If you can see this you are at the right place!

Kindly turn off your cameras and microphones!

Except the jury members!

We will start promptly at 4pm Paris time.

Supershear Earthquakes

Theory, Experiments & Observations

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M. Bouchon
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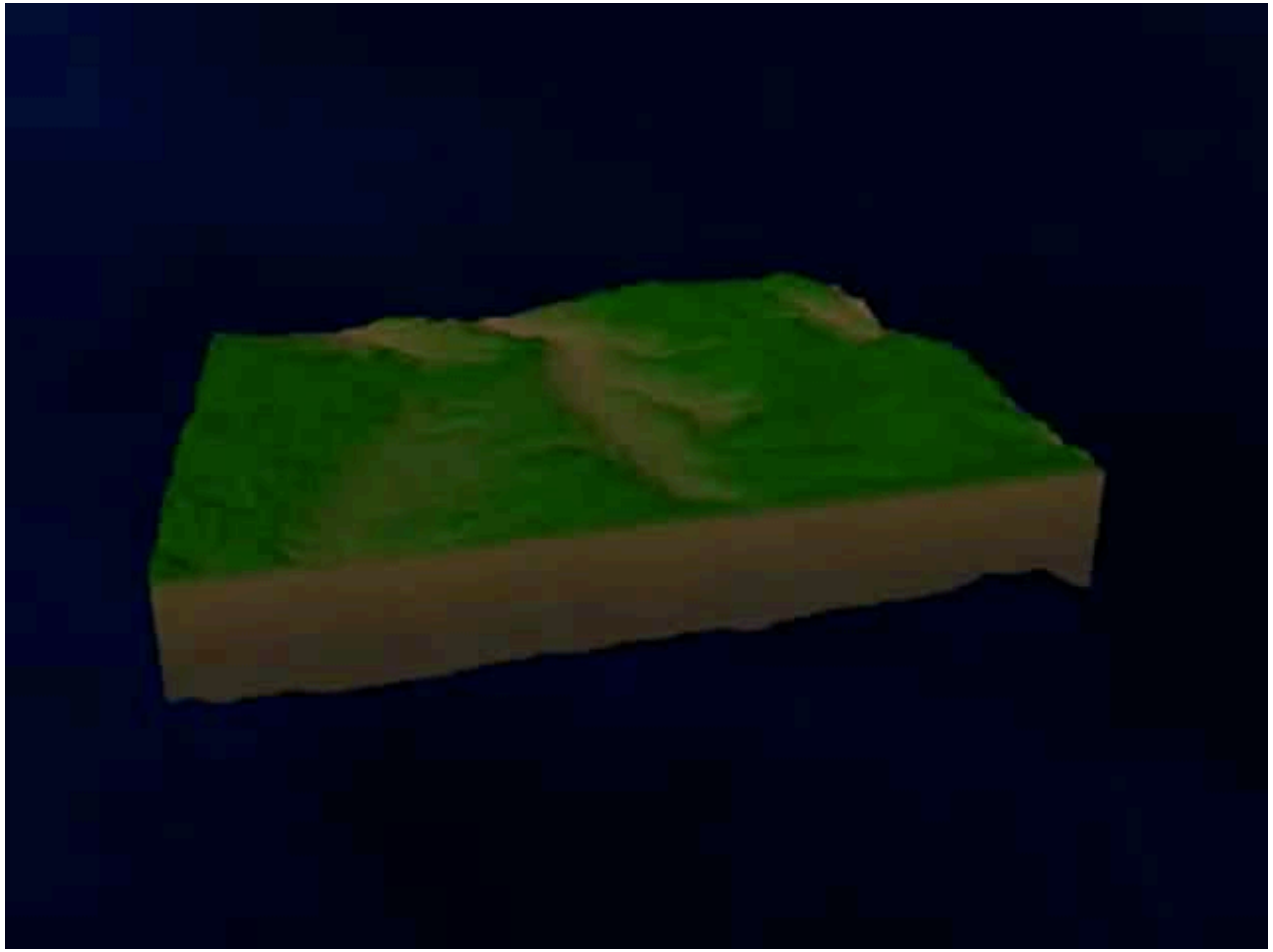
To obtain Habilitation à Diriger des Recherches from École Normale Supérieure

Classical View of an Earthquake

Video courtesy USGS

Classical View of an Earthquake

Tectonic plates try to slide past each around **faults**



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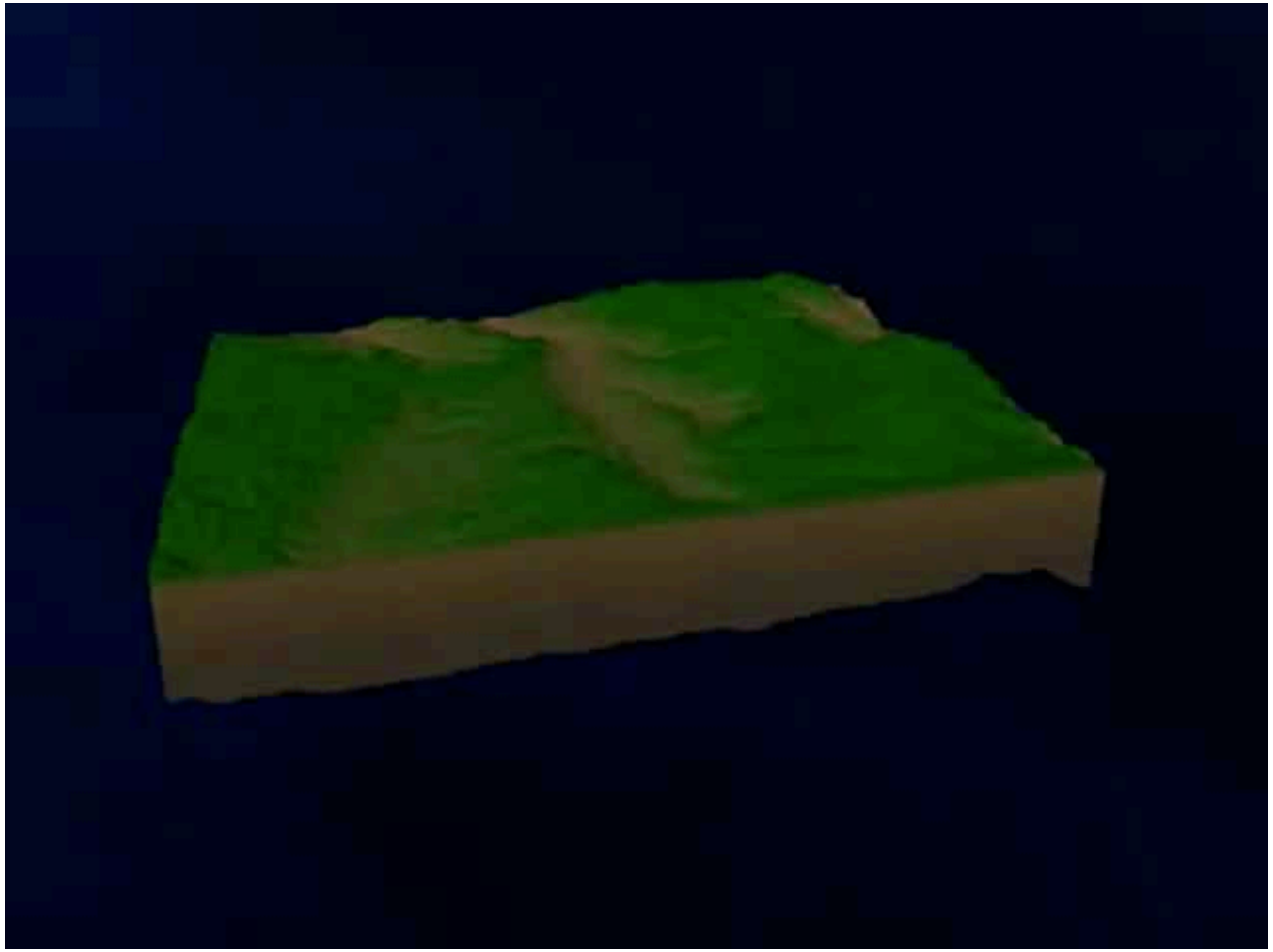

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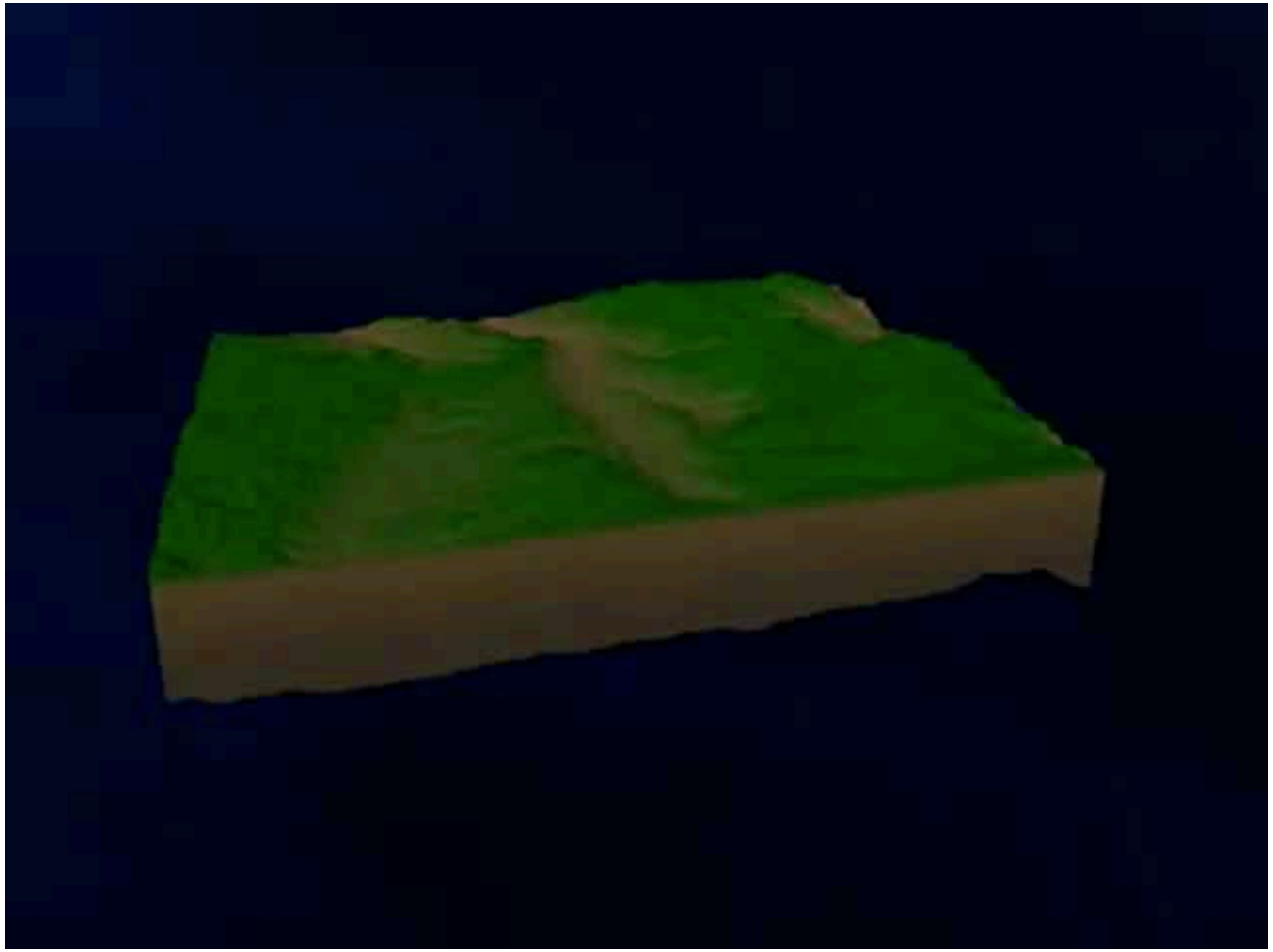

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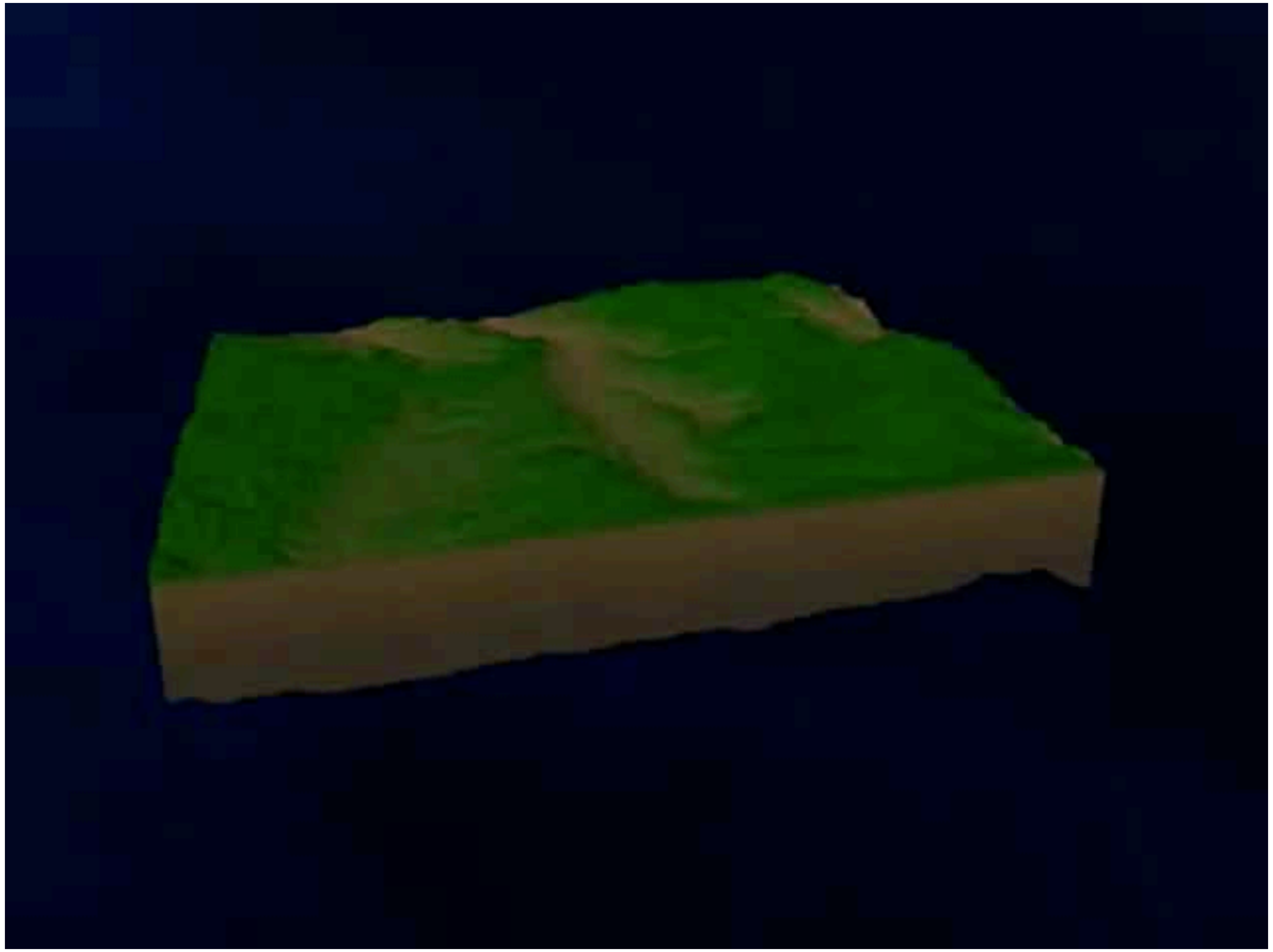

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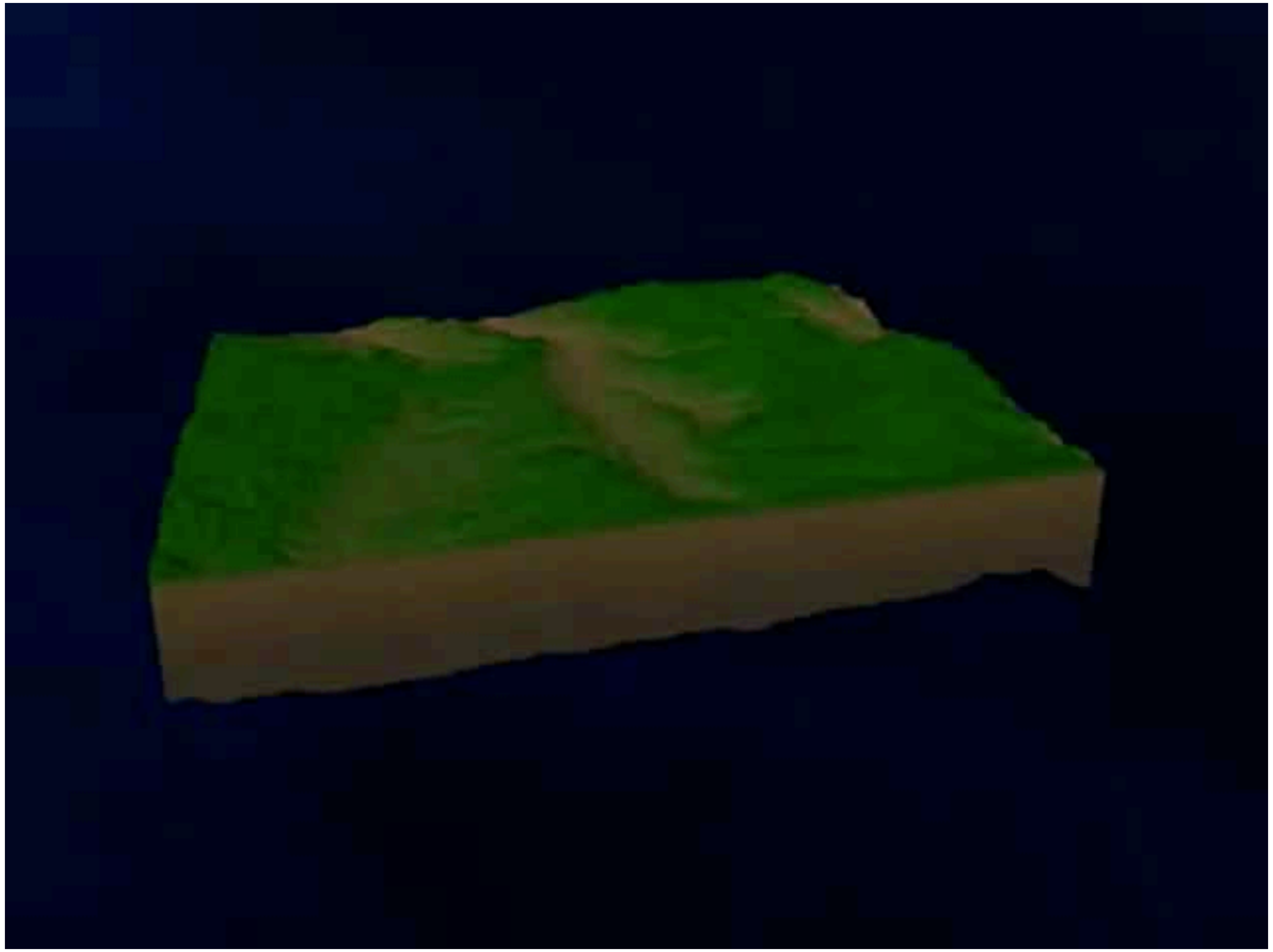
This leads to a sudden release of the stored energy called an **Earthquake**



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Rupture Speed

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A vast majority of earthquakes have rupture speed *slower* than the S-wave speed, around **2.5 km/s to 3 km/s**


S-waves
P-waves
Fault
Rupture Front

Rupture Speed

Rupture Speed

However, occasionally, the rupture tends to go _**faster**_ than the S-wave speed (but slower than the P-wave speed)

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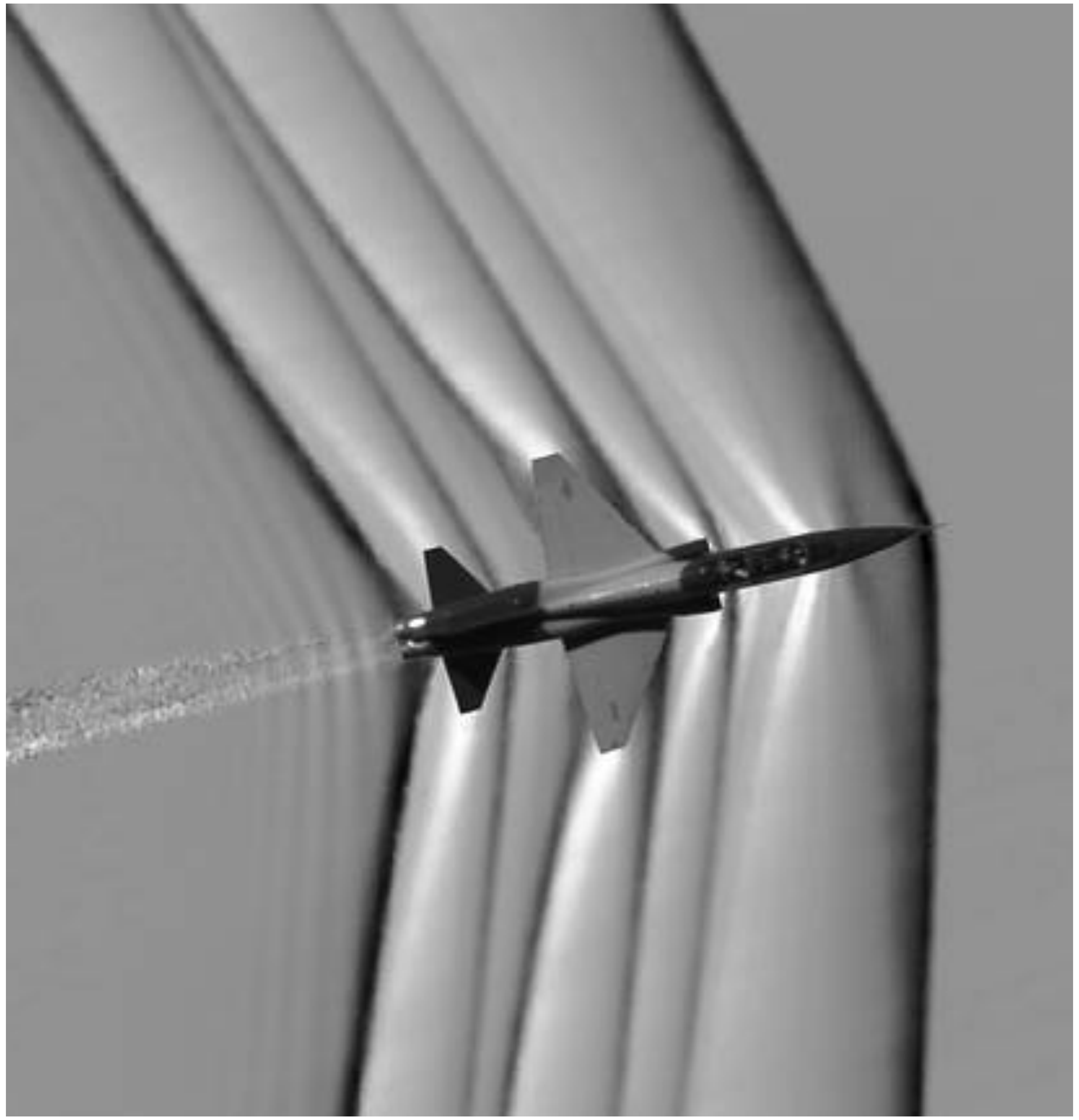
However, occasionally, the rupture tends to go *faster* than the S-wave speed (but slower than the P-wave speed)

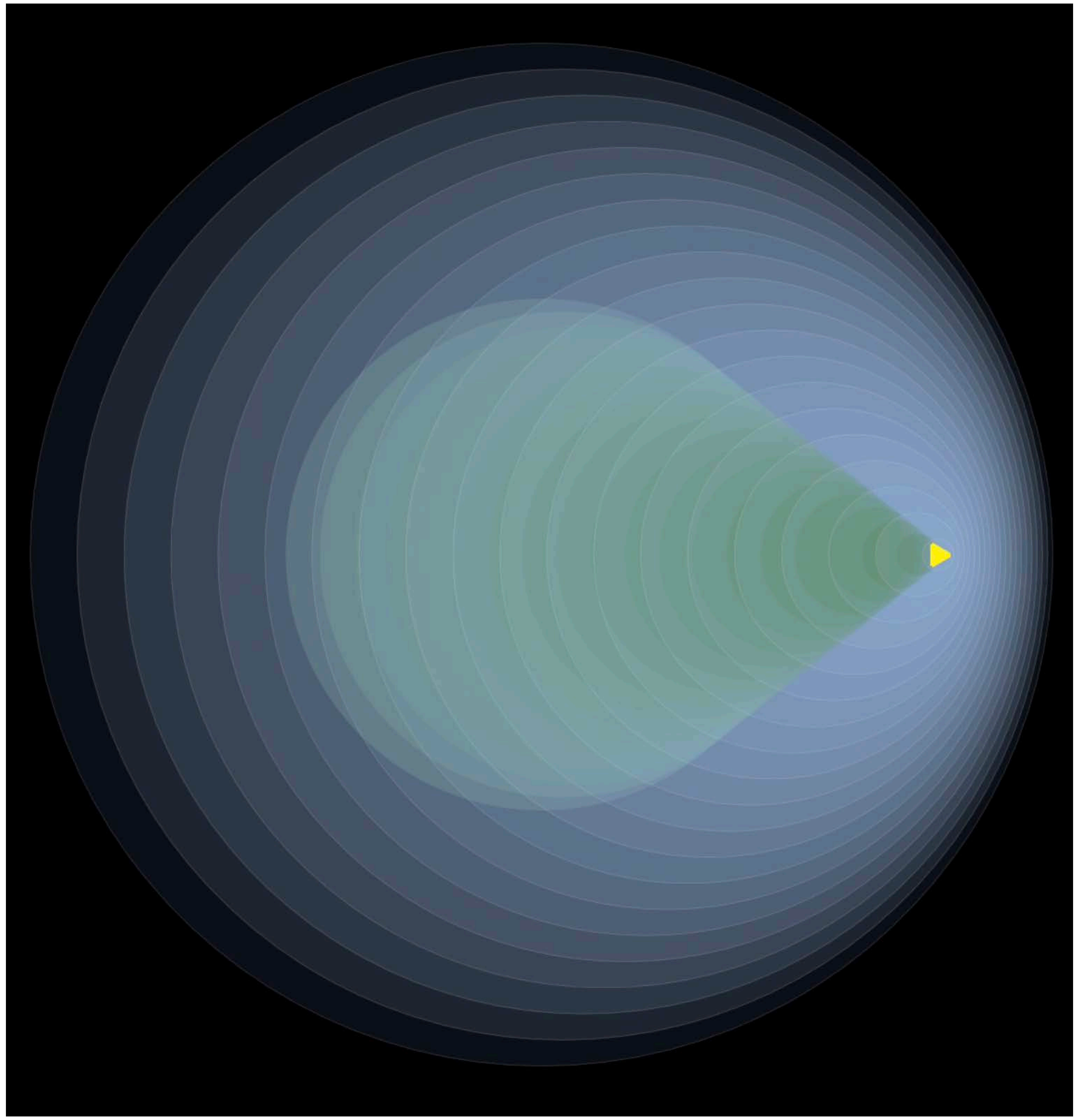
Such class of earthquakes are called **Supershear Earthquakes**

Super*sonic*



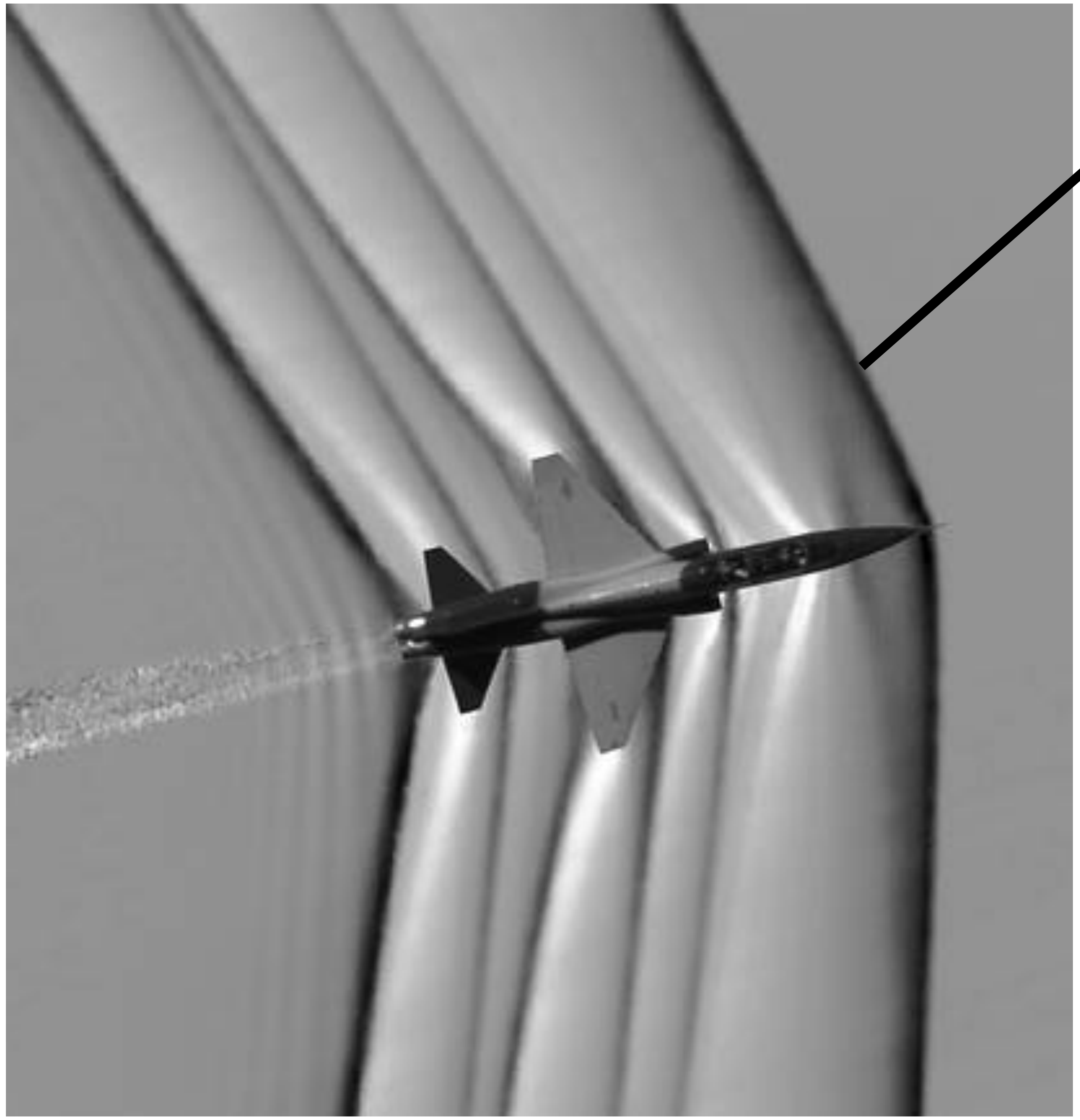
https://www.nasa.gov/image-feature/stark-beauty-of-supersonic-shock-waves

Super*shear*

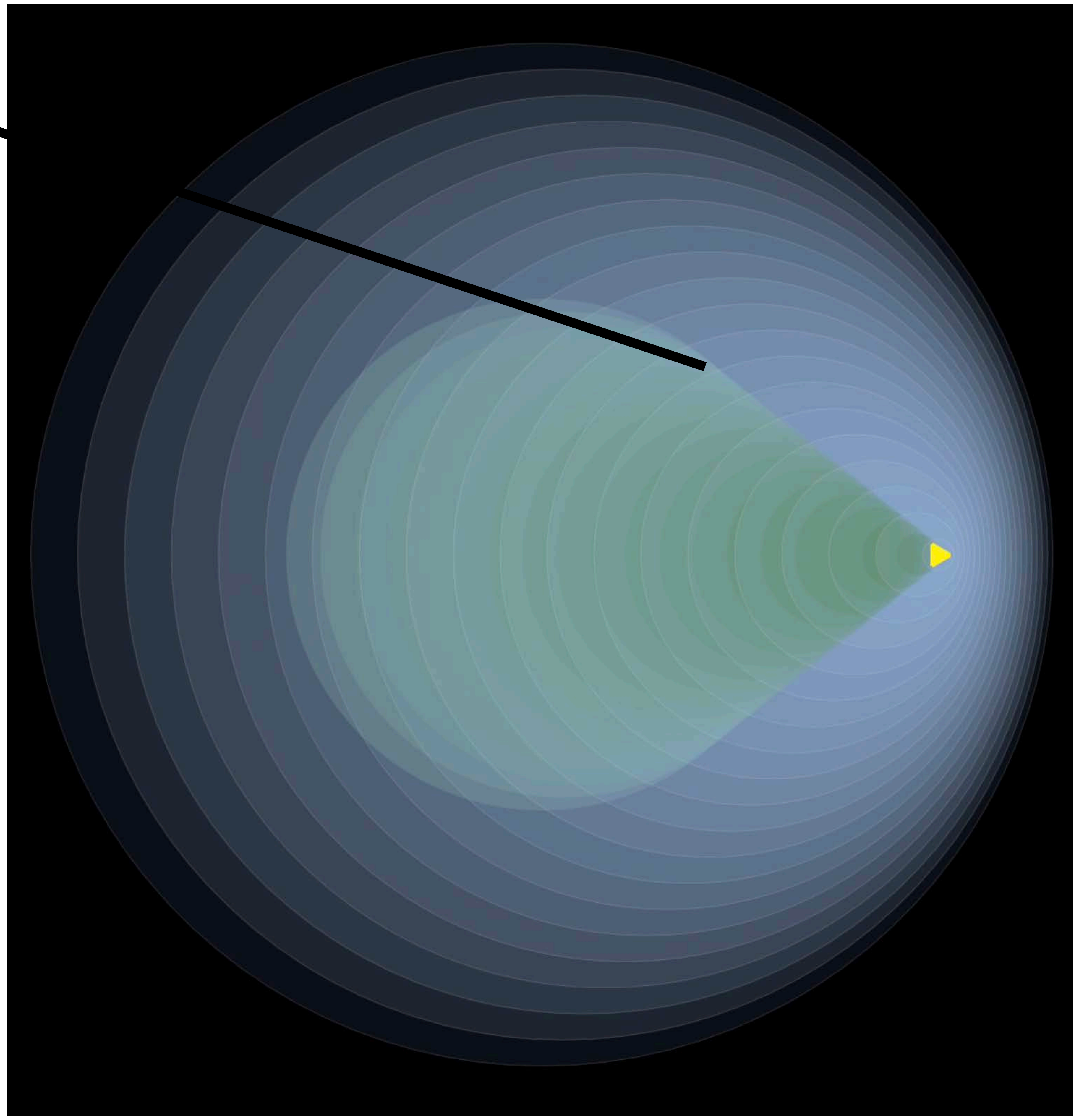


Supersonic

Supershear



Shock / Mach Front



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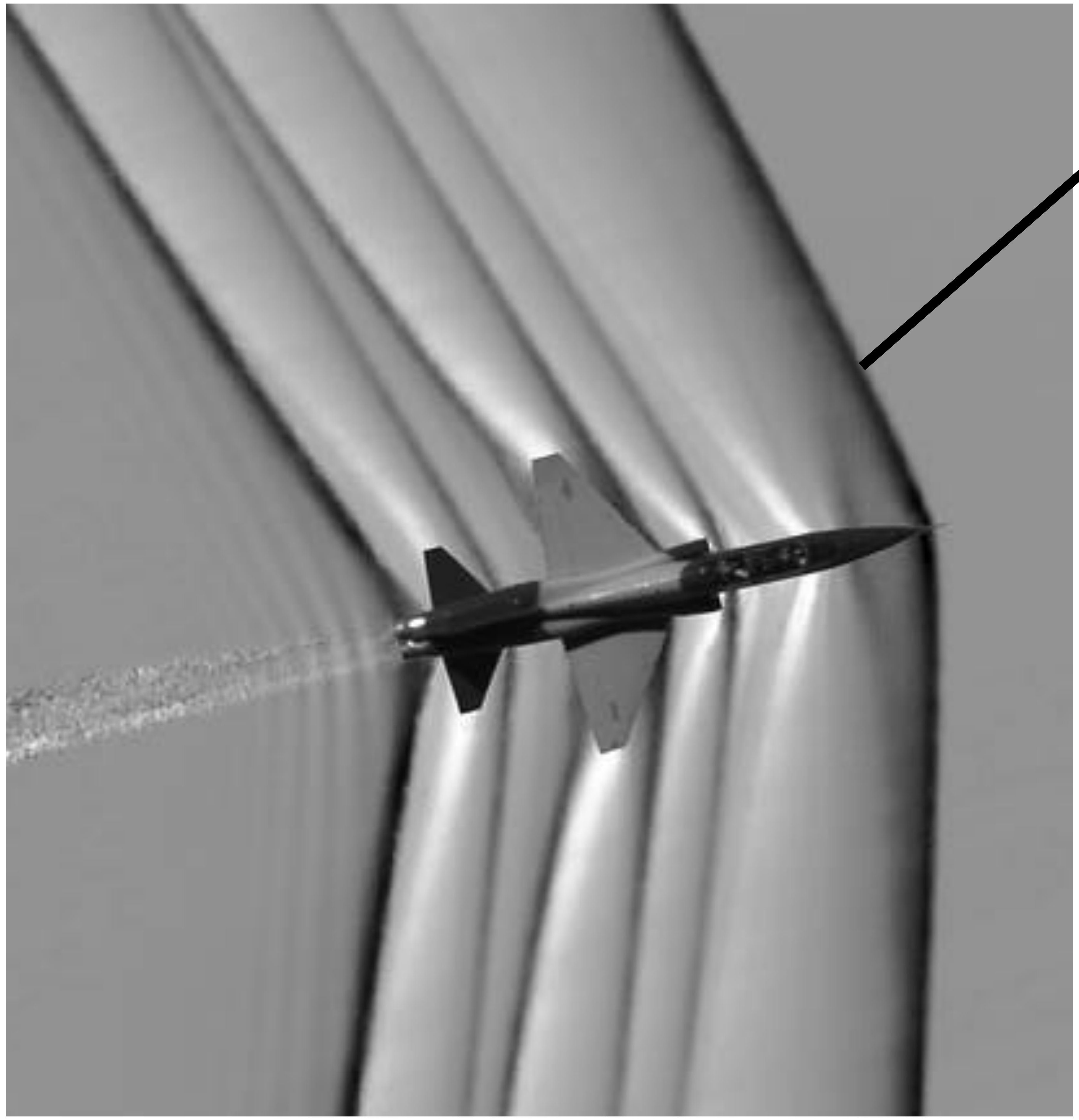

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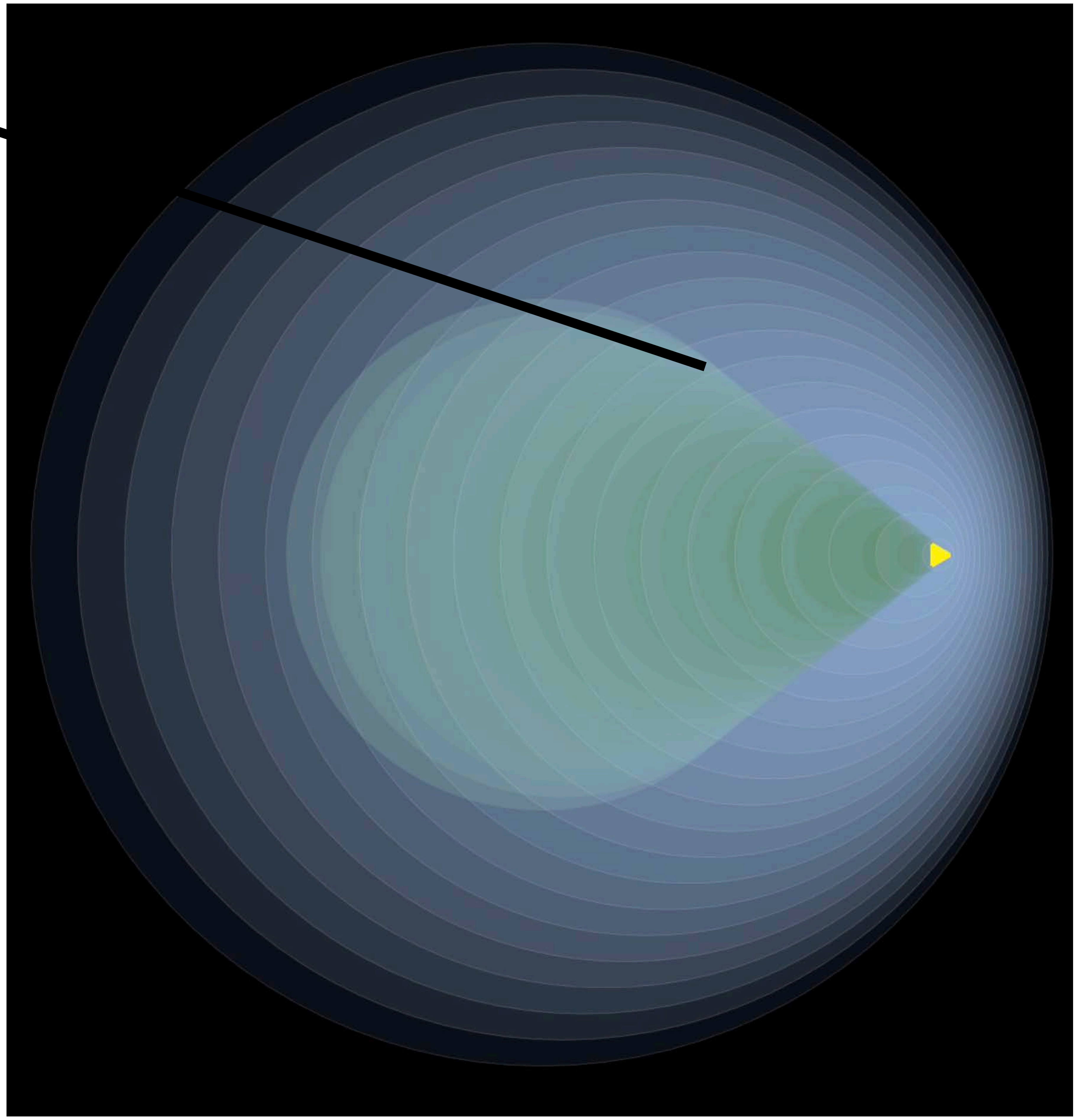
E. Mach

P. Salcher



Photographische Fixirung der durch Projectile in der Luft eingeleiteten Vorgänge," *Sitzungsber. k. Akad. Wiss., math.-naturwiss. Classe*, 95 (1887) 764-80

Supershear Earthquakes

Theory, Experiments & Observations

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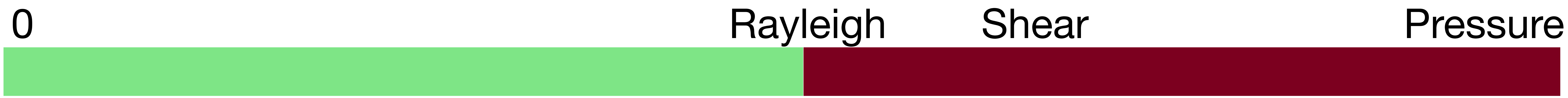

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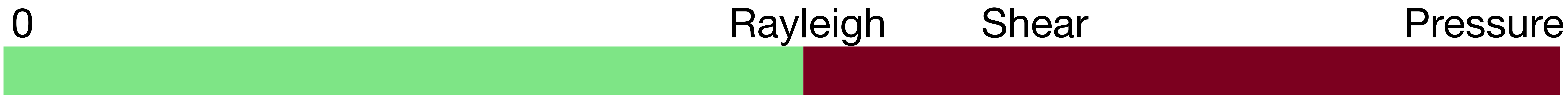

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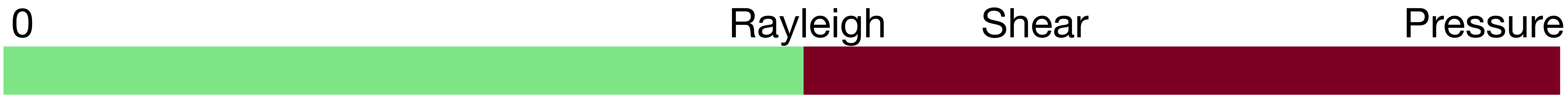

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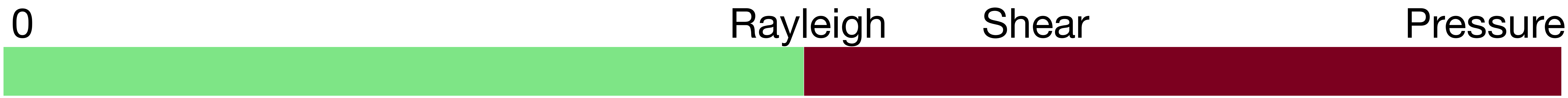

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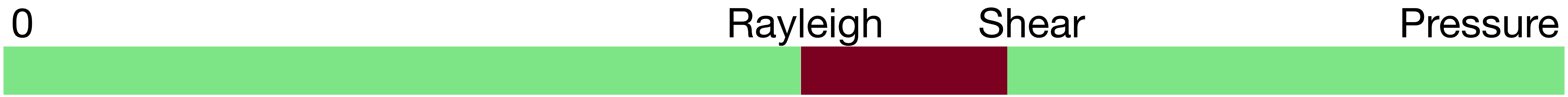

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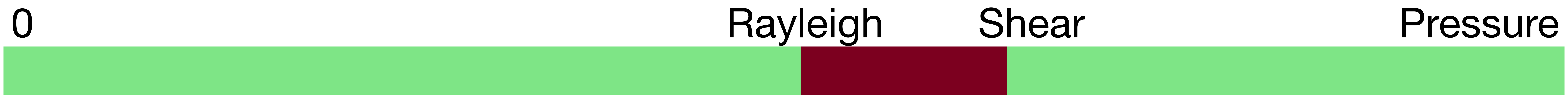

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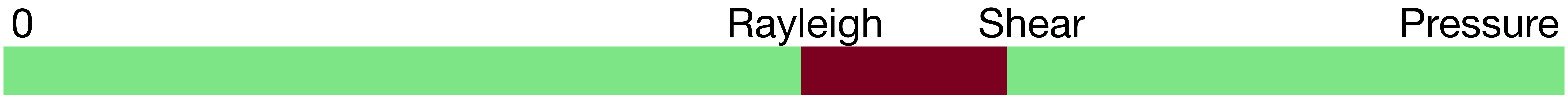

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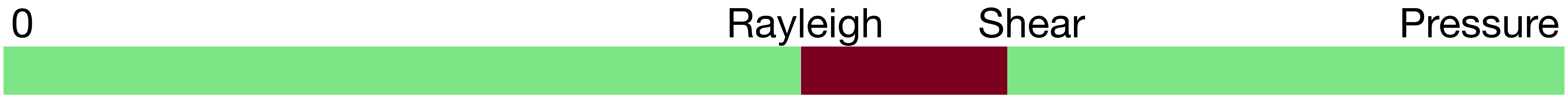

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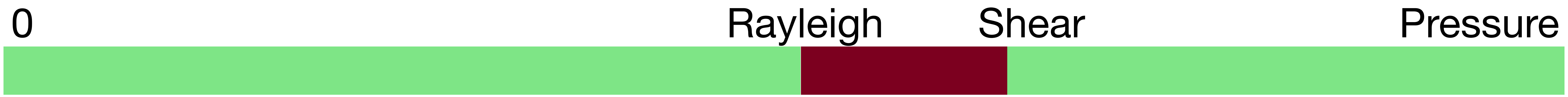

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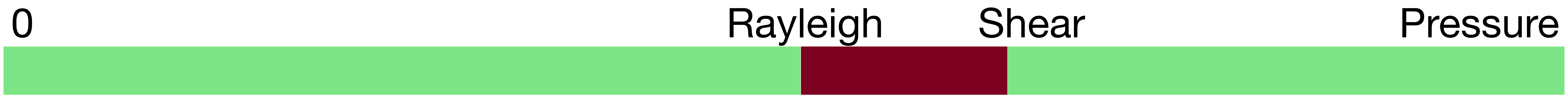

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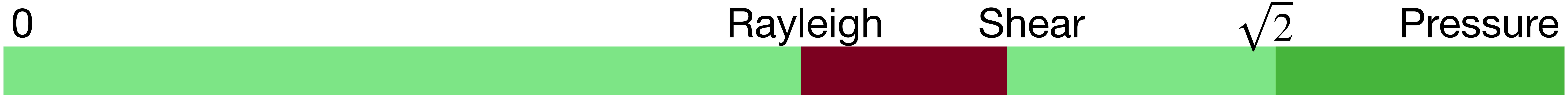

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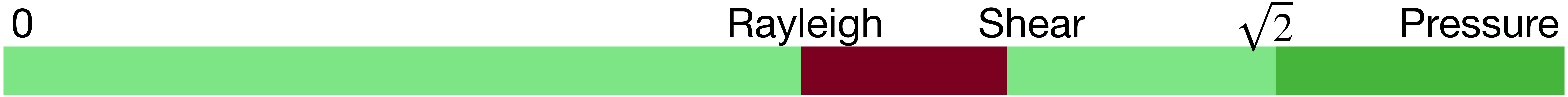

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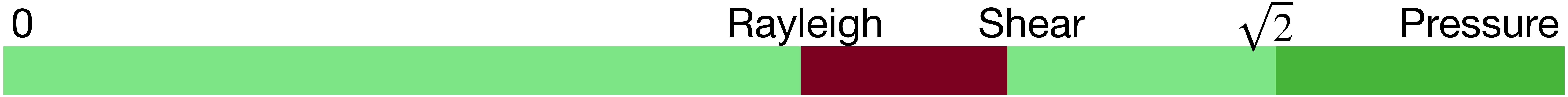

