Slow and Fast Slip Dynamics due to Fault and Fracture Networks

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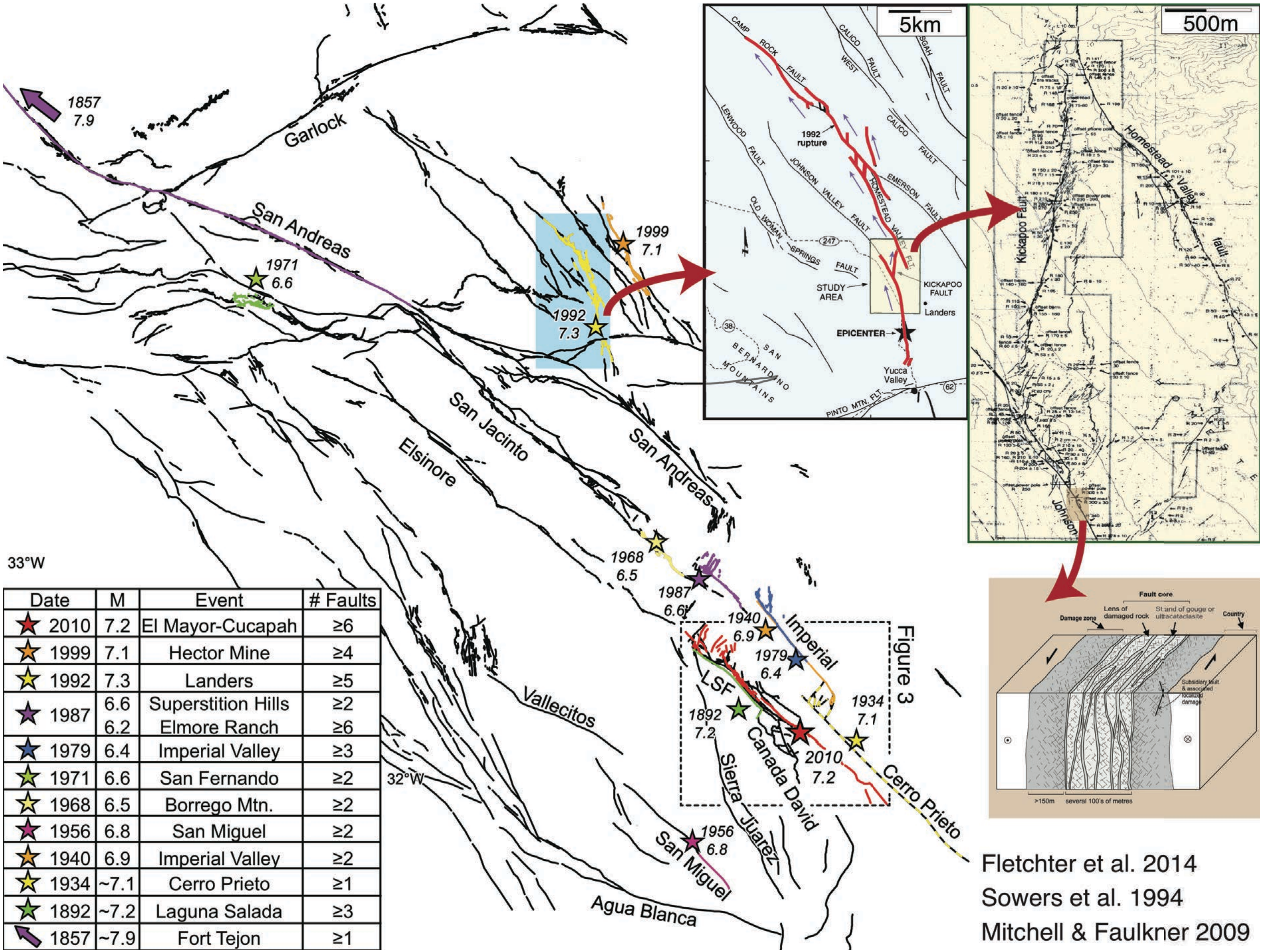
Complex fault and crack networks at all scales



Date	M	Event	# Faults
2010	7.2	El Mayor-Cucapah	≥6
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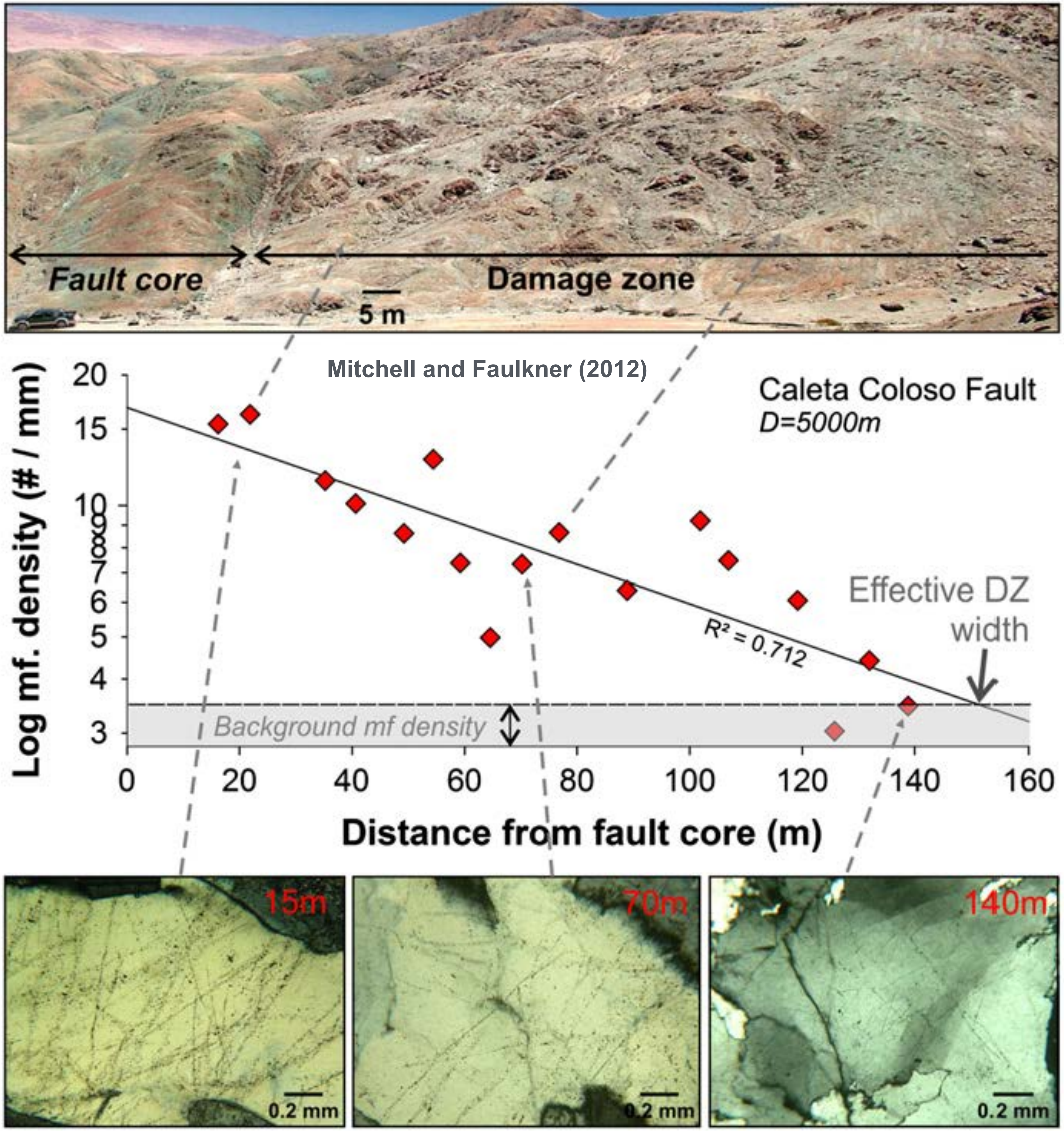
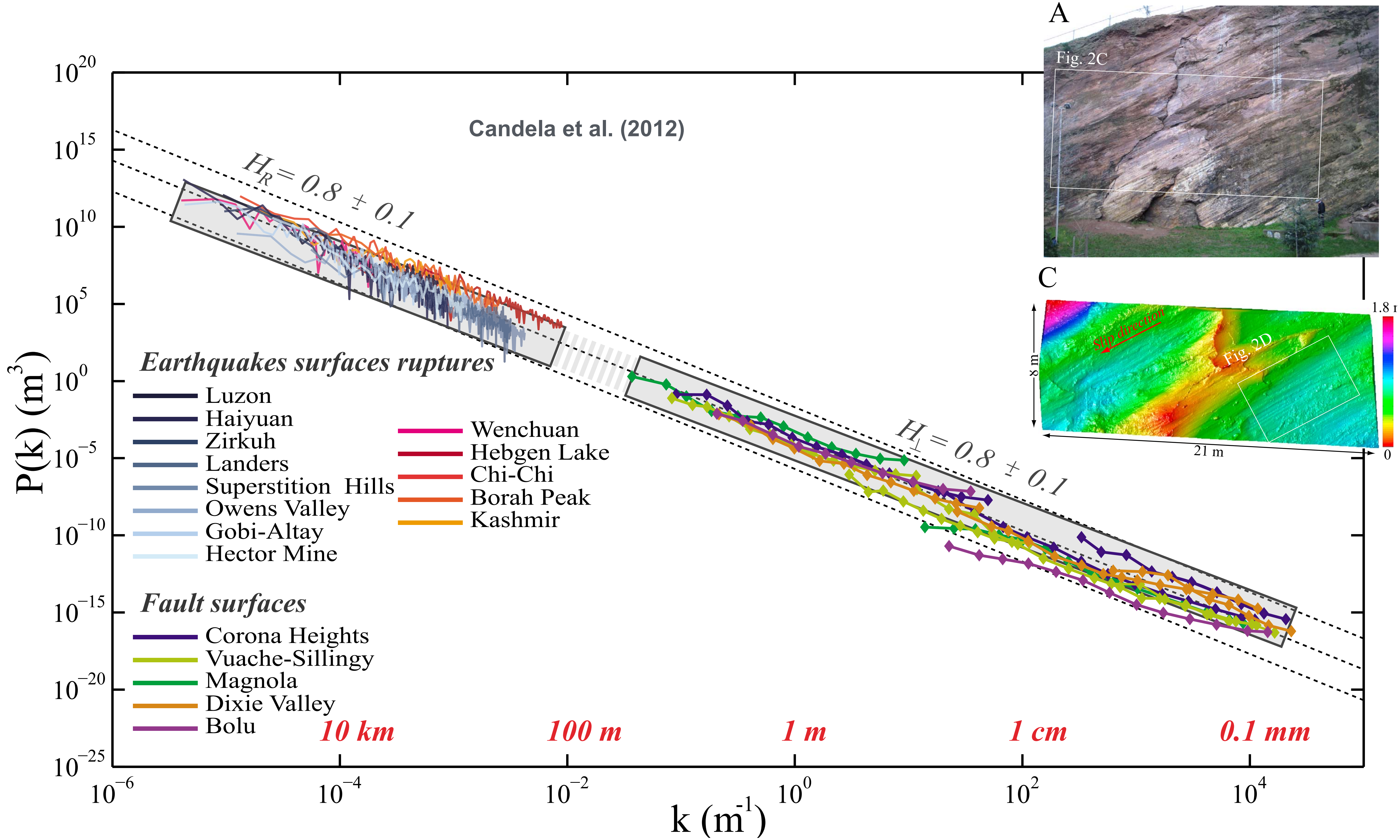
Fletchter et al. 2014
Sowers et al. 1994
Mitchell & Faulkner 2009



Fault core
Damage zone
5 m
Mitchell and Faulkner (2012)
Caleta Coloso Fault
D=5000m
Log mf. density (# / mm)
20
15
10
9
8
7
6
5
4
3
R² = 0.712
Effective DZ width
Background mf density
0
20
40
60
80
100
120
140
160
Distance from fault core (m)
15m
70m
140m
0.2 mm
0.2 mm
0.2 mm

And they are 'rough'



Complex Slip Dynamics

SSE : Nankai (Araki et al 2017)
Hikurangi (Wallace et al. 2017)

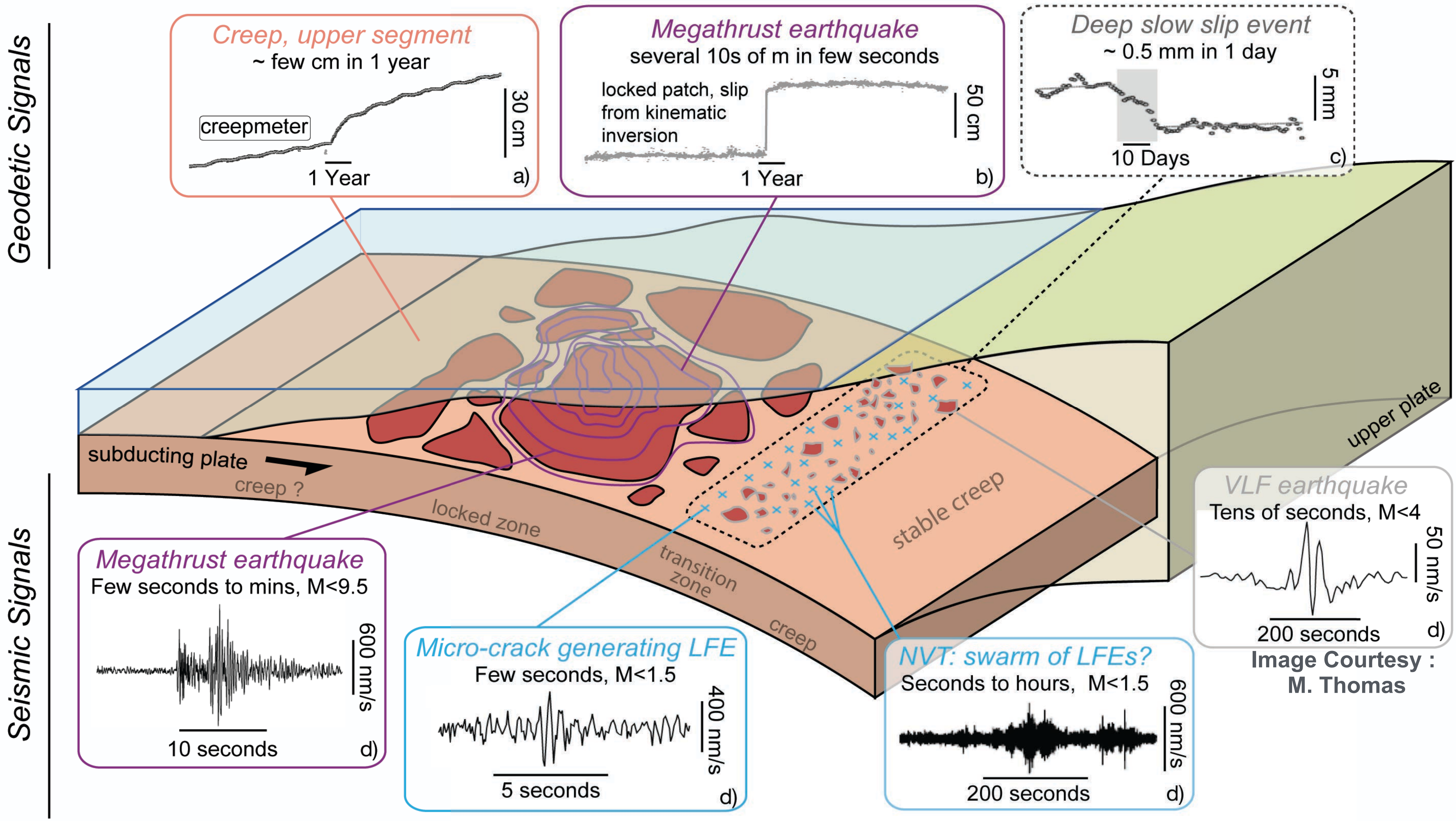


Image Courtesy : M. Thomas

What mechanical models exist that explain these range of slip dynamics?

Two Broad Themes

- **How do complex fault networks interact over long time scales (multiple seismic cycles)?**

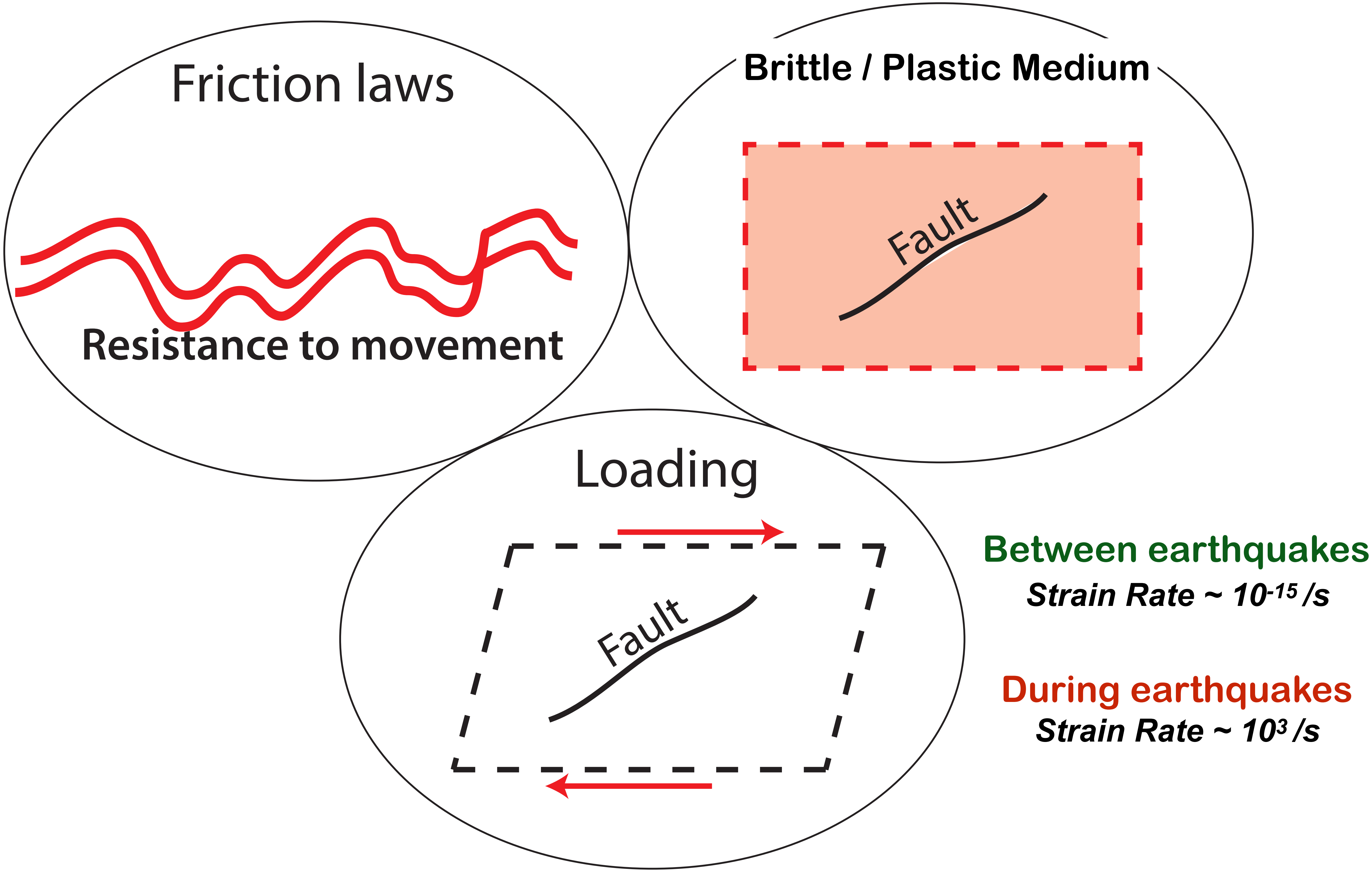
- **How do complex fault and off-fault fracture networks interact during an earthquake rupture** *(using homogenisation and explicit modelling of off-fault fracture networks)***?**

Missing ingredients (in this talk) :

Mechanical/Rheological Complexity
Hydrological Structure

Chemical & Mineralogical Complexity
Thermal Constraints
Far-field loading complexity

