Identifying the unique ground motion signatures of supershear earthquakes: The one-two punch effect on high-rise buildings

University of California, Los Angeles

The Civil & Environmental Engineering Department

Distinguished Lecture Series, February 7, 2012

ARES J. ROSAKIS

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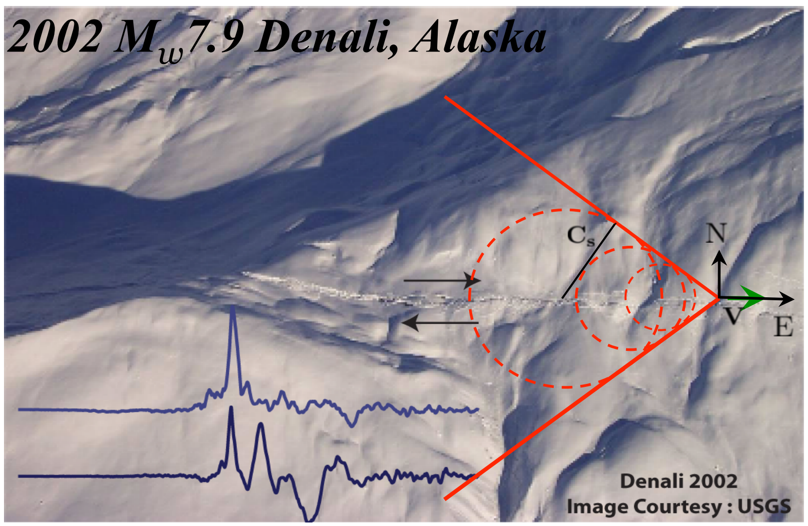
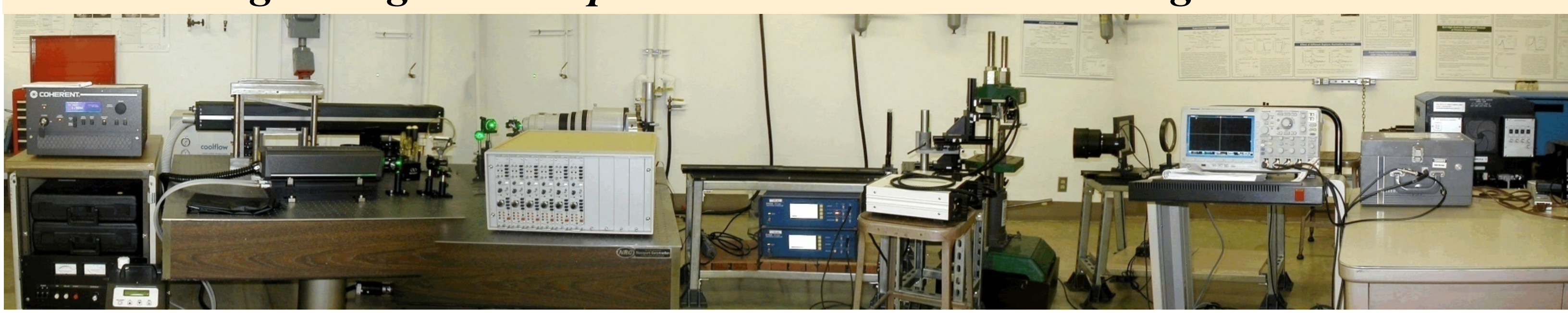
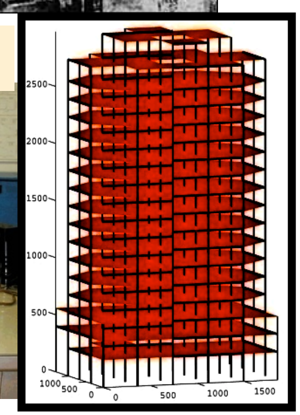


Producing surrogate earthquakes in GALCIT's seismological wind tunnel





What Is a crustal Earthquake ?

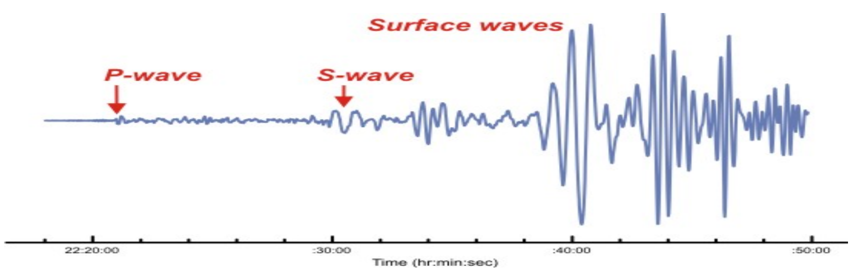
Earthquake is a term used to describe both sudden slip on a fault, and the resulting ground shaking and radiated seismic energy caused by the slip.

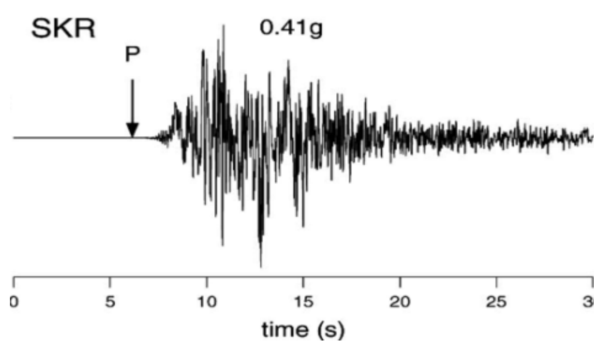
http://earthquake.usgs.gov/image_glossary/earthquake.html

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 (incoherent) interface. The rupture speed is the speed of dynamic unzipping and governs the nature of near-fault ground shaking.





A GLIMPSE AT A POTENTIALLY BIG PROBLEM

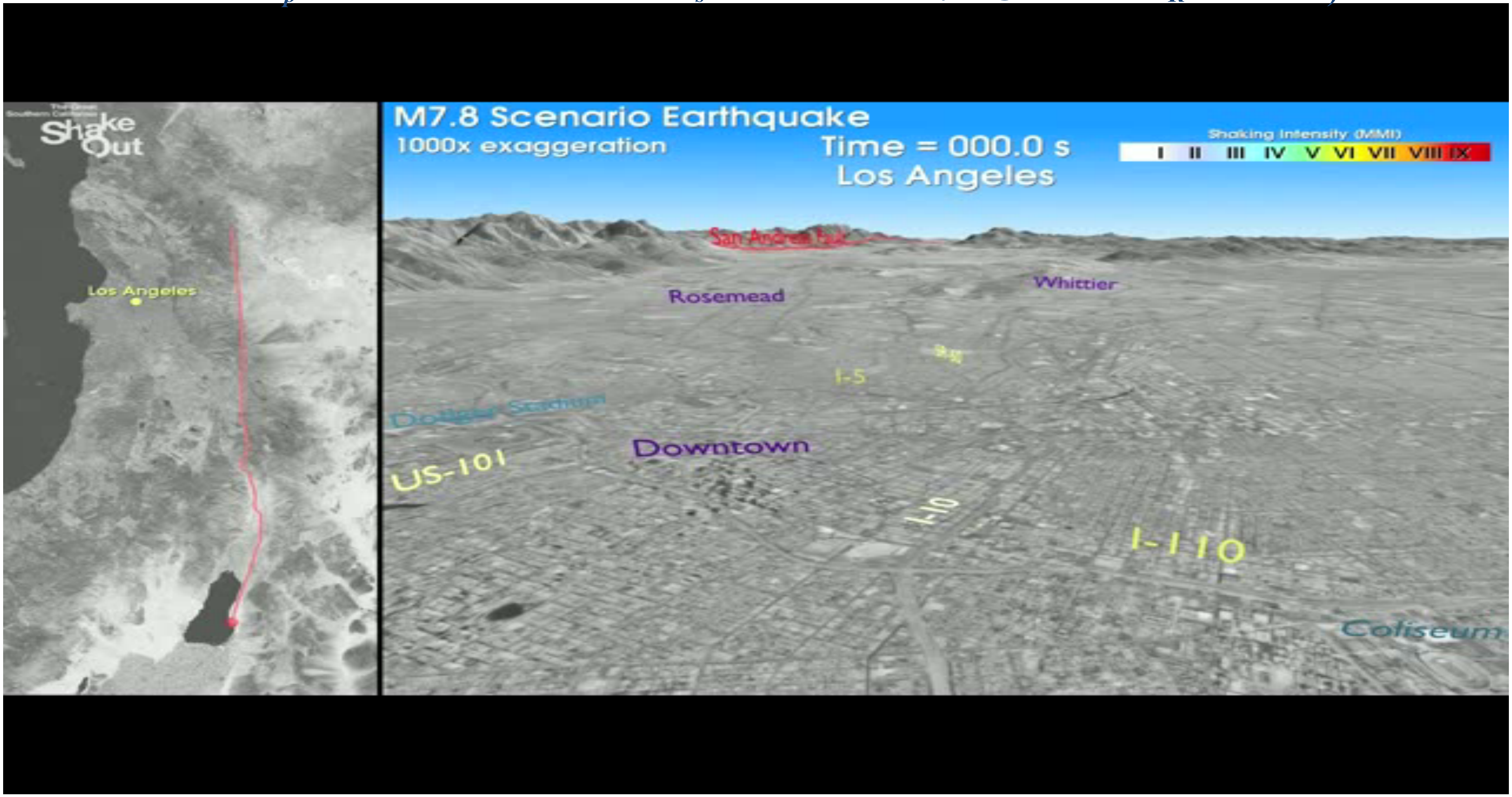
"Rupture" means propagation of slip along a frictional (incoherent) interface

Brad Aagaard (CE Ph.D, 2000)
Robert Graves (GPS PhD, 1990)

- Equivalent to fast unzipping -

SCEC ShakeOut Simulation workgroup

Pressure Wave ($c_p \sim 5$km/s) , Shear Wave ($c_s \sim 3.5$km/s) Rayleigh Wave ($c_R \sim 3$km/s)



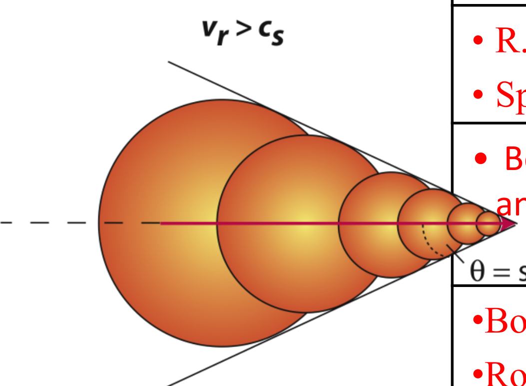
- *The ground-shaking intensity and radiated energy are related to rupture speed*

How big could the Rupture Speed (v)be ?

Evidence of Supershear ($c_S < v < c_P$) Rupture speeds
A shear wave Mach Cone only

- 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)

- Evidence of supershear ($C_S < v < C_P$) rupture bursts along fault segments.

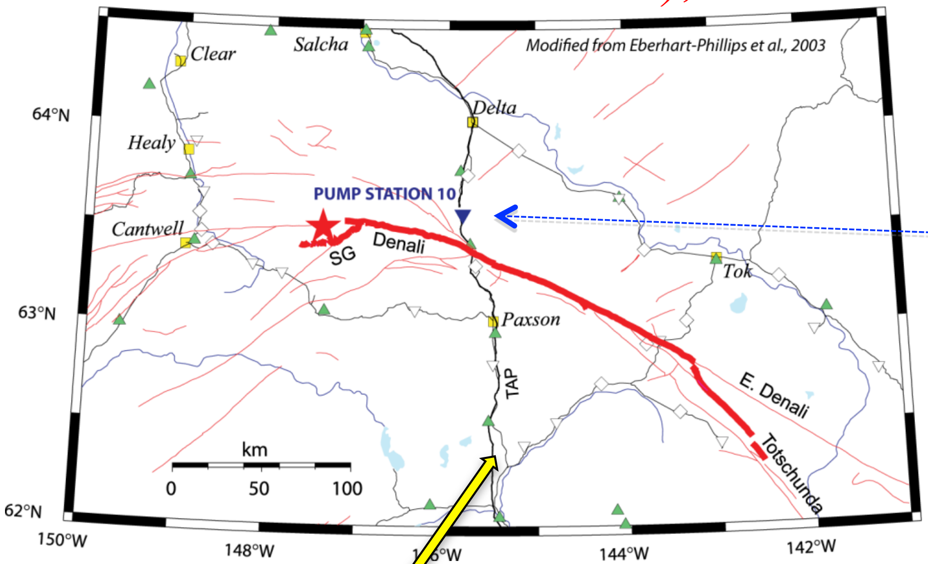


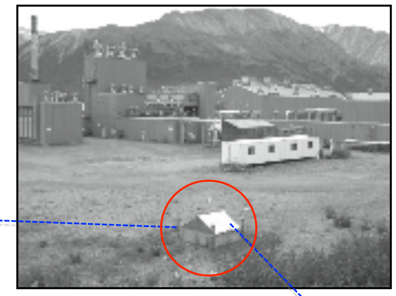
References	*Events*
• Song and Beroza, *BSSA* (2006)	1906 San Francisco,CA ; M_w 7.8
• R. Archuleta, *JGR* (1984) • Spudich and Kranswick, *BSSA* (1984)	1979 Imperial Valley, CA ; M_w 6.5
• Bouchon, Bouin ,Karabulet , Toksöz ,Dietrich and. Rosakis ,*GRL*, (2001)	1999 Izmit, Turkey ; M_w 7.4
•Bouchon and Vallee, *Science* (2003) •Robinson, Brough and Das, *JGR* (2006) •Das, *Science* (2007) •Walker and Shearer, *JGR* (2009)	2001 Kunlunshan, China ; M_w 7.8 (Transition)
• Ellsworth et al., (2004); • Walker and Shearer , *JGR* (2009)	2002 Denali, Alaska ; M_w 7.9 (Transition and near-fault record)

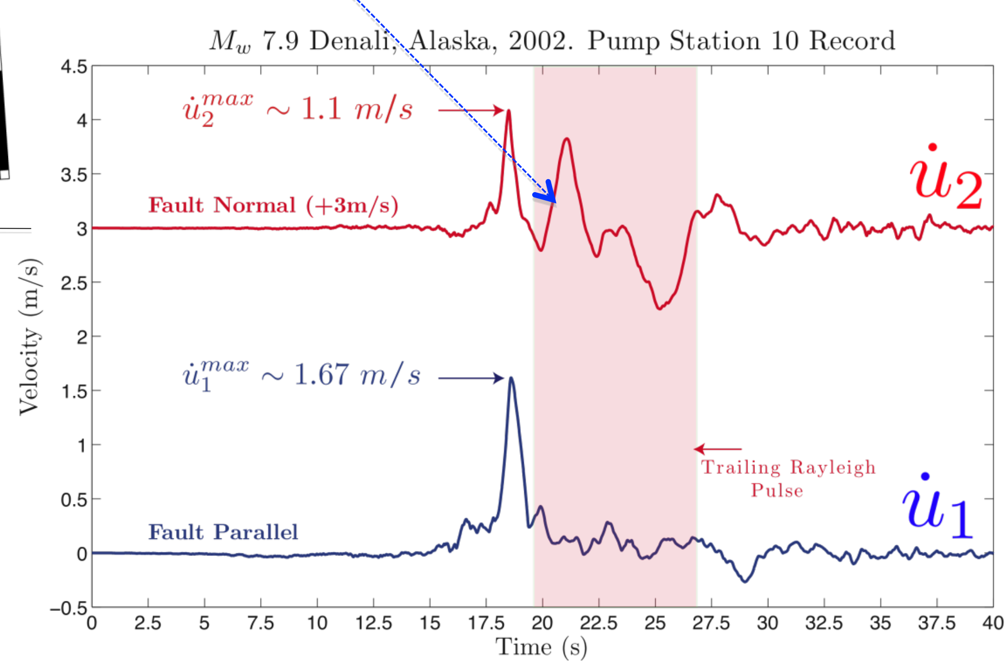
Personal favorites

A Rare NEAR-FAULT Record of a just transitioned, SUPERSHEAR event

Mw 7.9 , 2002 Denali, Alaska Earthquake. Transition at 72Km(18Km W. of pump 10 station located at 3Km north), Ellsworth et al.(2004).Right lateral slip, West to East .





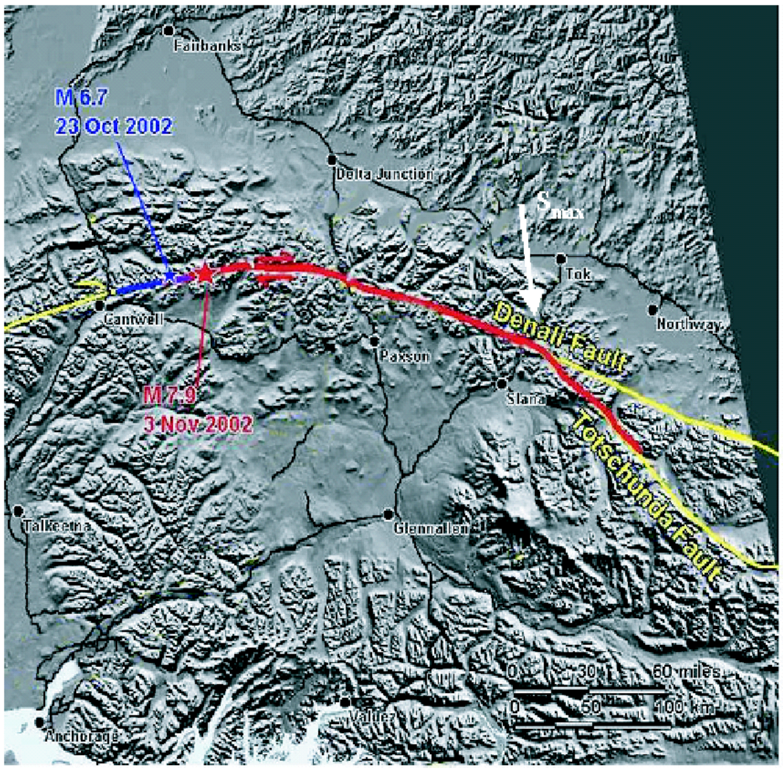


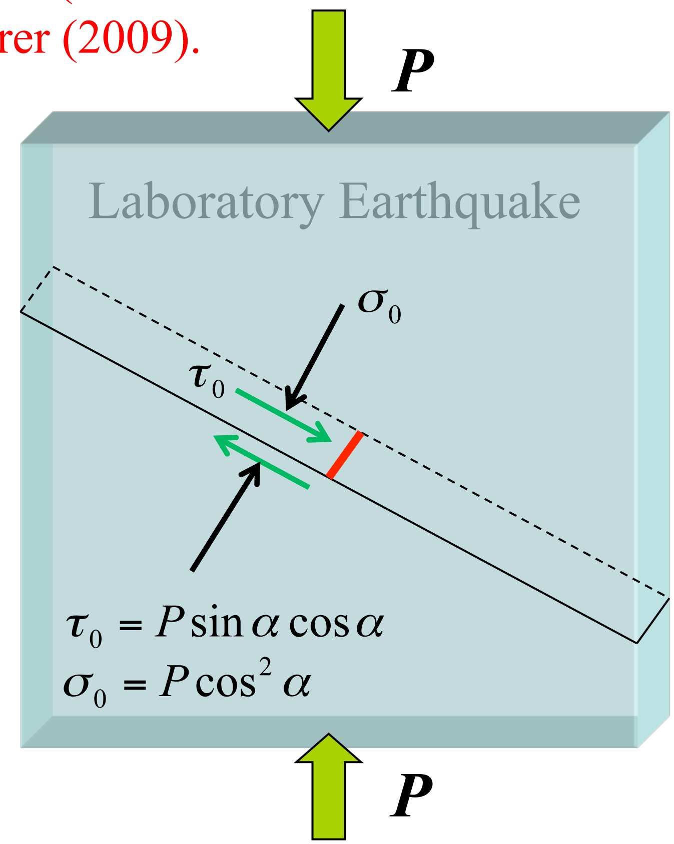
References: Dunham and Archuleta, (2004); Ellsworth et al., (2004); Eberhart-Phillips et al., (2003)

From Real to Laboratory Earthquakes

(Mimicking Spontaneous Rupture Events in Frictional interfaces)

Mw 7.9 , 2002 Denali, Alaska Earthquake. Transition at 72Km(18Km W. of pump 10 station).Elsworth et al.(2003), Walker and Shearer (2009).

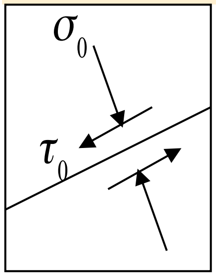


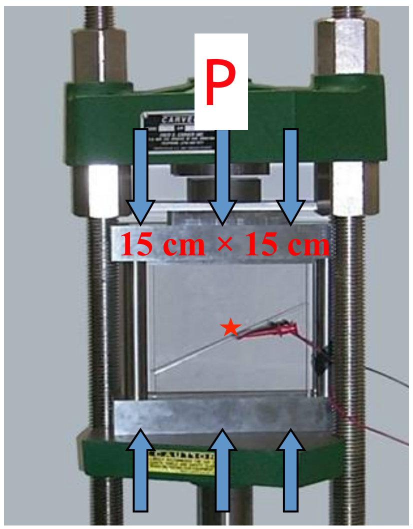


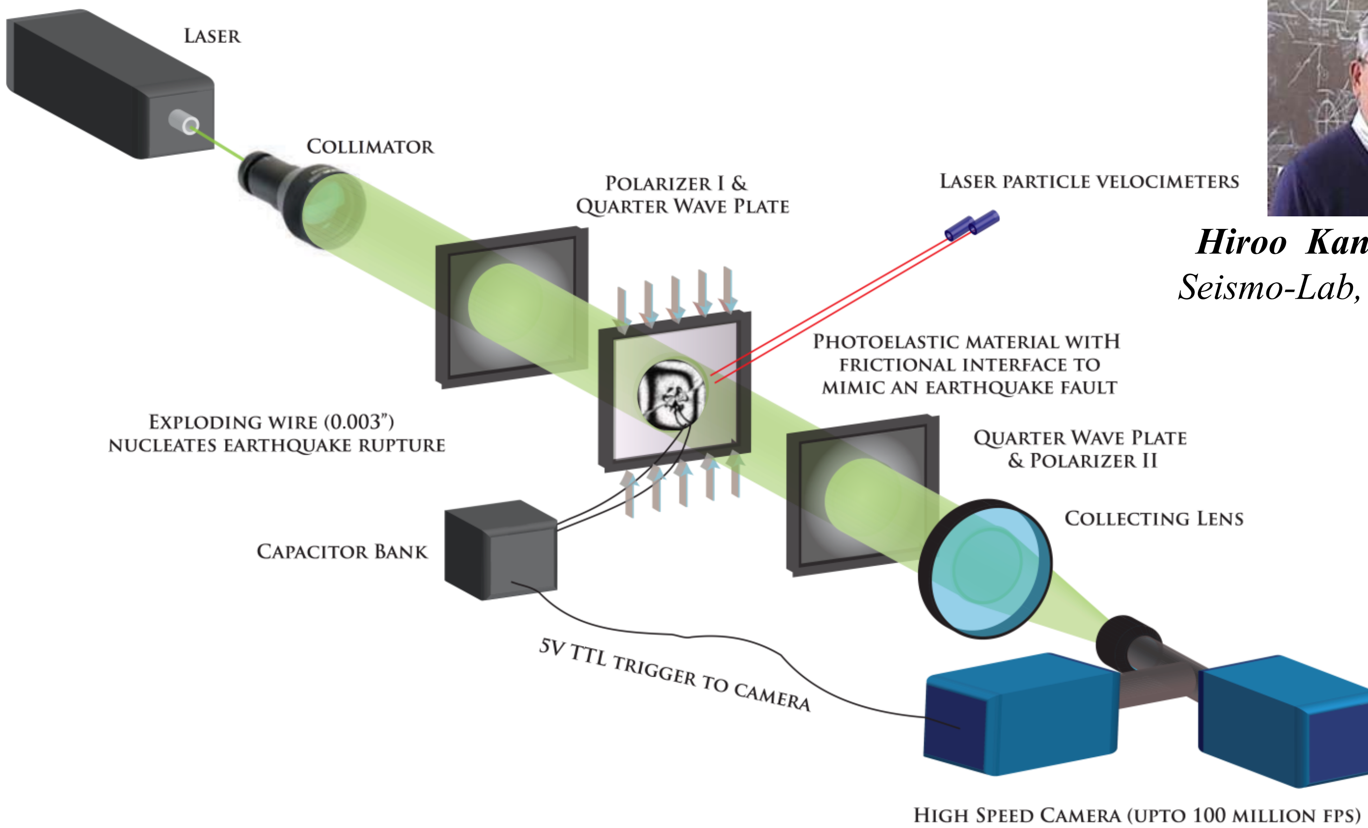
• **Rock**	→	**Photoelastic Polymer**
• **Fault**	→	**Inclined Contact Interface**
• **Tectonic stress**	→	**Far Field Load**
• **Hypocenter**	→	**Triggering Site**

Experimental setup that mimics pre-stressed faults

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



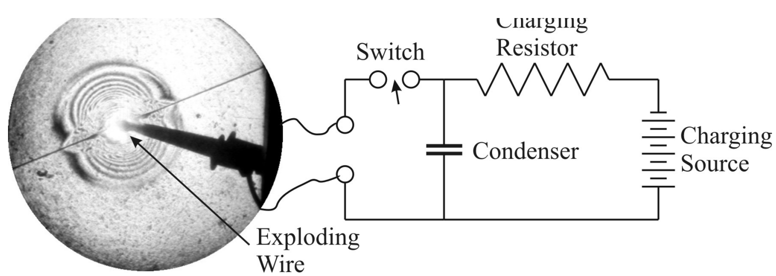




Hiroo Kanamori
Seismo-Lab, Caltech

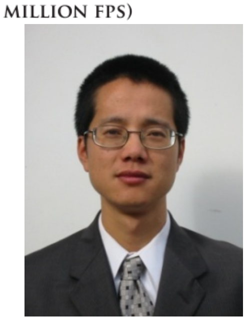
James R. Rice
SEAS/E&PS
Harvard

Exploding wire



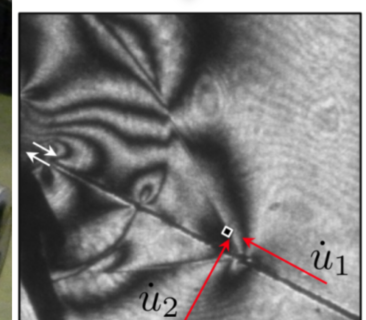
(K. Xia, AJ. Rosakis and H. Kanamori, Science 2004)

