INTERSONIC(or Super-shear) EARTHQUAKES:

What Can Mechanics and Laboratory Earthquakes Teach Us About Real Ones

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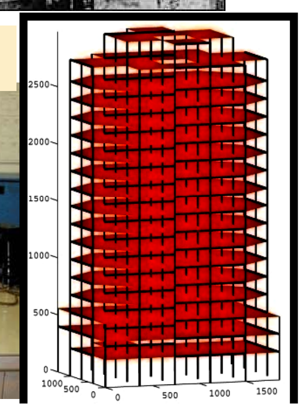
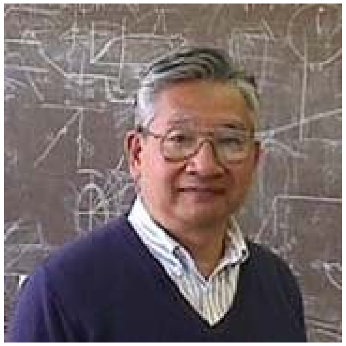
California Institute of Technology

Producing surrogate earthquakes in GALCIT's Laboratory Earthquake Setup



Inter-sonic or Super-shear Earthquakes:
The Seismo-Mechanics research team

Current Collaborators from across Geophysics and Engineering



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Nadia Lapusta
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James R. Rice
Engrg/GPS, Harvard

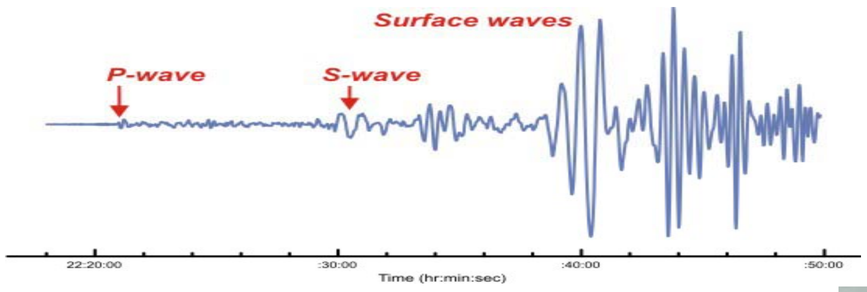
Swaminathan Krishnan
CE/GPS Caltech

Harsha S. Bhat
GALCIT, Caltech, USC

Michael Mello
GALCIT, Caltech

What is a crustal Earthquake?

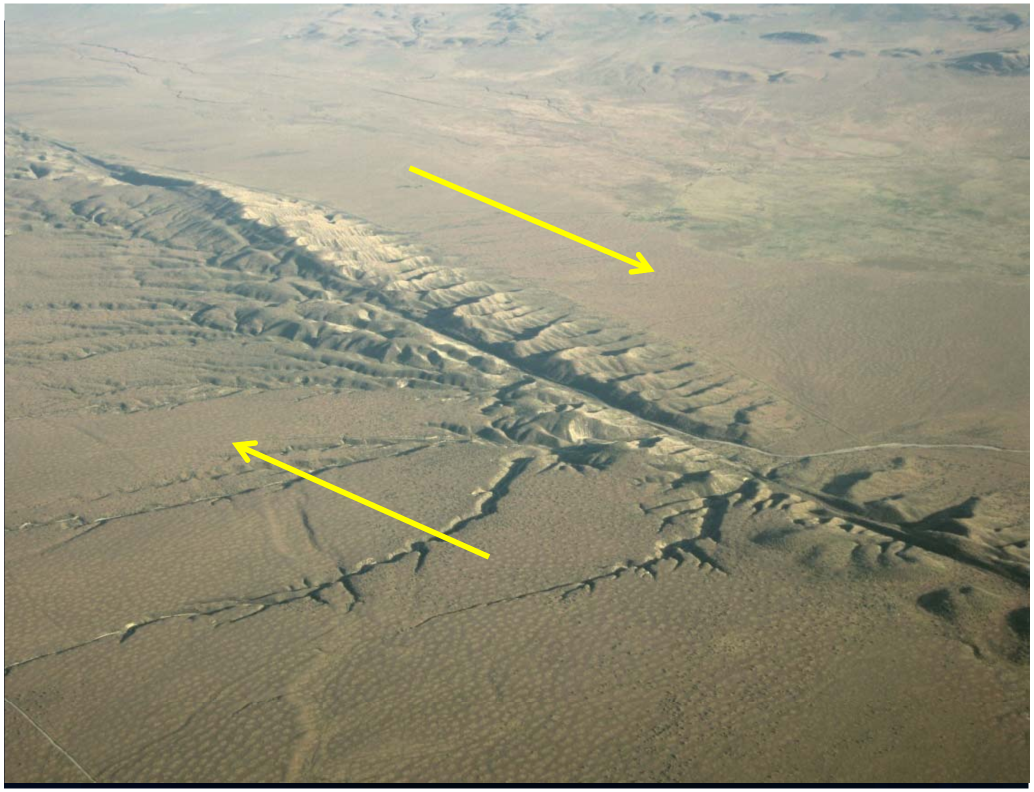
A vertically dipping, strike-slip fault is shown



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.

