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

Harsha Suresh Bhat

M. Bouchon
U. Grenoble Alpes

A. Schubnel
ENS

A. J. Rosakis
Caltech

D. Kondo
Sorbonne U.

P. A. Johnson
Los Alamos

S. Das
Oxford U.

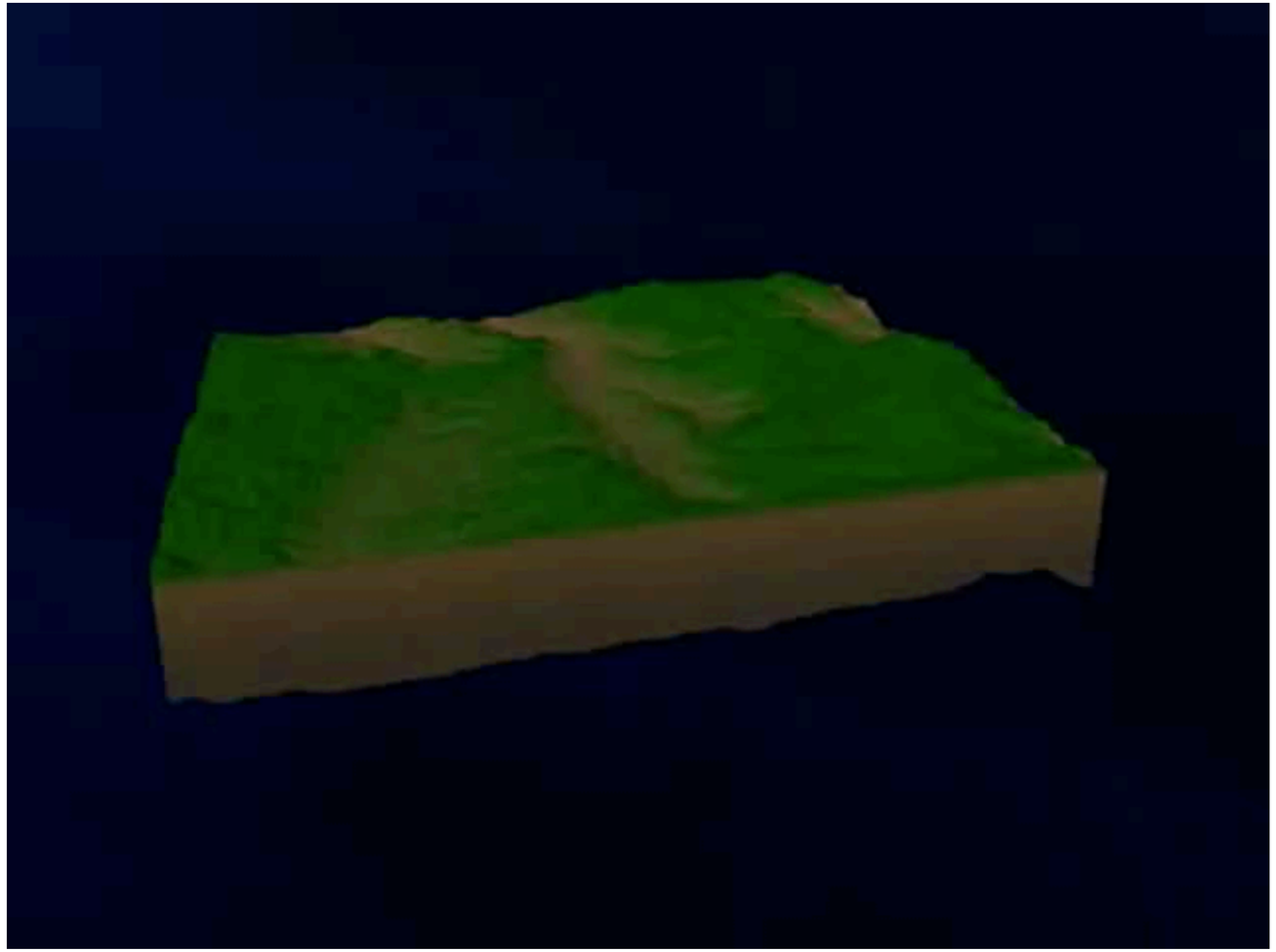
To obtain Habilitation à Diriger des Recherches from École Normale Supérieure

Classical View of an Earthquake

Video courtesy USGS

Classical View of an Earthquake

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

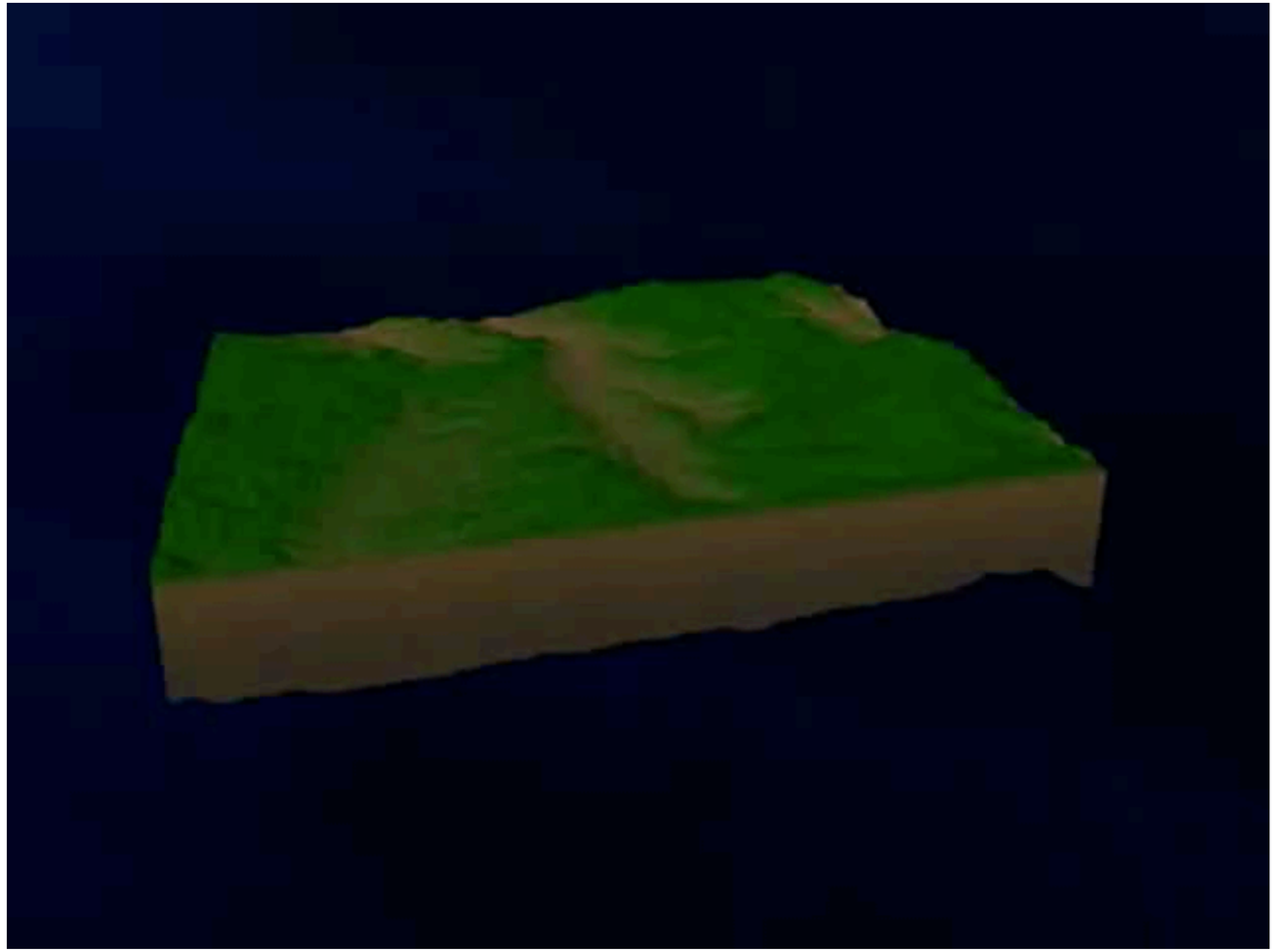


Video courtesy USGS

Classical View of an Earthquake

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

The faults resist this motion due to **friction**



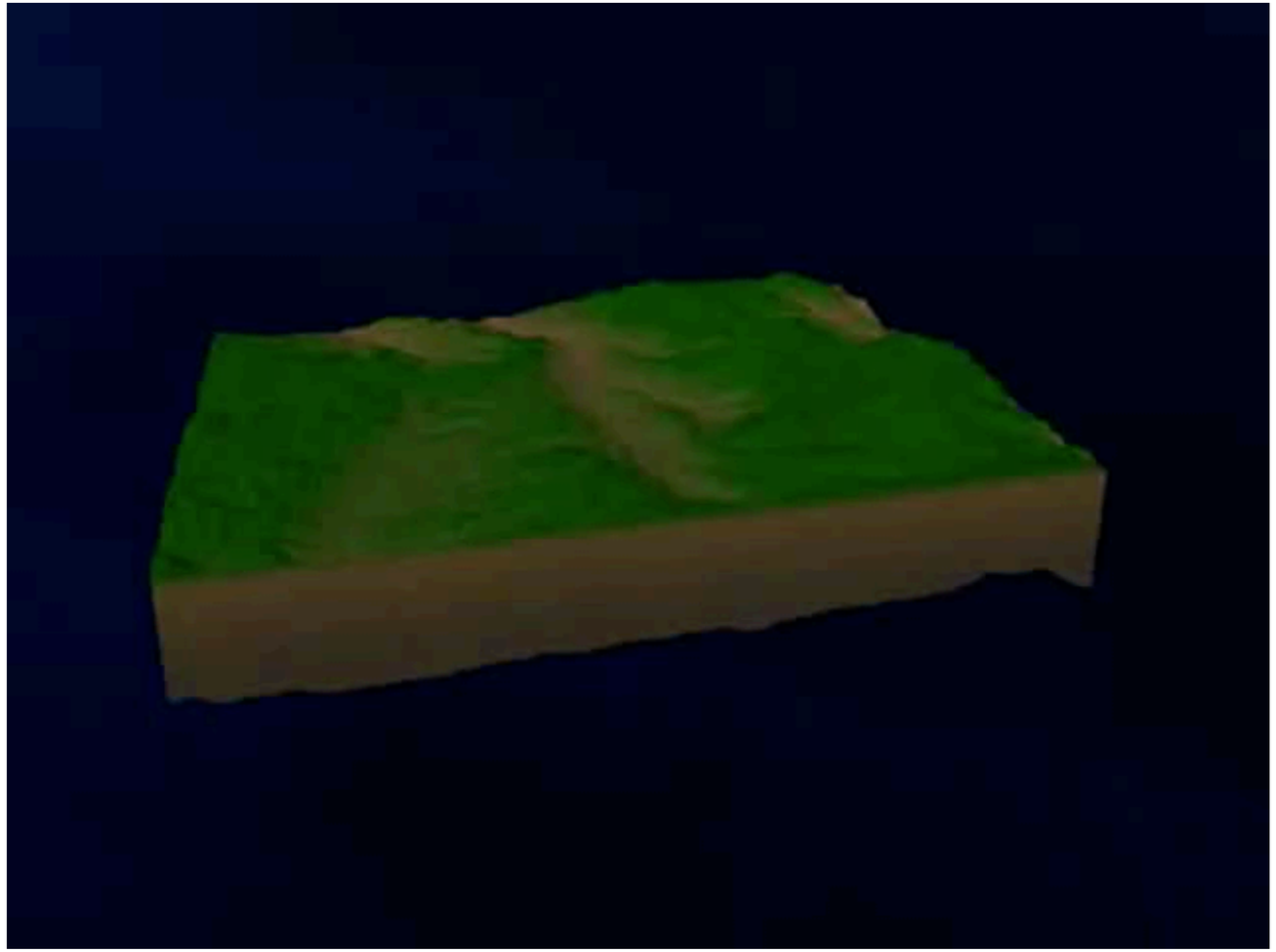
Video courtesy USGS

Classical View of an Earthquake

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

The faults resist this motion due to **friction**

This builds up **energy** in the medium and increases **stress** on the faults



Video courtesy USGS

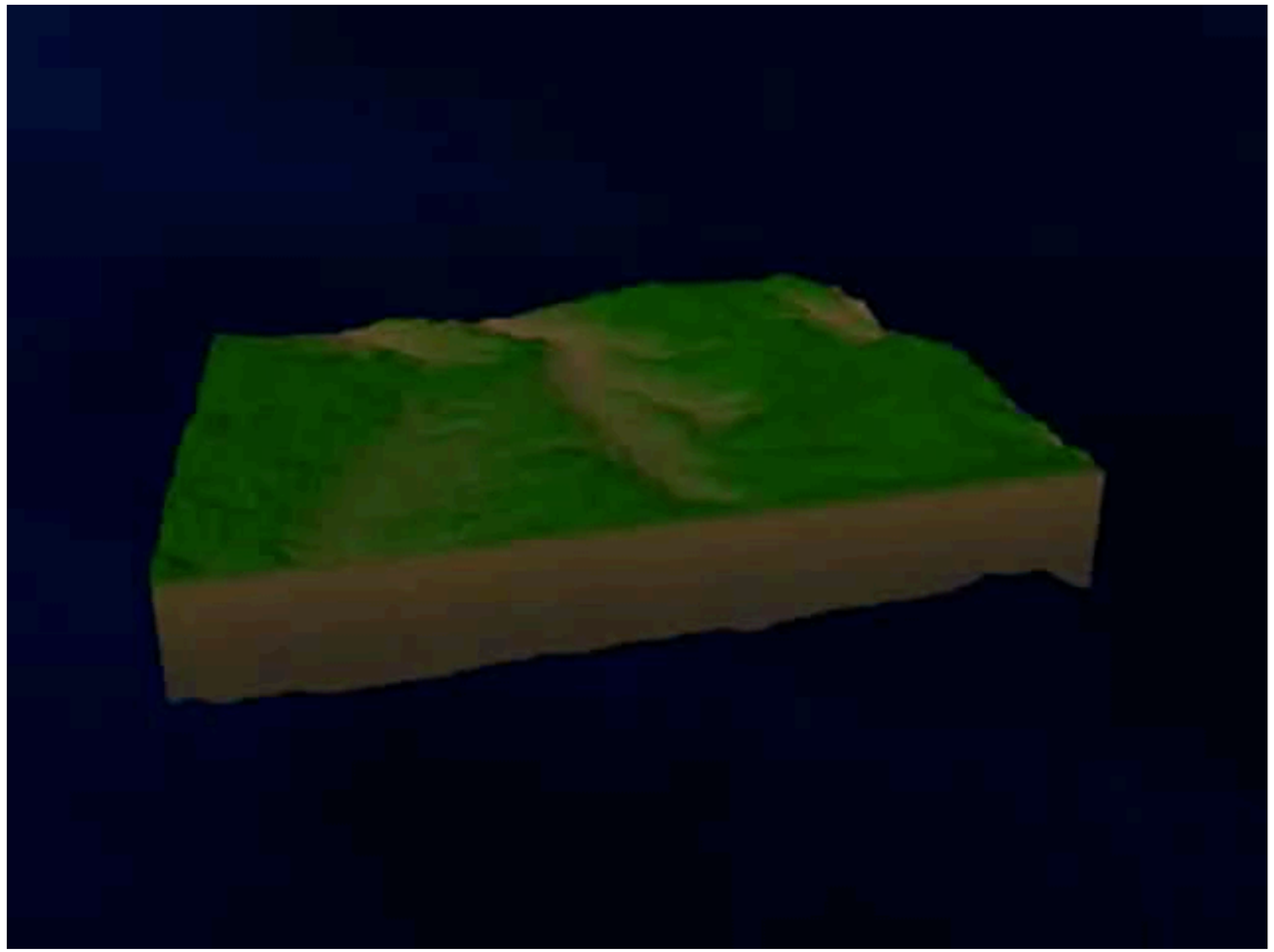
Classical View of an Earthquake

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

The faults resist this motion due to **friction**

This builds up **energy** in the medium and increases **stress** on the faults

Once the stresses exceed frictional resistance the plates slide past each other as the fault **ruptures** *(unzips)*



Video courtesy USGS

Classical View of an Earthquake

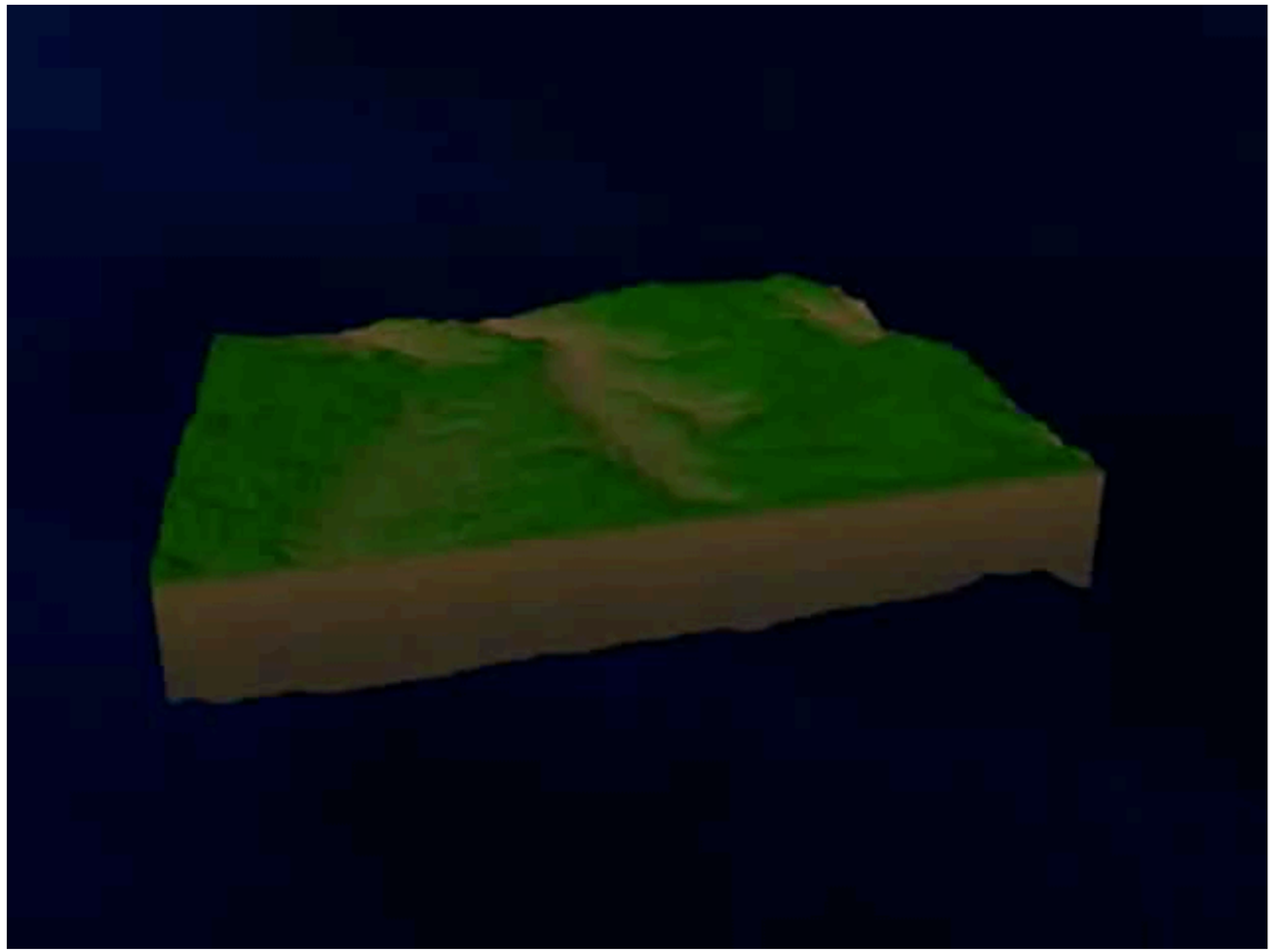
Tectonic plates try to slide past each around **faults**

The faults resist this motion due to **friction**

This builds up **energy** in the medium and increases **stress** on the faults

Once the stresses exceed frictional resistance the plates slide past each other as the fault **ruptures** *(unzips)*

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



Video courtesy USGS

Rupture Speed

Rupture Speed

As the fault **ruptures** *(unzips)* it radiates **P***ressure*-**waves** and **S***hear*-**waves** into the medium

Rupture Speed

As the fault **ruptures** *(unzips)* it radiates **P***ressure*-**waves** and **S***hear*-**waves** into the medium

Thus, three different **speeds** come into action

Rupture Speed

As the fault **ruptures** *(unzips)* it radiates **P***ressure***-waves** and **S***hear***-waves** into the medium

Thus, three different **speeds** come into action

- **rupture** speed

Rupture Speed

As the fault **ruptures** *(unzips)* it radiates **P***ressure*-**waves** and **S***hear*-**waves** into the medium

Thus, three different **speeds** come into action

- **rupture** speed
- **S-wave speed (~3.5 km/s)**

Rupture Speed

As the fault **ruptures** *(unzips)* it radiates **P***ressure***-waves** and **S***hear***-waves** into the medium

Thus, three different **speeds** come into action

- **rupture** speed
- **S-wave speed (~3.5 km/s)**
- **P-wave speed (~5 km/s)**

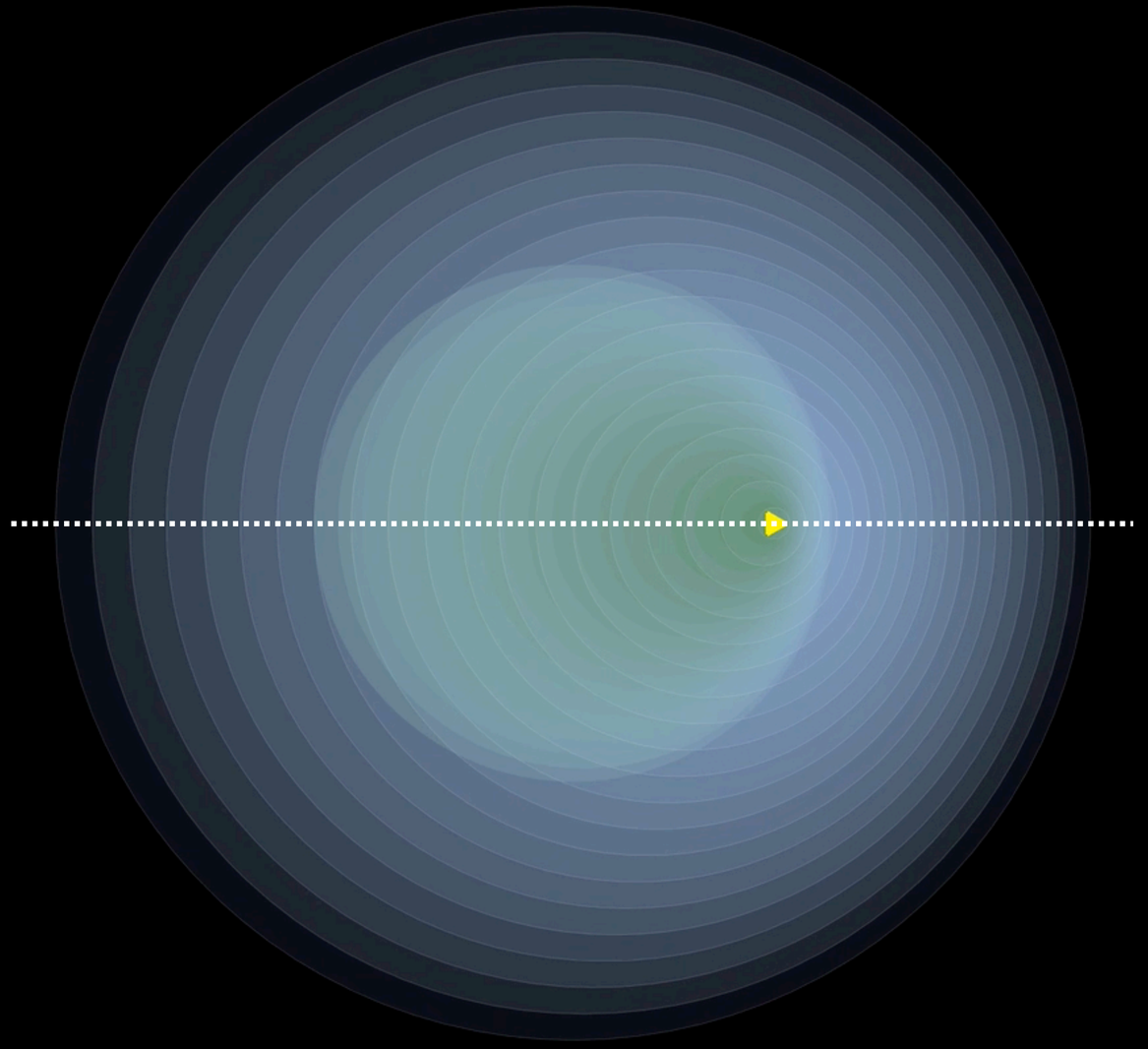
Rupture Speed

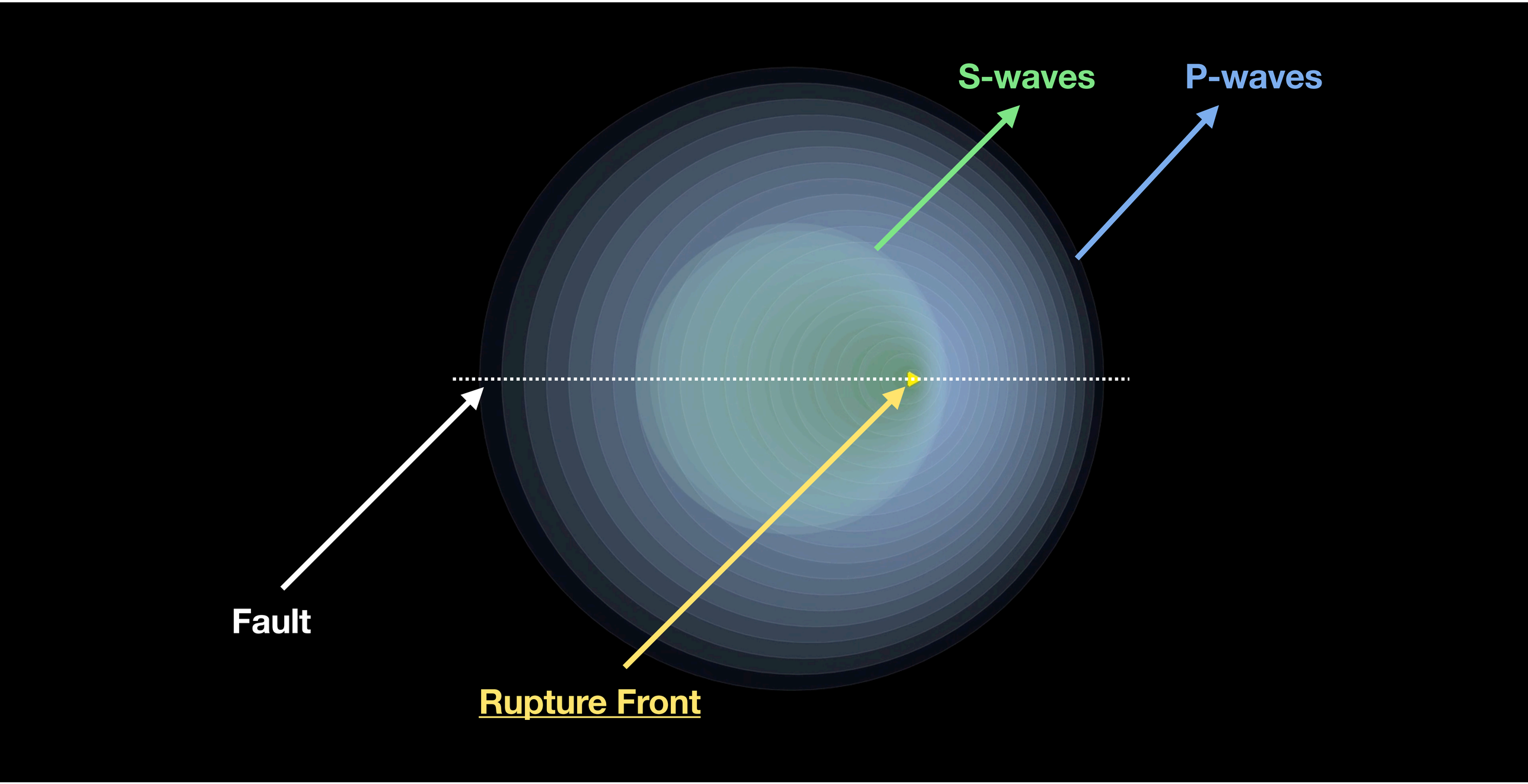
As the fault **ruptures** *(unzips)* it radiates **P***ressure***-waves** and **S***hear***-waves** into the medium

Thus, three different **speeds** come into action

- **rupture** speed
- **S-wave speed (~3.5 km/s)**
- **P-wave speed (~5 km/s)**

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

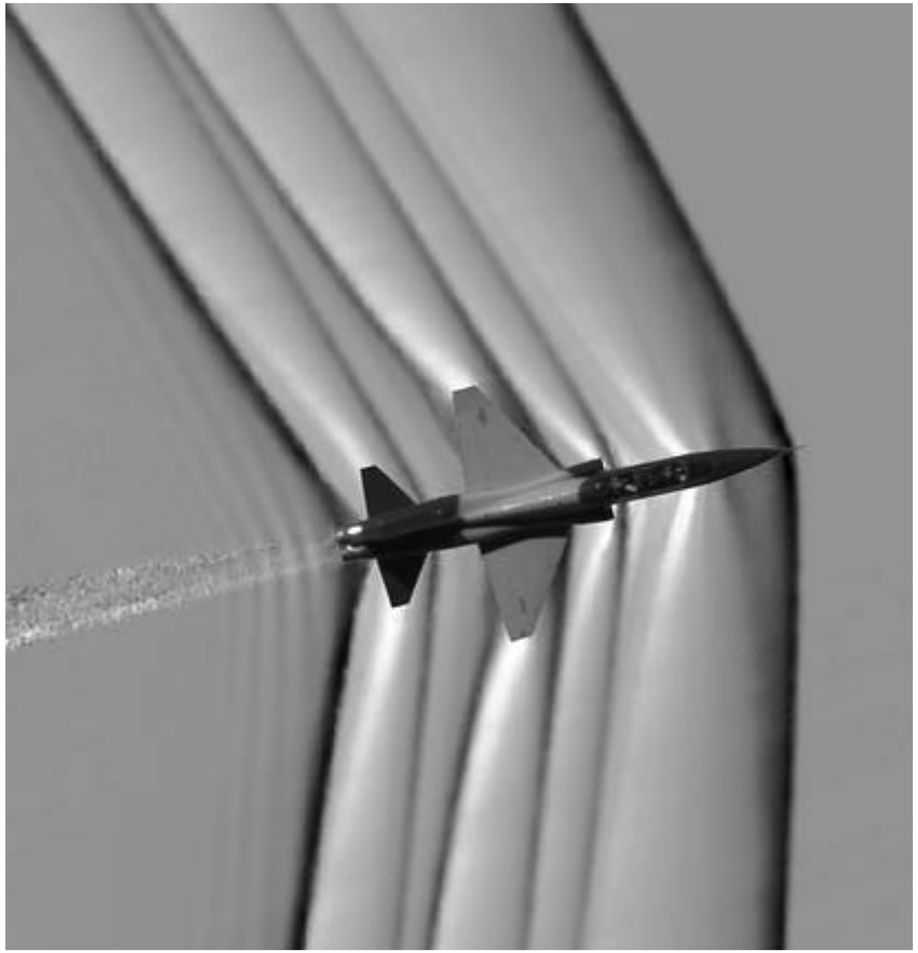
However, occasionally, the rupture tends to go *faster* than the S-wave speed (but slower than the P-wave speed)

Rupture Speed

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

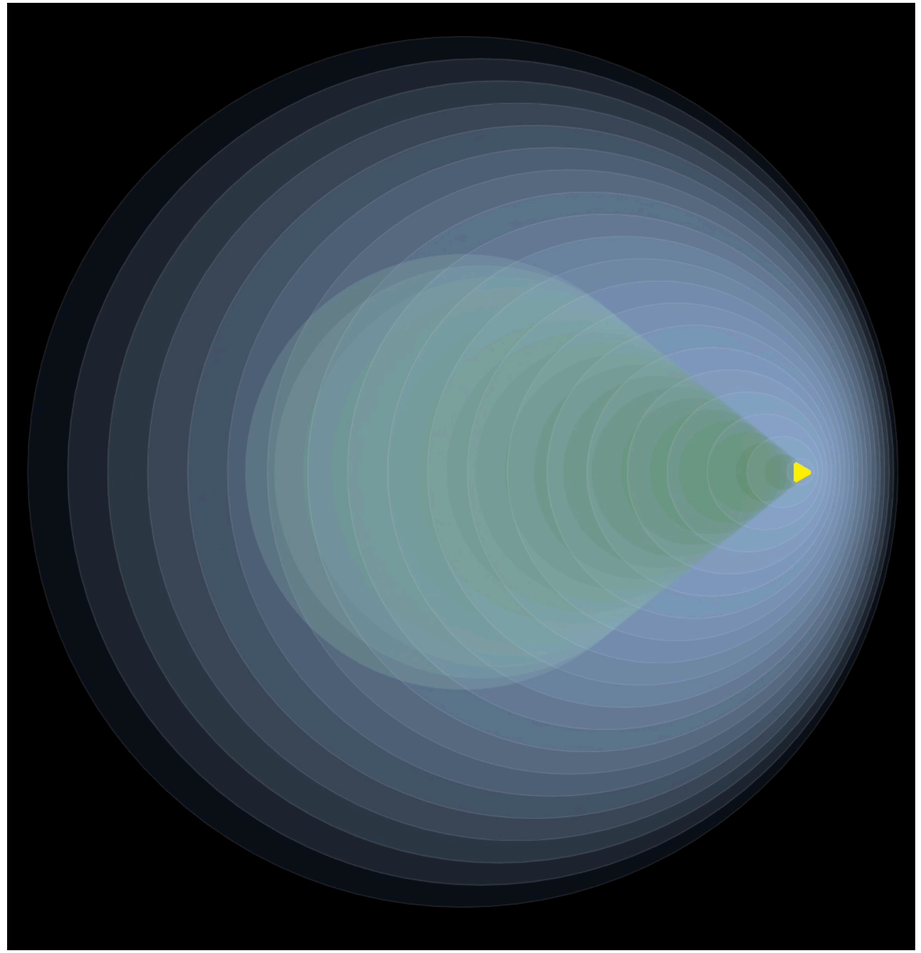
Such class of earthquakes are called **Supershear Earthquakes**

Supersonic



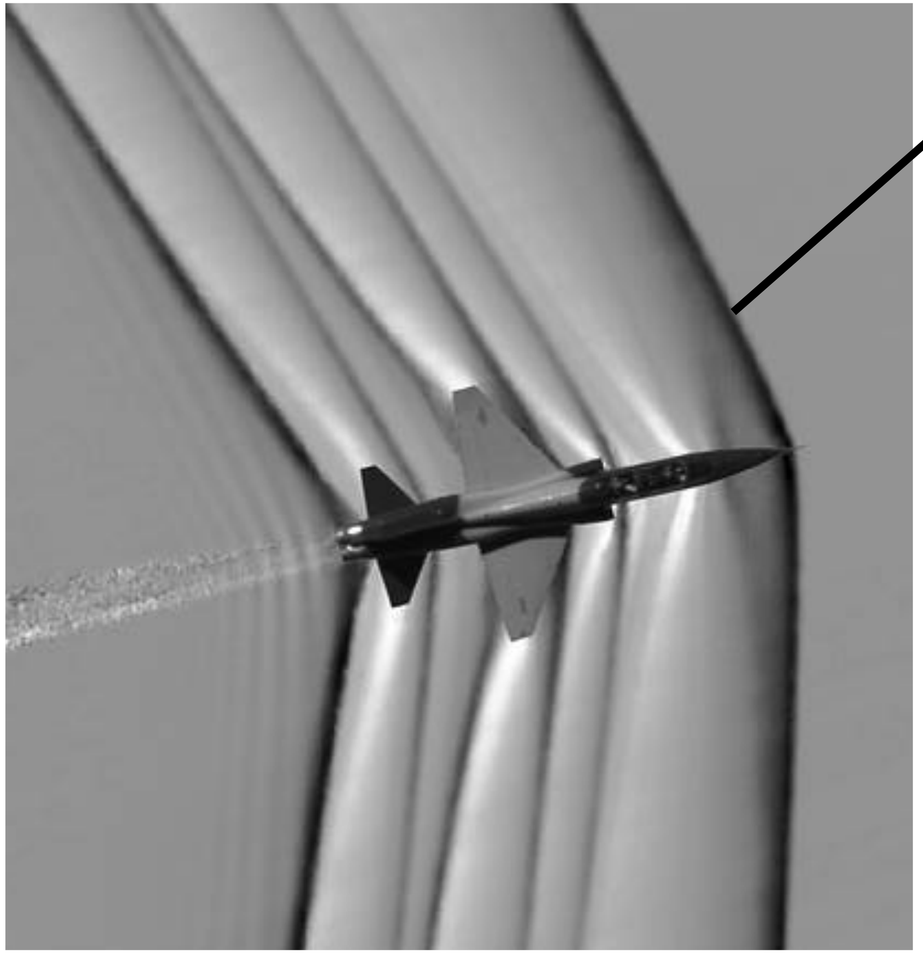
https://www.nasa.gov/image-feature/stark-beauty-of-supersonic-shock-waves

Supershear

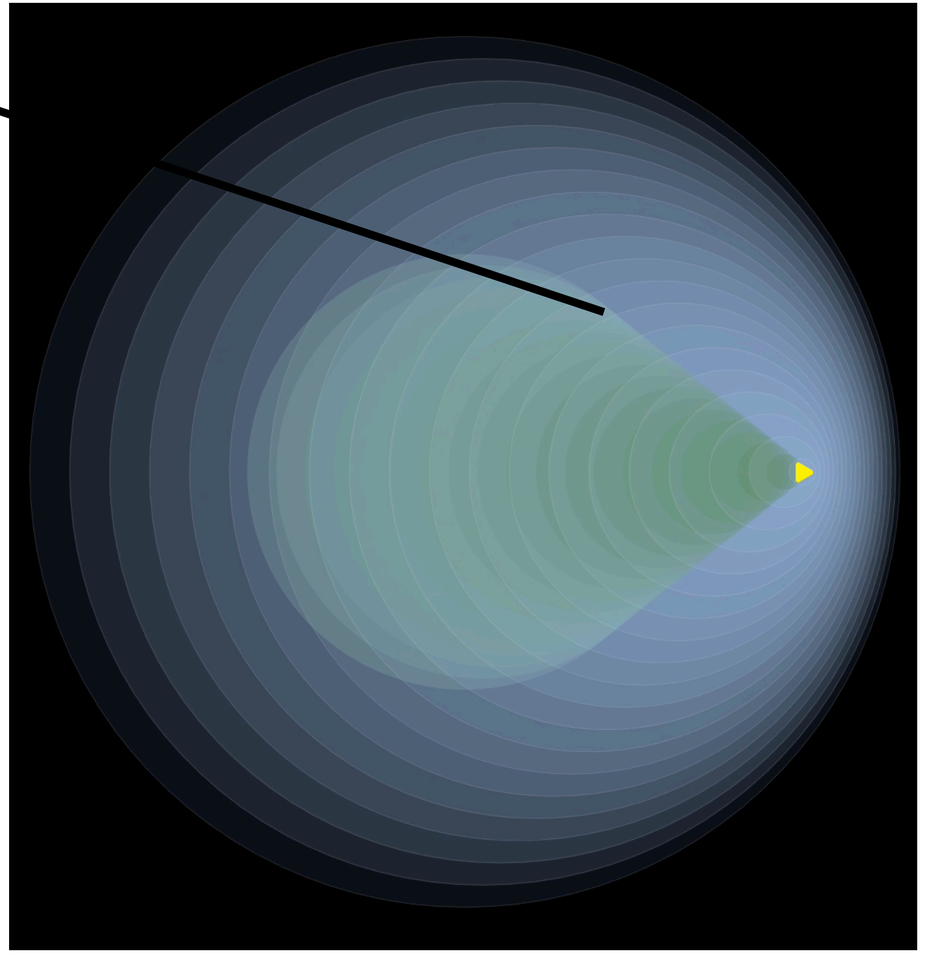


Supersonic

Supershear



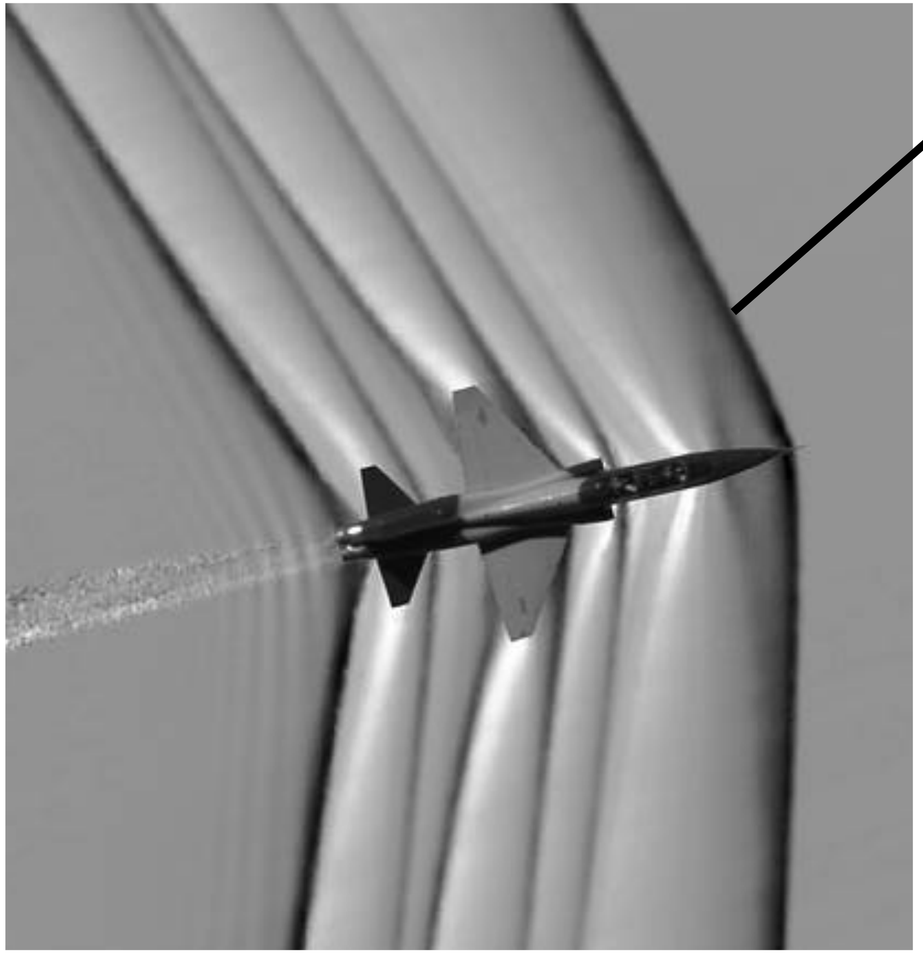
Shock / Mach Front



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

Supersonic

Supershear

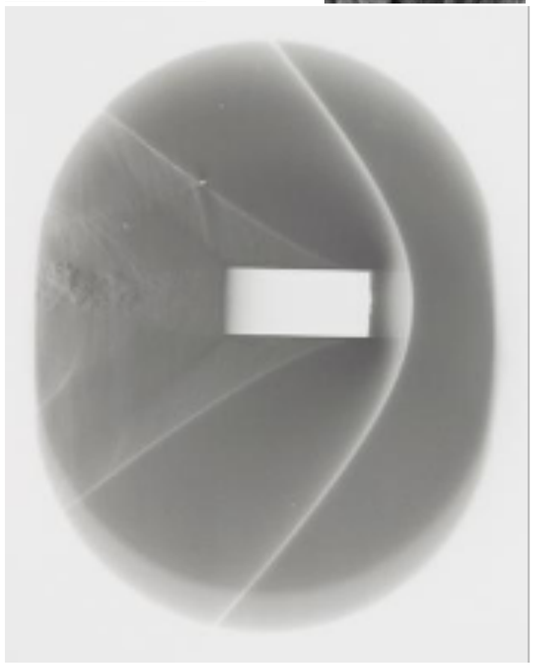


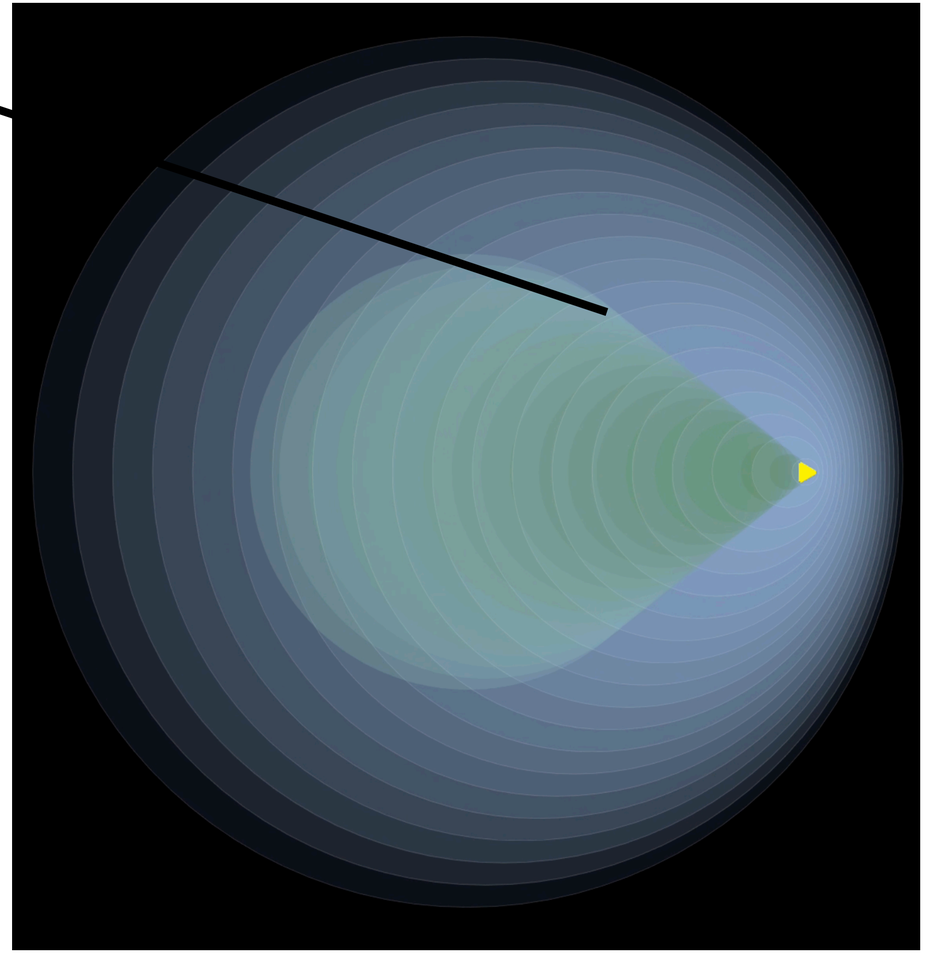
https://www.nasa.gov/image-feature/stark-beauty-of-supersonic-shock-waves

Shock / Mach Front

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

1) Jara, J., L. Bruhat, S. Antoine, K. Okubo, M. Y. Thomas, Y. Klinger, R. Jolivet, and H. S. Bhat (2021). “Signature of supershear transition seen in damage and aftershock pattern”. to be subm.

