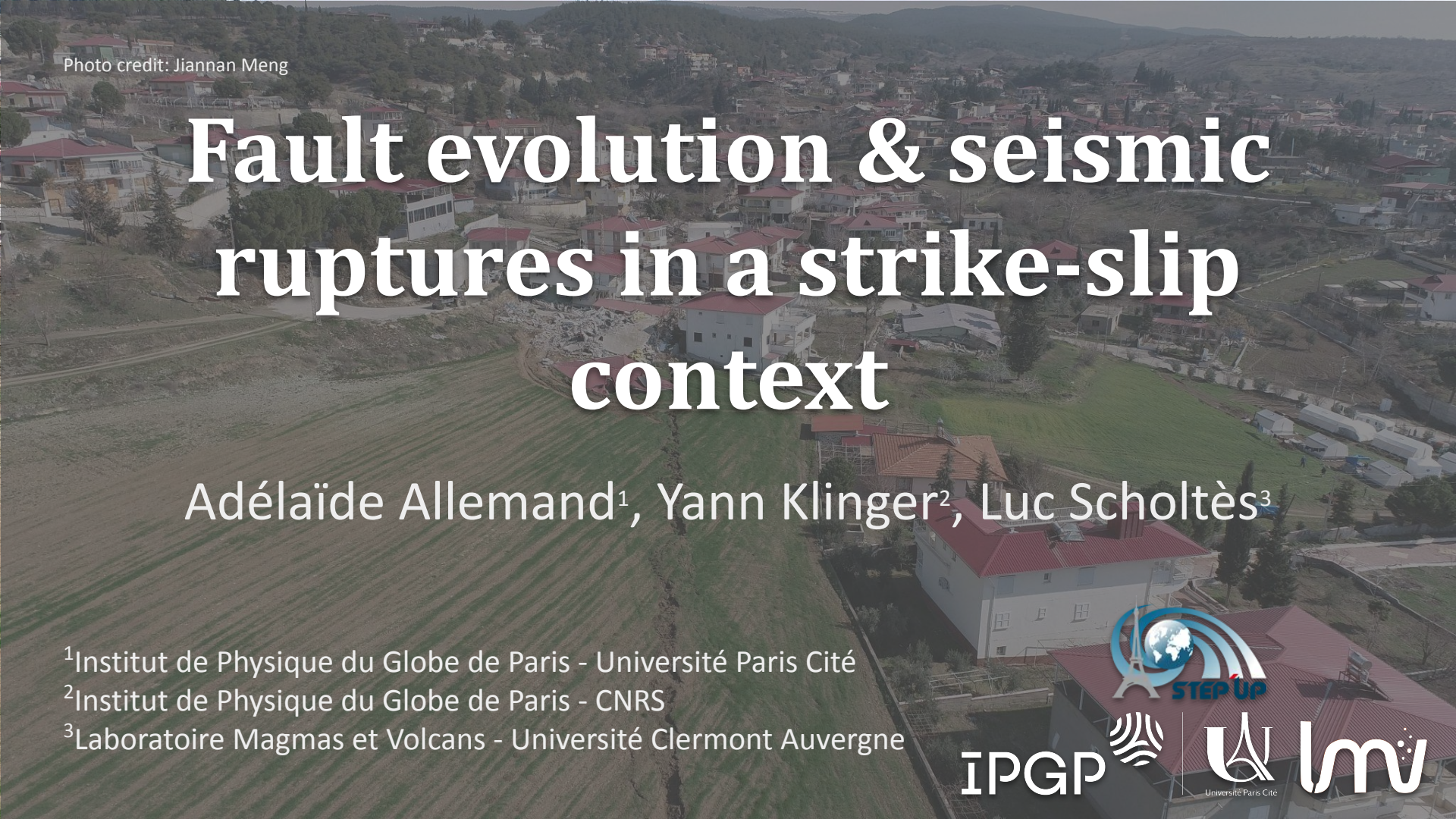


Photo credit: Jiannan Meng

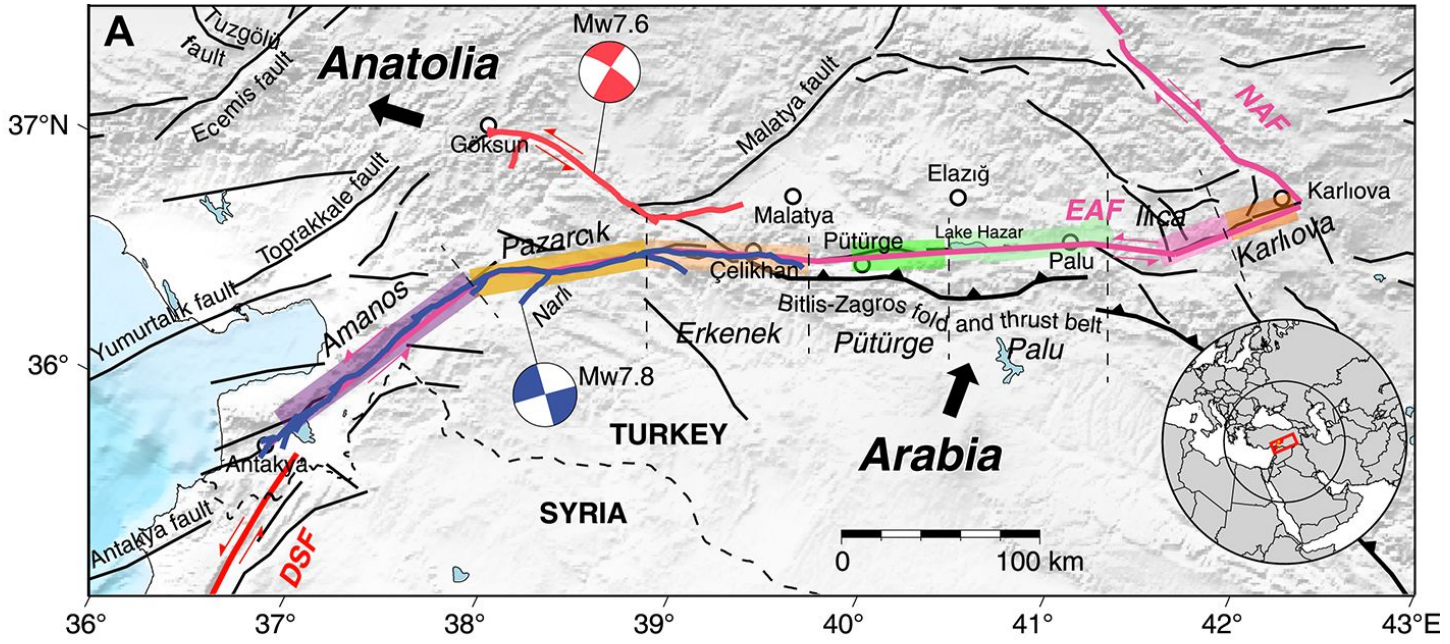
Fault evolution & seismic ruptures in a strike-slip context

Adélaïde Allemand[1], Yann Klinger[2], Luc Scholtès[3]

[1]Institut de Physique du Globe de Paris - Université Paris Cité
[2]Institut de Physique du Globe de Paris - CNRS
[3]Laboratoire Magmas et Volcans - Université Clermont Auvergne

Context and objectives

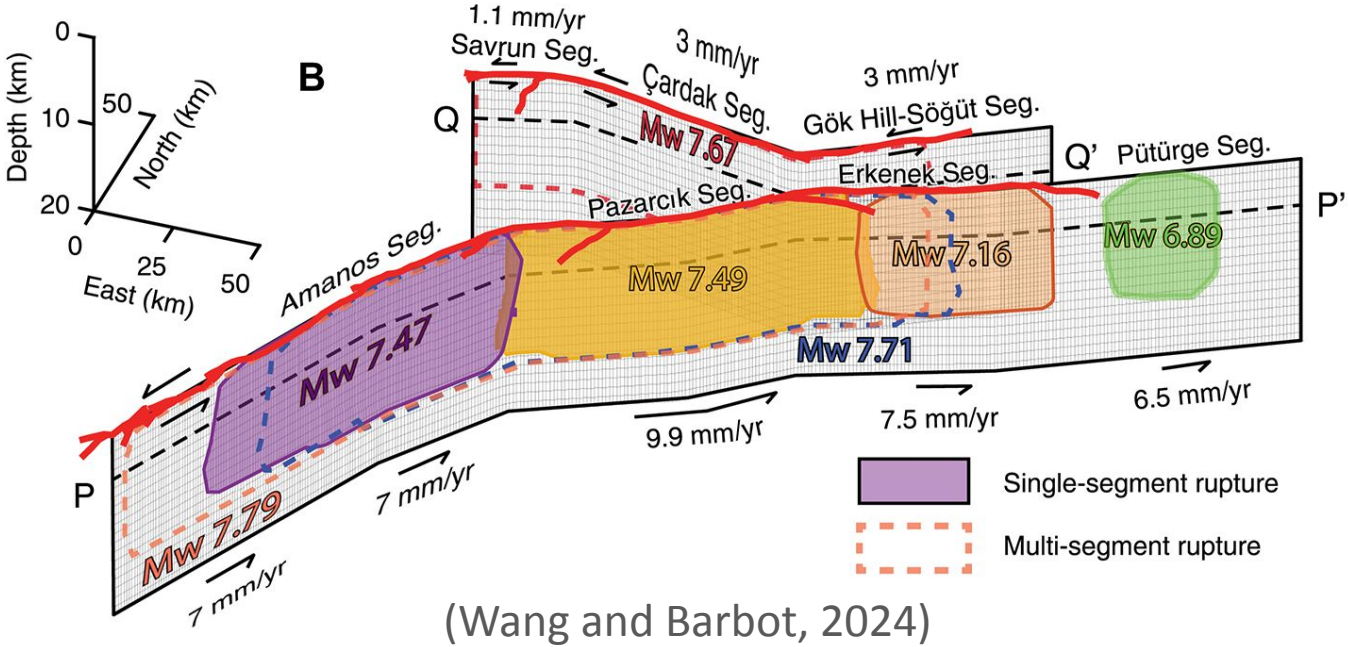
Continental, strike-slip faults are composed of segments of equal length (Klinger, 2010)



(Wang and Barbot, 2024)

Context and objectives

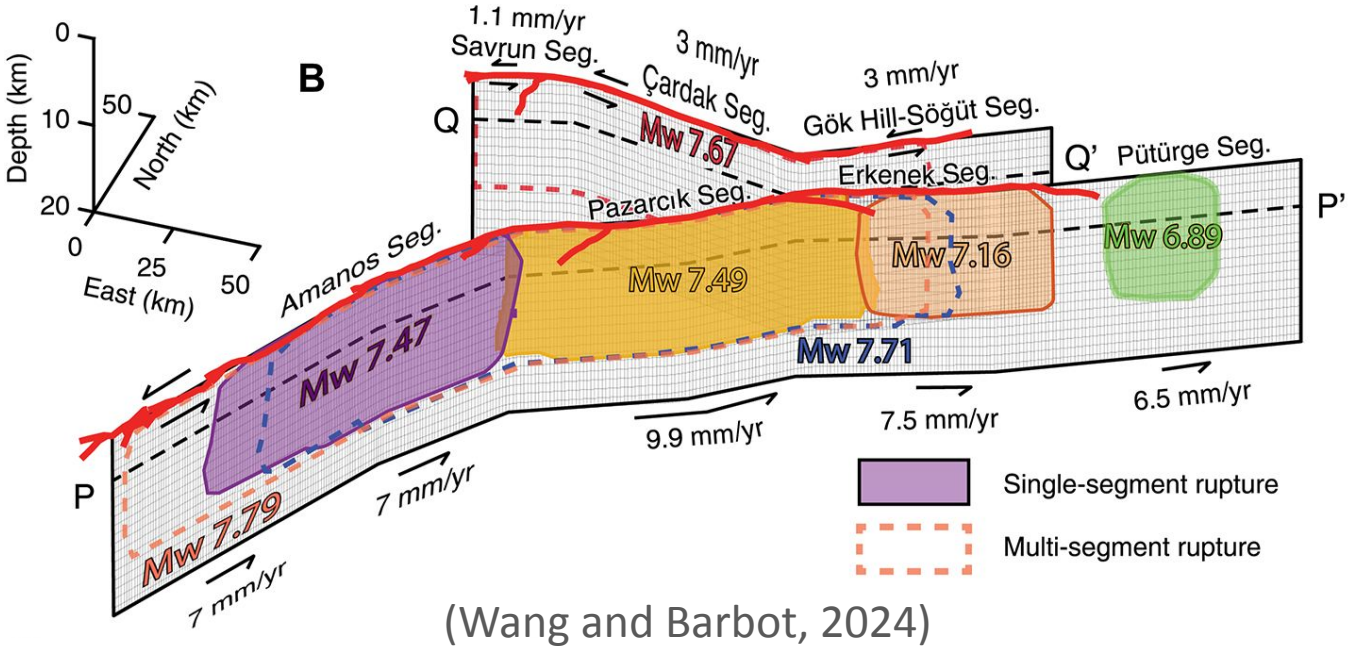
Connections between segments represent potential barriers for seismic ruptures (e.g.: Aki, 1984; King and Nabelek, 1985; Wesnousky, 2006; Manighetti et al, 2007)



(Wang and Barbot, 2024)

Context and objectives

Where does this geometry come from?



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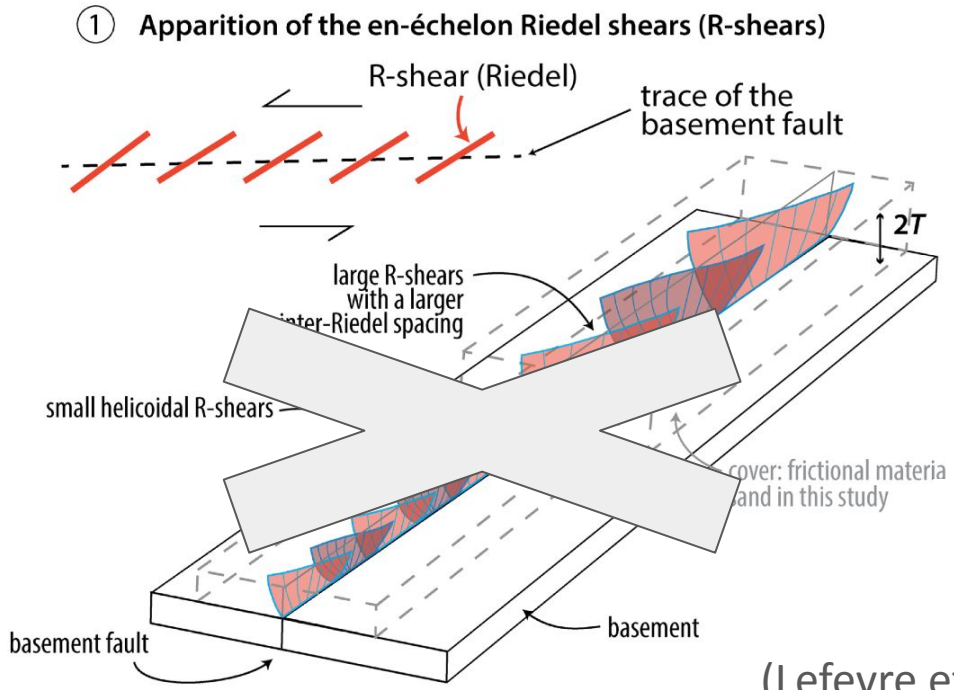

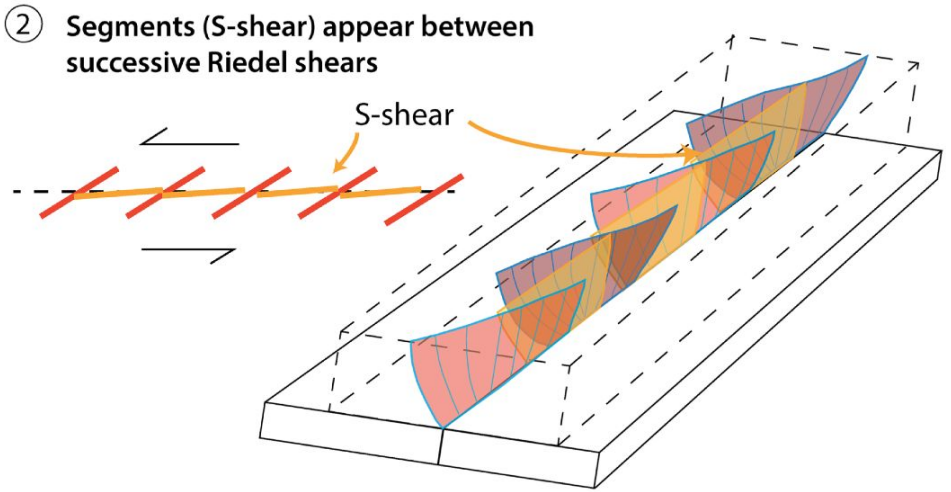

(Lefevre et al., 2020)

Context and objectives

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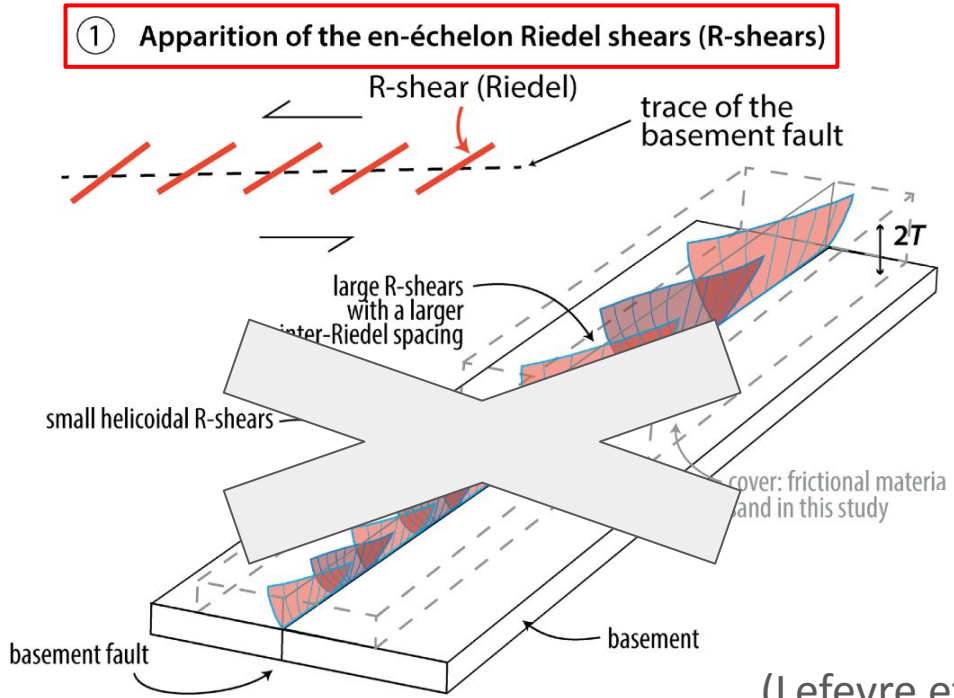

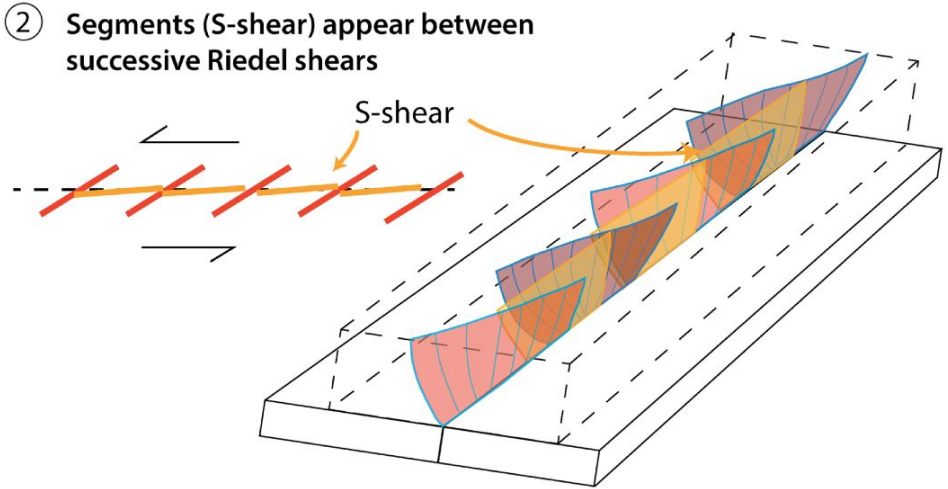

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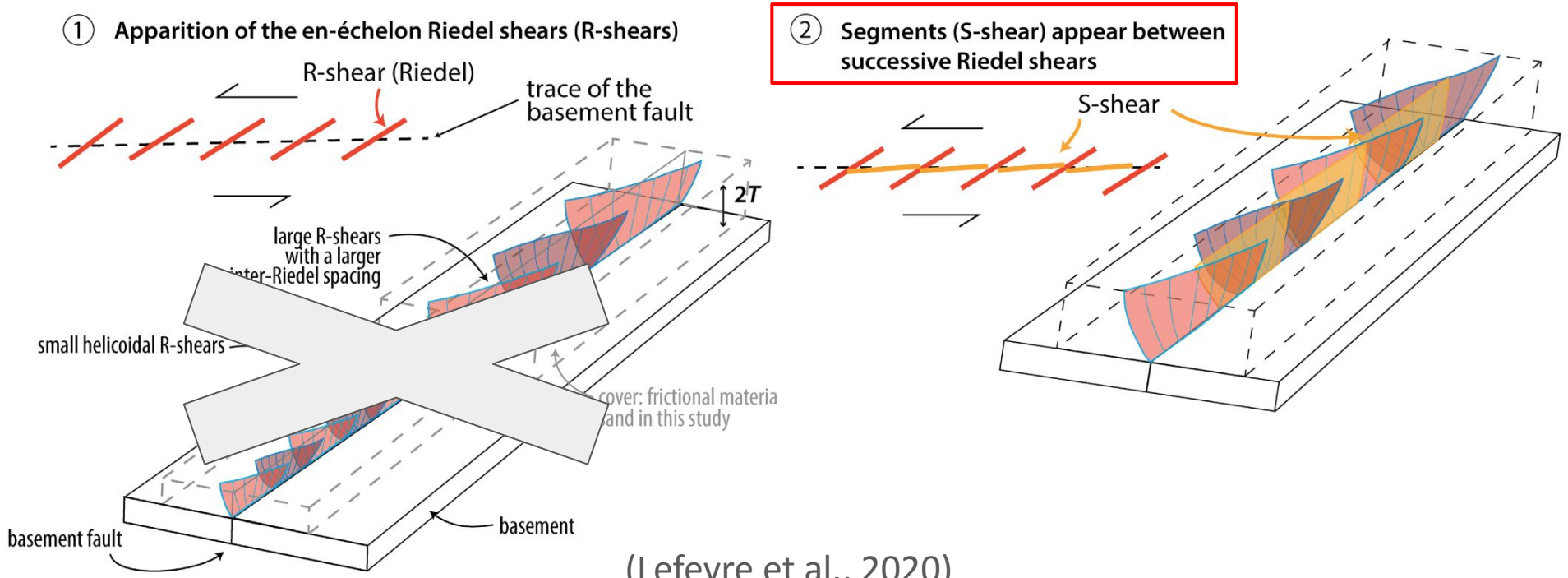

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Context and objectives

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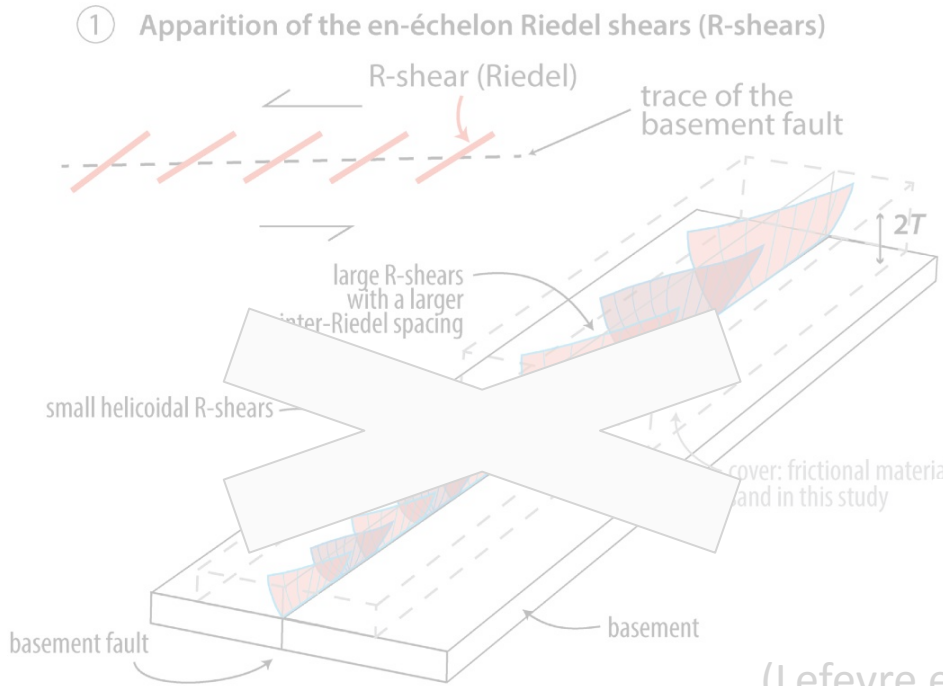
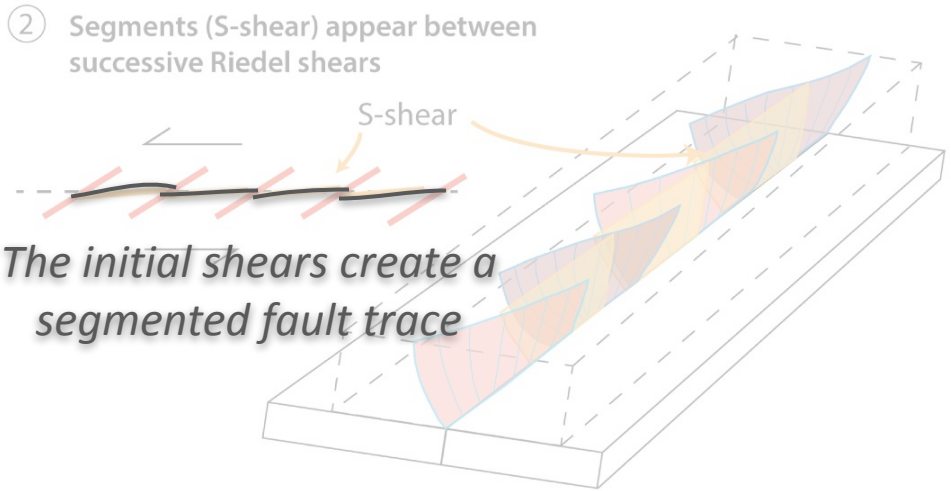


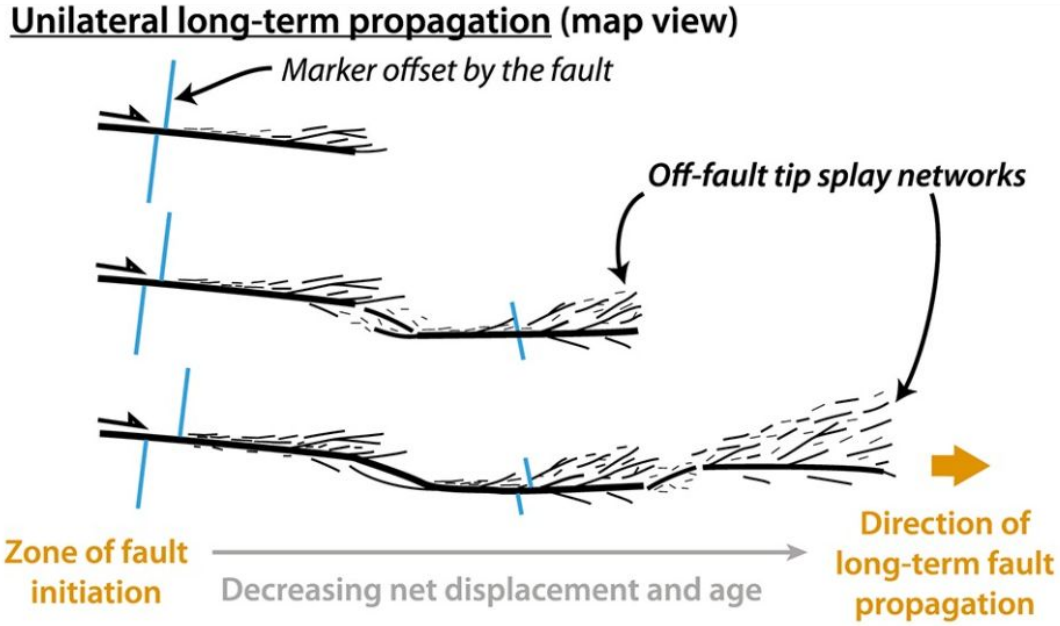


The initial shears create a segmented fault trace

(Lefevre et al., 2020)