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



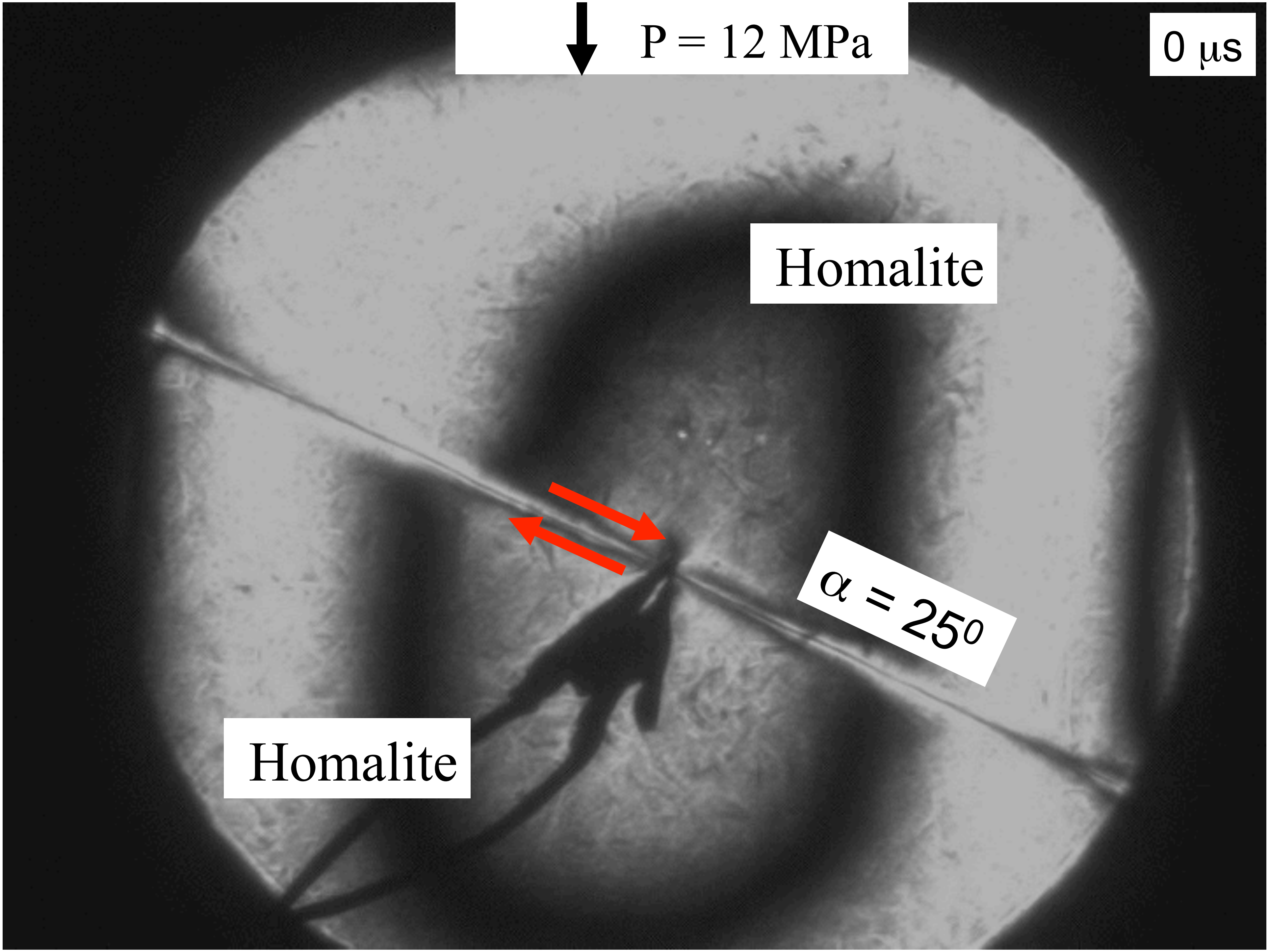
Kaiwen Xia
CE, Univ. of Toronto

The Laboratory Earthquake facility

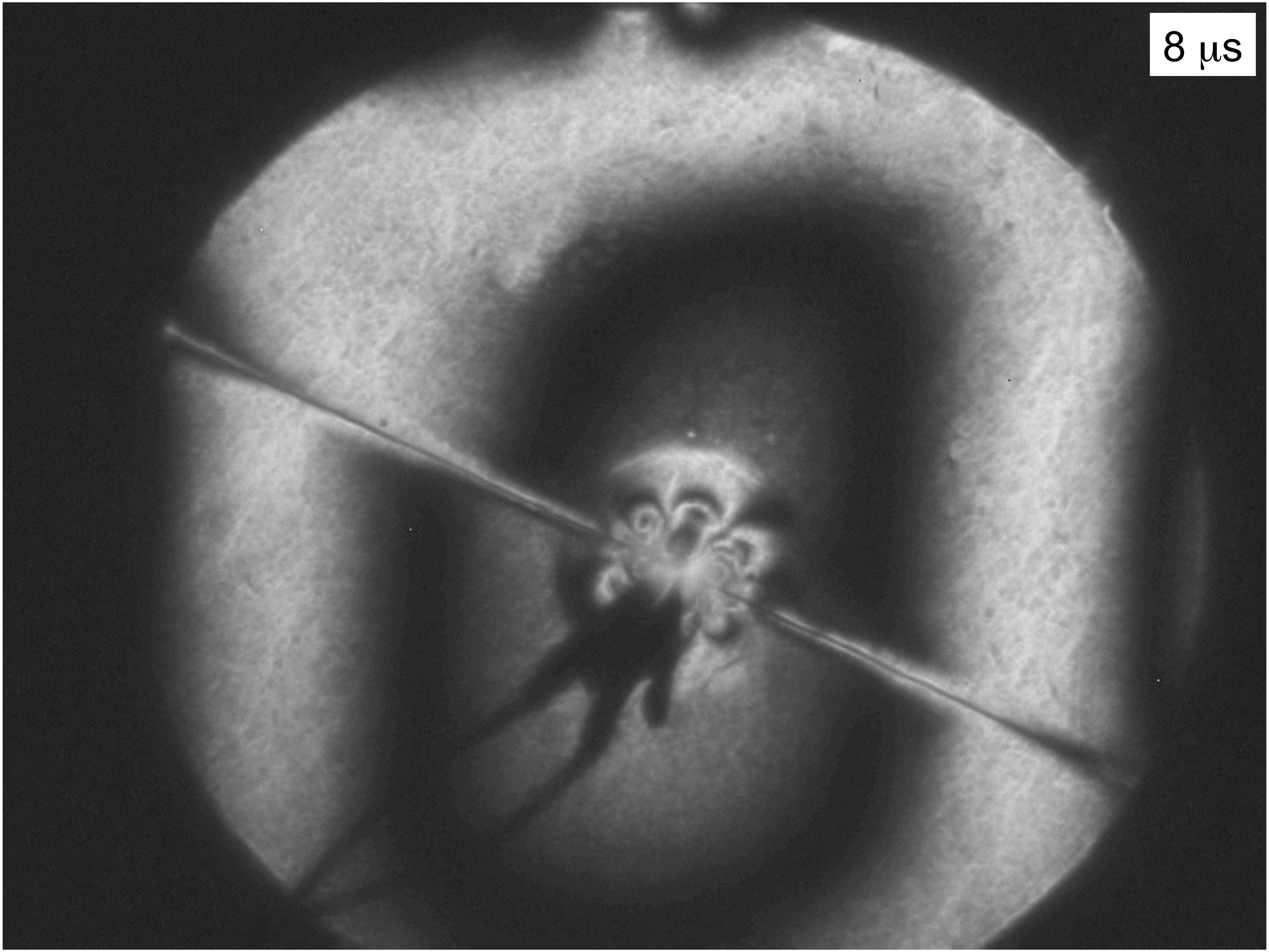


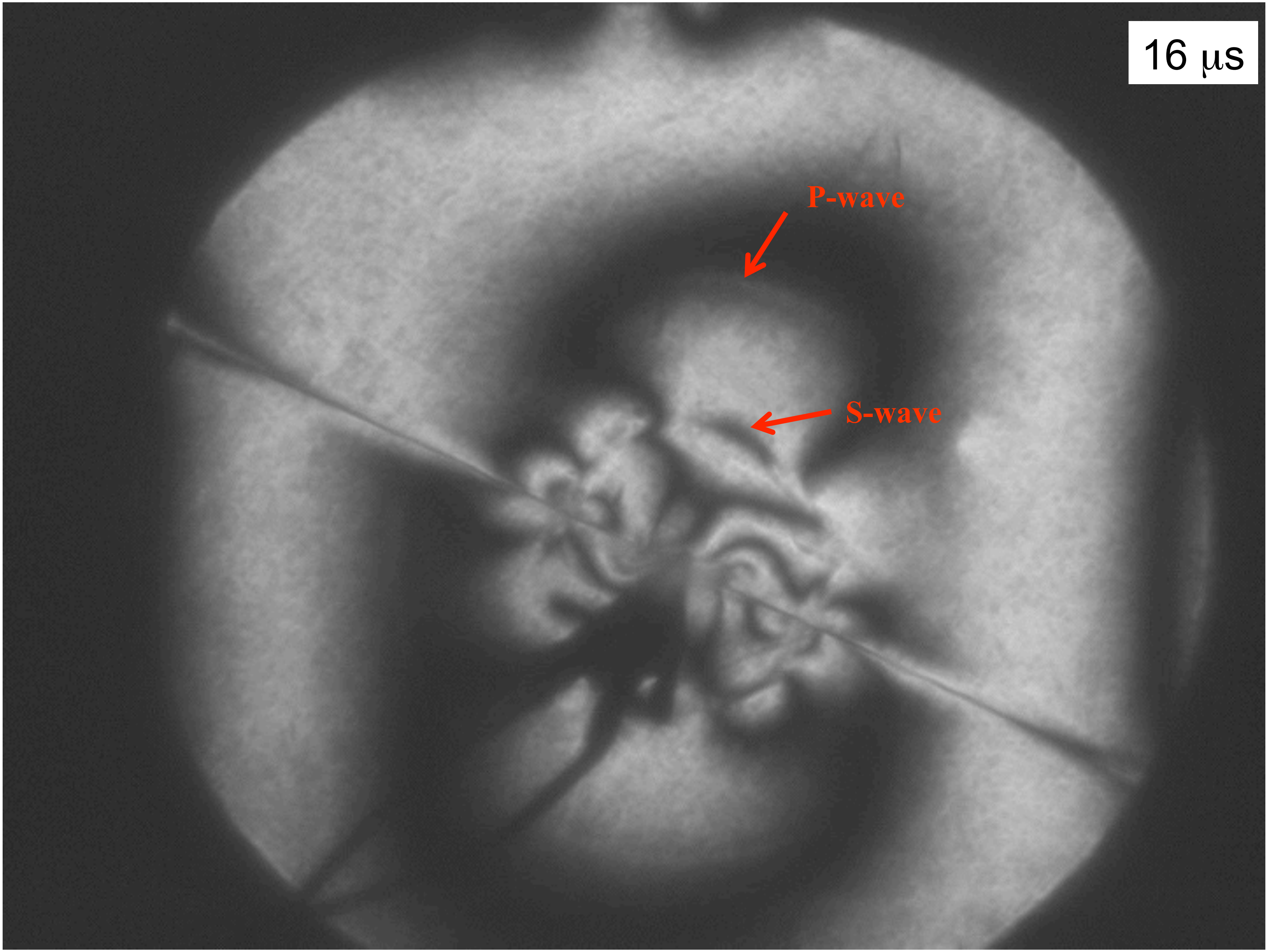
✧ ***Fiber optic heterodyne laser interferometers enable <u>continuous particle velocity records</u> at a fixed location with high temporal resolution. All three components measured.***

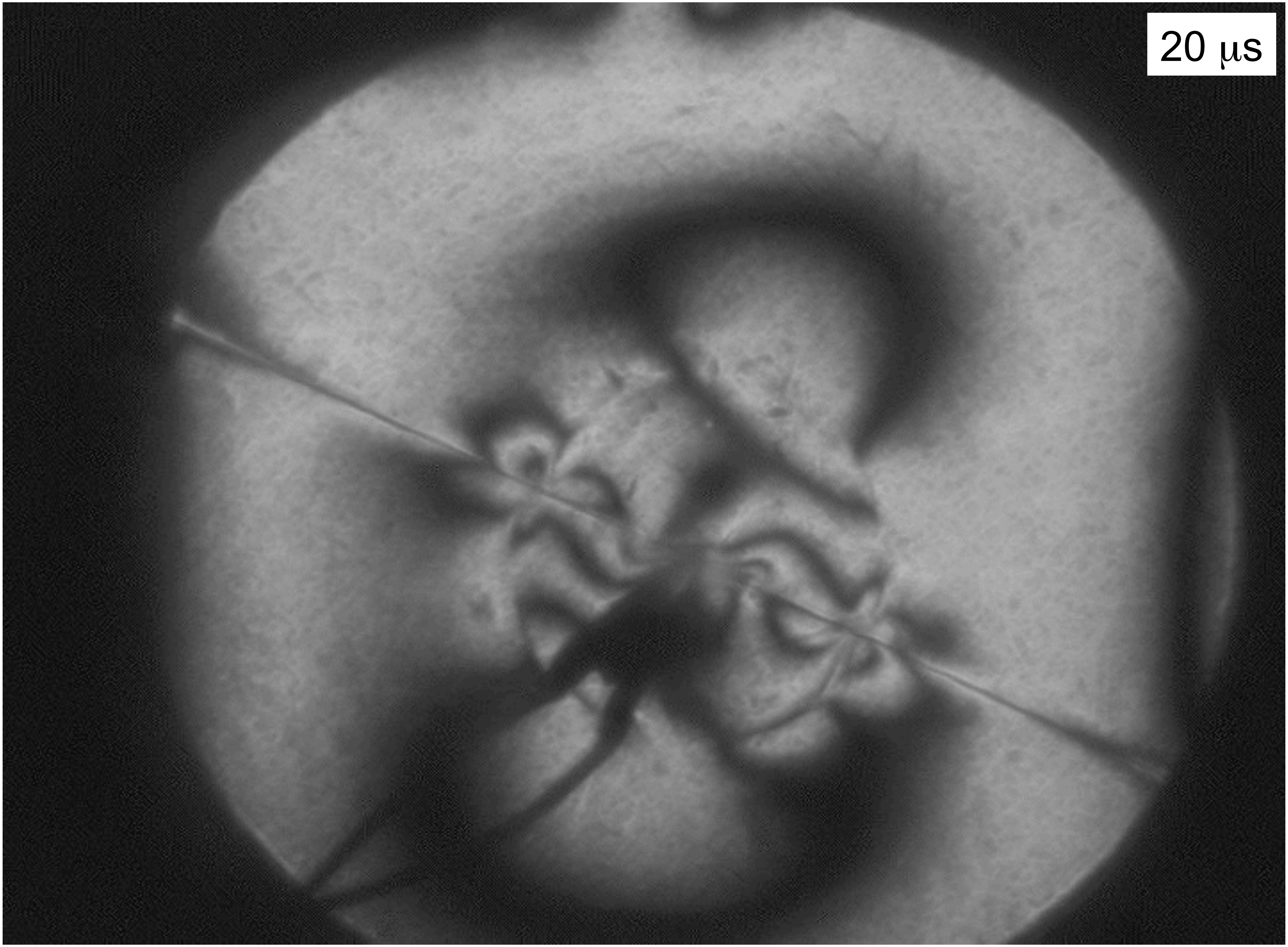
✧ ***Photo-elastic interferometer with high speed cameras: Interference fringes correspond to iso-contours of $\sigma_1 - \sigma_2 = 2\tau_{max}(x_1,x_2)$,camera operated at 1Million frames per second.***

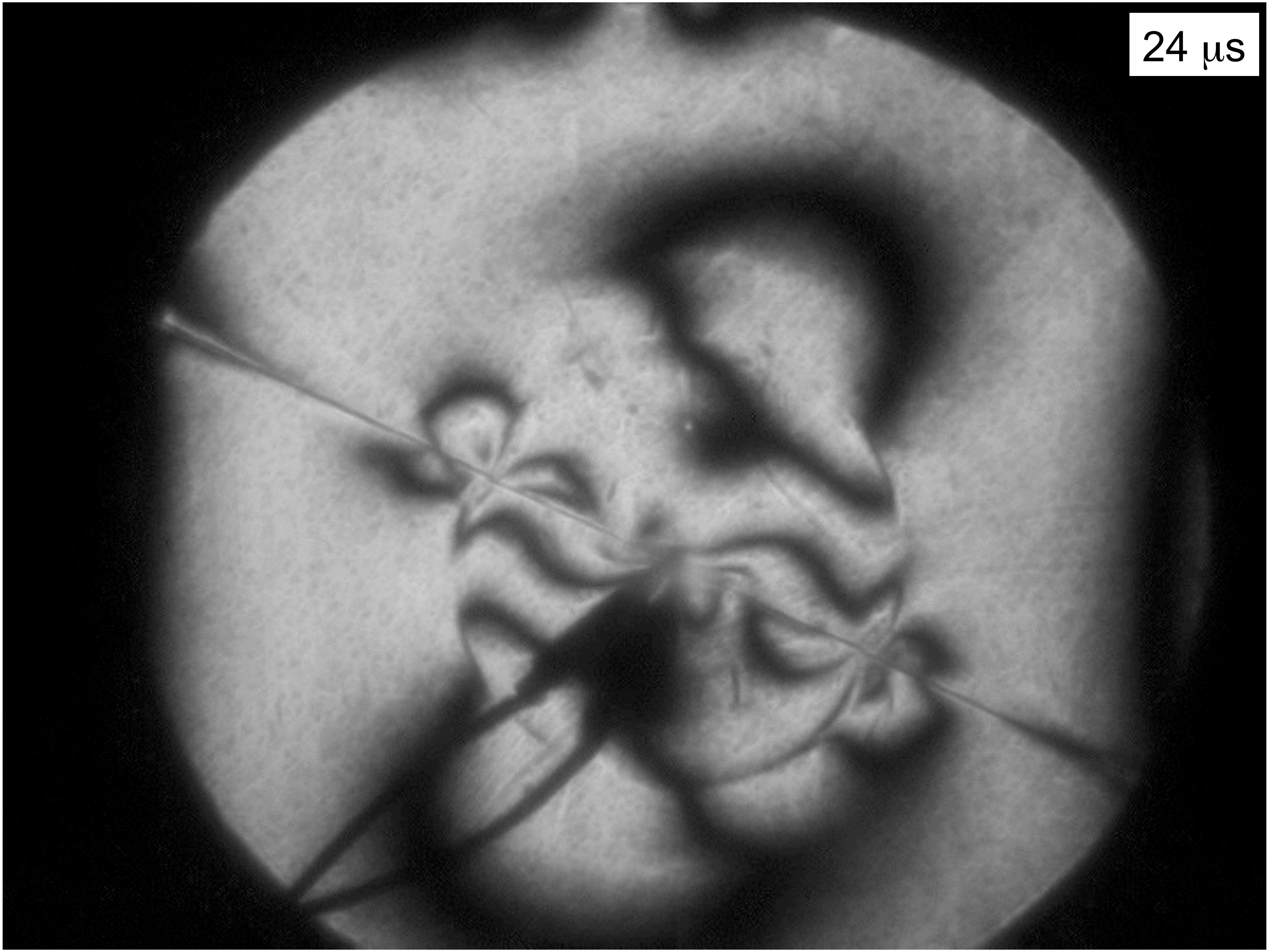


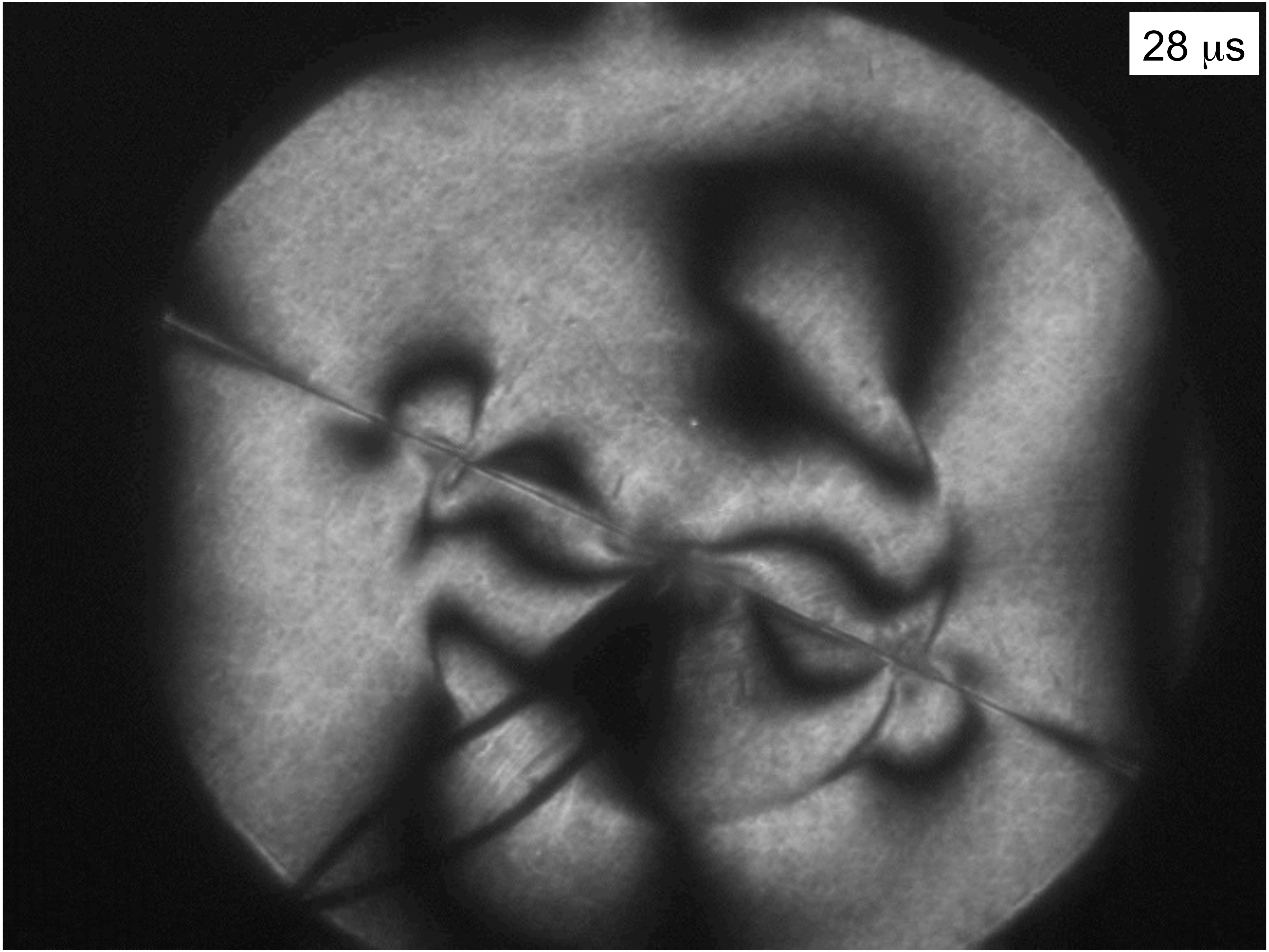
P = 12 MPa
0 μs
Homalite
α = 25⁰
Homalite

