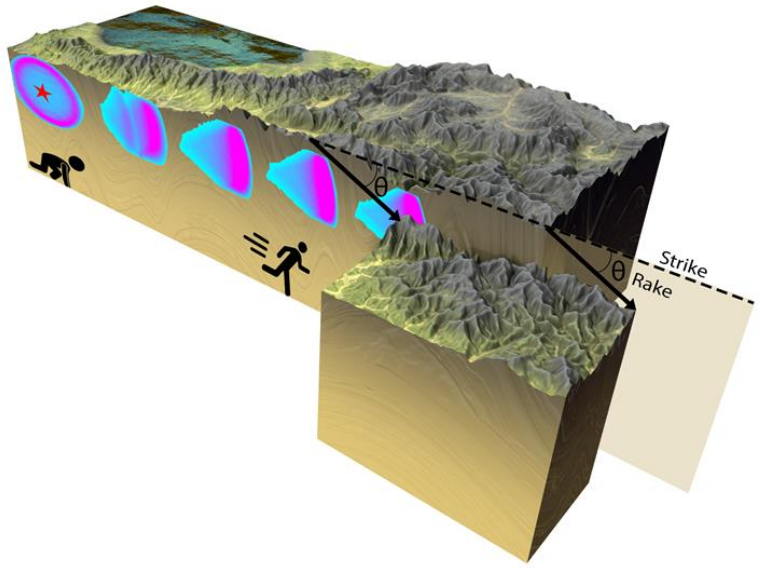


Theoretical insights on the rupture arrest of large earthquakes

Jean-Paul Ampuero

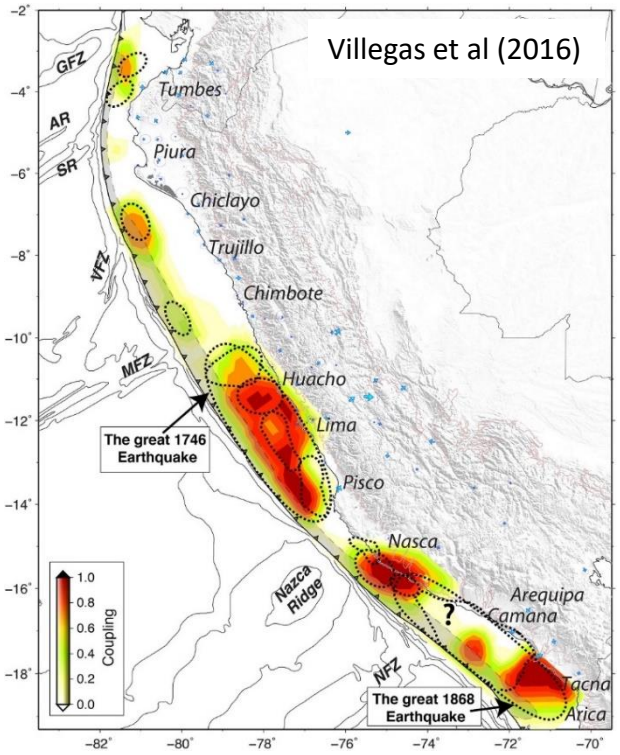
IRD/UCA - Géoazur Lab (France)

Institut de Recherche pour le Développement
FRANCE

UNIVERSITÉ CÔTE D'AZUR

GeoAzur
TERRE - OCÉAN - ESPACE

Open questions in earthquake mechanics



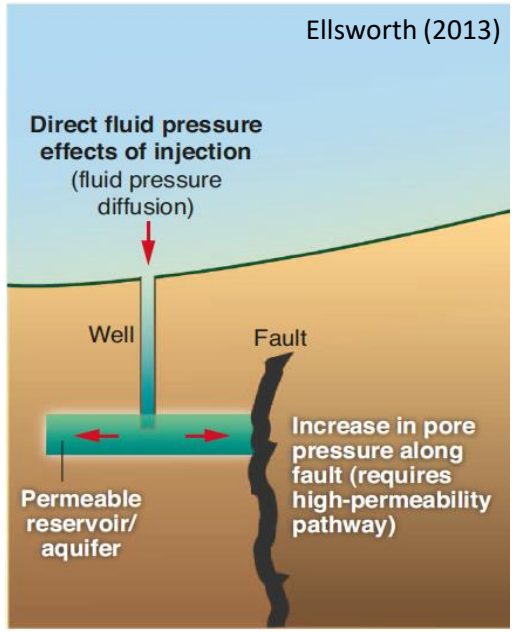
How do earthquakes start, propagate and stop?

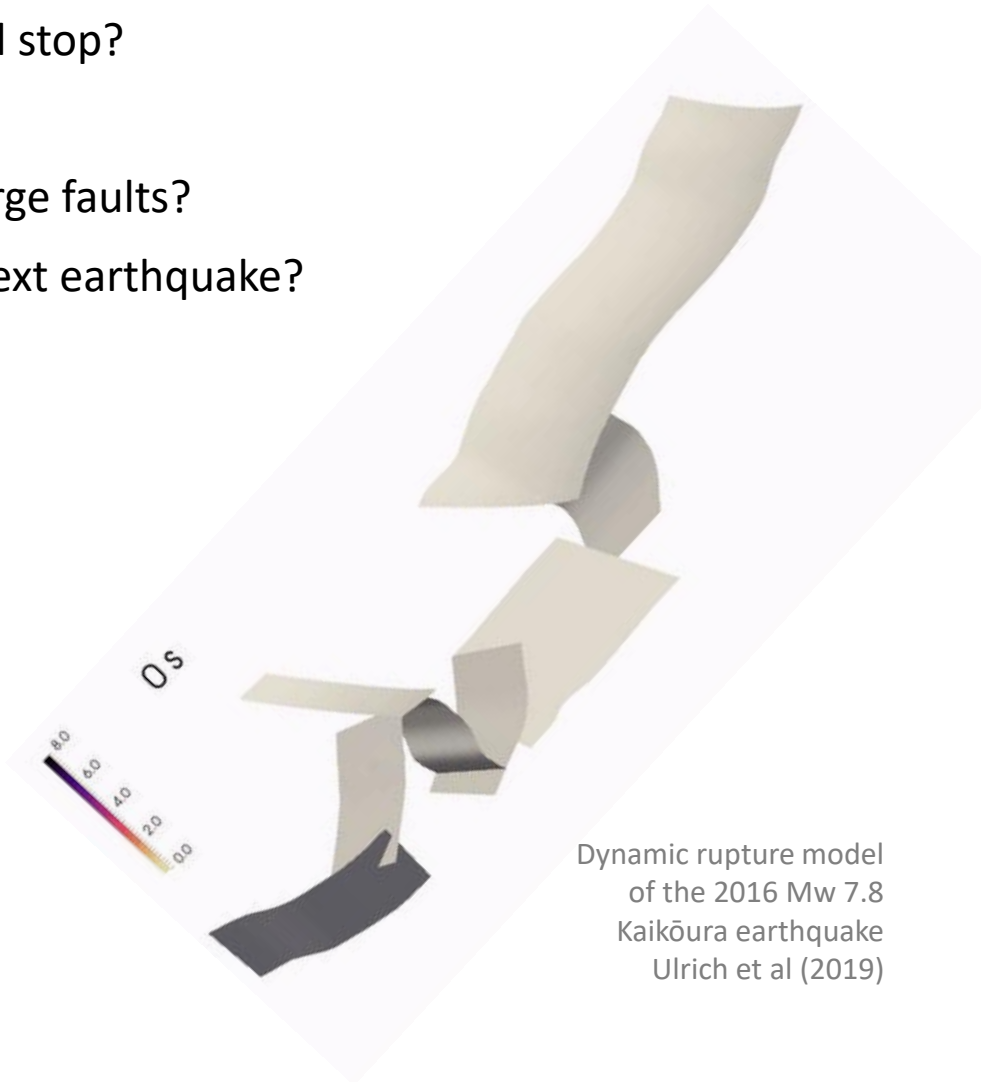
What controls the strength of faults?

What determines the segmentation of large faults?

Can we forecast the rupture size of the next earthquake?

Can we control induced seismicity?





Dynamic rupture model of the 2016 Mw 7.8 Kaikōura earthquake
Ulrich et al (2019)

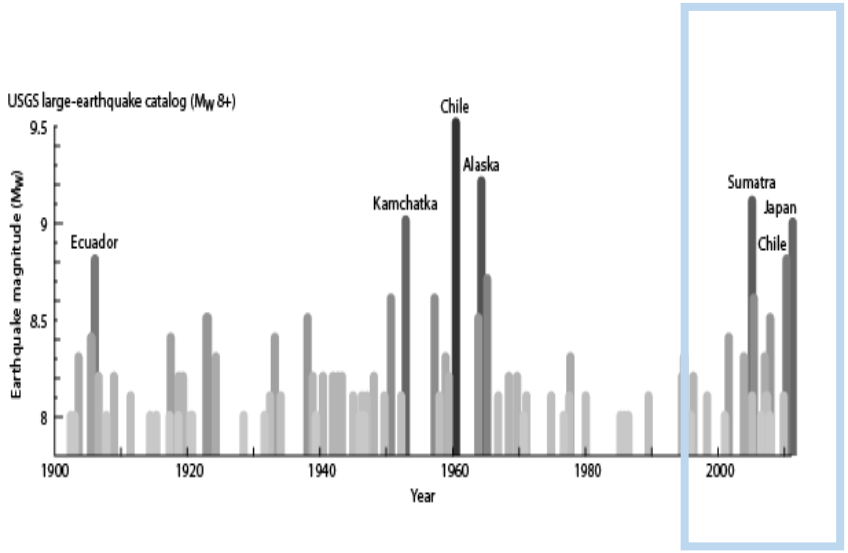
Challenges in earthquake mechanics

Deep process observed from the Earth's surface
Seismological observation hampered by scattering and attenuation

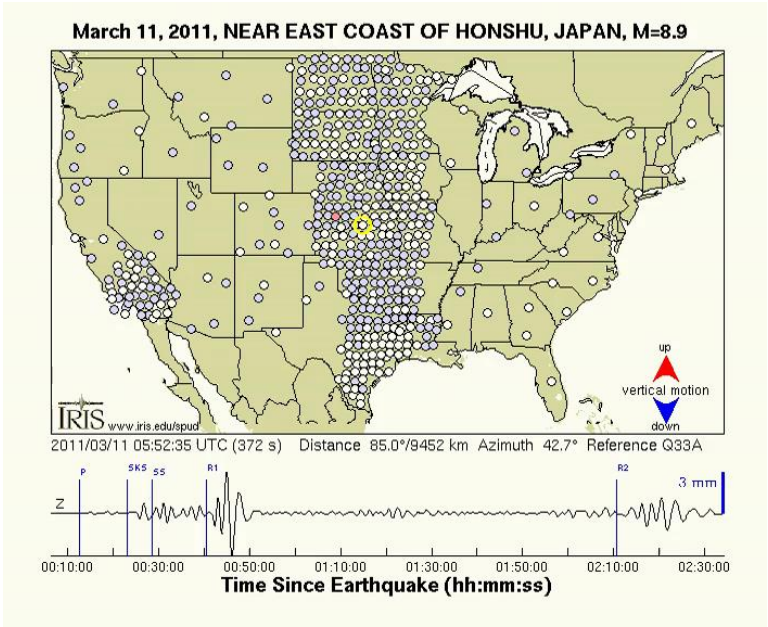
Laboratory experiments do not reproduce all conditions at depth
Diversity of coupled physical processes involved
Complex non-linear system
Modeling needs multi-physics, multi-scale approaches

Opportunities in earthquake mechanics

More earthquakes



More data



More computer power

Fault segmentation

Past earthquakes
along the
Peru subduction zone:

Can we predict earthquakes sizes in a segmented fault system?