Broad ingredients in seismic cycle models

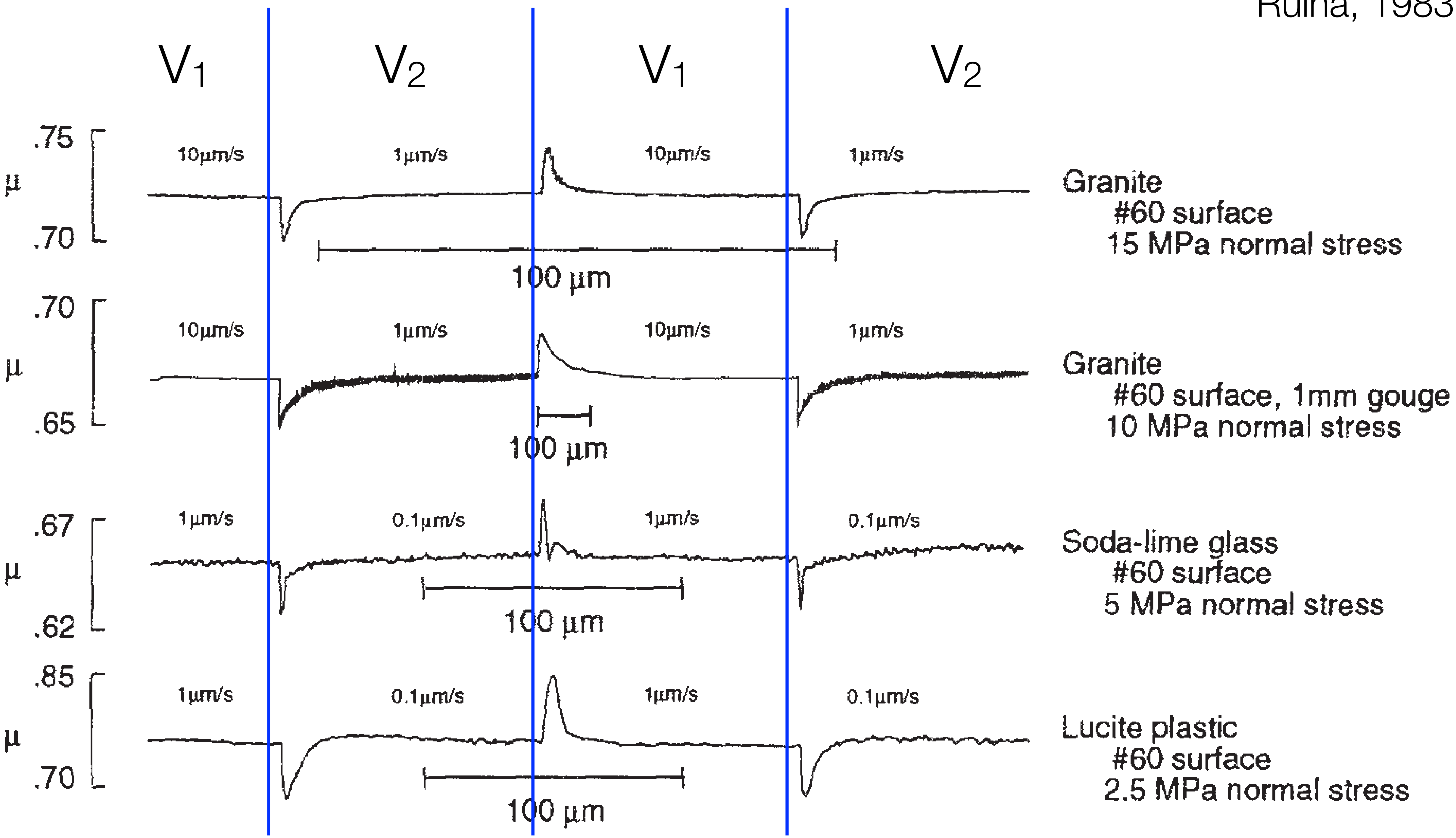


$$\boxed{\tau^{f}(s) = \tau_t^{el}(s) + \tau^{load}(s) + \tau^{rad}(s)}$$

Rate and state friction law

Experiment

Dieterich, 1979
Ruina, 1983



$V_1 > V_2$

From Dieterich and Kilgore 1994

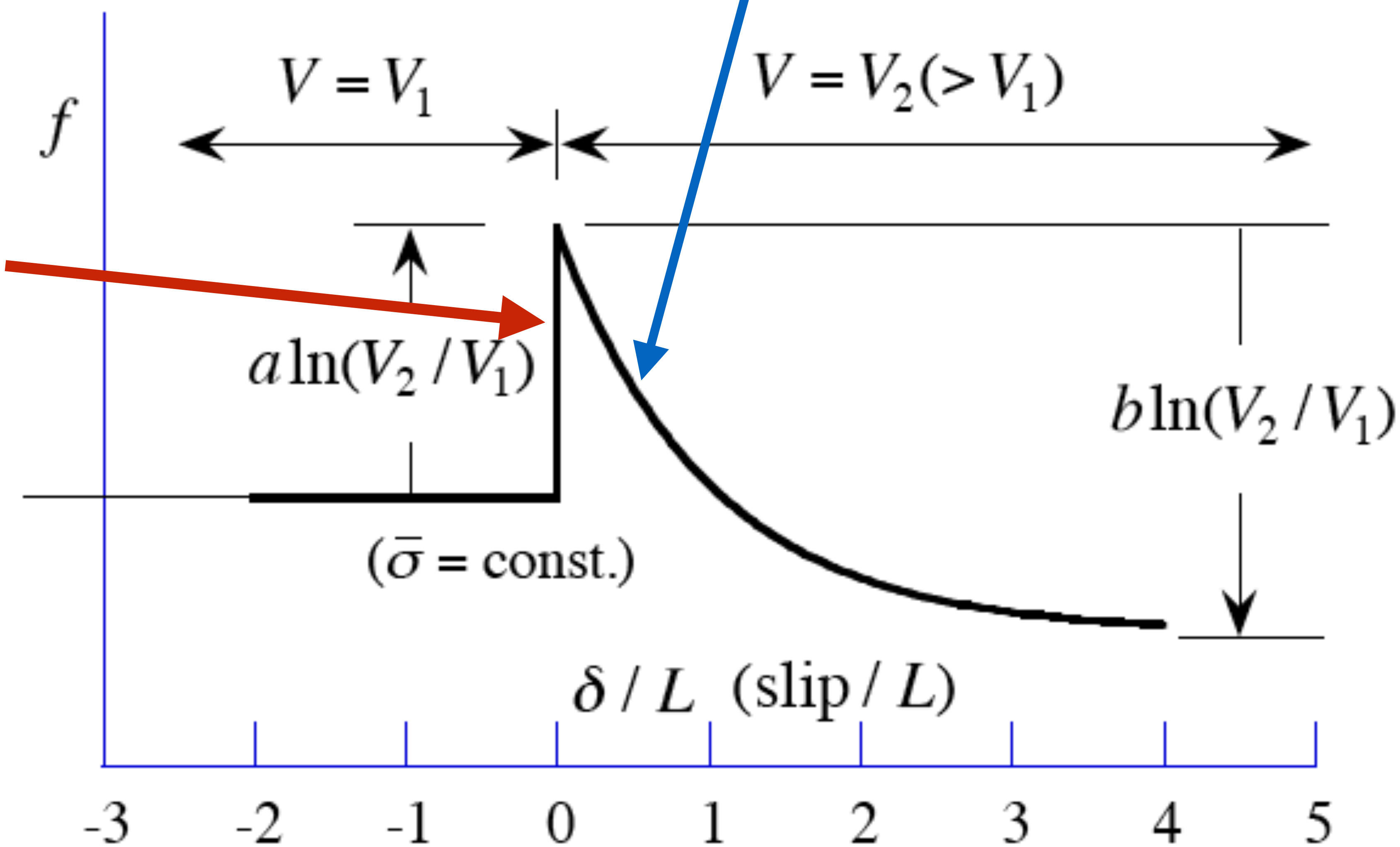
Rate and state friction law

Dieterich, 1979

Ruina, 1983

No change in contact shear rate but old, hence strong, contacts are slid out of existence and replaced with shorter-lived, hence weaker, ones.
State-dependence

No change in contact population, but they resist more because they are sheared faster.
Rate-dependence



a/b > 1 : rate strengthening ; 0 < a/b < 1 : rate weakening

✦ **Allows for restrengthening of the fault**

V_{slip} V_{rupt} V_{slip} V_{rupt}
Seismic (m/s & km/s) and Aseismic (µm/s & km/day) transients with R&S friction on planar faults

- Spatially heterogeneous a/b
- Newtonian viscous rheology + asperities
- Periodic normal stress perturbations →"Aseismic" Stick Slip
- Static stress perturbations from neighbouring faults
- 'Tuning' fault length : Failed nucleation
- Trade-off between dilatant strengthening/thermal pressurisation

Perfettini et al. [2001], Liu and Rice [2005], Liu and Rice [2007], Rubin [2008],
Segall and Rice [1995], Segall et al. [2010], Segall and Bradley [2012], Ando et al. [2012] and many others.

However….

Real world

- Complex fault network
- Non planar geometry of faults
- Interaction between faults
- Diversity of observed signals

Dominant modelling philosophy

- Single planar fault
- Linear elastic rheology
- Complexities coming from rheological variations

Complexities of the medium

=

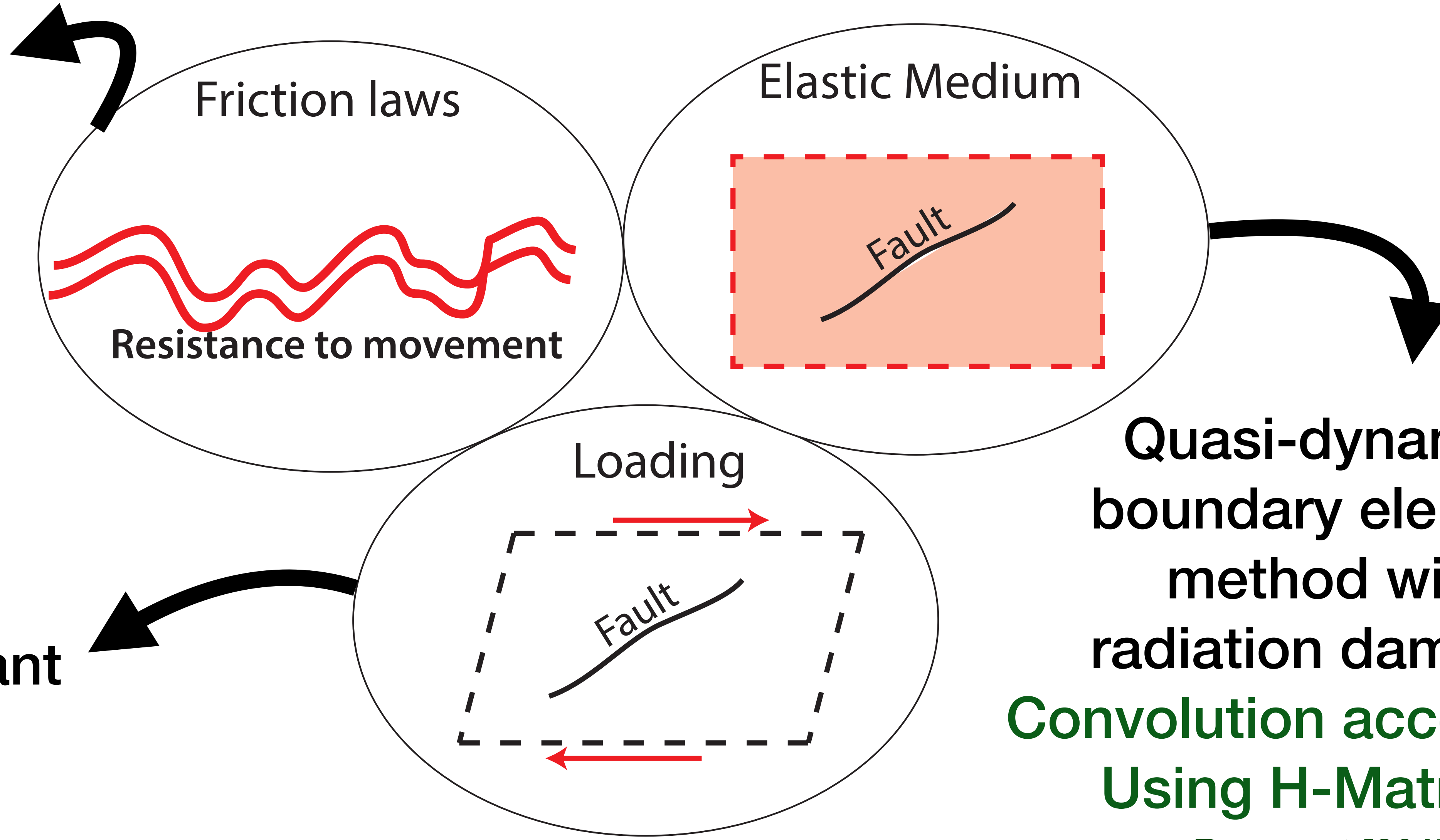
Resistance

✦**Can geometry control the observed complexity of the seismic cycle?**

(Fast) Seismic cycle models

Rate and state friction
Ageing state evolution

$$\tau_f = \sigma_n \left(f_0 + a \log\left(\frac{V}{V_0}\right) + b \log\left(\frac{V_0\theta}{D_c}\right)\right) \qquad \dot{\theta} = 1 - \frac{\theta V}{D_c}$$



Quasi-dynamic: boundary element method with radiation damping
Convolution accelerated Using H-Matrices
Romanet [2017]

Global constant stress rate

$$\boxed{\tau^f(s) = \tau_t^{el}(s) + \tau^{load}(s) + \tau^{rad}(s)}$$

Single rate weakening fault

$$L/L_{nuc} = 2$$

Dynamic instability when
L > $L_{nuc}(a/b)$

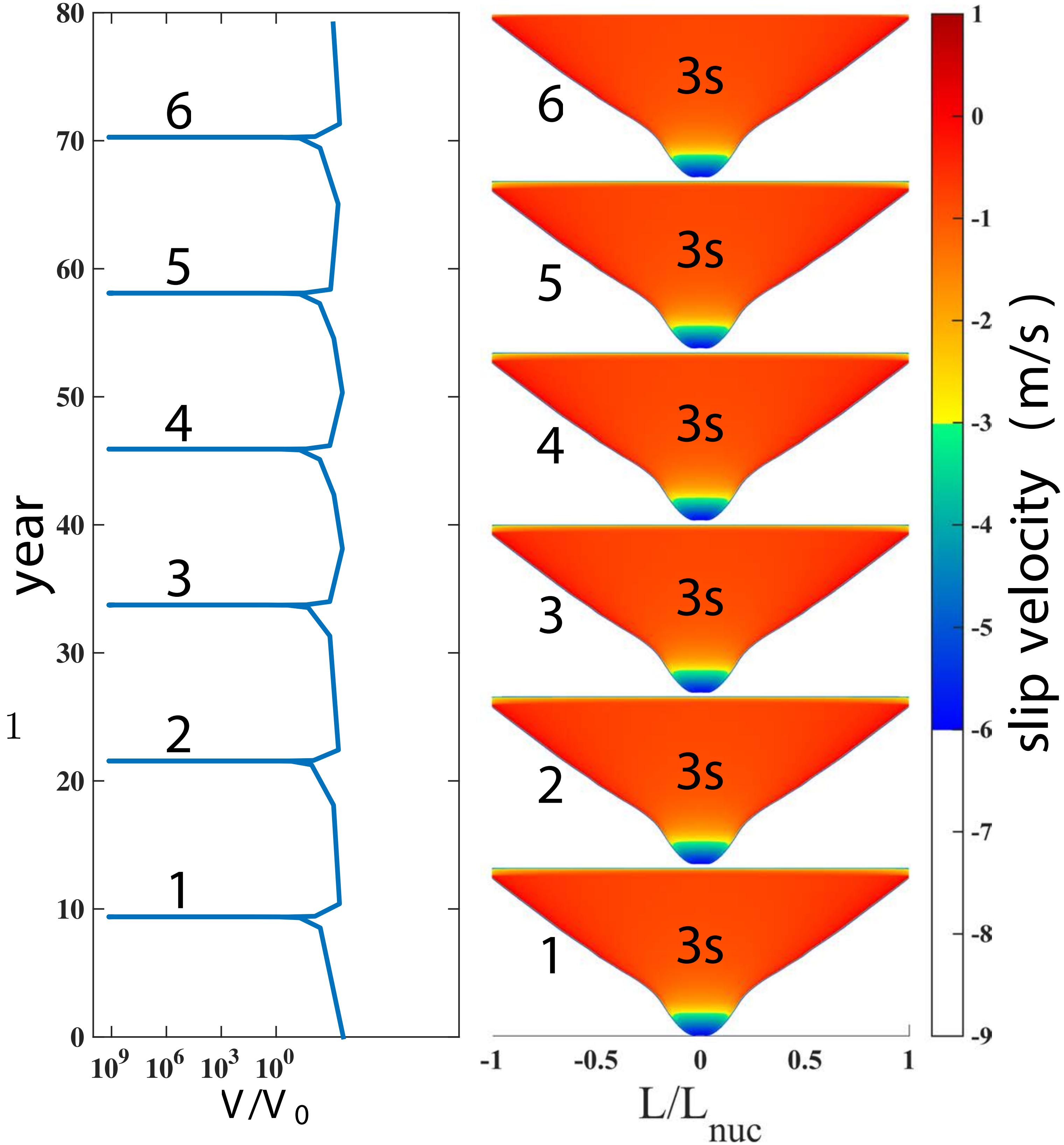
$$L_{nuc} = 2 \times 1.3774 \, \frac{\mu D_c}{\sigma_n b} \quad ; \quad 0 < a/b < 0.3781$$

$$L_{nuc} = 2 \times 1.3774 \, \frac{\mu D_c}{\pi \sigma_n b (1 - a/b)^2} \quad ; \quad a/b \to 1$$

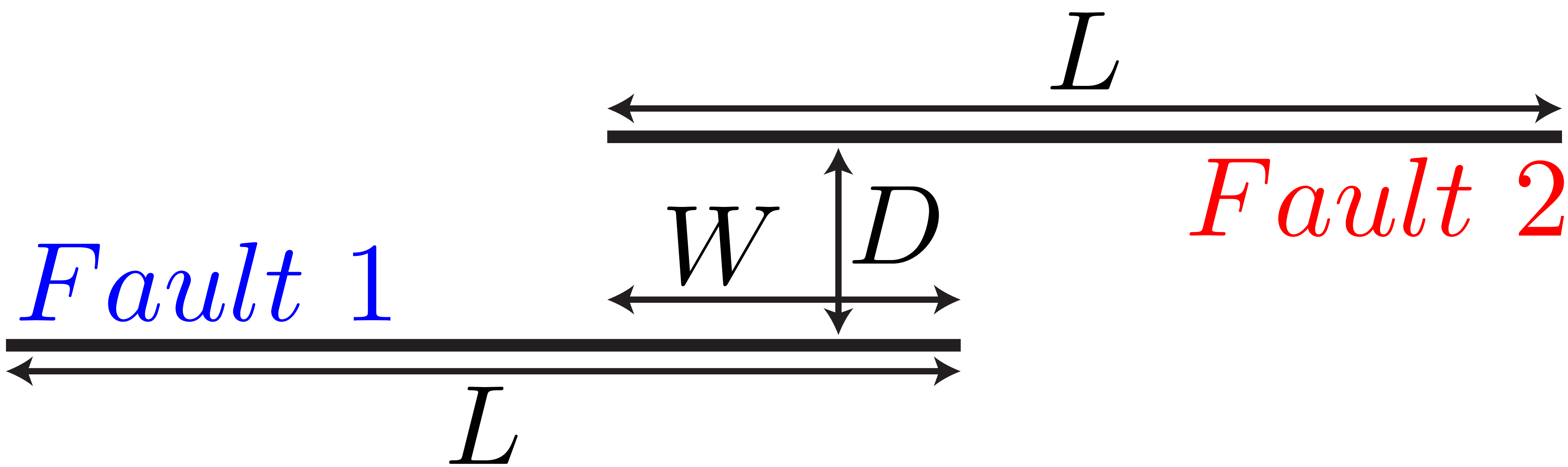
Rubin and Ampuero [2005] and Viesca [2016 a, b]

