LABORATORY EARTHQUAKES:
Directionality and Supershear

Ares J. Rosakis

Graduate Aeronautical Laboratories California Institute of Technology

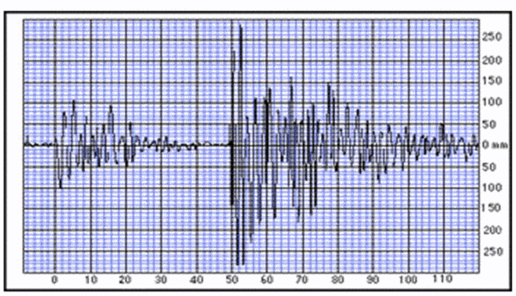
Kavli Institute for Theoretical Physics (KITP) UC Santa Barbara

Collaborations (Experiments):
H. Kanamori, California Institute of Technology
G. Lykotrafitis, California Institute of Technology
J. Rice, Harvard University
K. Xia, California Institute of Technology

Collaborations (Theory/Numerics):
D. Coker, Oklahoma State University
Y. Huang, University of Illinois UC
N. Lapusta, California Institute of Technology
X. Lu, California Institute of Technology
A. Needleman, Brown University

Office of Naval Research (Y.D.S. Rajapakse, Program Monitor)
National Science Foundation (Earth Sciences)

What Is a crustal Earthquake ?



Earthquake is a term used to describe both sudden slip on a fault, and the resulting ground shaking and radiated seismic energy caused by the slip.

http://earthquake.usgs.gov/image_glossary/earthquake.html

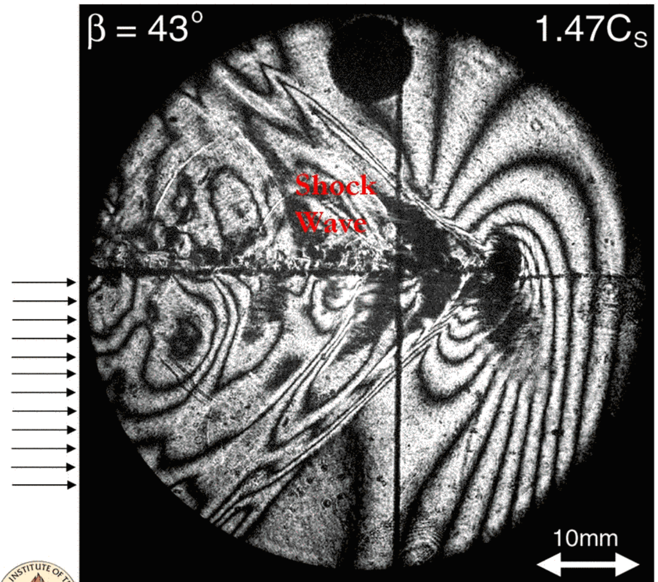
Earthquakes are spontaneous frictional (shear) ruptures occurring along weak planes in the crust :

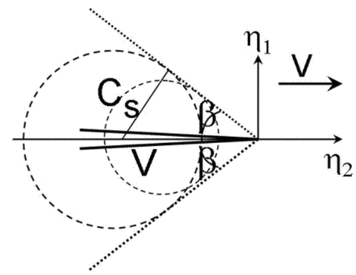
- **"spontaneous" implies quasi-static tectonic loading and sudden triggering of dynamic slip.**
- **"rupture" means propagation of slip along a frictional interface.**

DEMONSTRATING THAT INTERSONIC CRACKS EXIST

(Rosakis, Samudrala and Coker, Science 1999)

Motivation:Composites(ONR)





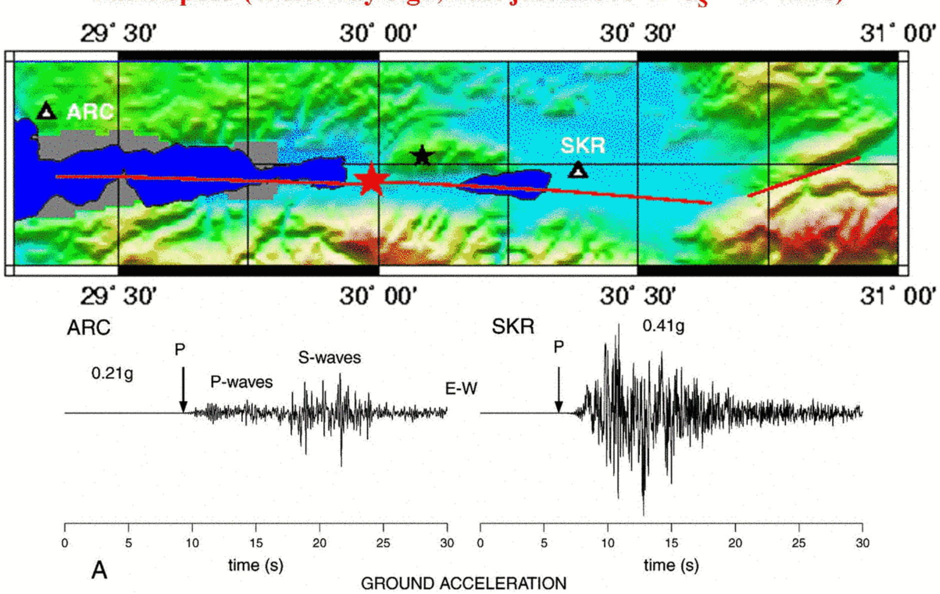
$V = C_S/\sin\beta$

Ruptures are:
Impact-induced,
non-spontaneous.
Coherent interfaces.

Field Evidence of Intersonic Rupture During the 1999 (M7.4) IZMIT Earthquake in Turkey

M. Bouchon, M. Bouin, H. Karabulet, M. Toksöz, M. Dietrich and A. Rosakis,
Geophysical Research Letters, 2001

Fault Speed (West: Rayleigh, East just above $\sqrt{2}\, C_S = 4.9$ km/s)



Average Rupture Speeds During Crustal Earthquakes

- Within resolution of the inversion process the majority of field evidence suggests rupture speeds, v, between $0.8\ C_R$ to C_R of crustal rock. Venkataraman and Kanamori , *JGR* (2004)
- Evidence of supershear ($C_S < v < C_P$) rupture bursts along fault segments.

References	*Events*
• R. Archuleta, *JGR* (1984) • Spudich and Kranswick, *BSSA* (1984)	1979 Imperial Valley, CA
• Olsen, Madariaga and Archuleta, *Science* (1997) • Hernandez, Cotton and Cambillo, *JGR* (1999)	1992 Landers, CA
• Bouchon et al., *GRL* (2001)	1999 Izmit, Turkey
• Bouchon and Vallee, *Science* (2003)	2001 Kunlunshan, China (Transition)
• Ellsworth et al., (2004)	2002 Denali, Alaska (Transition)

Personal favorites

Field Evidence of Sub-Rayleigh to Supershear Transition (Ms 8.1 2001 Kunlunshan, Tibet Earthquake)

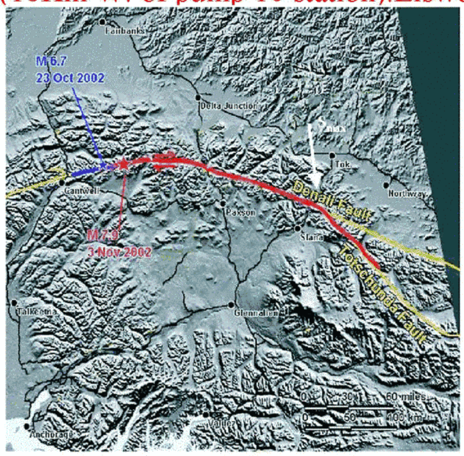
(Bouchon and Vallee, Science, August 2003)

- Unidirectional, left lateral slip. Very long, near-vertical, strike –slip fault segment.
- Eastward propagation over a 400 km fault segment
- Sub-Rayleigh over first 100 km (2.4 - 2.8 km/s)
- Transition to supershear (5 km/s)

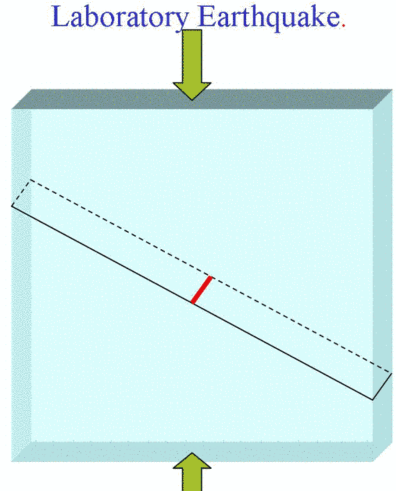
From Real to Laboratory Earthquakes

(*Mimicking Spontaneous Rupture Events in Frictional interfaces*)

M 7.9 , 2002 Denali, Alaska Earthquake.Transition at 72Km(18Km W. of pump 10 station).Elsworth(2003)



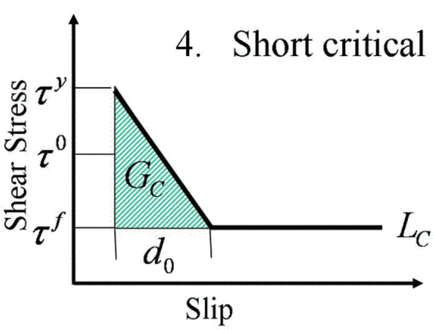
Laboratory Earthquake.



- **Rock** → **Photoelastic Polymer**
- **Fault** → **Inclined Contact Interface**
- **Tectonic stress** → **Far Field Load**
- **Hypocenter** → **Triggering Site**

Why Polymer ?

1. Birefringence.
2. Good linear-elastic material.
3. Qualitatively Similar frictional properties to rock (Dieterich, 1979).
4. Short critical initiation length $L_{C.}$

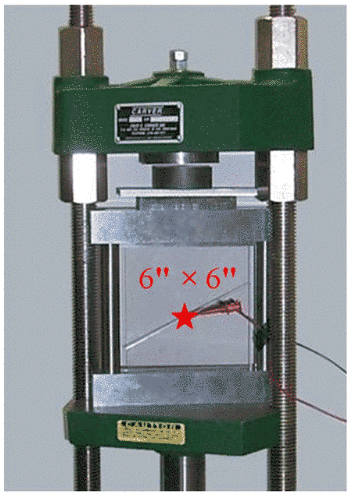


Slip Weakening Law

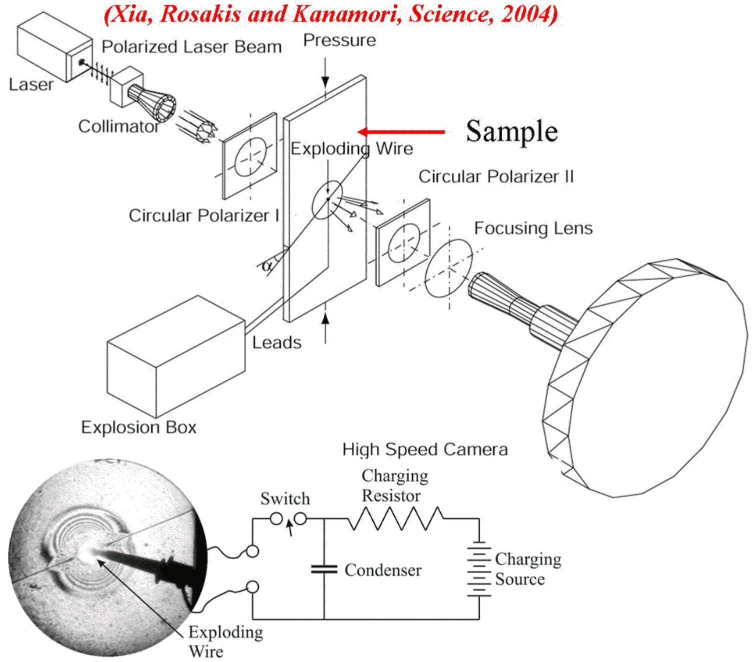
$$L_C = \frac{(1+\nu)G}{\pi} \frac{\tau^y - \tau^f}{(\tau^0 - \tau^f)^2} d_0 = \begin{cases} 5mm & \text{Polymer} \\ 135mm & \text{Rock} \end{cases}$$

Experimental Set-up

(Far-Field Loading and Local Release of Pressure: Spontaneous Rupture)



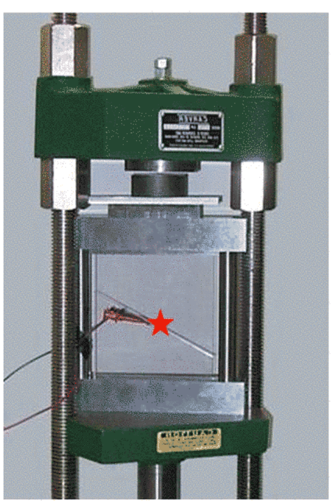
(Xia, Rosakis and Kanamori, Science, 2004)

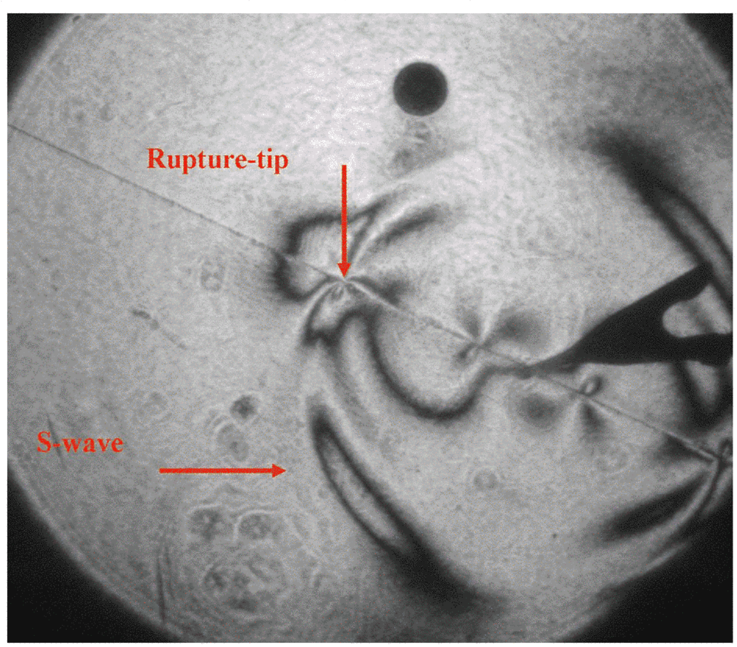


Classical Sub-Rayleigh Rupture

Angle=25°, Pressure=7MPa T=30μs

(Xia, Rosakis and Kanamori, Science, March 2004)