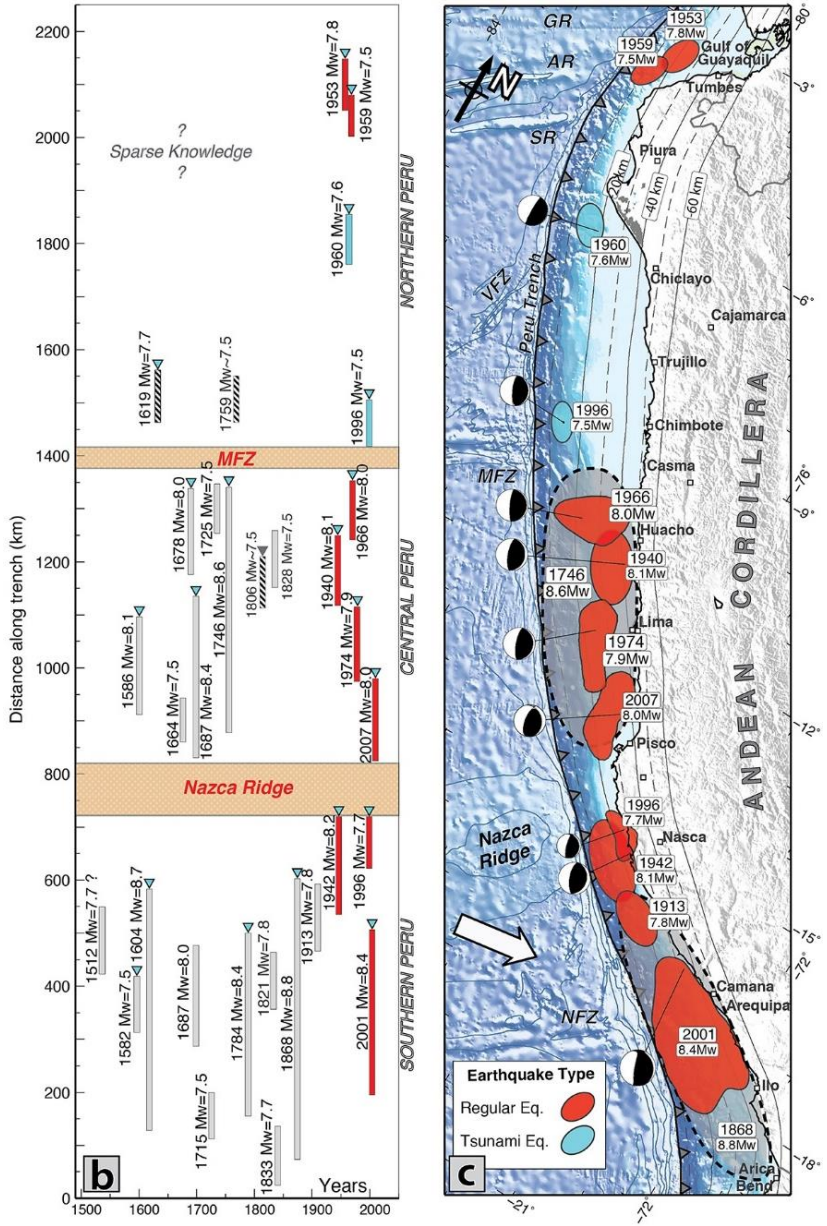
Segment 1

Barrier

Segment 2

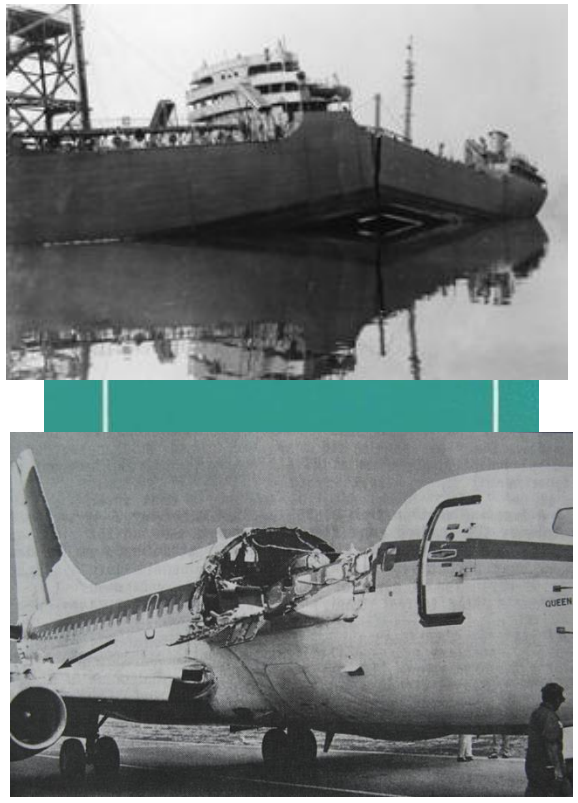
Barrier

Segment 3



(Villegas et al 2016)

Rupture arrest in classical fracture mechanics



Rupture stops at size $\boldsymbol{a}$ if

(fracture energy) > (energy release rate)

$$\boldsymbol{G_c > G_0 = \pi a \Delta\tau^2 / 2\mu}$$

Two possible mechanisms of rupture arrest:

1. Areas of low stress (low $\Delta\tau$), thus low G_0.
2. Areas of high resistance (large G_c).

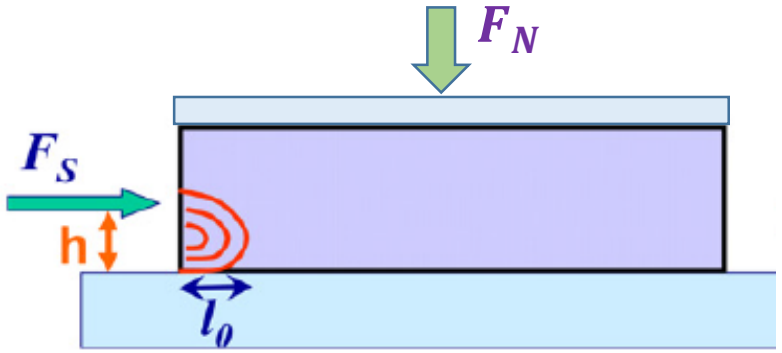
Tribol Lett (2015) 57:23
DOI 10.1007/s11249-014-0451-8

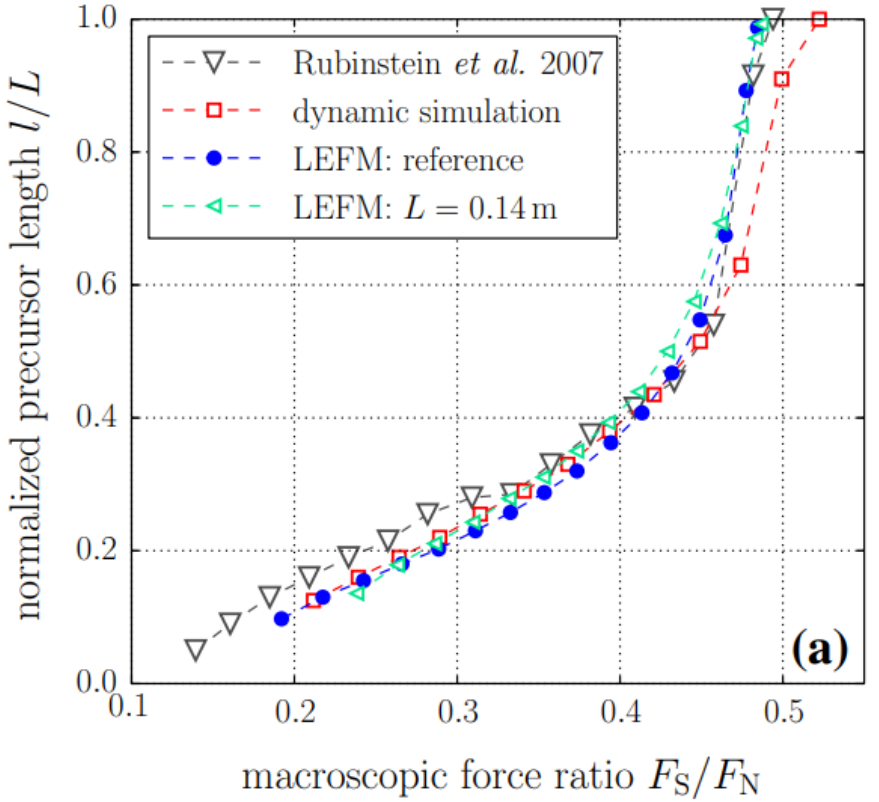
ORIGINAL PAPER

Linear Elastic Fracture Mechanics Predicts the Propagation Distance of Frictional Slip

David S. Kammer · Mathilde Radiguet · Jean-Paul Ampuero · Jean-François Molinari

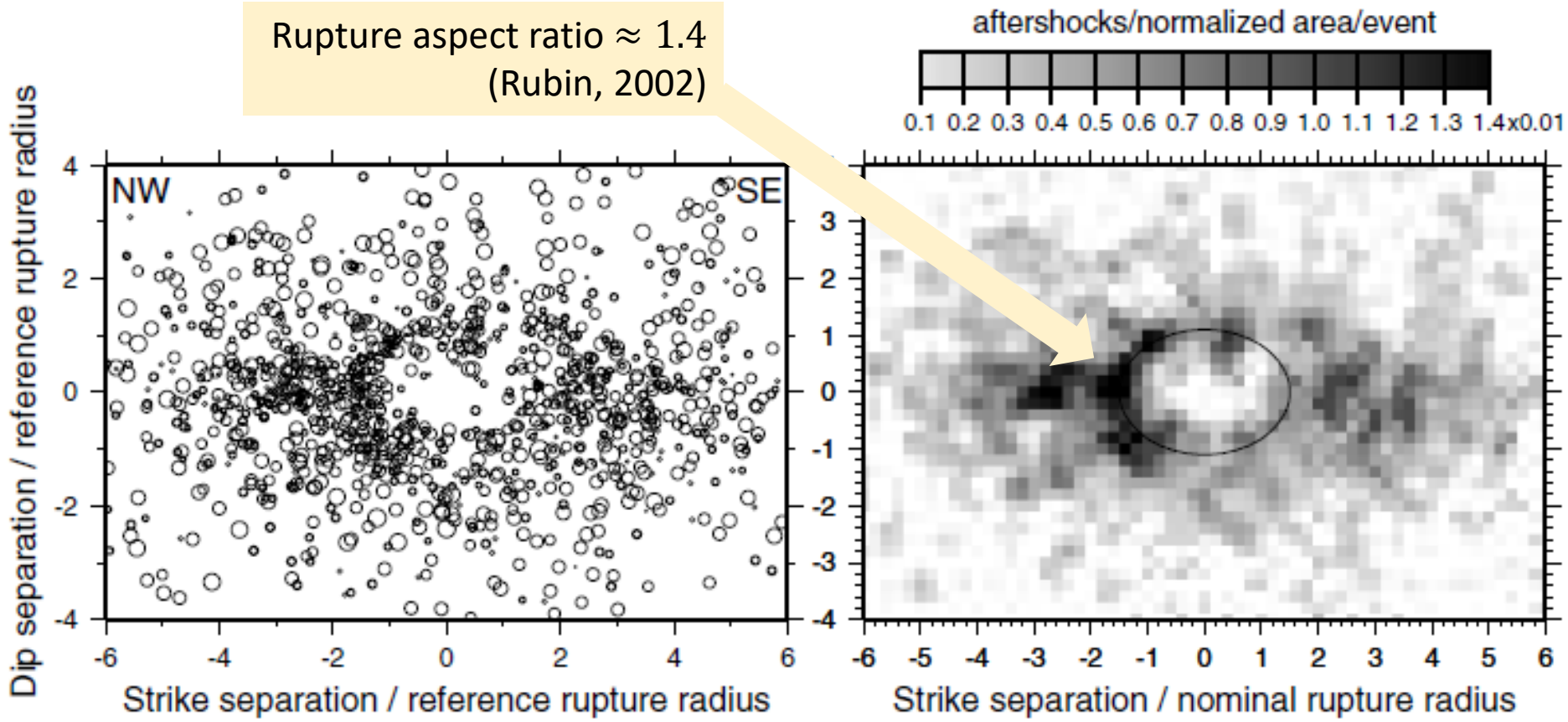
Size of laboratory quakes predicted by fracture mechanics





