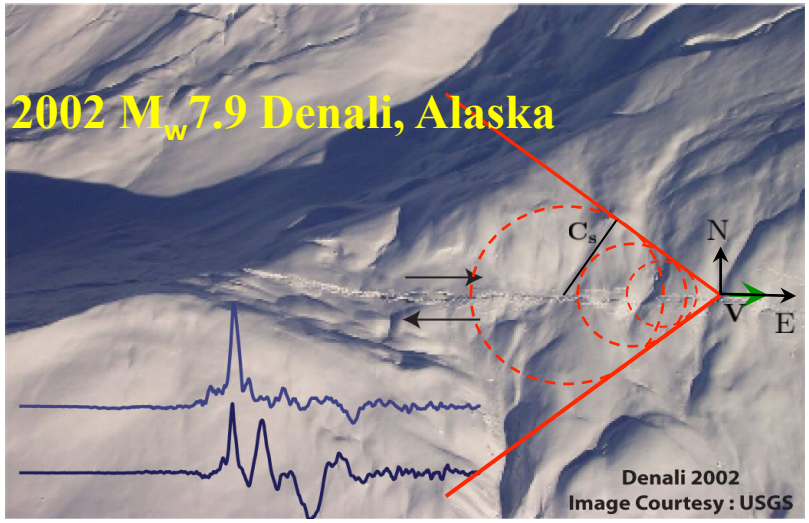
Representing Mega Earthquakes in the Laboratory:

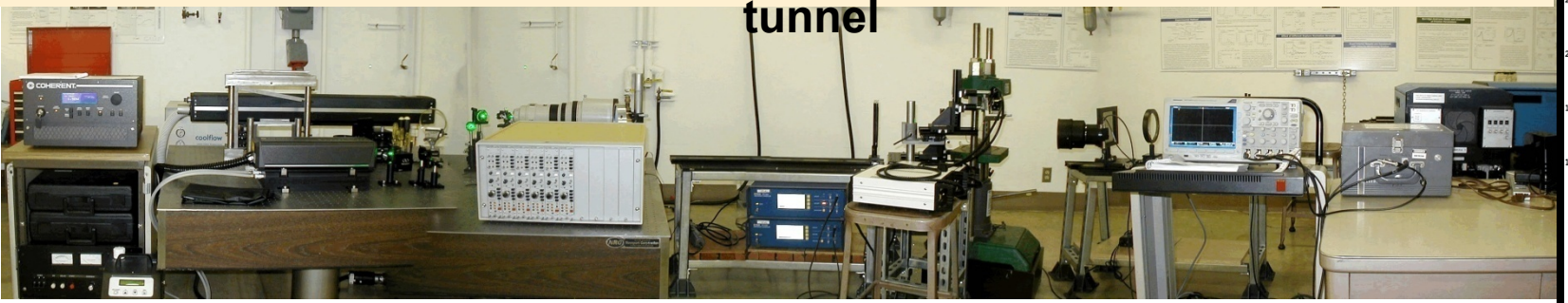
The discovery of Super-shear Earthquake Ruptures

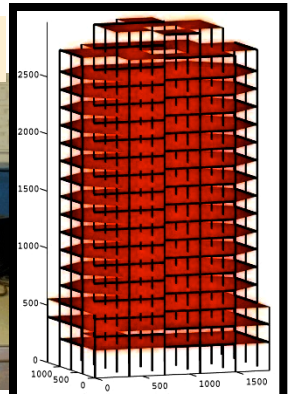
ARES J. ROSAKIS

Theodore von Kármán Professor of Aeronautics and Mechanical Engineering Graduate Aerospace Laboratories (GALCIT)



Producing surrogate earthquakes in GALCIT's seismological wind tunnel

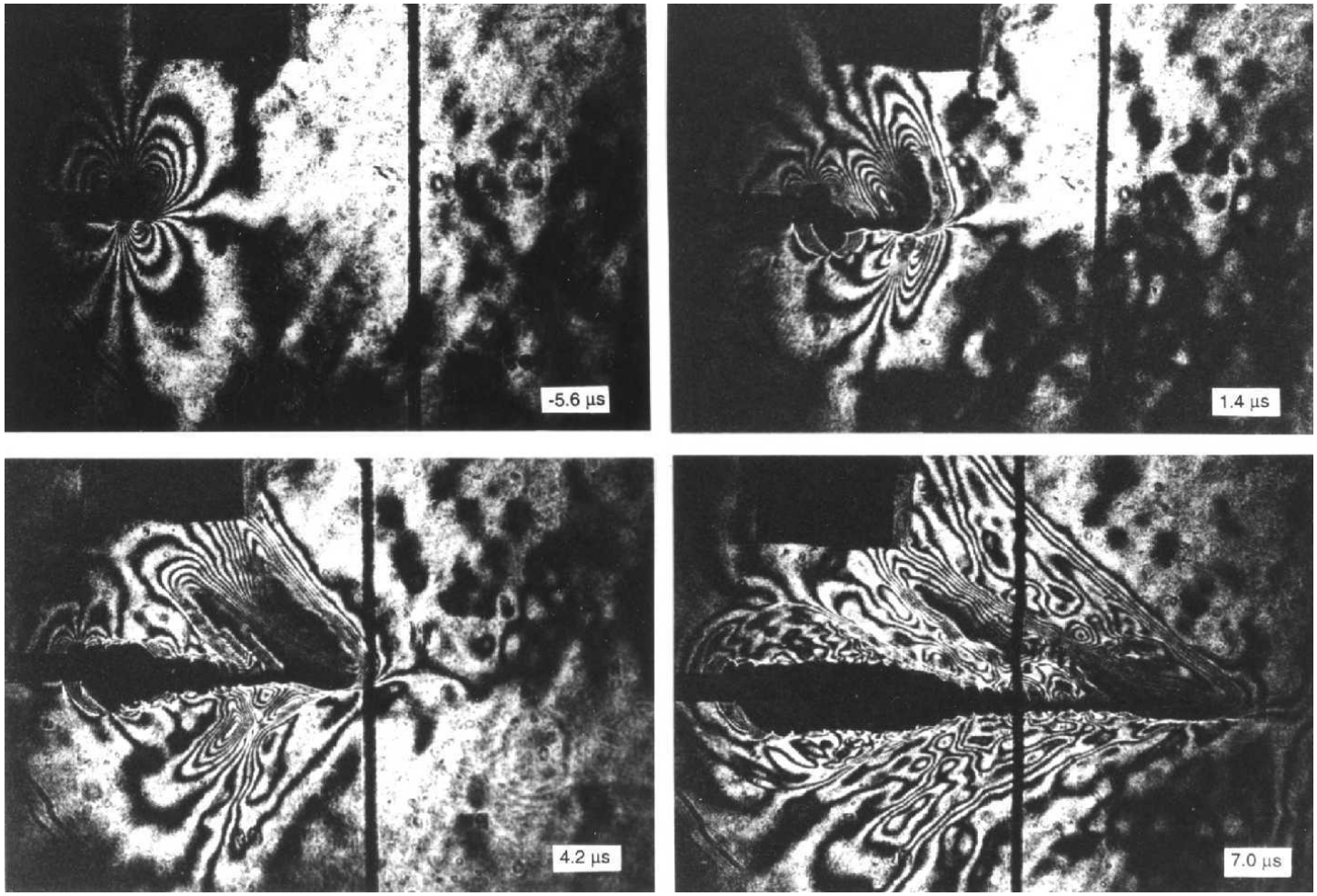




DISCOVERY OF THE FASTED CRACKS IN THE WORLD

Breaking The Speed Limit of Crack Growth in Composites subjected to Impact

(Orthotropic , Carbon–Fiber Reinforced Composite)



Rosakis , Coker & Samudrala,

Science (1999)

Coker & Rosakis,

Phil. Mag A., 2001

Super-Shear Rupture

($c_S < v \sim c_P$)

← ***7.5km/s!***

=22 Mach

BET WITH THE CALTECH SEISMOLAB DIRECTOR

WHAT WAS THE BET:

Is it possible to generate Super-Shear ($c_S < v < c_P$) ruptures in frictional interfaces under conditions of simple static tectonic loading and NOT impact.