2) Amlani, F., H. S. Bhat, W. J. F. Simons, A. Schubnel, C. Vigny, A. J. Rosakis, J. Efendi, A. Elbanna, and H. Z. Abidin (2021). “Supershear Tsunamis and insights from the Mw 7.5 Palu Earthquake”. to be subm.

3) Mello, M., H. S. Bhat, and A. J. Rosakis (2016). “Spatiotemporal properties of sub-Rayleigh and supershear rupture velocity fields : Theory and Experiments”. J. Mech. Phys. Solids. DOI: 10.1016/j. jmps.2016.02.031.

4) Mello, M., H. S. Bhat, A. J. Rosakis, and H. Kanamori (2014). “Reproducing The Supershear Portion Of The 2002 Denali Earthquake Rupture In Laboratory”. Earth Planet. Sc. Lett. DOI: 10.1016/j.epsl. 2013.11.030.

5) Passelègue, F. X., A. Schubnel, S. Nielsen, H. S. Bhat, and R. Madariaga (2013). “From Sub-Rayleigh to Supershear Ruptures During Stick-Slip Experiments on Crustal Rocks”. Science. DOI: 10.1126/ science.1235637.

6) Dunham, E. M. and H. S. Bhat (2008). “Attenuation of radiated ground motion and stresses from three-dimensional supershear ruptures”. J. Geophys. Res. DOI: 10.1029/2007JB005182.

7) Bhat, H. S., R. Dmowska, G. C. P. King, Y. Klinger, and J. R. Rice (2007). “Off- fault damage patterns due to supershear ruptures with application to the 2001 Mw 8.1 Kokoxili (Kunlun) Tibet earthquake”. J. Geophys. Res. DOI: 10.1029/2006JB004425.

Theory

Earthquake ruptures modelled as dynamic shear fractures

Theory

Earthquake ruptures modelled as dynamic shear fractures

Craggs (1960) : Solution for a steady state semi-infinite crack, subjected to combined mode I and mode II loading

Theory

Earthquake ruptures modelled as dynamic shear fractures

Craggs (1960) : Solution for a steady state semi-infinite crack, subjected to combined mode I and mode II loading

- Stable crack growth possible if energy from the surrounding linear elastic field is drawn into the crack tip

Theory

Earthquake ruptures modelled as dynamic shear fractures

Craggs (1960) : Solution for a steady state semi-infinite crack, subjected to combined mode I and mode II loading

- Stable crack growth possible if energy from the surrounding linear elastic field is drawn into the crack tip
- Only possible if rupture speed below the Rayleigh wave speed

Theory

Earthquake ruptures modelled as dynamic shear fractures

Craggs (1960) : Solution for a steady state semi-infinite crack, subjected to combined mode I and mode II loading

- Stable crack growth possible if energy from the surrounding linear elastic field is drawn into the crack tip
- Only possible if rupture speed below the Rayleigh wave speed

Kostrov (1964) : Self-similar solution of a propagating shear crack

Theory

Earthquake ruptures modelled as dynamic shear fractures

Craggs (1960) : Solution for a steady state semi-infinite crack, subjected to combined mode I and mode II loading

- Stable crack growth possible if energy from the surrounding linear elastic field is drawn into the crack tip
- Only possible if rupture speed below the Rayleigh wave speed

Kostrov (1964) : Self-similar solution of a propagating shear crack

- Energy will be radiated out from the crack tip if the rupture speed lies between the Rayleigh and shear wave speeds of the surrounding linear elastic medium. *Thus forbidden.*

Theory

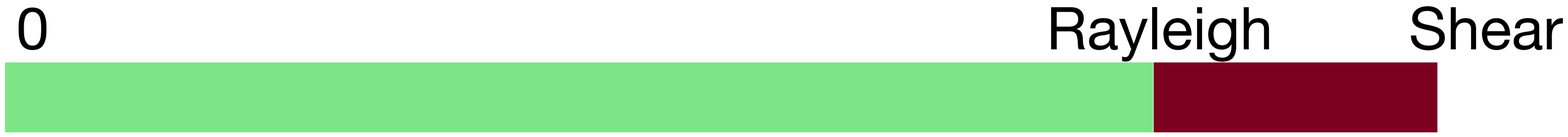
Earthquake ruptures modelled as dynamic shear fractures

Craggs (1960) : Solution for a steady state semi-infinite crack, subjected to combined mode I and mode II loading

- Stable crack growth possible if energy from the surrounding linear elastic field is drawn into the crack tip
- Only possible if rupture speed below the Rayleigh wave speed

Kostrov (1964) : Self-similar solution of a propagating shear crack

- Energy will be radiated out from the crack tip if the rupture speed lies between the Rayleigh and shear wave speeds of the surrounding linear elastic medium. *Thus forbidden.*
- Mode II shear crack will tend to propagate in the sub-Rayleigh rupture speed regime



Theory

Earthquake ruptures modelled as dynamic shear fractures

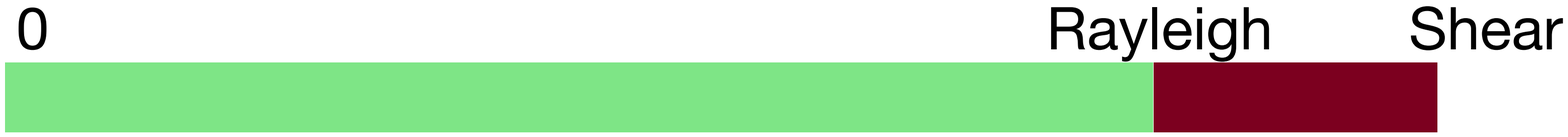
Craggs (1960) : Solution for a steady state semi-infinite crack, subjected to combined mode I and mode II loading

- Stable crack growth possible if energy from the surrounding linear elastic field is drawn into the crack tip
- Only possible if rupture speed below the Rayleigh wave speed

Kostrov (1964) : Self-similar solution of a propagating shear crack

- Energy will be radiated out from the crack tip if the rupture speed lies between the Rayleigh and shear wave speeds of the surrounding linear elastic medium. *Thus forbidden.*
- Mode II shear crack will tend to propagate in the sub-Rayleigh rupture speed regime

Weertman (1969) : Treated the crack as smeared-out dislocations



Theory

Earthquake ruptures modelled as dynamic shear fractures

Craggs (1960) : Solution for a steady state semi-infinite crack, subjected to combined mode I and mode II loading

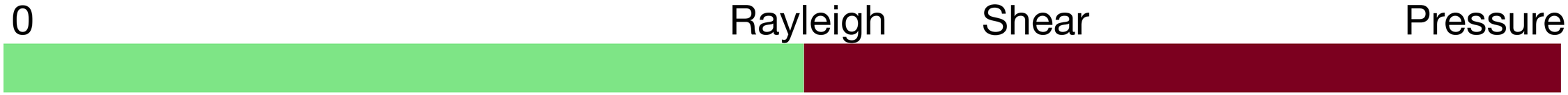
- Stable crack growth possible if energy from the surrounding linear elastic field is drawn into the crack tip
- Only possible if rupture speed below the Rayleigh wave speed

Kostrov (1964) : Self-similar solution of a propagating shear crack

- Energy will be radiated out from the crack tip if the rupture speed lies between the Rayleigh and shear wave speeds of the surrounding linear elastic medium. *Thus forbidden.*
- Mode II shear crack will tend to propagate in the sub-Rayleigh rupture speed regime

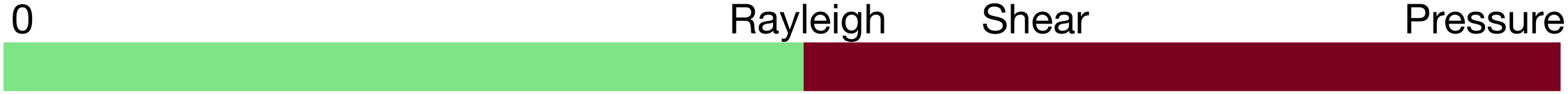
Weertman (1969) : Treated the crack as smeared-out dislocations

- Supershear velocity *is forbidden*



Theory

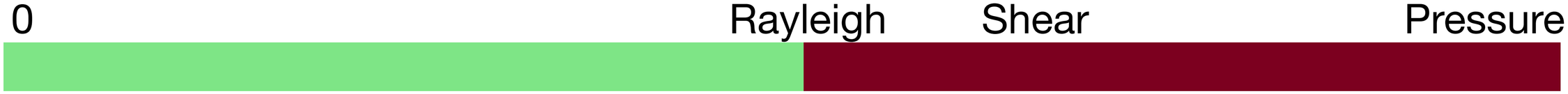
Earthquake ruptures modelled as dynamic shear fractures



Theory

Earthquake ruptures modelled as dynamic shear fractures

Burridge (1973) : Solution for a self-similar mode II crack

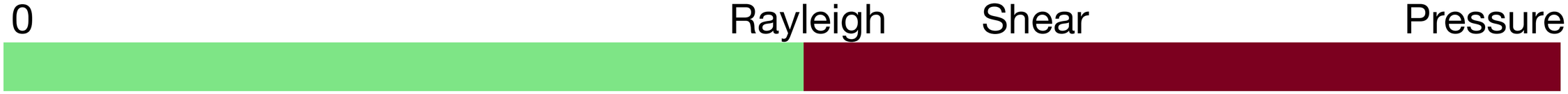


Theory

Earthquake ruptures modelled as dynamic shear fractures

Burridge (1973) : Solution for a self-similar mode II crack

- Showed how to by-pass the forbidden speed regime



Theory

Earthquake ruptures modelled as dynamic shear fractures

Burridge (1973) : Solution for a self-similar mode II crack

- Showed how to by-pass the forbidden speed regime
- A peak in the shear stress propagates ahead of the crack front at the S-wave speed nucleating a secondary (supershear) rupture ahead

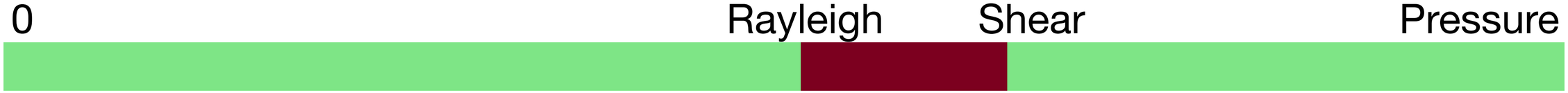
Theory

Earthquake ruptures modelled as dynamic shear fractures

Burridge (1973) : Solution for a self-similar mode II crack

- Showed how to by-pass the forbidden speed regime
- A peak in the shear stress propagates ahead of the crack front at the S-wave speed nucleating a secondary (supershear) rupture ahead

Hamano (1974) : Numerical solution of rupture propagation



Theory

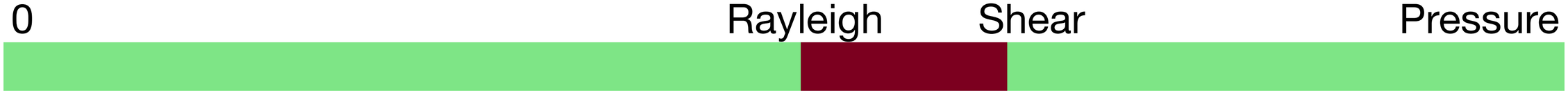
Earthquake ruptures modelled as dynamic shear fractures

Burridge (1973) : Solution for a self-similar mode II crack

- Showed how to by-pass the forbidden speed regime
- A peak in the shear stress propagates ahead of the crack front at the S-wave speed nucleating a secondary (supershear) rupture ahead

Hamano (1974) : Numerical solution of rupture propagation

- Propagation velocity increases monotonically up to the P-wave speed



Theory

Earthquake ruptures modelled as dynamic shear fractures

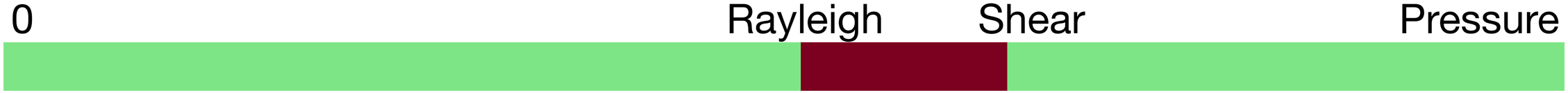
Burridge (1973) : Solution for a self-similar mode II crack

- Showed how to by-pass the forbidden speed regime
- A peak in the shear stress propagates ahead of the crack front at the S-wave speed nucleating a secondary (supershear) rupture ahead

Hamano (1974) : Numerical solution of rupture propagation

- Propagation velocity increases monotonically up to the P-wave speed

Andrews (1976) : Numerically simulated a sub-Rayleigh to supershear rupture transition



Theory

Earthquake ruptures modelled as dynamic shear fractures

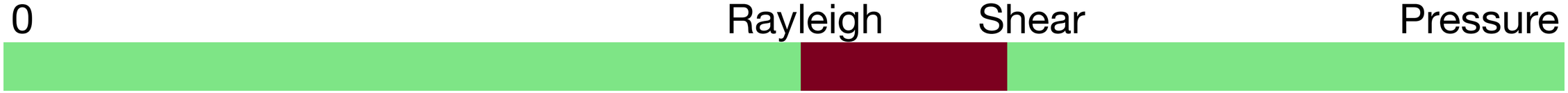
Burridge (1973) : Solution for a self-similar mode II crack

- Showed how to by-pass the forbidden speed regime
- A peak in the shear stress propagates ahead of the crack front at the S-wave speed nucleating a secondary (supershear) rupture ahead

Hamano (1974) : Numerical solution of rupture propagation

- Propagation velocity increases monotonically up to the P-wave speed

Andrews (1976) : Numerically simulated a sub-Rayleigh to supershear rupture transition



Theory

Earthquake ruptures modelled as dynamic shear fractures

Burridge (1973) : Solution for a self-similar mode II crack

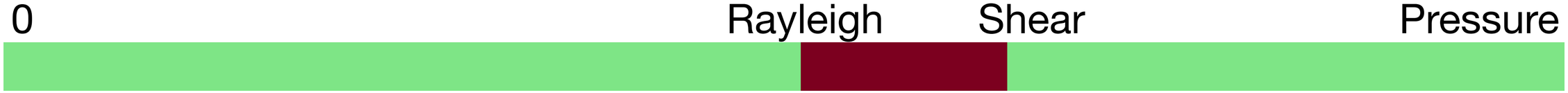
- Showed how to by-pass the forbidden speed regime
- A peak in the shear stress propagates ahead of the crack front at the S-wave speed nucleating a secondary (supershear) rupture ahead

Hamano (1974) : Numerical solution of rupture propagation

- Propagation velocity increases monotonically up to the P-wave speed

Andrews (1976) : Numerically simulated a sub-Rayleigh to supershear rupture transition

- Validated Burridge mechanism of bypassing forbidden regime



Theory

Earthquake ruptures modelled as dynamic shear fractures

Burridge (1973) : Solution for a self-similar mode II crack

- Showed how to by-pass the forbidden speed regime
- A peak in the shear stress propagates ahead of the crack front at the S-wave speed nucleating a secondary (supershear) rupture ahead

Hamano (1974) : Numerical solution of rupture propagation

- Propagation velocity increases monotonically up to the P-wave speed

Andrews (1976) : Numerically simulated a sub-Rayleigh to supershear rupture transition

- Validated Burridge mechanism of bypassing forbidden regime
- Identified mechanically stable portion of the supershear rupture speed regime

Theory

Earthquake ruptures modelled as dynamic shear fractures

Burridge (1973) : Solution for a self-similar mode II crack

- Showed how to by-pass the forbidden speed regime
- A peak in the shear stress propagates ahead of the crack front at the S-wave speed nucleating a secondary (supershear) rupture ahead

Hamano (1974) : Numerical solution of rupture propagation

- Propagation velocity increases monotonically up to the P-wave speed

Andrews (1976) : Numerically simulated a sub-Rayleigh to supershear rupture transition

- Validated Burridge mechanism of bypassing forbidden regime
- Identified mechanically stable portion of the supershear rupture speed regime
- Introduced the notion of a 'transition' length

Theory

Earthquake ruptures modelled as dynamic shear fractures

Theory

Earthquake ruptures modelled as dynamic shear fractures

Das (1976) , Das & Aki (1977) : Numerically simulated a sub-Rayleigh to supershear rupture transition

Theory

Earthquake ruptures modelled as dynamic shear fractures

Das (1976) , Das & Aki (1977) : Numerically simulated a sub-Rayleigh to supershear rupture transition

- Introduced the S - ratio , a non-dimensional measure of the strength of a fault

Theory

Earthquake ruptures modelled as dynamic shear fractures

Das (1976) , Das & Aki (1977) : Numerically simulated a sub-Rayleigh to supershear rupture transition

- Introduced the S - ratio , a non-dimensional measure of the strength of a fault
- Showed that for $S \leq 1.77$ results in supershear rupture

Theory

Earthquake ruptures modelled as dynamic shear fractures

Das (1976) , Das & Aki (1977) : Numerically simulated a sub-Rayleigh to supershear rupture transition

- Introduced the S - ratio , a non-dimensional measure of the strength of a fault
- Showed that for $S \leq 1.77$ results in supershear rupture

Burridge (1979) : Stability analysis of a steady-state shear crack driven by a point load

Theory

Earthquake ruptures modelled as dynamic shear fractures

Das (1976) , Das & Aki (1977) : Numerically simulated a sub-Rayleigh to supershear rupture transition

- Introduced the S - ratio , a non-dimensional measure of the strength of a fault
- Showed that for $S \leq 1.77$ results in supershear rupture

Burridge (1979) : Stability analysis of a steady-state shear crack driven by a point load

- Verified the various admissible speed regimes

Theory

Earthquake ruptures modelled as dynamic shear fractures

Das (1976) , Das & Aki (1977) : Numerically simulated a sub-Rayleigh to supershear rupture transition

- Introduced the S - ratio , a non-dimensional measure of the strength of a fault
- Showed that for $S \leq 1.77$ results in supershear rupture

Burridge (1979) : Stability analysis of a steady-state shear crack driven by a point load

- Verified the various admissible speed regimes

Freund (1979) : Solutions for the stress and particle velocities due to a 2D steady state shear crack

- Stability of sub-shear crack propagation

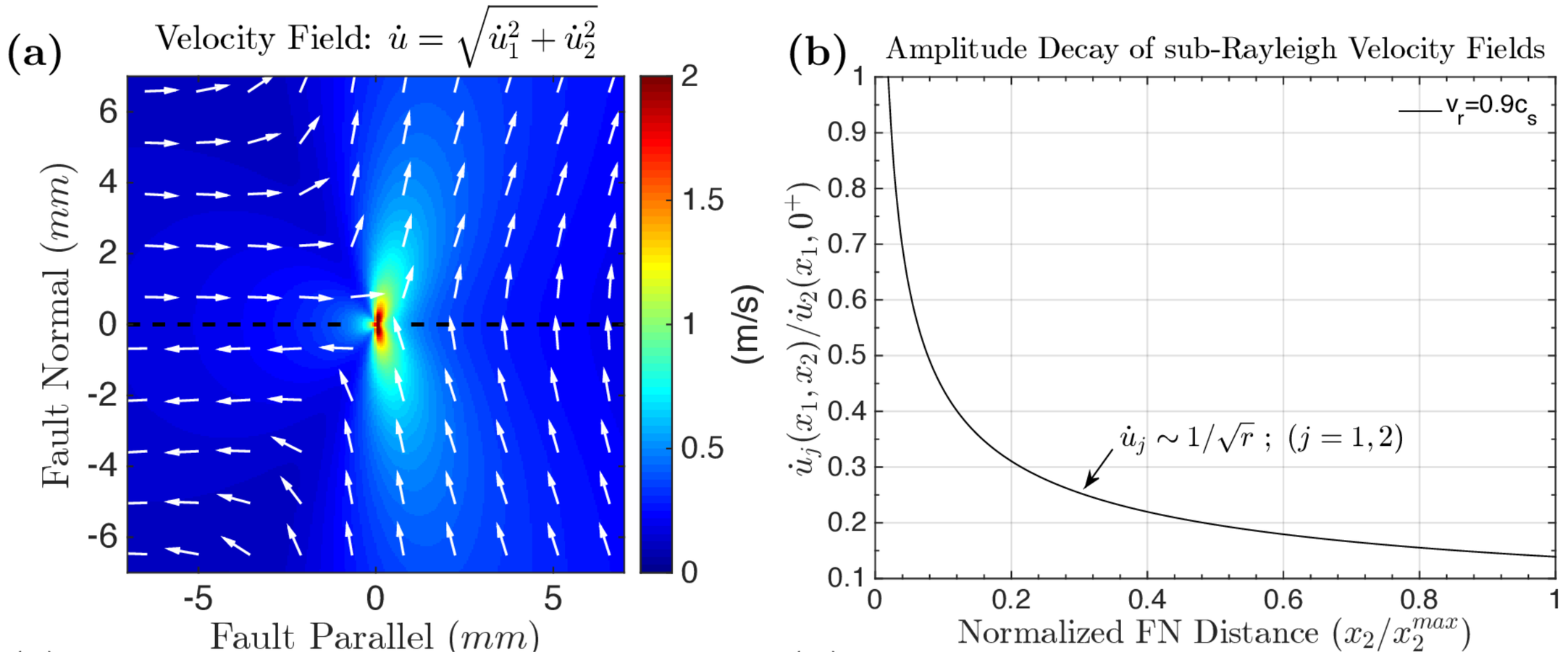
Theory

2D Steady State Singular Elastic Model : Sub-Rayleigh

Mello, Bhat et al. 2016

Theory

2D Steady State Singular Elastic Model : Sub-Rayleigh



Mello, Bhat et al. 2016

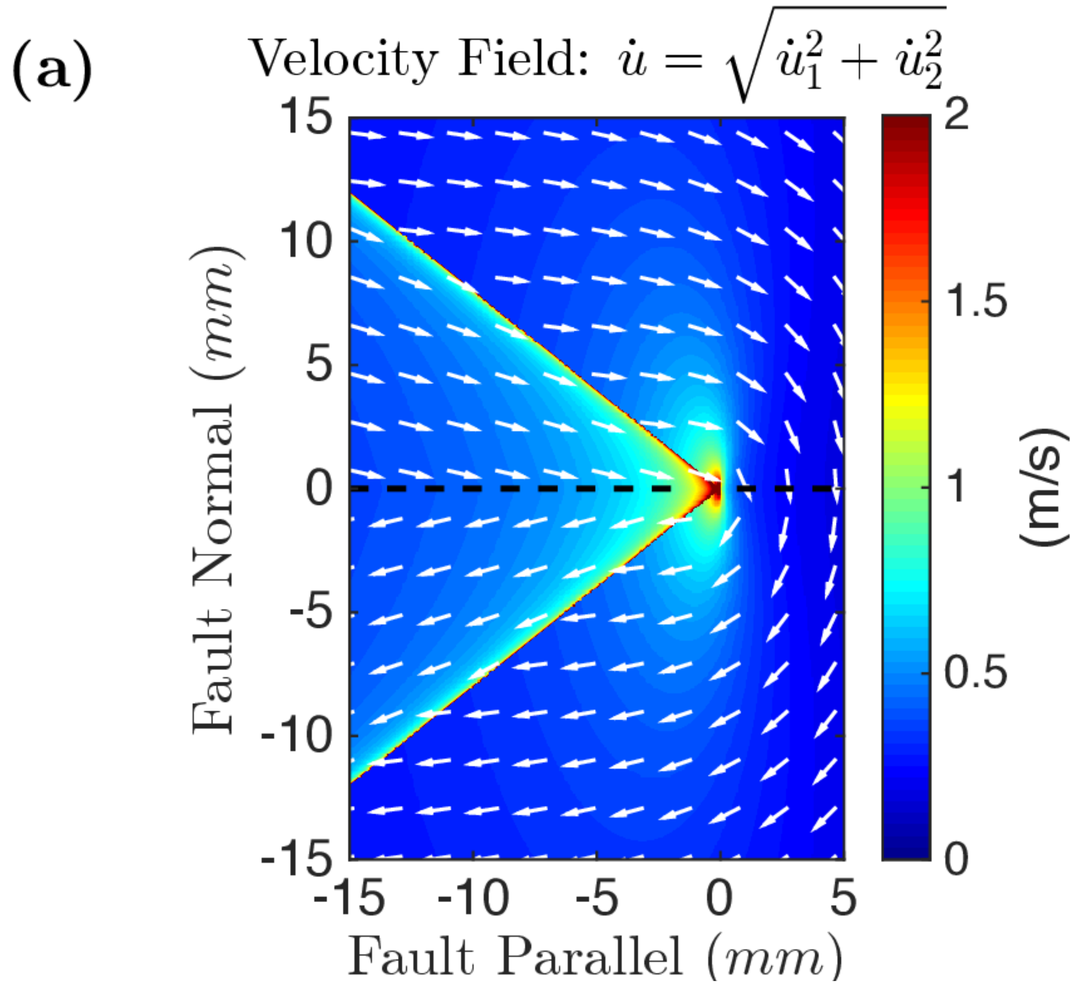
Theory

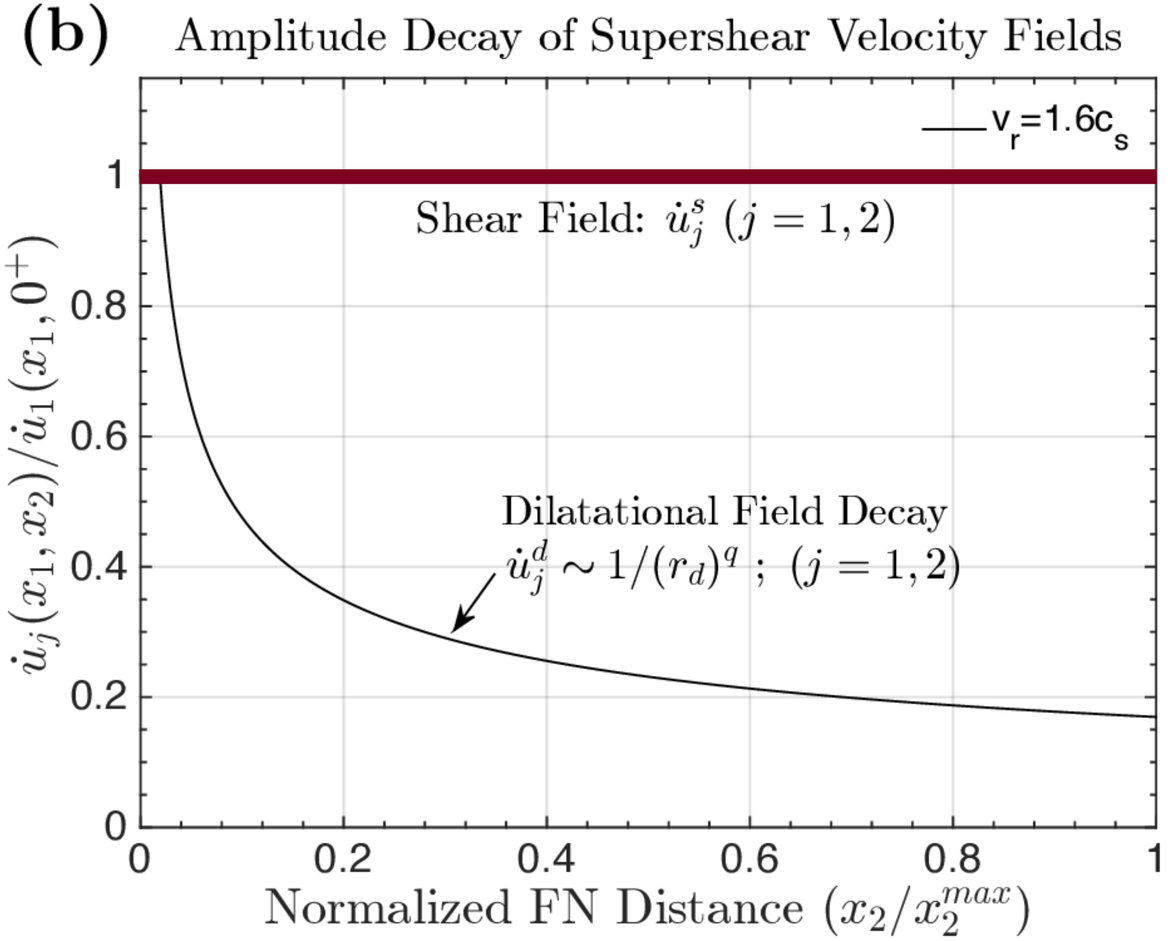
2D Steady State Singular Elastic Model : Supershear

Mello, Bhat et al. 2016

Theory

2D Steady State Singular Elastic Model : Supershear





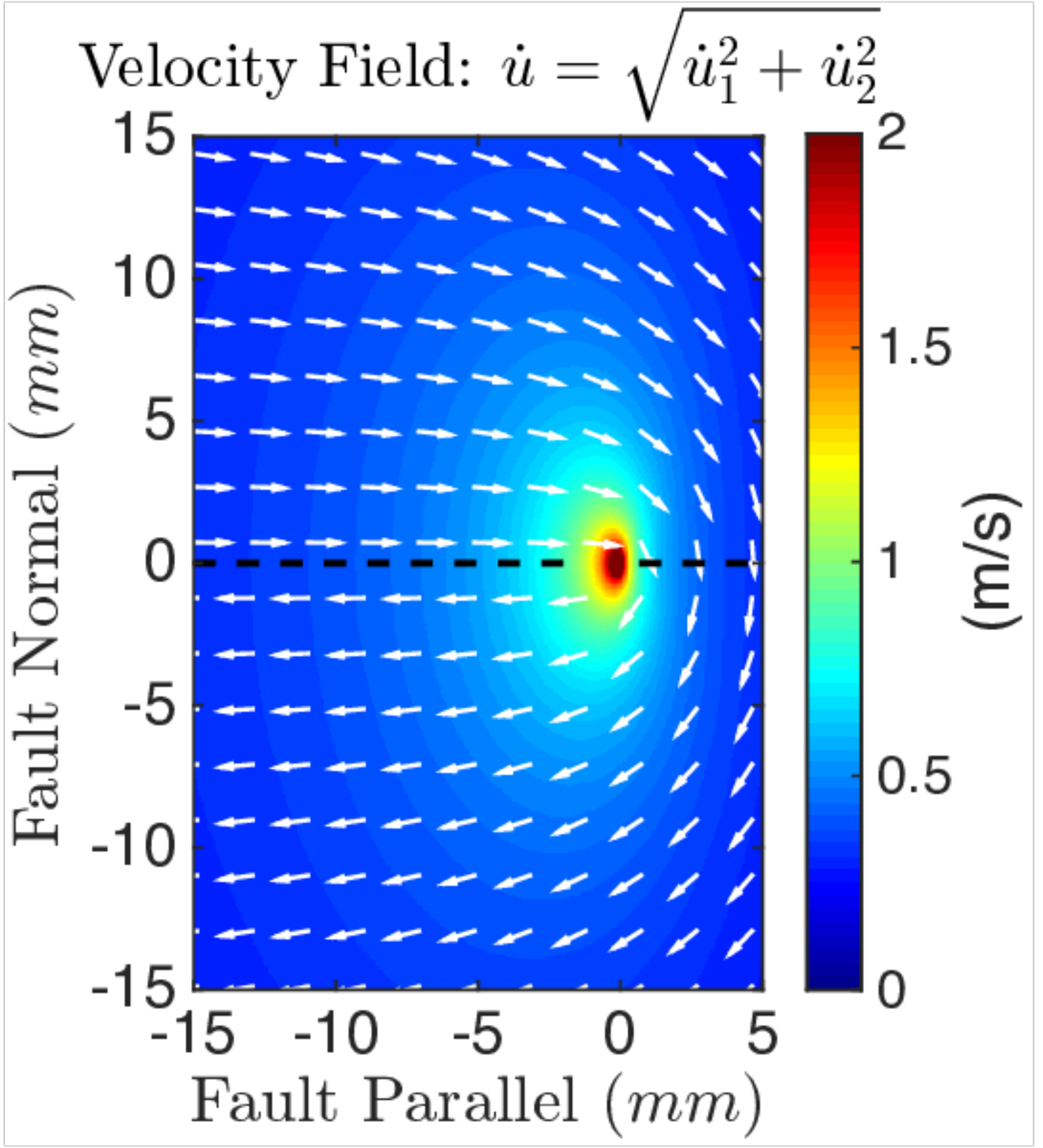
Mello, Bhat et al. 2016

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

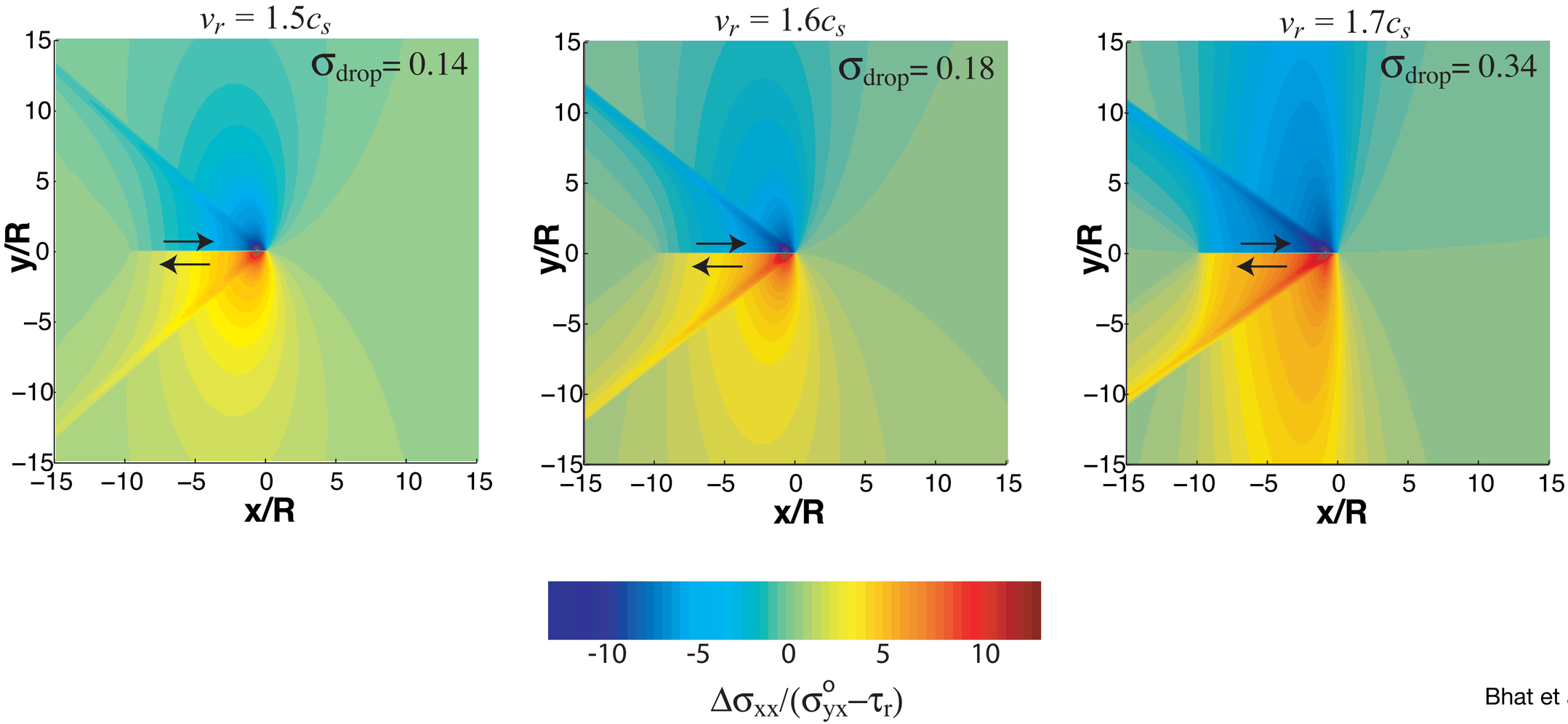
Theory

2D Steady State Cohesive Zone Model : Supershear Stress Field

Bhat et al. 2007

Theory

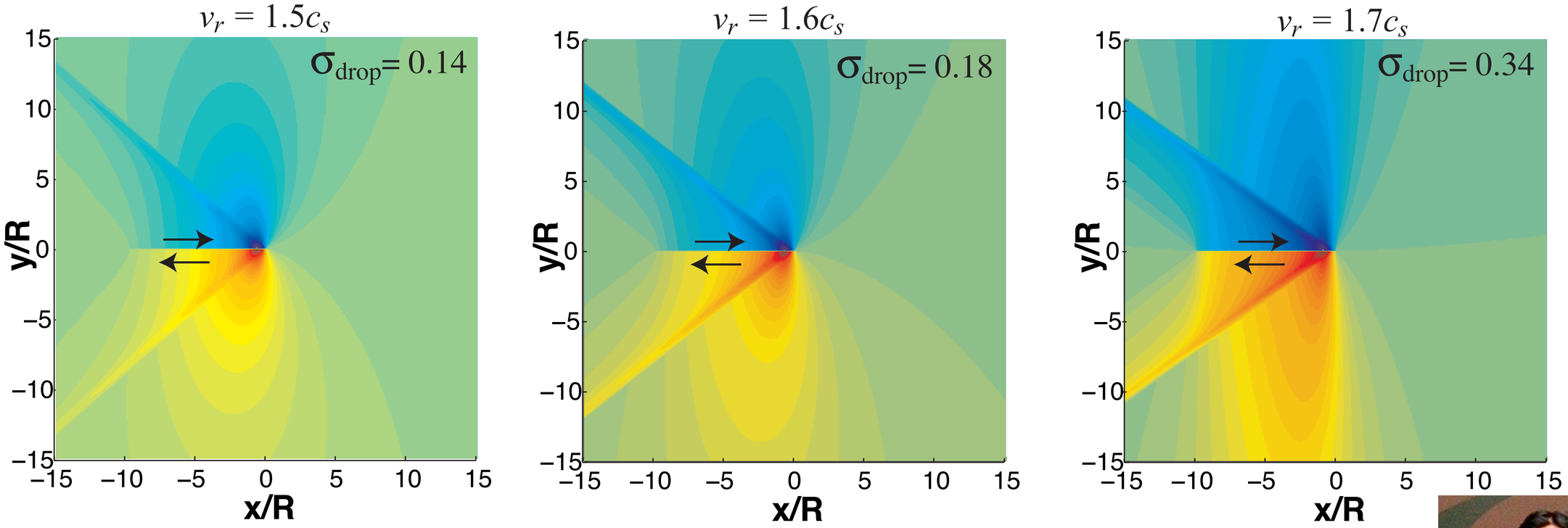
2D Steady State Cohesive Zone Model : Supershear Stress Field