Rupture shape of micro-earthquakes on the San Andreas fault

Rupture aspect ratio ≈ 1.4
(Rubin, 2002)



Fracture mechanics predicts aspect ratio $= 1/(1-\nu) \approx 1.4$
where ν is Poisson's ratio

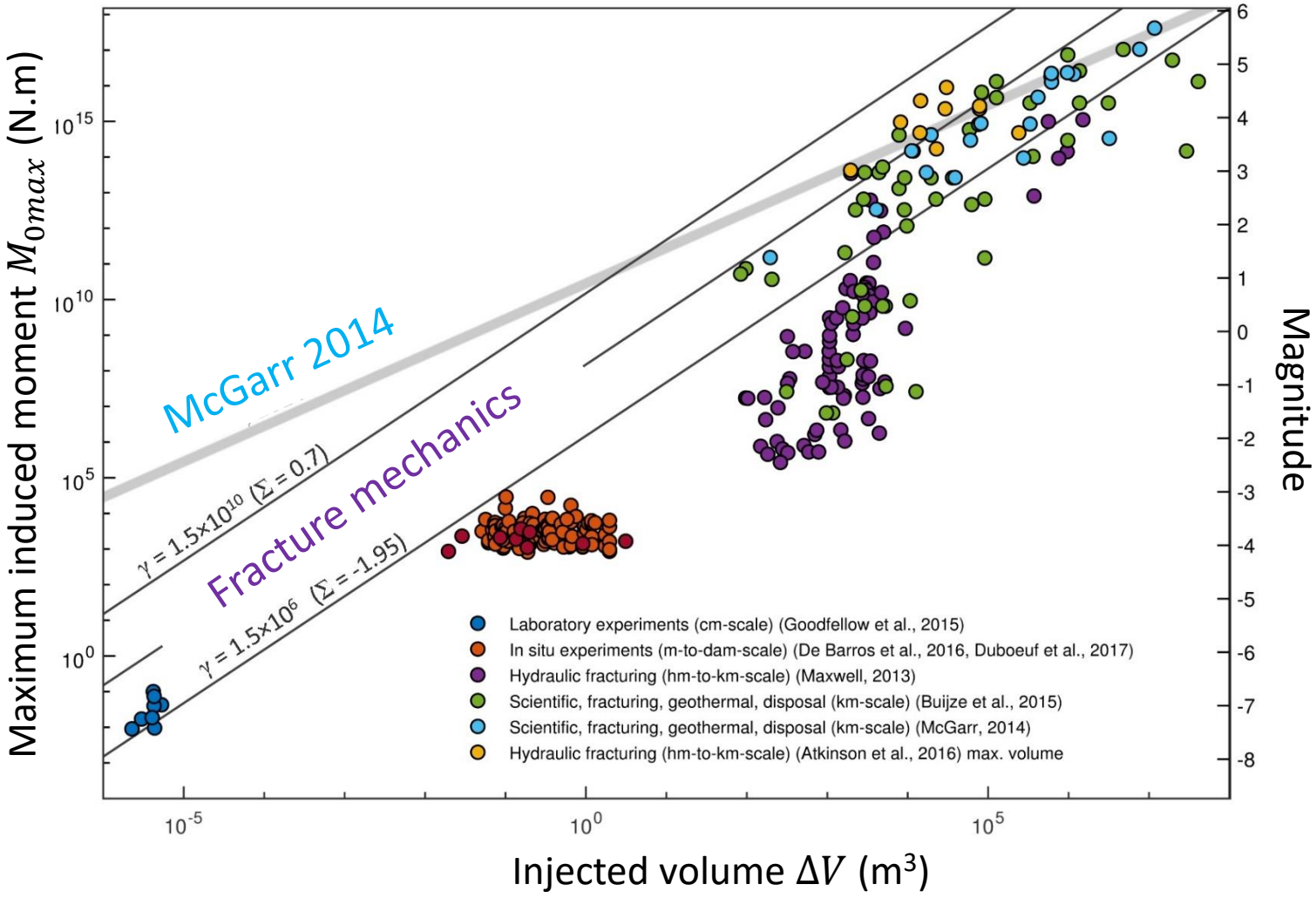
SCIENCE ADVANCES | RESEARCH ARTICLE

GEOPHYSICS

Induced seismicity provides insight into why earthquake ruptures stop

Martin Galis,[1*†] Jean Paul Ampuero,[2] P. Martin Mai,[1] Frédéric Cappa[3,4]

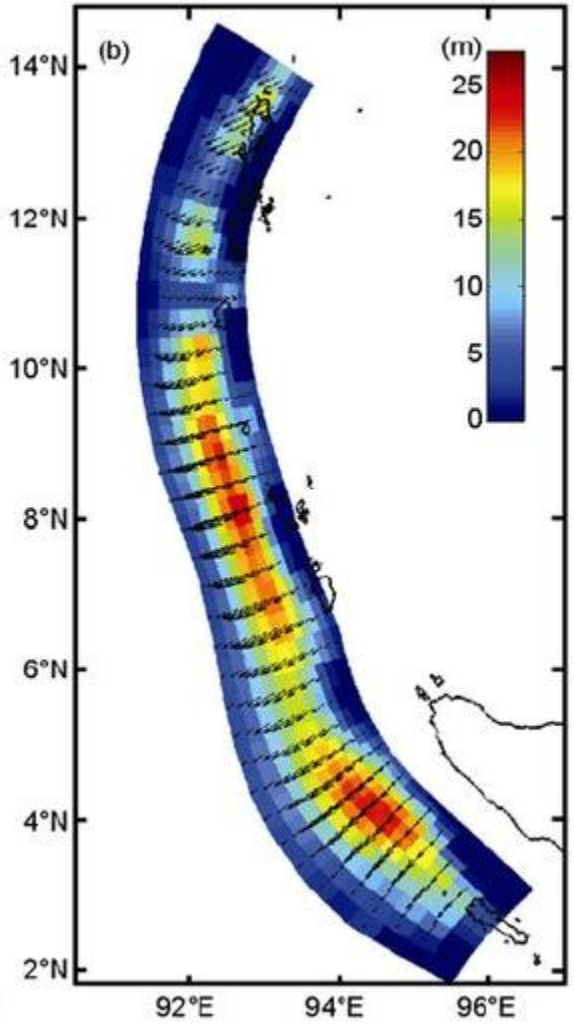
Fracture mechanics of rupture arrest applied to induced seismicity: $M_{0max} \propto \Delta V^{3/2}$



Large earthquakes have elongated ruptures

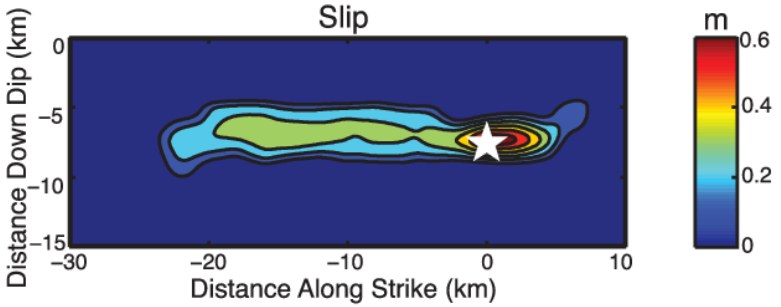
Large length/width ratio (L/W)

2004 M9.2 Sumatra



Le Teil, France Mw 4.9

2004 M6 Parkfield



Ma et al (2008)

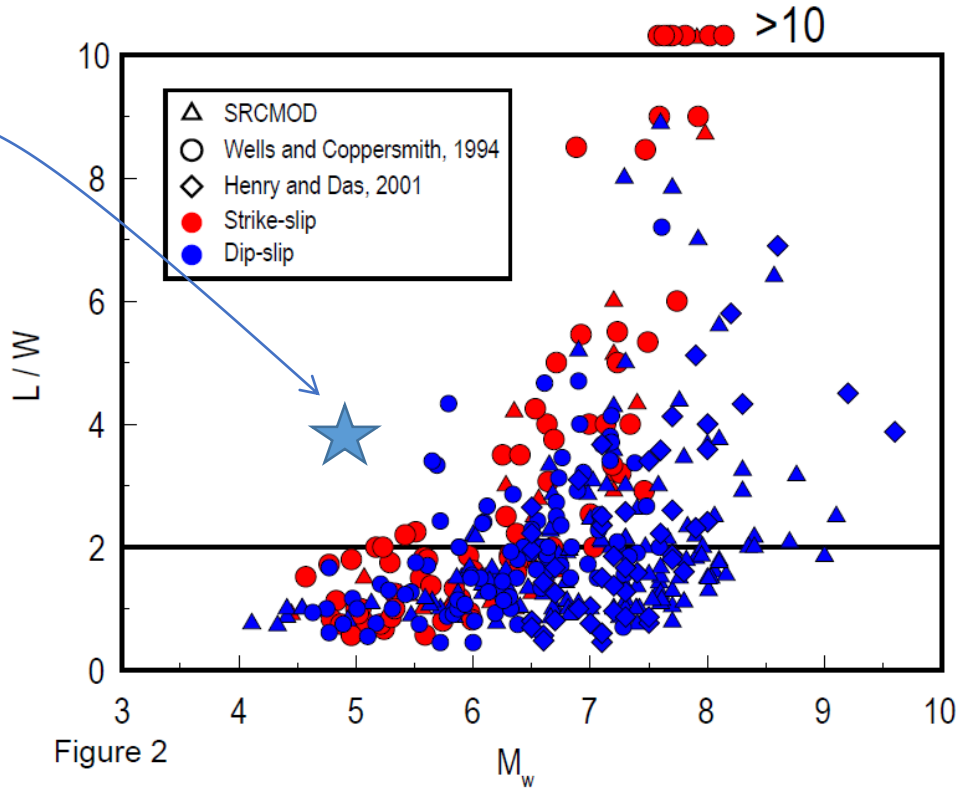
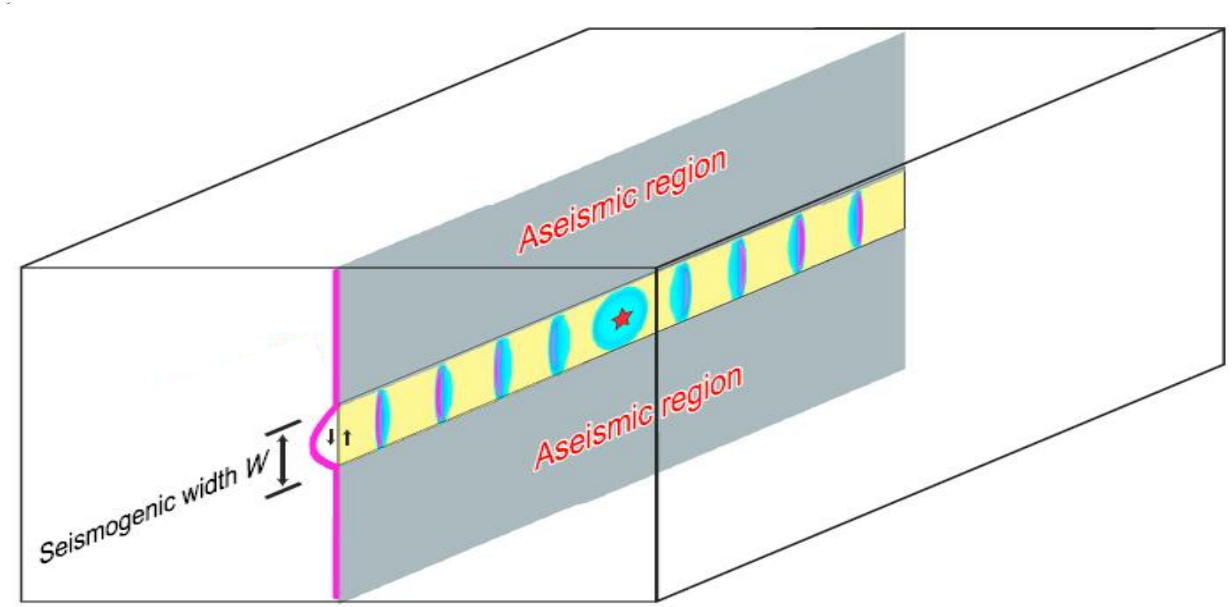
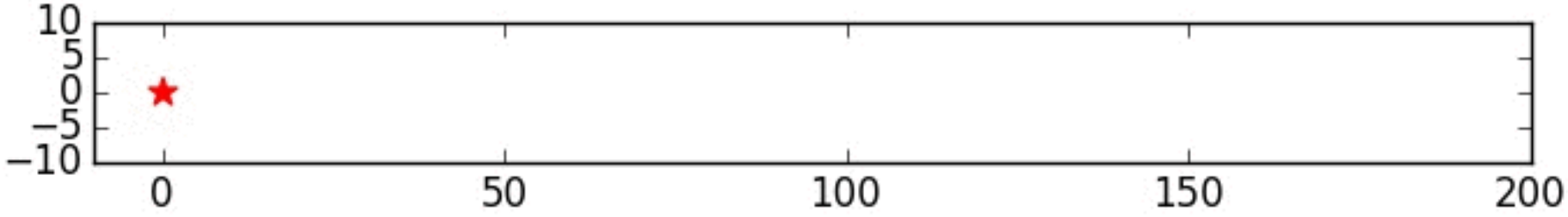