1- Periodic events
2- Only dynamic events

a/b=0.9 mildly rate weakening



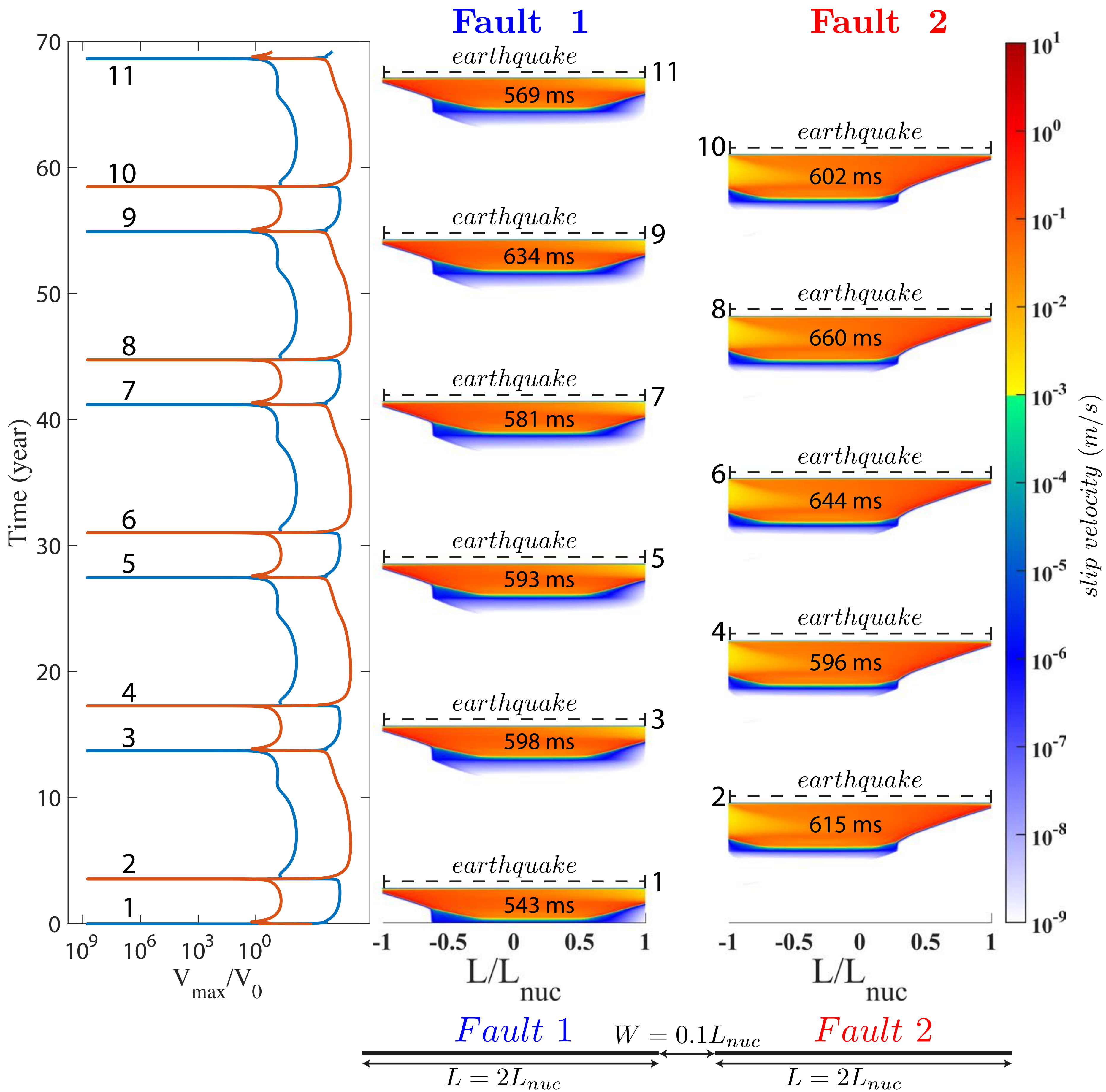
Simplest "Conceptual" Model of Fault Geometric Complexity



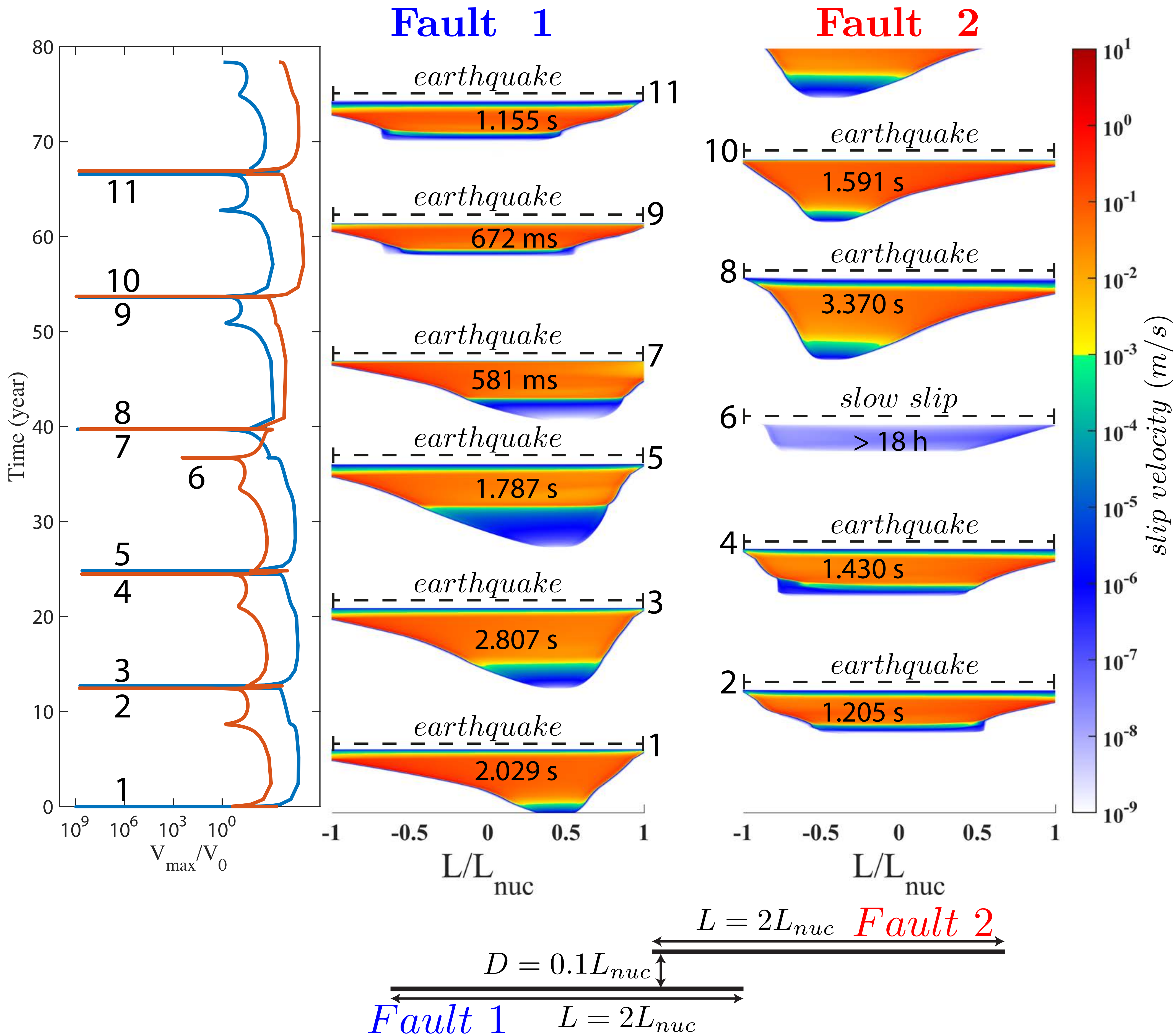
- Non-Dimensionalise length scales by $L_{nuc}(a/b)$
- Keep **loading rate constant**
- Keep ***a/b* constant and rate-weakening** ($0<a/b<1$)
- Anti-plane sense of motion⇒ **No normal traction change**

Do spontaneously emerging "stress" heterogeneities produce slow and fast dynamics?

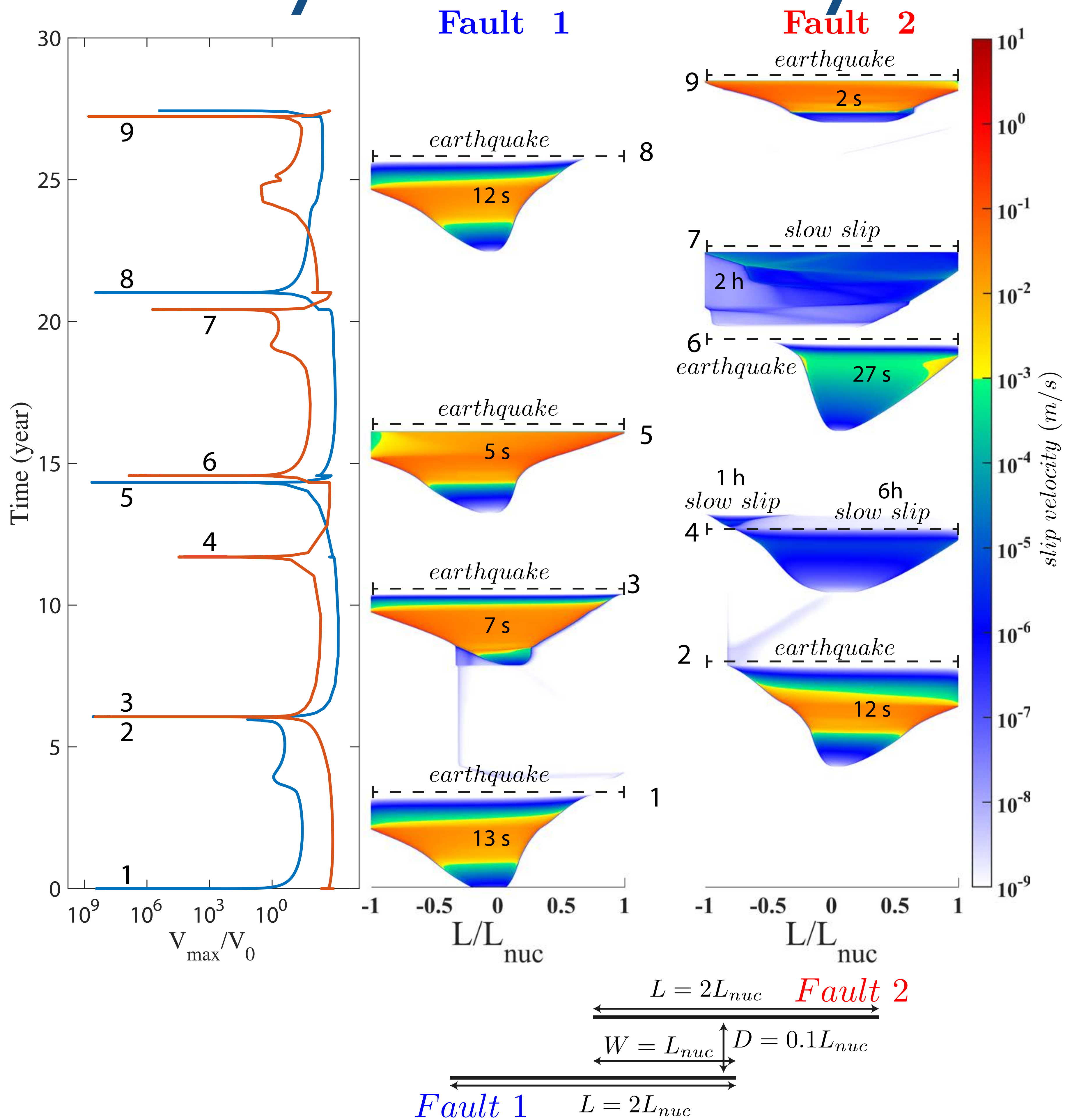
Geometry induced fault dynamics



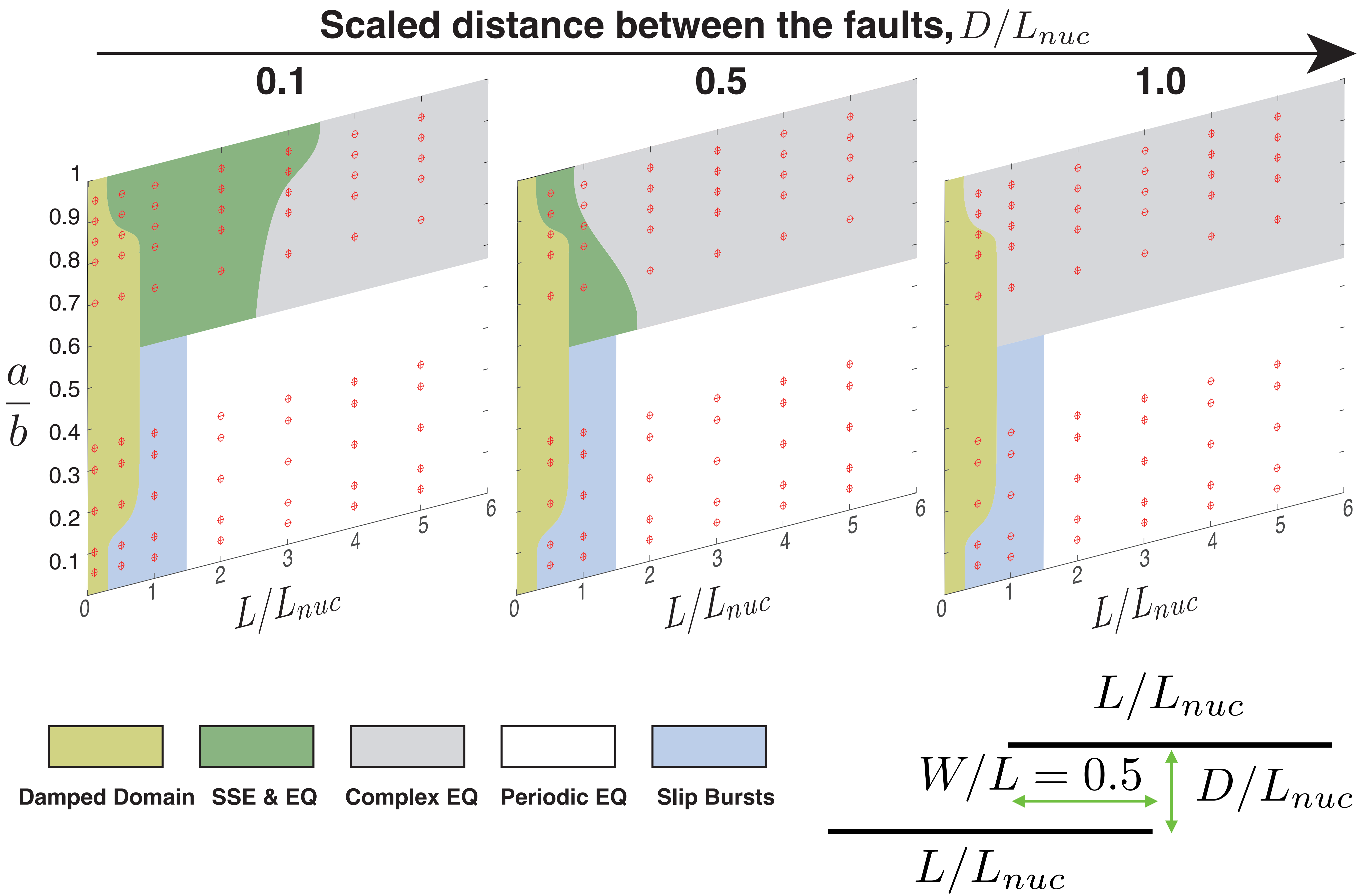
Geometry induced fault dynamics



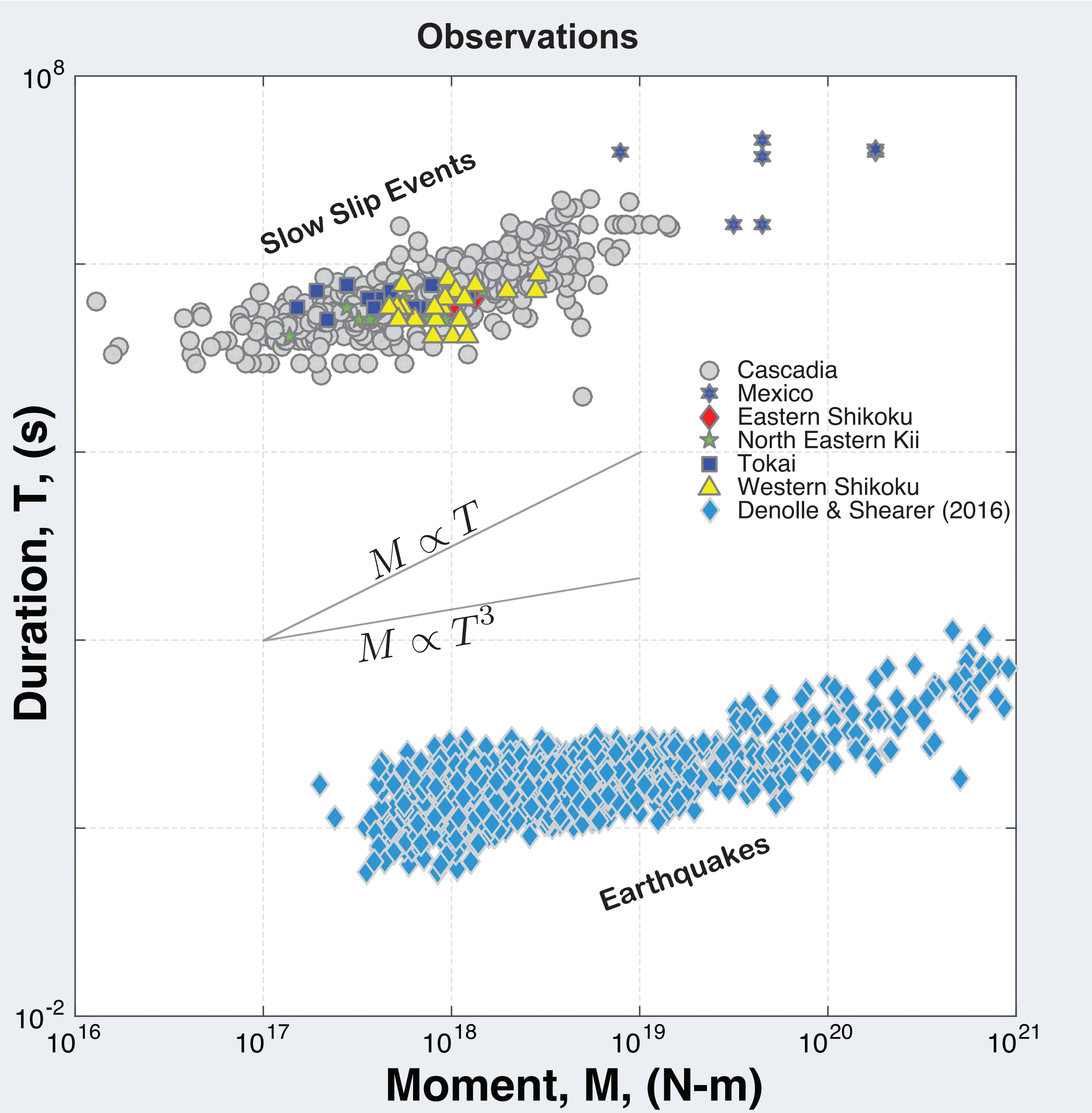
Geometry induced fault dynamics



‘Phase Diagram’ (for fixed overlap distance)



Can we reproduce the observed scaling laws?