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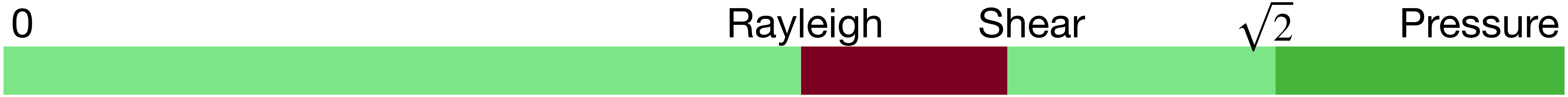

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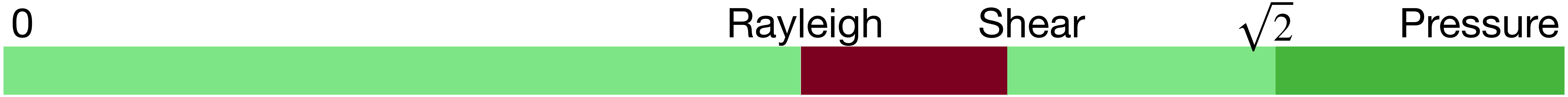

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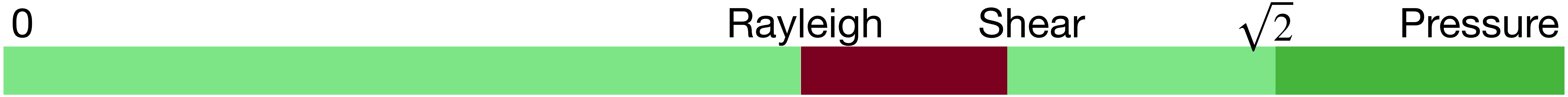

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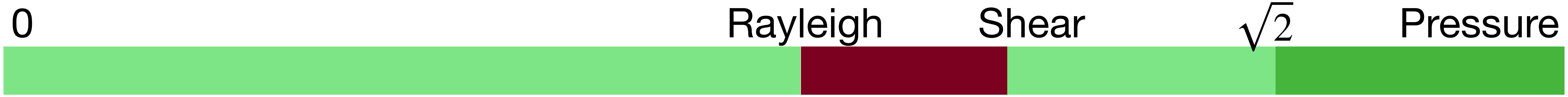

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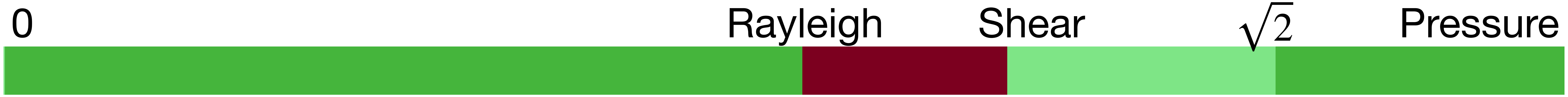

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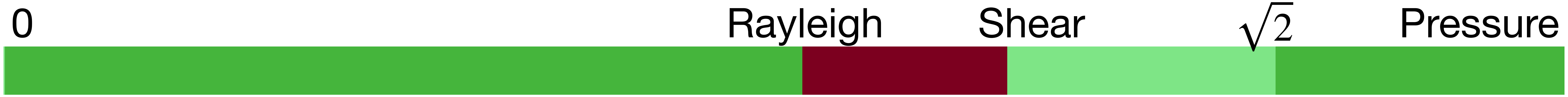
- Stability of sub-shear crack propagation



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2D Steady State Singular Elastic Model : Sub-Rayleigh

Mello, Bhat et al. 2016

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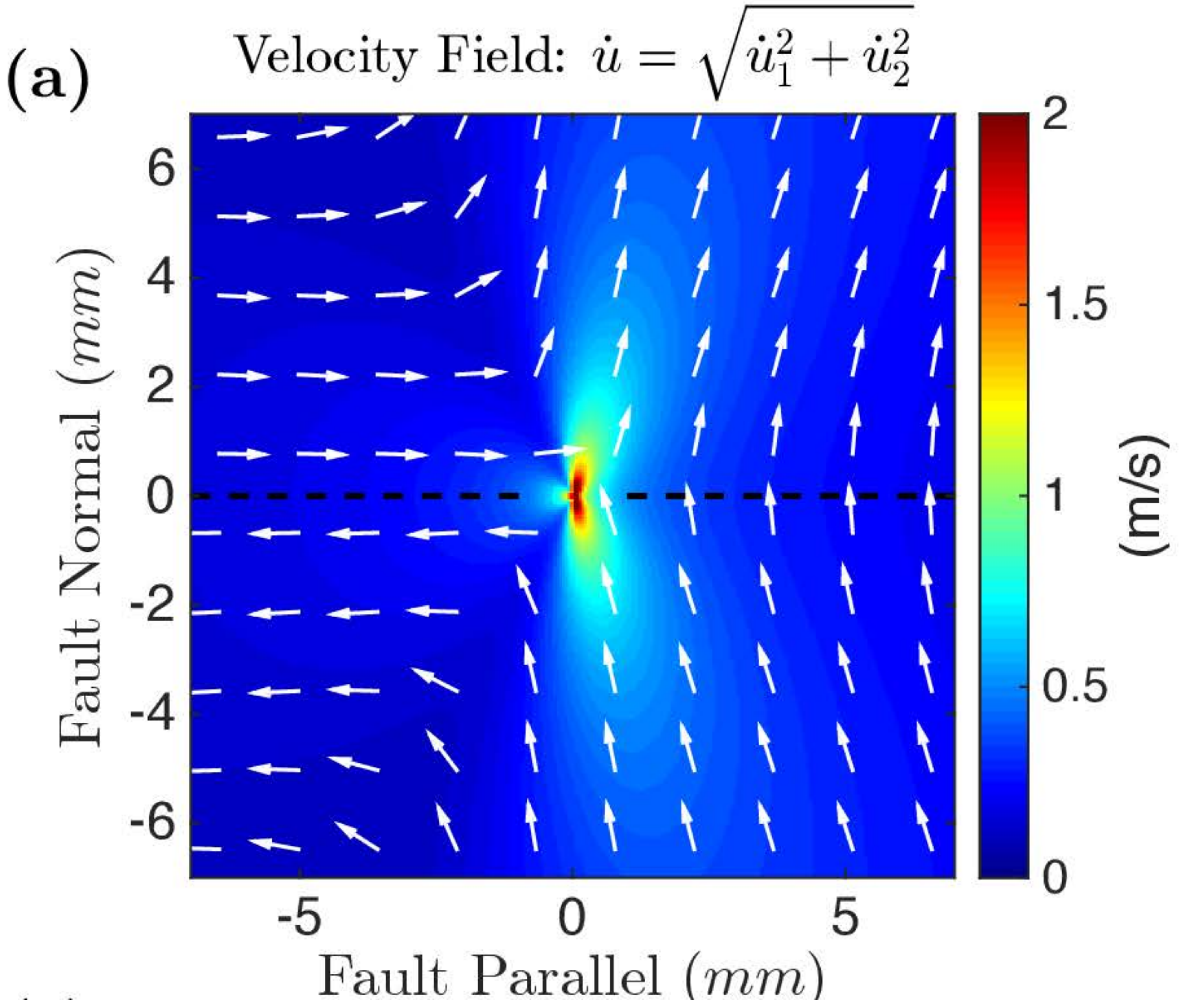

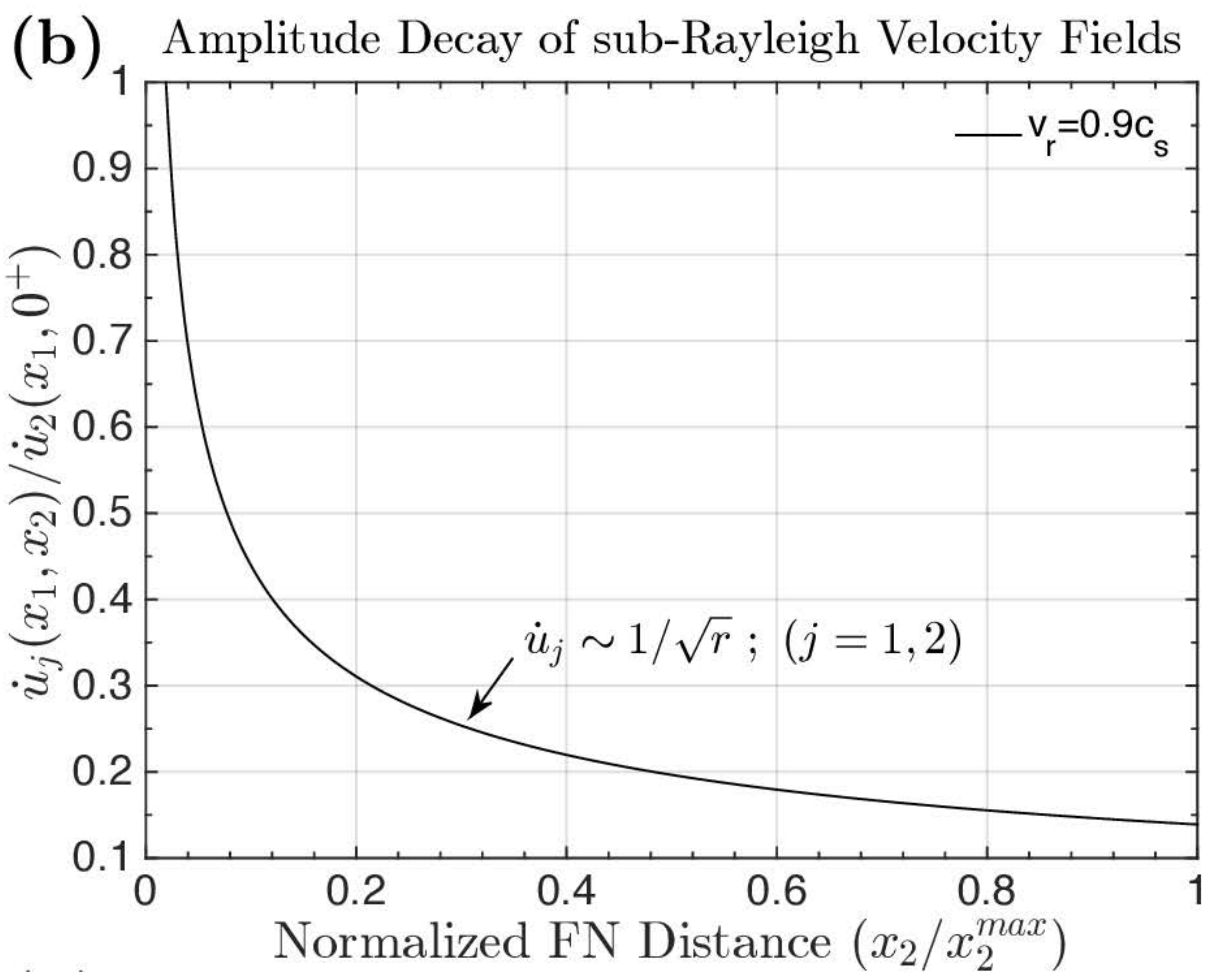

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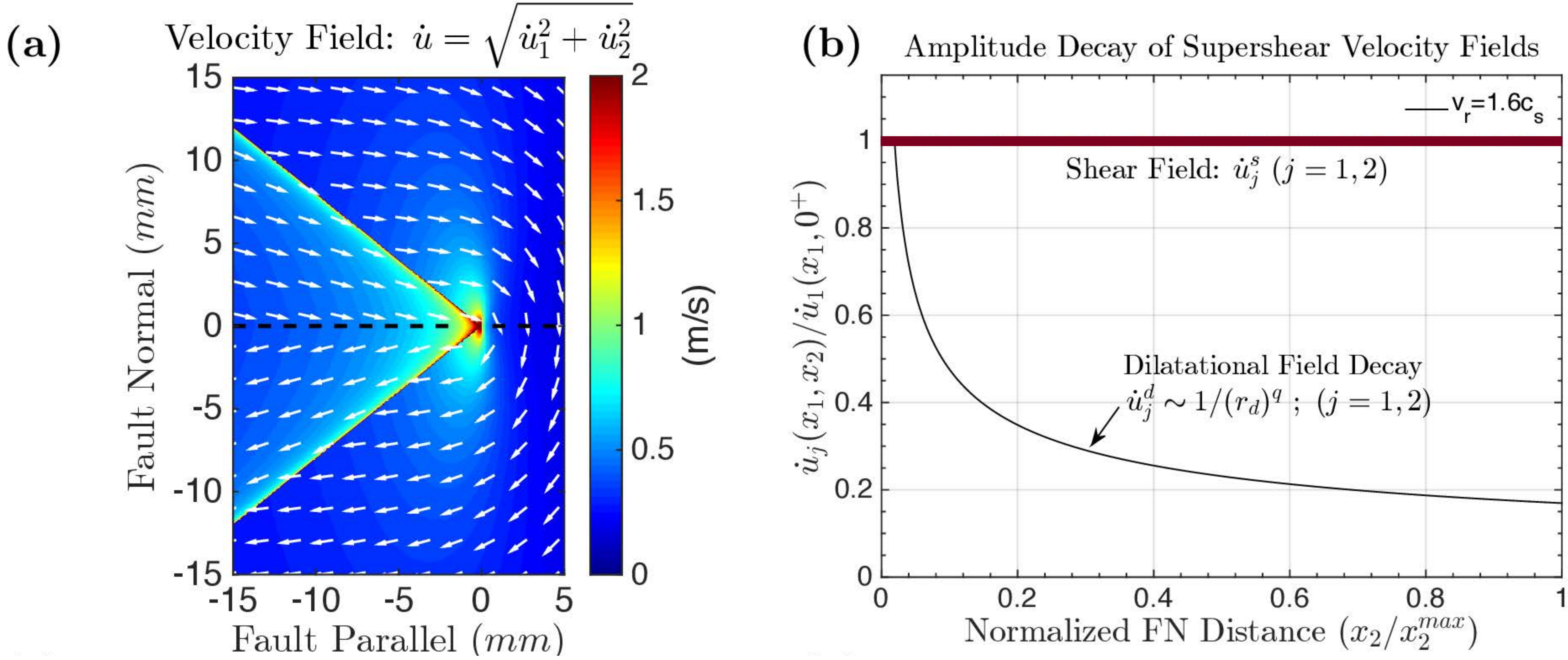
Theory

2D Steady State Singular Elastic Model : Supershear



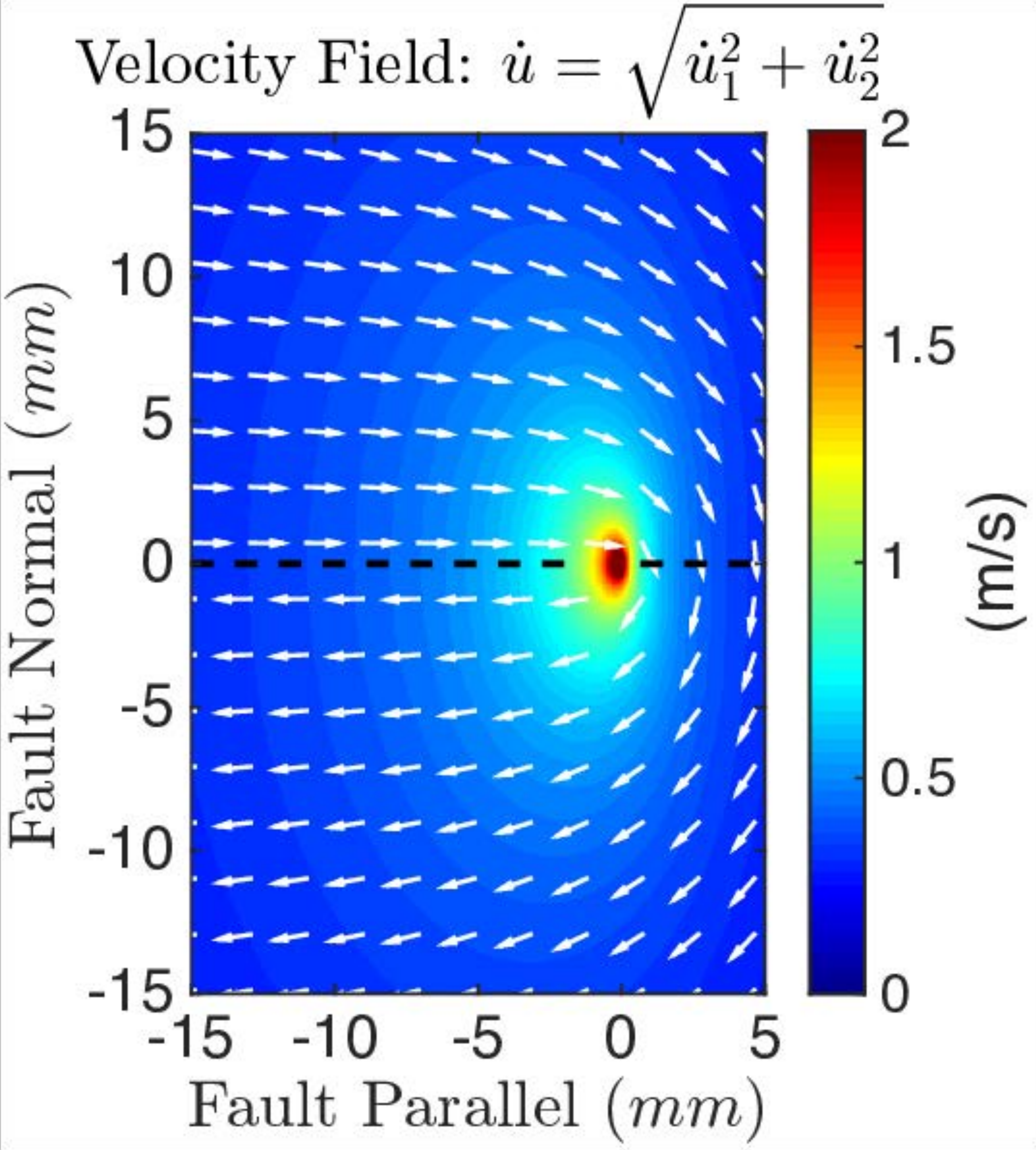
Mello, Bhat et al. 2016

Theory

2D Steady State Singular Elastic Model : Supershear $\sqrt{2}c_s$ case

Eshelby 1949

Mello, Bhat et al. 2016



Eshelby 1949

Mello, Bhat et al. 2016

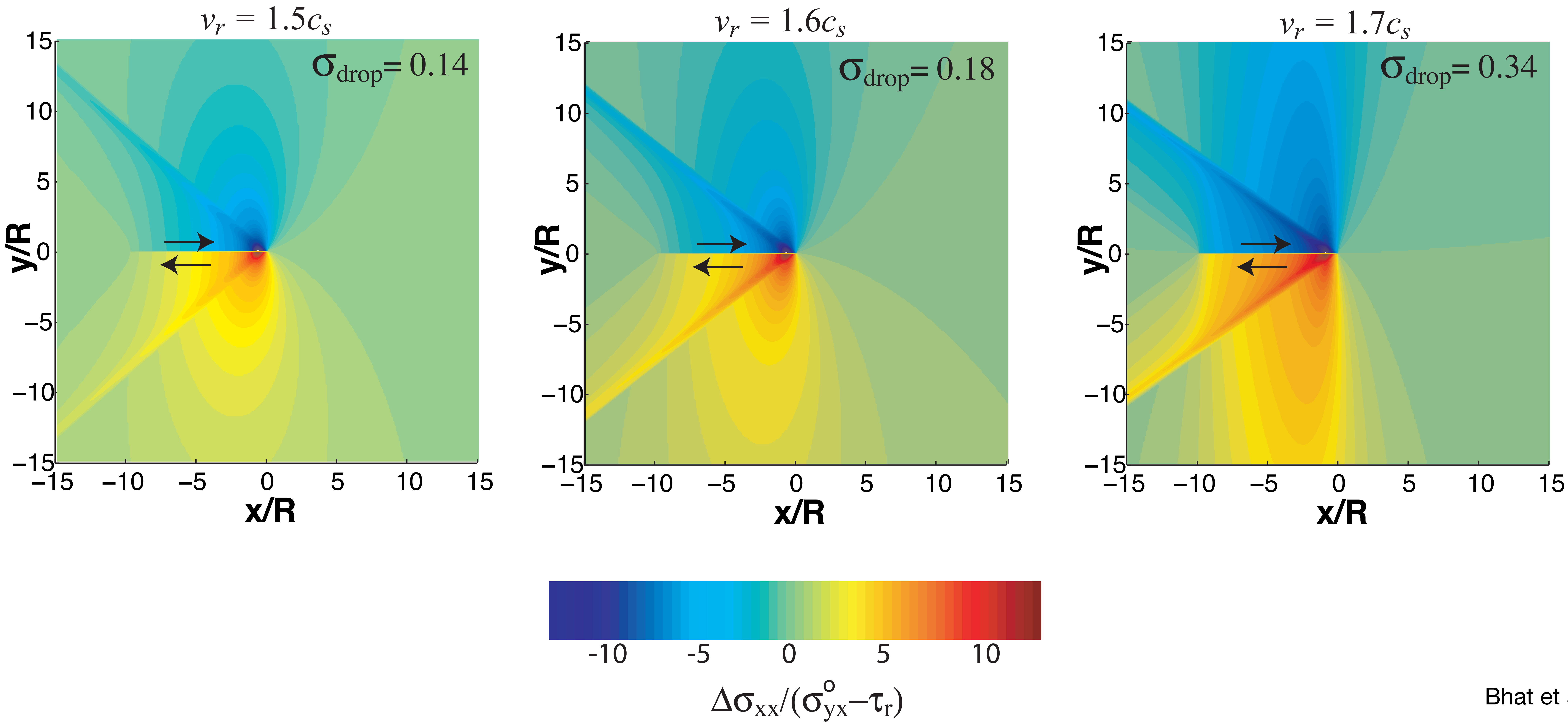
Theory

2D Steady State Cohesive Zone Model : Supershear Stress Field

Bhat et al. 2007

Theory

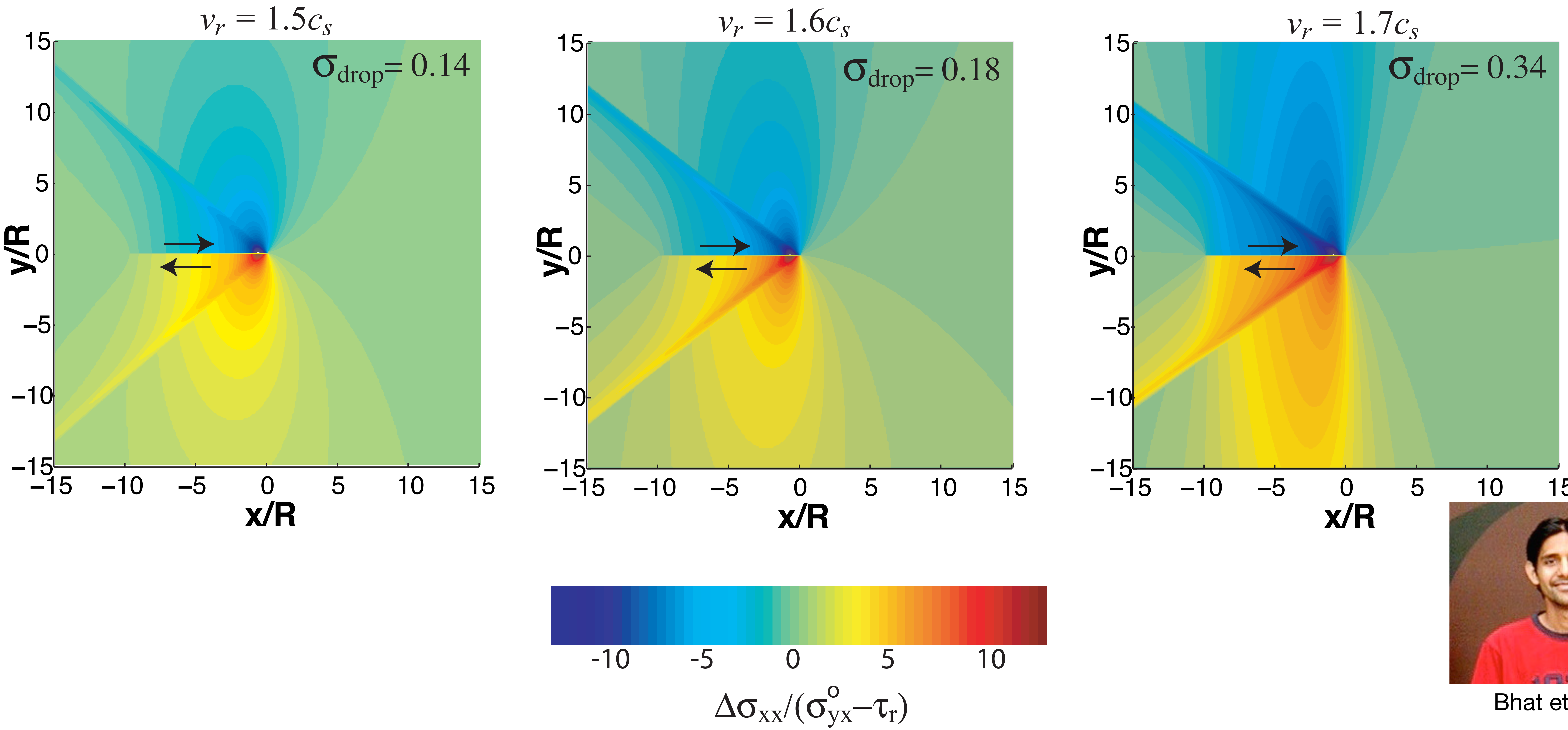
2D Steady State Cohesive Zone Model : Supershear Stress Field



Bhat et al. 2007

Theory

2D Steady State Cohesive Zone Model : Supershear Stress Field



Bhat et al. 2007

Theory

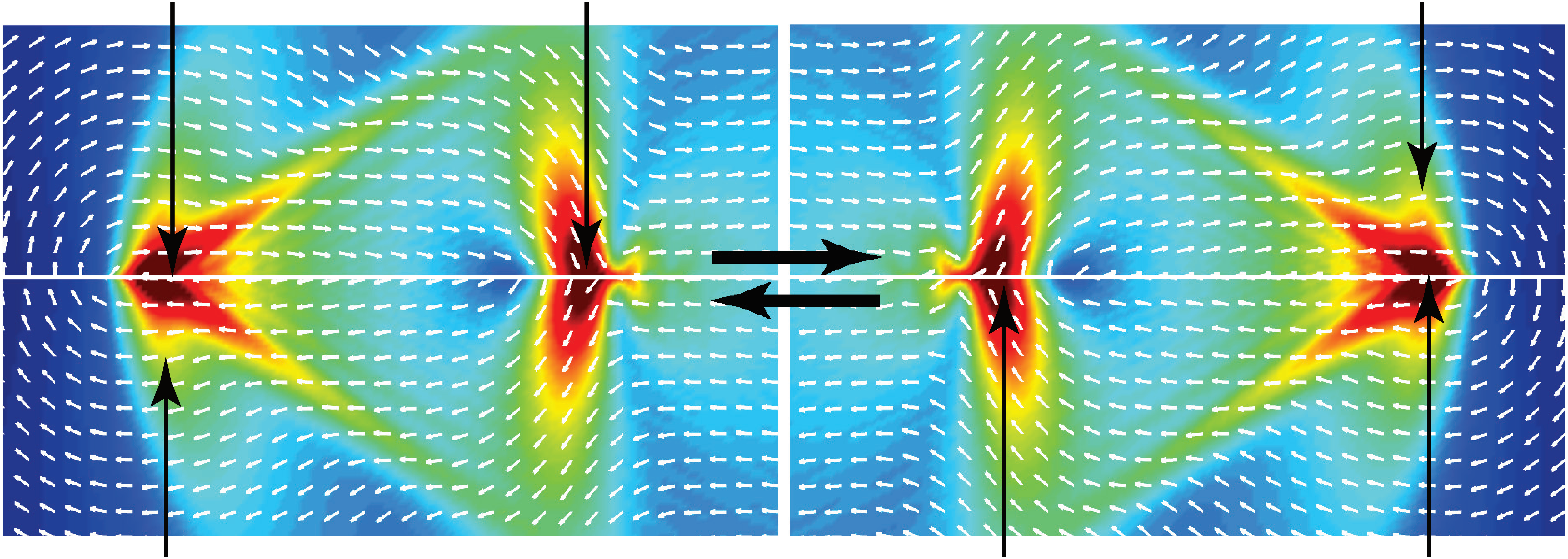
Mello, Bhat et al. 2016

2D Spontaneous Rupture Model : Supershear

Theory

Mello, Bhat et al. 2016

2D Spontaneous Rupture Model : Supershear



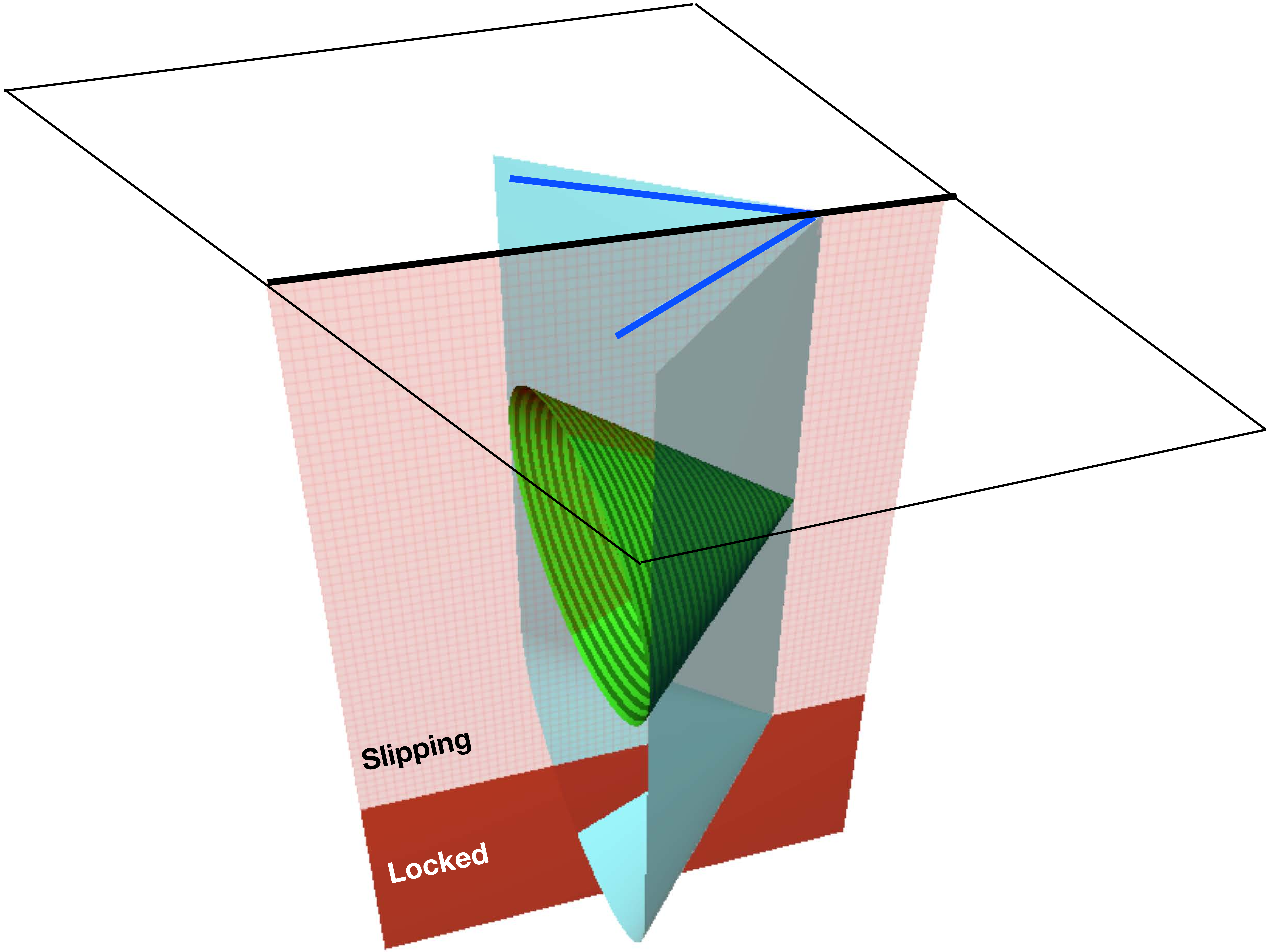
Dunham & Bhat 2008

Theory

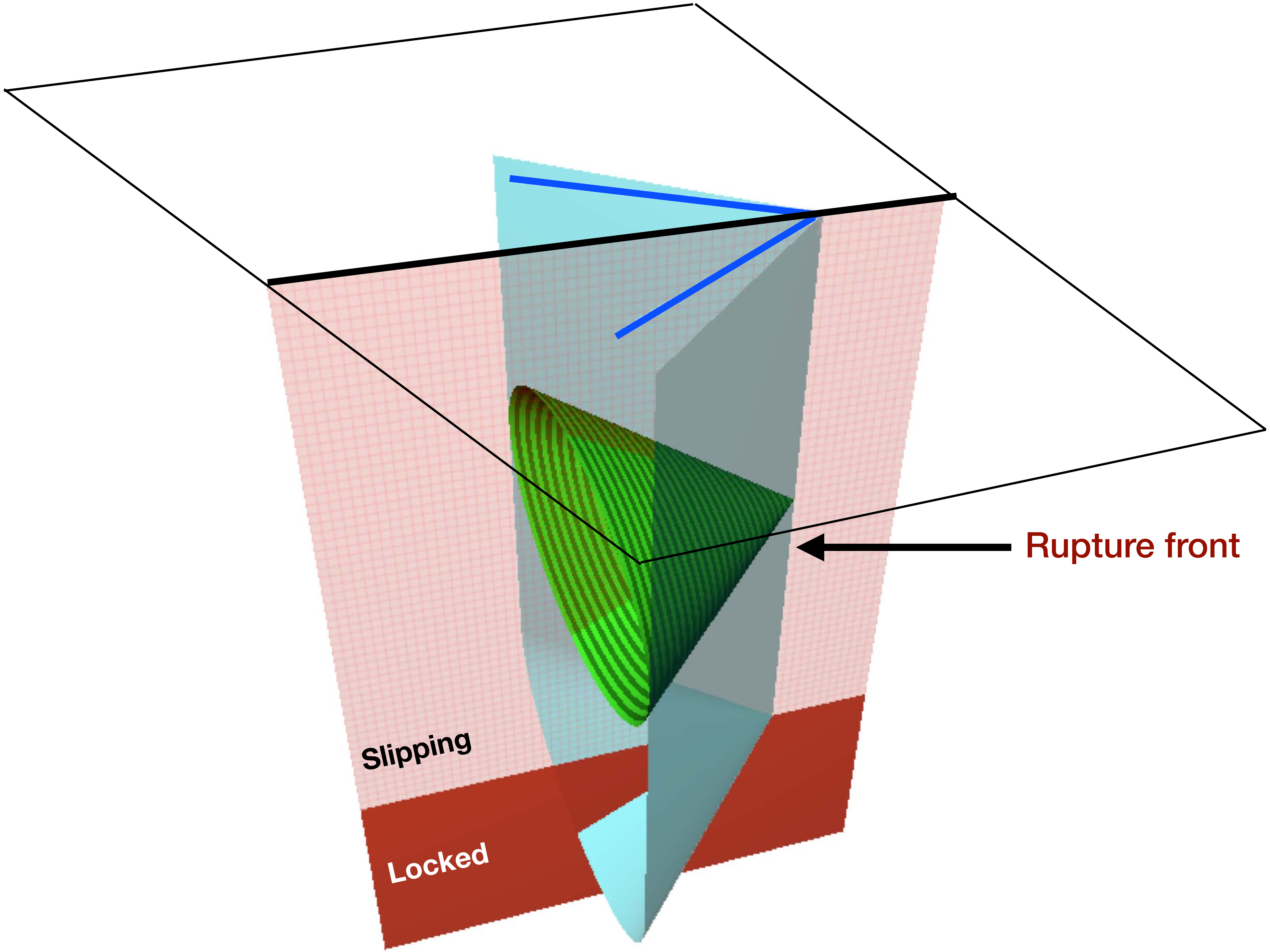
3D Steady State Cohesive Zone Model : Supershear

Dunham & Bhat 2008

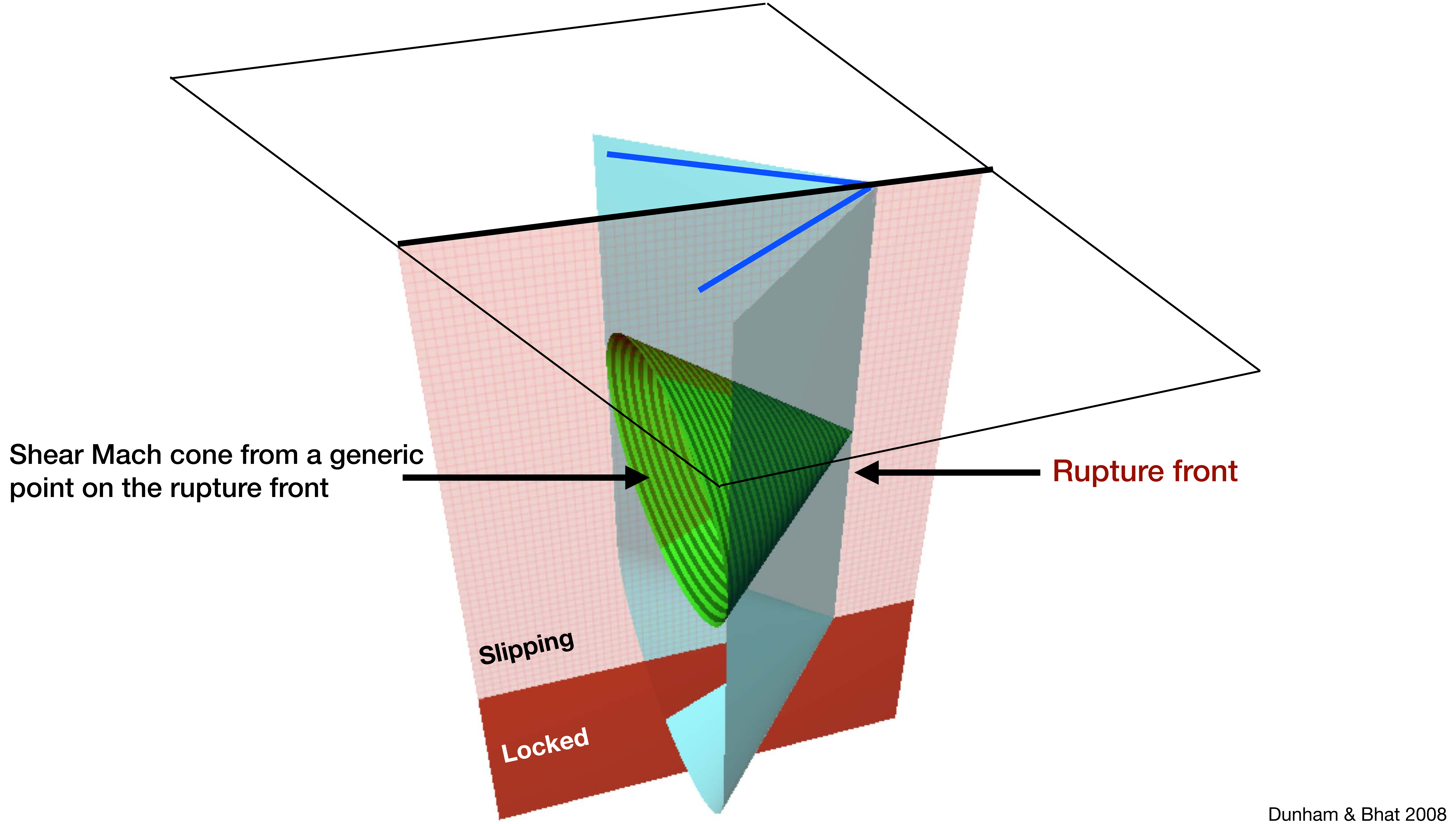
Dunham & Bhat 2008



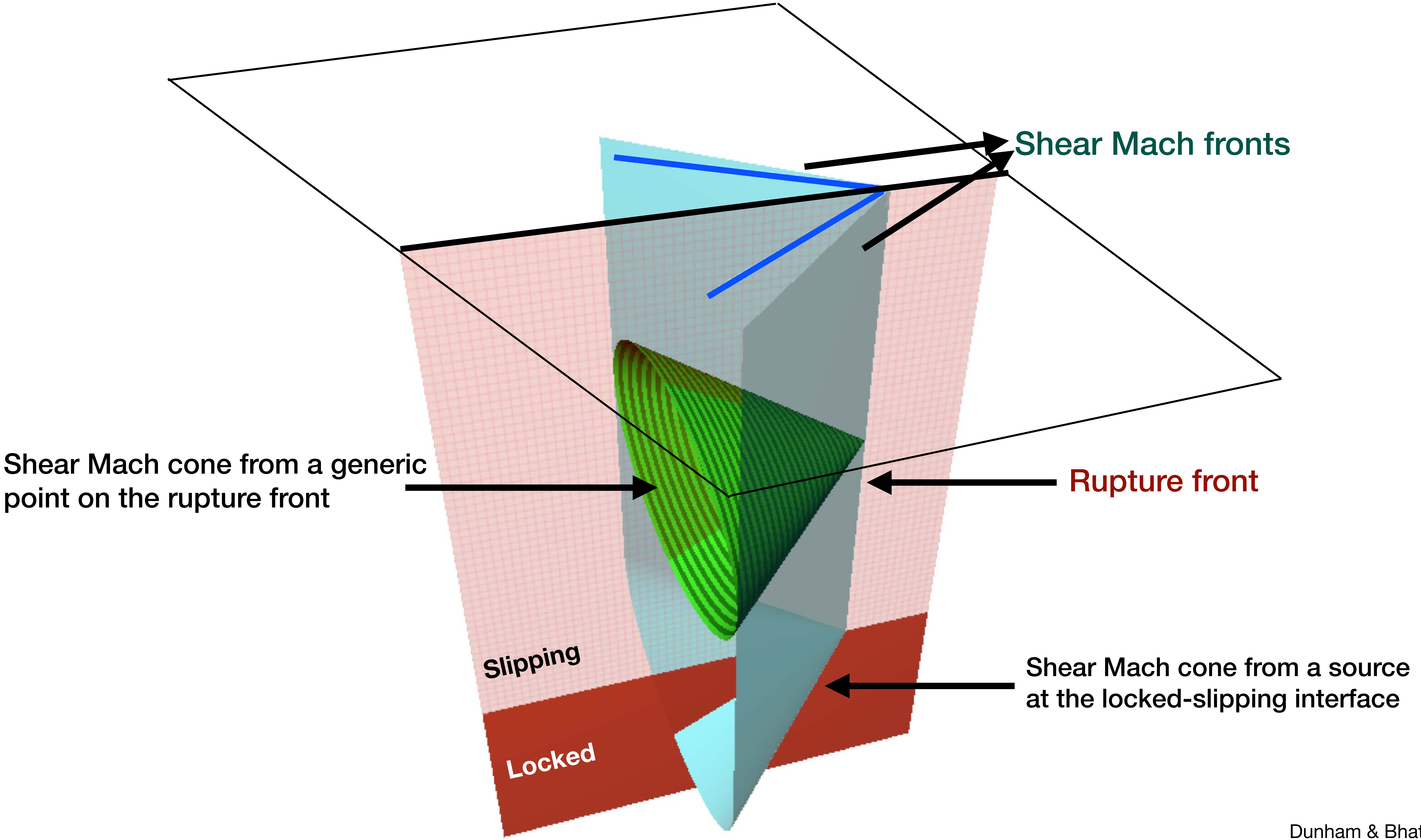
Dunham & Bhat 2008



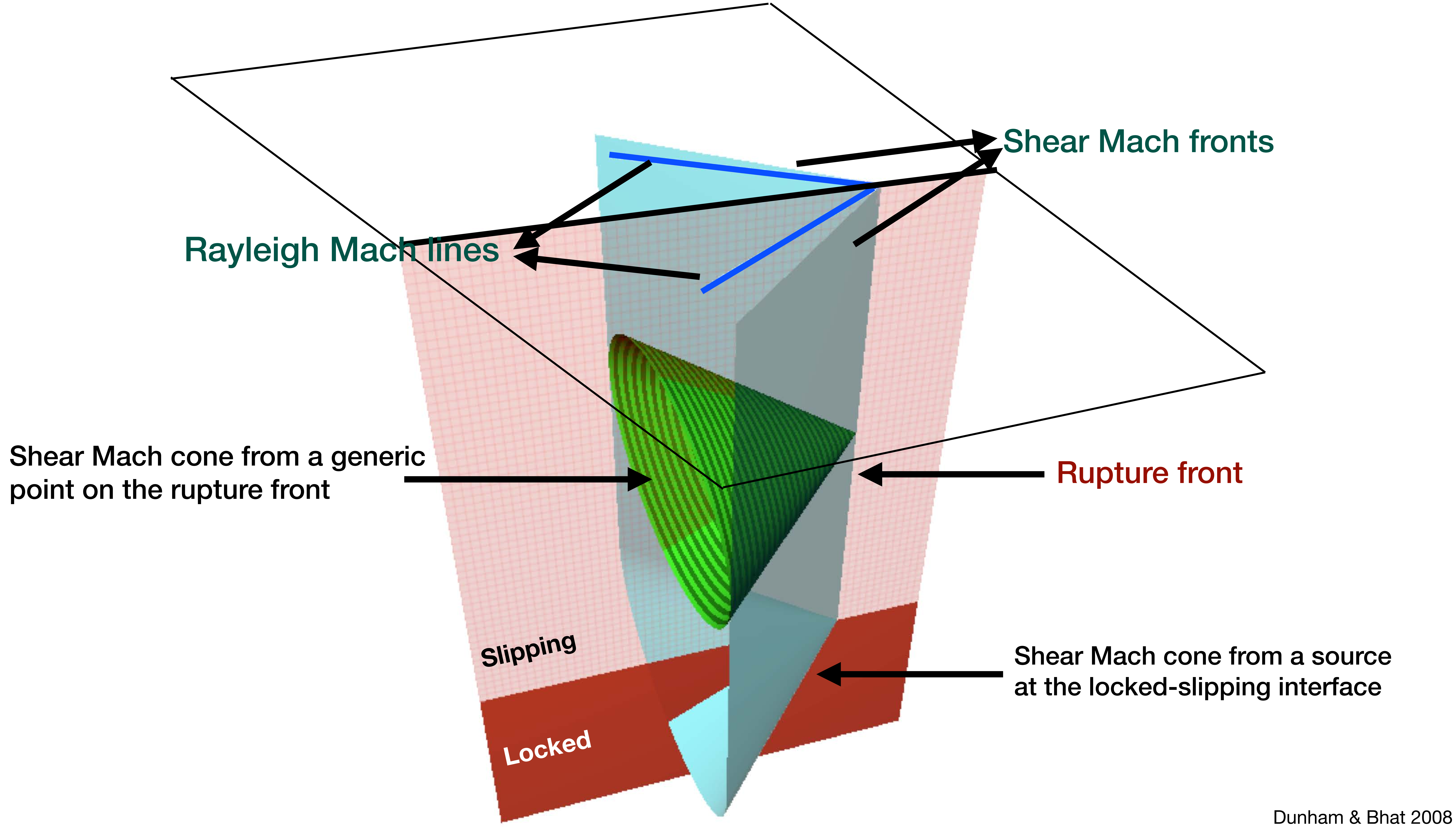
Dunham & Bhat 2008


Shear Mach cone from a generic point on the rupture front
Rupture front
Slipping
Locked
Dunham & Bhat 2008

Shear Mach cone from a generic point on the rupture front
Rupture front
Slipping
Locked
Shear Mach cone from a source at the locked-slipping interface
Dunham & Bhat 2008

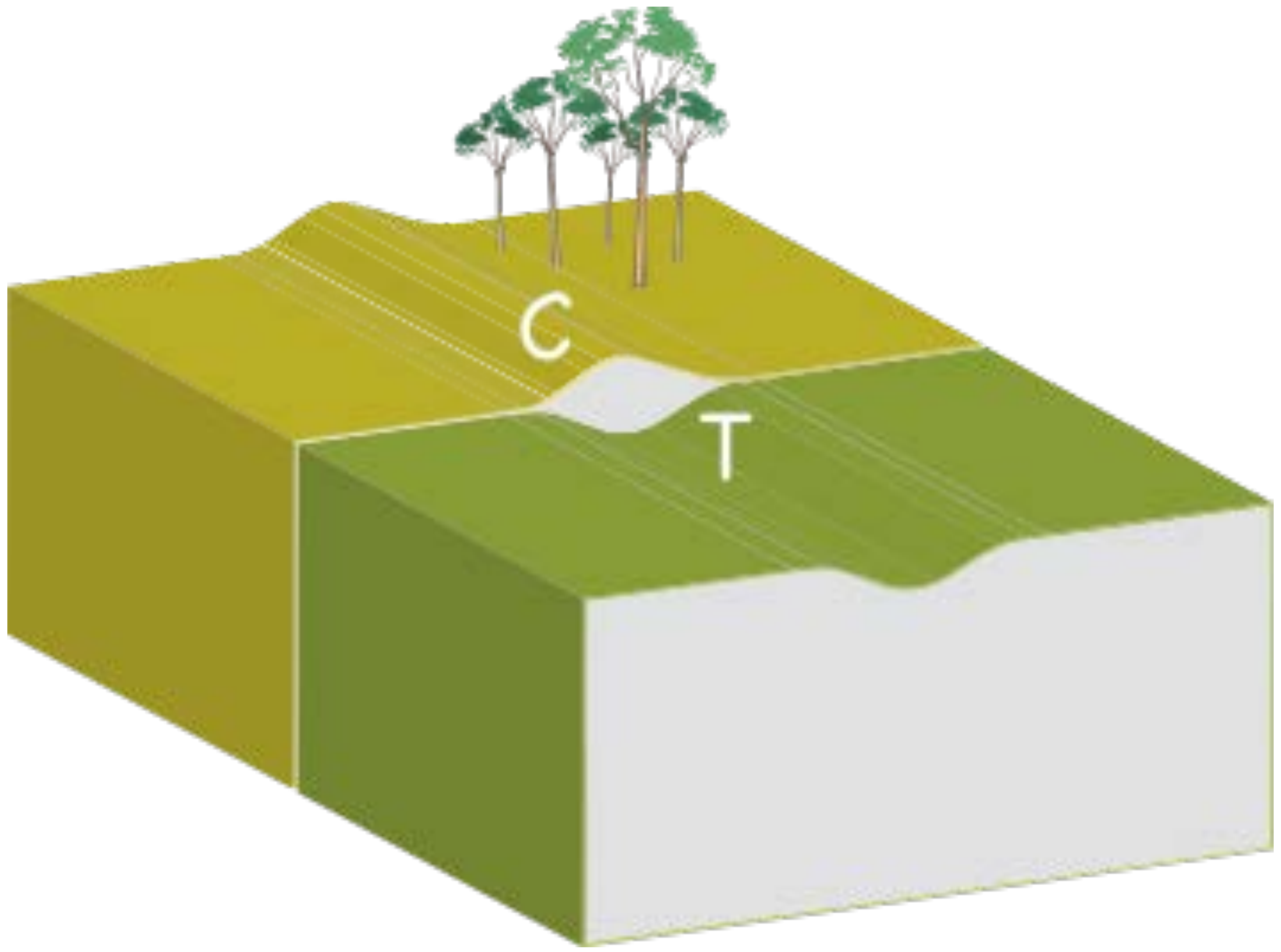


Dunham & Bhat 2008


Shear Mach fronts
Rayleigh Mach lines
Shear Mach cone from a generic point on the rupture front
Rupture front
Slipping
Locked
Shear Mach cone from a source at the locked-slipping interface
Dunham & Bhat 2008

