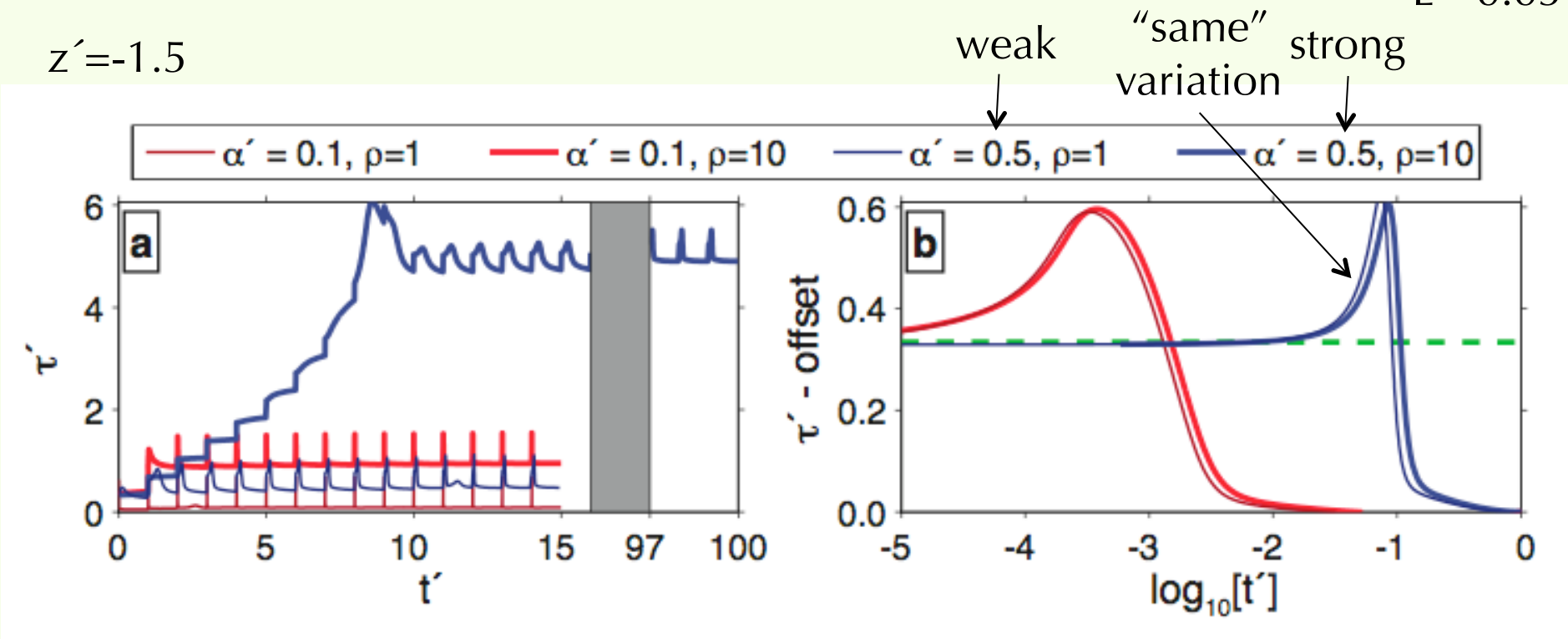


$$\Omega = \frac{\theta' v'}{L'}$$

2D model – Spin-Up: mature tractions outside asperity

γ=0.9
L´=0.05

z´=-1.5



average traction supported on the fault once spun-up =
τ_f´ = (absolute) fault strength

linear viscous – $\tau_f' = \alpha_1'$

non-linear viscous – $\tau_f' = (\alpha_n')^{1/n}$

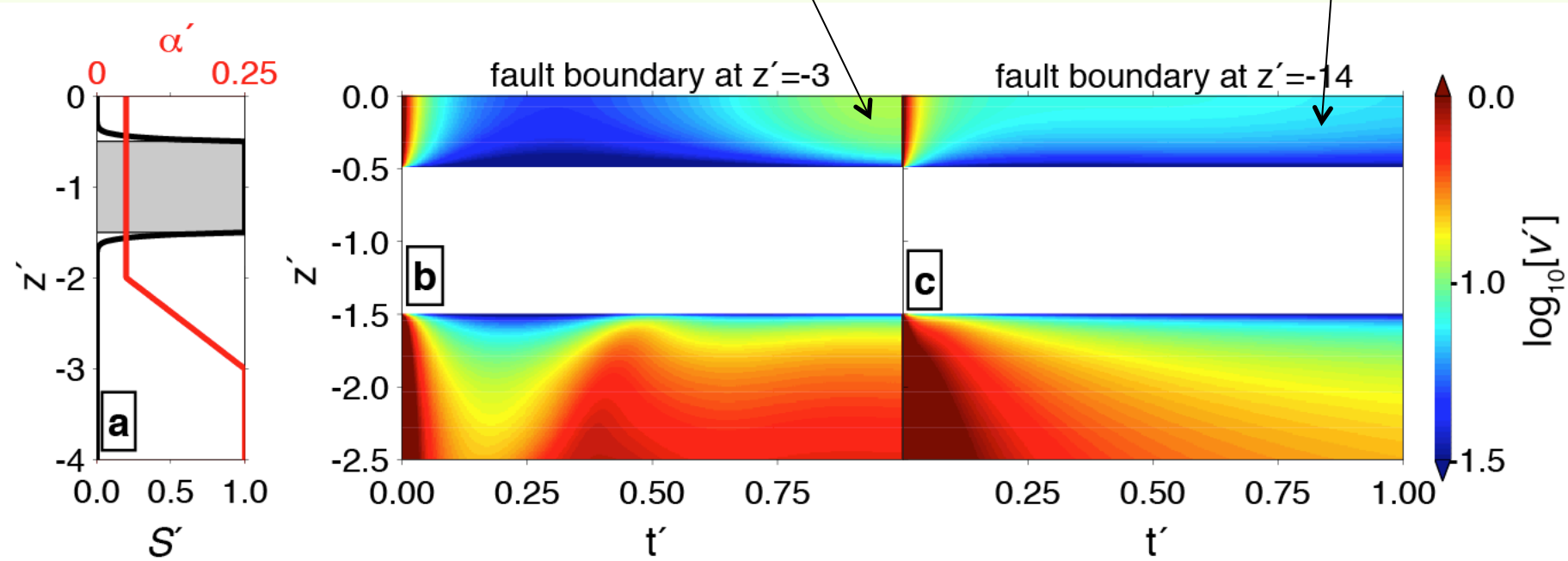
frictional – $\tau_f' = \alpha_h'\rho_h = \alpha'\rho$