Figure 2

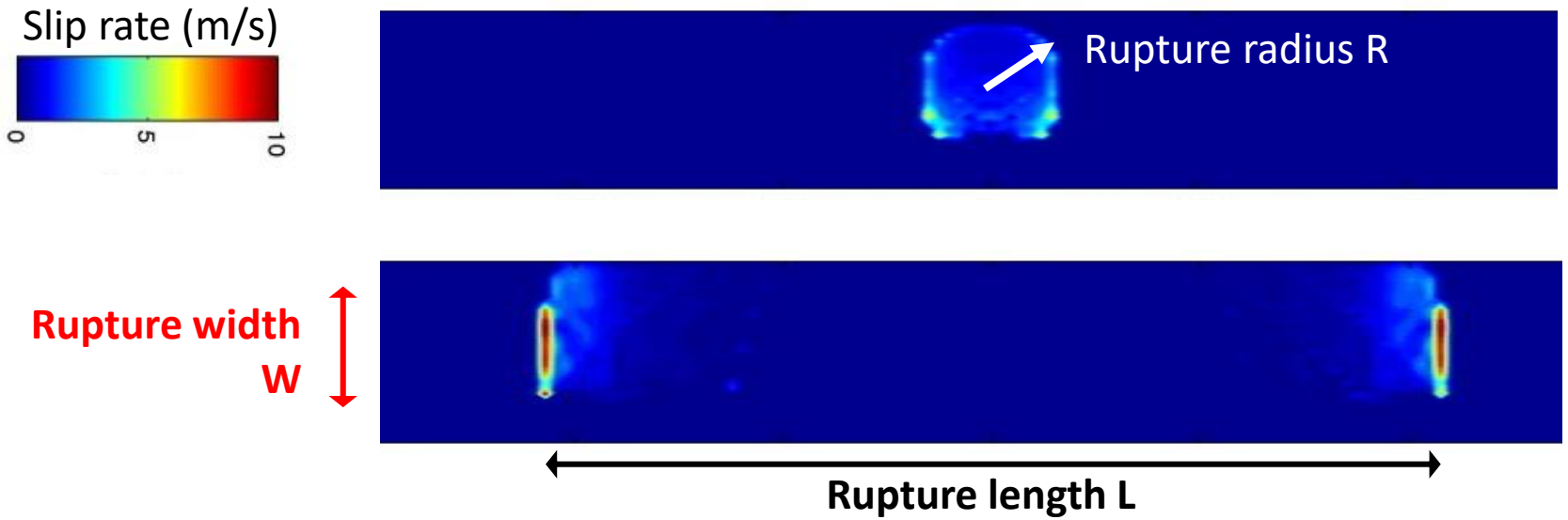
Weng and Ampuero (2019)

Long ruptures develop as slip pulses





Energy scaling



$G_0 \propto R$

vs.

$G_0 \propto$ **?**

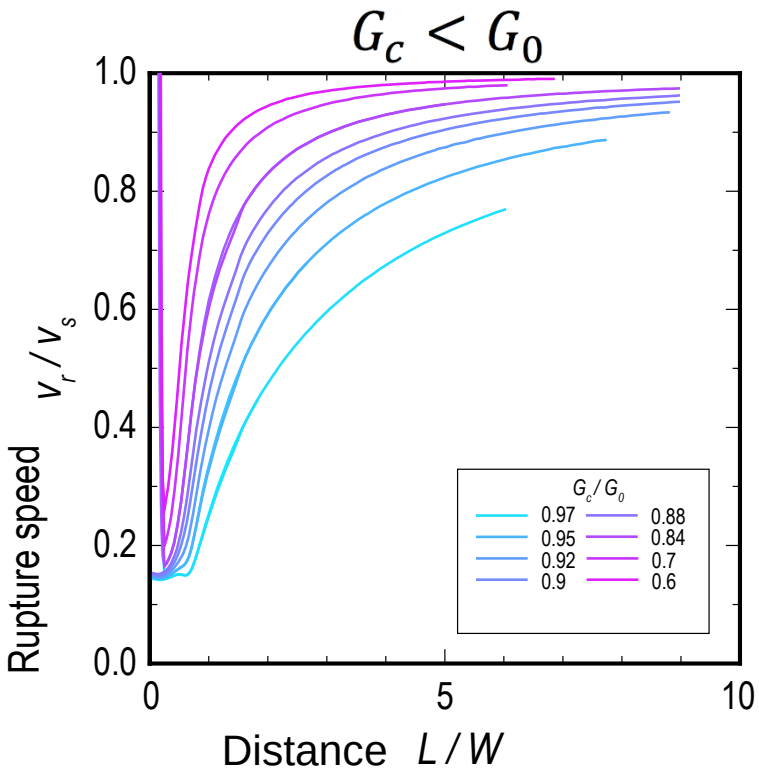
Research gap:
Dynamic theory for long ruptures?

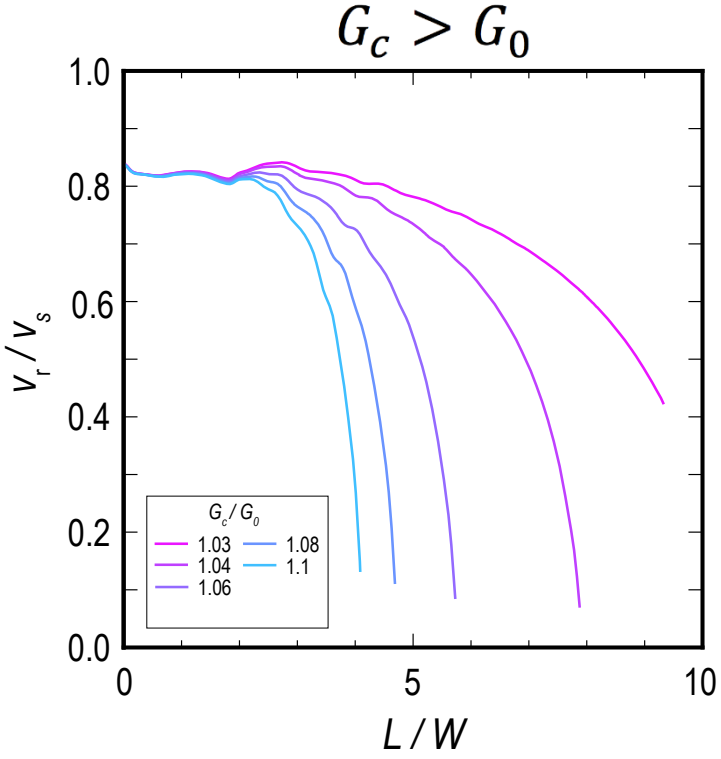
JGR Solid Earth

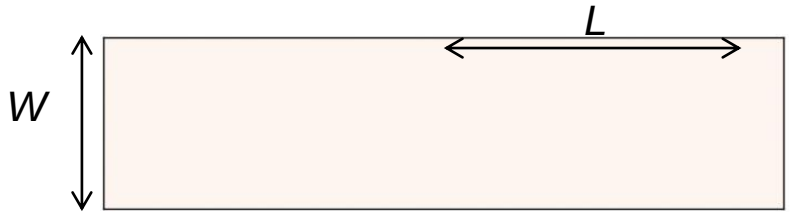
RESEARCH ARTICLE
10.1029/2019JB017684

The Dynamics of Elongated Earthquake Ruptures

Huihui Weng[1] and Jean-Paul Ampuero[1,2]





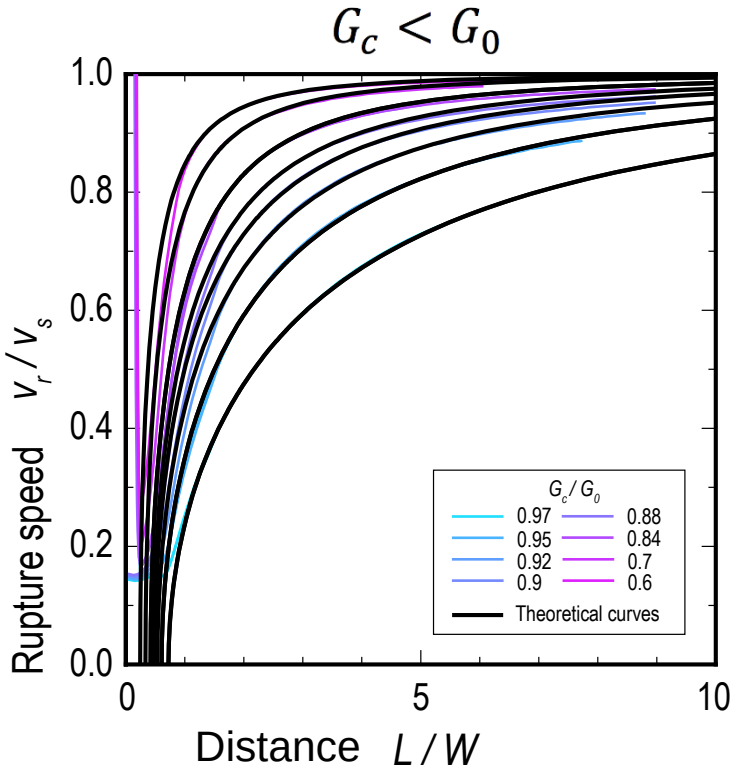


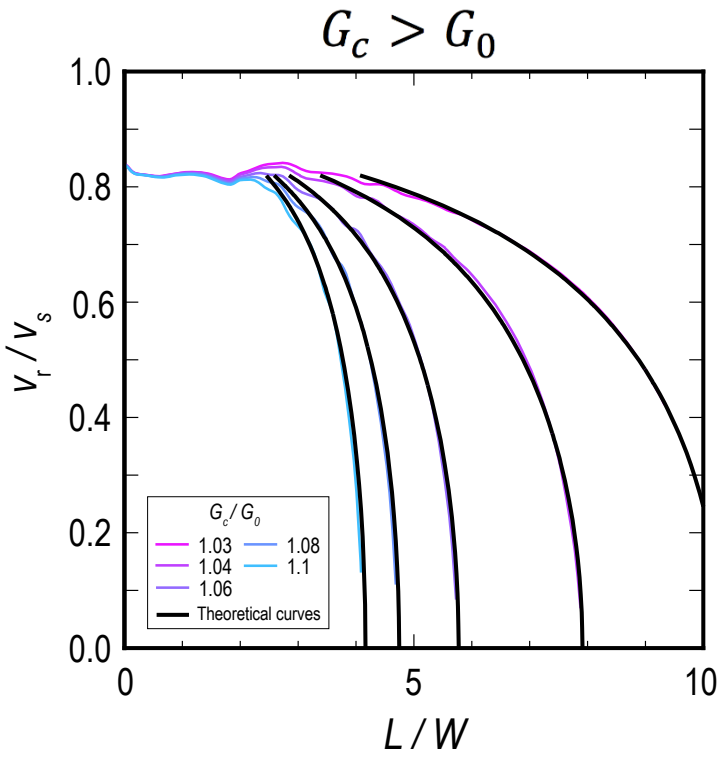
JGR Solid Earth

RESEARCH ARTICLE
10.1029/2019JB017684

The Dynamics of Elongated Earthquake Ruptures

Huihui Weng[1] and Jean-Paul Ampuero[1,2]