Theory

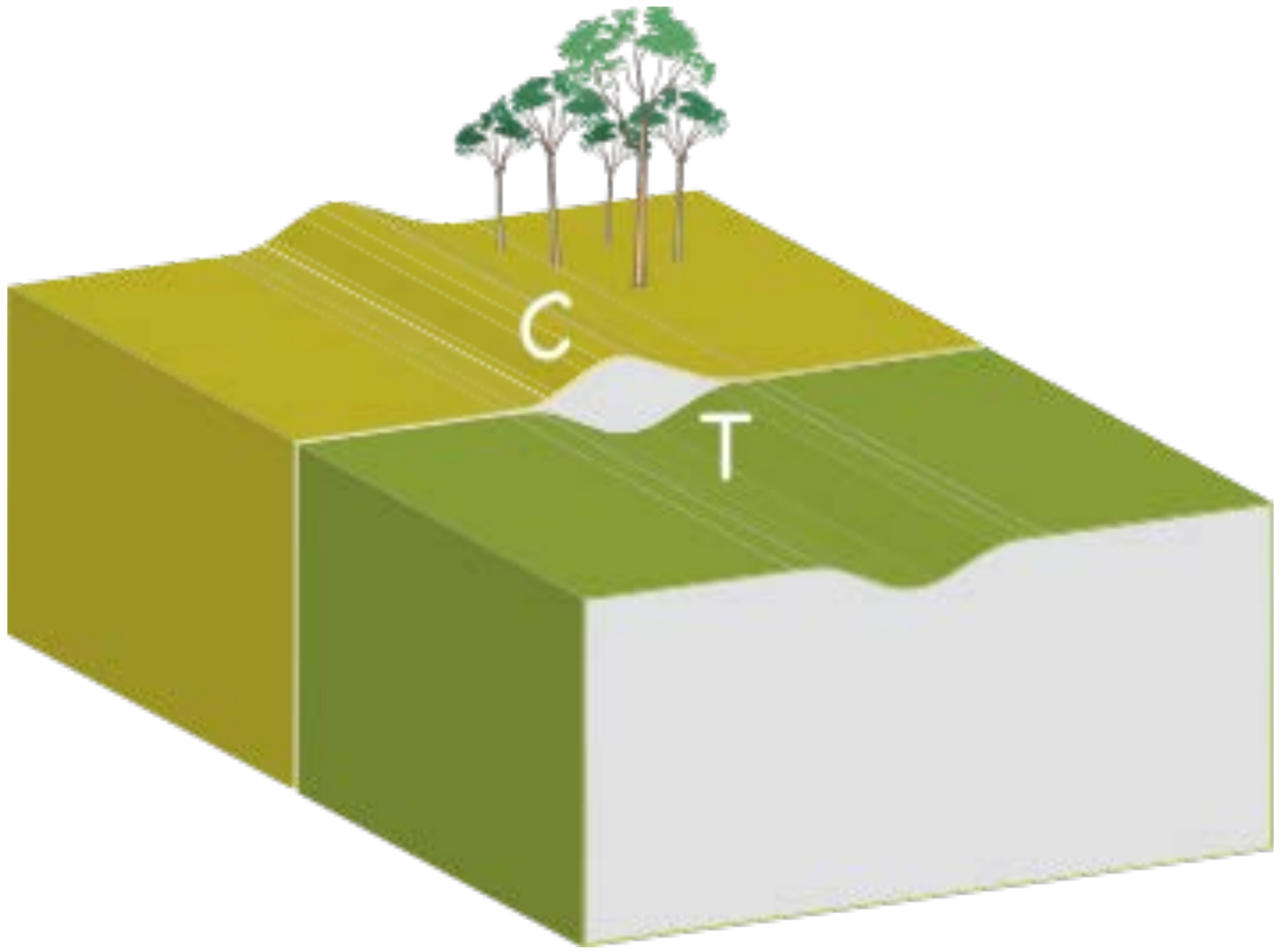
3D Steady State Cohesive Zone Model : Supershear



Dunham & Bhat 2008

Theory

3D Steady State Cohesive Zone Model : Supershear

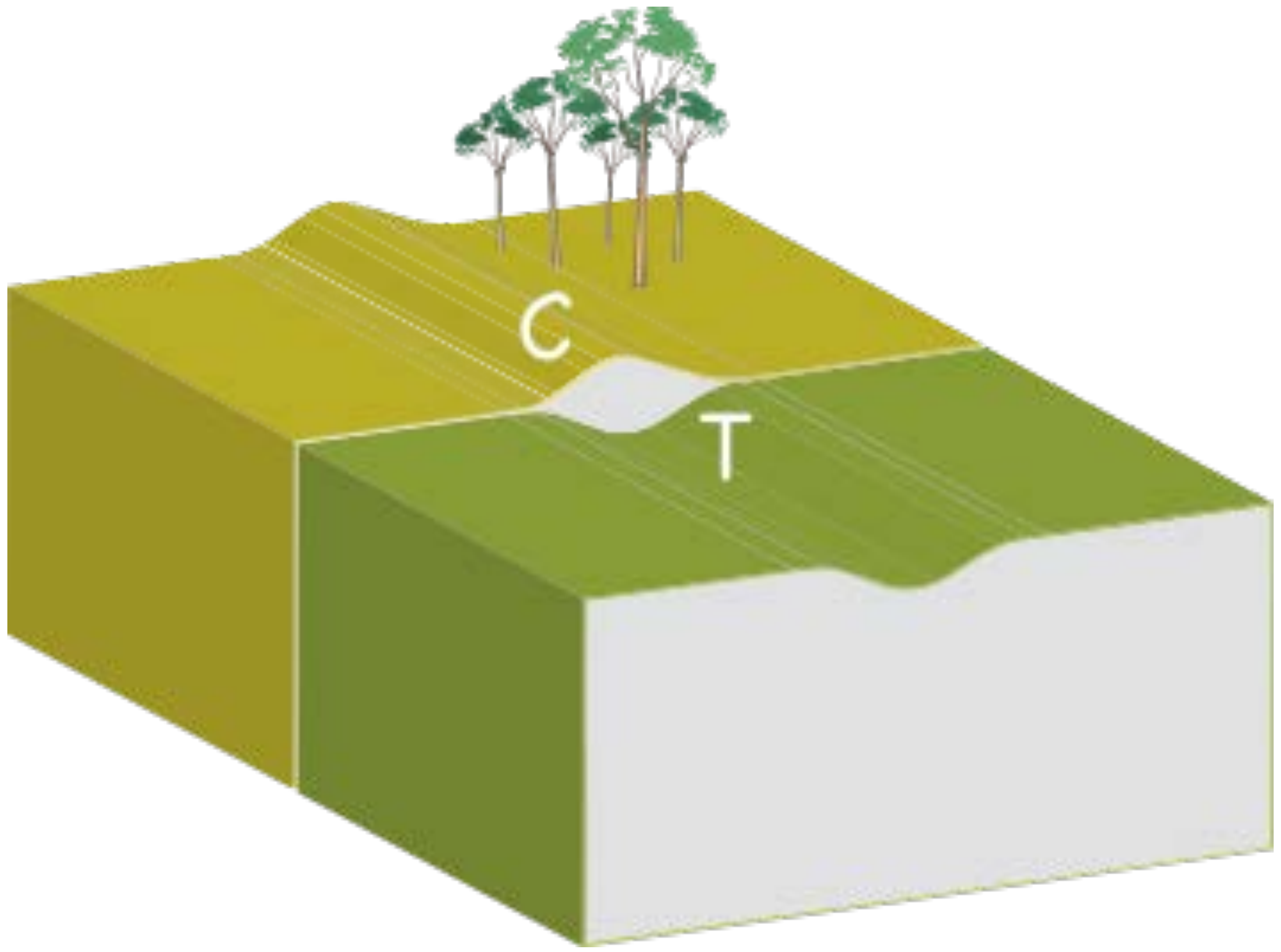


- Rupture tip causes medium to bulge on the compressional side and dimple on the extensional side

Dunham & Bhat 2008

Theory

3D Steady State Cohesive Zone Model : Supershear

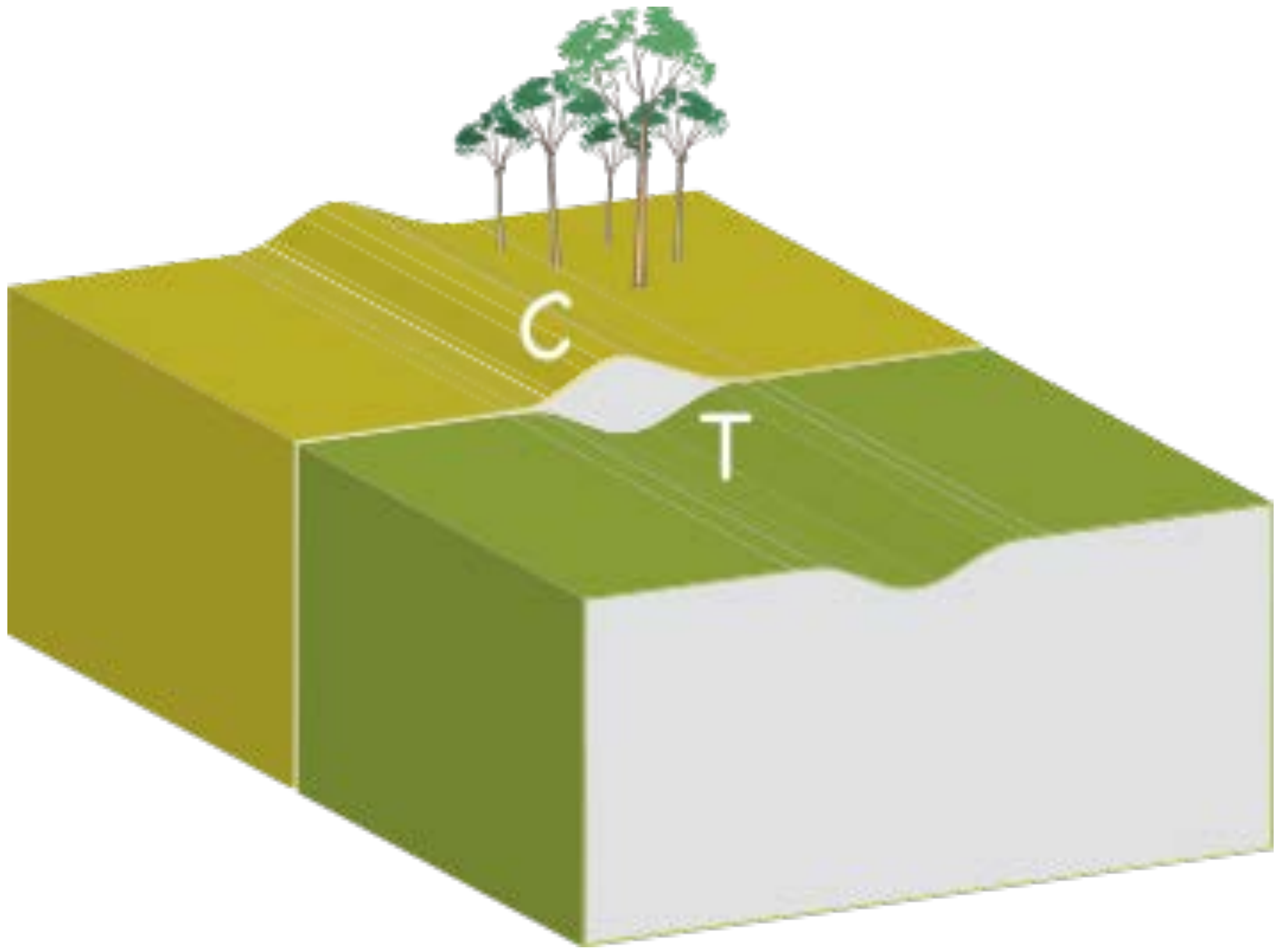


- Rupture tip causes medium to bulge on the compressional side and dimple on the extensional side
- To maintain the traction-free surface, Rayleigh waves are generated

Dunham & Bhat 2008

Theory

3D Steady State Cohesive Zone Model : Supershear



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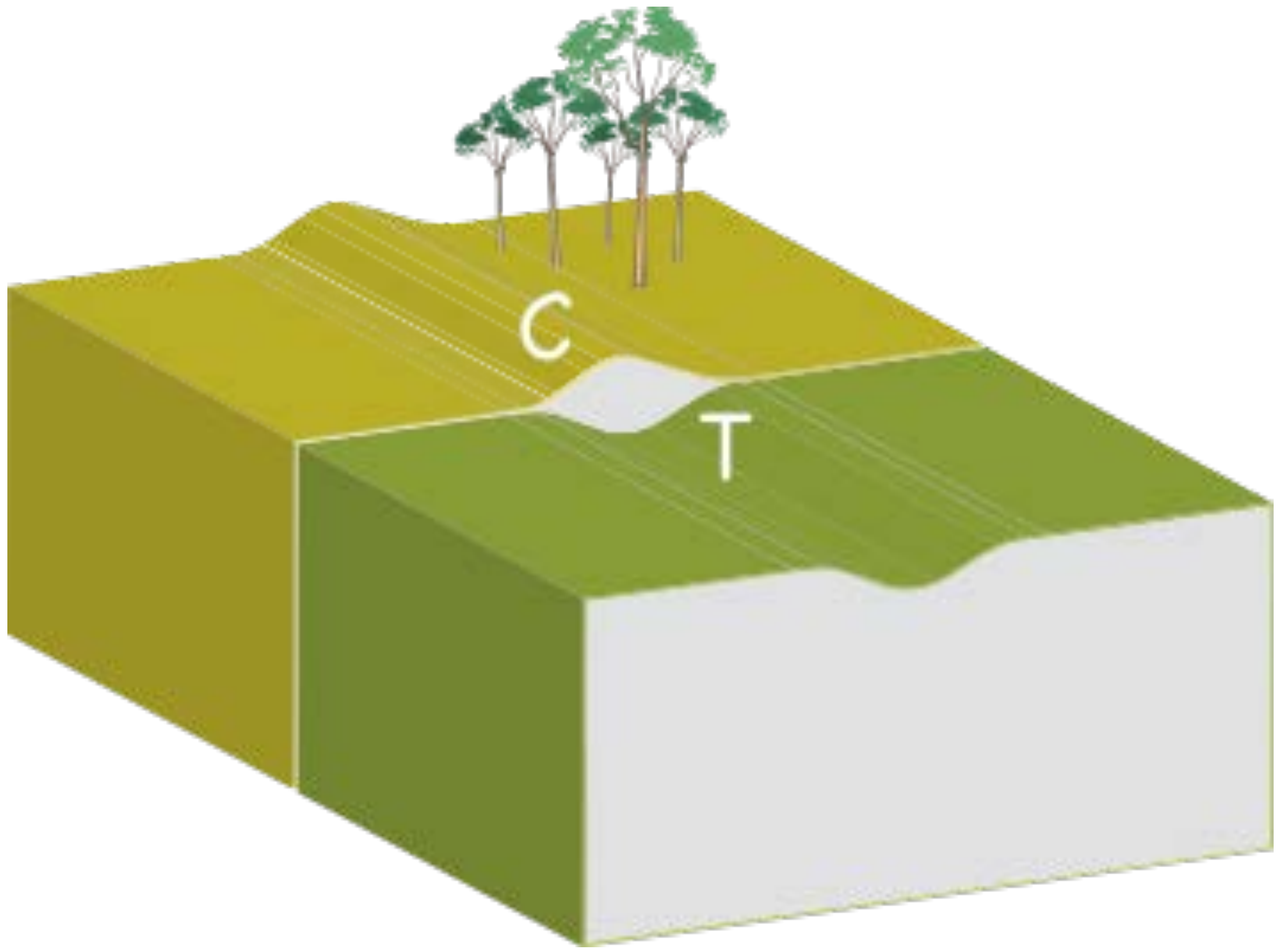
- If rupture is supershear => superRayleigh => Rayleigh Mach fronts

Dunham & Bhat 2008

Theory

3D Steady State Cohesive Zone Model : Supershear



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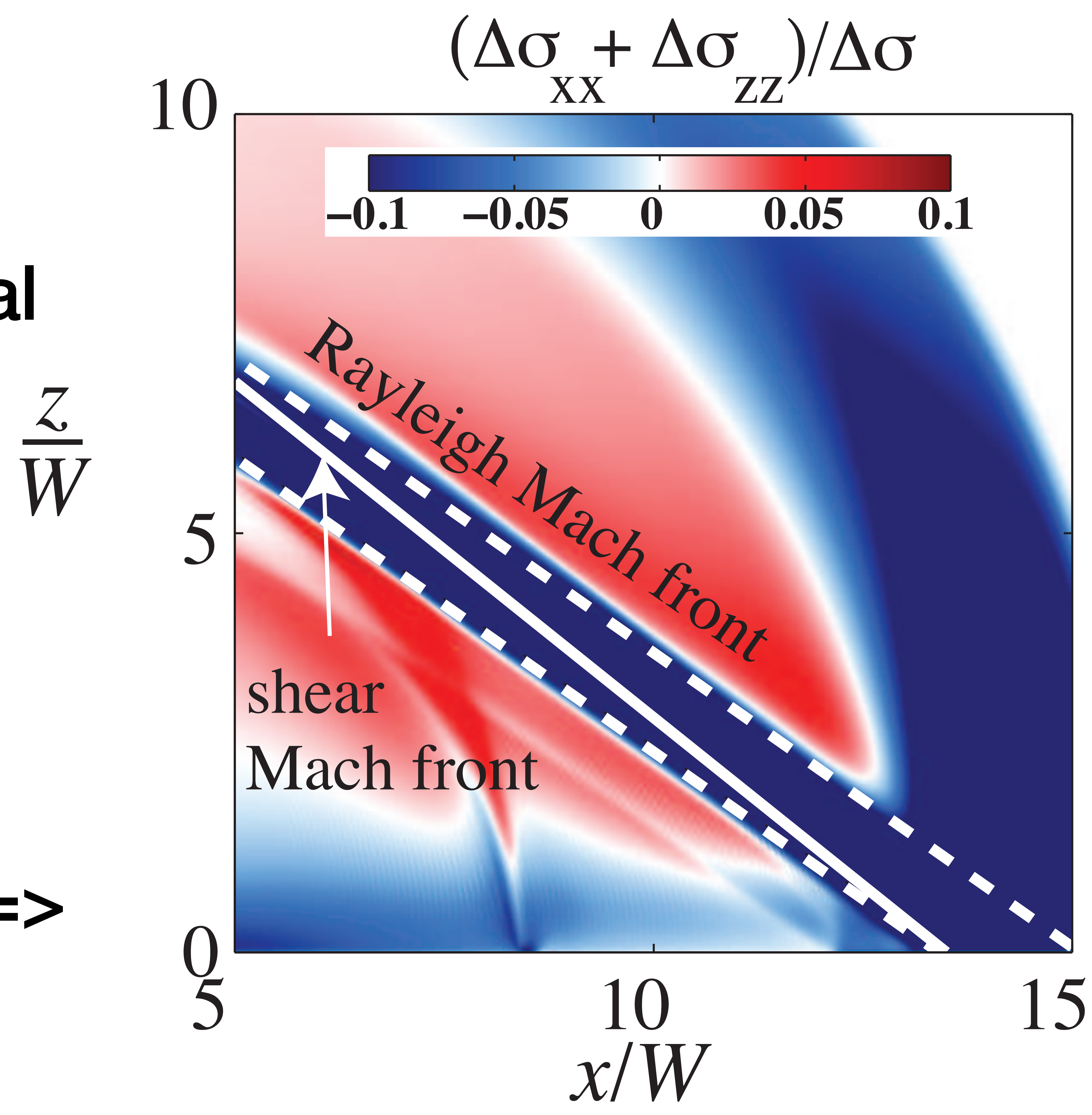
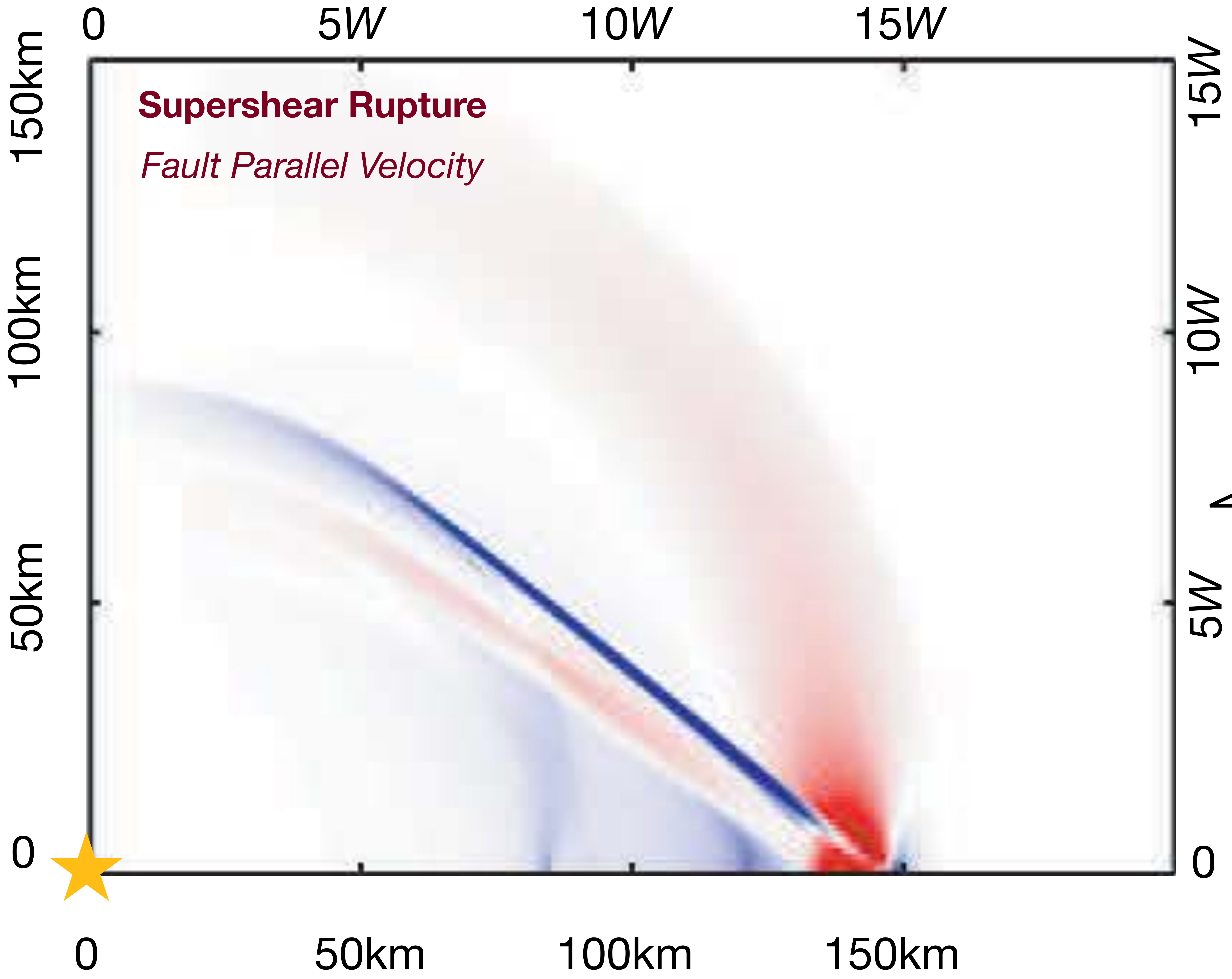
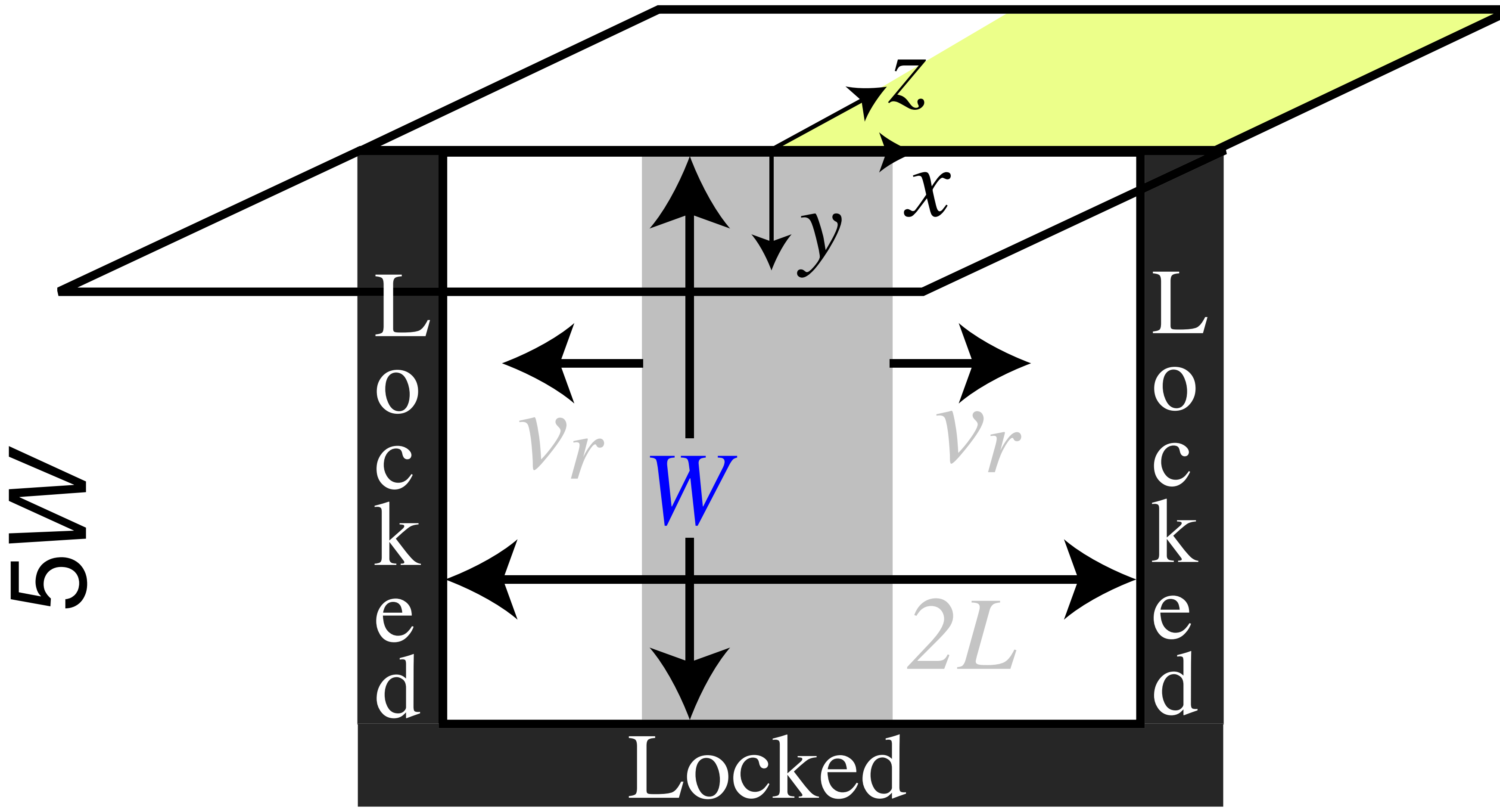


Dunham & Bhat 2008

Dunham & Bhat 2008





Dunham & Bhat 2008

Theory

Sub to Supershear Transition

Theory

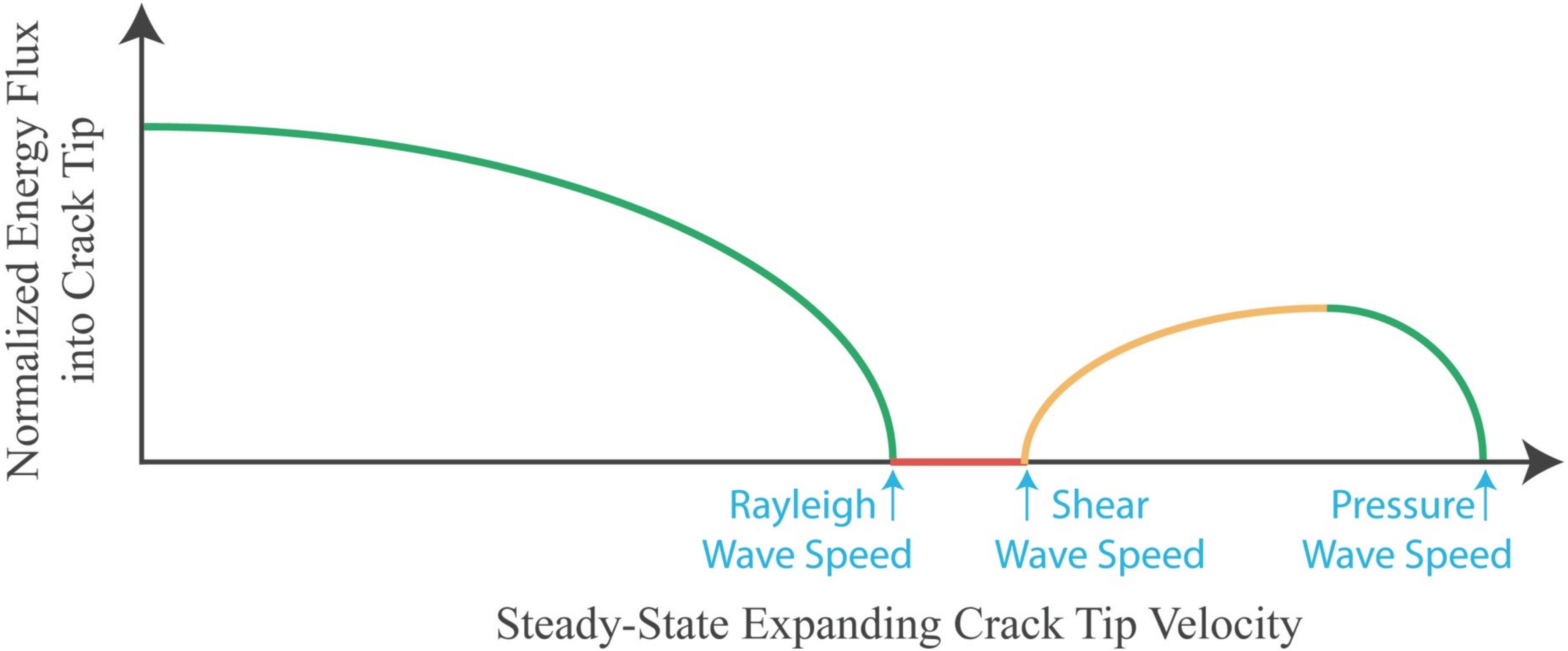
Sub to Supershear Transition

Burridge (1973) & Andrews (1976) : Mother-Daughter transition mechanism

Theory

Sub to Supershear Transition

Burridge (1973) & Andrews (1976) : Mother-Daughter transition mechanism



Theory

Sub to Supershear Transition

Dunham 2007

Theory

Sub to Supershear Transition

Burridge (1973) & Andrews (1976) : Mother-Daughter transition mechanism

Dunham 2007

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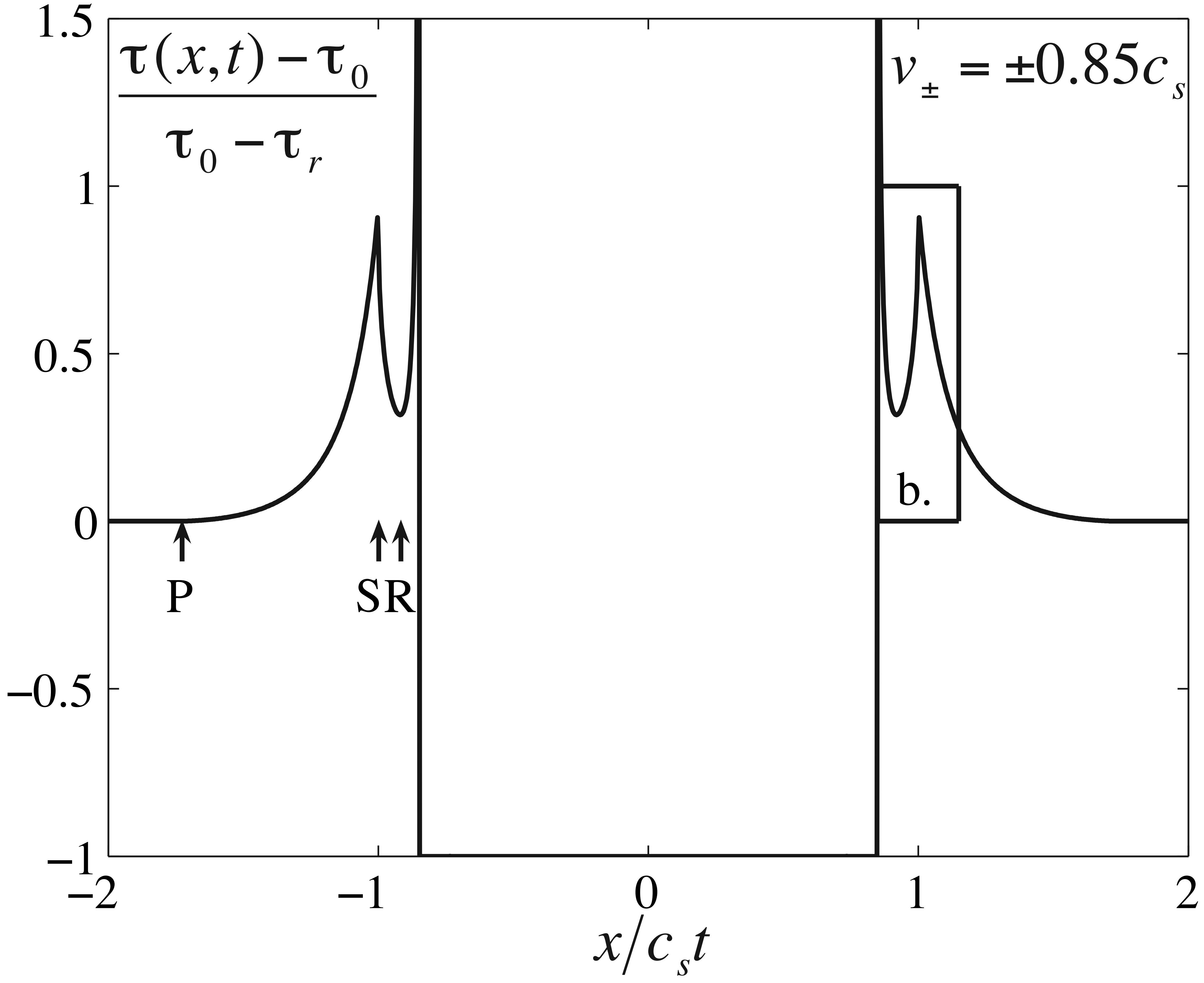
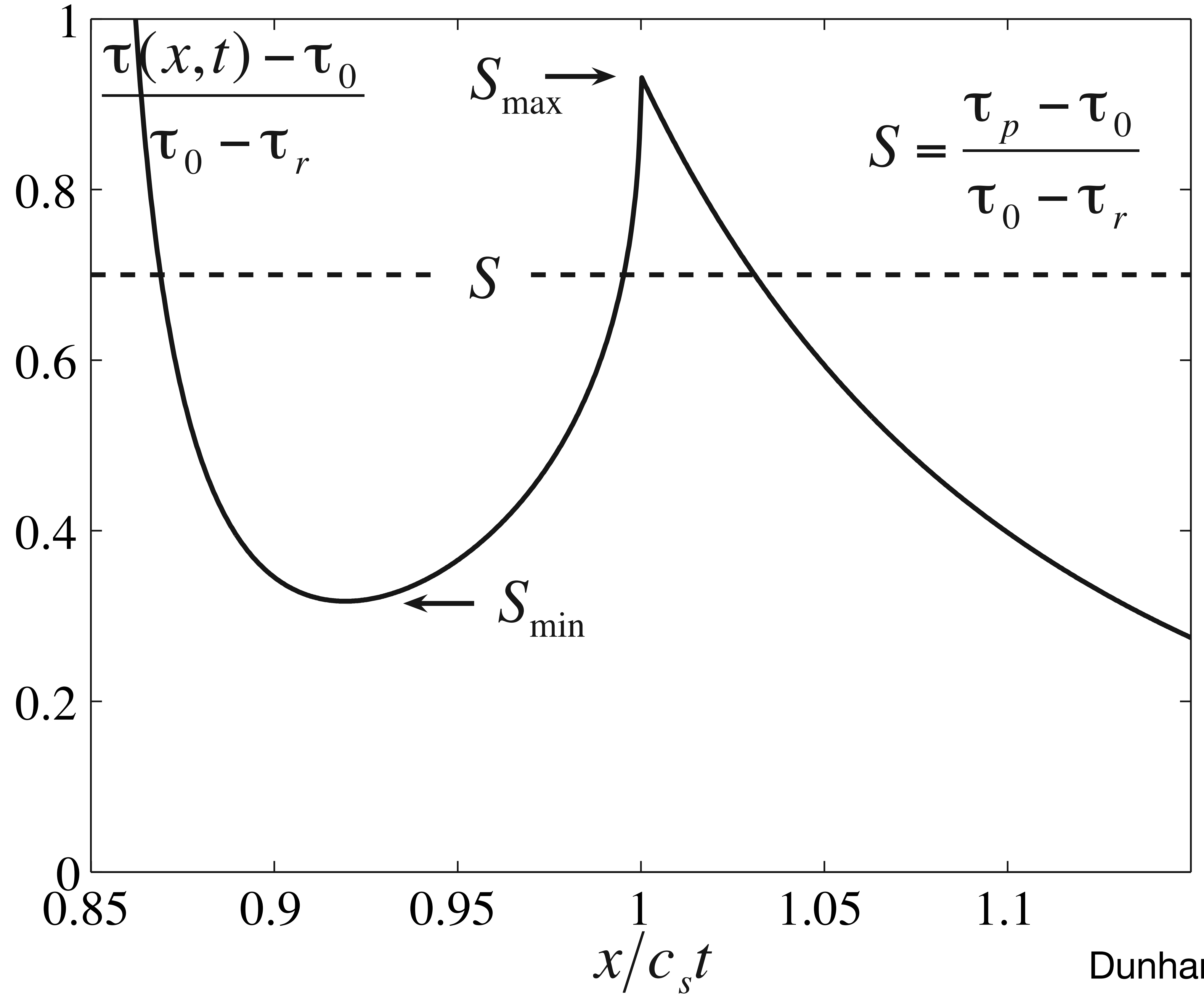
Burridge (1973) & Andrews (1976) : Mother-Daughter transition mechanism





Dunham 2007

Theory

Sub to Supershear Transition

Liu et al 2014

Theory

Sub to Supershear Transition

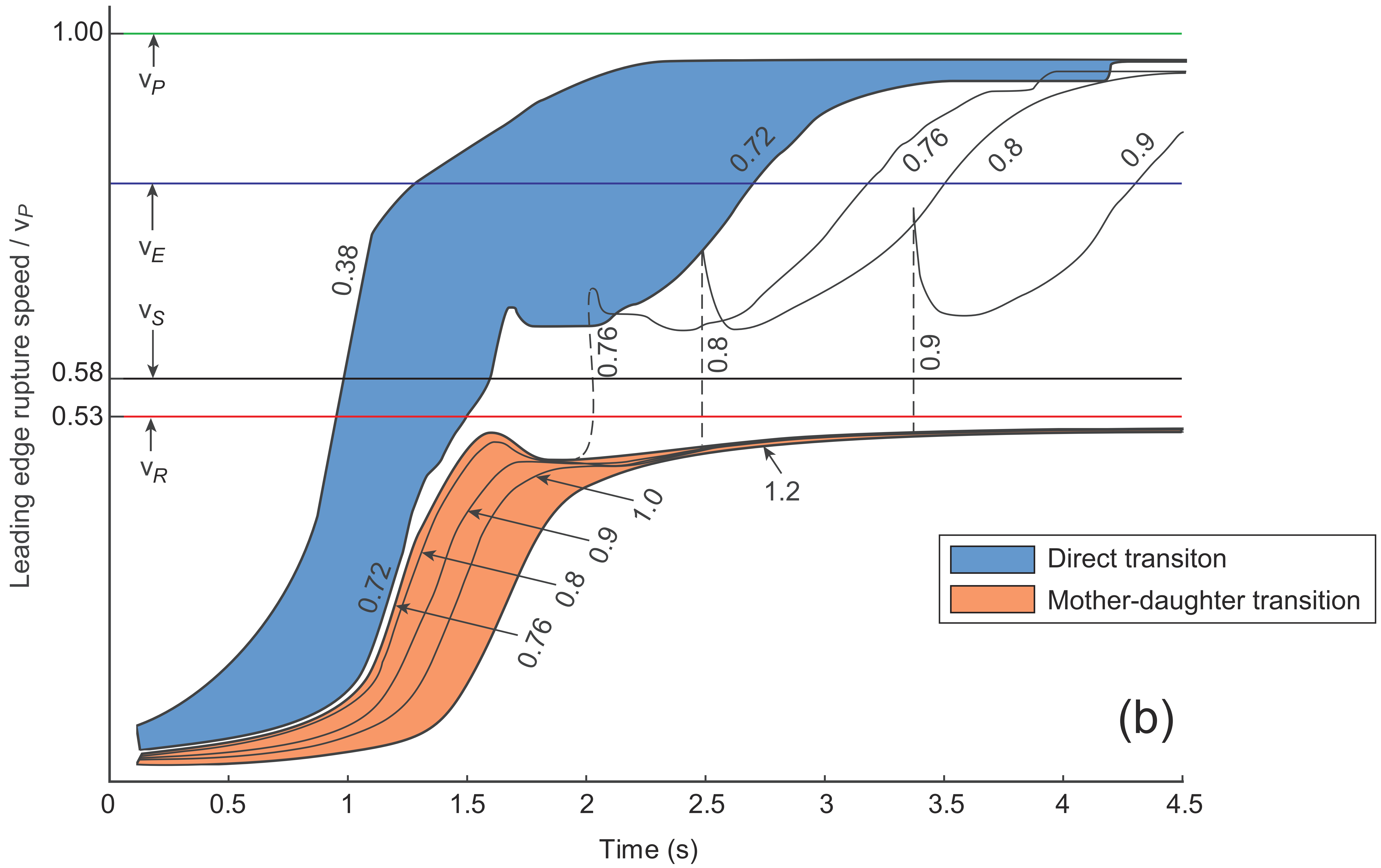
Bizzarri & Das (2012) & Liu et al. (2014) : Continuous transition possible under certain conditions

Liu et al 2014

Theory

Sub to Supershear Transition

Bizzarri & Das (2012) & Liu et al. (2014) : Continuous transition possible under certain conditions



Liu et al 2014

Theory

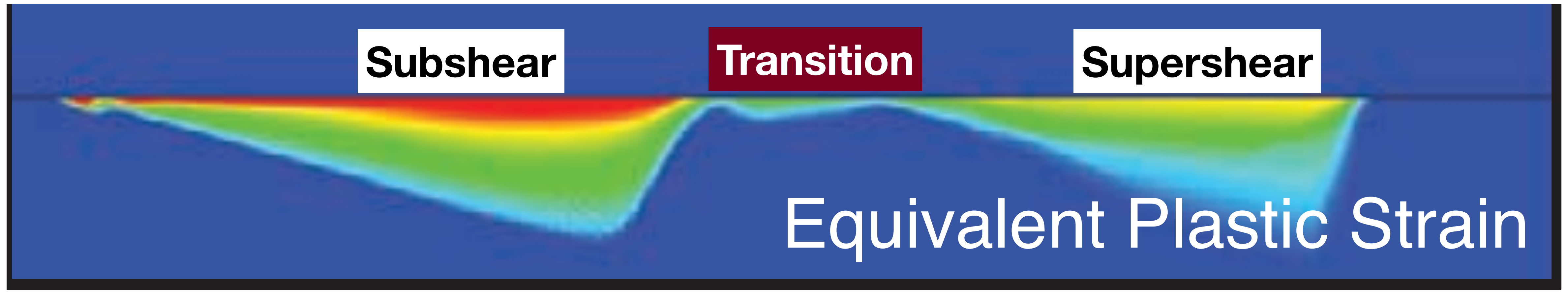
Sub to Supershear Transition : Off-Fault Damage

Jara, Bruhat et al. 2021

Theory

Sub to Supershear Transition : Off-Fault Damage

Mohr-Coulomb Plasticity



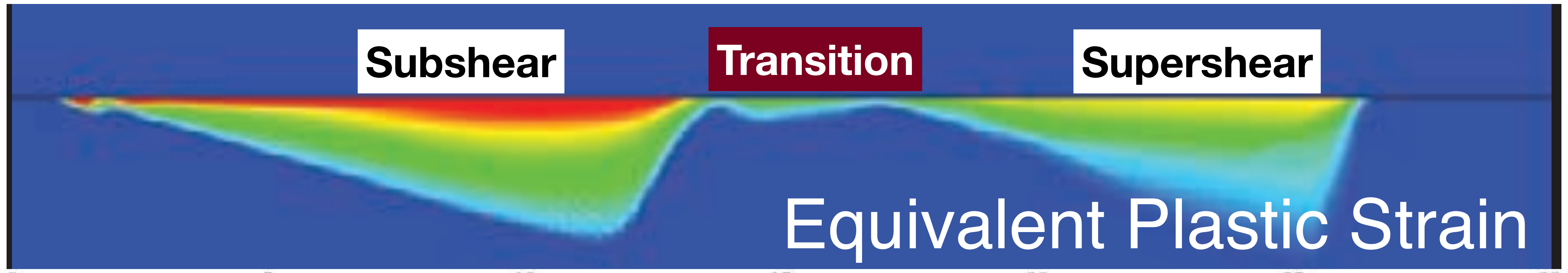
Templeton & Rice 2008

Jara, Bruhat et al. 2021

Theory

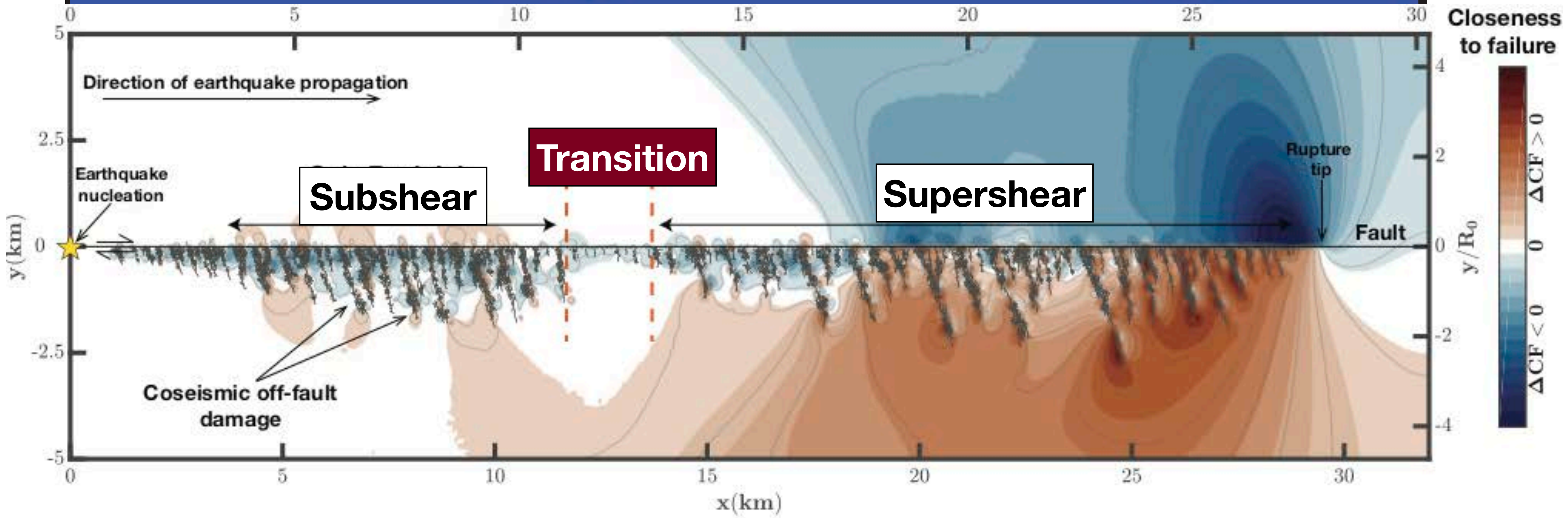
Sub to Supershear Transition : Off-Fault Damage