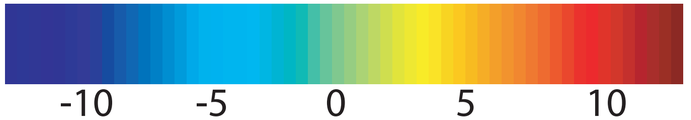


Bhat et al. 2007

Theory

2D Steady State Cohesive Zone Model : Supershear Stress Field





$\Delta\sigma_{xx}/(\sigma^{o}_{yx}-\tau_r)$

Bhat et al. 2007

Theory

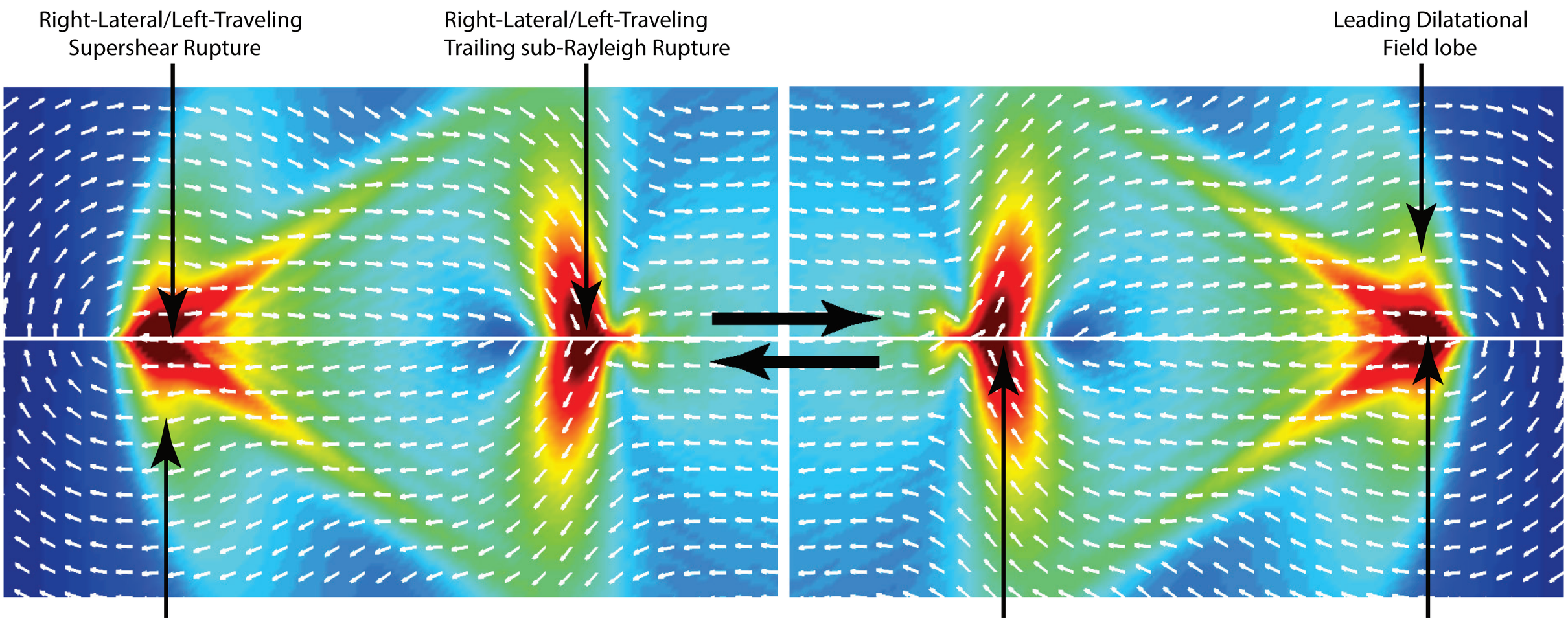
Mello, Bhat et al. 2016

2D Spontaneous Rupture Model : Supershear

Theory

Mello, Bhat et al. 2016

2D Spontaneous Rupture Model : Supershear



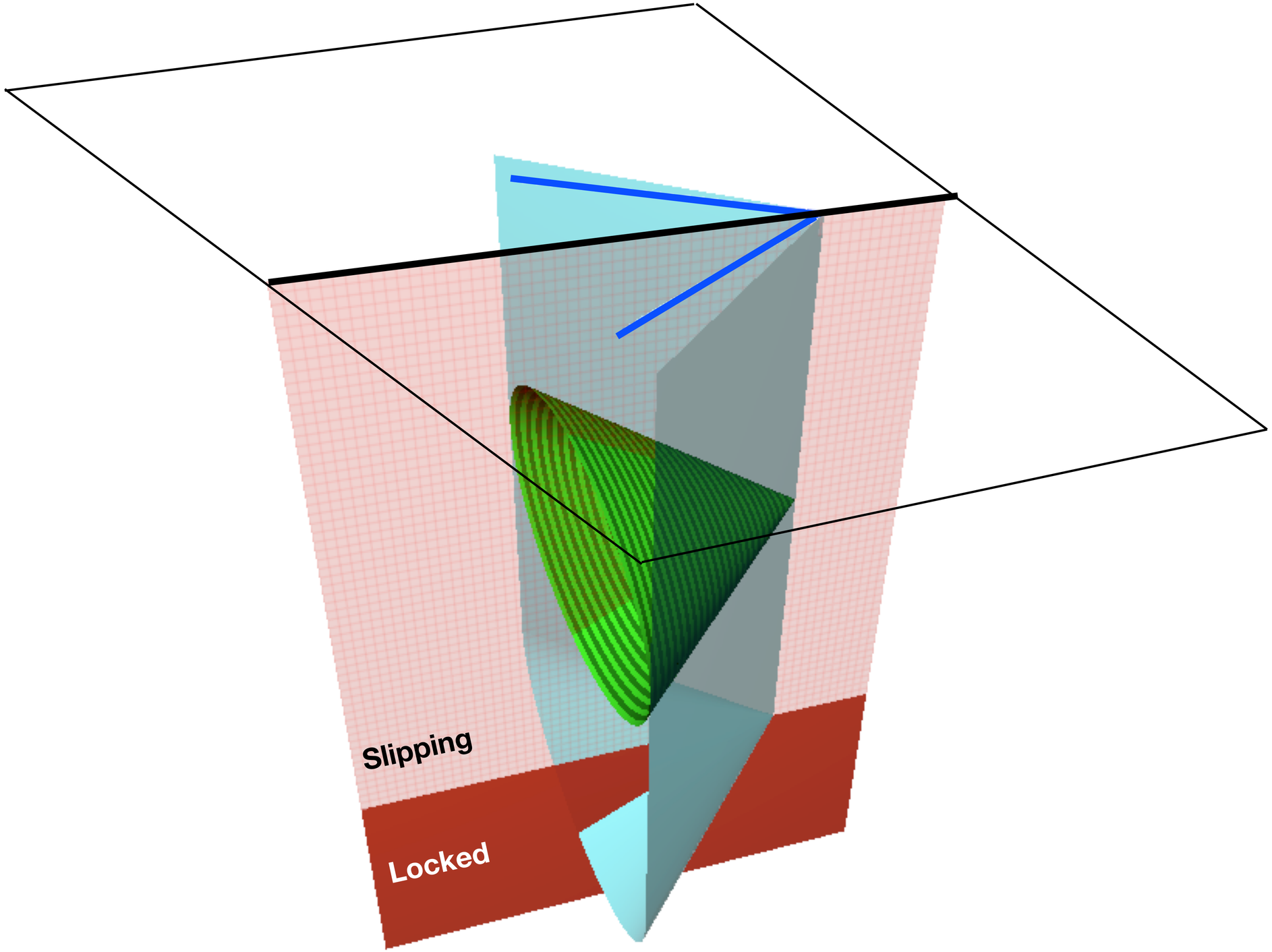
Dunham & Bhat 2008

Theory

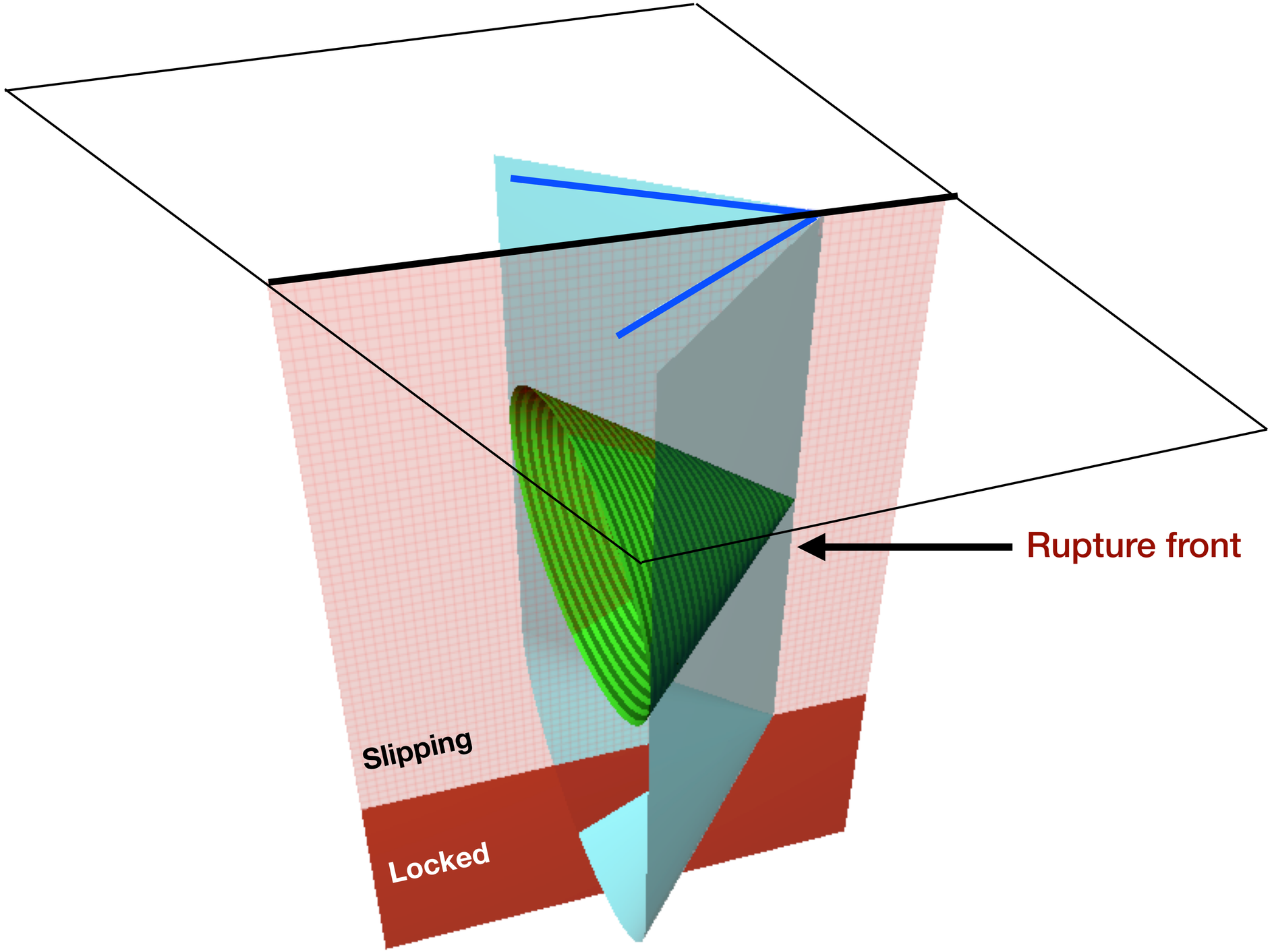
3D Steady State Cohesive Zone Model : Supershear

Dunham & Bhat 2008

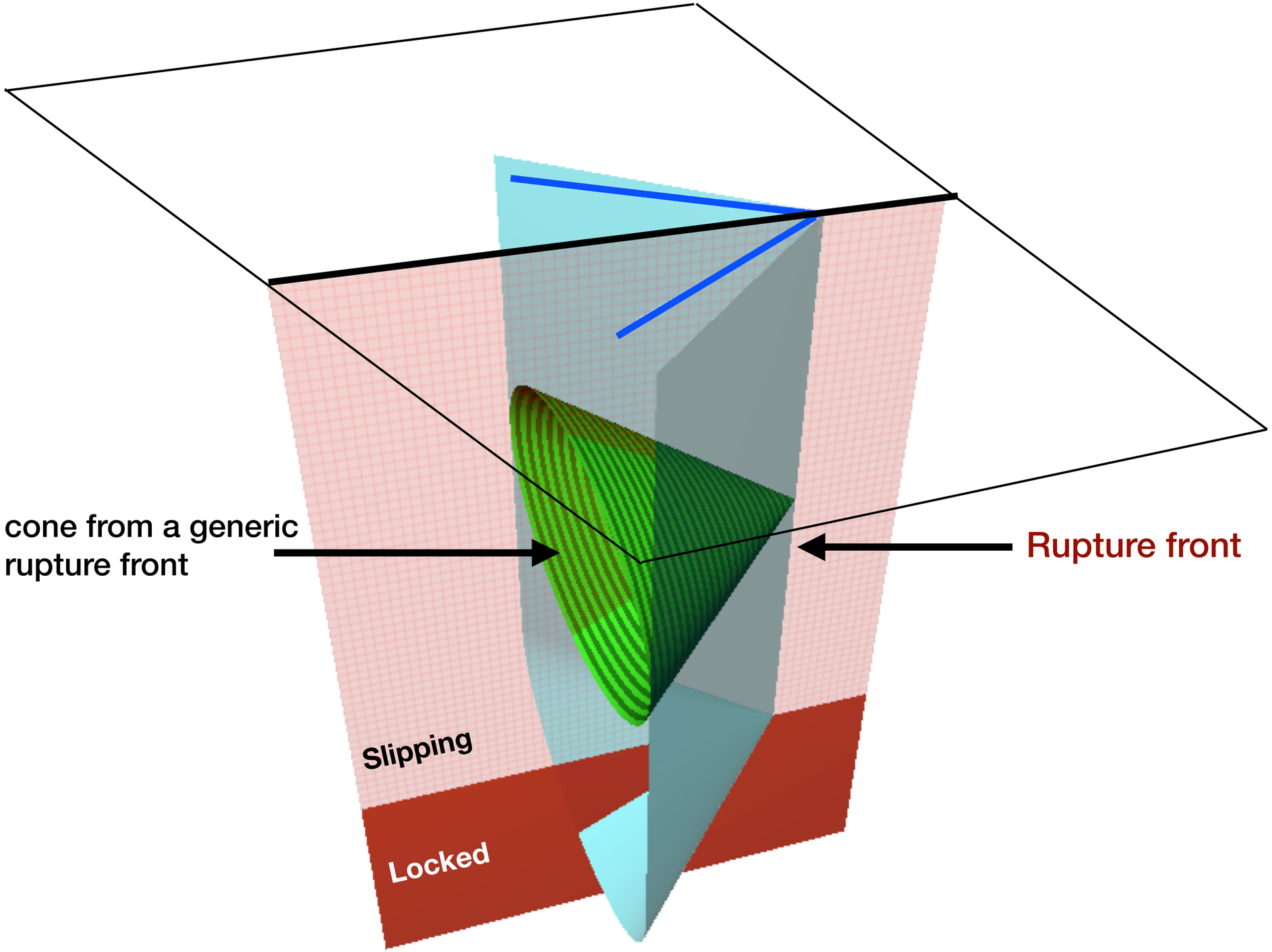
Dunham & Bhat 2008



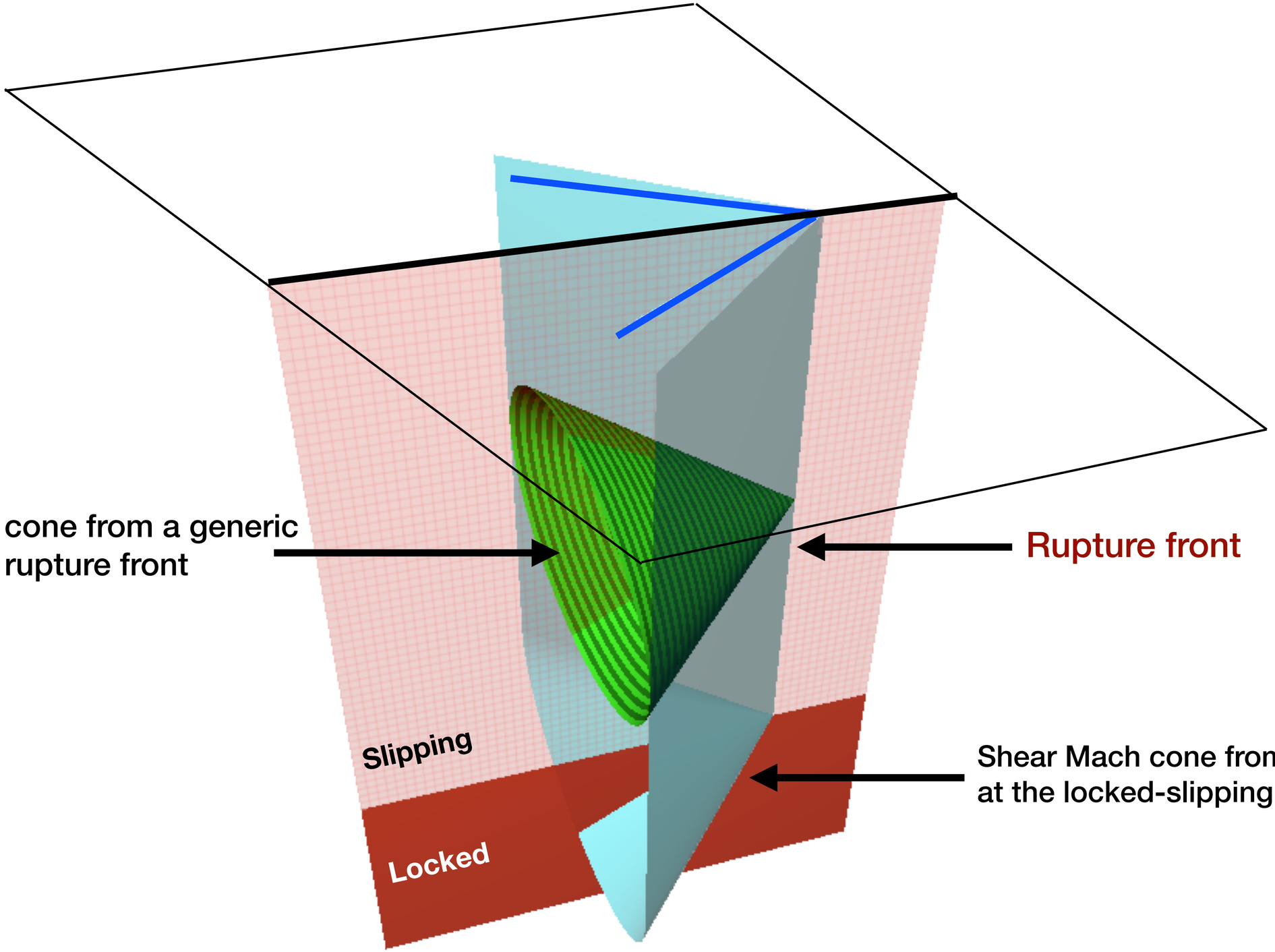
Dunham & Bhat 2008



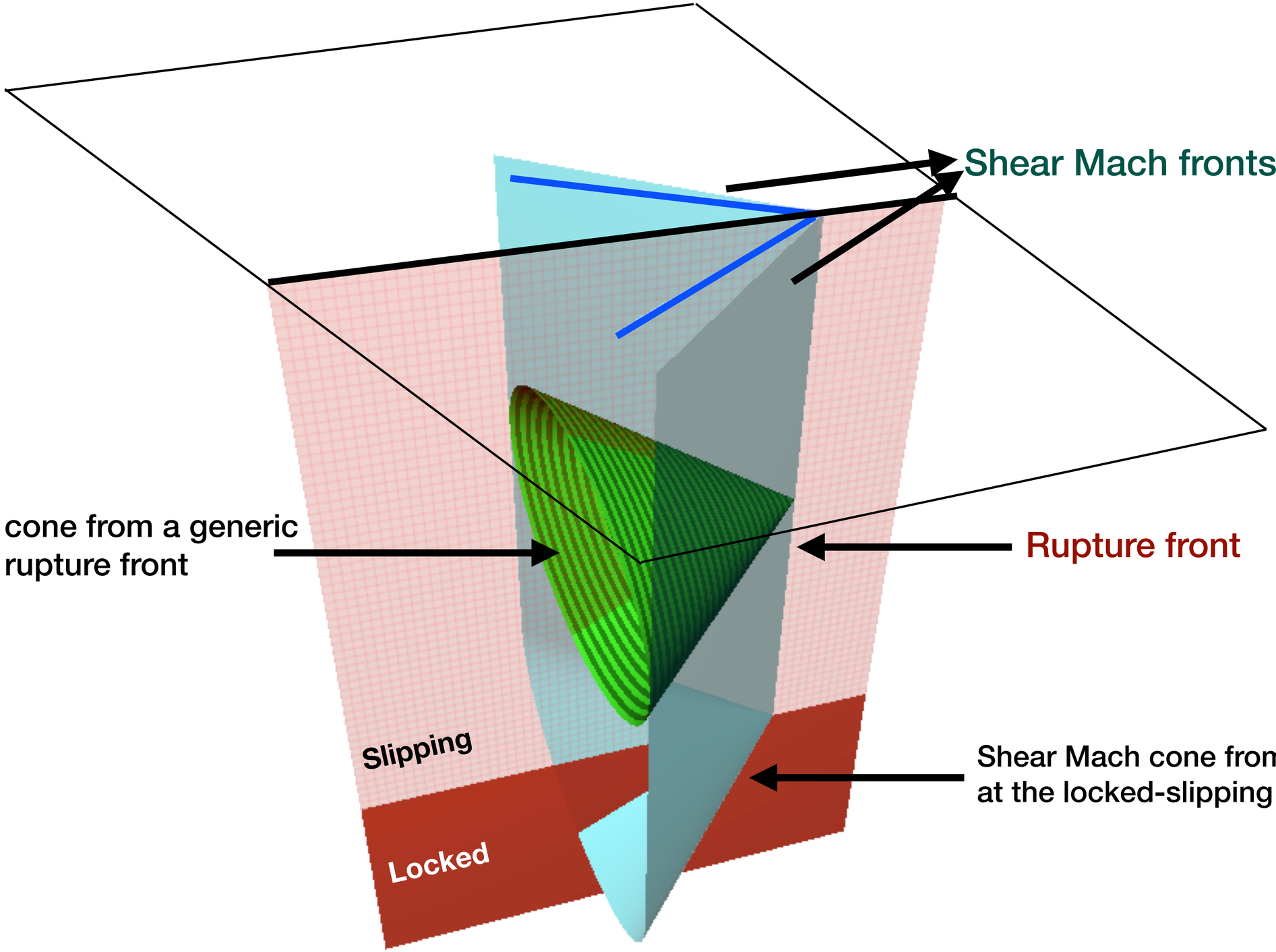
Dunham & Bhat 2008



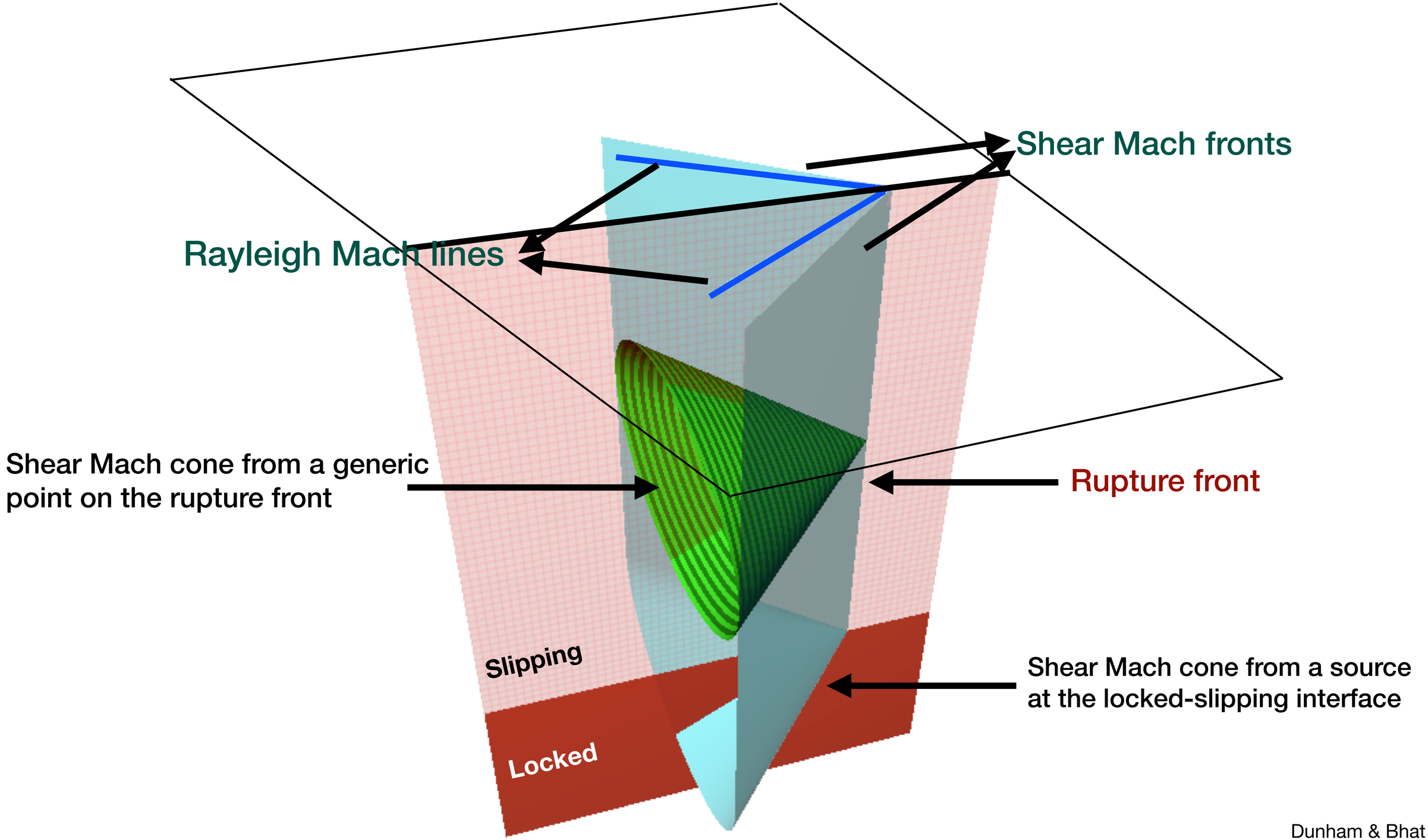
Dunham & Bhat 2008



Dunham & Bhat 2008



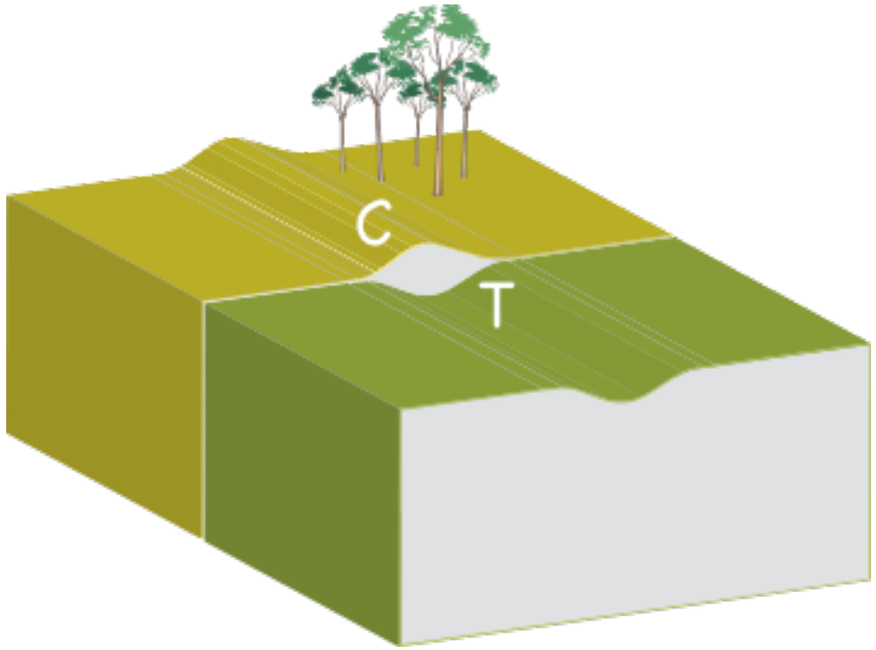
Dunham & Bhat 2008



Dunham & Bhat 2008

Theory

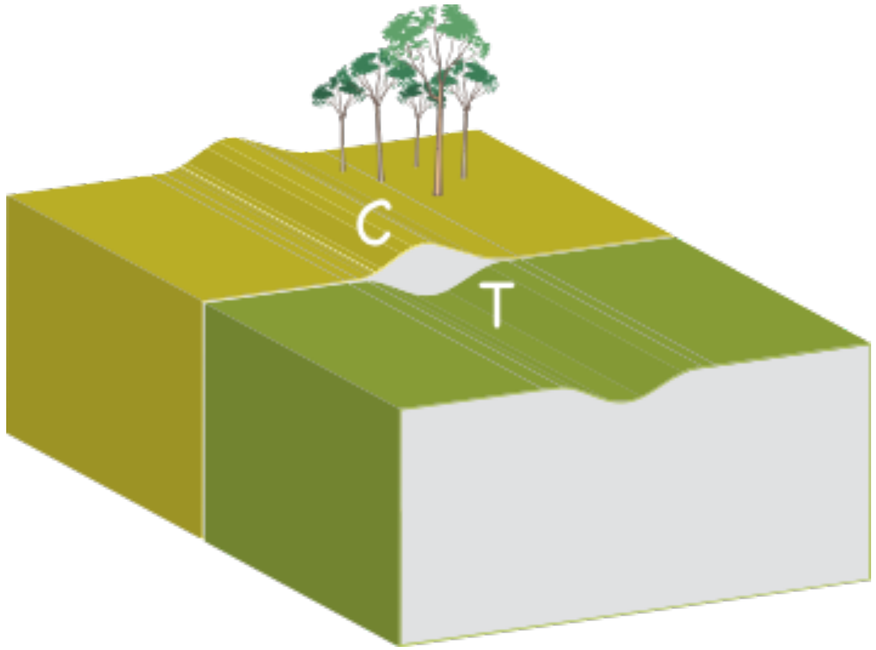
3D Steady State Cohesive Zone Model : Supershear



Dunham & Bhat 2008

Theory

3D Steady State Cohesive Zone Model : Supershear

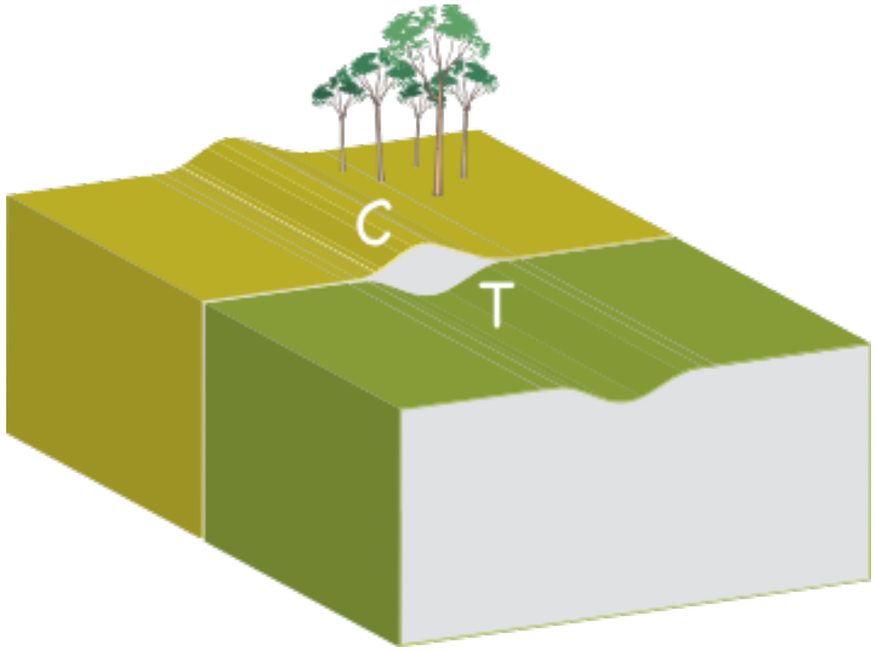


- Rupture tip causes medium to bulge on the compressional side and dimple on the extensional side

Dunham & Bhat 2008

Theory

3D Steady State Cohesive Zone Model : Supershear



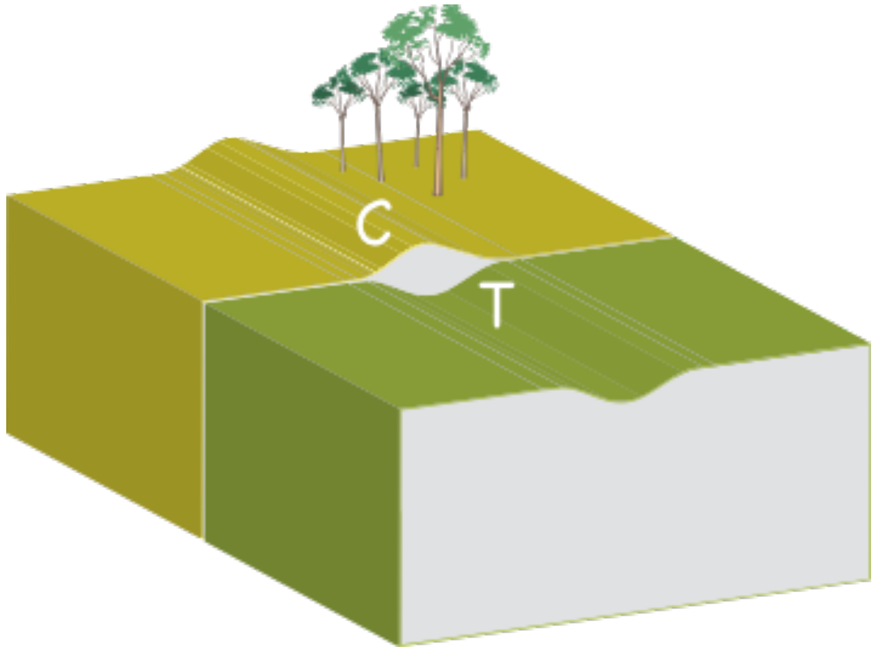
- Rupture tip causes medium to bulge on the compressional side and dimple on the extensional side

- To maintain the traction-free surface, Rayleigh waves are generated

Dunham & Bhat 2008

Theory

3D Steady State Cohesive Zone Model : Supershear



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

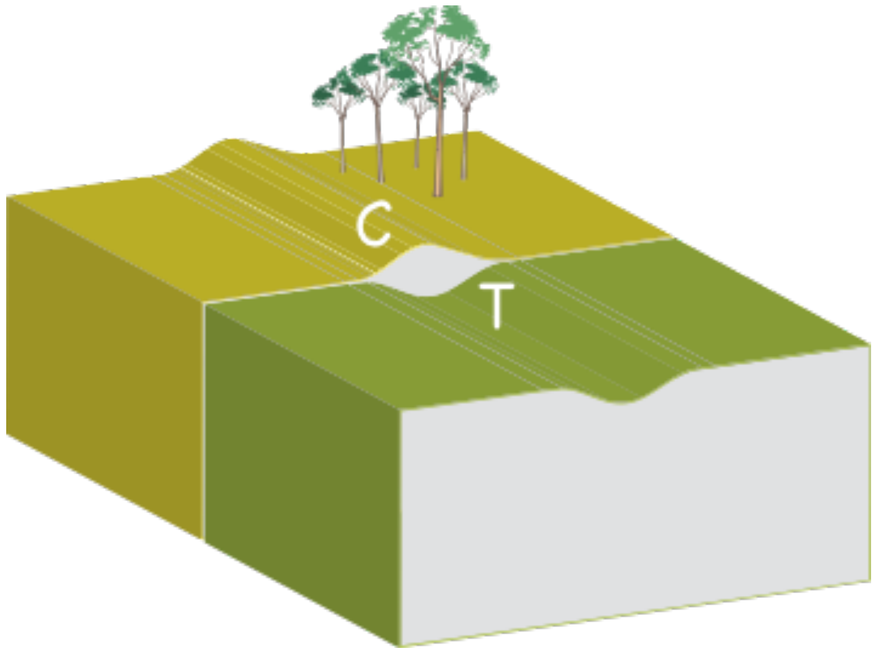
- To maintain the traction-free surface, Rayleigh waves are generated

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

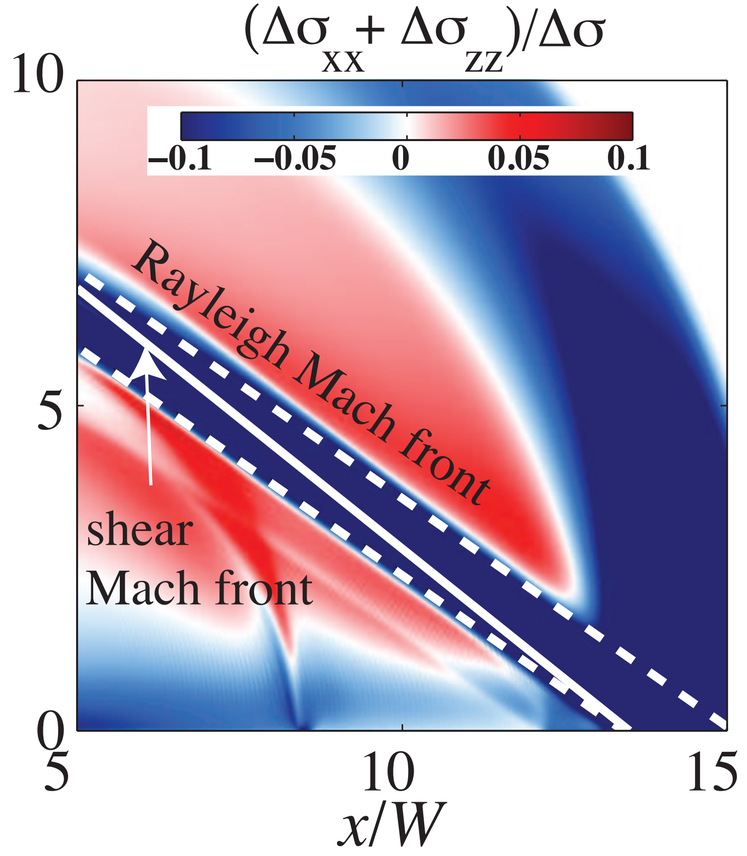
Dunham & Bhat 2008

Theory

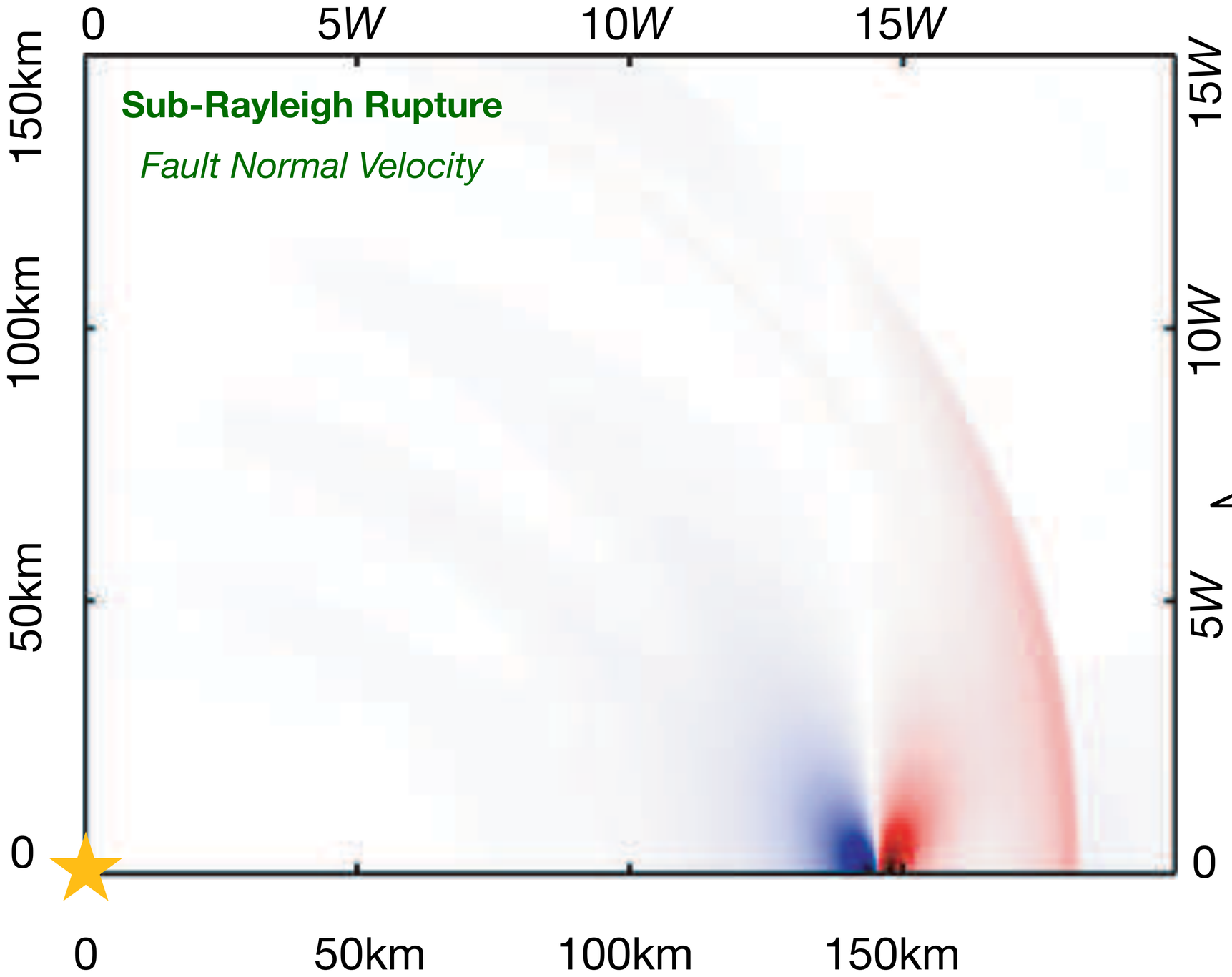
3D Steady State Cohesive Zone Model : Supershear

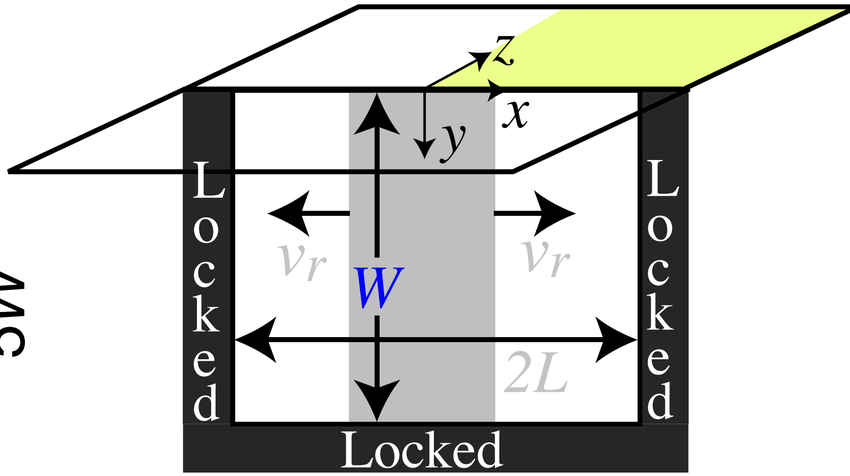


- Rupture tip causes medium to bulge on the compressional side and dimple on the extensional side
- To maintain the traction-free surface, Rayleigh waves are generated
- If rupture is supershear => superRayleigh => Rayleigh Mach fronts