$$M_0 \propto T$$

Slow events

$$M_0 \propto T^3$$

Classic 3D earthquakes

$$M_0 \propto T^2$$

Classic 2D earthquakes

Ide et al., 2007
Gomberg et al., 2016

Sekine et al., 2010
Gao et al., 2012
Denolle and Shearer, 2016

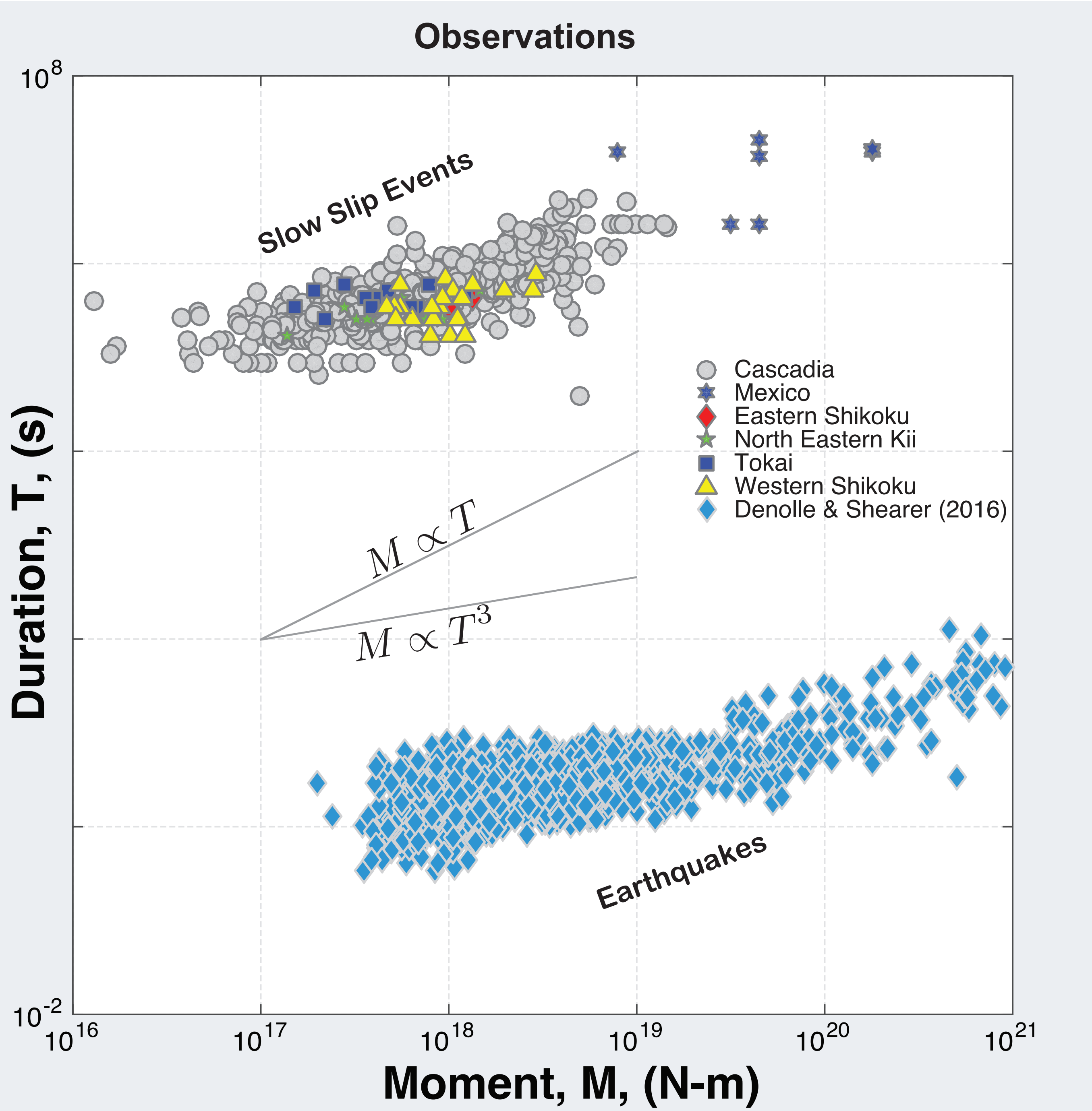
Slow events

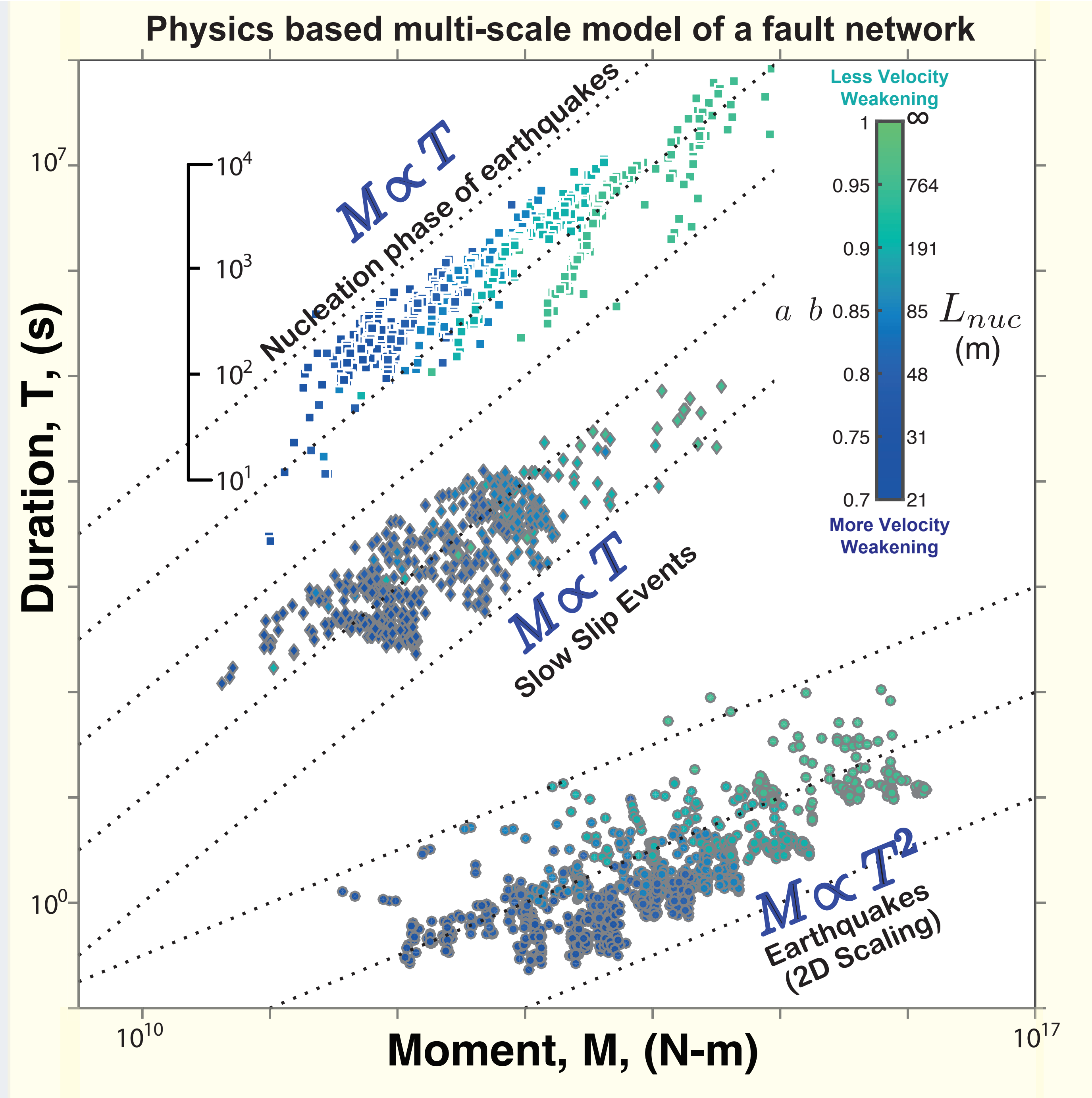
Rupture Velocity < $0.01 V_s$ &
1μm/s < Slip Velocity < 1mm/s

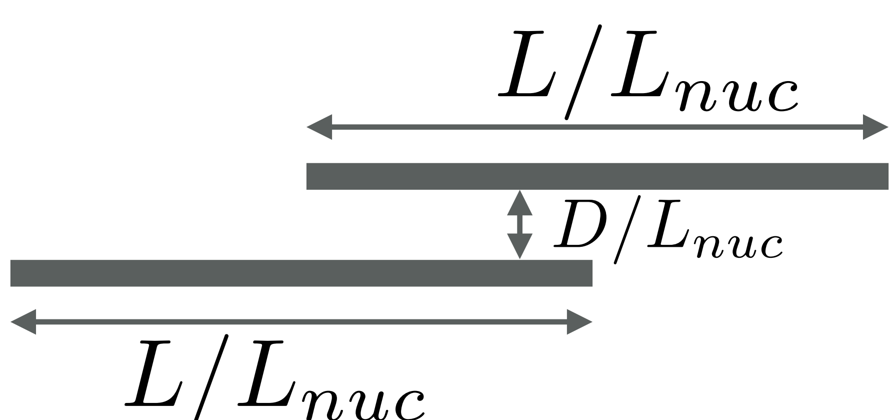
Earthquakes

Rupture Velocity > $0.01 V_s$ &
Slip Velocity >1mm/s

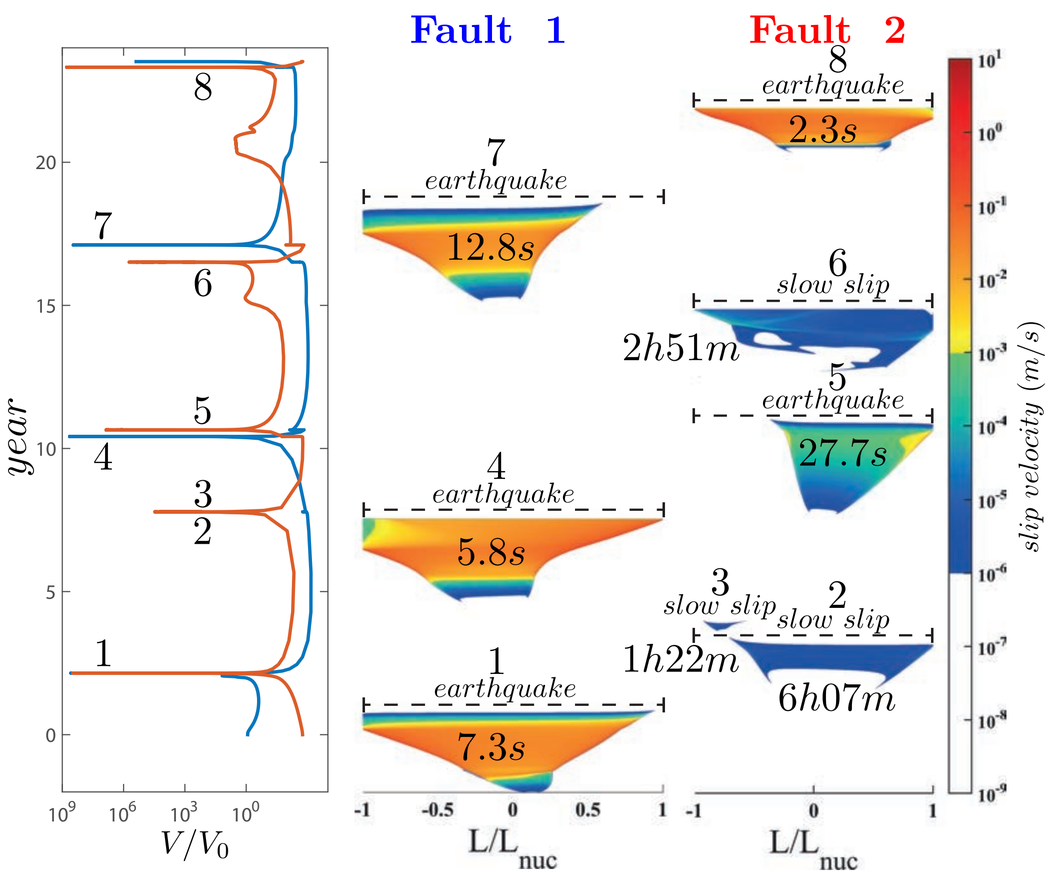
Can we reproduce the observed scaling laws?





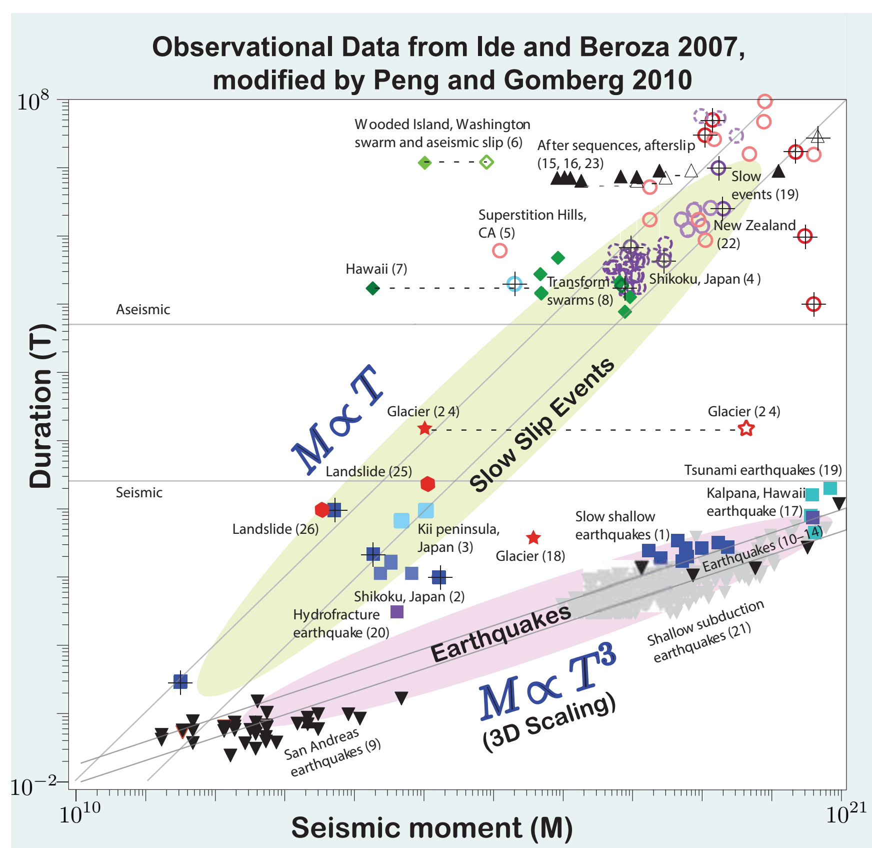


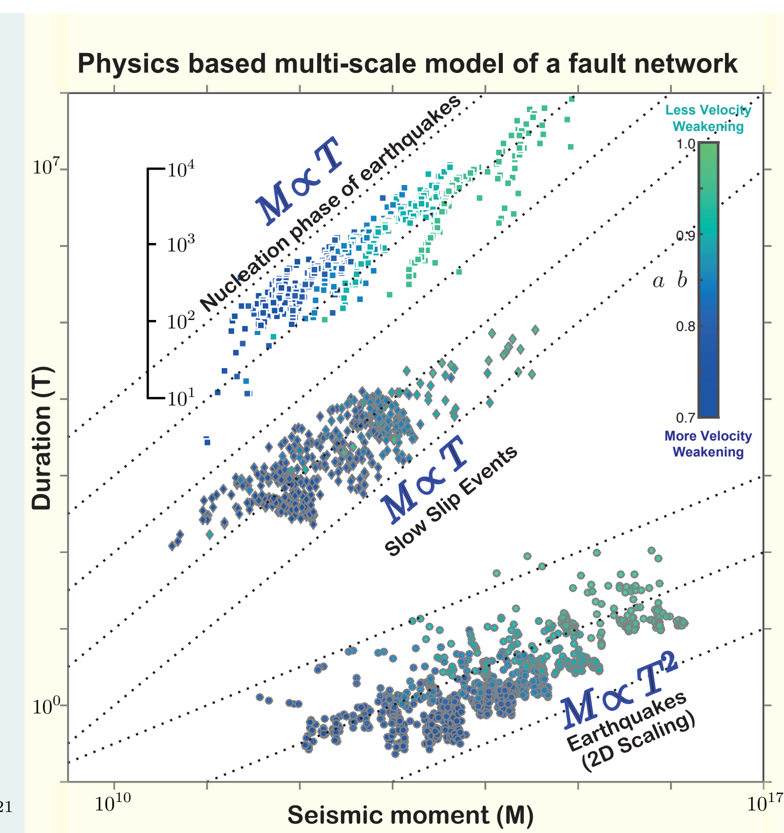
Conclusion



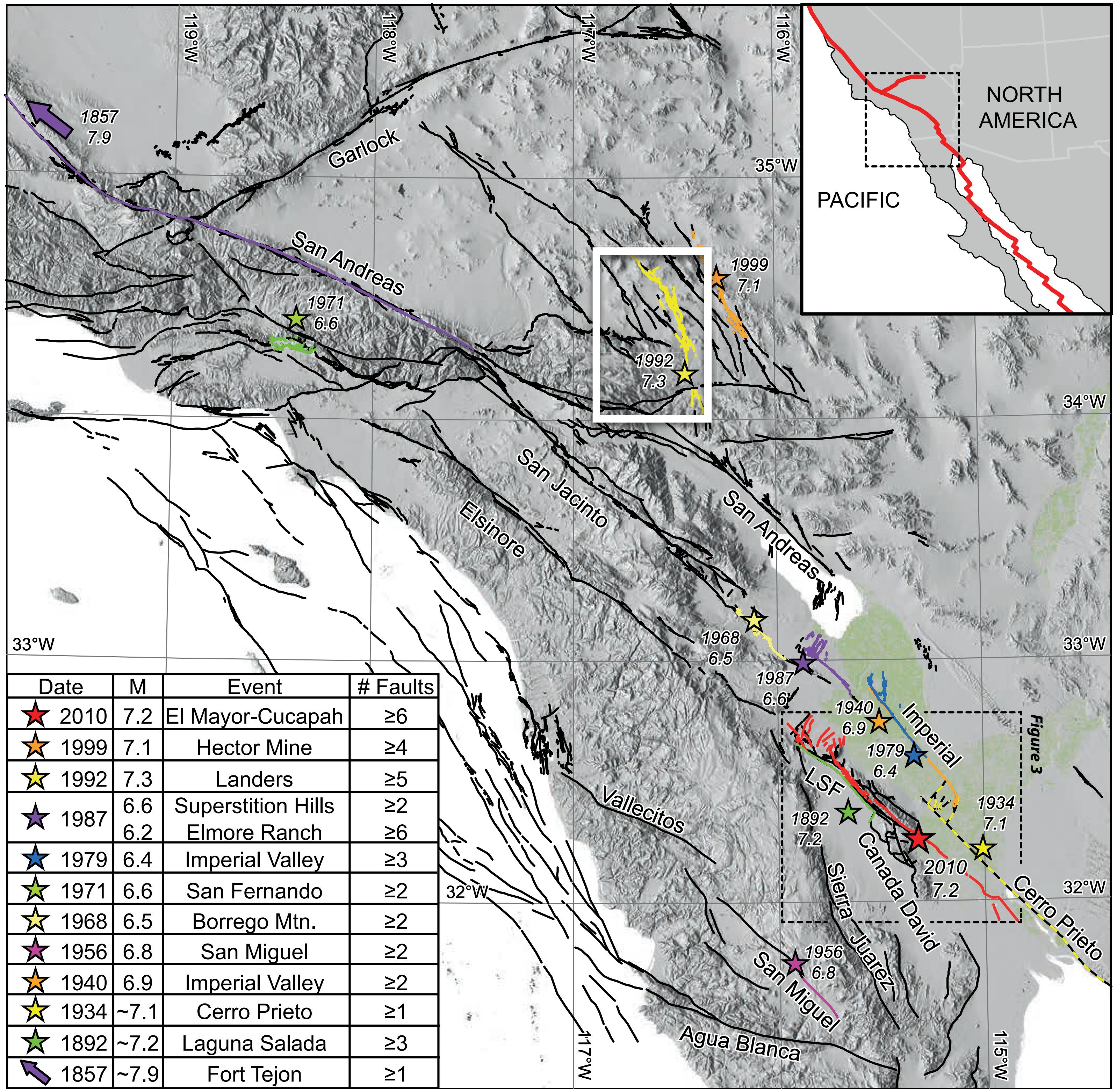
Most basic geometrical fault complexity can give rise to both slow and fast dynamics on purely rate weakening faults