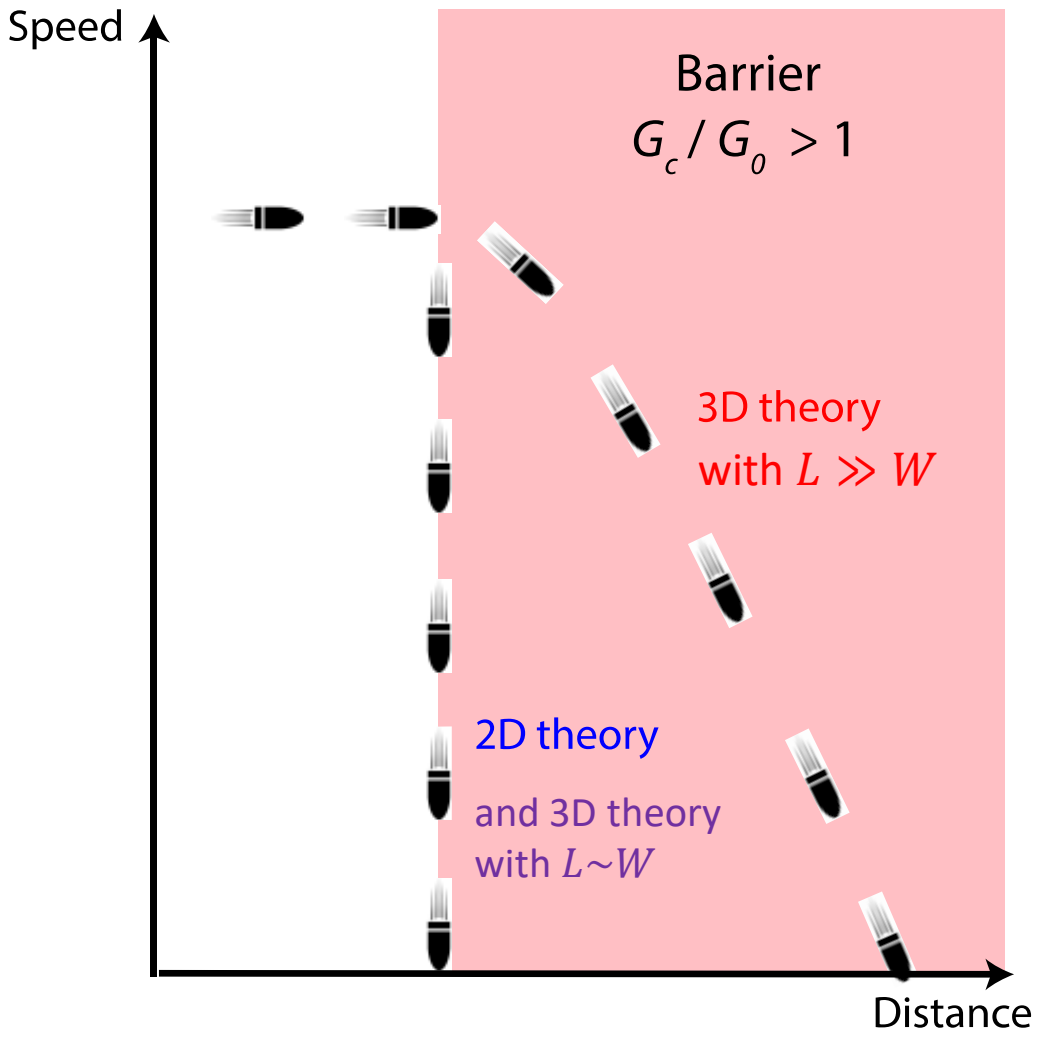




$$1 - G_c/G_0 = \mathcal{M}(v_r) \cdot \dot{v}_r$$

"Force" = "Mass" × Acceleration

Implications for rupture arrest



nature geoscience

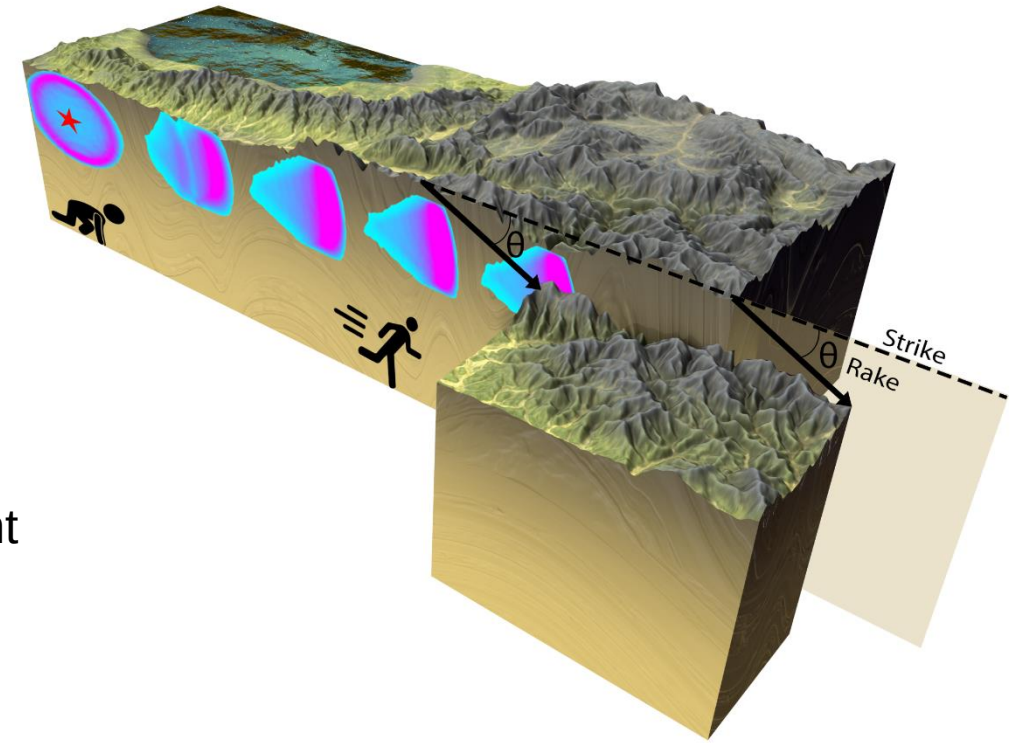
ARTICLES

https://doi.org/10.1038/s41561-020-00654-4

Check for updates

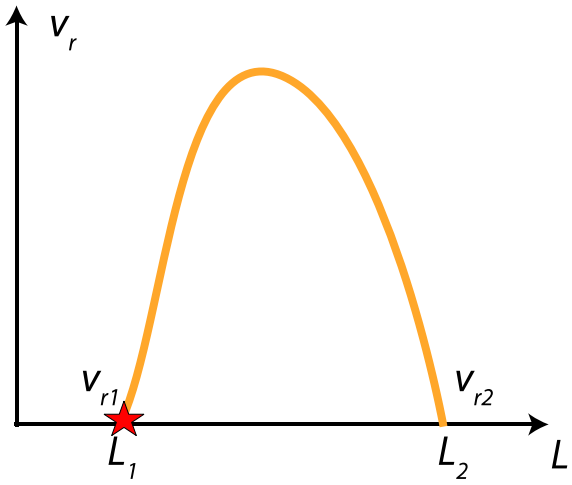
Continuum of earthquake rupture speeds enabled by oblique slip

Huihui Weng ✉ and Jean-Paul Ampuero (2020)



→ Conceptual implications
for time-dependent seismic hazard assessment

Rupture potential



$$\mathcal{F}(G_c/G_0\quad) = \mathcal{M}(v_r)\cdot \dot{v}_r$$

$$\dot{v}_r = v_r \frac{dv_r}{dL}$$

$$\int_{L_1}^{L_2} \mathcal{F}(G_c/G_0\quad) dL = \int_{v_{r1}}^{v_{r2}} v_r \mathcal{M}(v_r)\, dv_r = 0$$

Potential energy change

Kinetic energy change

Rupture potential

$$\int_0^{L_1} \mathcal{F}(G_c/G_0\quad) dL = \int_0^{L_2} \mathcal{F}(G_c/G_0\quad) dL$$