Context and objectives

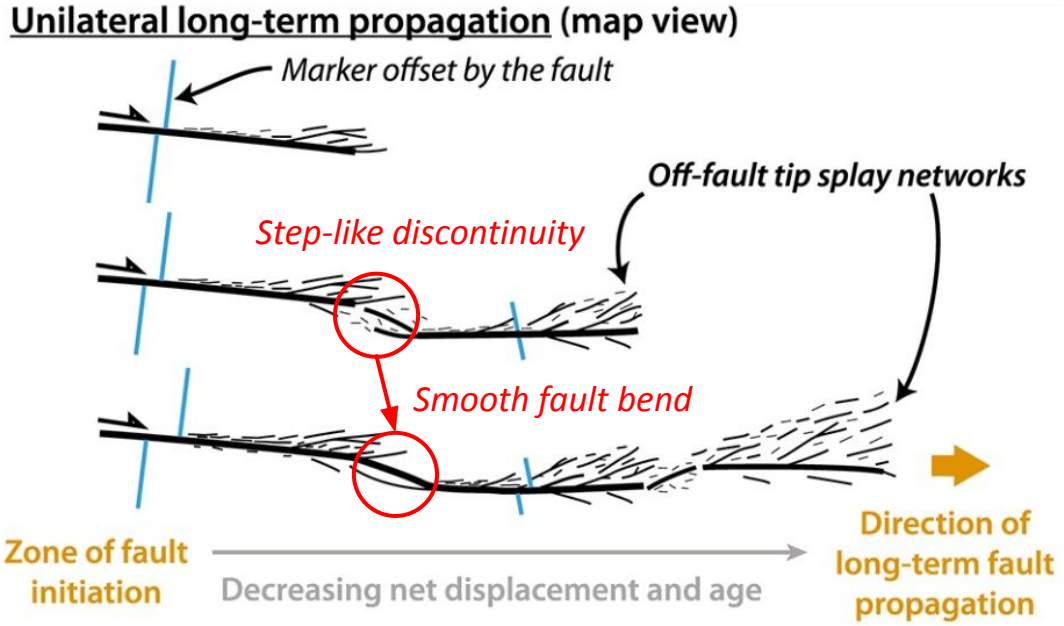
Long term evolution a strike-slip fault



(Perrin et al., 2016)

Context and objectives

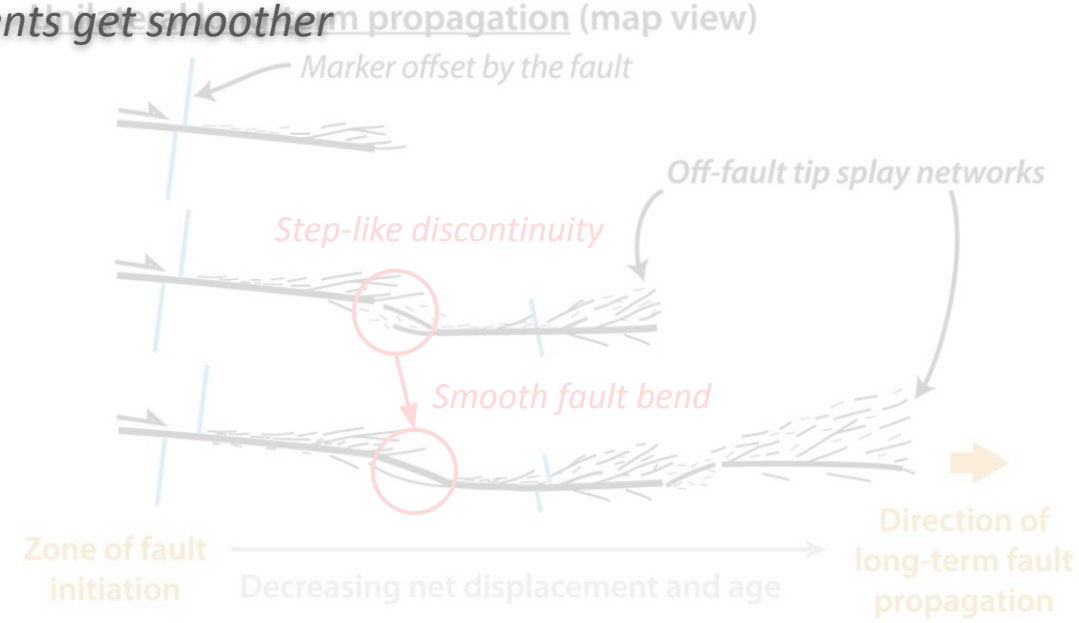
Long term evolution a strike-slip fault



(Perrin et al., 2016)

Context and objectives

Over the long term, the connections between segments get smoother



(Perrin et al., 2016)

Context and objectives

Mutual interactions between long term evolution and seismicity

Context and objectives

Mutual interactions between long term evolution and seismicity

- Modelling a continental strike-slip fault with **complex** and **evolving** geometry
- Generate **earthquake cycles** on that fault

Context and objectives

Mutual interactions between long term evolution and seismicity

- Modelling a continental strike-slip fault with **complex** and **evolving** geometry
- Generate **earthquake cycles** on that fault

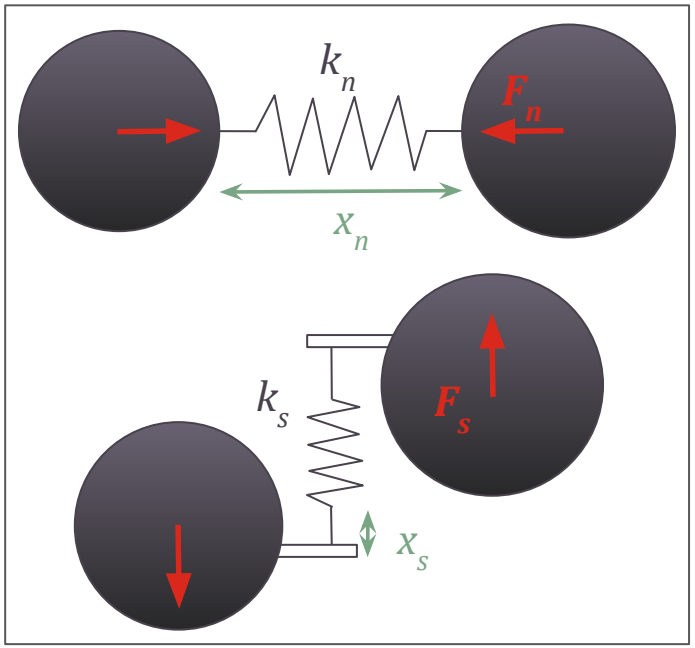
Discrete Element Method (DEM)

➢ Inhomogeneous stresses and element arrangement can emerge and evolve naturally → ***fault geometry evolution***

➢ A simple contact law enables stick-slip behaviour → ***earthquakes***

Numerical method: Discrete Element Method

Calibration of the contact properties (k_n, k_s, …)



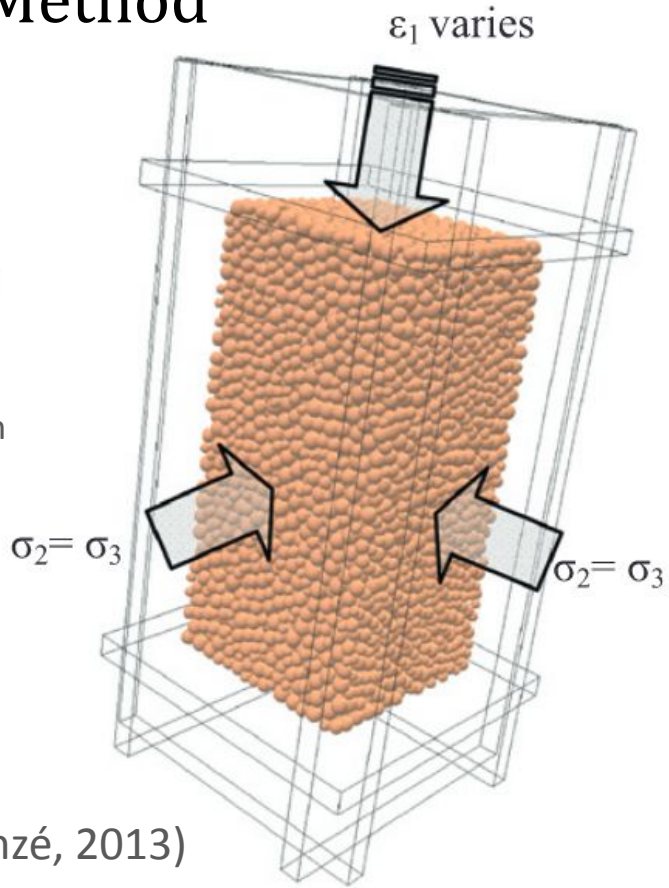
5 contact parameters:

Elastic parameters:

- Normal stiffness
- Tangential stiffness

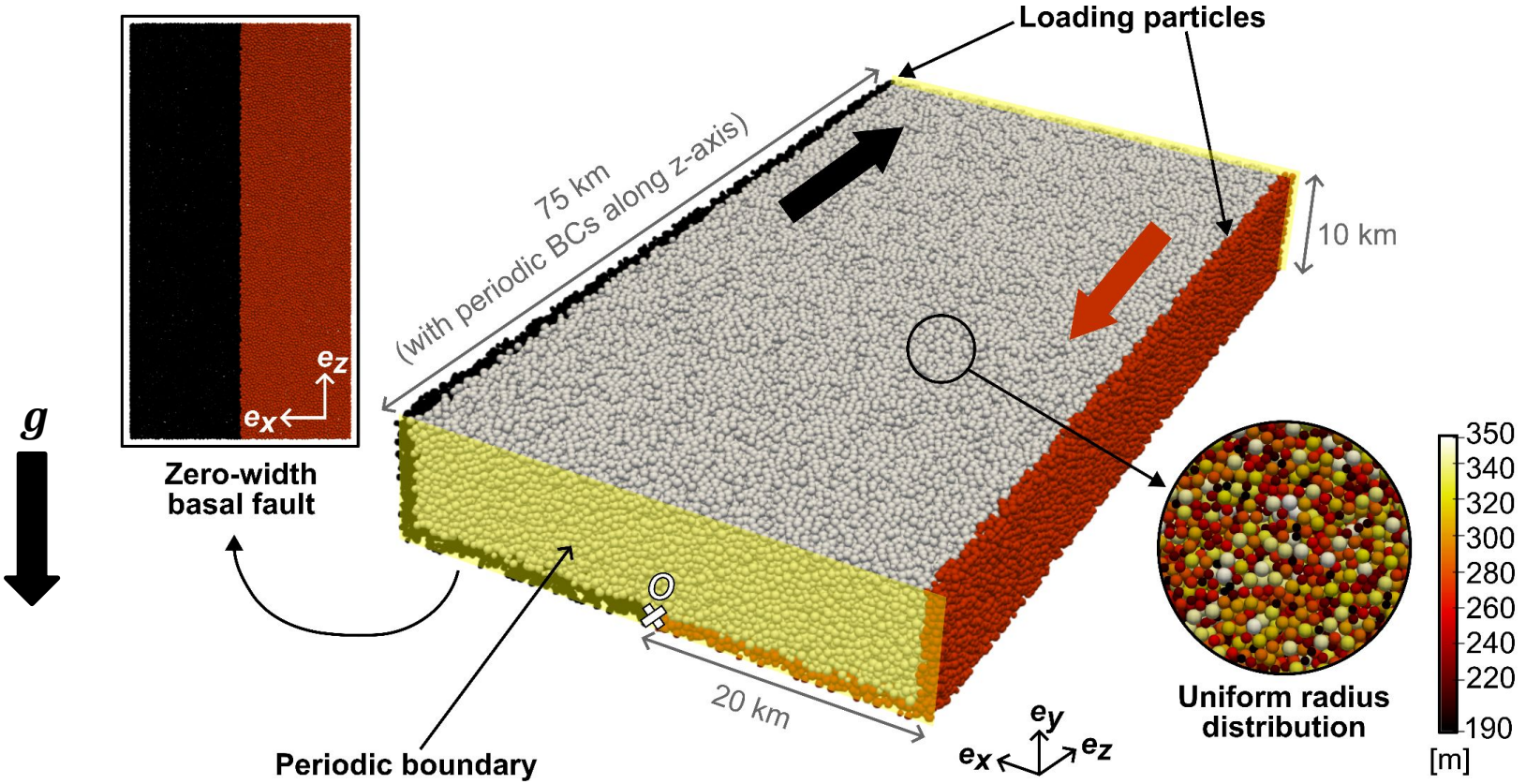
Strength parameters:

- Compressive strength
- Tensile strength
- Friction

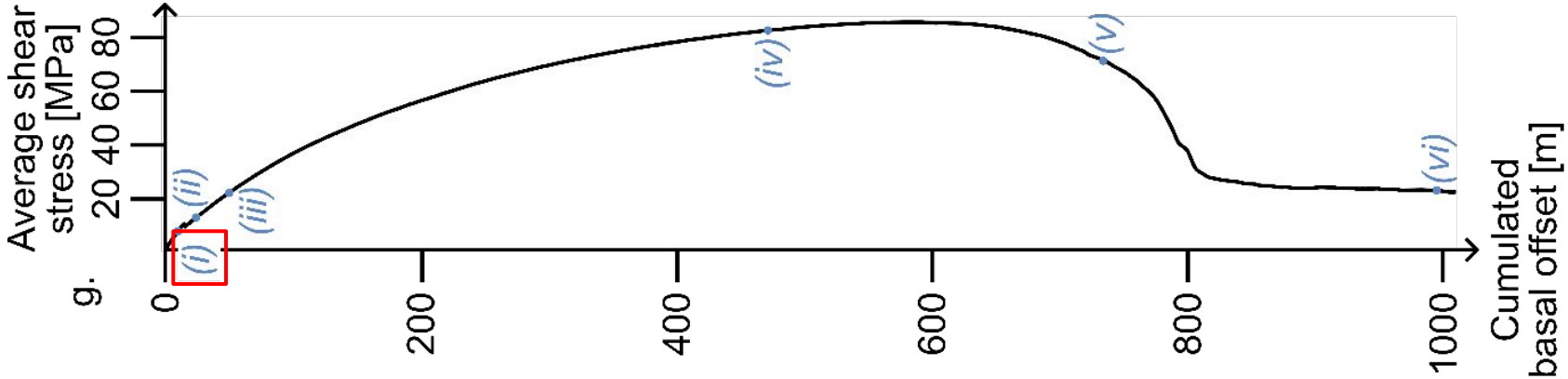


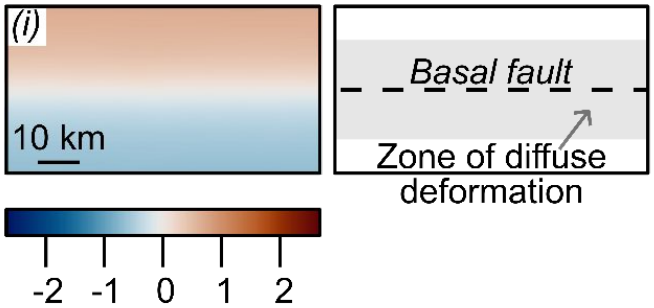
(Scholtès and Donzé, 2013)

Model setup


Loading particles
75 km
(with periodic BCs along z-axis)
10 km
e_z
e_x
Zero-width
basal fault
g
Periodic boundary
20 km
e_y
e_x
e_z
Uniform radius
distribution
350
340
320
300
280
260
240
220
190
[m]

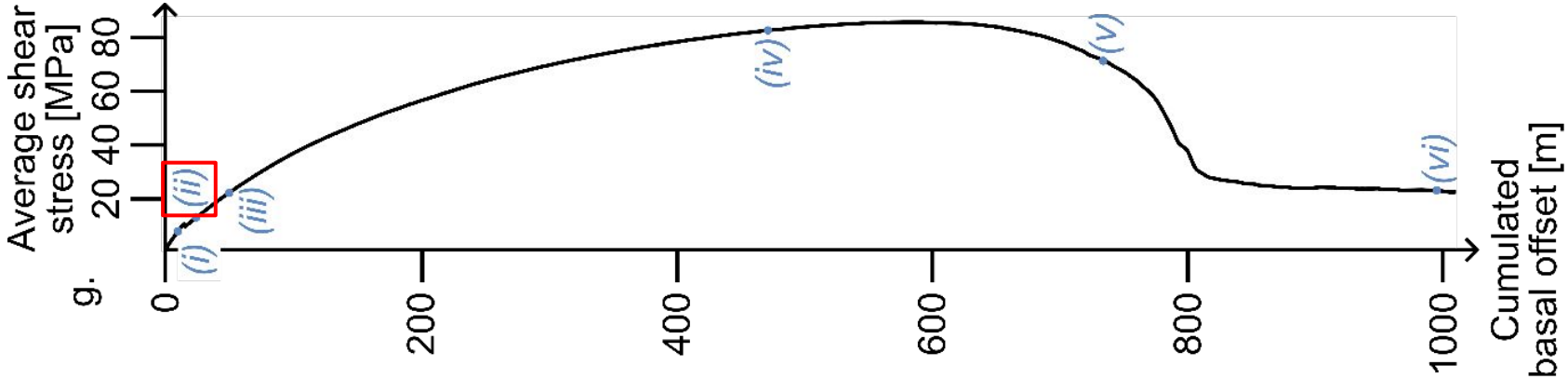
Long term evolution of the fault

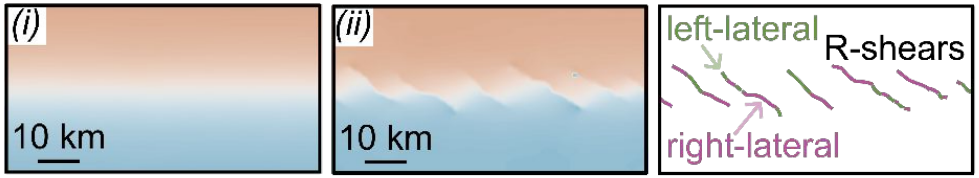


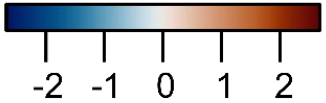


Surface displacement parallel to the basal fault [m]

Long term evolution of the fault







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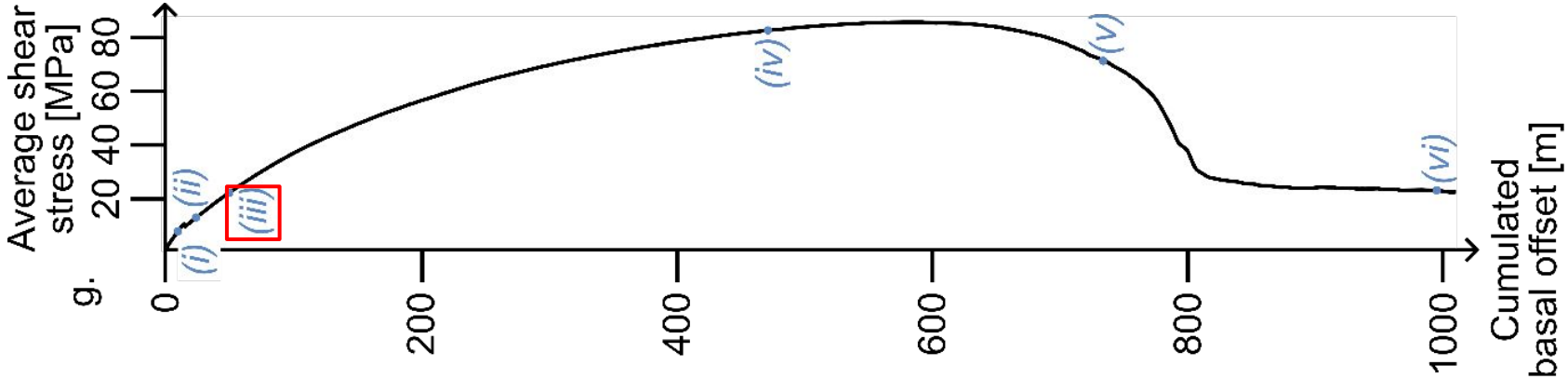

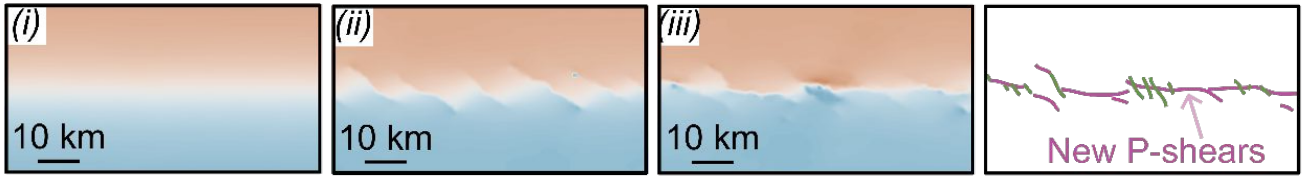

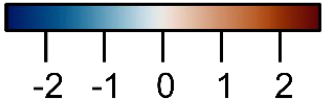

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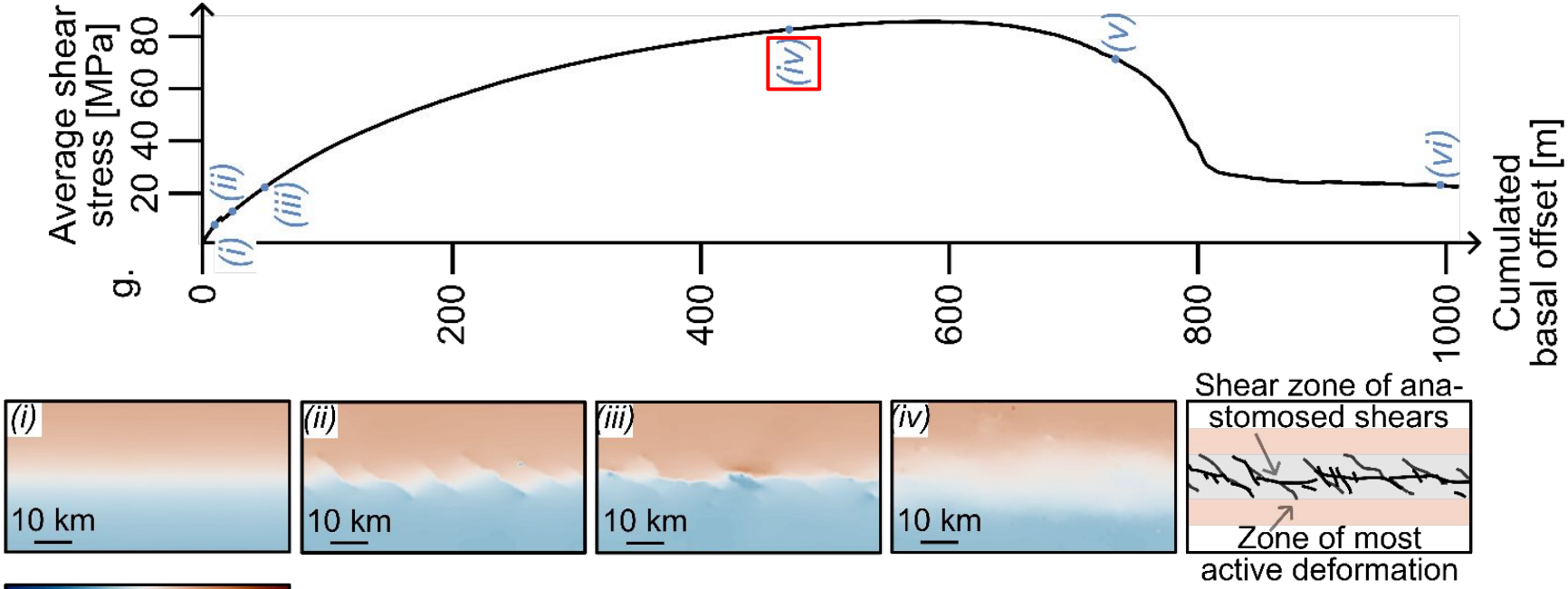

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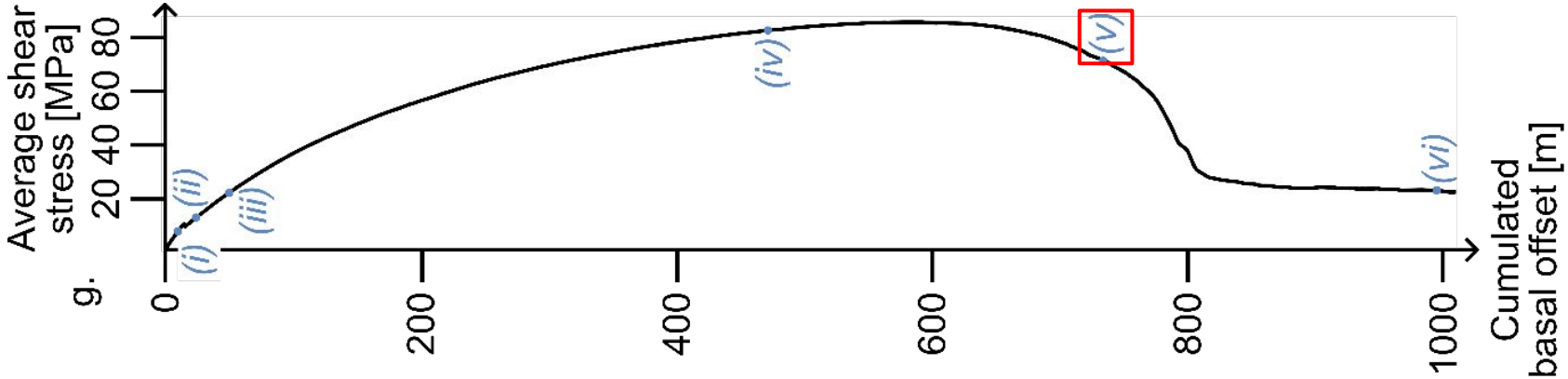