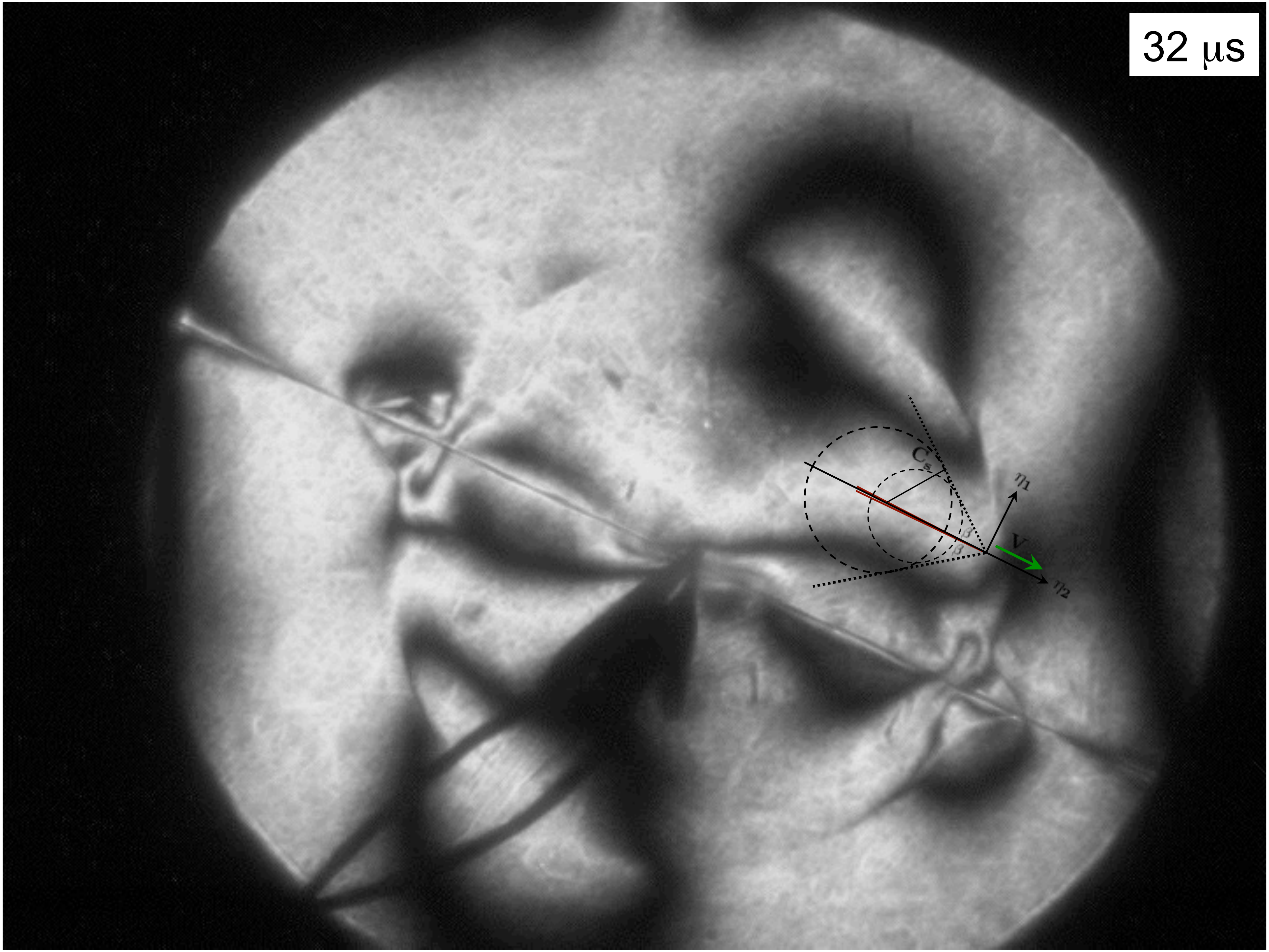

8 μs


16 μs
P-wave
S-wave

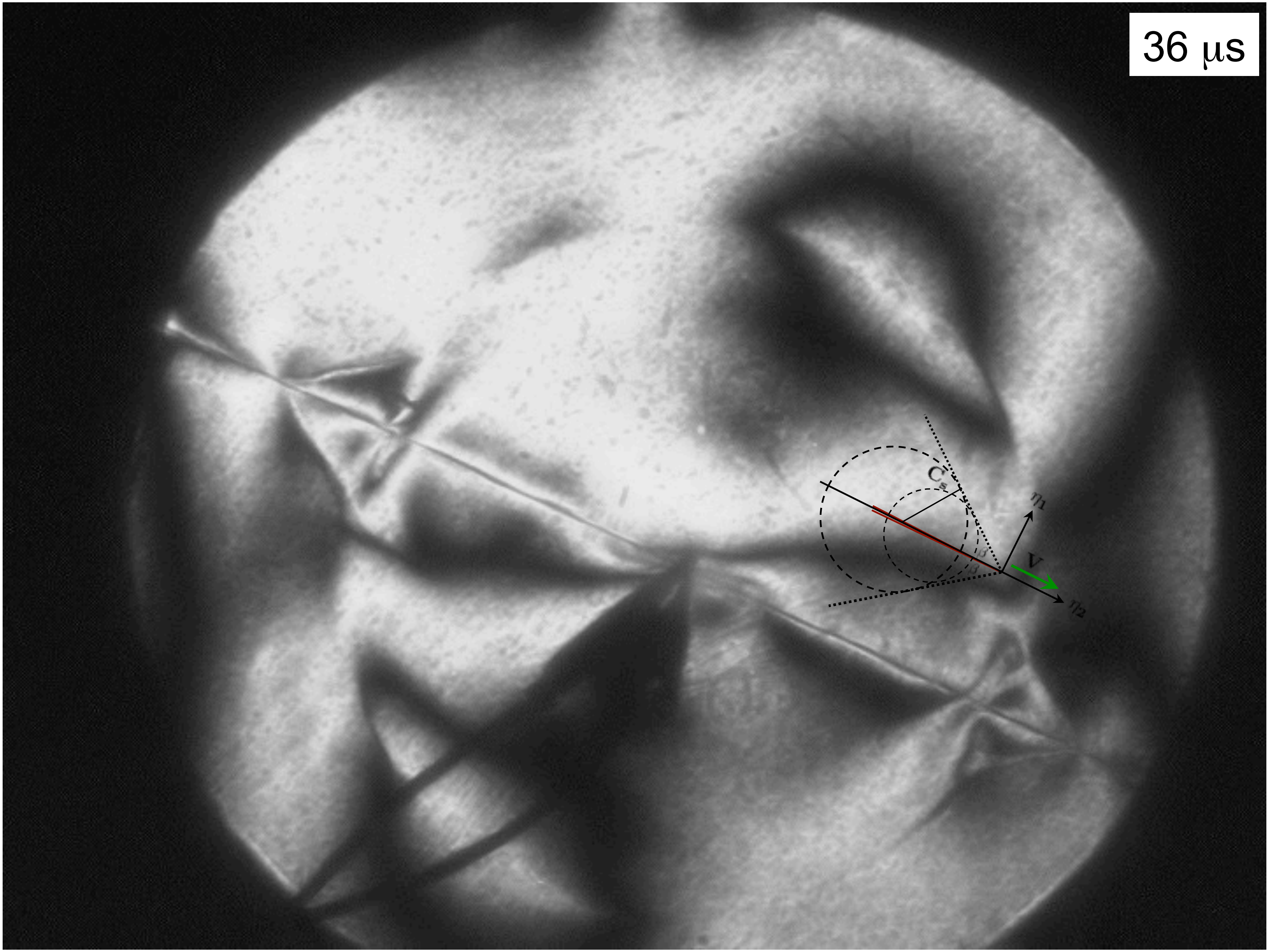

20 μs


24 μs


28 μs



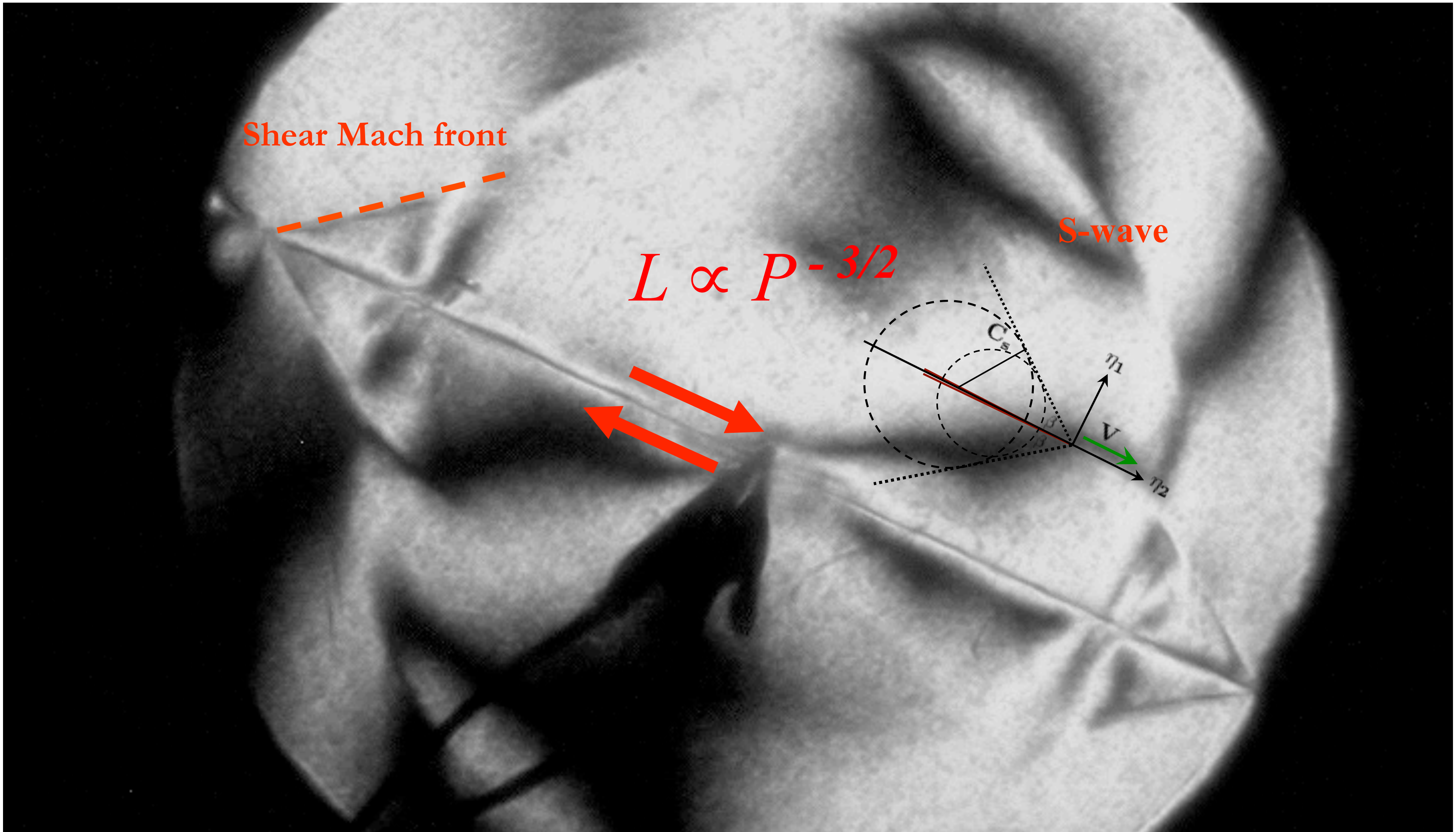
32 μs
C_s
η_1
η_2
$\mathbf{V}$
β
β


36 μs
$\mathbf{C_s}$
η_1
$\mathbf{V}$
η_2

Transition: From Sub-Rayleigh to Supershear

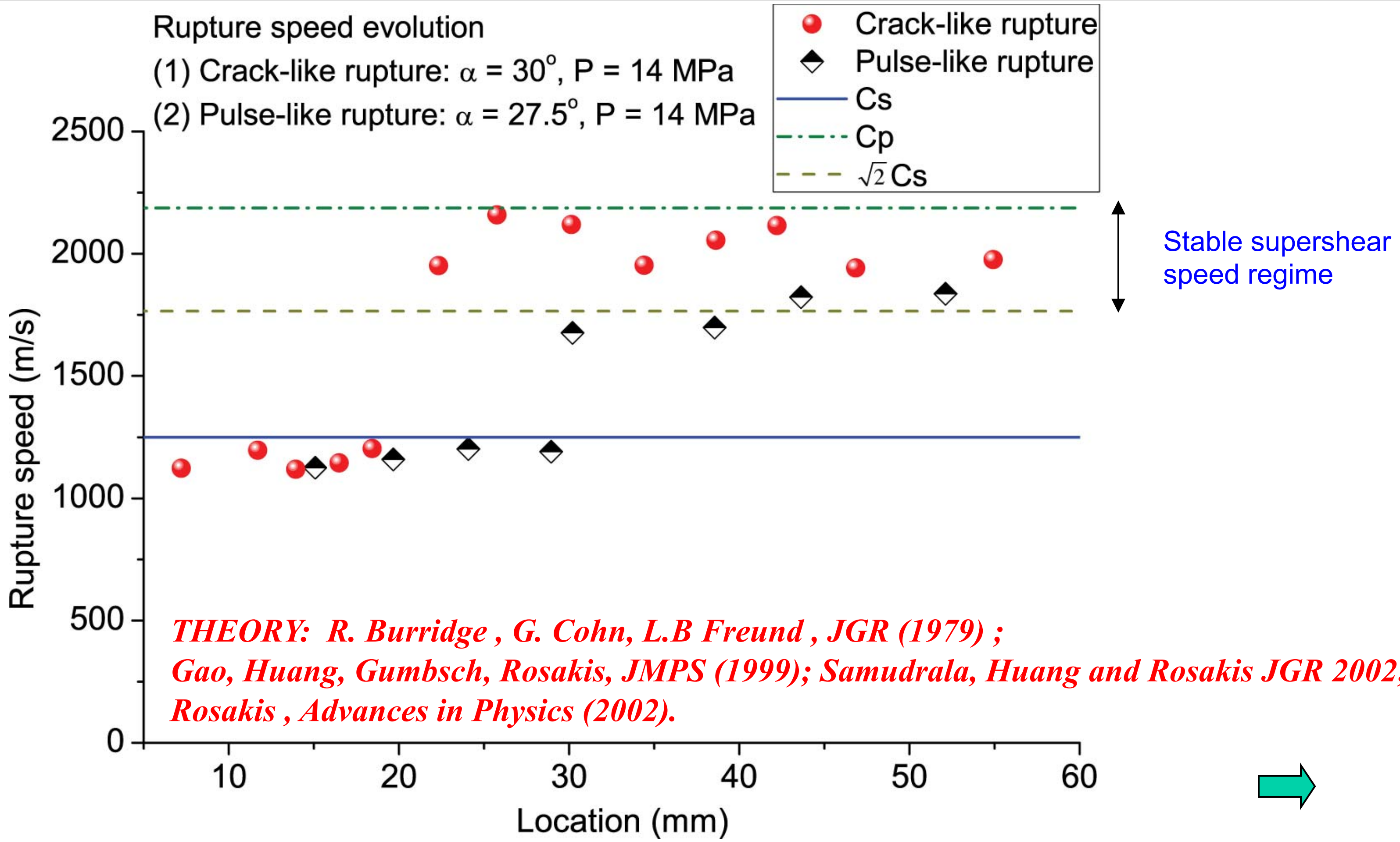
(*Xia, Rosakis and Kanamori, Science 2004*)

40 μs



R. Burridge , G. Cohn, L.B Freund "The stability of a rapid mode II shear crack with finite cohesive traction", JGR (1979) VOL. 85 NO. B5, 2210 – 2222

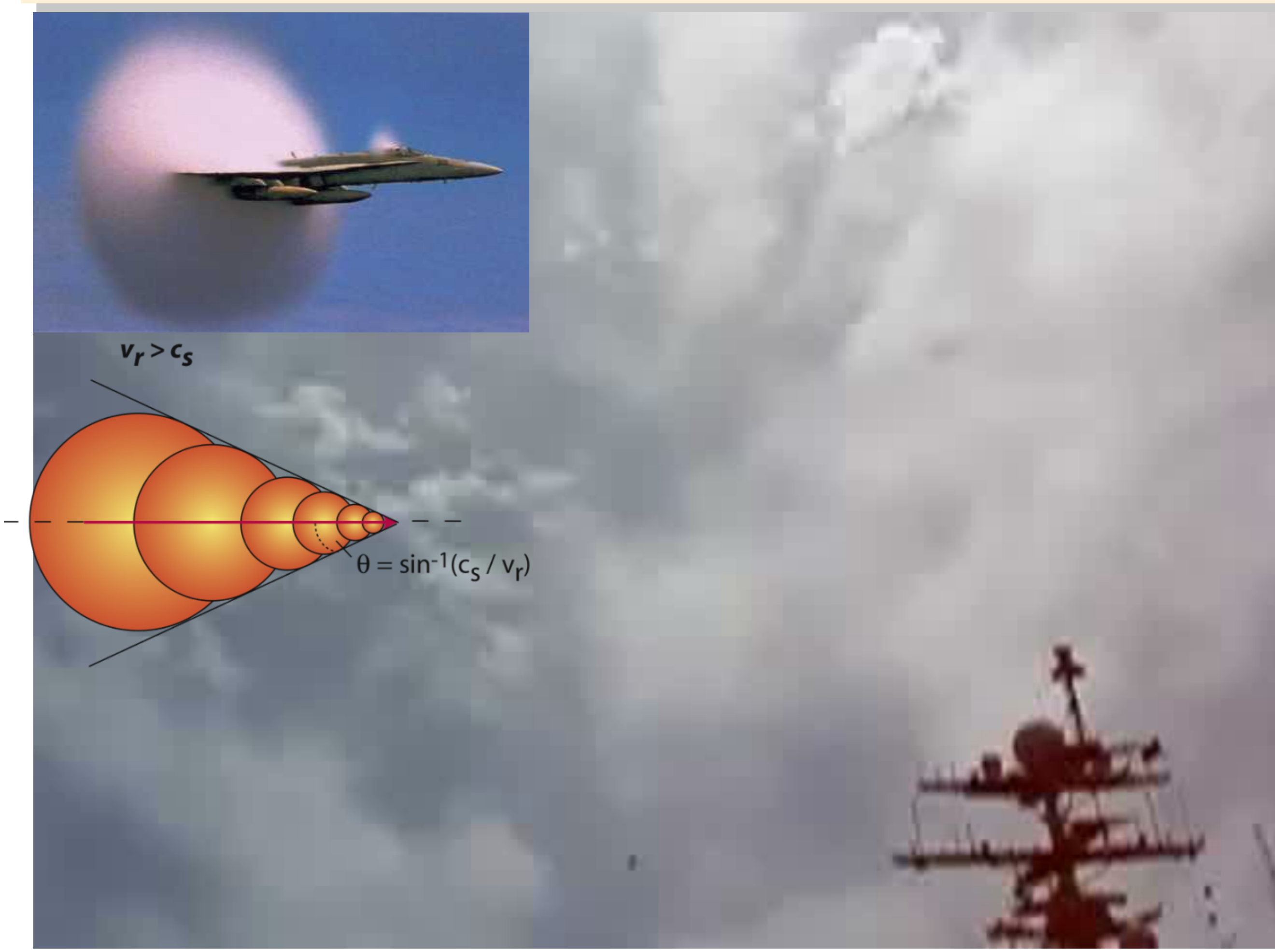
Evolution of Rupture Speed for Supershear Ruptures



THEORY: R. Burridge , G. Cohn, L.B Freund , JGR (1979) ;
Gao, Huang, Gumbsch, Rosakis, JMPS (1999); Samudrala, Huang and Rosakis JGR 2002;
Rosakis , Advances in Physics (2002).

1. $\left[\sqrt{2}c_s, c_p\right]$ is the stable supershear rupture speed regime
2. Higher interface pre-stress results in higher super-shear speeds

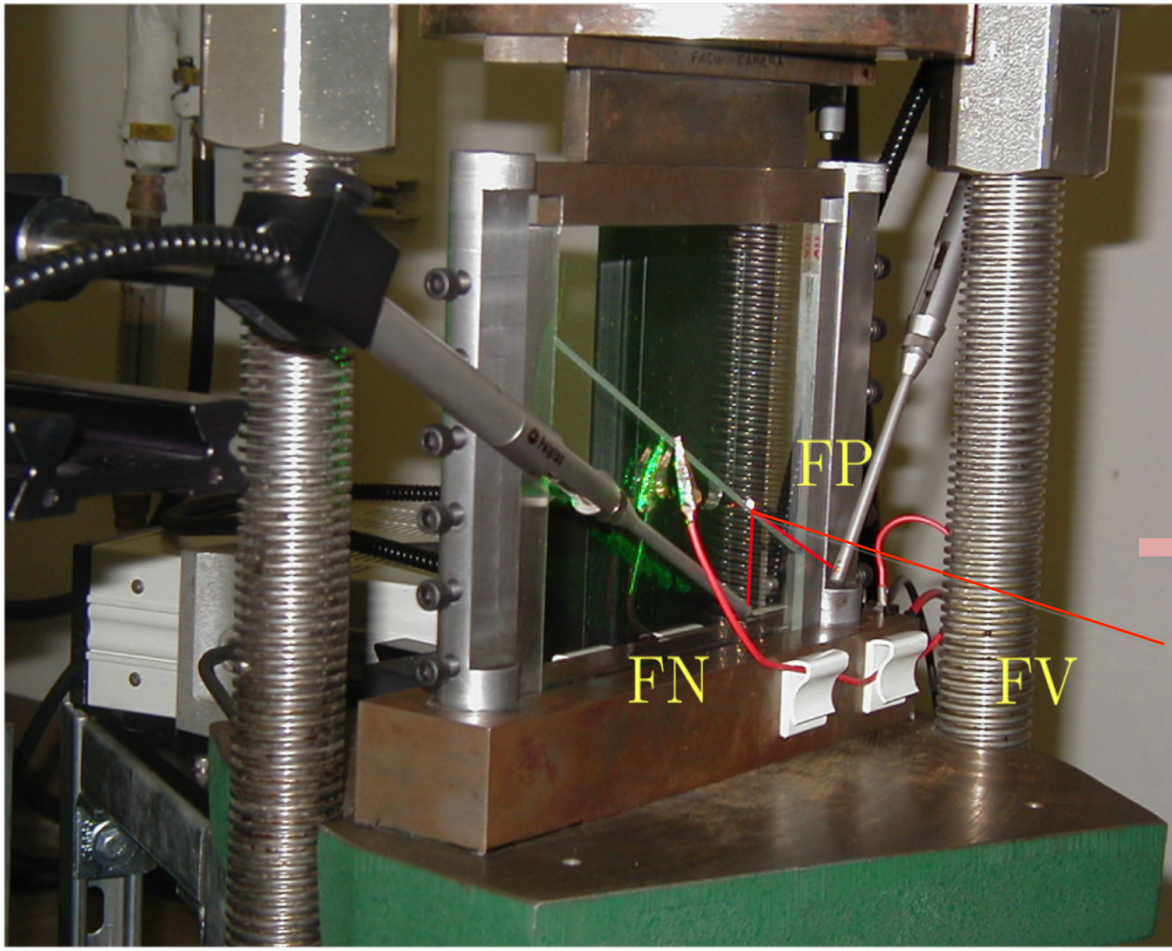
How does a Mach front sound?

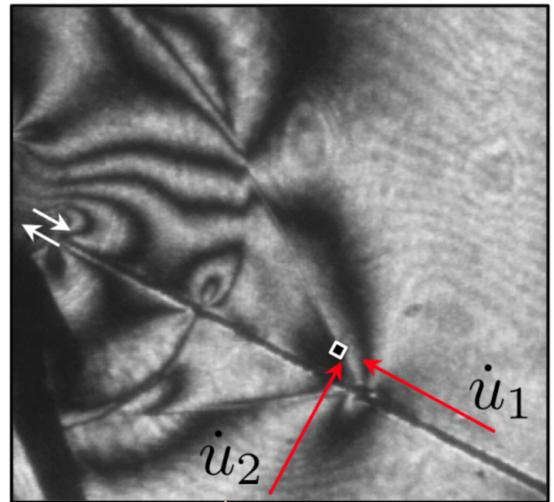


• In this example from Aeronautics , Mach Fronts correspond to sudden (audible) Jumps in Pressure while in earthquakes they are Jumps in Shear stress.

•We want to study the effect of Shear "Mach Fronts" generated by super-shear ruptures

Laser Interferometers to Record Ground Shaking in both Super-shear and Sub-Rayleigh Ruptures

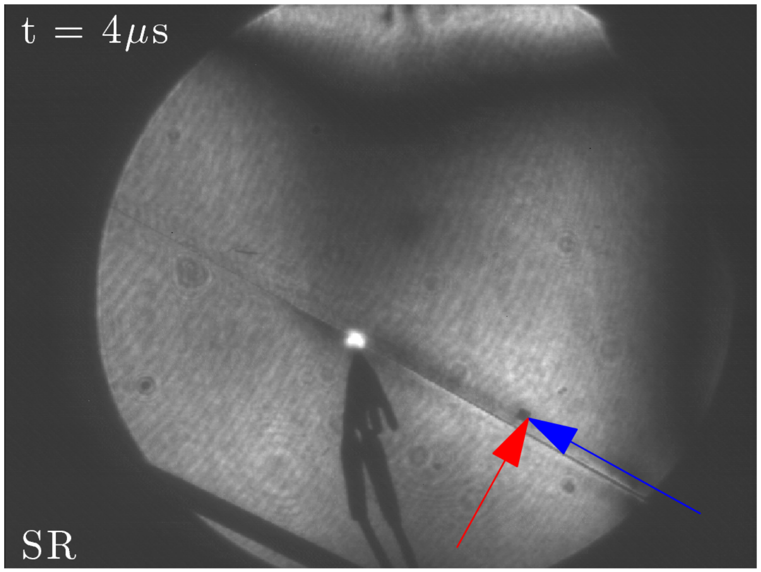


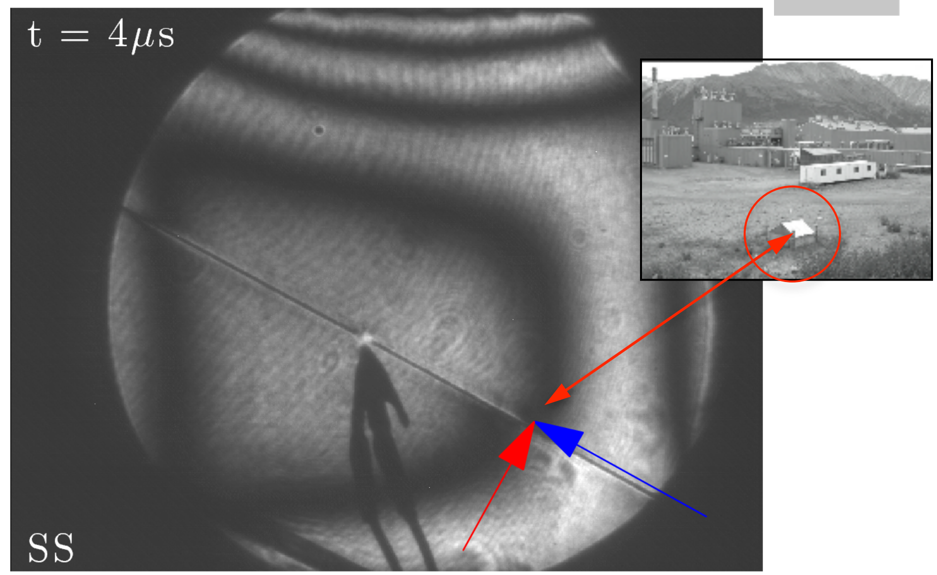


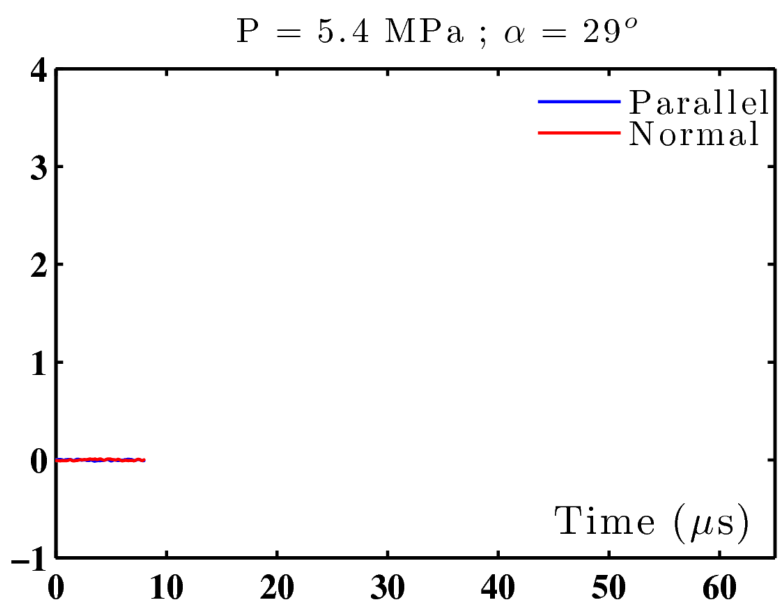
Simultaneous Pair of Fault Normal & Fault Parallel Velocity Measurements

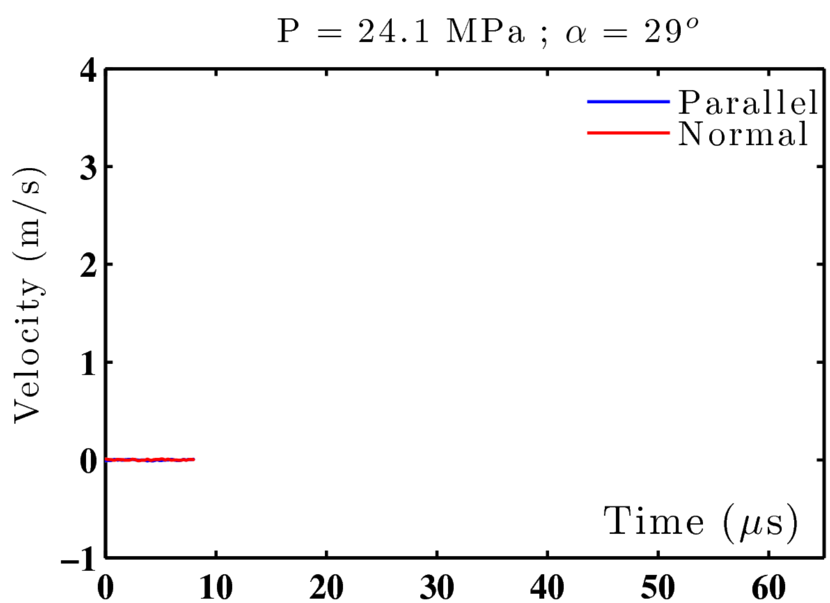
Mello, Bhat, Rosakis and Kanamori, *Tectonophysics, Special Volume on Supershear 2010*

FP and FN Ground Velocity histories for a Sub-Rayleigh and a Supershear Rupture (station, north of Fault in compressive side)