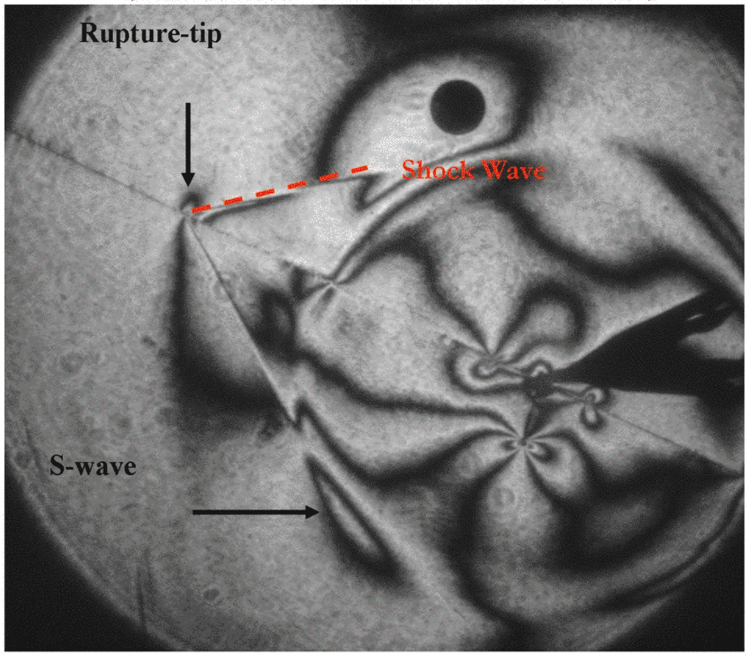




Supershear Rupture

Angle=25°, Pressure=13MPa T=30μs

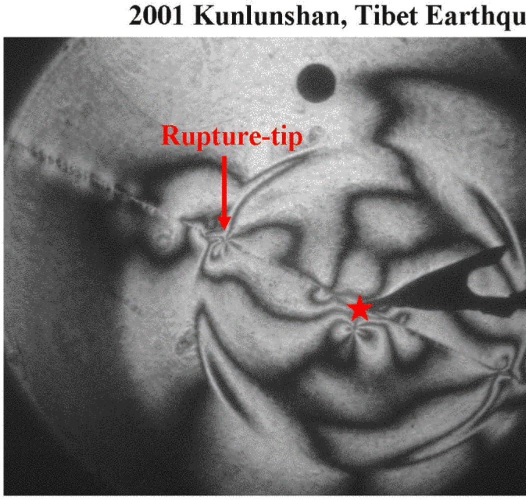
(Xia, Rosakis and Kanamori, Science, March 2004)



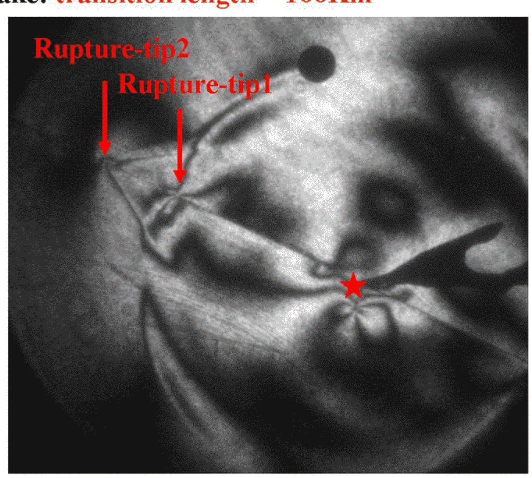
Transition: From Sub-Raleigh to Supershear

(Xia, Rosakis and Kanamori, Science 2004)

Angle=25°, Pressure = 10MPa: transition length = 20mm
2001 Kunlunshan, Tibet Earthquake: transition length = 100Km



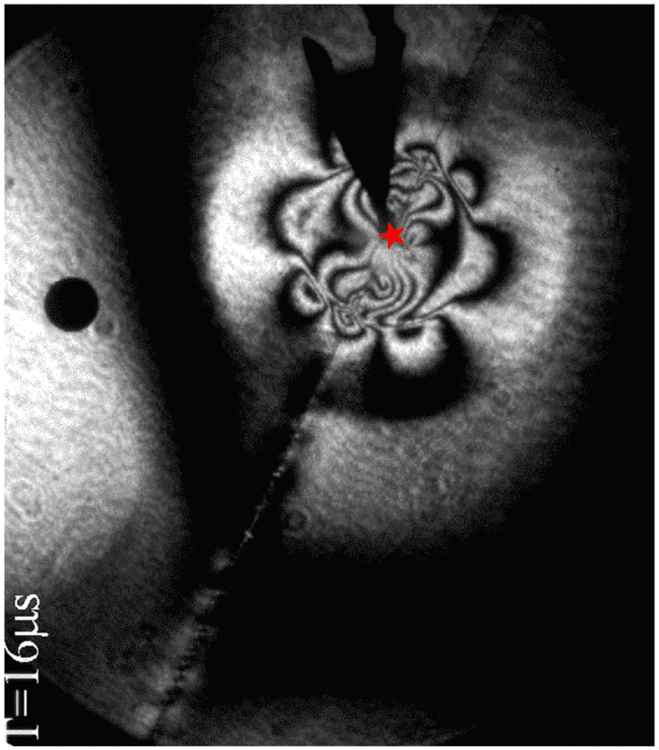
T=30μs



T=38μs

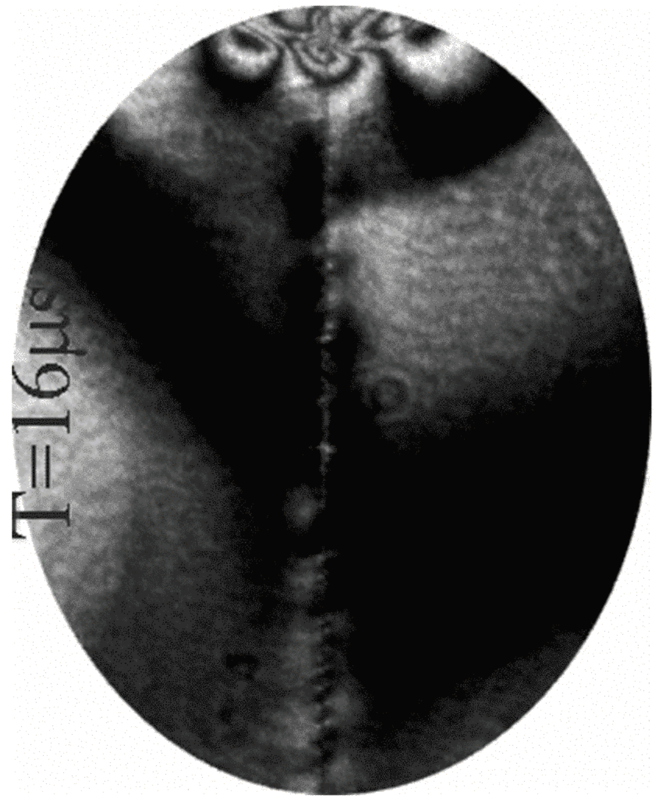
Transition Movie

Angle=25°, Pressure=10MPa



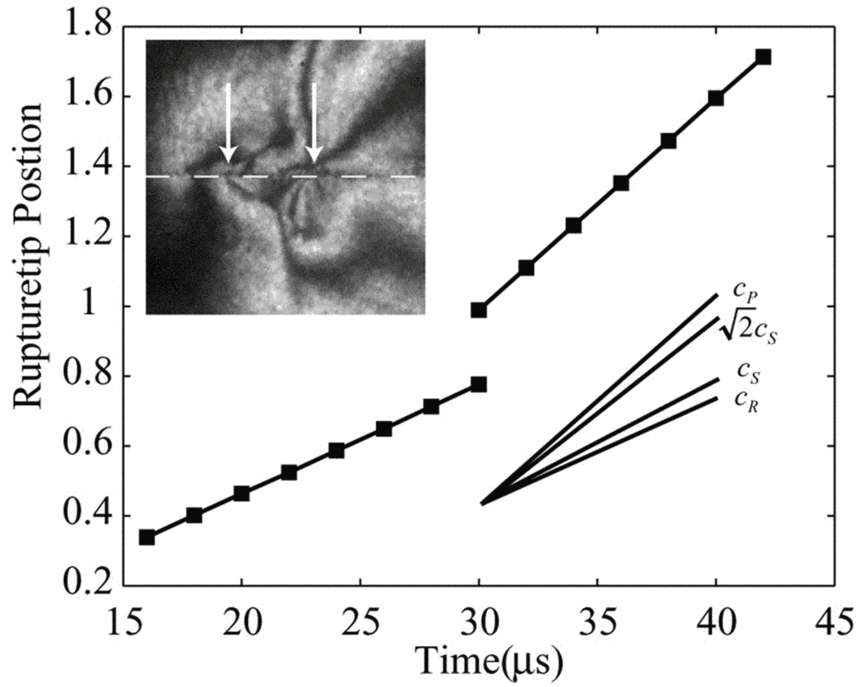
Transition Movie(detail)

Angle=25°, Pressure=10MPa



Rupture Speed Before and After Transition

(Xia, Rosakis and Kanamori, Science, March 2004)



Results and Questions from the Homogeneous Case

RESULTS:

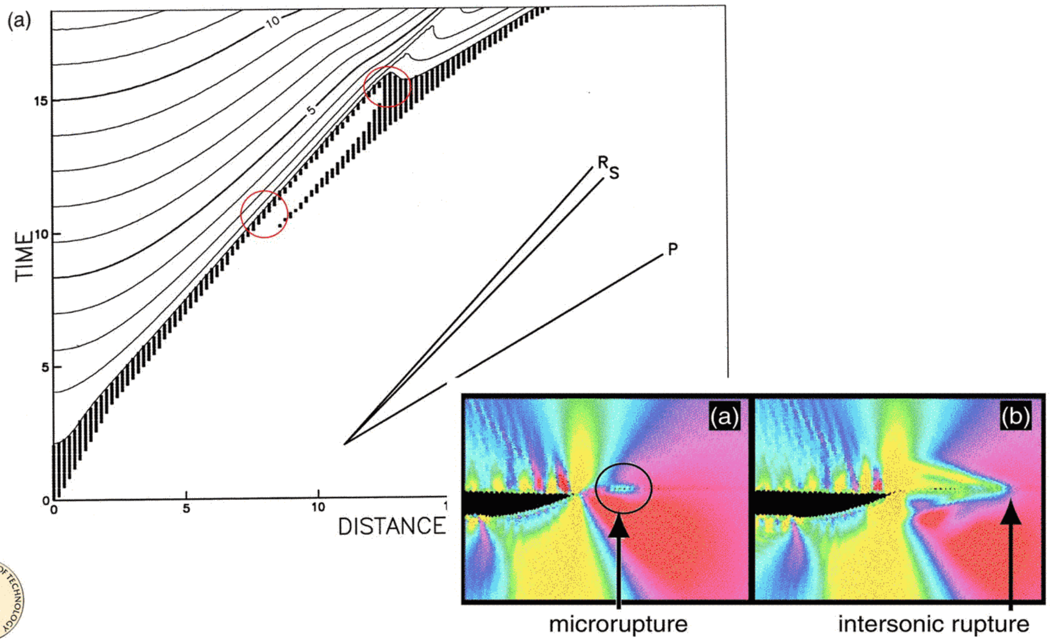
- Small load or angle: SUBRAYLEIGH RUTPURE
- Large load or angle: SUPERSHEAR RUPTURE
- Sub-shear to supershear transition is observed.
- The transition length increases with decreasing load and angle.

QUESTIONS:

- What would happen if the fault was perfectly uniform, straight and infinite? Would all ruptures eventually transition to supershear?
- Is there a connection between LARGE earthquakes and super shear rupture? A large earthquake is one that goes on for a long time.

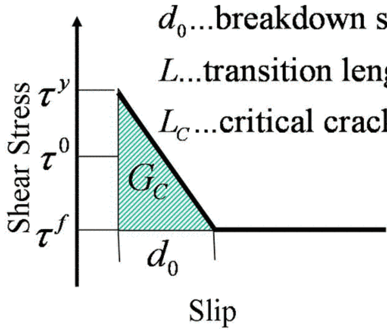
Transition-Burridge Andrews Mechanism

(Andrews, BSSA, 1985; Gao and Abraham, PRL, 2000)



Andrew's Numerical Calculation of Transition Length L

(Andrews, BSSA, 1985)



d_0...breakdown slip

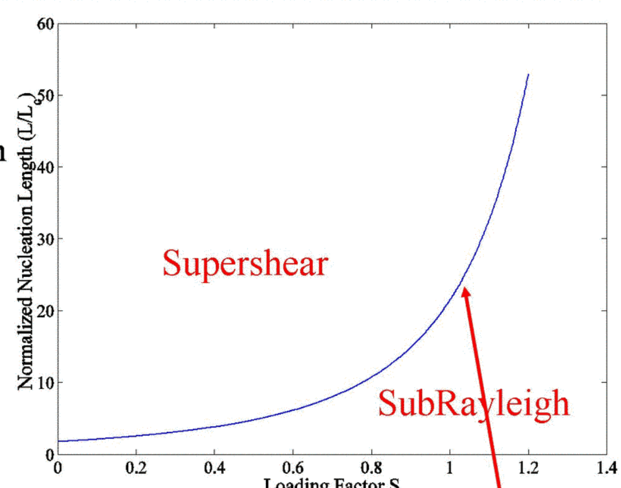
L...transition length

L_C...critical crack length

Slip Weakening Law

$$S = \frac{\tau^y - \tau^0}{\tau^0 - \tau^f}, \text{ driving stress,}$$

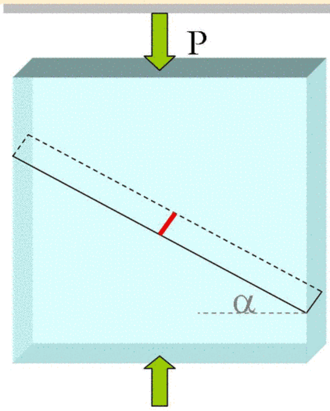
$$L_c = \frac{2}{\pi}\left(\frac{1+\nu}{2}\right)G\frac{(\tau^y - \tau^f)}{(\tau^0 - \tau^f)^2}d_0$$



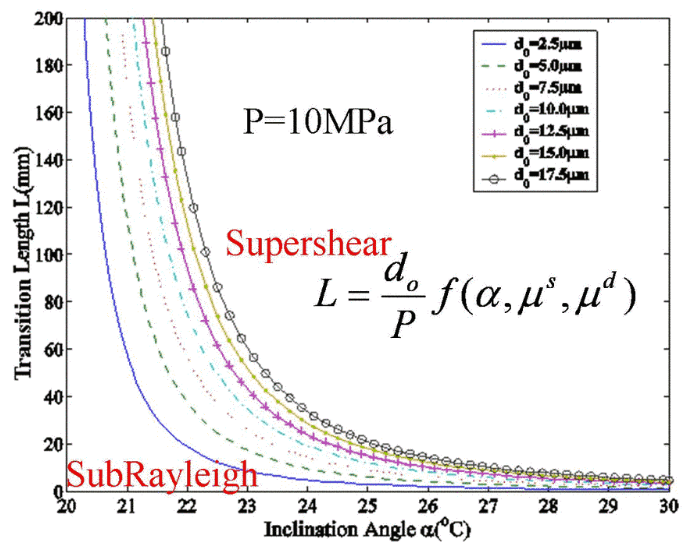
$$L = 9.8/(1.77 - S)^3 L_c$$

Supershear Transition Length Versus Angle

(Also see Parameter K by Madariaga and Olsen, 2000)