Mohr-Coulomb Plasticity



Templeton & Rice 2008

Discrete Damage



Okubo et al 2019

Jara, Bruhat et al. 2021

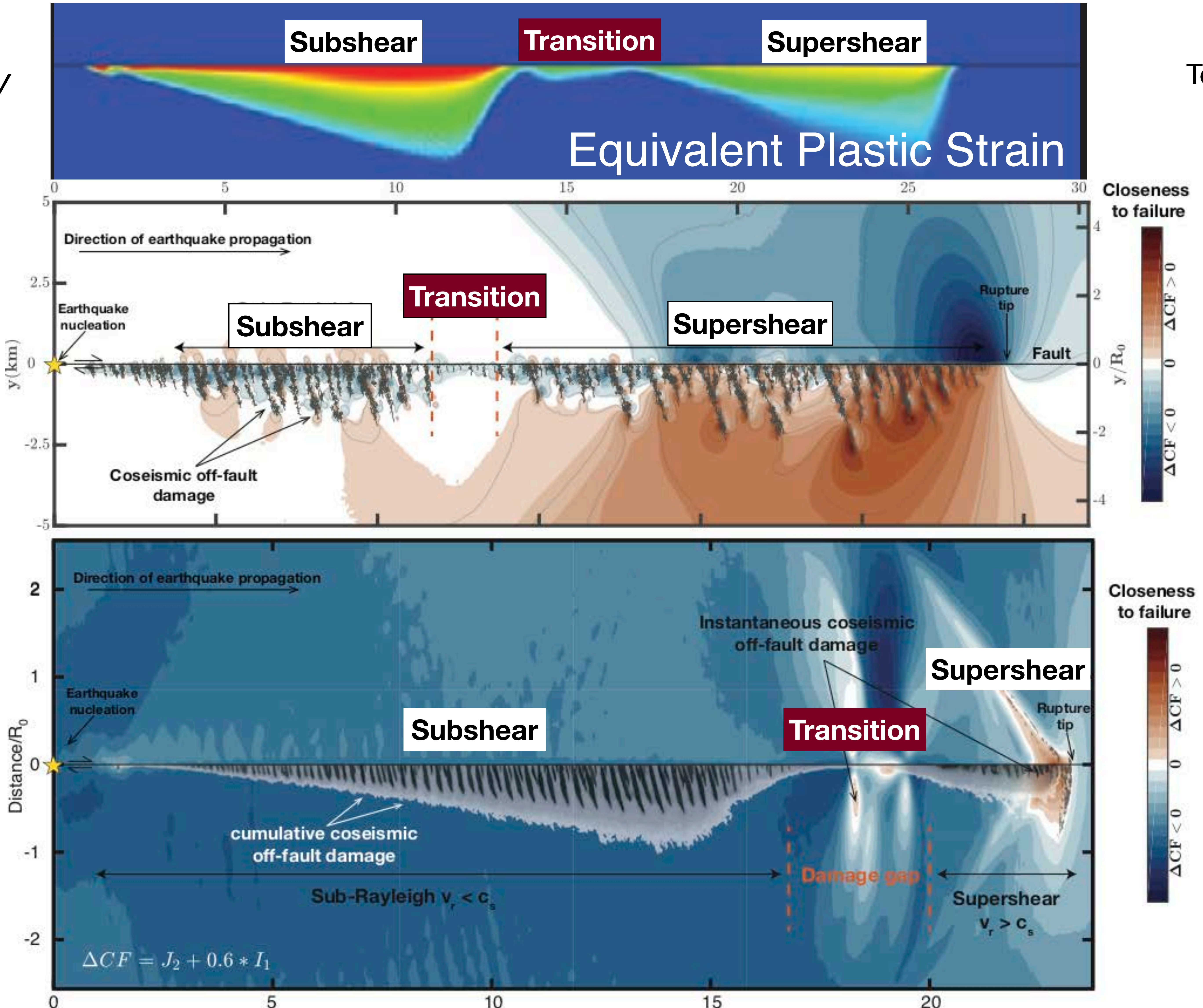
Theory

Sub to Supershear Transition : Off-Fault Damage

Mohr-Coulomb Plasticity — Templeton & Rice 2008

Discrete Damage — Okubo et al 2019

Continuum Damage — Thomas & Bhat 2018



Jara, Bruhat et al. 2021

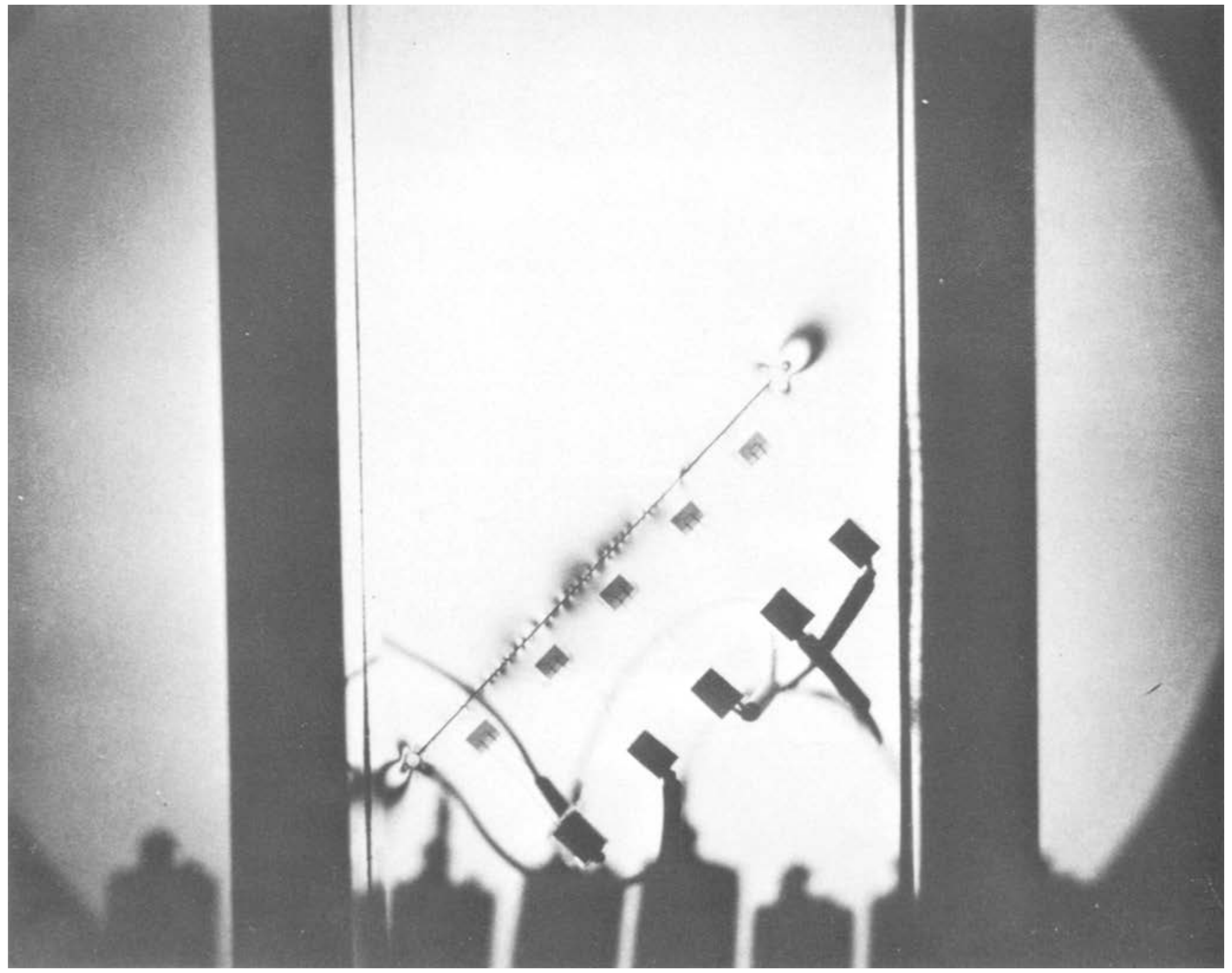
Experiments

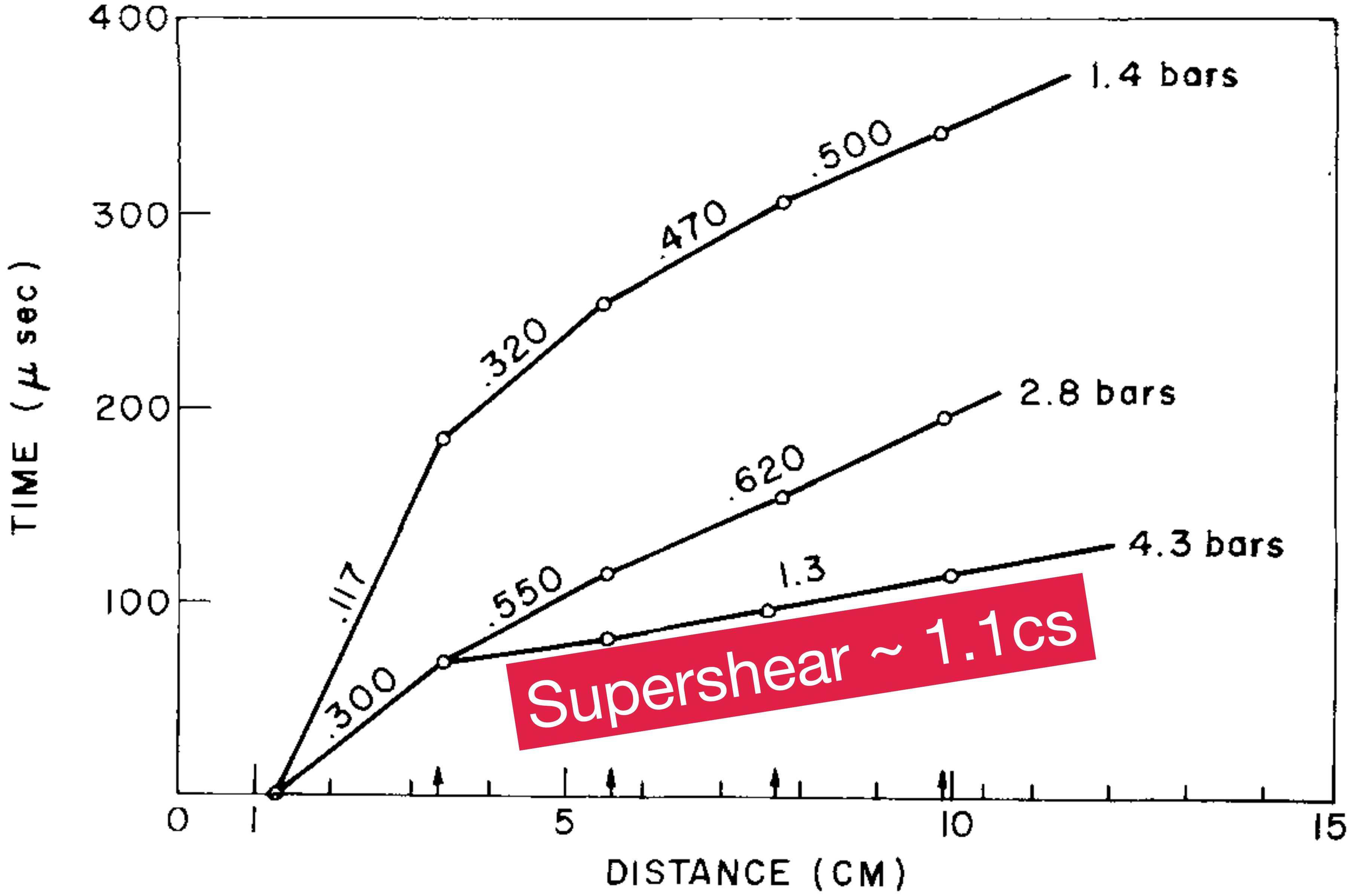
Experiments

Wu (1972) : Stick-Slip experiments in Columbia Resin

Experiments

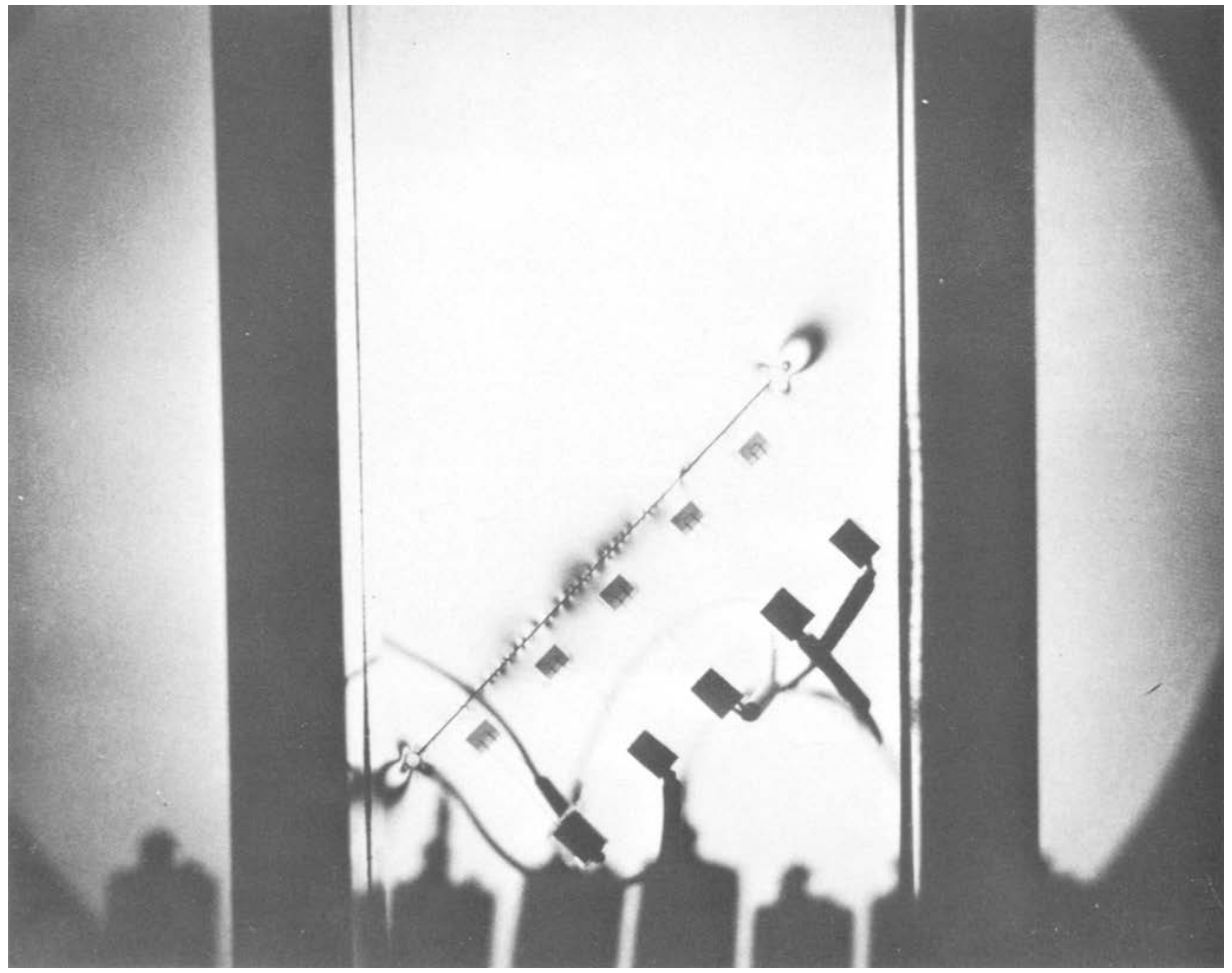
Wu (1972) : Stick-Slip experiments in Columbia Resin

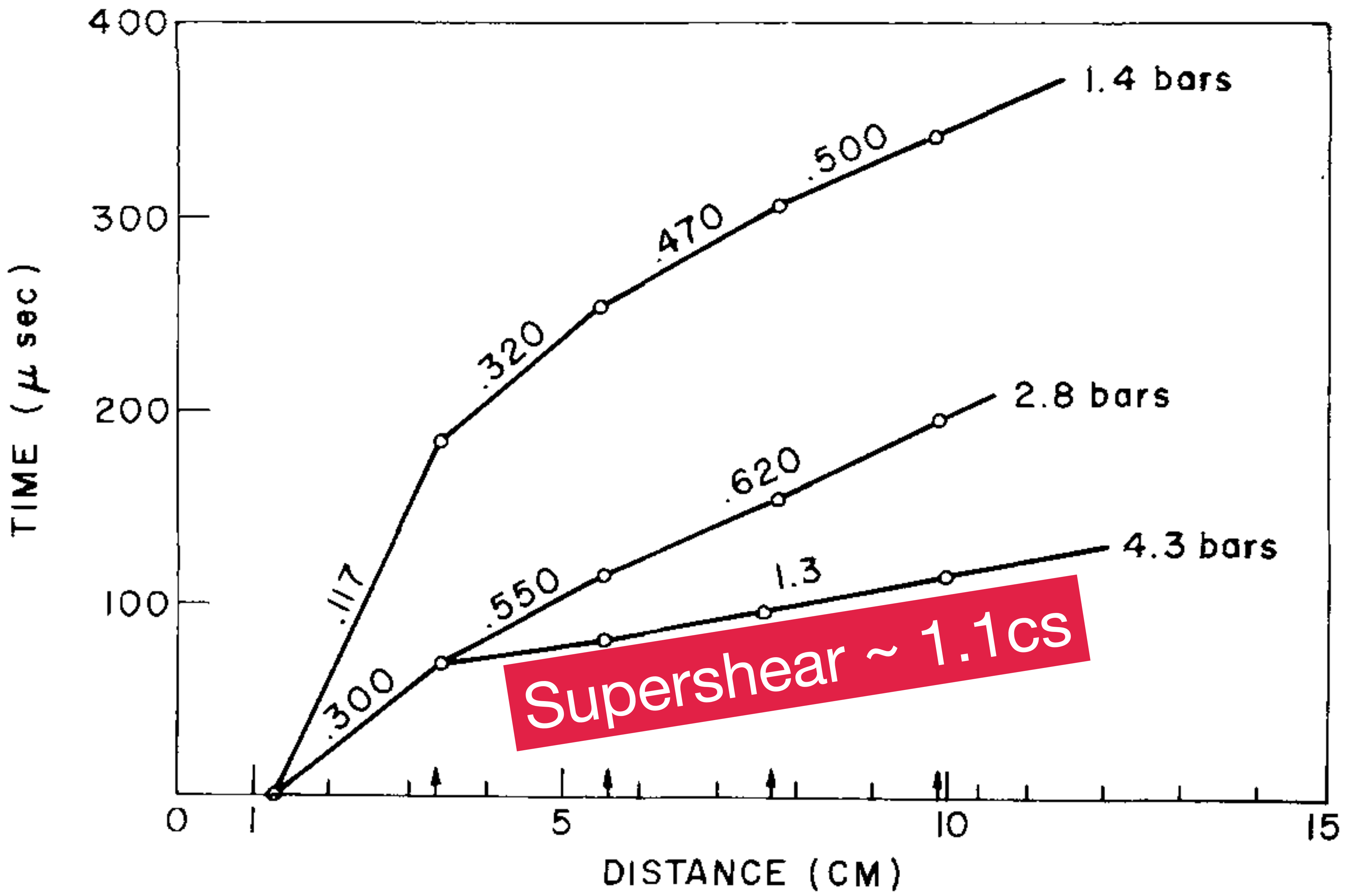




Experiments

Wu (1972) : Stick-Slip experiments in Columbia Resin





- As Weertman (1969) theory disallowed supershear, it was forgotten. Probably!

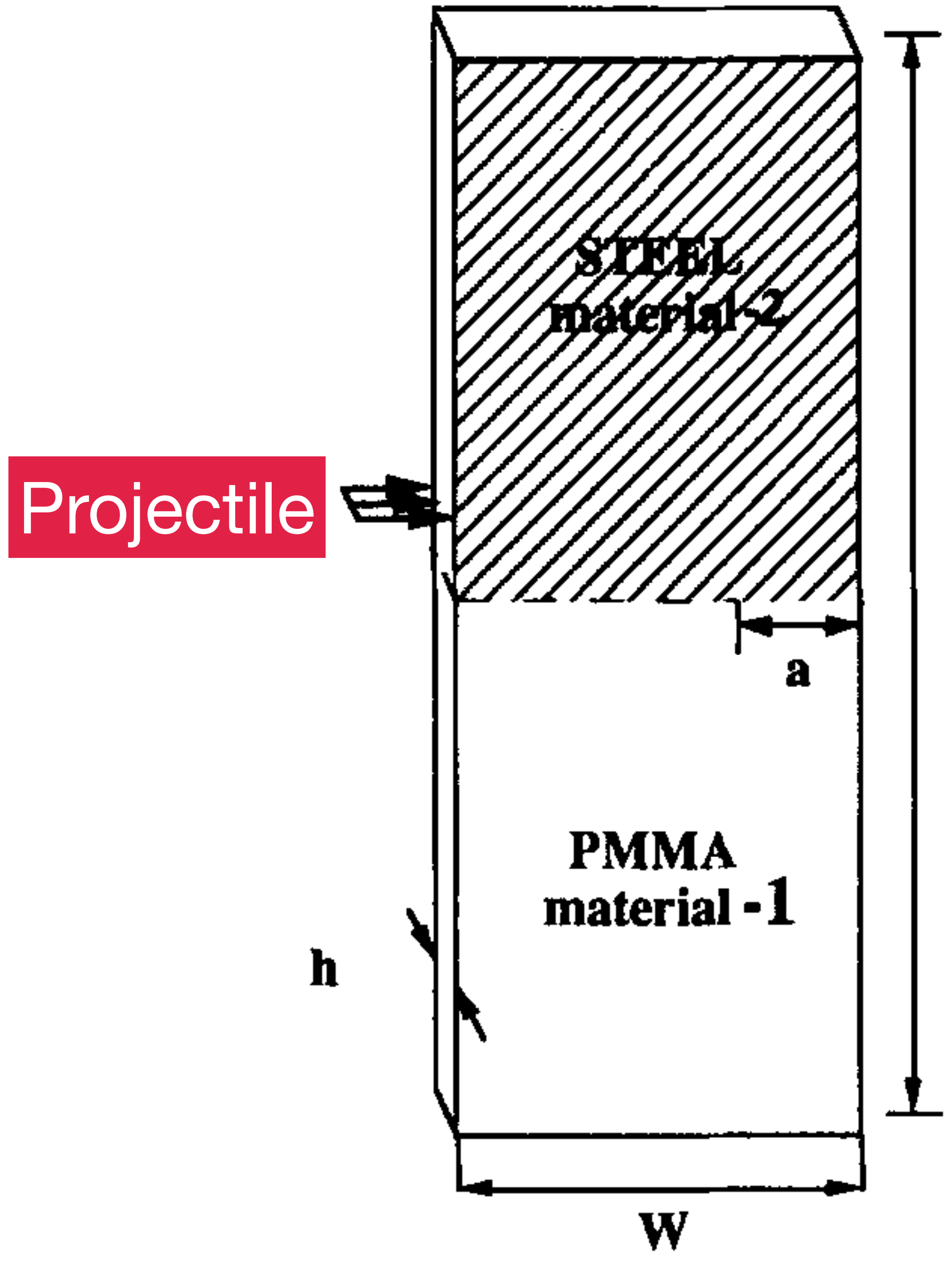
Experiments

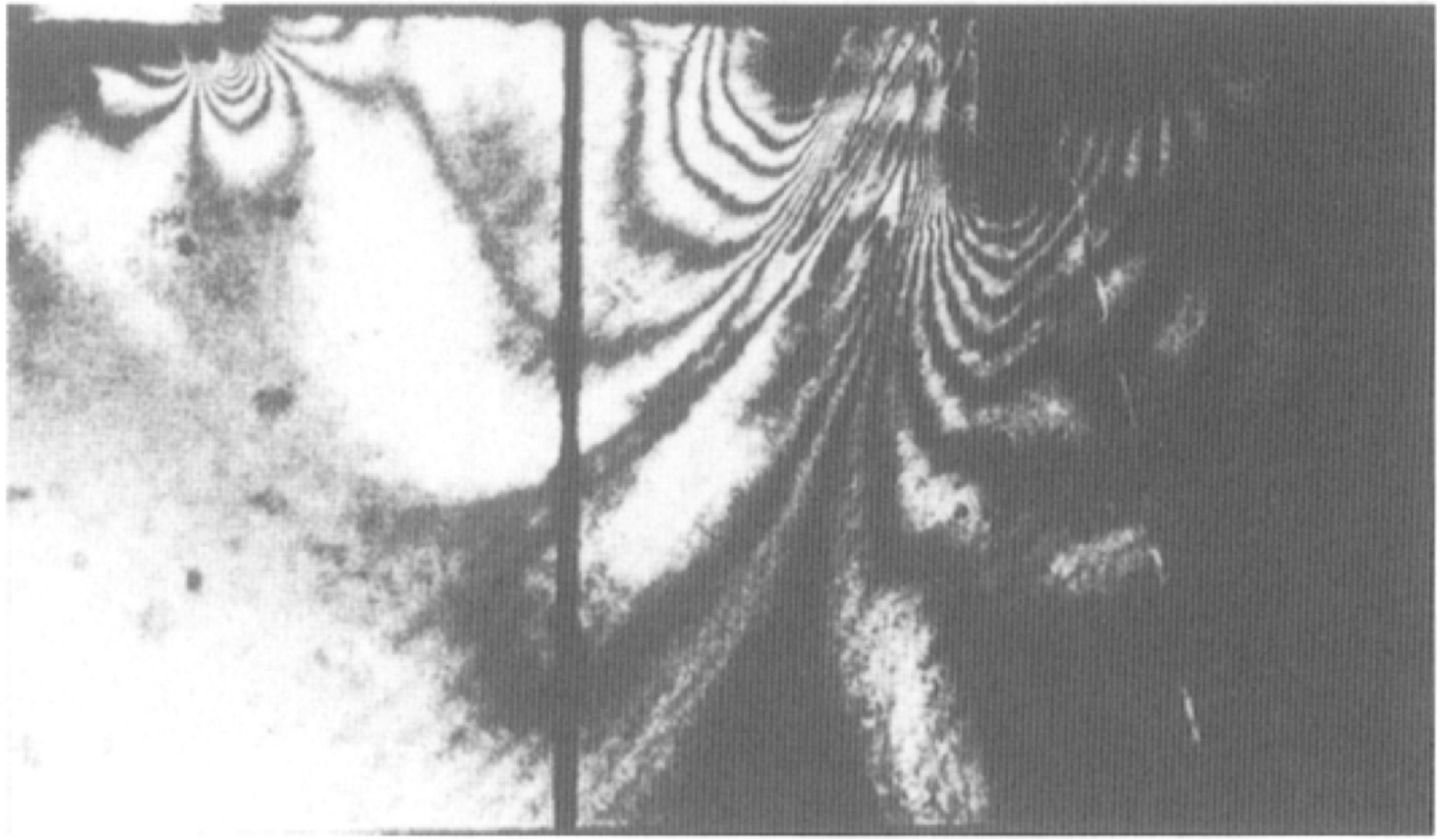
Experiments

Lambros & Rosakis (1995) : Bi-Material shear impact experiments

Experiments

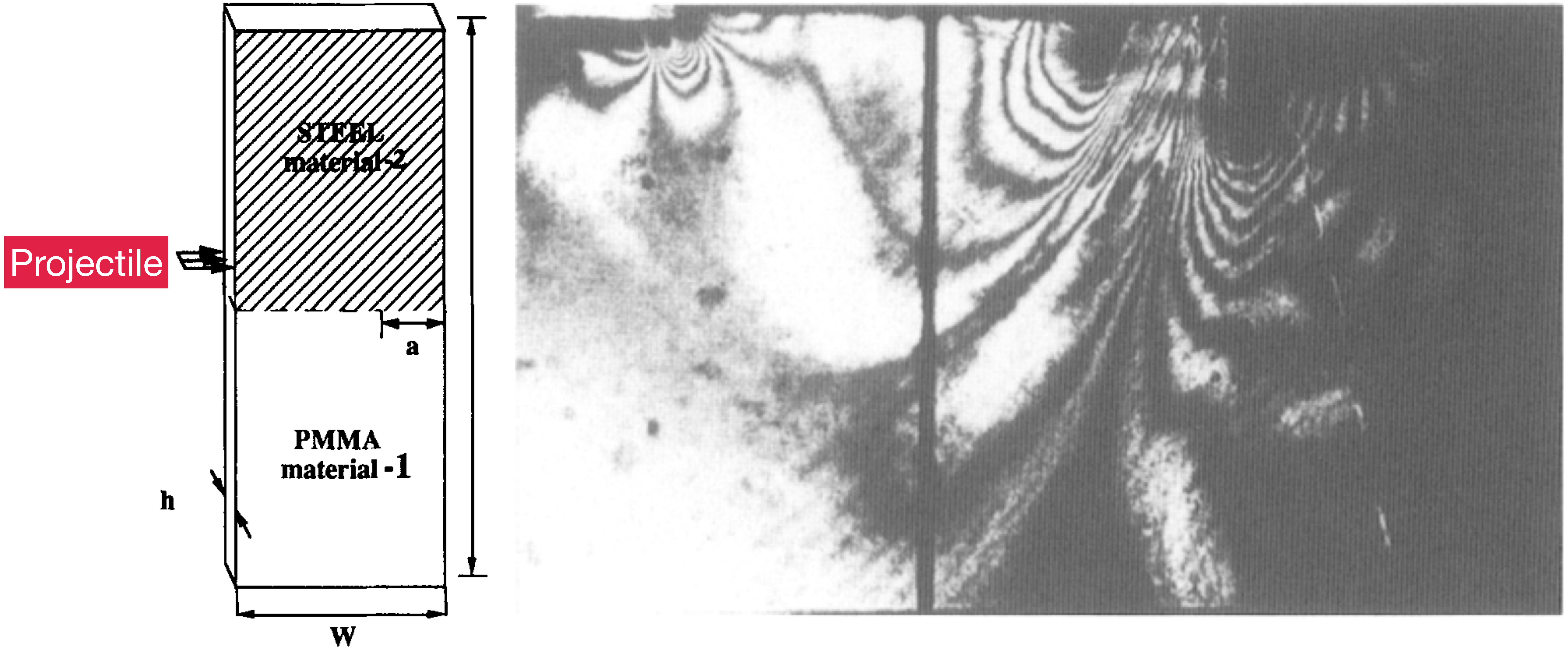
Lambros & Rosakis (1995) : Bi-Material shear impact experiments





Experiments

Lambros & Rosakis (1995) : Bi-Material shear impact experiments



- First recorded image of a supershear rupture!

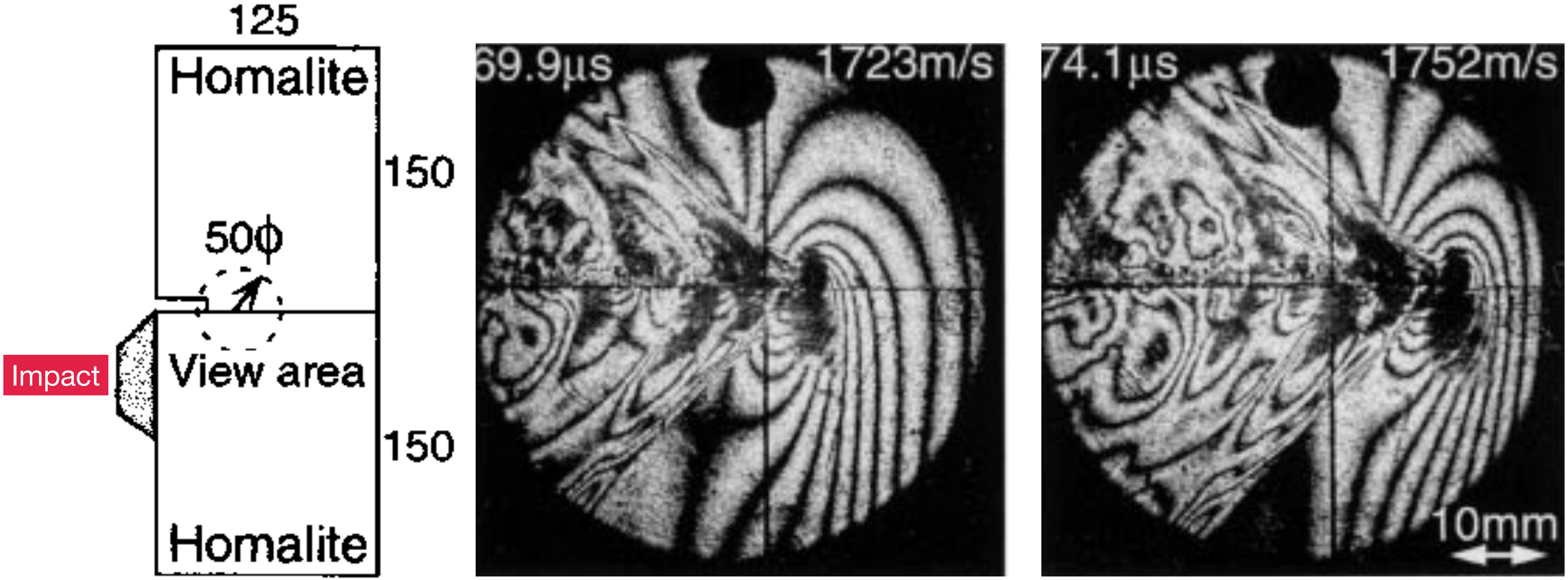
Experiments

Experiments

Rosakis et al. (1999) : Shear impact experiments

Experiments

Rosakis et al. (1999) : Shear impact experiments



Experiments

Experiments

Xia et al. (2004) : Spontaneous shear ruptures along a frictional interface *a.k.a* Laboratory Earthquakes

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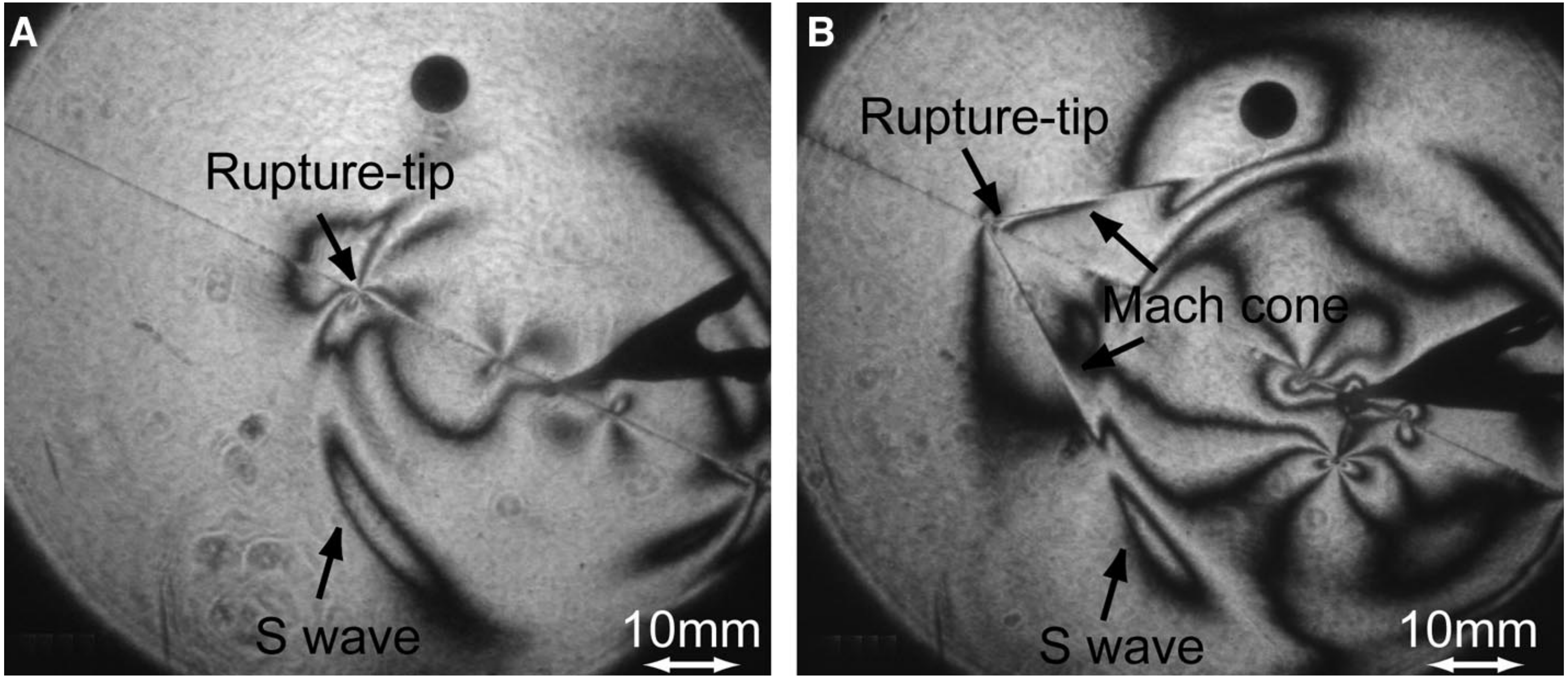
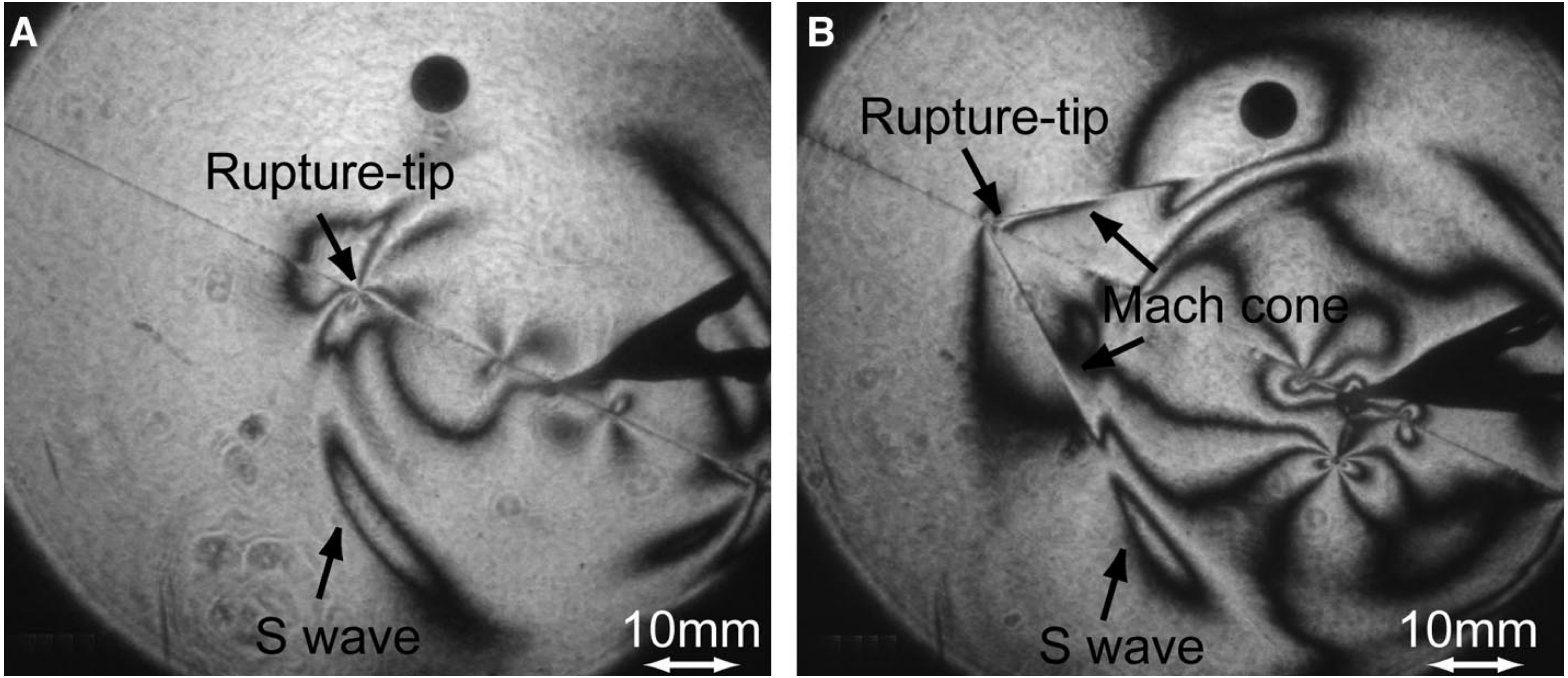
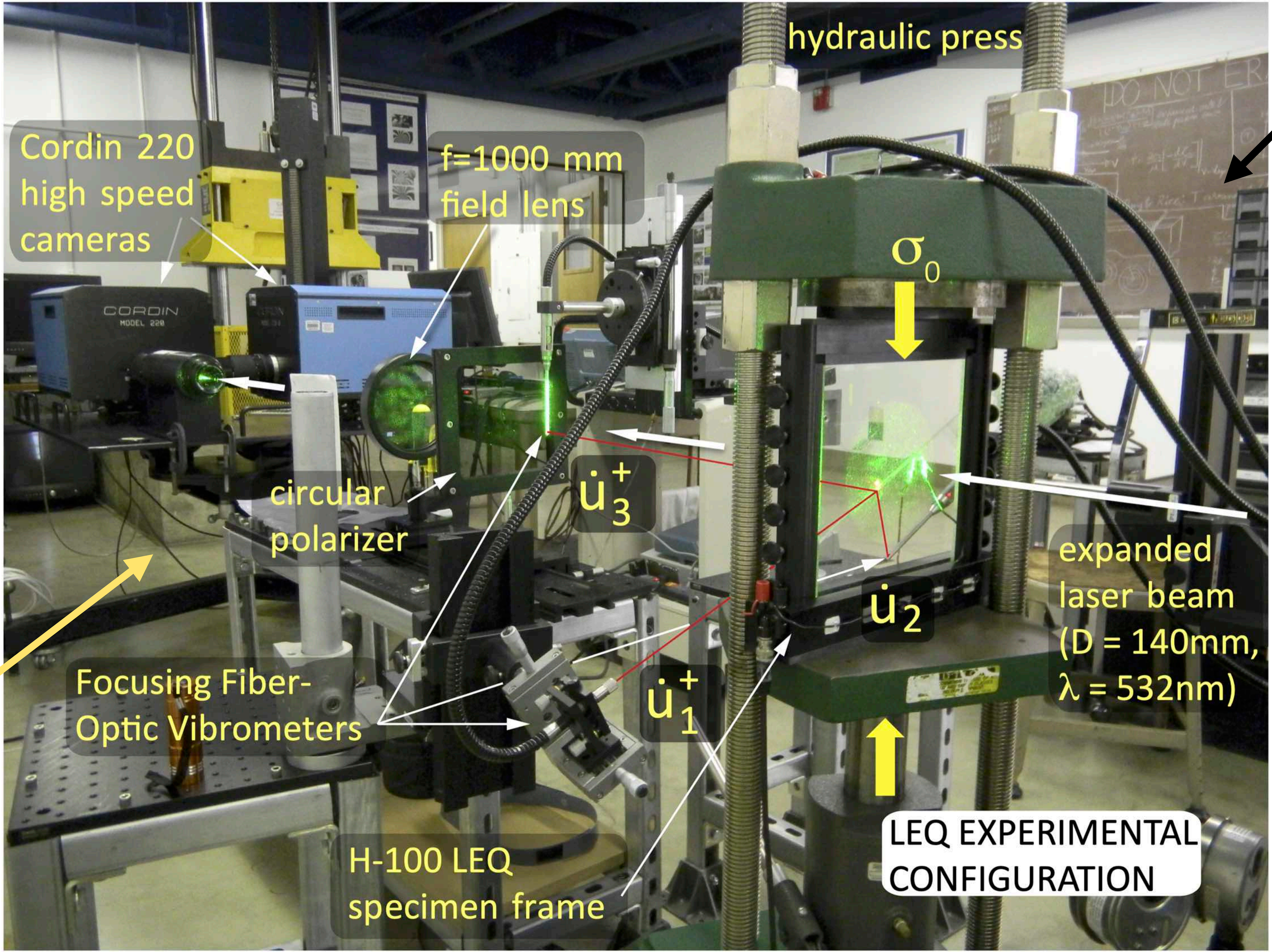


Experiments

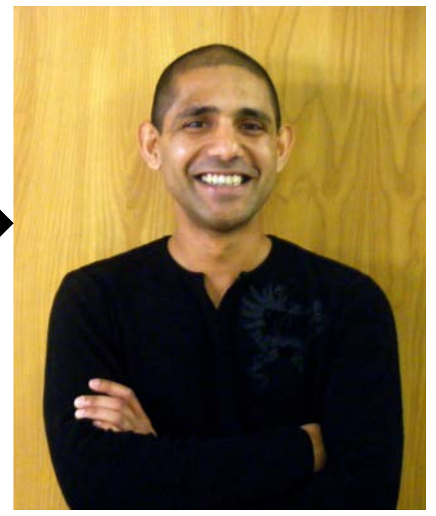
Xia et al. (2004) : Spontaneous shear ruptures along a frictional interface *a.k.a* Laboratory Earthquakes



- First laboratory evidence of Supershear Ruptures



hydraulic press
Cordin 220 high speed cameras
CORDIN MODEL 220
f=1000 mm field lens
σ_0
circular polarizer
$\dot{u}_3^+$
expanded laser beam (D = 140mm, λ = 532nm)
$\dot{u}_2$
Focusing Fiber-Optic Vibrometers
$\dot{u}_1^+$
H-100 LEQ specimen frame
LEQ EXPERIMENTAL CONFIGURATION



Experiments

Experiments

Mello, Bhat et al. (2010, 2016) : Experimental Validation of Ground Motion Signatures of Supershear Earthquakes

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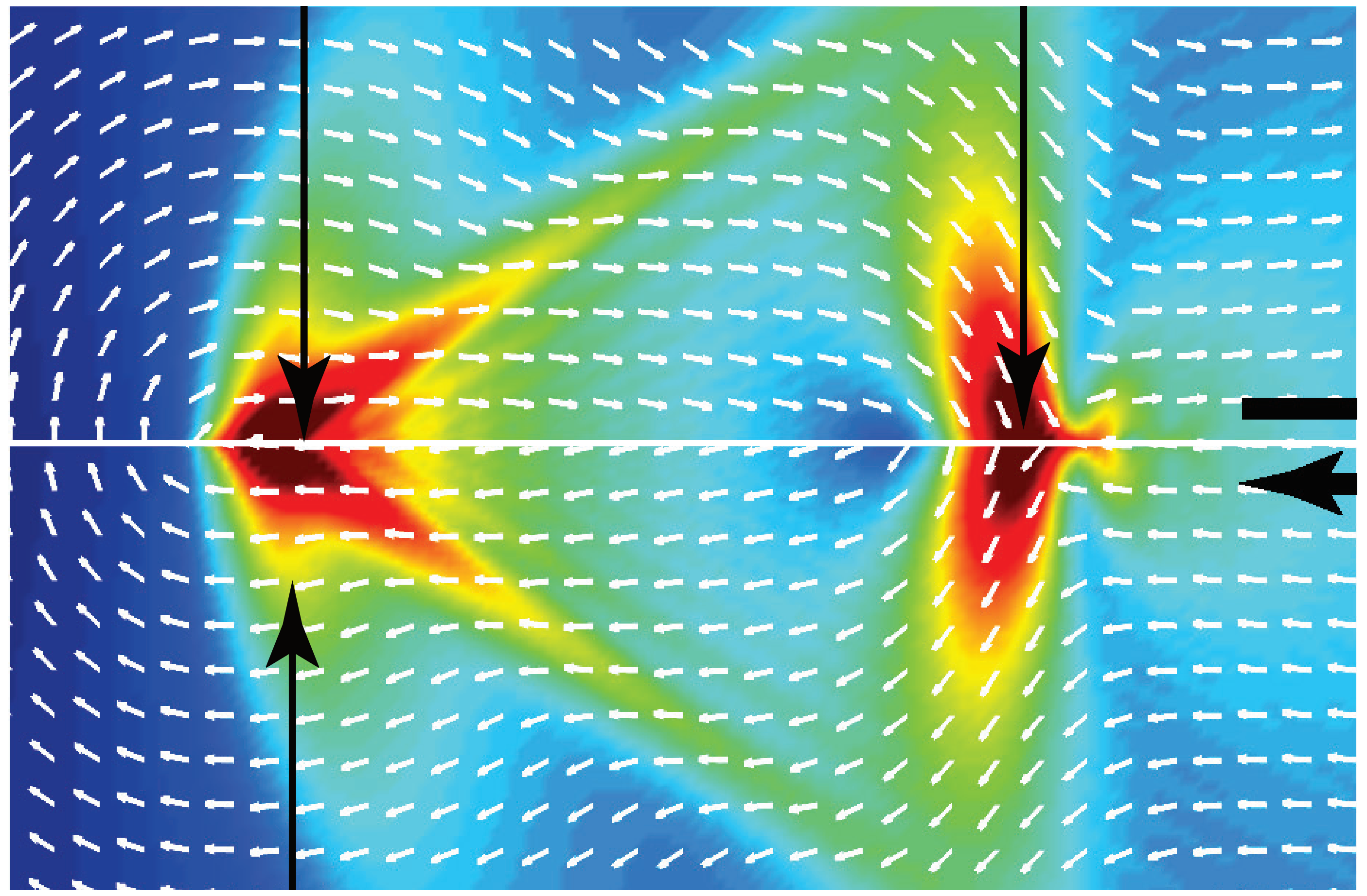