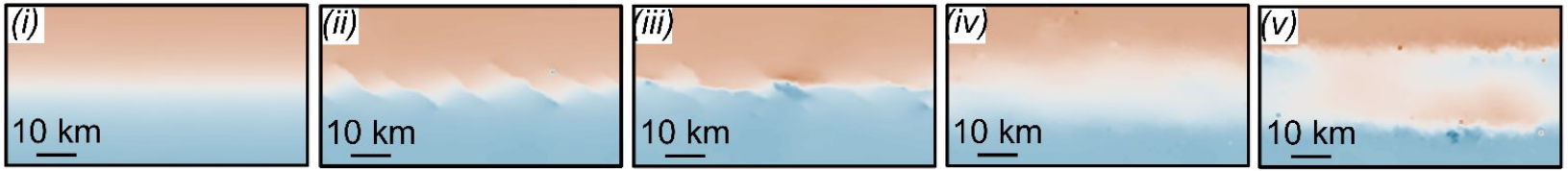

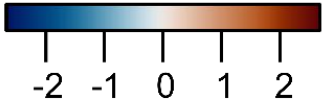

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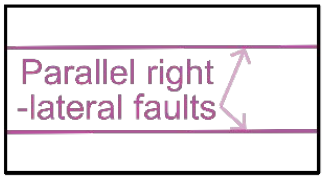
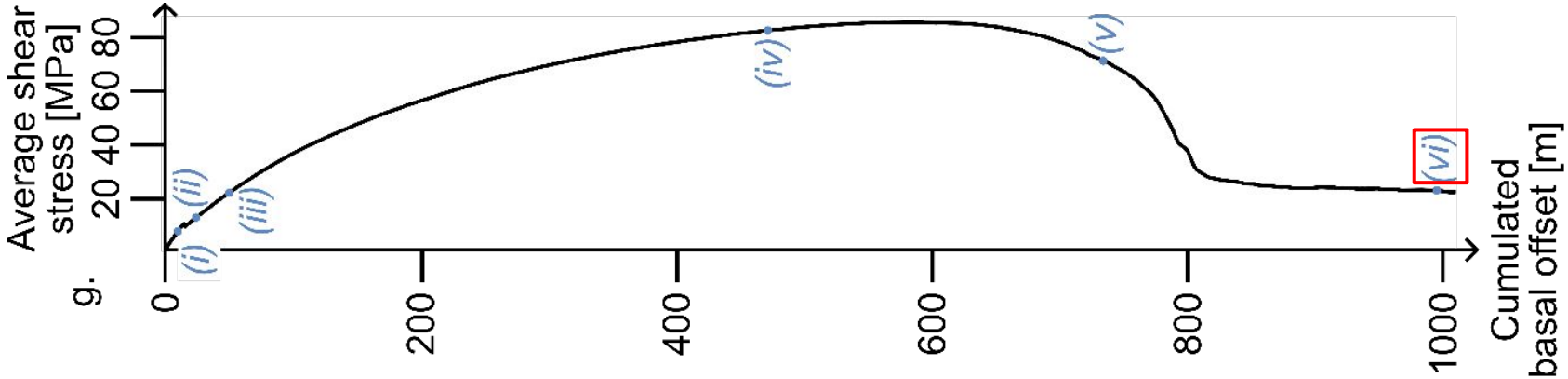
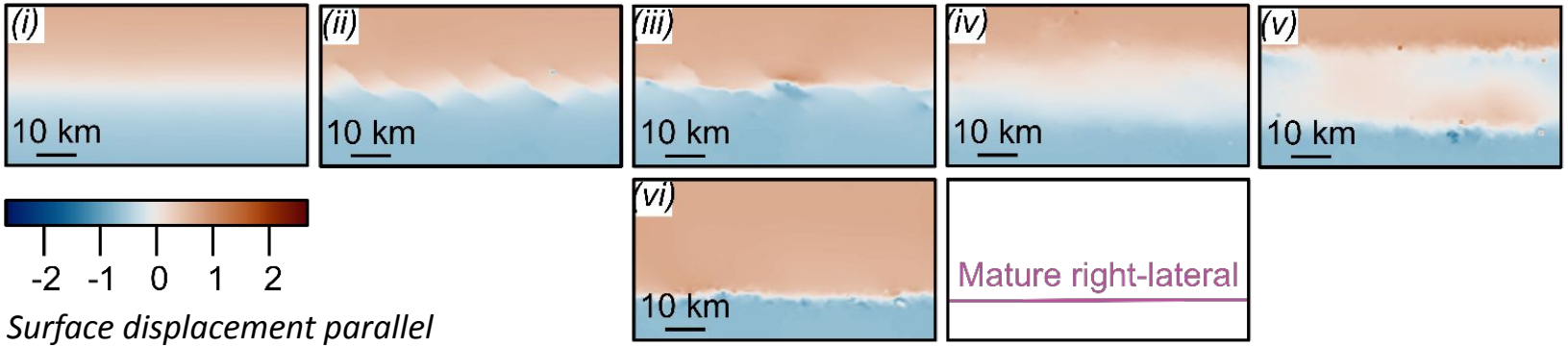


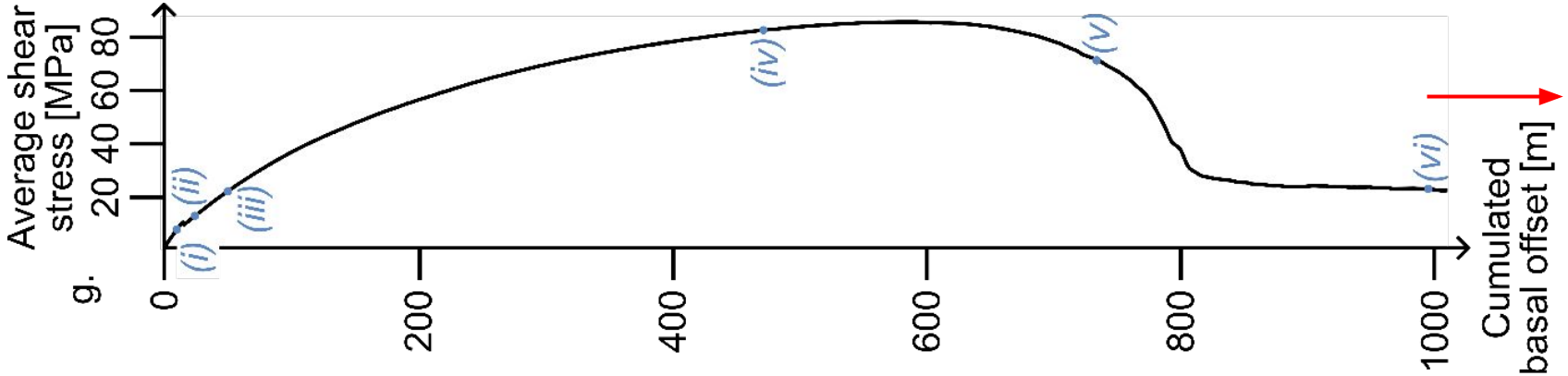
Long term evolution of the fault

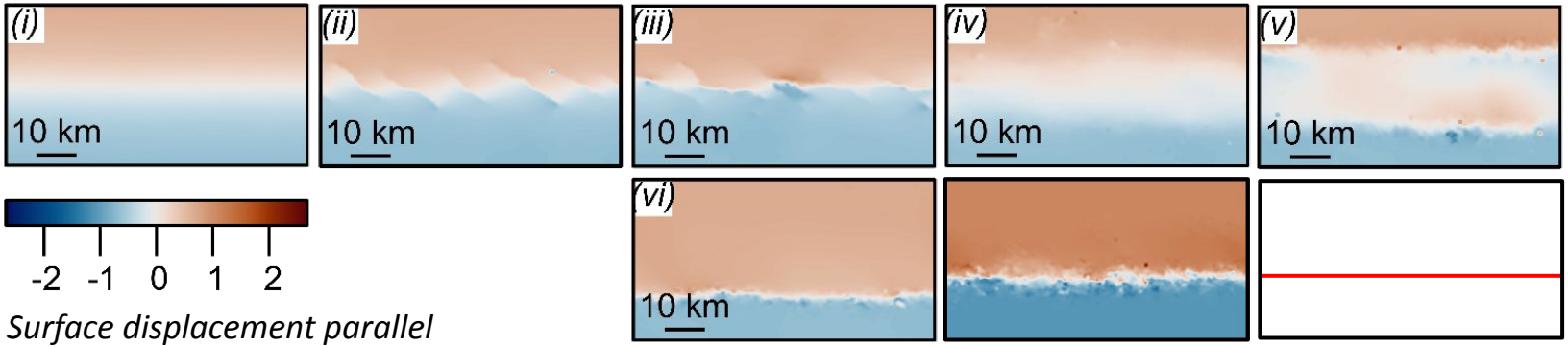




Surface displacement parallel to the basal fault [m]

Long term evolution of the fault





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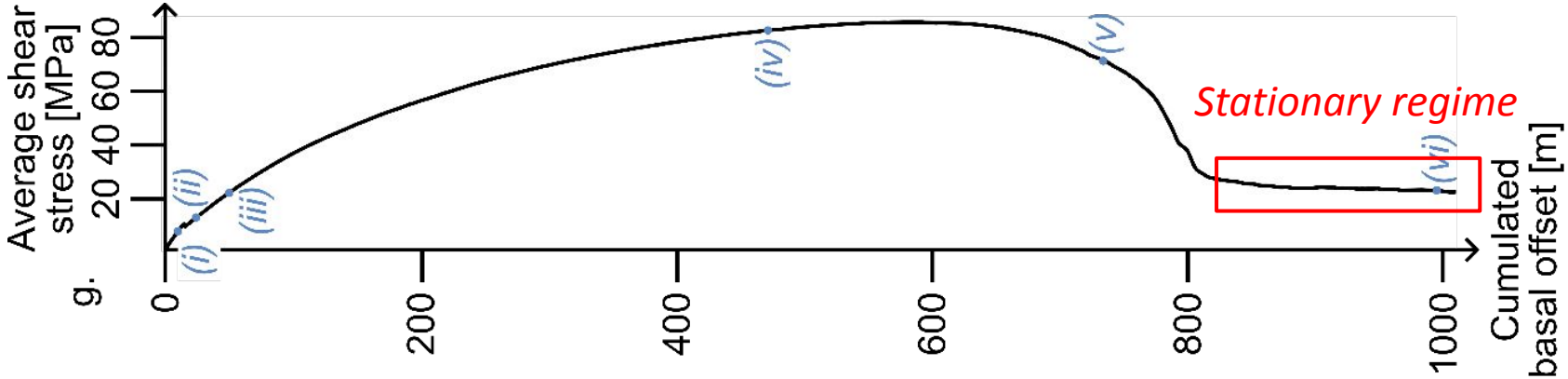
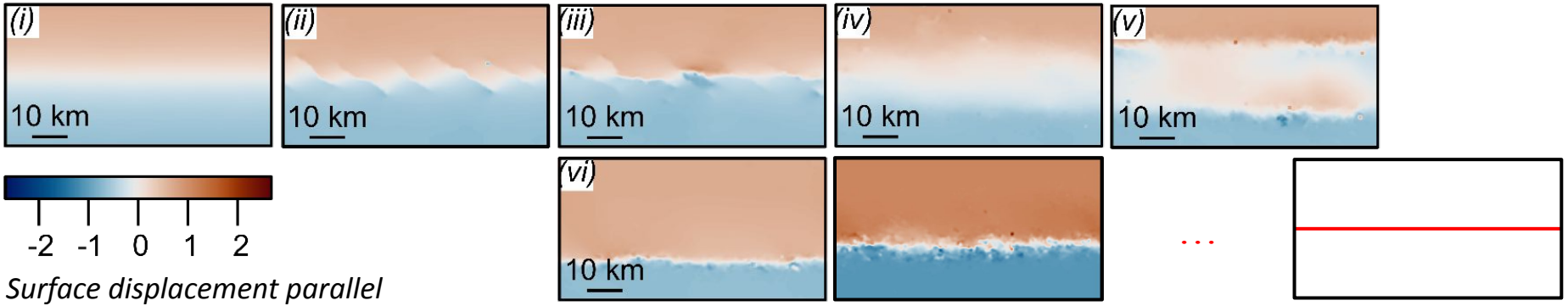
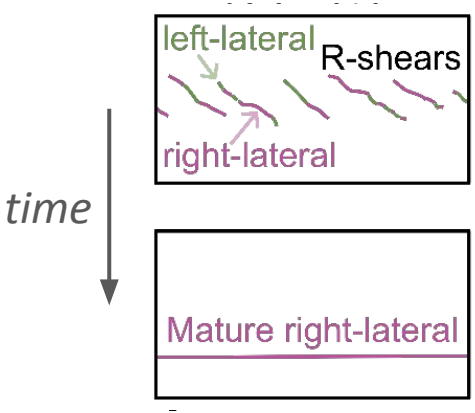




Surface displacement parallel to the basal fault [m]

Long term evolution of the fault

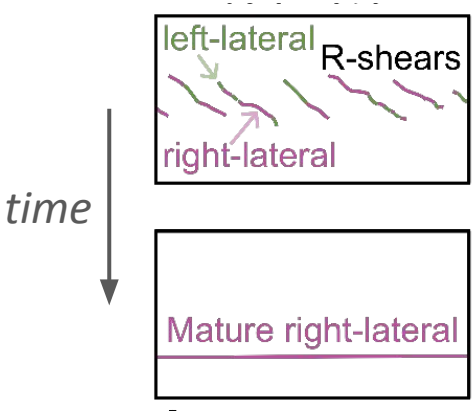
From an en échelon pattern to a throughgoing fault…

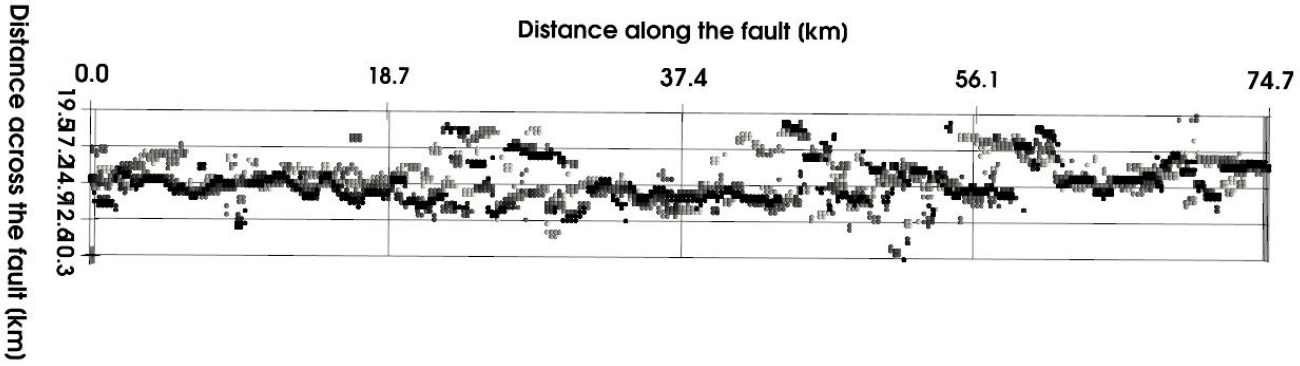


Long term evolution of the fault

From an en échelon pattern to a throughgoing fault…

…with some remaining degree of complexity





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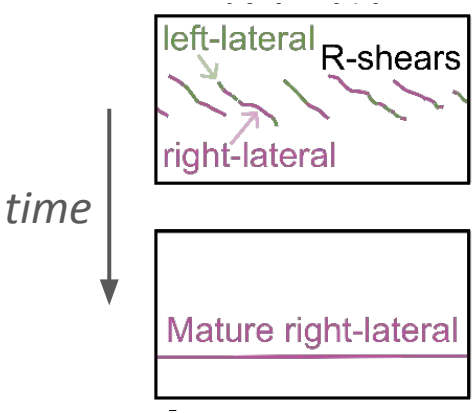
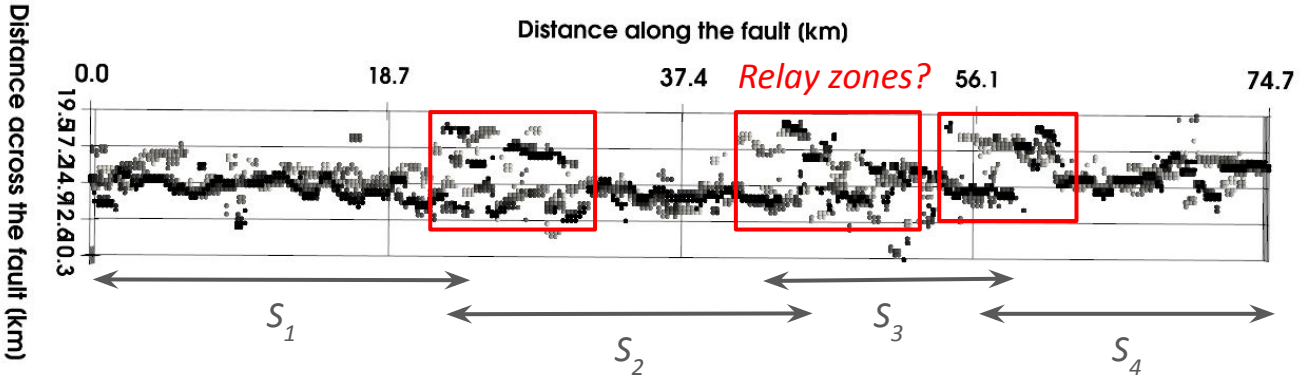
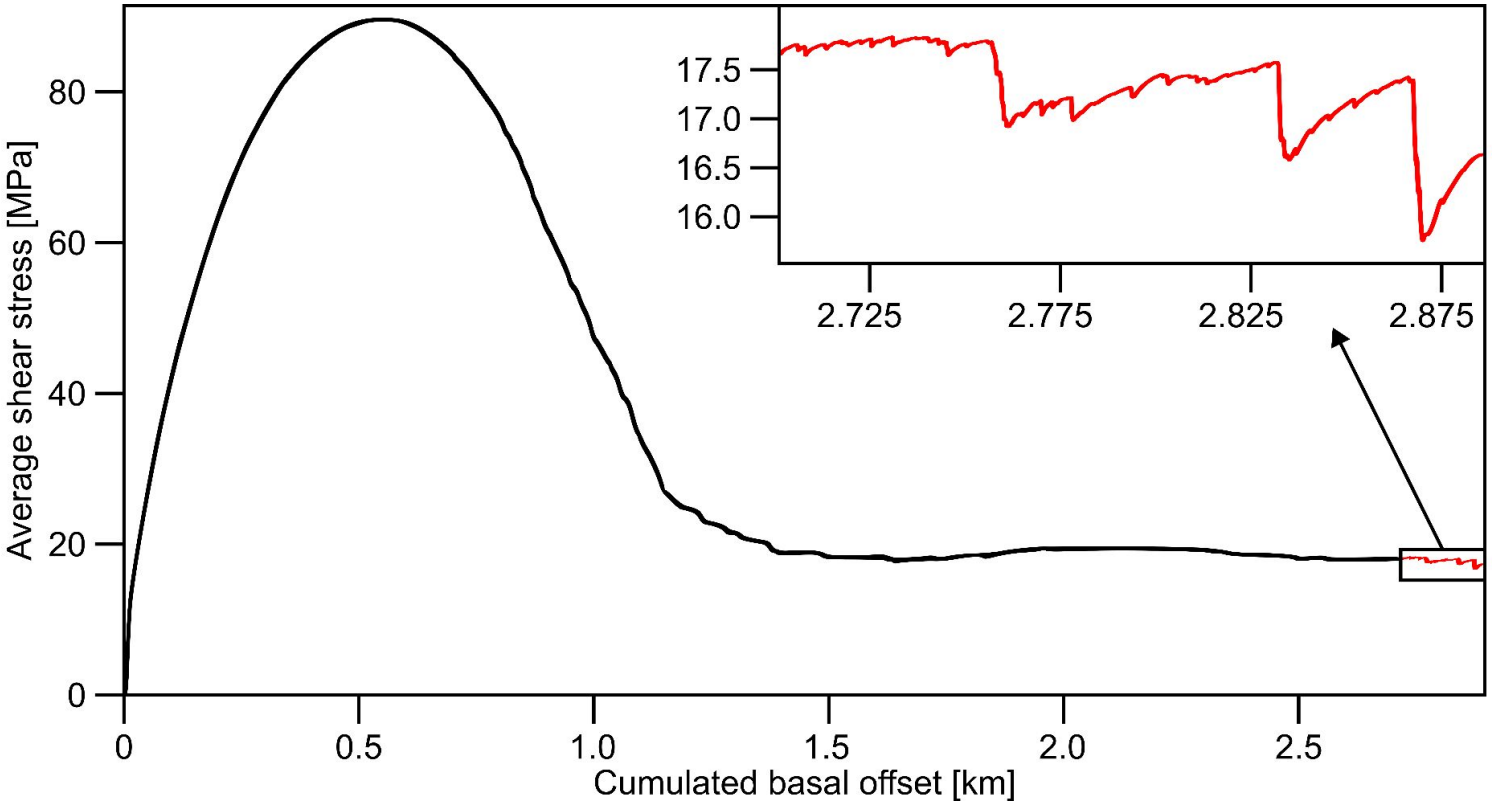




Short term seismicity on the fault



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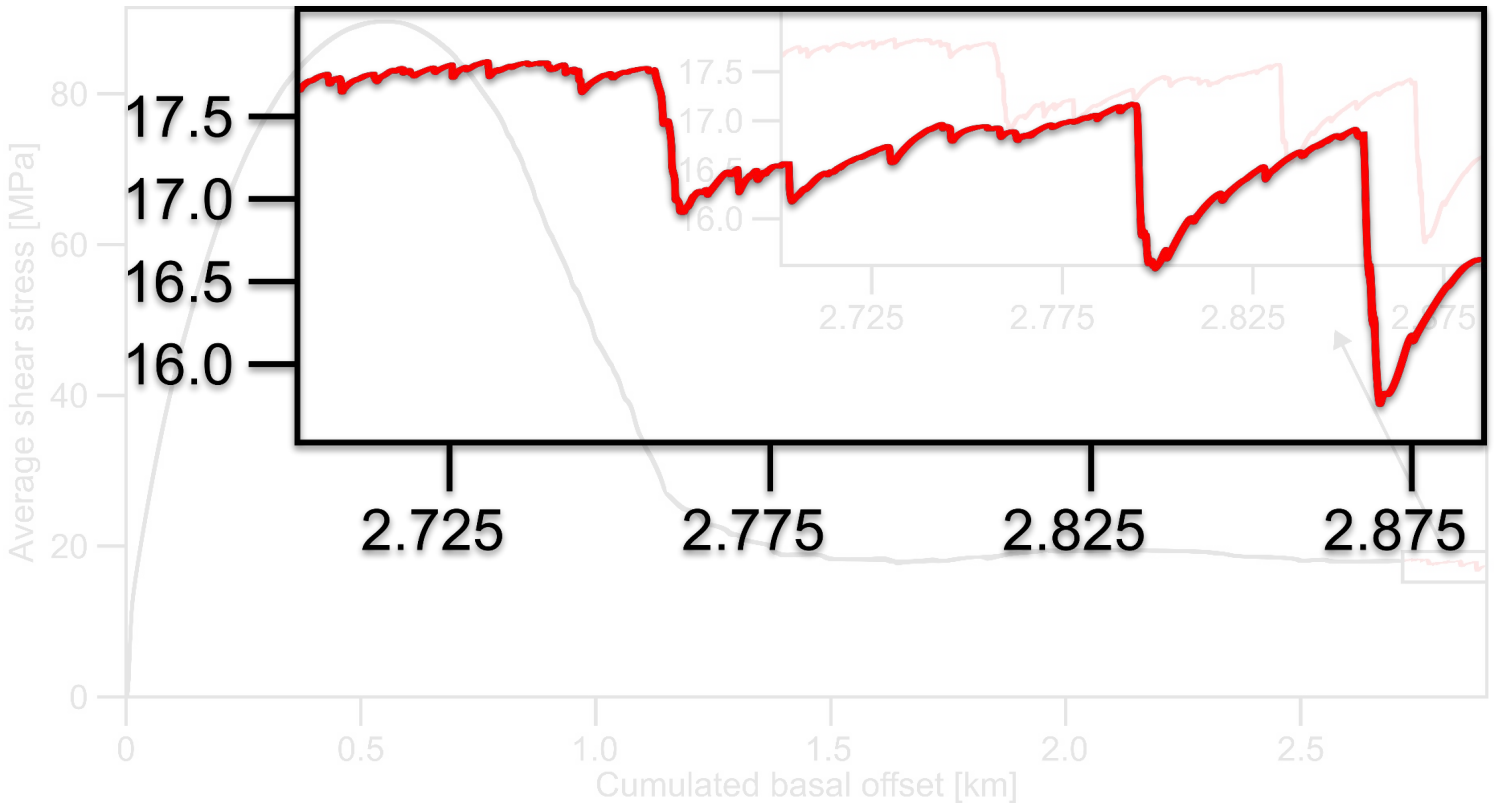

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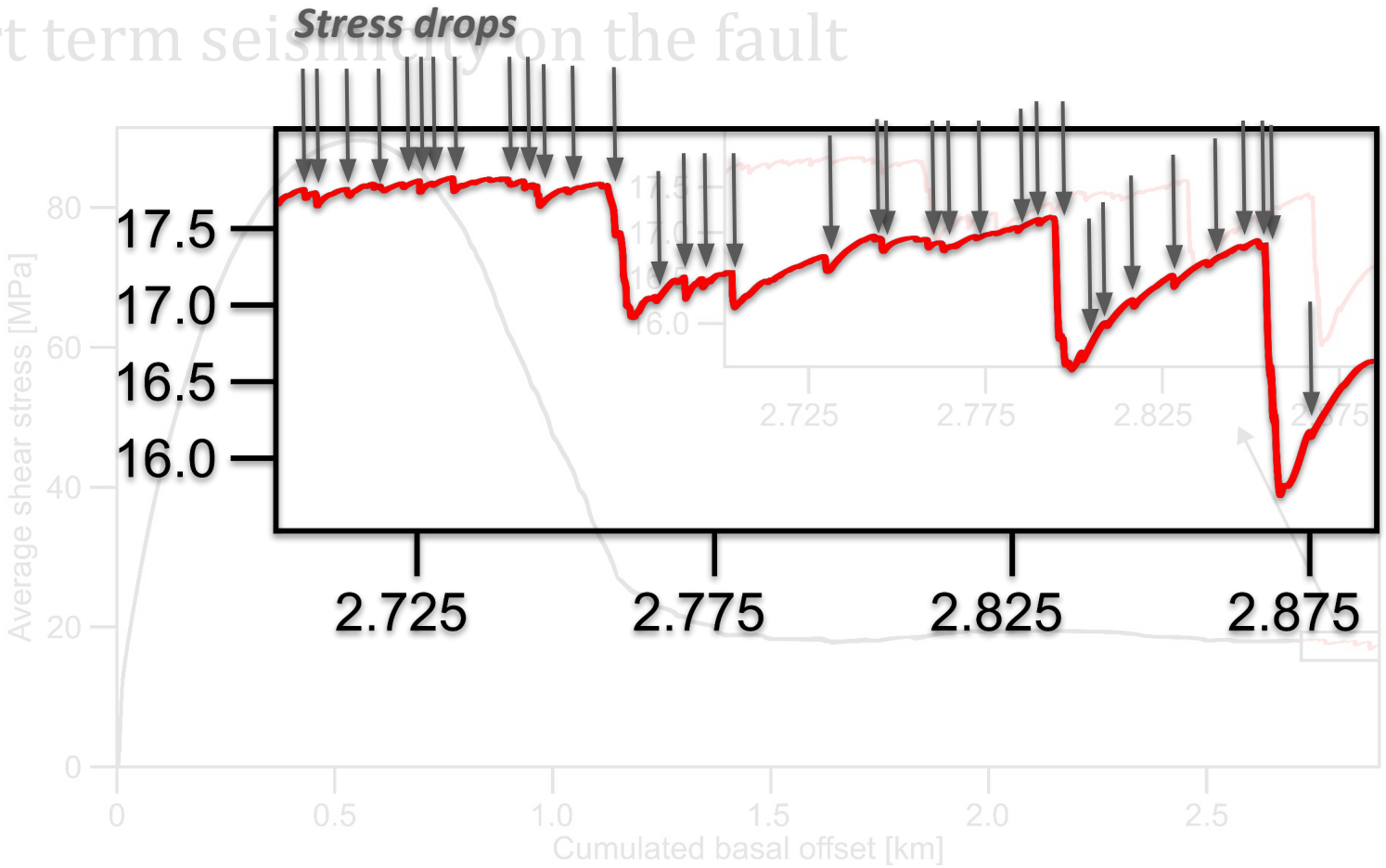