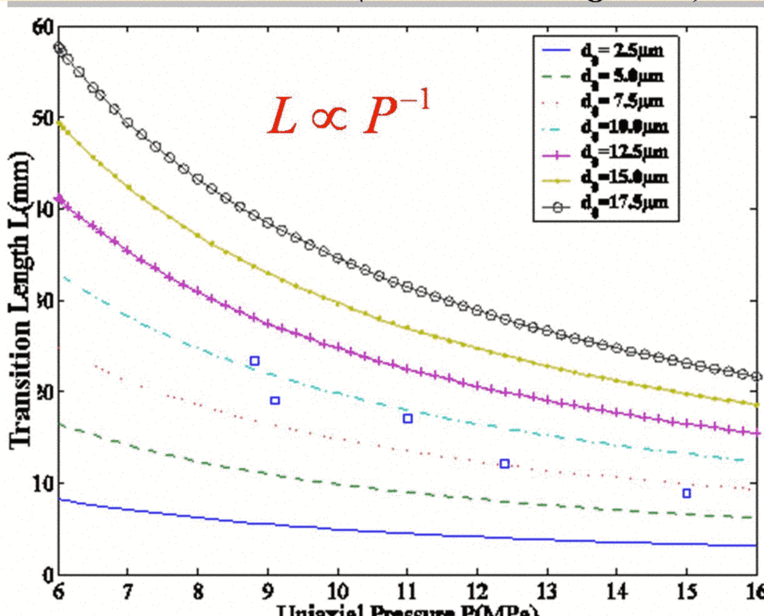
$$S = \frac{\mu^s \cos(\alpha) - \sin(\alpha)}{\sin(\alpha) - \mu^d \cos(\alpha)}$$



$$L = \frac{2\mu}{\pi}\left(\frac{1+\nu}{2}\right)\frac{\mu^s - \mu^d}{(\sin(\alpha) - \mu^d \cos(\alpha))^2}\frac{d_o}{P} f(s)$$

Pressure Dependence of Transition Length

(Inclination angle 25°)

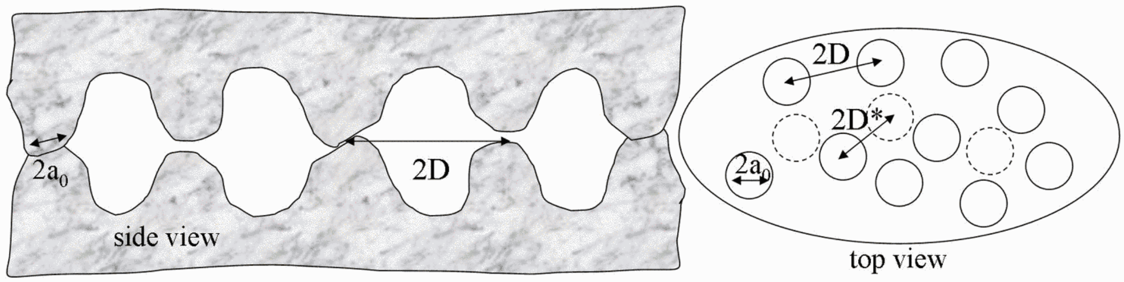


$$L = \frac{d_o}{P} f(\alpha, \mu^s, \mu^d)$$

Assumption: d_0 independent of pressure

Micromechanical Model of Plastic Contact

$N = HA_r = \sigma_n A,$ (Bowden & Tabor, 1964)



N...normal force
H...hardness
A_r...real contact area
A...apparent contact area
σ_n...average normal stress
a_0...asparity contact radius
$2D$...distance between contacts, n...number of contacts

$A_r = n\pi a_0^2,$
$A = n\pi D^2$

$$D = \sqrt{H} a_0 \sigma_n^{-1/2}$$

Pressure Dependence of Breakdown of Slip and Transition Length

$$D = \sqrt{H} a_0 \sigma_n^{-1/2}$$

$$d_0 = c[(\sigma_y - \sigma_f)/\sigma_y]^M 2D$$ (Ohnaka, 2003)

$$\sigma_n = P\cos^2(\alpha)$$

$$d_0 = 2c\left(\frac{\mu^s - \mu^d}{\mu^s}\right)^M \sqrt{H} a_0 \sigma_n^{-\frac{1}{2}}$$

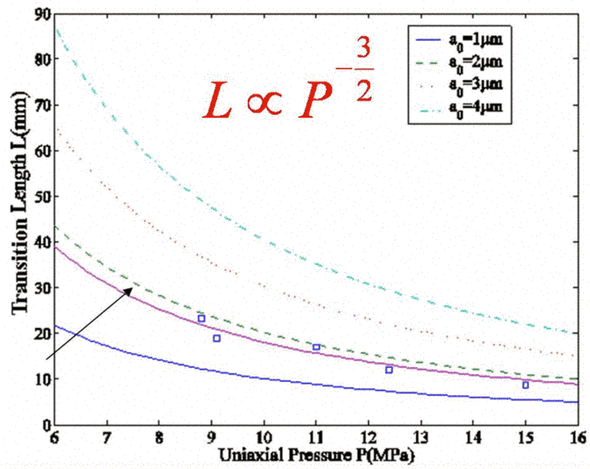
fault: $d_o \sim 1m$
lab: $d_o \sim 10\ \mu m$

$$L = f[s(\alpha)]\frac{1+\nu}{\pi}\mu\frac{\mu^s - \mu^d}{[\sin(\alpha) - \mu^d\cos(\alpha)]^2} 2c\left(\frac{\mu^s - \mu^f}{\mu^s}\right)^M \sqrt{H} a_0 P^{-\frac{3}{2}} \cos^{-1}(\alpha)$$

$$L \propto P^{\frac{-3}{2}}$$

Supershear Transition Length Versus Pressure
(Pressure Dependent d_0)

(Xia, Rosakis and Kanamori, Science, March 2004)



$a_0 = 1.78\mu m$

a_0… average asparity radius. Angle = 25deg

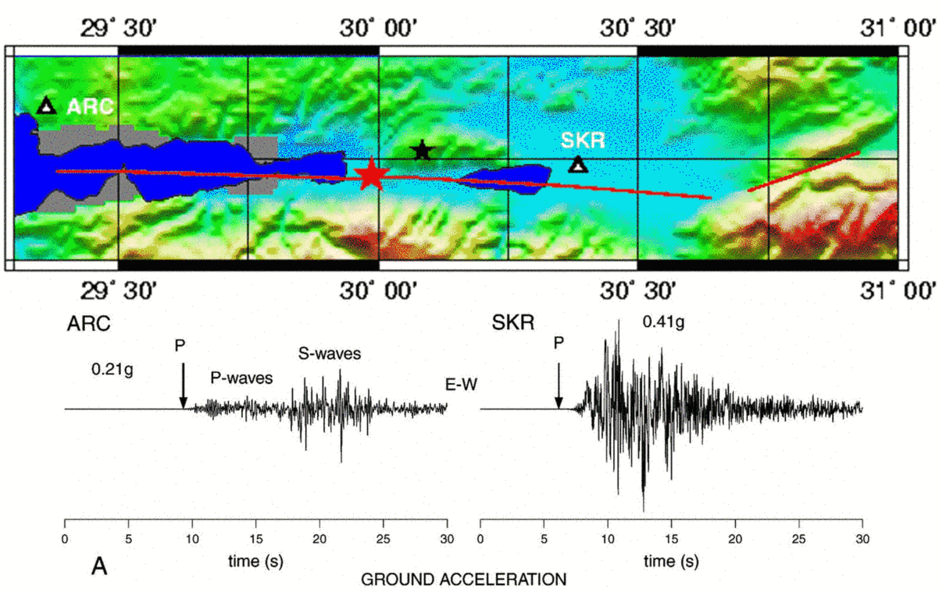
$$L = f[s(\alpha)]\frac{1+\nu}{\pi}\mu\frac{\mu^s-\mu^d}{[\sin(\alpha)-\mu^d\cos(\alpha)]^2}2c\left(\frac{\mu^s-\mu^f}{\mu^s}\right)^M\sqrt{H}\,a_0P^{-\frac{3}{2}}\cos^{-1}(\alpha)$$

By using: **P = 100 bar d_o = 1m, α = 25, mat properties of rock,**

$L \sim 80$km (Kunlun (100 km), Denali (70km))

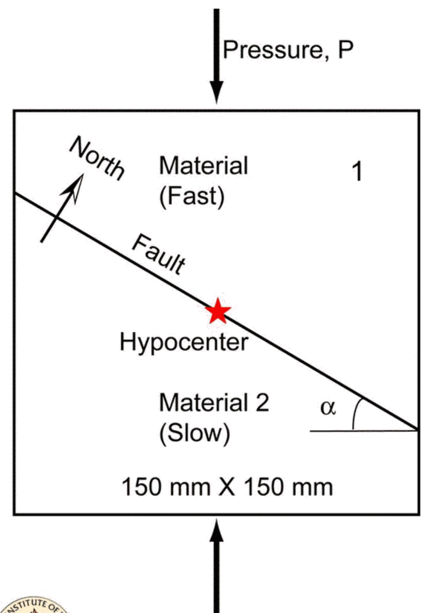
Field Evidence of Rupture ASYMMETRY
(The N. Anatolian fault near the sea of Marmara has bimaterial structure)

Le Pichon, Chamot-Rooke, Rangin and Sengor. J.G.R. 2003.
Softer material to the South



Inhomogeneous (Bimaterial) Fault Model

(Xia, Rosakis, Kanamori and Rice, Science, 2005)



- Homalite shear wave speed (Fast): 1200 m/s
- Polycarbonate shear wave speed (slow): 960 m/s

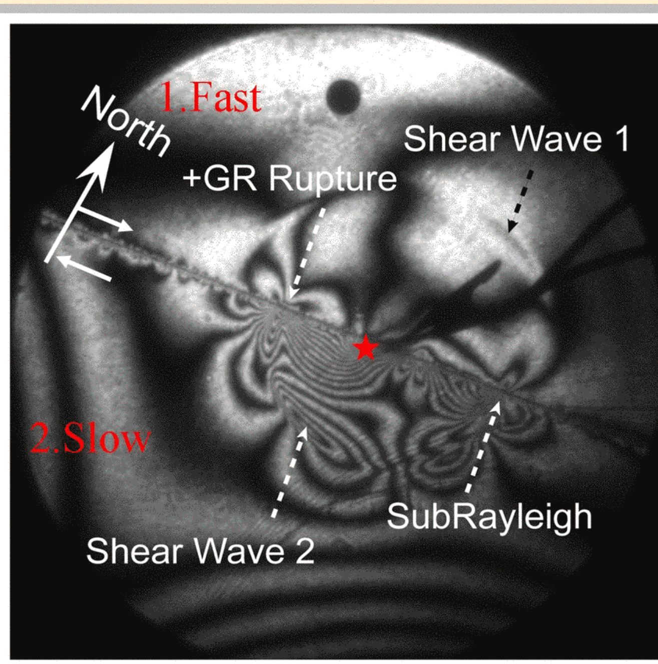
- Shear wave difference: 25%
- The generalized Rayleigh wave speed: 950 m/s

Generalized Rayleigh (GR) wave speed: Propagation speed of sliding in frictionless contact.

Experimental Examples: GR Speed (POSITIVE)& Sub-shear (NEGATIVE) *Angle=25°, Pressure=10 MPa*

POSITIVE:

Rupture direction same as direction of slip of the lower velocity side $V= +C_{GR}$



(Small P)

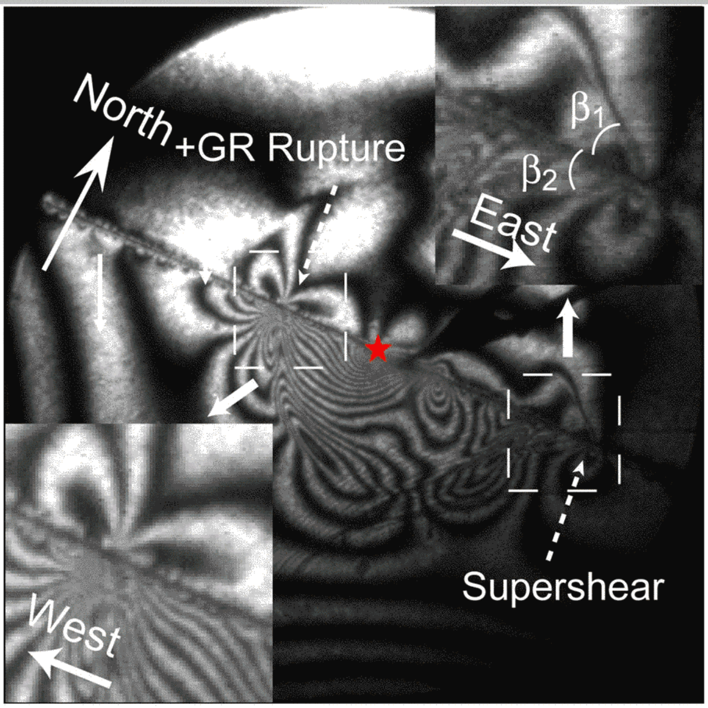
Generalized Rayleigh (GR) wave speed: Propagation speed of sliding in frictionless contact.

This Figure is oriented according to the 1999 Izmit event

Experimental Examples: GR (POSITIVE)& -P_{SLOW} (NEGATIVE)

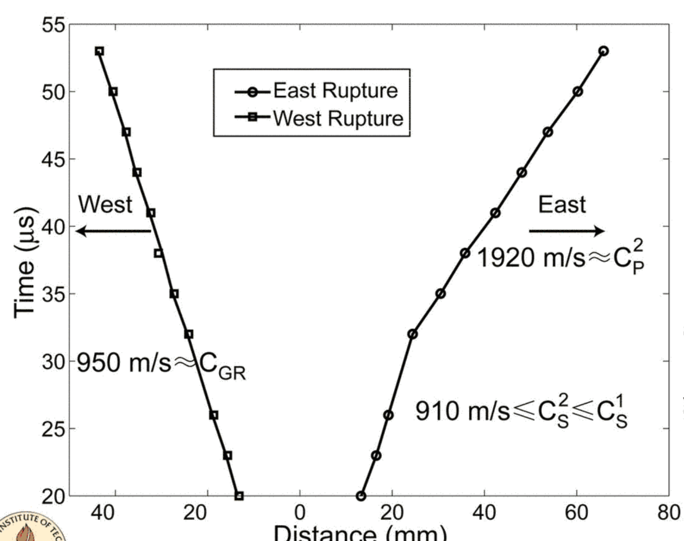
Angle=25°, Pressure=17MPa

(Large P)



Supershear Transition-Only along the NEGATIVE Direction

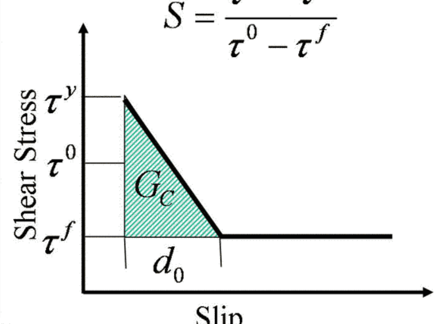
(Angle=25°, Pressure=13MPa)



(Intermediate P)

Equivalent observations in terms of loading factor:

$$S = \frac{\tau^y - \tau^0}{\tau^0 - \tau^f}$$



Slip Weakening Law

Summary of Experimental Results

- All ruptures are bilateral.
- The rupture in one direction (POSITIVE) always propagates at the generalized Rayleigh wave speed $+C_{GR}$, irrespective of P and α.
- Depending on loading, the rupture in the NEGATIVE direction is either sub-shear or supershear.
- For either large P or large α (small S), rupture in the NEGATIVE direction eventually transitions to supershear ($V=-P_{SLOW}$)
- The transition length decreases with increasing P and increasing α (decreasing S) .
- Connection between large earthquakes and supershear growth in the NEGATIVE Direction.