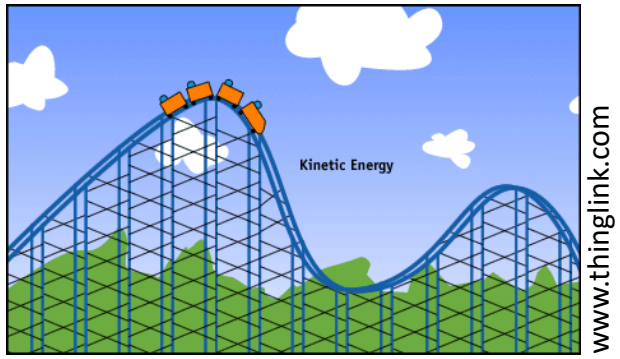
Determine earthquake size

Rupture potential

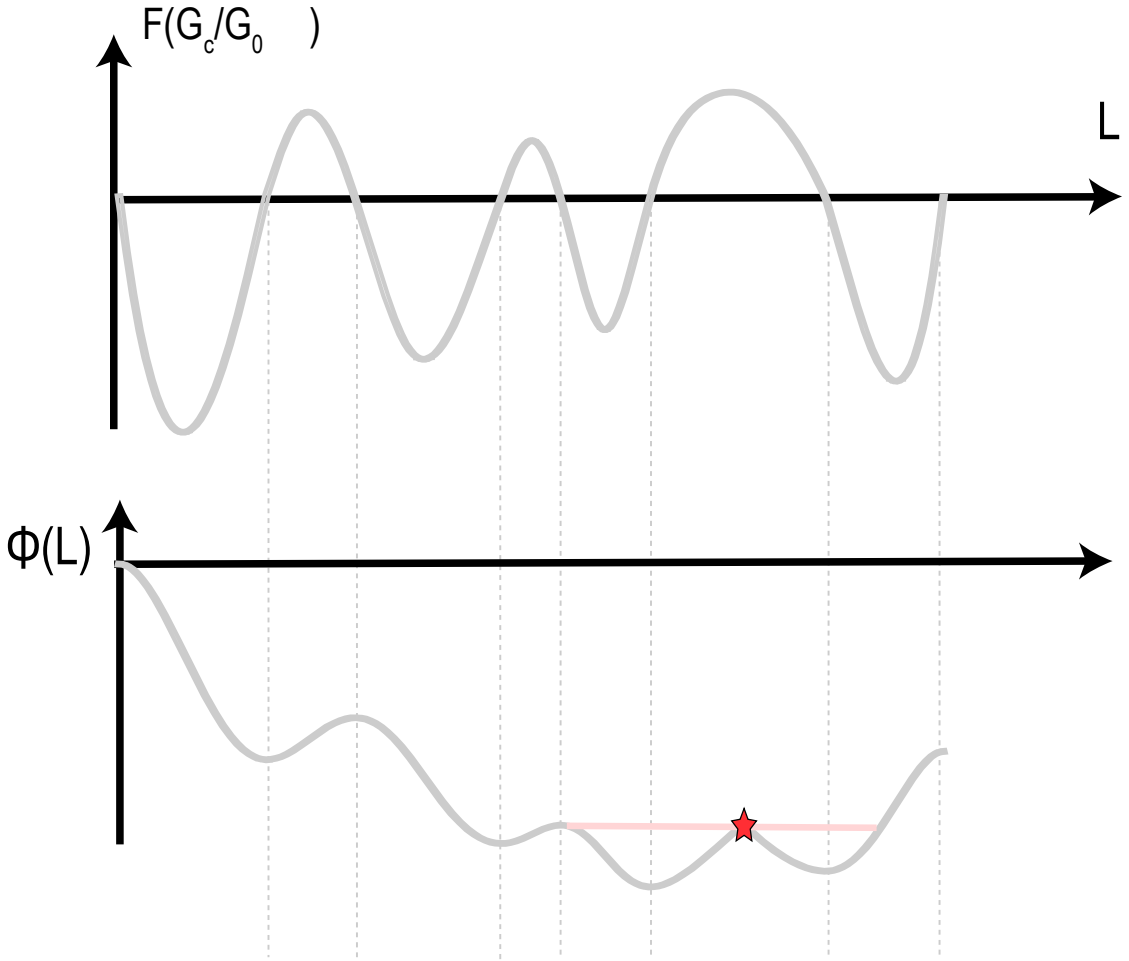
$$\Phi(L) = \int_0^L \mathcal{F}(G_c/G_0 \quad) dL$$