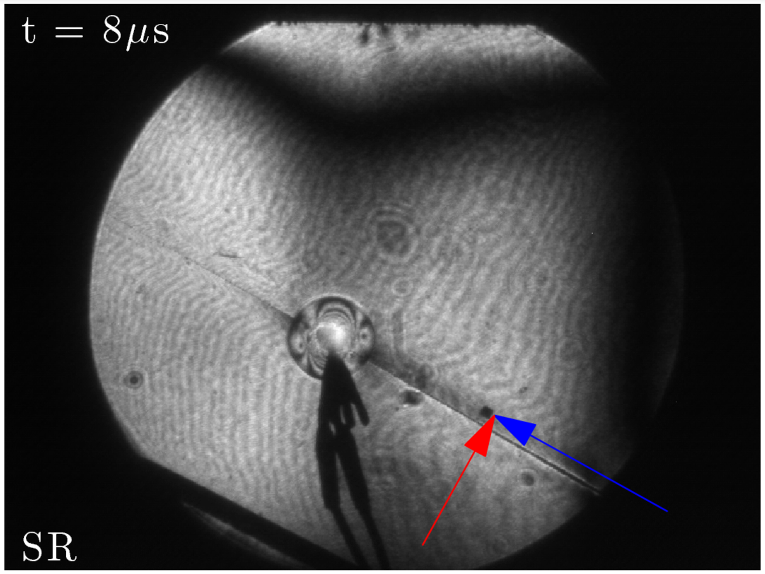


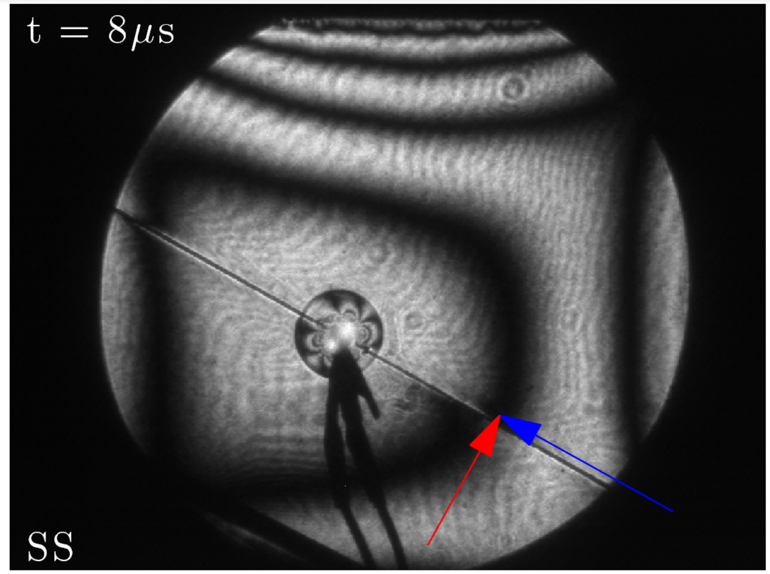




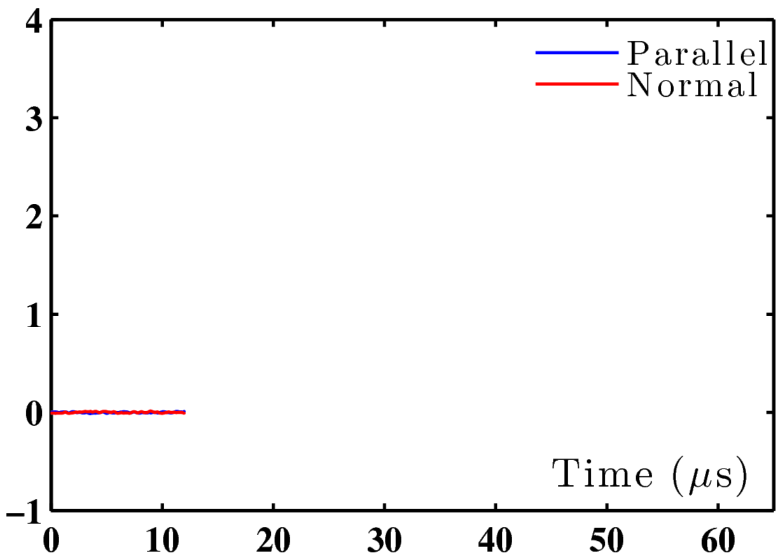


FP and FN Ground Velocity histories for a Sub-Rayleigh and a Supershear rupture

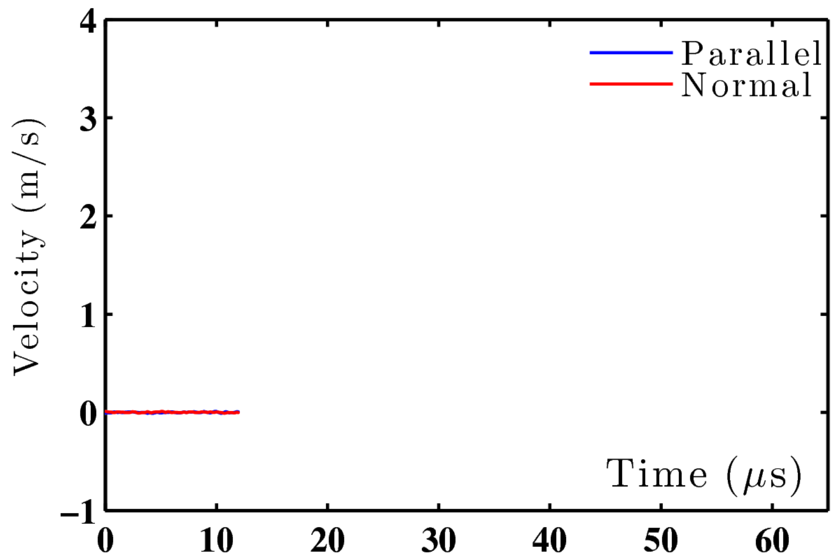




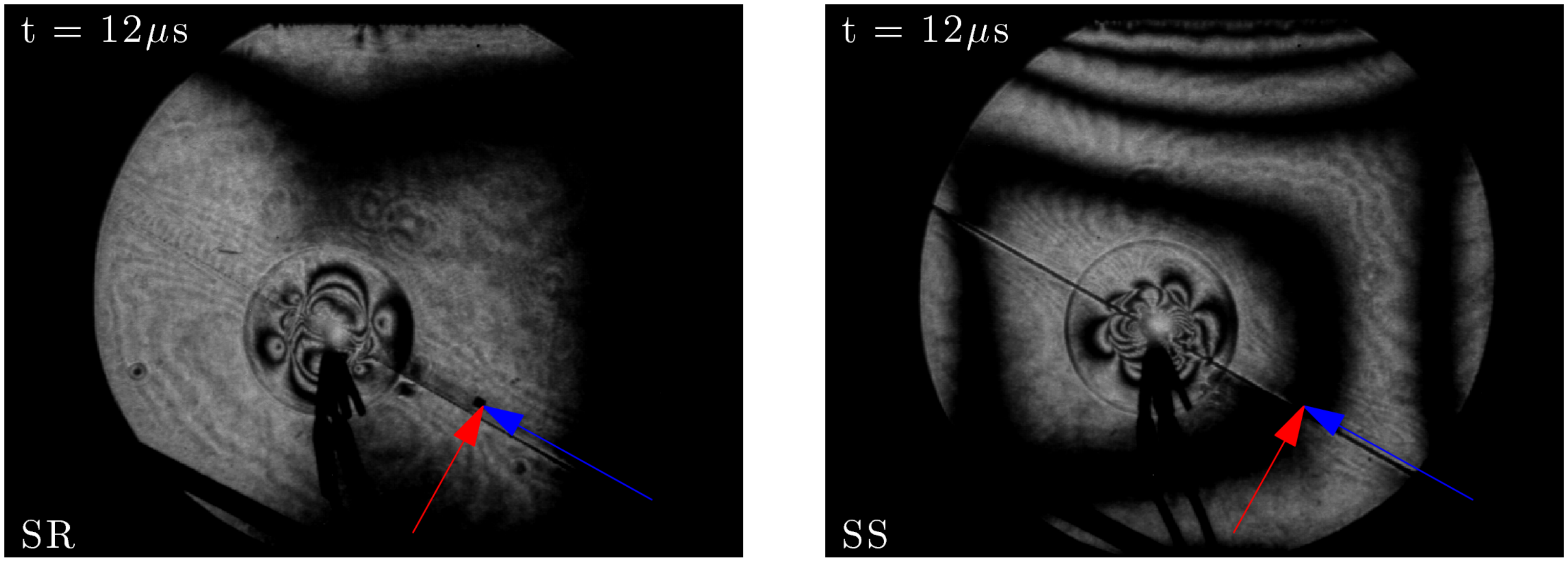
P = 5.4 MPa ; α = 29^o

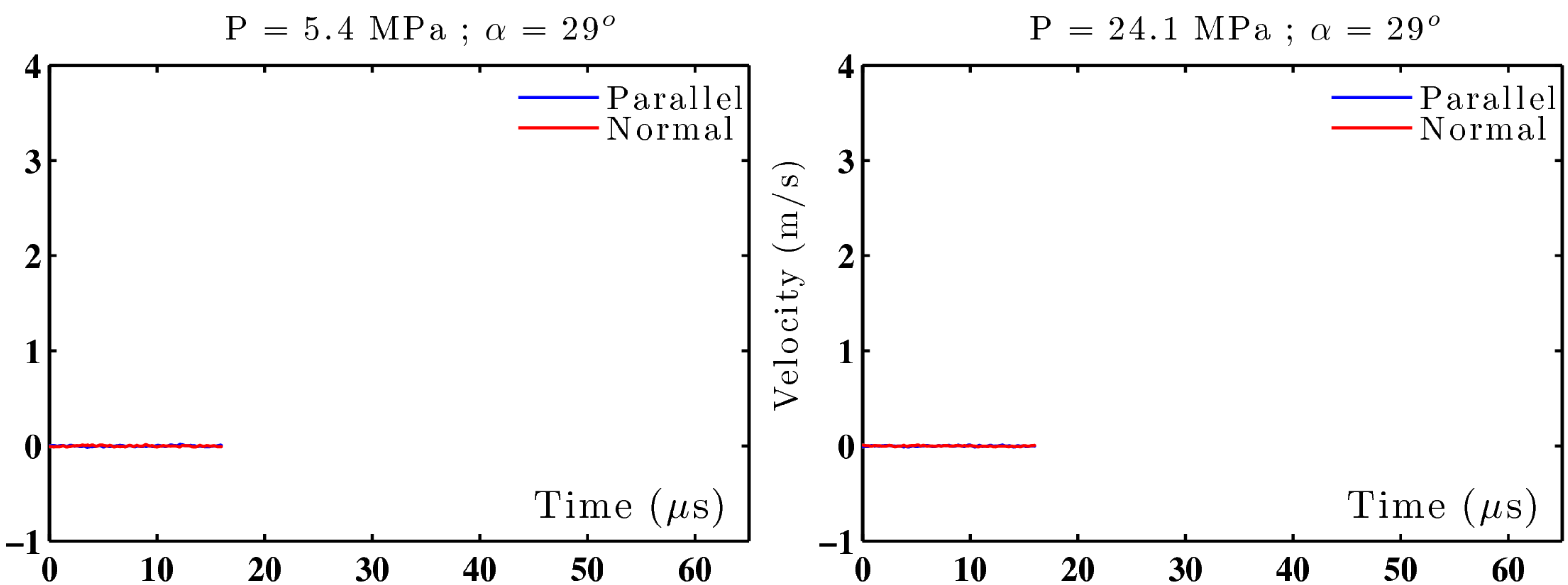


P = 24.1 MPa ; α = 29^o

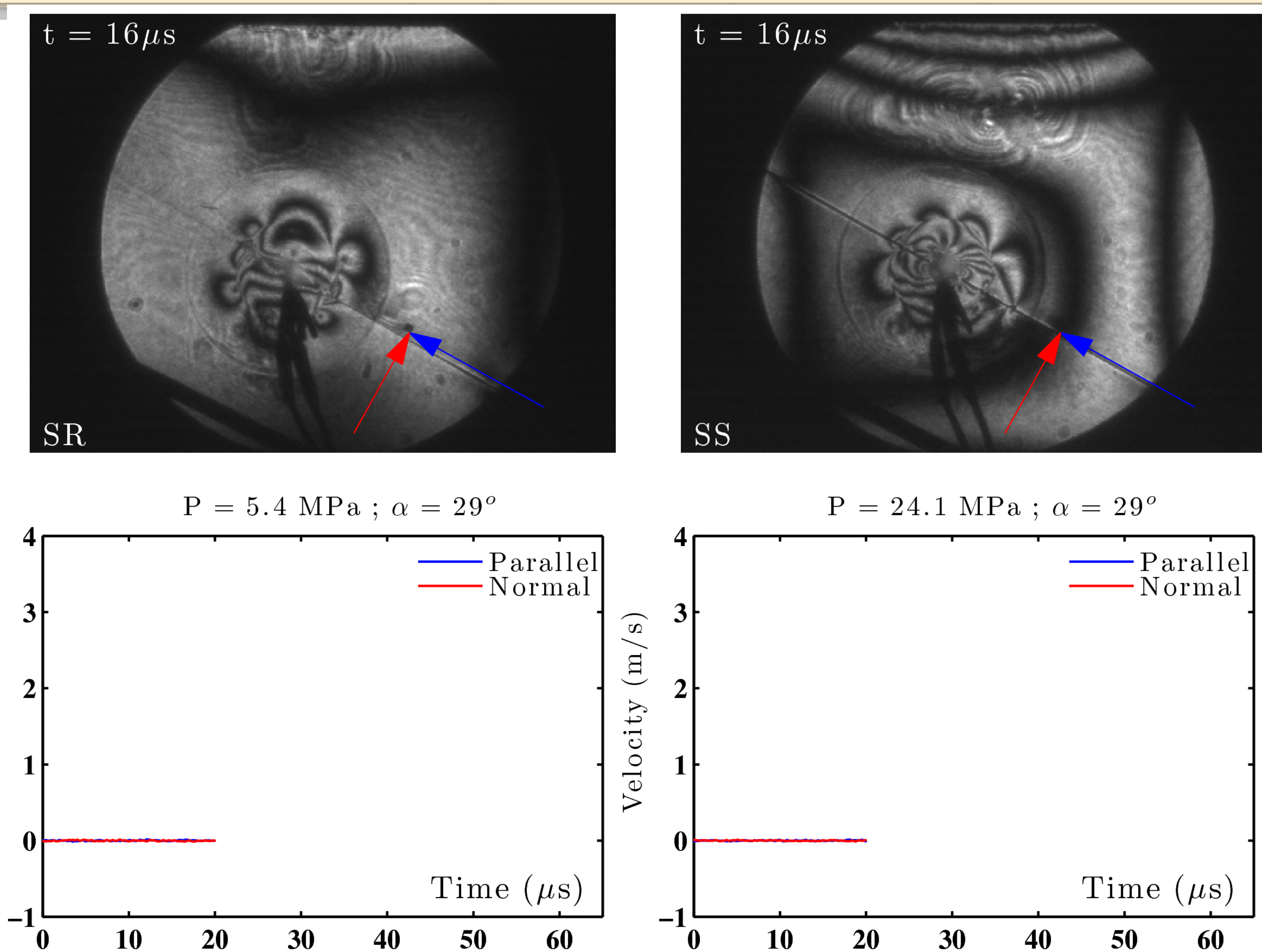


FP and FN Ground Velocity histories for a Sub-Rayleigh and a Supershear rupture

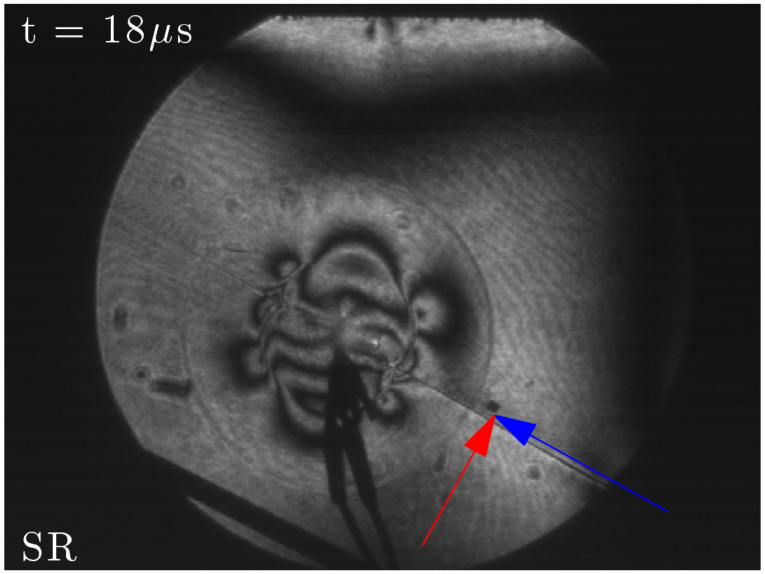


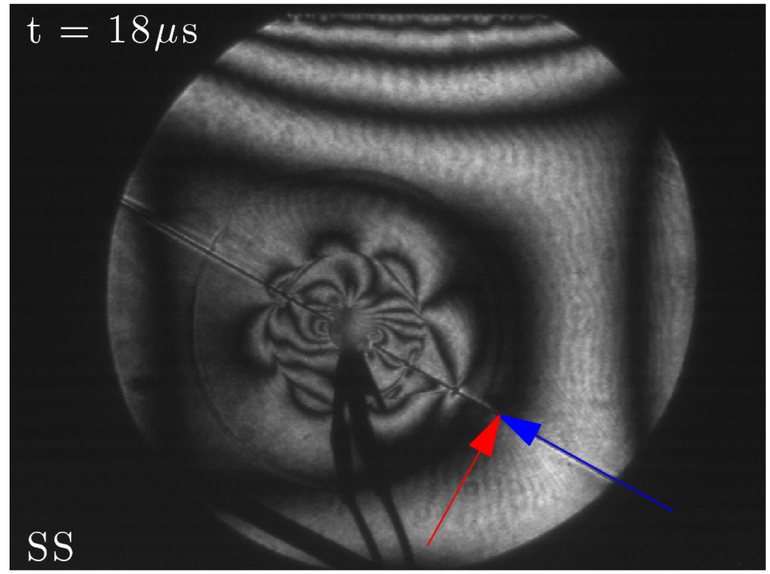


FP and FN Ground Velocity histories for a Sub-Rayleigh and a Supershear Rupture

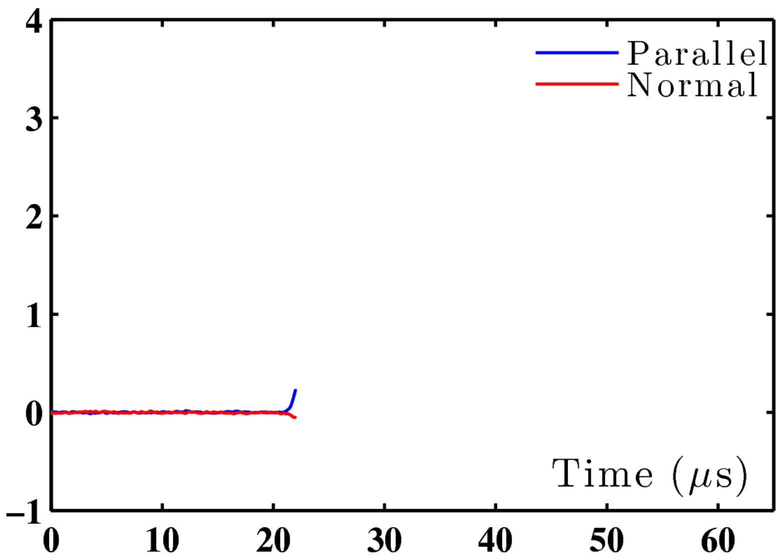


FP and FN Ground Velocity histories for a Sub-Rayleigh and a Supershear Rupture

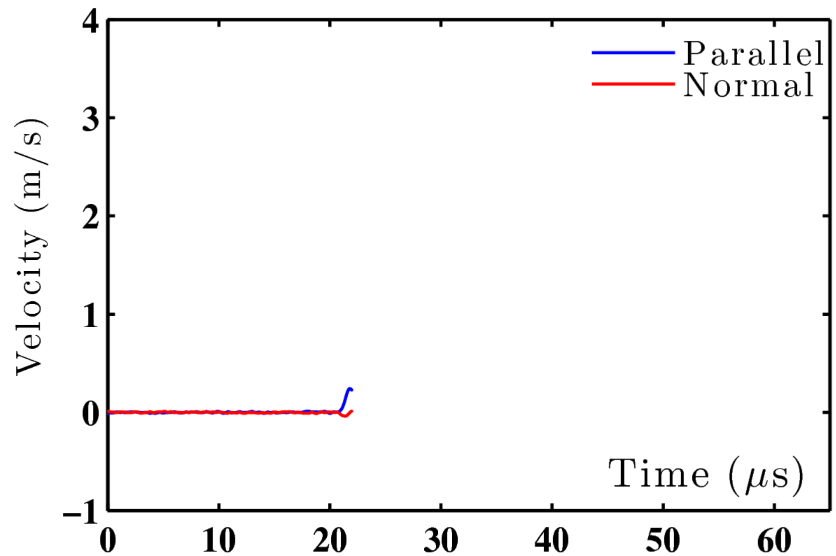




P = 5.4 MPa ; $\alpha = 29^o$



P = 24.1 MPa ; $\alpha = 29^o$



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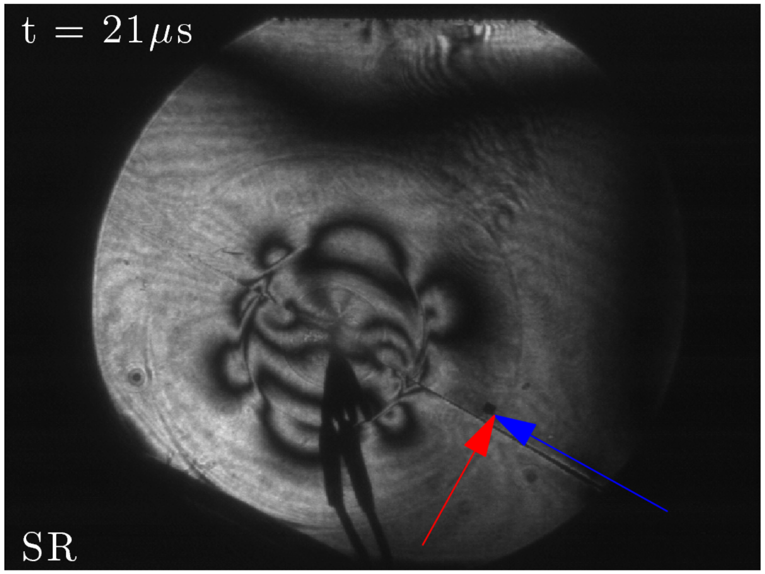