Numerical & Theoretical Self-sustained Rupture Modes

(Speeds and Directionality)

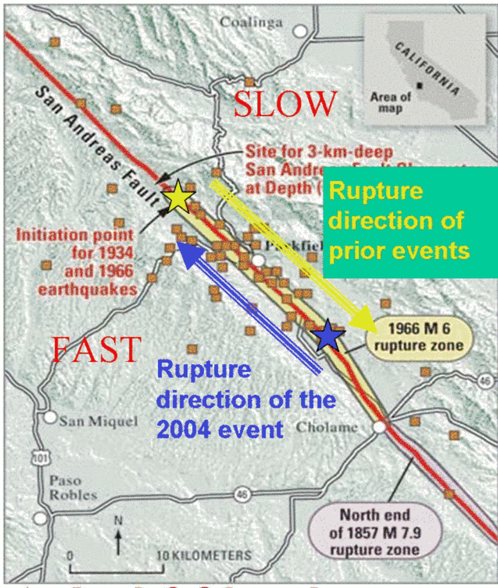
Coulomb type of friction laws: *(Weertman, 1980; Adams, 1995, 98; Andrews & Ben-Zion, 1997; Ranjith and Rice, 1999, Cochard & Rice, 2001)*

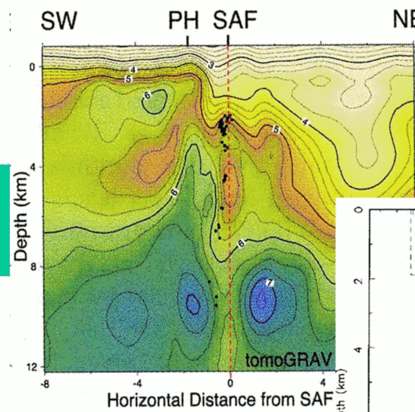
- Positive direction: $V \approx +C_{GR}$ (Strong numerical preference)
- Negative direction: $V \approx -P_{SLOW}$ (Difficult to excite)
- Never excited simultaneously in numerics.
- Positive direction was postulated as beeing PREFERABLE

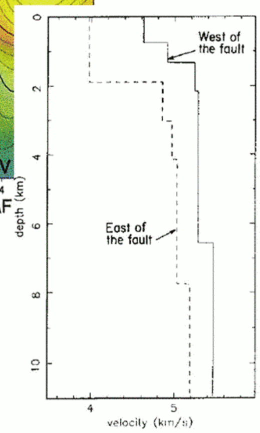
Weakening frictional law: (*Harris and Day, 1999*)

- Bilateral ruptures
- Both $+C_{GR}$ and $-P_{SLOW}$ modes observed
- No finite transition to supershear reported

Bimaterial Crust Structure at Parkfield -Evidence Against an Exclusive Direction-





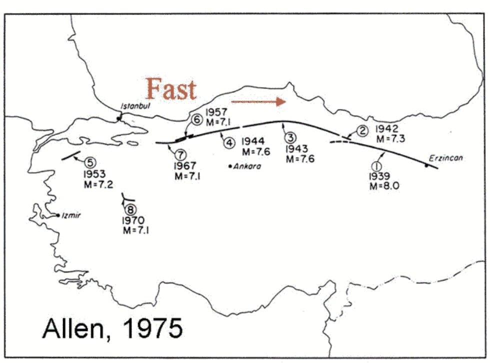


Thurber et al. (2004)

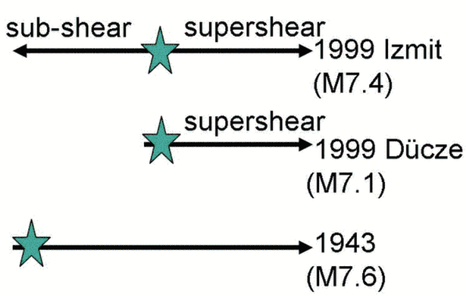
(Ben-Zion et al., 1992)

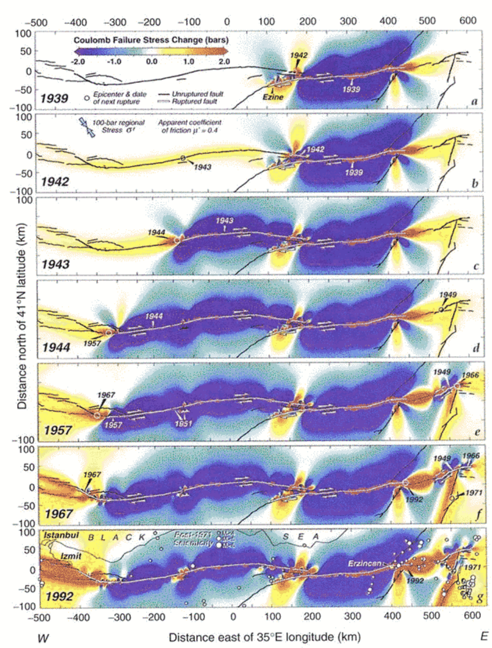
At depth 3-8 km, shear wave speed contrast is 10-20% with east side being slower.

Variability of Rupture directions Observed in North Anatolian Fault Sequence(Large events –supershear to east?)



Allen, 1975

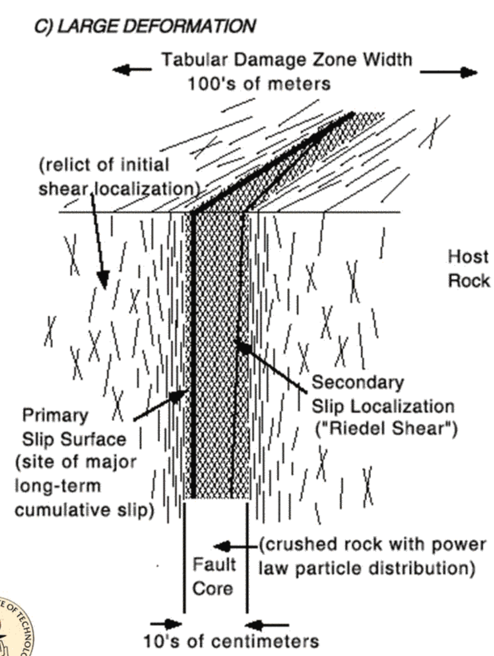


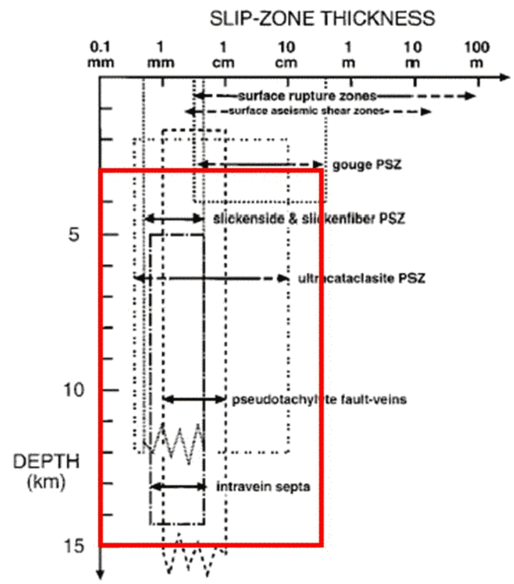


Stein et al., 1997

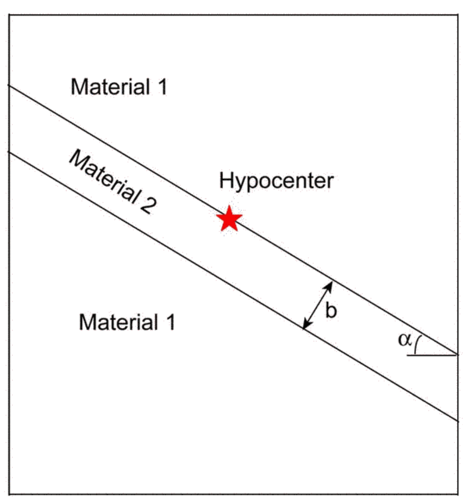
Structure of Geological Faults

(Ben-Zion and Sammis, PAGEO 2003; Sibson, BSSA 2003)





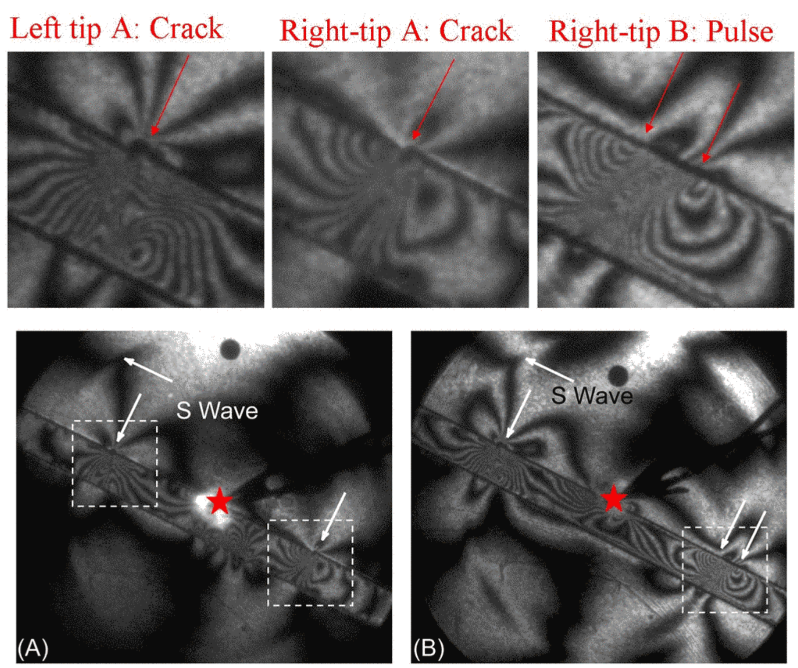
Sandwiched Fault Model



- Homalite shear wave speed (1): 1200 m/s
- Polycarbonate shear wave speed (2): 960 m/s

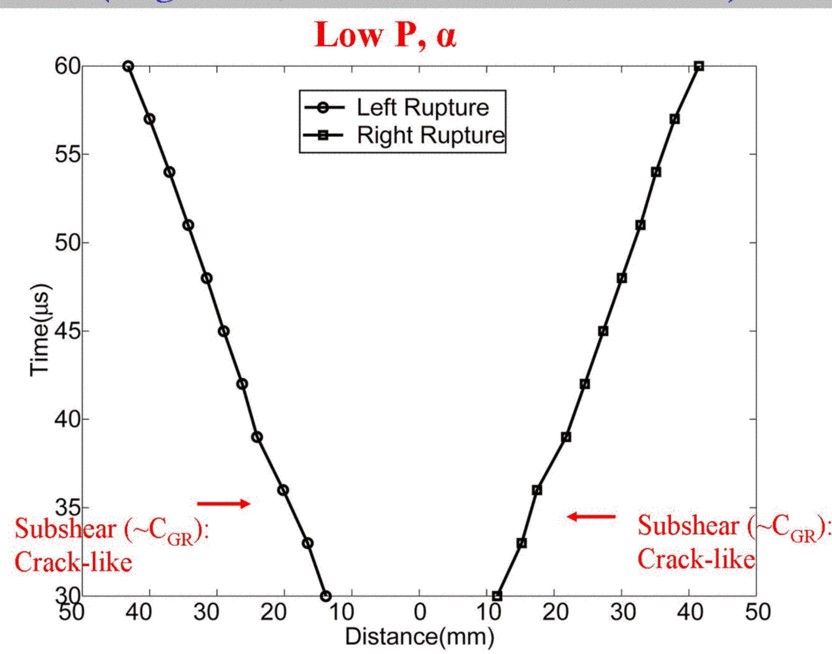
- Fault Core → Material 2
- Primary Slip Interface → Upper Interface
- Secondary Slip Interface → Lower Interface

Mode Transition and Directionality As P(or α) Increases



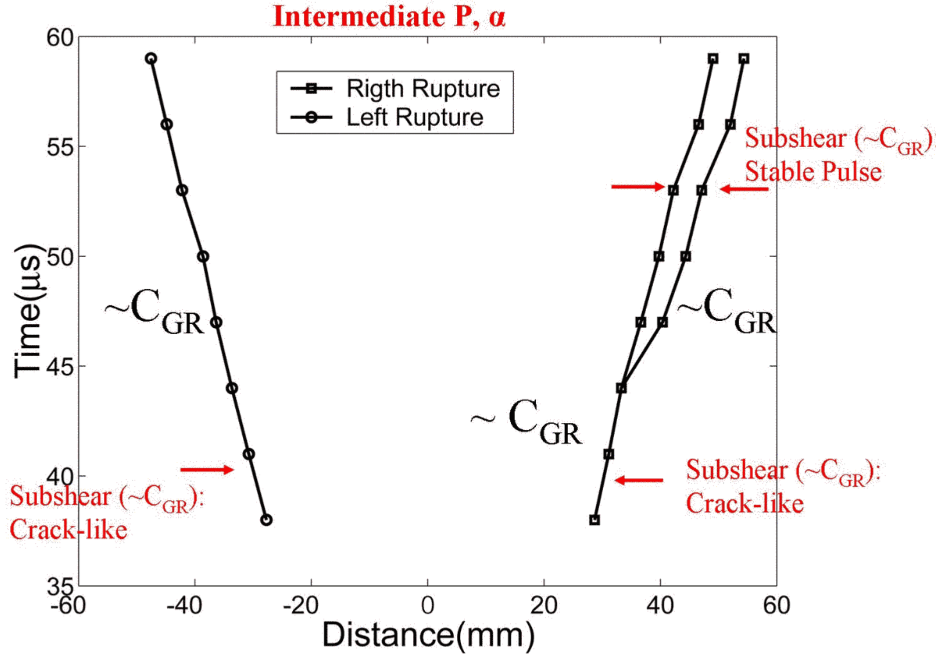
At Low P or α, Both Ruptures are Crack Like and Subshear

(Angle=25°, Pressure=15MPa, b=0.125")