•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 (~2.9Km/s)
Venkataraman and Kanamori , *JGR* (2004)

•These ruptures ate called Sub-Shear ***($v < c_s$) .***

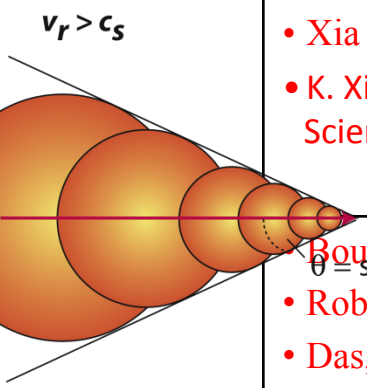
Until 1999 there were only ***indirect*** evidence of ***Super-Shear ($c_S < v < c_P$)*** rupture speeds along small fault segments.

References	*Events*
• R. Archuleta, *JGR* (1984) • Spudich and Kranswick, *BSSA* (1984)	1979 Imperial Valley, CA; M_w 6.5

After the discovery of Super-Shear ruptures in composite materials, , our laboratory, begun to look for experimental proof for the existence of Super-shear rupture under conditions mimicking tectonic, far-field loading.

Direct Evidence of Super-shear ($c_S < v < c_P$) Rupture Speeds from the Field in three Earthquakes after 1999.

In parallel and together with our collaborators from Seismology, we begun seeking for direct field evidence of super-shear occurrences in both past (Historic) and new Earthquakes around the world.

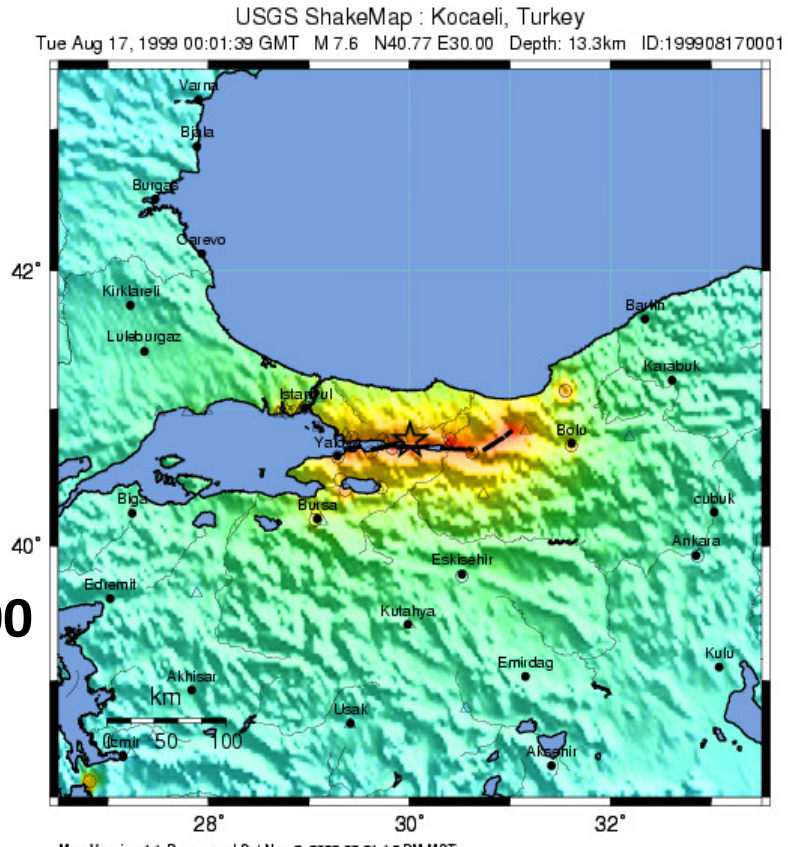


References	*Events*
• Bouchon, Bouin, Karabulet, Toksöz, Dietrich and Rosakis, *GRL* (2001) • Xia , Rosakis and Kanamori ,Science, 2004. • K. Xia, A.J. Rosakis, H. Kanamori and J.R. Rice, Science 2005)	1999 Izmit (Νικομήδια), Turkey; M_w 7.4
• Bouchon and Vallee, *Science* (2003) • Robinson, Brough and Das, *JGR* (2006) • Das, *Science (*2007) • Walker and Shearer, *JGR* (2009)	2001 Kunlunshan, Tibet ,China; M_w 7.8 (Transition)
• Ellsworth et al., (2004) • Walker and Shearer, *JGR* (2009) • Melo, Bhat, Rosakis and Kanamori , *Earth and Planetary, Science (20013)*	2002 Denali, Alaska; M_w 7.9 (Transition and near-fault record)

Personal favorites

The 1999 (M7.5) Earthquake in IZMIT ruptured 150 km of the North Anatolian Fault.

The Maximum Slip Along the ruptured part of the fault was 5,7 meters . The fault, starts near the boarder of Turkey with Iran , extends parallel to the Black sea, και continues underwater the sea of Marmara towards Constantinople and the Aegean sea in Greece .



The Earthquake lasted 37 seconds,killed 17.000 people and left half a million homeless.

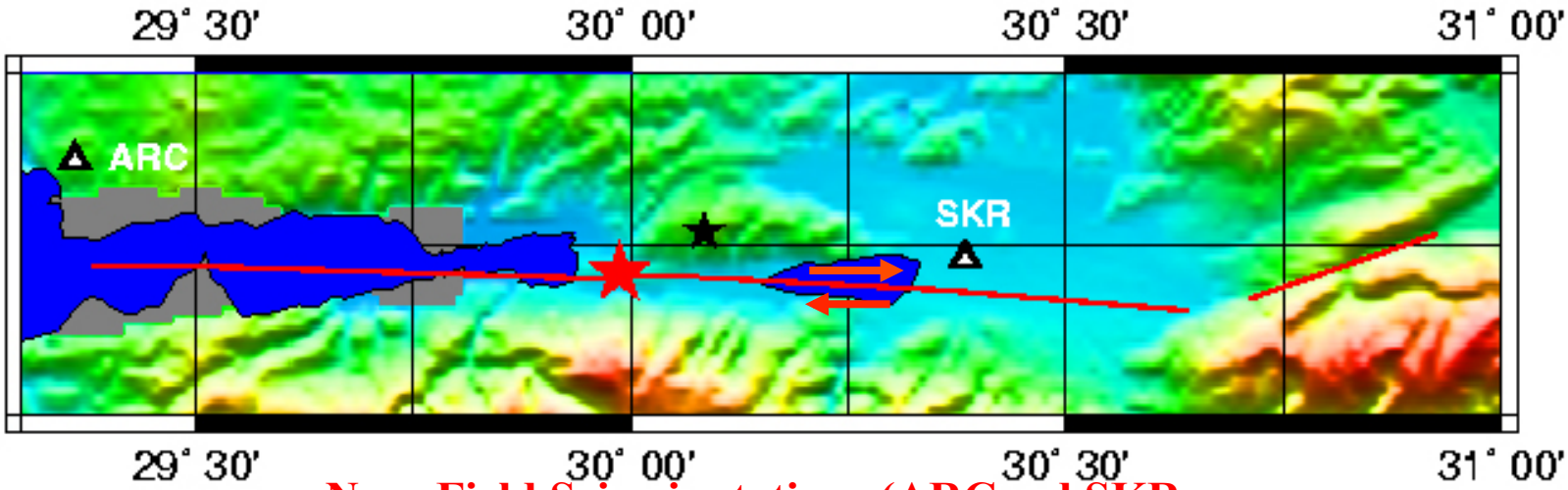
Why was it so destructive?