Rupture arrest condition

$$\Phi(L_1) = \Phi(L_2)$$



Analogy: gravity potential

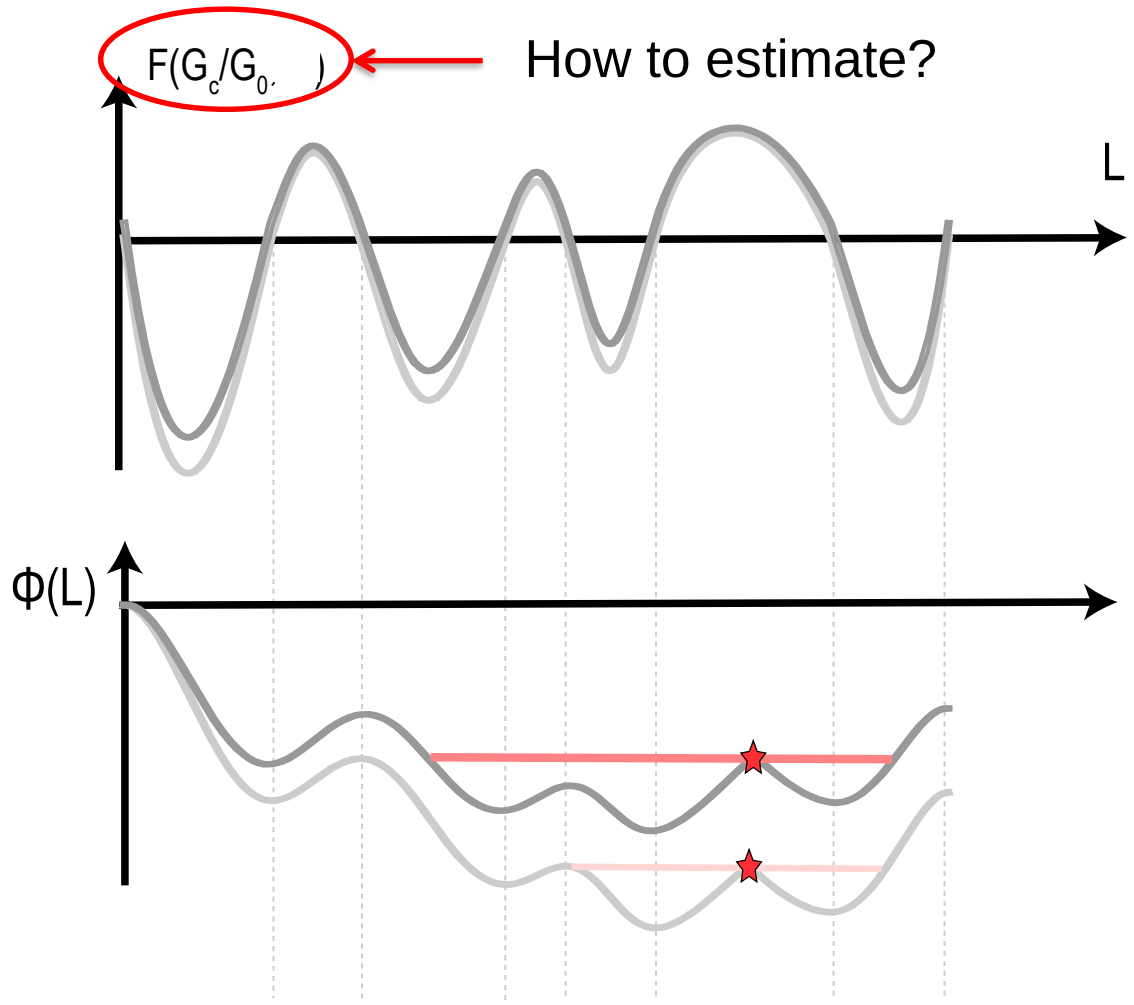


Determine earthquake size

Rupture potential

$$\Phi(L) = \int_0^L \mathcal{F}(G_c/G_0 \quad) dL$$

$$\Phi(L_1) = \Phi(L_2)$$

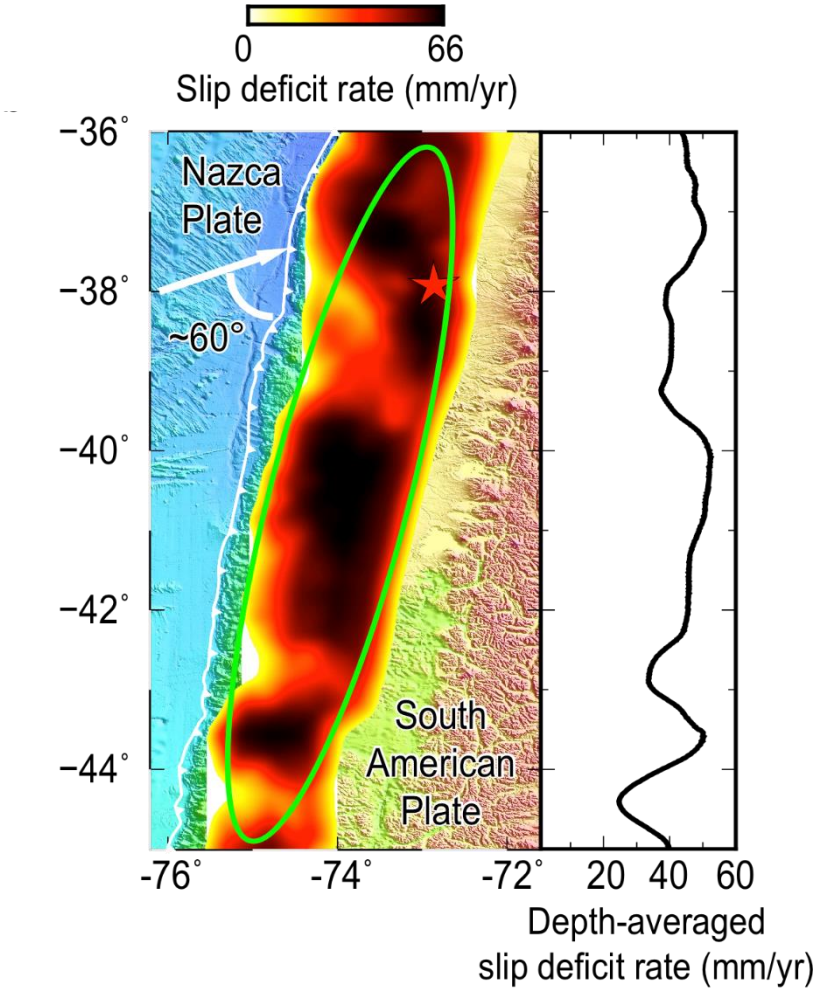


Constraints on energy release rate G_0

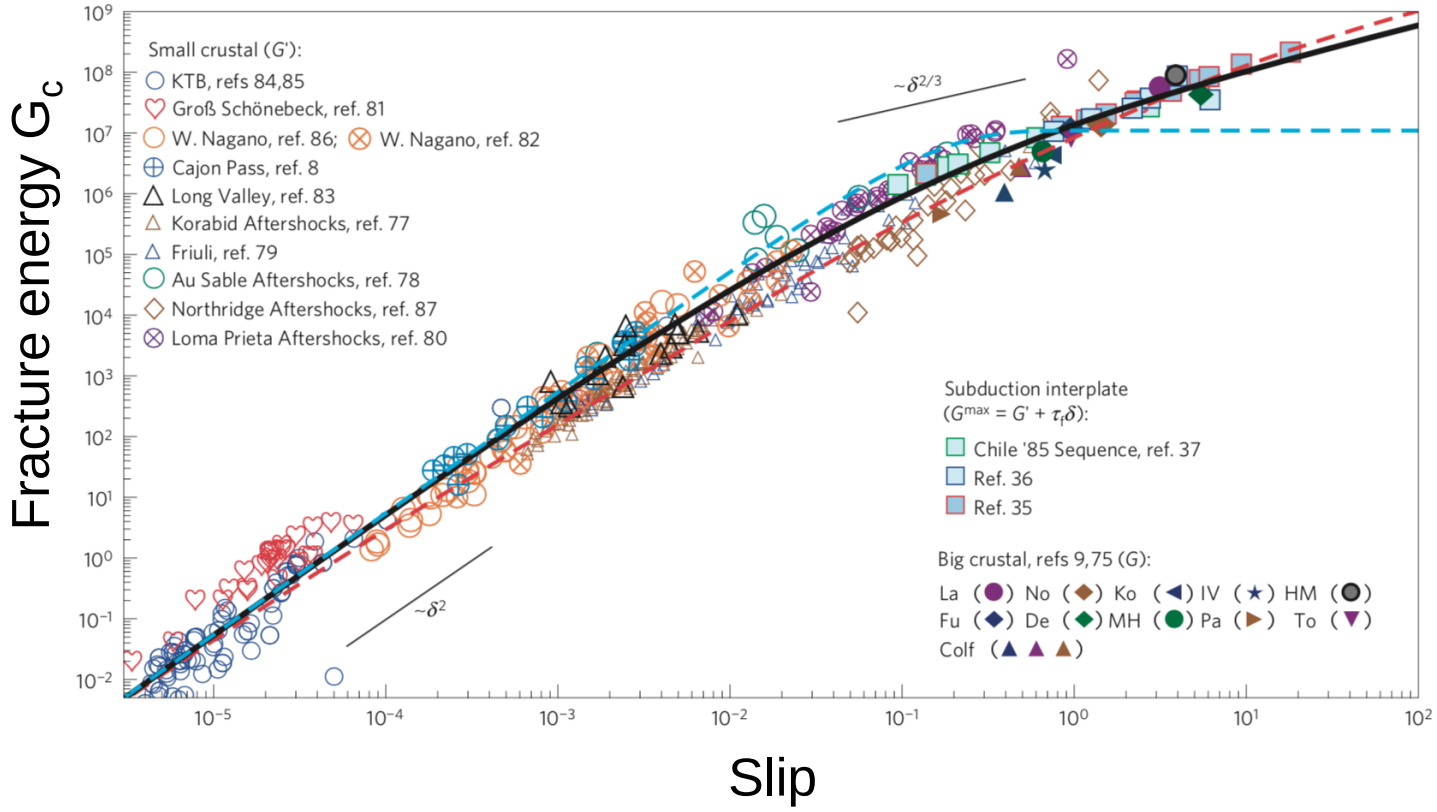
$$G_0 = \frac{\Delta\tau^2 W}{\pi\mu}$$

$$\Delta\tau = \frac{C\mu D}{W}$$

$$G_0 \sim \frac{\mu}{W} D^2$$



Constraints on fracture energy G_c



$$G_c \sim D^{0.7}$$

Viesca and Garagash, 2015

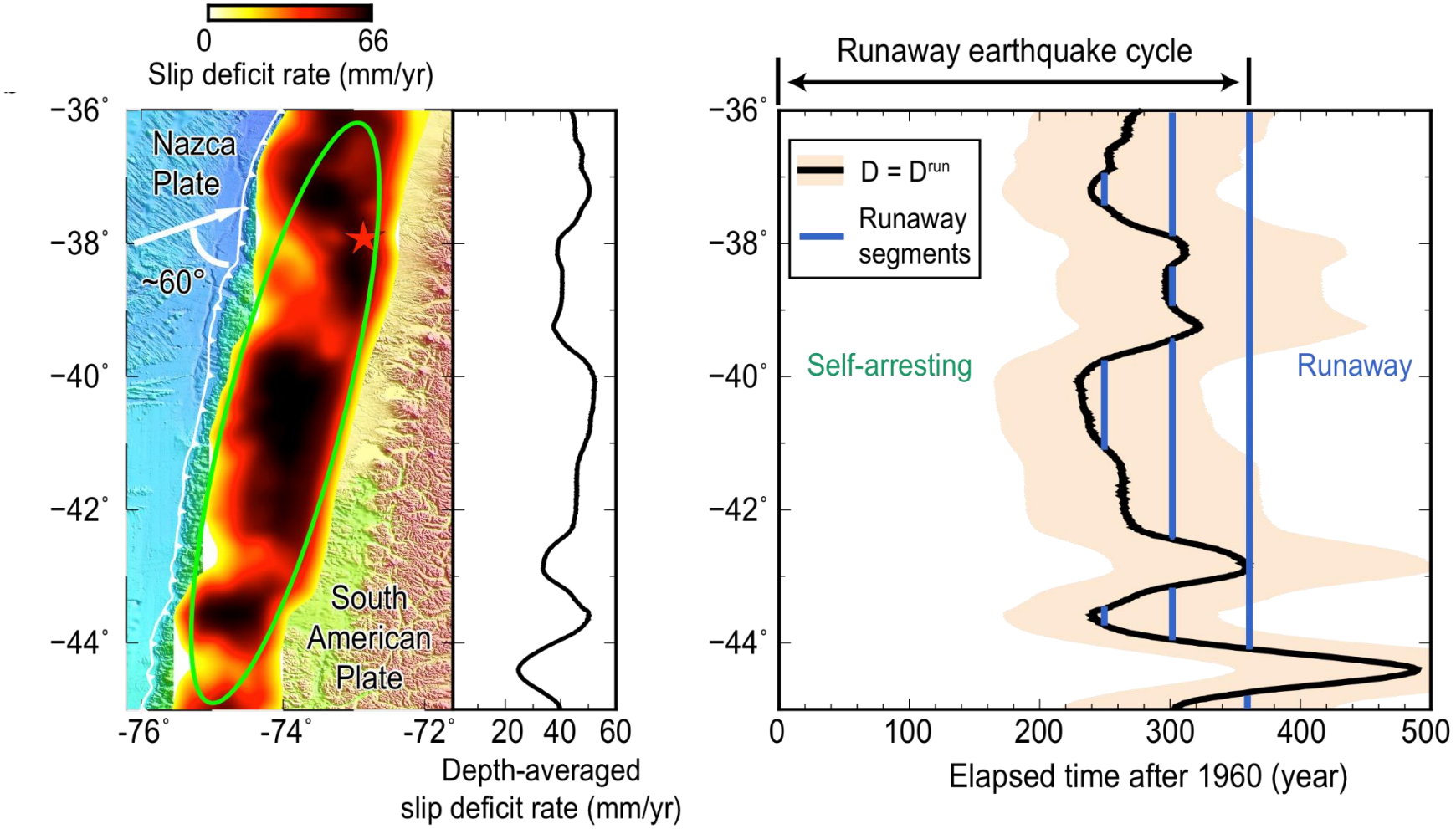
Physical constraints on earthquake size

Runaway rupture if $G_0 > G_c$

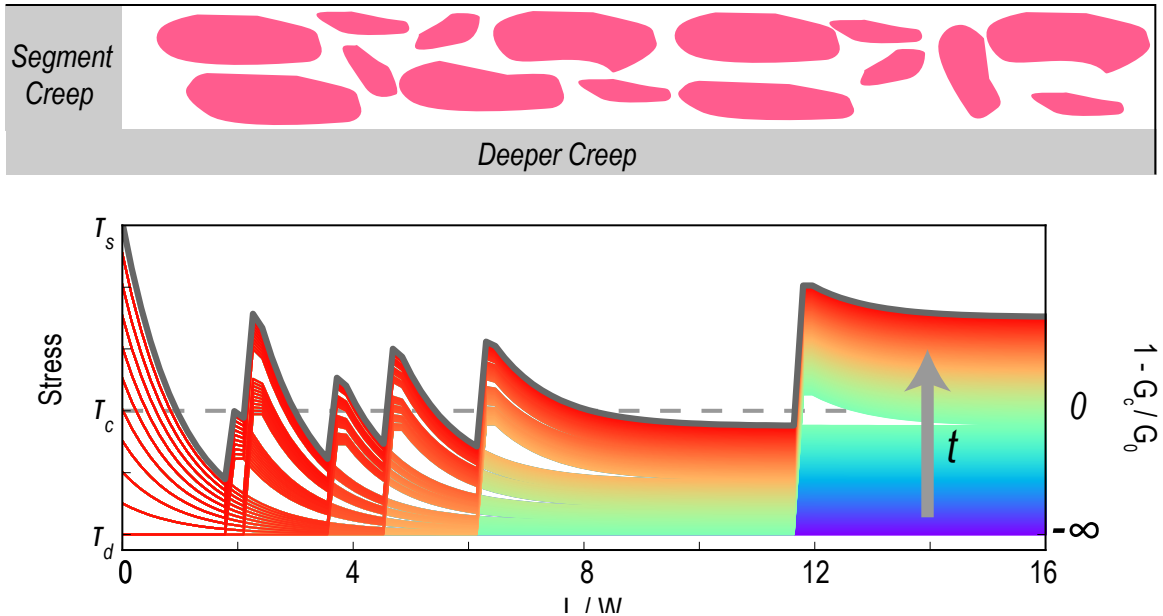
$G_c \sim D^{0.7}$

$G_0 \sim D^2$

Runaway if $D > D^{run}$



A toy model for earthquake super-cycles



Weng and Ampuero, 2019

Slip behavior of Velocity-Weakening barriers.

Diego Molina, Jean-Paul Ampuero, Andrés Tassara

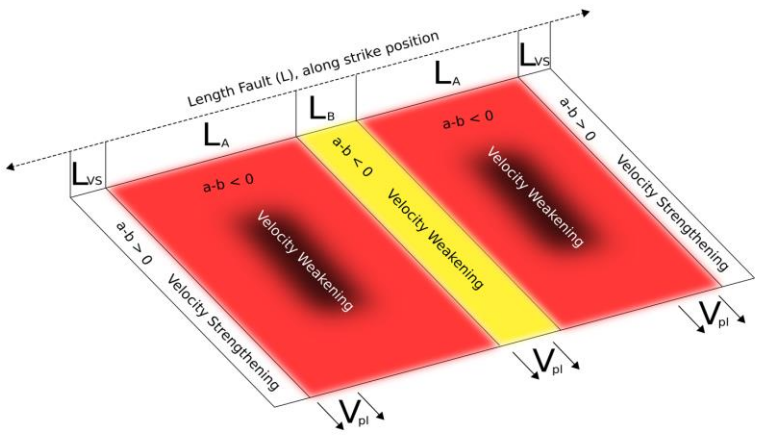
This is a preprint; it has not been peer reviewed by a journal.

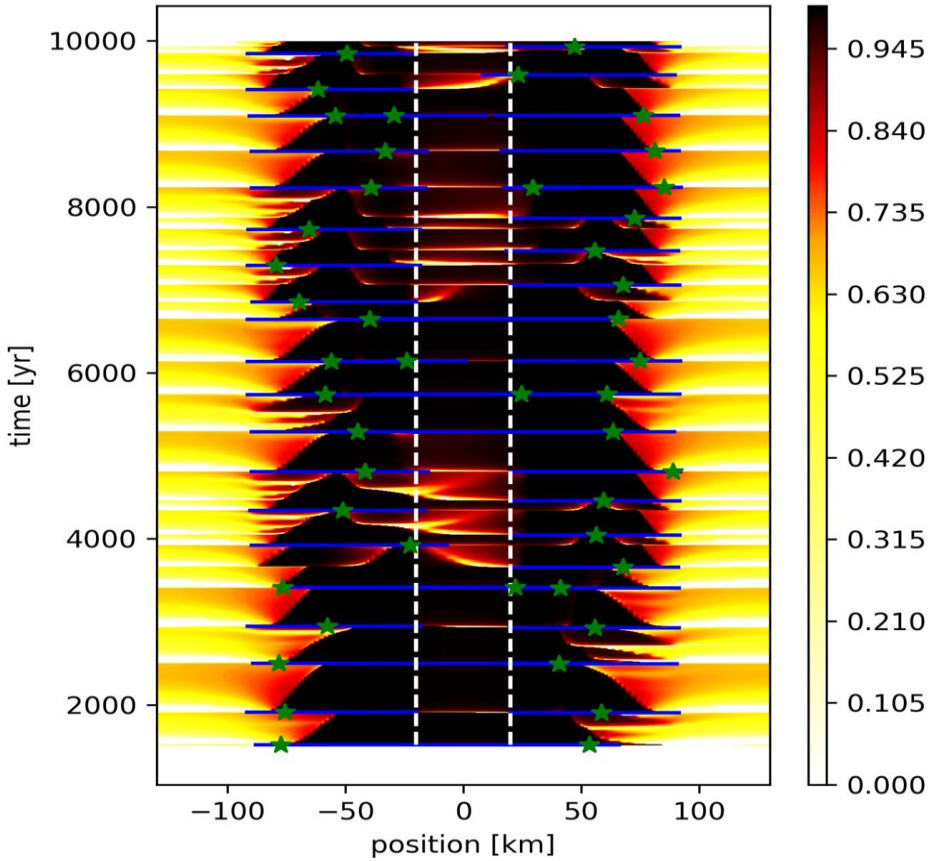
https://doi.org/10.21203/rs.3.rs-1479134/v1