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

- ***"spontaneous" implies quasi-static tectonic loading and sudden triggering of dynamic slip.***

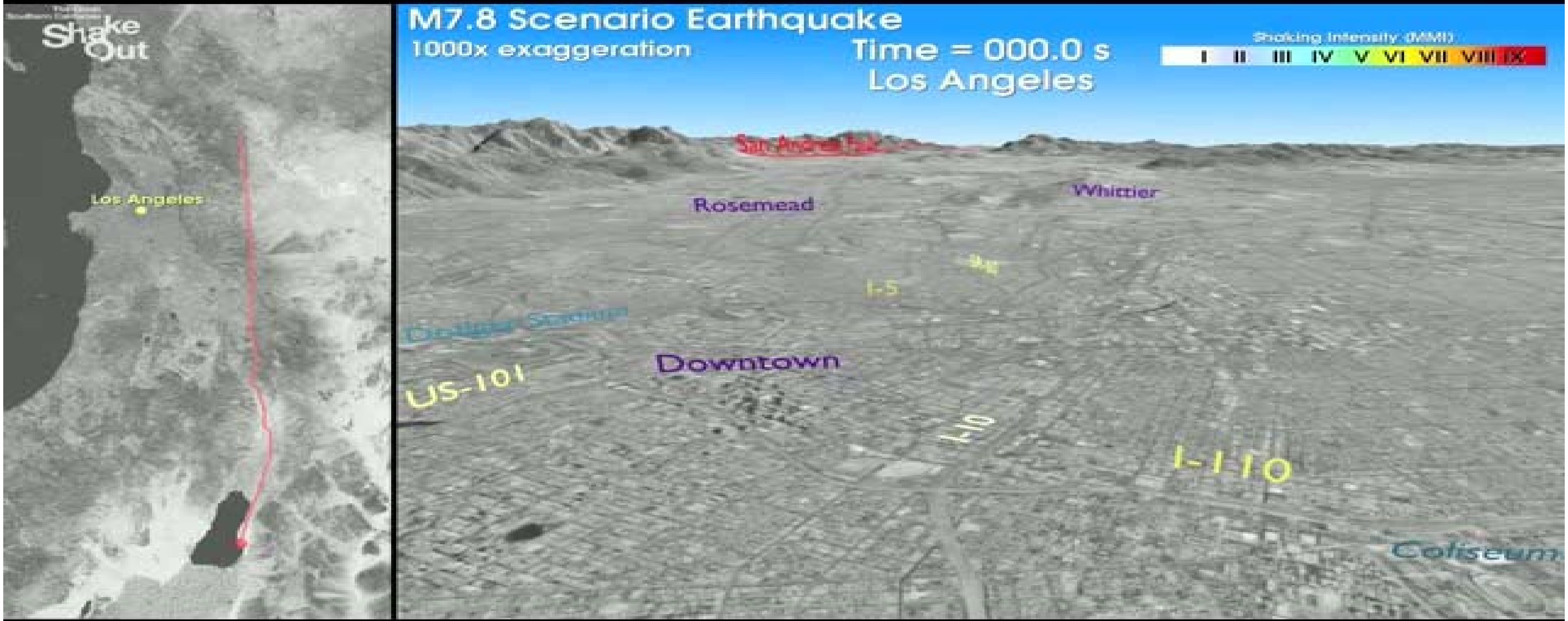


Rate of Relative Plate motion ~ 20mm per year

WHAT IS A RUPTURE AND A RUPTURE SPEED?