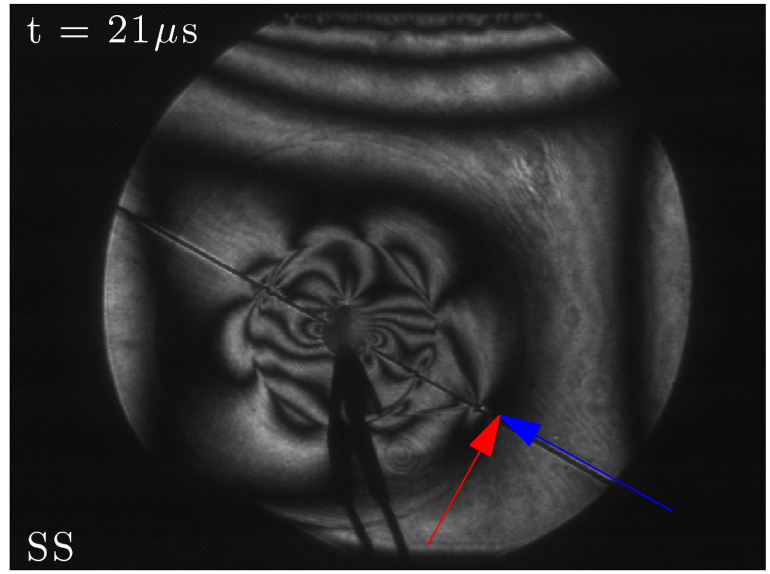

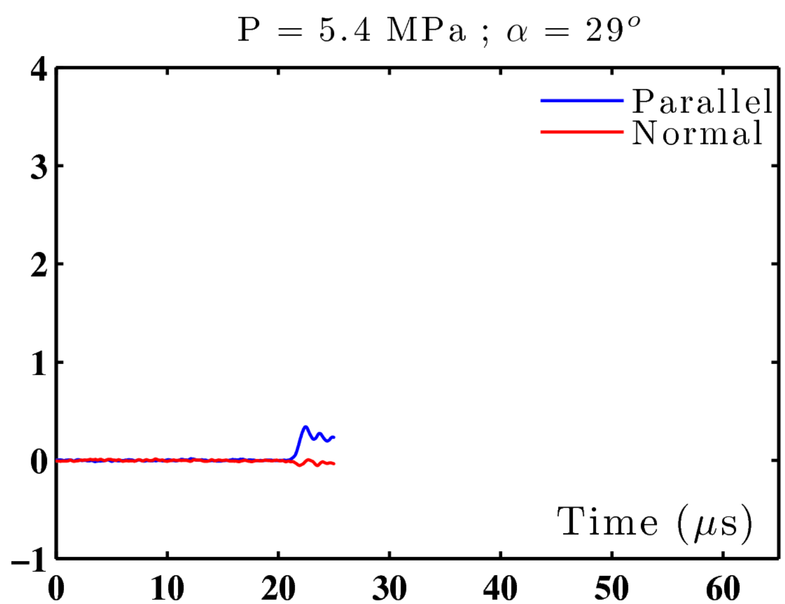

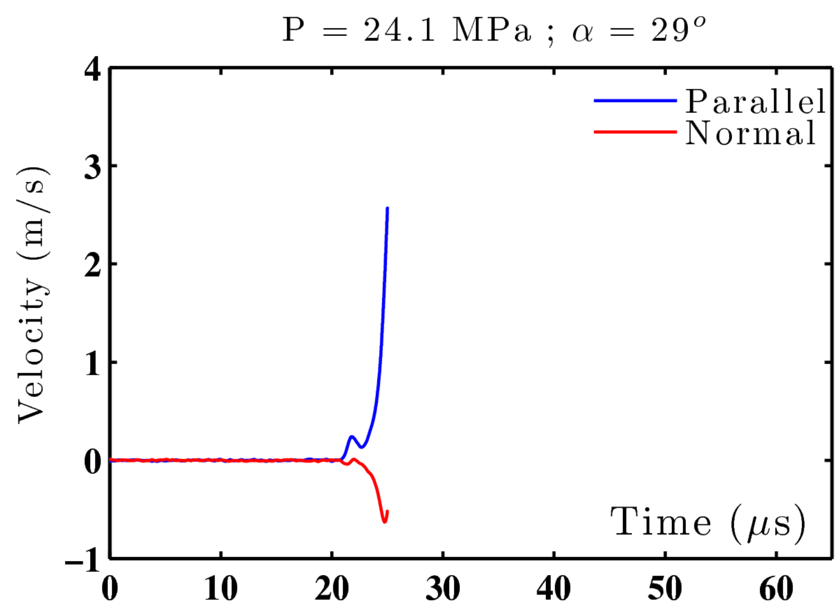

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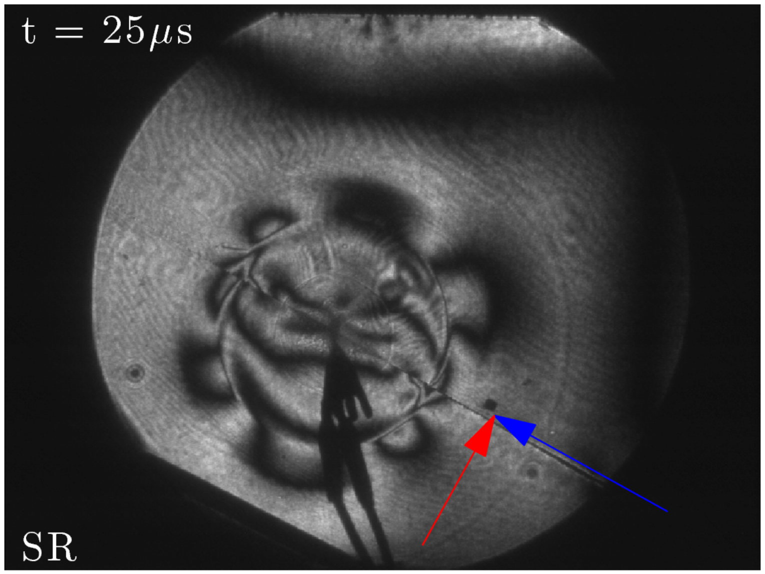
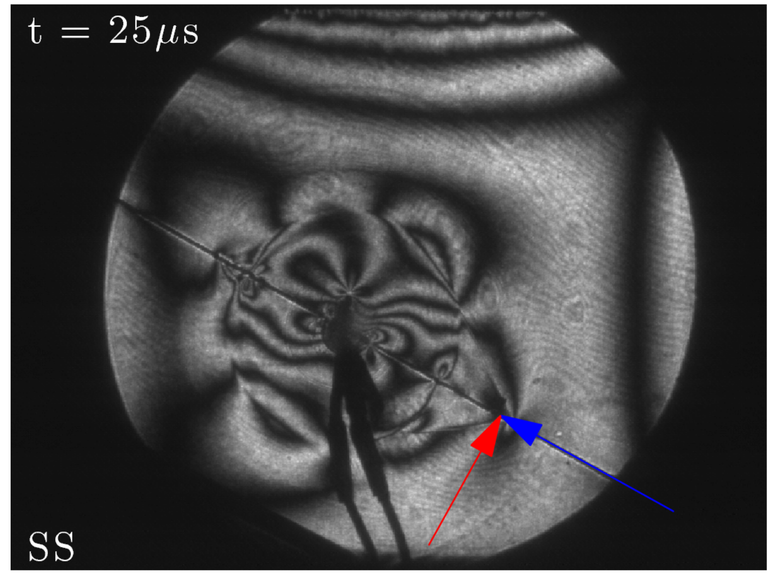
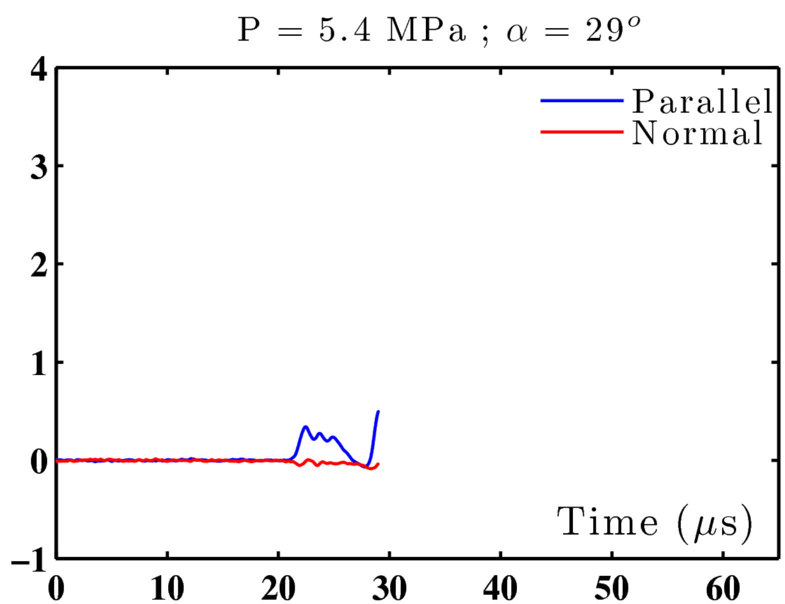
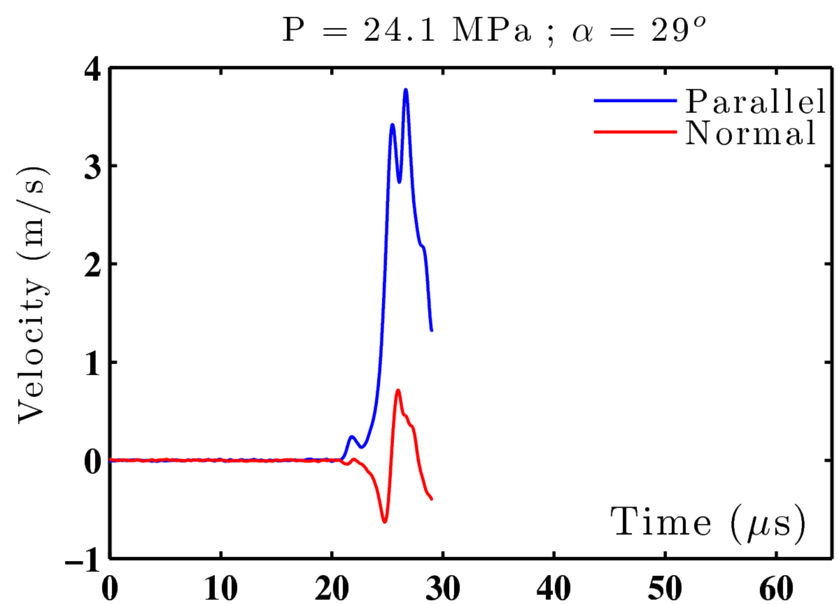
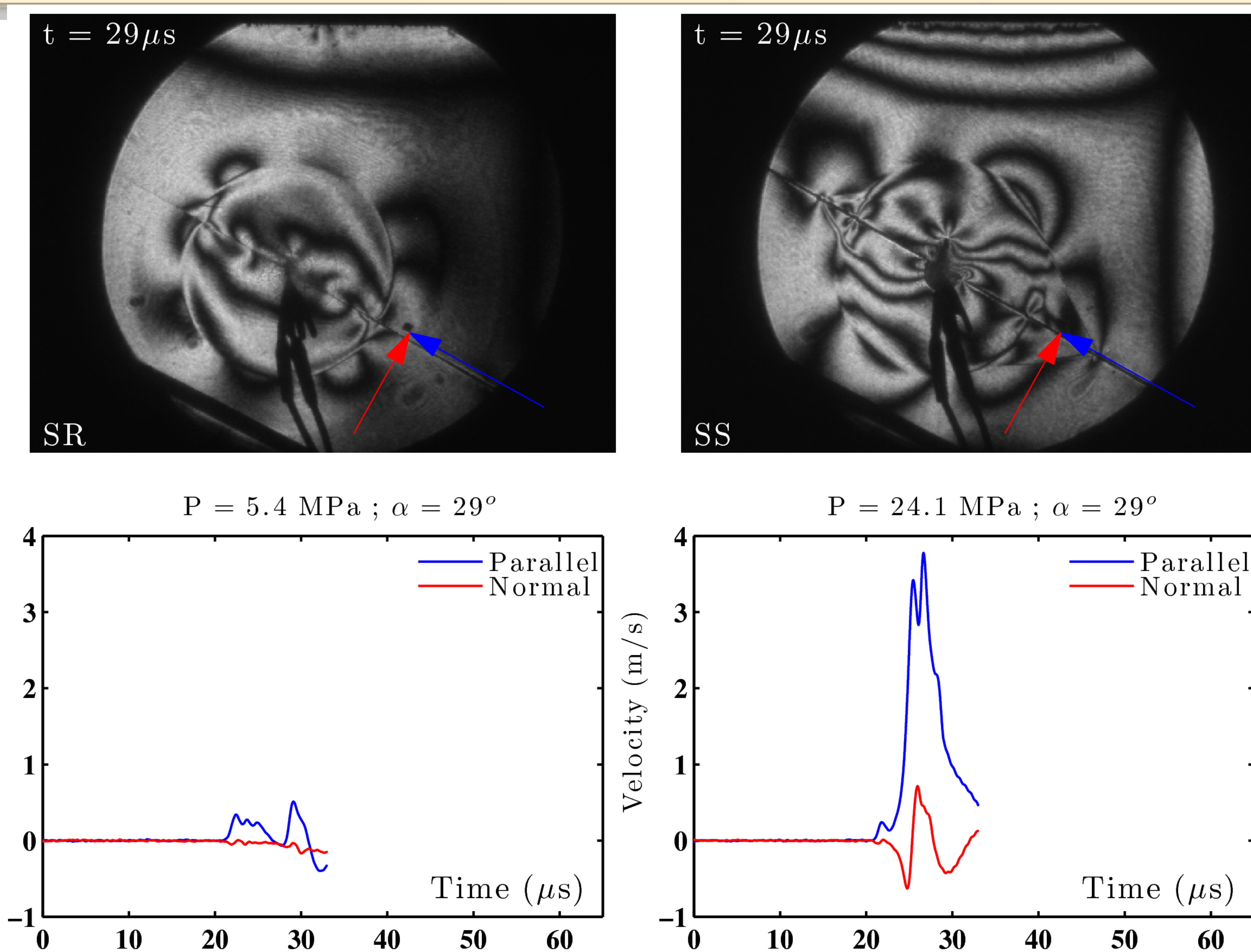








FP and FN Ground Velocity histories for a Sub-Rayleigh and a Supershear Rupture



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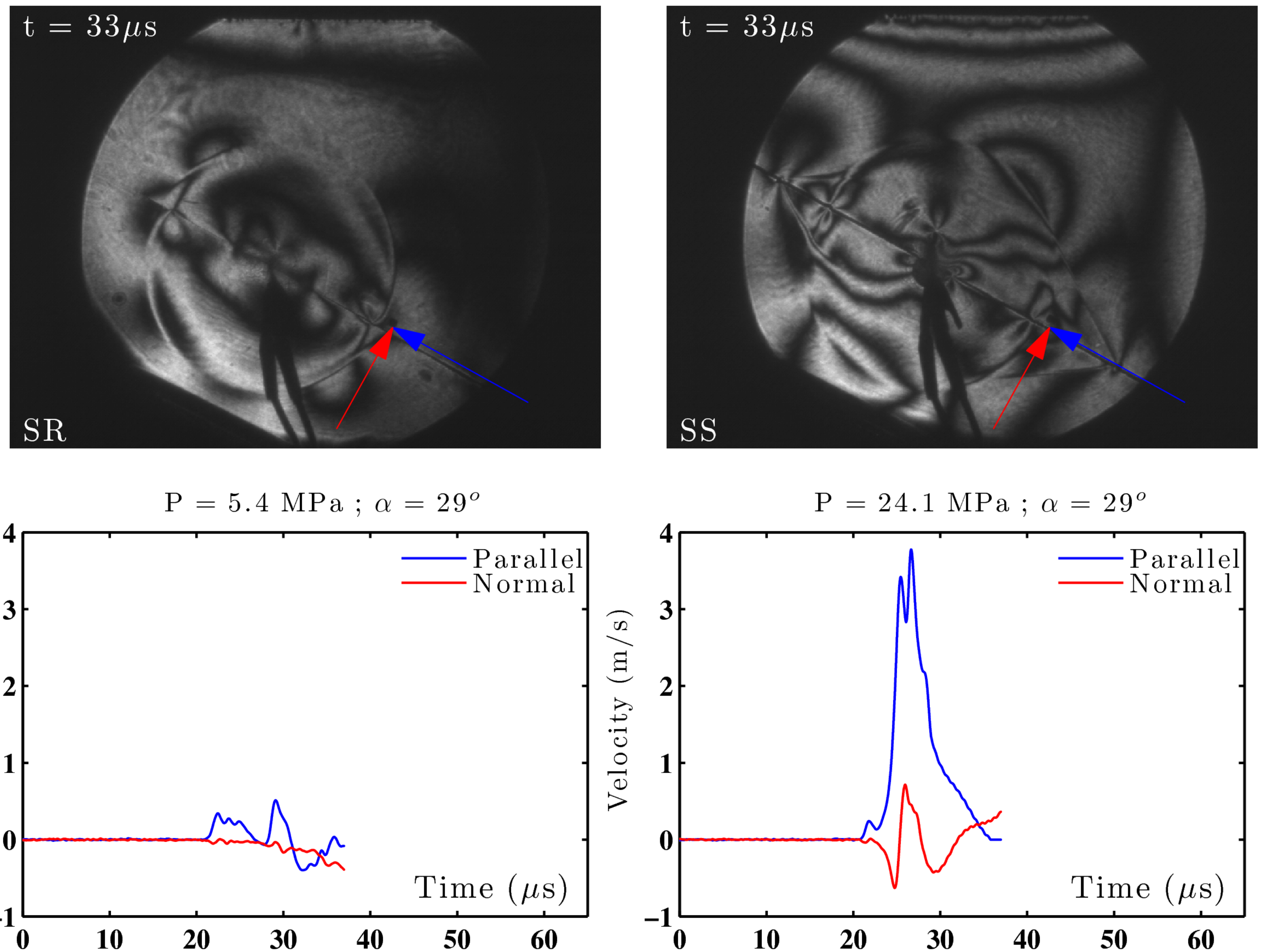
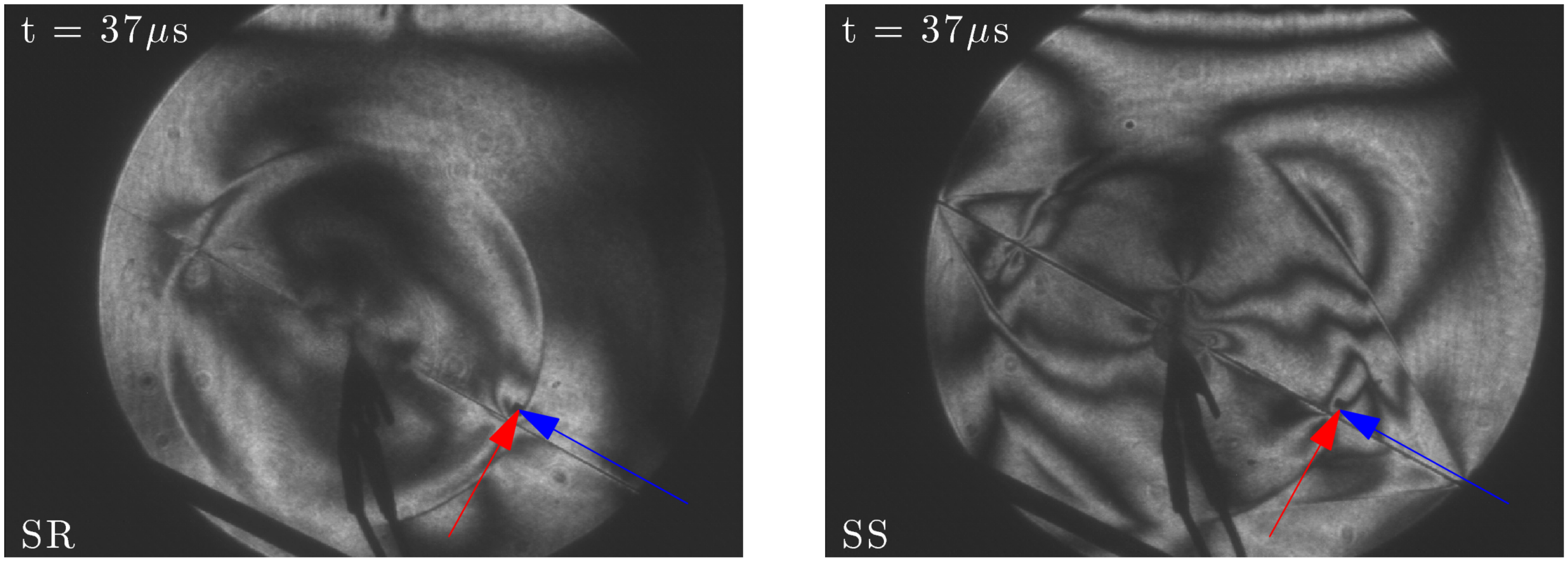
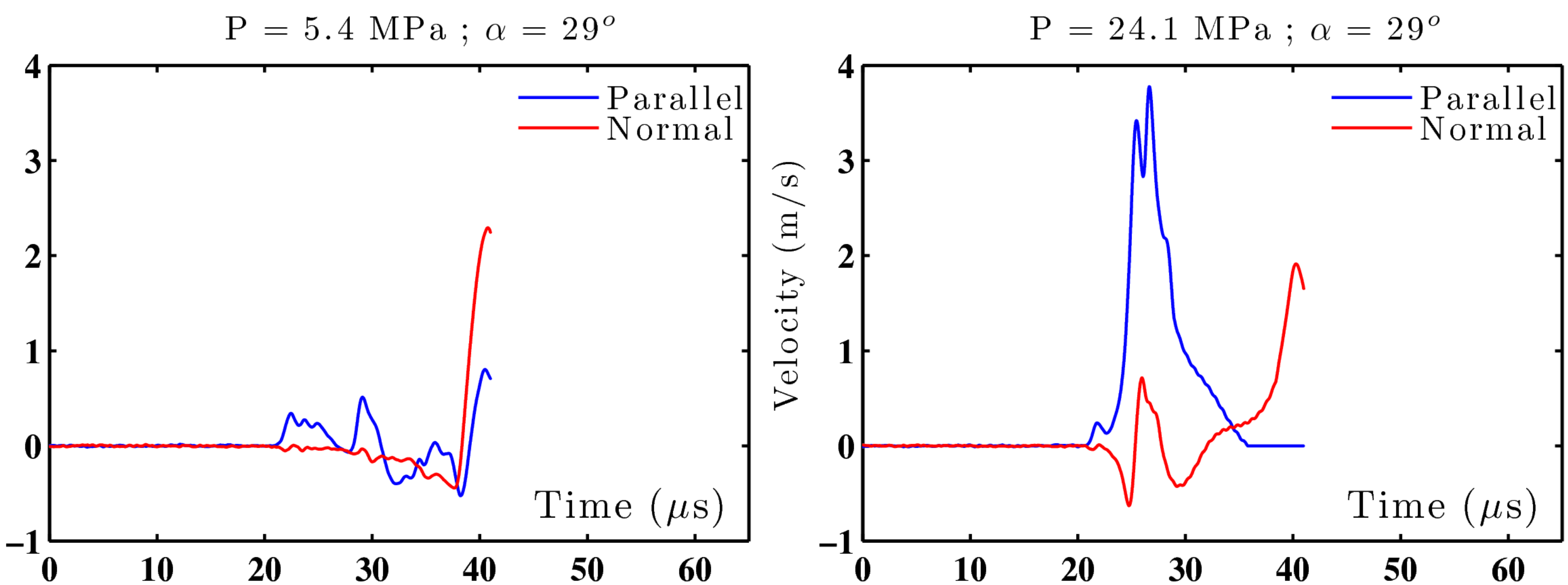
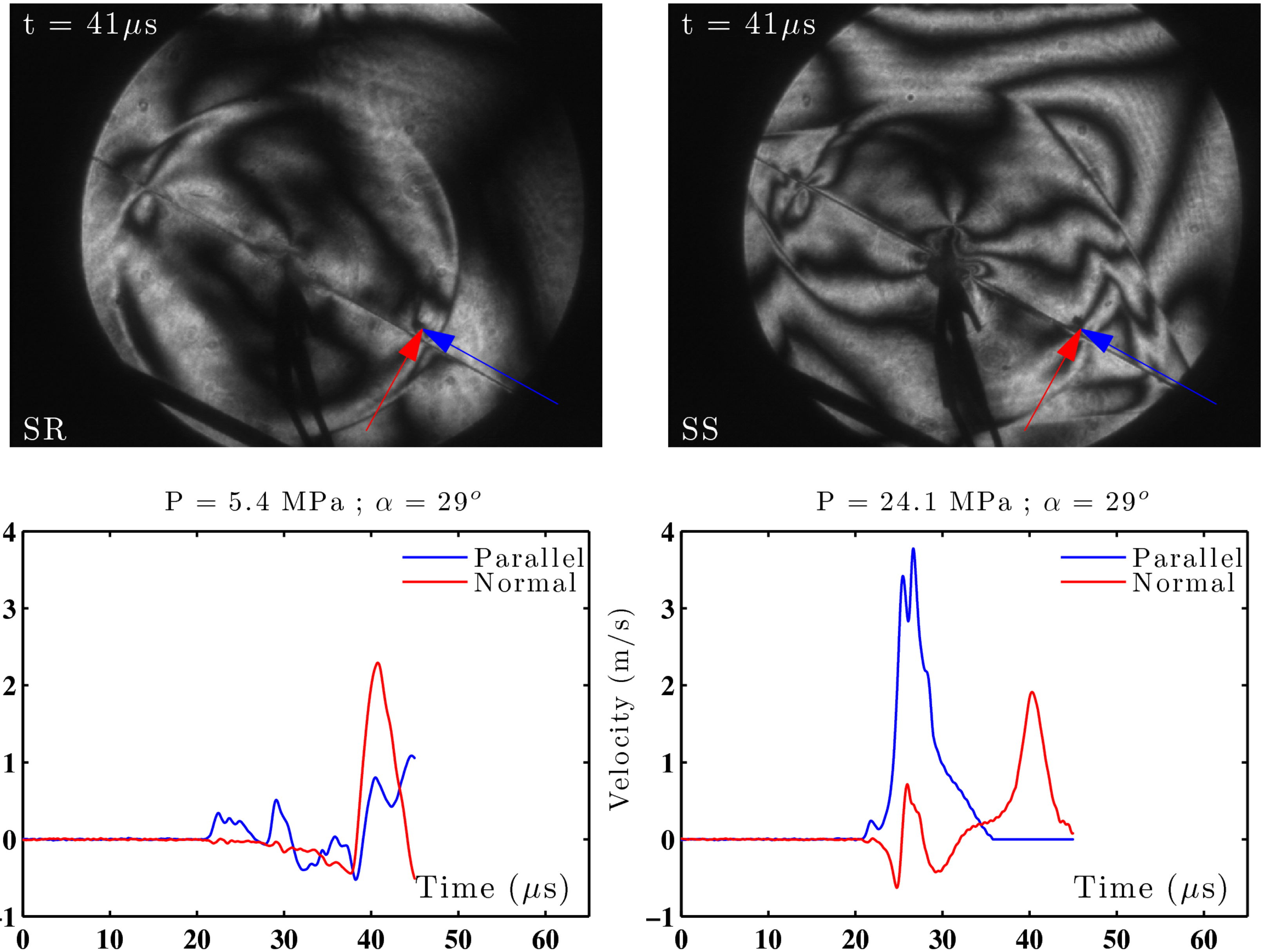


FP and FN Ground Velocity histories for a Sub-Rayleigh and a Supershear Rupture

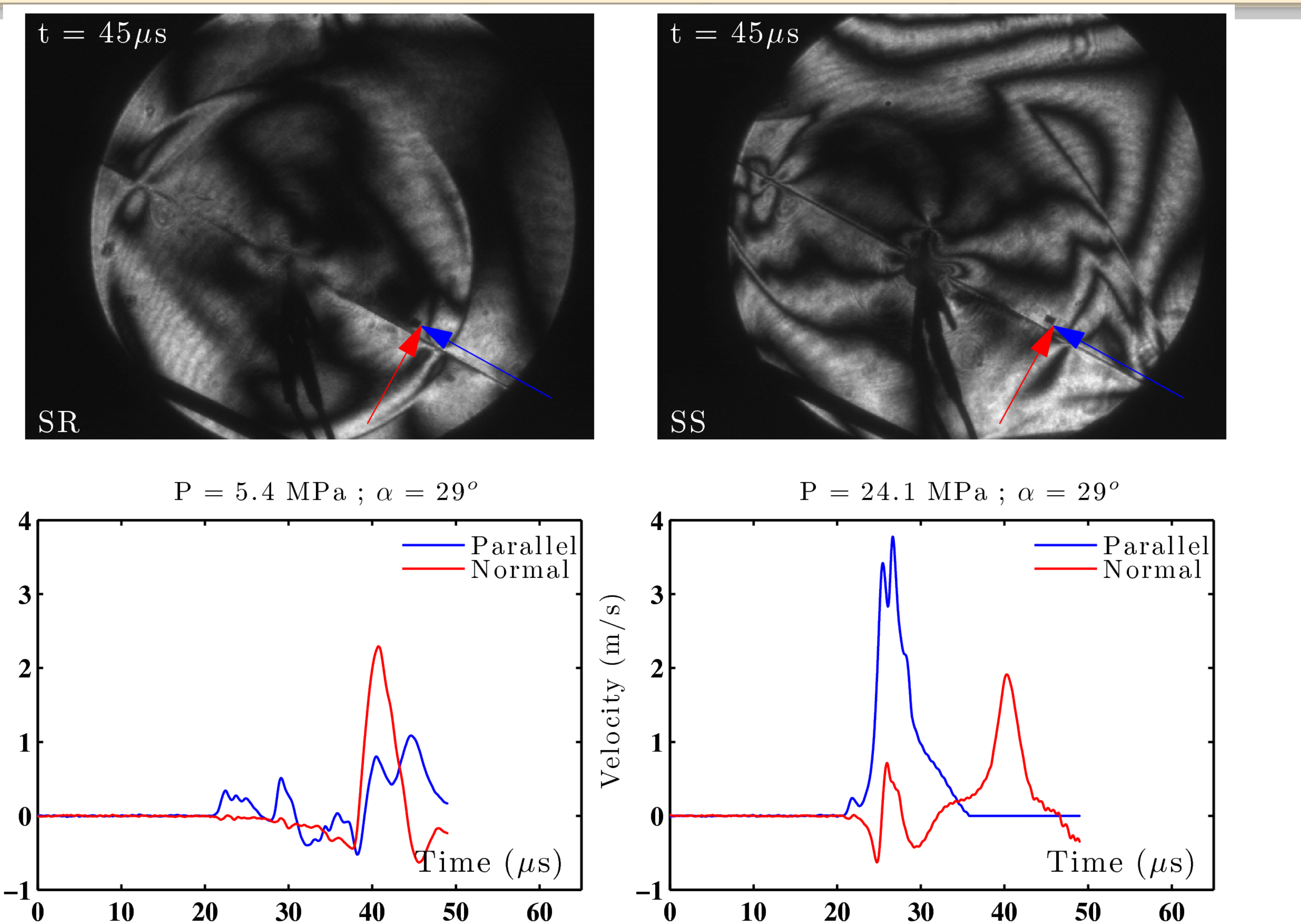




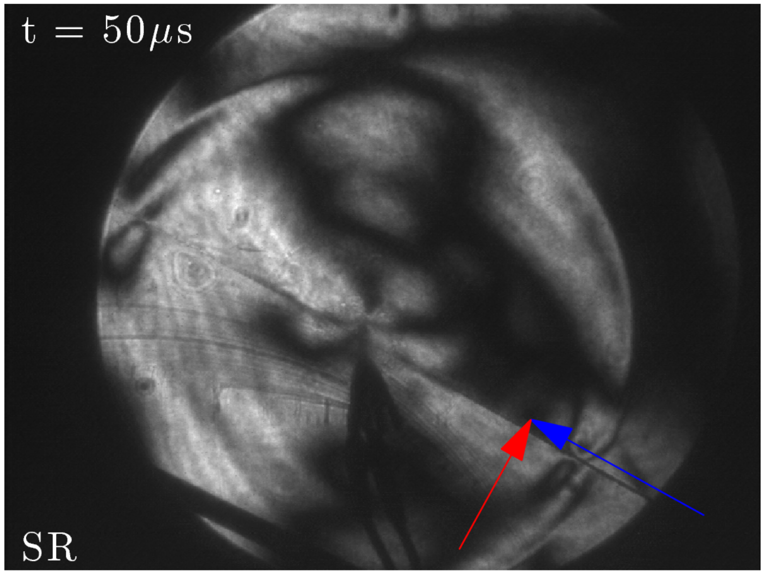
FP and FN Ground Velocity histories for a Sub-Rayleigh and a Supershear Rupture

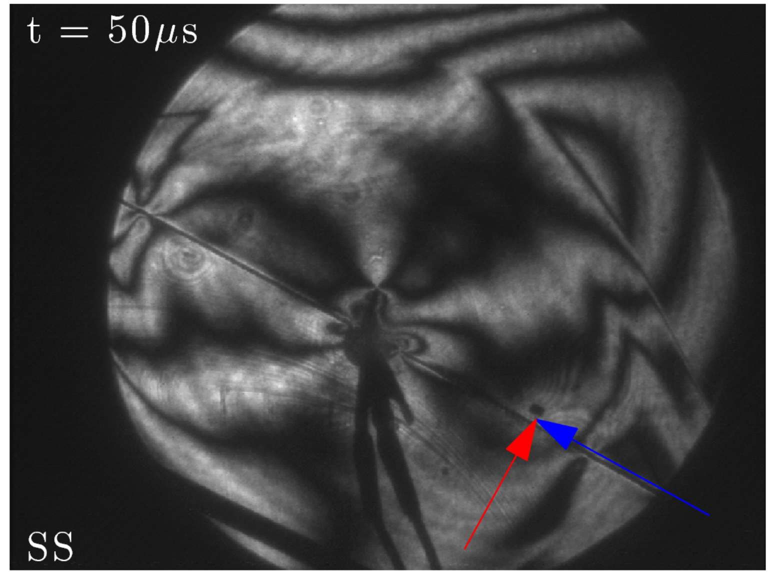


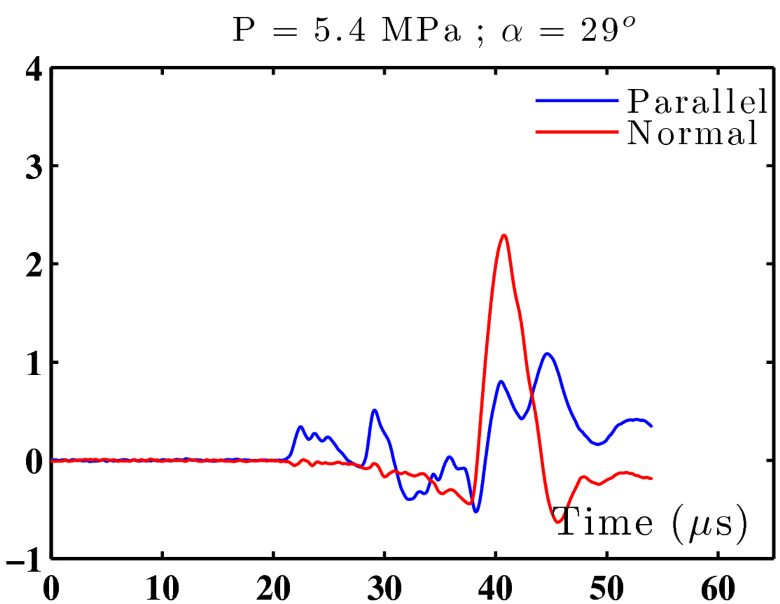
FP and FN Ground Velocity histories for a Sub-Rayleigh and a Supershear Rupture