Direct Indications of Super-shear Rupture during the 1999 (M7.5) Earthquake in IΣMIT

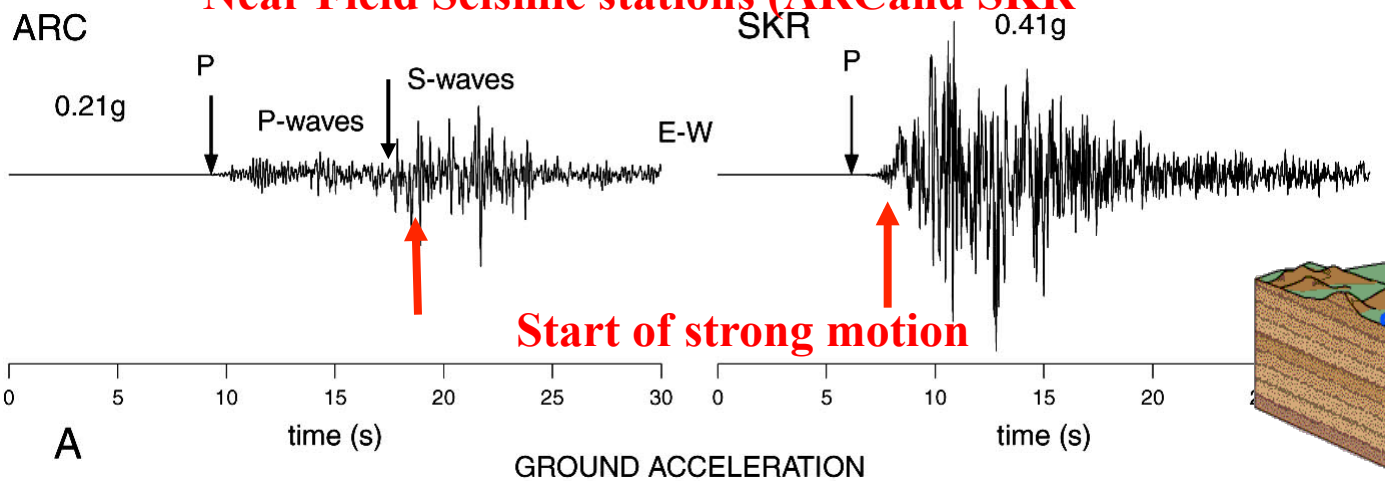
M. Bouchon, M. Bouin, H. Karabulet, M. Toksöz, M. Dietrich and A. Rosakis

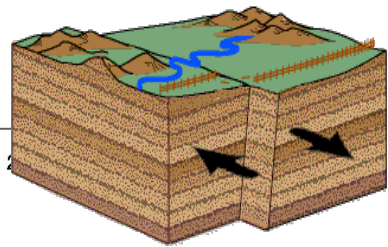
Geophysical Research Letters, 2001

Bilateral rupture. Rupture speed(West : Rayleigh, East: ?2 C_S = 4.9 km/s)



Near Field Seismic stations (ARCand SKR



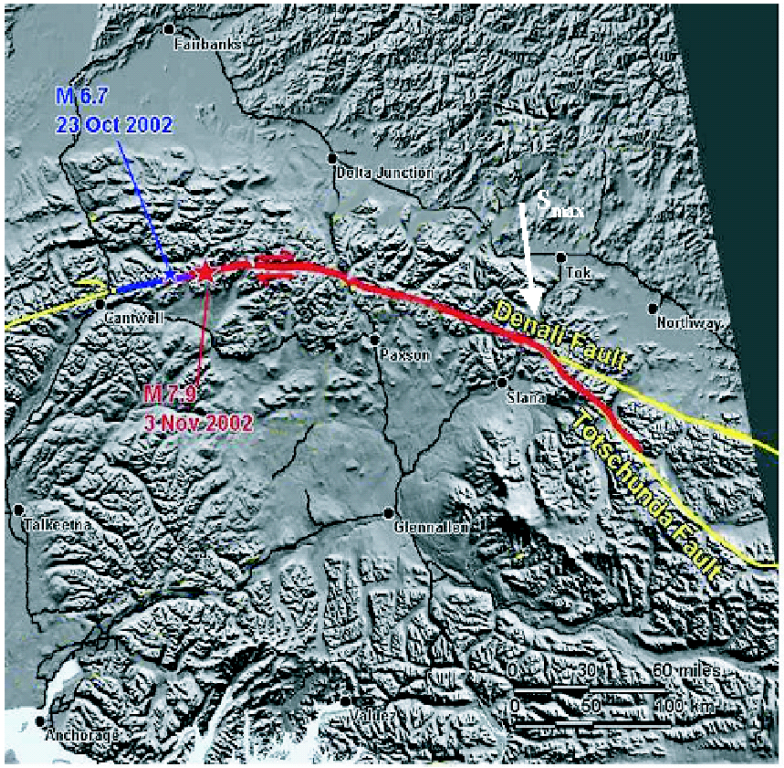


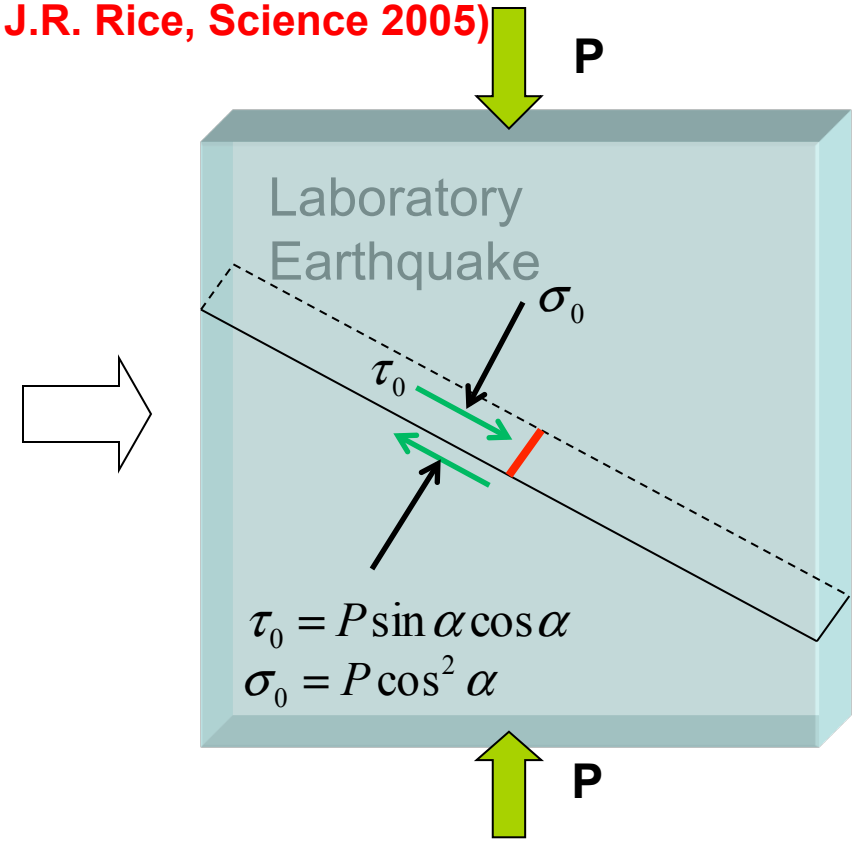
From Real to Laboratory Earthquakes

(Mimicking Spontaneous Rupture Events in Frictional interfaces)