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

- Equivalent to fast unzipping - ***SCEC ShakeOut Simulation workgroup***

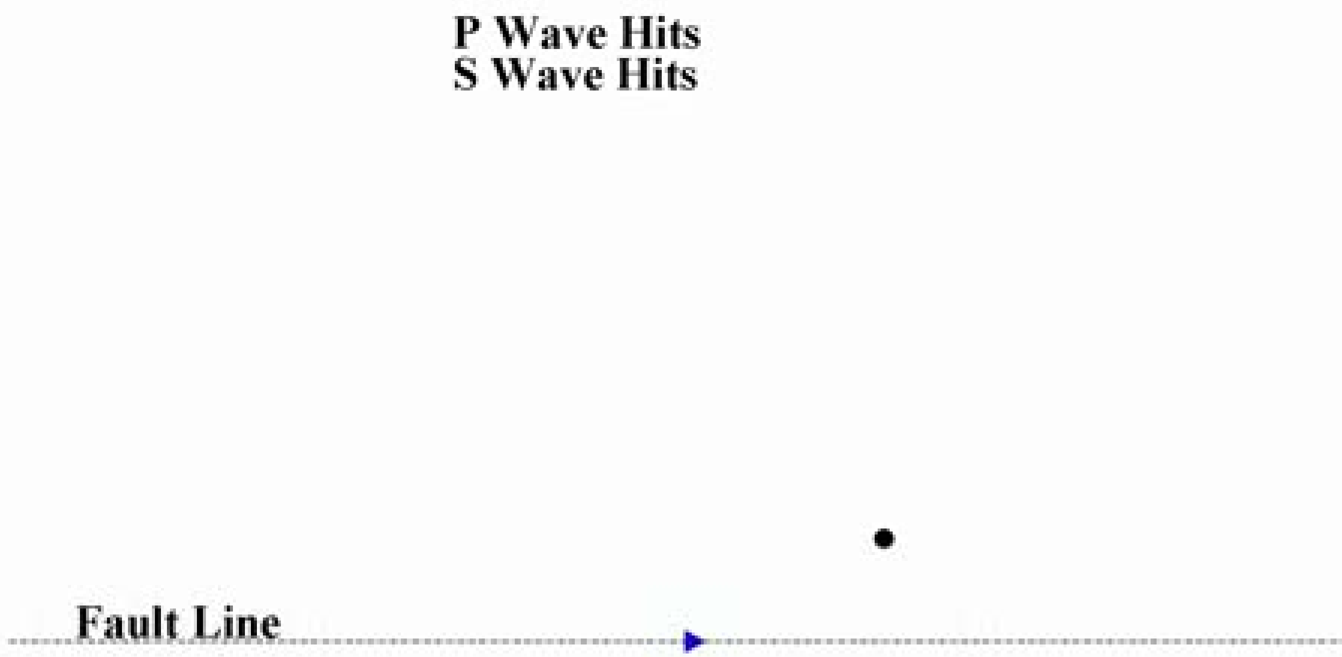


Pressure Wave (c_p ~ 5km/s) , Shear Wave (c_s ~ 3.5km/s) Rayleigh Wave (c_R ~ 3km/s)

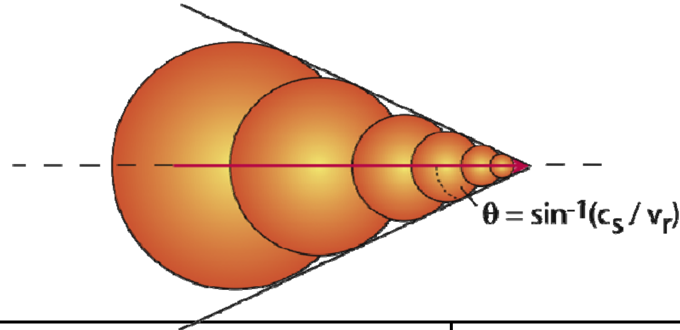
- ***The ground-shaking intensity and radiated energy are related to rupture speed***

How big could the Rupture Speed (v)be ?

P Wave Hits
S Wave Hits


P Wave Hits
S Wave Hits
Fault Line

Evidence of super-shear ($c_S < v < c_P$) rupture speeds
A shear wave Mach Cone only



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)