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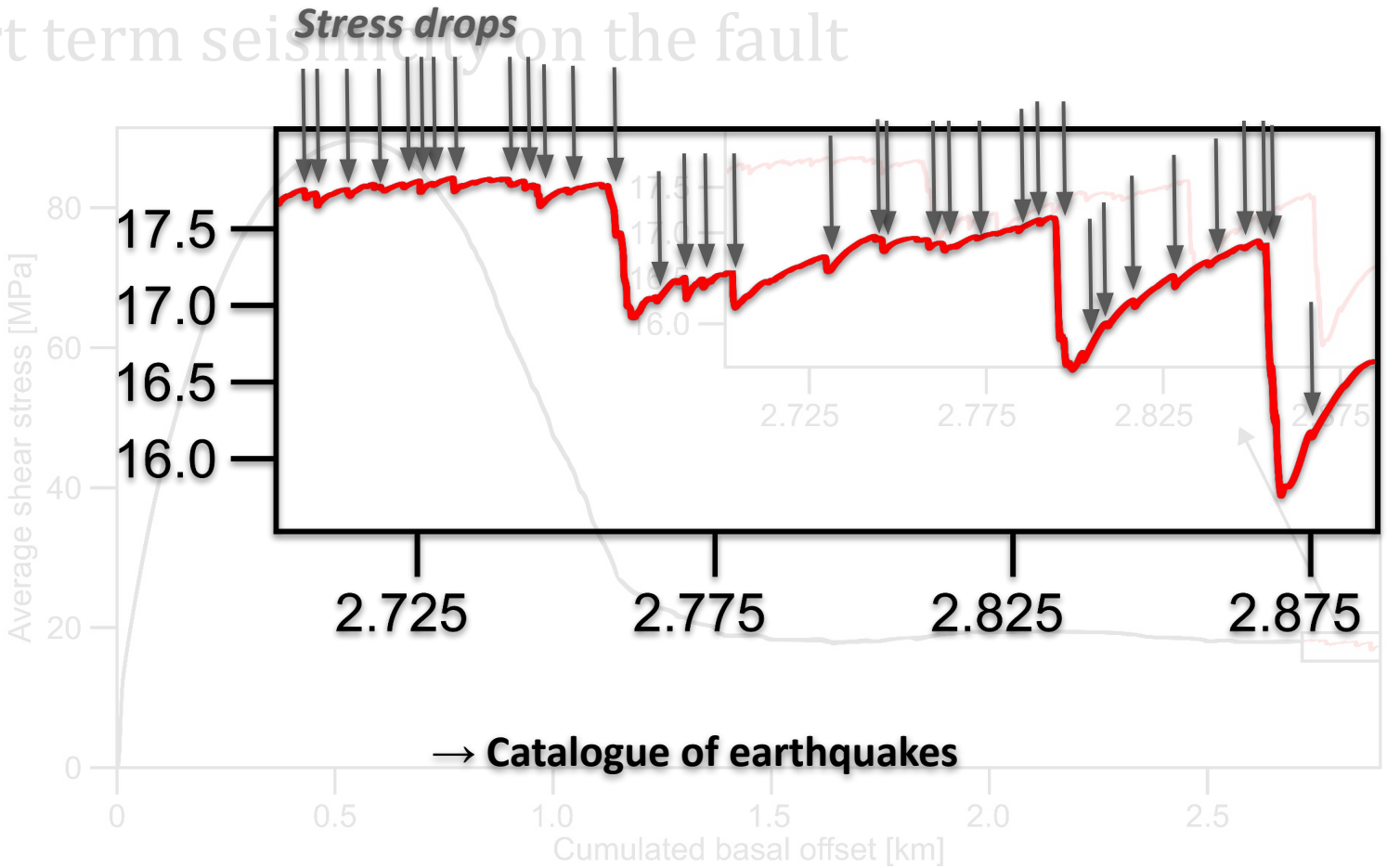
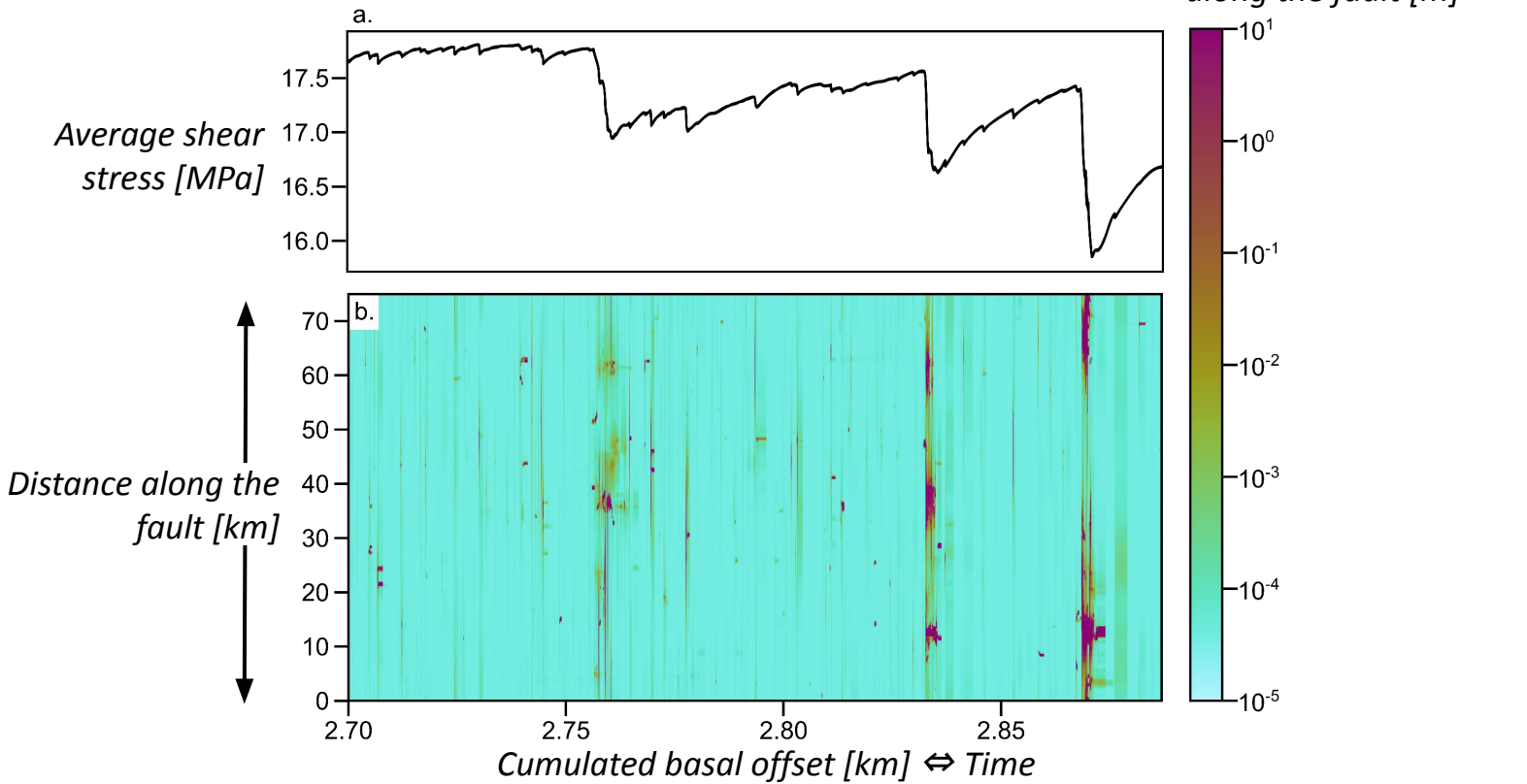


→ **Catalogue of earthquakes**

Short term seismicity on the fault

Map view of the earthquake catalogue



Short term seismicity on the fault

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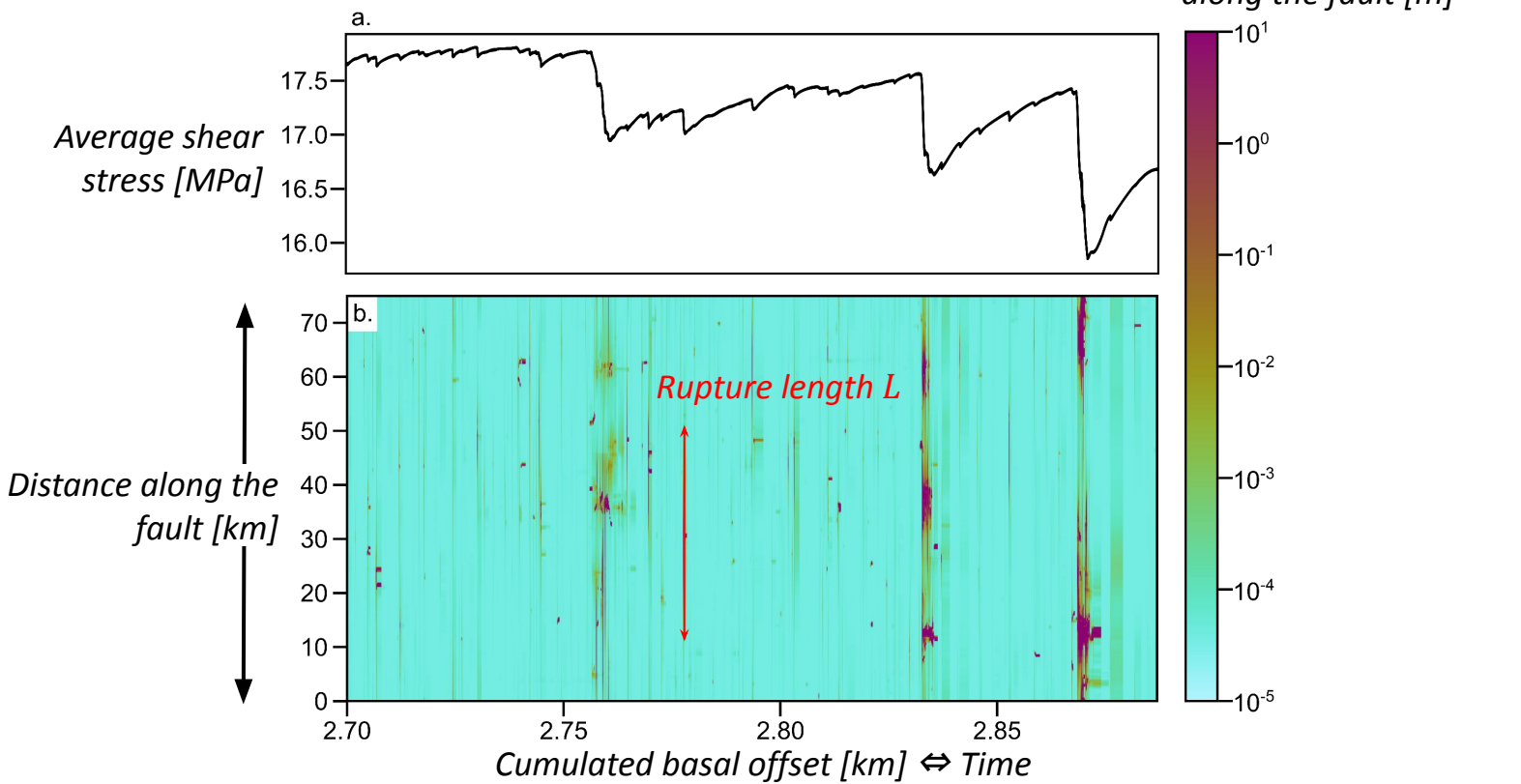
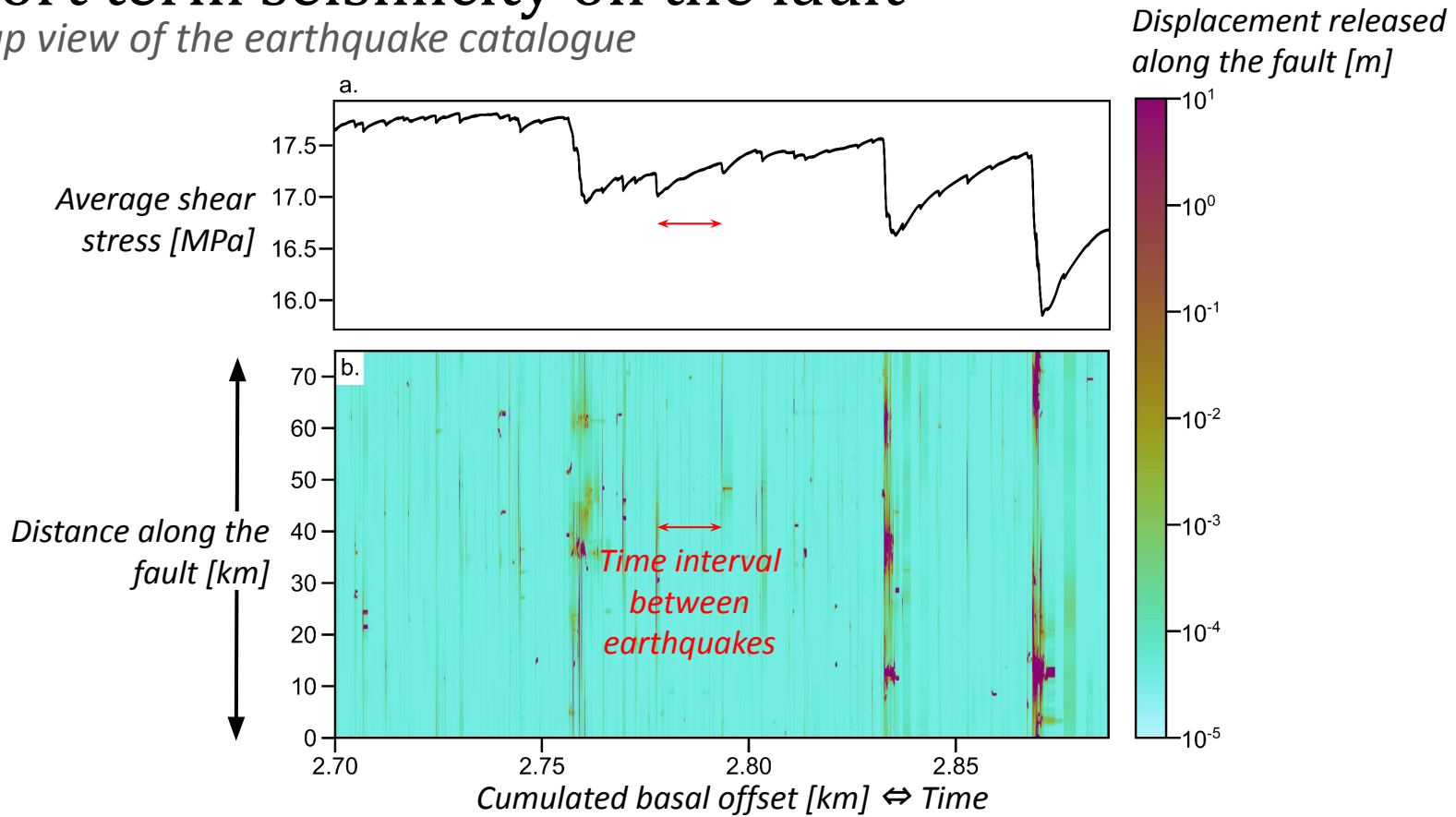


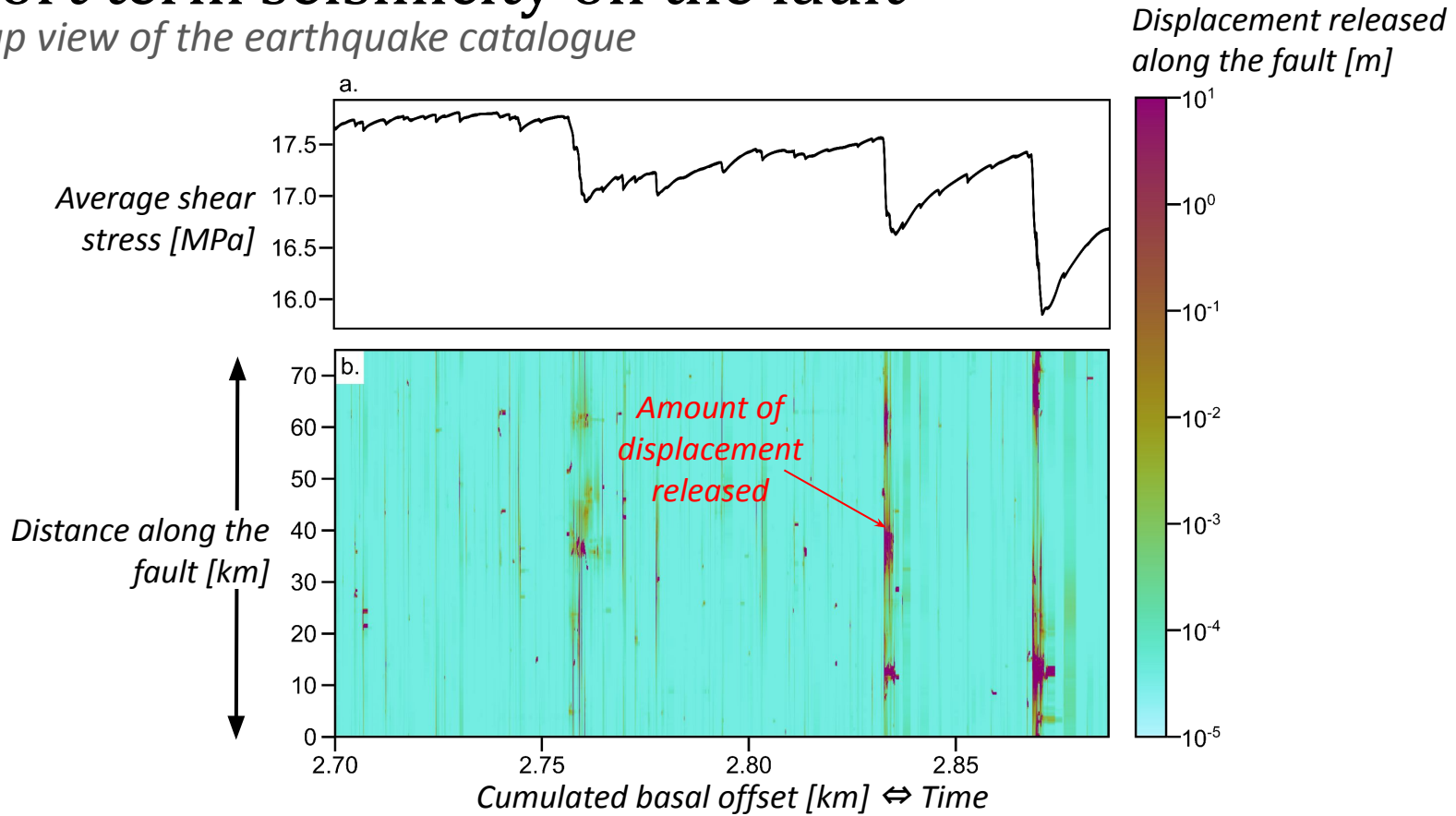
Short term seismicity on the fault

Map view of the earthquake catalogue



Short term seismicity on the fault

Map view of the earthquake catalogue



Short term seismicity on the fault

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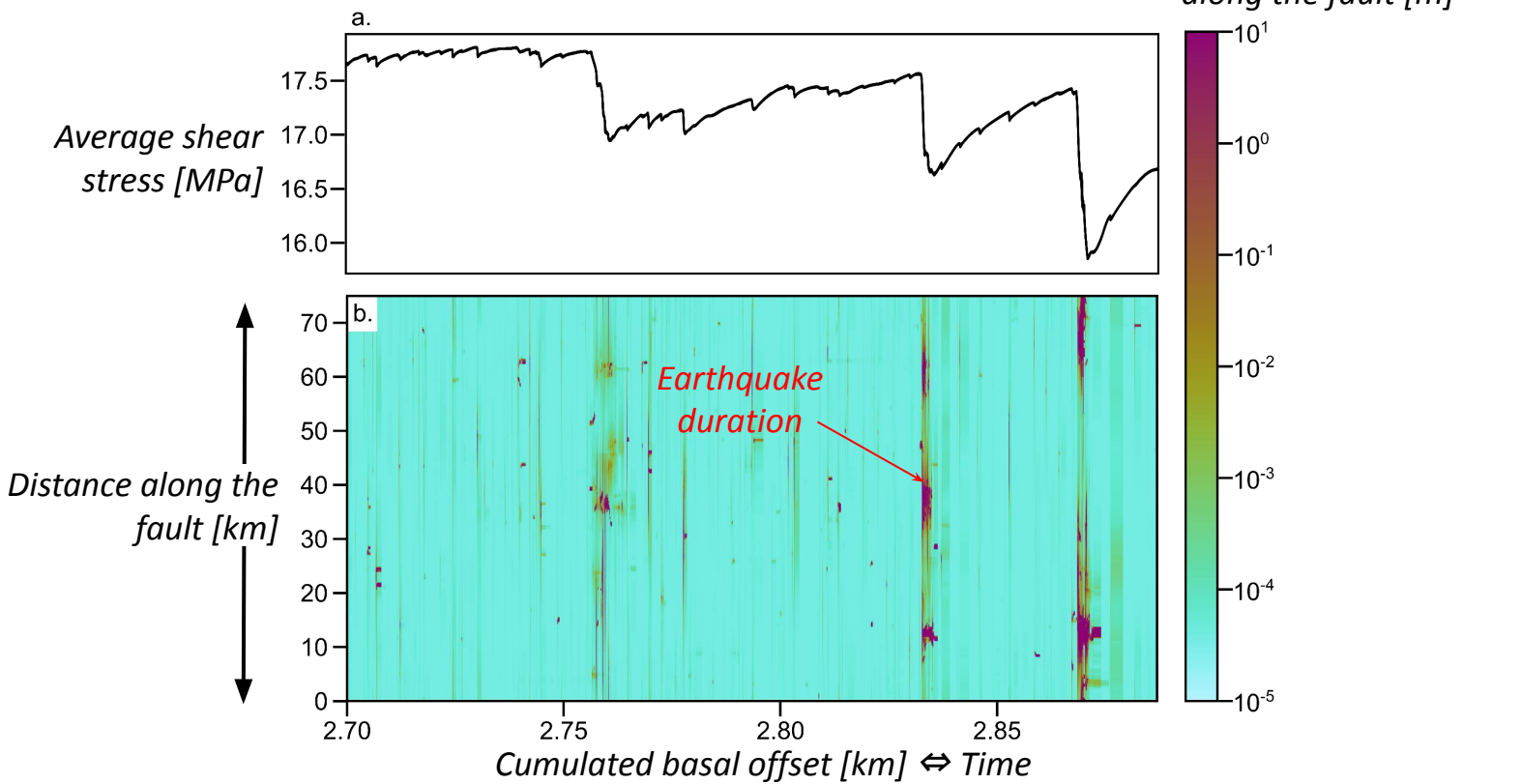
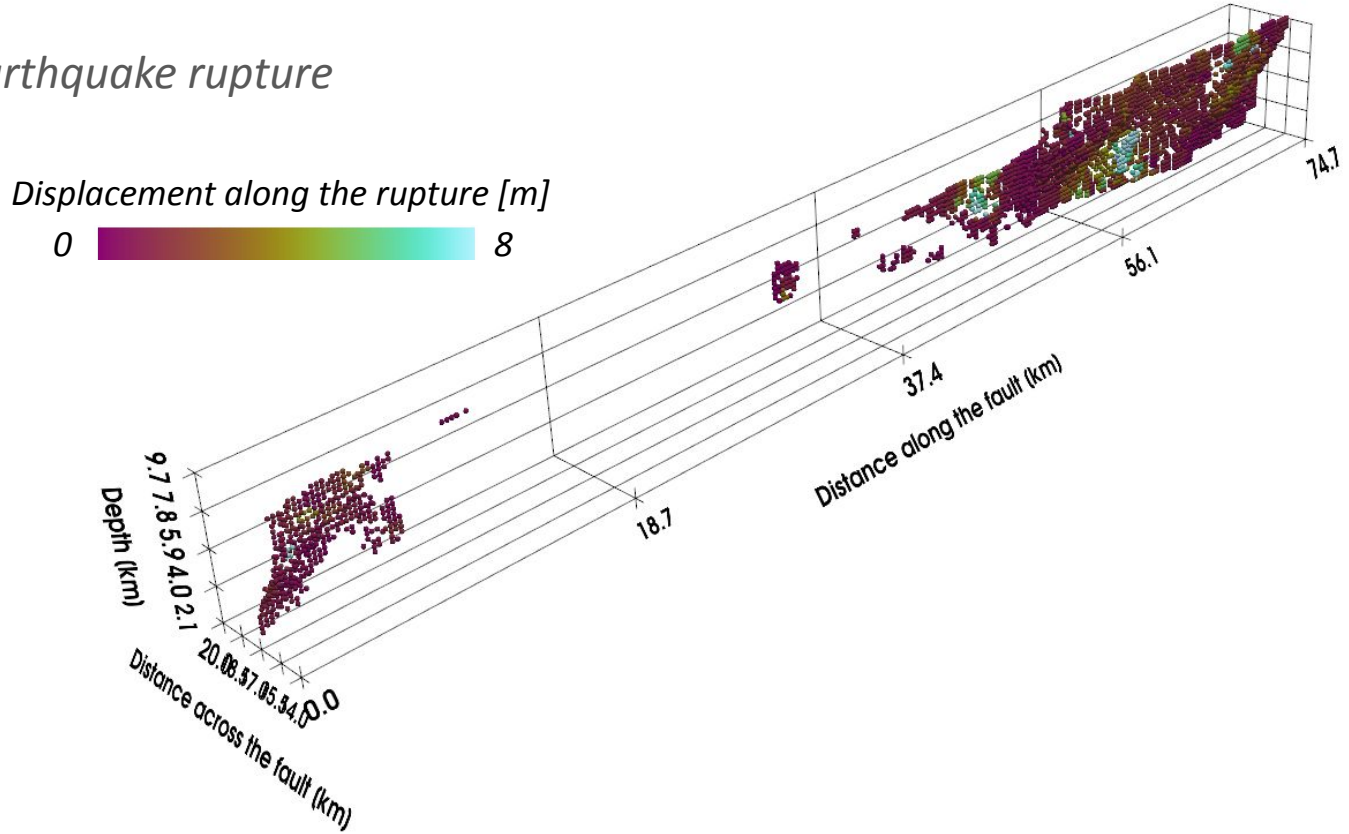