(K. Xia, AJ. Rosakis and H. Kanamori, Science 2004)

(K. Xia, A.J. Rosakis, H. Kanamori and J.R. Rice, Science 2005)





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

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(Mimicking Spontaneous Rupture Events in Frictional interfaces)

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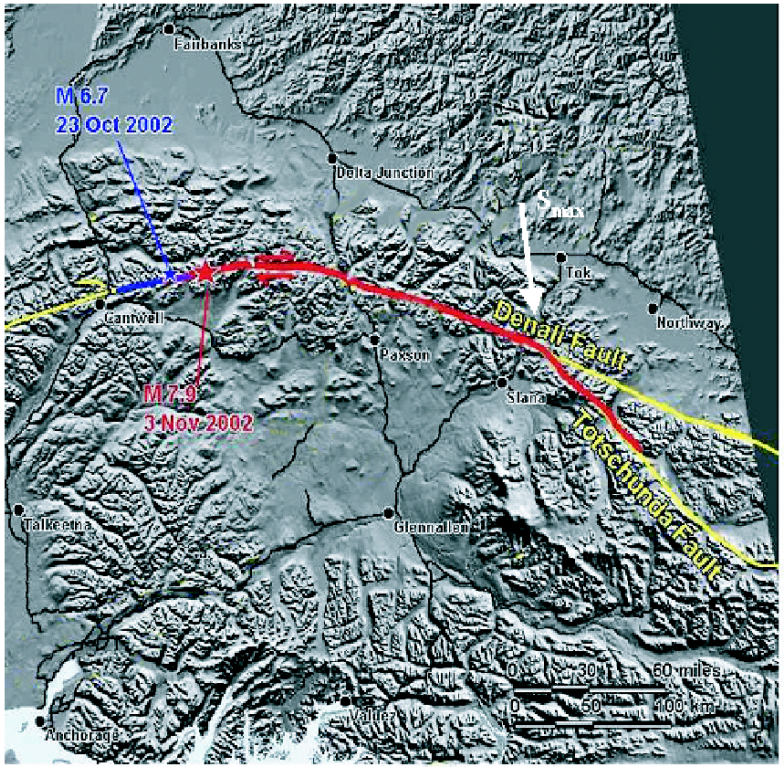

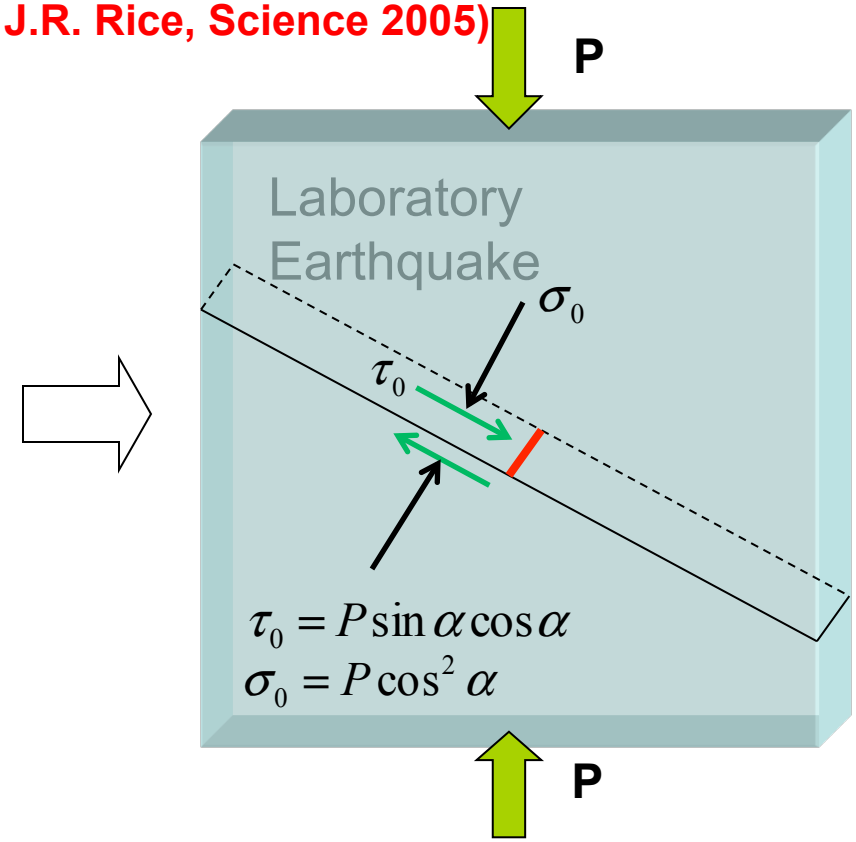

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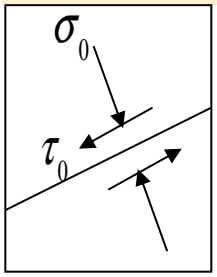
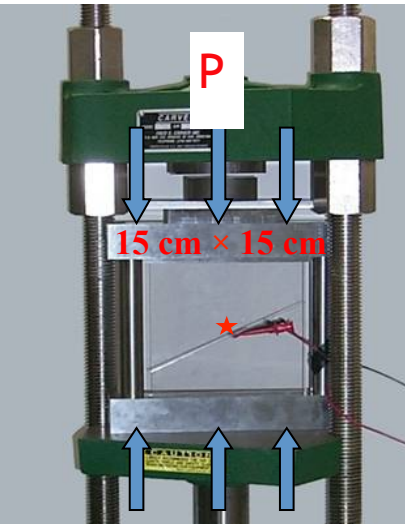
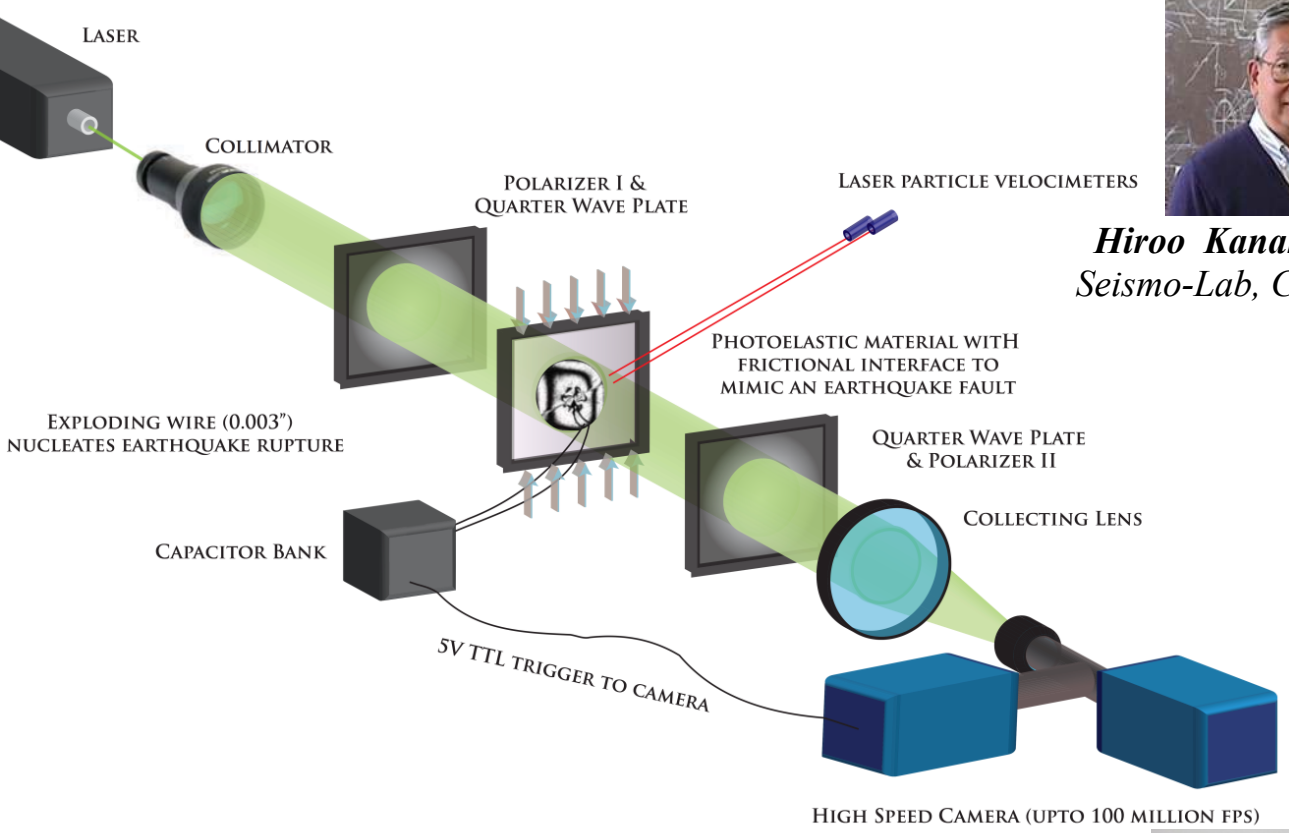
Experimental setup that mimics pre-stressed faults