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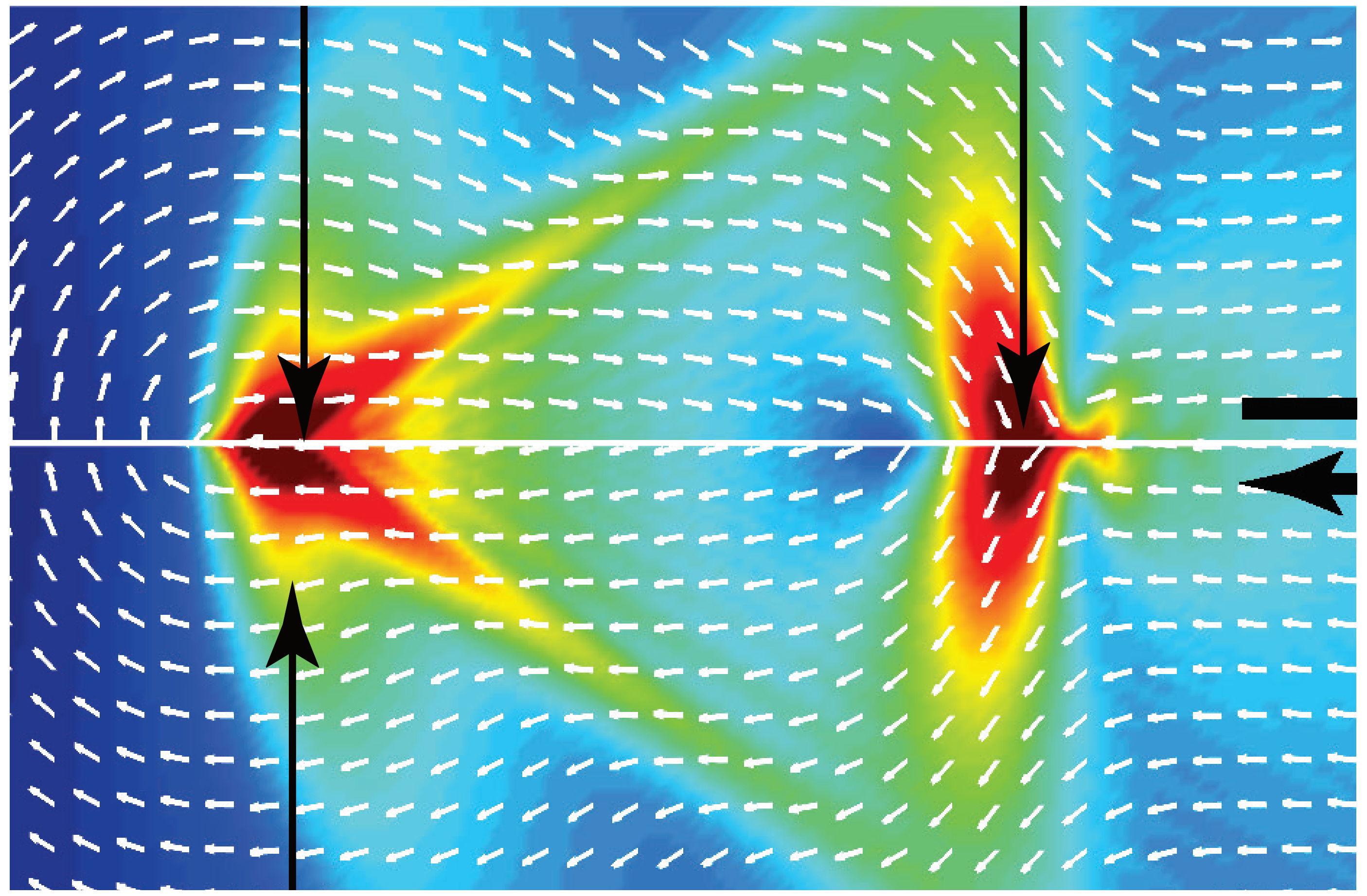

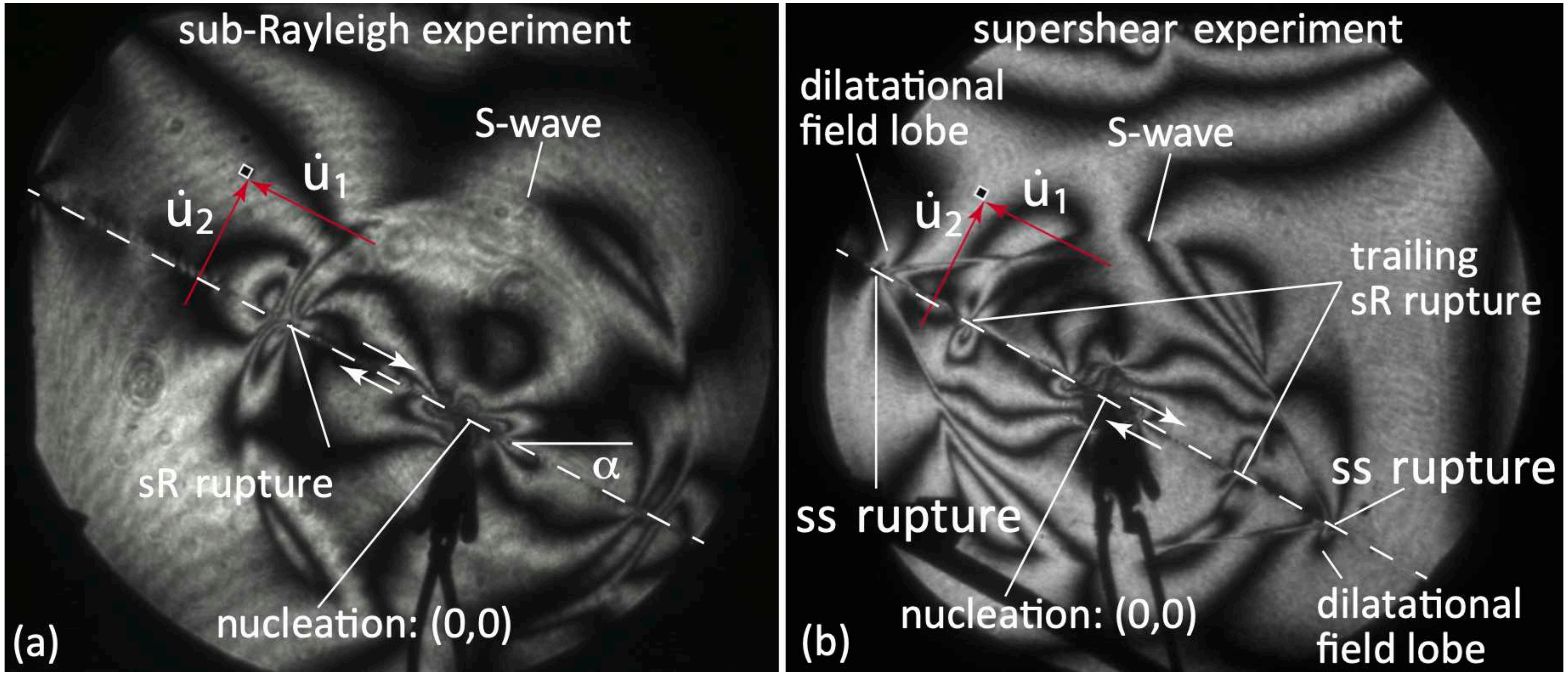

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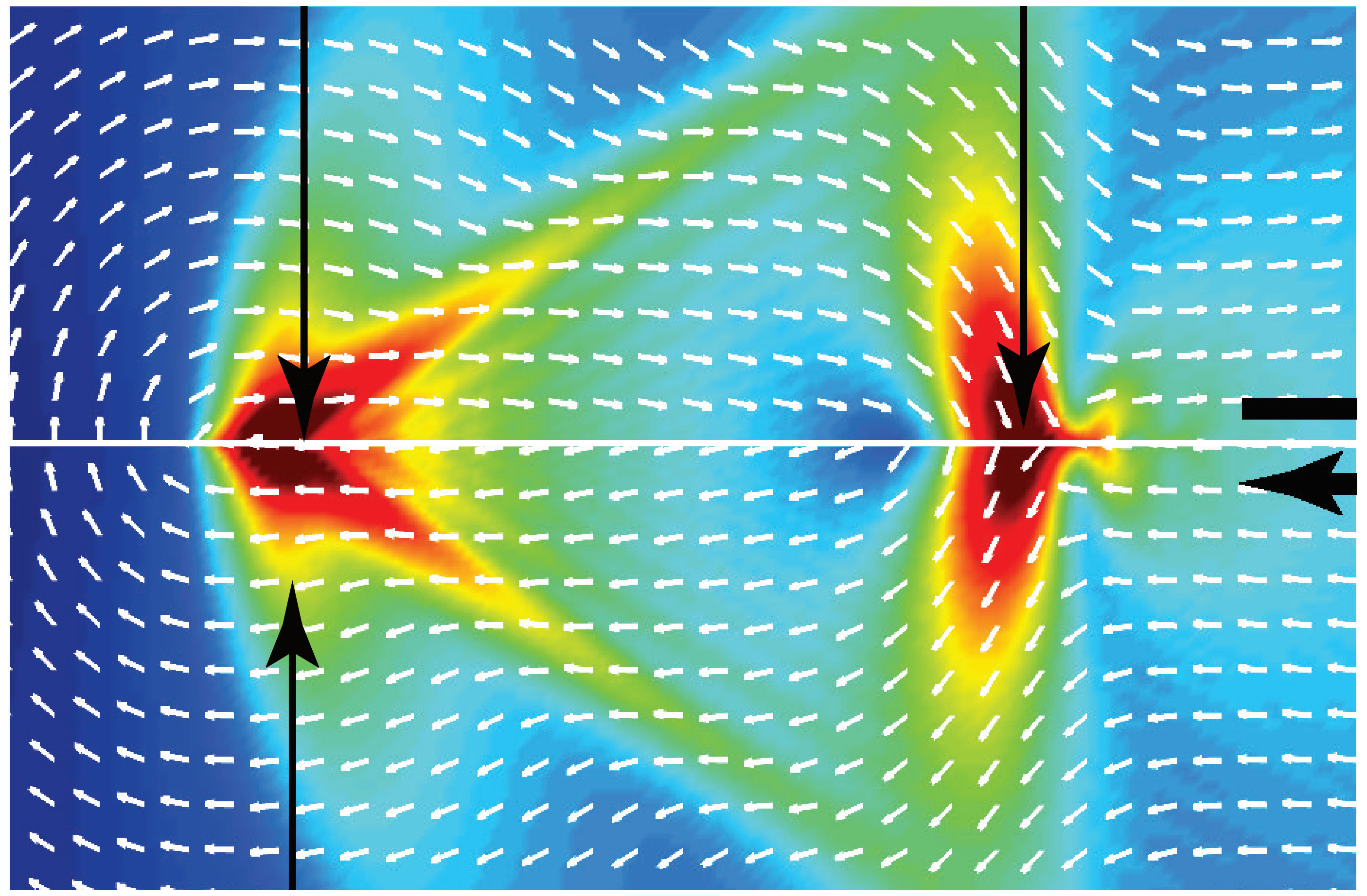

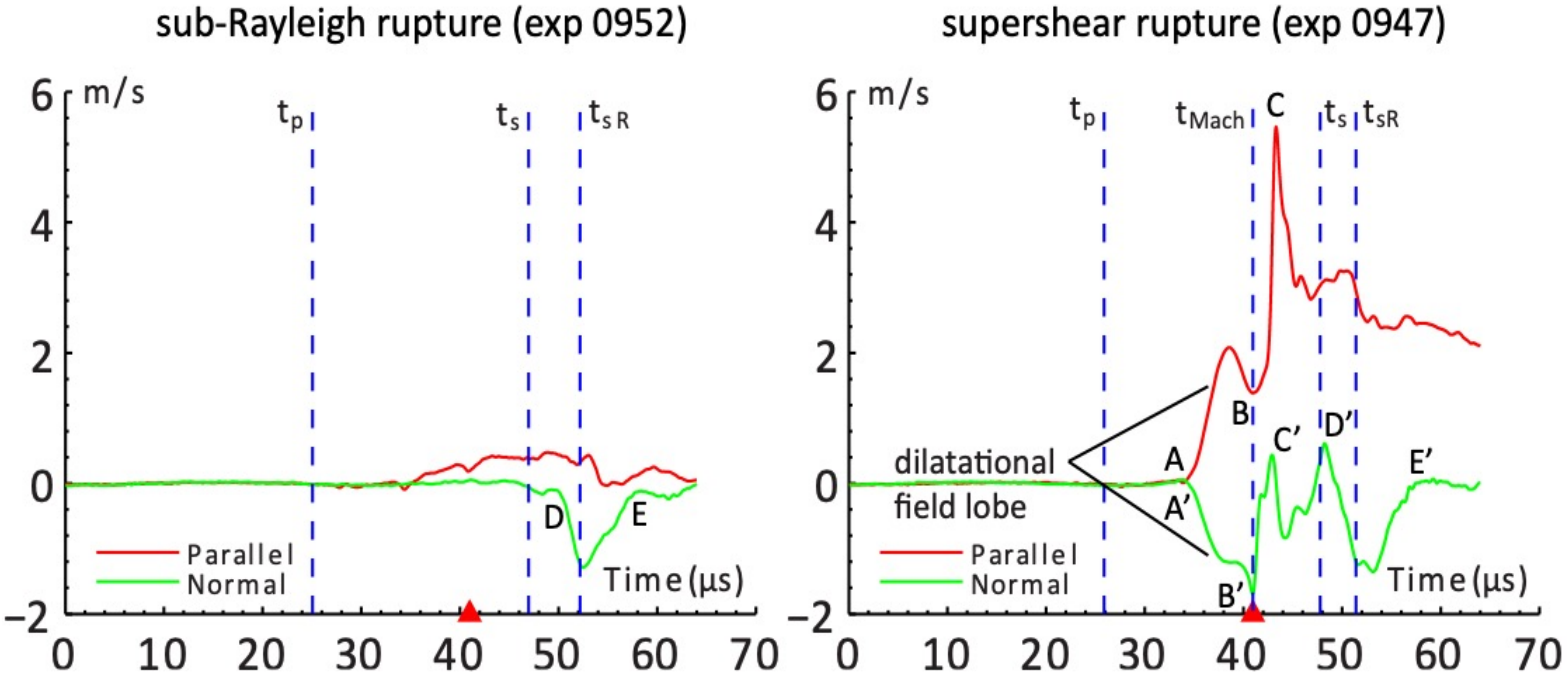

Experiments

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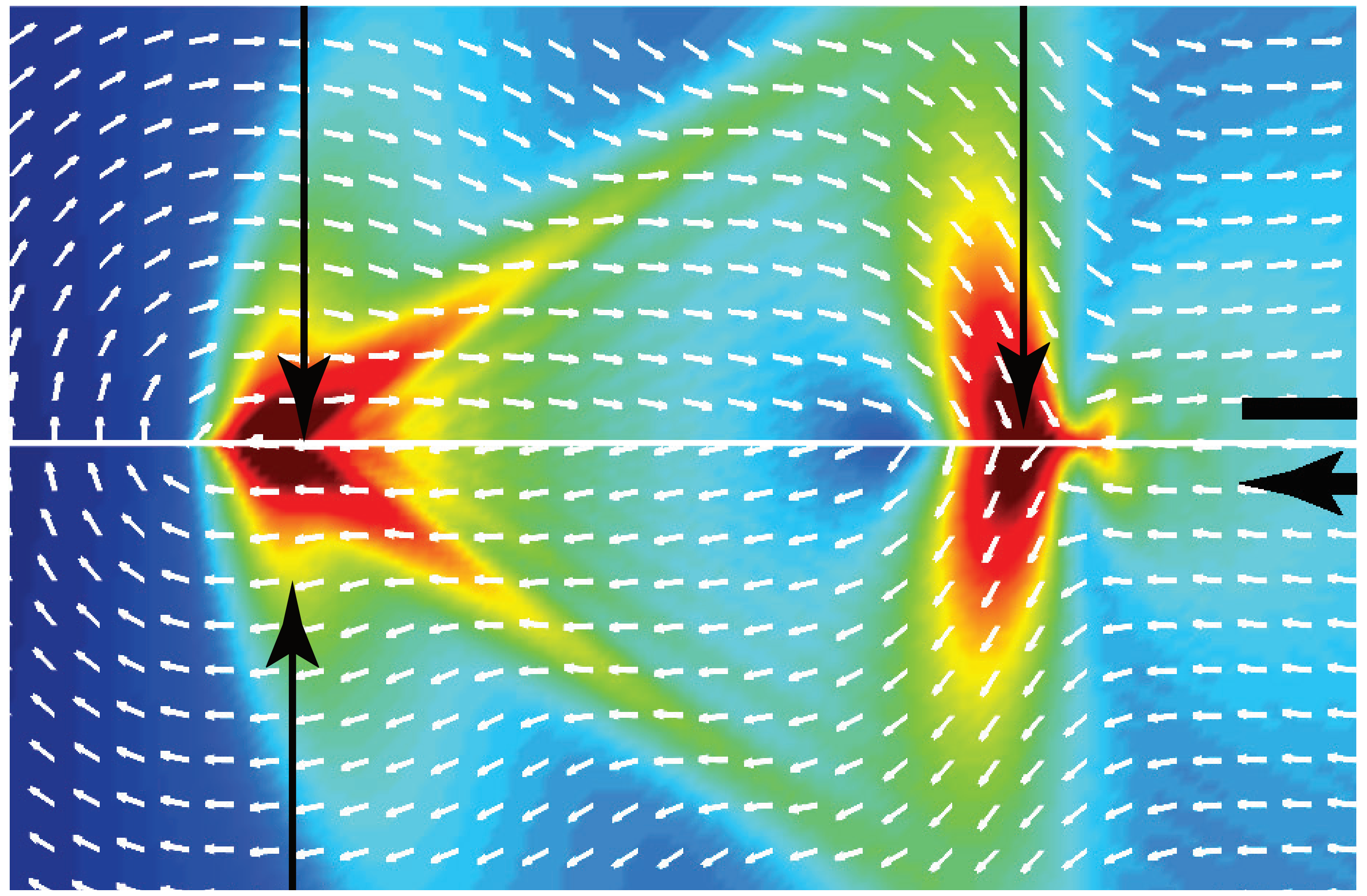

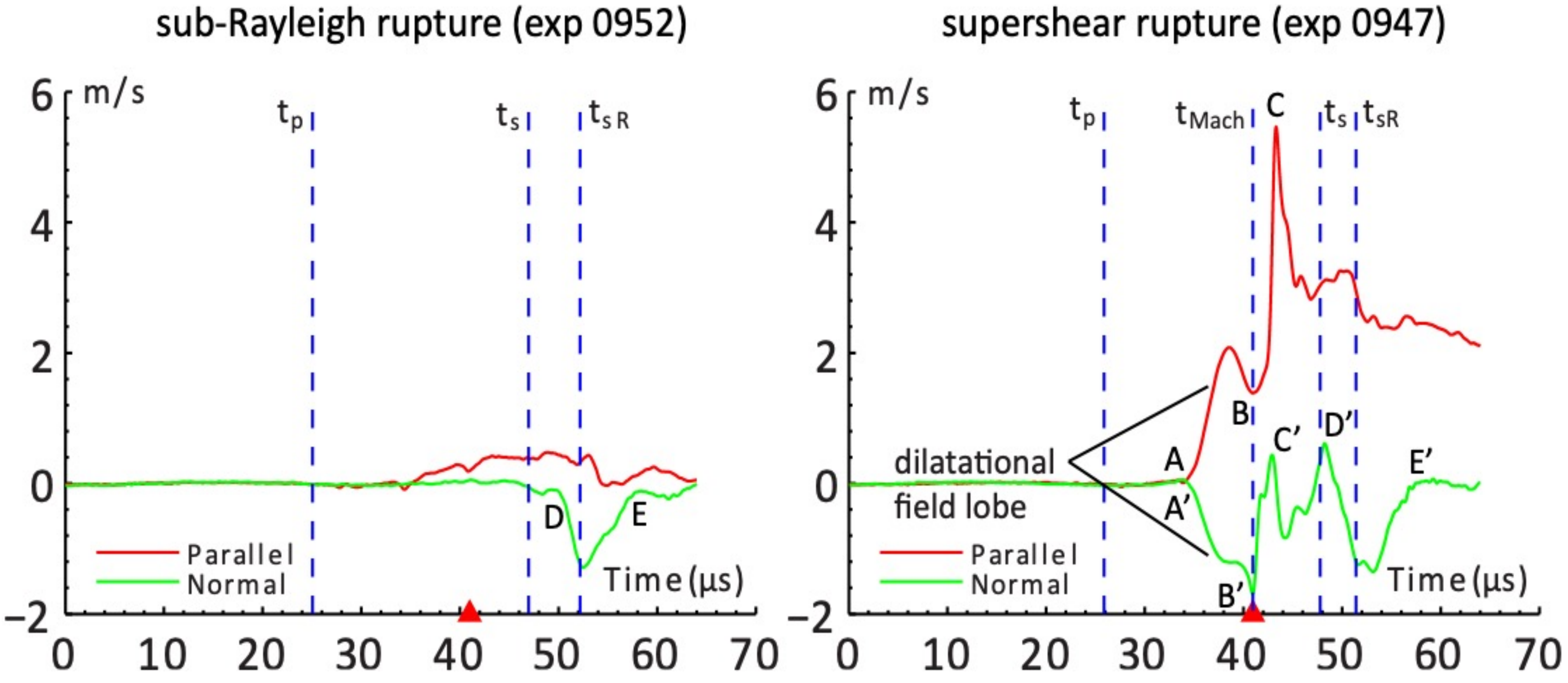

- Fault Parallel Motion > Fault Normal Motion for Supershear ruptures
- Supershear rupture front is followed by a "Trailing Rayleigh Rupture"

Experiments

Experiments

Mello, Bhat et al. (2014) : Scaled Reproduction of the 2002 Denali, Alaska Supershear Earthquake

Experiments

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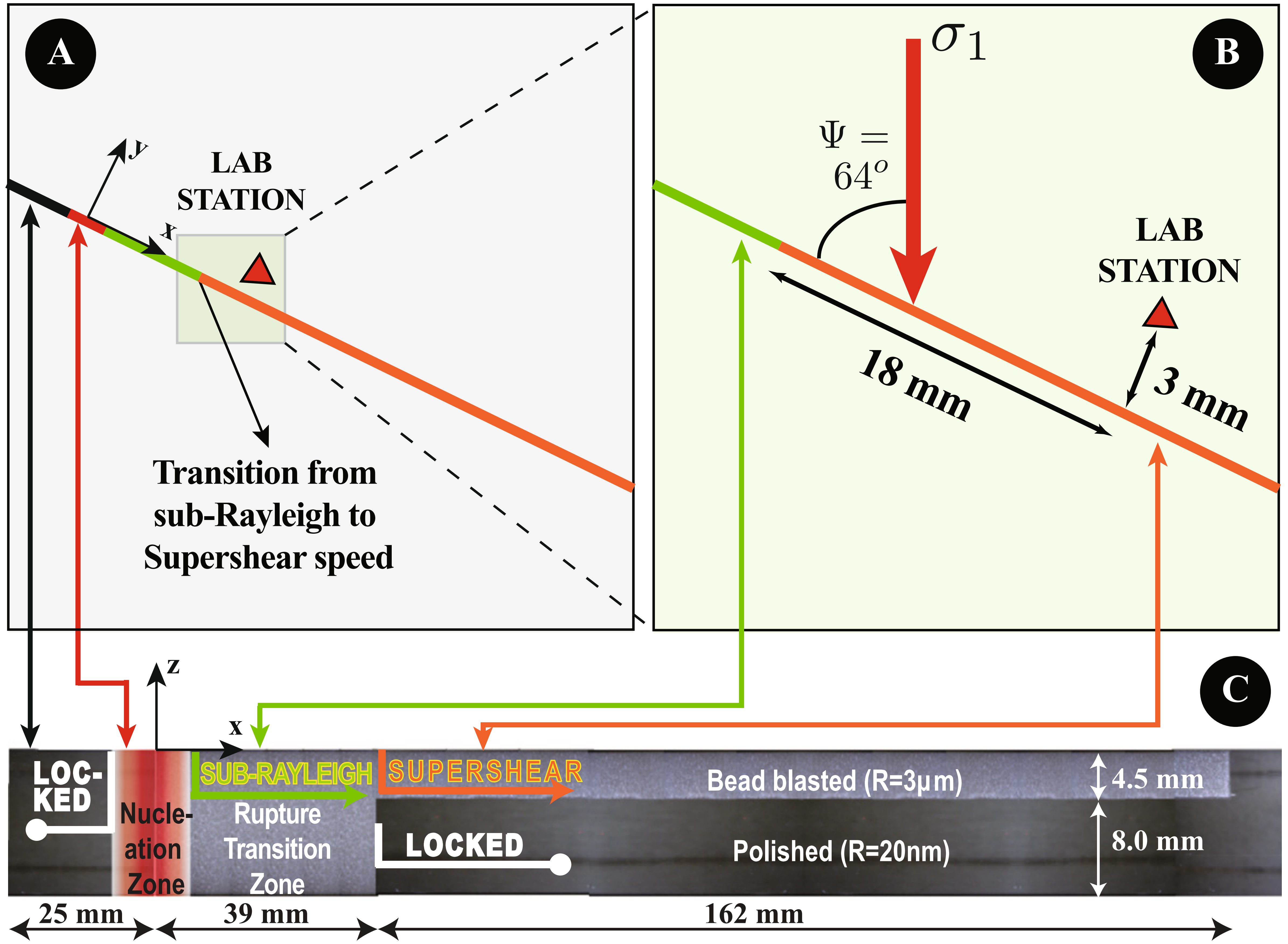
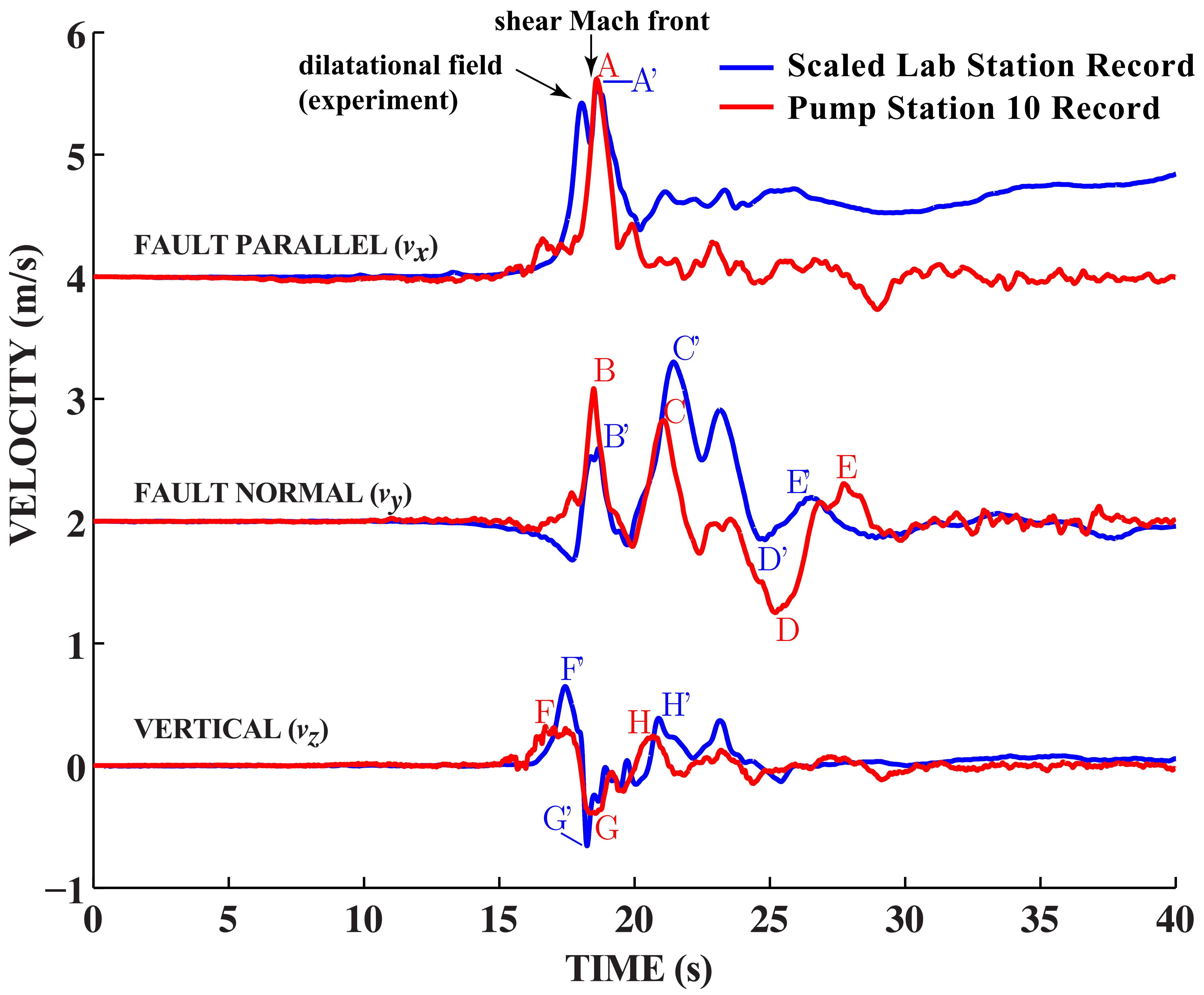




Experiments

Experiments

Mello (2012, PhD Thesis) : Transition to Supershear Rupture Speed

Experiments

Mello (2012, PhD Thesis) : Transition to Supershear Rupture Speed

Experiments

Mello (2012, PhD Thesis) : Transition to Supershear Rupture Speed

- Very Rare Mother-Daughter Transition Observed

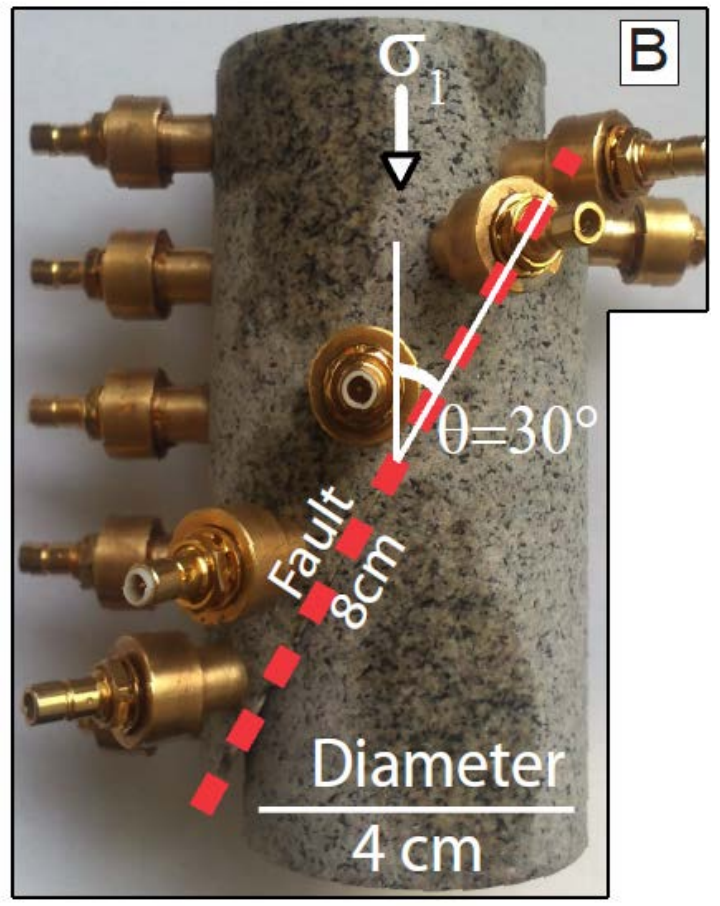
Experiments

Experiments

Passelégue et al. (2013) : Experimental Evidence of Supershear Rupture Speed in Rocks

Experiments

Passelégue et al. (2013) : Experimental Evidence of Supershear Rupture Speed in Rocks



Experiments

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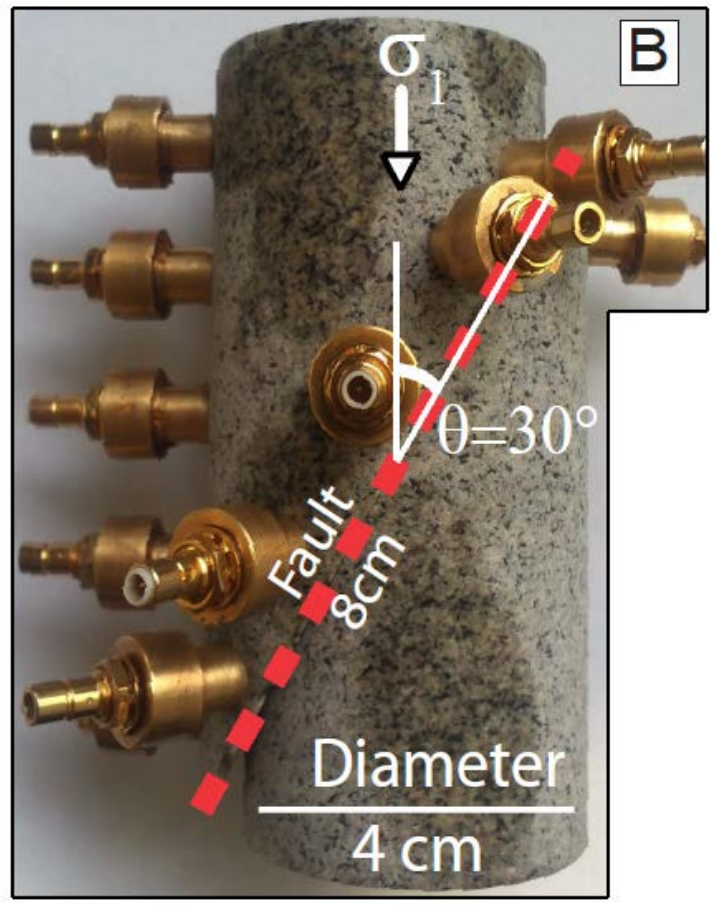

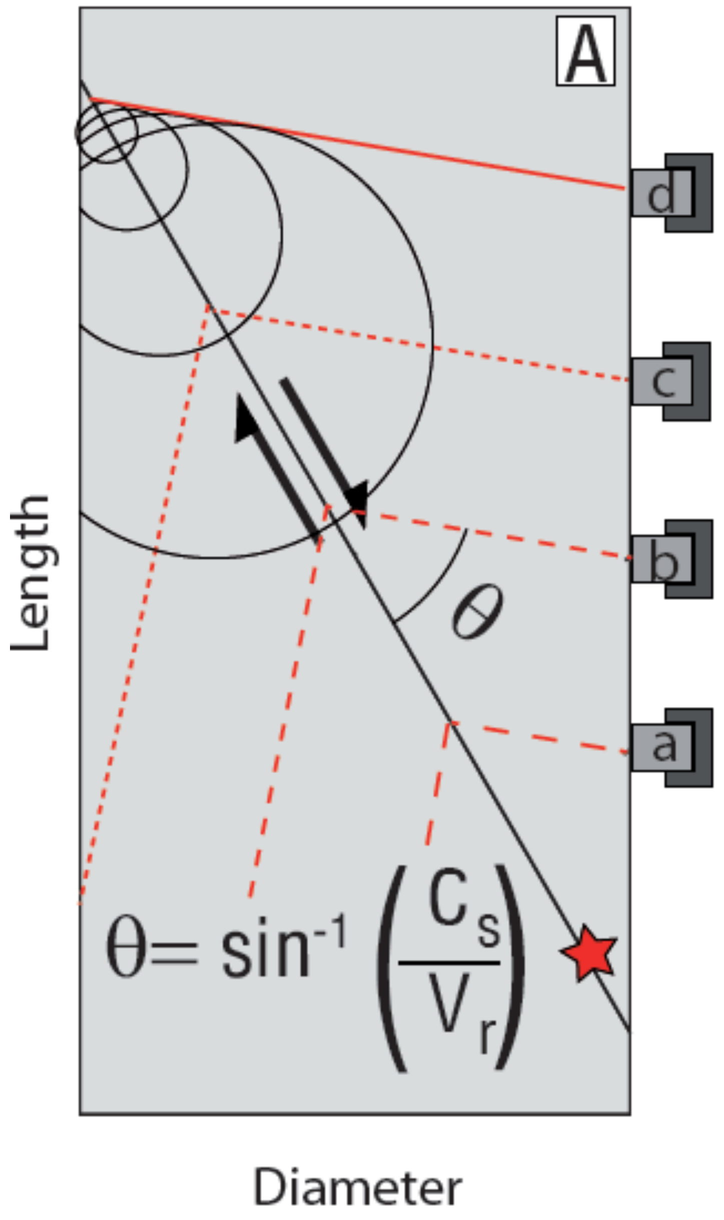

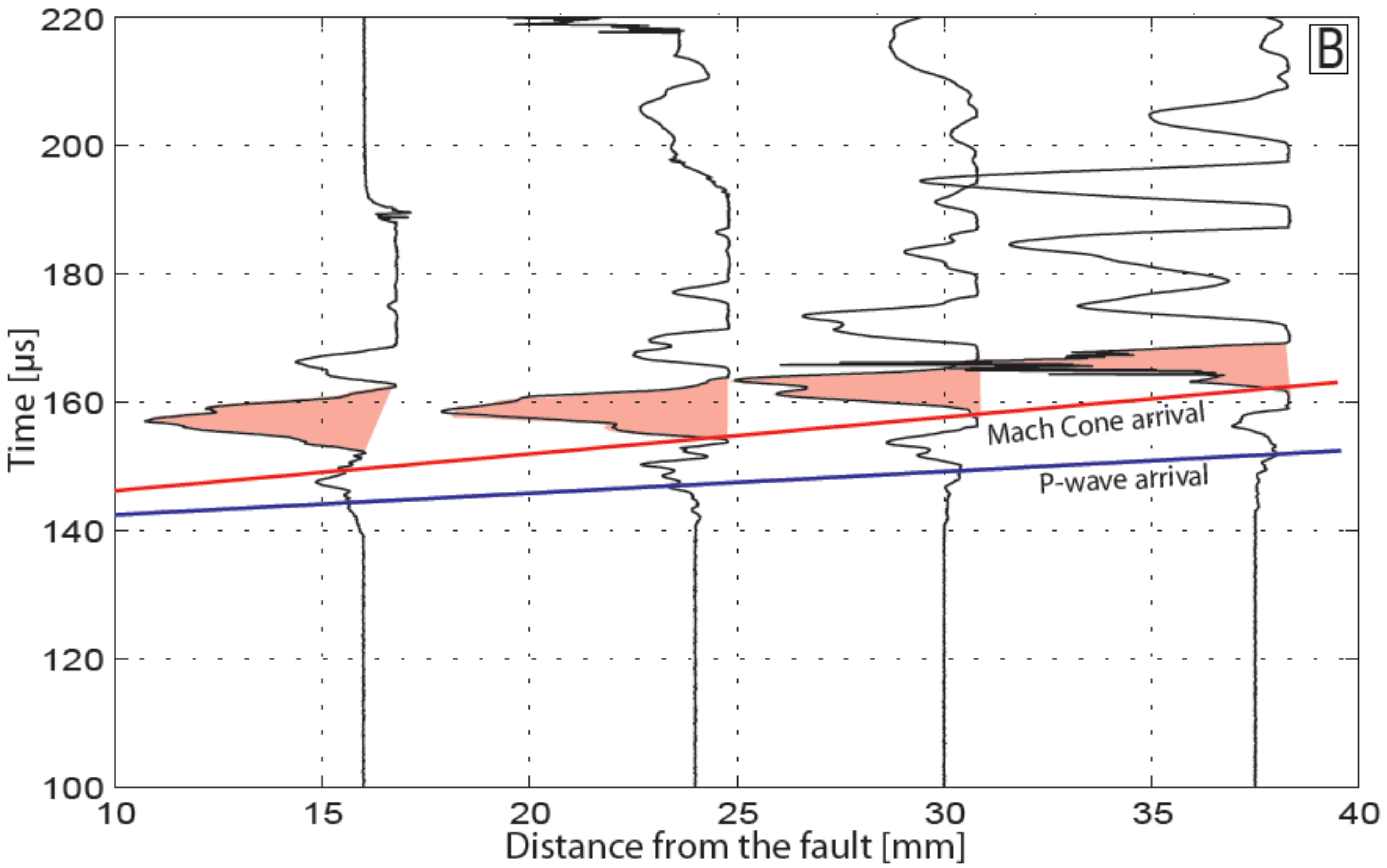

Experiments

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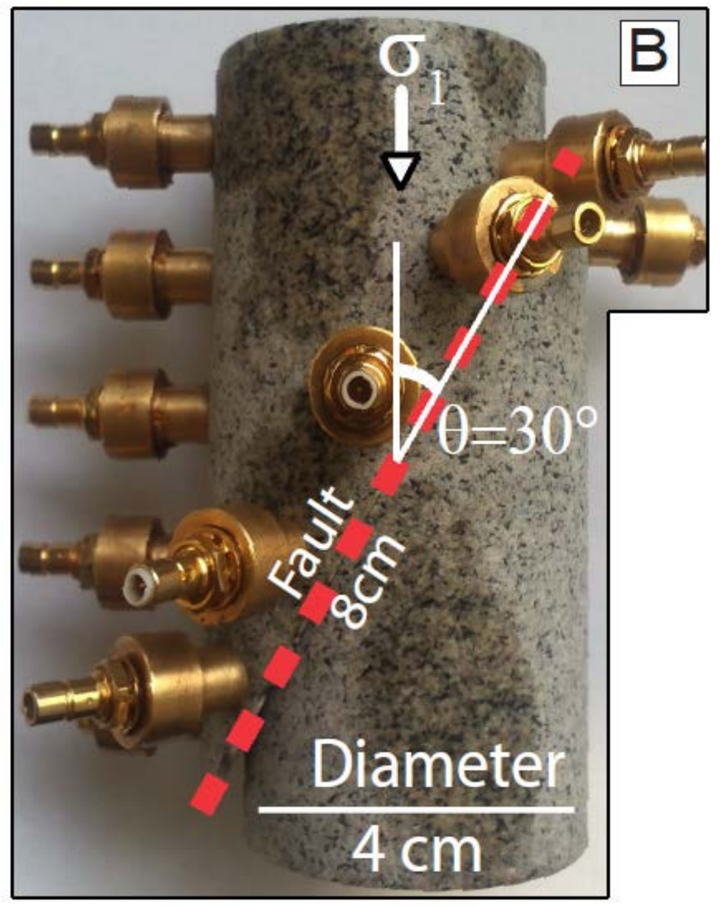

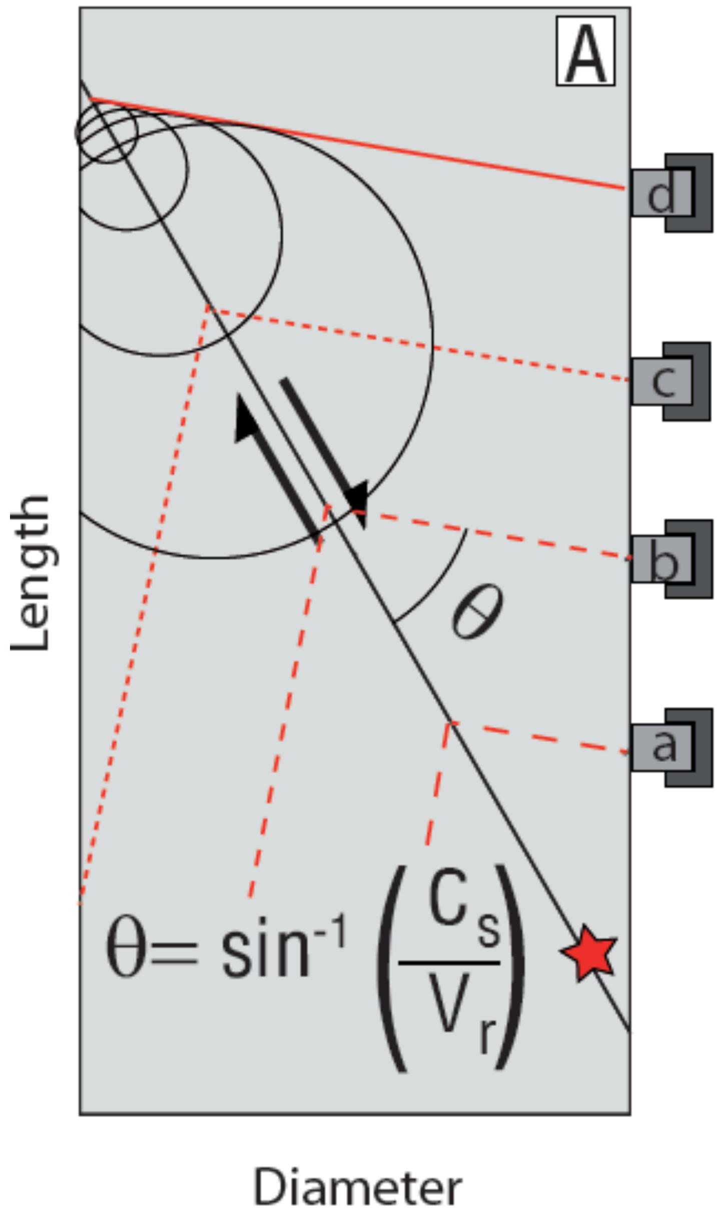

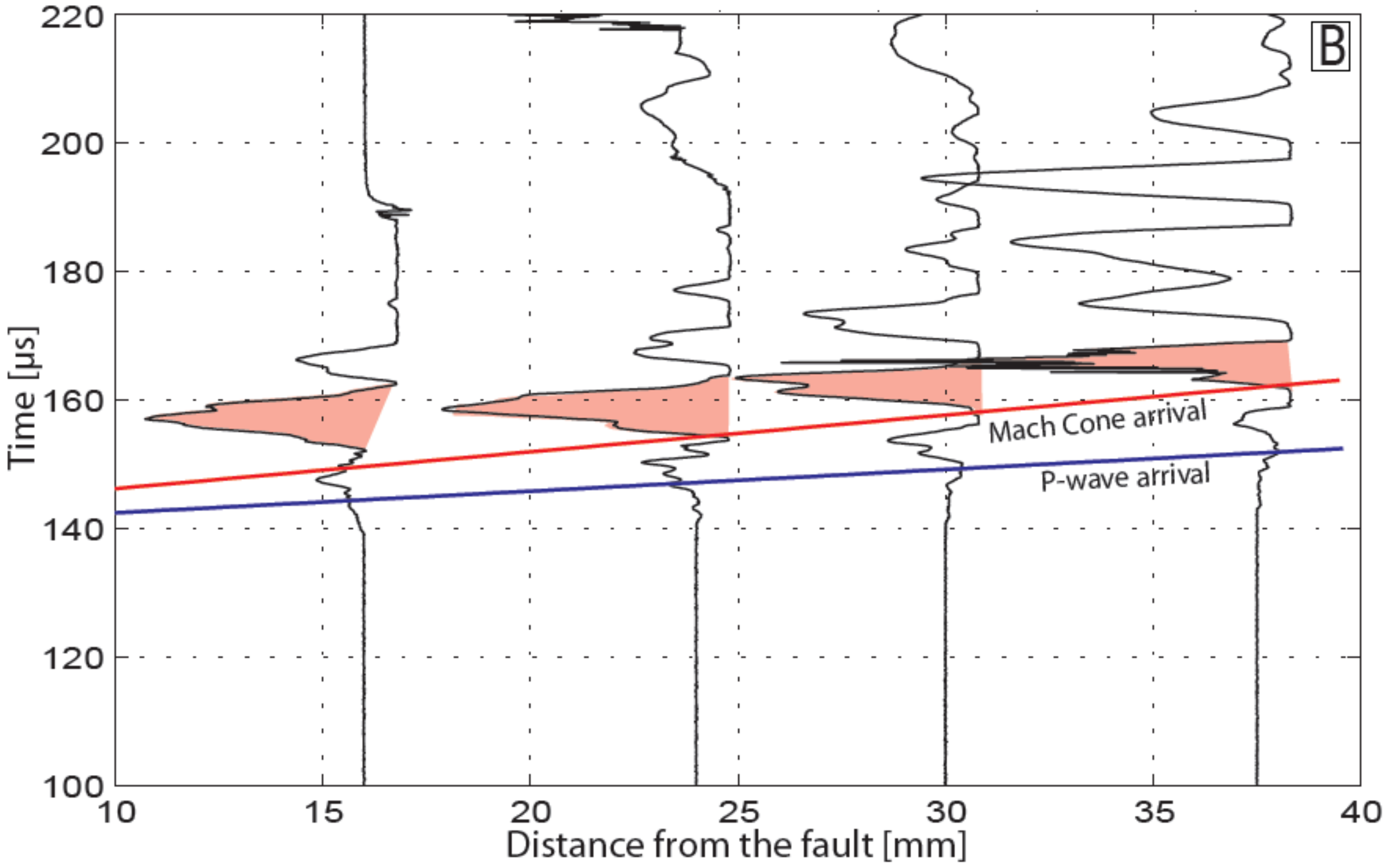

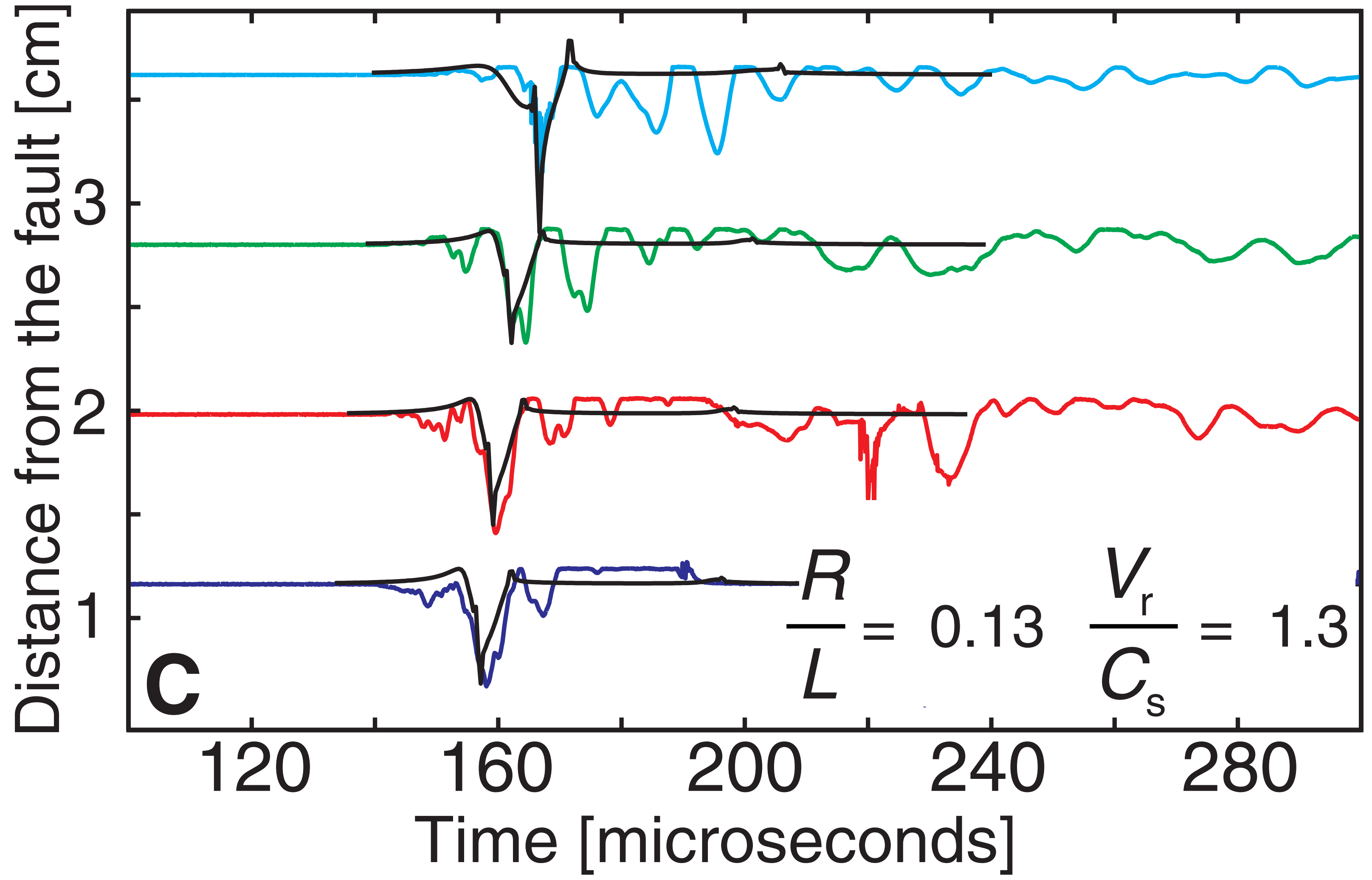

Experiments

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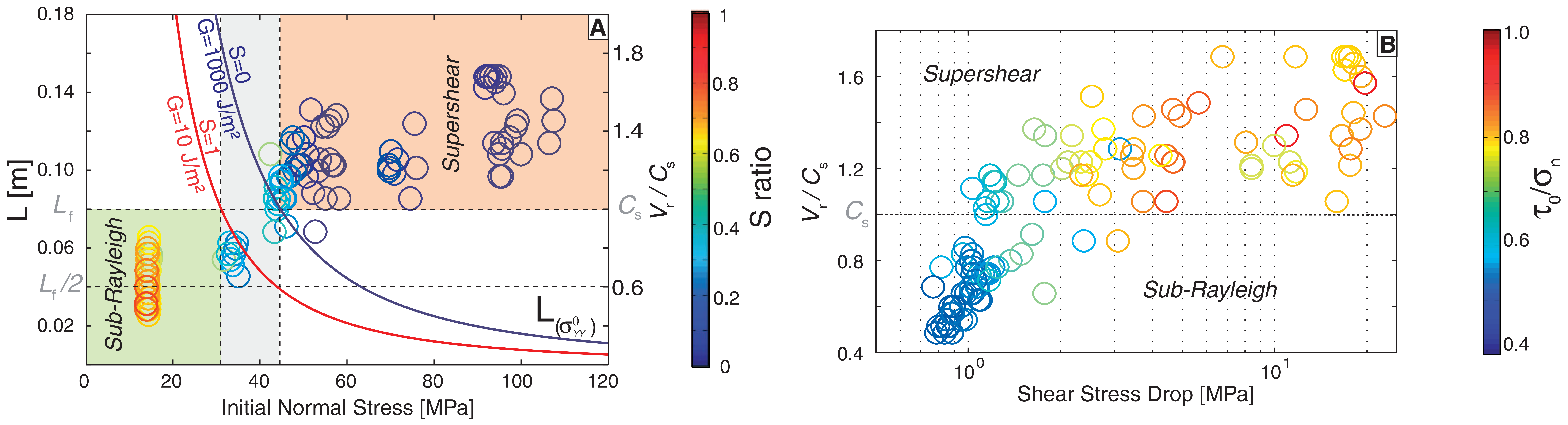
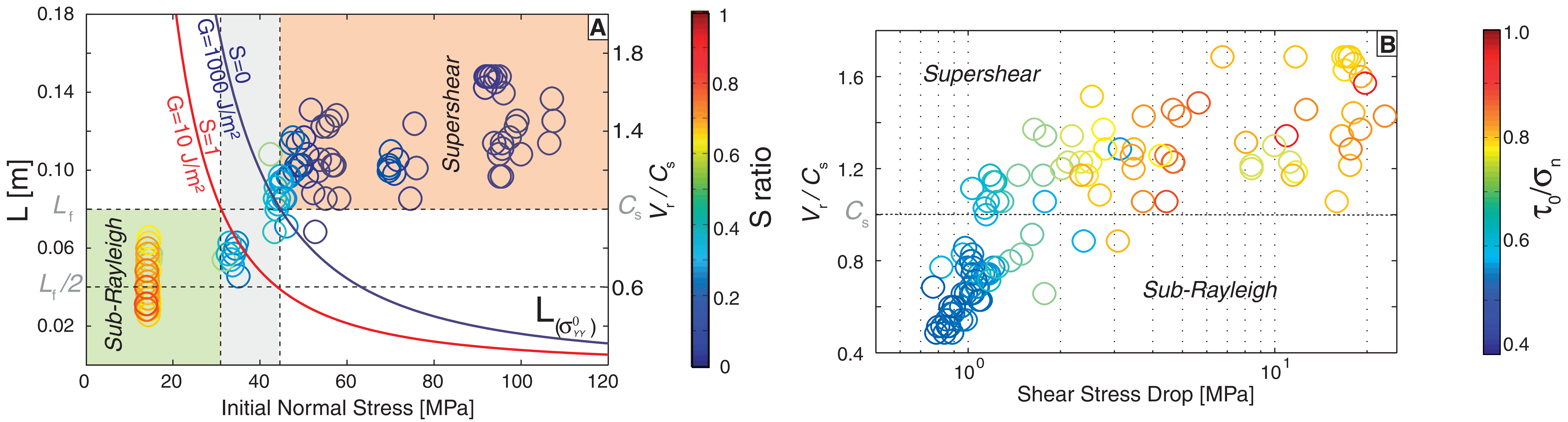