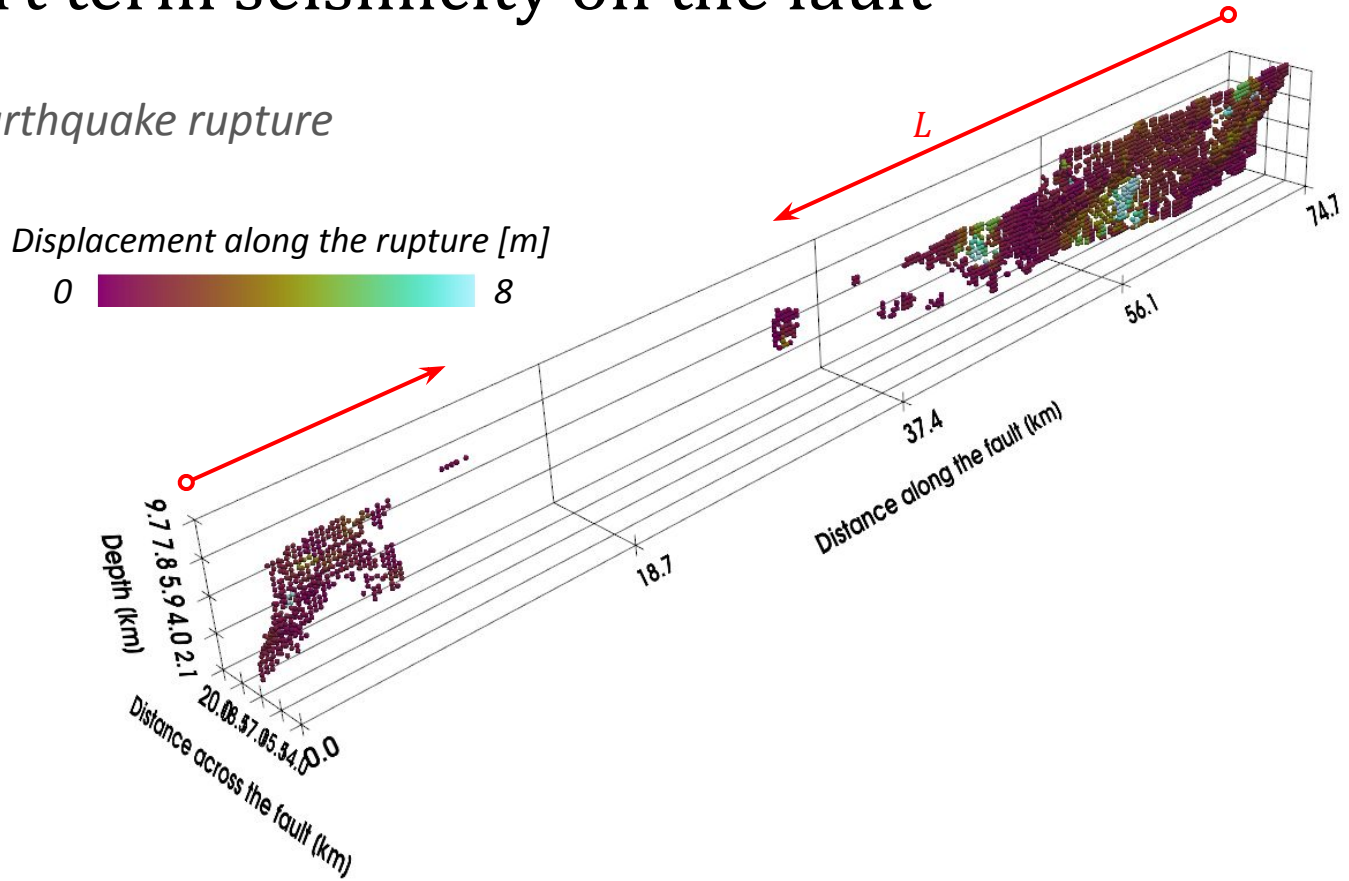
Short term seismicity on the fault

3D earthquake rupture



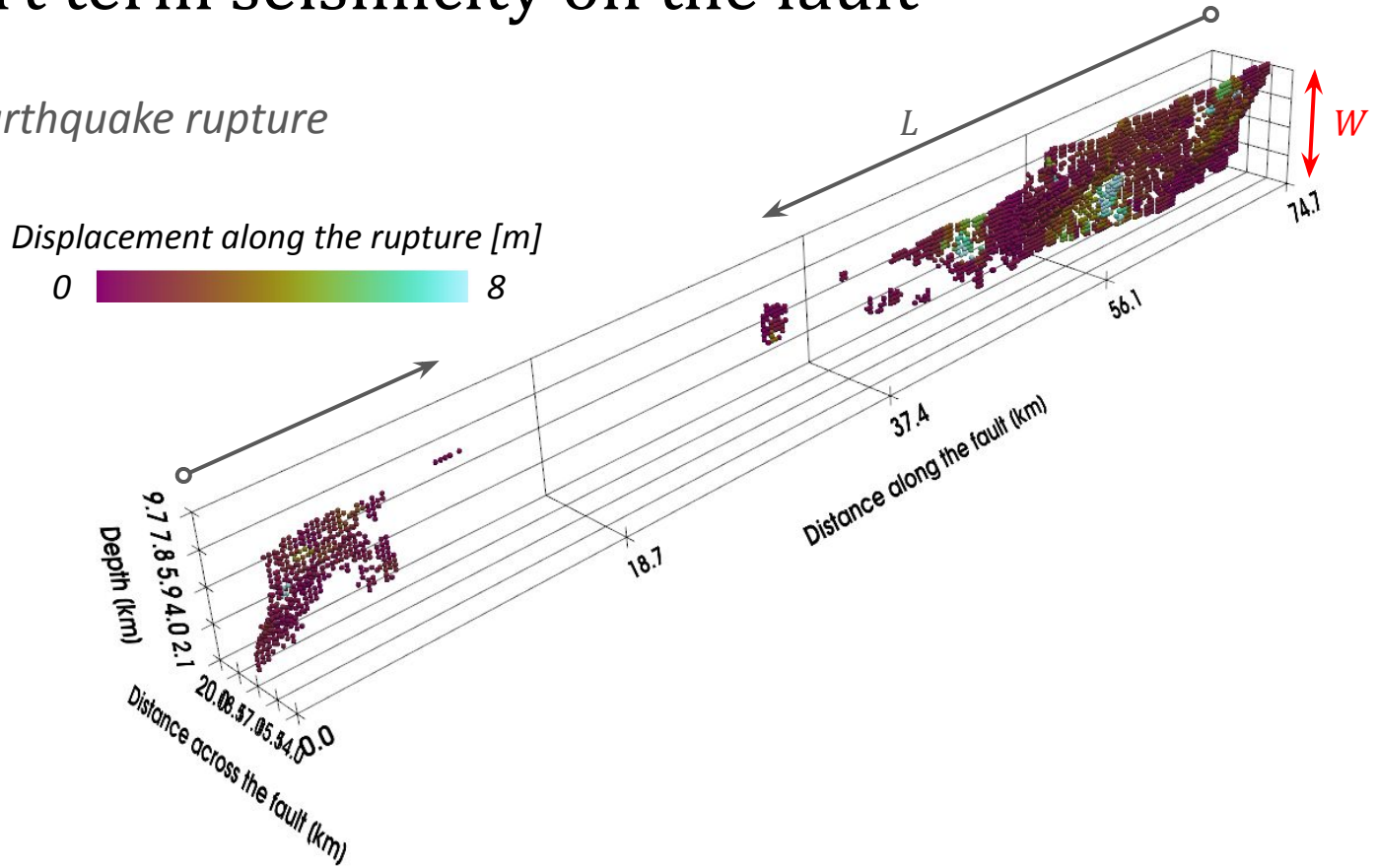
Short term seismicity on the fault

3D earthquake rupture



Short term seismicity on the fault

3D earthquake rupture



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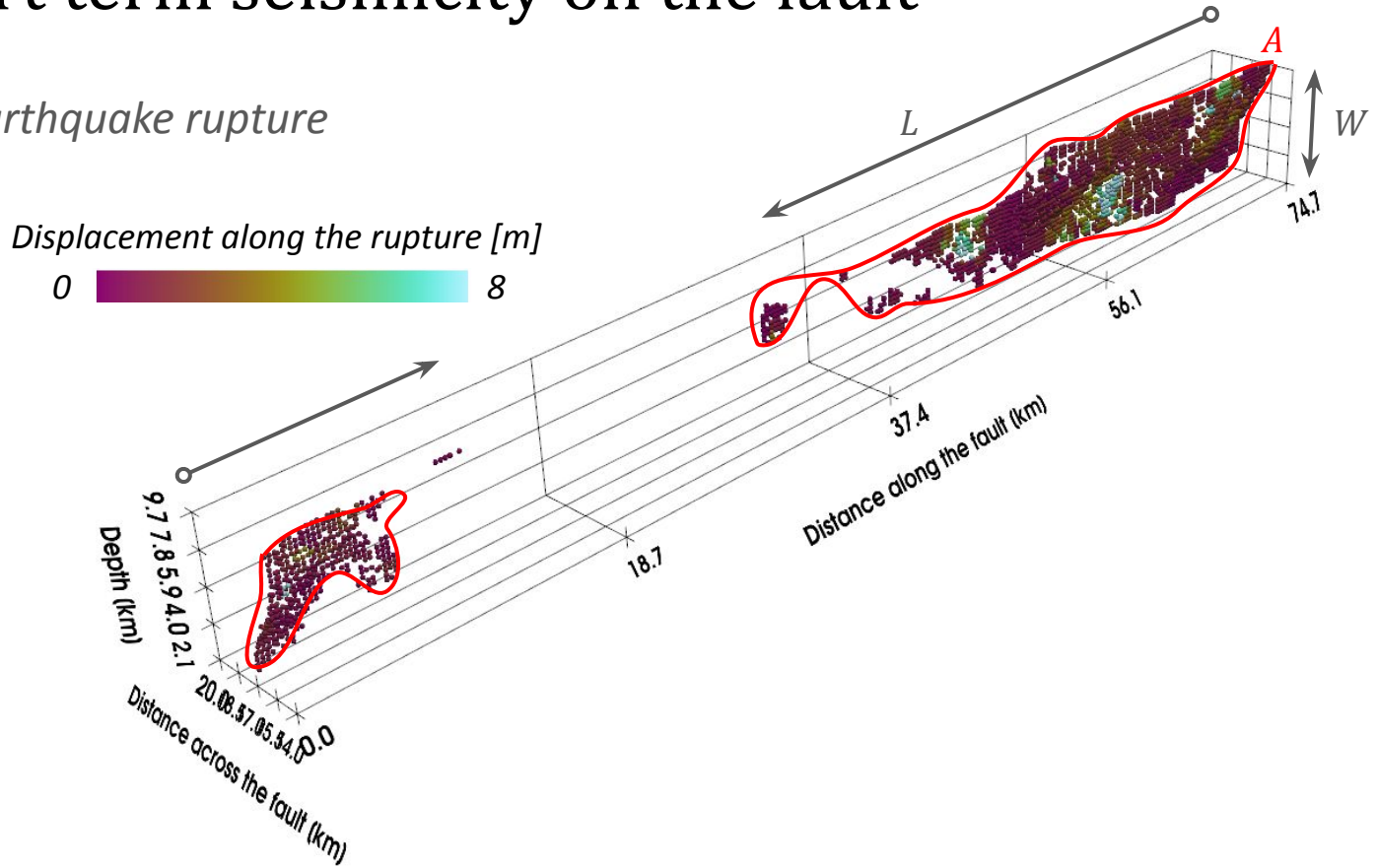

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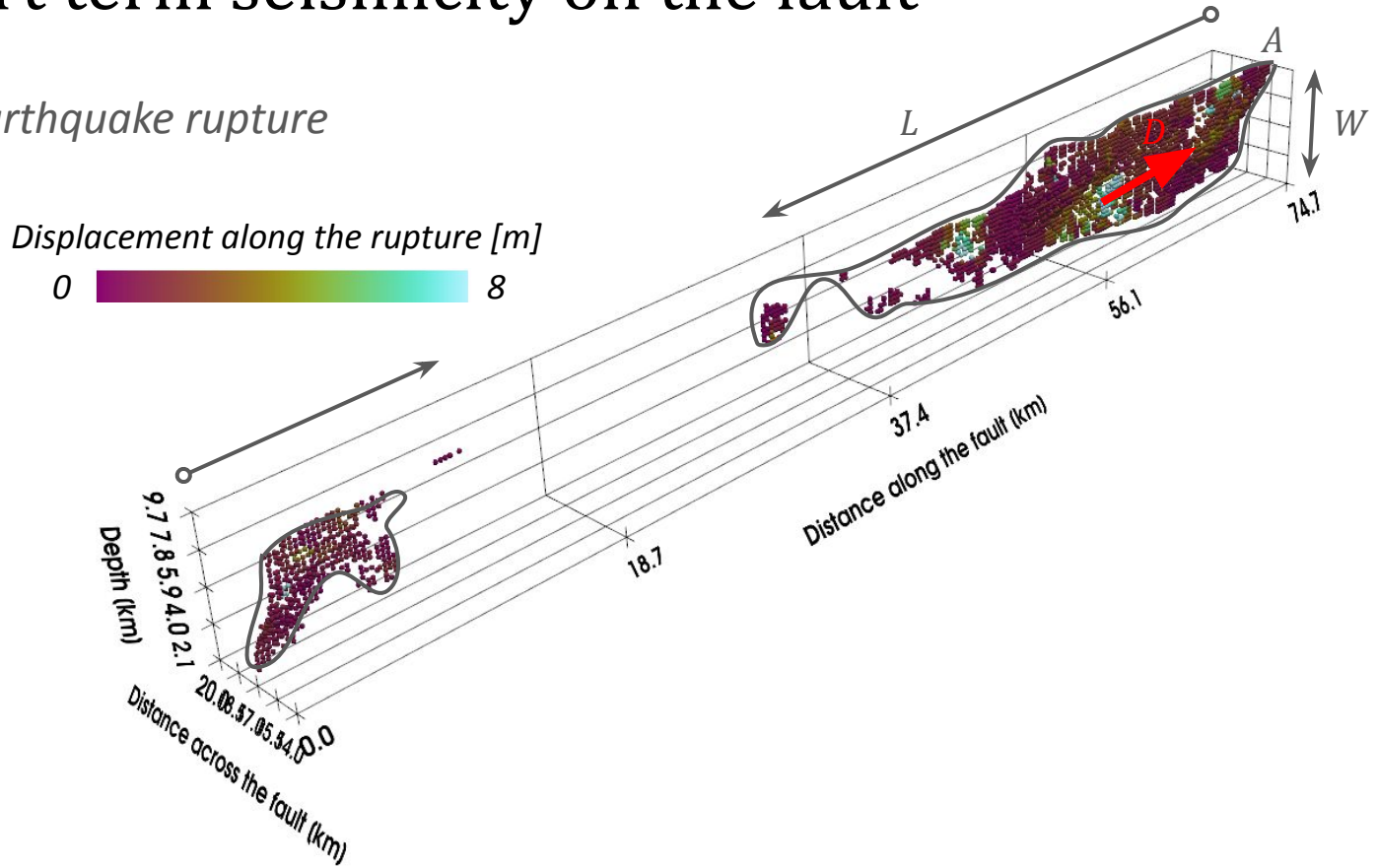

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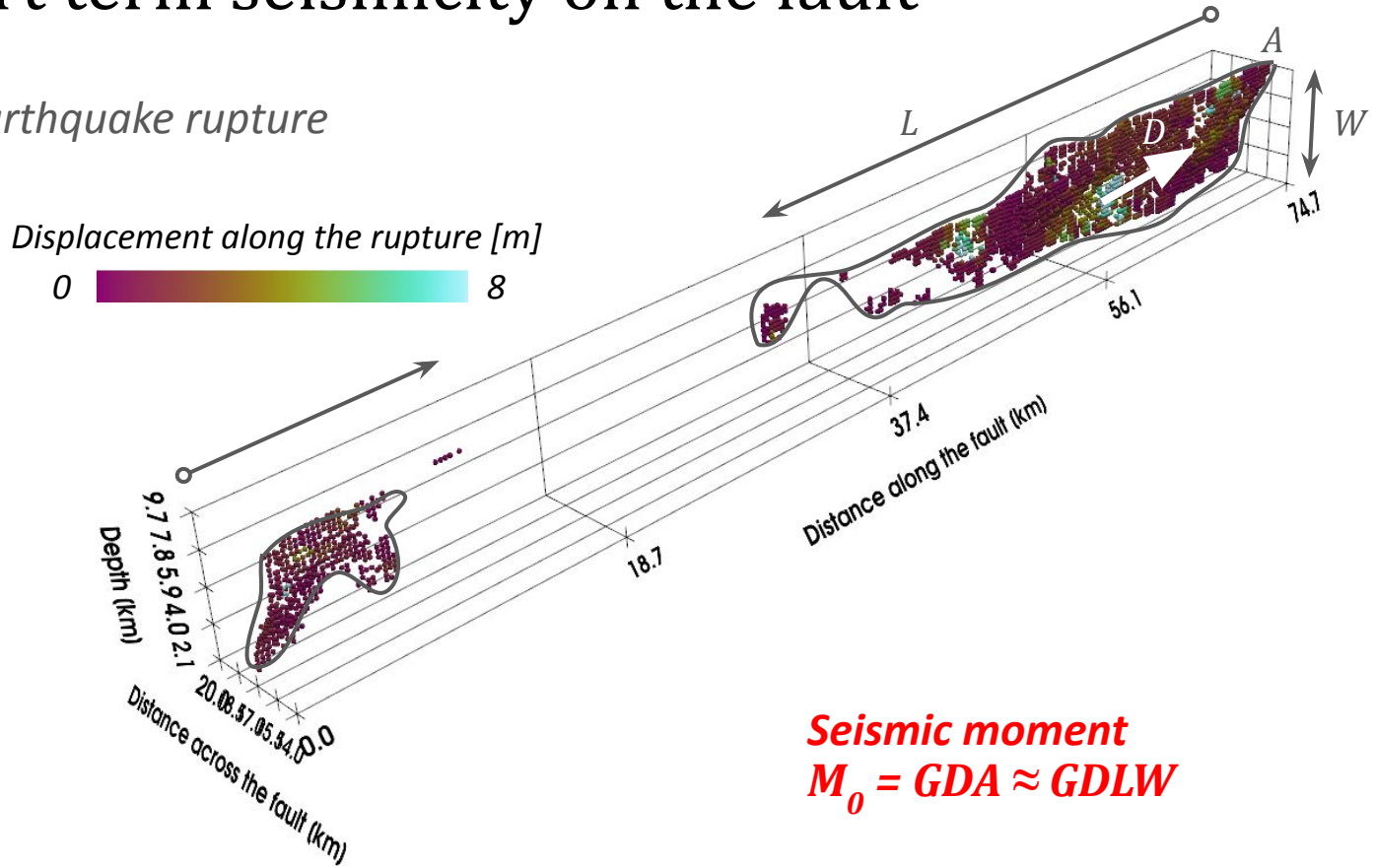
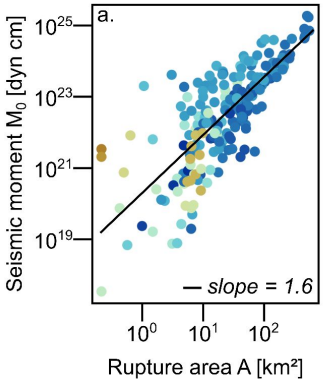
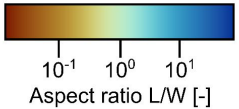


Seismic moment
$M_0 = GDA \approx GDLW$

Short term seismicity on the fault

$$M_0 = GDLW$$

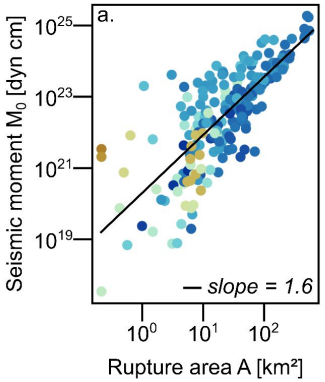


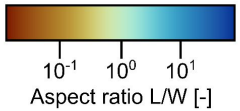


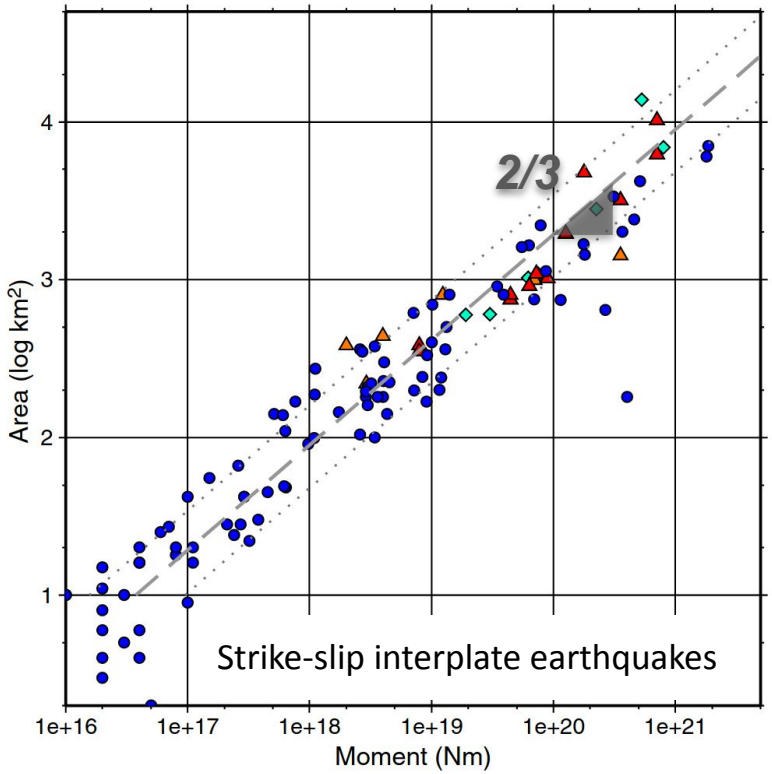
Short term seismicity on the fault

(Leonard, 2010)

$M_0 = GDLW$







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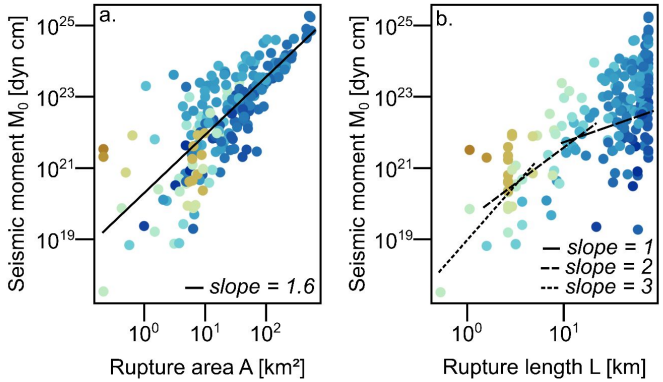

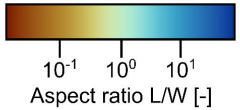

Short term seismicity on the fault

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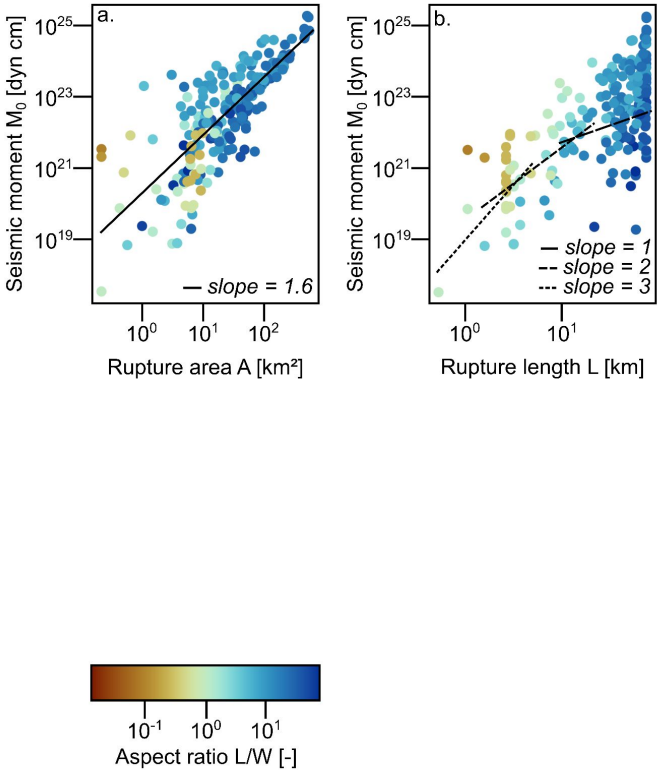
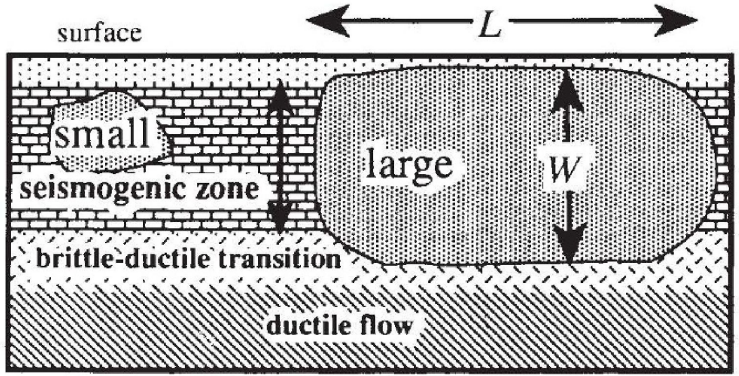


Small earthquakes (L~W)

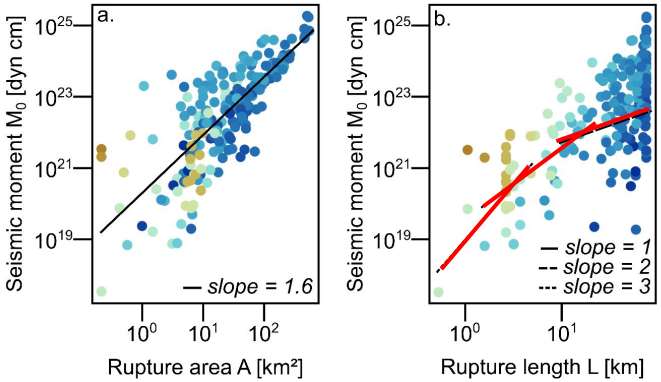
Large earthquakes (L>W or L>>W)

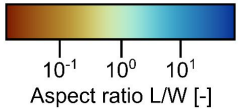


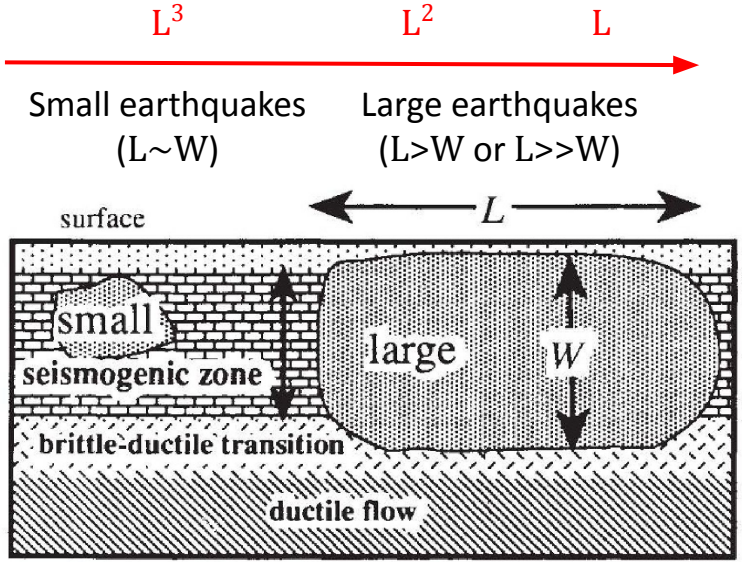
(Pacheco, 1992)

Short term seismicity on the fault

$M_0 = GDLW$







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Short term seismicity on the fault

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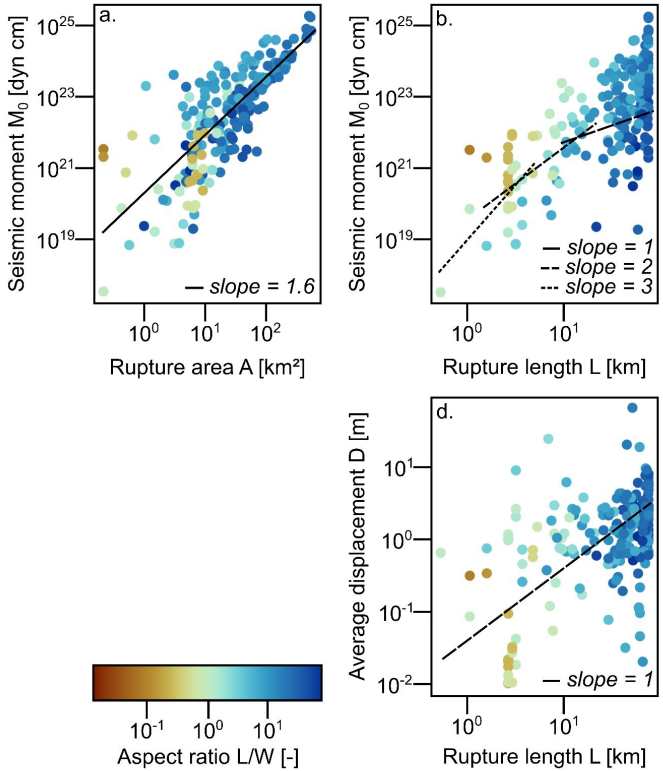
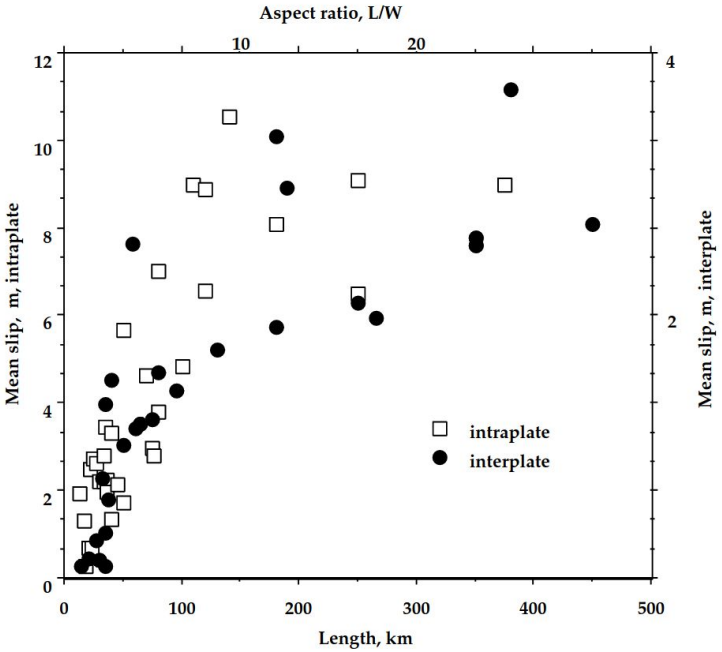


(Shaw and Scholz, 2001)



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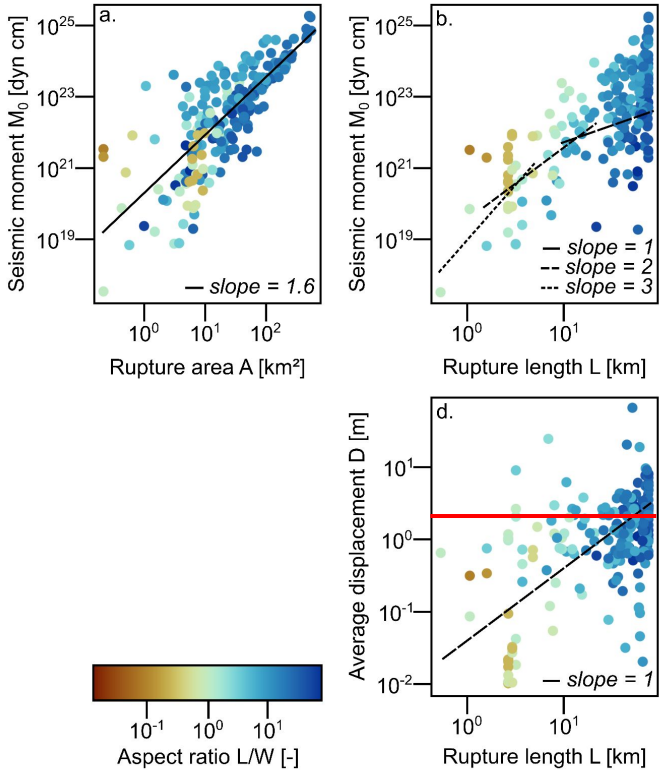