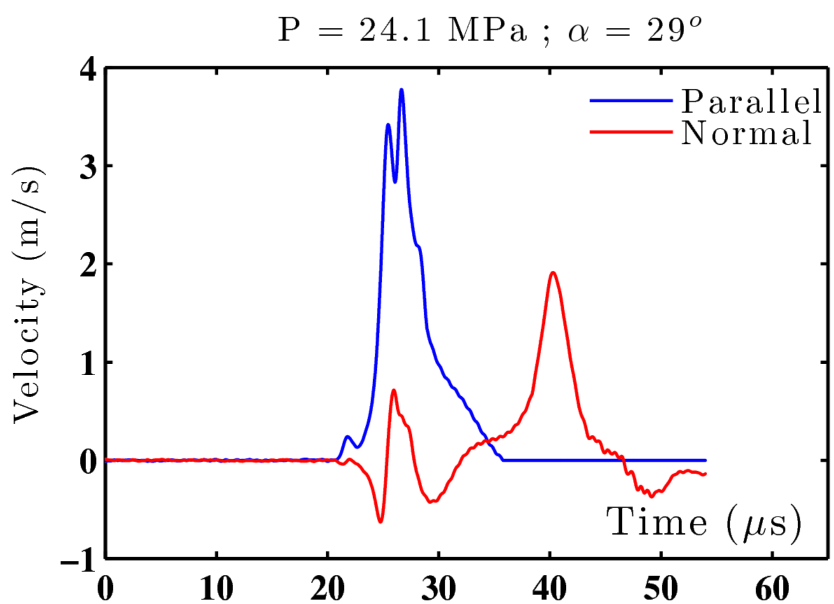


FP and FN Ground Velocity histories for a Sub-Rayleigh and a Supershear Rupture

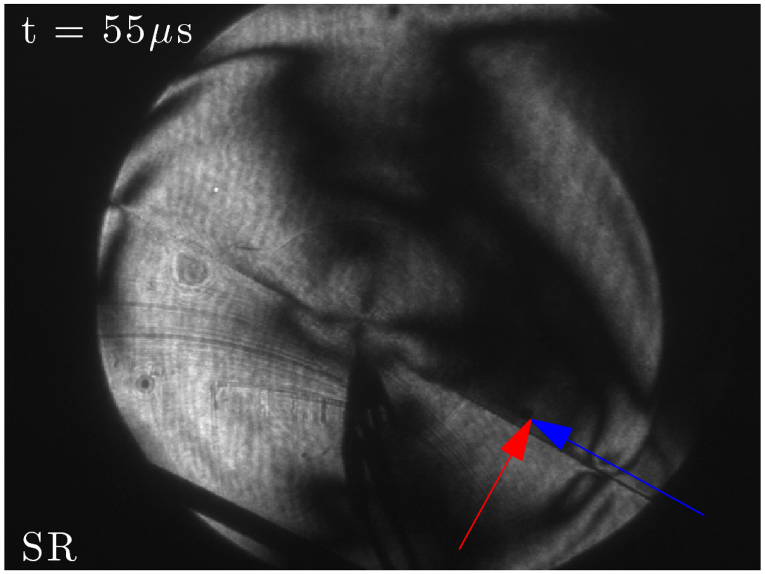


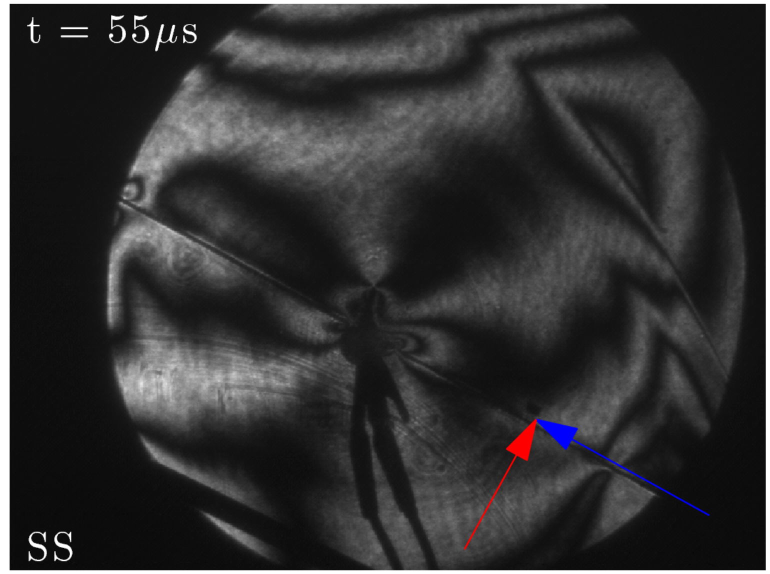


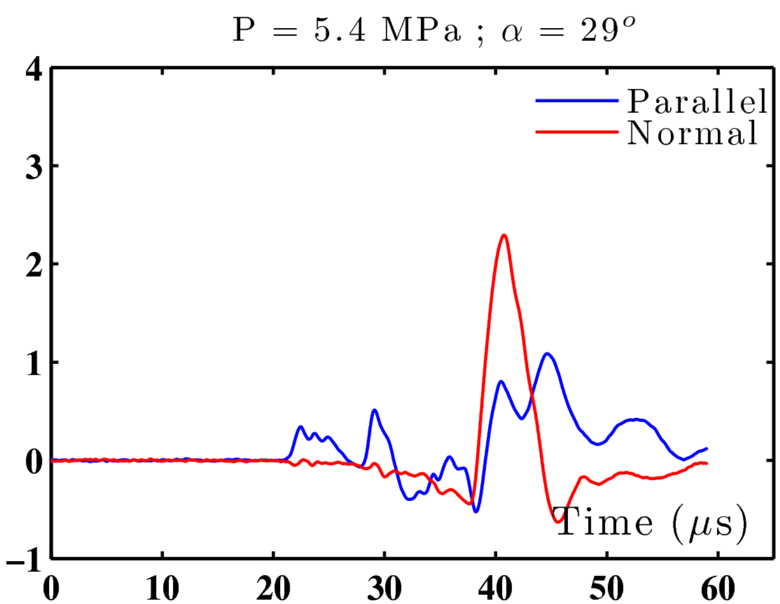


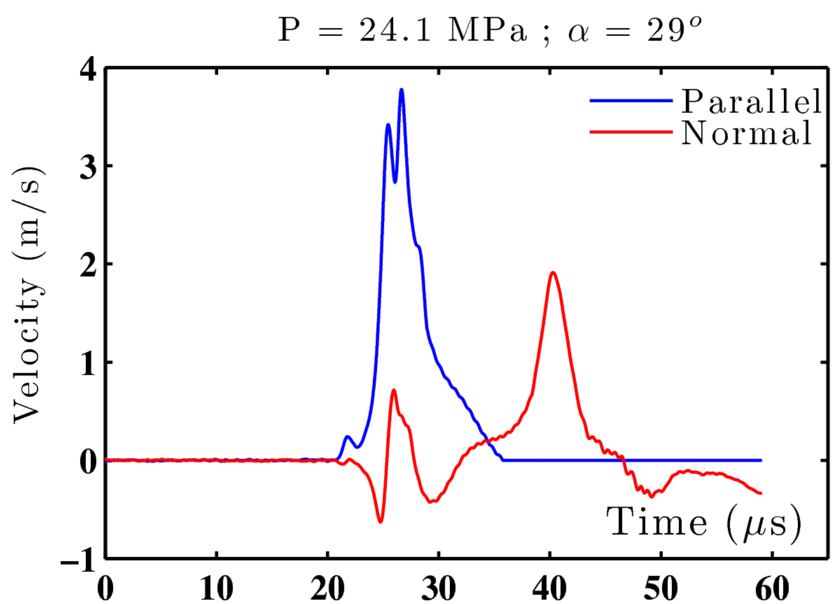


FP and FN Ground Velocity histories for a Sub-Rayleigh and a Supershear Rupture

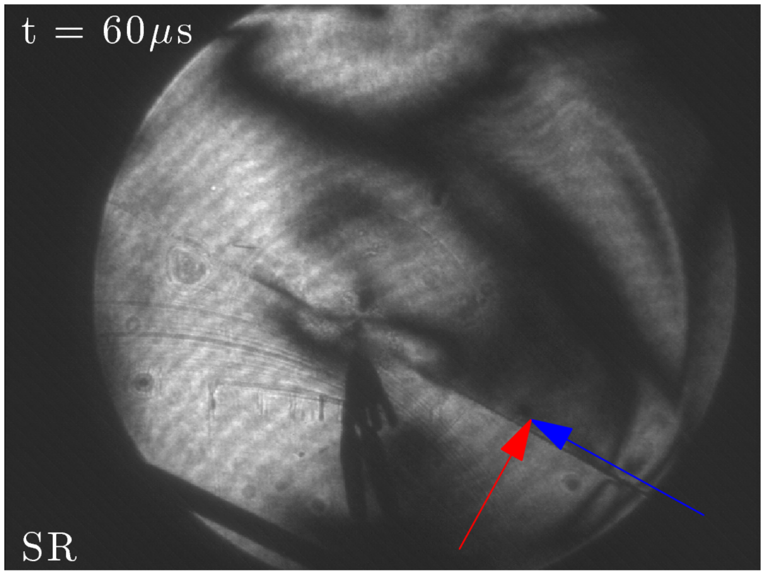


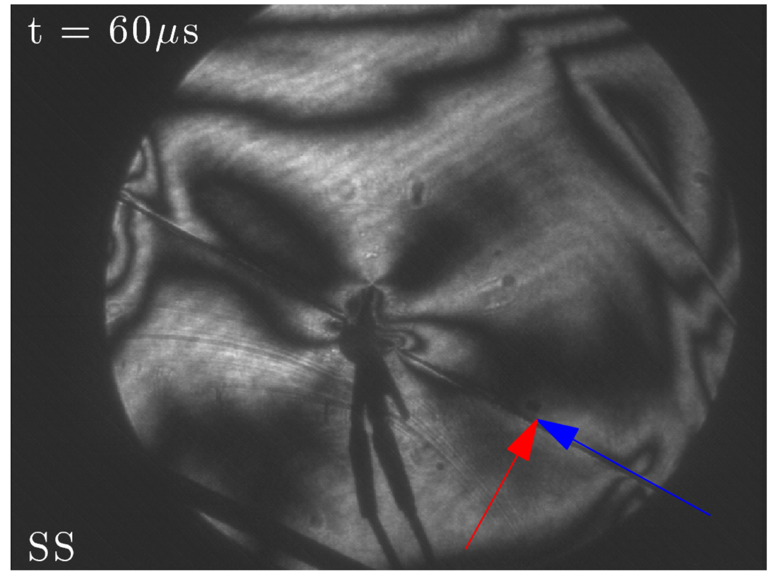


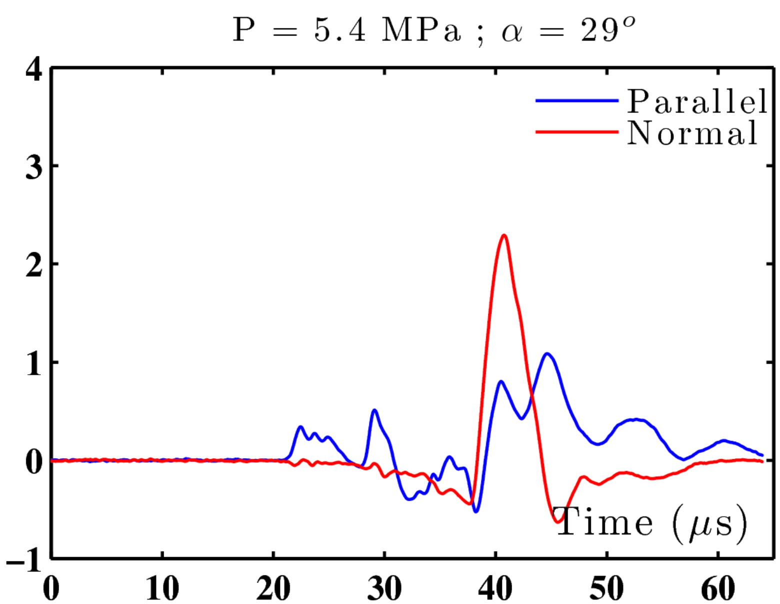


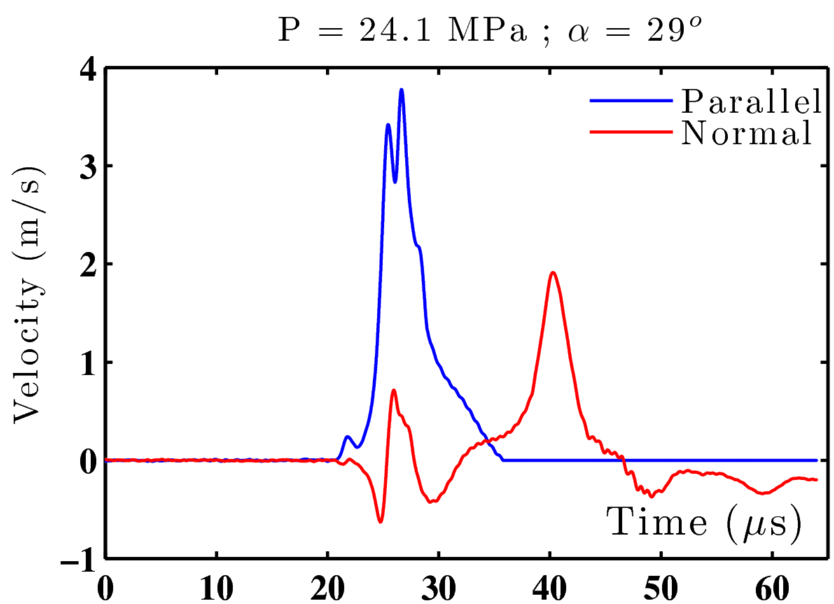


FP and FN Ground Velocity histories for a Sub-Rayleigh and a Supershear Rupture

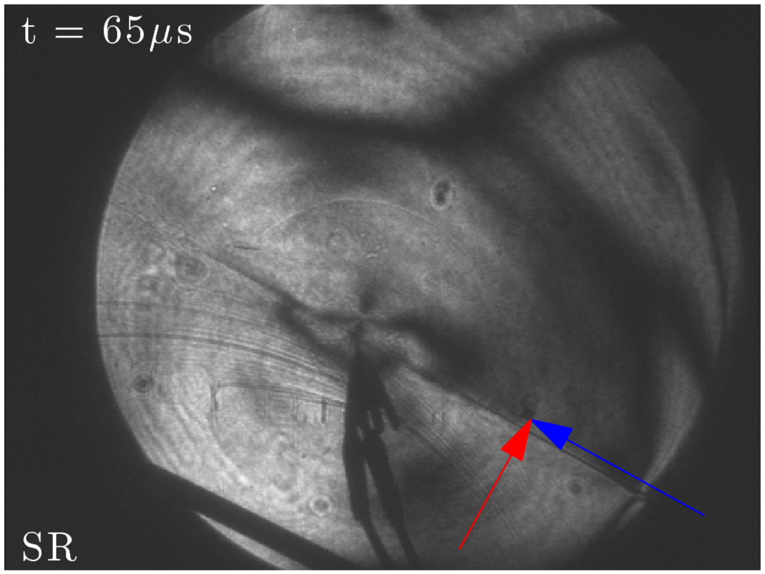


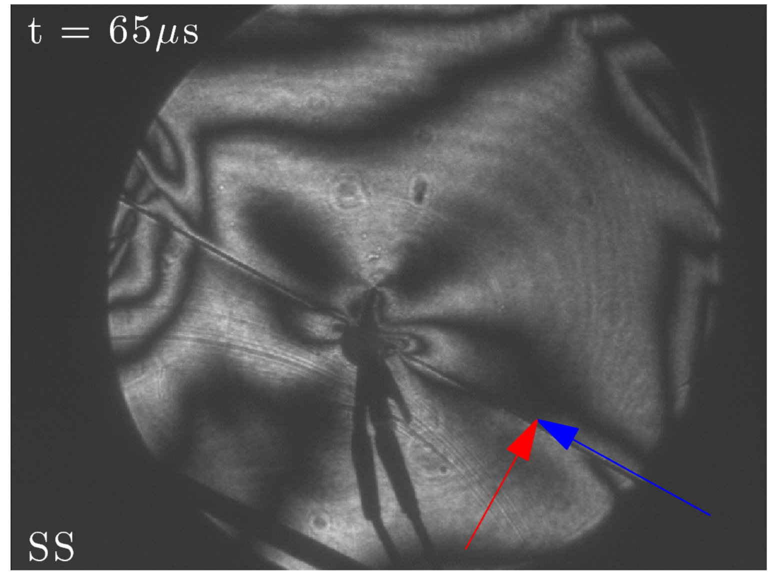


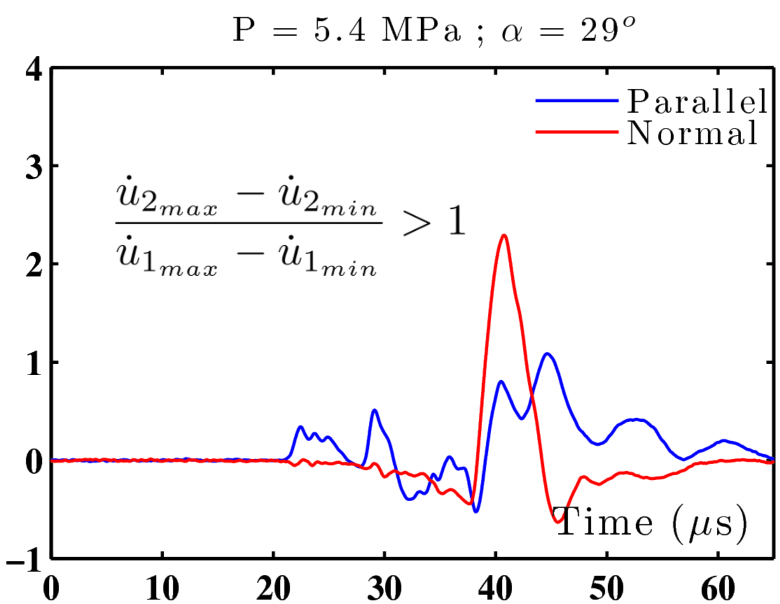


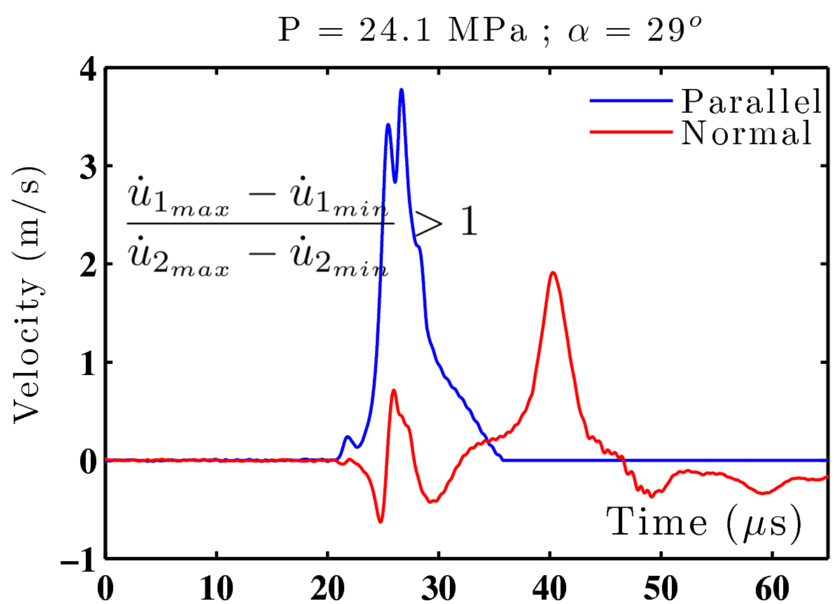


FP and FN Ground Velocity histories for a Sub-Rayleigh and a Supershear Rupture



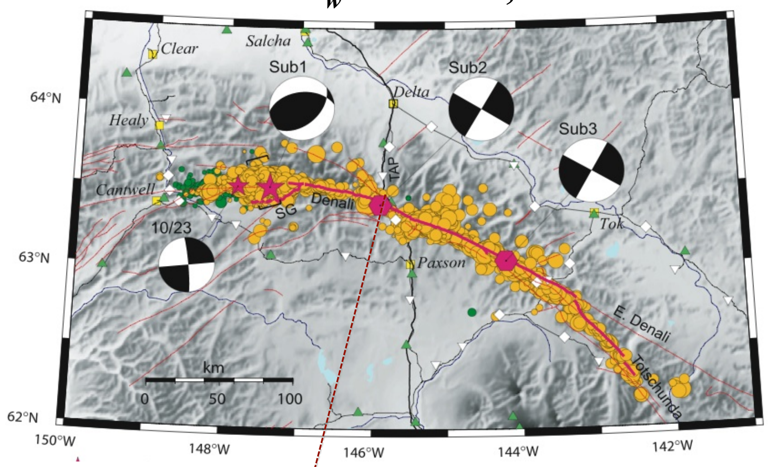


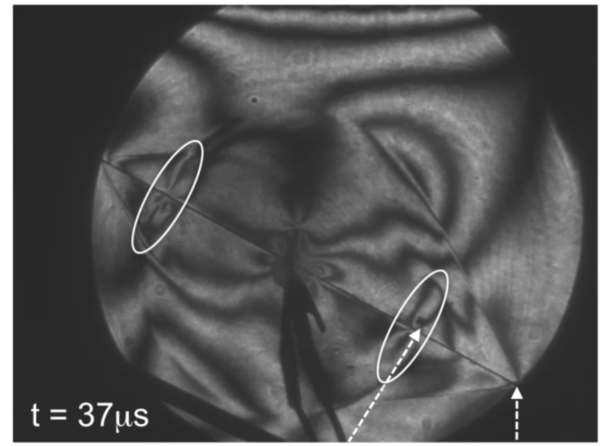




Comparison between Lab and Natural Earthquake
(The trailing Rayleigh and the one-two Punch)

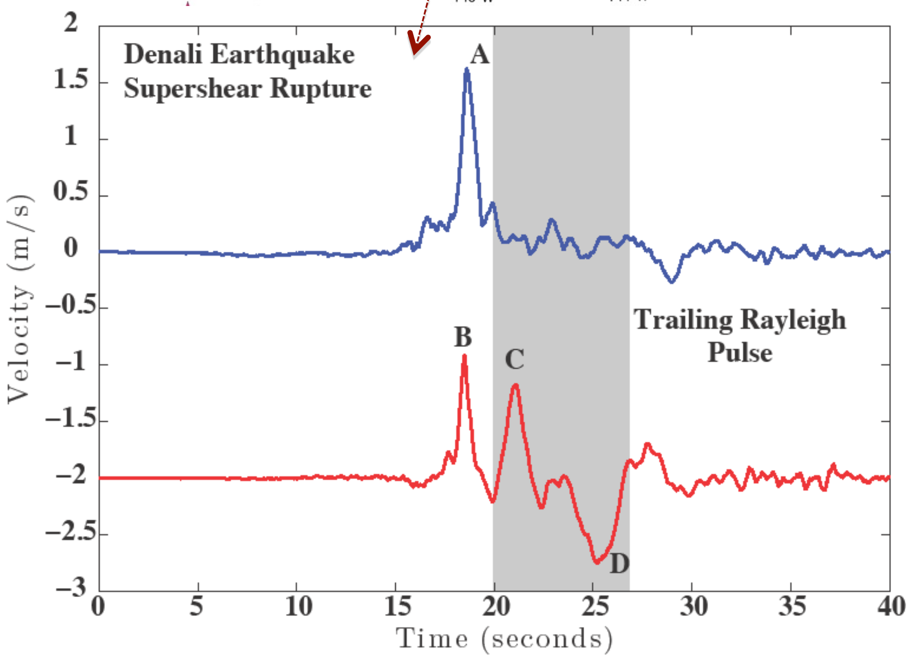
2002 M_w 7.9 Denali, Alaska

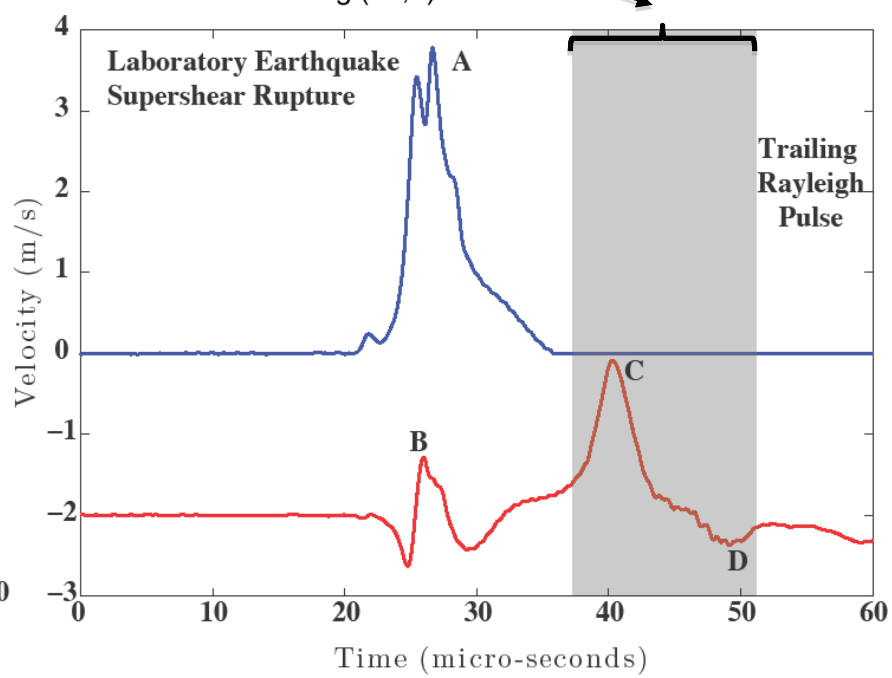




Trailing Rayleigh Pulse crossing (40,2) mm

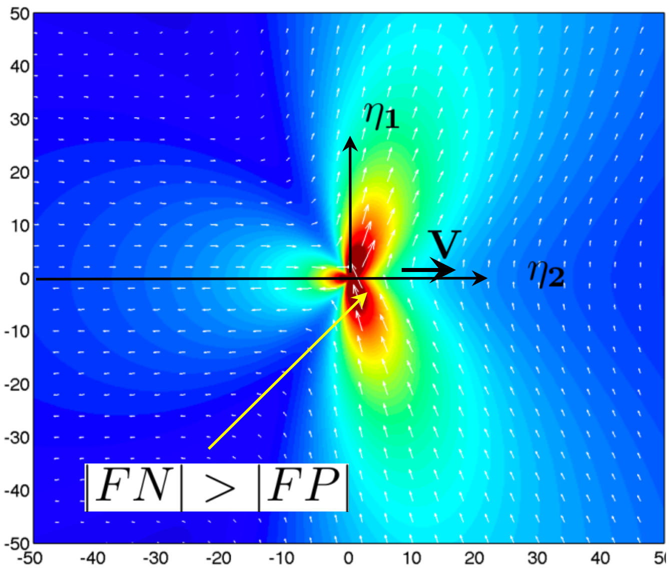
SS rupture tip



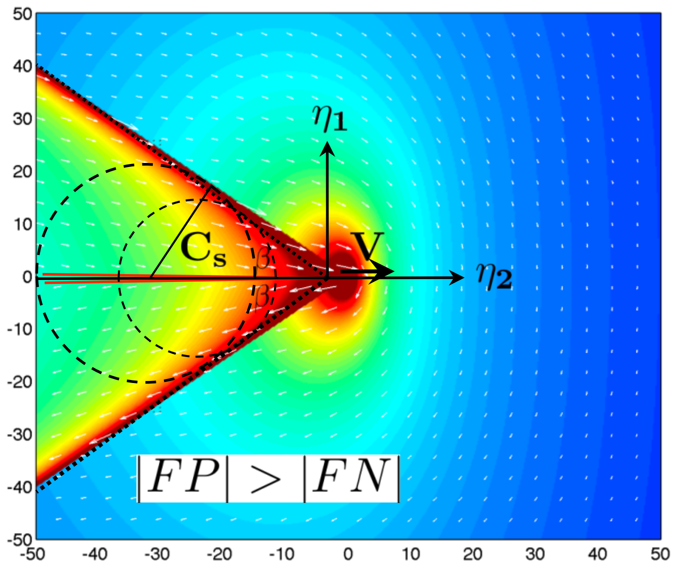


Reference: Dunham and Archuleta, (2004); Ellsworth et al., (2004); Eberhart-Phillips et al., (2003)

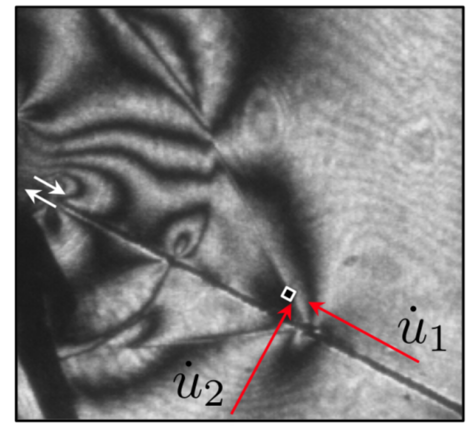
Classification of Earthquakes: Ground motion signatures of steady-state, Sub-Rayleigh and Supershear Ruptures