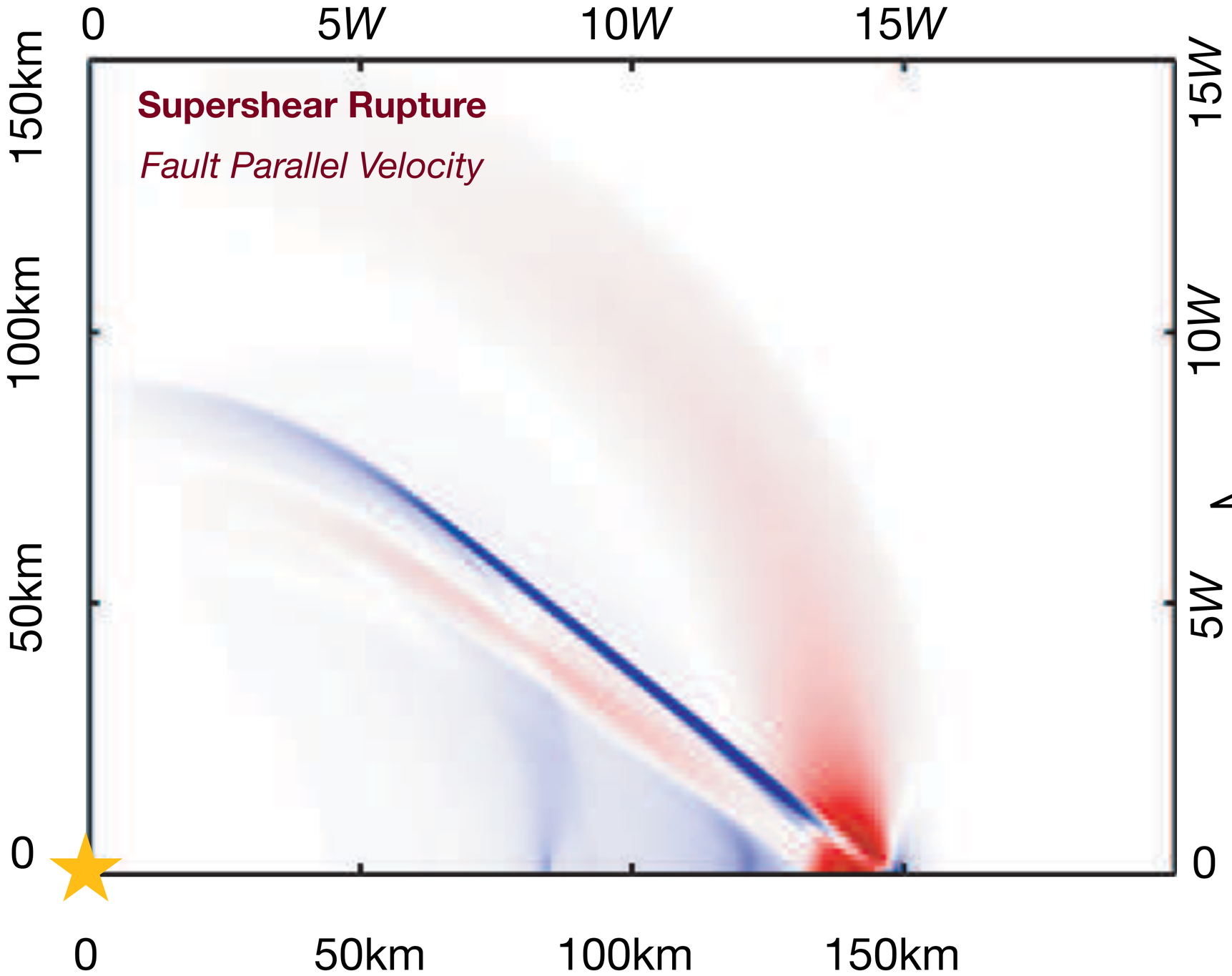


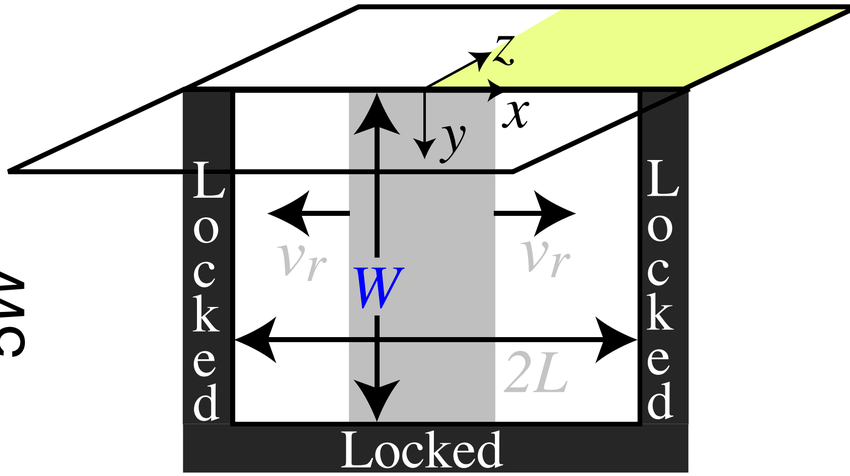
Dunham & Bhat 2008





Dunham & Bhat 2008





Dunham & Bhat 2008

Theory

Sub to Supershear Transition

Theory

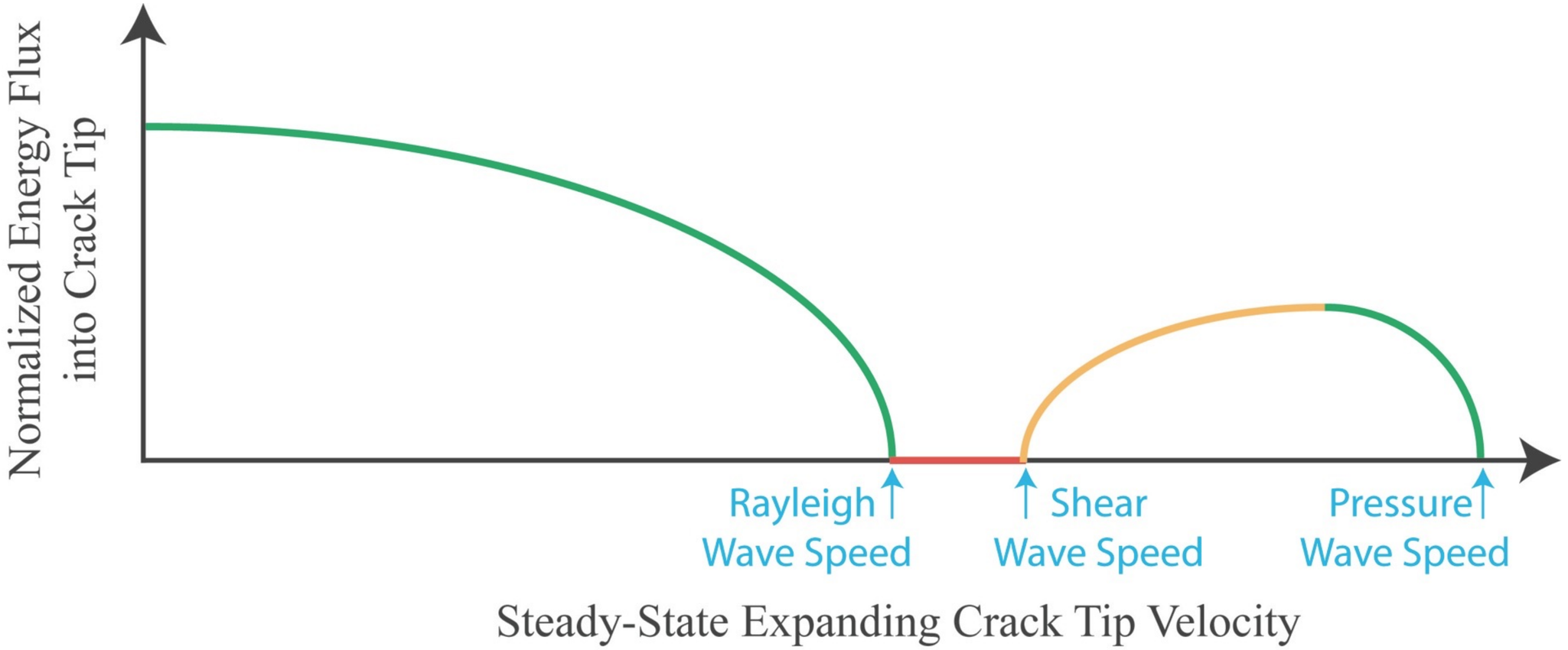
Sub to Supershear Transition

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

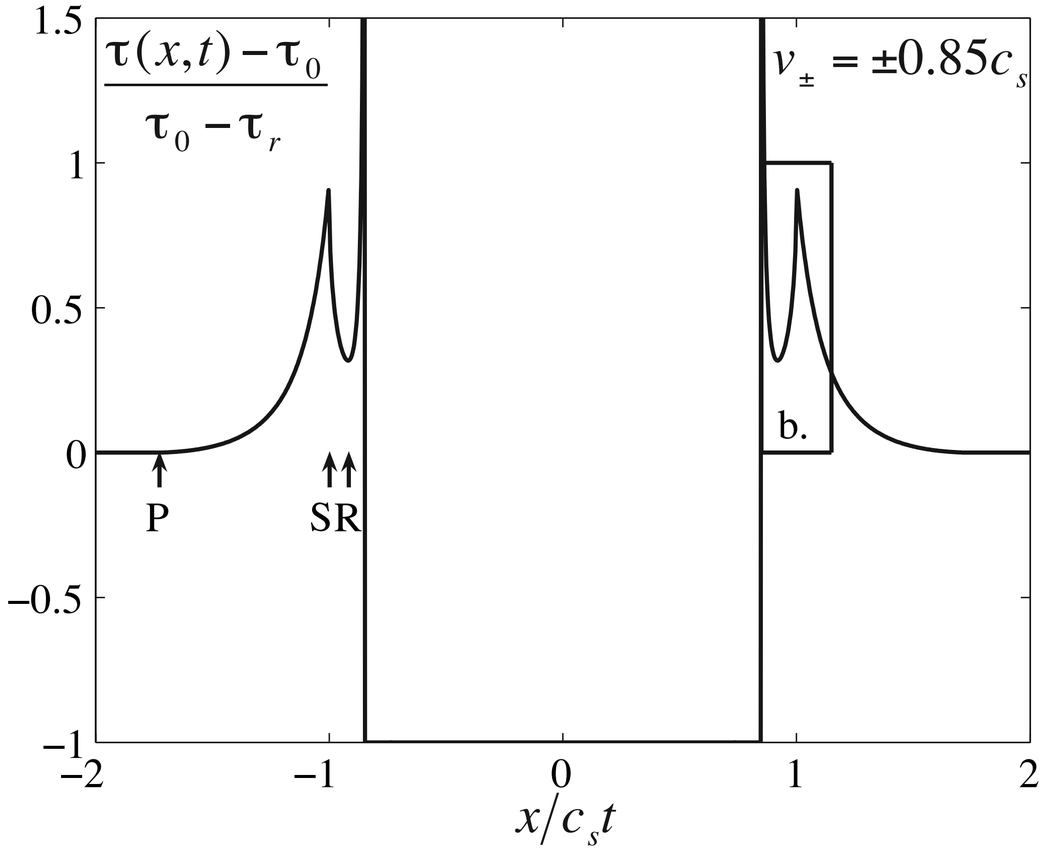
Burridge (1973) & Andrews (1976) : Mother-Daughter transition mechanism

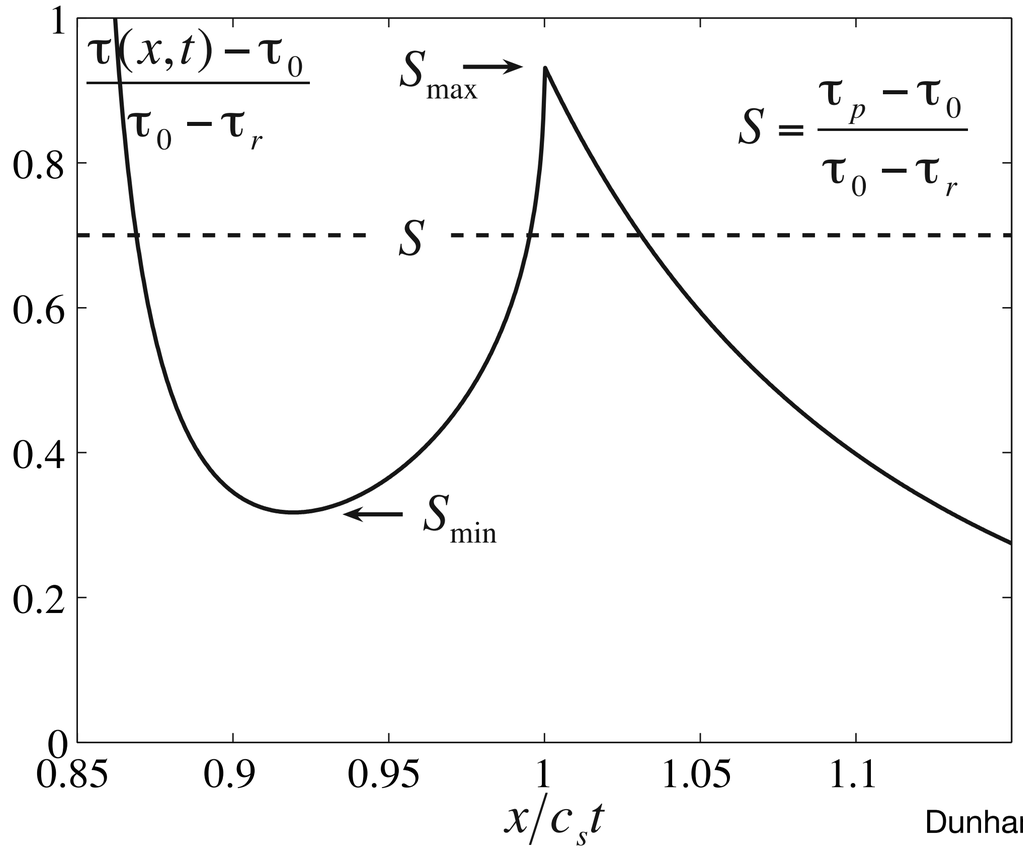
Dunham 2007

Theory

Sub to Supershear Transition

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





Dunham 2007

Theory

Sub to Supershear Transition

Liu et al 2014

Theory

Sub to Supershear Transition

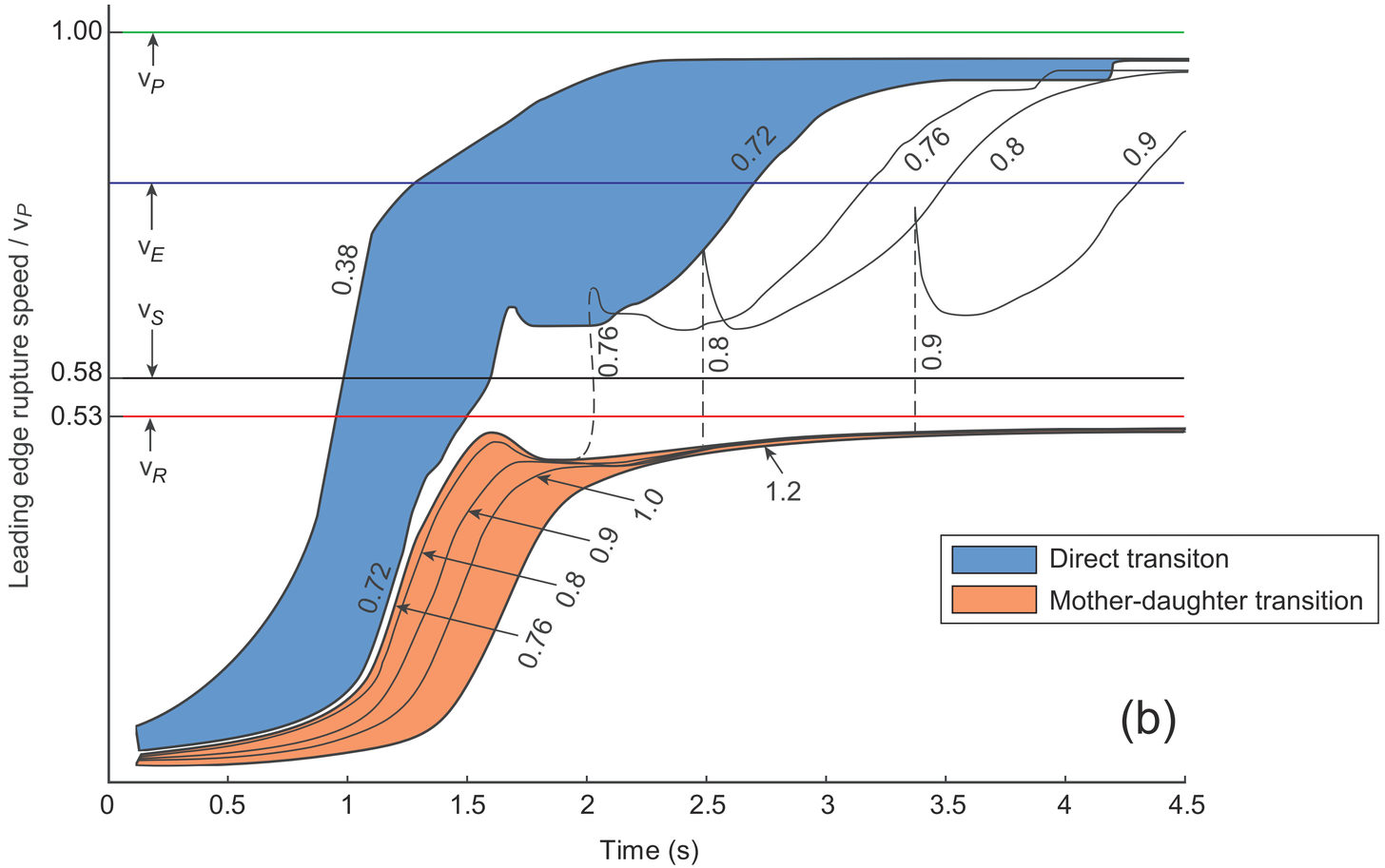
Bizzarri & Das (2012) & Liu et al. (2014) : Continuous transition possible under certain conditions

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

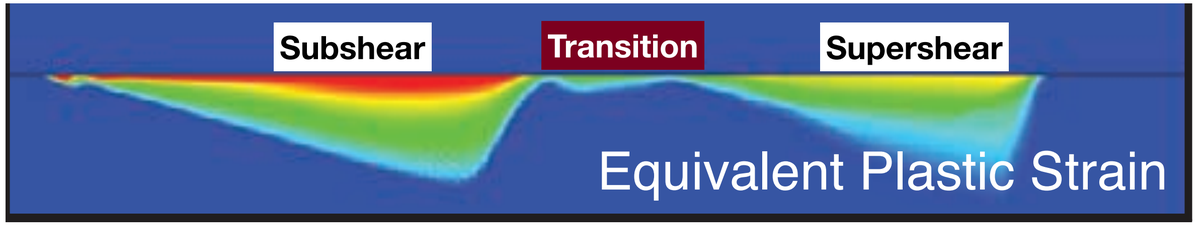
Sub to Supershear Transition : Off-Fault Damage

Jara, Bruhat et al. 2021

Theory

Sub to Supershear Transition : Off-Fault Damage

Mohr-Coulomb Plasticity



Templeton & Rice 2008

Jara, Bruhat et al. 2021

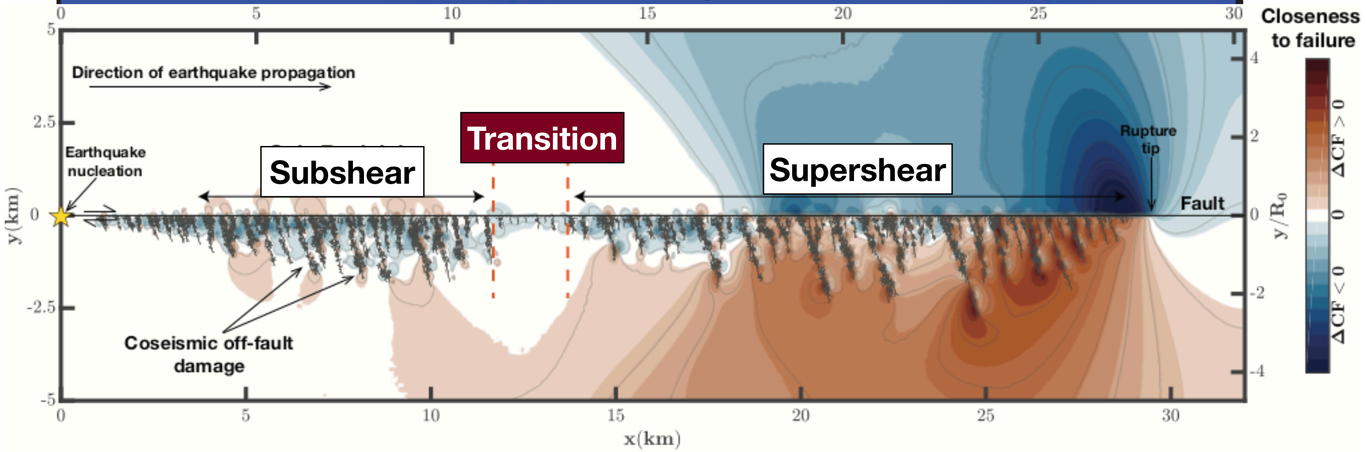
Theory

Sub to Supershear Transition : Off-Fault Damage

Mohr-Coulomb Plasticity

Templeton & Rice 2008

Discrete Damage



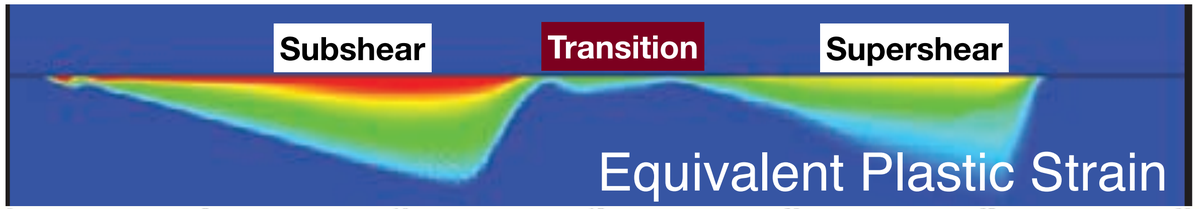
Okubo et al 2019

Jara, Bruhat et al. 2021

Theory

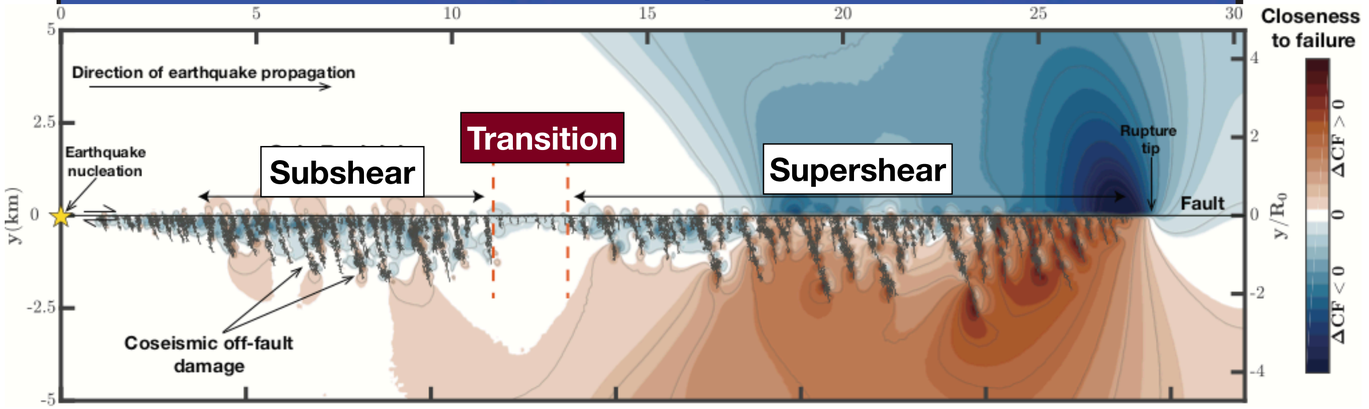
Sub to Supershear Transition : Off-Fault Damage

Mohr-Coulomb Plasticity



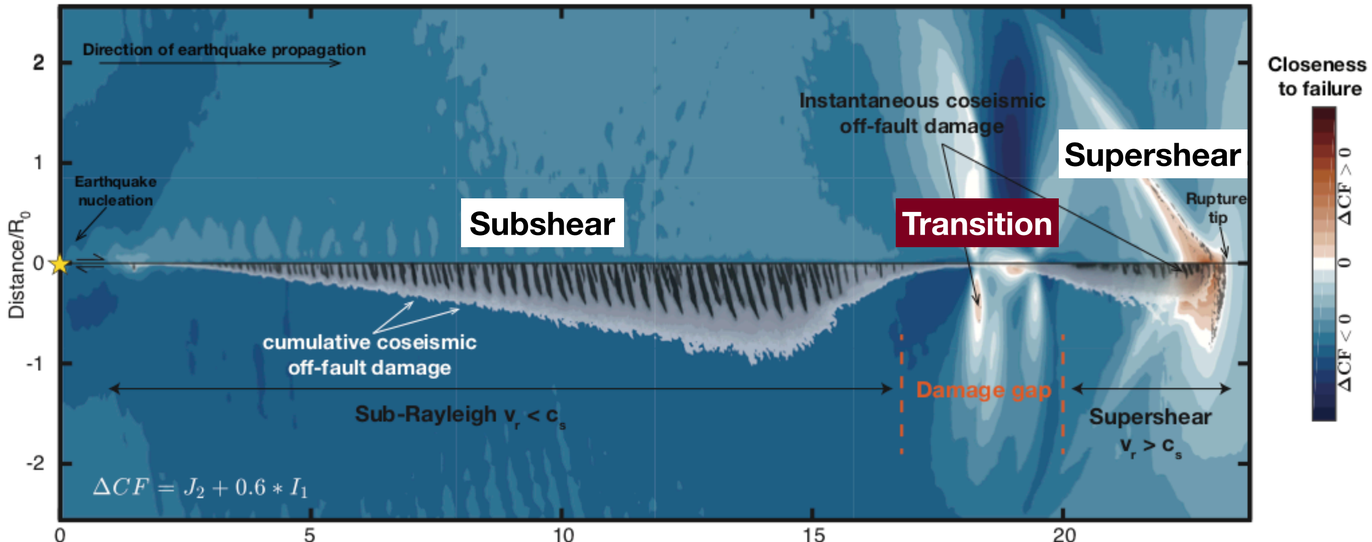
Templeton & Rice 2008

Discrete Damage



Okubo et al 2019

Continuum Damage



Thomas & Bhat 2018

Jara, Bruhat et al. 2021

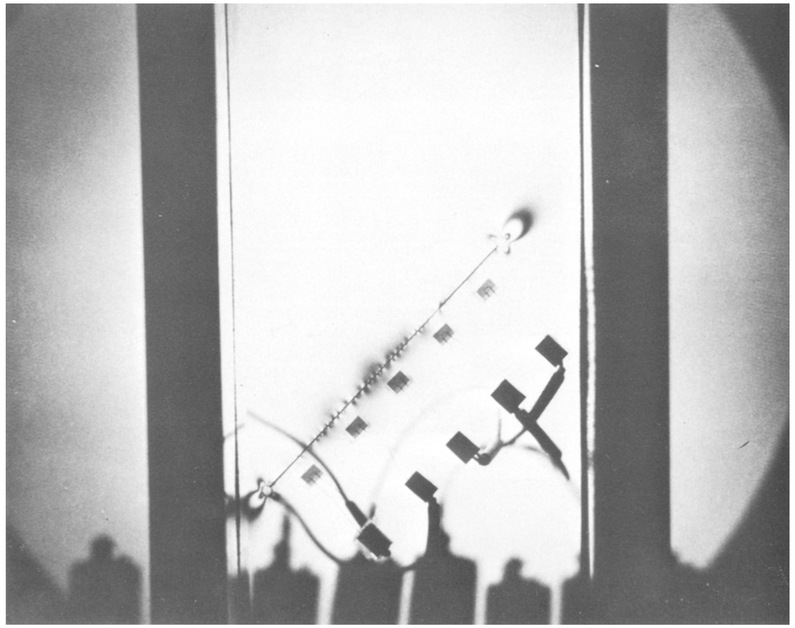
Experiments

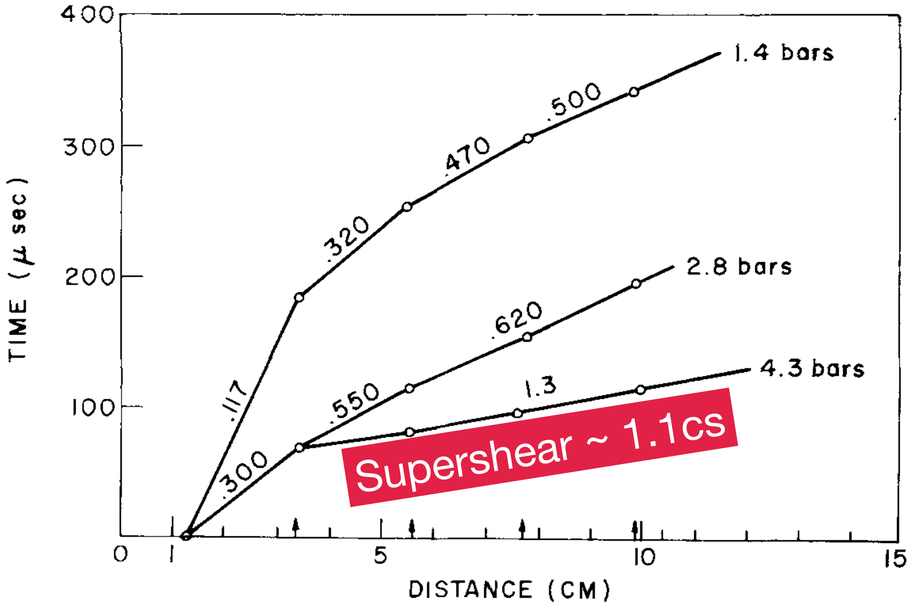
Experiments

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

Experiments

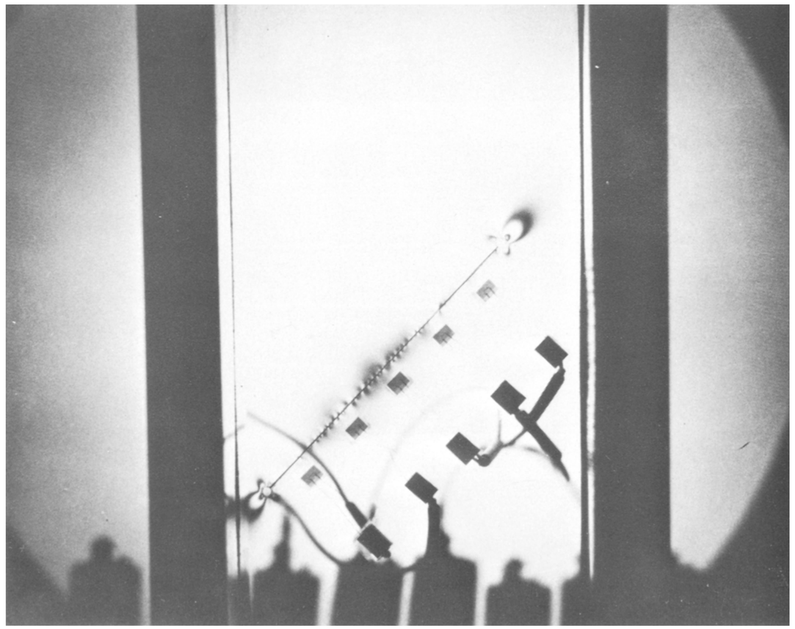
Wu (1972) : Stick-Slip experiments in Columbia Resin

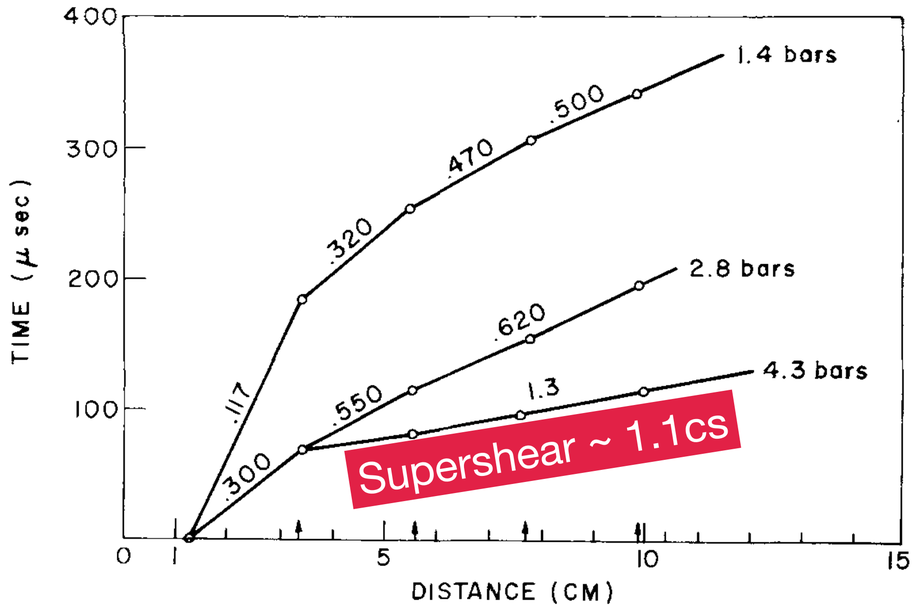




Experiments

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





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

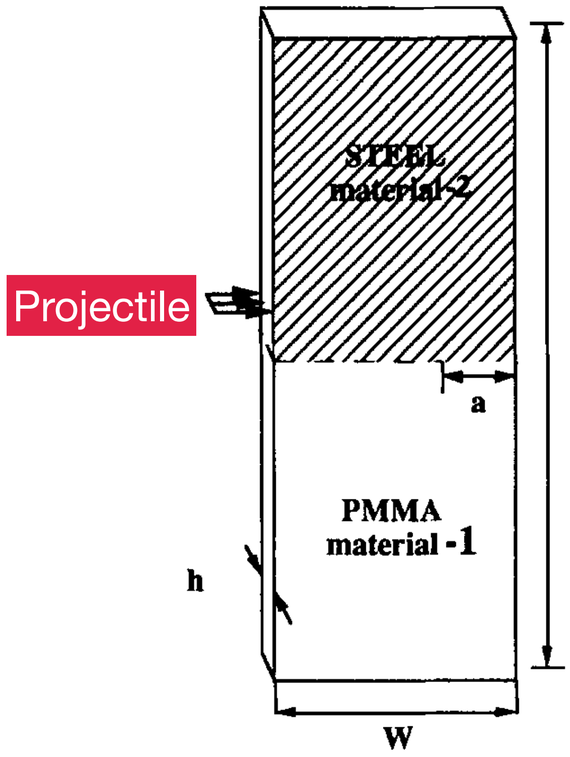
Experiments

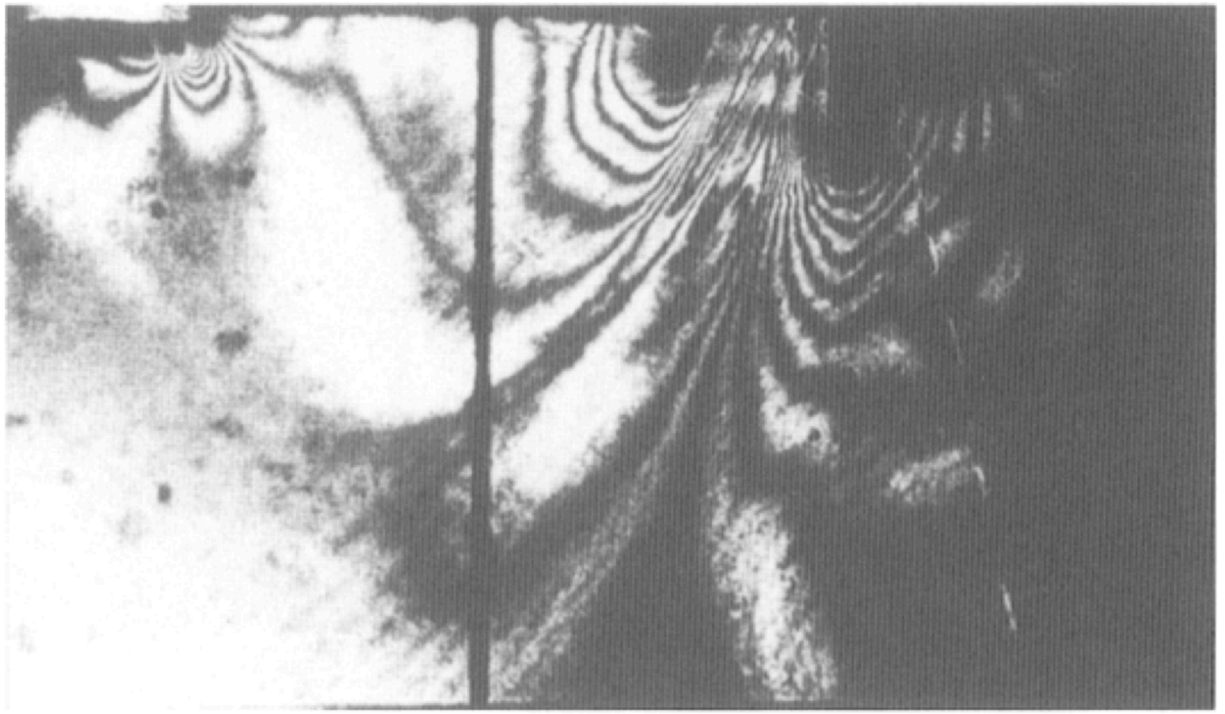
Experiments

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

Experiments

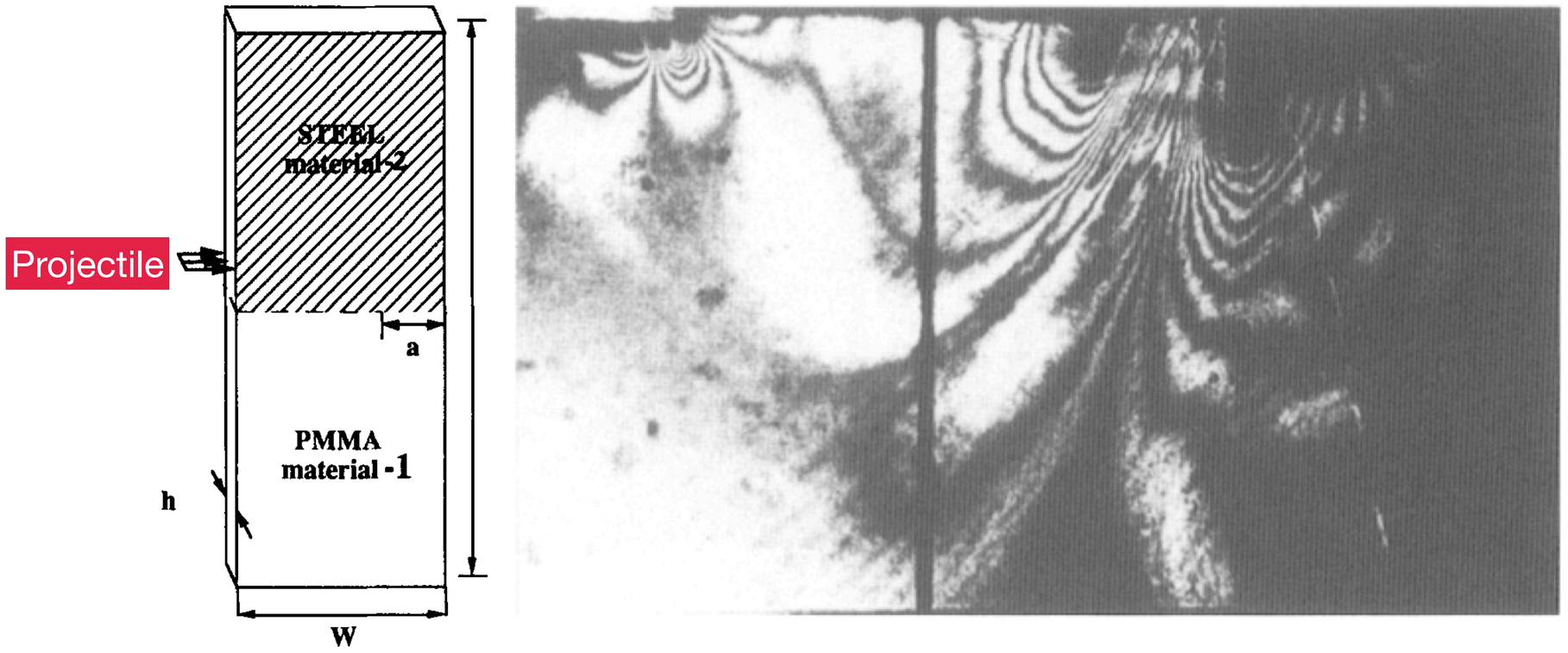
Lambros & Rosakis (1995) : Bi-Material shear impact experiments





Experiments

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



- First recorded image of a supershear rupture!