Experiments

Passelégue et al. (2013) : Experimental Evidence of Supershear Rupture Speed in Rocks



- Supershear ruptures possible under crustal conditions and in rocks
- Transition to Supershear speed requires:
  - S < 1.77 (1.19 in 3D) Andrews 1976, Das & Aki 1977, Dunham 2007
  - Fault Length > Transition Length, L

Observations

Supershear earthquakes in the wild

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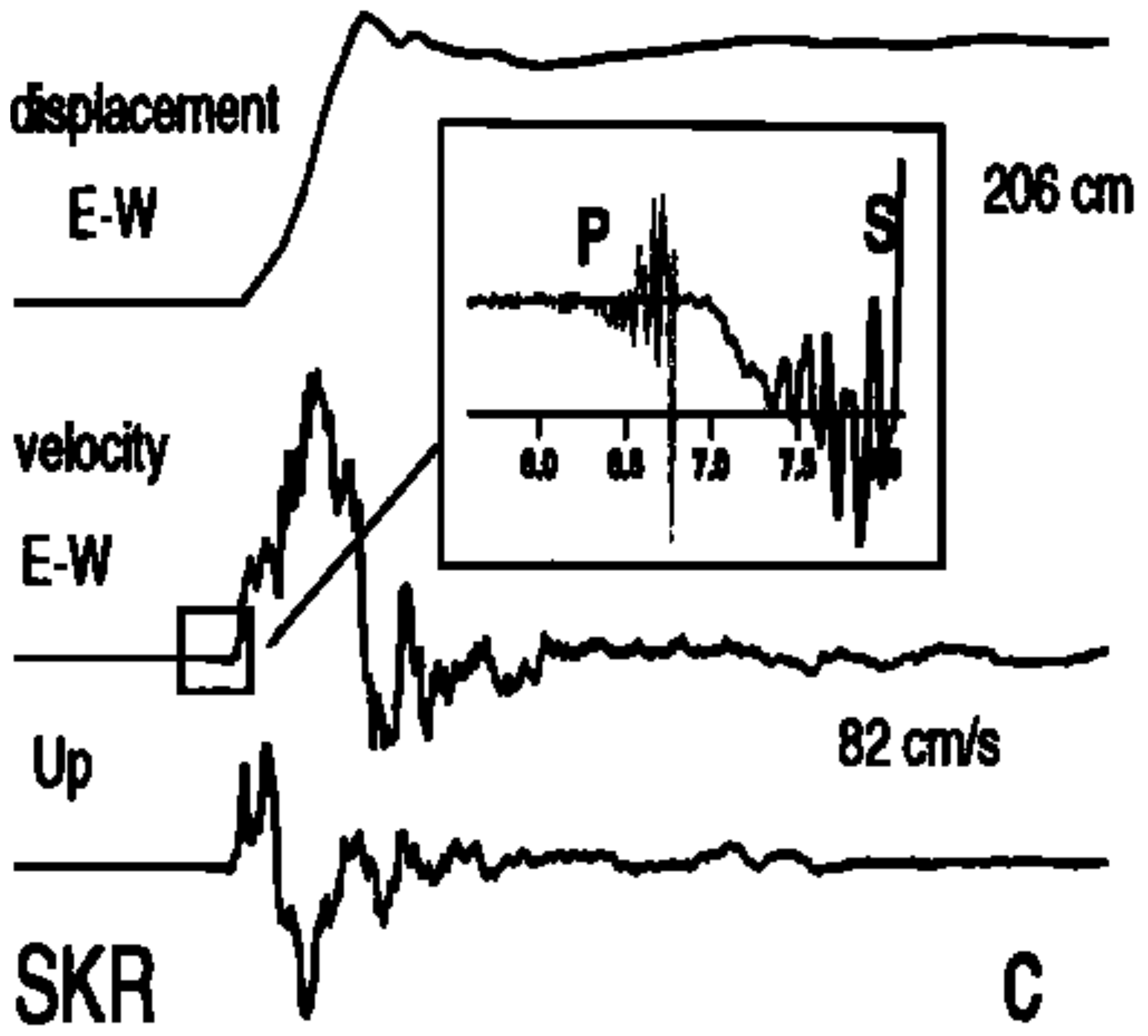

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Jara, Bruhat et al. 2021

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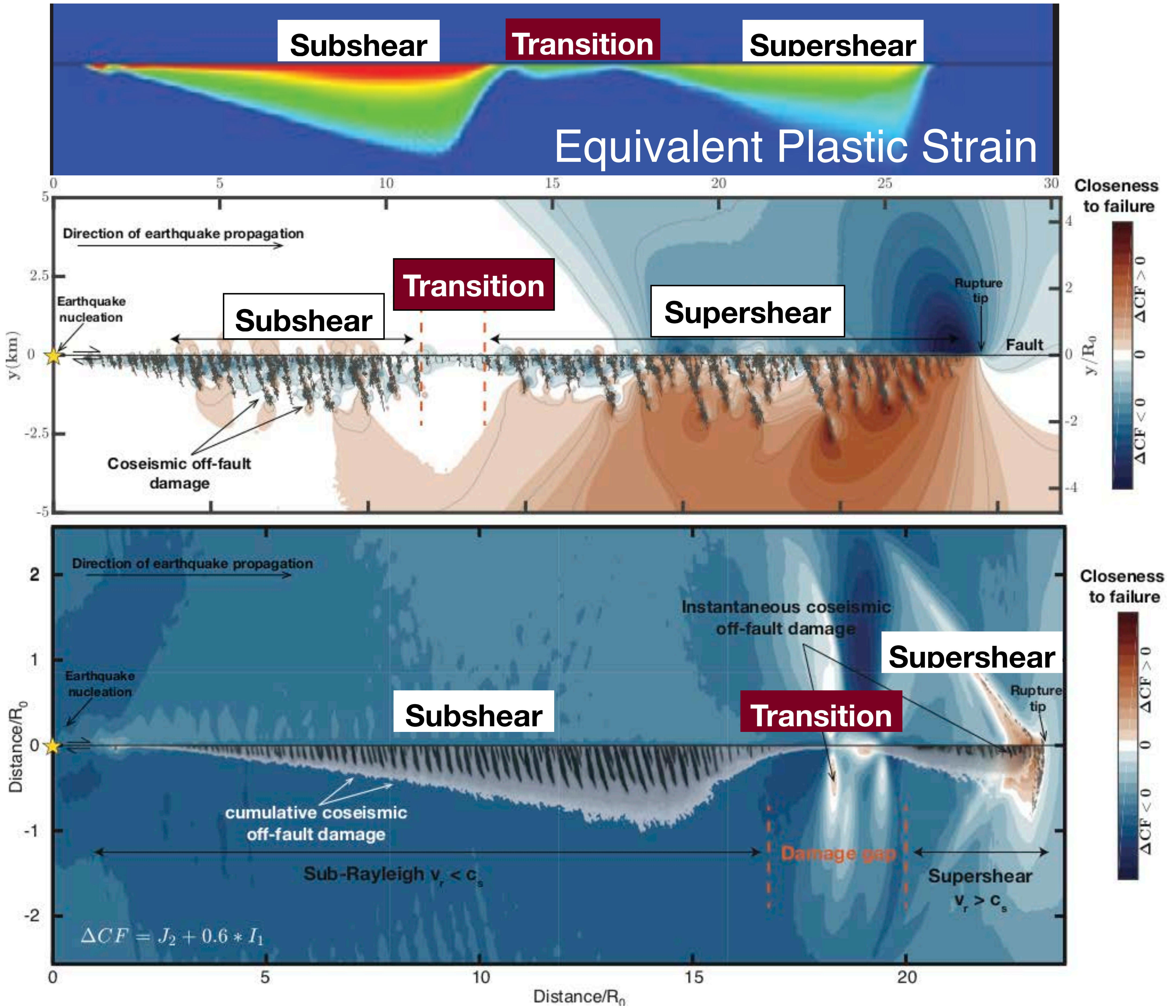

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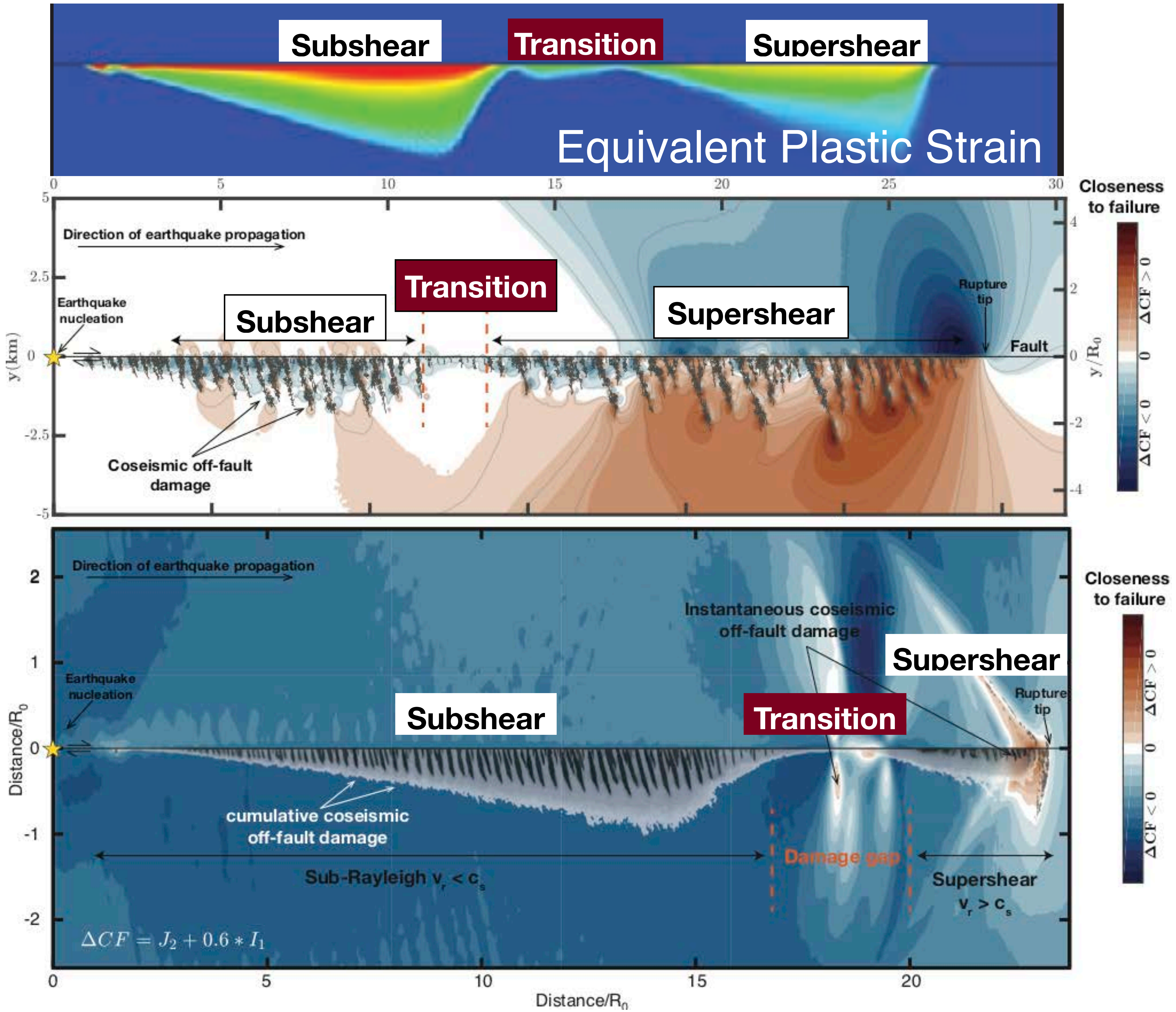

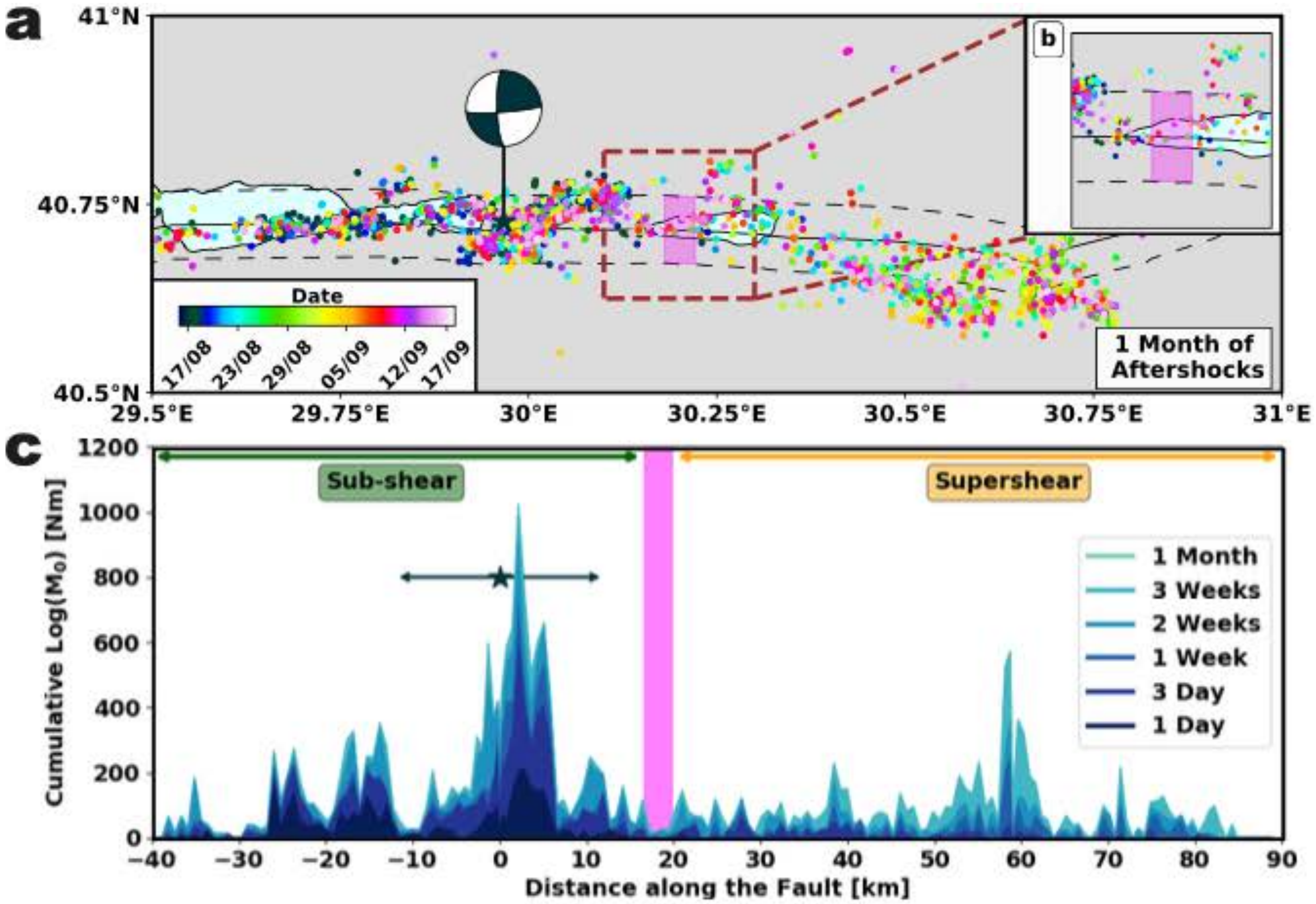

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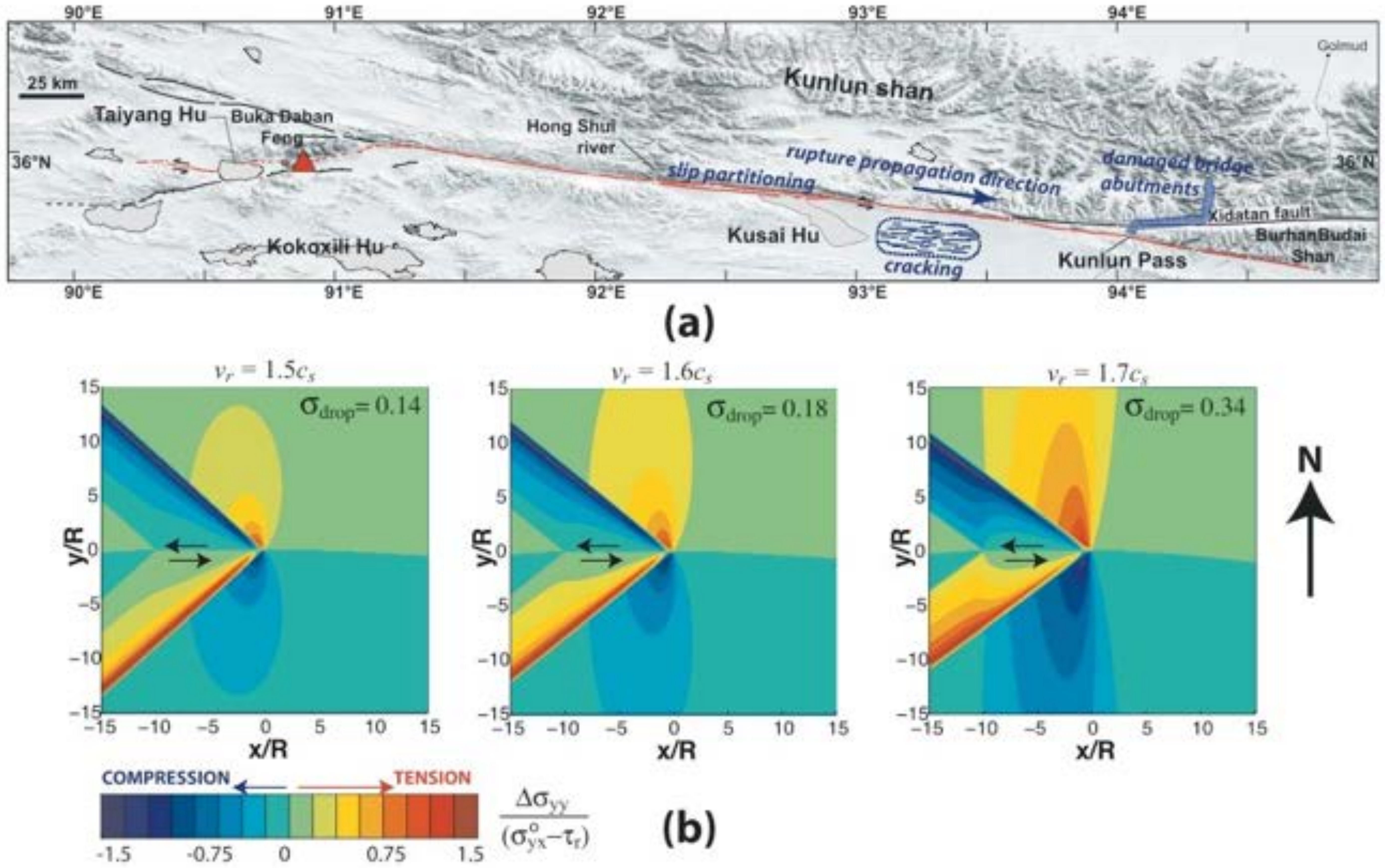

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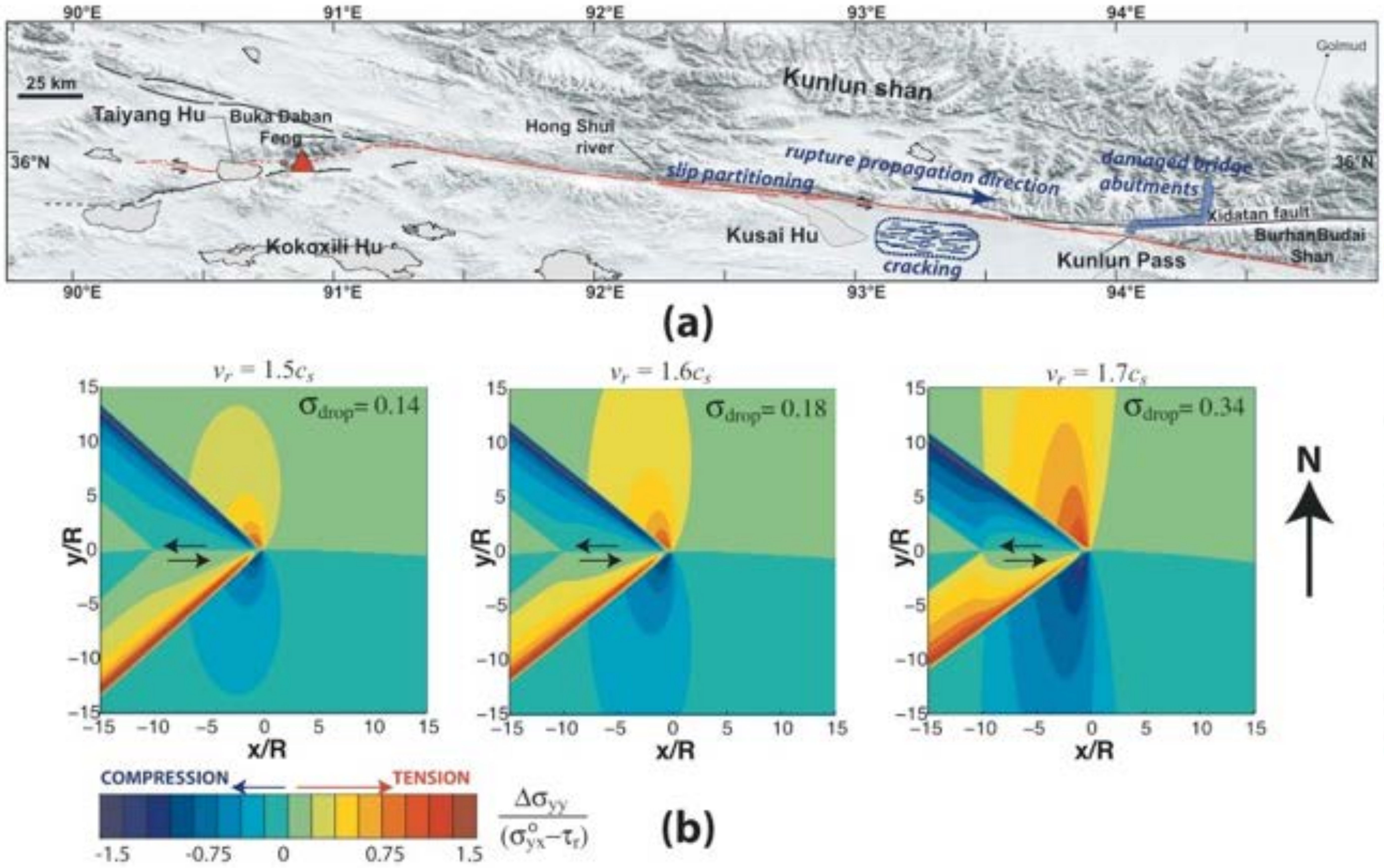

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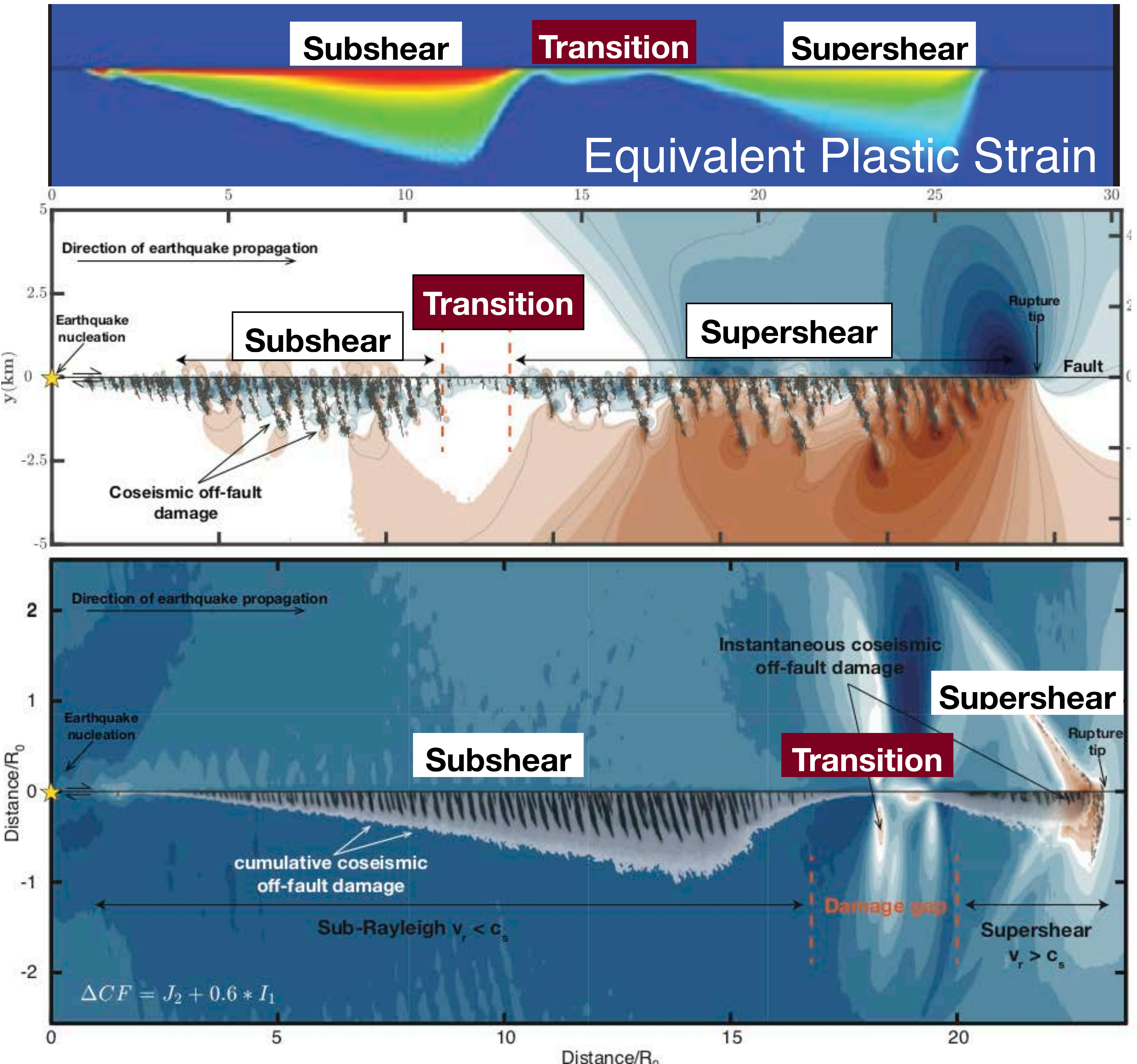

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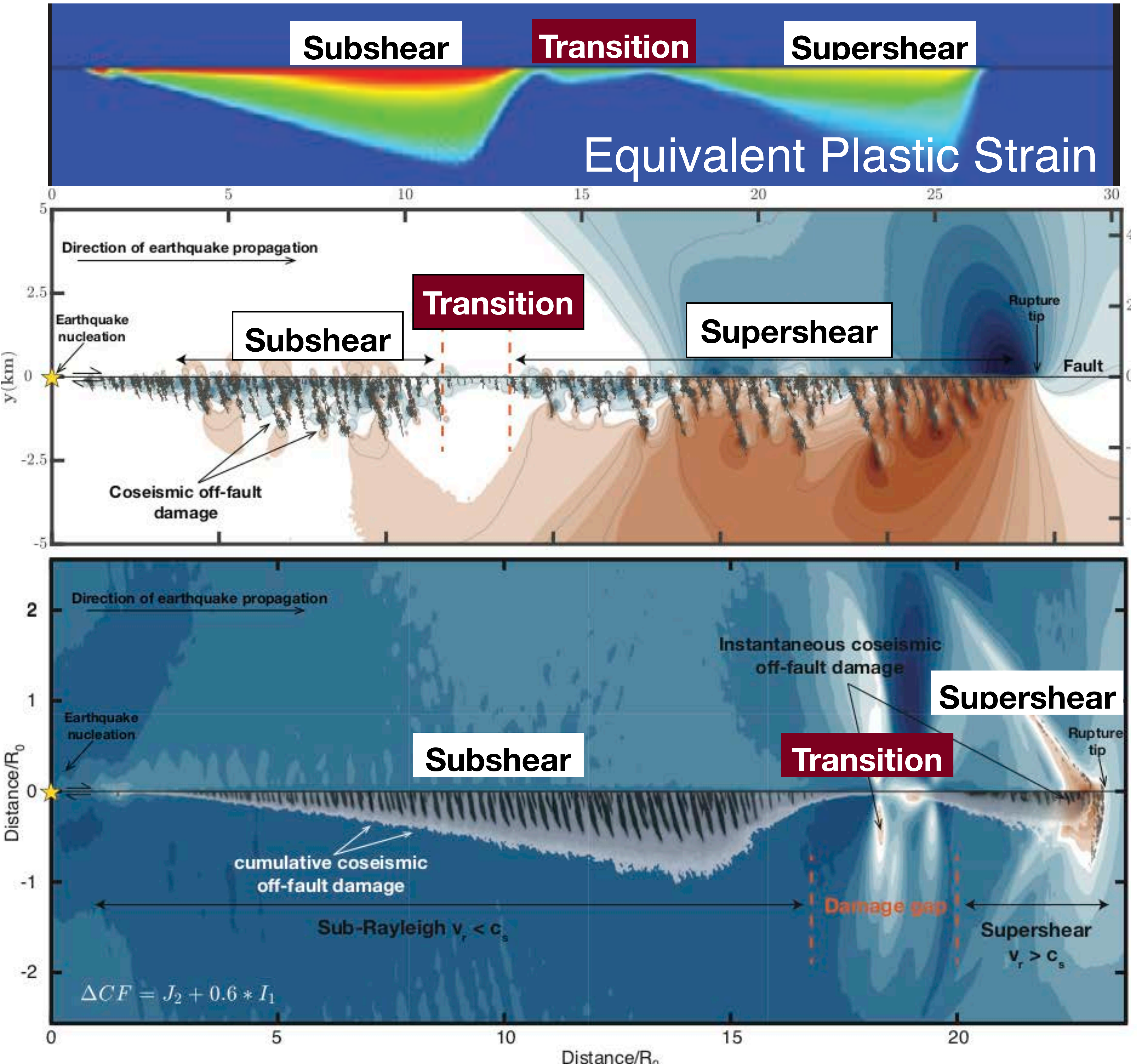

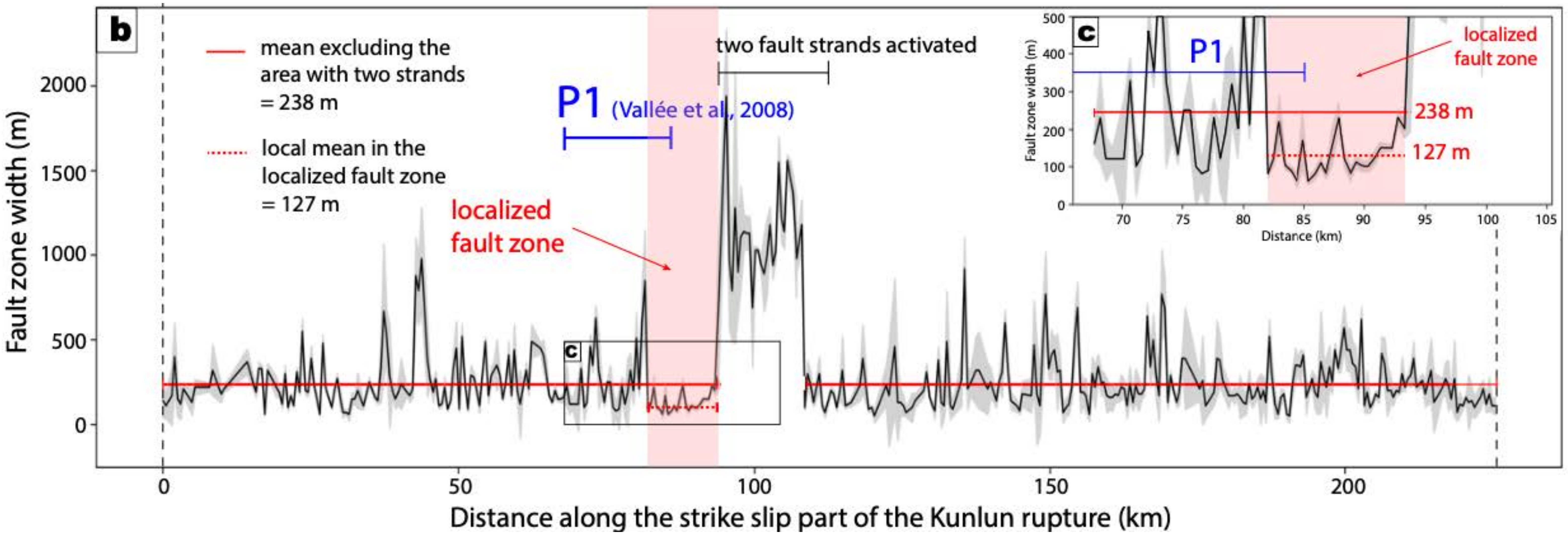

Jara, Bruhat et al. 2021

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Mello, Bhat et al. 2014

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Dunham & Archuleta (2004) Ellsworth et al. (2004) & others : 2002 M_w 7.8 Denali earthquake

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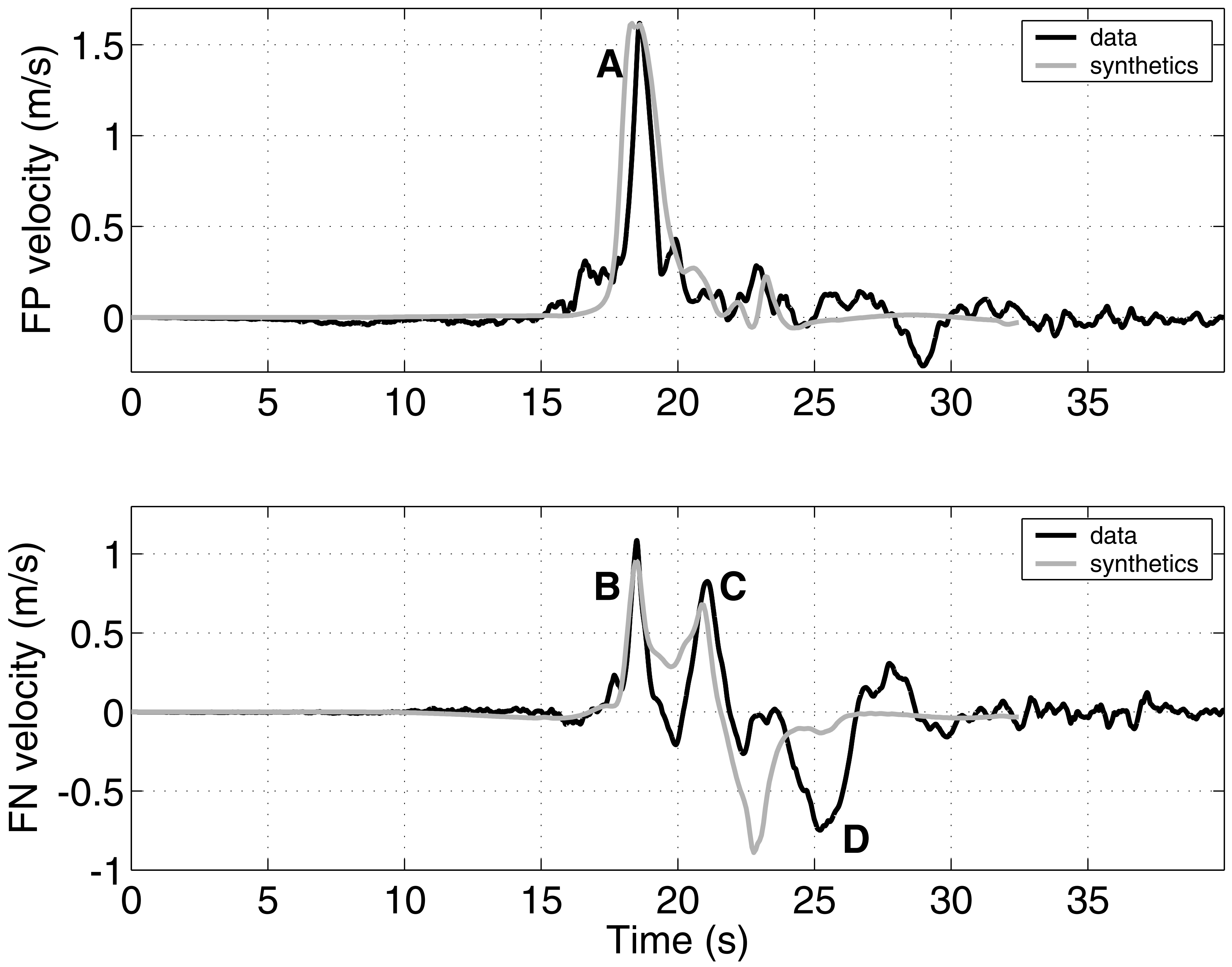

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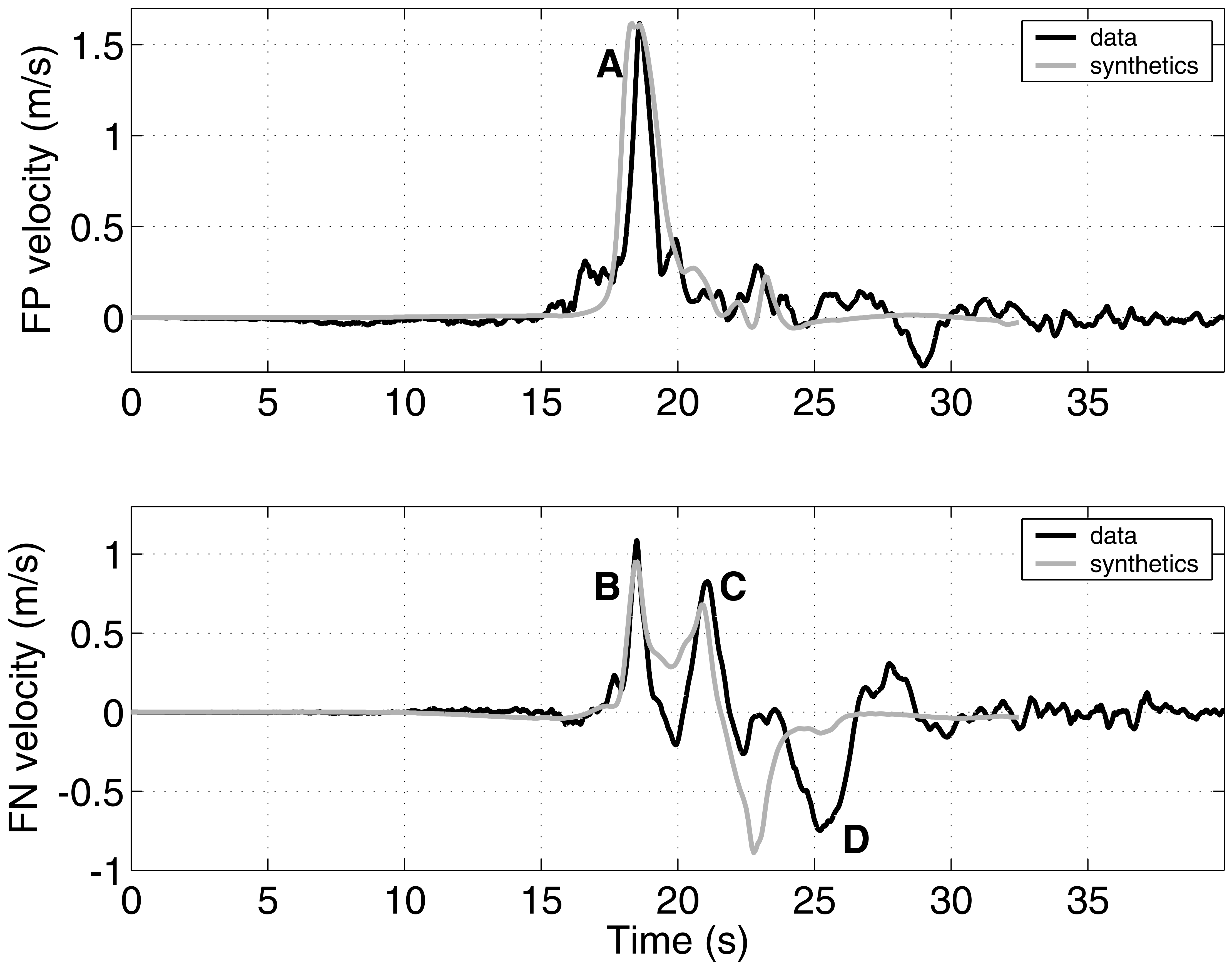

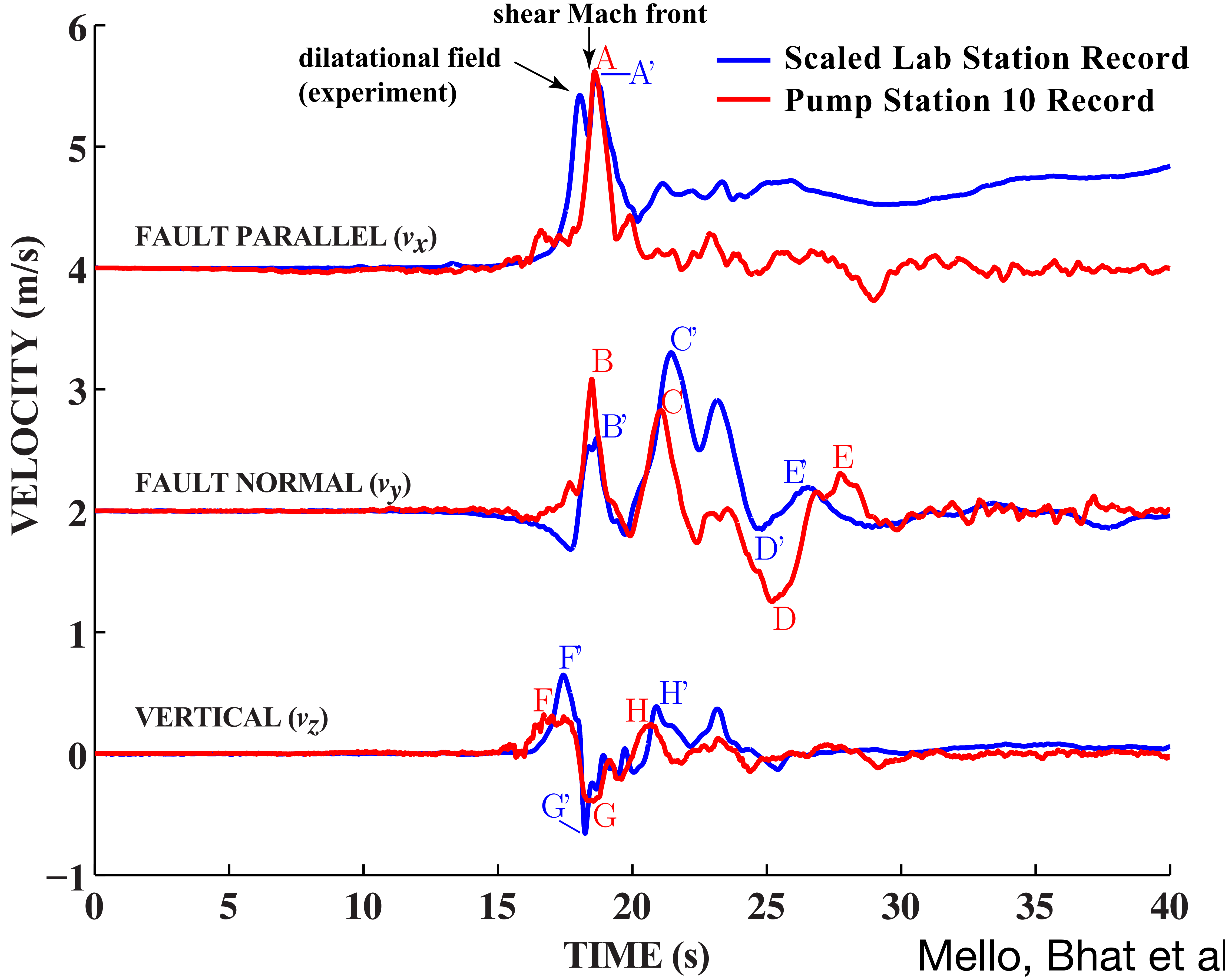

Mello, Bhat et al. 2014

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Supershear earthquakes in the wild