Non-dimensional shear prestress $= \tau_0 / \sigma_0 = f_0 = \tan\alpha$



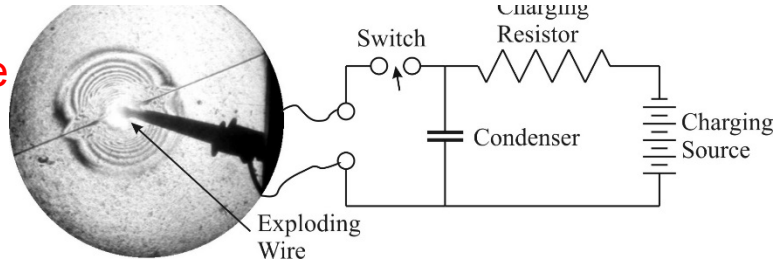


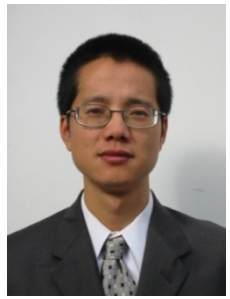


Hiroo Kanamori
Seismo-Lab, Caltech

James R. Rice
SEAS/E&PS
Harvard

Exploding wire





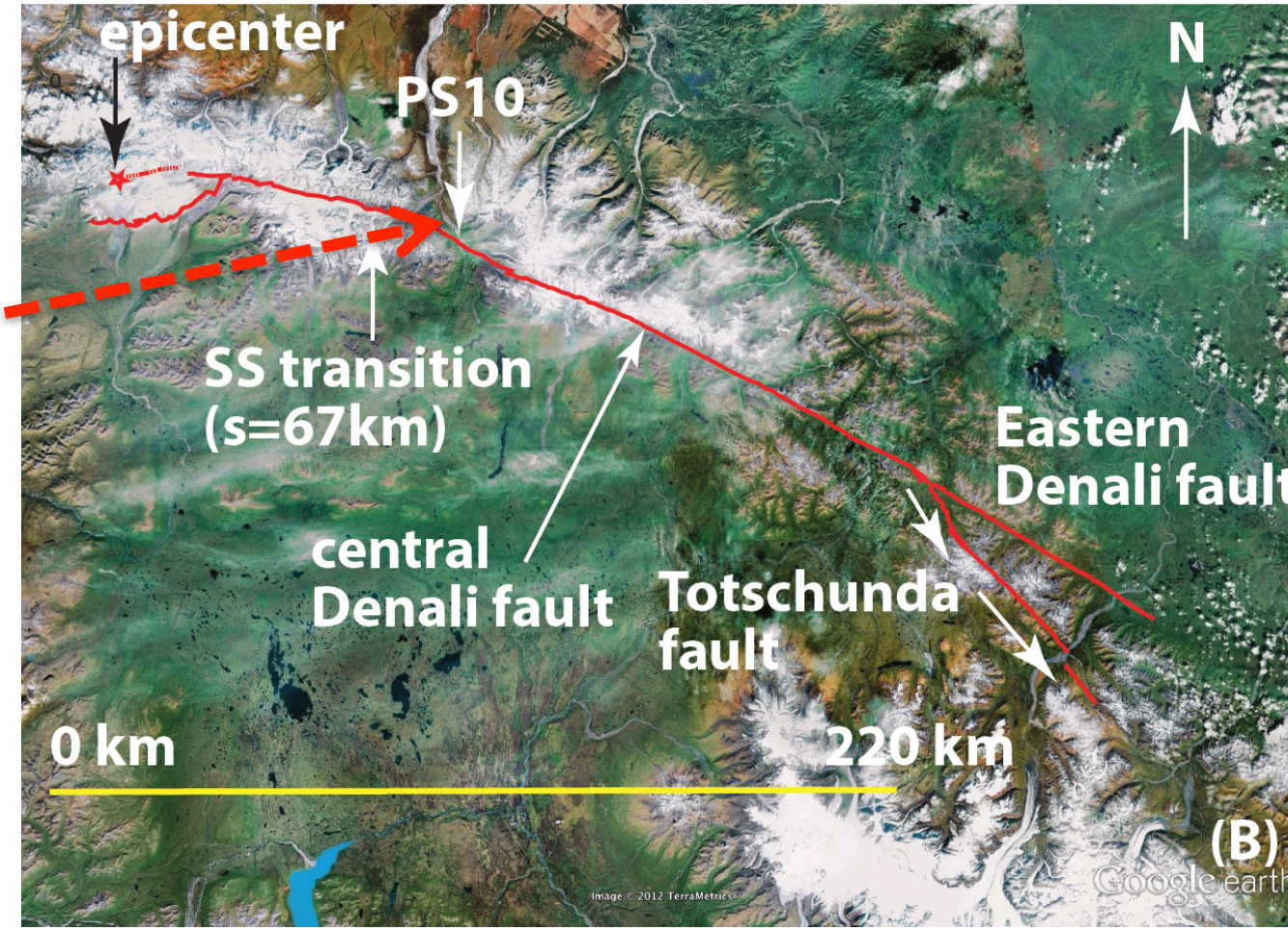
Kaiwen Xia
CE, Univ. of Toronto

(K. Xia, AJ. Rosakis and H. Kanamori, Science 200(K)

(K. Xia, A.J. Rosakis, H. Kanamori and J.R. Rice, Science 2005)