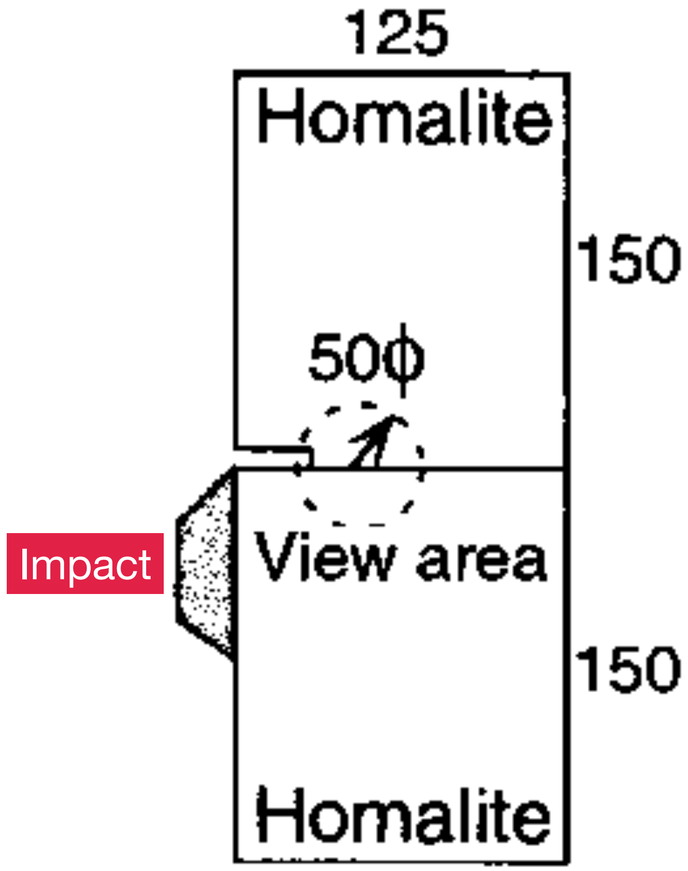
Experiments

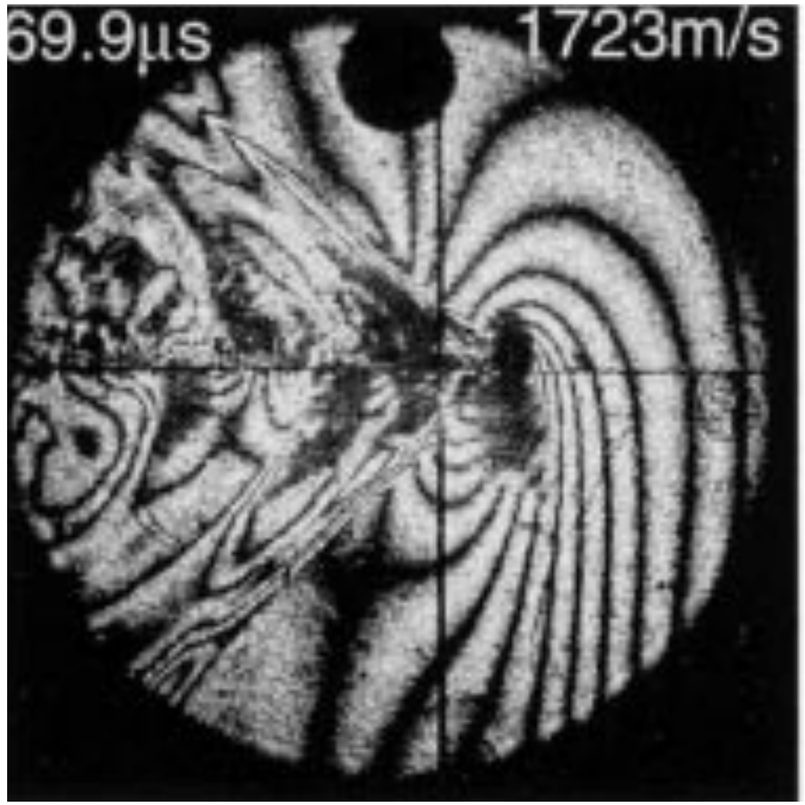
Experiments

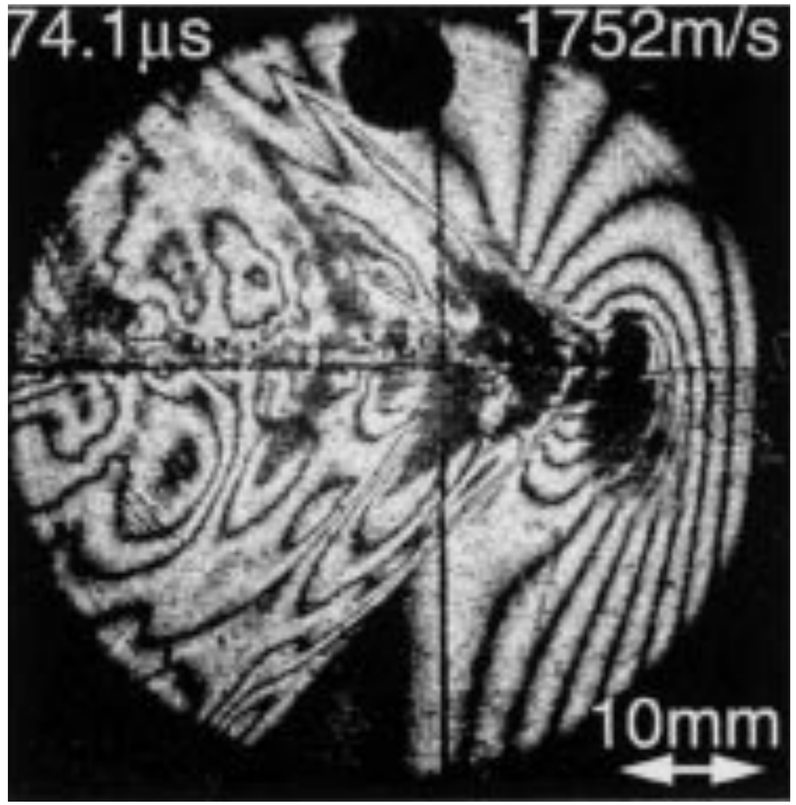
Rosakis et al. (1999) : Shear impact experiments

Experiments

Rosakis et al. (1999) : Shear impact experiments







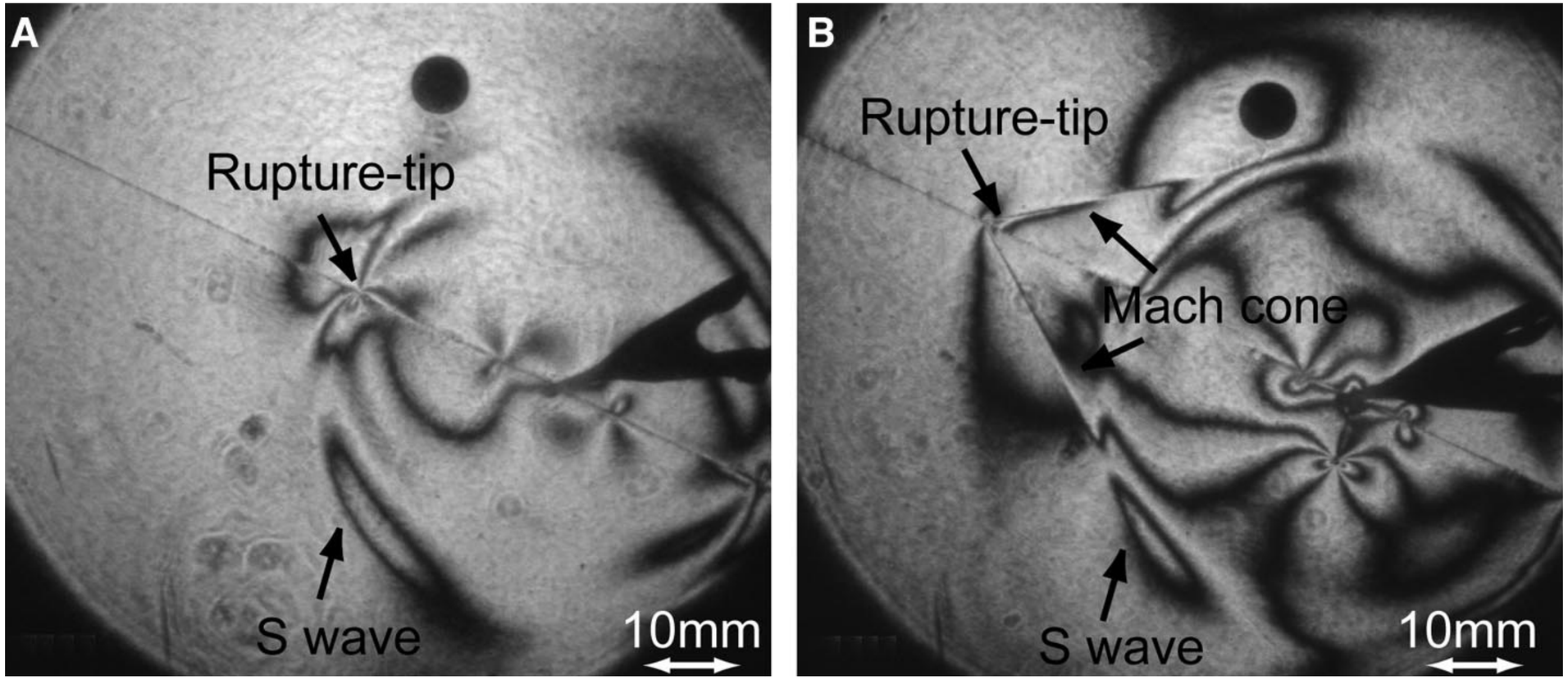
Experiments

Experiments

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

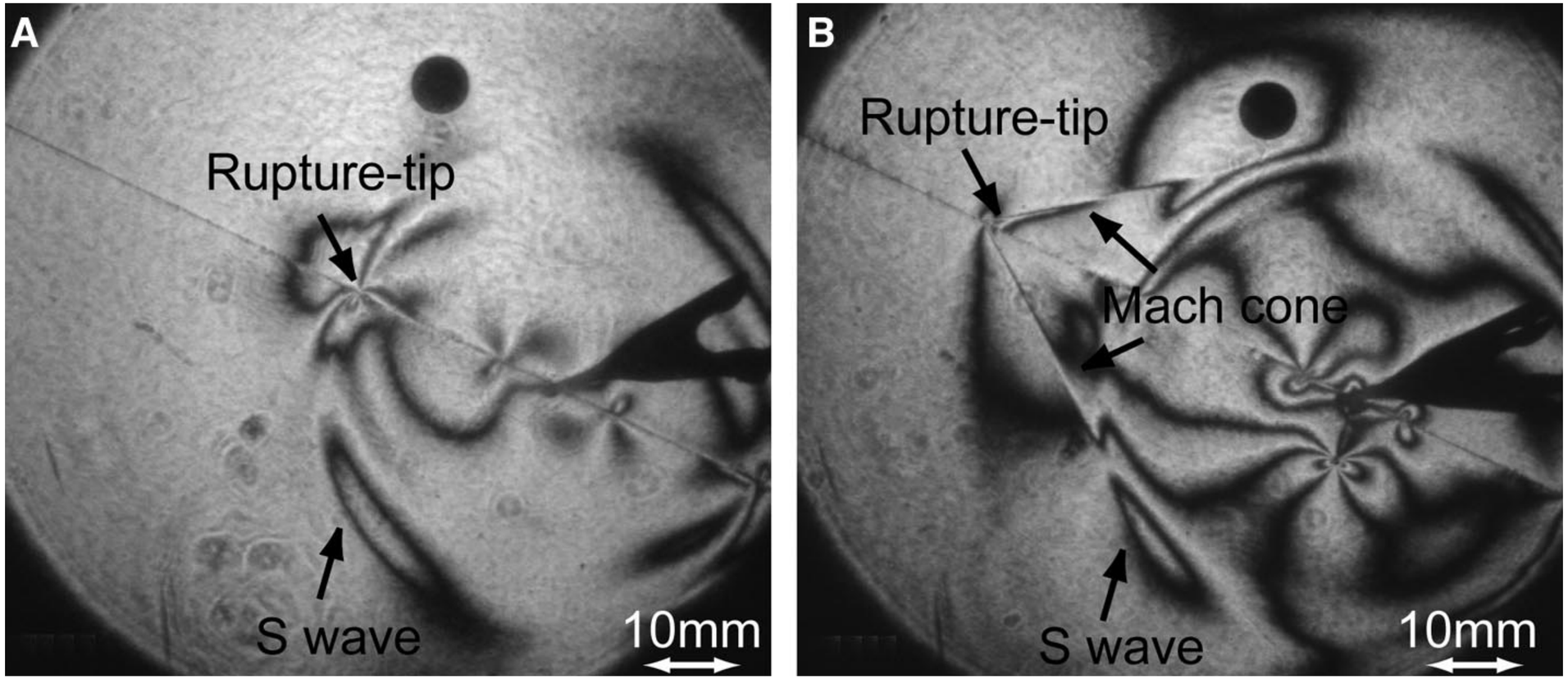
Experiments

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

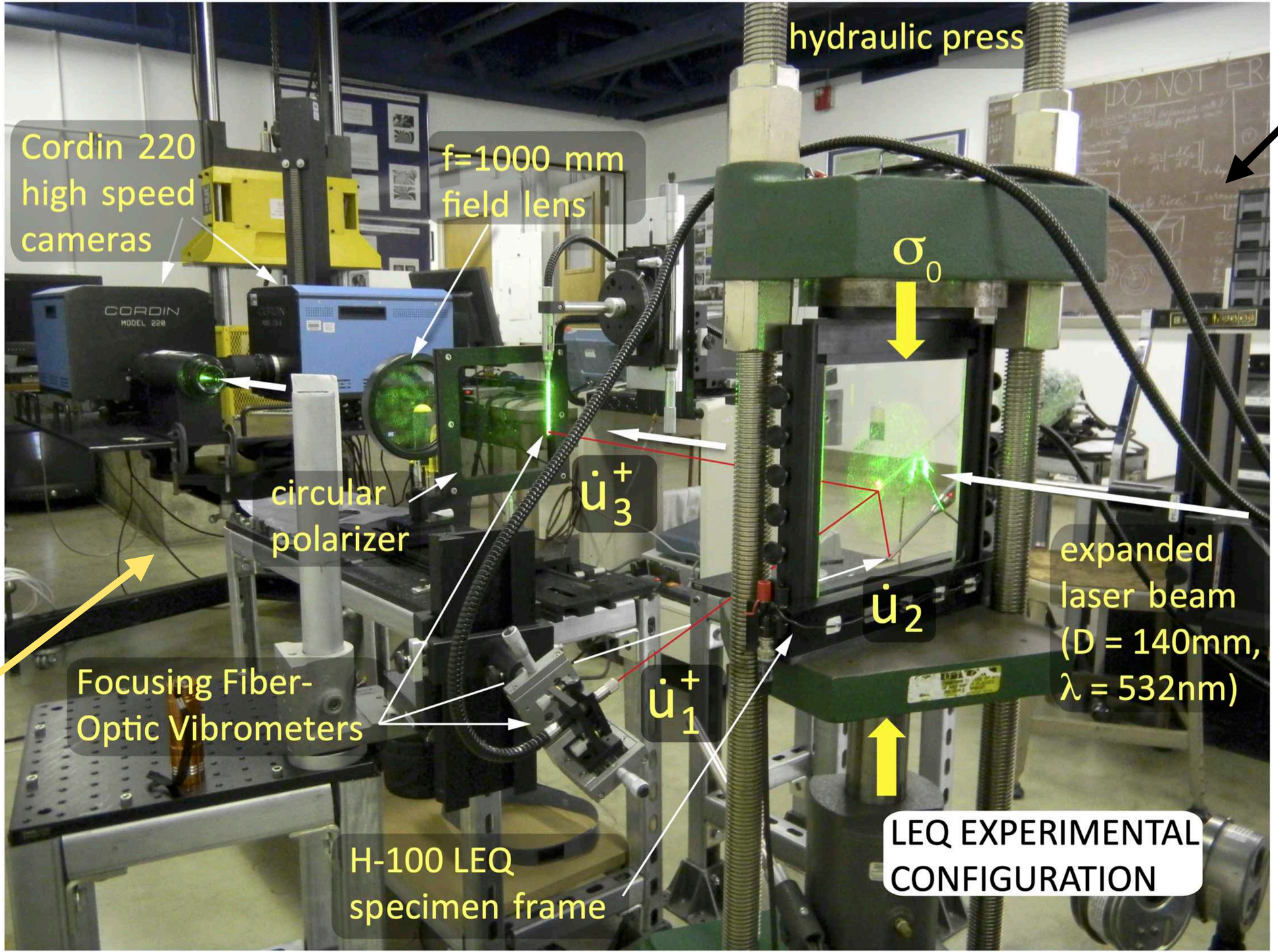


Experiments

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
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

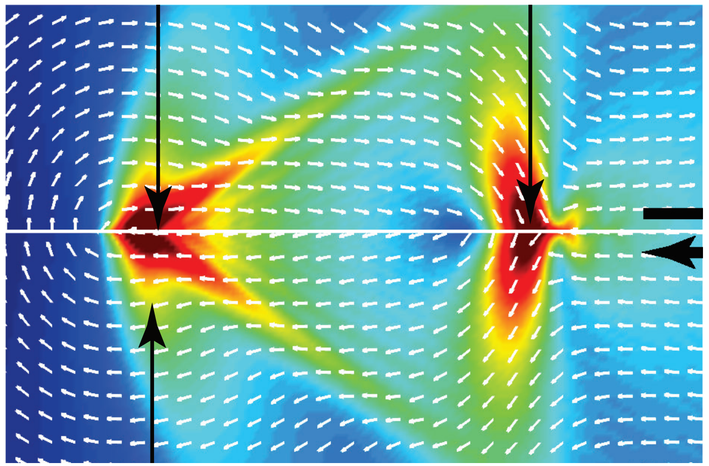
Experiments

Experiments

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

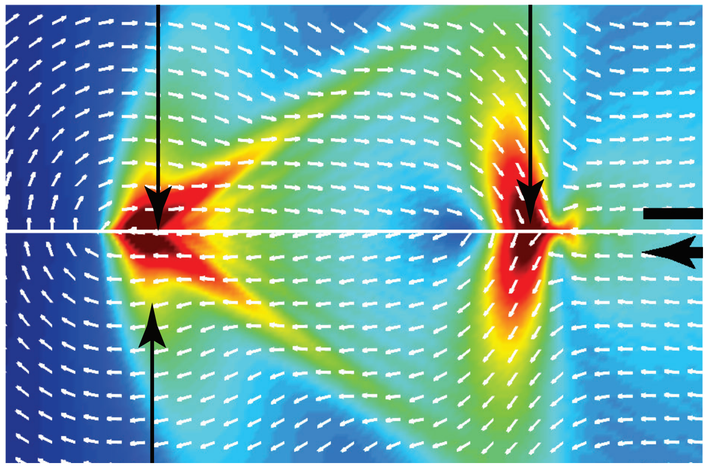
Experiments

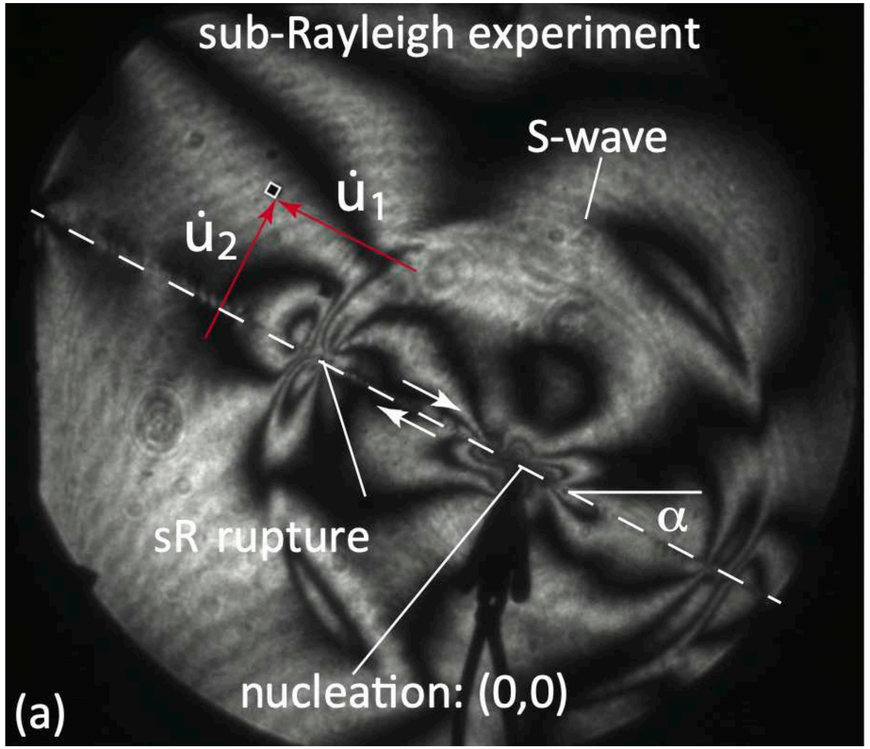
Mello, Bhat et al. (2010, 2016) : Experimental Validation of Ground Motion Signatures of Supershear Earthquakes

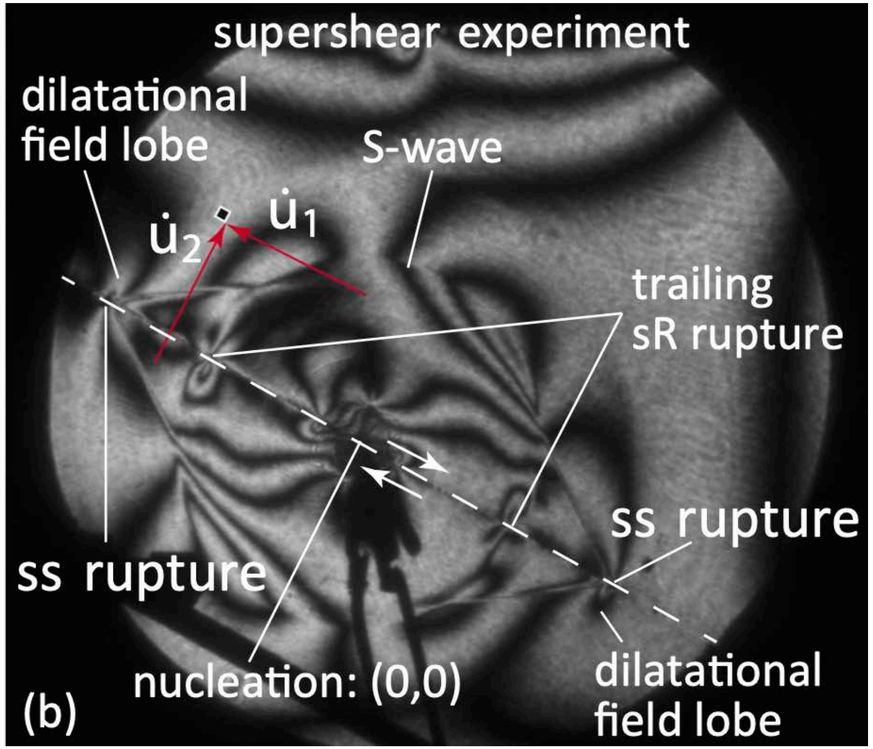


Experiments

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

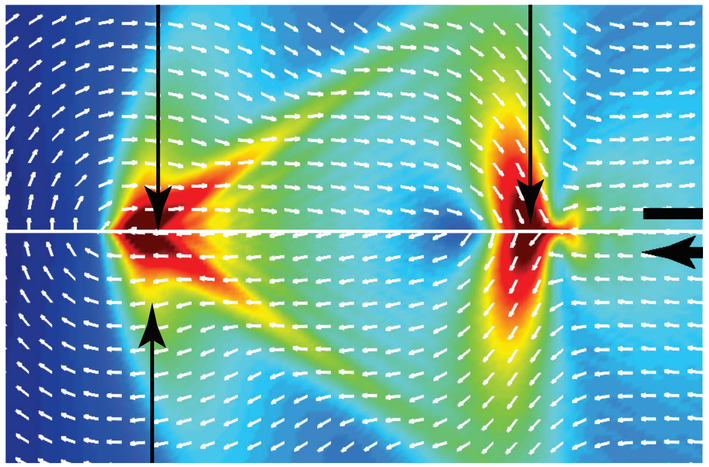


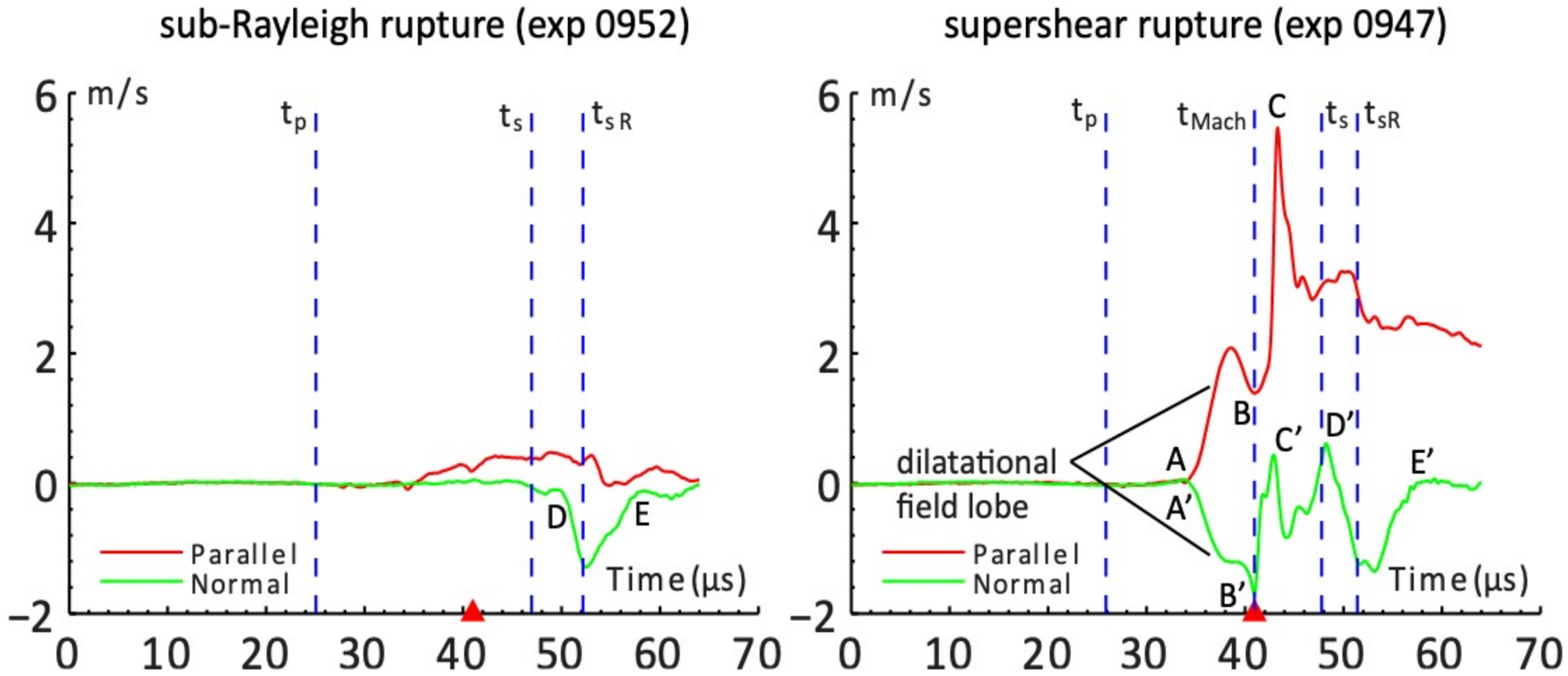




Experiments

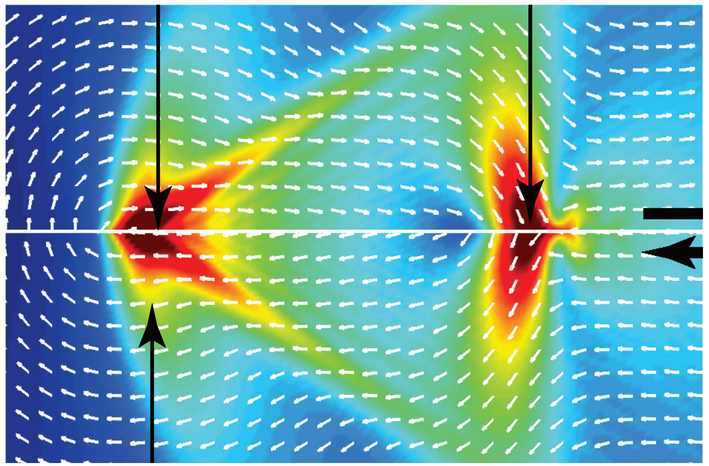
Mello, Bhat et al. (2010, 2016) : Experimental Validation of Ground Motion Signatures of Supershear Earthquakes

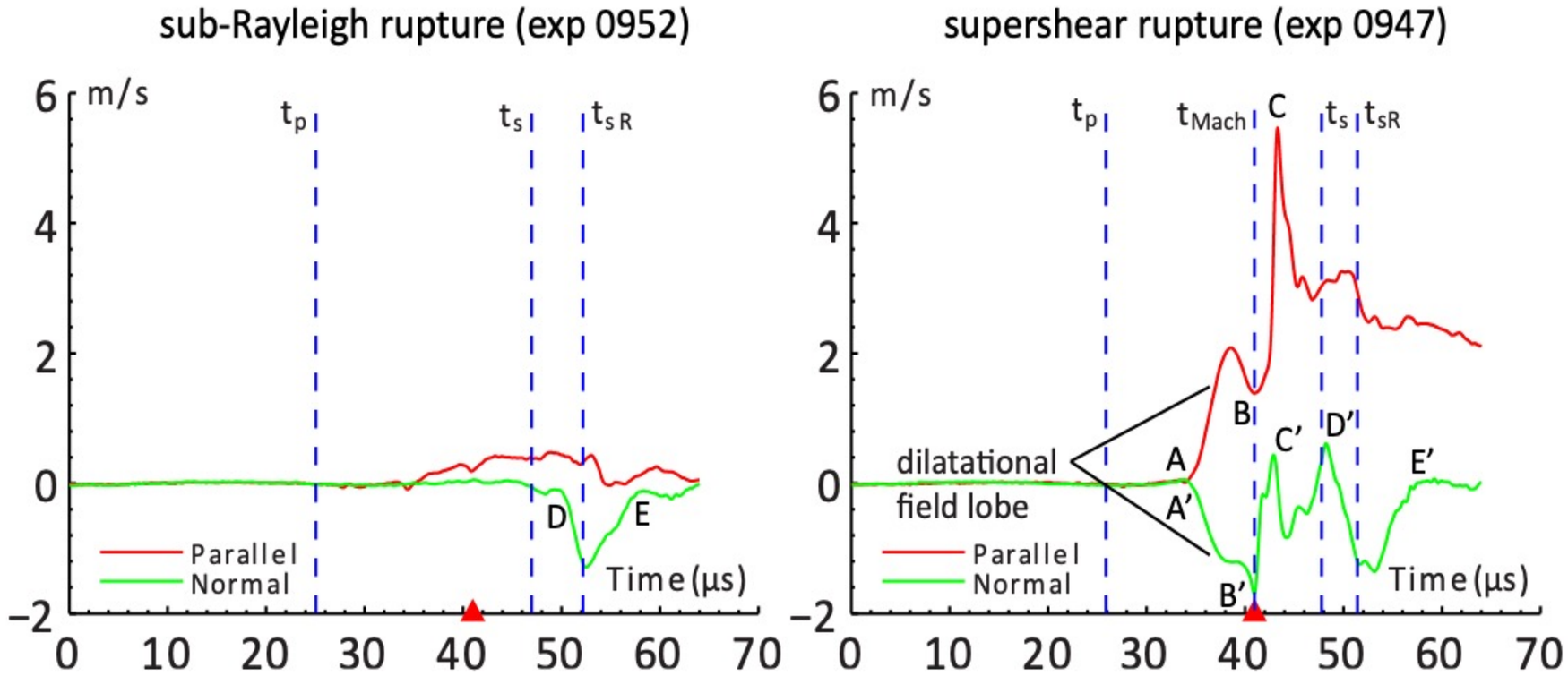




Experiments

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





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

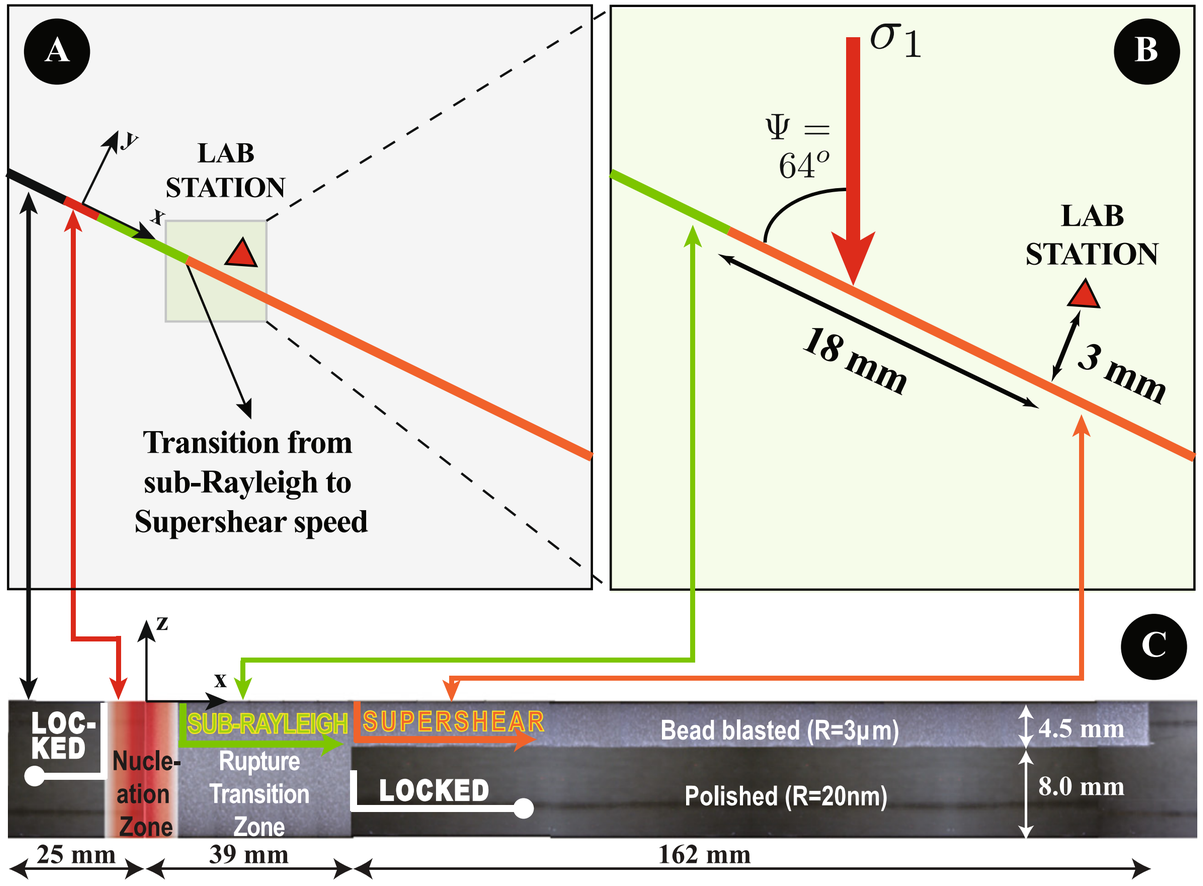
Experiments

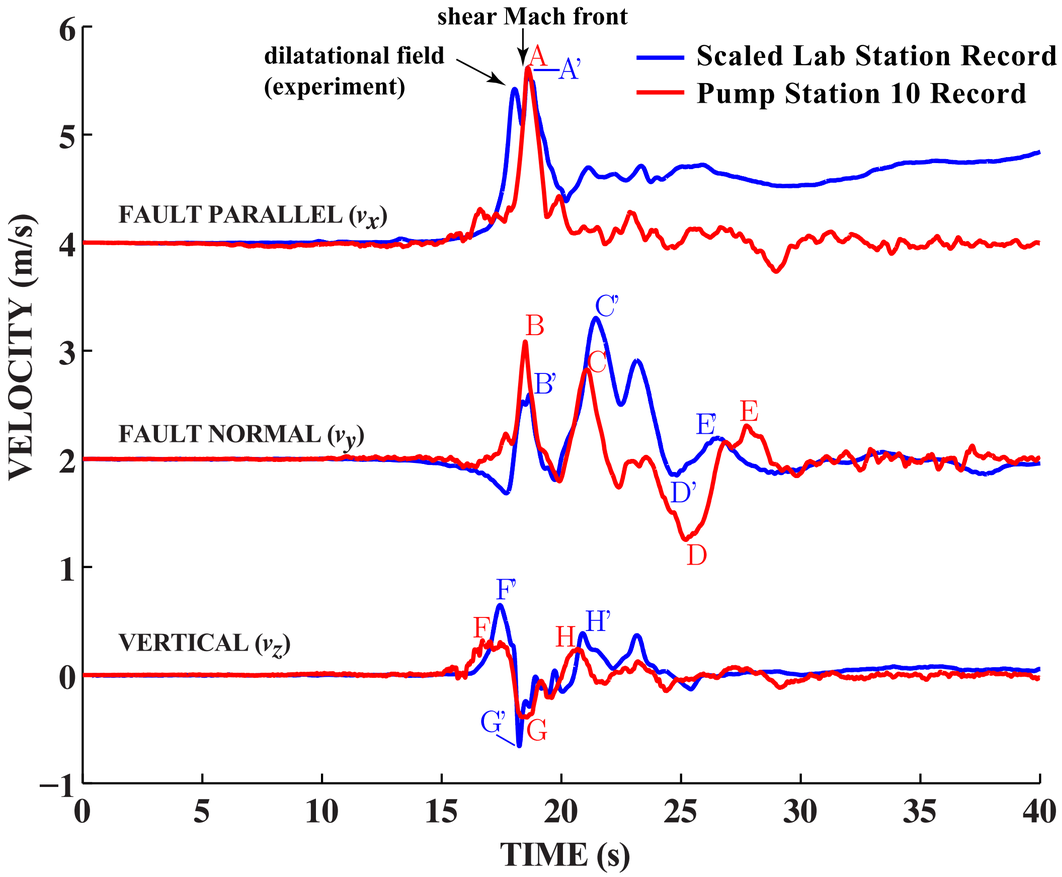
Experiments

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

Experiments

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





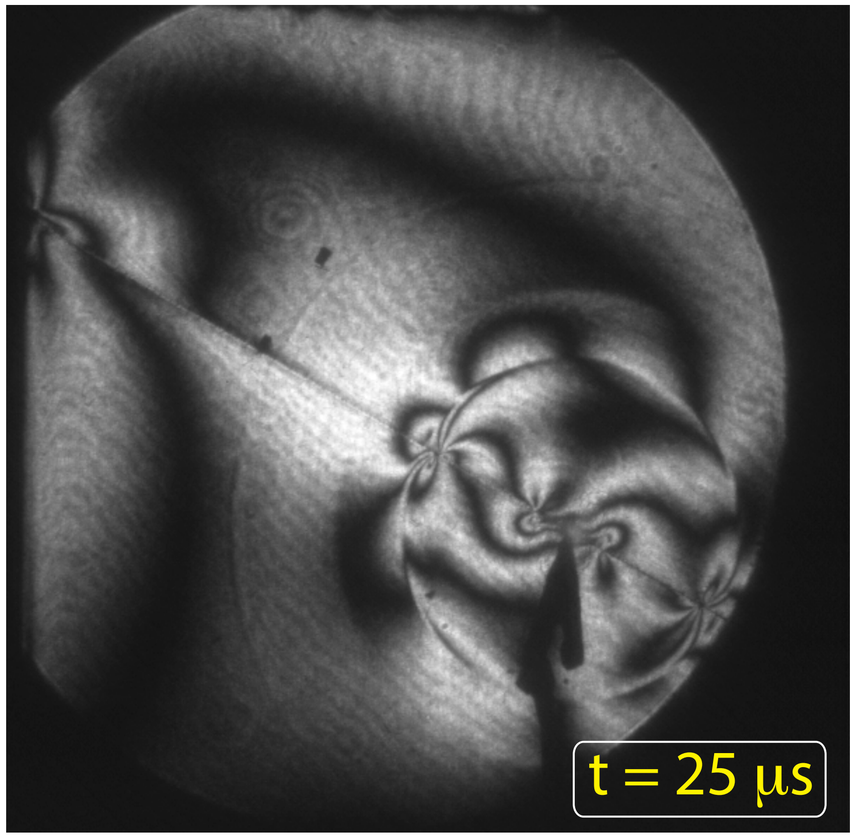
Experiments

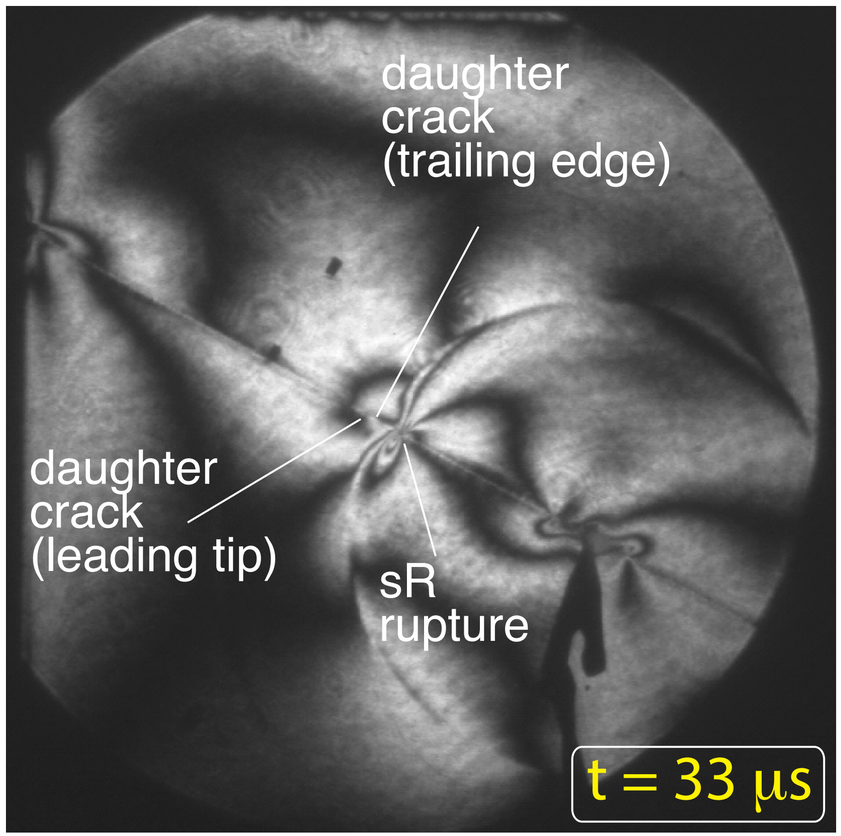
Experiments

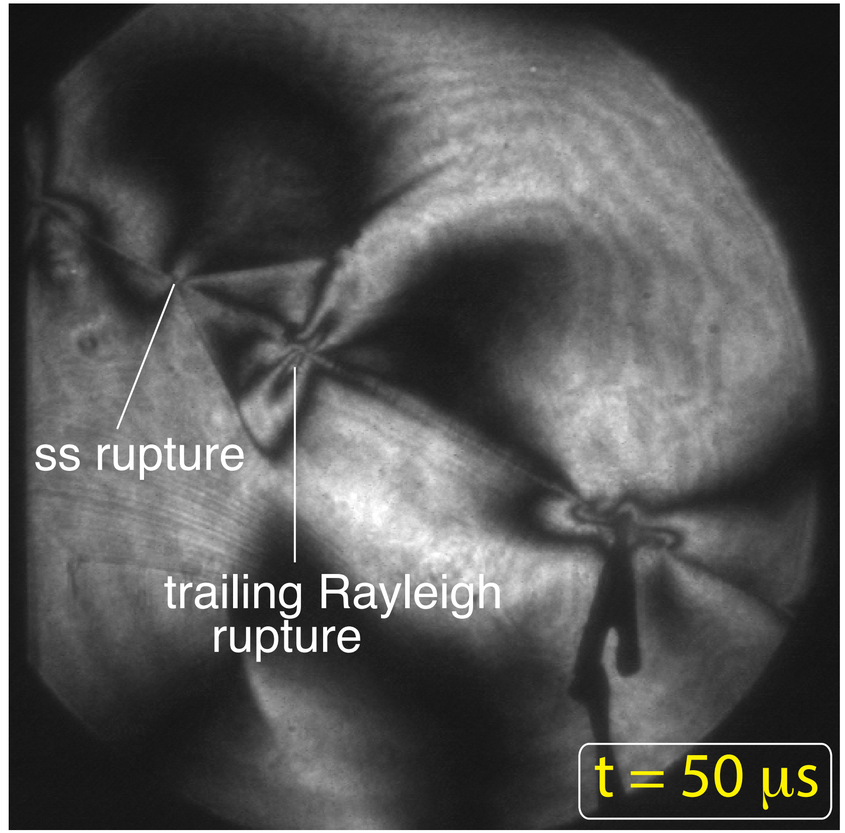
Mello (2012, PhD Thesis) : Transition to Supershear Rupture Speed