fault domain size I **RS friction**

$\rho = 10$
$\gamma = 0.9$
$L' = 0.01$

stresses from fault loading dominate

stress shadow

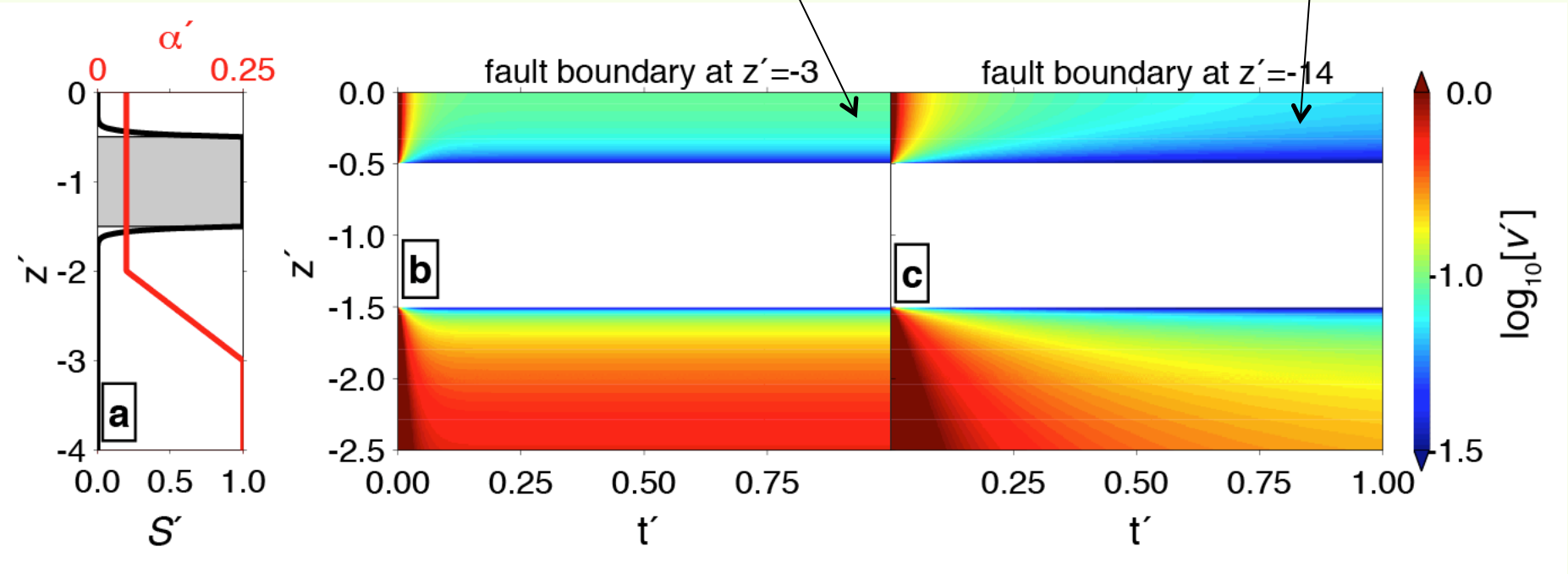


fault domain size II **RD friction**

$\rho = 10$
$\gamma = 0.9$

stresses from fault loading dominate

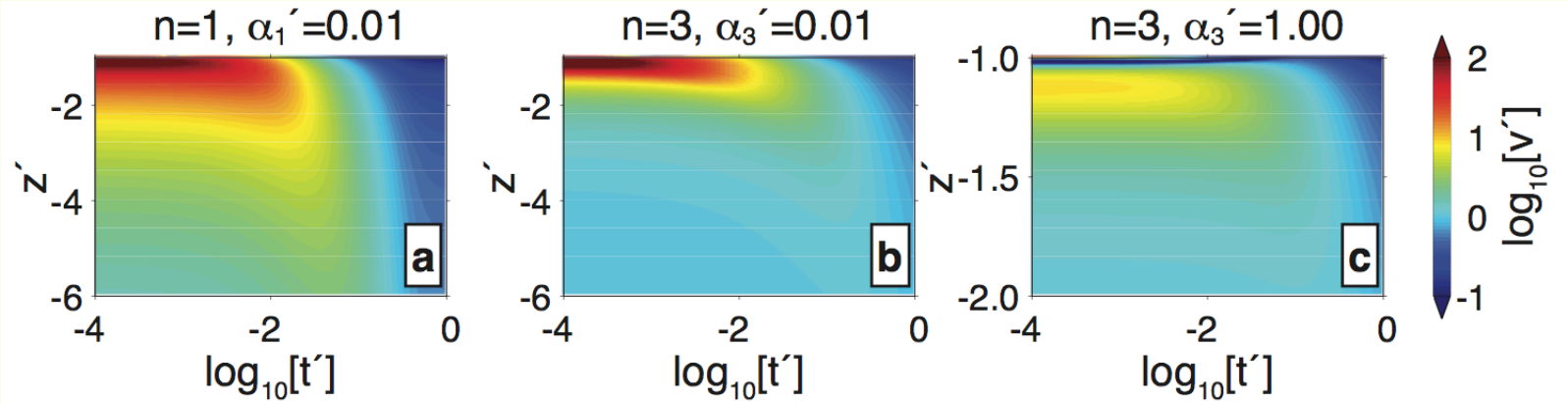
stress shadow



fault zone rheology: viscous & RD/hot friction I

n>1 → more localized

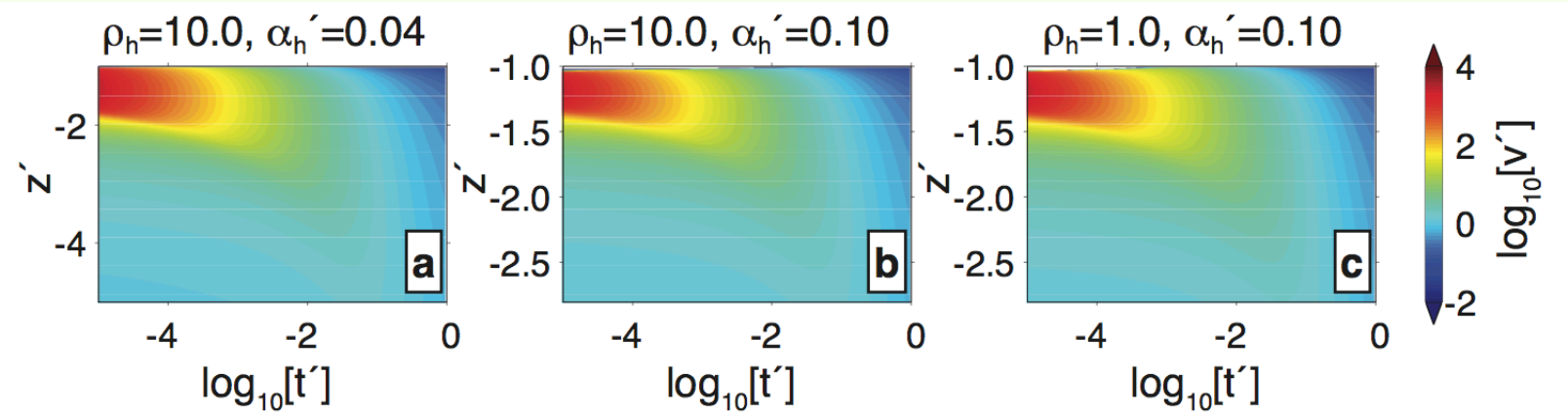
α_n small → more variation



α_h small → postseismic creep over broader region

$\alpha_h = (a\text{-}b)\sigma_E'$ small → unclamped fault

ρ_h → little effect



fault zone rheology: rate-state friction

pulse-like postseismic creep