Suspicion of Sub-Rayleigh to Super-shear Transition 67km from the Epicenter

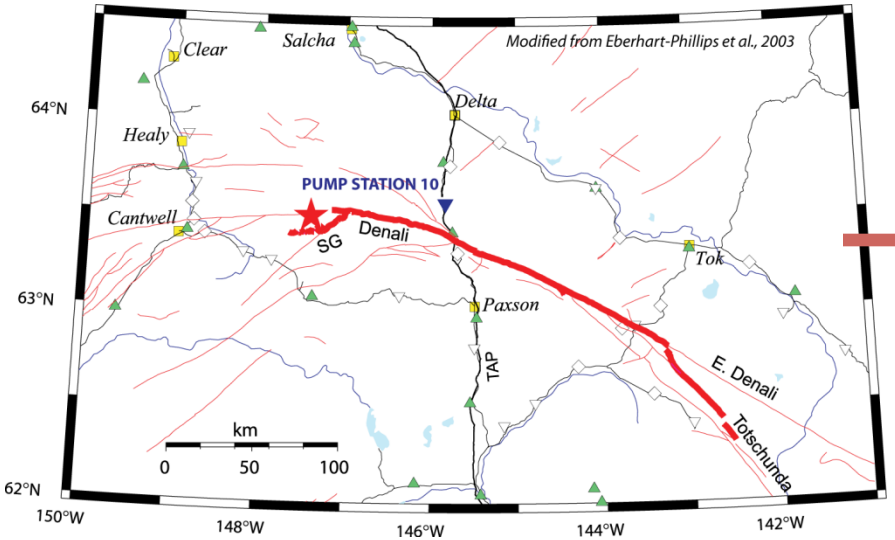
Ground shaking recorded at the Seismograph of the Trans-Alaskan Pipeline(Station PS10)

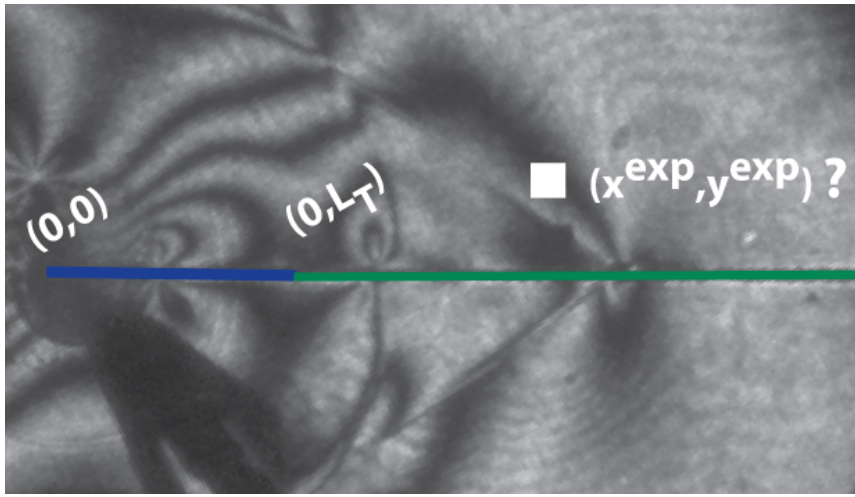


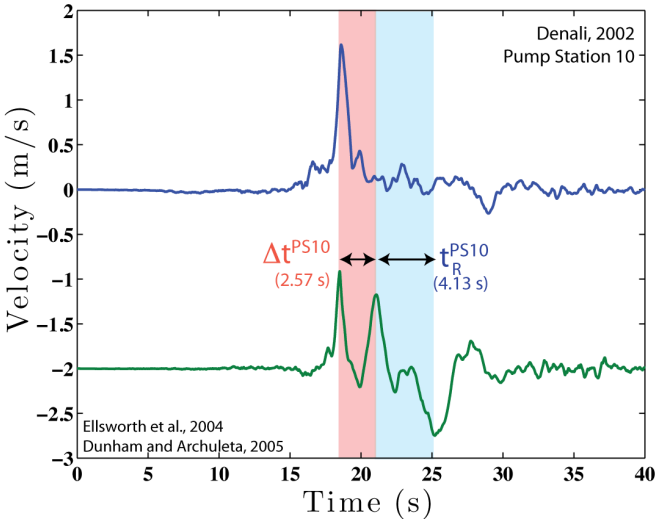
Station PS10 is located at ~ 3km N/NE from the Denali fault

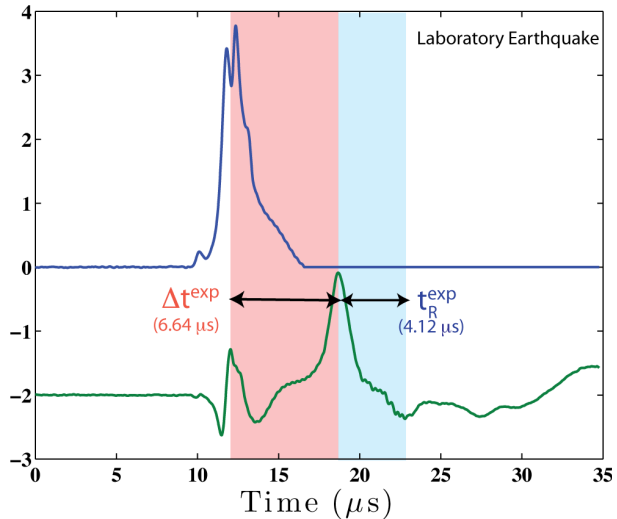
Spatially Scaling Laboratory Earthquake to Match PS10 Record

Spatial Scaling achieved by solving for a station location in the laboratory specimen that would give the same time difference between the arrival of the Main Pulse and the Trailing Rayleigh Signature both in the temporally scaled laboratory record and the PS10 record.







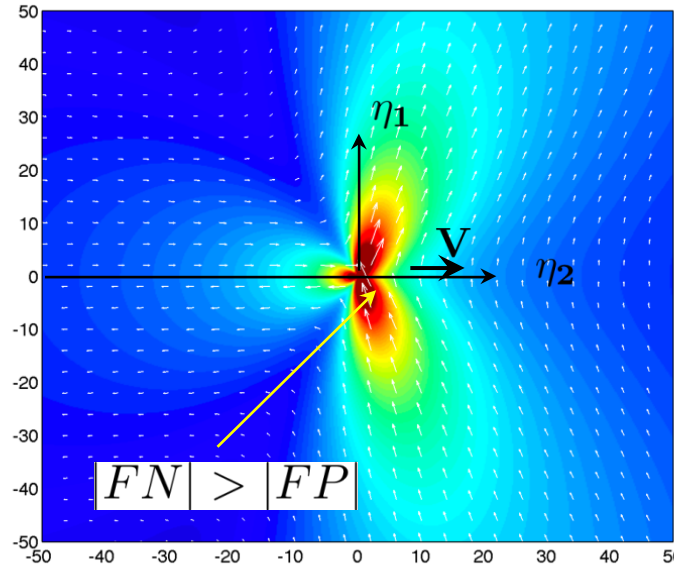


PROBLEM STATEMENT

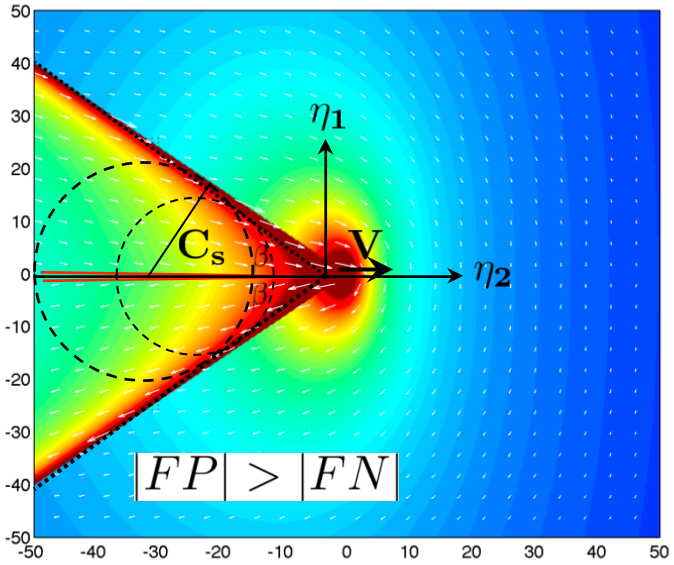
Given specific transition lengths, L_T and L_T^{exp} in the real and the laboratory earthquakes, find (x^{exp},y^{exp}) in the laboratory earthquake such that