Experiments

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

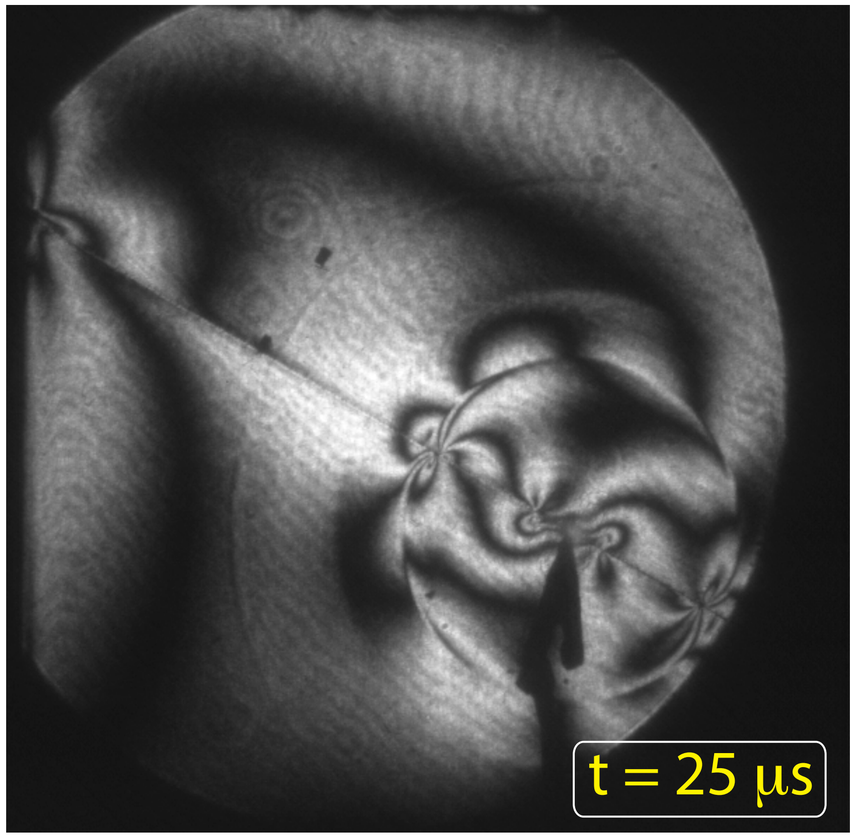


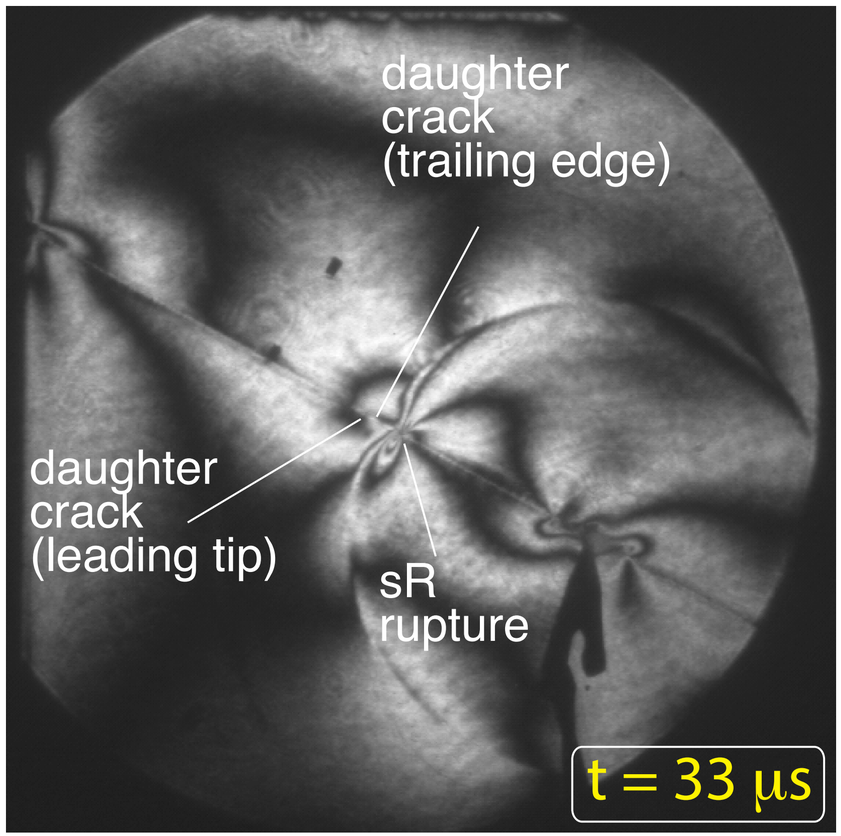


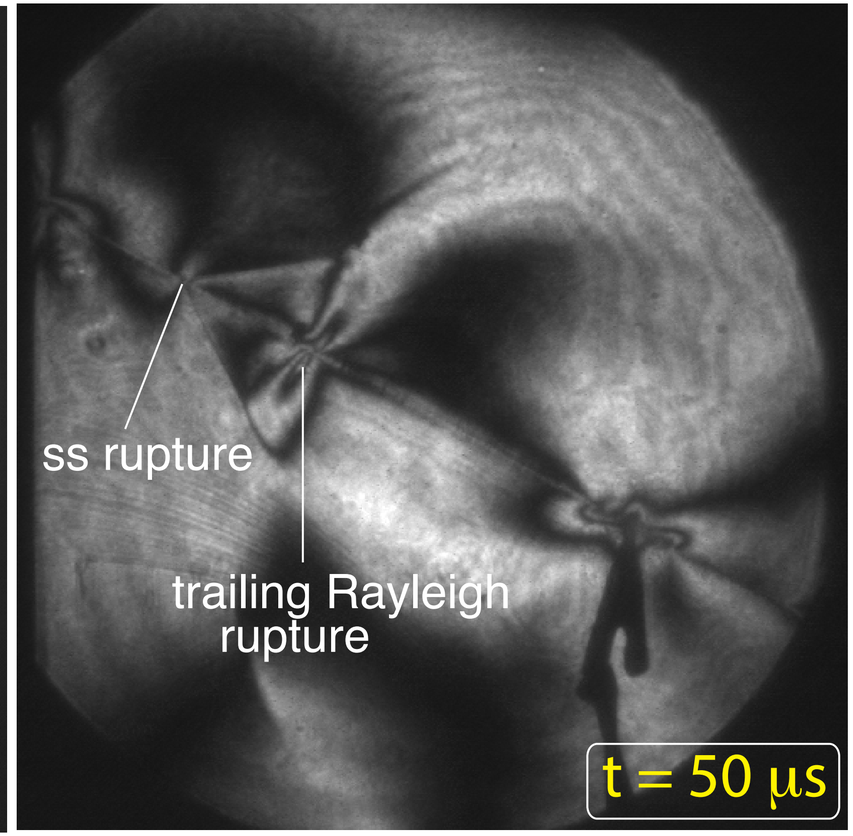


Experiments

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







- Very Rare Mother-Daughter Transition Observed

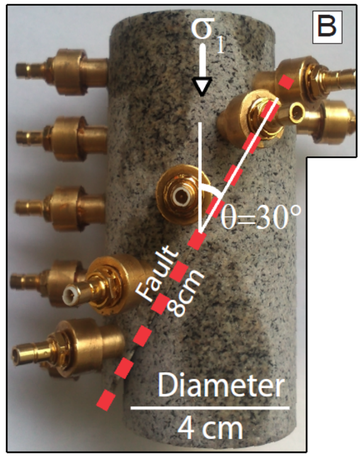
Experiments

Experiments

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

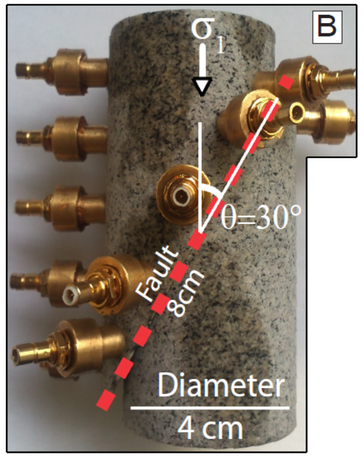
Experiments

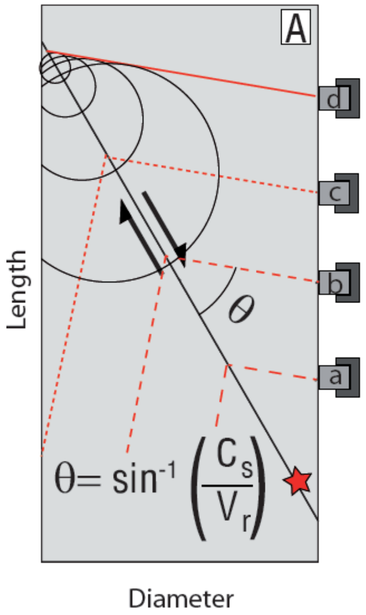
Passelégue et al. (2013) : Experimental Evidence of Supershear Rupture Speed in Rocks

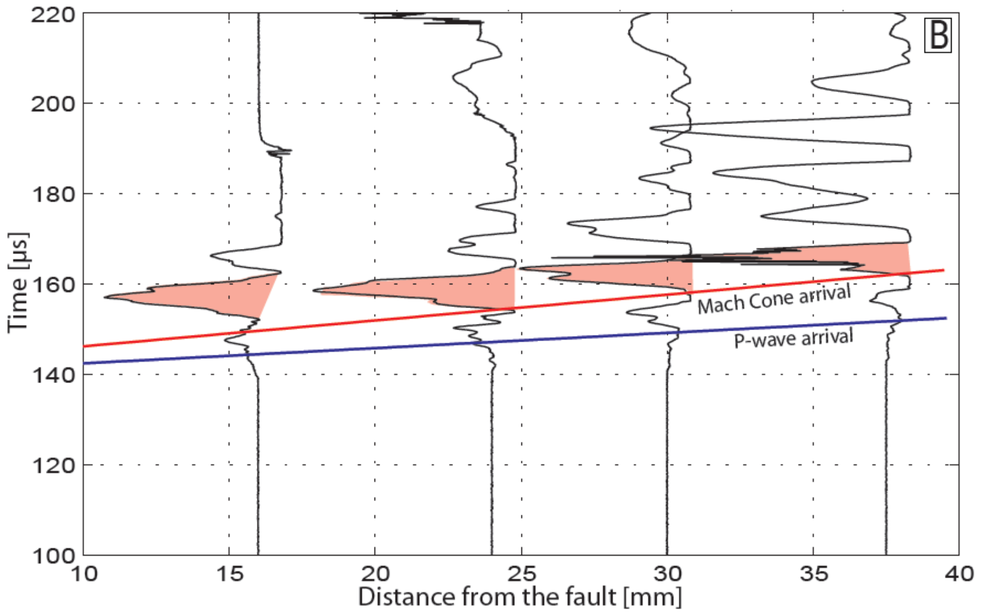


Experiments

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

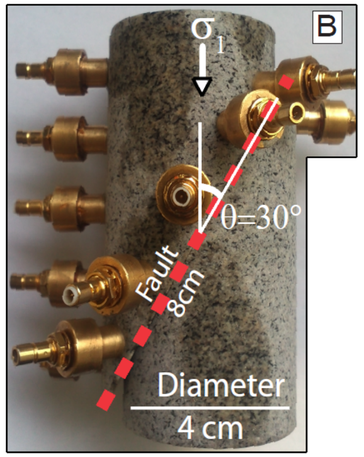


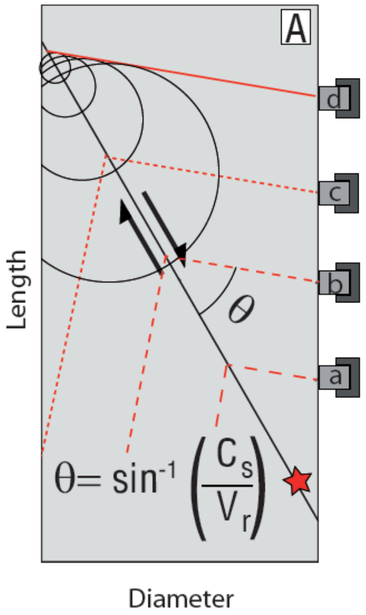


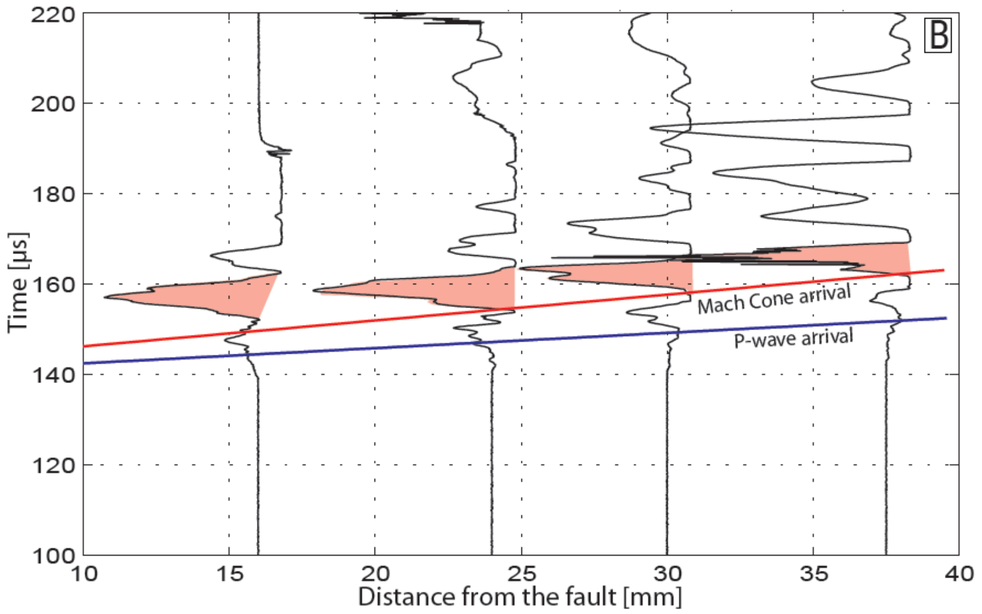


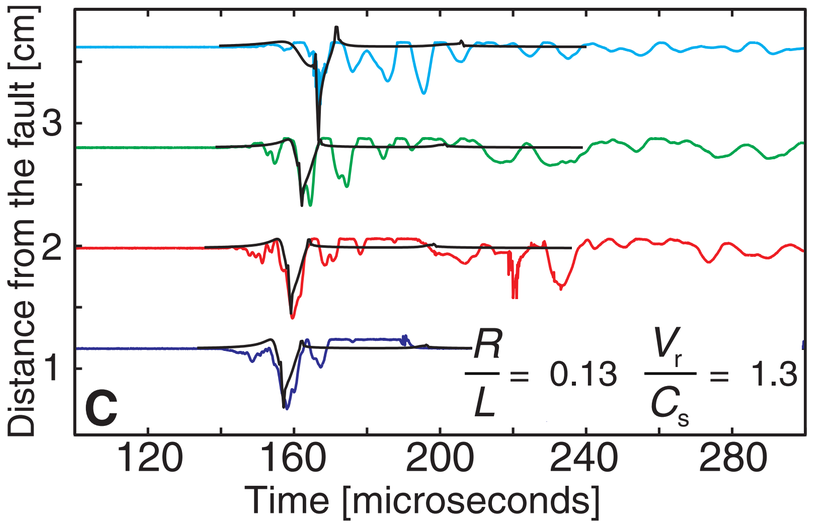
Experiments

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









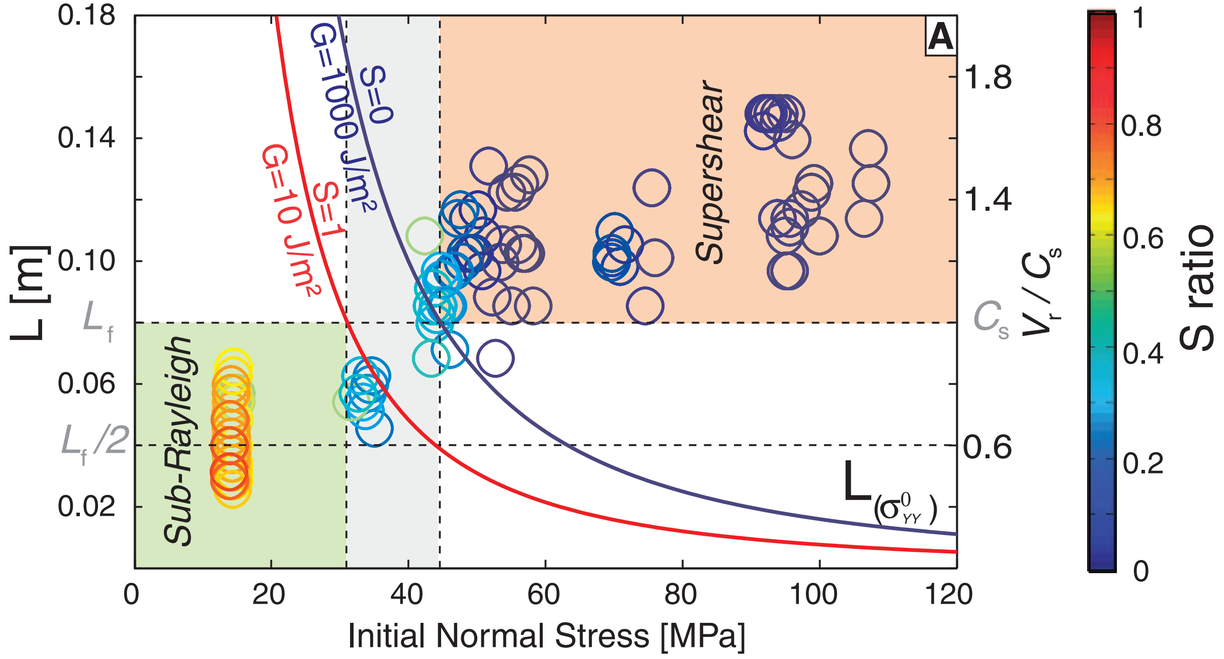
Experiments

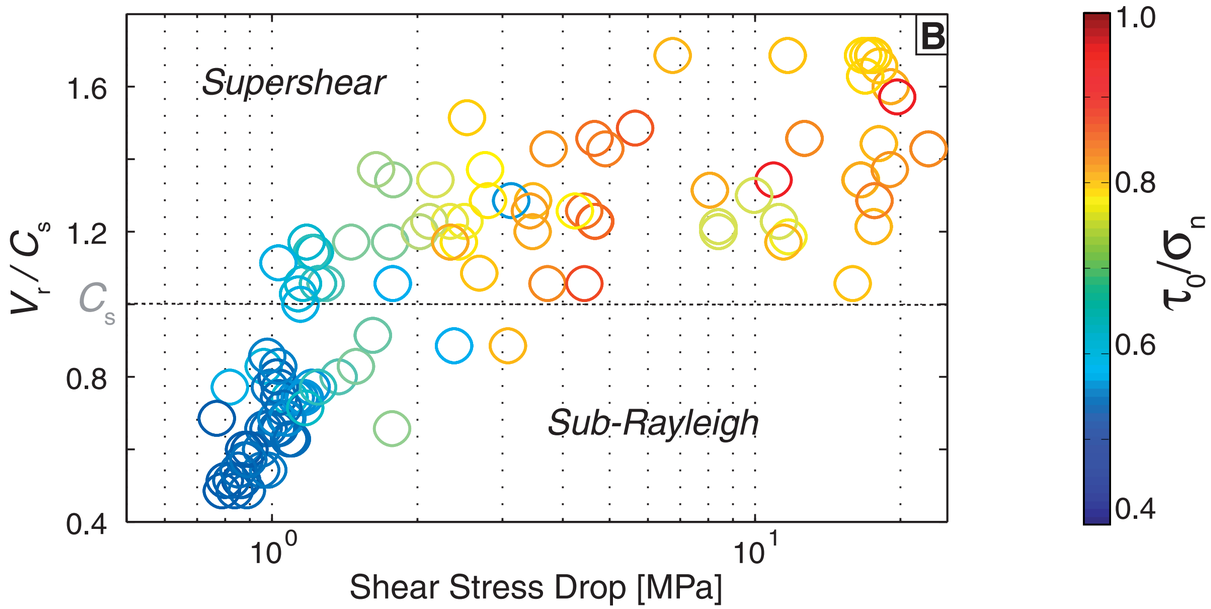
Experiments

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

Experiments

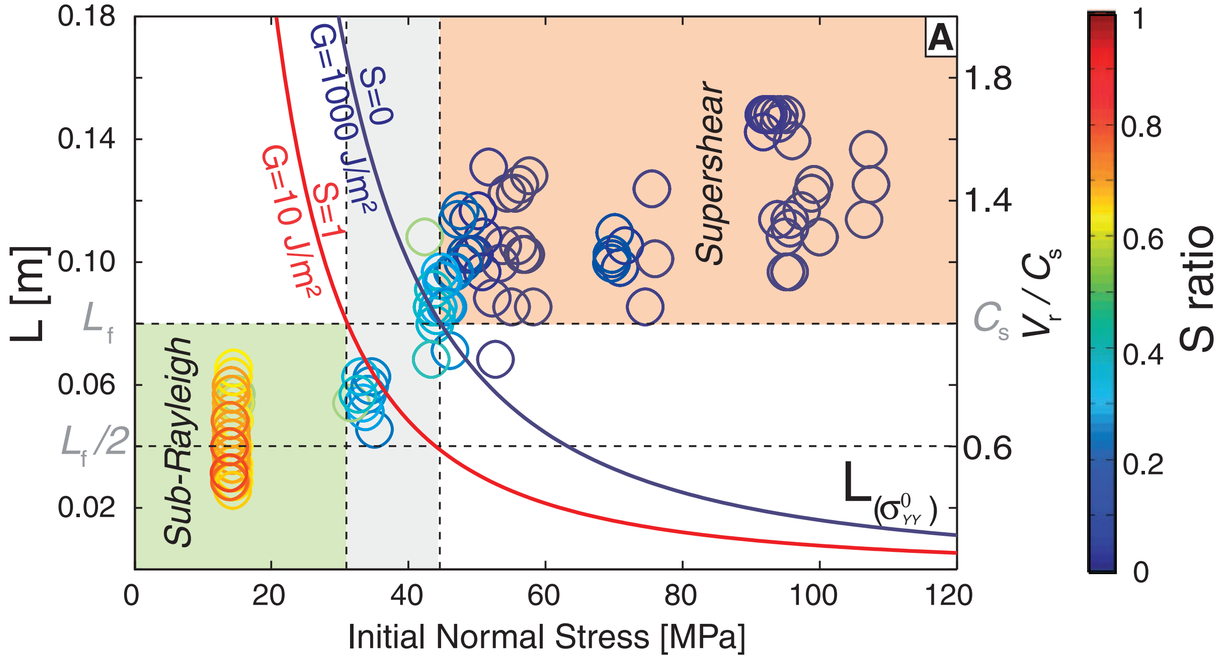
Passelégue et al. (2013) : Experimental Evidence of Supershear Rupture Speed in Rocks

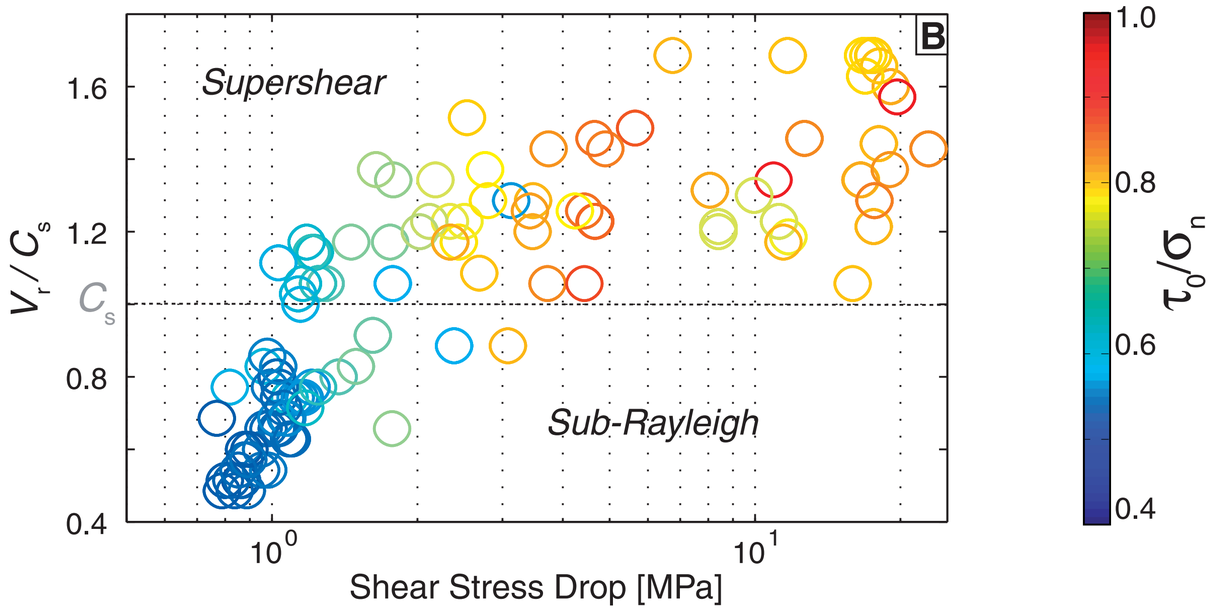




Experiments

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

Observations

Supershear earthquakes in the wild

Olson & Apsel (1982), Archuleta (1984) and Spudich & Cranswick (1984) : 1979 M_w 6.5 Imperial Valley earthquake

Observations

Supershear earthquakes in the wild

Olson & Apsel (1982), Archuleta (1984) and Spudich & Cranswick (1984) : 1979 M_w 6.5 Imperial Valley earthquake

- This was not universally accepted and the scale tipped in the favour of supershear skeptics for more than 25 years (Das, 2015)

Observations

Supershear earthquakes in the wild

Olson & Apsel (1982), Archuleta (1984) and Spudich & Cranswick (1984) : 1979 M_w 6.5 Imperial Valley earthquake

- This was not universally accepted and the scale tipped in the favour of supershear skeptics for more than 25 years (Das, 2015)

Bouchon et al (2000, 2001) : 1999 M_w 7.5 Izmit & M_w 7.1 Düzce earthquakes

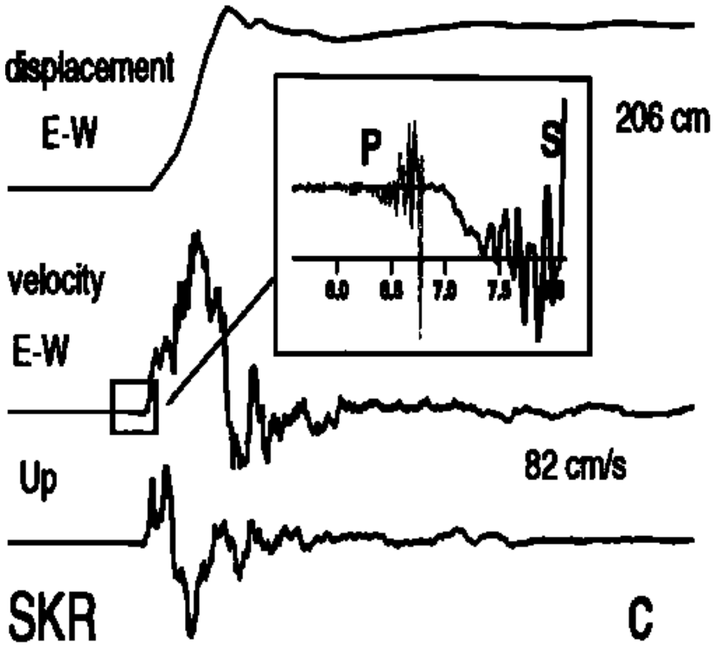
Observations

Supershear earthquakes in the wild

Olson & Apsel (1982), Archuleta (1984) and Spudich & Cranswick (1984) : 1979 M_w 6.5 Imperial Valley earthquake

- This was not universally accepted and the scale tipped in the favour of supershear skeptics for more than 25 years (Das, 2015)

Bouchon et al (2000, 2001) : 1999 M_w 7.5 Izmit & M_w 7.1 Düzce earthquakes



Observations

Supershear earthquakes in the wild

Jara, Bruhat et al. 2021

Observations

Supershear earthquakes in the wild

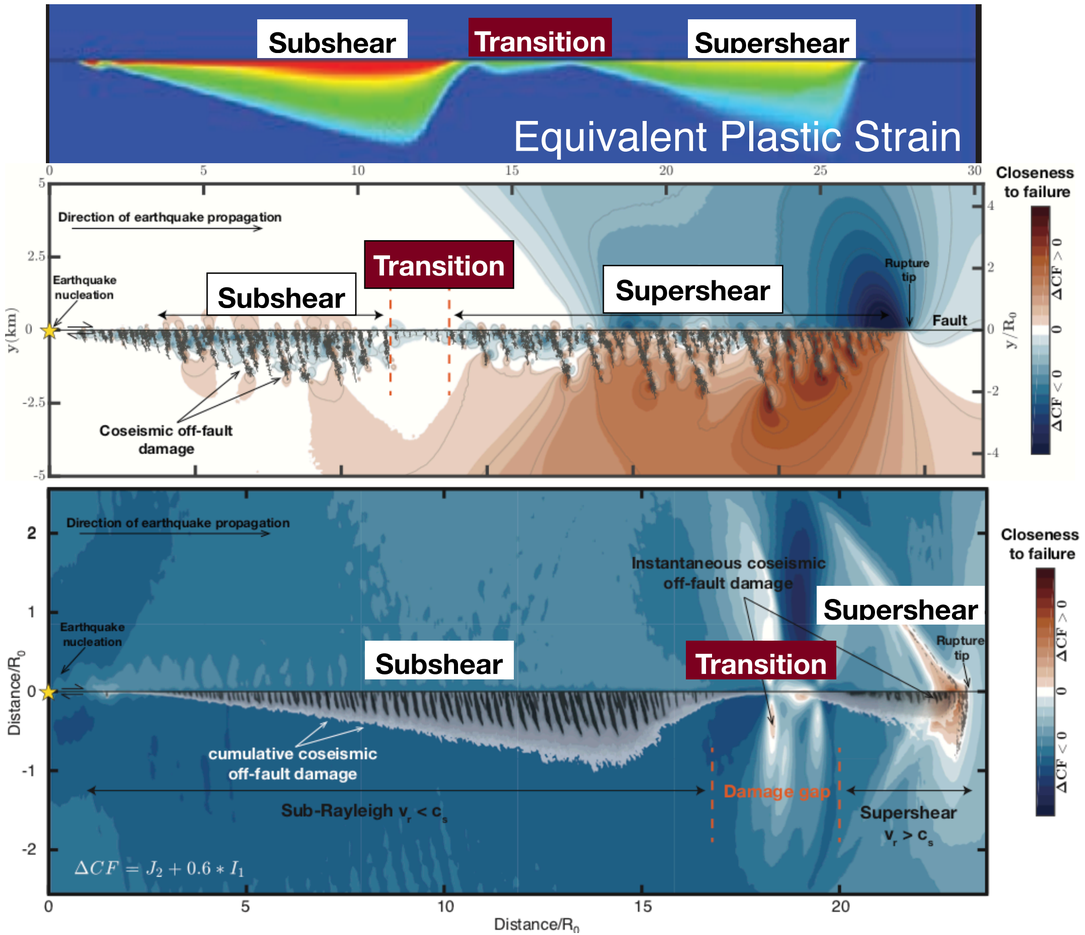
Bouchon et al (2000, 2001) : 1999 M_w 7.5 Izmit & M_w 7.1 Düzce earthquakes

Jara, Bruhat et al. 2021

Observations

Supershear earthquakes in the wild

Bouchon et al (2000, 2001) : 1999 M_w 7.5 Izmit & M_w 7.1 Düzce earthquakes

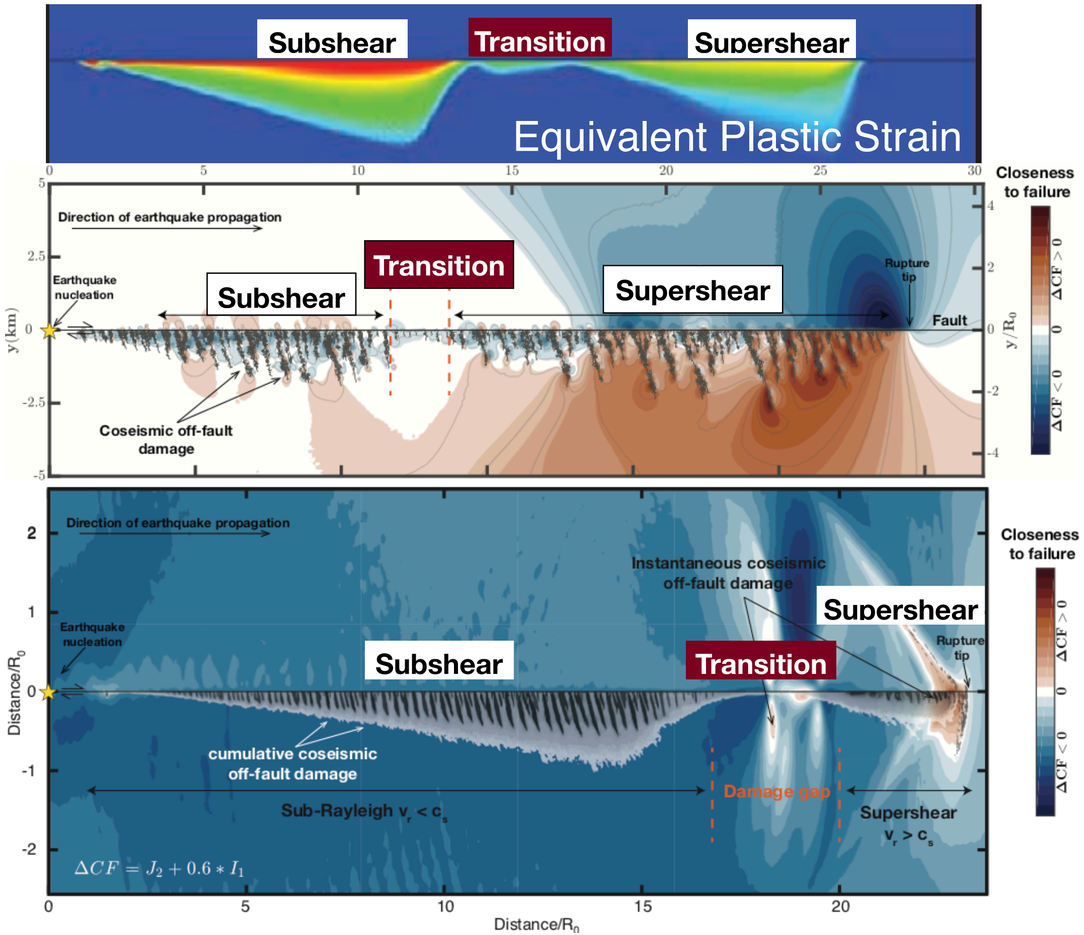


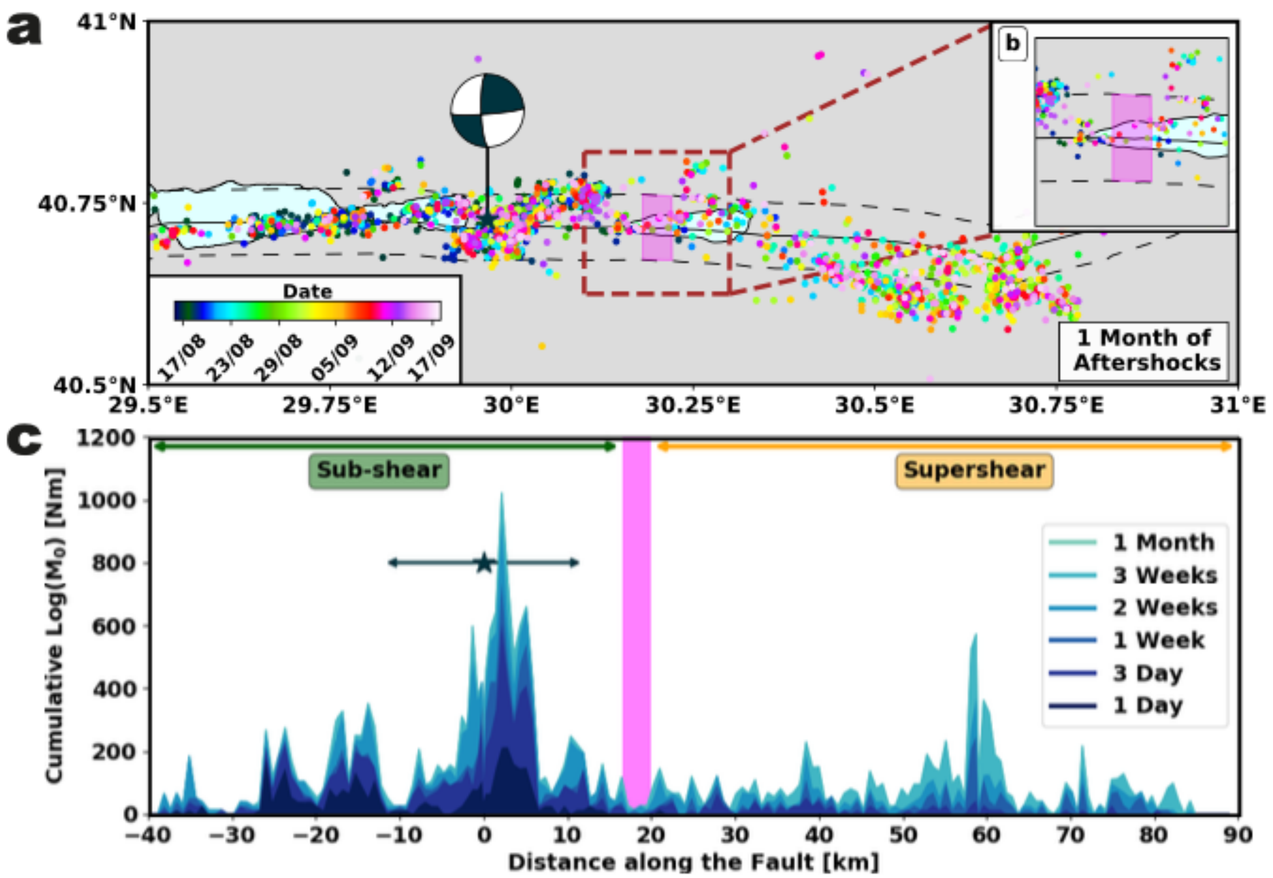
Jara, Bruhat et al. 2021

Observations

Supershear earthquakes in the wild

Bouchon et al (2000, 2001) : 1999 M_w 7.5 Izmit & M_w 7.1 Düzce earthquakes





Jara, Bruhat et al. 2021

Observations

Supershear earthquakes in the wild

Bhat et al. 2007

Observations

Supershear earthquakes in the wild

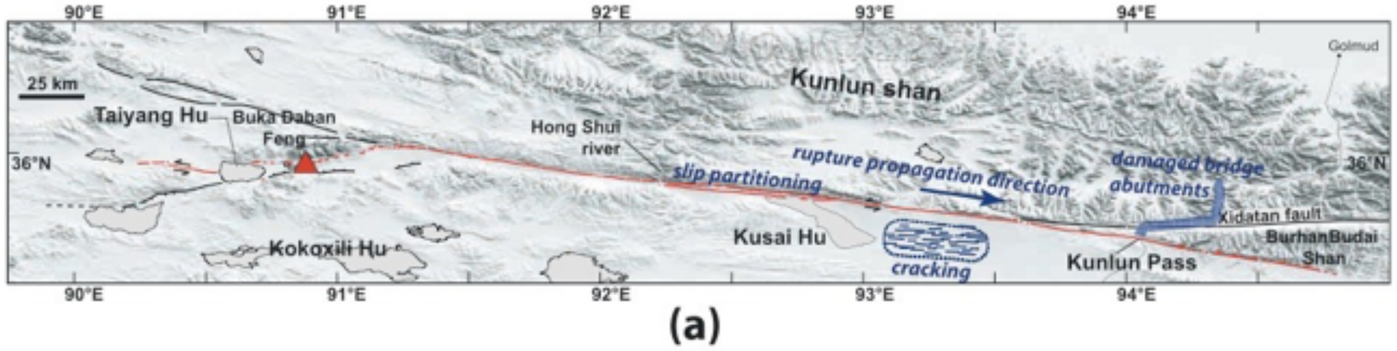
Bouchon & Vallée (2003) Robinson et al (2006) & others : 2001 M_w 7.8 Kunlun, Tibet earthquake

Bhat et al. 2007

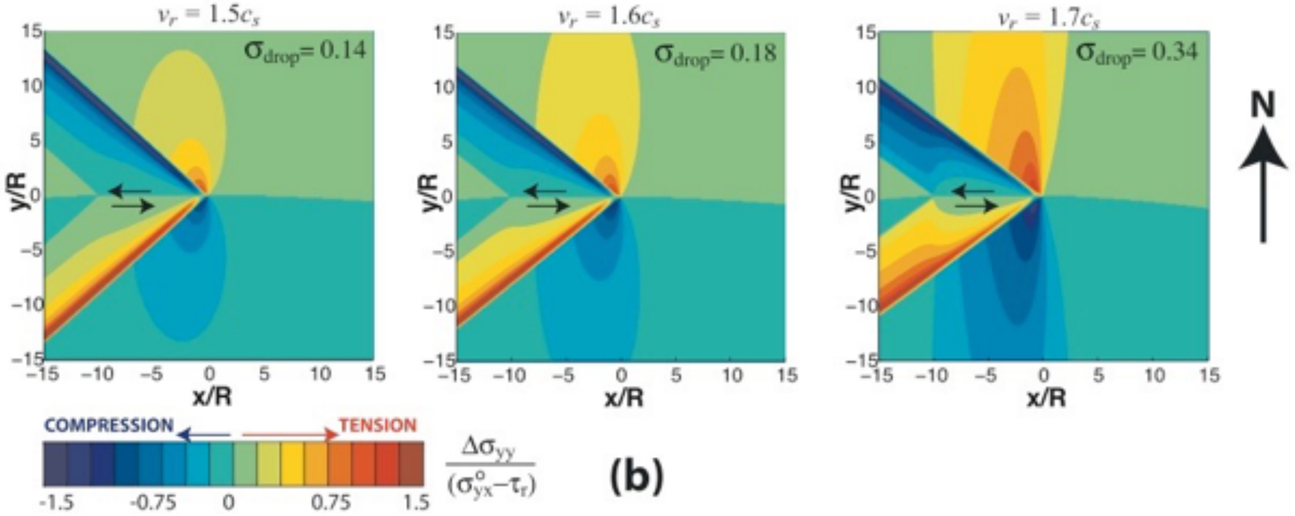
Observations

Supershear earthquakes in the wild

Bouchon & Vallée (2003) Robinson et al (2006) & others : 2001 M_w 7.8 Kunlun, Tibet earthquake



(a)