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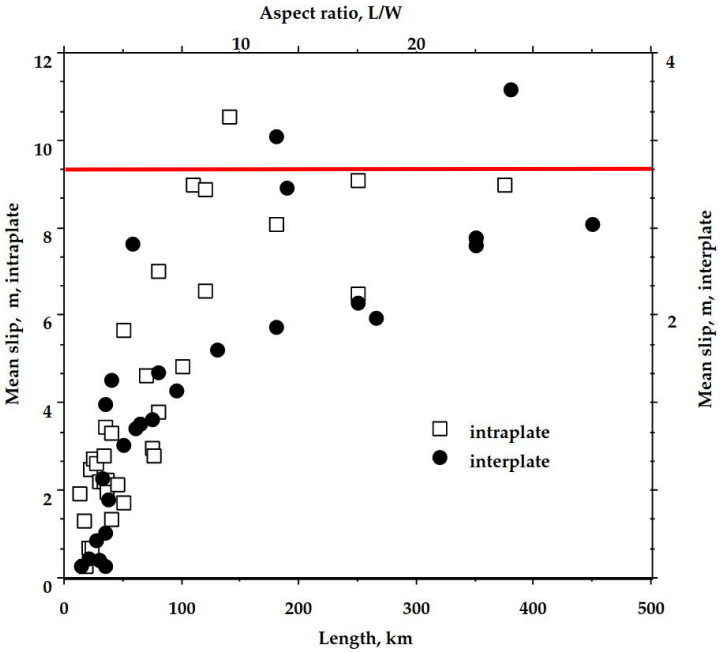

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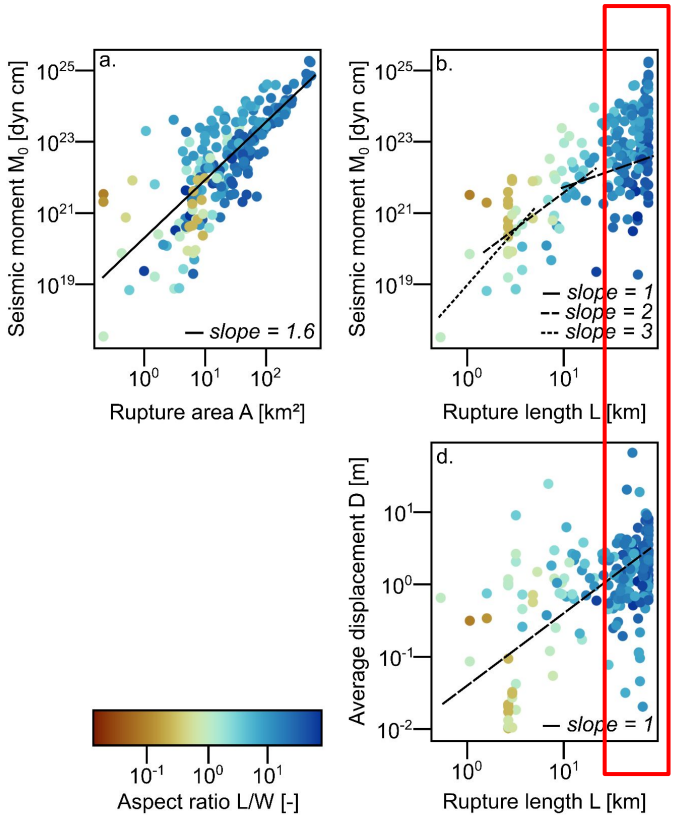
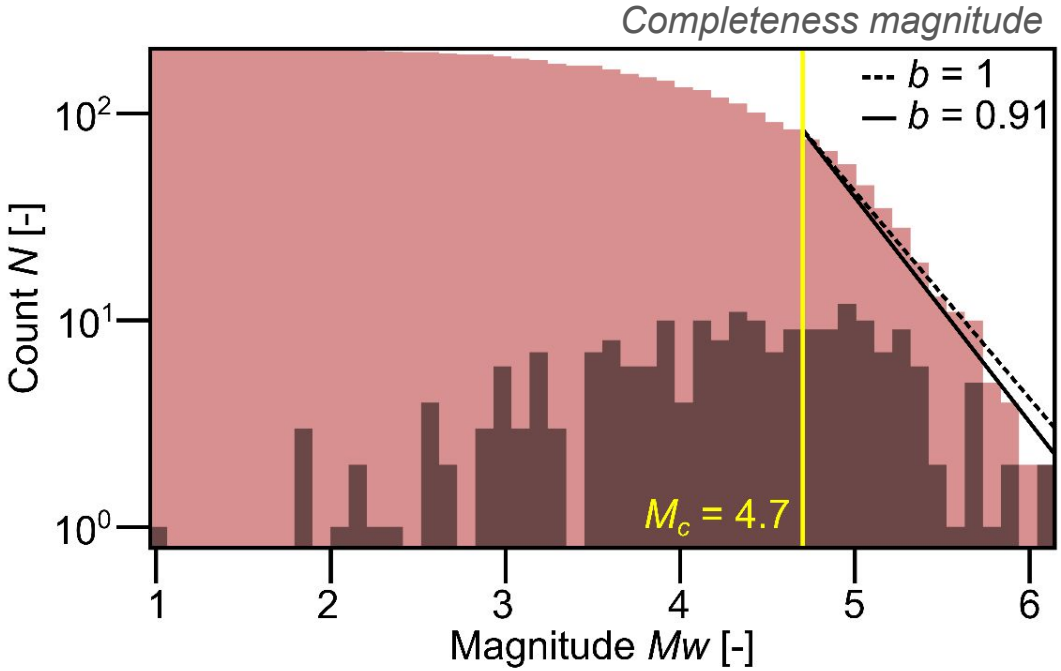


Rupture length saturation (finite model dimensions)

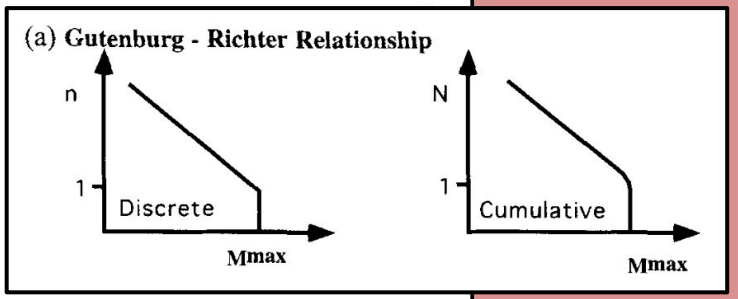
Short term seismicity on the fault



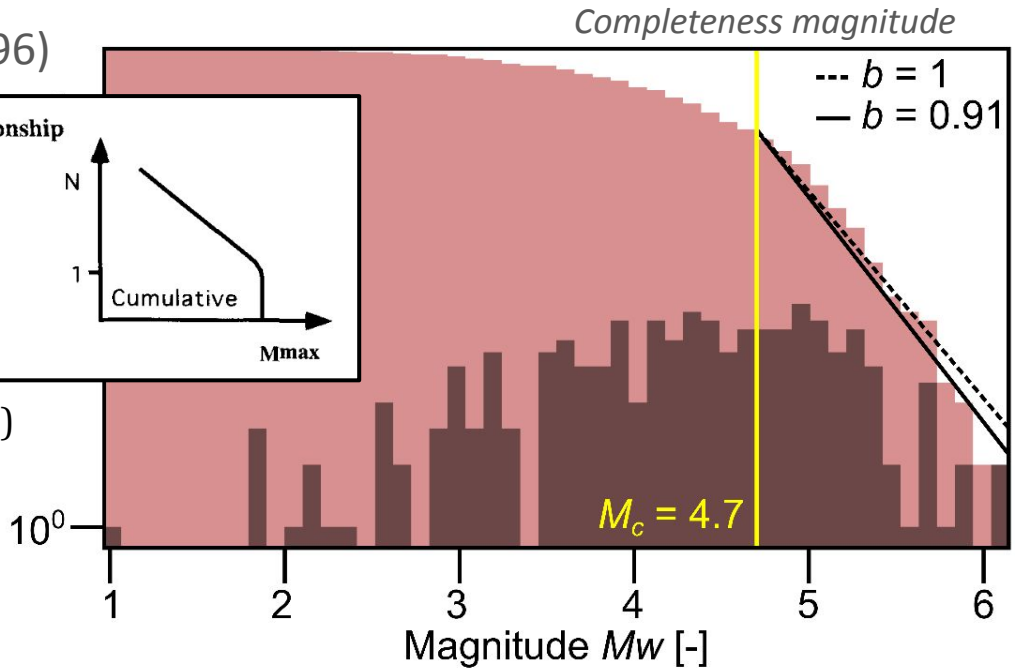
$$\mathbf{Mw = \tfrac{2}{3} \log(M_0) - 6.07}$$

Short term seismicity on the fault

(Stirling et al., 1996)



$\log(N) = a - b\,(Mw - M_c)$



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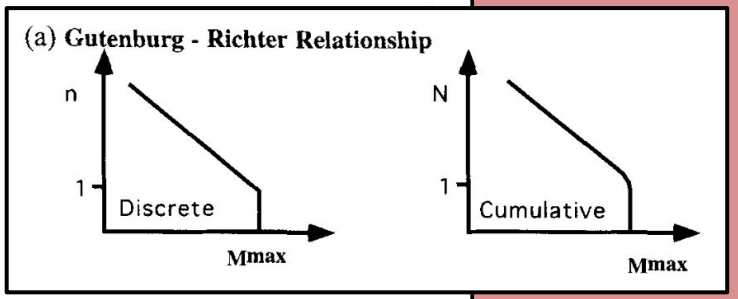

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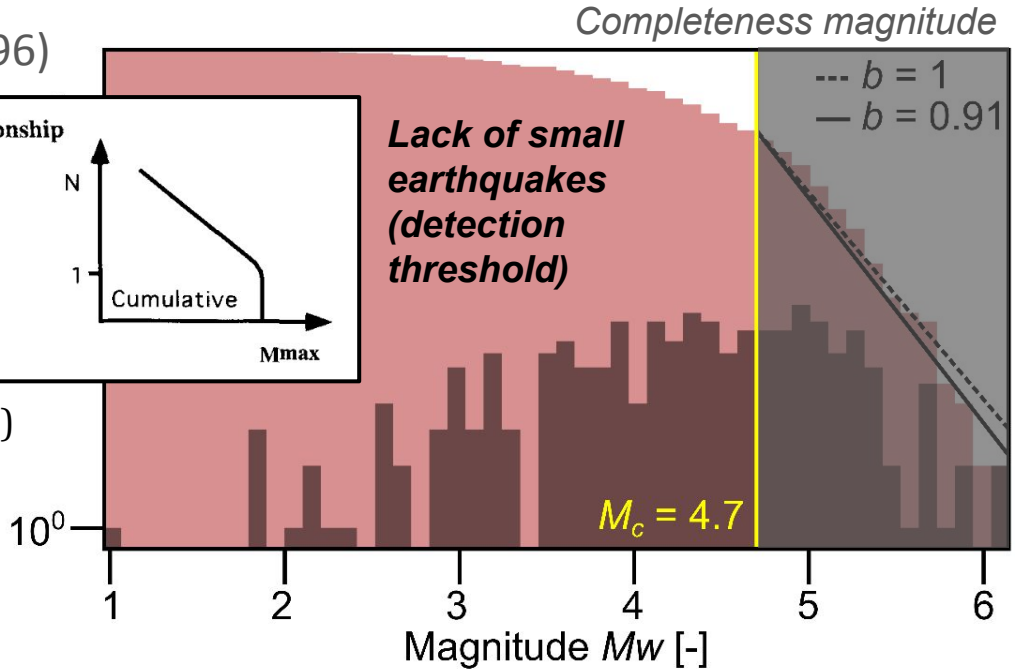

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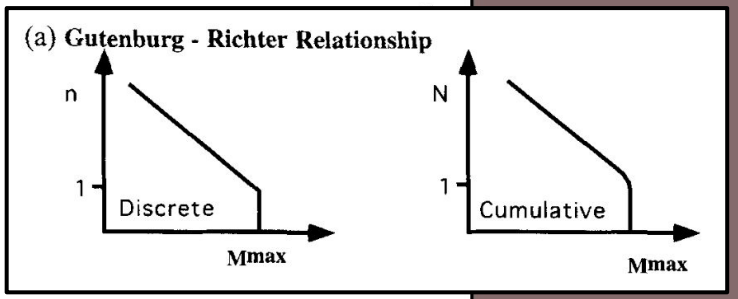

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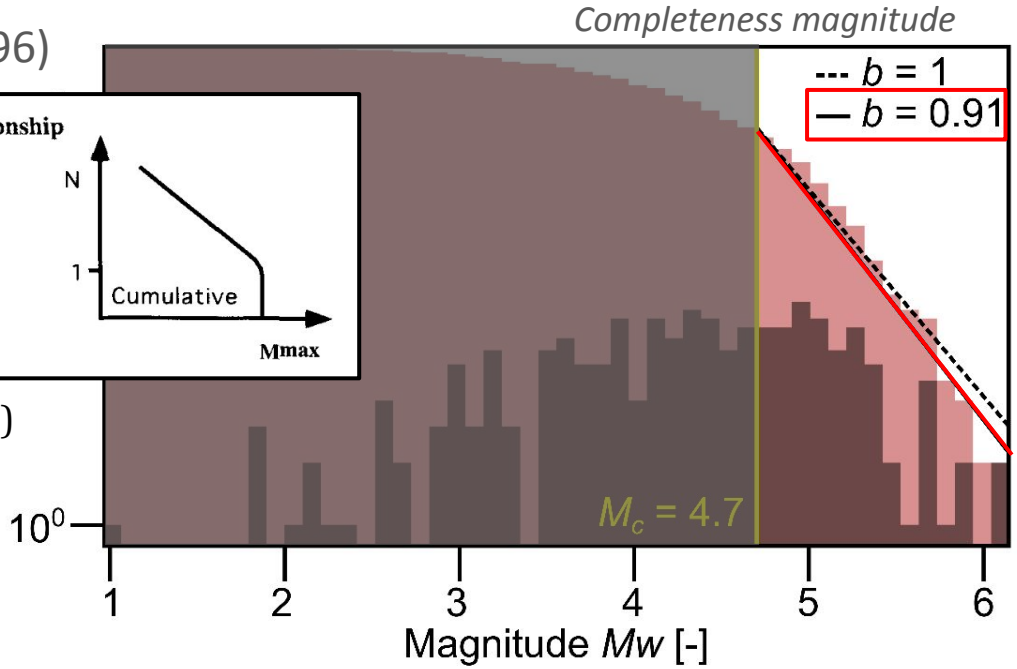

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Short term seismicity on the fault

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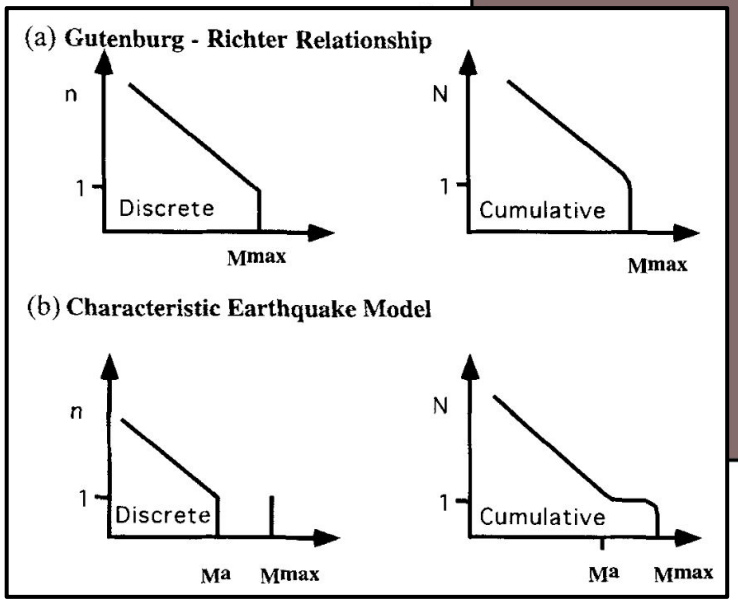

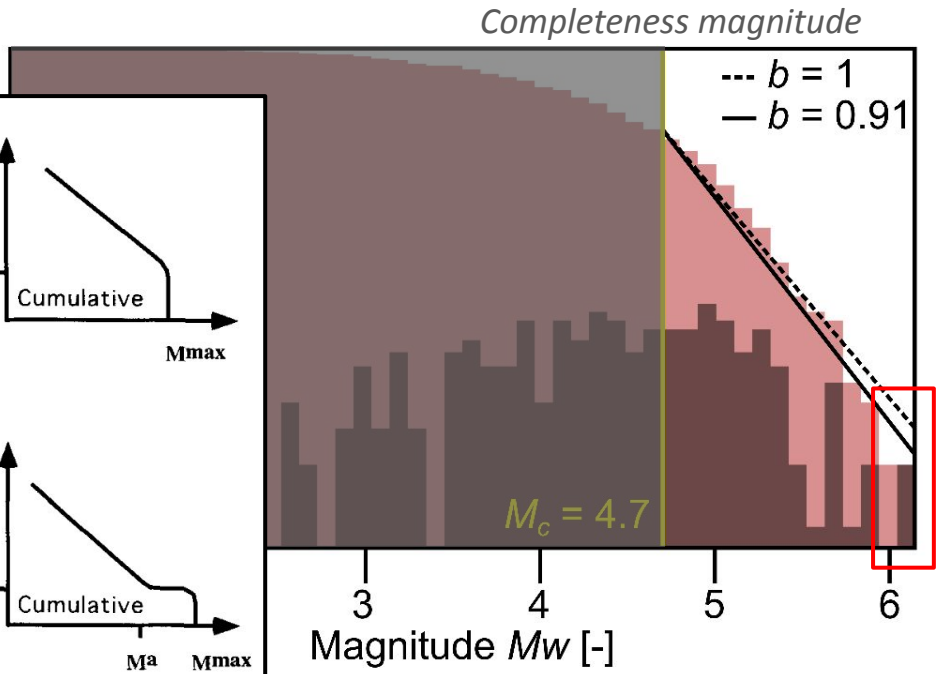

Single fault → characteristic earthquake

$$\mathbf{Mw = \tfrac{2}{3}\log(M_0) - 6.07}$$

Conclusions and perspectives

- ✔ Long term evolution generates a **complex** fault geometry
- ✔ **Earthquake cycles** occur
- ✔ S**caling laws** are consistent with natural observations

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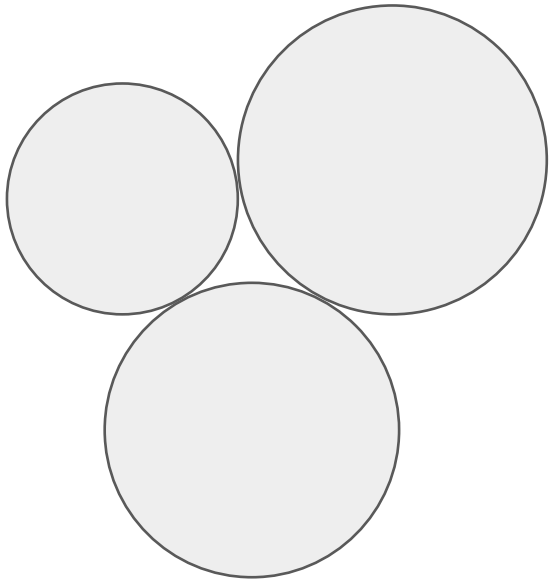
📝 ***In process of publication!***

Contact me: allemand@ipgp.fr

Supplementary slides

Numerical method: Discrete Element Method

Material = assembly of rigid spherical particles in contact



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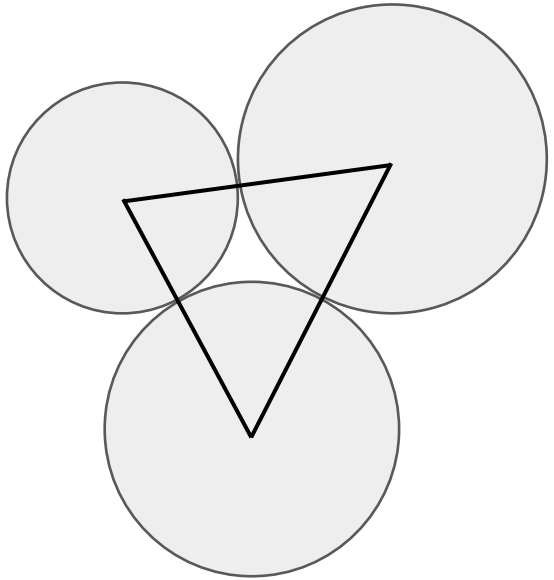
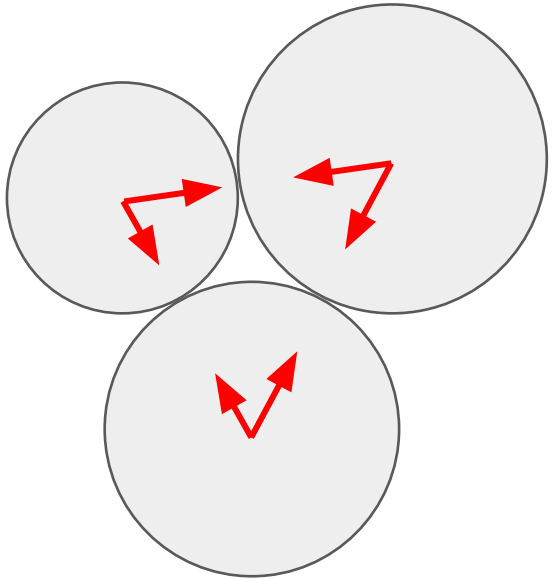


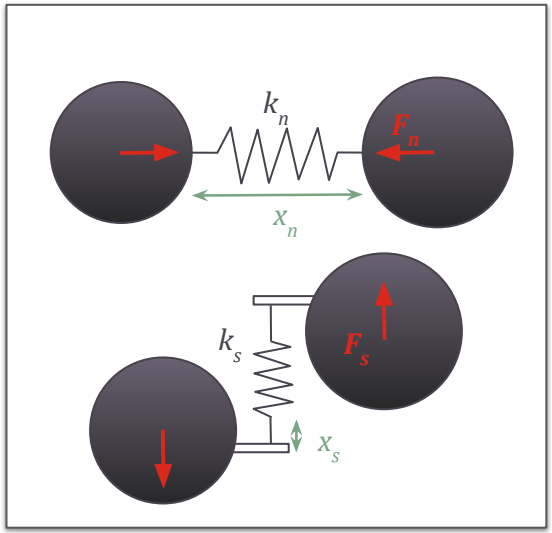
1. **Detect the contact between particles**

Numerical method: Discrete Element Method

Material = assembly of rigid spherical particles in contact



1. Detect the contact between particles
2. **Compute the forces at each contact**



Numerical method: Discrete Element Method

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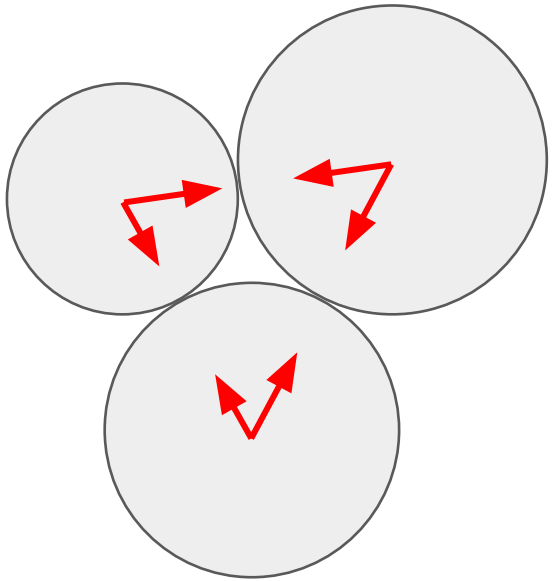
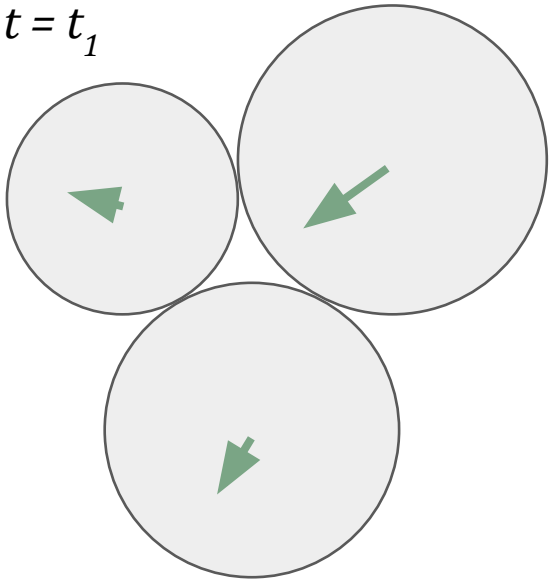


1. Detect the contact between particles
2. Compute the forces at each contact
3. **Compute the acceleration of each particle**

Numerical method: Discrete Element Method

Material = assembly of rigid spherical particles in contact



1. Detect the contact between particles
2. Compute the forces at each contact
3. Compute the acceleration of each particle
4. **Integrate twice to get the displacement**

Numerical method: Discrete Element Method

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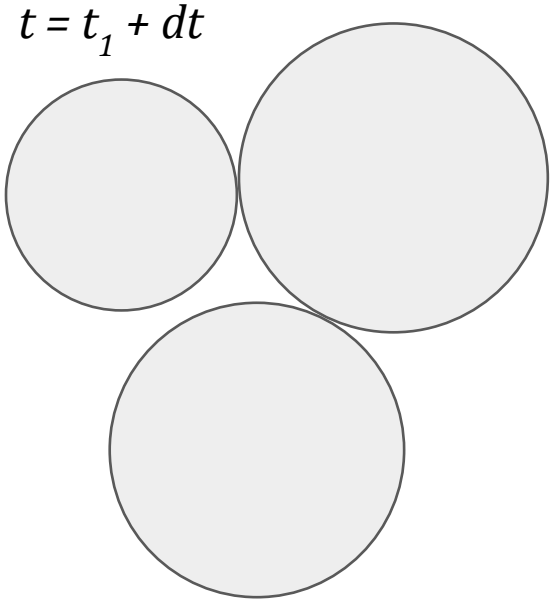

1. Detect the contact between particles
2. Compute the forces at each contact
3. Compute the acceleration of each particle
4. Integrate twice to get the displacement
5. **Move the particles**

Numerical method: Discrete Element Method

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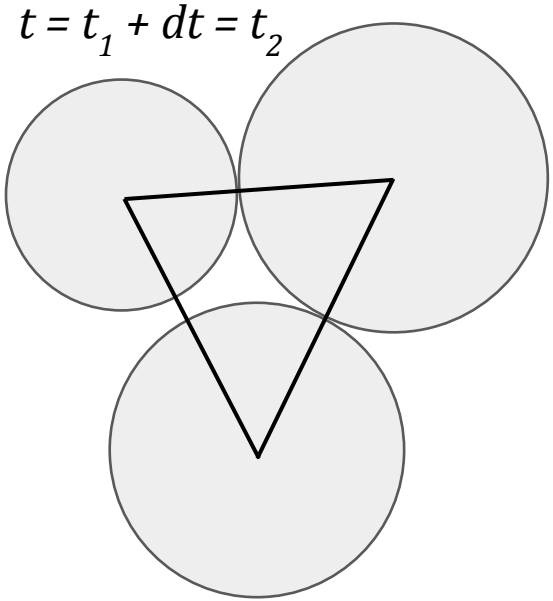
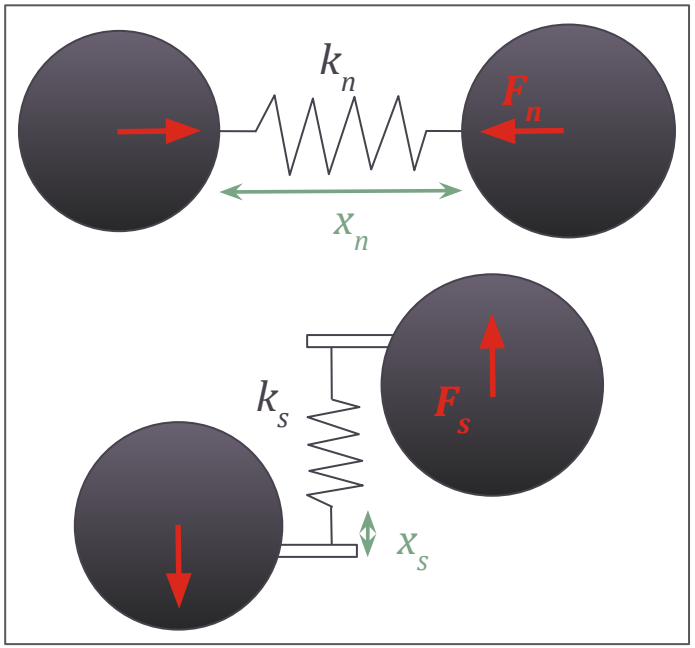