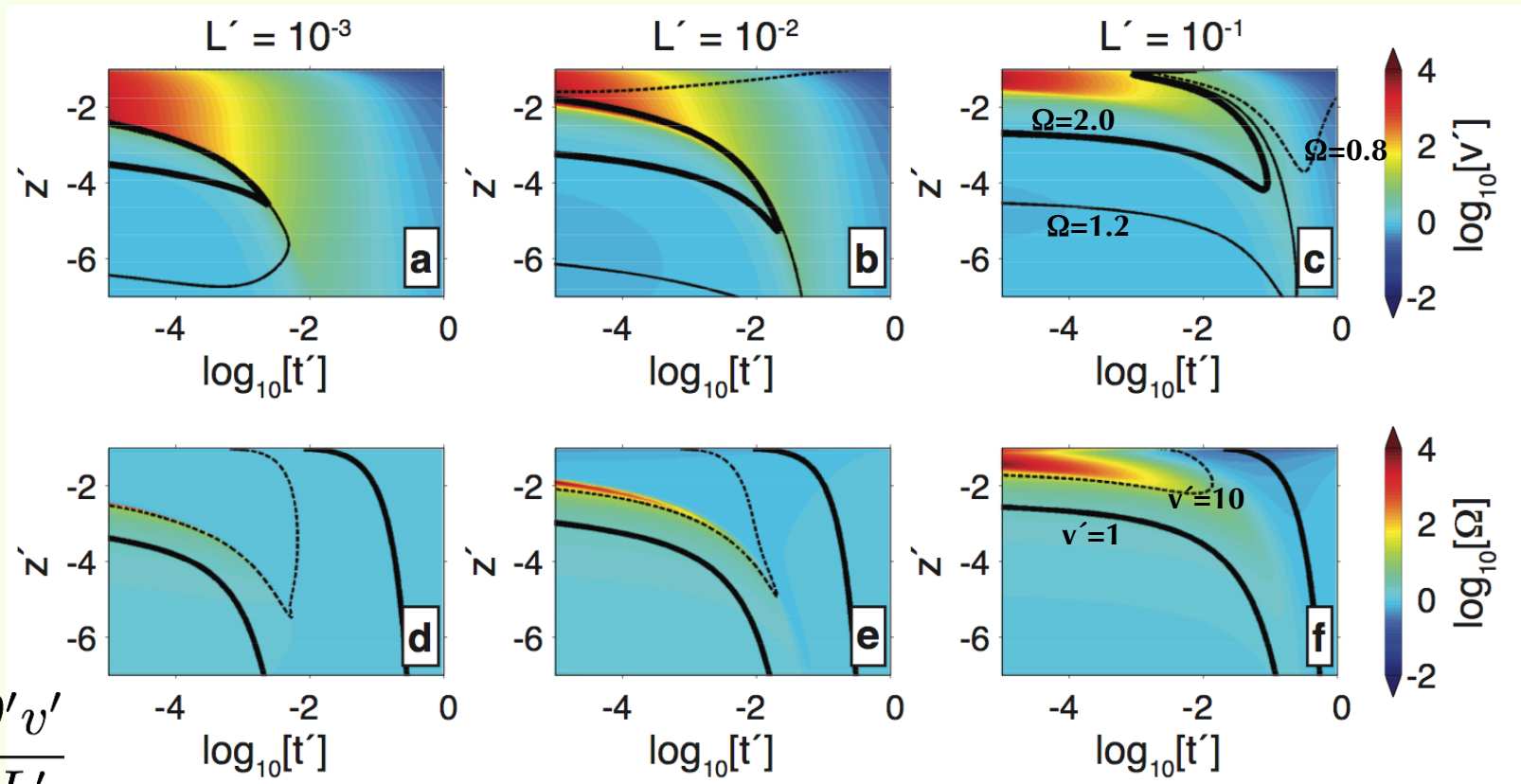
ρ=10
γ=0.9
α'=0.1

L´ large → isolated postseismic creep pulse, gentle front

Ω>1 for entire postseismic

L´ small → **sharp onset of postseismic creep pulse**

$\Omega \neq 1$ only before postseismic creep



$$\Omega = \frac{\theta' v'}{L'}$$

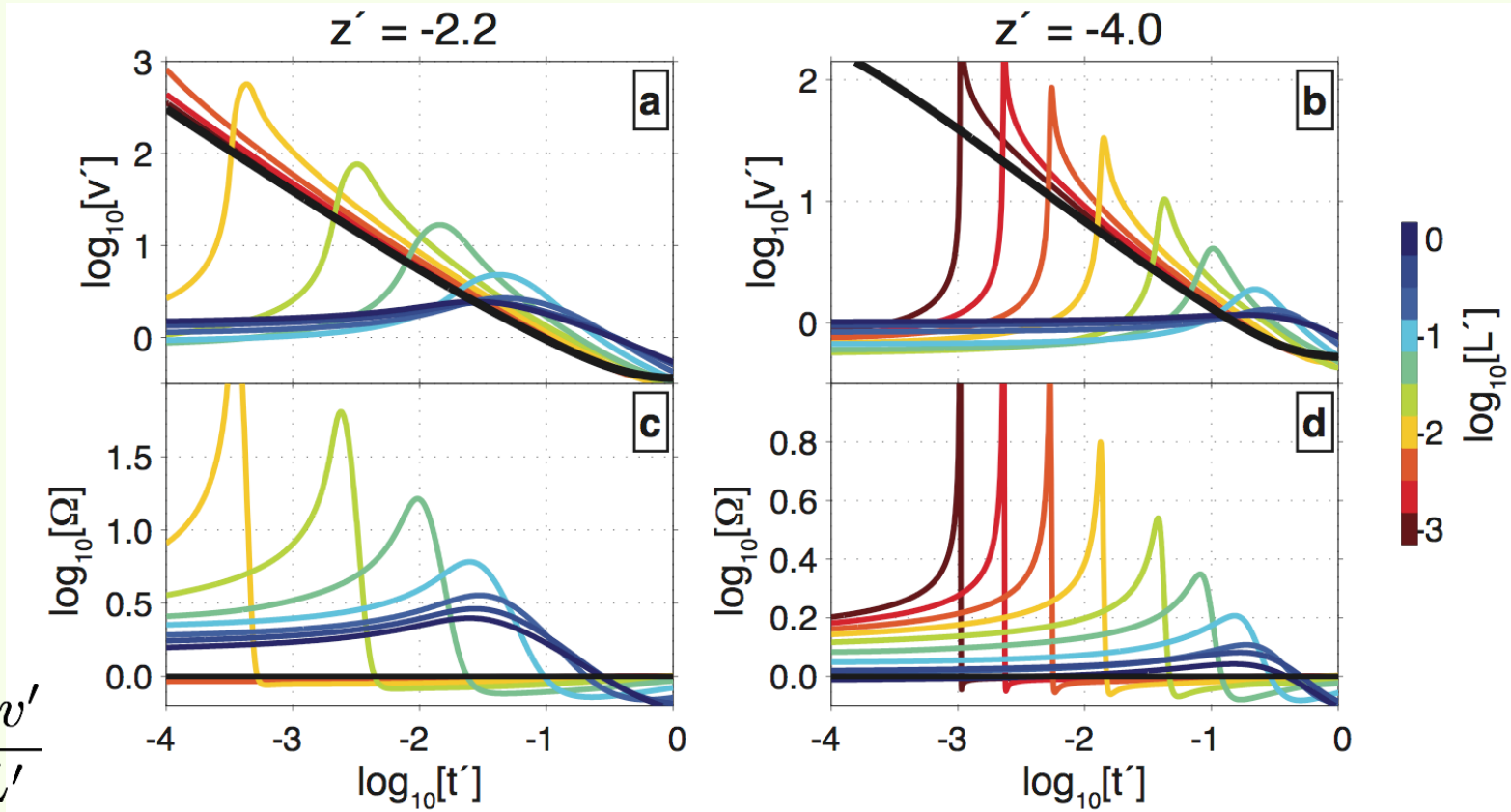
RS friction vs RD/hot friction

colored lines: RS friction
γ=0.9, ρ=10, α'=0.1
black lines: RD/hot friction
ρ_h=100, α_h'=0.01

L´ → 0: onset of postseismic sharp at depth

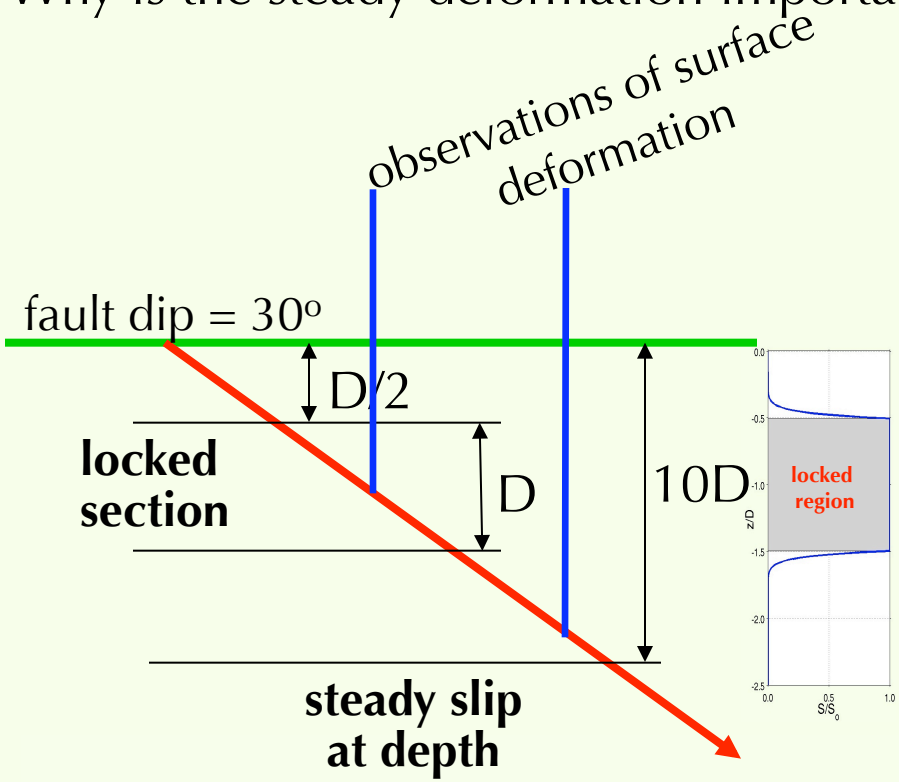
Ω≈1 for most of postseismic

except for very *early postseismic* times, RD/hot friction is a *good approximation* of interseismic fault creep (also, Perfetinni & Ampuero, 2008)