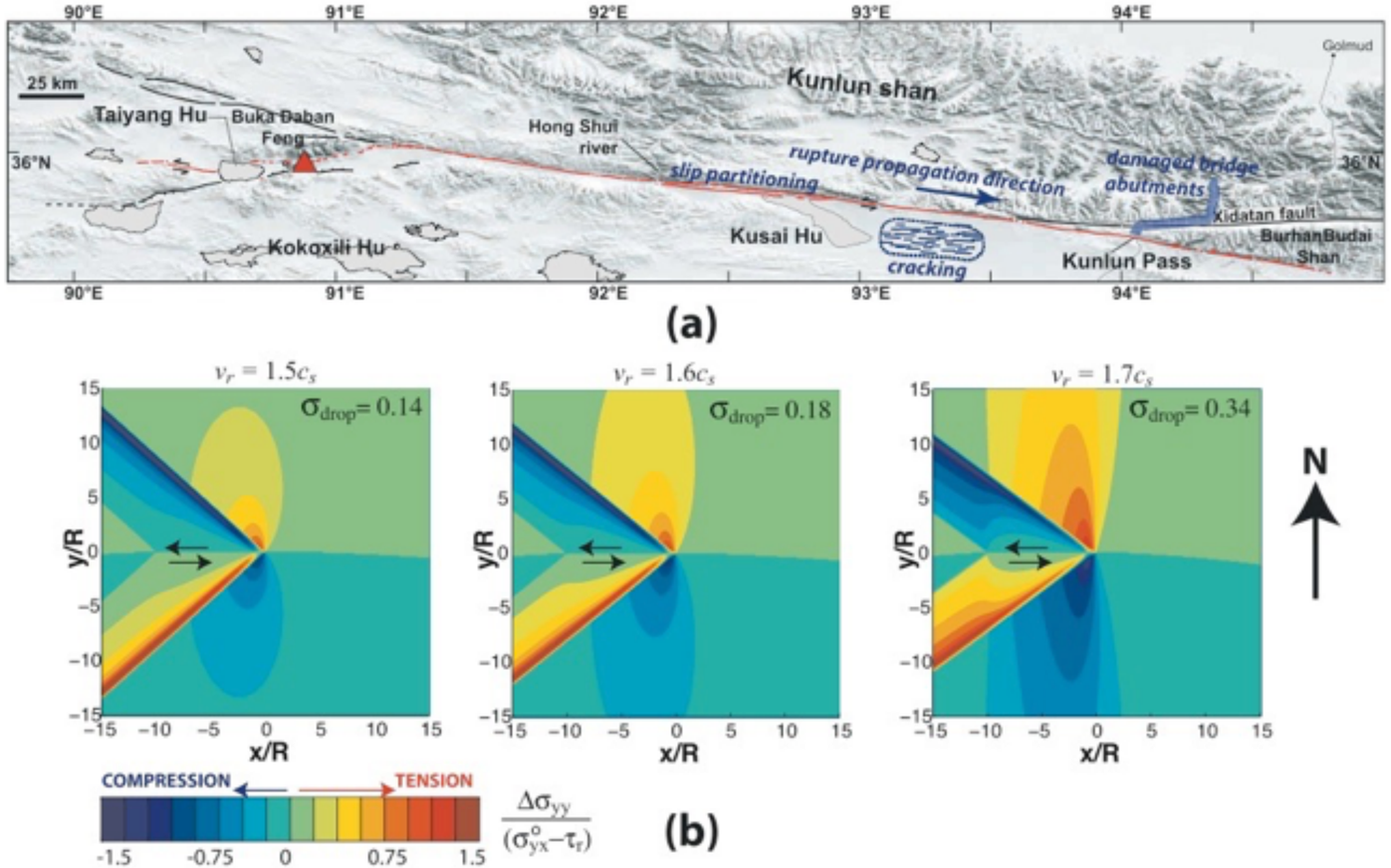
(b)

Bhat et al. 2007

Observations

Supershear earthquakes in the wild

Bouchon & Vallée (2003) Robinson et al (2006) & others : 2001 M_w 7.8 Kunlun, Tibet earthquake



Bhat et al. 2007

Observations

Supershear earthquakes in the wild

Jara, Bruhat et al. 2021

Observations

Supershear earthquakes in the wild

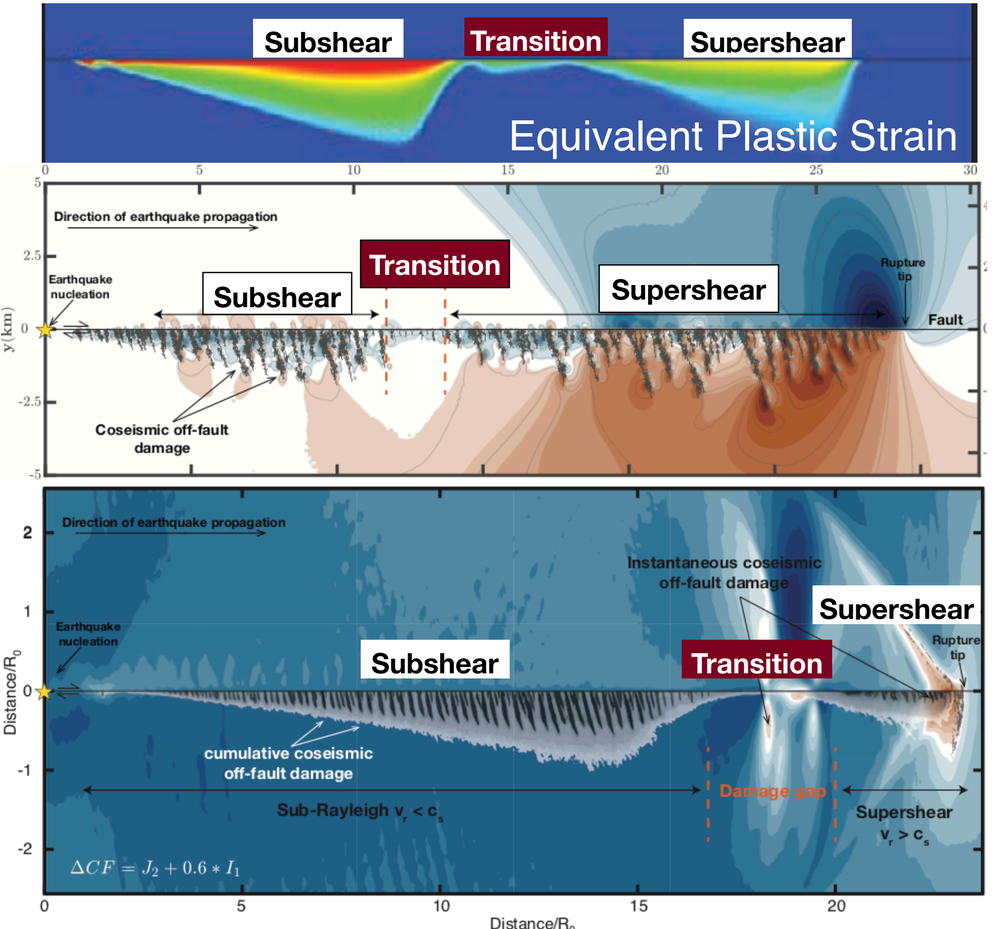
Bouchon & Vallée (2003) Robinson et al (2006) & others : 2001 M_w 7.8 Kunlun, Tibet earthquake

Jara, Bruhat et al. 2021

Observations

Supershear earthquakes in the wild

Bouchon & Vallée (2003) Robinson et al (2006) & others : 2001 M_w 7.8 Kunlun, Tibet earthquake

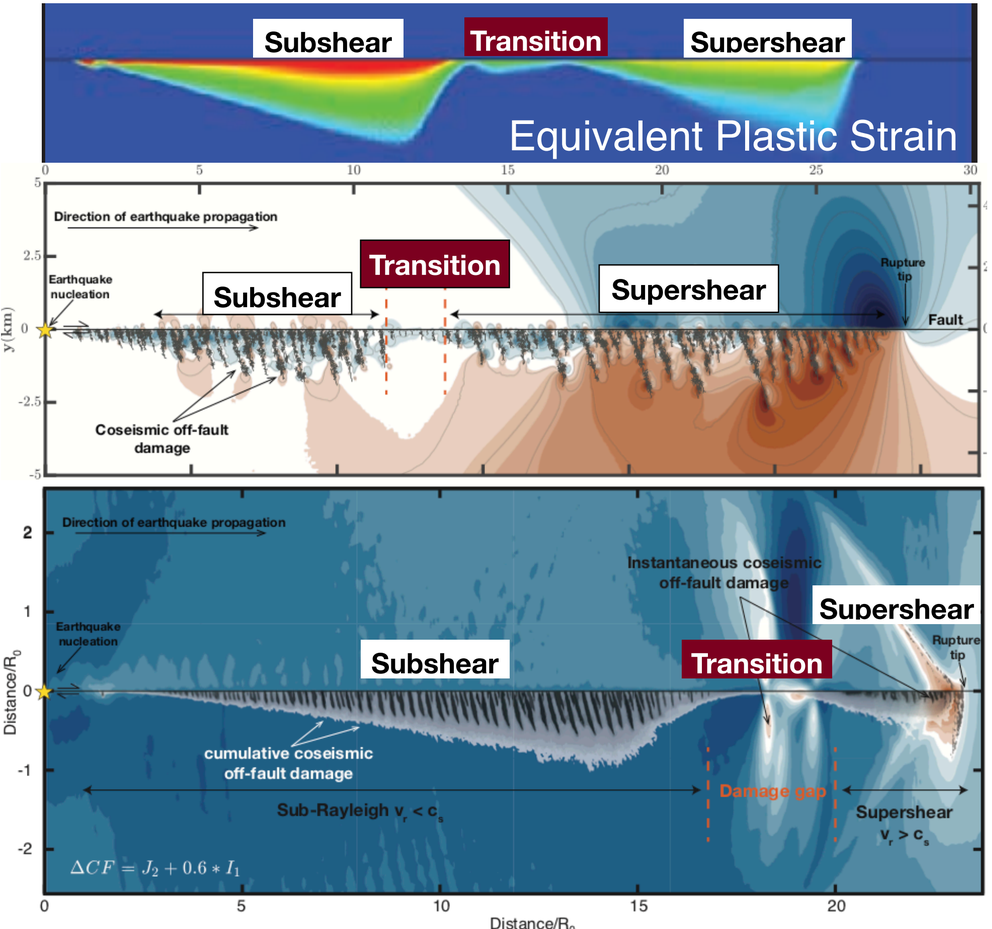


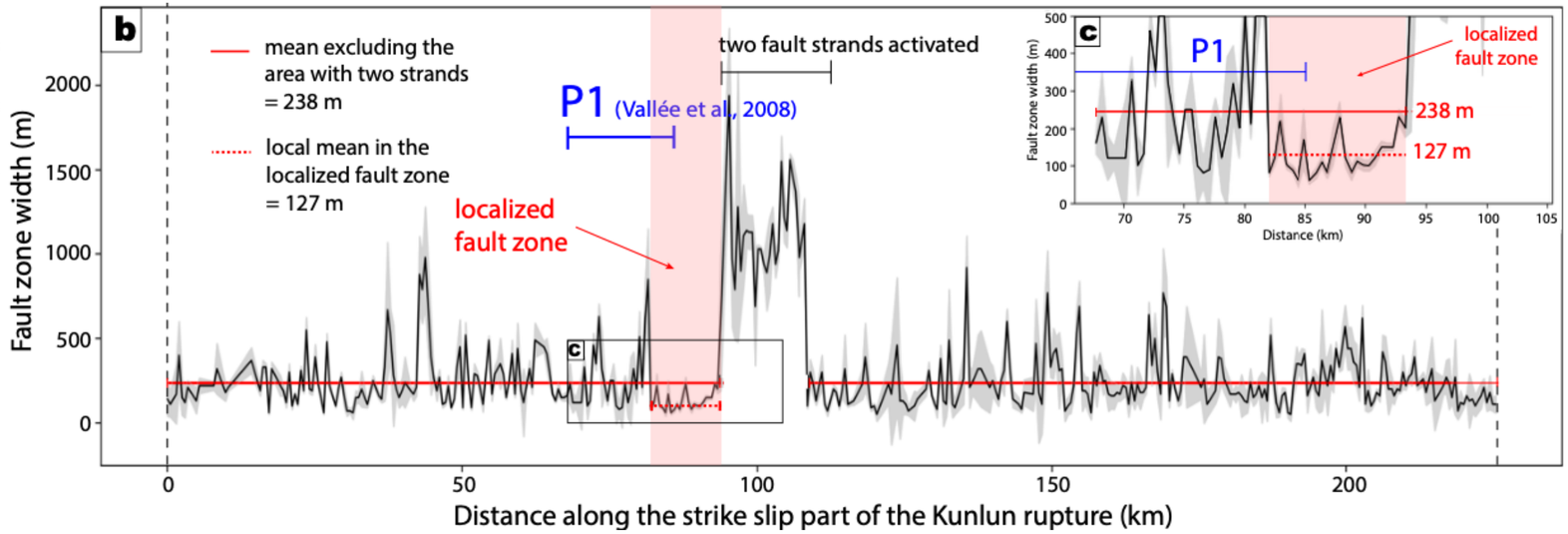
Jara, Bruhat et al. 2021

Observations

Supershear earthquakes in the wild

Bouchon & Vallée (2003) Robinson et al (2006) & others : 2001 M_w 7.8 Kunlun, Tibet earthquake





Jara, Bruhat et al. 2021

Observations

Supershear earthquakes in the wild

Mello, Bhat et al. 2014

Observations

Supershear earthquakes in the wild

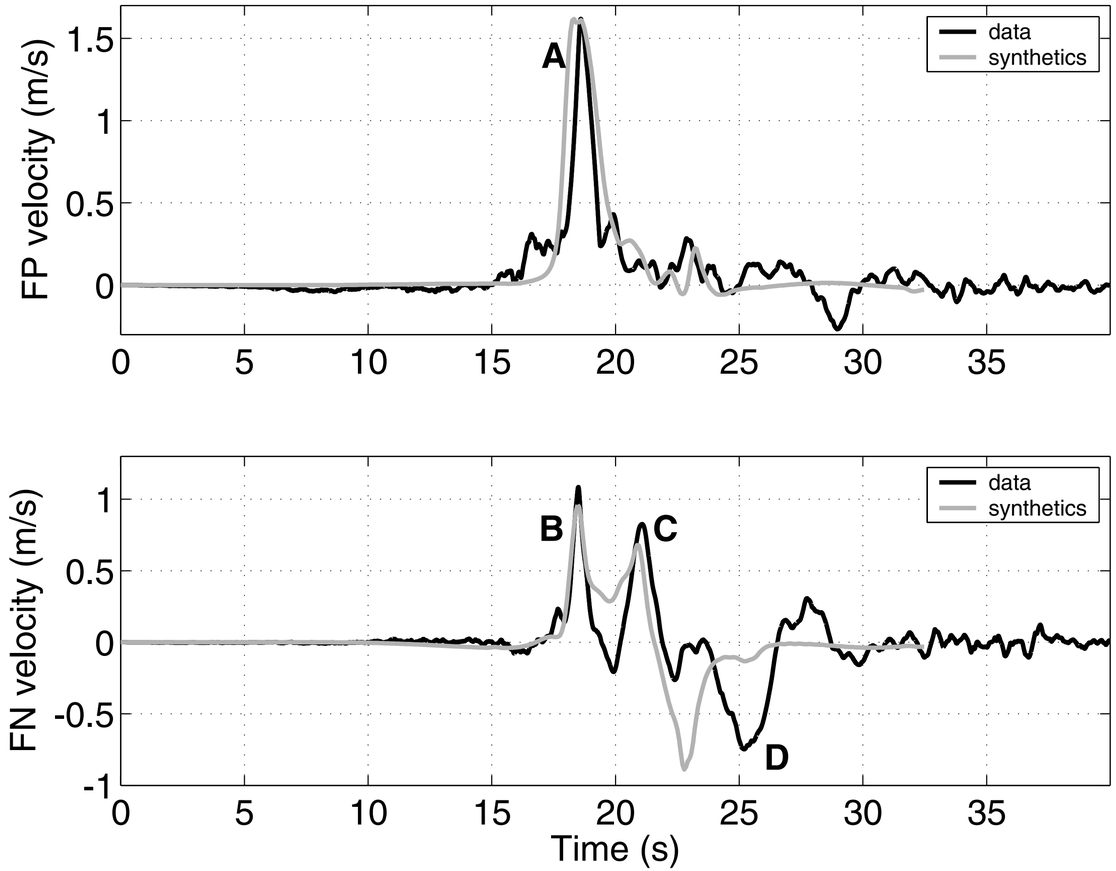
Dunham & Archuleta (2004) Ellsworth et al. (2004) & others : 2002 M_w 7.8 Denali earthquake

Mello, Bhat et al. 2014

Observations

Supershear earthquakes in the wild

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

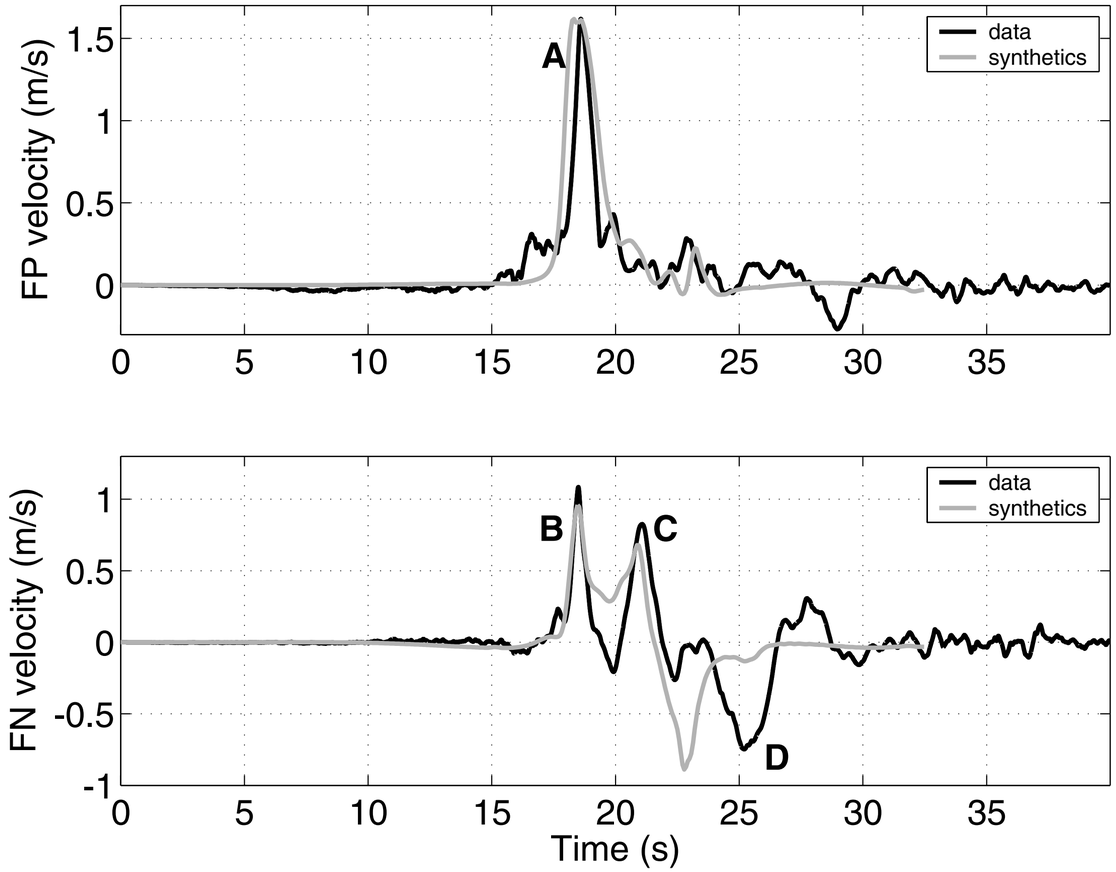


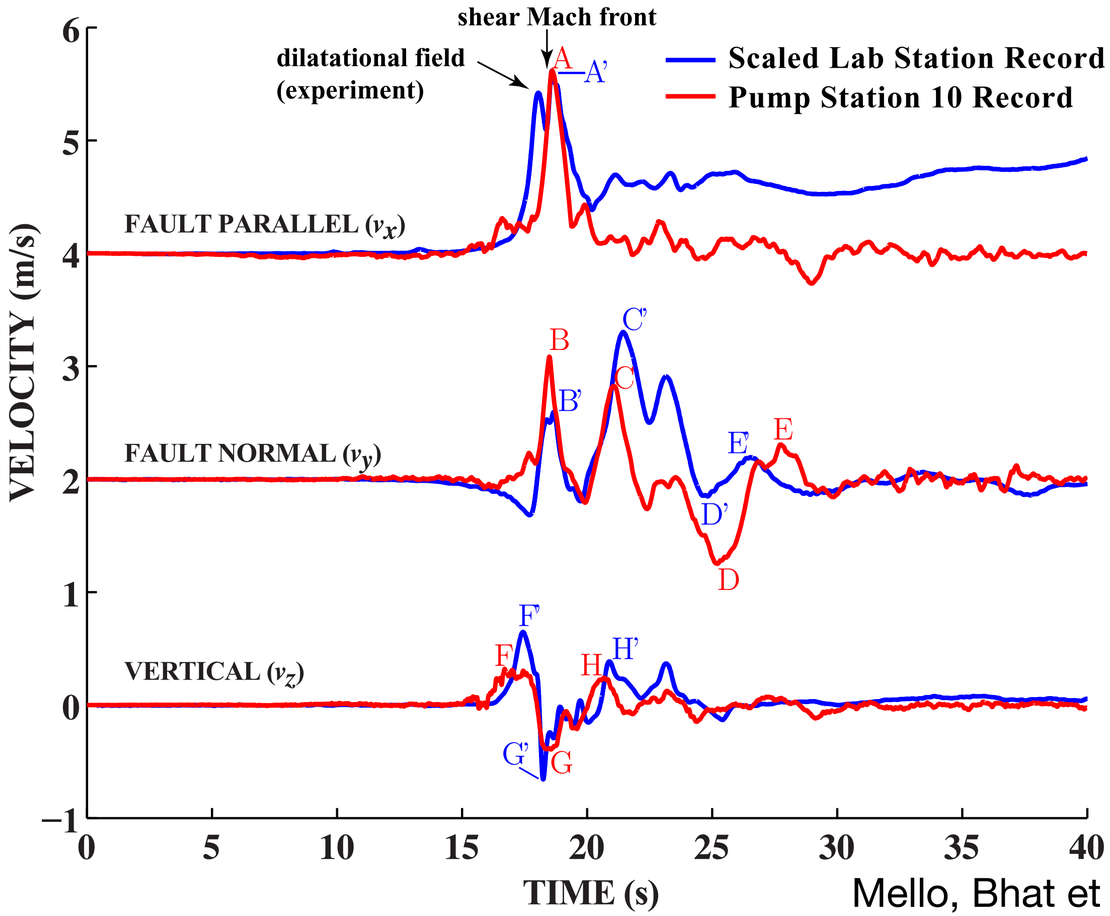
Mello, Bhat et al. 2014

Observations

Supershear earthquakes in the wild

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





Mello, Bhat et al. 2014

Observations

Supershear earthquakes in the wild

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

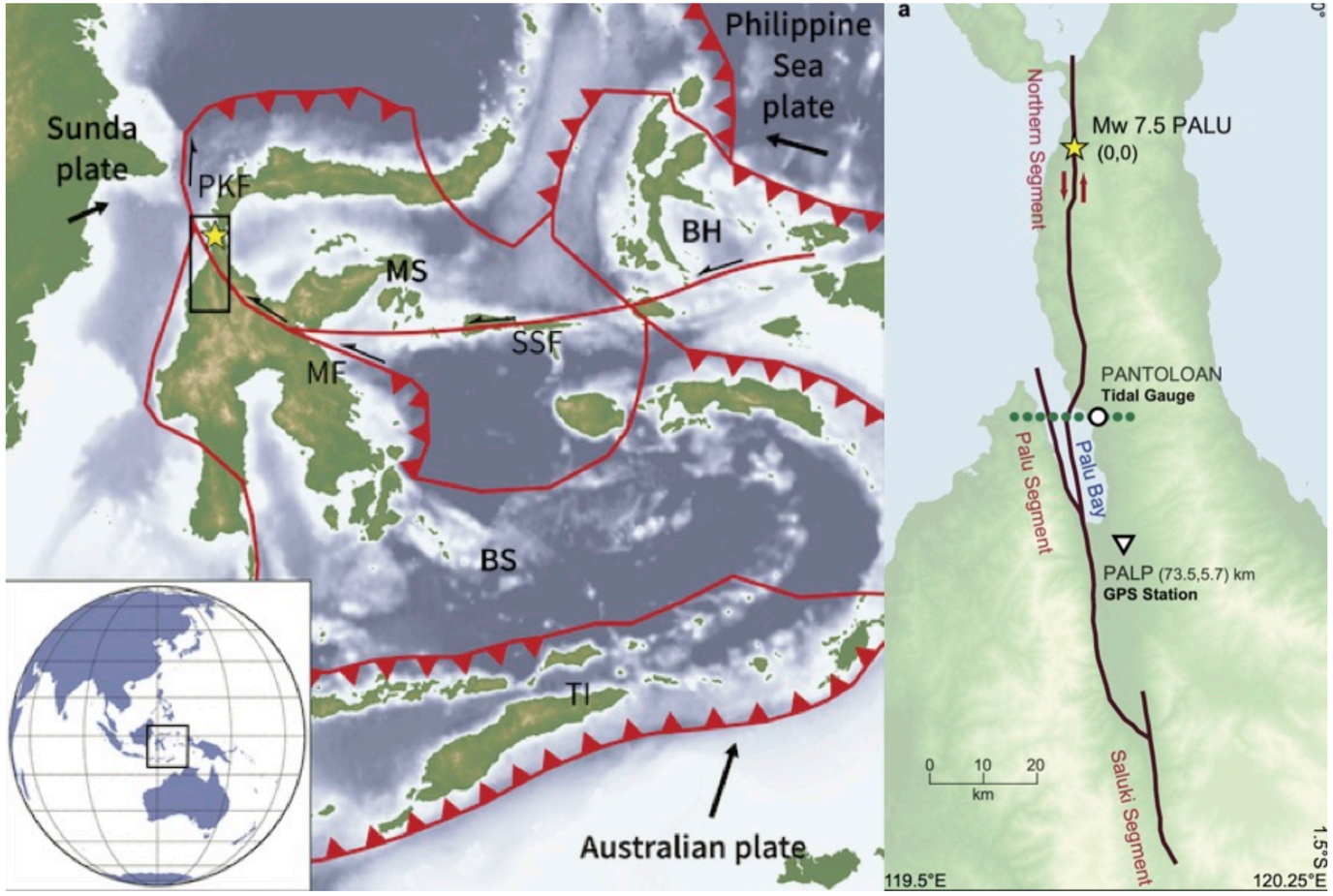
Zhan et al (2014) : 2013 M_w 6.7 Okhotsk, Kamtchatka earthquake. *Deepest and fastest earthquake recorded*

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

Observations

Supershear earthquakes in the wild

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

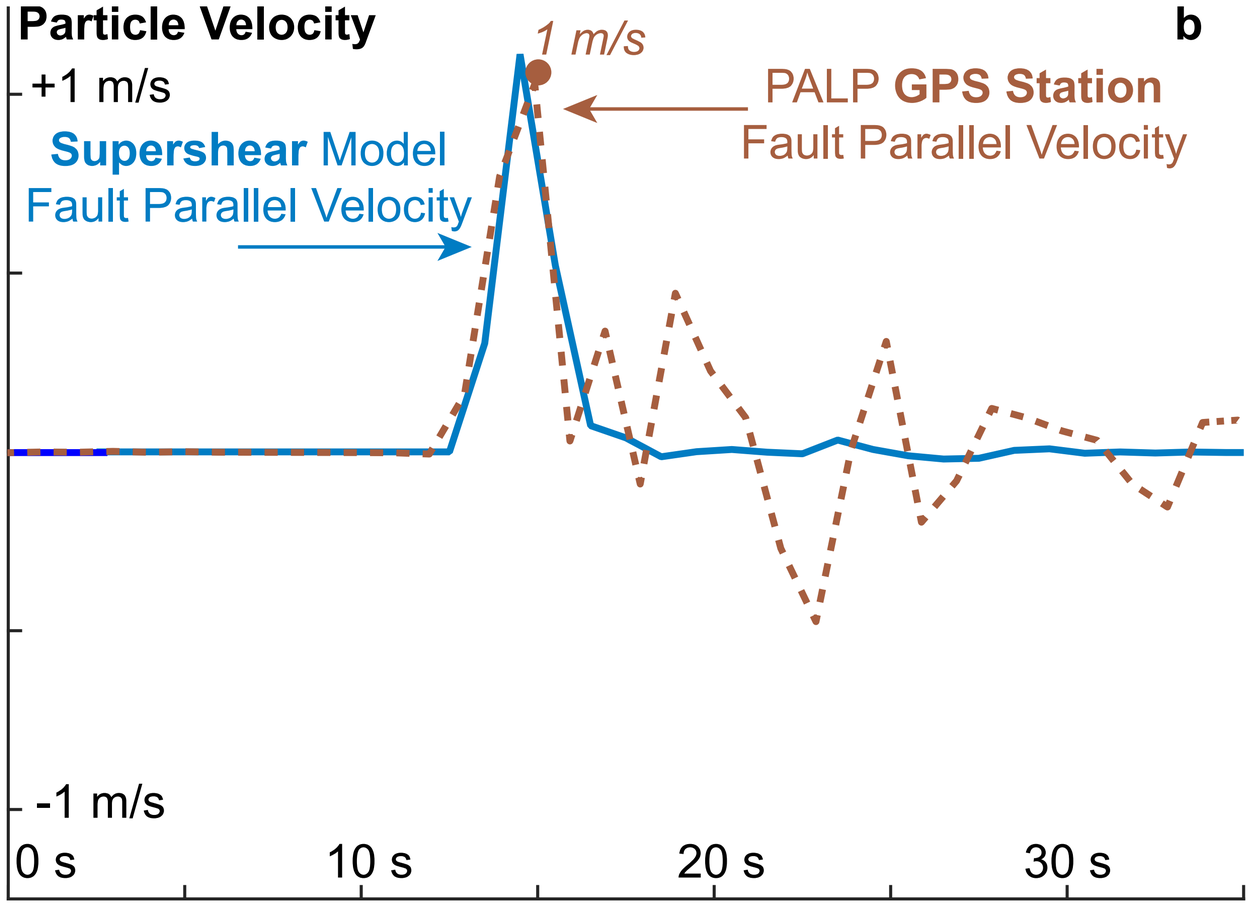


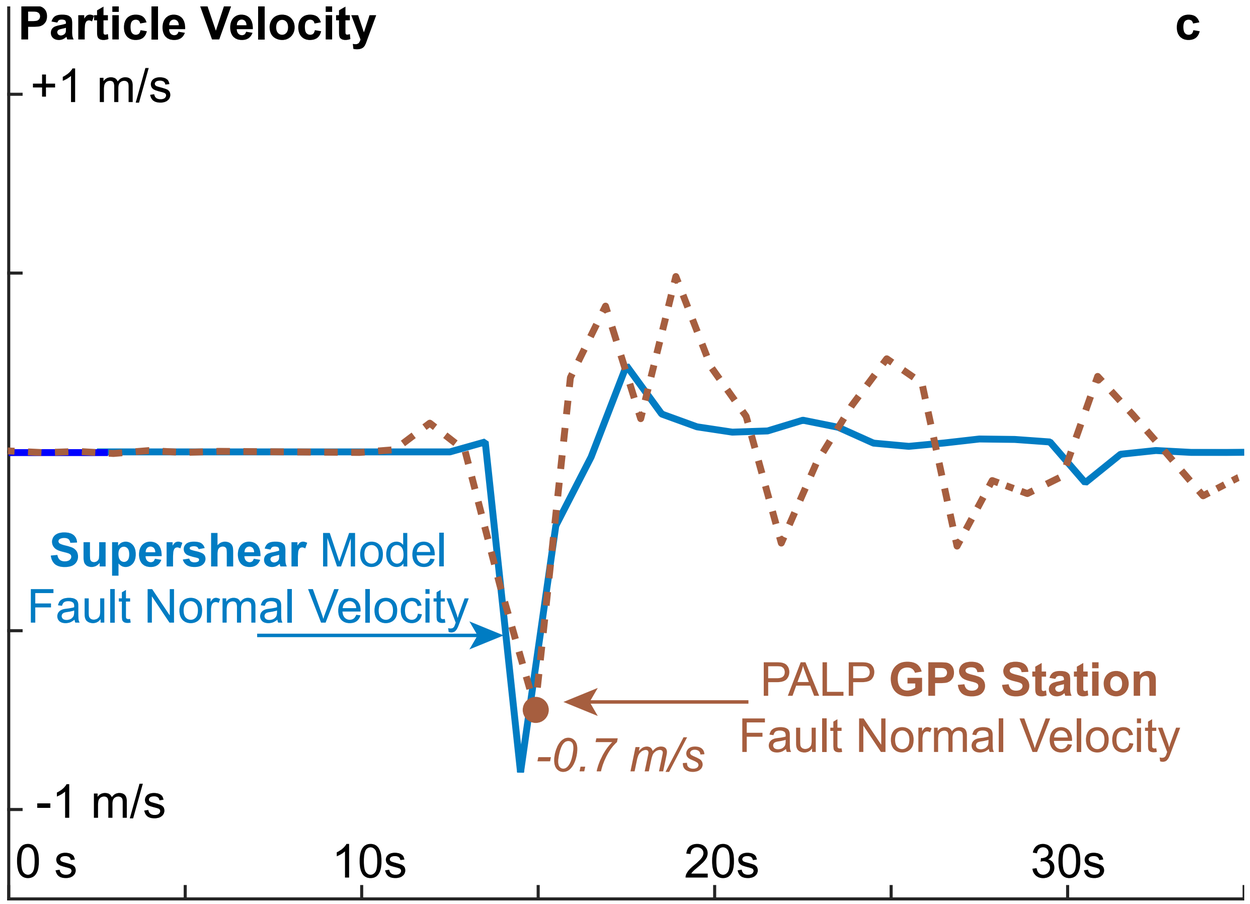
Ulrich et al. 2019
Amlani et al. 2021

Observations

Supershear earthquakes in the wild

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





Dynamic shear ruptures, including earthquakes, can attain supershear speeds

Dynamic shear ruptures, including earthquakes, can indubitably attain supershear speeds

Dynamic shear ruptures, including earthquakes, can indubitably attain supershear speeds

- **Supershear ruptures are stable above the Eshelby speed, $\sqrt{2}c_s$**

Dynamic shear ruptures, including earthquakes, can indubitably attain supershear speeds

- **Supershear ruptures are stable above the Eshelby speed, $\sqrt{2}c_s$**

- **The near field particle velocity is dominated by the fault parallel component for such ruptures. The opposite is true for sub-Rayleigh/ sub-shear ruptures.**

Dynamic shear ruptures, including earthquakes, can indubitably attain supershear speeds

- **Supershear ruptures are stable above the Eshelby speed, $\sqrt{2}c_s$**

- **The near field particle velocity is dominated by the fault parallel component for such ruptures. The opposite is true for sub-Rayleigh/ sub-shear ruptures.**

- **There is a clear separation of the dilatational and the shear fields which manifest in the ground motion.**

Dynamic shear ruptures, including earthquakes, can indubitably attain supershear speeds

- **Supershear ruptures are stable above the Eshelby speed, $\sqrt{2}c_s$**
- **The near field particle velocity is dominated by the fault parallel component for such ruptures. The opposite is true for sub-Rayleigh/ sub-shear ruptures.**
- **There is a clear separation of the dilatational and the shear fields which manifest in the ground motion.**
- **Supershear ruptures are, usually, trailed by a pulse traveling exactly at the Rayleigh wave speed. This pulse has dominantly fault normal motion.**

Dynamic shear ruptures, including earthquakes, can indubitably attain supershear speeds

- Supershear ruptures are stable above the Eshelby speed, $\sqrt{2}c_s$
- The near field particle velocity is dominated by the fault parallel component for such ruptures. The opposite is true for sub-Rayleigh/ sub-shear ruptures.
- There is a clear separation of the dilatational and the shear fields which manifest in the ground motion.
- Supershear ruptures are, usually, trailed by a pulse traveling exactly at the Rayleigh wave speed. This pulse has dominantly fault normal motion.
- In 3D, supershear ruptures manifest Rayleigh Mach fronts, in addition to the shear ones. The Rayleigh Mach fronts suffer no attenuation with distance from the fault for an ideal medium.

Dynamic shear ruptures, including earthquakes, can <u>indubitably</u> attain supershear speeds

- **Supershear ruptures are stable above the Eshelby speed, $\sqrt{2}c_s$**
- **The near field particle velocity is dominated by the fault parallel component for such ruptures. The opposite is true for sub-Rayleigh/ sub-shear ruptures.**
- **There is a clear separation of the dilatational and the shear fields which manifest in the ground motion.**
- **Supershear ruptures are, usually, trailed by a pulse traveling exactly at the Rayleigh wave speed. This pulse has dominantly fault normal motion.**
- **In 3D, supershear ruptures manifest Rayleigh Mach fronts, in addition to the shear ones. The Rayleigh Mach fronts suffer no attenuation with distance from the fault for an ideal medium.**
- **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

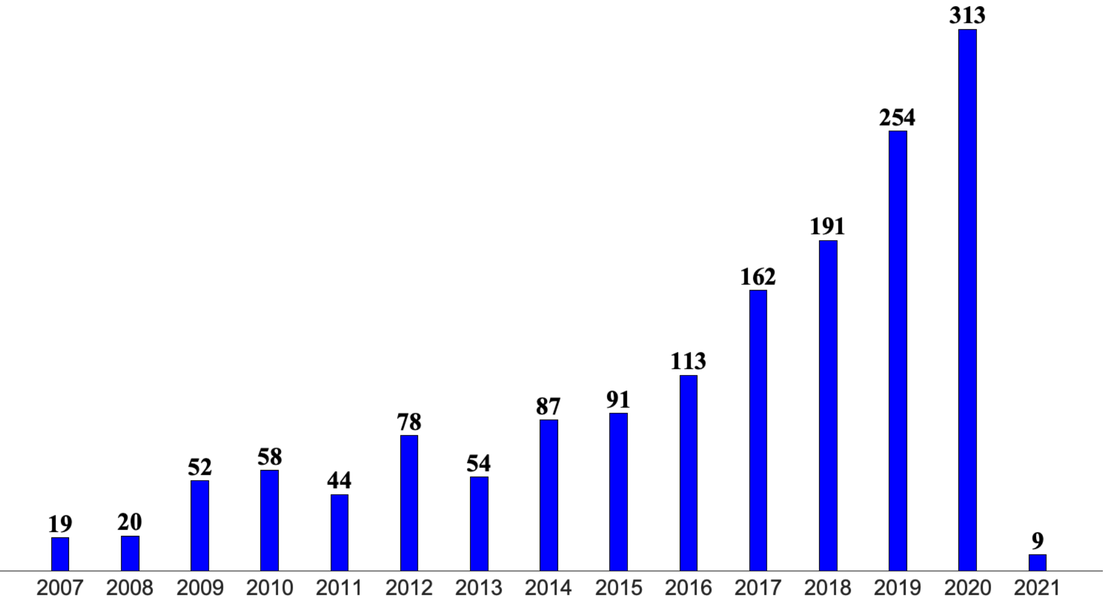
Past Employment

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



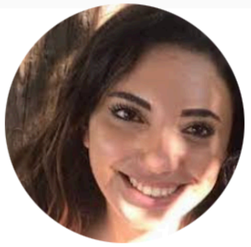
- Over 45 publications in peer reviewed international journals including Nature, Nature Communications and Science
- Over 30 publications since joining CNRS
- 1 Book Chapter
- 2 Edited Volumes