1. **Detect the contact between particles**

Numerical method: Discrete Element Method

Calibration of the contact properties (k_n, k_s, …)



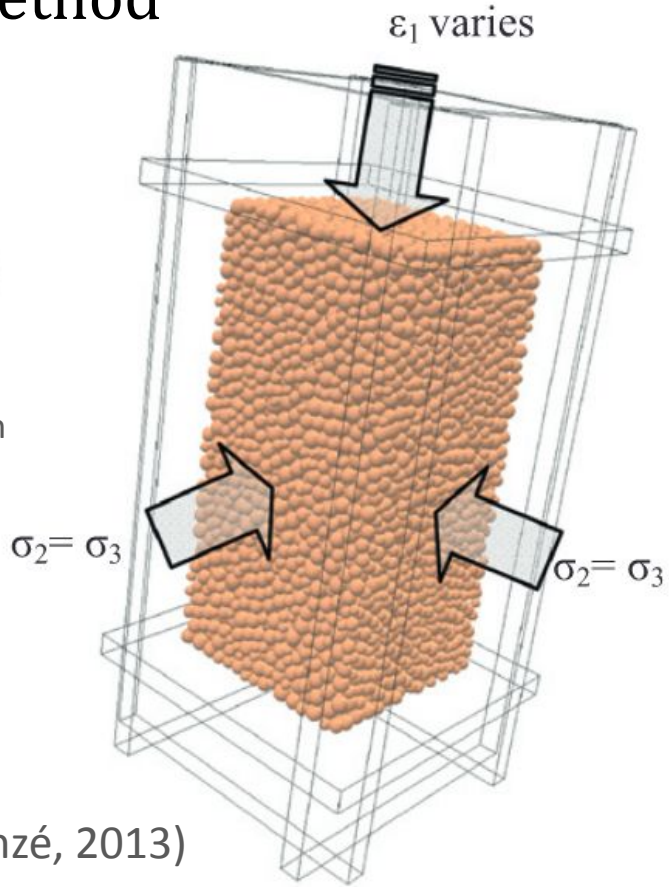
5 contact parameters:

Elastic parameters:

- Normal stiffness
- Tangential stiffness

Strength parameters:

- Compressive strength
- Tensile strength
- Friction



(Scholtès and Donzé, 2013)

Numerical method: Discrete Element Method

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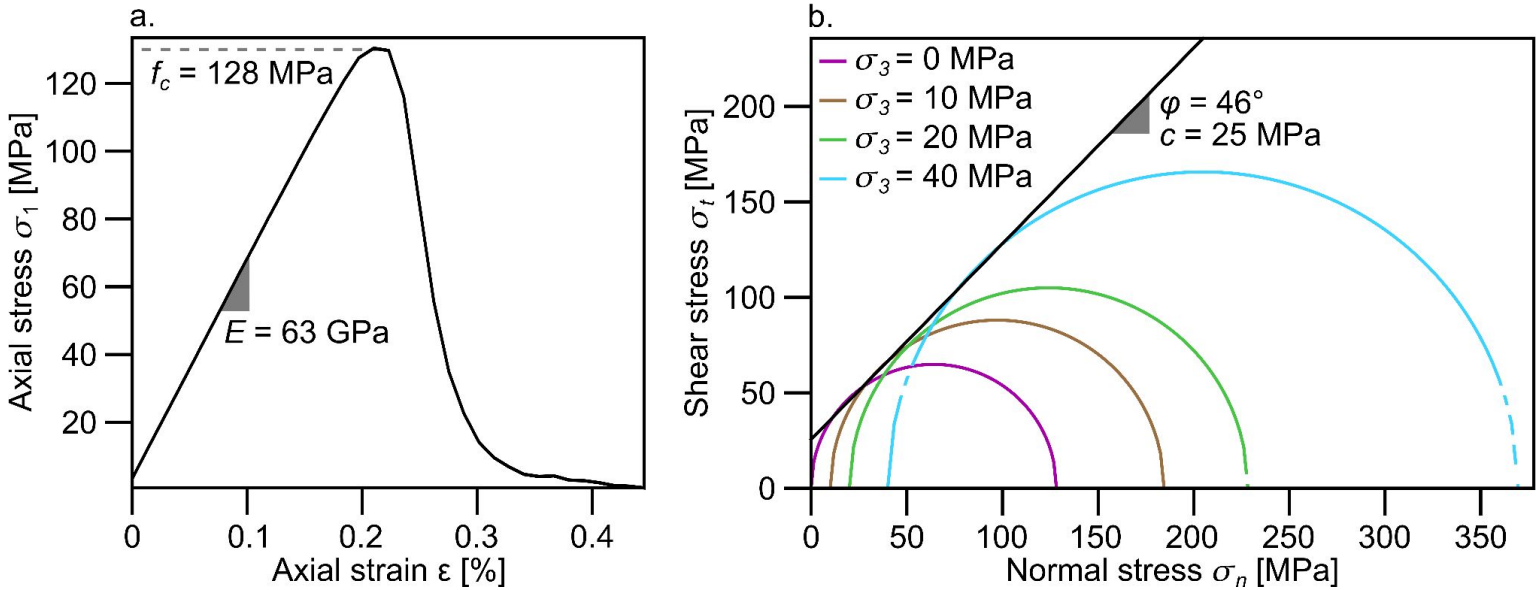

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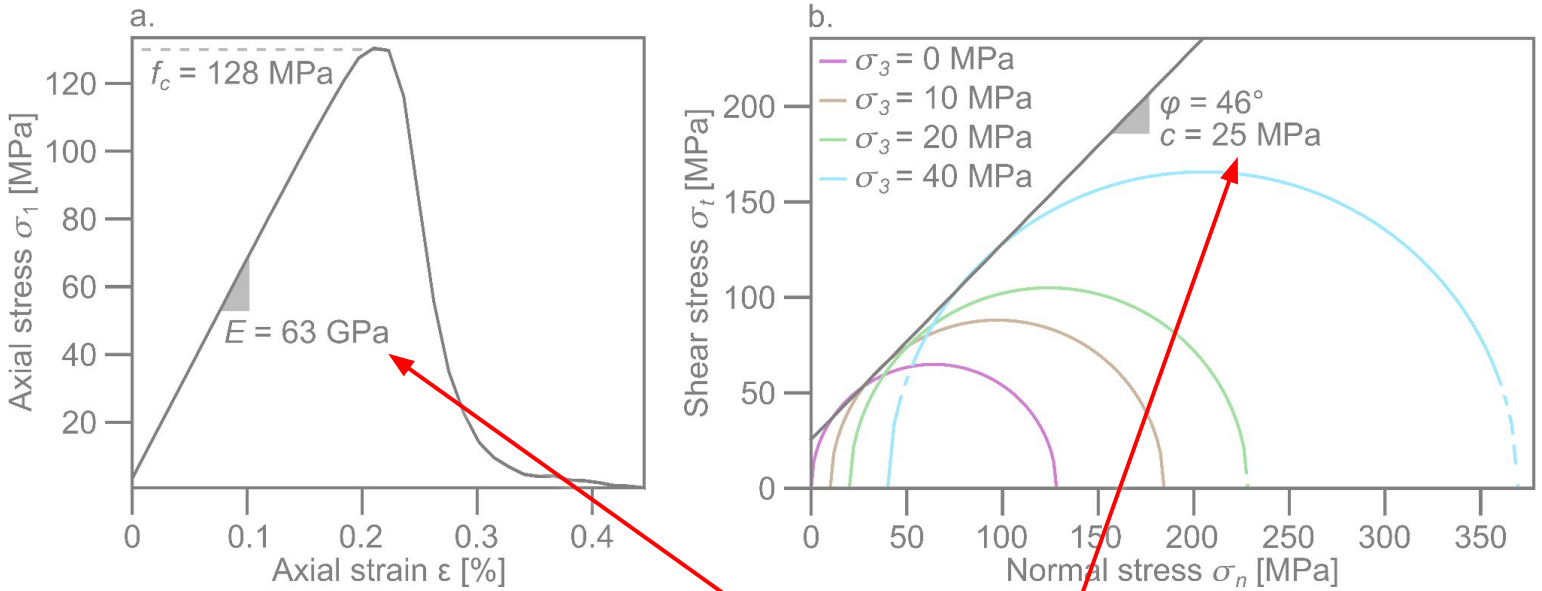
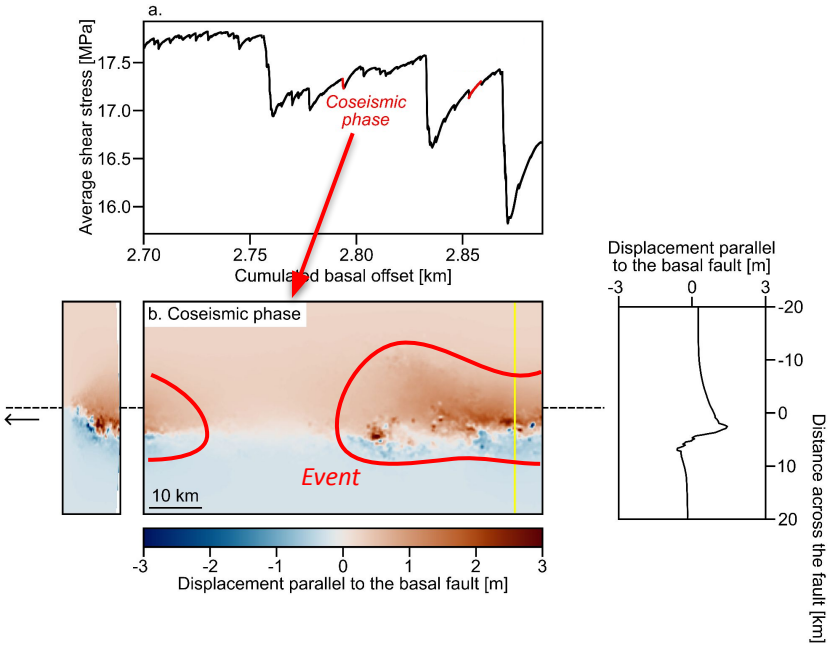
Calibration of the contact properties (k_n, k_s, …)

Contact parameters



Emergent mechanical properties

Short term seismicity on the fault



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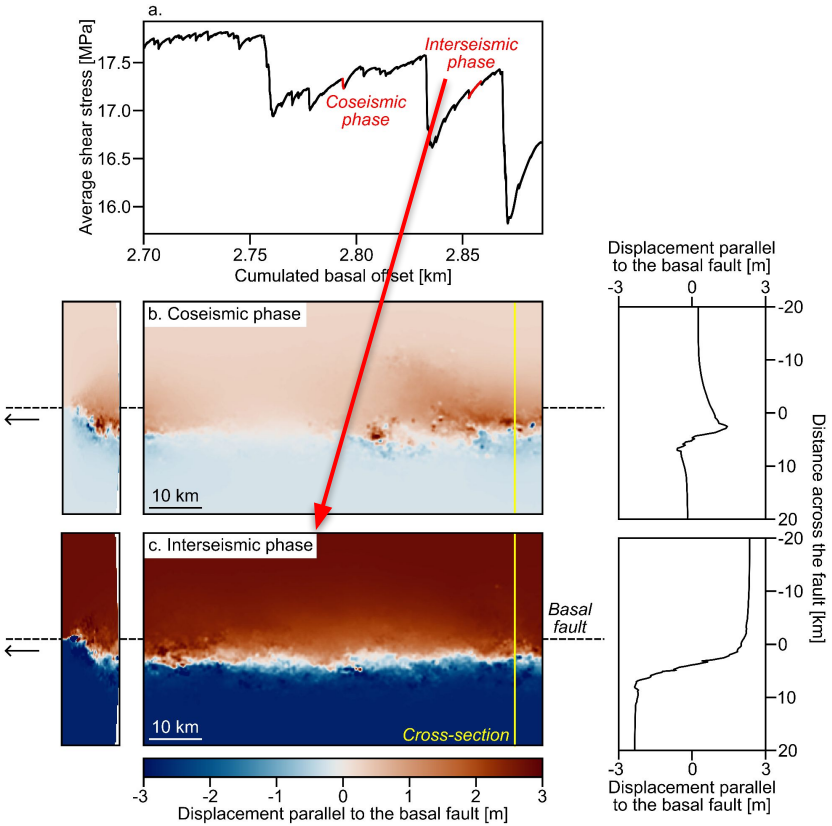

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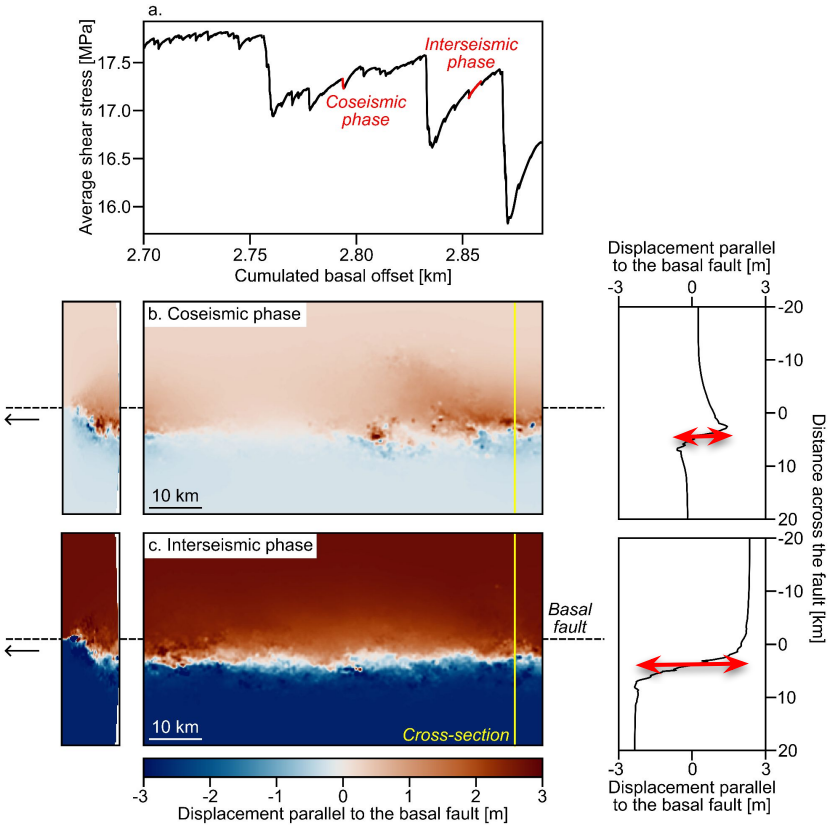
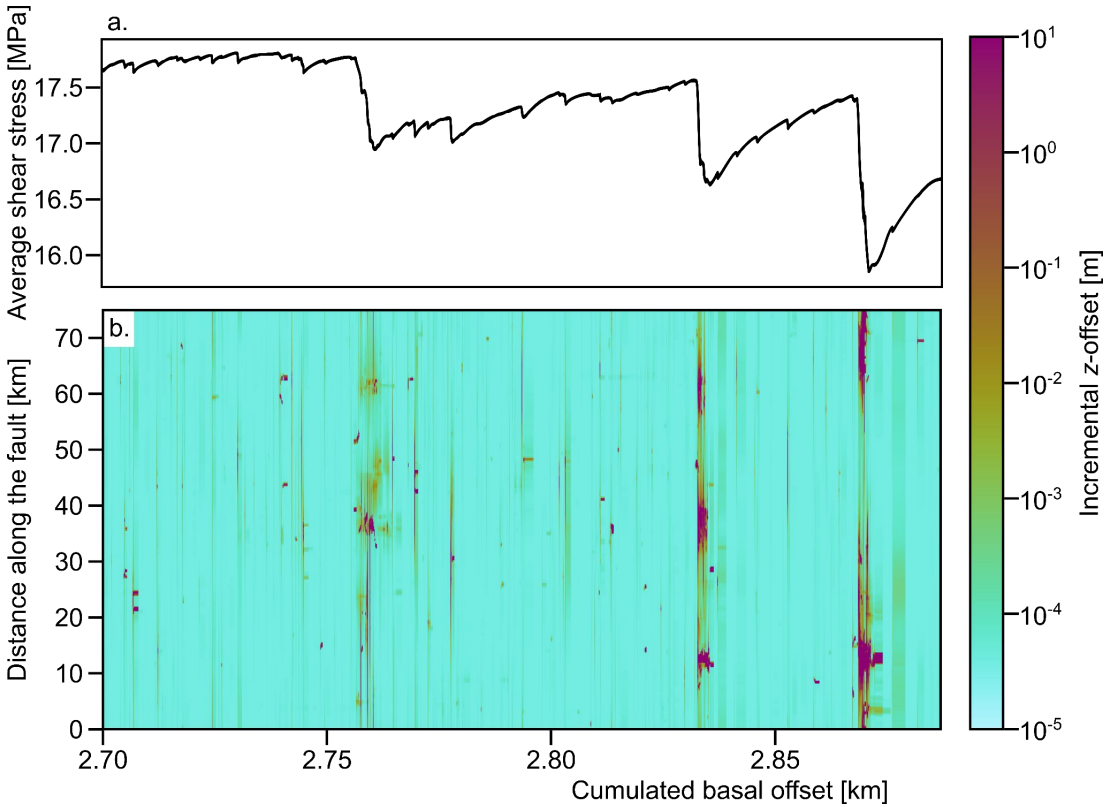


Incremental z-offset [m]

Short term seismicity on the fault



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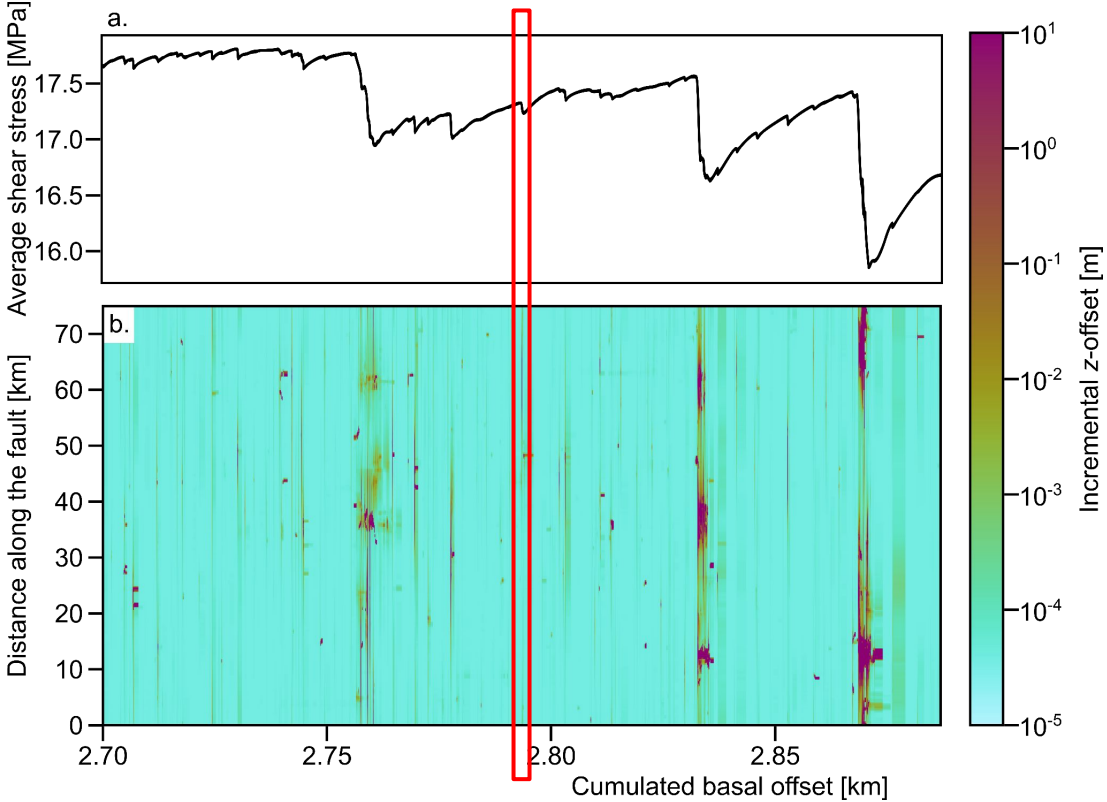

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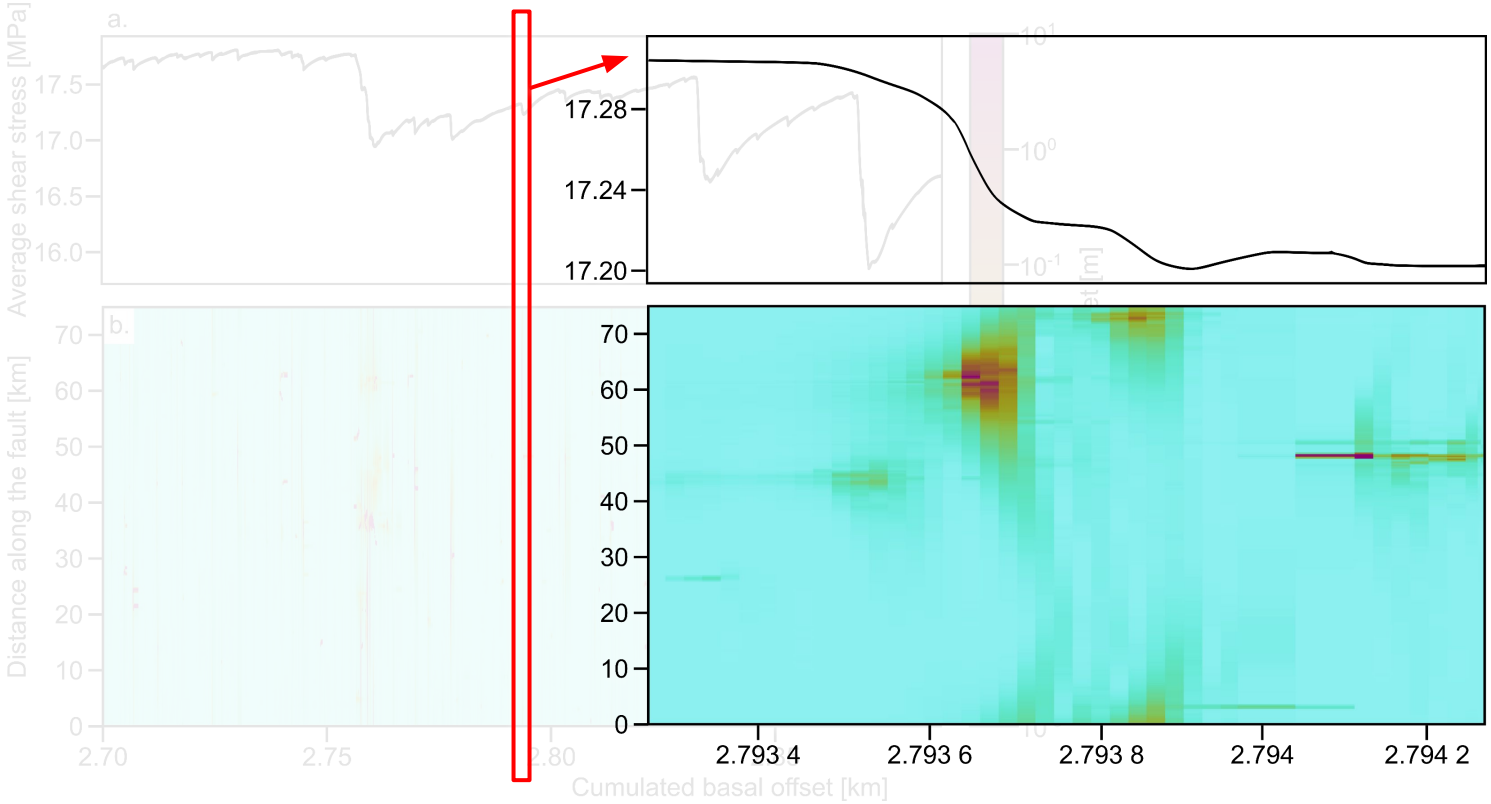

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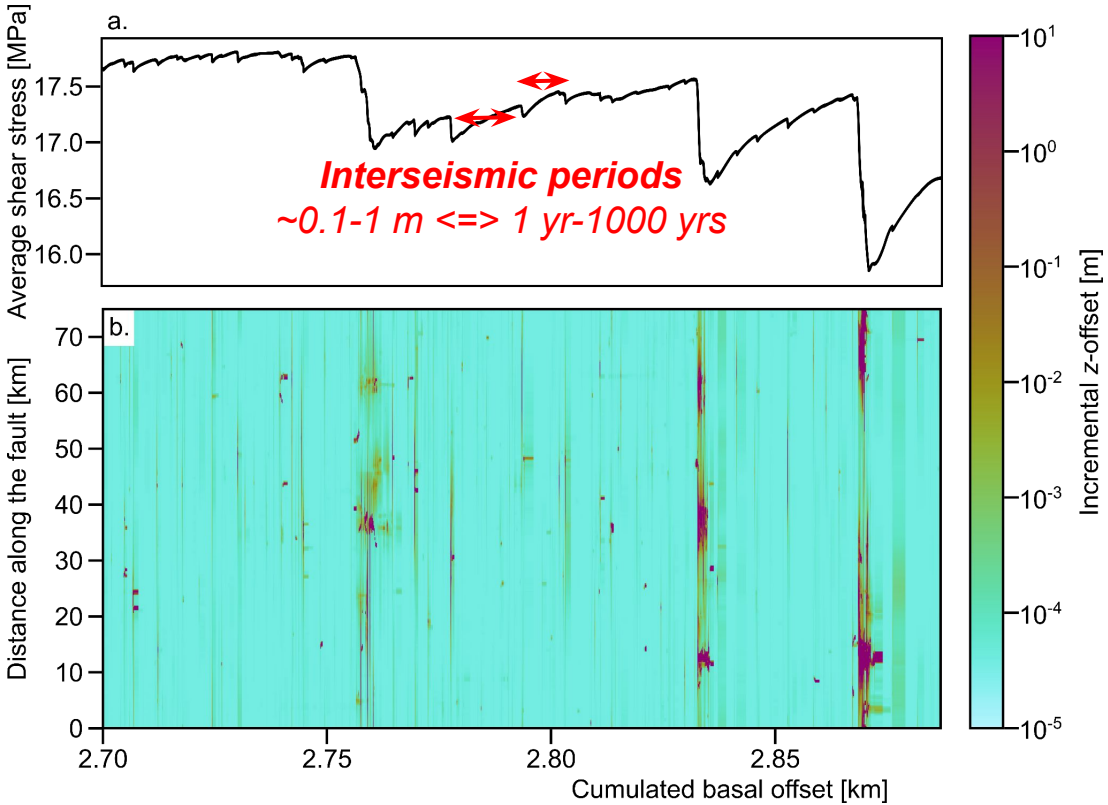
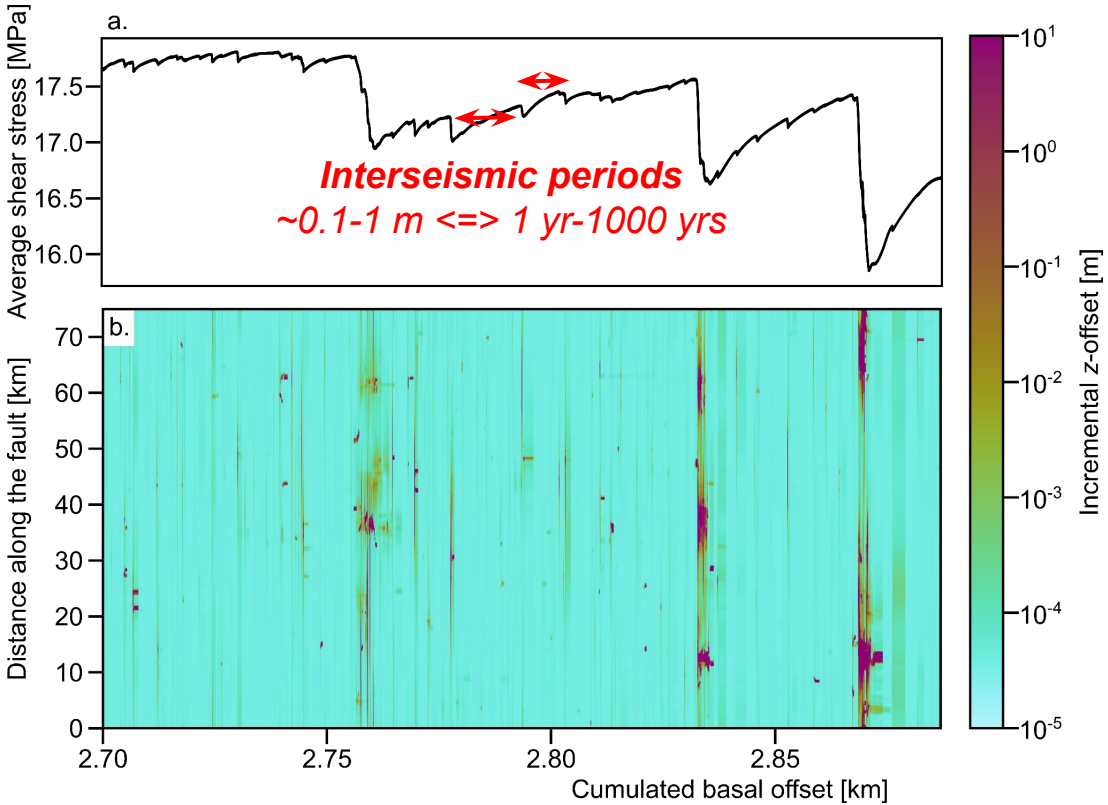


Short term seismicity on the fault

The cumulated basal displacement controls the interseismic duration.