$$\Omega = \frac{\theta' v'}{L'}$$

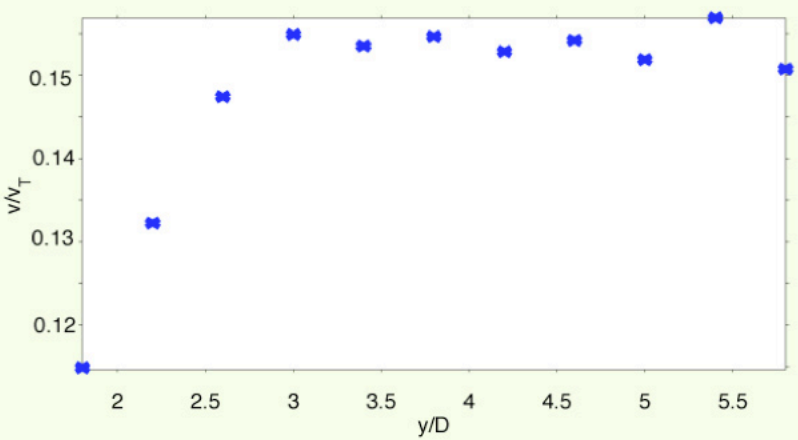
Why is the steady deformation important? A 2D toy model:

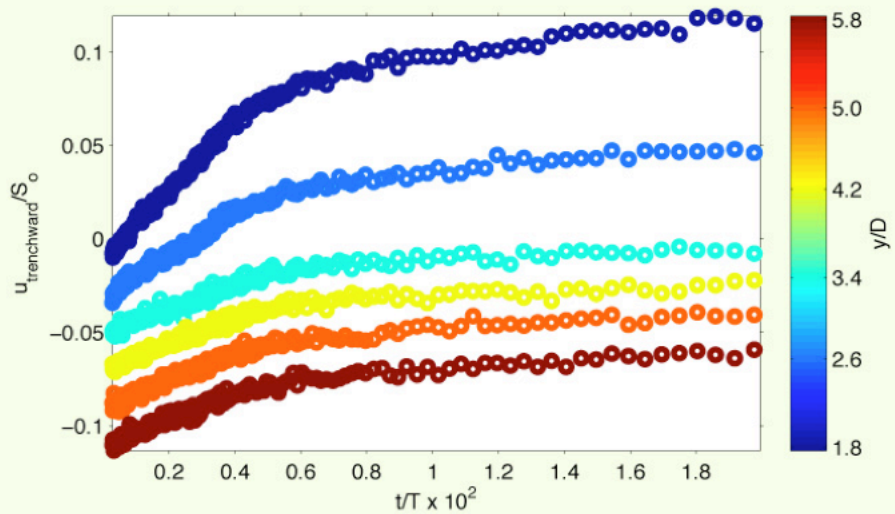


determine homogeneous RSF parameters from forward model with (slightly) heterogenous RSF

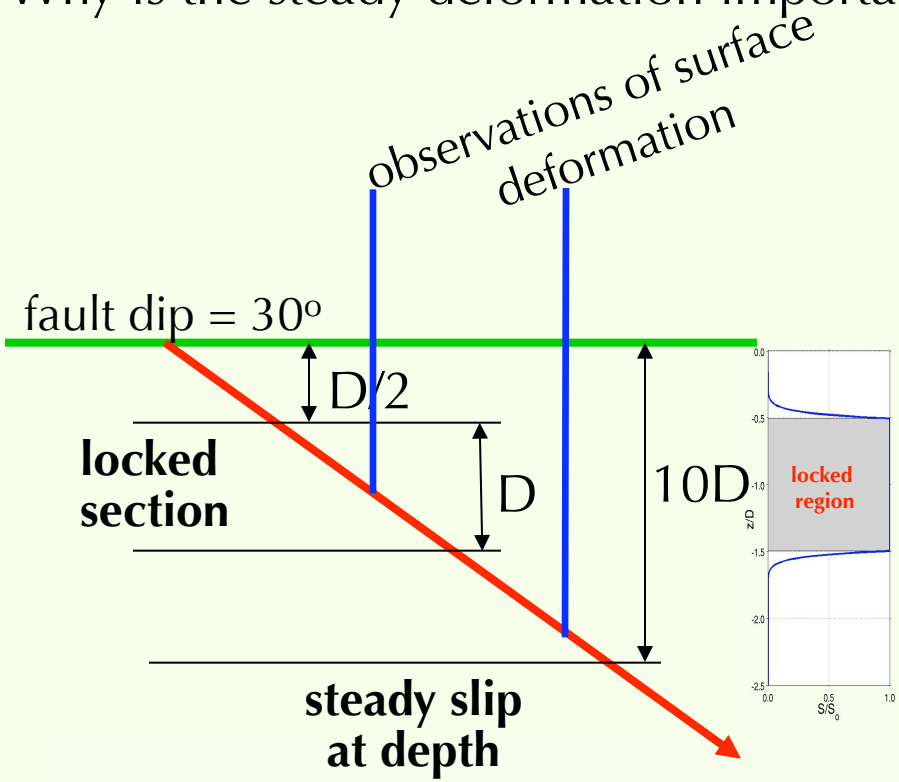
→ model is spun-up assuming periodic earthquakes

→ use both steady late-interseismic velocities and transient postseismic displacements





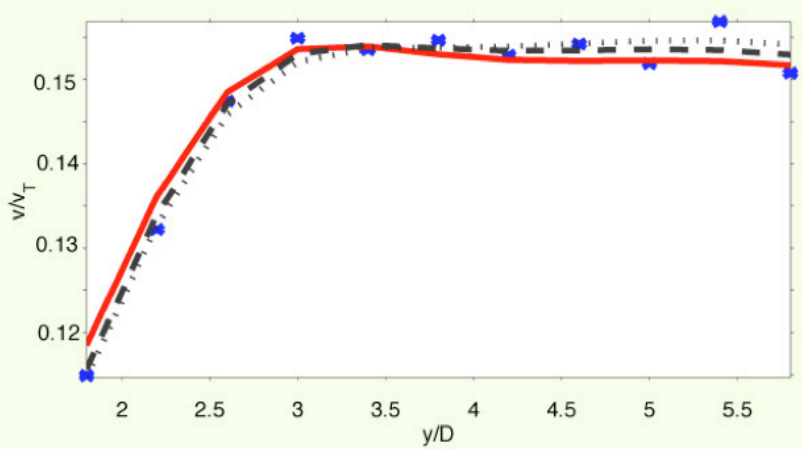
Why is the steady deformation important? A 2D example:

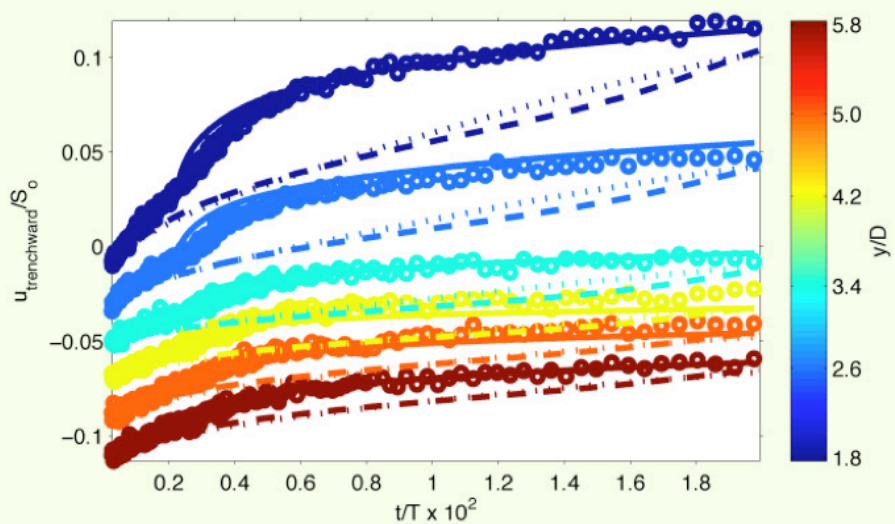


determine homogeneous RSF parameters from forward model with (slightly) heterogenous RSF

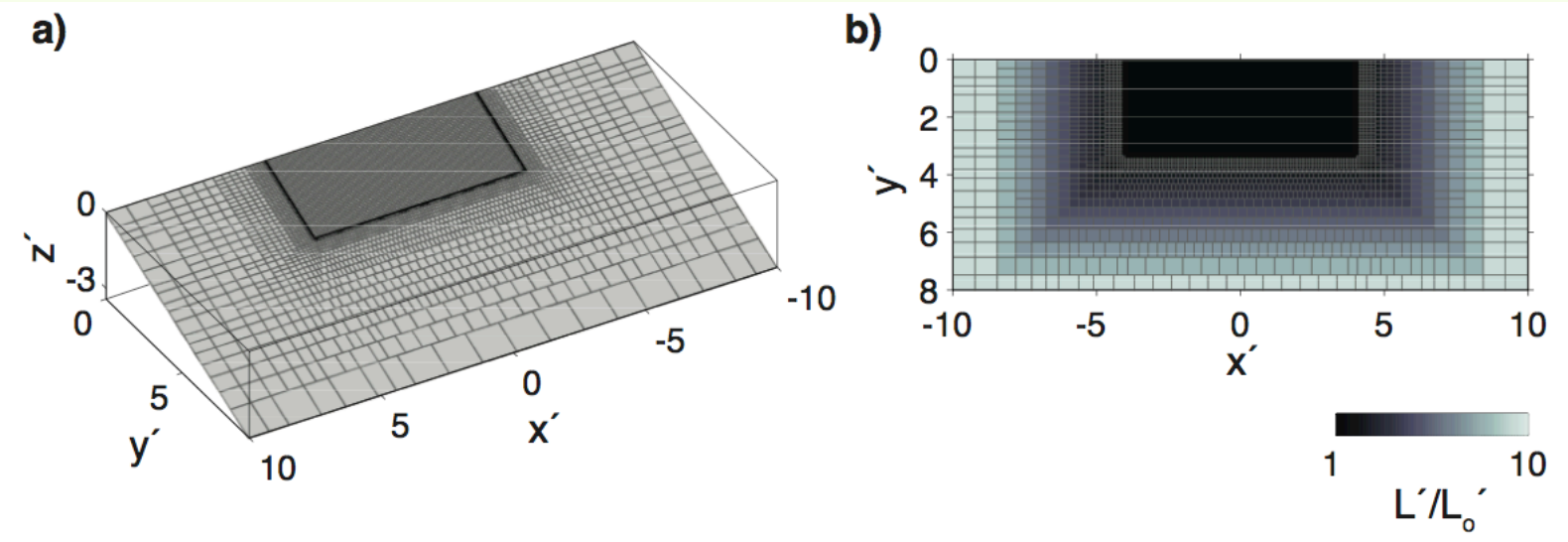
→ broad range of models fit the late-cycle interseismic velocities

→ **only small range of models fit both interseismic and postseismic displacements**





toy megathrust – model:

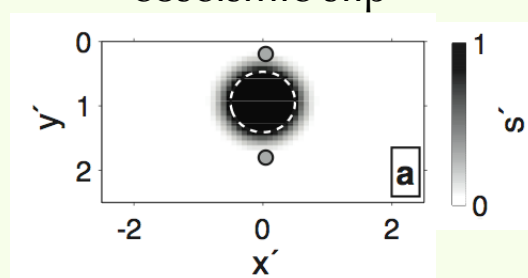


x′ = x/asperity size
L′ = L/coseismic slip

- **planar fault, 20° dip, ~8k cells**
- **velocity strengthening friction**
- **L′ increases in far field to match fault cell size**

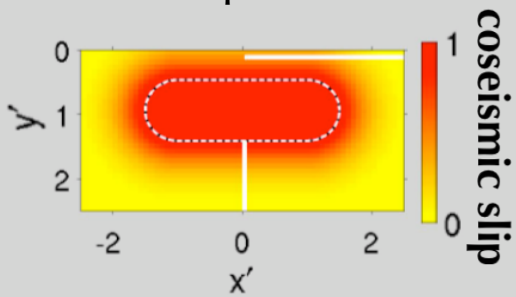
  (Perfettini and Apuero, 2008)
- **other frictional parameters constant over fault**
- **spun-up with periodic eqs. from steady fault tractions (<5 cycles, <<10 minutes)**

coseismic slip

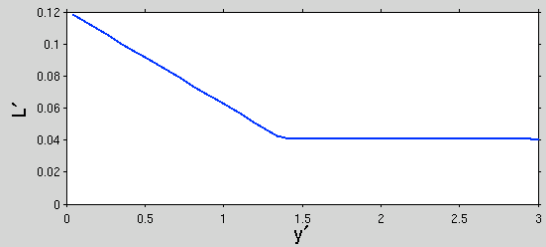


toy megathrust – heterogeneous fault zone → complicated fault creep:

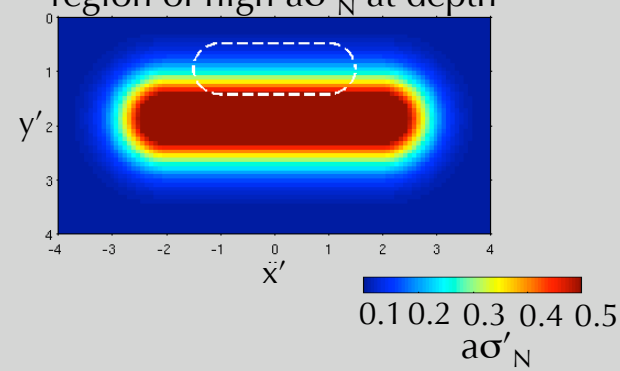
coseismic slip extends to surface



L′ increases by x3 at surface



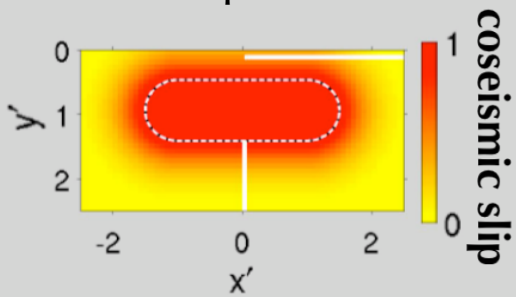
region of high $a\sigma'_N$ at depth



$f_o/a = 10$, $b/a = 0.9$, $L_o' = 0.04$, $a\sigma'_N = 0.10$

toy megathrust – heterogeneous fault zone → complicated fault creep:

coseismic slip extends to surface



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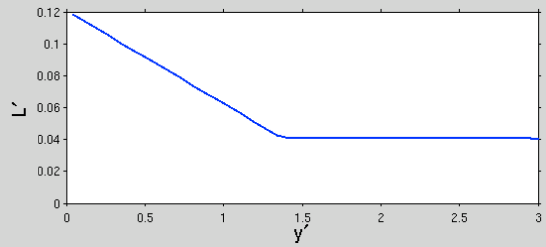
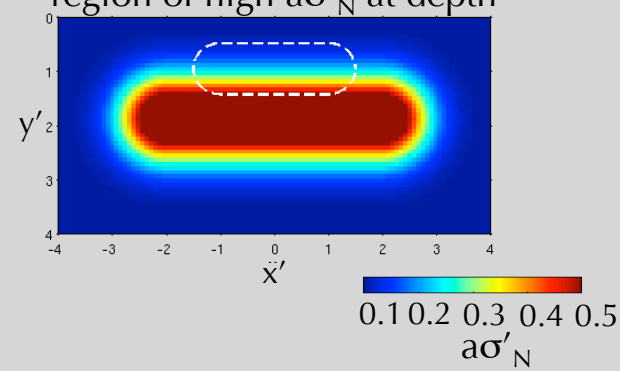
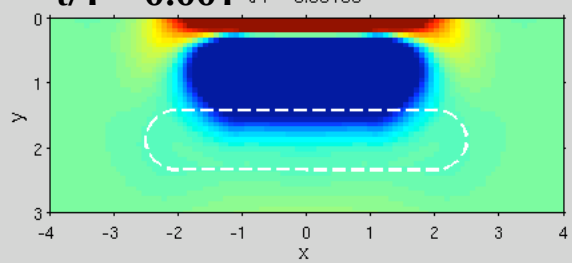


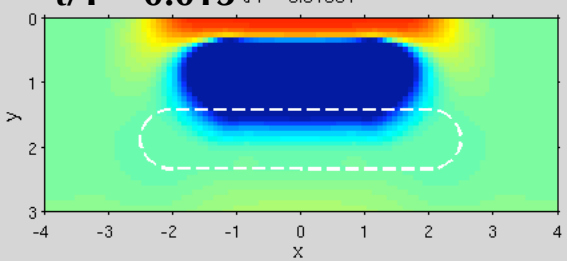
region of high $a\sigma'_N$ at depth

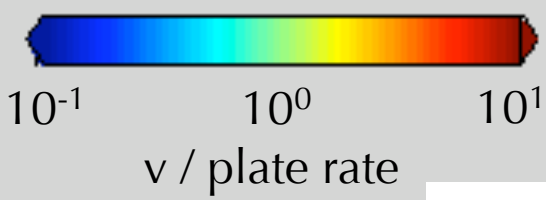


t/T ≈ 0.001 t/T = 0.00108



t/T ≈ 0.013 t/T = 0.01331





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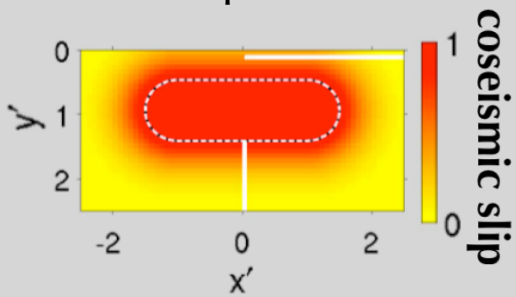
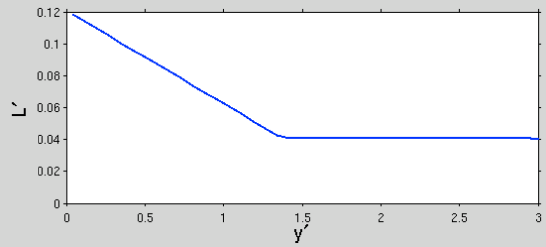
toy megathrust – heterogeneous fault zone → complicated fault creep:

coseismic slip extends to surface

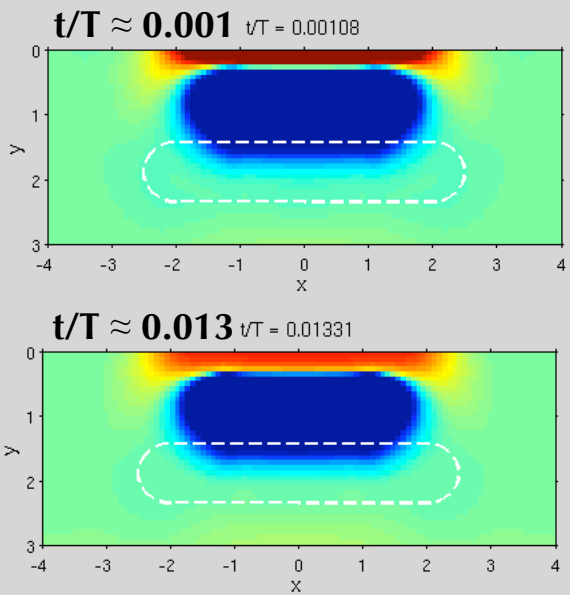


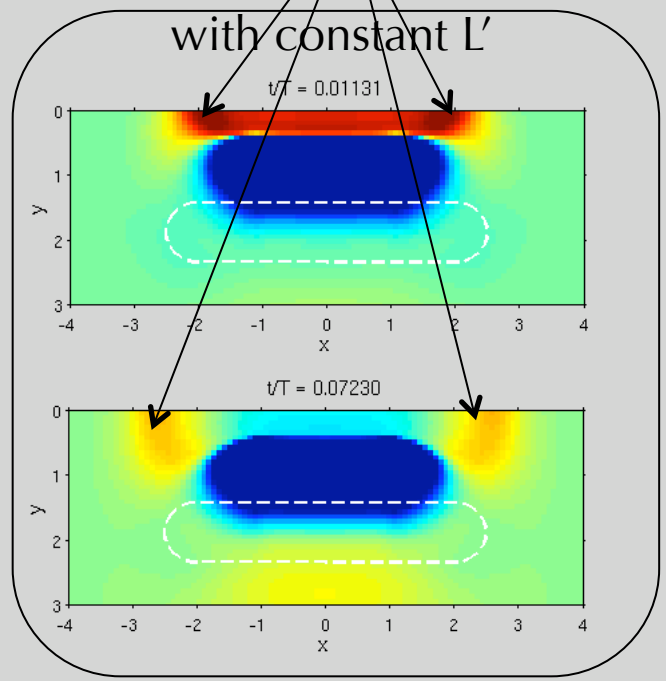
L′ increases by x3 at surface

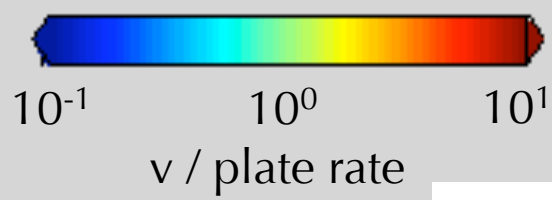


pulses of high creep rates (10x plate rate!) propagate along free surface

with constant L′







$f_o/a = 10$, $b/a = 0.9$, $L_o' = 0.04$, $a\sigma'_N = 0.10$

toy megathrust – heterogeneous fault zone → complicated fault creep:

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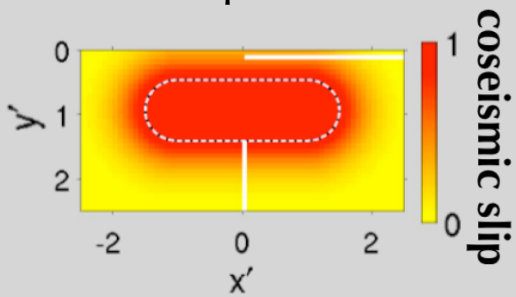
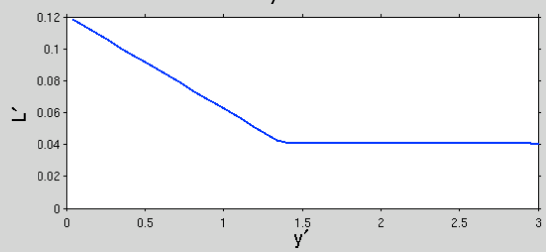
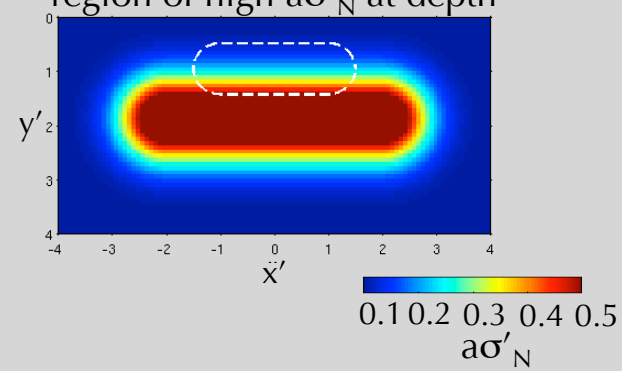