Status: Under Review

nature portfolio

Version 1
posted 27 Apr, 2022

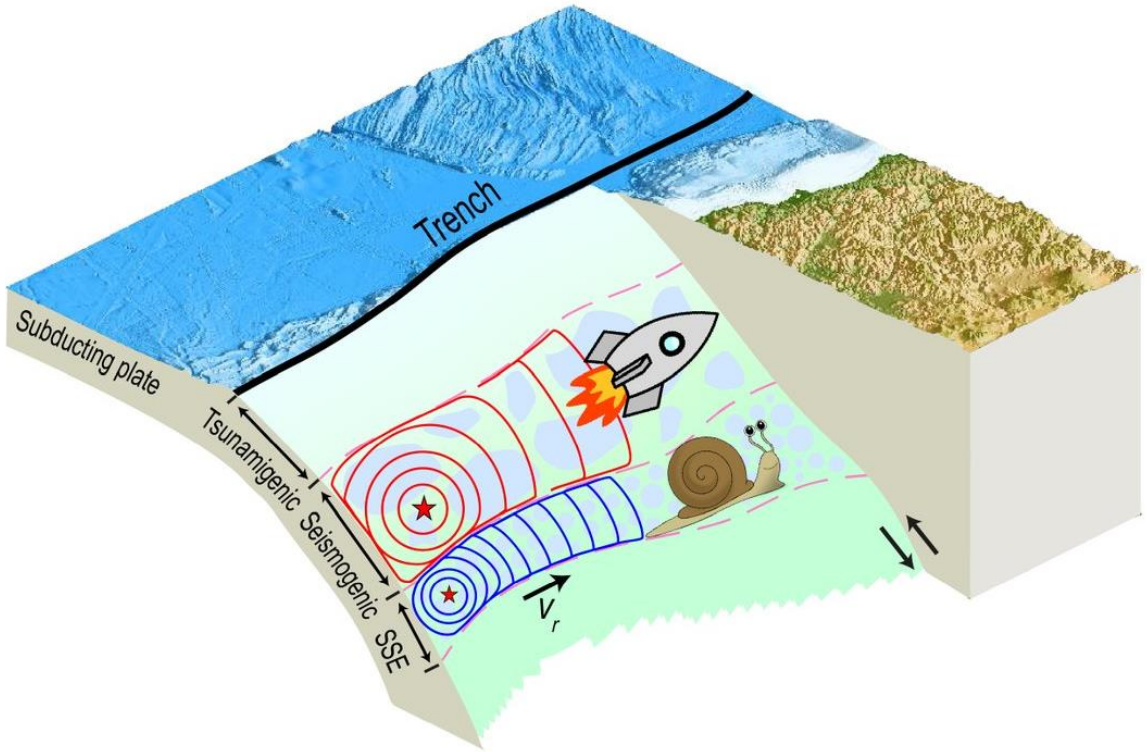




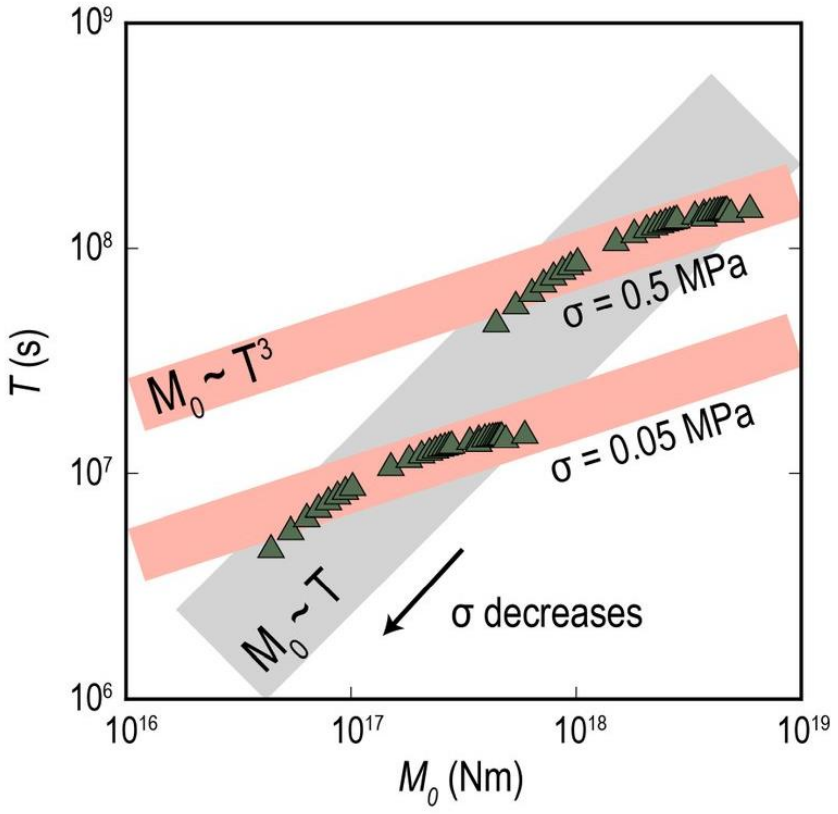
Integrated rupture mechanics for slow slip events and earthquakes

Weng and Ampuero (preprint 2022)

Unifying slow slip events and earthquakes



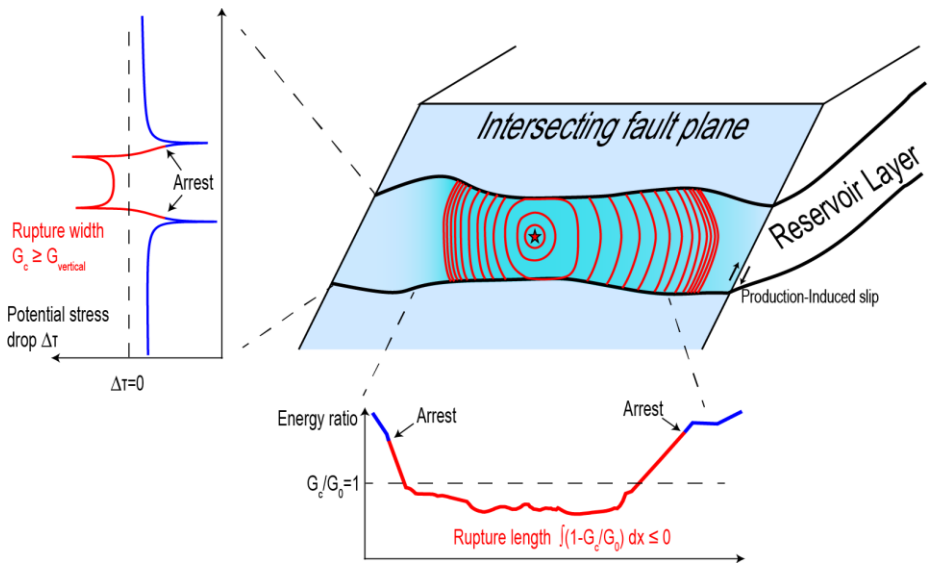
Reconciling debated scaling relations



New preprint @researchsquare : www.researchsquare.com/article/rs-448196/v1

Physics-based estimates of induced Mmax in the Groningen gas field, The Netherlands

J.P. Ampuero & H. Weng (Geoazur), L. Buijze (TNO) - Funded by NAM (2021/2022)

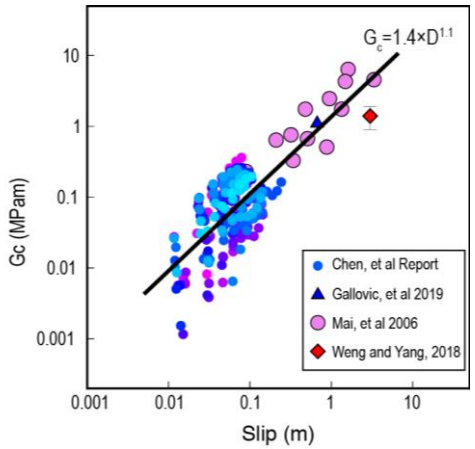


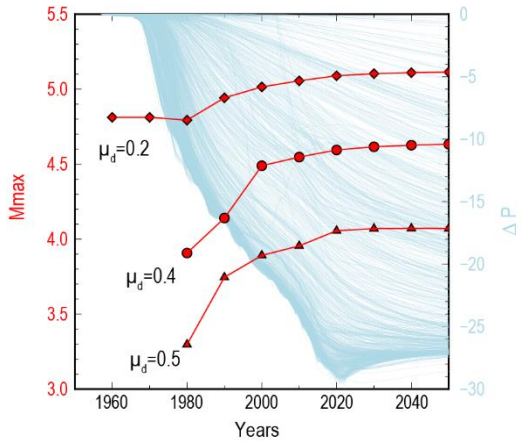
Efficient dynamic rupture modeling includes:

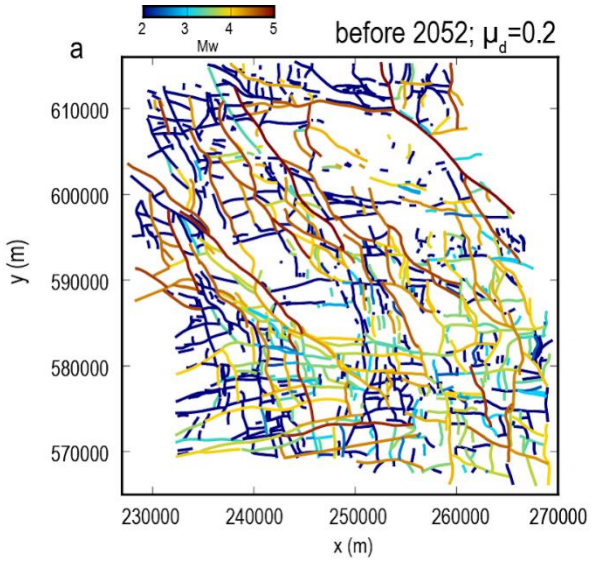
- Combined along-dip 2D LEFM and along-strike 2.5D LEFM
- Fault friction constrained by lab and seismological observations
- Groningen fault network geometry
- Models of fault stress induced by reservoir depletion

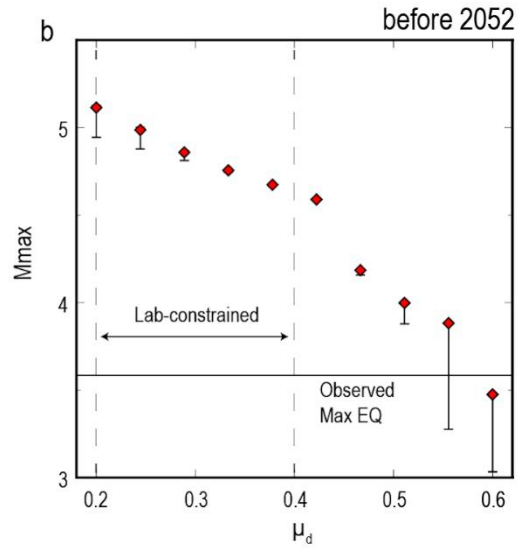
Outputs:

- Mmax as a function of space and time
- Sensitivity to model parameters and their uncertainties









Conclusions

New 3D theory of rupture dynamics for long ruptures (L>W)
accounting for finite rupture width and oblique slip
yields a simple equation governing rupture propagation

→insights on rupture arrest

→ towards physics-based hazard assessment

Perspectives: validation in lab experiments,
earthquake cycle simulations
and real slow slip events

References:

Weng and Ampuero (JGR 2019) *The dynamics of elongated earthquake ruptures*

Weng and Ampuero (Nature Geo 2020) *Continuum of earthquake rupture speeds enabled by oblique slip*

Weng and Ampuero (preprint 2022) *Integrated rupture mechanics for slow slip events and earthquakes*

Molina et al (preprint 2022) *Slip behavior of velocity-weakening barriers*

Funding acknowledgments

INITIATIVE D'EXCELLENCE

UCA J.E.D.I.
UNIVERSITÉ CÔTE D'AZUR

AGENCE NATIONALE DE LA RECHERCHE
ANR