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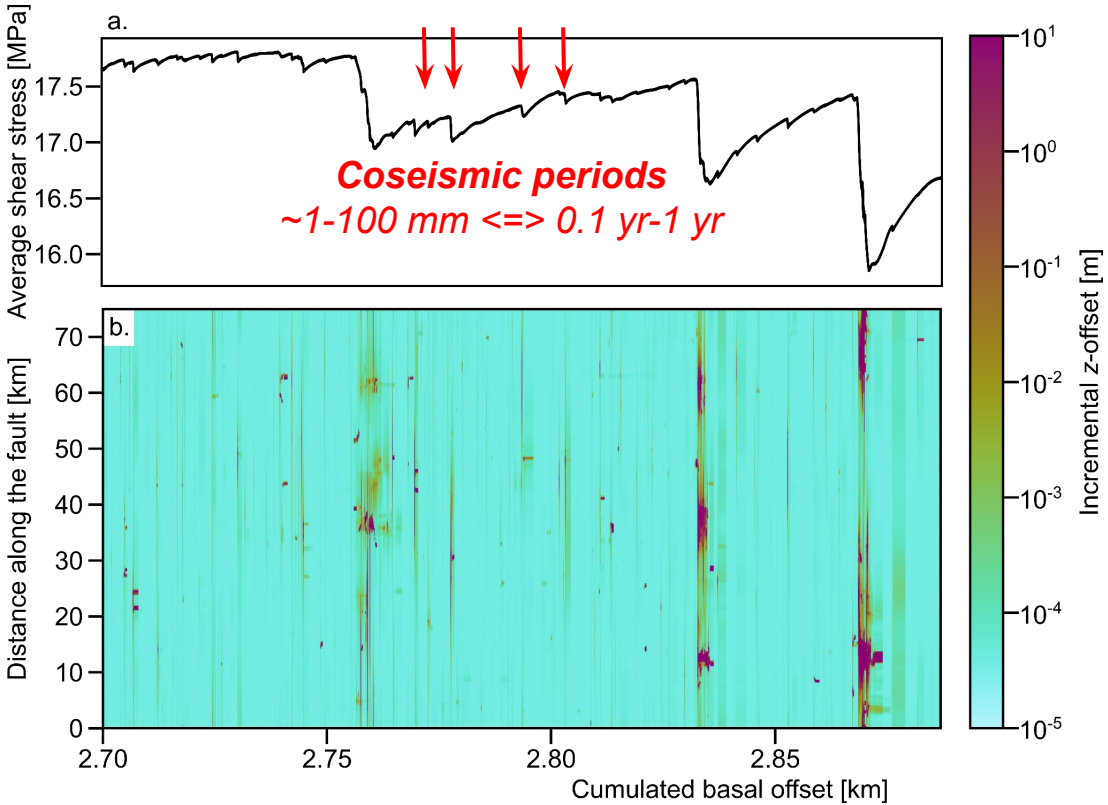
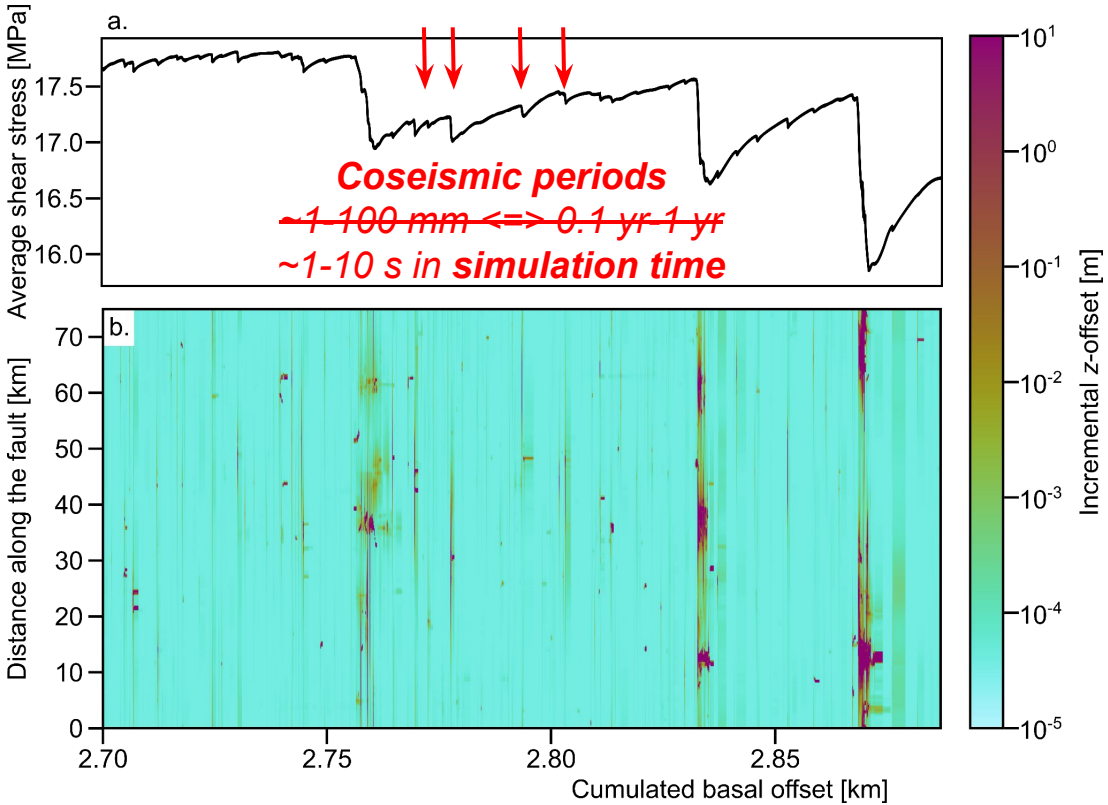


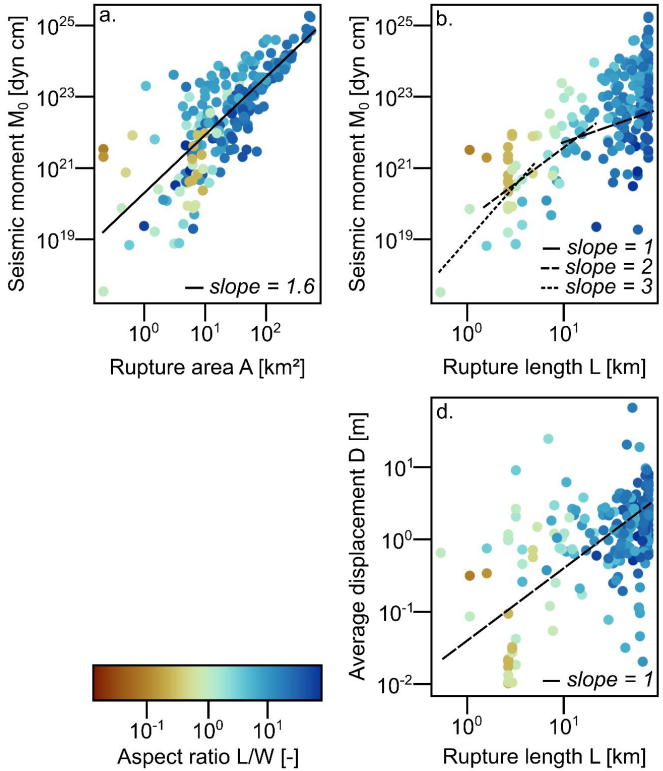
Short term seismicity on the fault

The mechanical properties control the coseismic duration.



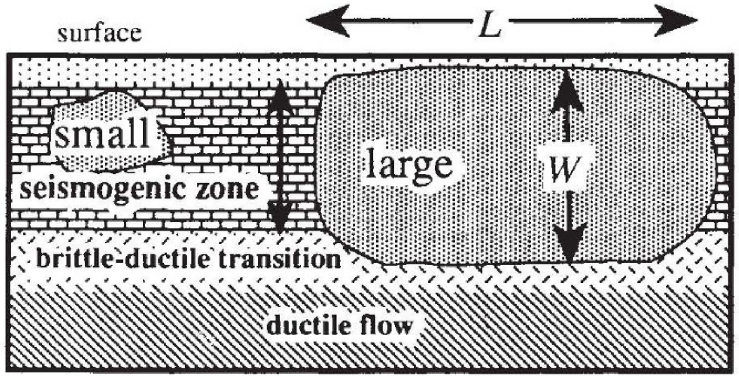
Short term seismicity on the fault

$M_0 = GDLW$



Small earthquakes

$L \approx W$



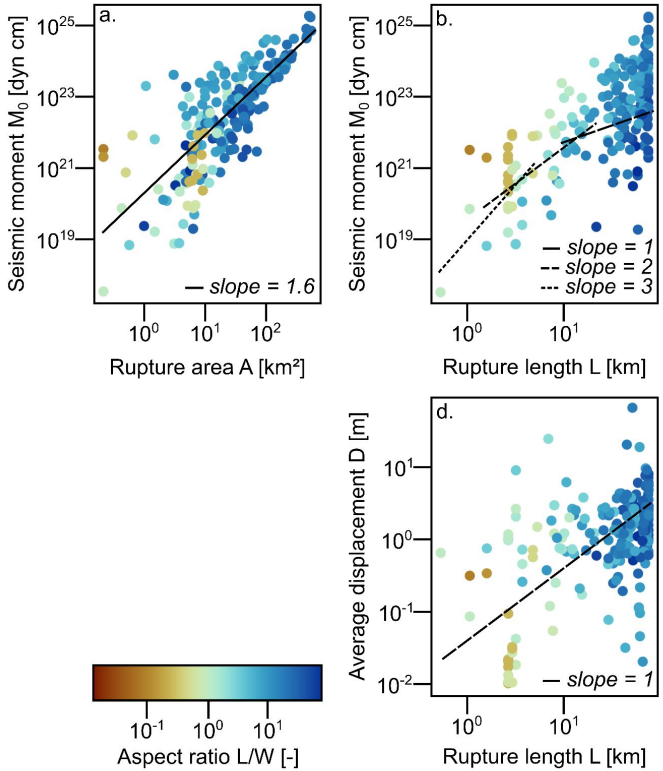
(Pacheco, 1992)

Short term seismicity on the fault

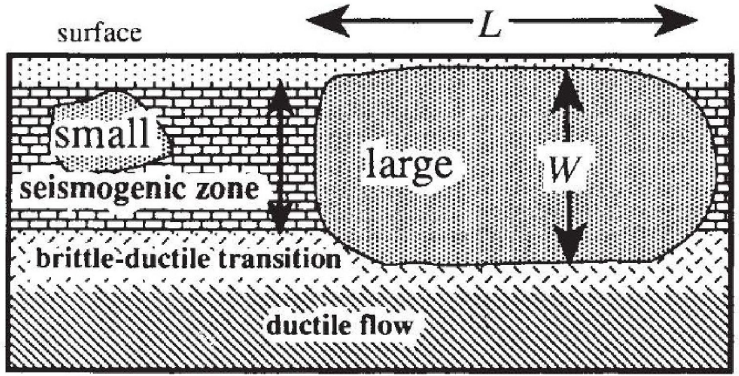
$M_0 = GDLW$

$D=kL$

(observations)



$L \approx W$



(Pacheco, 1992)

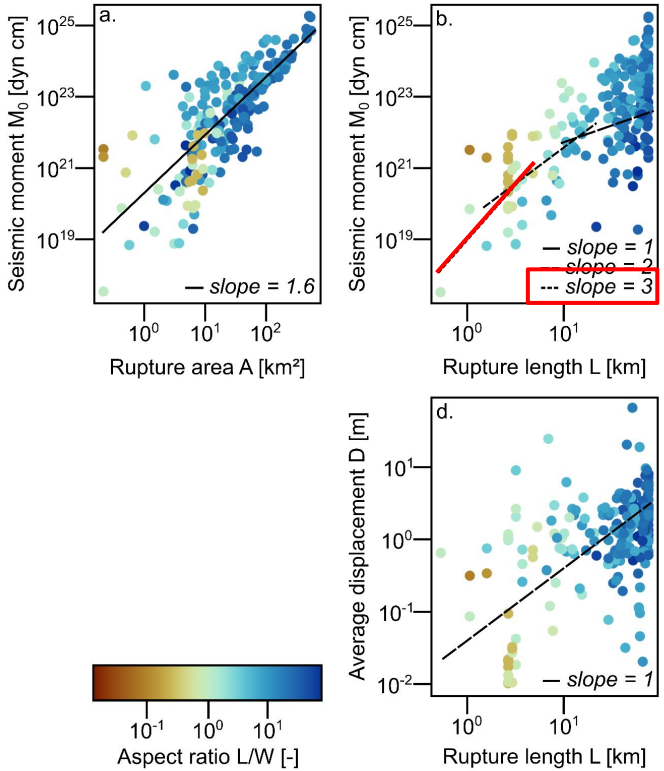
Short term seismicity on the fault

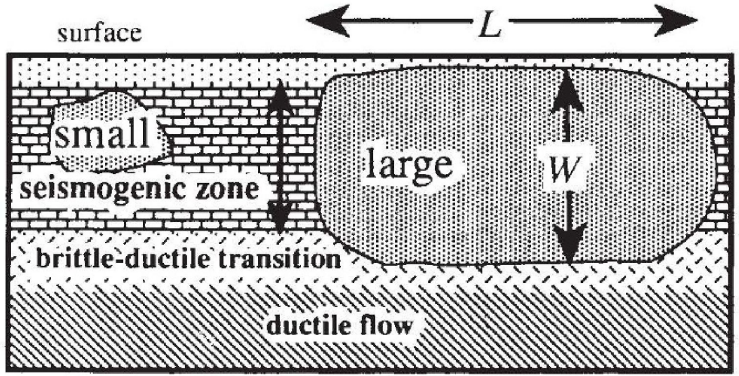
$M_0 = GDLW$

$D=kL$

$M_0 = GkL^3$

$L \approx W$



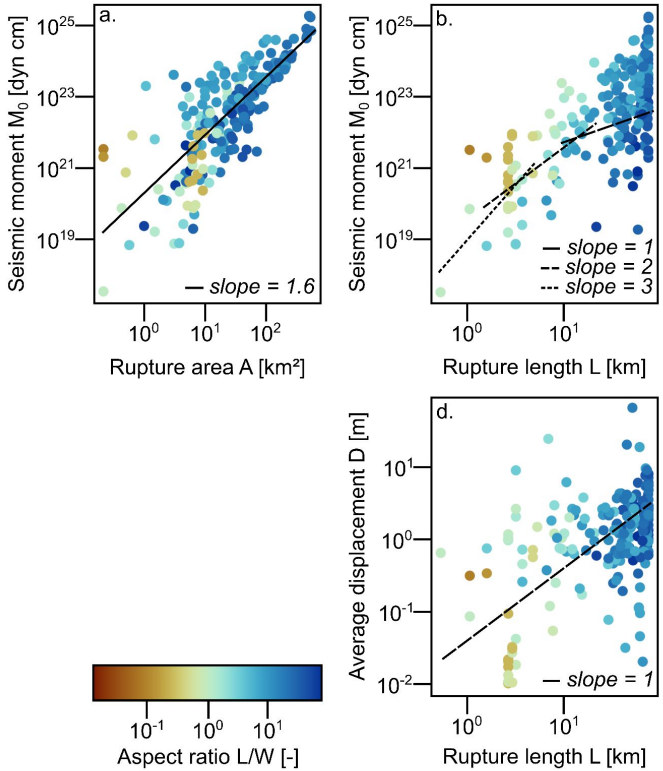


(Pacheco, 1992)

Short term seismicity on the fault

$M_0 = GDLW$

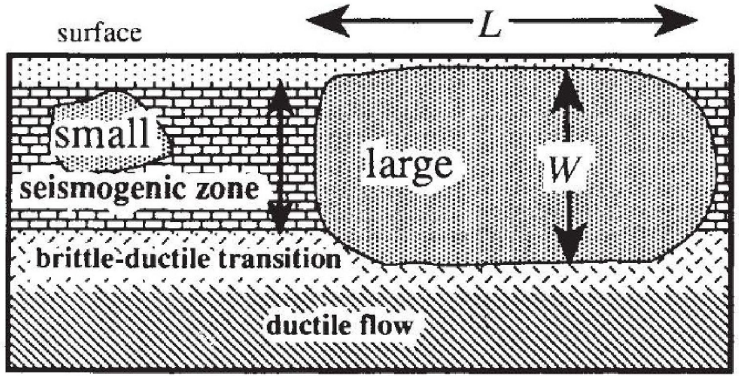
$D=kL$



$L \approx W$

Large earthquakes

$L>W=W_0$



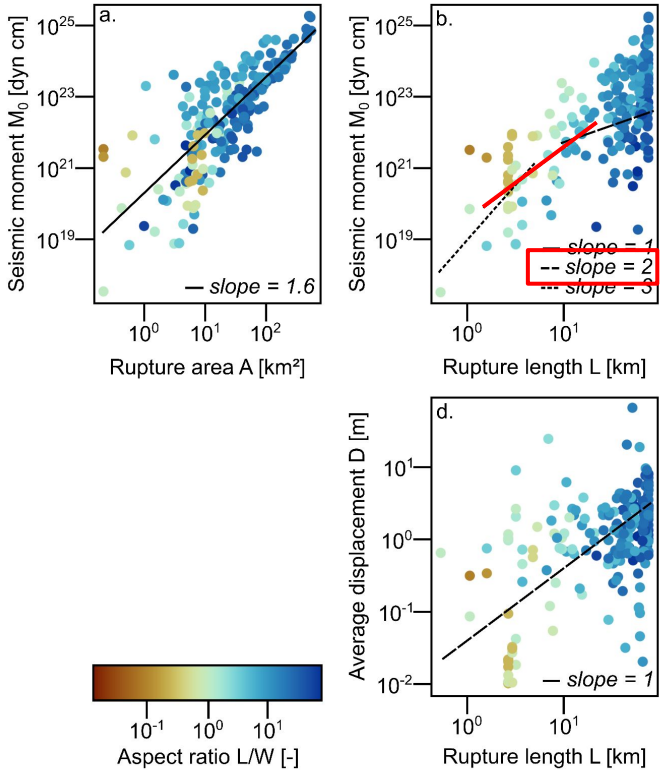
(Pacheco, 1992)

Short term seismicity on the fault

$M_0 = GDLW$

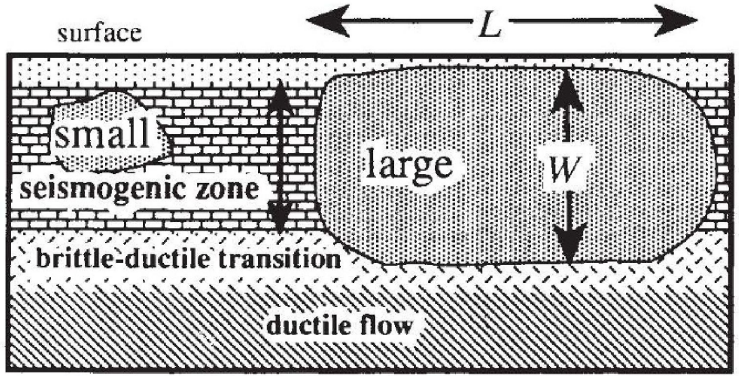
$D=kL$

$M_0 = GkW_0L^2$



$L \approx W$

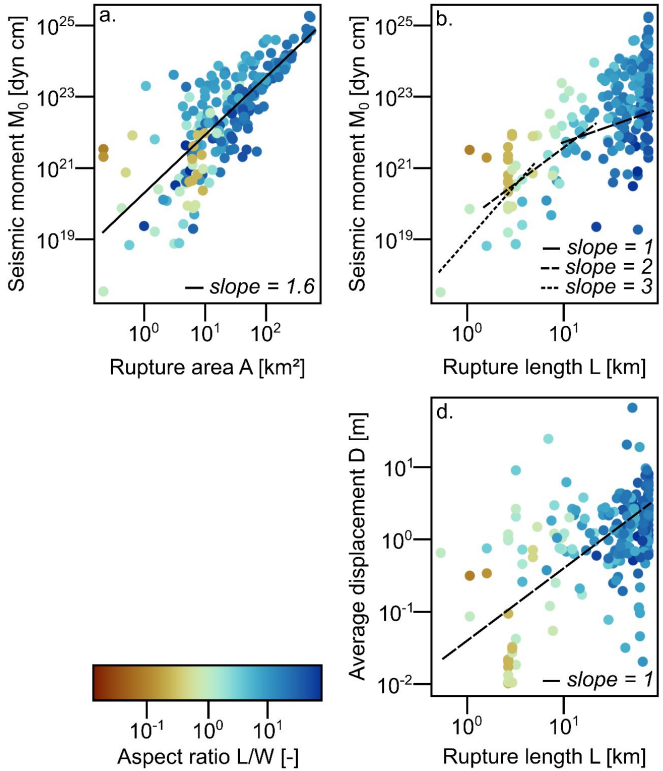
$L>W=W_0$



(Pacheco, 1992)

Short term seismicity on the fault

$M_0 = GDLW$



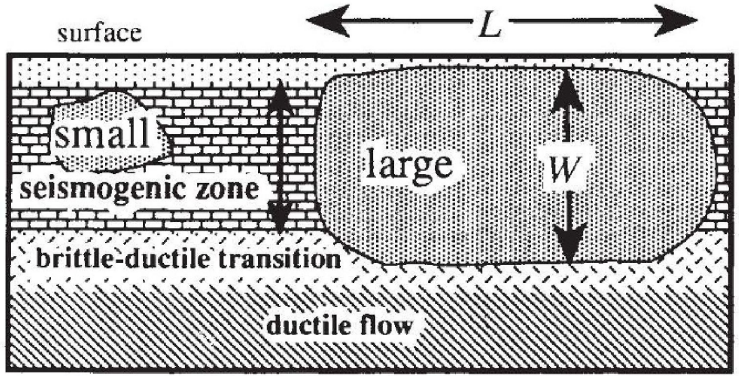
$D=D_0$

(observations)

Very large earthquakes

$L \approx W$

$L>>W=W_0$



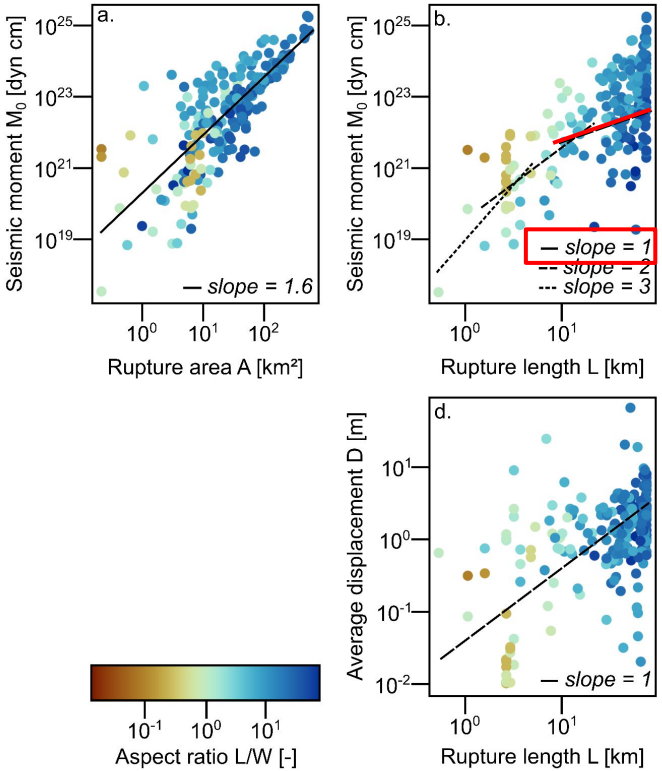
(Pacheco, 1992)

Short term seismicity on the fault

$M_0 = GDLW$

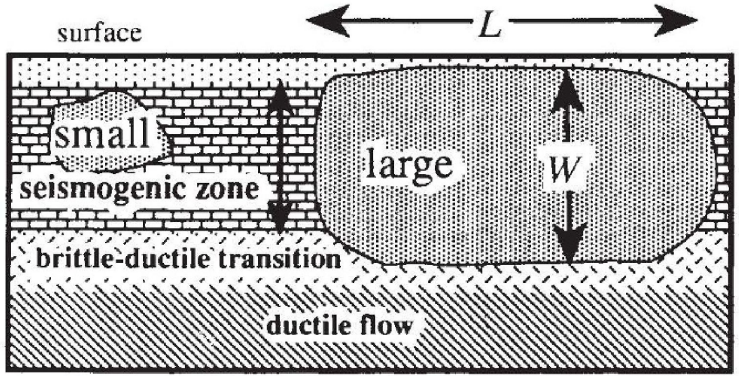
$D=D_0$

$M_0 = GD_0W_0L$



$L \approx W$

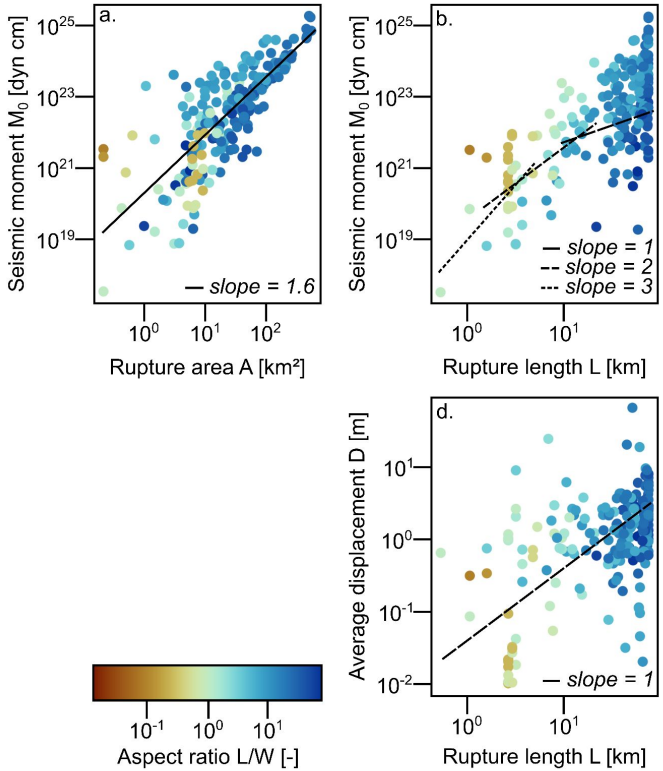
$L>>W=W_0$



(Pacheco, 1992)

Short term seismicity on the fault

$M_0 = GDLW$



(Shaw and Scholz, 2001)