Scaling laws arise from simple fault networks in rate and state framework





A real world application



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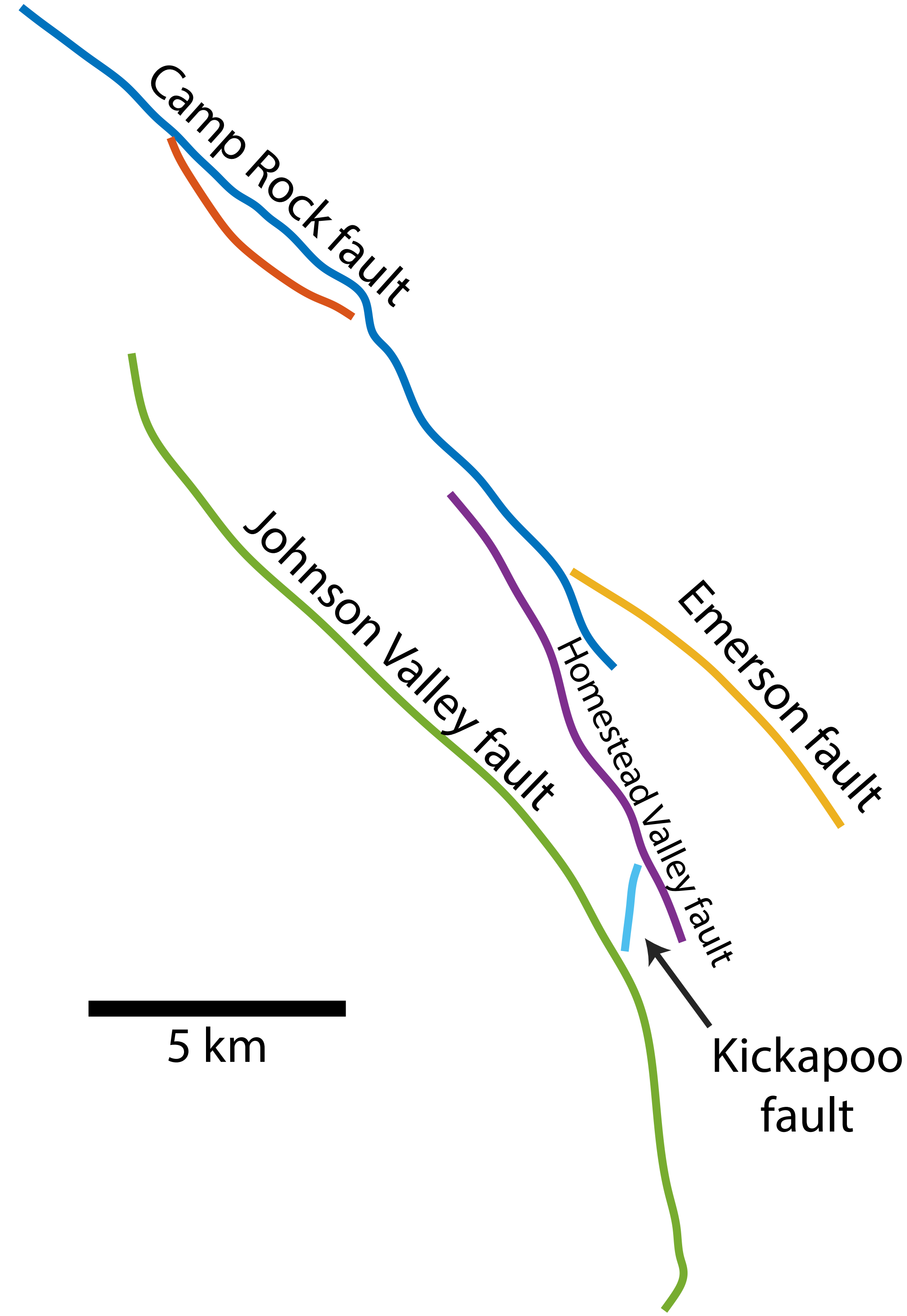
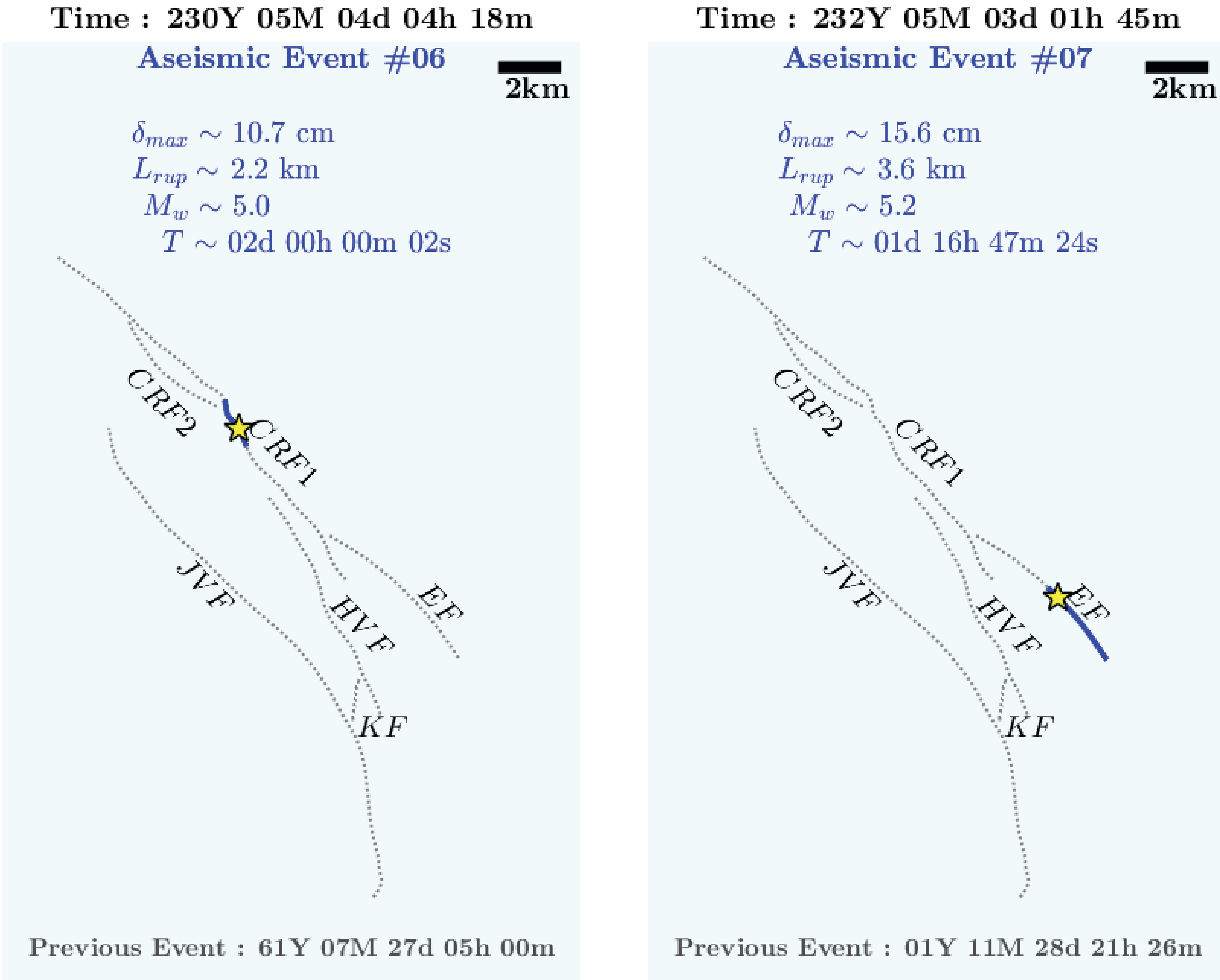
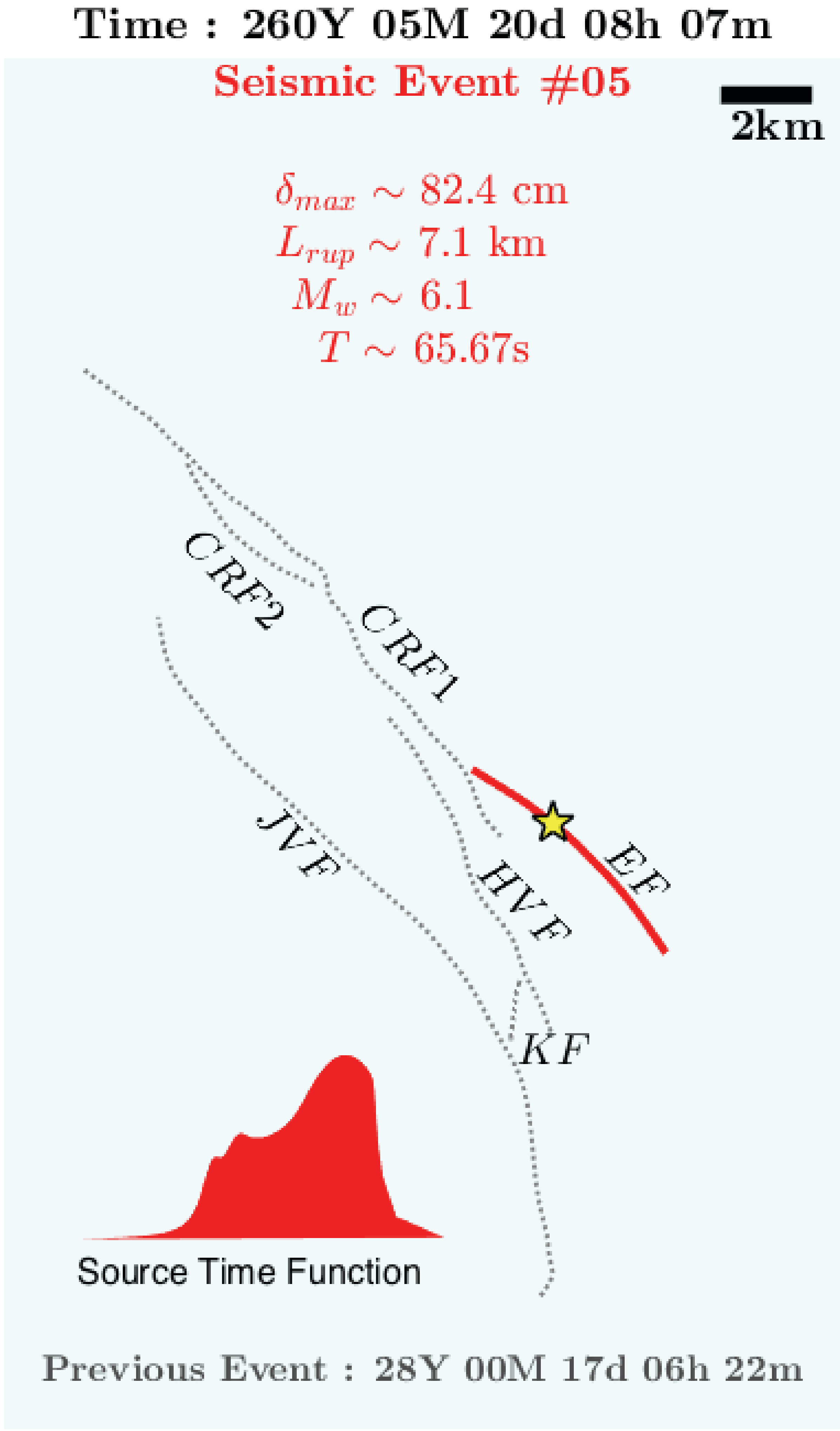
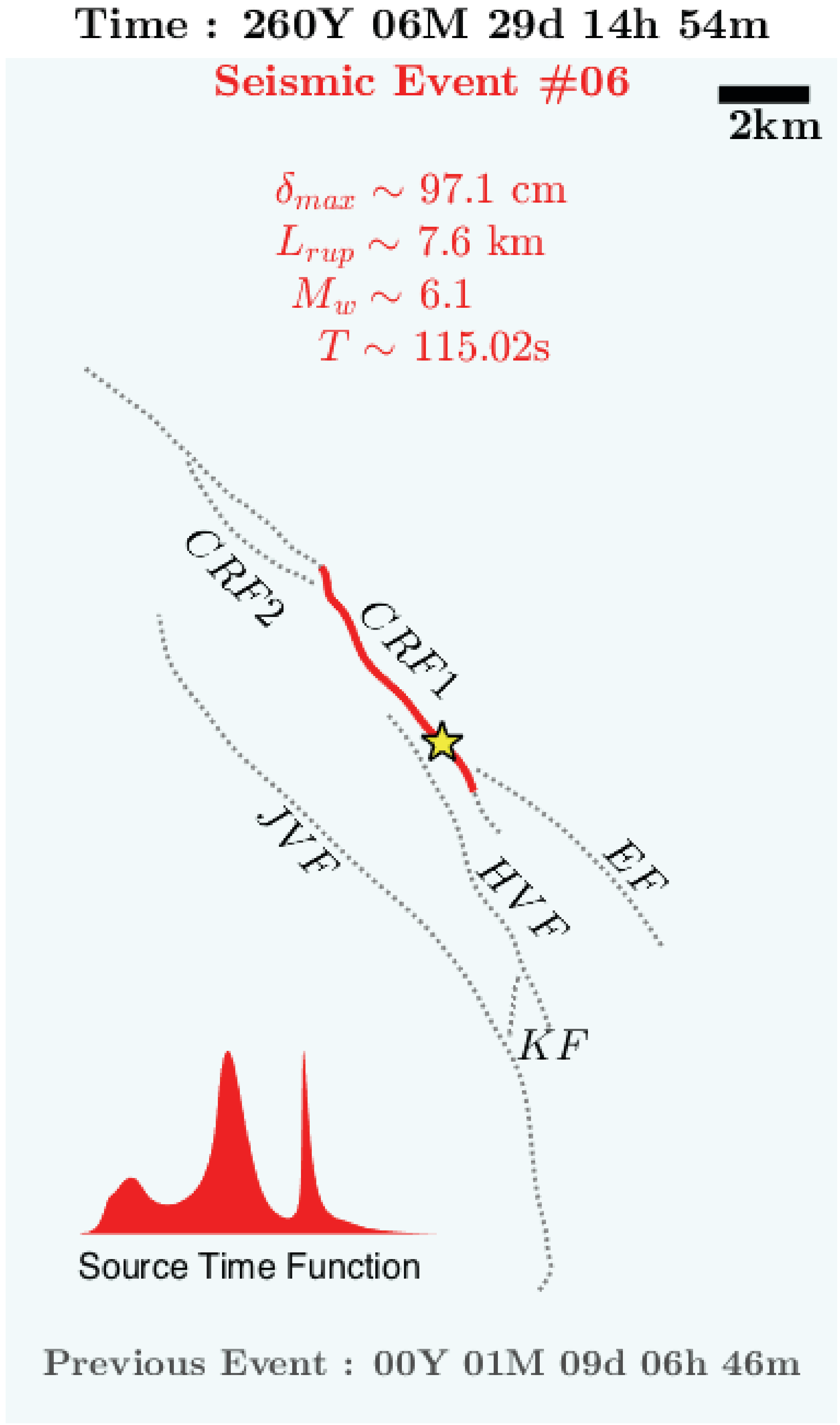


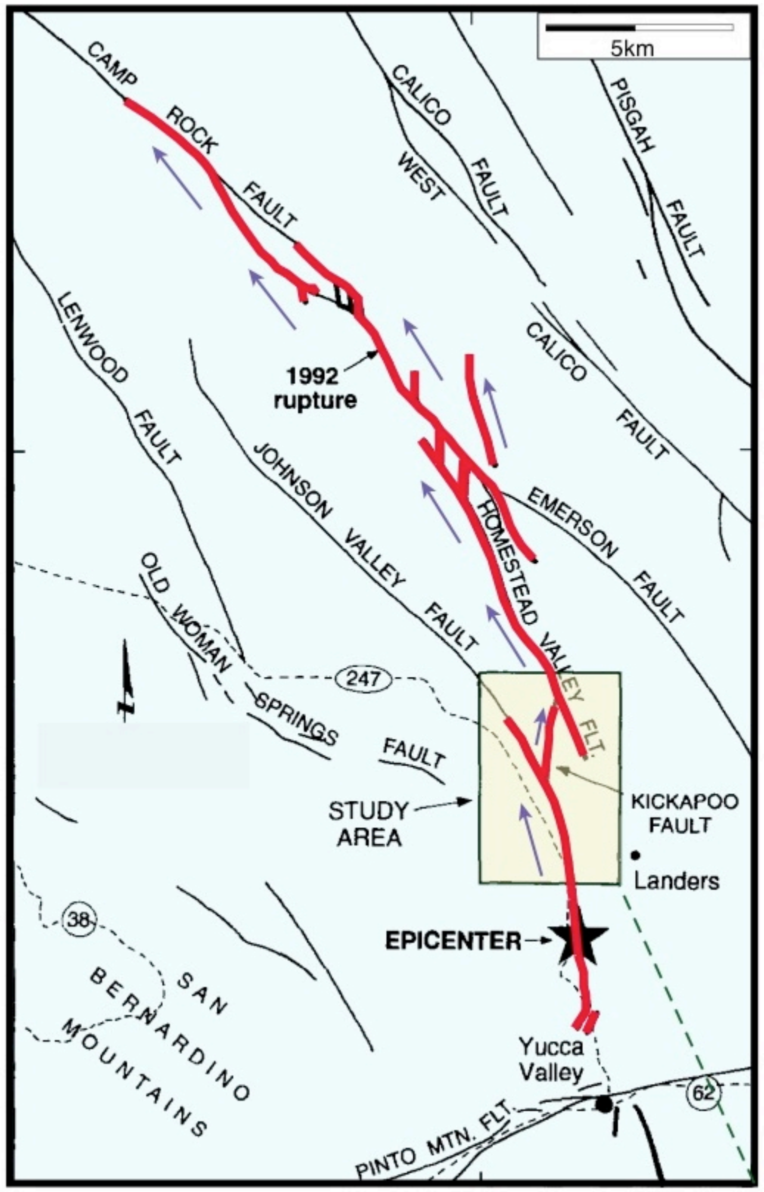

Time : 230Y 05M 04d 04h 18m
Aseismic Event #06
2km
$\delta_{max} \sim 10.7$ cm
$L_{rup} \sim 2.2$ km
$M_w \sim 5.0$
$T \sim$ 02d 00h 00m 02s
CRF2
CRF1
JVF
HVF
EF
KF
Previous Event : 61Y 07M 27d 05h 00m
Time : 232Y 05M 03d 01h 45m
Aseismic Event #07
2km
$\delta_{max} \sim 15.6$ cm
$L_{rup} \sim 3.6$ km
$M_w \sim 5.2$
$T \sim$ 01d 16h 47m 24s
CRF2
CRF1
JVF
HVF
EF
KF
Previous Event : 01Y 11M 28d 21h 26m

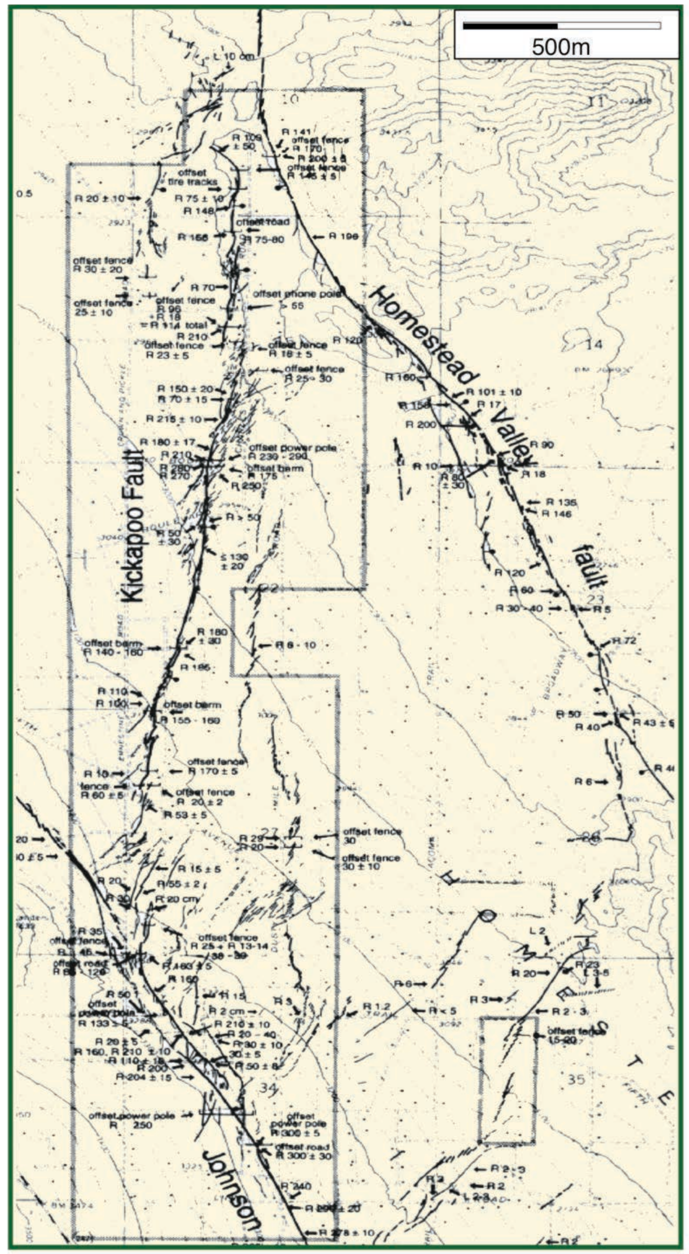

Time : 260Y 05M 20d 08h 07m
Seismic Event #05
2km
$\delta_{max} \sim$ 82.4 cm
$L_{rup} \sim$ 7.1 km
$M_w \sim$ 6.1
$T \sim$ 65.67s
CRF2
CRF1
JVF
HVF
EF
KF
Source Time Function
Previous Event : 28Y 00M 17d 06h 22m