$$Dt^{exp} = Dt^{PS10,scaled}$$

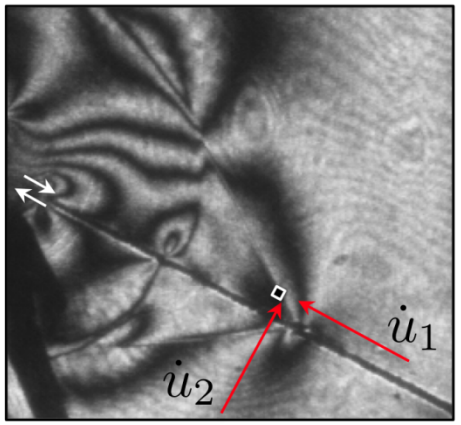
Classification of Earthquakes: Ground motion signatures of steady-state, Sub-Rayleigh and Super-shear Ruptures

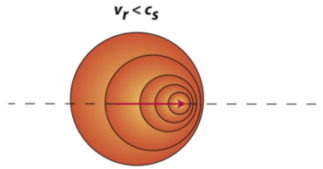
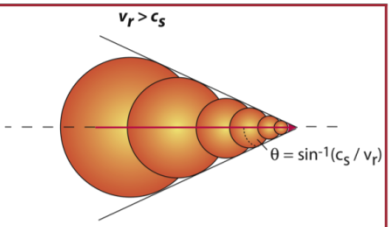


$$\frac{V_r}{C_s} = 0.875$$



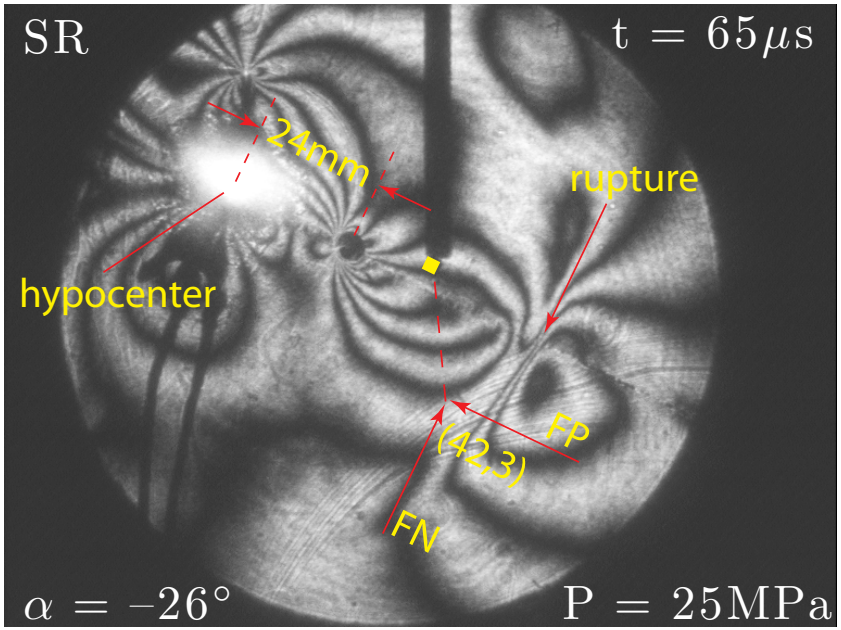
$$\frac{V_r}{C_s} = 1.6$$

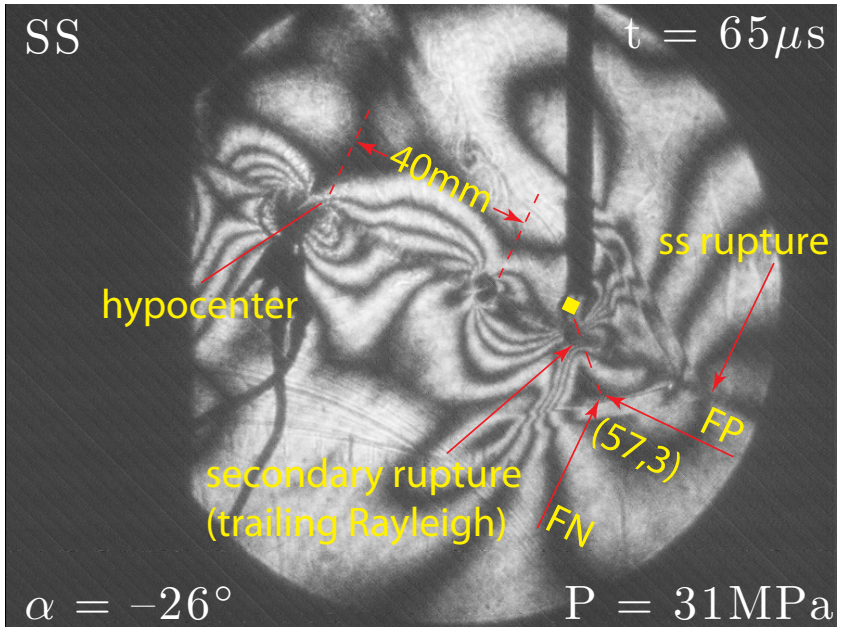


$V_r < C_R$ 	$\sqrt{2}C_s < V_r < C_p$ 
$\left\|\frac{\dot{u}_{2_{max}} - \dot{u}_{2_{min}}}{\dot{u}_{1_{max}} - \dot{u}_{1_{min}}}\right\| > 1$	$\left\|\frac{\dot{u}_{1_{max}} - \dot{u}_{1_{min}}}{\dot{u}_{2_{max}} - \dot{u}_{2_{min}}}\right\| > 1$

1906 M_w 7.8 San Francisco, CA?
1979 M_w 6.5 Imperial Valley, CA.
1999 M_w 7.4 Izmit, Turkey
1999 M_w 7.2 Duzce, Turkey
2001 M_w 7.8 Kunlunshan, Tibet
2002 M_w 7.9 Denali, Alaska