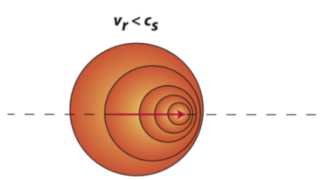
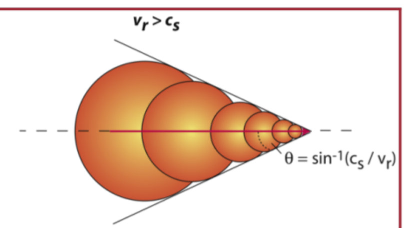


$$\frac{V_r}{C_s} = 0.875$$



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



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

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

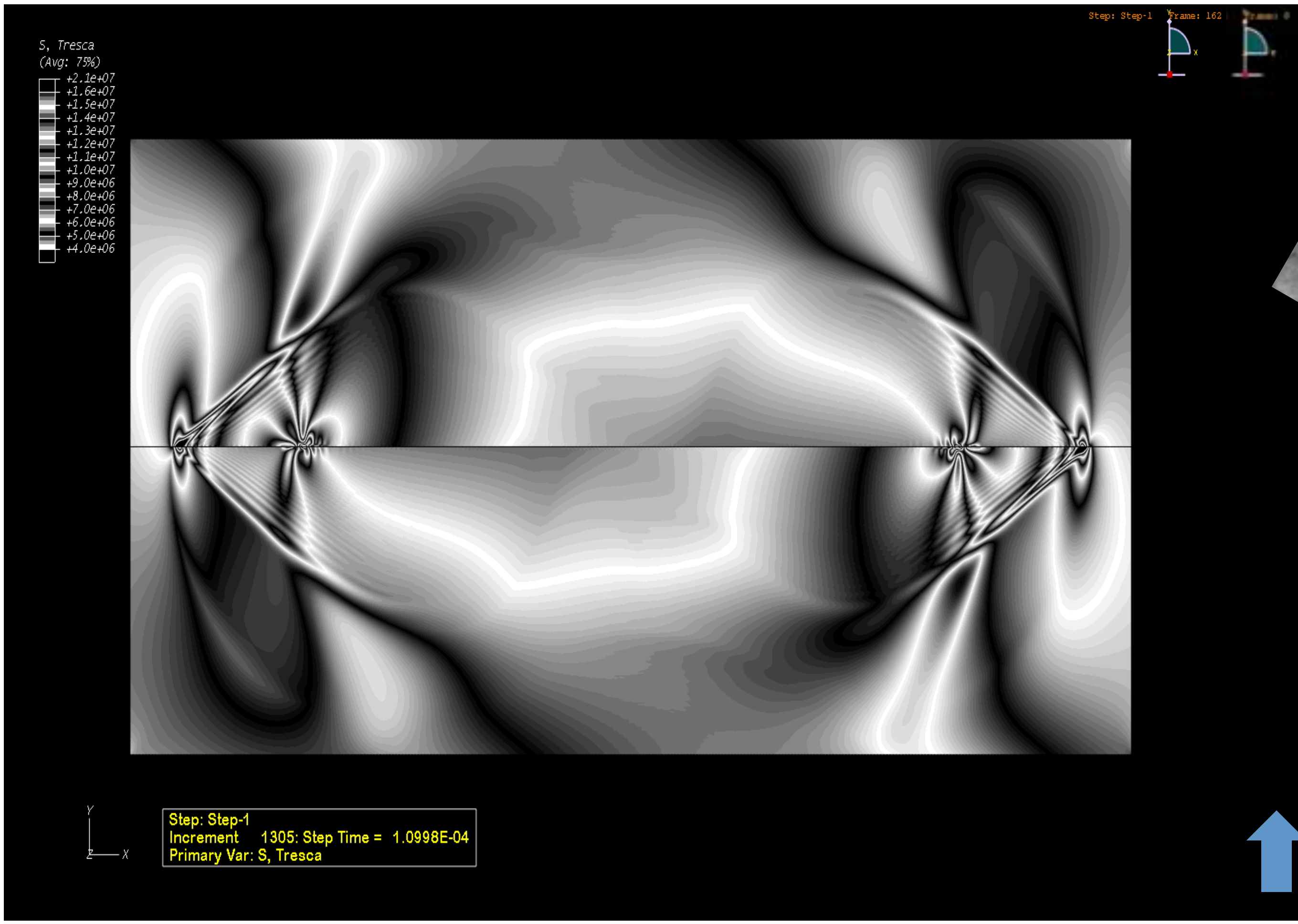
References: Freund and Clifton (1974); Freund (1979&1990); Aagaard and Heaton (2004); Dunham and Archuleta (2004) Bhat et al., (2007), Dunham and Bhat, (2008)

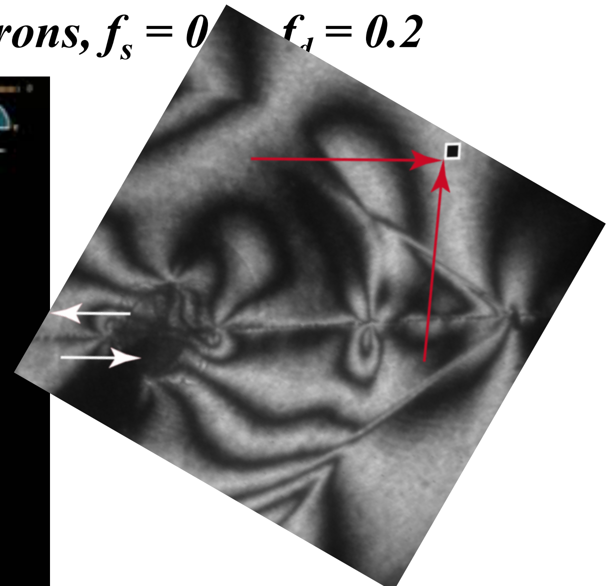
Using 2D Numerics to identify Basic Signatures: Delivering the one-two punch

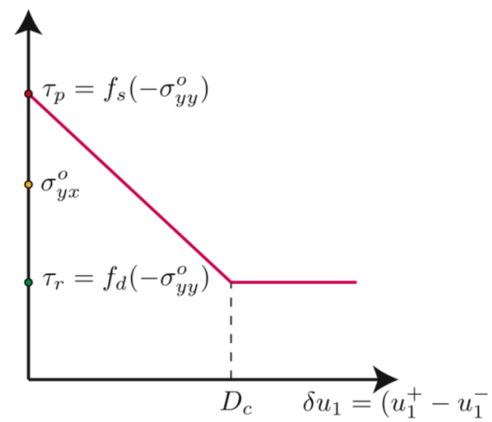
2D Plane-Stress Finite Element simulations using a commercial code, ABAQUS.

Simulation conducted on model material (Homalite-100)

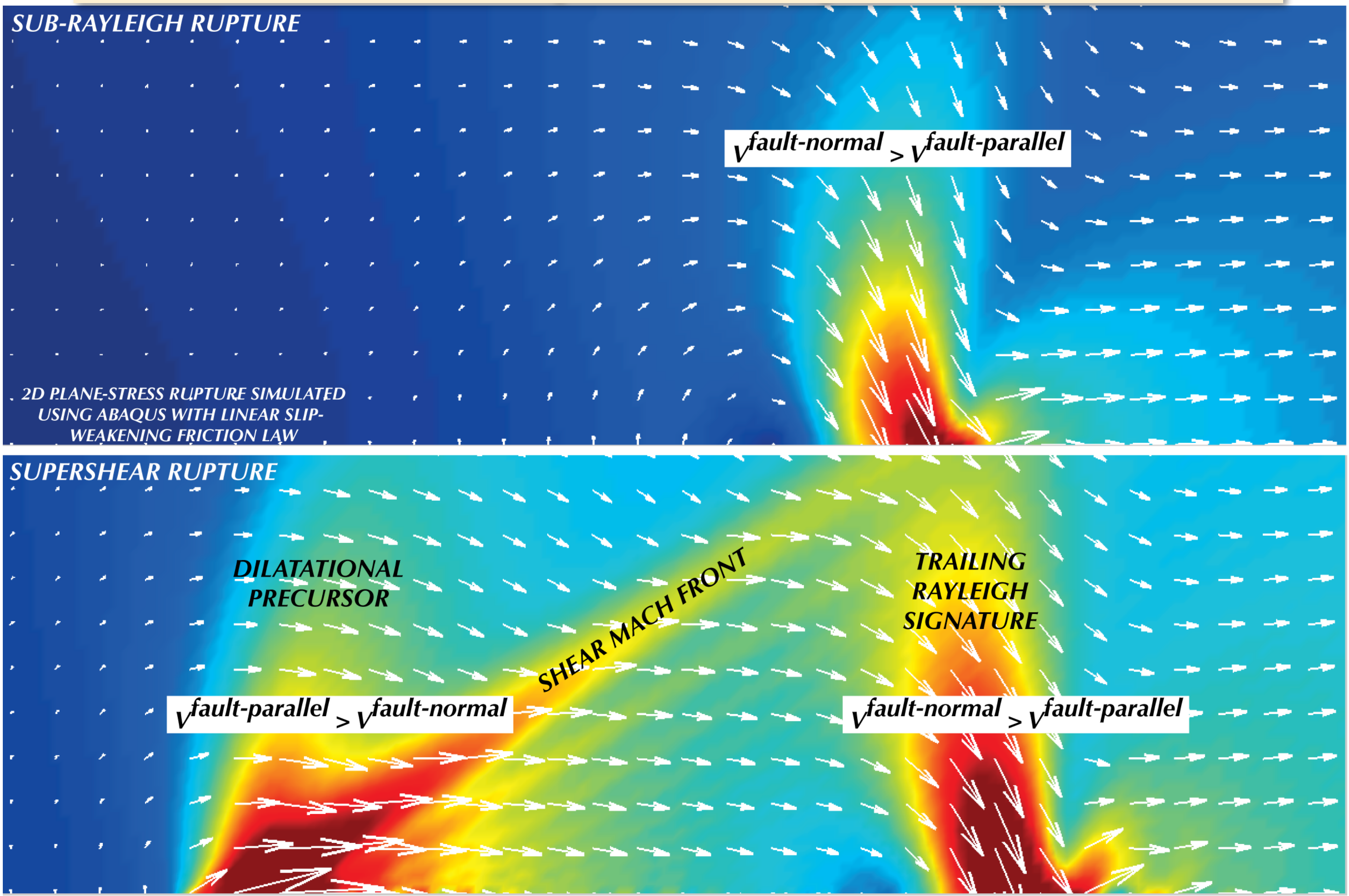
Slip-Weakening frictional constitutive description : D_c = 10 microns, f_s = 0 f_d = 0.2







Velocity Signatures of Sub-Rayleigh and Supershear Ruptures



The One-Two Punch: *Effect of Supershear Earthquakes on Buildings*

We have studied the special , ground shaking , signatures of transitioning super-shear earthquakes.

What are the implications for building safety and Seismic hazard?

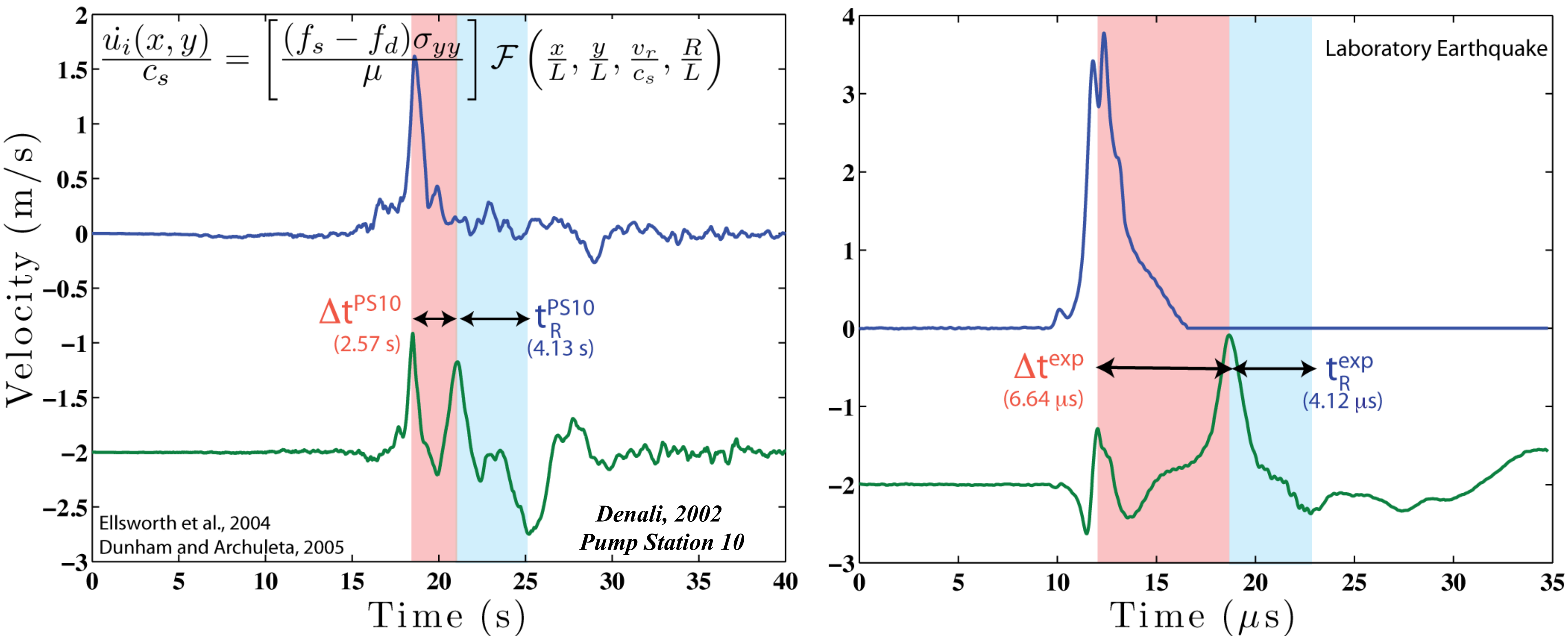
Mello, Bhat, Rosakis and Kanamori ,
Tectonophysics, Special Volume on Supershear 2010.

Song and Beroza, BSSA (2006), 1906 San Francisco,CA; M 7.8

Temporally Scaling Laboratory Earthquake to Match Pump Station 10

Unique ground motion feature common to both sub-Rayleigh and Supershear Earthquakes:

Trailing Rayleigh Signature

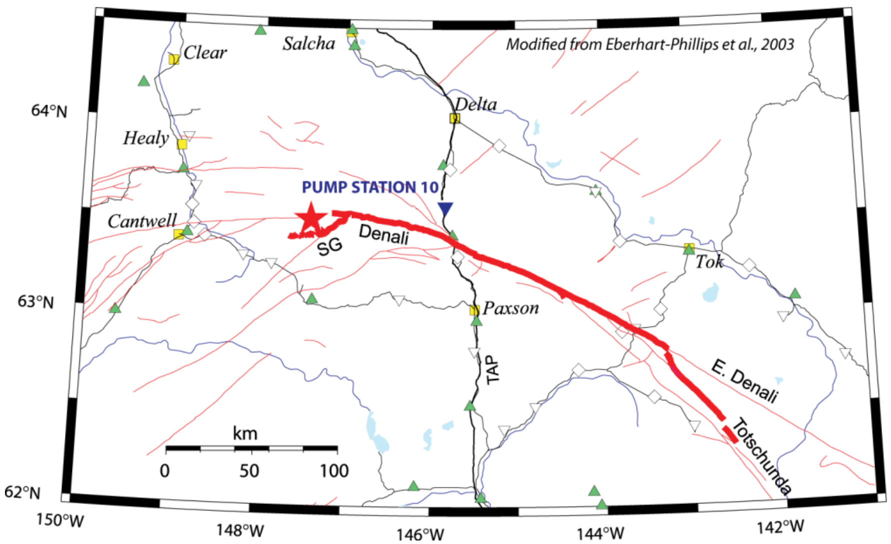


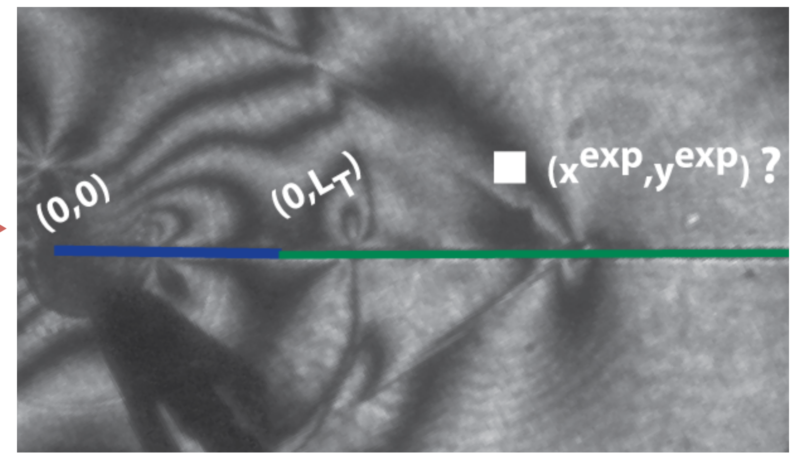
- Temporal Scaling achieved by stretching the laboratory record (t_R^{exp}) to match the Trailing Rayleigh Signature in PS10 record (t_R^{PS10}).Common to sub-Rayleigh and Super-shear.

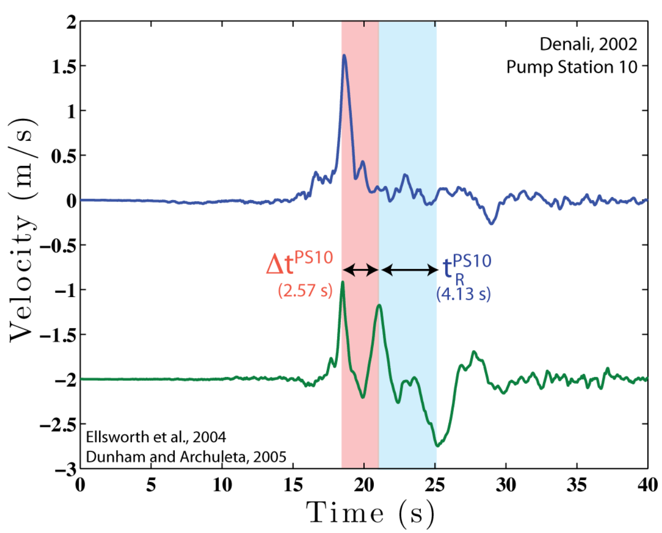
- Velocity Magnitude Scaling achieved by matching the amplitudes of the trailing Rayleigh signature between PS 10 and experiment. Note that by using non-dimensional arguments from steady-state rupture dynamics also results in Denali PS10-like velocity magnitudes.

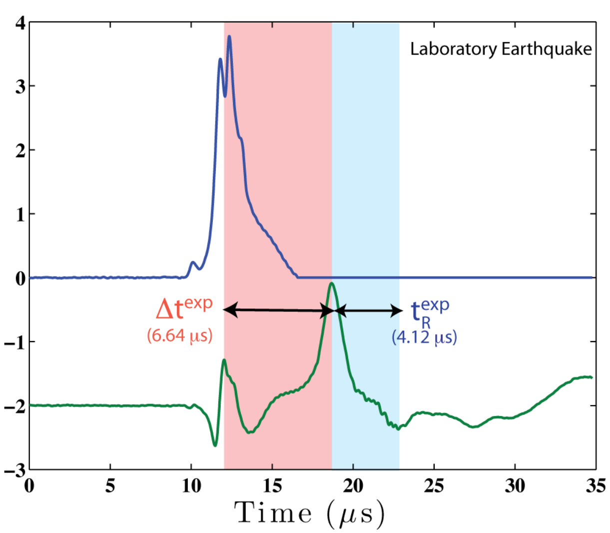
Spatially Scaling Laboratory Earthquake to Match PS10 Record

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.







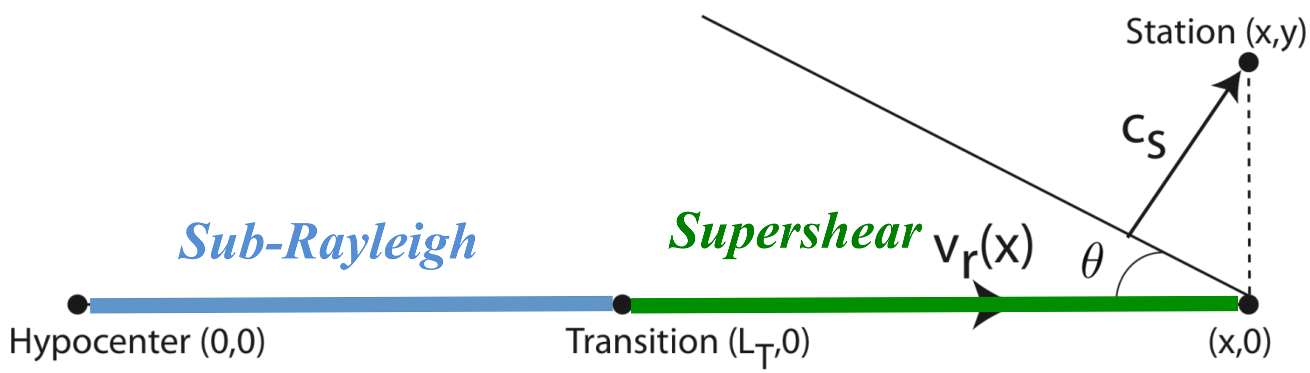


PROBLEM STATEMENT

Given a specific transition length, L_T, in the real earthquake, find $(x^{exp},y^{exp},L_T^{exp})$ in the laboratory earthquake such that

$$\Delta t^{exp} = \Delta t^{PS10,scaled}$$

Calculating Δt for a Supershear Rupture



Arrival time of the main Supershear pulse at Station

$$t_{SS} = \int_0^{L_T} \frac{dx}{v_r(x)} + \int_{L_T}^{x} \frac{dx}{v_r(x)} + \frac{y\cos\theta}{c_s}, \quad \sin\theta = \frac{c_s}{v_r}$$

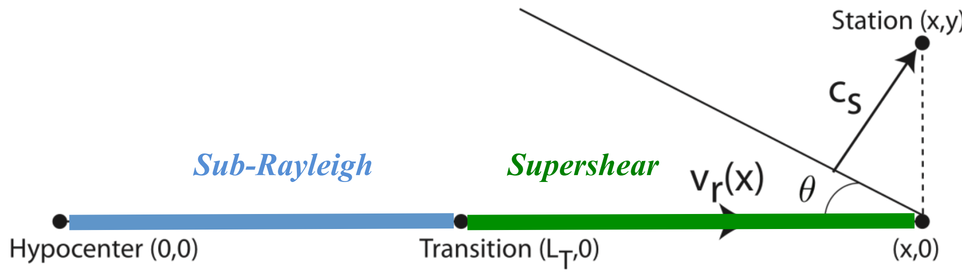
Arrival time of the Trailing Rayleigh Signature at the Station

$$t_R = \int_0^{L_T} \frac{dx}{v_r(x)} + \int_{L_T}^{x} \frac{dx}{c_R} = \int_0^{L_T} \frac{dx}{v_r(x)} + \frac{x - L_T}{c_R}$$

Difference in arrival time of the Trailing Rayleigh Signature and Supershear pulse

$$\Delta t = t_R - t_{SS} = \frac{x - L_T}{c_R} - \int_{L_T}^{x} \frac{dx}{v_r(x)} - \frac{y\cos\theta}{c_s}$$

Stations (x,y) With the Same Δt

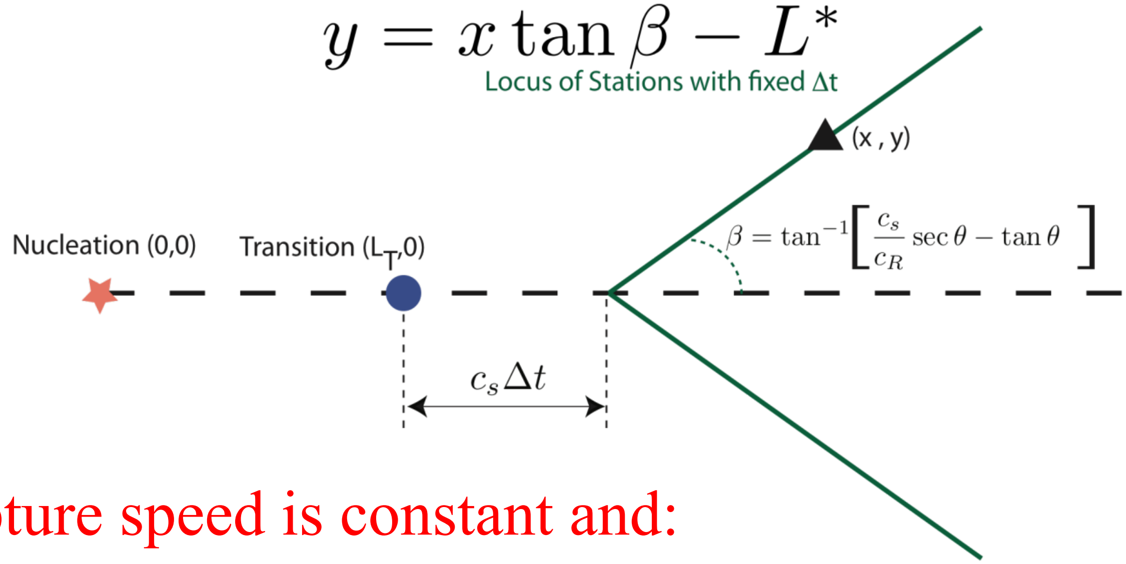


Difference in arrival time of the trailing Rayleigh Signature and Supershear pulse

$$\Delta t = t_R - t_{SS} = \frac{x - L_T}{c_R} - \int_{L_T}^{x} \frac{dx}{v_r(x)} - \frac{y}{c_s}\sqrt{1 - \frac{c_s^2}{v_r^2}}$$

Solving for (x,y) one obtains a locus of stations with same Δt for a fixed transition length

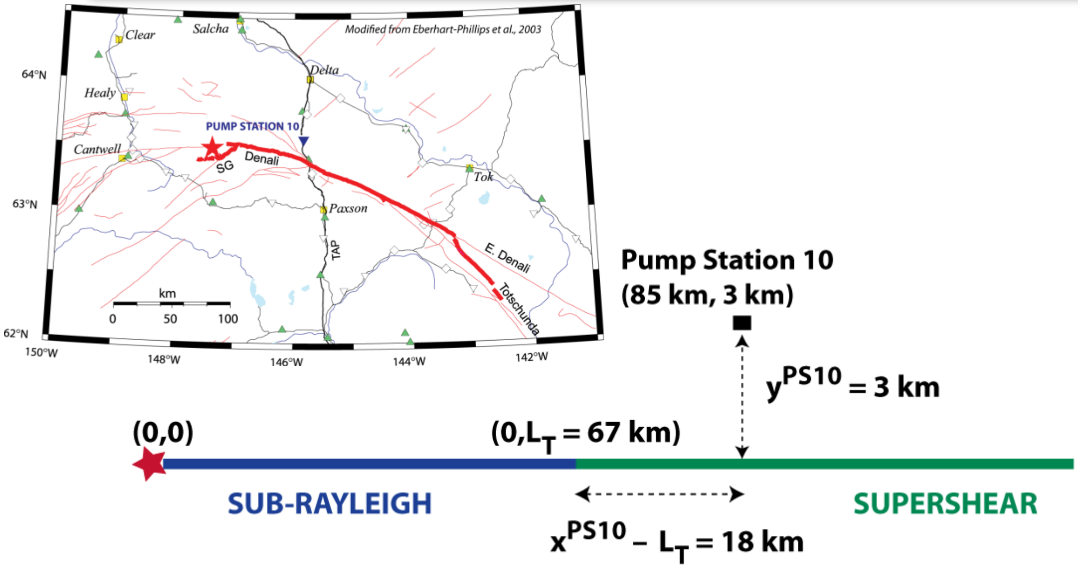
$$y = x \tan\beta - L^*$$



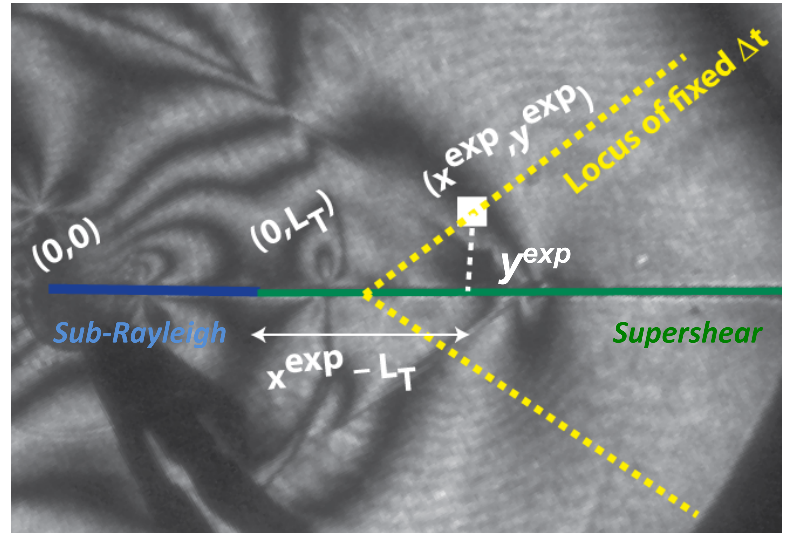
Where the rupture speed is constant and:

$$\beta = \tan^{-1}\left[c_s \sec\theta / c_R - \tan\theta\right] \;\; ; \;\; L^* = (L_T + c_s\Delta t)\tan\beta \;\; ; \;\; \sin\theta = c_s/v_r$$