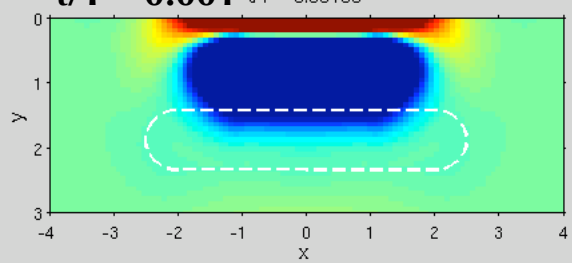
L′ increases by x3 at surface



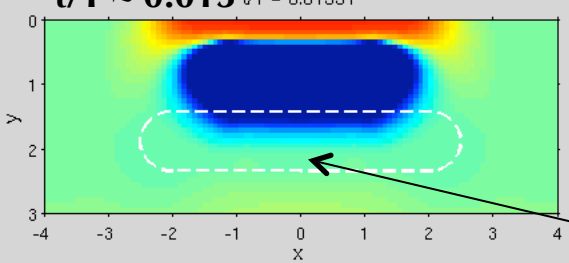
region of high $a\sigma'_N$ at depth



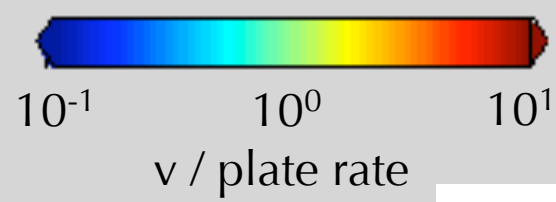
t/T ≈ 0.001 t/T = 0.00108



t/T ≈ 0.013 t/T = 0.01331

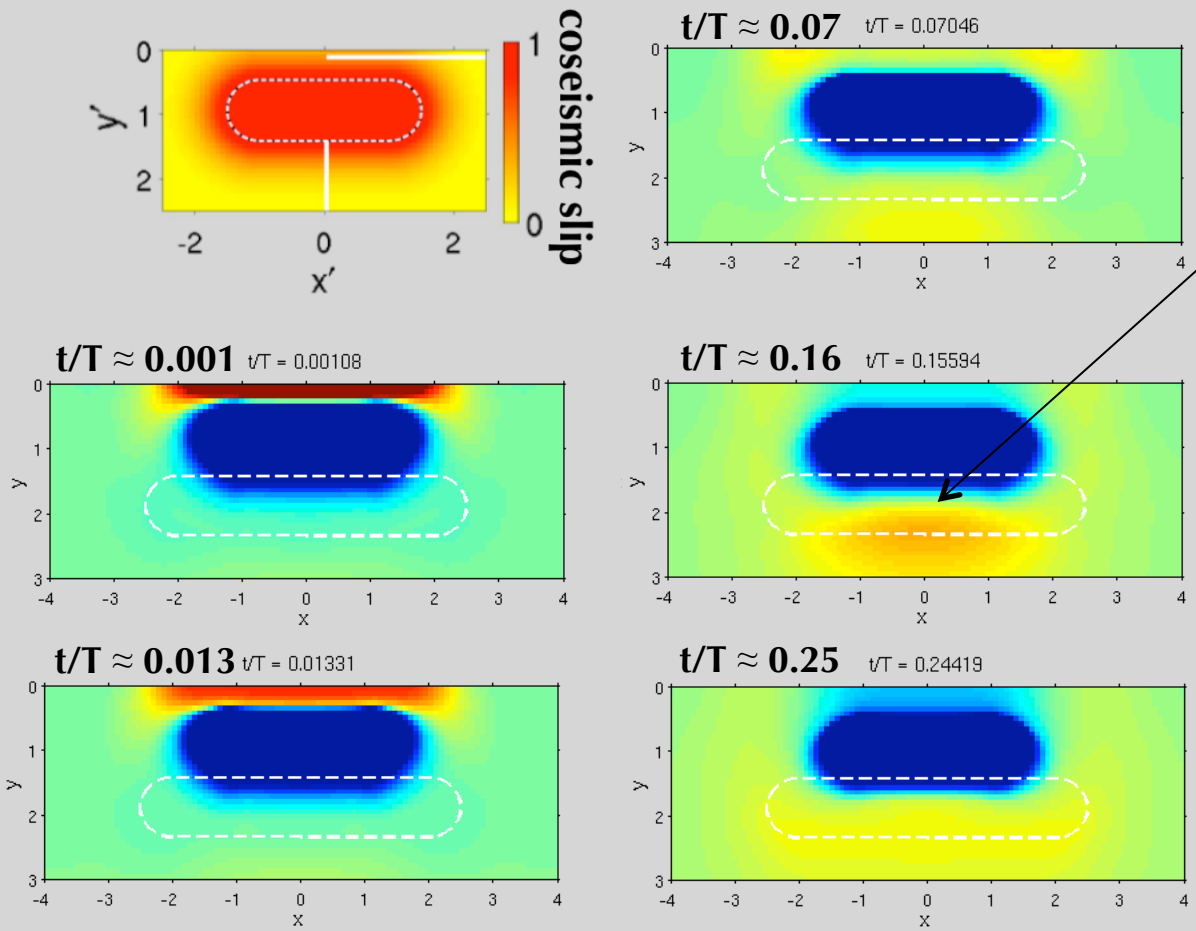


creep rates below plate rate during postseismic period



$f_o/a = 10$, $b/a = 0.9$, $L_o' = 0.04$, $a\sigma'_N = 0.10$

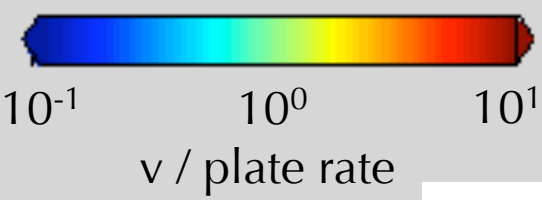
toy megathrust – heterogeneous fault zone → complicated fault creep:



creep rates > plate rate
max at ~16% of cycle
last ~18% of cycle

"clamped" fault eventually creeps

lower L, transient creep is faster, shorter, and earlier



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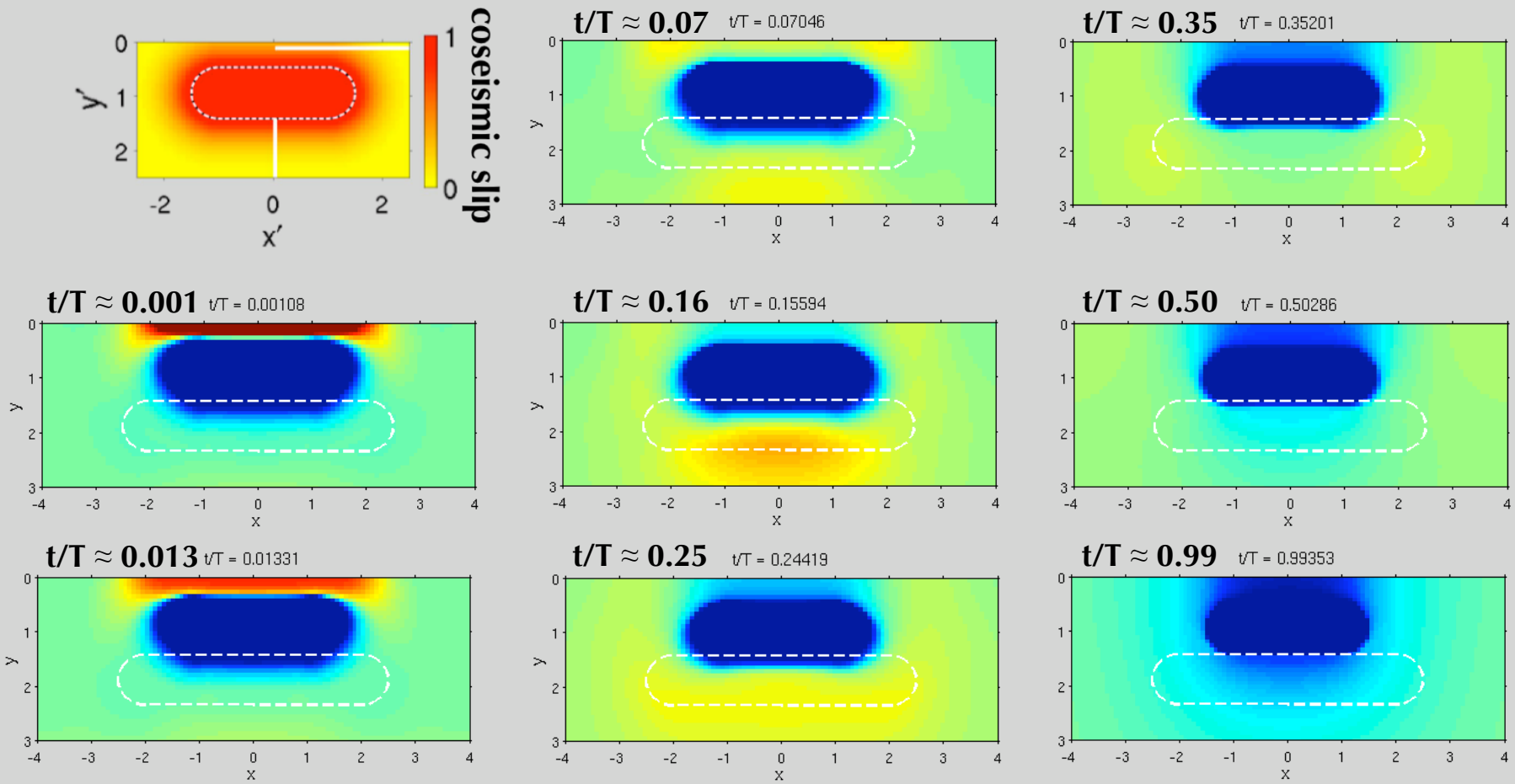
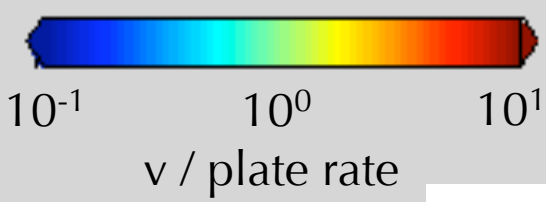
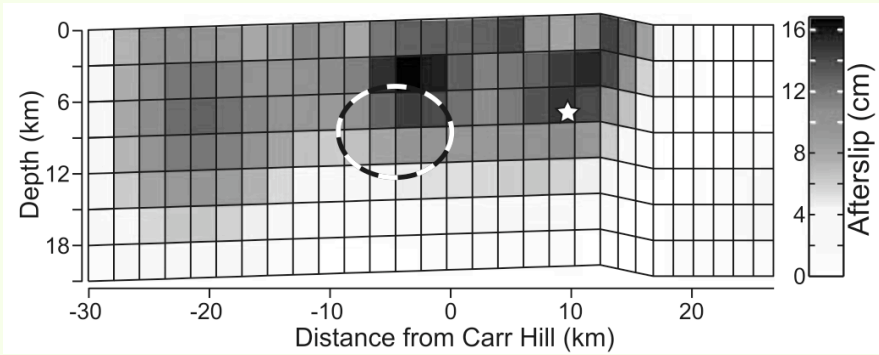


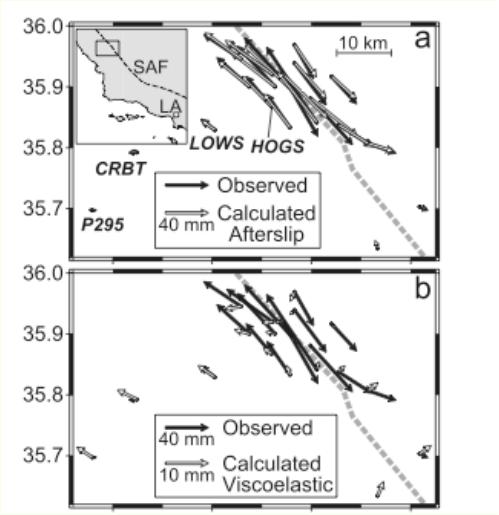


$f_o/a = 10$, $b/a = 0.9$, $L_o' = 0.04$, $a\sigma'_N = 0.10$

"transition" regions:



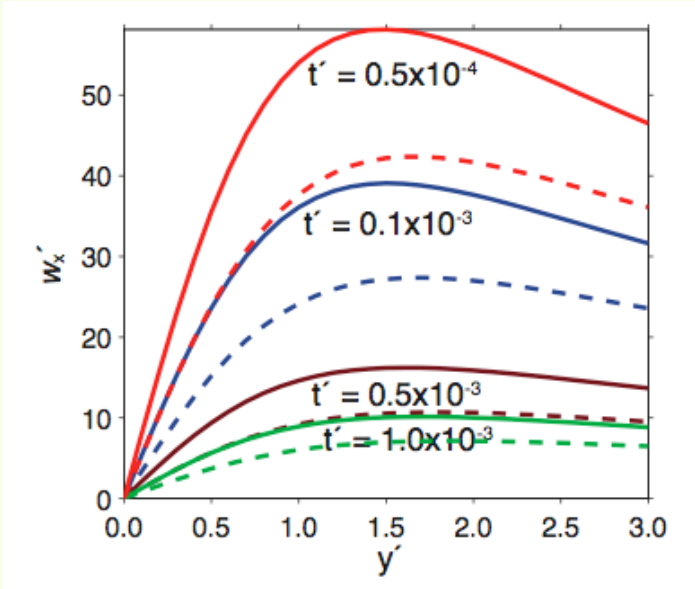
Freed 2007



if coseismic slip & postseimic slip occur on same region of the fault, should consider the coseismic change in frictional state

strike-slip model, coseismic slip tapers to zero over a "transition region at depth ~50% size of the asperity, drop θ to L/v_{coslip} during coseismic slip

postseismic surface velocities



some ending points:

- spin-up is important (spin-up in these models requires assuming ruptures)
  - stresses should be consistent with long-term fault activity
  - locking/directivity constraints should be consistent with long-term fault activity
  - stress-shadows contain information about fault rheology
  - – simultaneous modeling of interseismic and postseismic geodetic observations can constrain plausible fault zone rheologies
- fault domain size is important – pervasive creep late in cycle due to BC stresses when driving slip too close
- at low L (D_c)
  - postseismic creep pulse sharp onset
  - RD friction ≈ RS friction except for immediate postseismic (e.g., Johnson et al., 2006; Perfettini and Ampuero, 2008)
- delayed postseismic creep at low L and increased $\alpha = a\sigma_E$

more to think about:

- "geodetically motivated" full seismic cycle model:
  - need high resolution (space&time) during coseismic slip
  - need lower resolution (space&time) during interseismic slip, but BC's farther away
  - matching calculations to known earthquakes requires solving for many unknowns simultaneously
- BC's relatively simple in these models, is local loading ("back-slip") sufficient for interseismic stress-driven creep?
- shear-zones in lower crust may have finite thickness
- faults/shear-zones may "seed" into zone of distributed creep at lower crust/upper mantle depths
- grain-size-dependent ductile creep may be appropriate for shear-zones at depth (Montési and Hirth, 2003)

CFEM: Crustal Finite Element Modeling