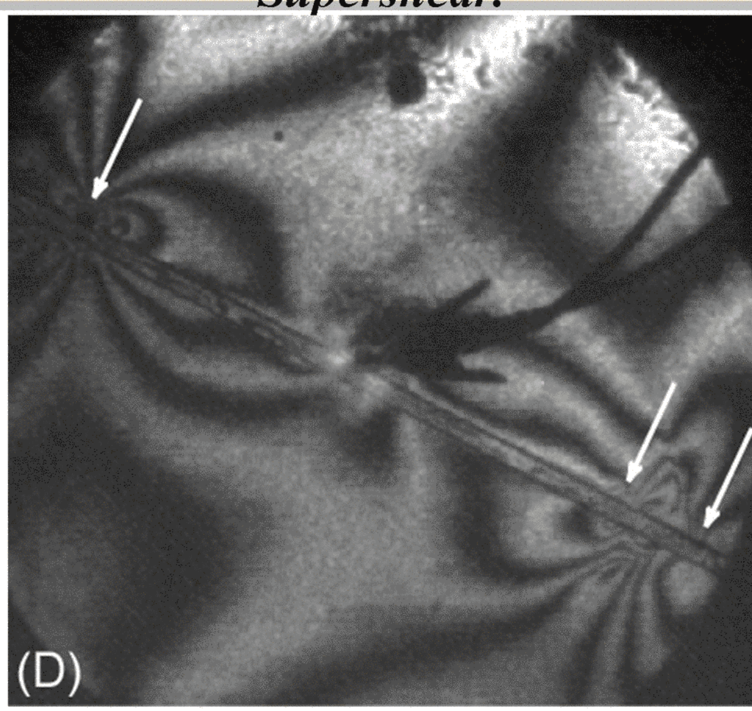


Transition From Crack to a Subshear, Stable Pulse

(Angle=25°, Pressure=17MPa, b=0.125")

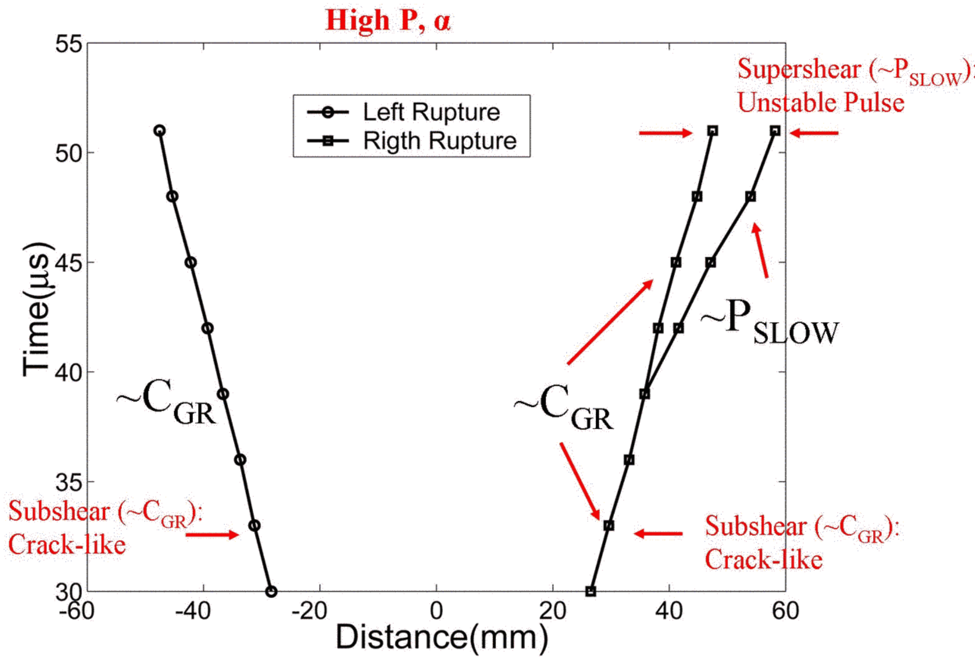


With Further Load Increase,Pulse transitions To Supershear.



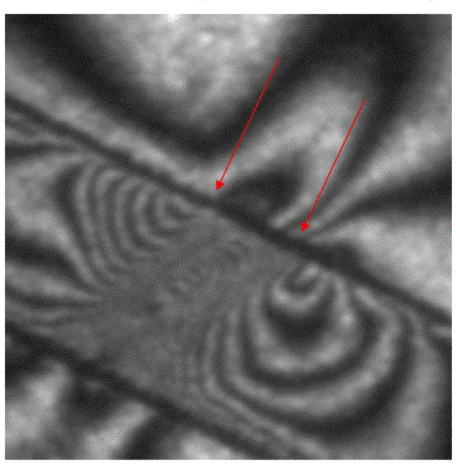
Transition From Crack to Unstable Supershear Pulse

(Angle=25°, Pressure=20MPa, b=0.125")

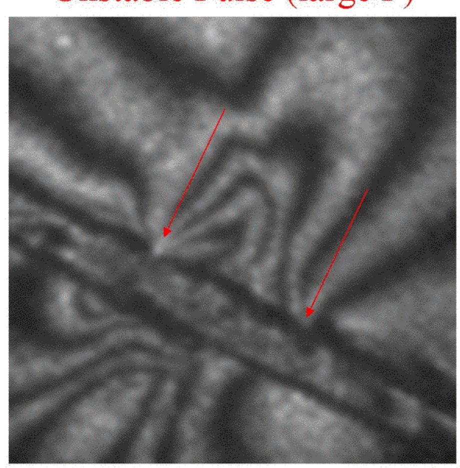


Pulse Types

Stable Pulse (Intermediate P)



Unstable Pulse (large P)



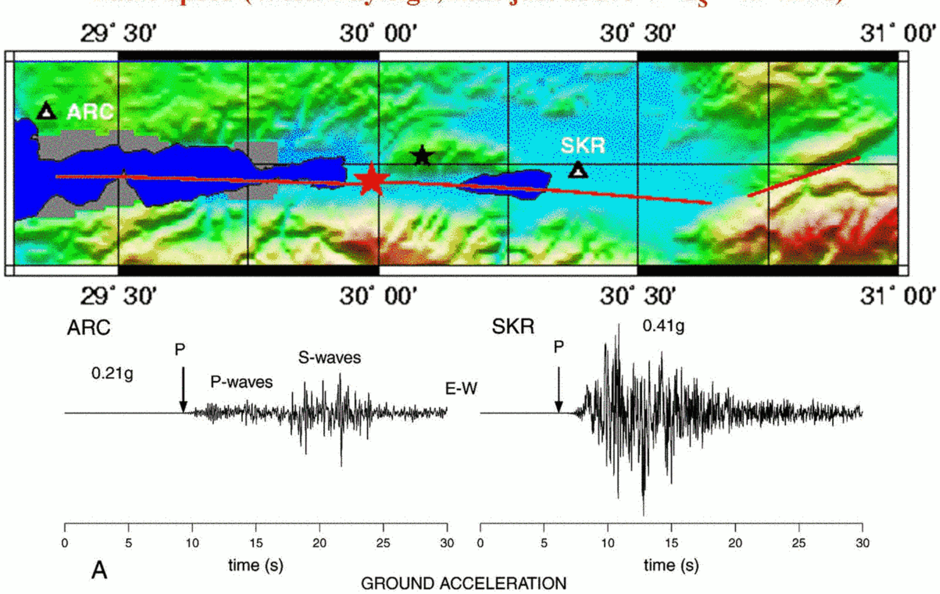
Rupture in the presence of a compliant core

- Ruptures remain in one interface and are always bilateral.
- POSITIVE direction ruptures always propagates at the generalized Rayleigh wave speed, C_{GR}, as a "crack".
- Depending on loading, the rupture in the NEGATIVE direction is either crack-like (small load or angle) or pulse-like (large load or angle).
- In the NEGATIVE direction there is a transition from a crack-like to a pulse-like type of rupture.
- The healing edge of the self-healing pulse propagates close to the GR speed; the leading edge grows at either a speed close to C_{GR} (small load or angle) or at a supershear speed close to $V= -P_{slow}$, (core speed) (larger load or angle).
- Pulse widths are independent of core width. The core seems to trigger the pulse by providing a reflection interface.

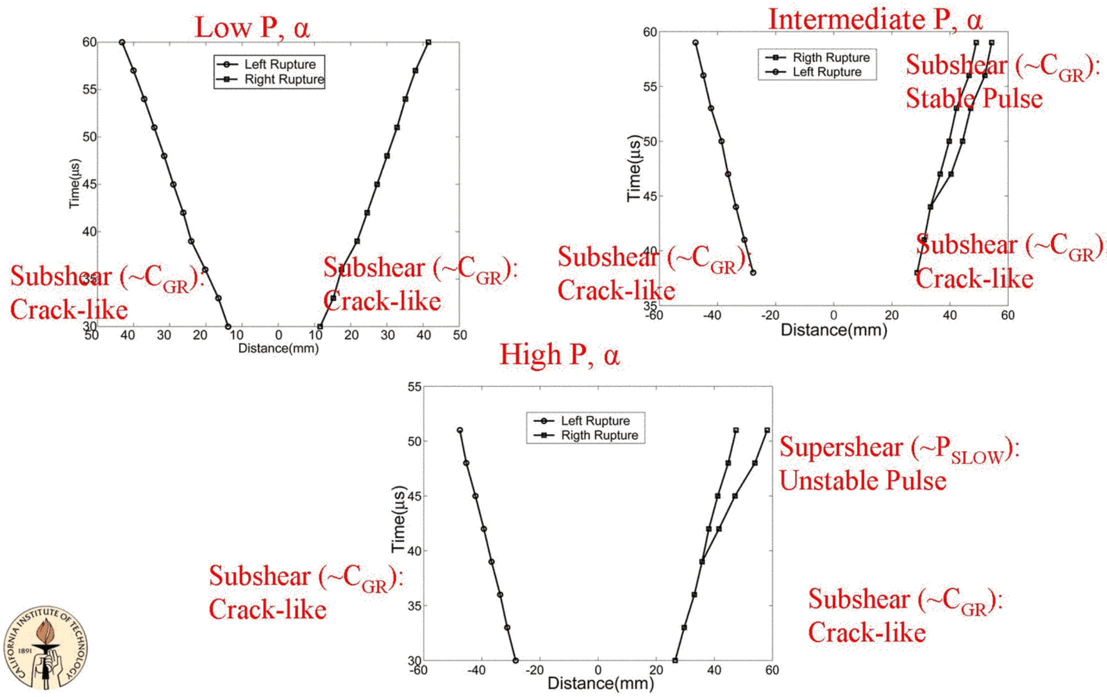
Field Evidence of Intersonic Rupture During The 1999 Izmit Earthquake in Turkey

M. Bouchon, M. Bouin, H. Karabulet, M. Toksöz, M. Dietrich and A. Rosakis, *Geophysical Research Letters, 2001*

Fault Speed (West: Rayleigh, East just above $\sqrt{2}\,C_S = 4.9$ km/s)

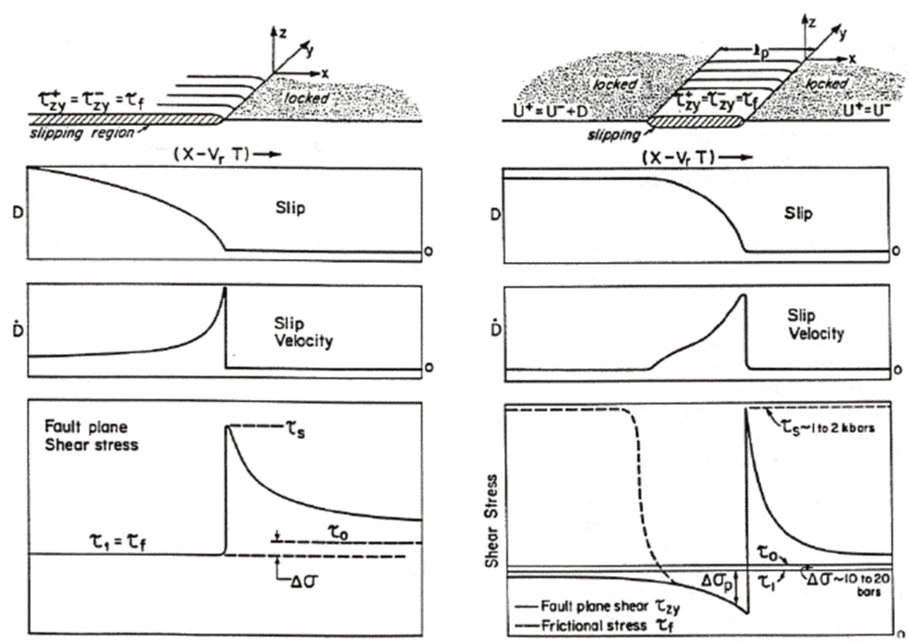


Speeds and Mode Transitions

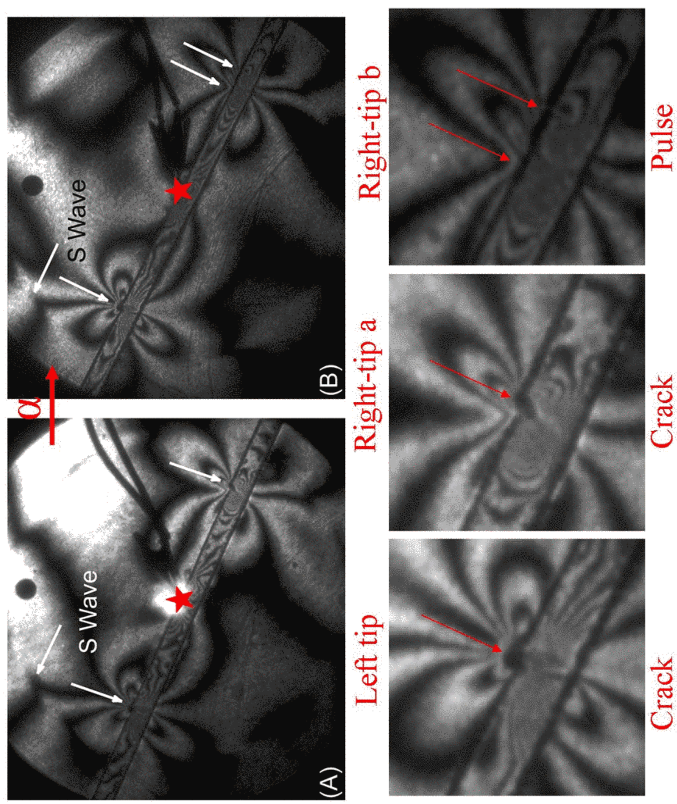


Crack Mode vs. Pulse Mode: Physical Pictures

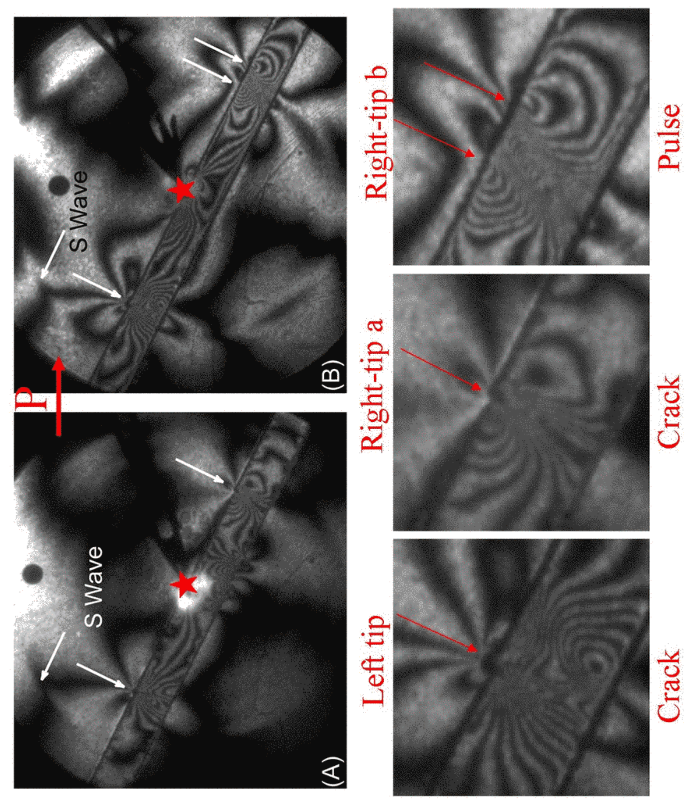
(Heaton, PEPI, 1990)