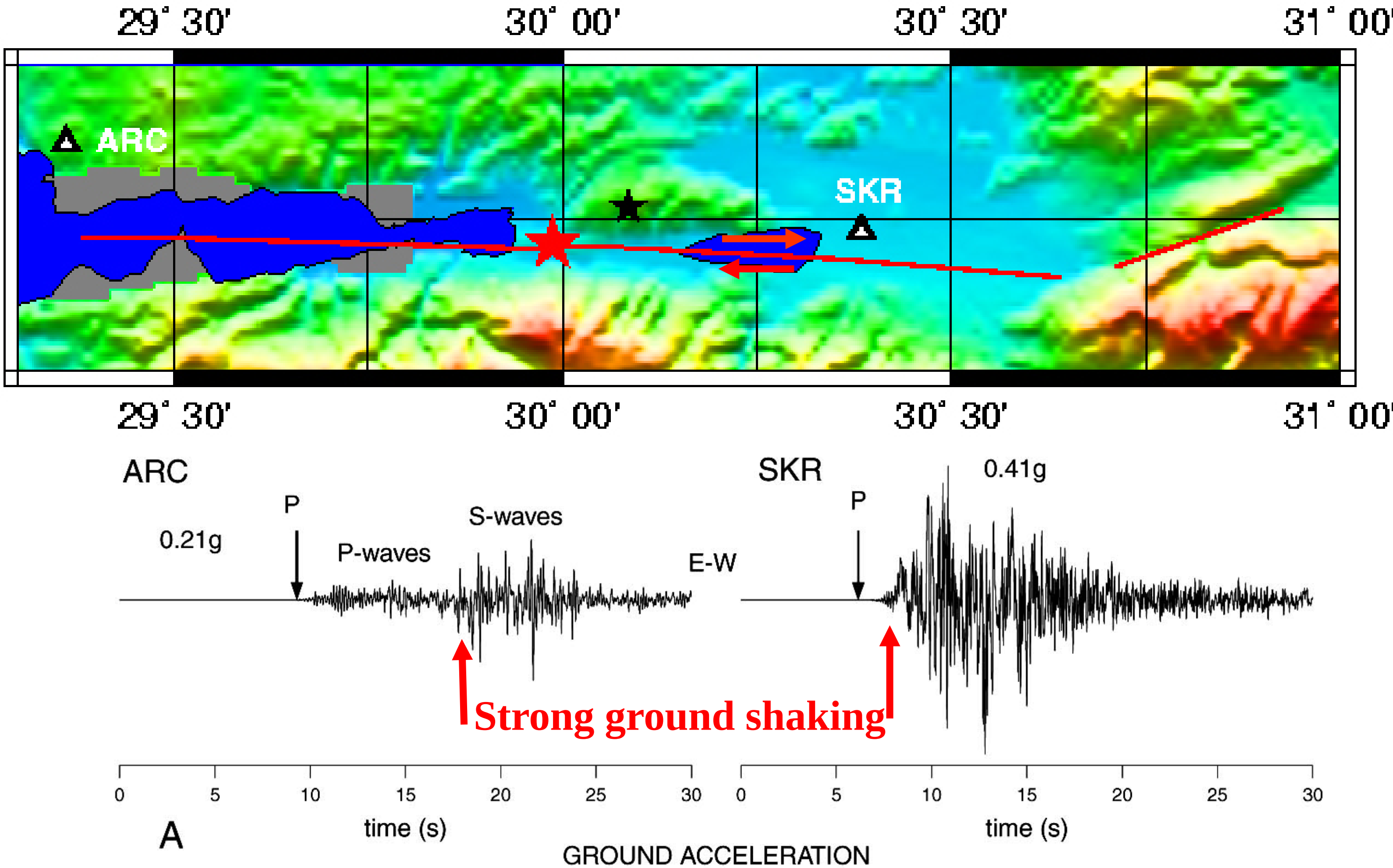
Personal favorites

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

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

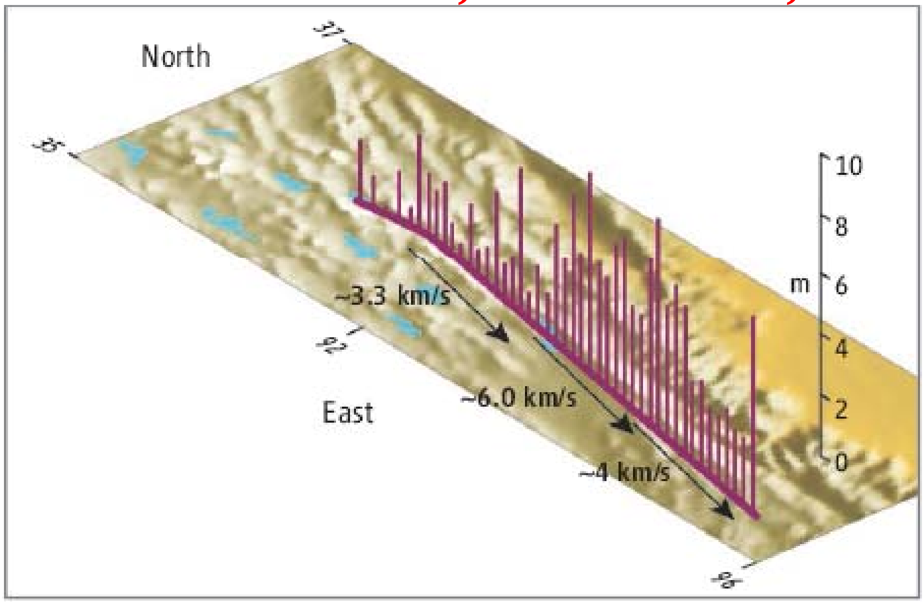
Geophysical Research Letters, 2001

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



Field Evidence of Sub-Rayleigh to Supershear Transition of pulse-like ruptures (Mw 7.8 2001 Kunlunshan, Tibet Earthquake)

Bouchon and Vallee, Science 2003, Robinson, Brough and Das, JGR 2006, Das, Science 2007 , Walker and Shearer, JGR (2009)