Geometric Scaling



Ellsworth et al. (2004)



Constrain the locus of stations with same Δt = $\Delta t^{PS10,scaled}$,with geometric scaling:

$$y = x\tan\beta - L^*$$

$$\frac{y^{PS10}}{(x-L_T)^{PS10}} = \frac{1}{6} = \frac{y^{exp}}{(x-L_T)^{exp}} = S_L \quad (\text{say})$$

Solving now for station coordinates with geometric scaling constraint gives

$$\Rightarrow x^{exp} = \frac{L^* - L_T^{exp} S_L}{\tan\beta - S_L} \quad ; \quad y^{exp} = S_L(x^{exp} - L_T^{exp})$$

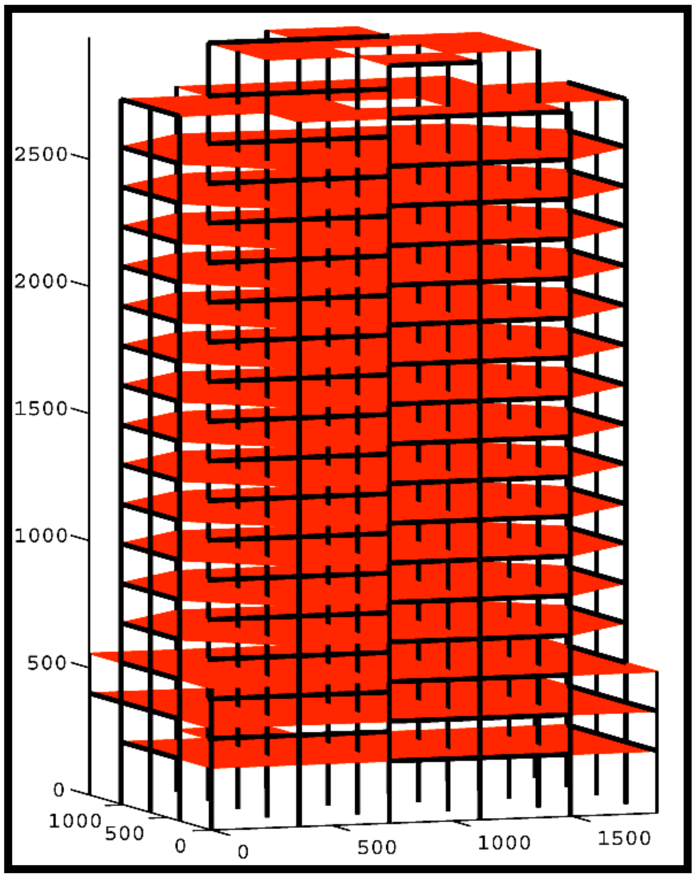
$$\beta = \tan^{-1}\left[c_s \sec\theta / c_R - \tan\theta\right] \quad ; \quad L^* = (L_T^{exp} + c_s \Delta t)\tan\beta \quad ; \quad \sin\theta = c_s / v_r^{exp}$$

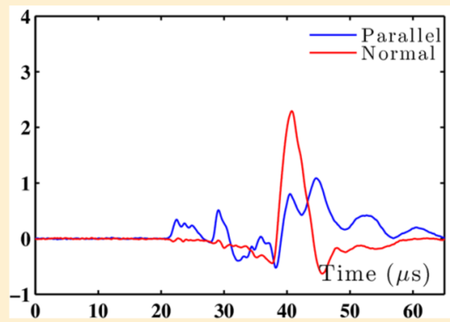
Implications of Supershear Ruptures on Buildings

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

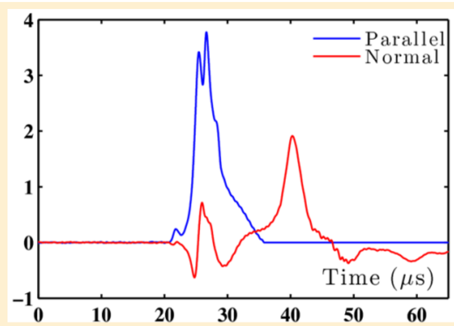
- ***3D Finite Element simulations using FRAME3D***
- ***Developed at Caltech by Prof. Swaminathan Krishnan***

Swaminathan Krishnan
CE/GPS Caltech





Sub-Rayleigh Earthquake Rupture



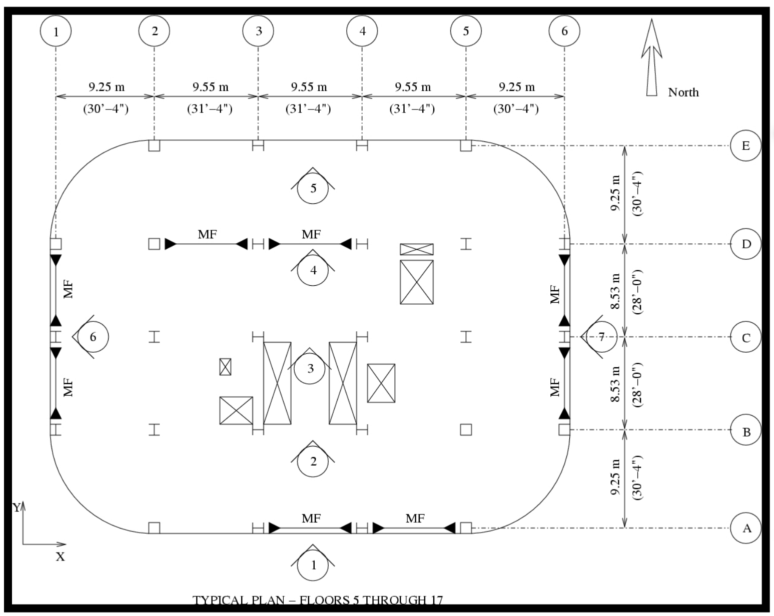
Supershear Earthquake Rupture

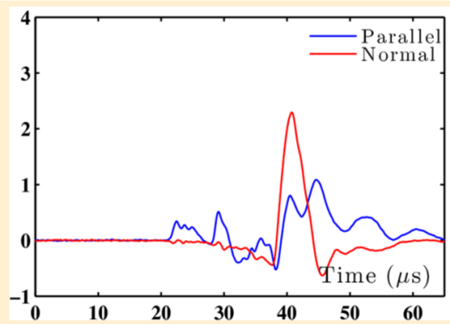
Existing Building (Woodland Hills), isometric view
(designed according to UBC82 provisions)
$T_1 = 4.43s;\ T_2 = 4.22s;\ T_3 = 2.47s$

Asymmetric placement of Moment Frames (Center of resistance and Center of Mass don’t coincide)

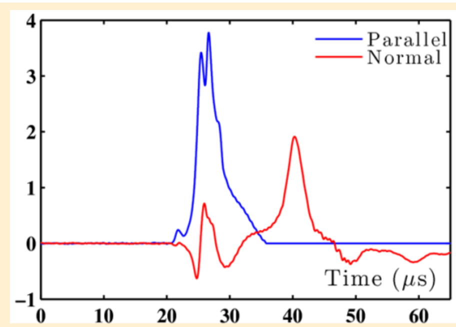
Building Studied : Existing steel moment-frame building of the 20-story class

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





Sub-Rayleigh Earthquake Rupture



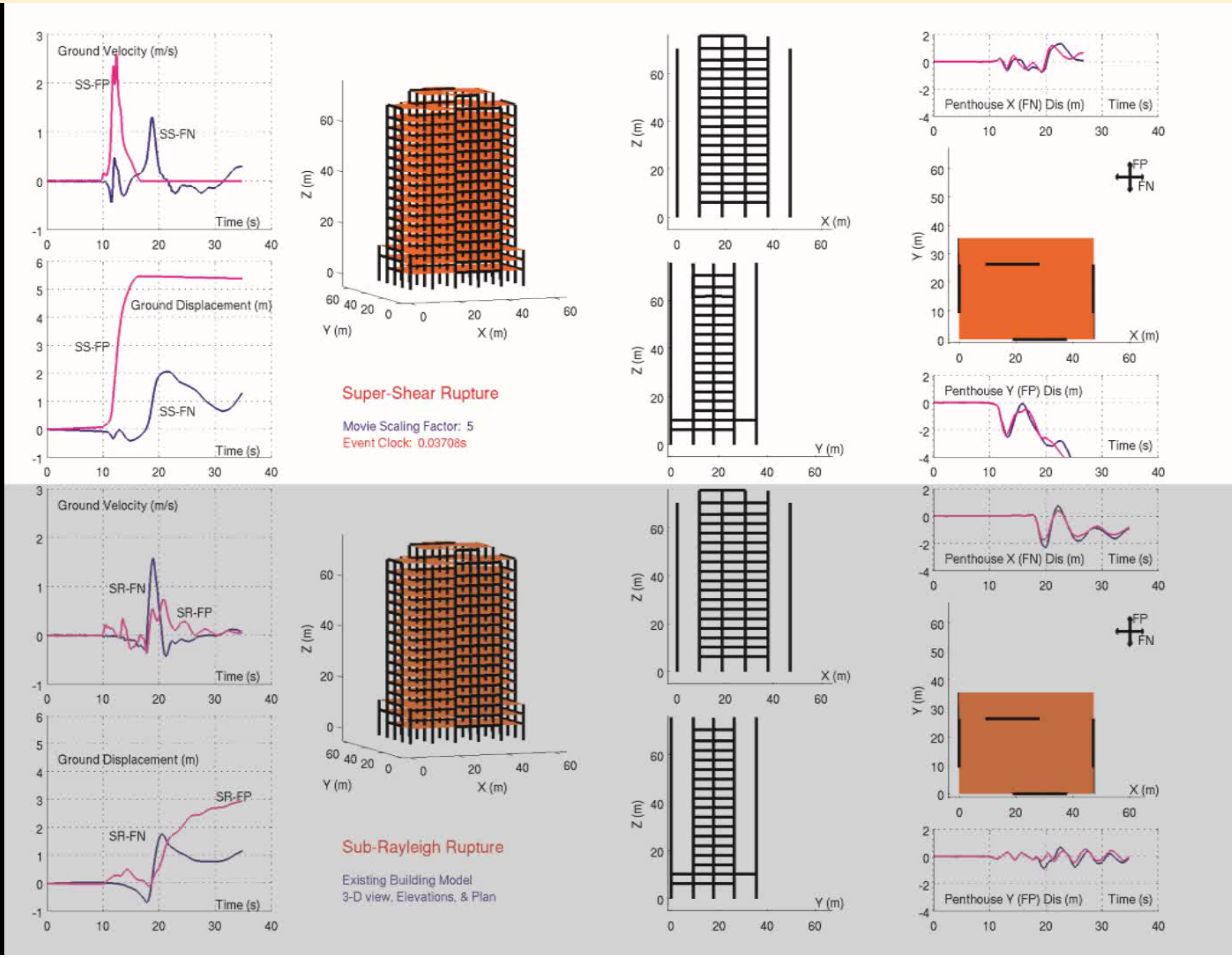
Supershear Earthquake Rupture

Existing Building (Woodland Hills), isometric view

(designed according to UBC82 provisions)

$T_1 = 4.43s$; $T_2 = 4.22s$; $T_3 = 2.47s$

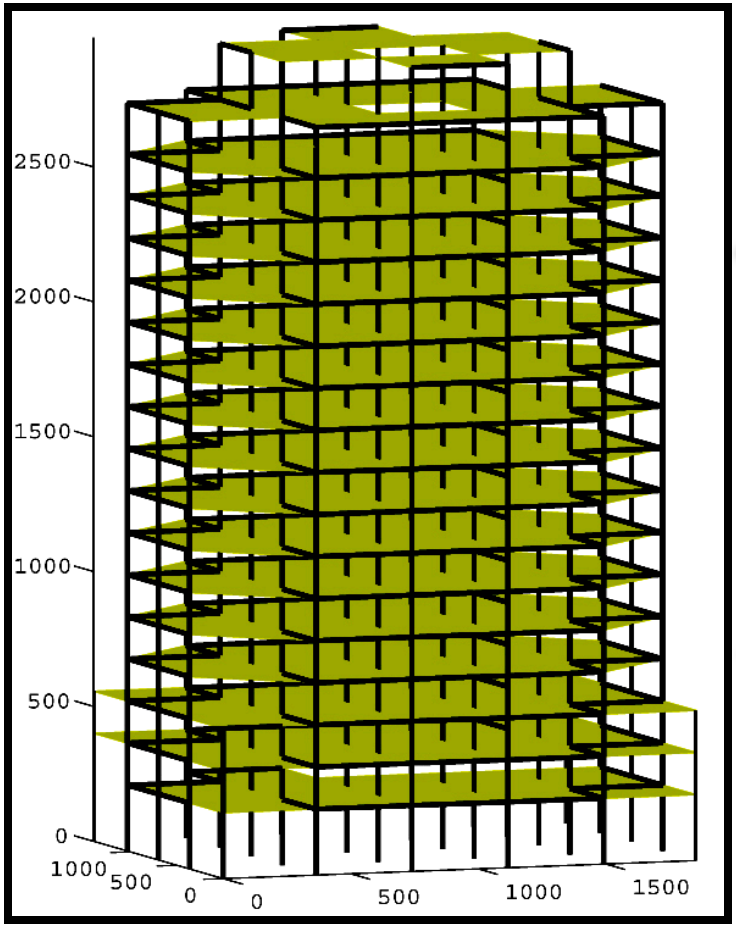
Identical Buildings at two near-fault locations subjected to excitation from Supershear or Sub-Rayleigh ruptures

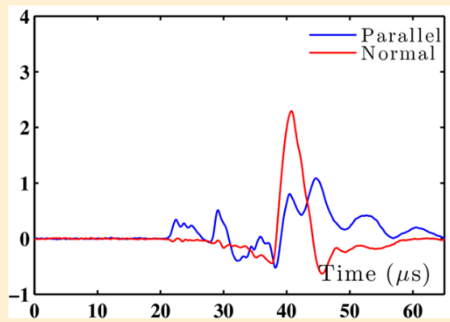


Implications of Supershear Ruptures on Buildings

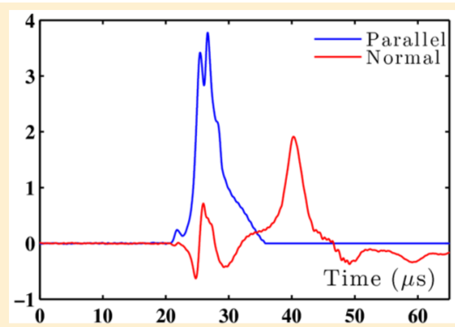
Building Studied : Redesigned steel moment-frame building of the 20-story class

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





Sub-Rayleigh Earthquake Rupture



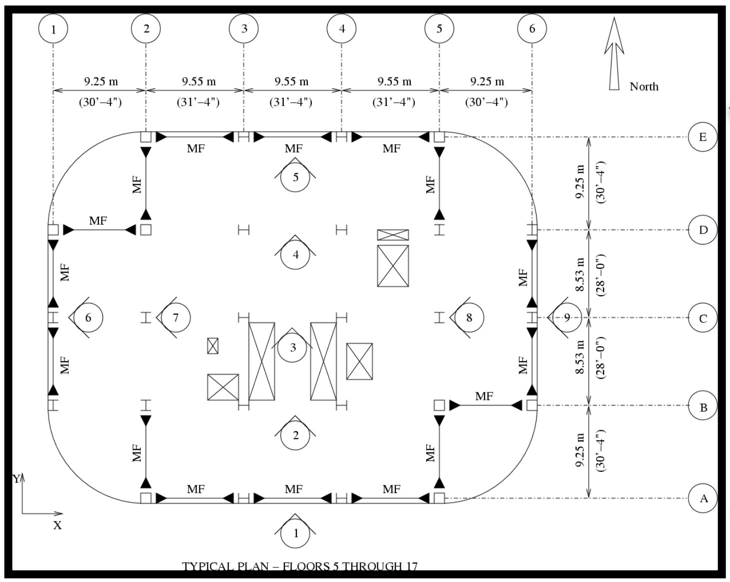
Supershear Earthquake Rupture

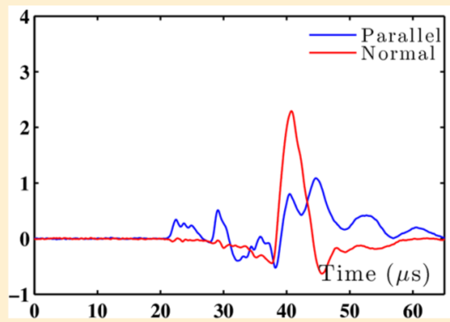
Redesigned Building
(designed according to UBC97 provisions)
T_1 = 3.72s; T_2 = 3.51s; T_3 = 2.24s

Symmetric placement of Moment Frames (Center of resistance and Center of Mass coincide)

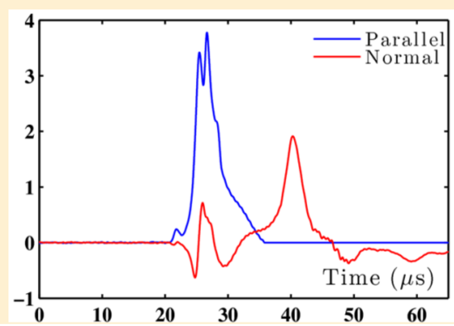
Building Studied :Redesigned, Steel moment-frame building of the 20-story class

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





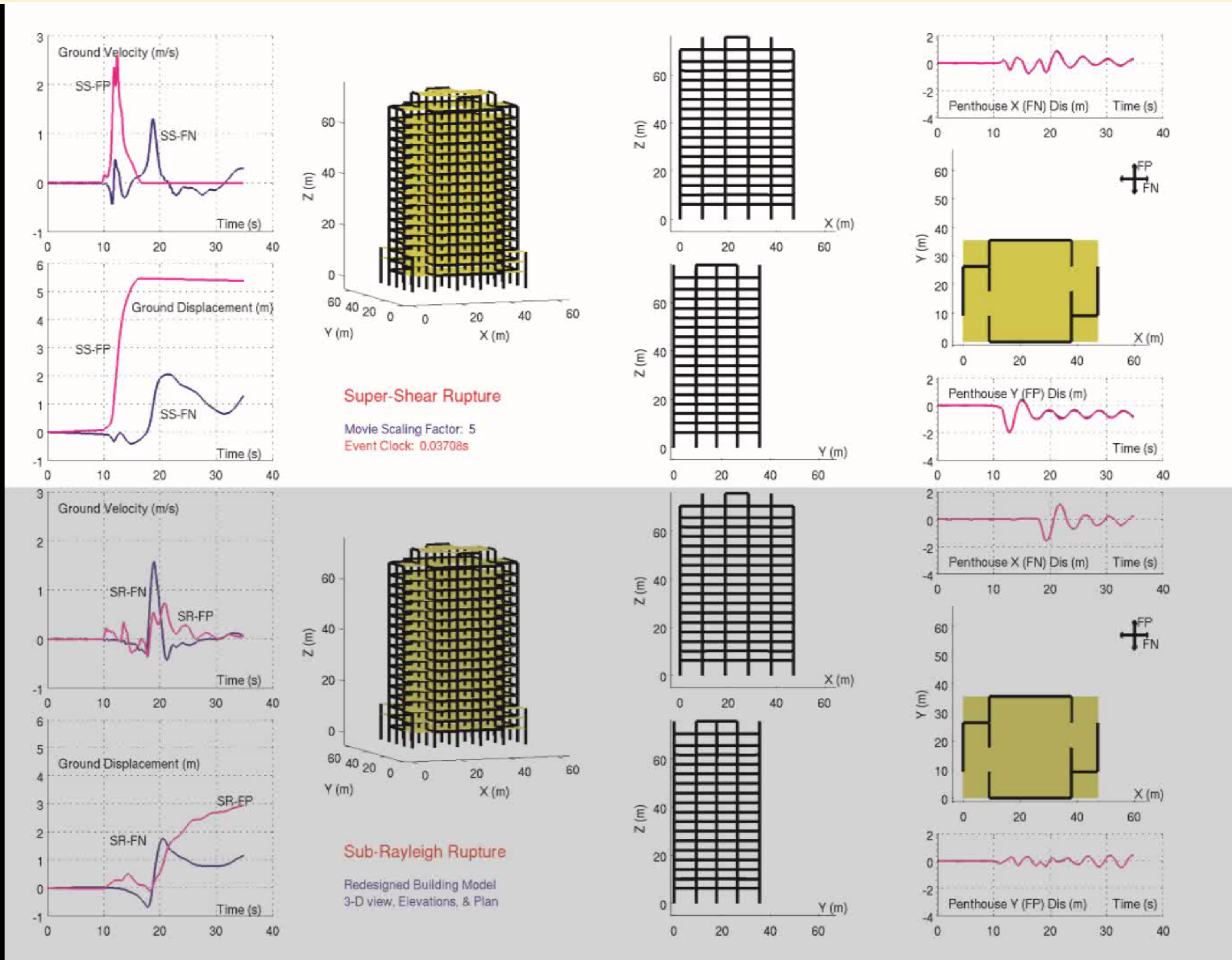
Sub-Rayleigh Earthquake Rupture



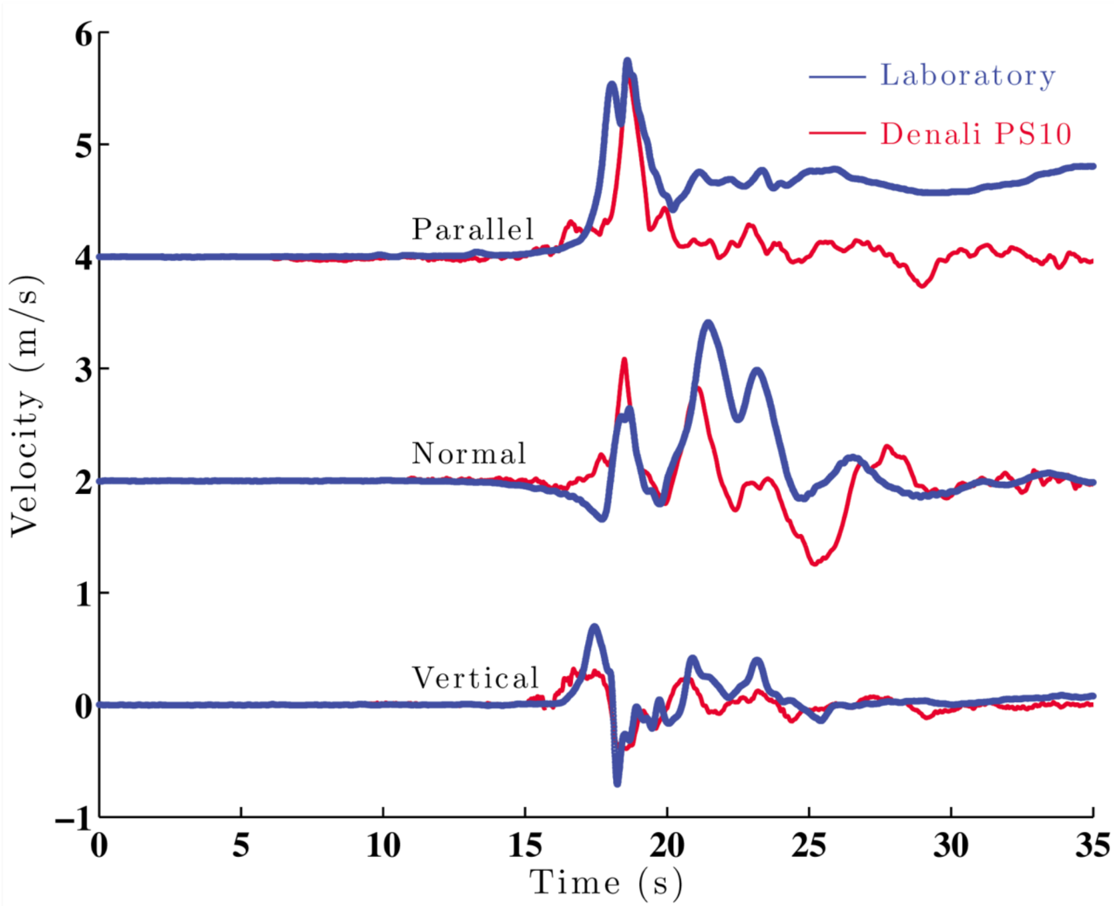
Supershear Earthquake Rupture

Redesigned Building
(designed according to UBC97 provisions)
T_1 = 3.72s; T_2 = 3.51s; T_3 = 2.24s

Identical Buildings at two near-fault locations subjected to excitation from Supershear or Sub-Rayleigh ruptures



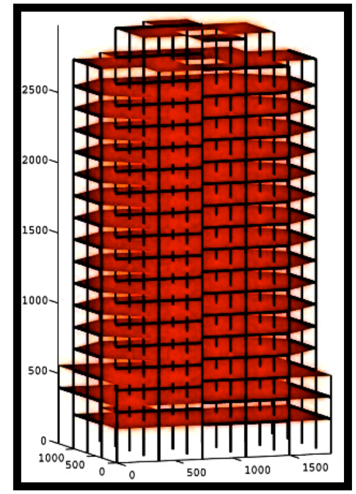
Scaled Laboratory Earthquake Record vs. Denali Pump Station 10



✧*After Scaling , the dominant features of 2002 Denali PS10 record captured by laboratory record*

Summary and Conclusions

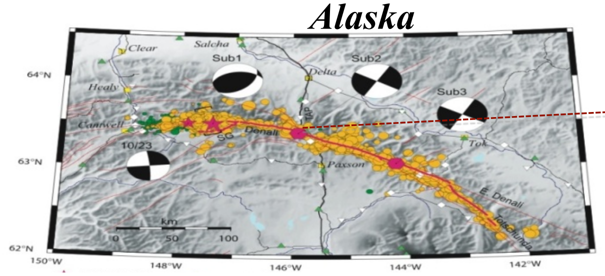
- **We have experimentally shown that:**
  - **In the stable supershear rupture velocity regime, the FAULT PARALLEL ground motion velocity component DOMINATES over the fault normal component.**
  - **In the SUB-RAYLEIGH velocity regime , the FAULT NORMAL ground motion component dominates.**

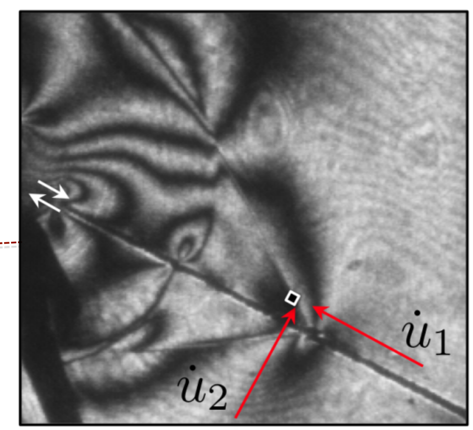


- **We have explored transitions to super-shear and have identified the unique "one-two punch" effect on ground shaking signatures.**

- **We also have demonstrated the potentially catastrophic effect of such supershear ruptures on buildings.**

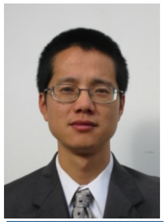
2002 M_w 7.9 Denali, Alaska





ACKNOWLEDGEMENTS

Past and Current Students and Post-Doctoral Scholars







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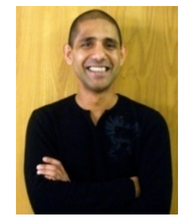

Office of Naval Research (Y.D.S. Rajapakse, Program Monitor)
National Science Foundation (Geophysics)

ACKNOWLEDGEMENTS

Mentors and Collaborators

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