Yue et al (2013): 2013 M_w 7.5 Craig, Alaska earthquake

Zhan et al (2014) : 2013 M_w 6.7 Okhotsk, Kamtchatka earthquake. *Deepest and fastest earthquake recorded*

Bao et al (2019) Socquet et al (2019) Amlani et al (2021): 2018 M_w 7.5 Palu, Sulawesi earthquake

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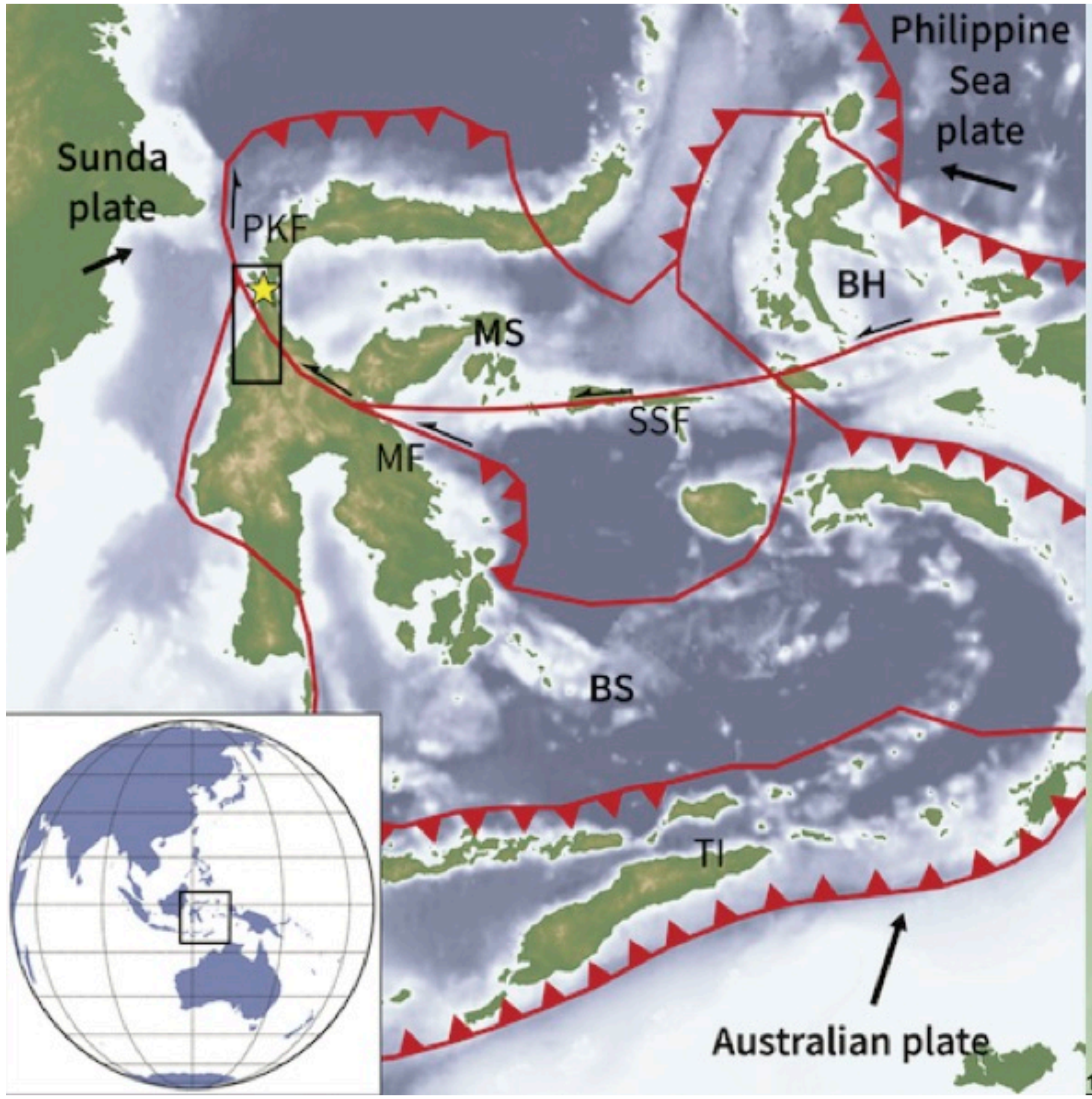

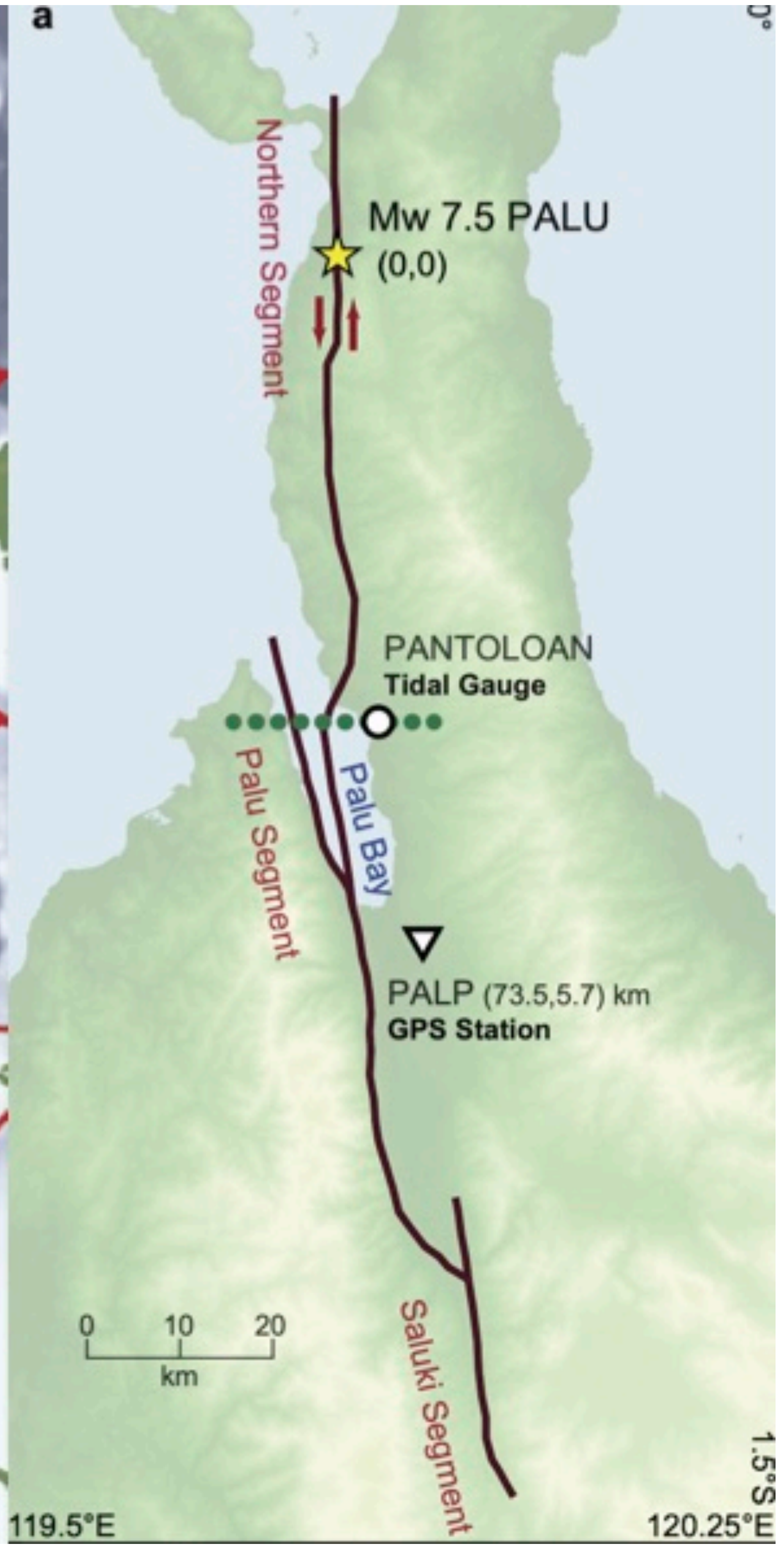

Ulrich et al. 2019
Amlani et al. 2021

Observations

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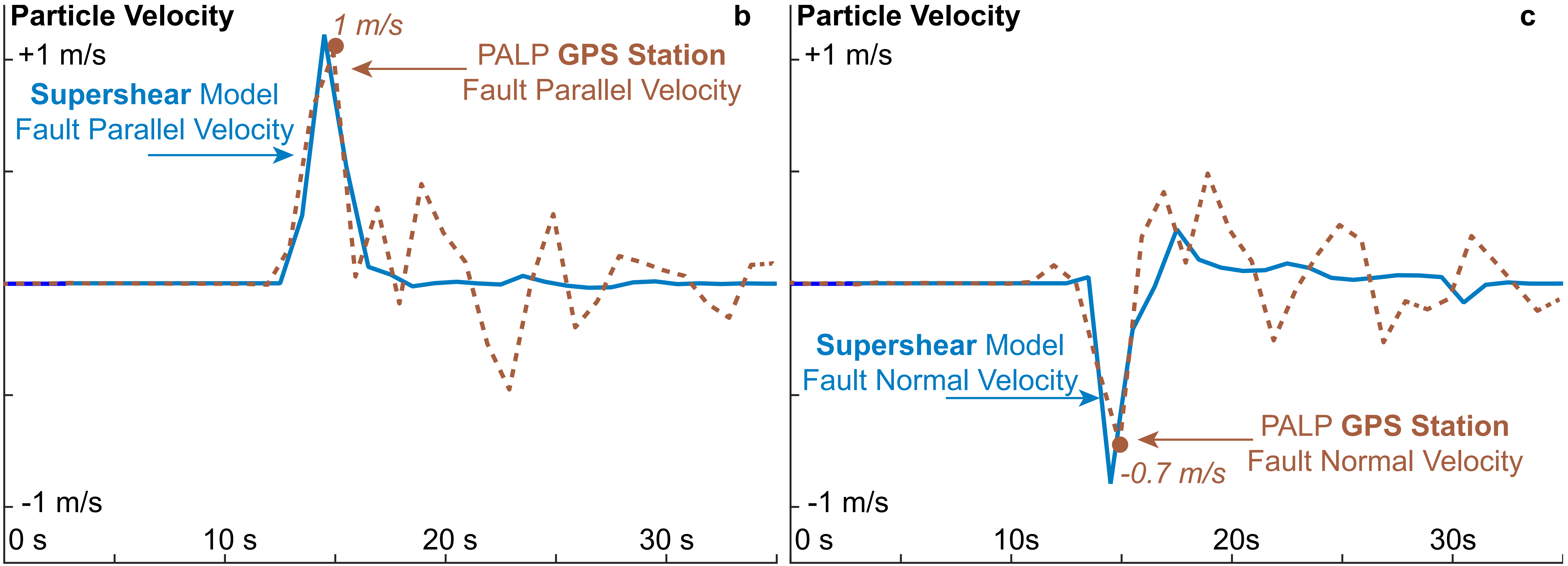
Amlani et al. (2021) : First observation of Supershear Earthquake on a GPS station



Dynamic shear ruptures, including earthquakes, can attain supershear speeds

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- **At the location of transition from sub to supershear speeds, severe Lorentz-like contraction of the stress field should lead to minimal off-fault damage.**

Education

Harvard University, USA	Ph. D.	Mechanical Sciences	2007/06
Harvard University, USA	M. S.	Engineering Sciences	2002/06
NITK, India	B. E.	Civil Engineering	2001/06

Post Doctoral Work

University of Southern California, USA	2010/03 ▶ 2011/12	Asst. Professor (Research)
University of Southern California, USA	2007/11 ▶ 2010/03	Post Doctoral Fellow
California Institute of Technology, USA	2007/11 ▶ 2010/03	Visitor in Aeronautics

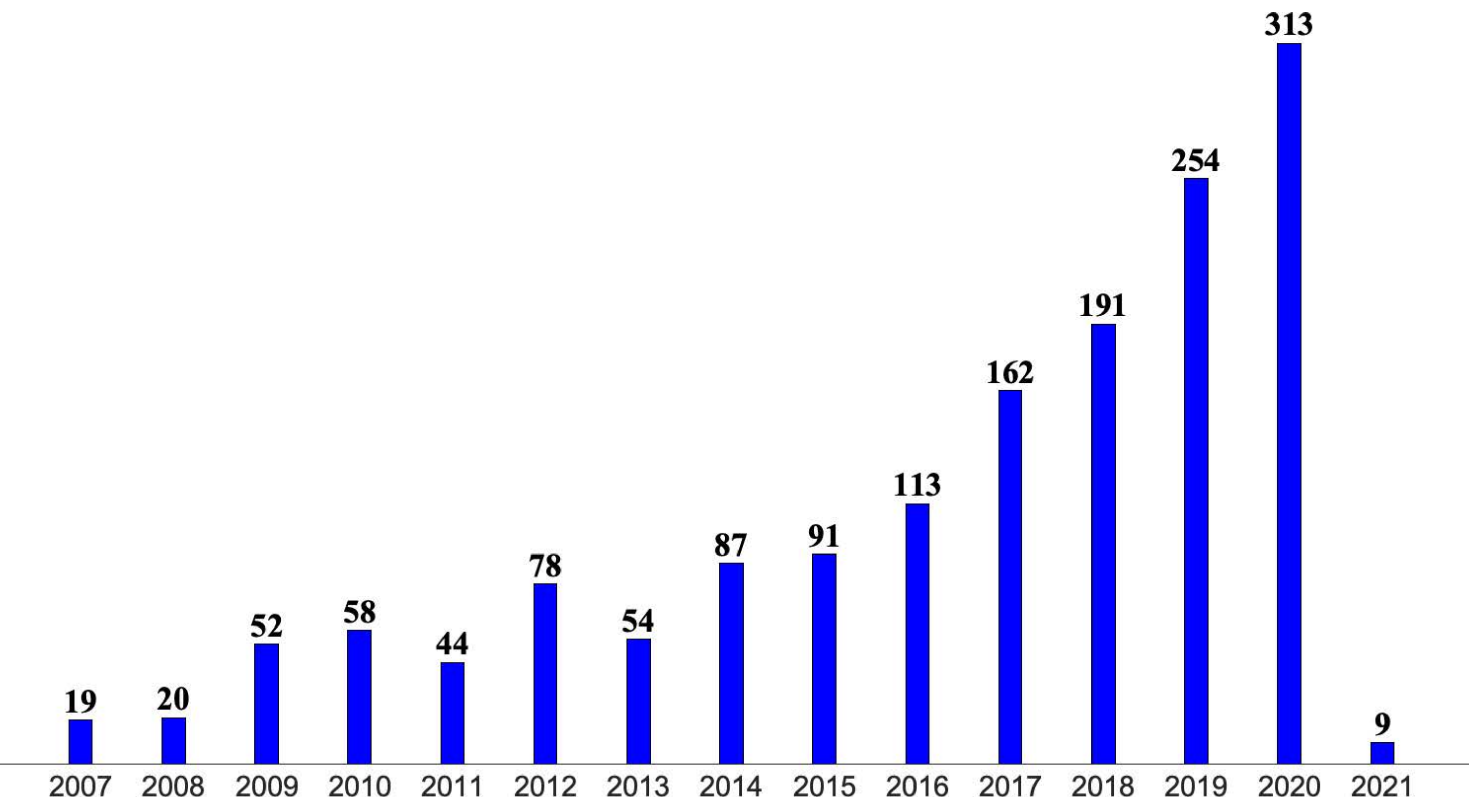
Past Employment

Institut de Physique du Globe de Paris, France	2012/01 ▶ 2016/05	CNRS Research Scientist

Current Position

École Normale Supérieure, France	2016/05 ▶ Present	CNRS Research Scientist
California Institute of Technology, USA	2018/12 ▶ Present	Visiting Professor in Aeronautics

Research Funding & Publications

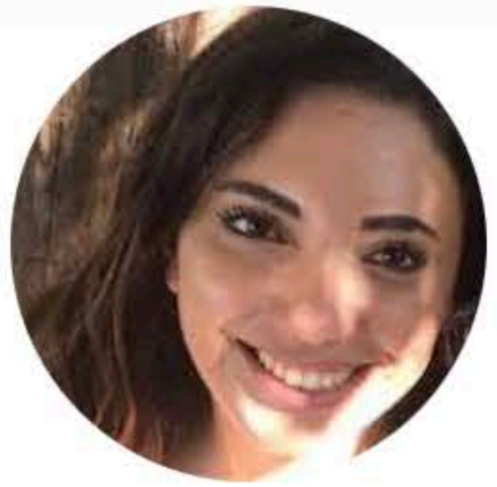
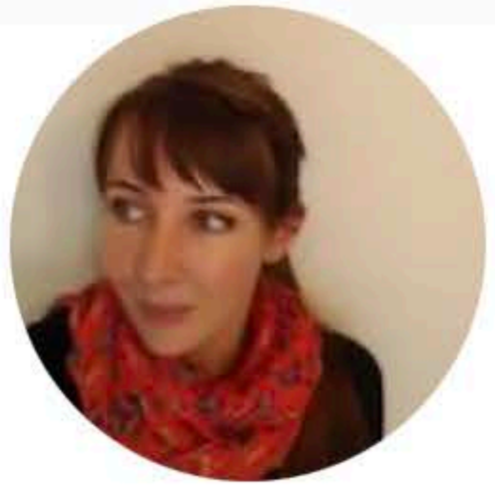


- Over 45 publications in peer reviewed international journals including Nature, Nature Communications and Science
- Over 30 publications since joining CNRS
- 1 Book Chapter
- 2 Edited Volumes

	Year	Country	Funding Agency	Status
1	2008	USA	NSF	Accept
2	2008	USA	NSF	Accept
3	2010	USA	NNSA	Accept
4	2011	USA	SCEC	Accept
5	2011	USA	NSF	Reject
6	2012	FRANCE	ANR	Reject
7	2013	FRANCE	ANR	Reject
8	2013	FRANCE	Paris - EMERGENCE	Reject
9	2013	EU	ERC Starting Grant	Reject
10	2014	FRANCE	ANR	Reject
11	2013	EU	ERC Starting Grant	Reject
12	2014	FRANCE	Paris - EMERGENCE	Reject
13	2014	FRANCE	Université Sorbonne Paris Cité	Reject
14	2015	FRANCE	ANR	Reject
15	2015	FRANCE	Paris - EMERGENCE	Reject
16	2016	FRANCE	ANR	Reject
17	2016	FRANCE	INSU	Accept
18	2017	FRANCE	Simone and Cino Del Duca Foundation	Reject
19	2017	FRANCE	INSU Mi-Lourds	Reject
20	2017	FRANCE	ENS-Action Incitatives	Accept
21	2017	FRANCE	Thomas Jefferson Fund	Reject
22	2018	FRANCE	Thomas Jefferson Fund	Reject
23	2019	EU	ERC Consolidator Grant	Accept
24	2019	FRANCE	INSU	Reject


Lucile Bruhat

Ekeabino Momoh

Carlos D. Villafuerete

Michelle Almakari

Marion Y. Thomas

Lisa Gordeliy

Claudia Hulbert

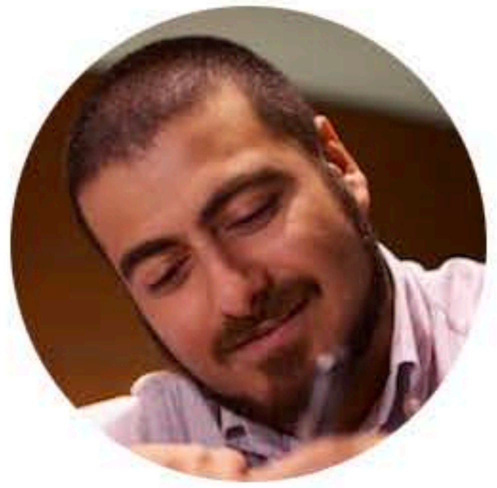
Joseph M. Flores Cuba

Augustin Thomas

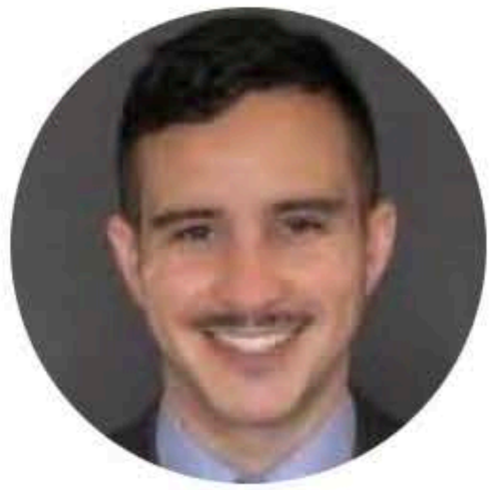
Jinhui Cheng

Michael Mello

Jonathan Mihaly

François X. Passelègue

Vahe Gabuchian

Pierre Romanet

Kurama Okubo

Marshall A. Rogers-Martinez

Samson Marty

Sonia Fliss

Marion Olives

Aurélie Baudet

Thibaut Perol

Victor Barolle

Eleni Kolokytha

Luc Illien

Nicolas Mercury

Philippe Danré

Hugo Lestrelin

Roxanne Ferry

Scientific Contributions

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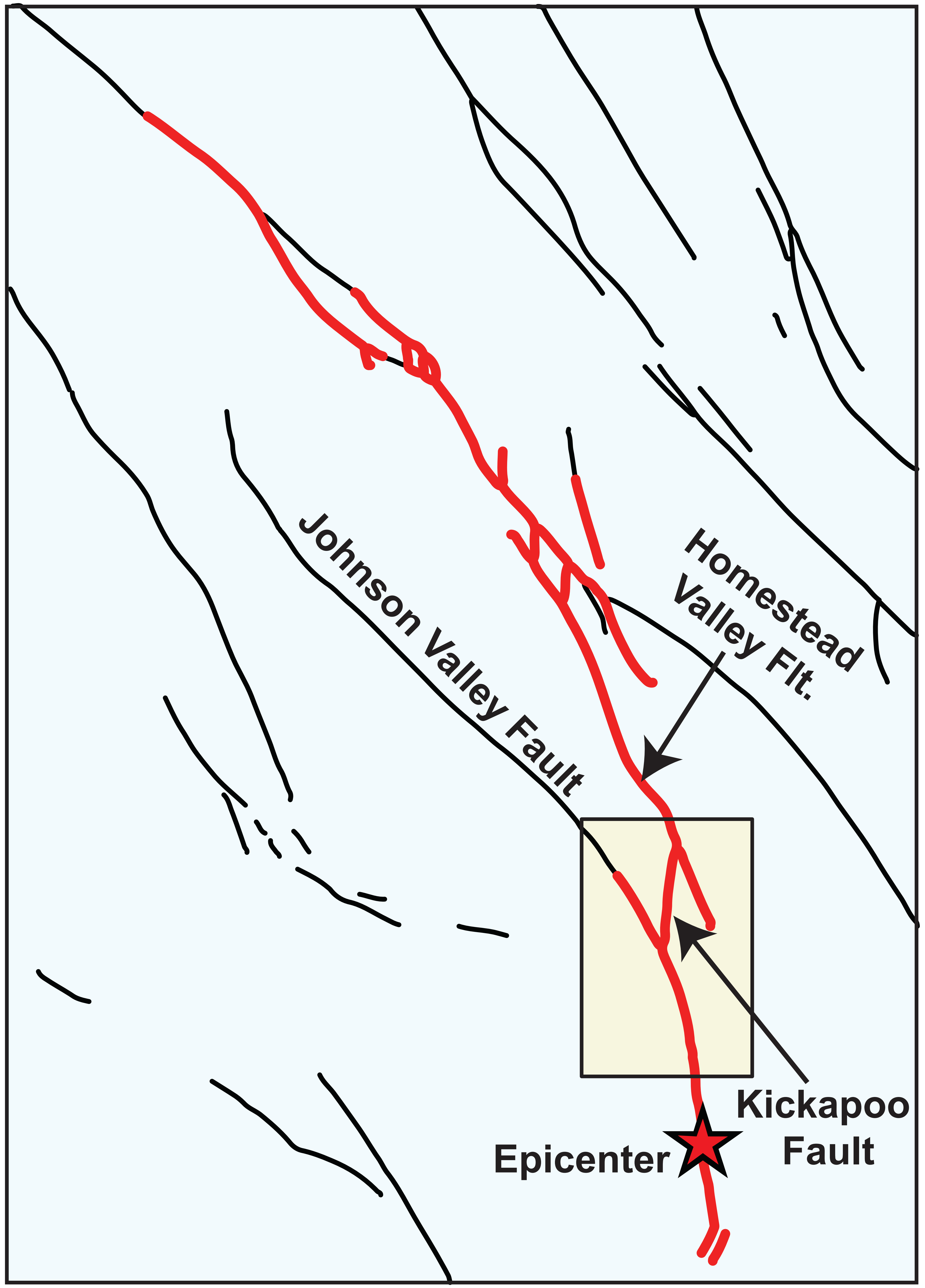

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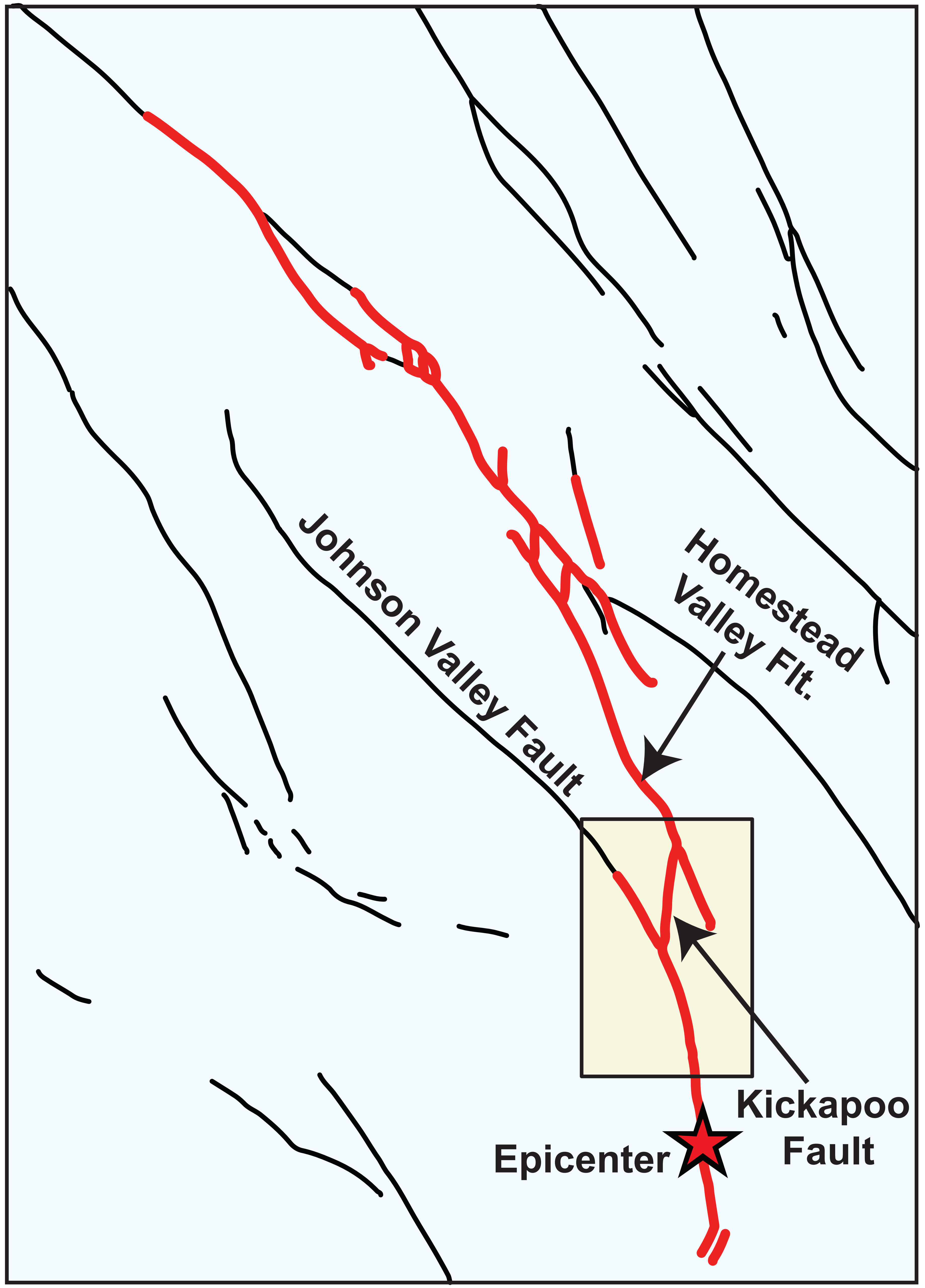

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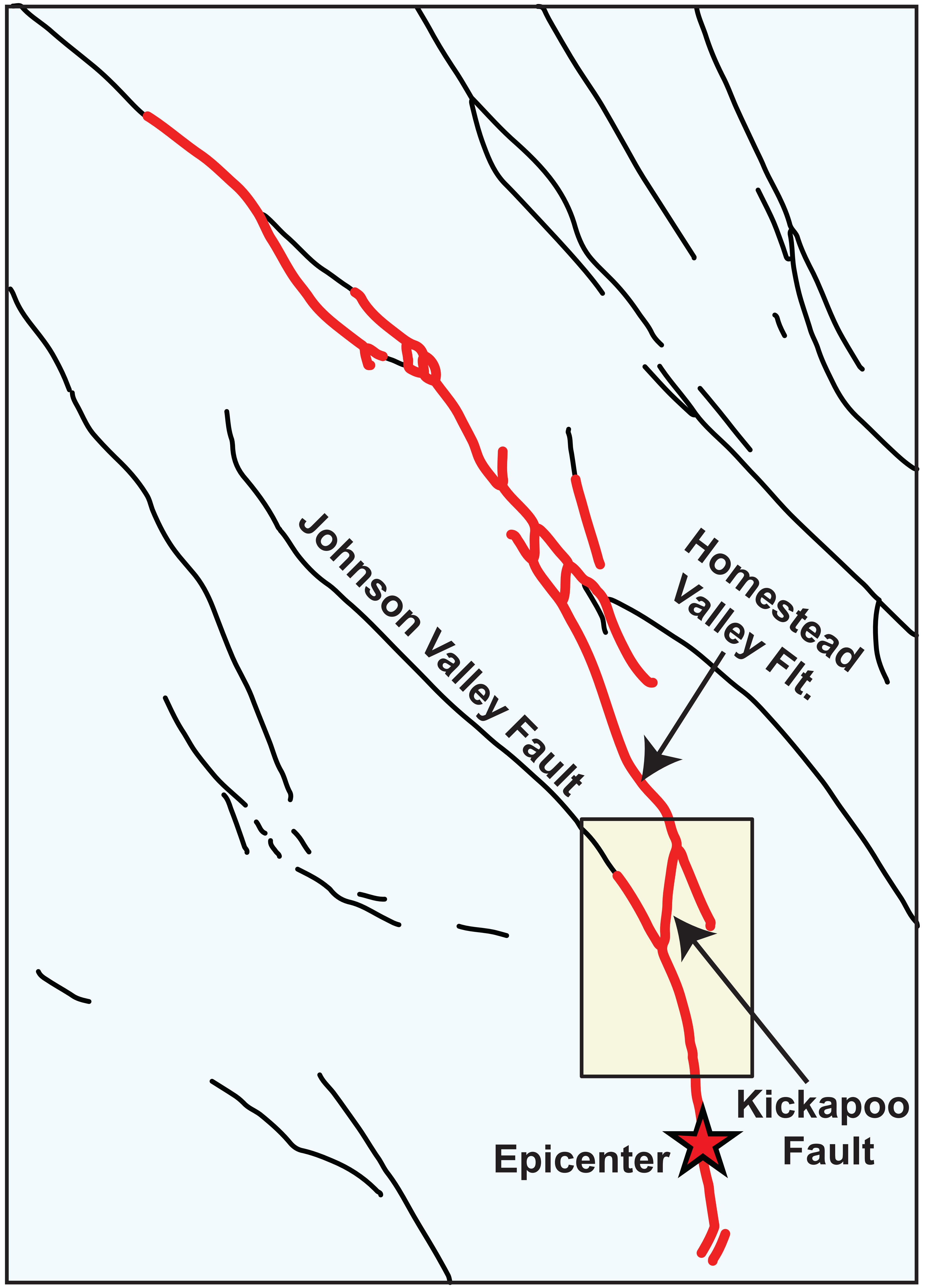

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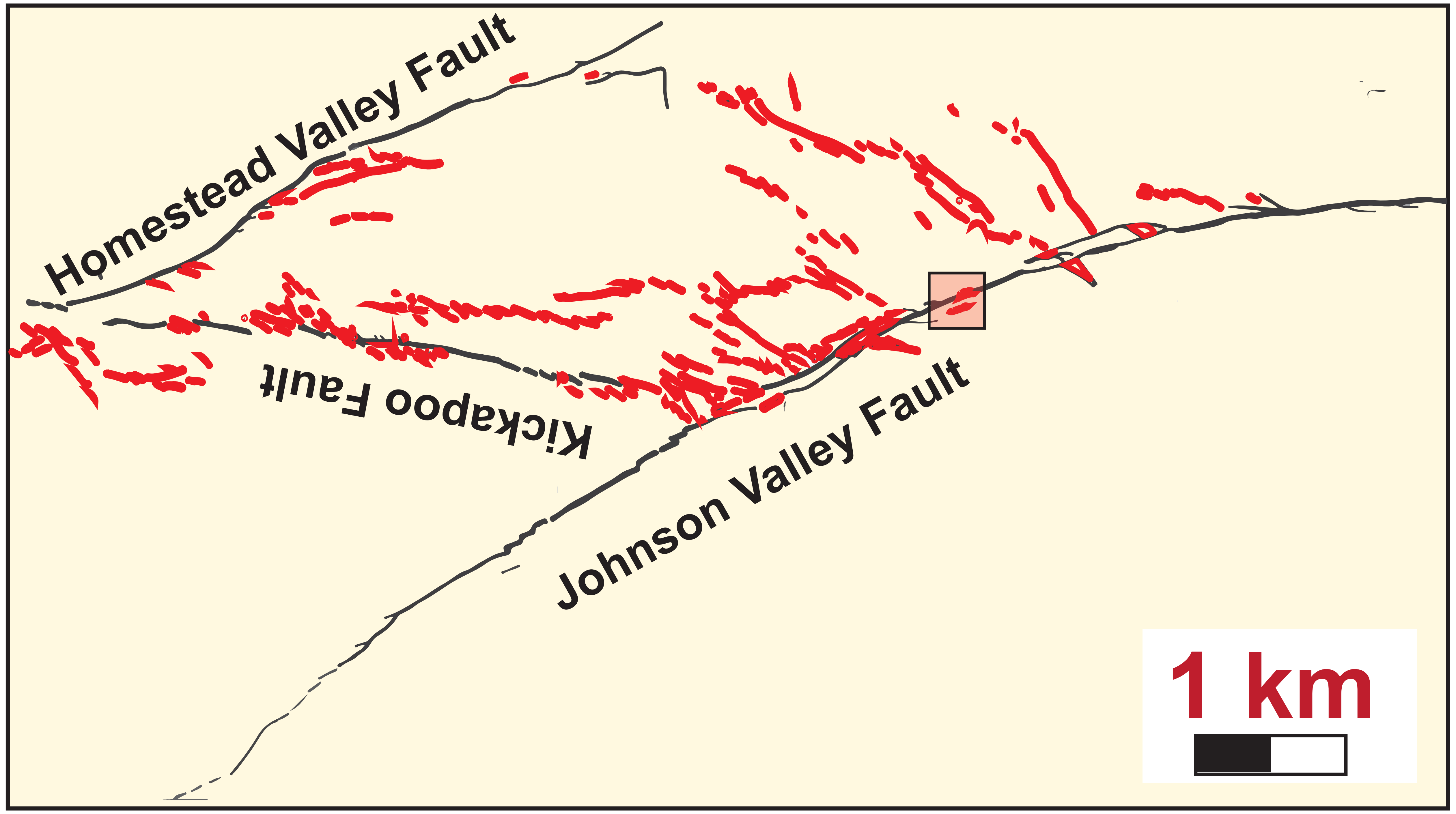

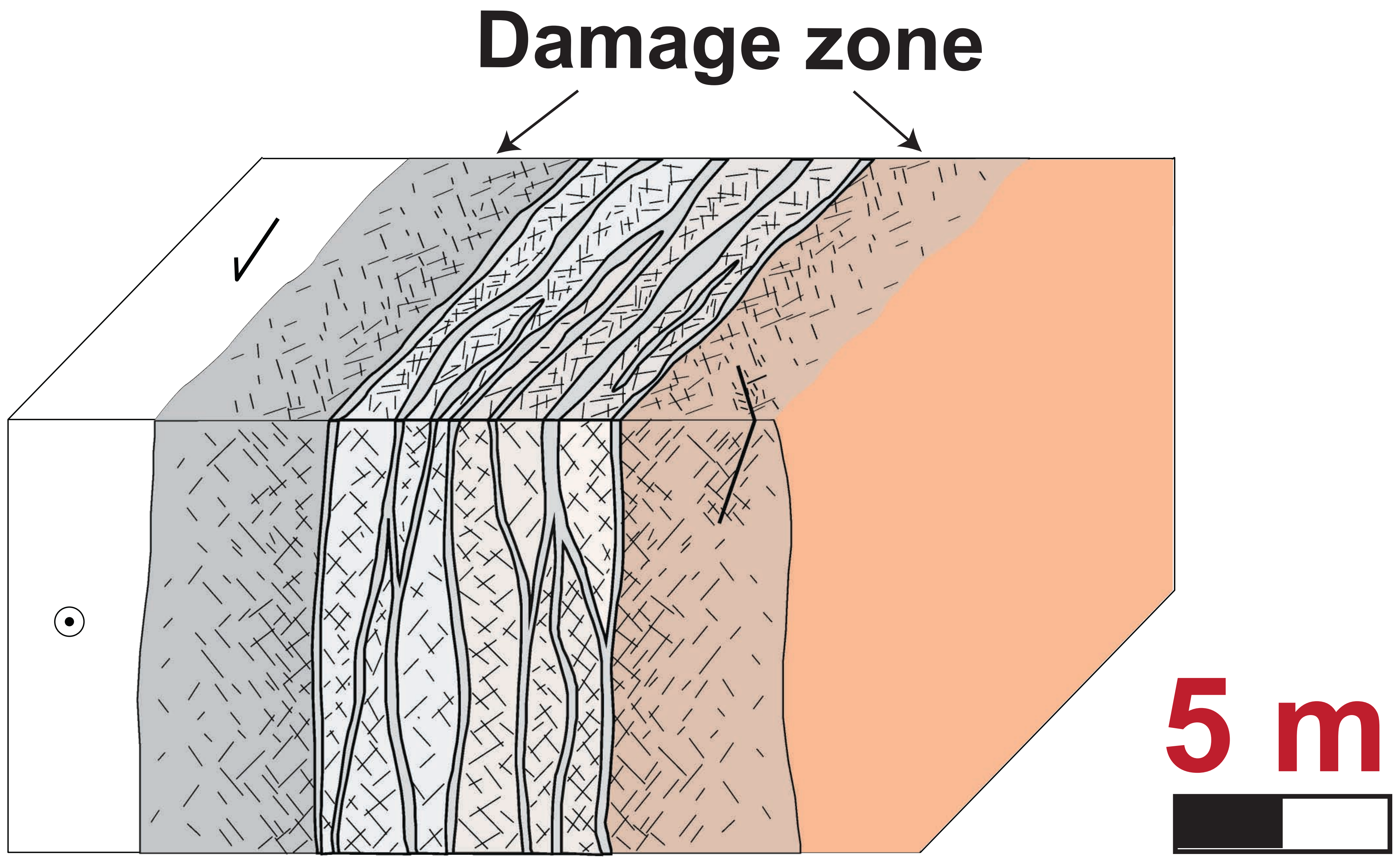

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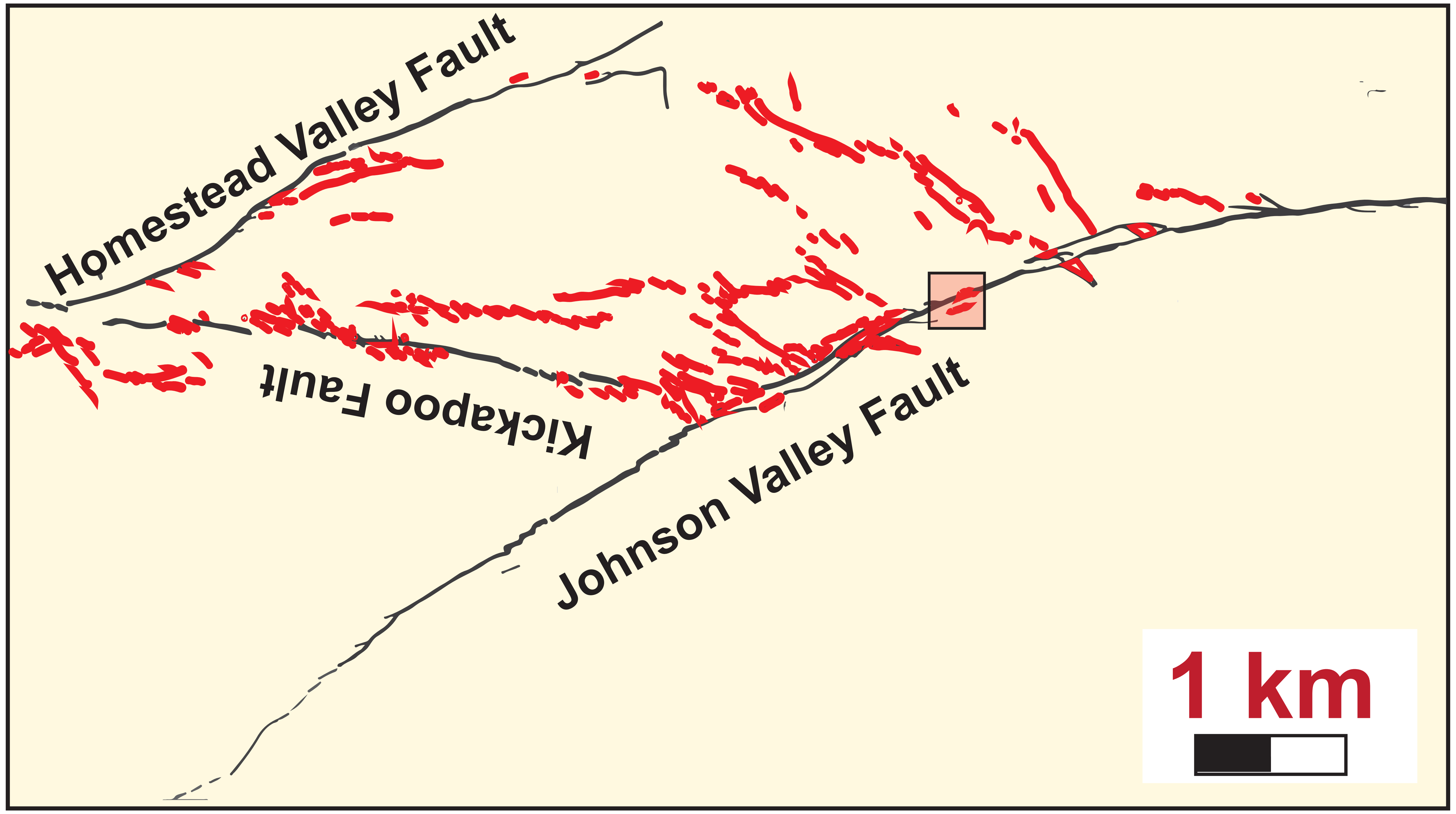

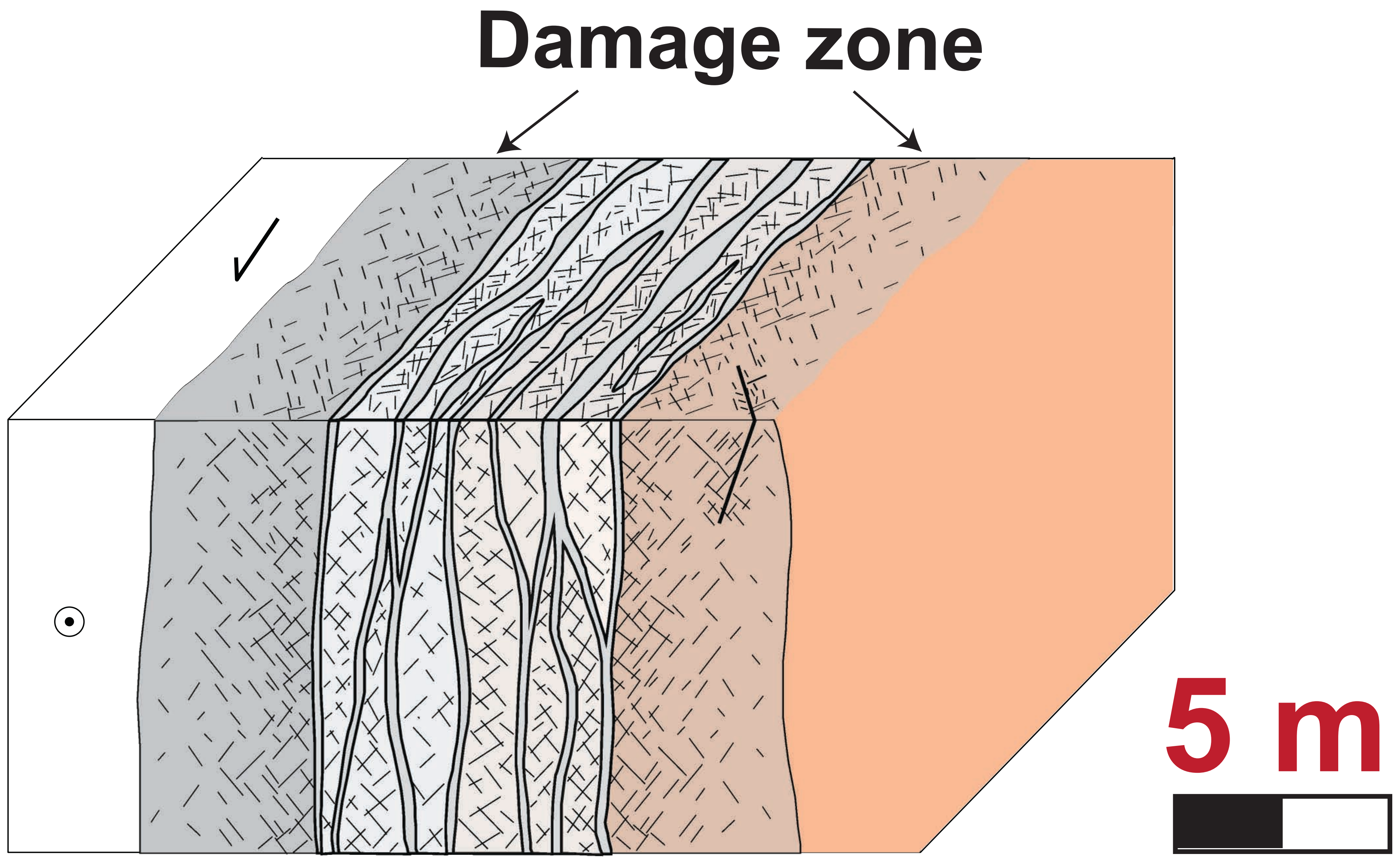

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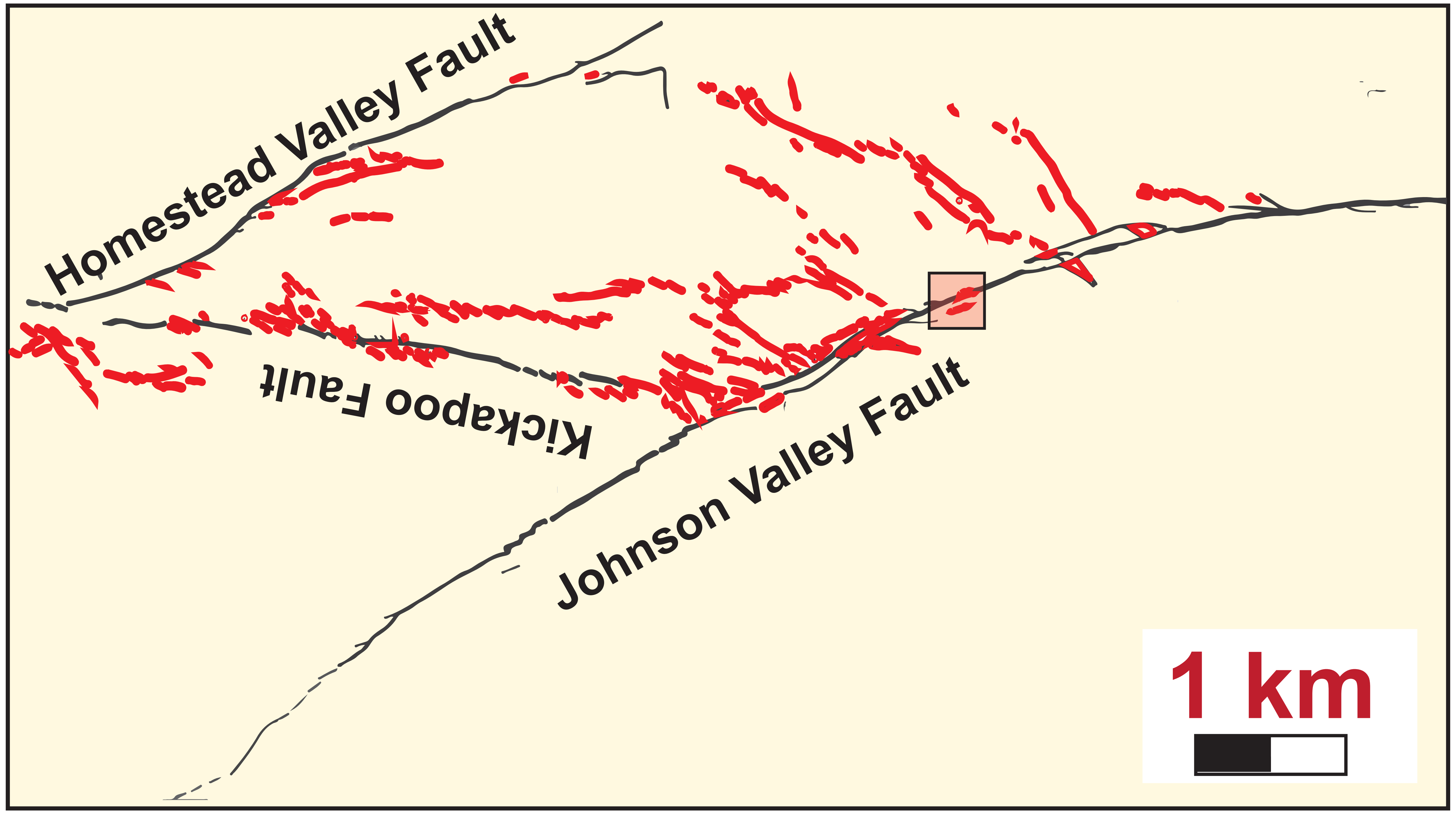