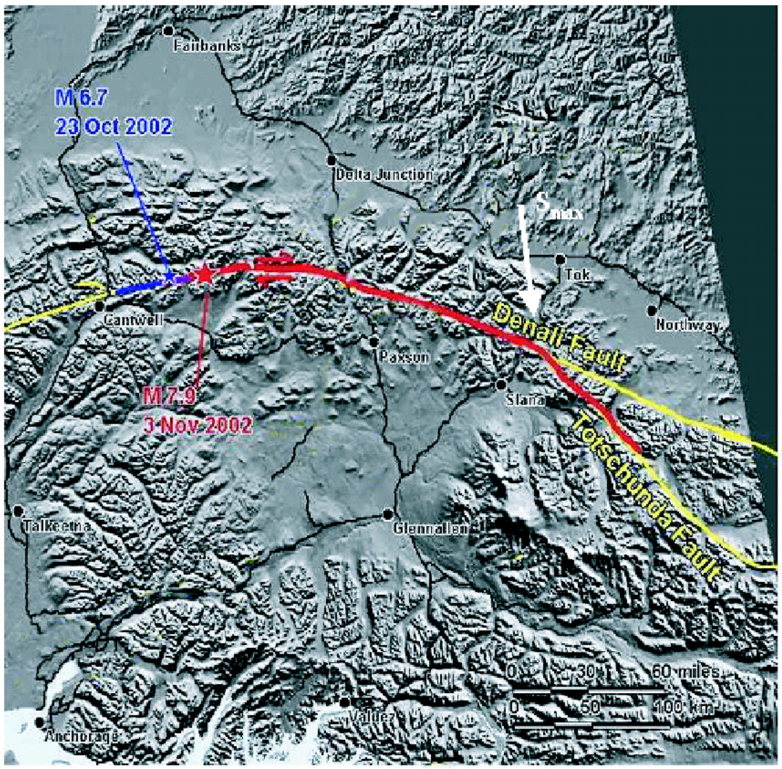


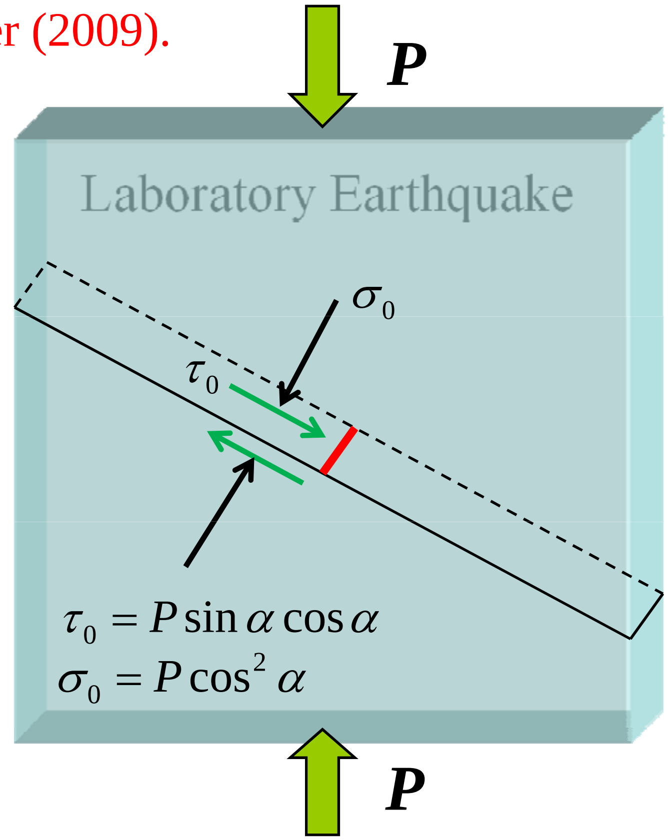
- Unidirectional, left lateral slip occurring over a very long, near-vertical, strike –slip fault segment.(slip:7-8m max)
- Eastward pulse-like propagation over a 400 km fault segment
- Sub-Rayleigh over first 100 km (2.8-3.3 km/s)
- Transition to supershear (6 km/s ~P-wave speed)

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).



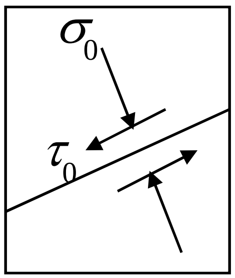


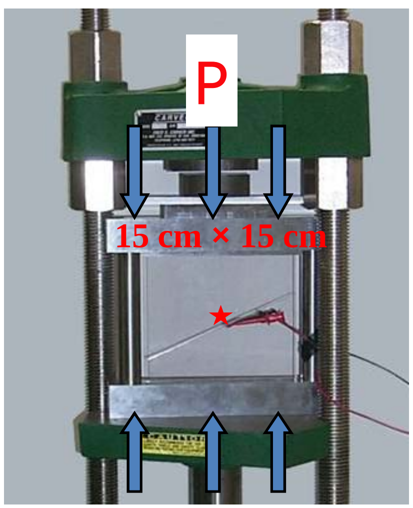
- **Rock** → **Photoelastic Polymer**
- **Fault** → **Inclined Contact Interface**
- **Tectonic stress** → **Far Field Load**
- **Hypocenter** → **Triggering Site**

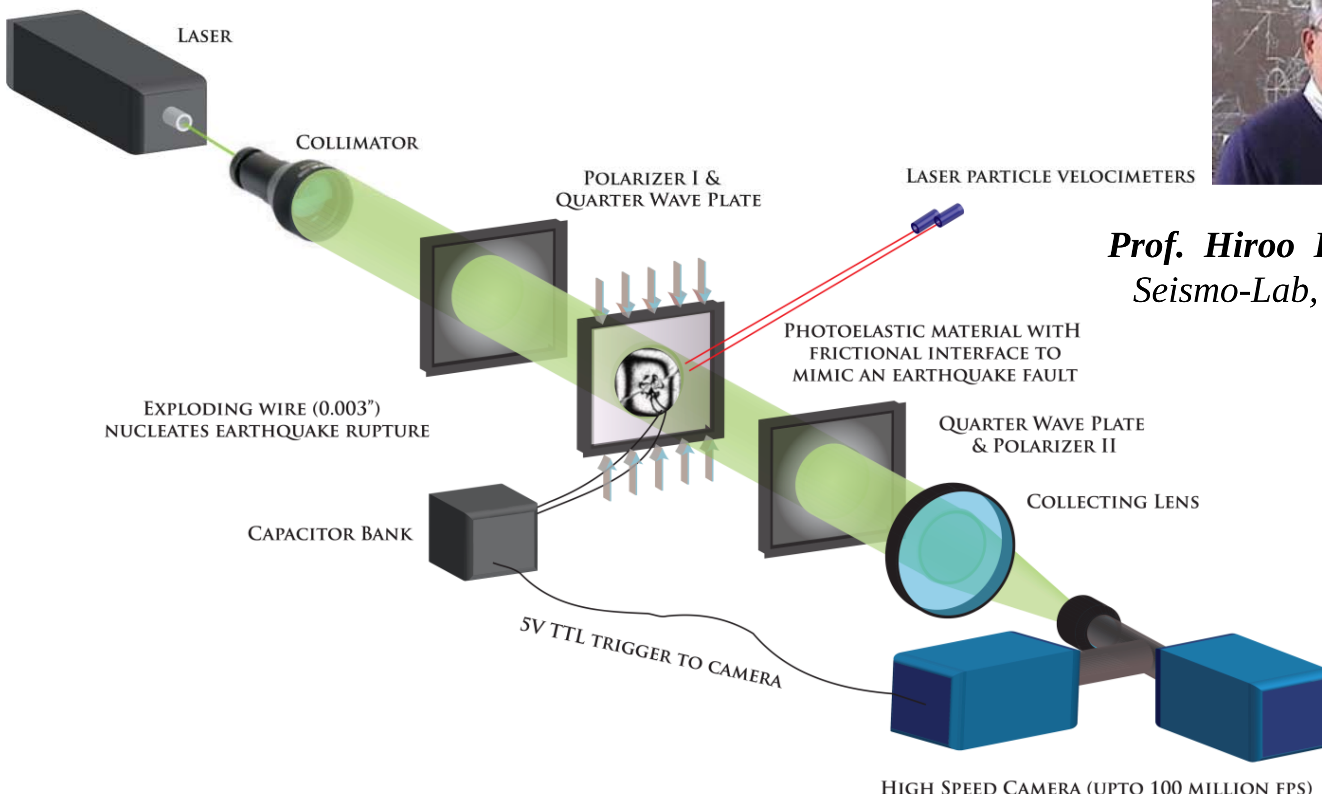
Experimental setup that mimics pre-stressed faults