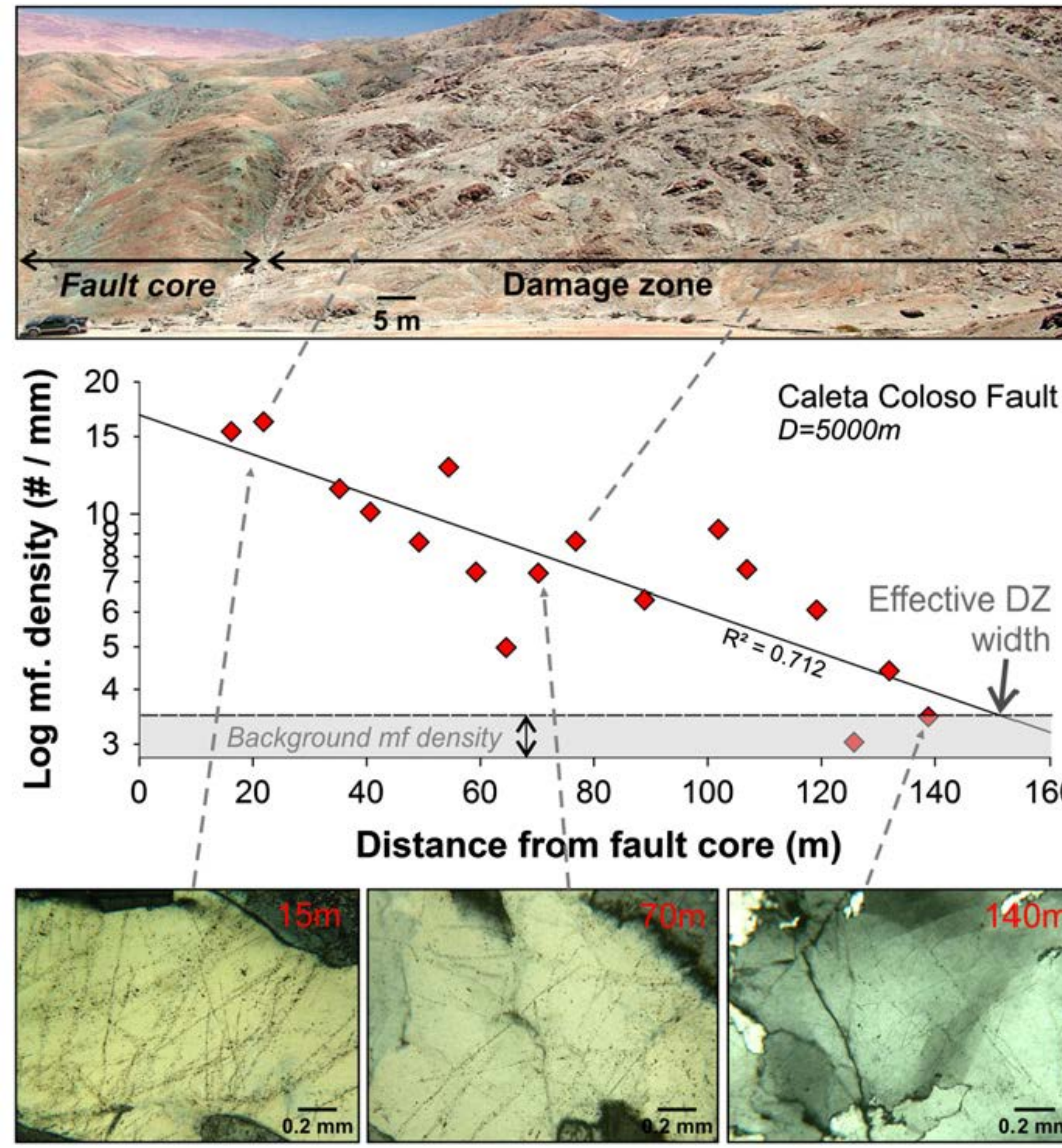

Time : 260Y 06M 29d 14h 54m
Seismic Event #06
2km
$\delta_{max} \sim$ 97.1 cm
$L_{rup} \sim$ 7.6 km
$M_w \sim$ 6.1
$T \sim$ 115.02s
CRF2
CRF1
JVF
HVF
EF
KF
Source Time Function
Previous Event : 00Y 01M 09d 06h 46m

Complex off-fault crack networks

5km 500m 5m







Sowers *et al.* (1994)

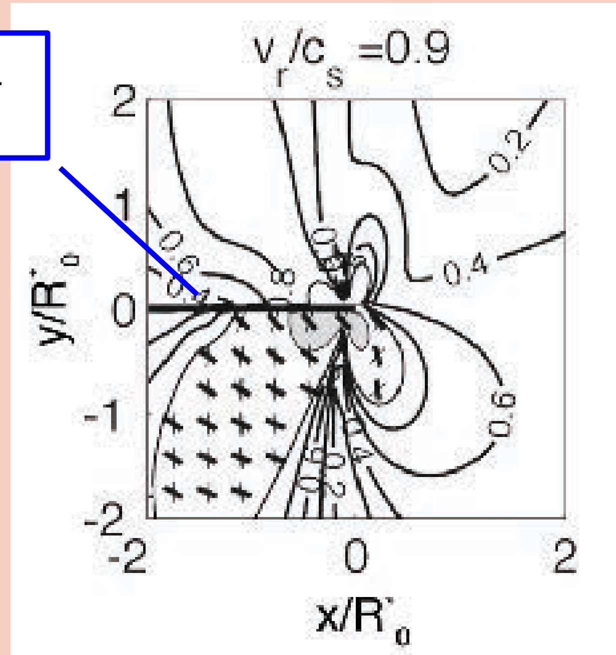
Mitchell and Faulkner (2012)

Complex fault network in kilometric scale to smaller scale off-fault crack network

Coseismic off-fault damage and radiation

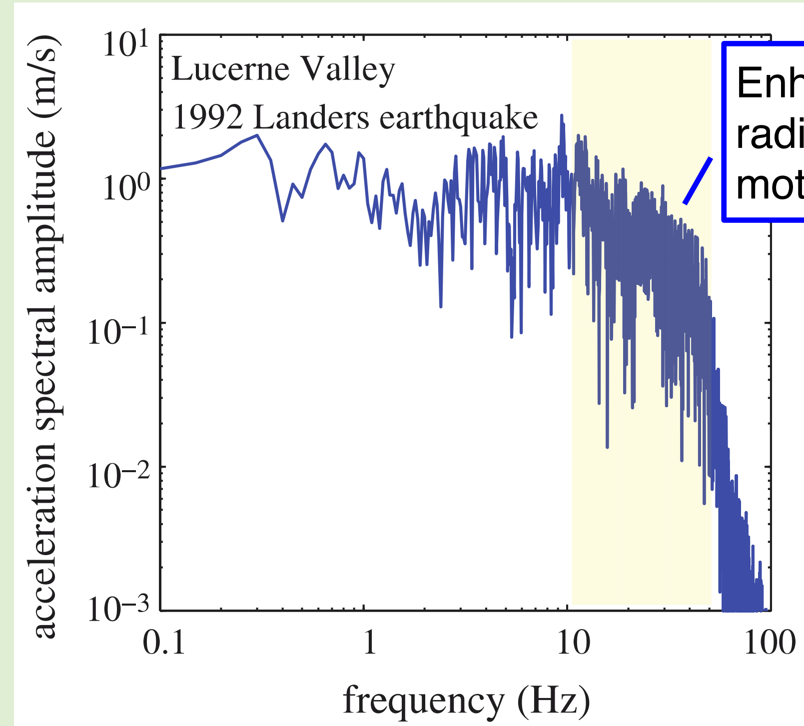
Theoretical analysis

Shaded region shows the area of potential shear cracks.



Rice *et al.* (2005)

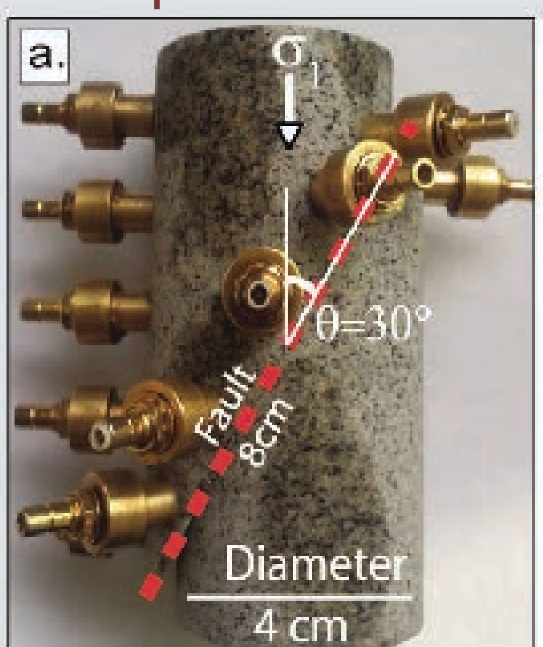
Observations

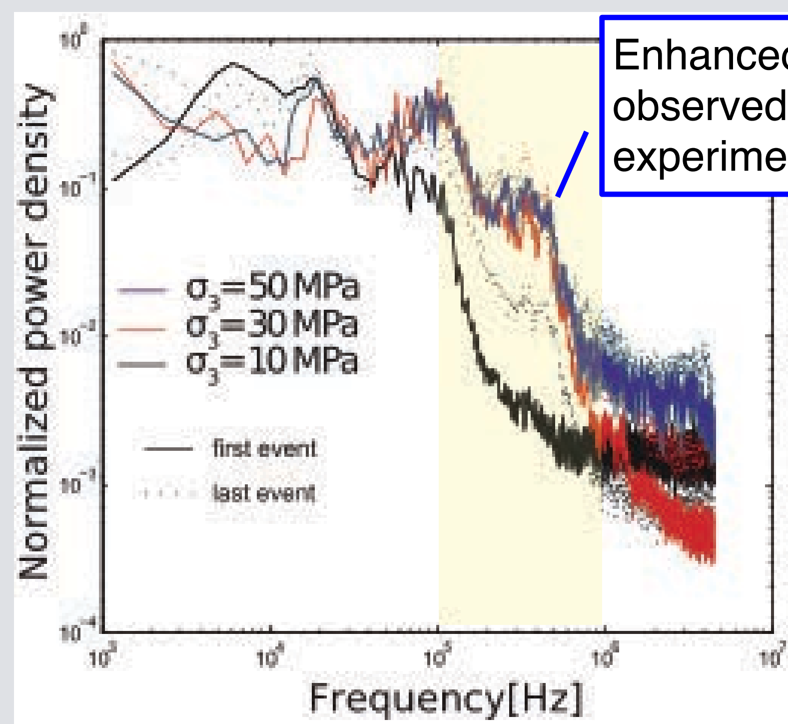


Enhanced High-frequency radiation in near field ground motion

Dunham *et al.* (2011)

Experiments

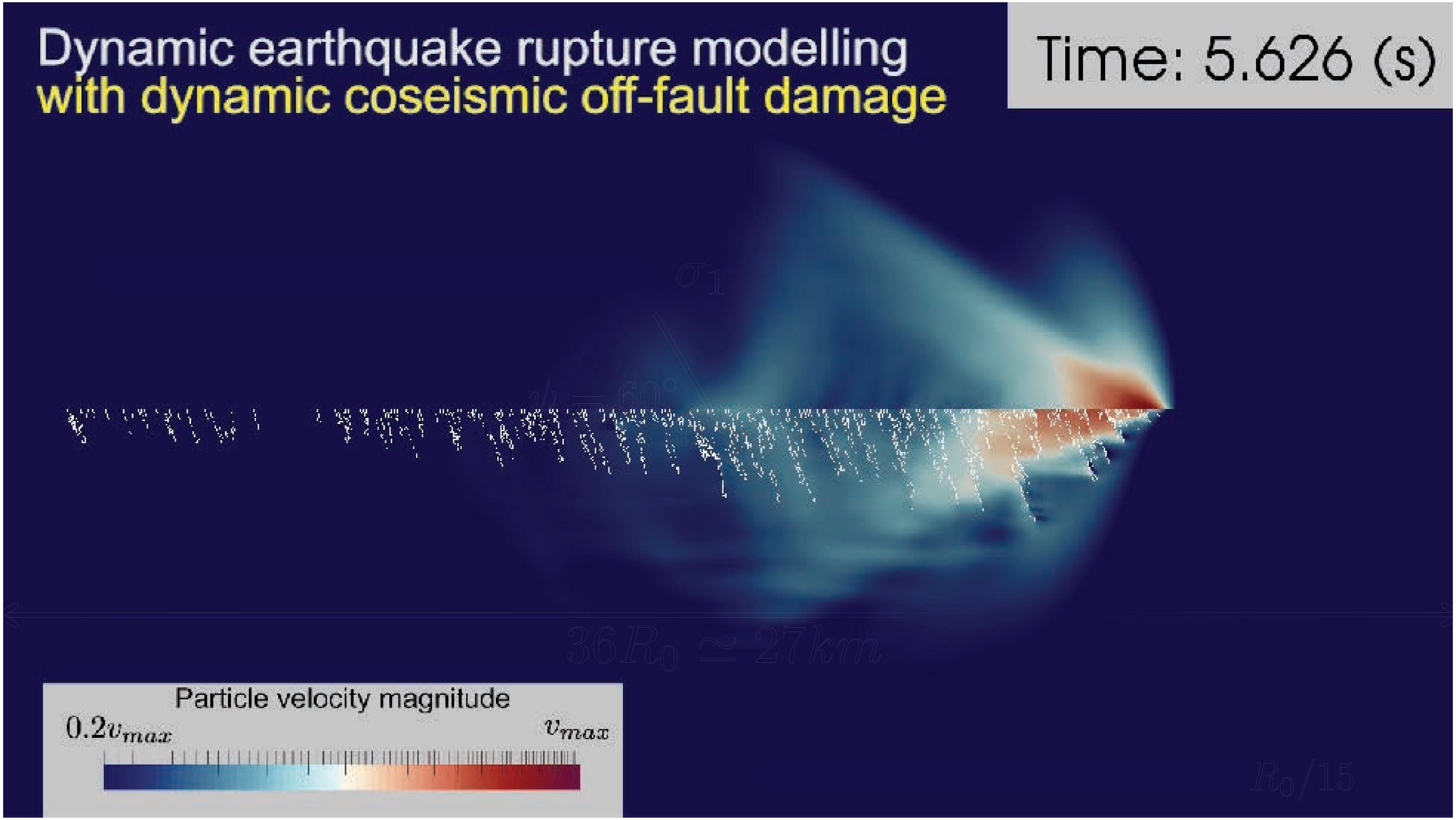




Enhanced High-frequency radiation observed from laboratory experiments

Passelègue *et al.* (2016); Marty, M2 thesis (2016)

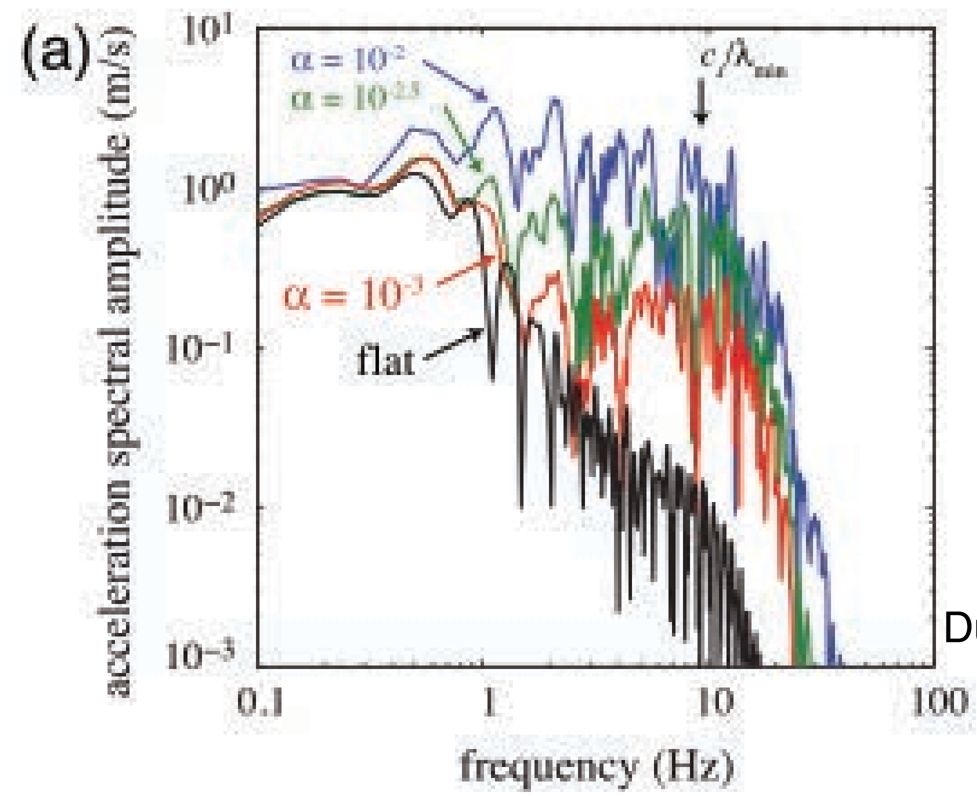
Co-seismic dynamic damage generation



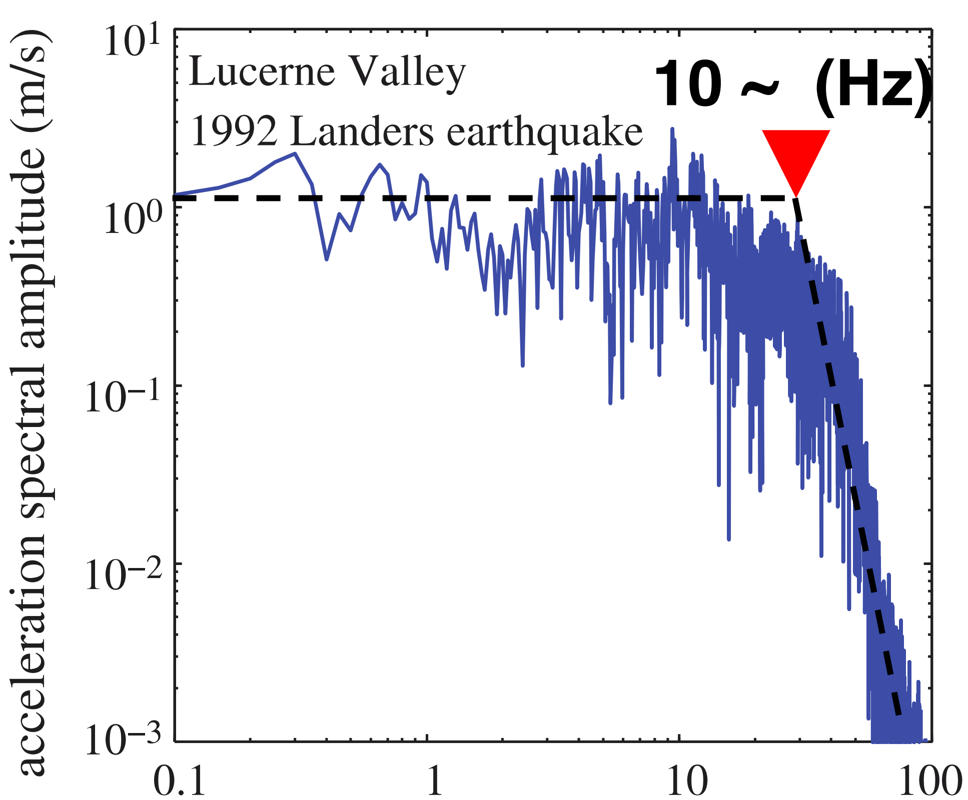
- We use the Combined Finite-Discrete Element Method (FDEM) package, Hybrid Optimisation Software Suite (HOSS), developed by Los Alamos National Laboratory

Analysis of Acceleration amplitude spectrum in near-field ground motion

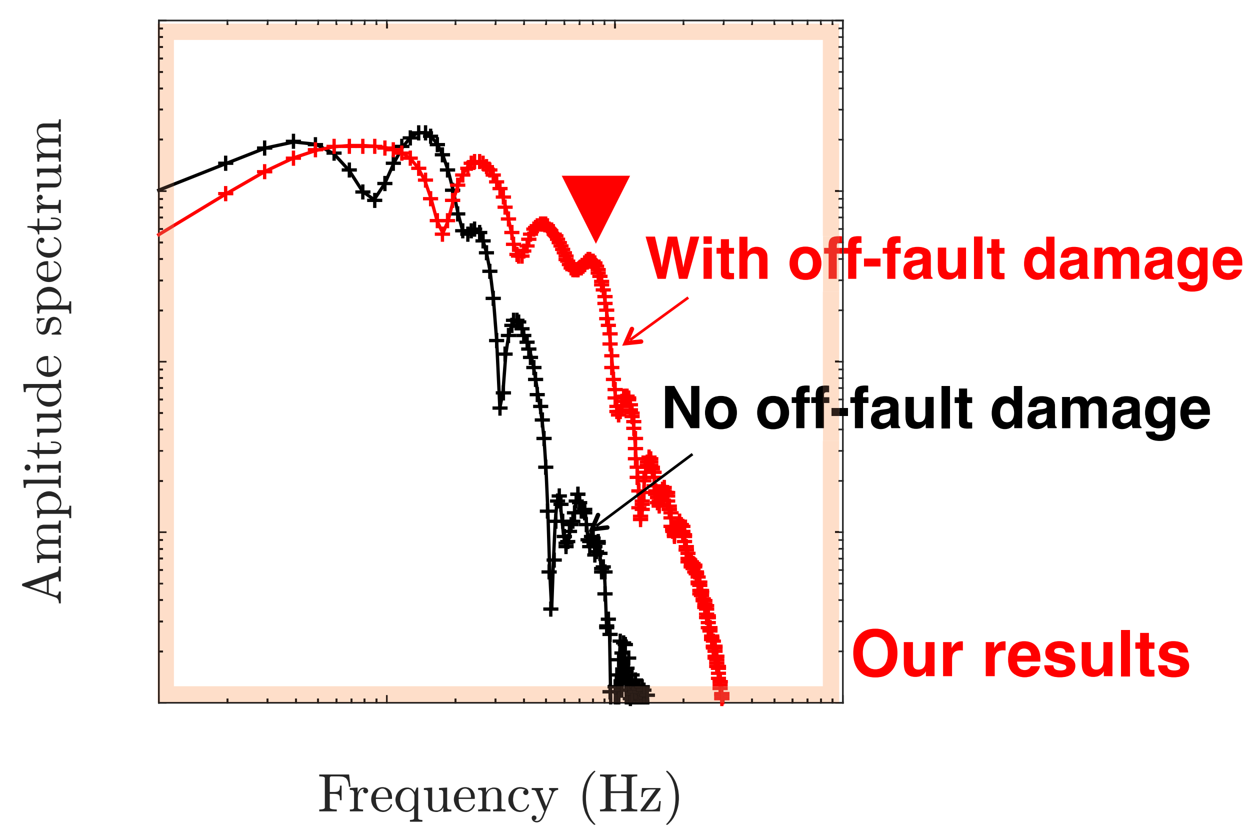
- Relatively high-frequency content (10 ~ Hz) is observed in near-field ground motion
- Focus on the **Maximum cut-off frequency** in acceleration amplitude spectrum