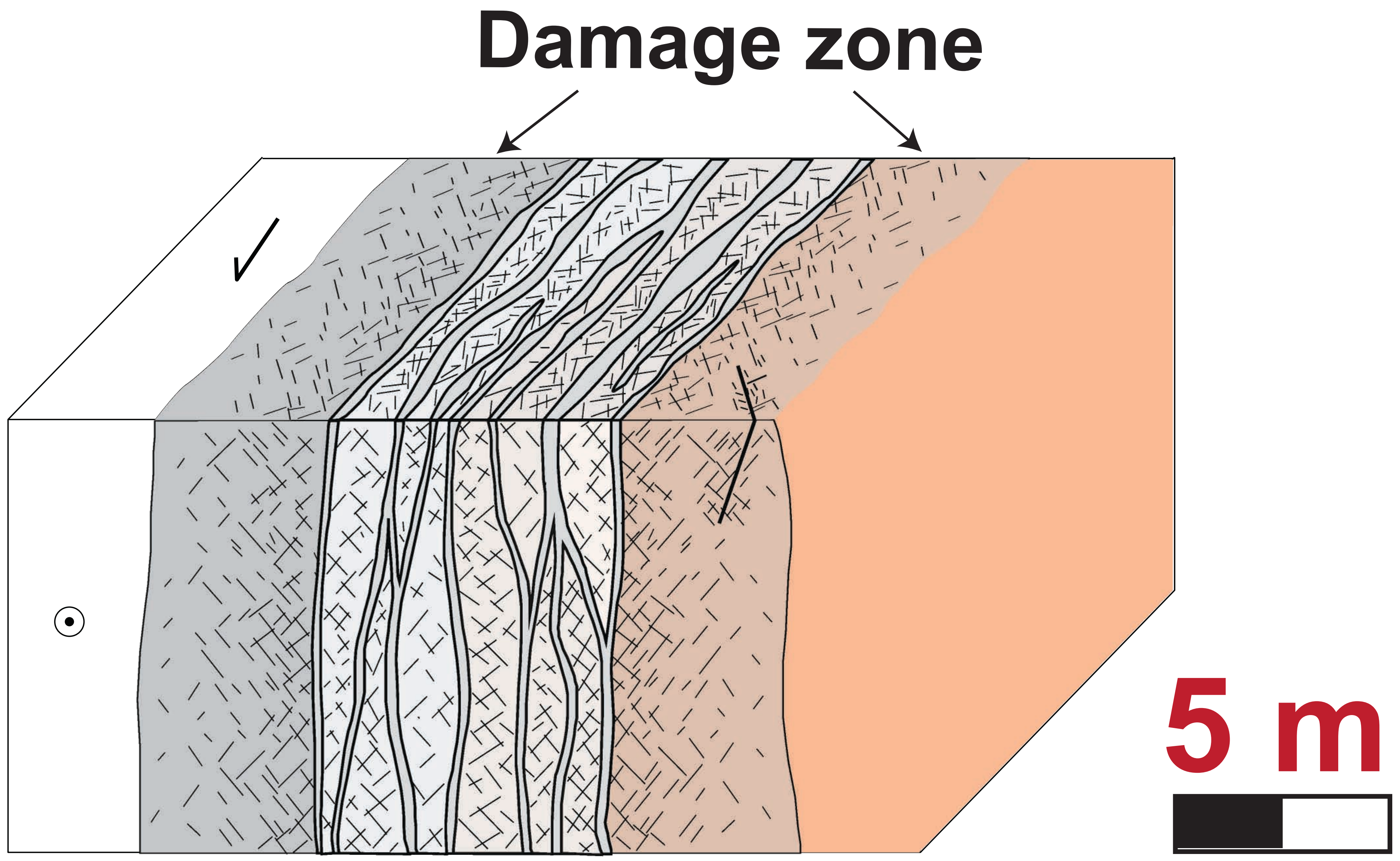

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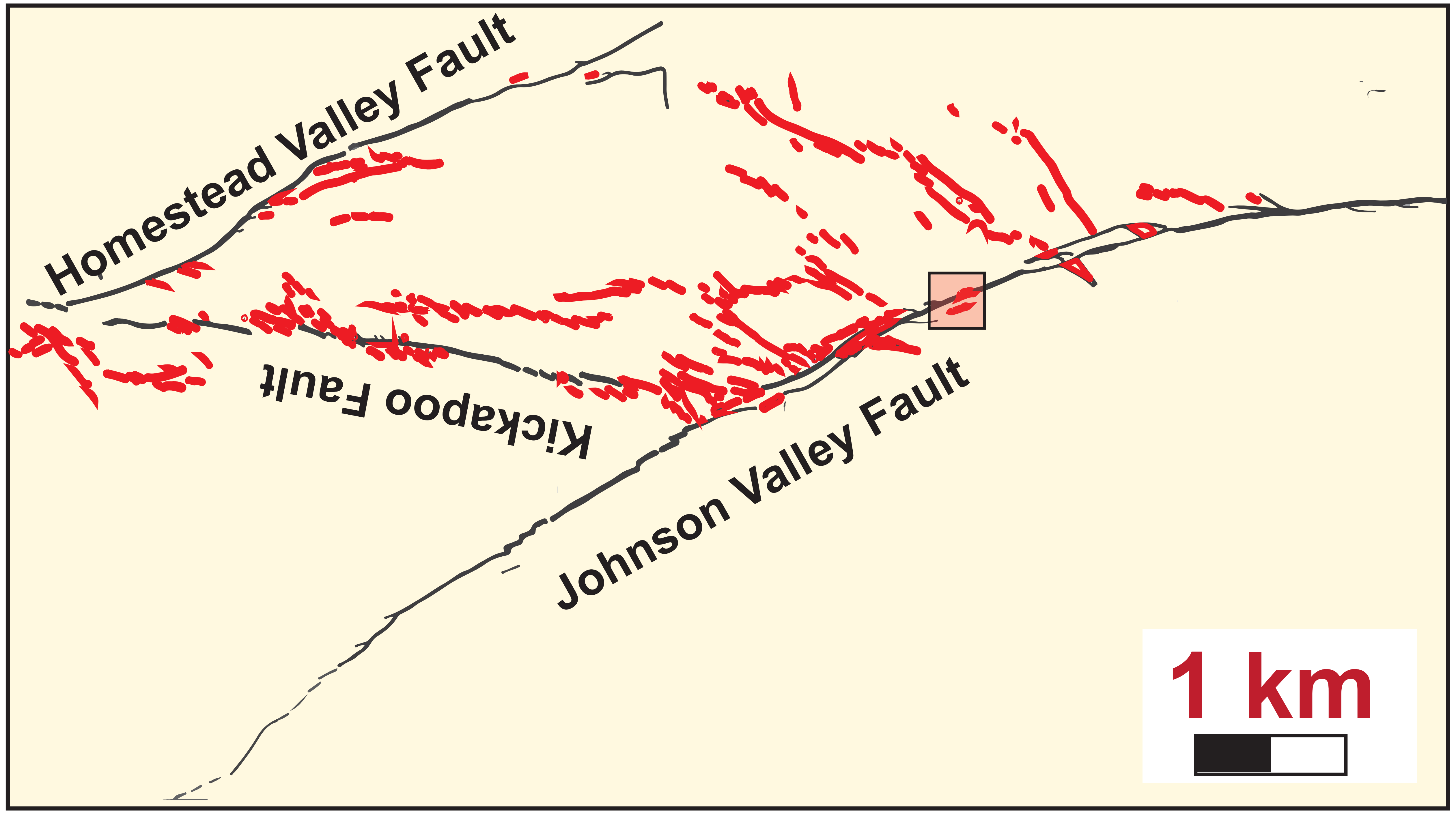
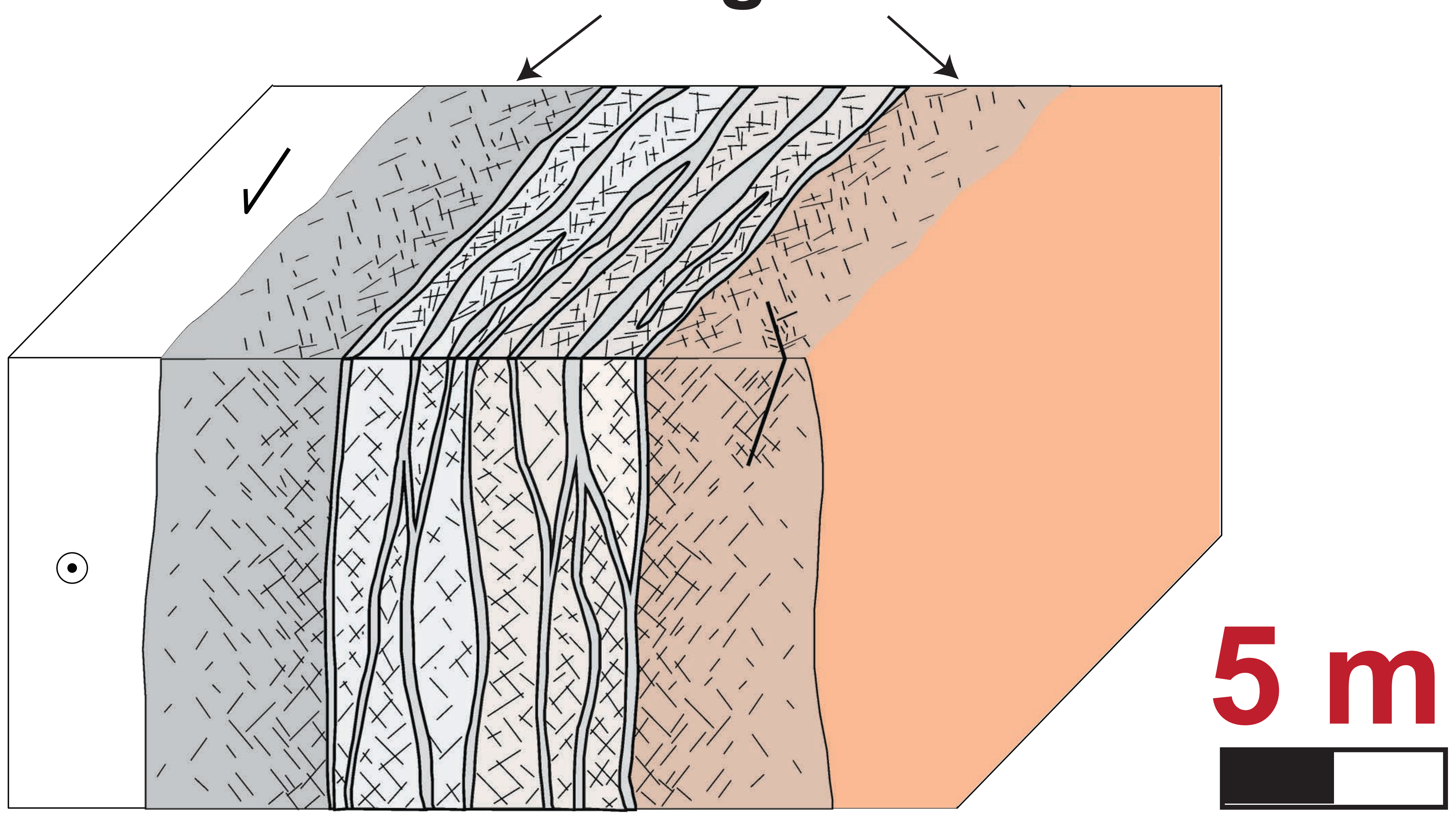


Damage zone



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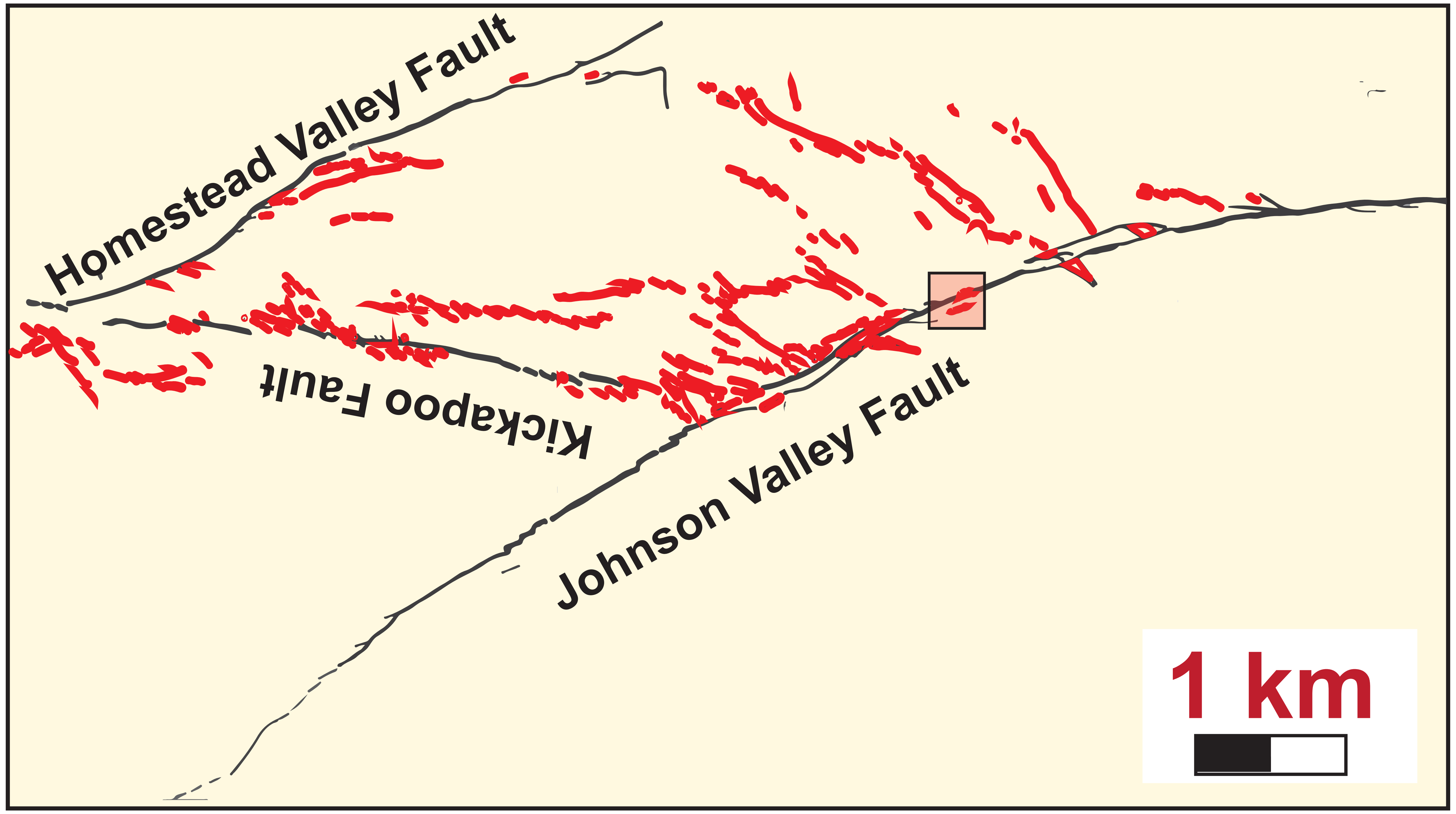

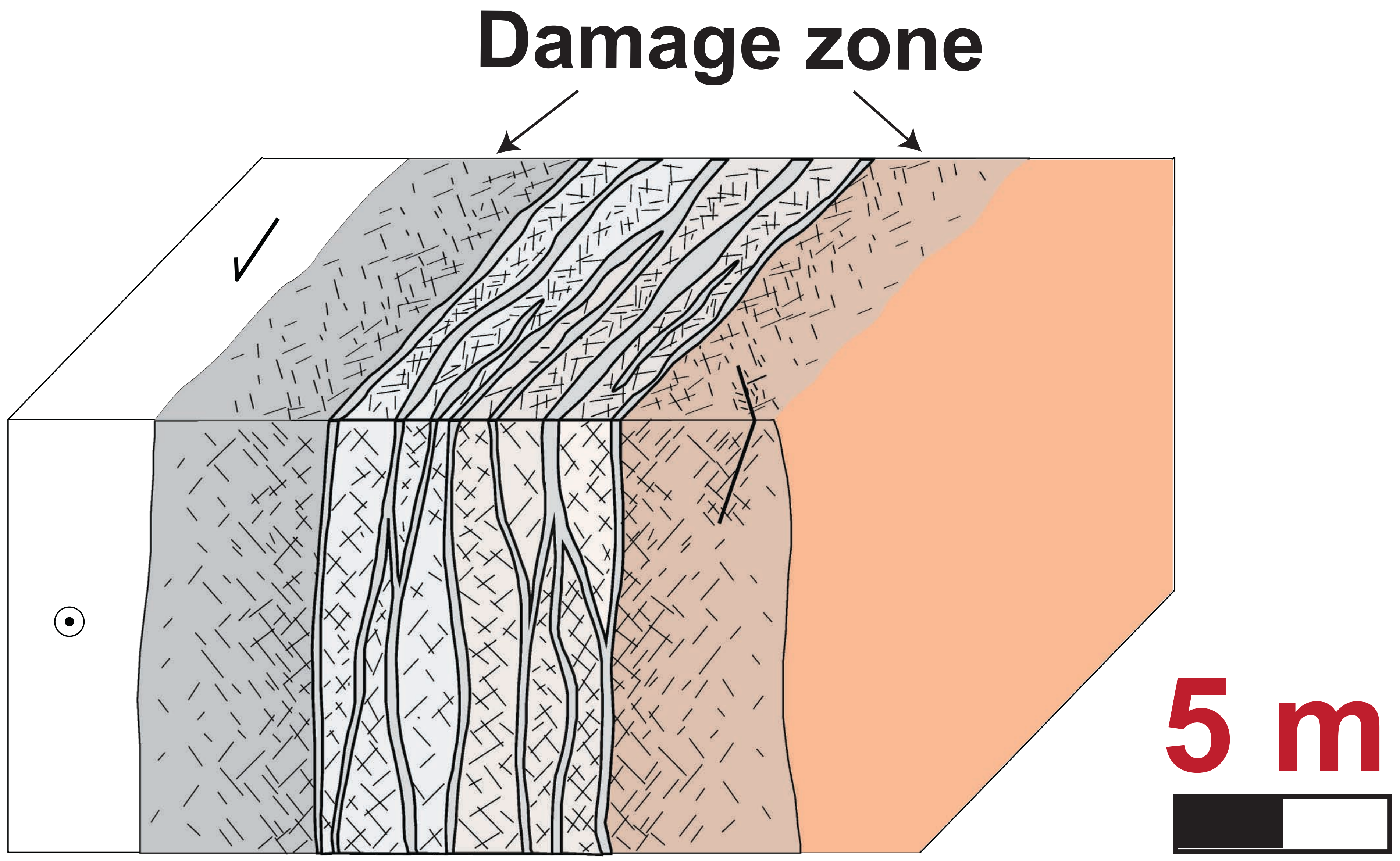

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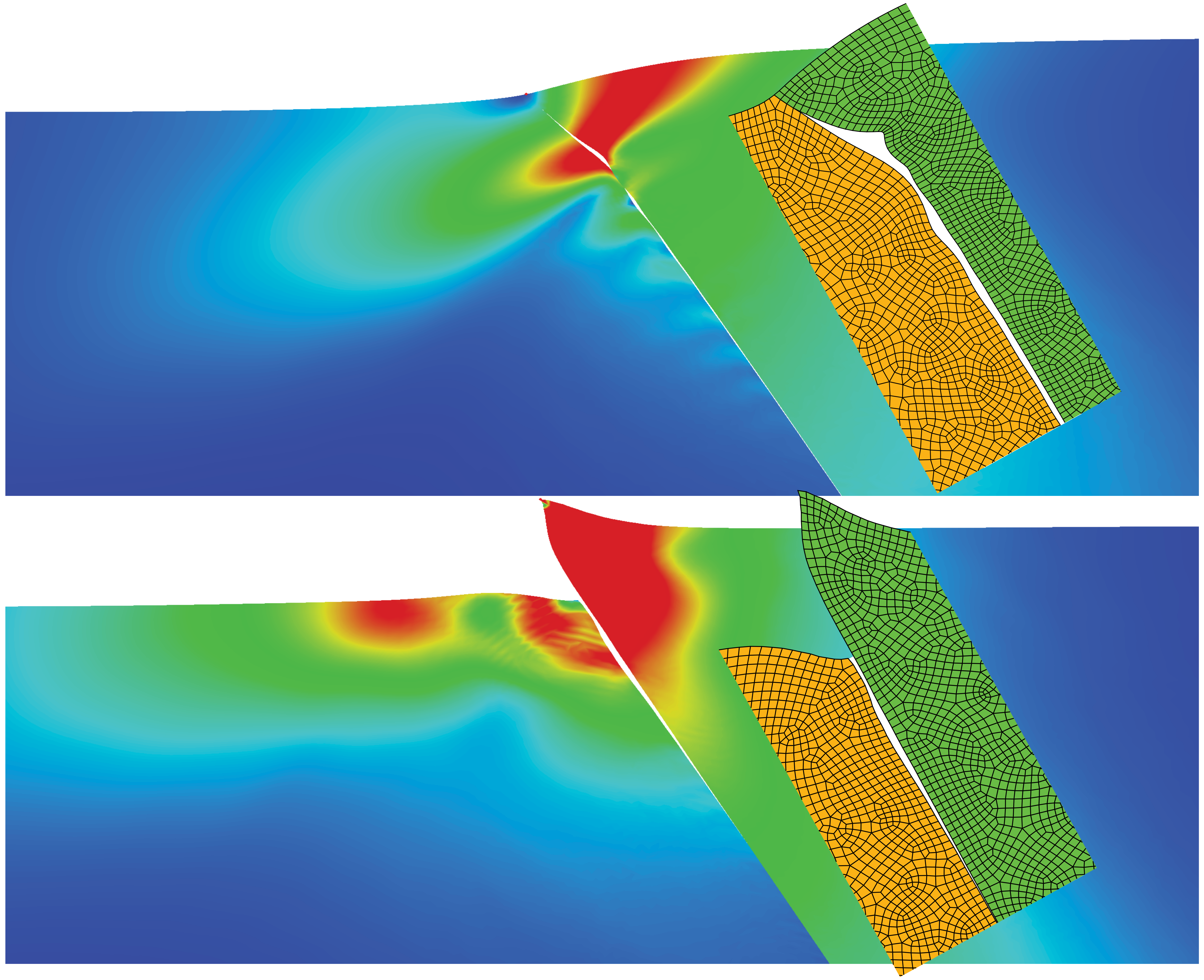

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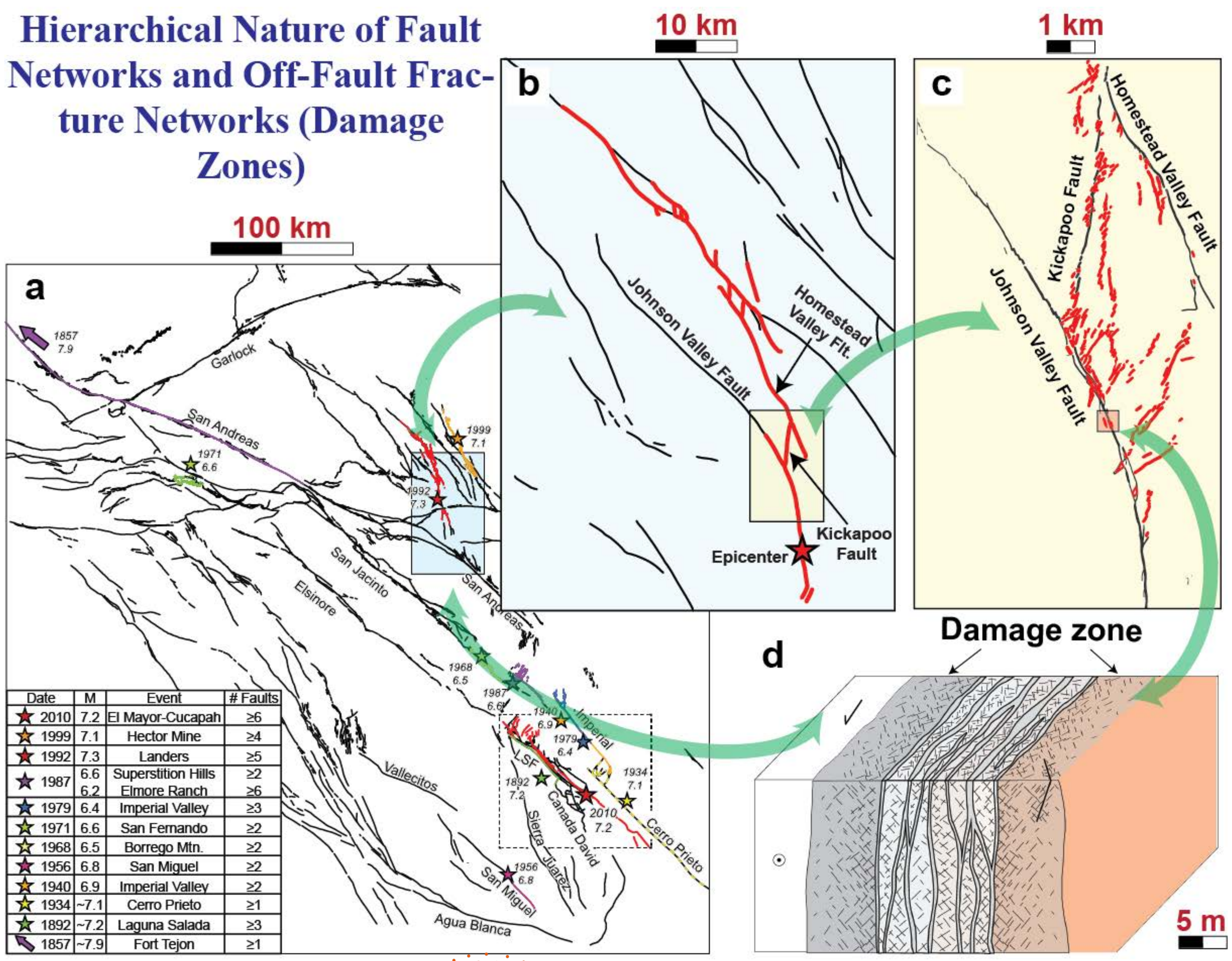


Date	M	Event	# Faults
2010	7.2	El Mayor-Cucapah	≥6
1999	7.1	Hector Mine	≥4
1992	7.3	Landers	≥5
1987	6.6	Superstition Hills	≥2
	6.2	Elmore Ranch	≥6
1979	6.4	Imperial Valley	≥3
1971	6.6	San Fernando	≥2
1968	6.5	Borrego Mtn.	≥2
1956	6.8	San Miguel	≥2
1940	6.9	Imperial Valley	≥2
1934	~7.1	Cerro Prieto	≥1
1892	~7.2	Laguna Salada	≥3
1857	~7.9	Fort Tejon	≥1

PERSISMO
Jan 2021 - Dec 2025

We developed **simple rules for rupture branching (forward & backward)**, in a fault network

We **developed new algorithms to model earthquake cycles on realistic fault networks**

We showed that **slow slip events and earthquakes emerge naturally** in non-planar faults

We showed that the **off-fault damage dynamically interacts with rupture**

We **developed micromechanical models of fracture networks for mechanical & hydraulic evolution**

We showed that **high frequency ground motion emerged from Damage Zone**

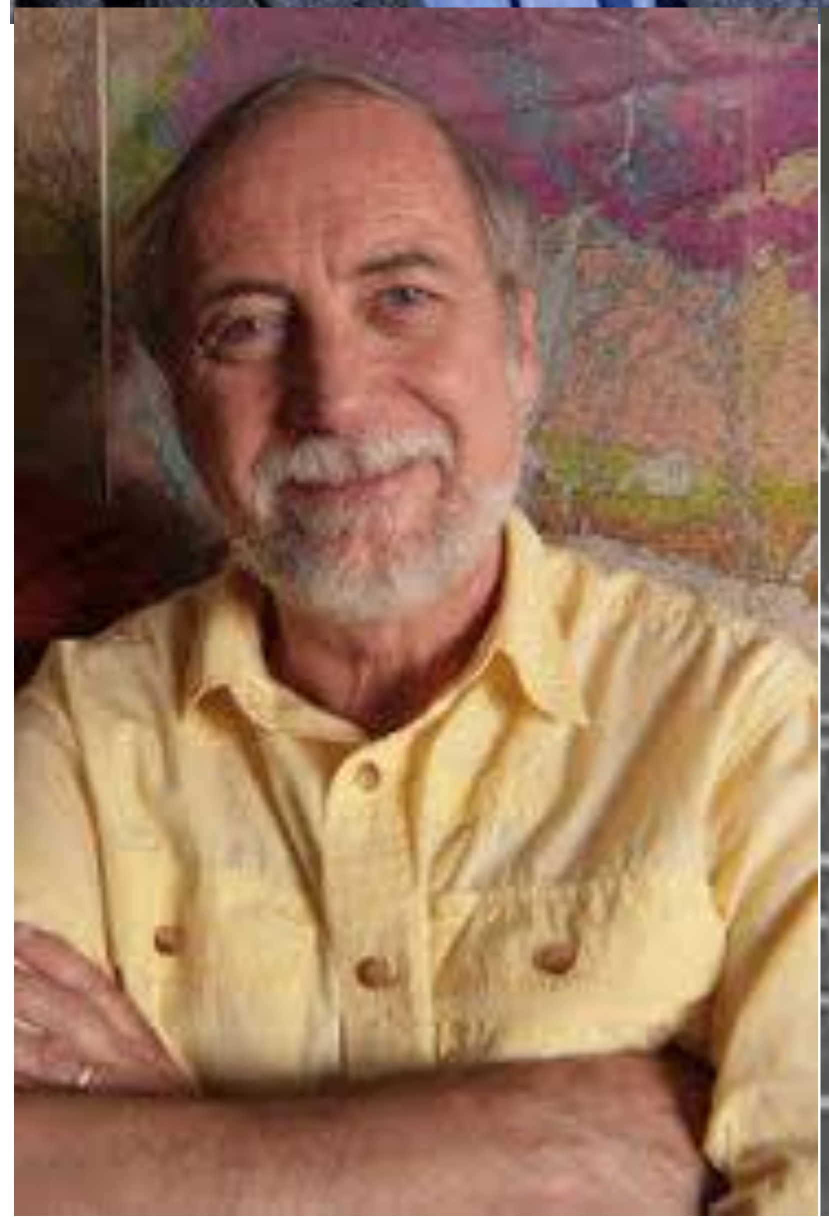
We **co-developed numerical algorithms to spontaneously activate off-fault fracture networks**

We were able to explain **migration of tremors by non-linear fluid diffusion mechanism**

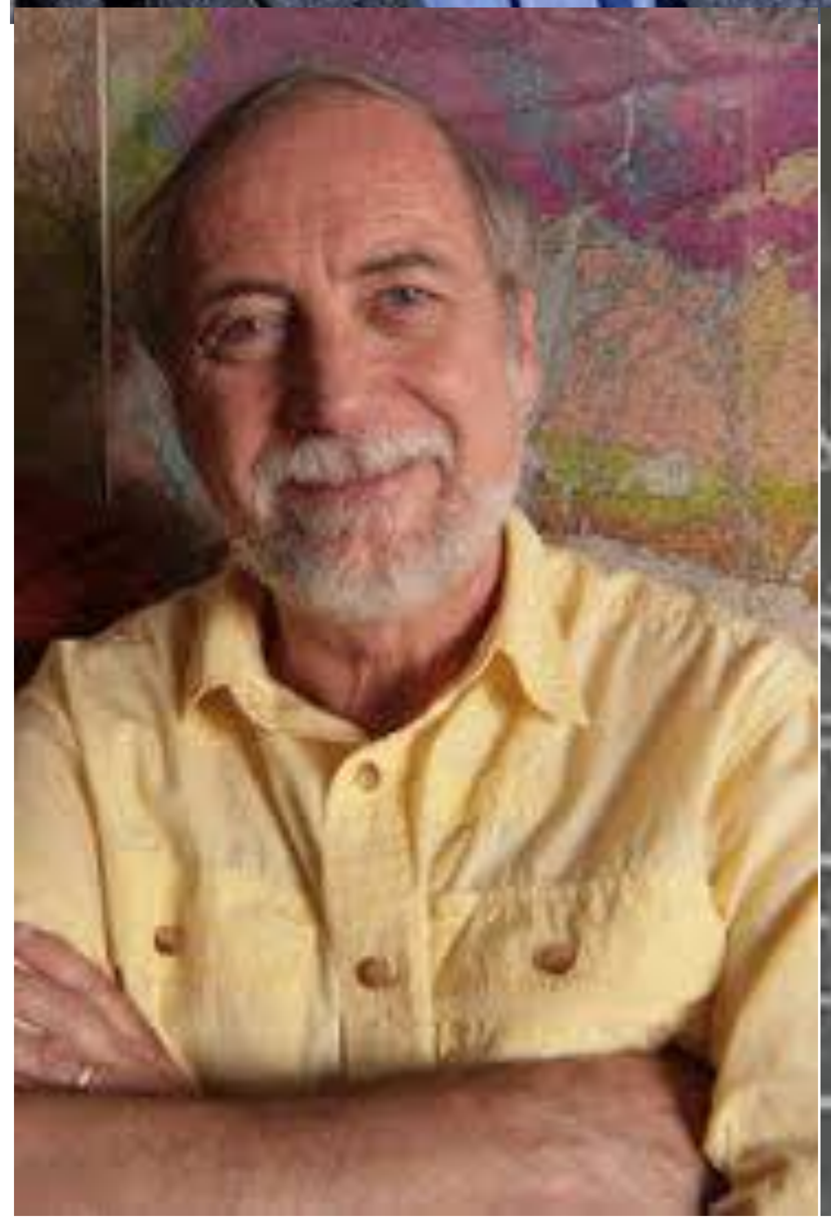
We showed that **thrust faults can actually open**

Merci



Enhanced

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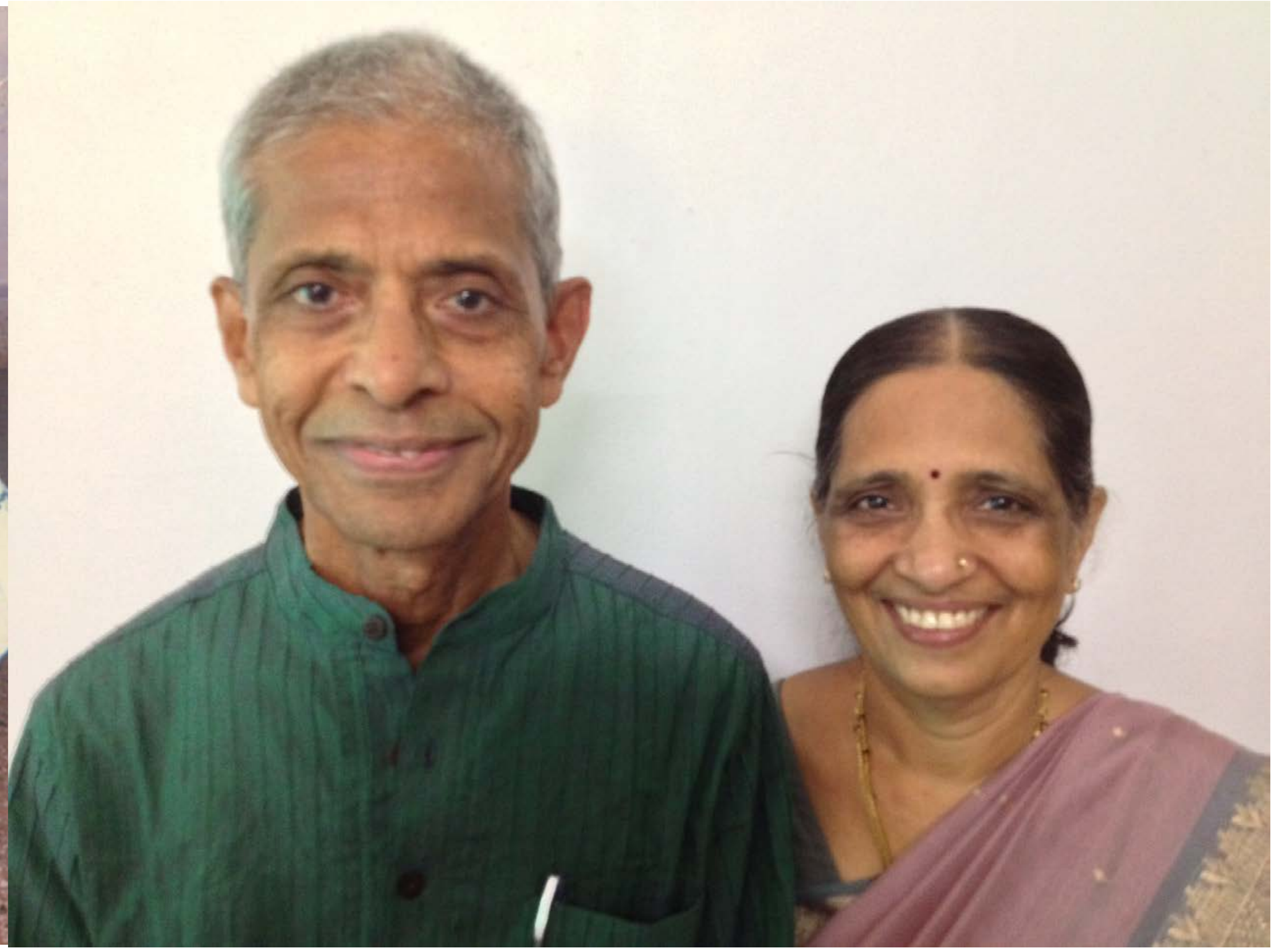
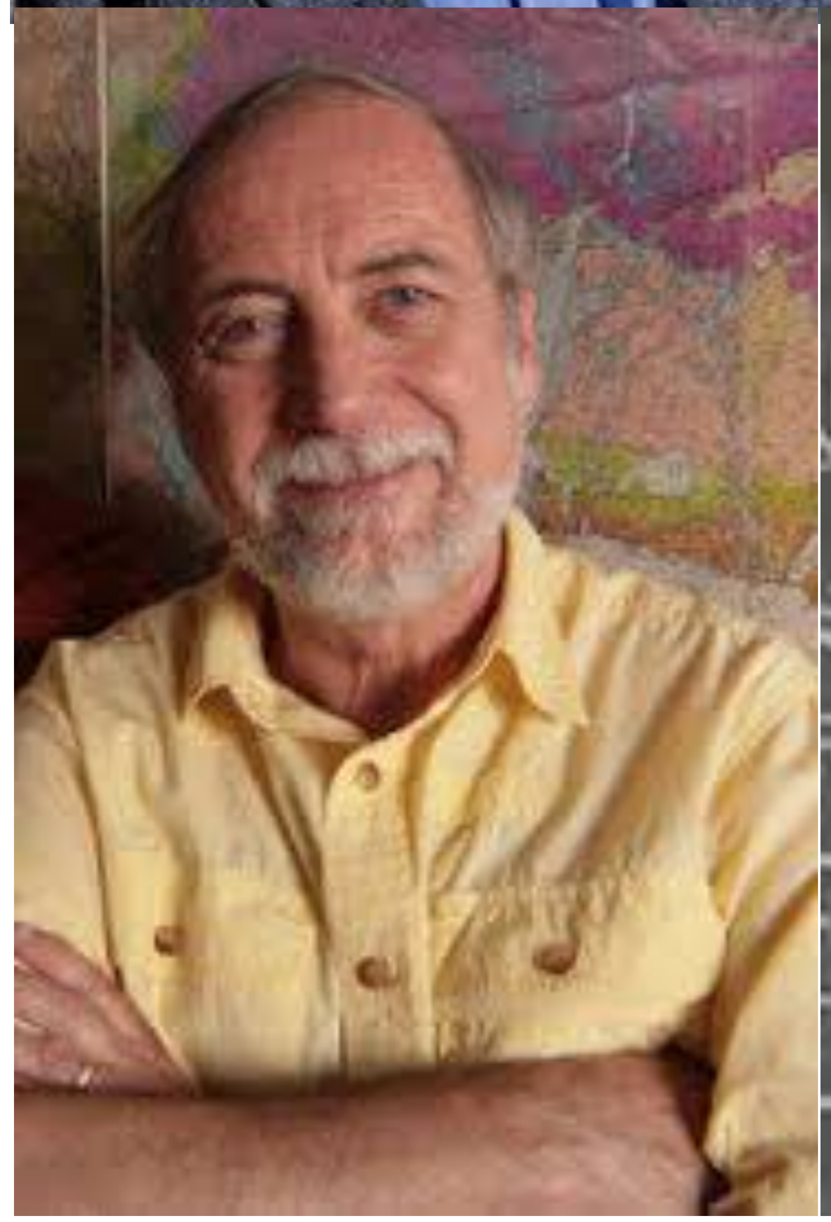





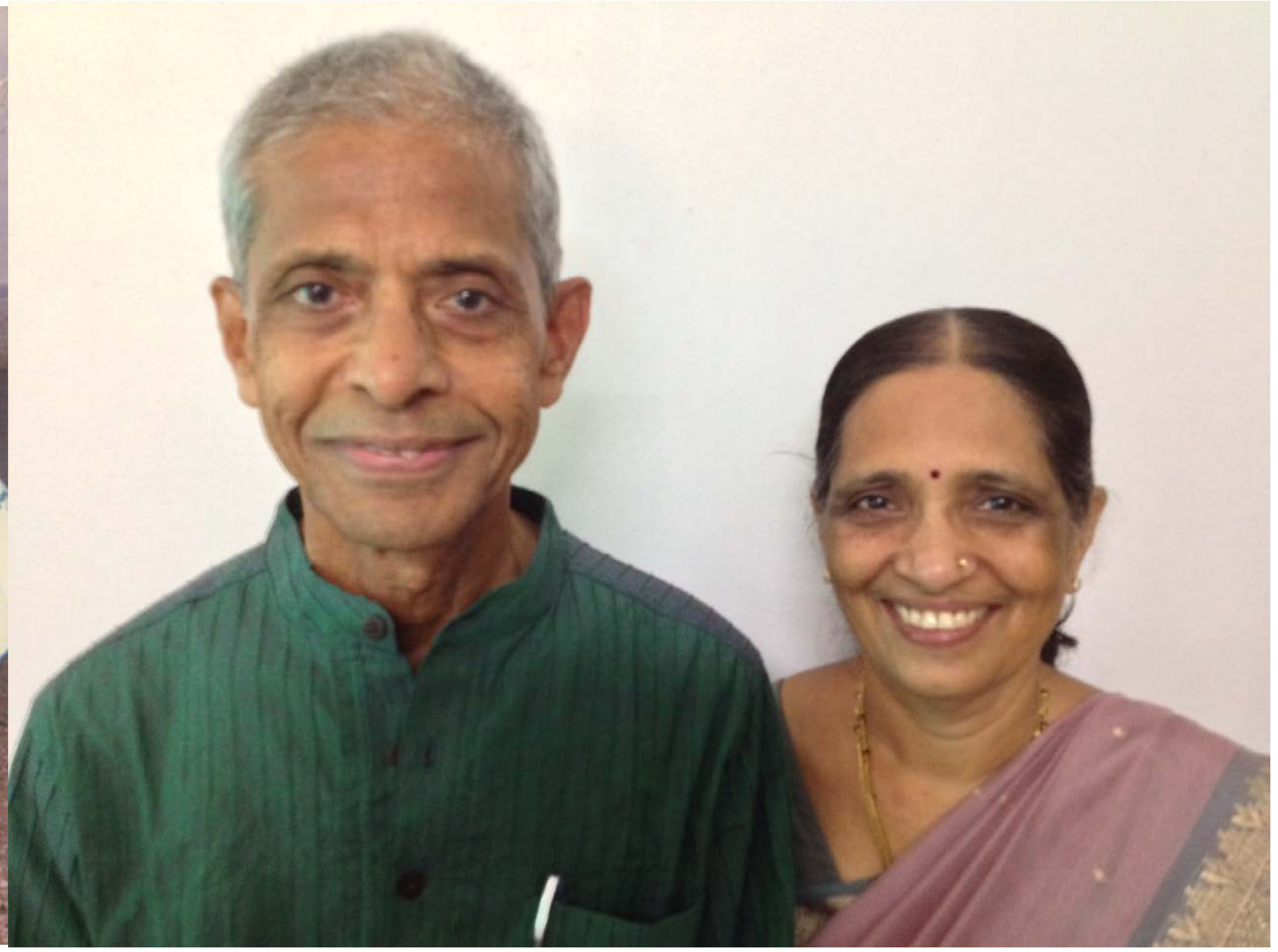
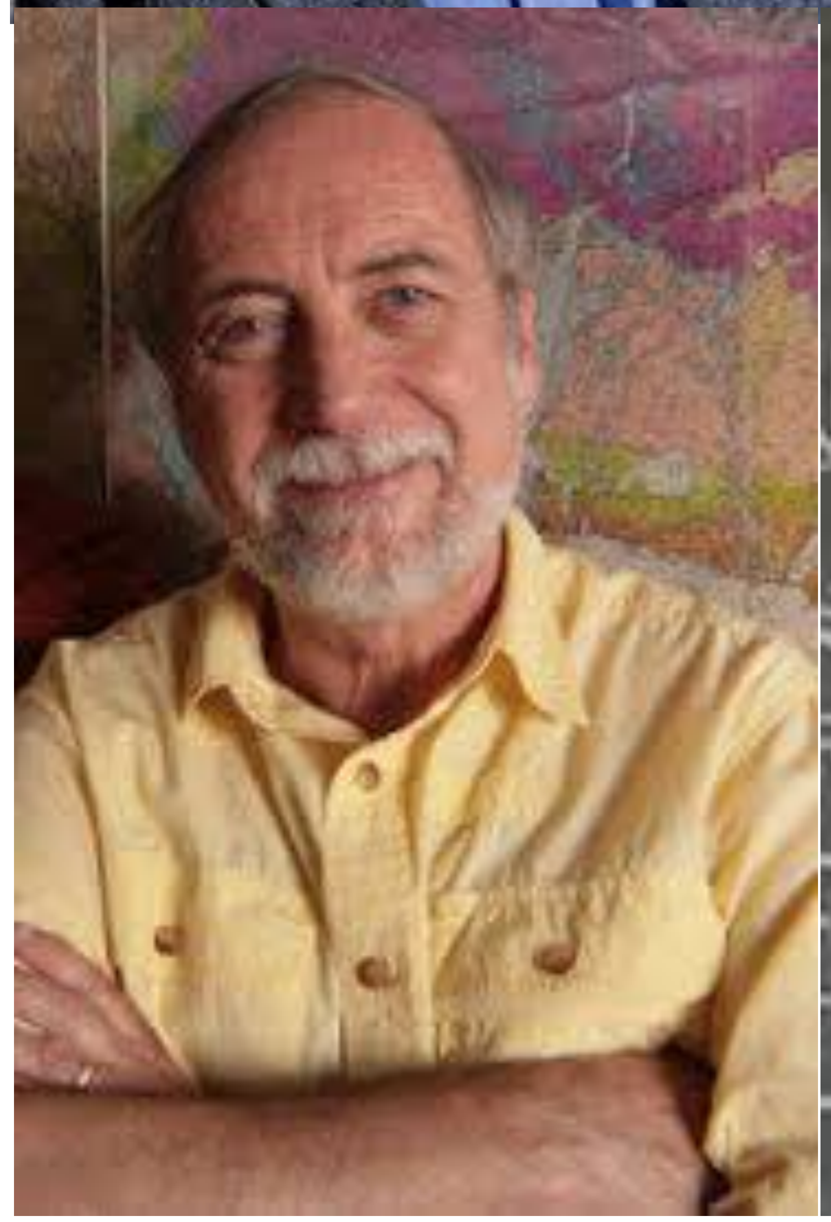


Thom-Thom & Nana loves you to bits!