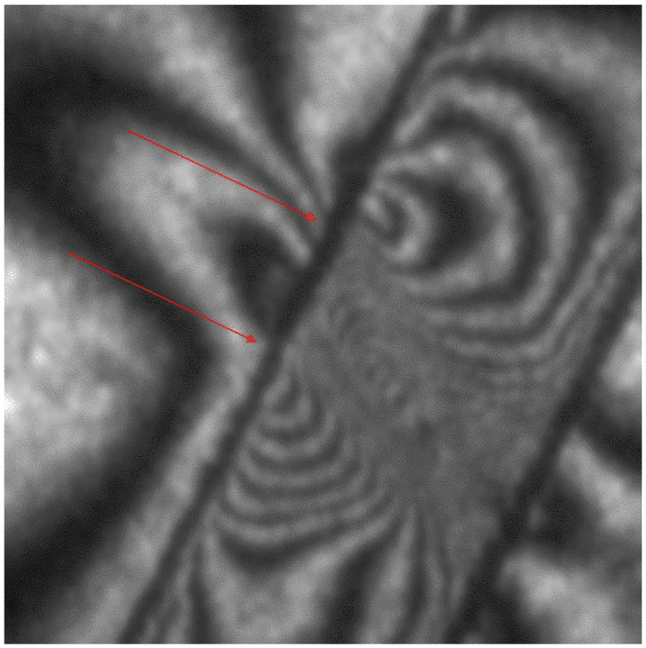
Crack Mode vs. Pulse Mode



Crack Mode vs. Pulse Mode

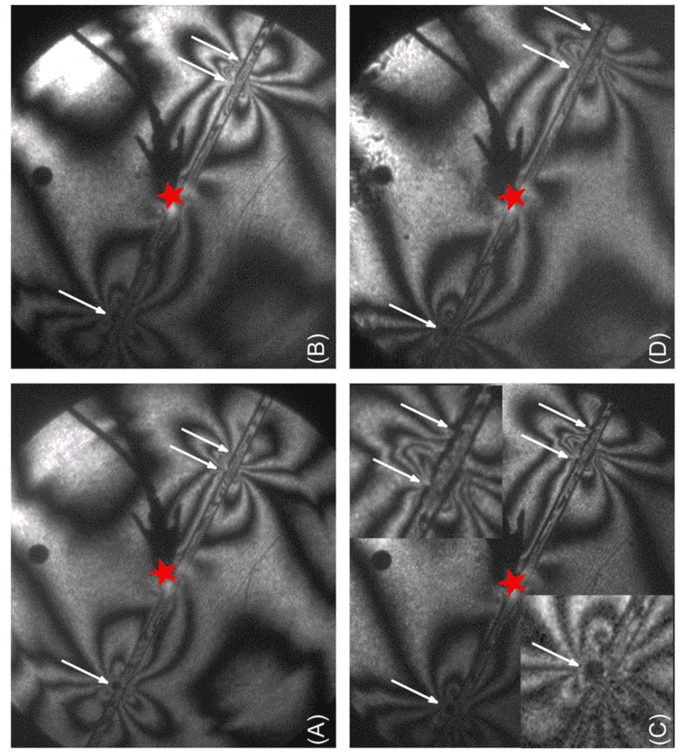


Detail of a Stable Pulse

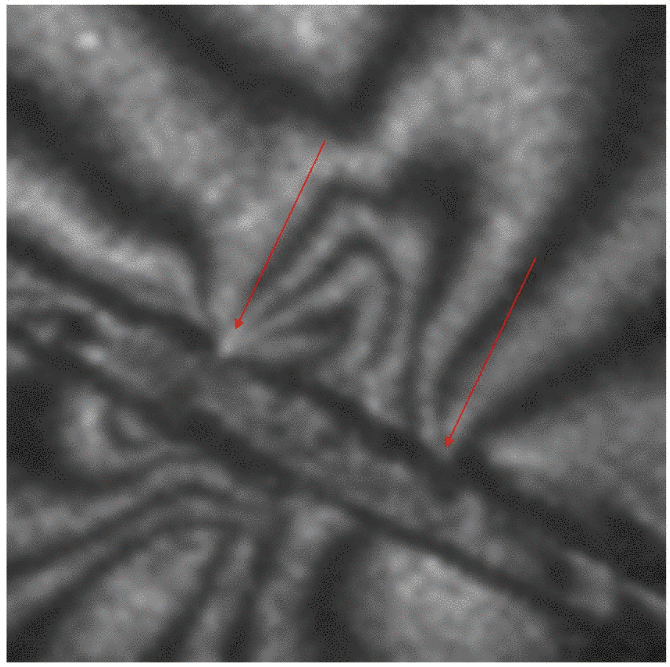


An Extending Pulse (Unstable)

(Angle=25°, Pressure=20MPa, b=0.125")



Detail of an Unstable Pulse

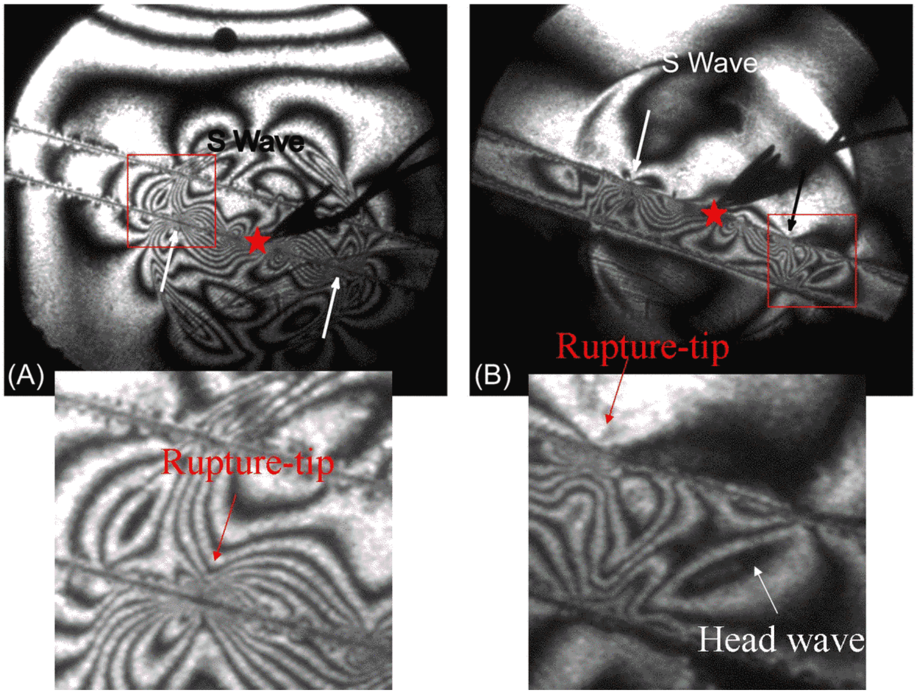


Experimental Results of Sandwich Case (Cont.)

- Transition from a crack-like to a pulse-like earthquake rupture.
- The role of the core is to provide the reflection interface so as to trigger the crack-like to pulse-like transition.
- The width of the stable pulse is determined by the frictional property of the interface.

General Effects of Core on Faulting

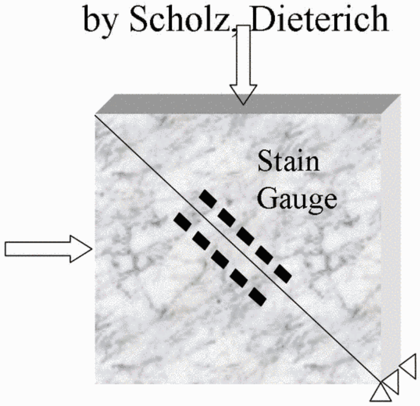
(Angle=17.5°, Pressure=10MPa)



Existing Experimental Designs

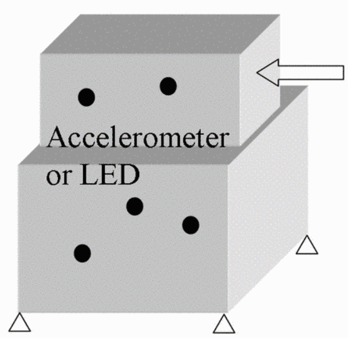
(Meters in Size)

Biaxial Loading Model
by Scholz, Dieterich



- Low temporal resolution
- Low spatial resolution
- Point measurements

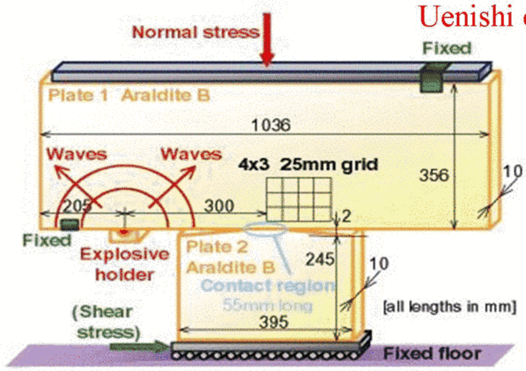
Foam Model
by Brune

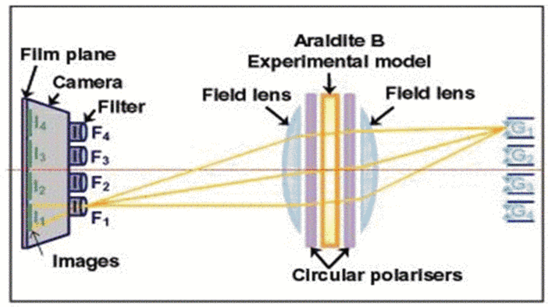


- Large deformation
- Viscous model material
- Point measurements
- Edge effects

An Interesting Experimental Design

Uenishi et al., 1999

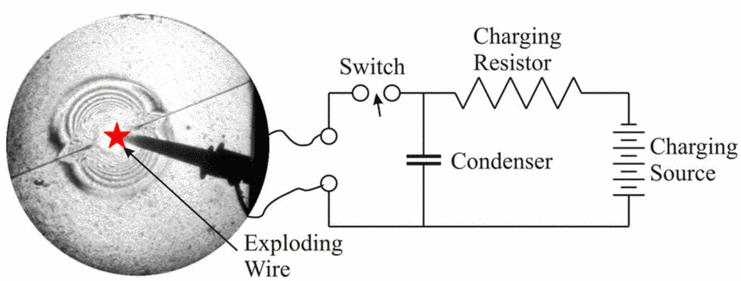




- Full-field measurements
- Controlled

- Non-uniform fault strength
- Not spontaneous ruptures

Triggering Mechanism (Principles)



Voltage V: 0~5 kv

Capacity C: 15 μF

Resistance R: 1 Ω

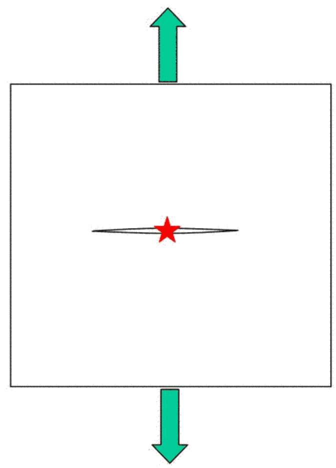
Grüneisen γ: 1.78

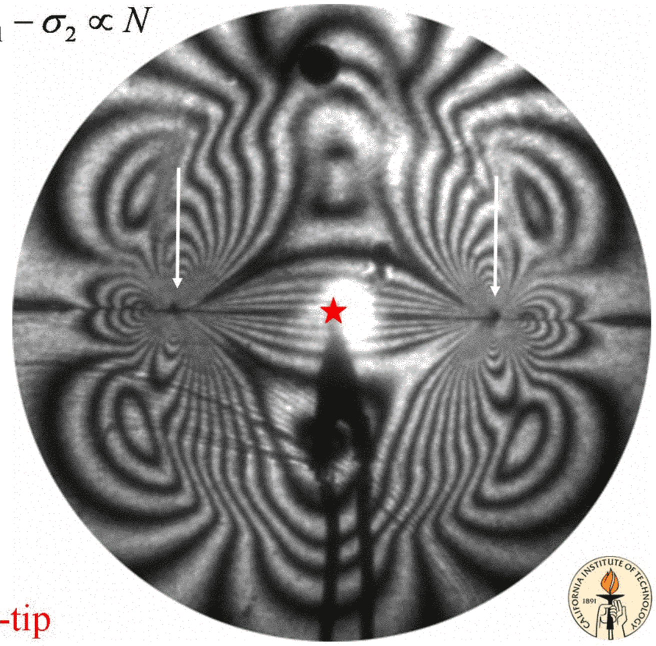
$$E = \frac{1}{2}CV^2$$

$$p_0 \propto \frac{\gamma(v)}{v}E$$

Photoelastic Method

$\sigma_1 - \sigma_2 \propto N$





Singular Point → Crack-tip

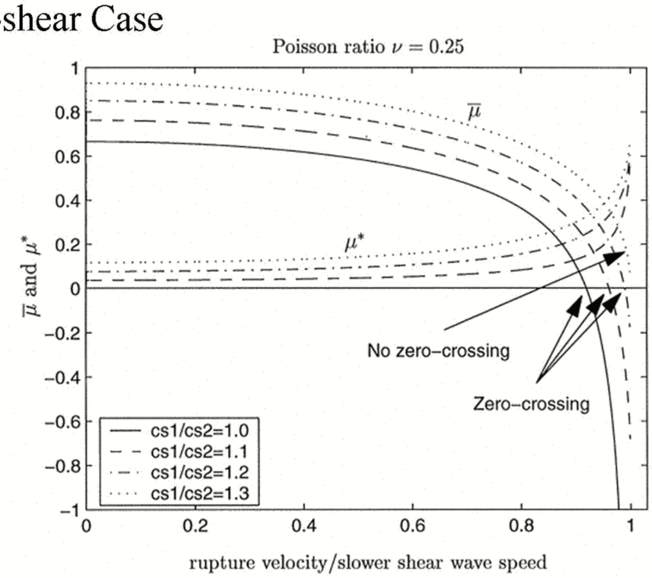
Coupling between Slip and Normal Stress (Coulomb's Law) *(Weertman, 1980; Ben-Zion, 2001)*

Dislocation Analysis of Sub-shear Case

$$\tau(x) = \tau^{\infty} + \frac{\bar{\mu}(c)}{\pi} \int_{-\infty}^{+\infty} \frac{B(x')}{x - x'} dx',$$

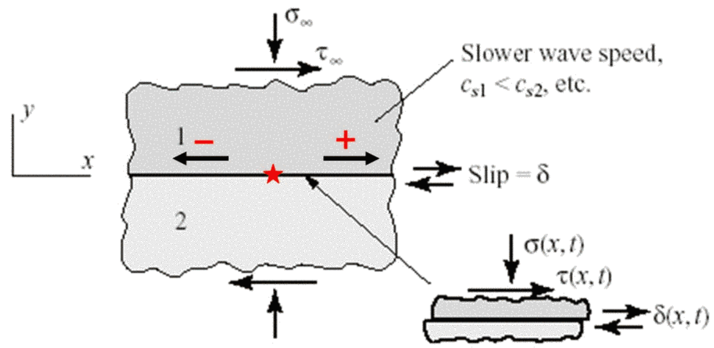
$$\sigma(x) = \sigma^{\infty} - \mu^{*}(c) B(x),$$

Generalized Rayleigh (GR) wave speed: Propagation speed of sliding in frictionless contact.