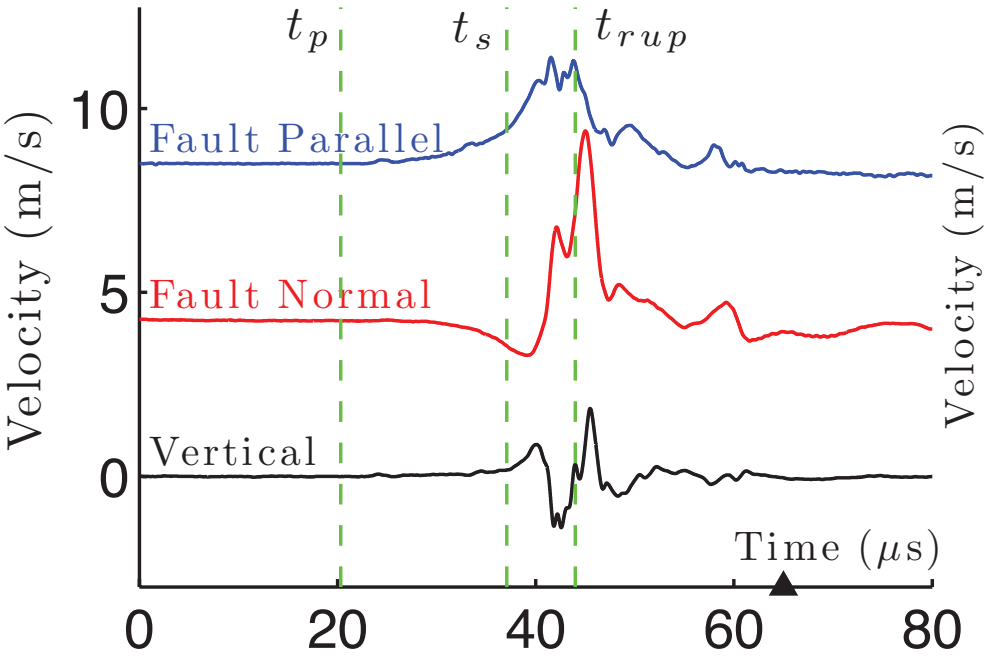
References: Freund and Clifton (1974); Freund (1979&1990); Rosakis (2002). Aagaard and Heaton (2004); Dunham andArchuleta (2004) Bhat et al., (2007), Dunham and Bhat, (2008);

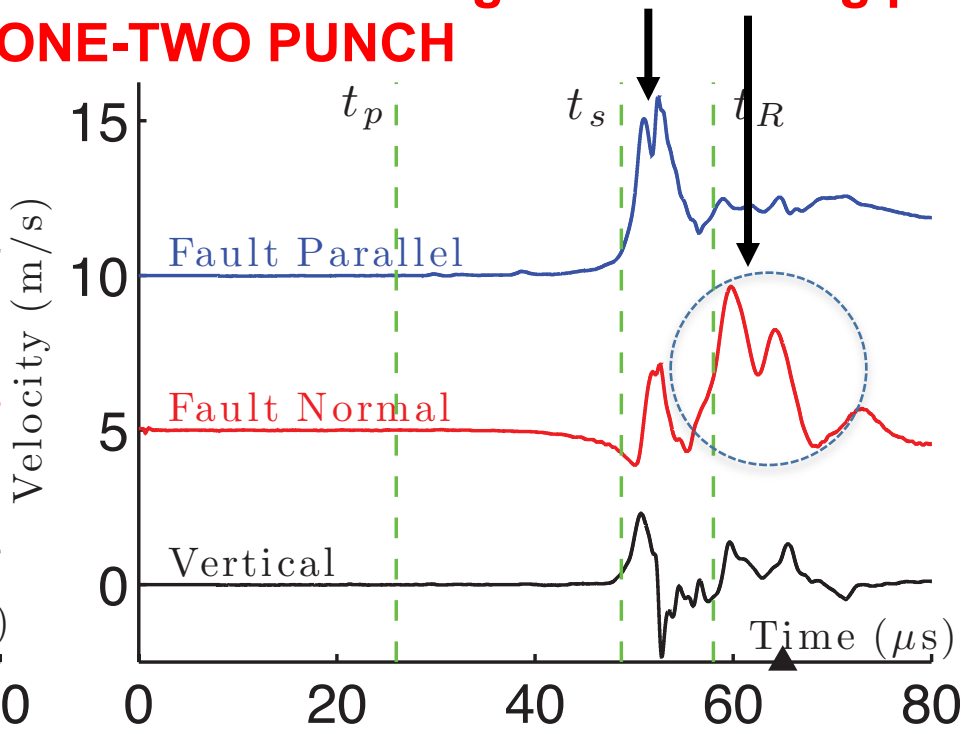




Sequential, fault parallel and fault normal ground shaking peal

THE ONE-TWO PUNCH



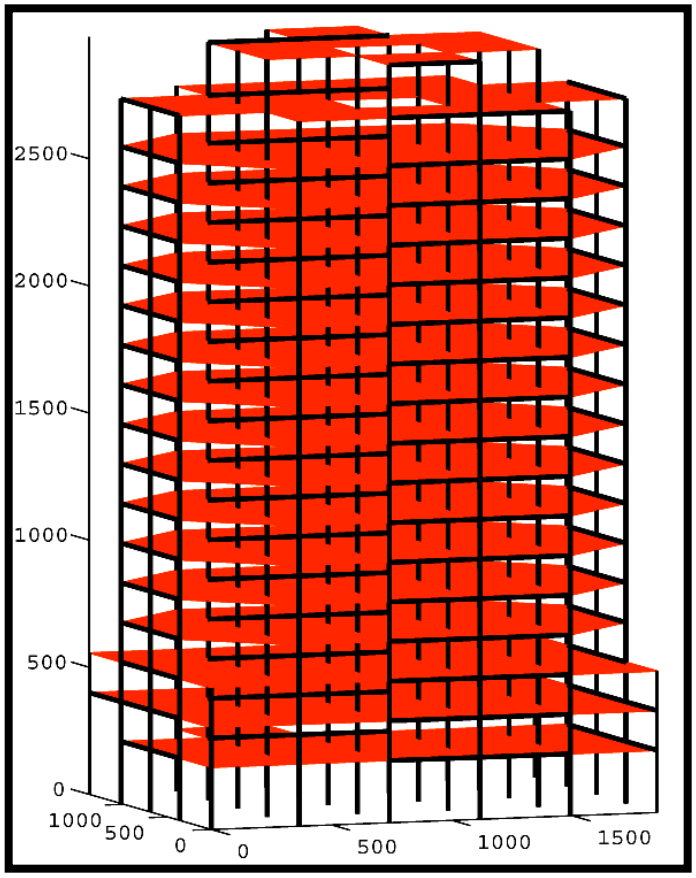


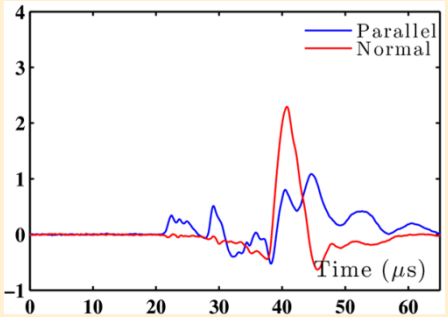
Implications of Super-shear Ruptures on Buildings

Building Studied : Existing, steel moment-frame building of the 20-story class

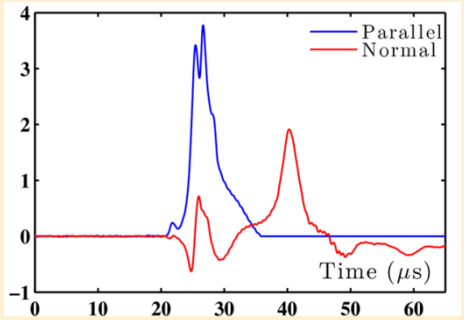
- **3D Finite Element simulations using FRAME3D**
- **Developed at Caltech by Prof. Swaminathan Krishnan**

Swaminathan Krishnan
CE/GPS Caltech





Sub-Rayleigh Earthquake Rupture



Super-shear Earthquake Rupture

Existing Building (Woodland Hills), isometric view
(designed according to UBC82 provisions)
$T_1 = 4.43s;\ T_2 = 4.22s;\ T_3 = 2.47s$