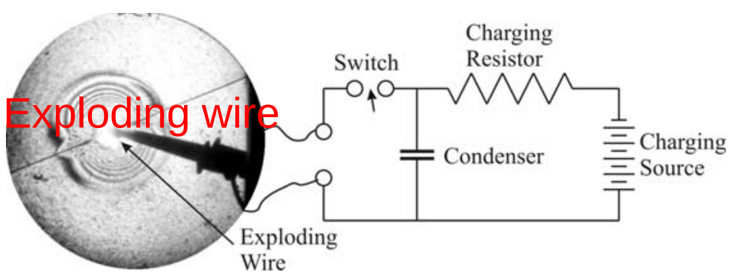
Non-dimensional shear prestress = $\tau_0 / \sigma_0 = f_0 = \tan \alpha$

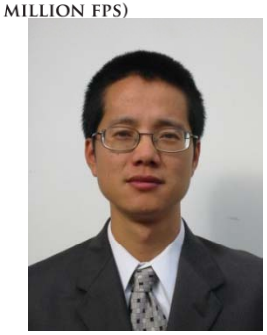
Prof. Hiroo Kanamori
Seismo-Lab, Caltech











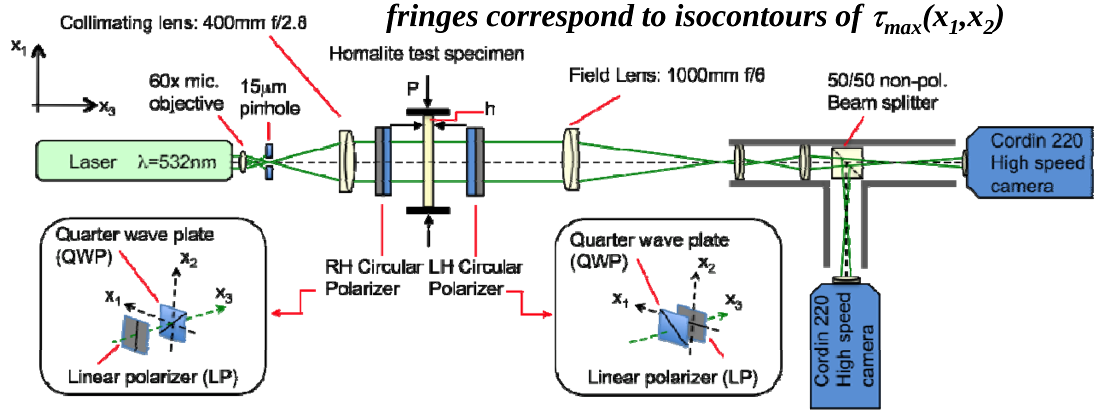
Kaiwen Xia
CE, Univ. of Toronto

(K. Xia, AJ. Rosakis and H. Kanamori, Science 2004)
(K. Xia, A.J. Rosakis, H. Kanamori and J.R. Rice, Science 2005)

Laboratory Earthquake Experiment

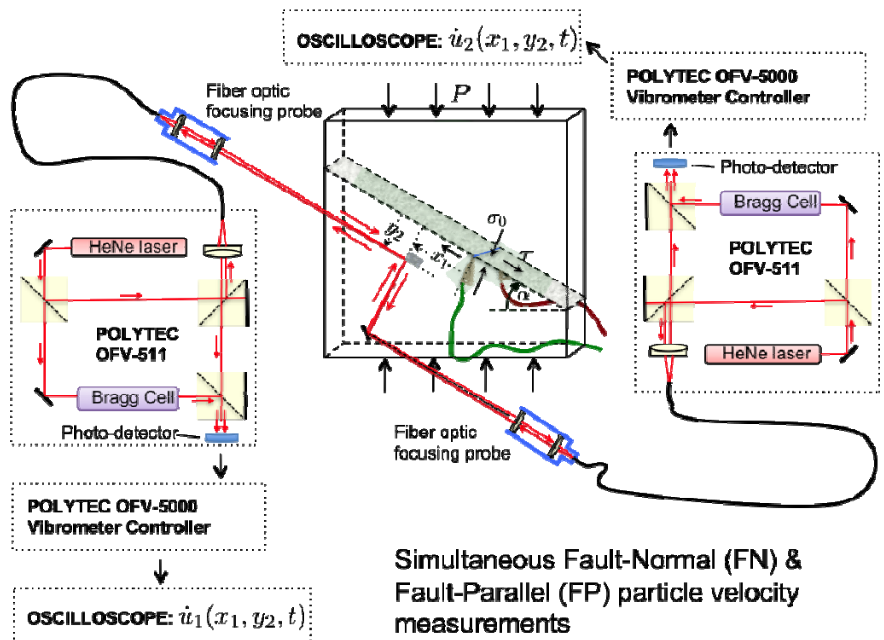
Homalite LE specimen under static load

Photo-elastic interferometer with high speed imaging: fringes correspond to isocontours of $\tau_{max}(x_1,x_2)$