Numerical and Theoretical Models

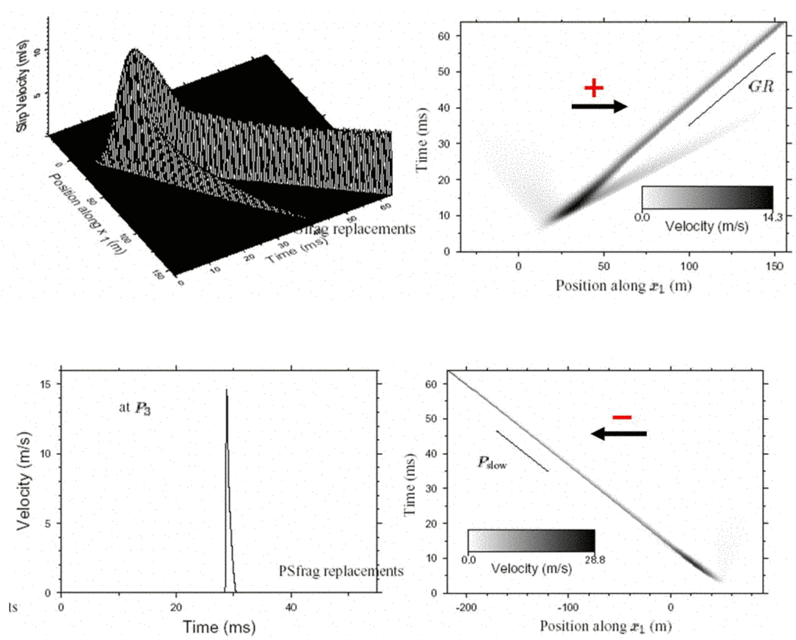
(Cochard and Rice, GRL, 2001; Ranjith and Rice, JMPS, 2001)



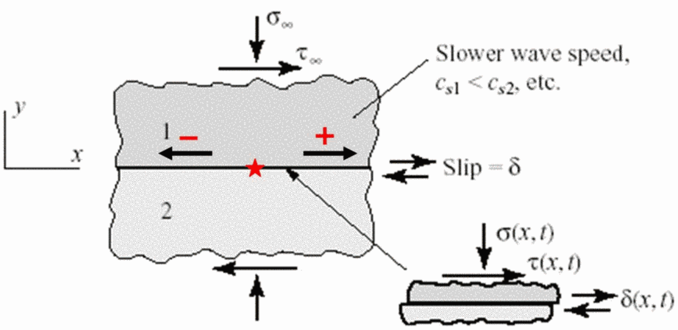
$$\tau = f\sigma \qquad \frac{d\tau(t)}{dt} = -\frac{V(t)}{L}\left[\tau(t) - f\sigma(t)\right]$$

Numerical and Theoretical Results

(Cochard and Rice, JGR, 2001)

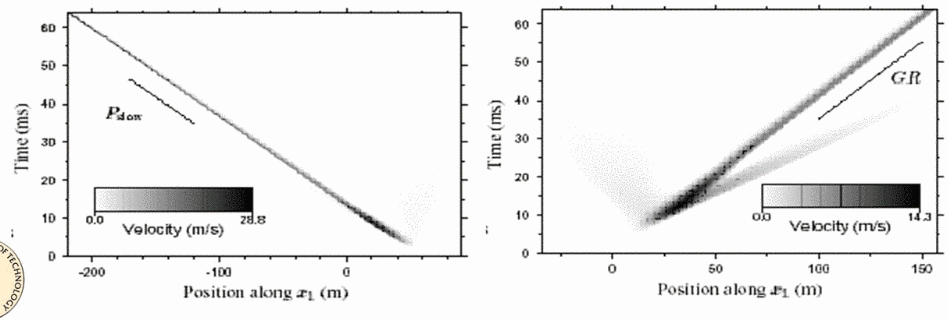


Numerical Results by Cochard and Rice, JGR, 2000



POSITIVE:

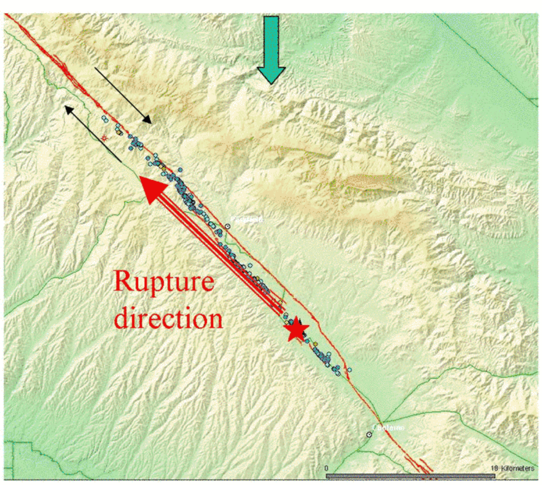
Rupture in the direction of slip of the lower velocity side.



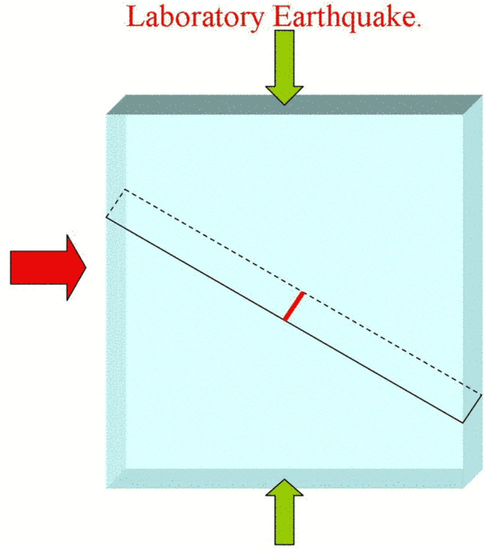
From Real to Laboratory Earthquakes

(Mimicking Spontaneous Rupture Events in Frictional interfaces)

M 6.0 2004 Parkfield Earthquake



Laboratory Earthquake.

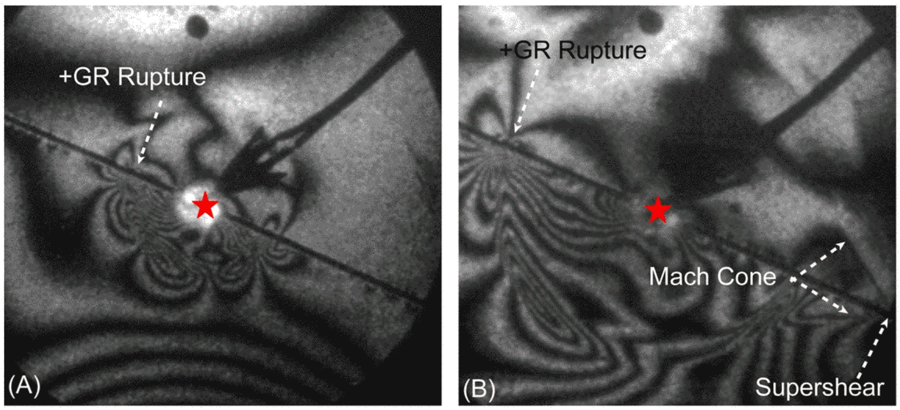


- **Fault** → **Inclined Contact Interface**
- **Tectonic stress** → **Far Field Load**
- **Hypocenter** → **Triggering Site**

Supershear Transition-Only along the Negative Direction

(Angle=25°, Pressure=13MPa) ***(Intermediate P)***

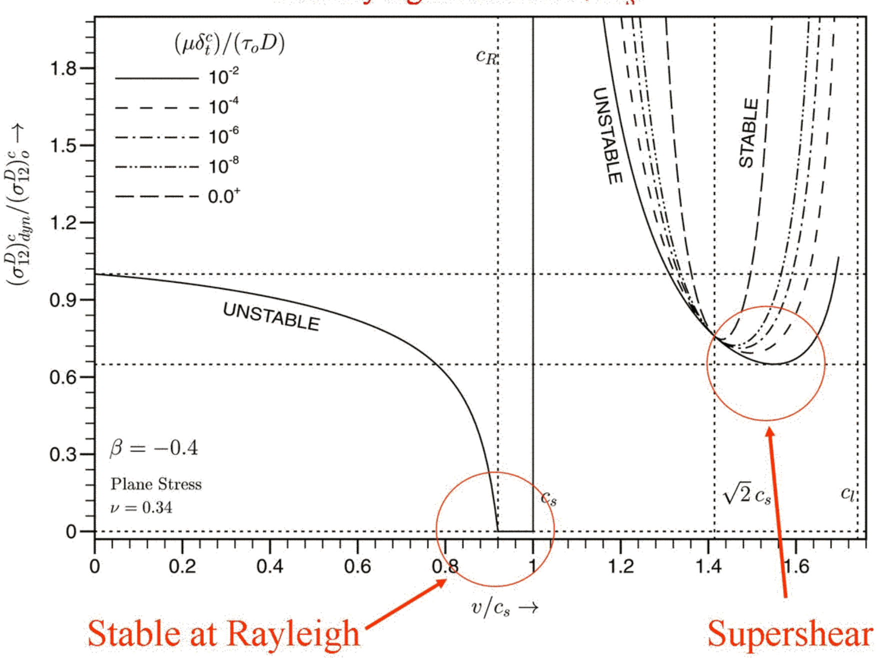
POSITIVE NEGATIVE



Far Field Shear Stress Required to Drive a Rupture at Various Speeds

(Samudrala, Huang and Rosakis, JGR, 2002)

Stability significance of $\sqrt{2}c_s$

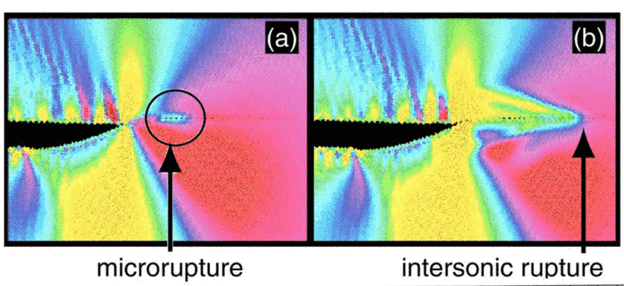


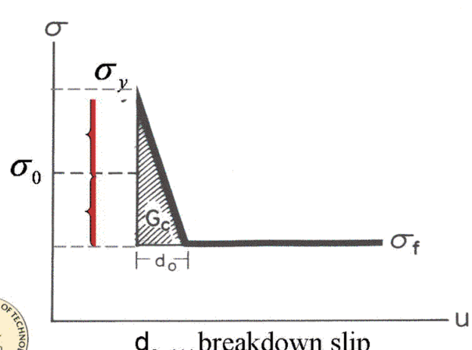
Outline

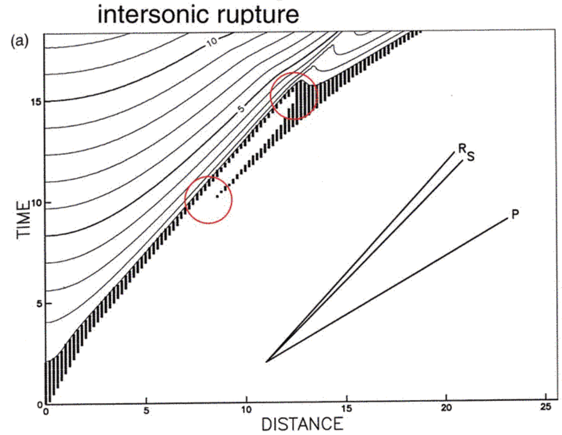
- Introduction
- Experimental Set-up
- Homogeneous Case
  - Supershear rupture
  - Sub-Rayleigh to supershear rupture transition
- Inhomogeneous Case
  - Directionality
  - The generalized Rayleigh wave speed rupture
  - Supershear and sub-shear to supershear rupture transition
- Sandwiched Case
  - Crack mode vs. Pulse mode
  - Characteristics of Heaton pulse
  - Sub-shear and supershear pulse
- Conclusions

Transition: Burridge-Andrews Mechanism

(Burridge, 1973; Andrews, 1976, 1985; Gao and Abraham, 2000)

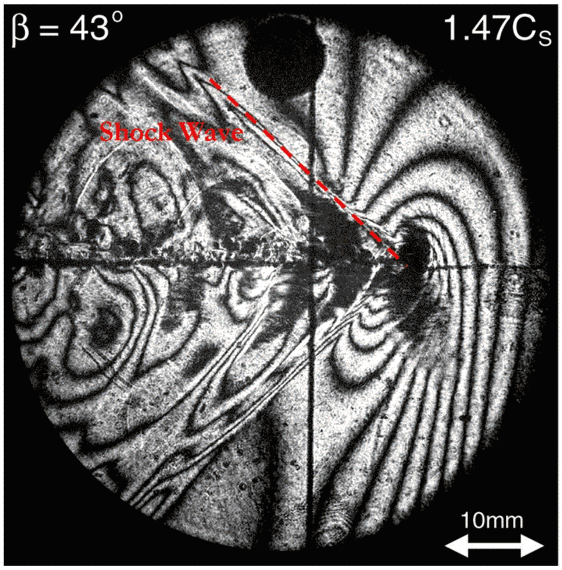


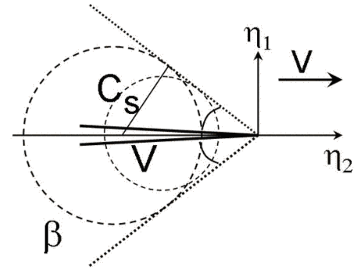




Supershear Rupture in a Coherent Interface

(Rosakis, Samudrala and Coker, Science, 1999)