Dunham *et al.* (2011)



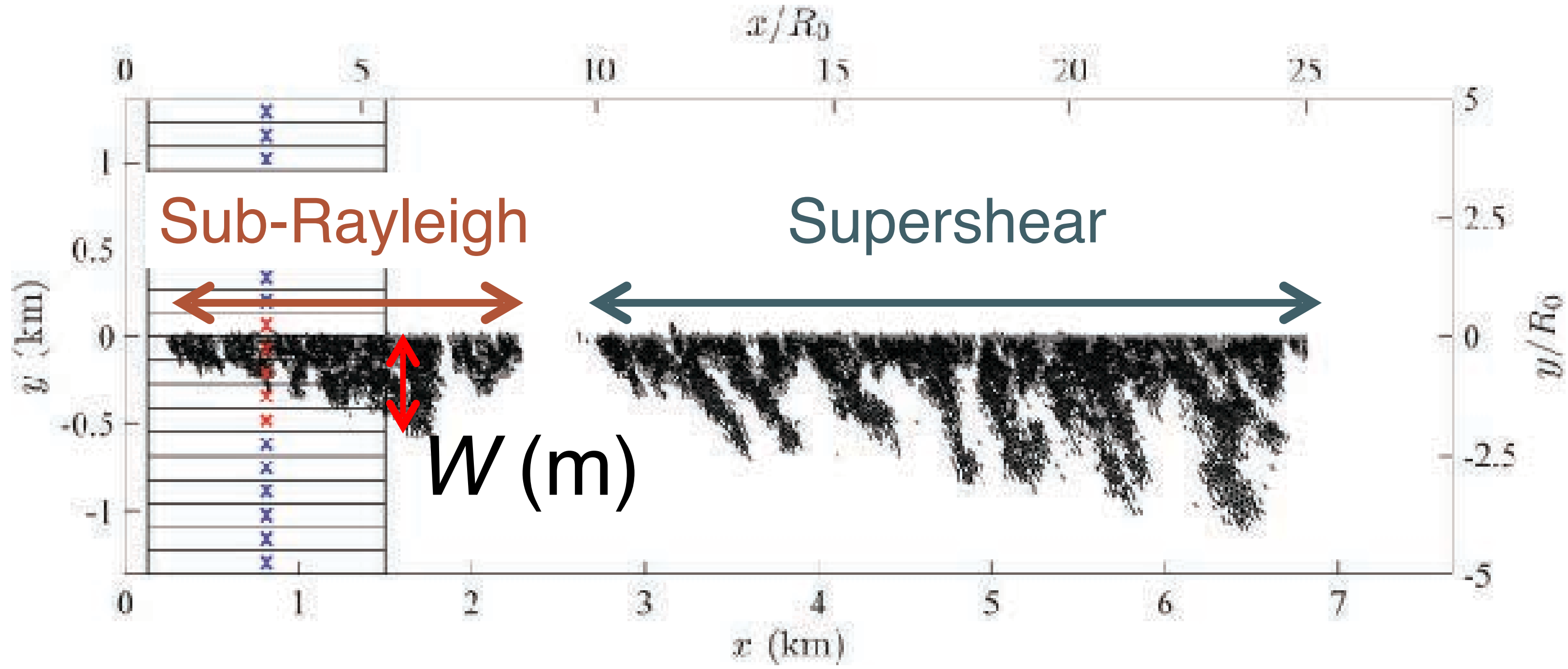
Dunham *et al.* (2011)

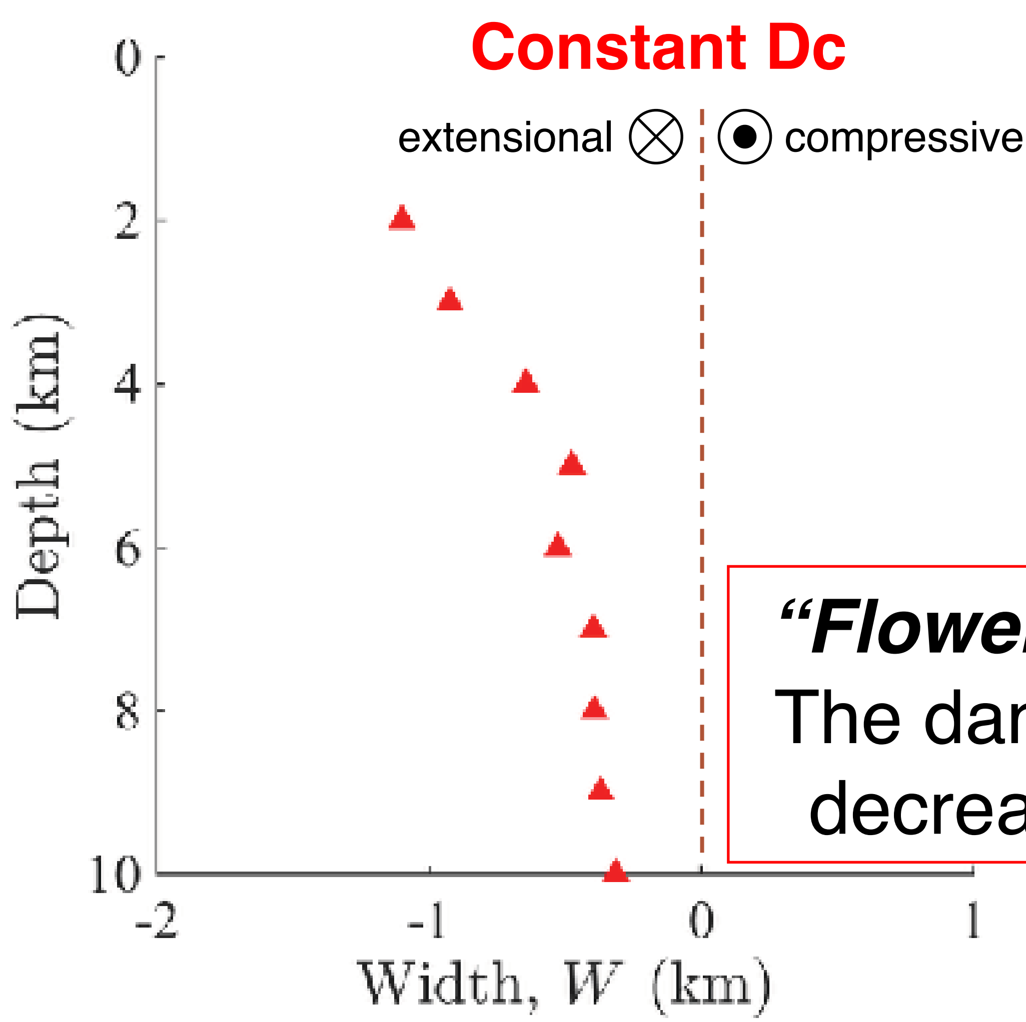


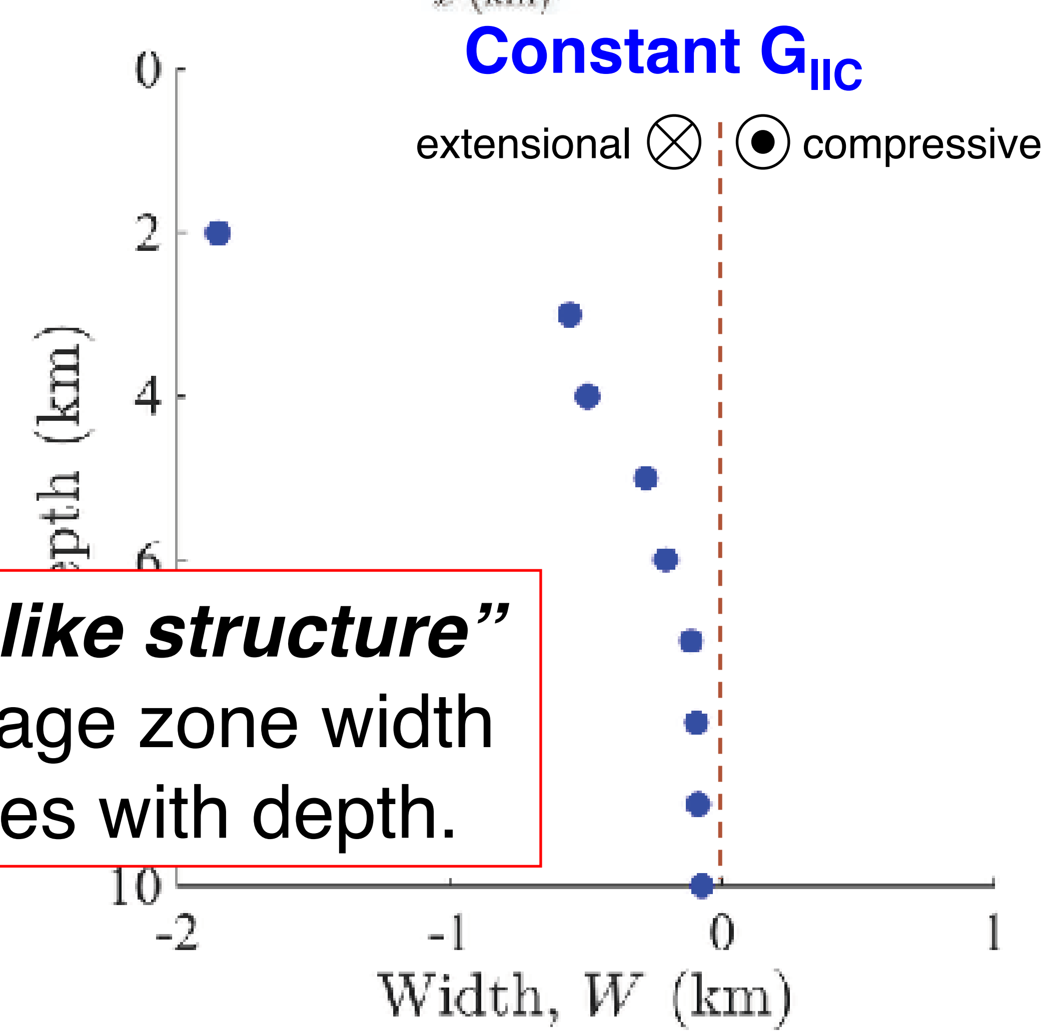
Damage evolution in depth

- Q. How does the damage zone width evolve in depth?

- Measure the damage zone width at every 1 km depth with **Constant Dc** and **Constant G_{IIC}** cases



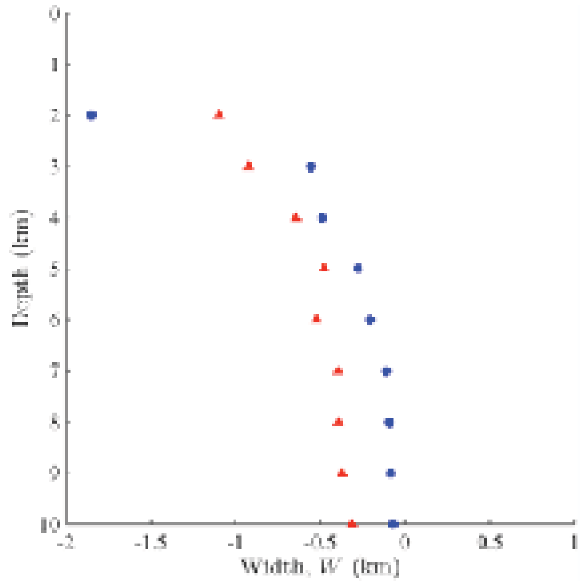




"Flower-like structure"
The damage zone width decreases with depth.

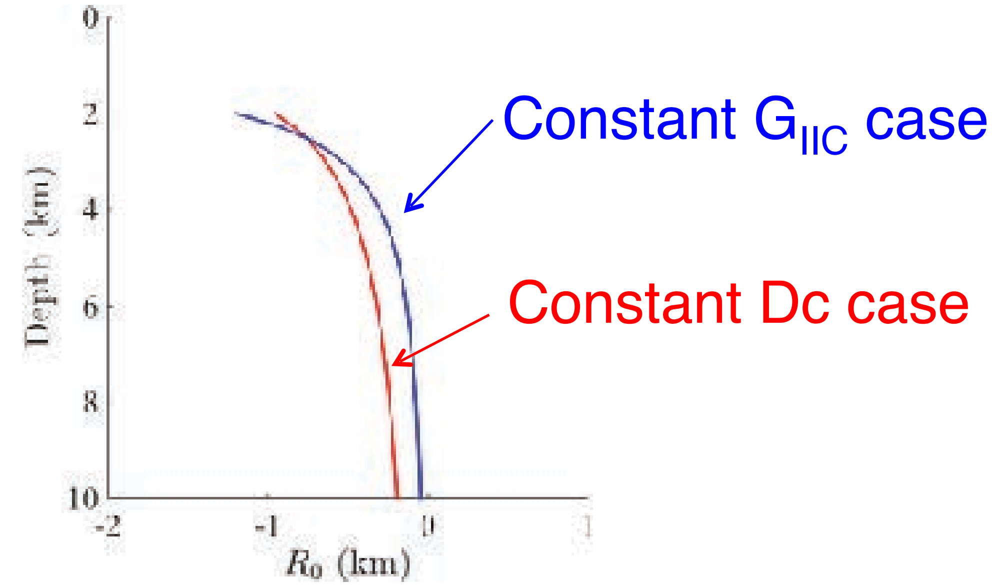
Non dimensionalised damage zone width in depth