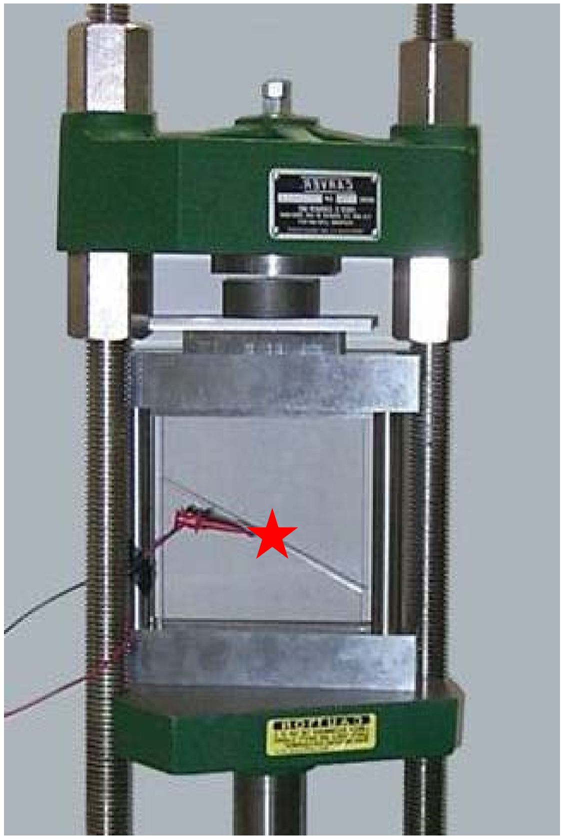
High Speed cameras: 16 image frames

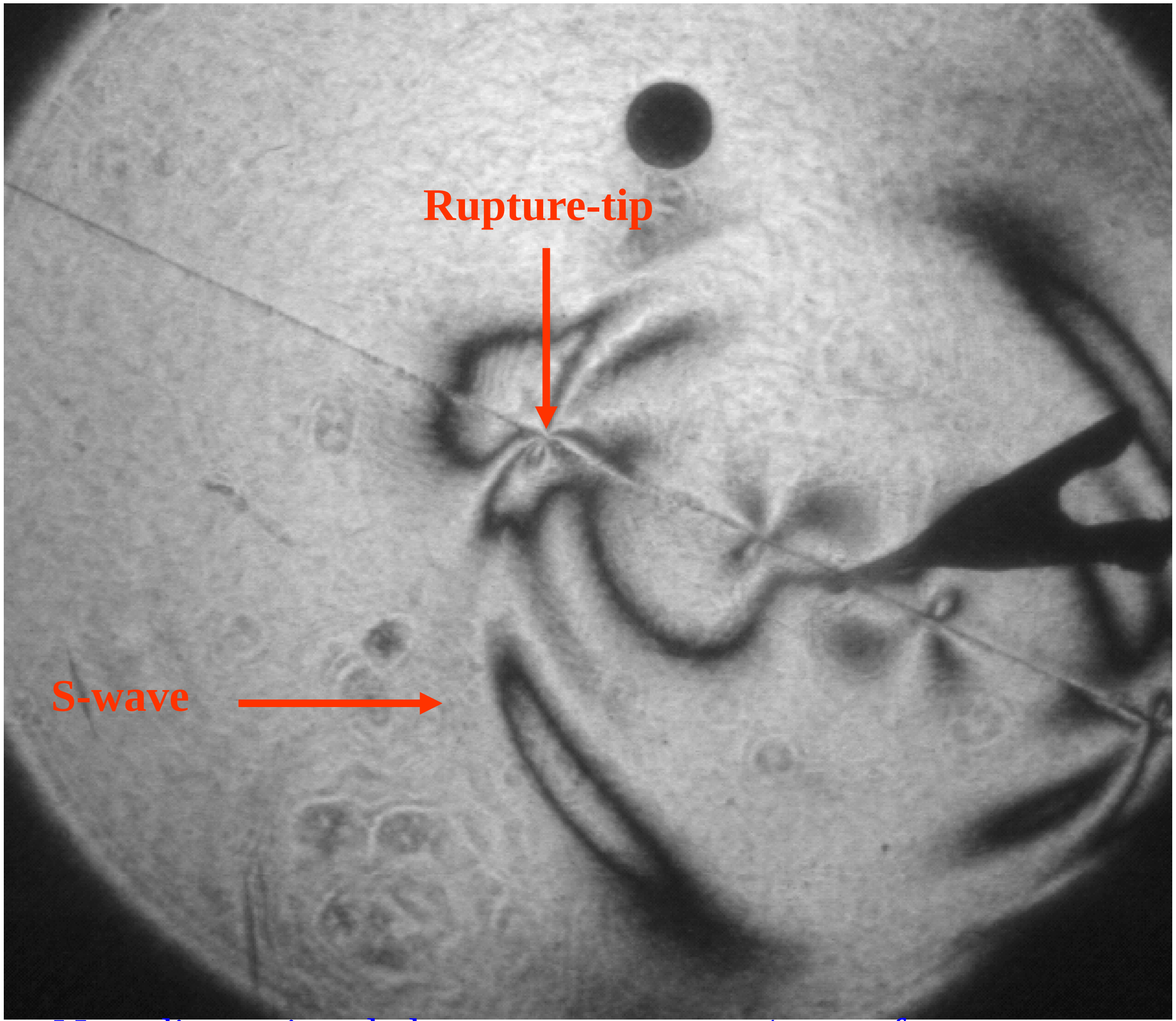
Heterodyne laser interferometers: Enable continuous particle velocity records with high temporal resolution