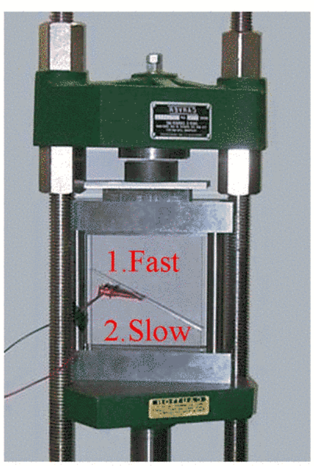


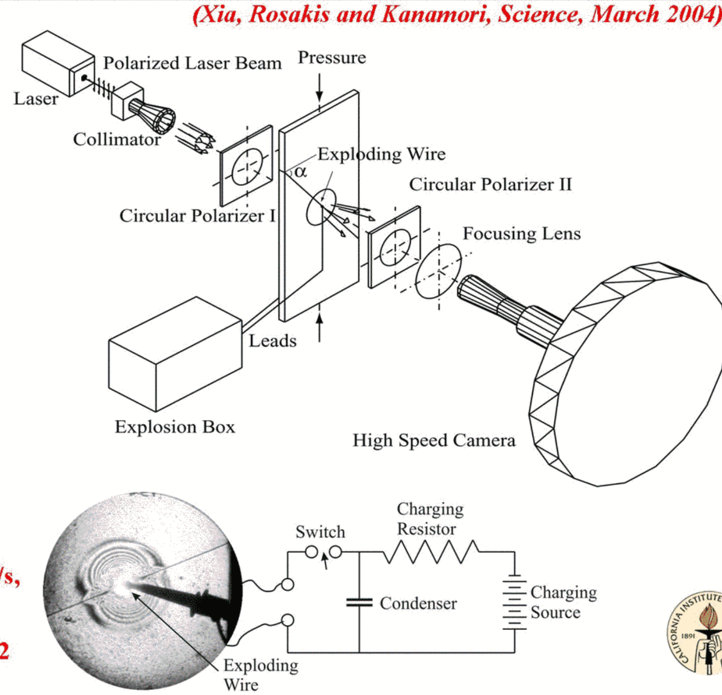
$V = C_s / \sin\beta$

Experimental Set-up

(Far-Field Loading and Local Release of Pressure: Spontaneous Rupture)

(Xia, Rosakis and Kanamori, Science, March 2004)





Material Contrast in shear wave speed: 25%

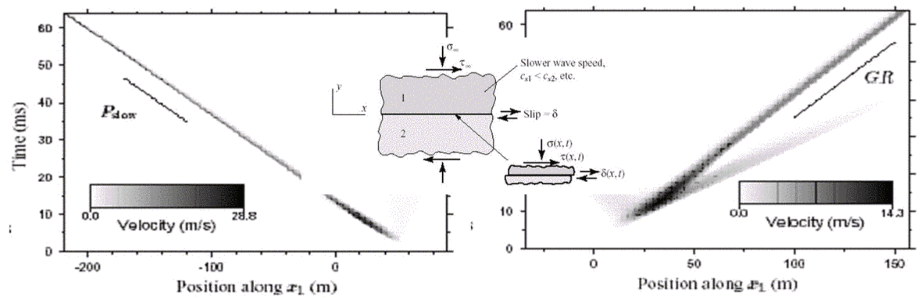
- **Fast (Homalite), C_P= 2.5 km/s, C_S=1.2 km/s**
- **Slow (Polycarbonate), C_P=2.2 km/s, C_S=0.96km/s**

Numerical & Theoretical Self-sustained Rupture Modes Speeds and Directionality

Self-sustained Rupture Modes

Coulomb type of friction laws: ***(Weertman, 1980; Adams, 1995, 98; Andrews & Ben-Zion, 1997; Ranjith and Rice, 1999, Cochard & Rice, 2001)***

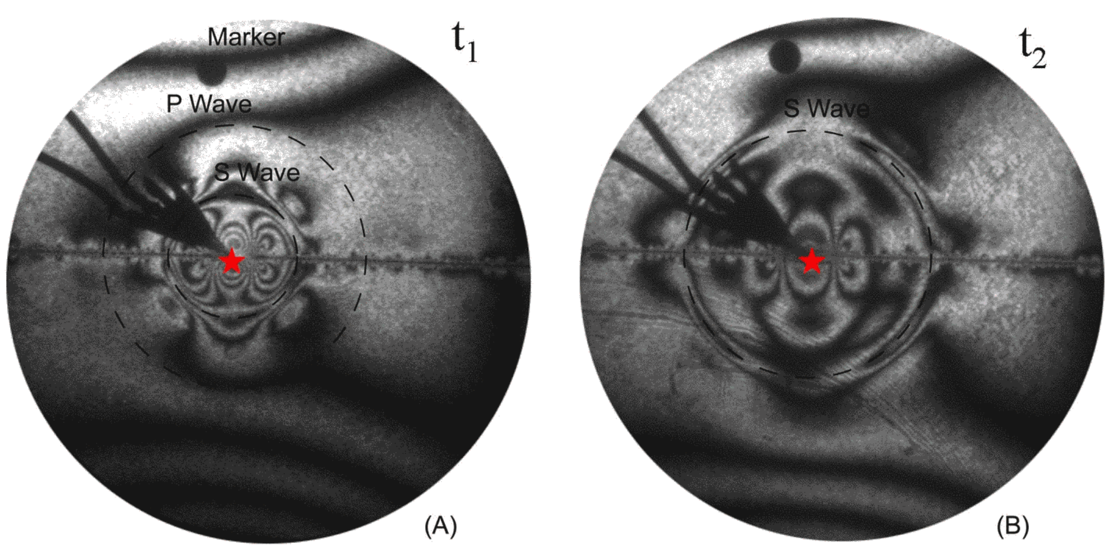
- **Positive direction: V≈+C_{GR} (Strong numerical preference)**
- **Negative direction: V≈−P_{SLOW} (Difficult to excite)**
- **Never excited simultaneously**



Weakening frictional law: **(*Harris and Day, 1999*)**

- **Bilateral ruptures**
- **Both +C_{GR} and –P_{SLOW} modes observed**
- **No finite transition to supershear reported**

Triggering Mechanism (Justification)



5 mm away from hypocenter, dynamic stress is smaller than 0.5 MPa !!!

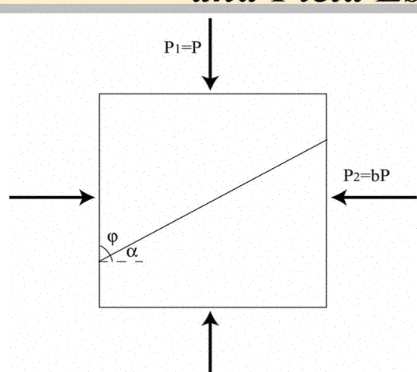
Why Experiments ?

1. Natural earthquakes are not well constrained.
2. Too complicated for detailed theoretical analysis.
3. Arbitrary assumptions concerning dynamic friction are needed to model rupture.
4. Spontaneous dynamic rupture experiments non-existent in engineering.

Advantages of Experiments:

1. "Conclusive" observations with proper diagnostics.
2. Bench mark problems for code validation.

Extension to Biaxial Loading and Field Estimates of Transition



$$\tau = (1-b)P\sin\alpha\cos\alpha$$
$$\sigma = bP\sin^2\alpha + P\cos^2\alpha$$

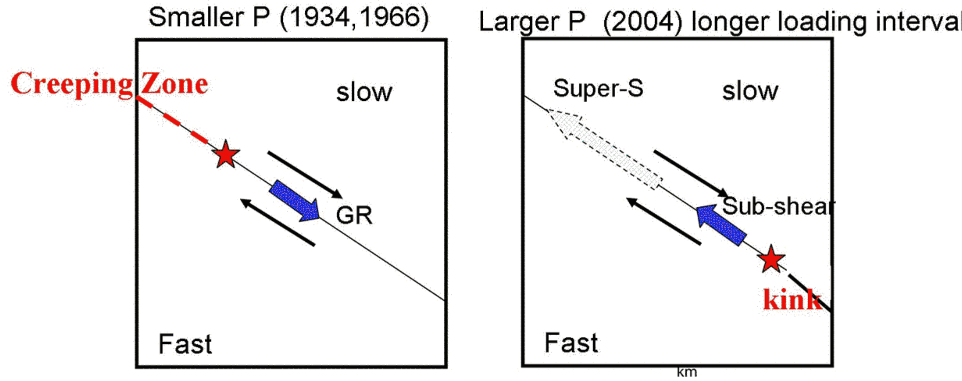
$$s = \frac{\mu^s(b\sin^2\alpha+\cos^2\alpha)-(1-b)\sin\alpha\cos\alpha}{(1-b)\sin\alpha\cos\alpha-\mu^d(b\sin^2\alpha+\cos^2\alpha)}$$

$$L = f[s(\alpha)] * L_c = f[s(\alpha)]\frac{1+\nu}{\pi}G\frac{(\mu^s-\mu^d)(\cos^2\alpha+b\sin^2\alpha)}{\left[(1-b)\sin\alpha\cos\alpha-\mu^d(\cos^2\alpha+b\sin^2\alpha)\right]^2}\frac{d_0}{P}$$

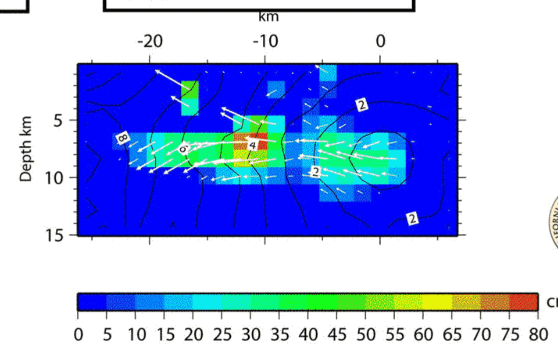
$$L = f[s(\alpha)]\frac{1+\nu}{\pi}G\frac{(\mu^s-\mu^d)^{1+M}(\cos^2\alpha+b\sin^2\alpha)^{1.5}}{\left[(1-b)\sin\alpha\cos\alpha-\mu^d(\cos^2\alpha+b\sin^2\alpha)\right]^2}2c(\mu^s)^{-M}\sqrt{H}a_0P^{-\frac{3}{2}}$$

By using: **P = 100 bar d_o = 1m, α = 25, mat properties of rock,**
→ **$L \sim$ 80km (Kunlun (100 km), Denali (70km))**

For The Same Rupture Zone in A Bimaterial Setting Both Rupture Directions are Possible



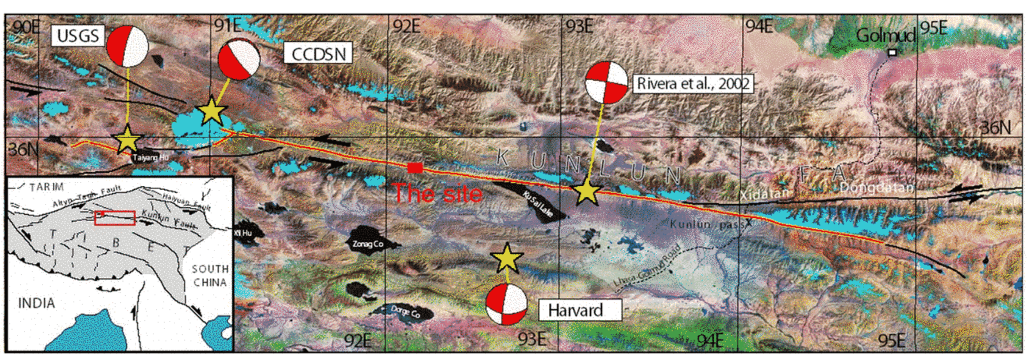
- Bilateral initiation (Ji, 2004; Spudich et al., 2004)
- POSITIVE rupture arrested
- NEGATIVE rupture grew for 25 km (v=2.85 km/s)



Field Evidence Of SubRayleigh to Supershear Transition

(*Ms 8.1 2001 Kunlunshan, Tibet Earthquake*)

(Bouchon and Vallee, Science, August 2003)



- Eastward propagation over a 400 km fault segment
- SubRayleigh over first 100 km (2.4 - 2.8 km/s)
- Transition to supershear (5 km/s)

ACKNOWLEDGEMENTS
Past and Current Students

R. Narasimhan	(1986)	Professor of Mechanical Engineering, Indian Institute of Science, Bangalore, India
A.T. Zehnder	(1987)	Professor of Theoretical and Applied Mechanics, Cornell University
S. Krishnaswamy	(1989)	Professor of Mechanical Engineering, Northwestern University
X. Deng	(1990)	Professor of Mechanical Engineering, University of South Carolina
L. Lu	(1991)	Team Leader, EDS/Unigraphics
J. Mason	(1993)	Associate Professor of Mechanical Engineering, University of Notre Dame
J. Lambros	(1994)	Associate Professor of Aeronautics, University of Illinois/Urbana-Champaign
C. Liu	(1994)	Senior Technical Staff Member, The Los Alamos National Laboratory (LANL)
H.A. Bruck	(1995)	Associate Professor of Mechanical Engineering, University of Maryland
K. Fey	(1996)	Biomedical Engineer, Alfred E. Mann Foundation for Scientific Research
J. Hodowany	(1997)	Rosetta Inpharmetics
D. Conner	(1998)	Visiting Associate, Department of Materials Science, California Institute of Technology
K. Haberman	(2000)	Los Alamos National Laboratory
P. Guduru	(2001)	Assistant Professor, Brown University
D. Coker	(2001)	Assistant Professor, Oklahoma State University
L.R. Xu	(2001)	Assistant Professor of Civil Engineering and Materials Science, Vanderbilt University
B. Chow	(2001)	Senior Analyst, Rustic Canyon Ventures
O. Samudrala	(2001)	Senior Technical Staff Member, General Electric Global Research Center
D. Anderson	(2002)	Senior Technical Staff Member, General Electric Global Research Center
K. Xia	(2005)	Postdoctoral Scholar, Brown University
G. Lykotrafitis	(2006)	California Institute of Technology
M. Brown	(2006)	California Institute of Technology
X. Lu	(2006)	California Institute of Technology

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H. Lee	nLight Photonics, Seattle, WA
Y.J. Lee	Senior Scientist, Dow Corning, Midland, MI
D. Owen	Chief Technical Officer, Oraxion Diagnostics, Fremont, CA
T.-S. Park	Senior Research Scientist, Oraxion Diagnostics, Fremont, CA
C. Rousseau	Assistant Professor, University of Rhode Island, Kingston, RI
O. Samudrala	Senior Technical Staff Member, General Electric Global Research Center
R. Singh	Assistant Professor, Stony Brook State University of New York
H. Tippur	Professor of Mechanical Engineering, Auburn University
M. Zhou	Associate Professor of Mechanical Engineering, Georgia Tech

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National Science Foundation (Geophysics)

Possible Shear Rupture Speeds: "Phase Diagram" from cohesive-zone analysis.(Velocity weakening)

(Samudrala, Huang and Rosakis, JGR, 2002)