- Scaling the damage zone width *W* by estimated process zone size R_0, W/R_0

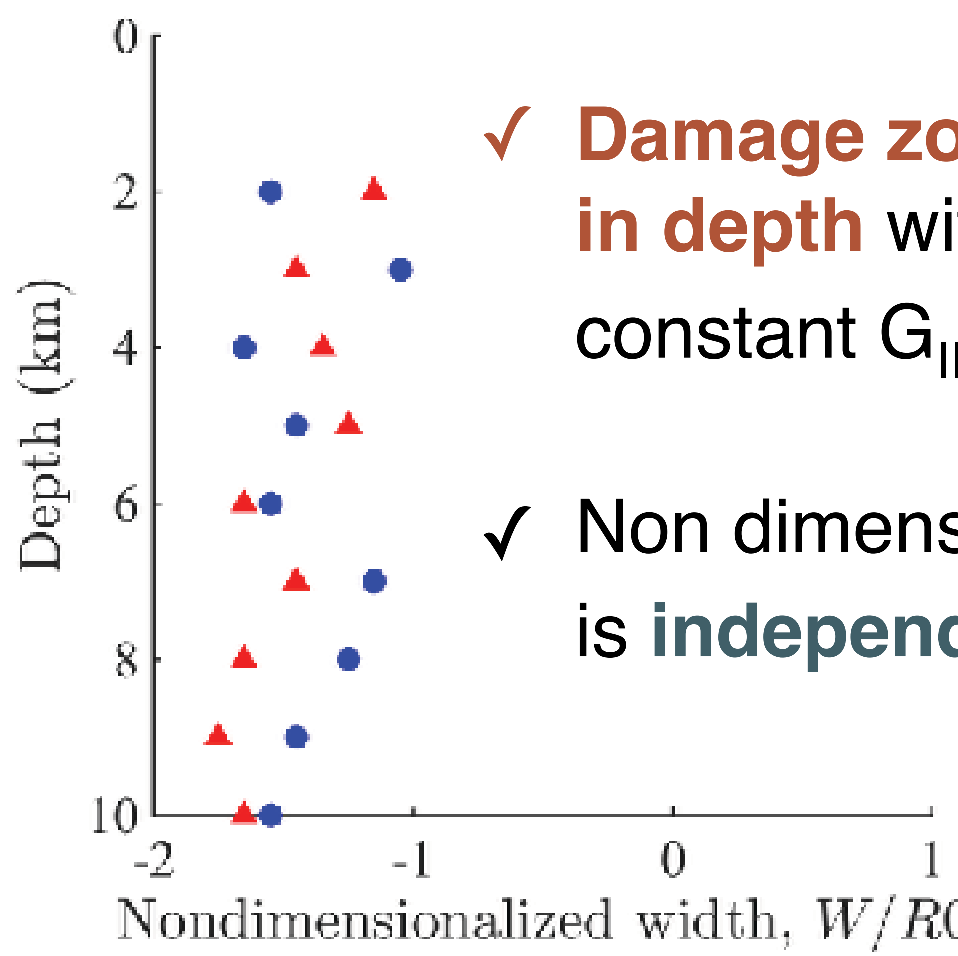


Damage zone width W

/



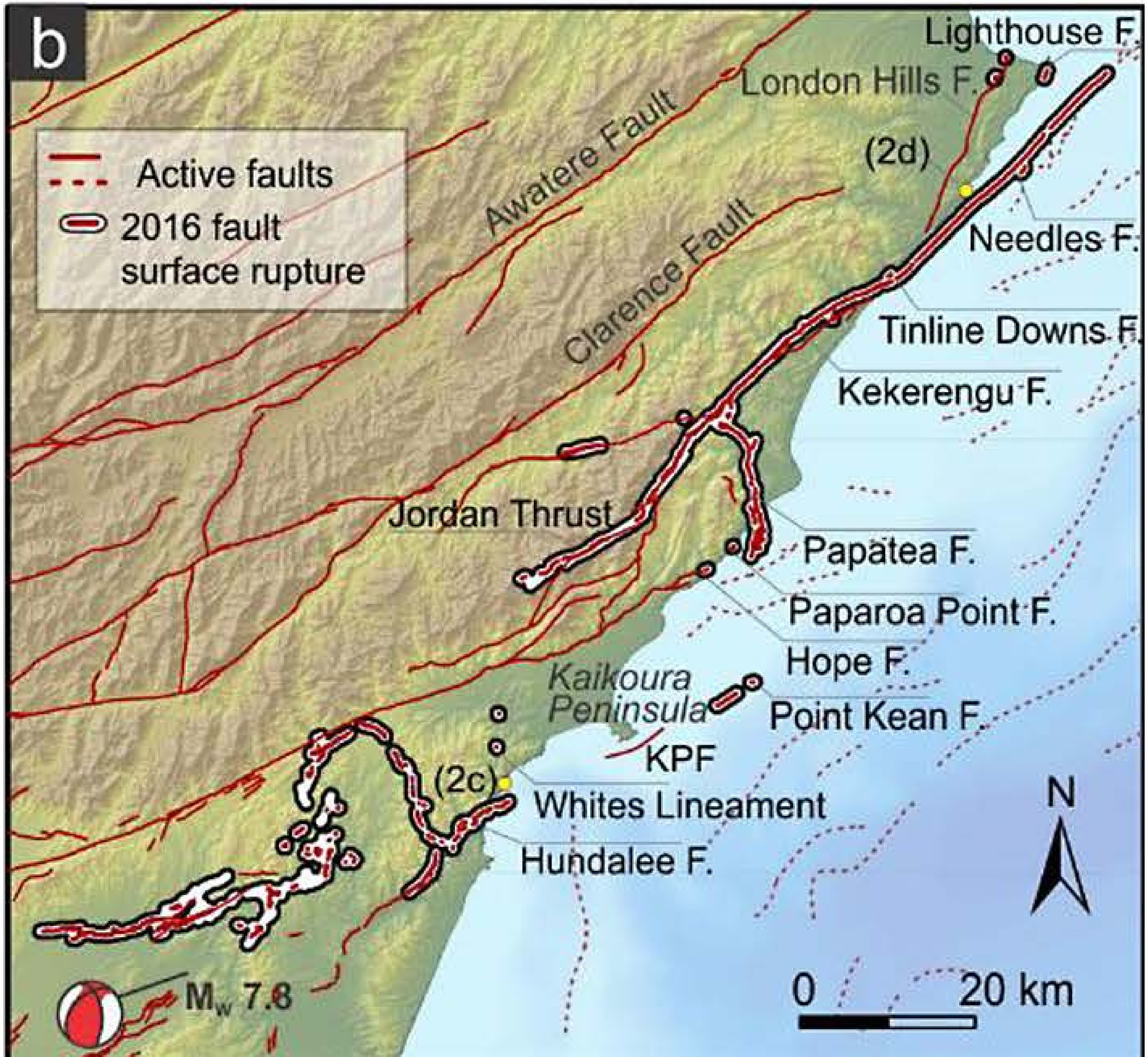
Process zone size R_0



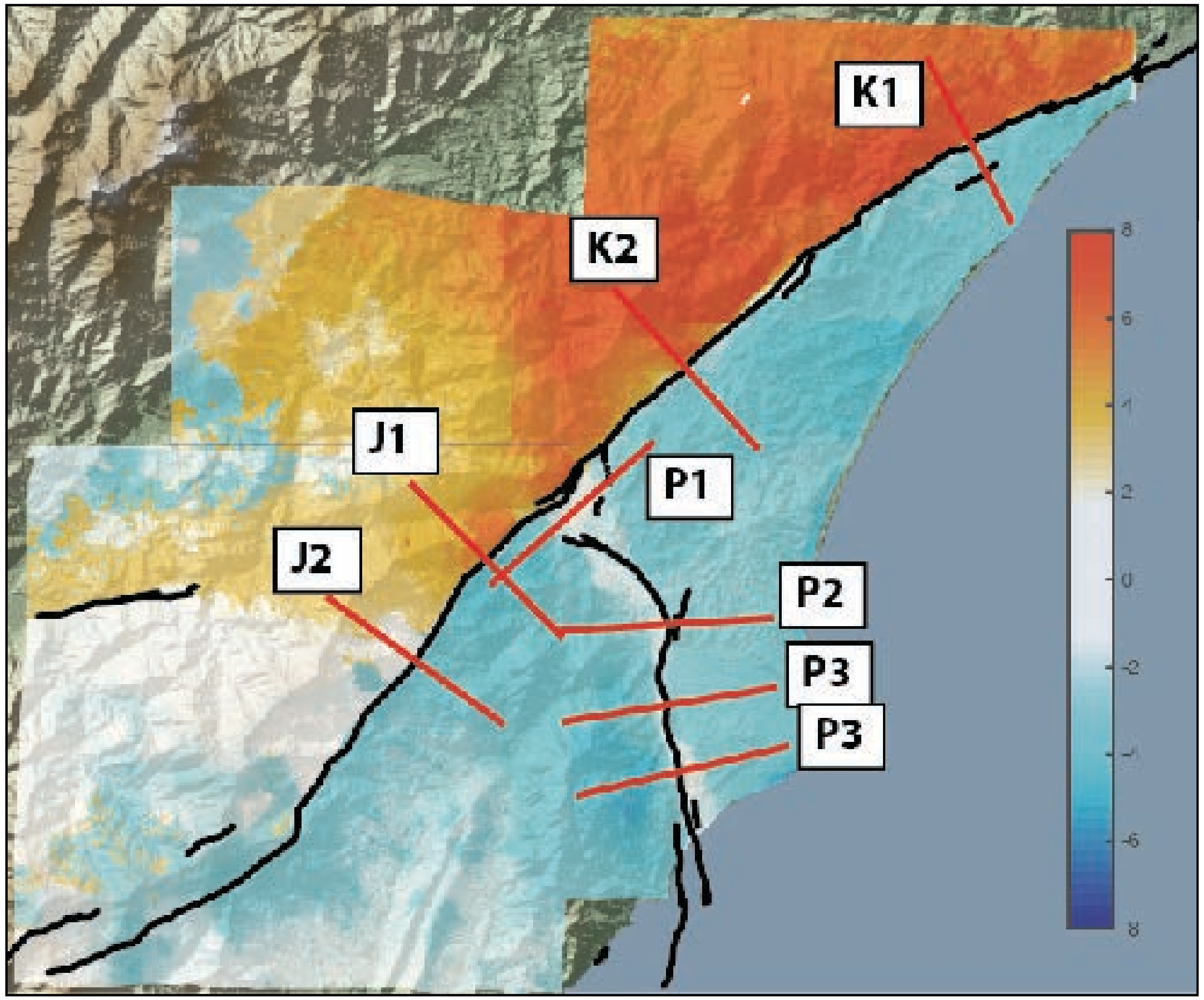
✓ **Damage zone width decreases in depth** with both constant D_c and constant G_{IIC} cases.

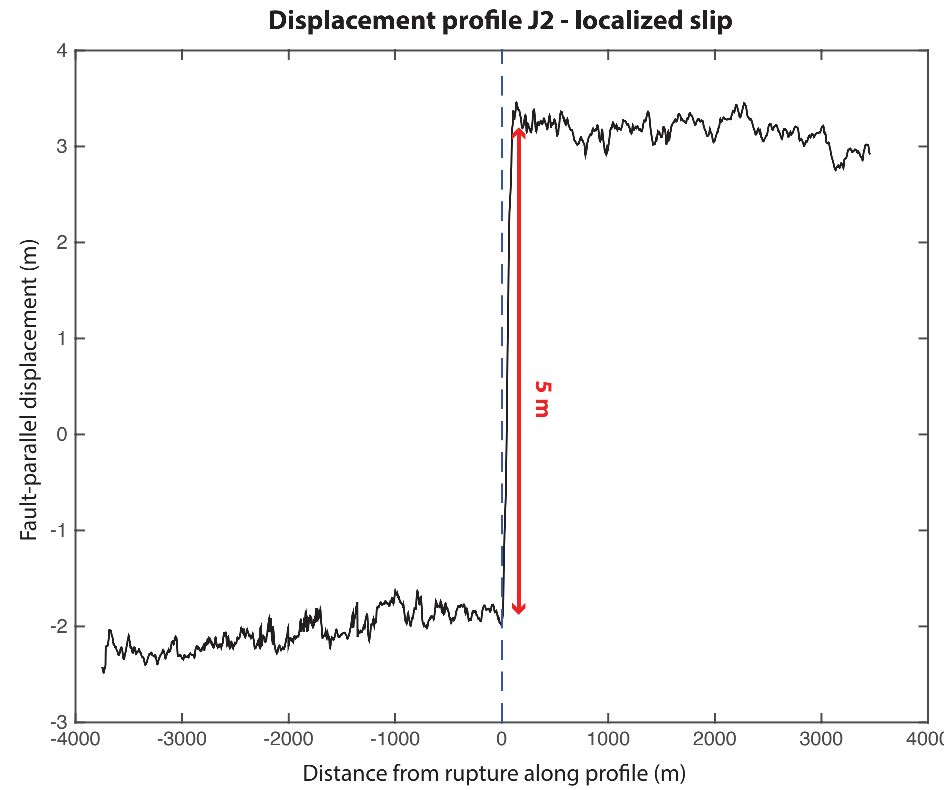
✓ Non dimensionalised width, W/R_0 , is **independent of depth**.

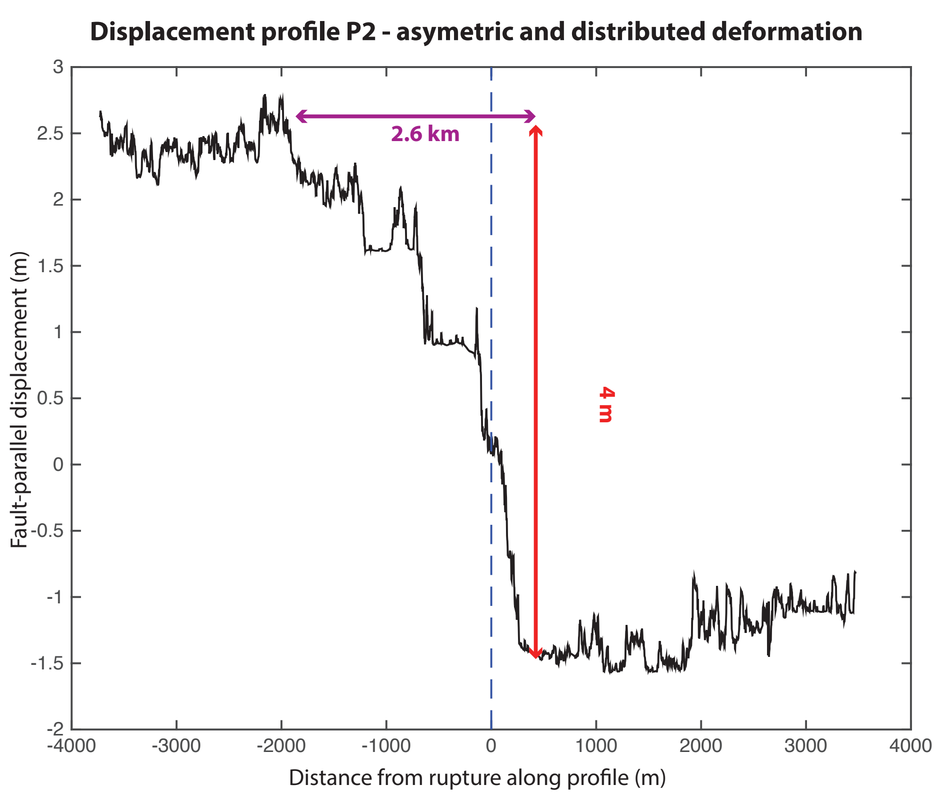
2016 M_w 7.8 Kaikoura Earthquake, NZ

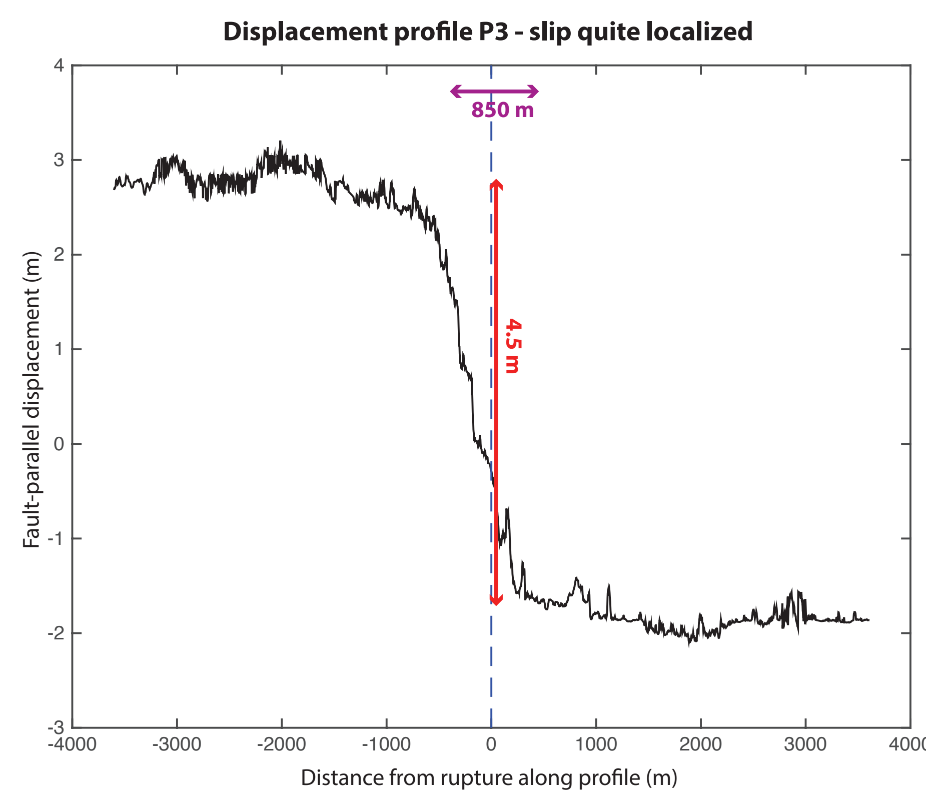


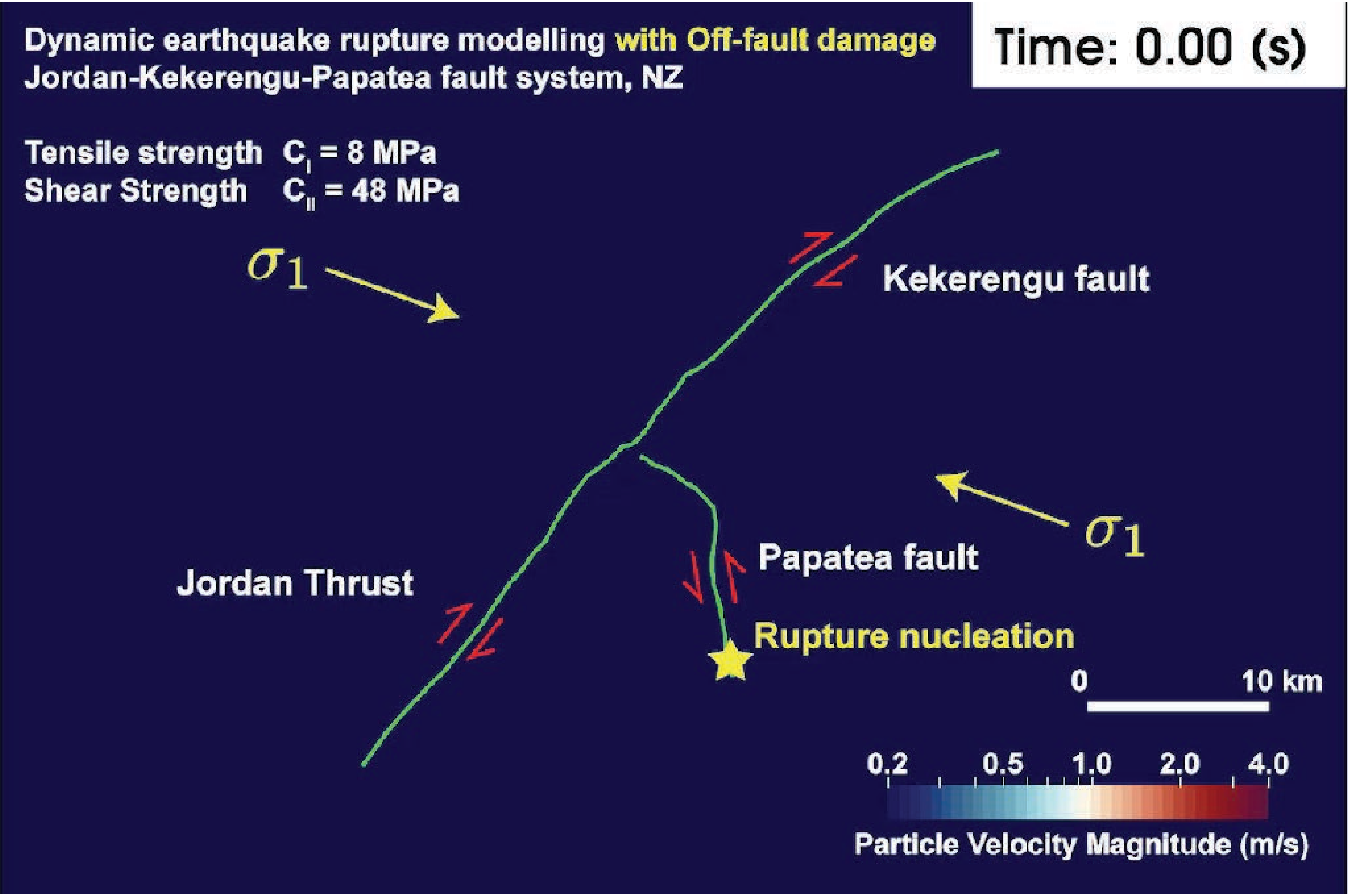
Optical Image Correlation





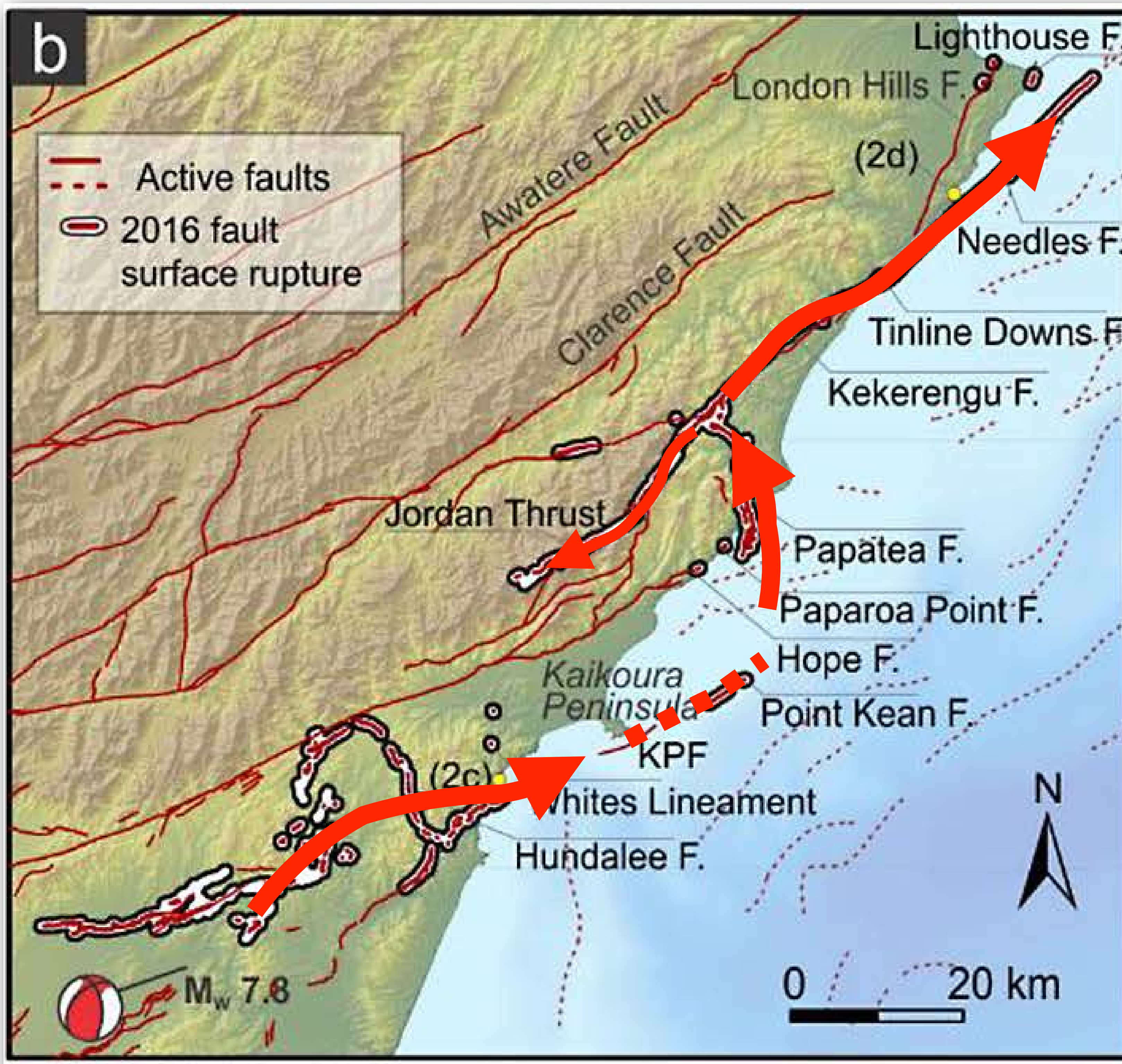





Dynamic earthquake rupture modelling with Off-fault damage
Jordan-Kekerengu-Papatea fault system, NZ
Time: 0.00 (s)
Tensile strength C_I = 8 MPa
Shear Strength C_{II} = 48 MPa
σ_1
Kekerengu fault
σ_1
Papatea fault
Jordan Thrust
Rupture nucleation
0
10 km
0.2
0.5
1.0
2.0
4.0
Particle Velocity Magnitude (m/s)

Combination of high-resolution deformation field and dynamic rupture modelling including off-fault damage

=> unambiguous evidence for rupture along Papatea F. triggering bilateral rupture along Jordan Thrust - Kekerengu Fault



Conclusion

- Secondary crack network can be generated by dynamic earthquake rupture. 2D distribution of frequency contents shows that the **high frequency (10-100Hz) radiation is enhanced** by the secondary crack network.

- Macroscopic shear wave velocity in the damage zone decreases by ~20%

- Our case study shows the damage evolution in depth with **more intricate crack networks in deeper cases**.

- It shows that the width of damaged zone decreases in depth, forming **"flower-like" structure** as the characteristic slip distance in linear slip-weakening law or the fracture energy on the fault is kept constant with depth.

- This method has been applied to the complex fault system with the same framework.