	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

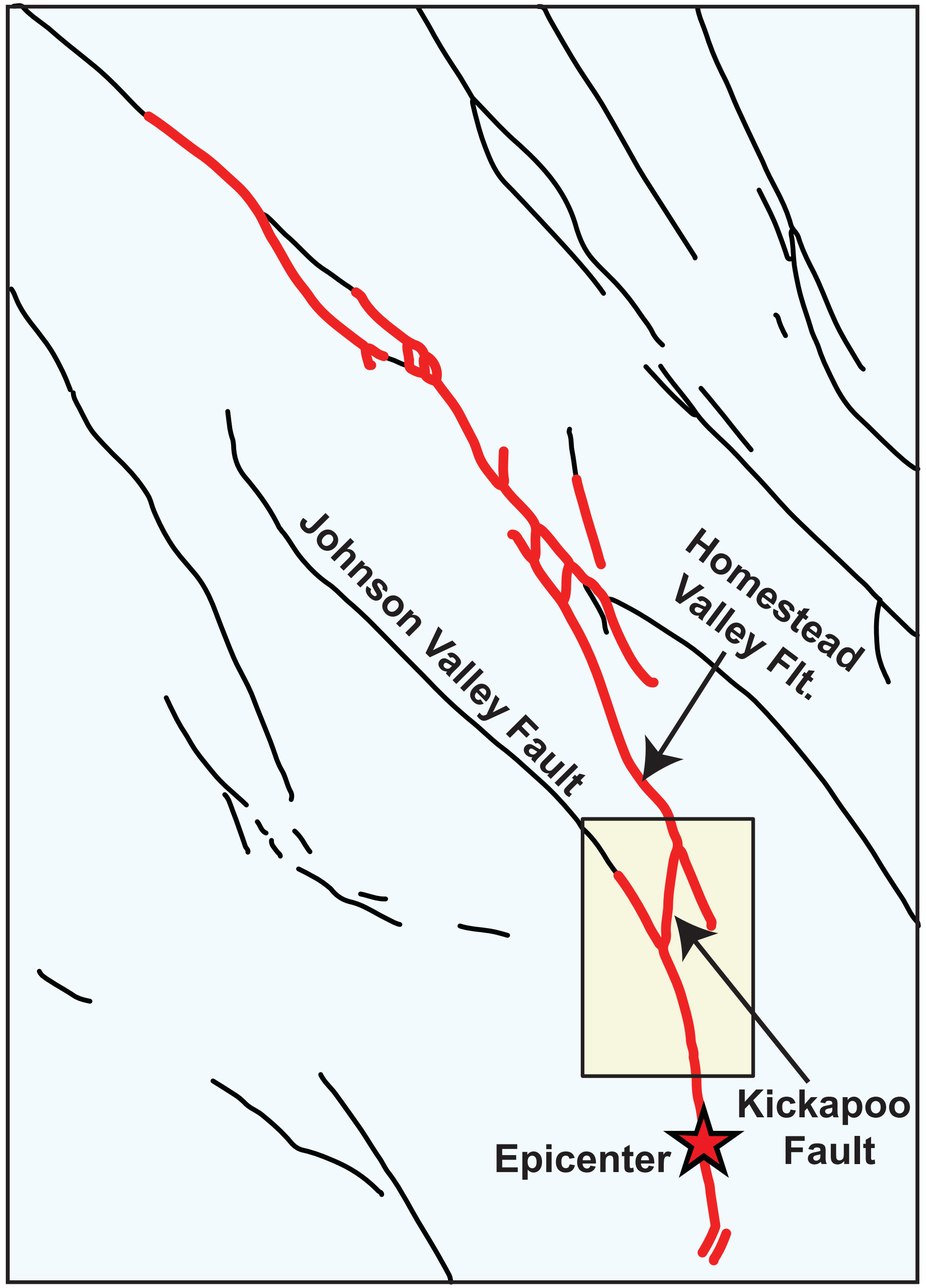
Philippe Danré

Hugo Lestrelin

Roxanne Ferry

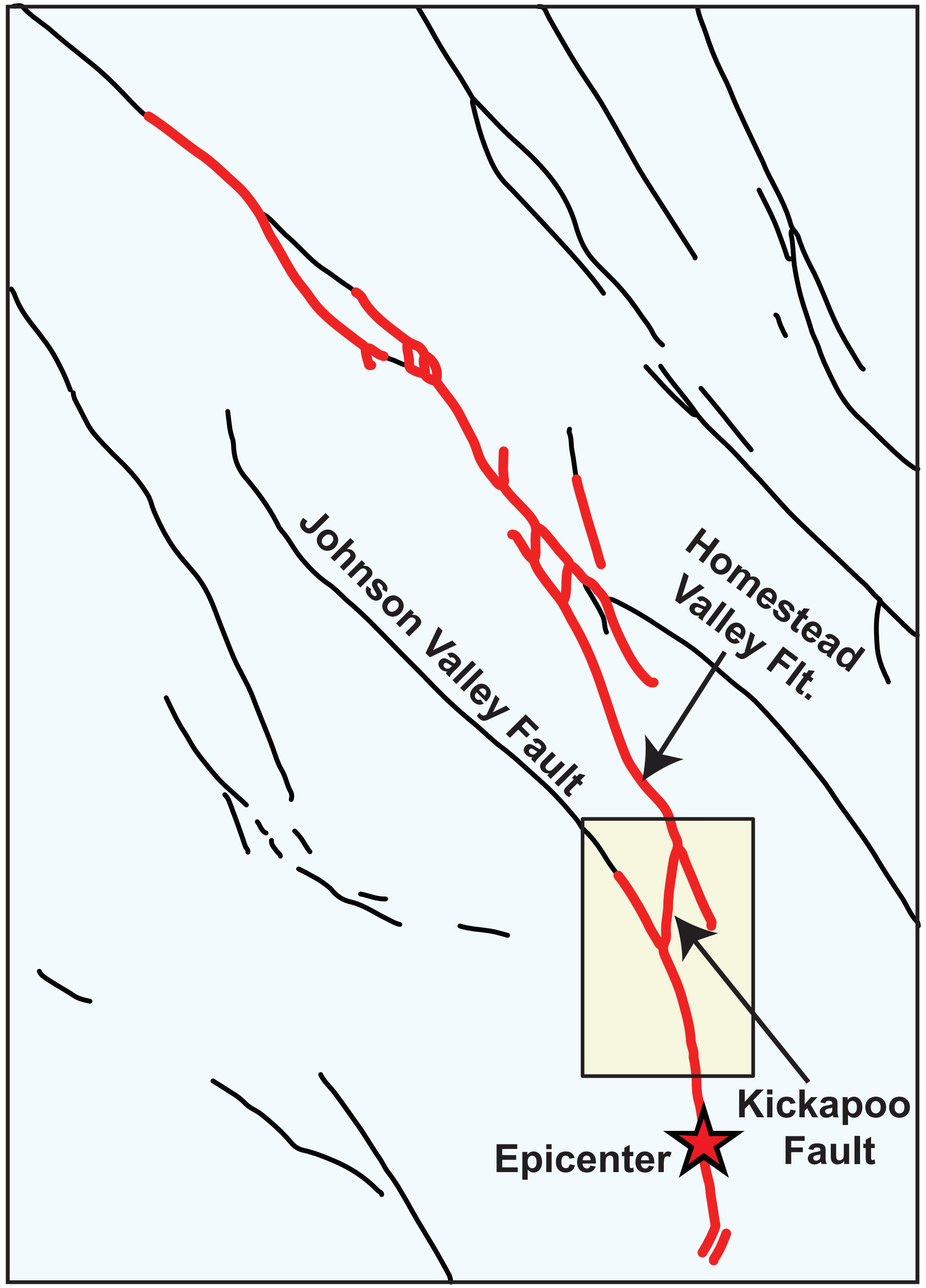
Scientific Contributions

Scientific Contributions



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

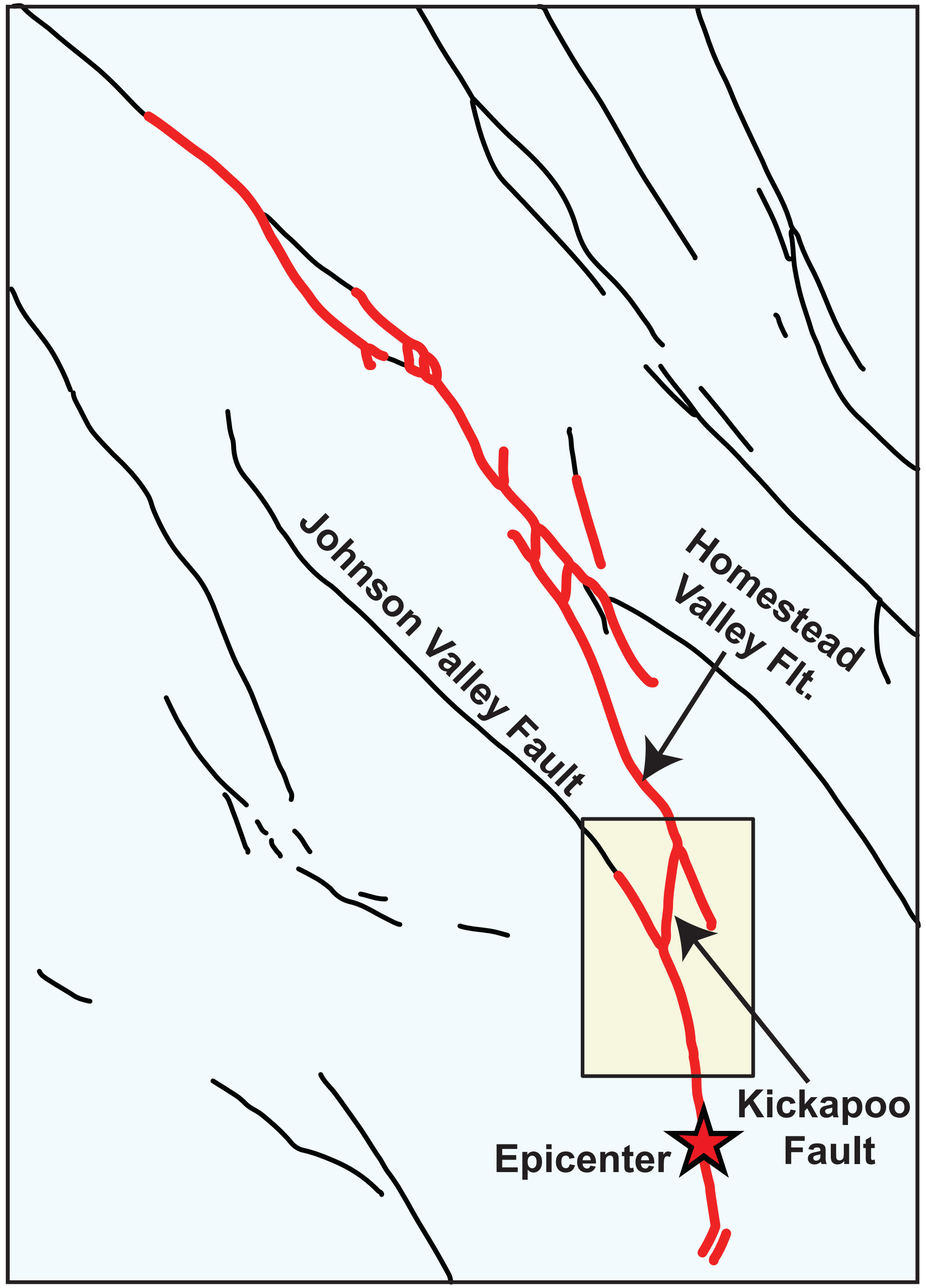
Scientific Contributions



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**

Scientific Contributions

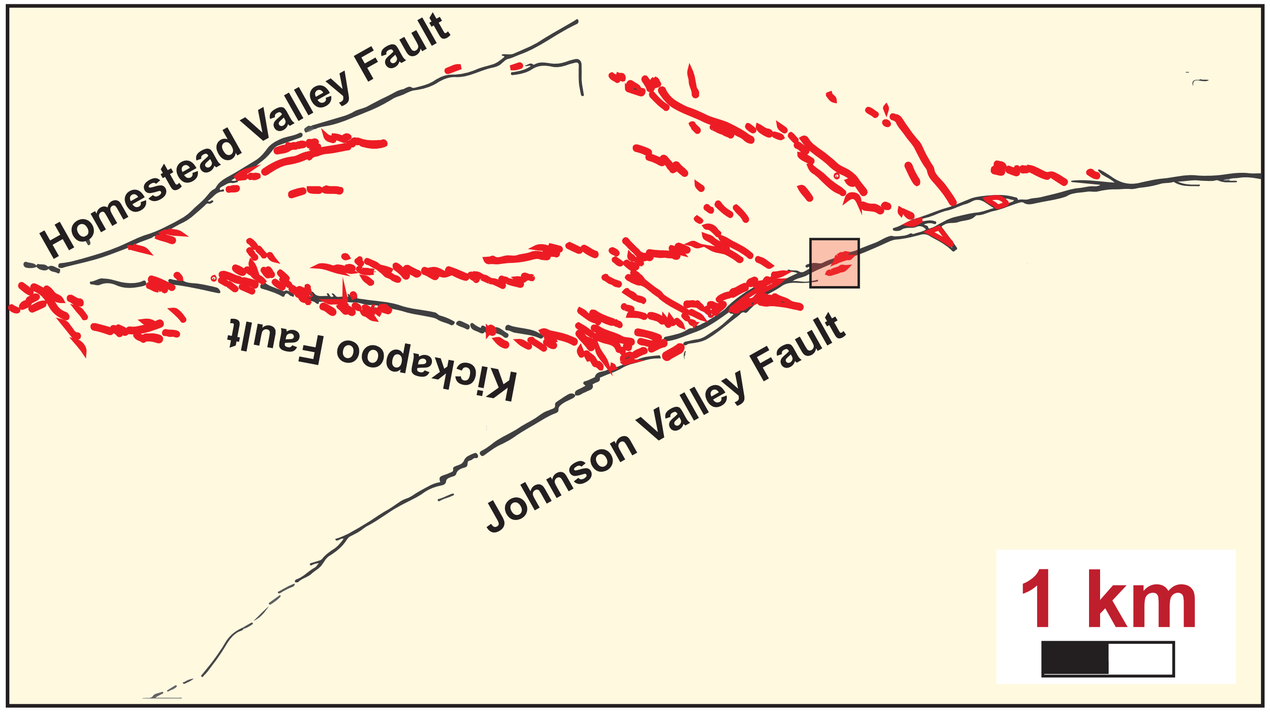


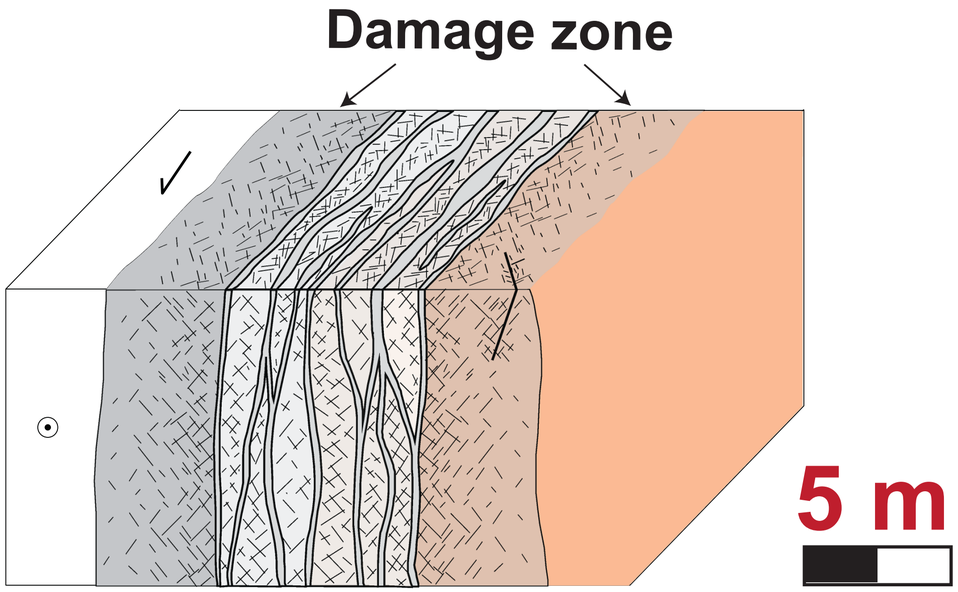
We developed **simple rules for rupture branching (forward & backward)**, in a fault network

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

Scientific Contributions





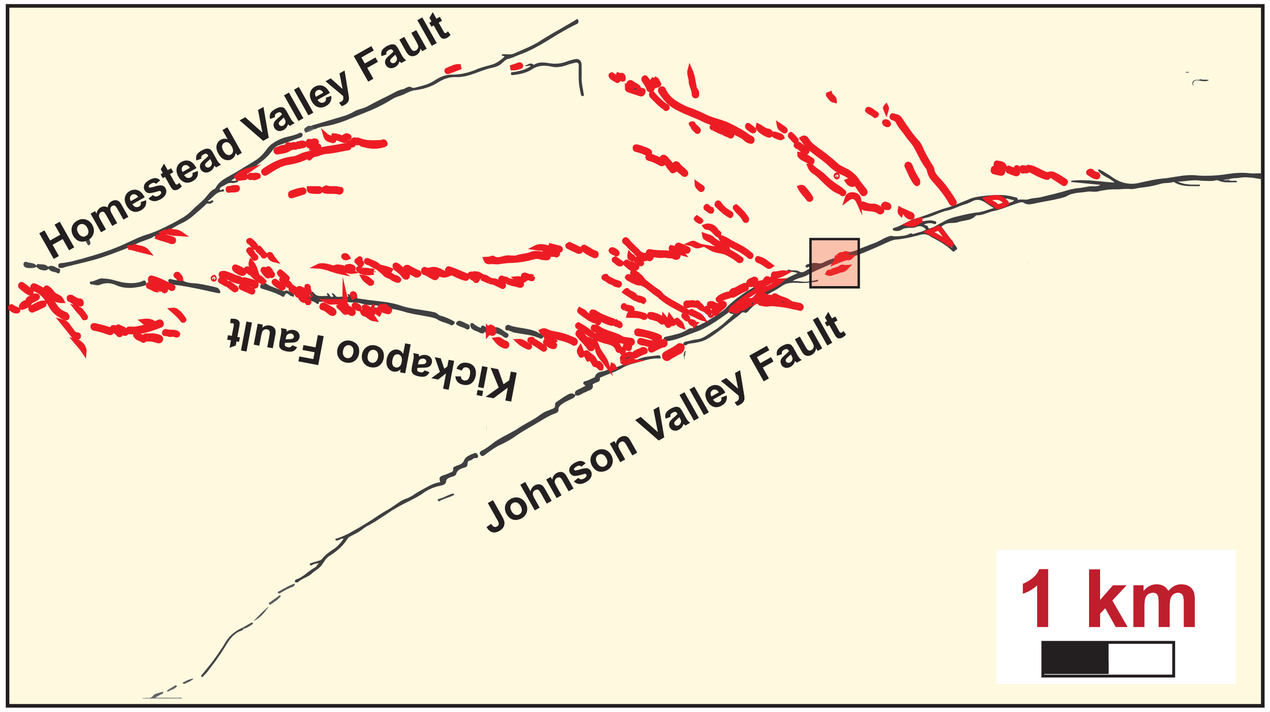
We developed **simple rules for rupture branching (forward & backward)**, in a fault network

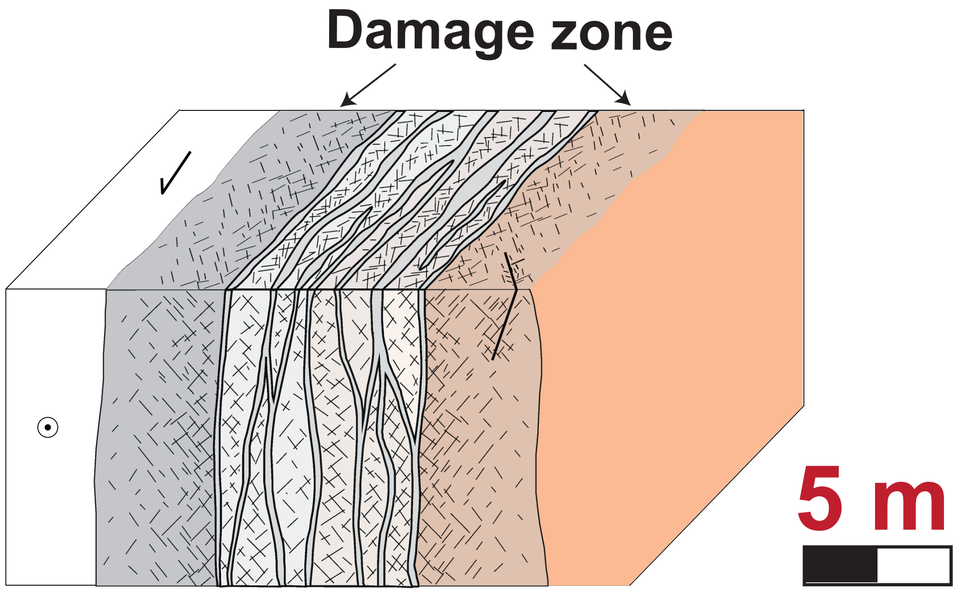
We **developed new algorithms to model earthquake cycles on realistic fault networks**

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**

Scientific Contributions





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

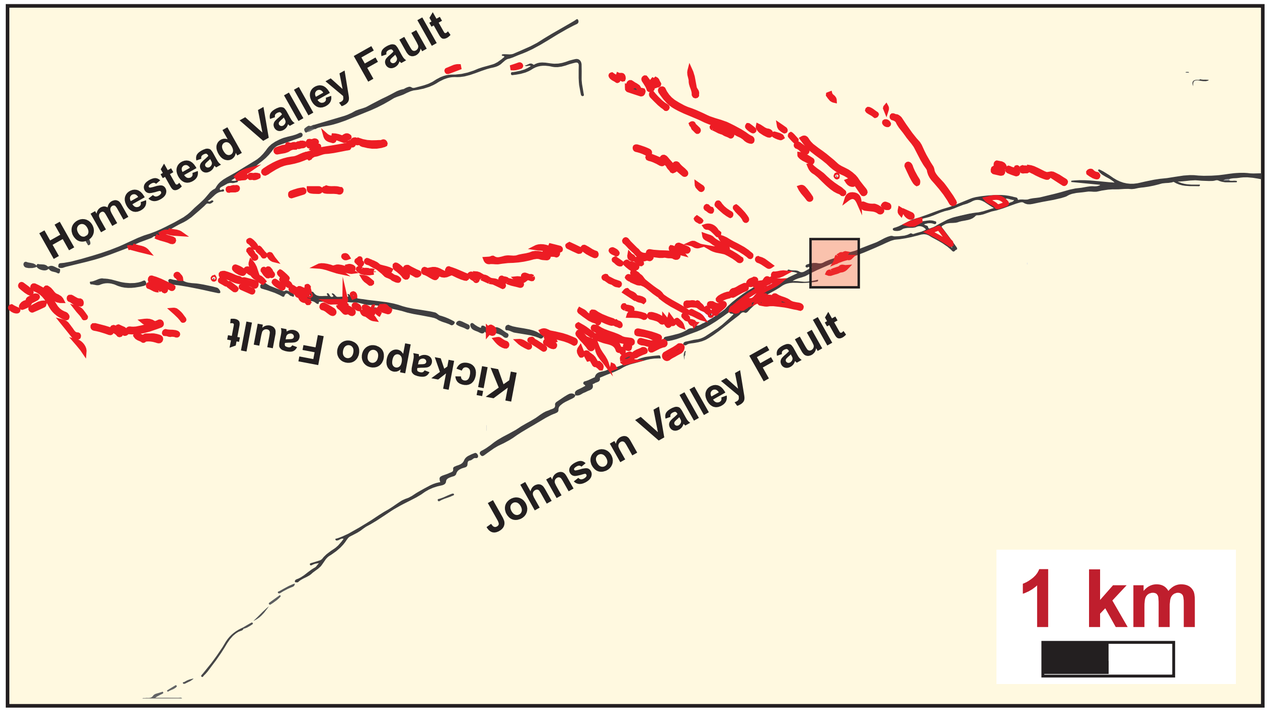
We **developed new algorithms to model earthquake cycles on realistic fault networks**

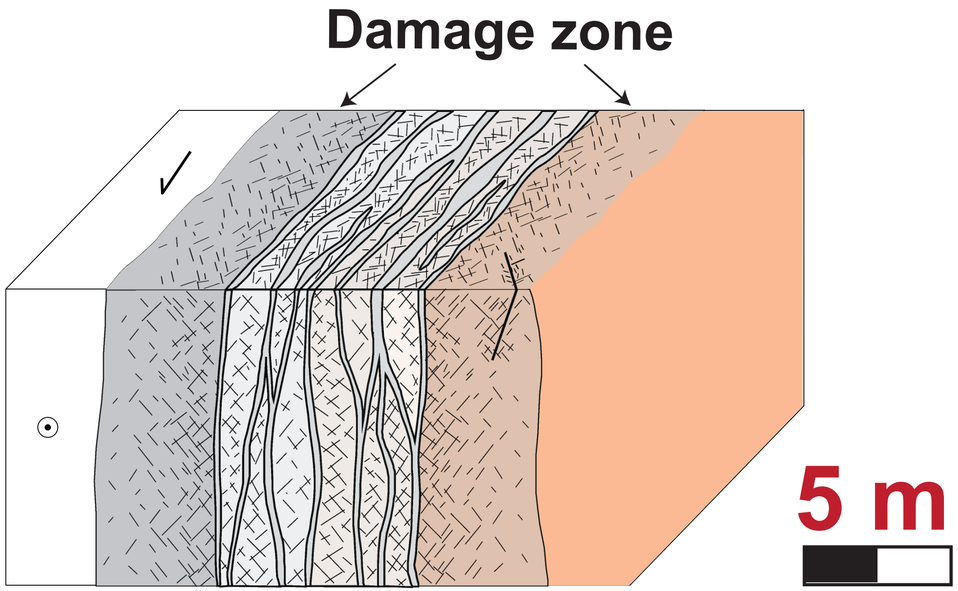
We showed that **slow slip events and earthquakes emerge naturally** in non-planar faults

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

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

Scientific Contributions





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**

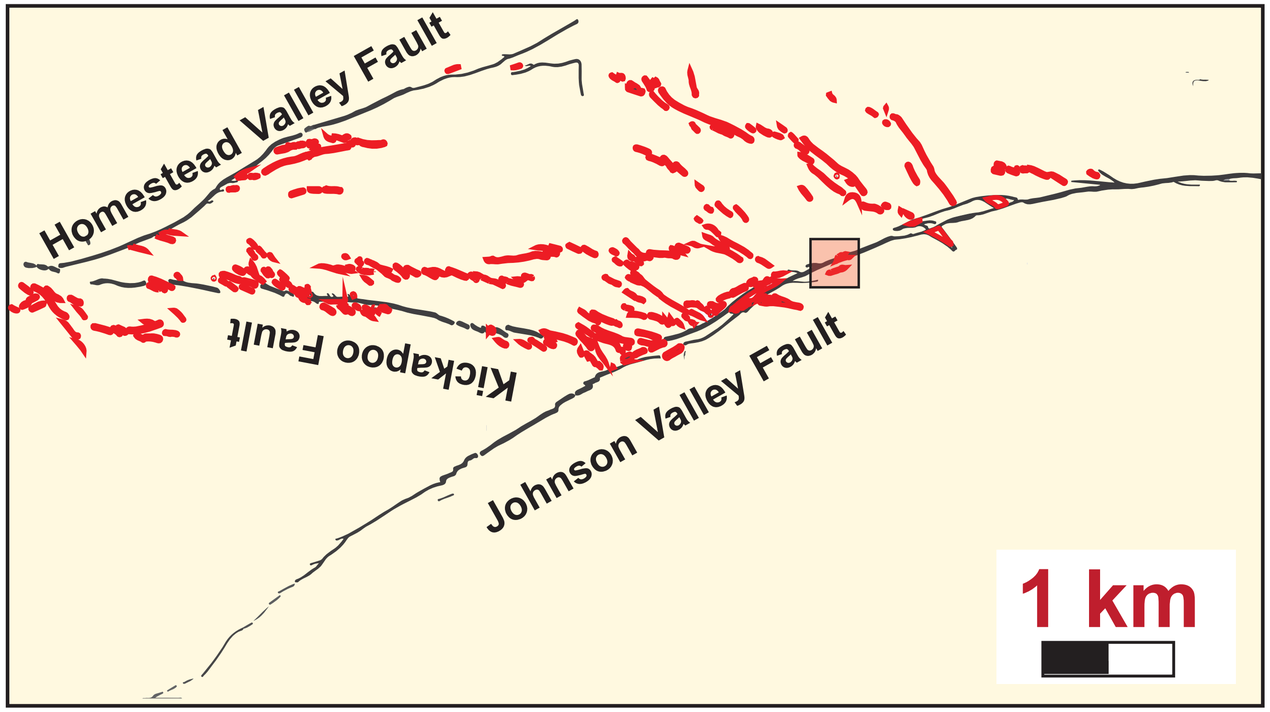
We showed that **slow slip events and earthquakes emerge naturally** in non-planar faults

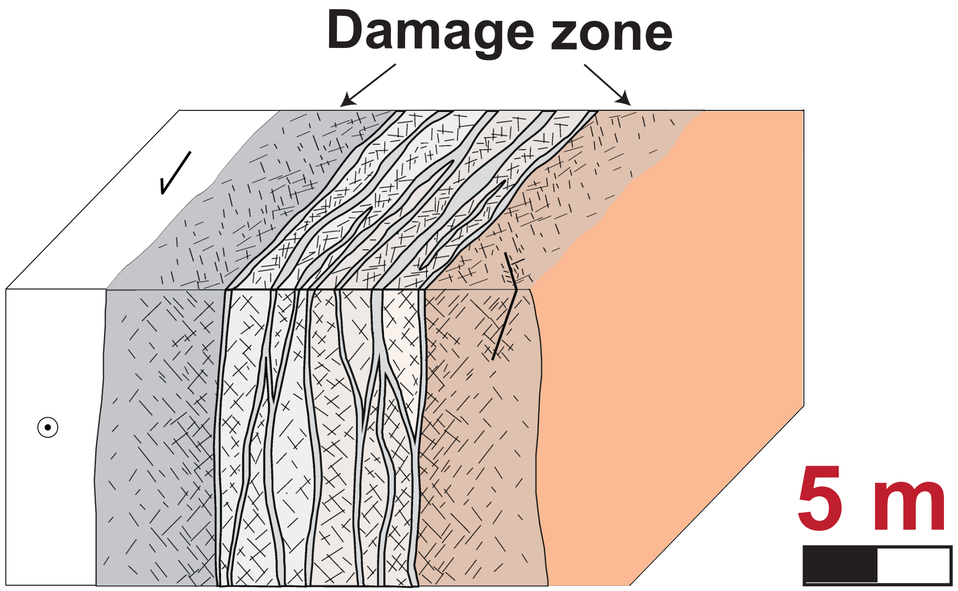
We showed that the **off-fault damage dynamically interacts with rupture**

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

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

Scientific Contributions





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

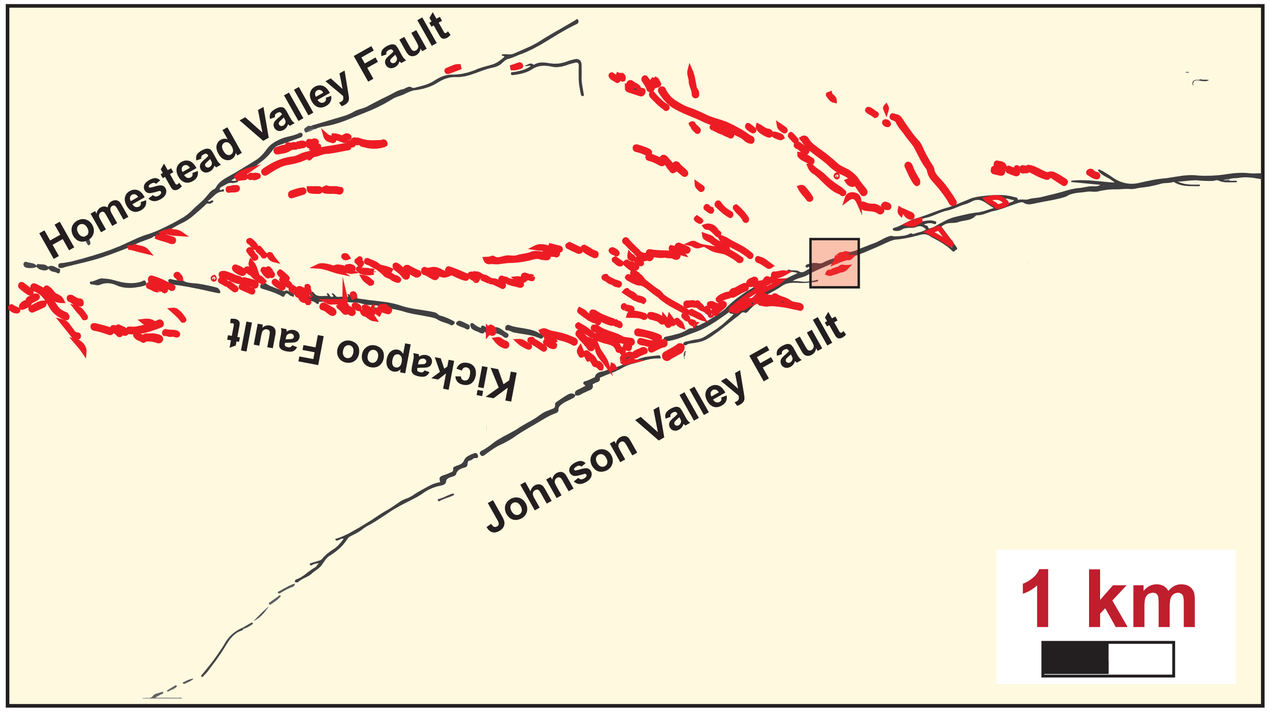
We showed that the **off-fault damage dynamically interacts with rupture**

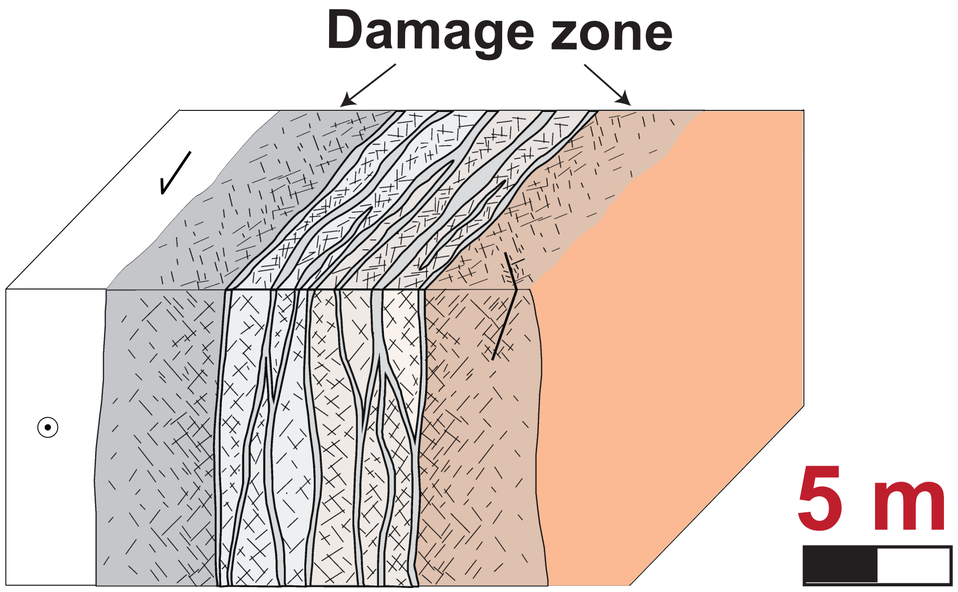
We **developed micromechanical models of fracture networks for mechanical & hydraulic evolution**

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

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

Scientific Contributions





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**

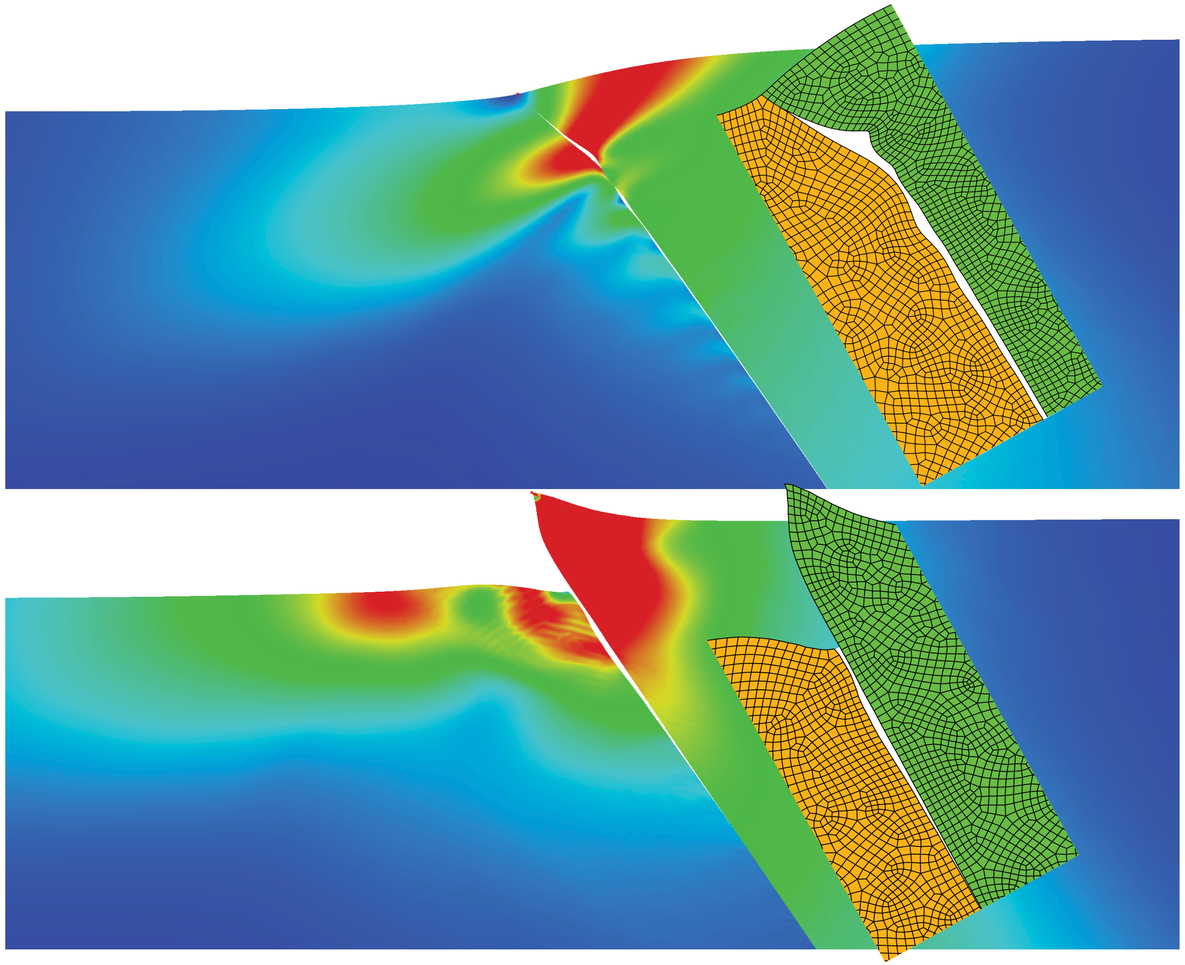
We **developed micromechanical models of fracture networks for mechanical & hydraulic evolution**

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**

Scientific Contributions



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**

Scientific Contributions

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**

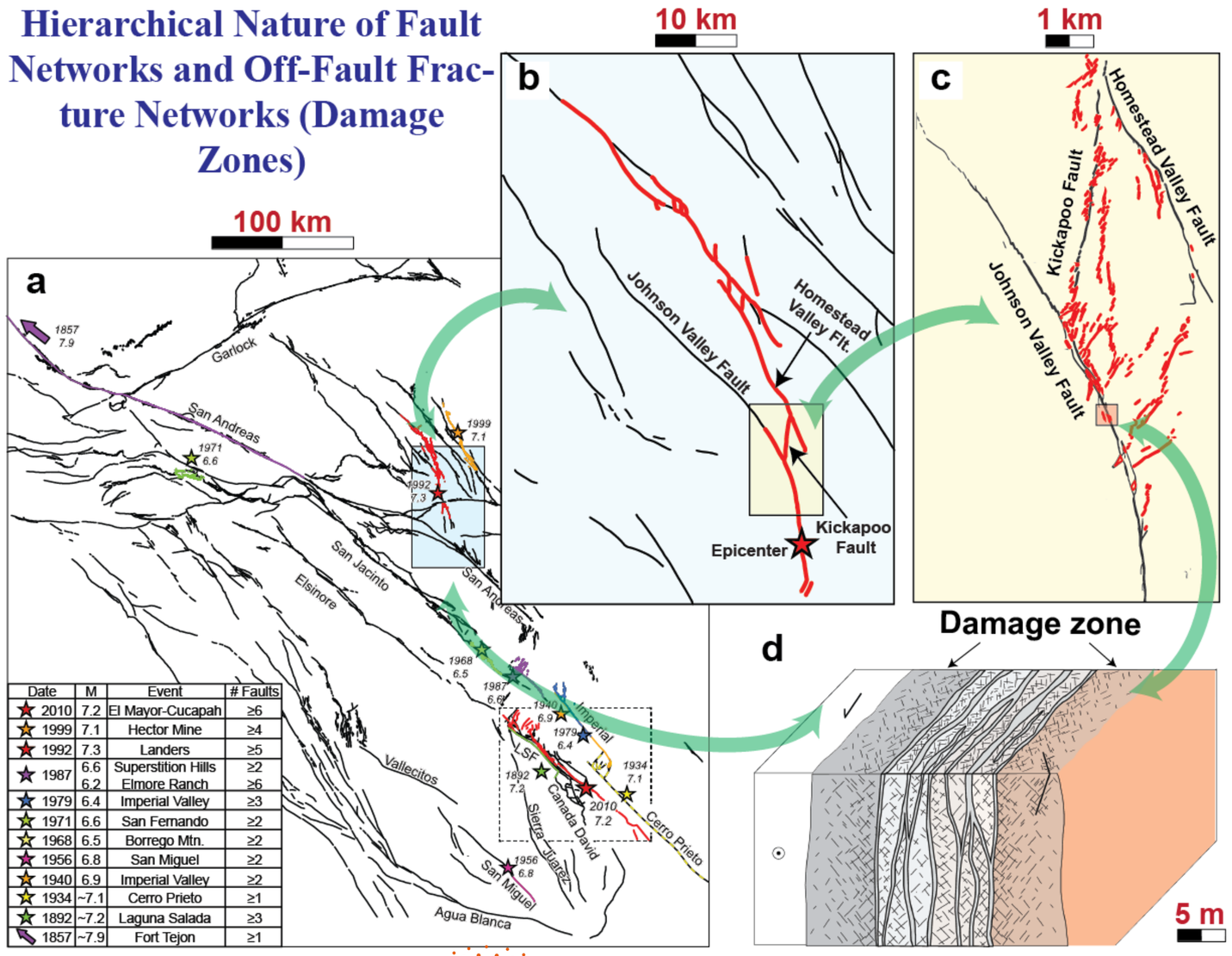
We showed that **high frequency ground motion emerged from Damage Zone**

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**

Scientific Contributions



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**

erc **PERSISMO**

Jan 2021 - Dec 2025

Merci

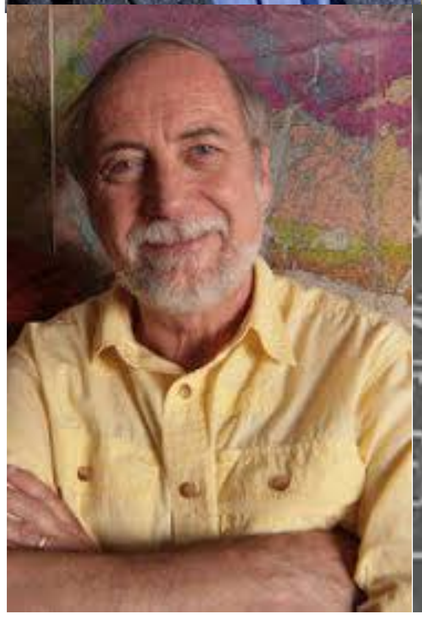




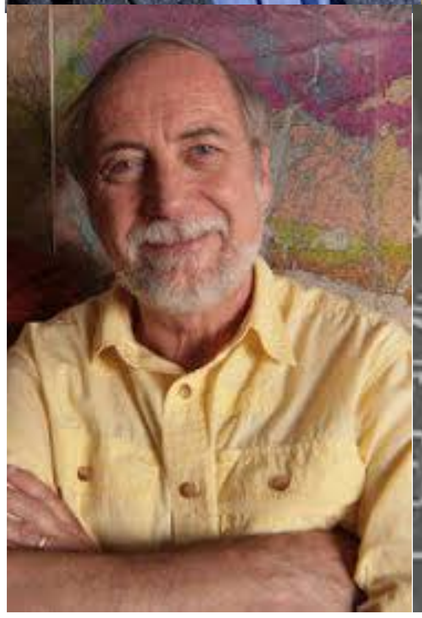






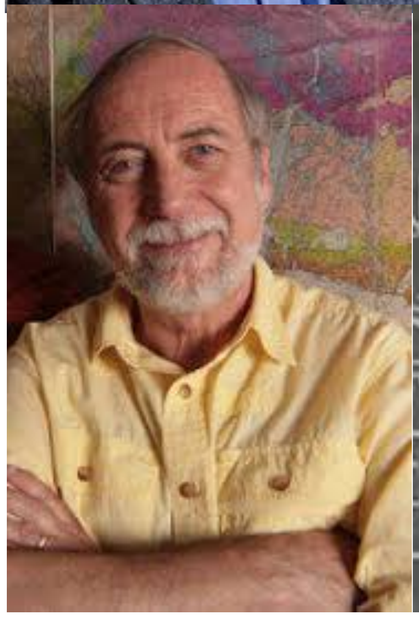


Enhanced Velocity



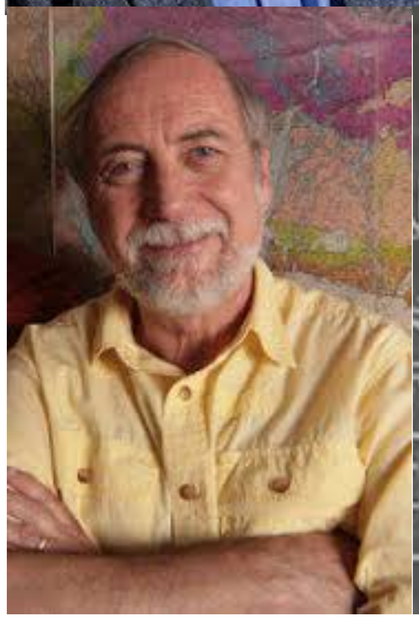




Enhanced Velocity








Thom-Thom & Nana loves you to bits!