Classical ***Sub-Rayleigh*** *Rupture*
Angle=25°, Pressure=7MPa T=30μs

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

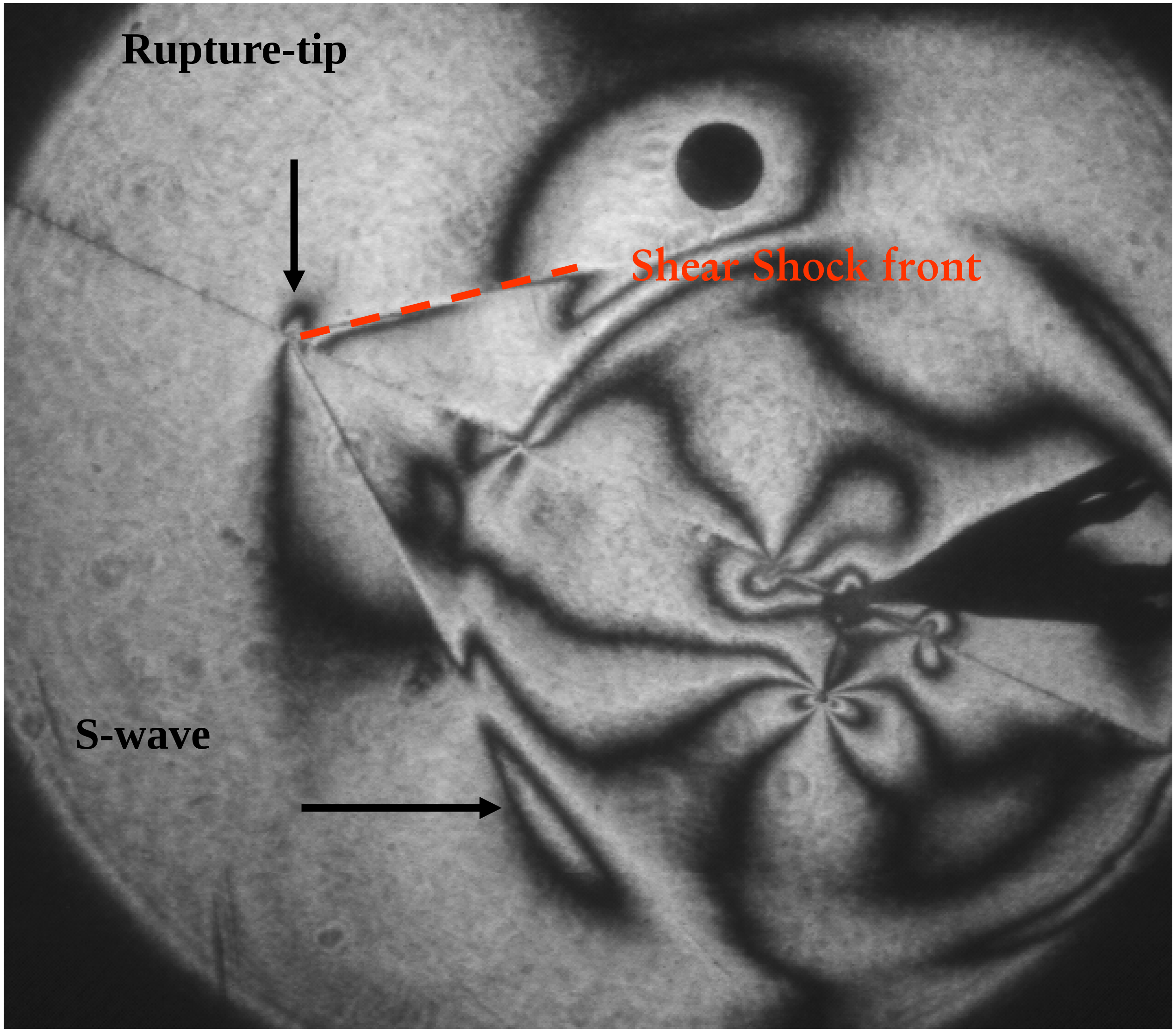




Non-dimensional shear prestress $= \tau_0 / \sigma_0 = f_0 = \tan\alpha$

Supershear or *Intersonic, Rupture*
Angle=25°, Pressure=13MPa   T=30μs

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

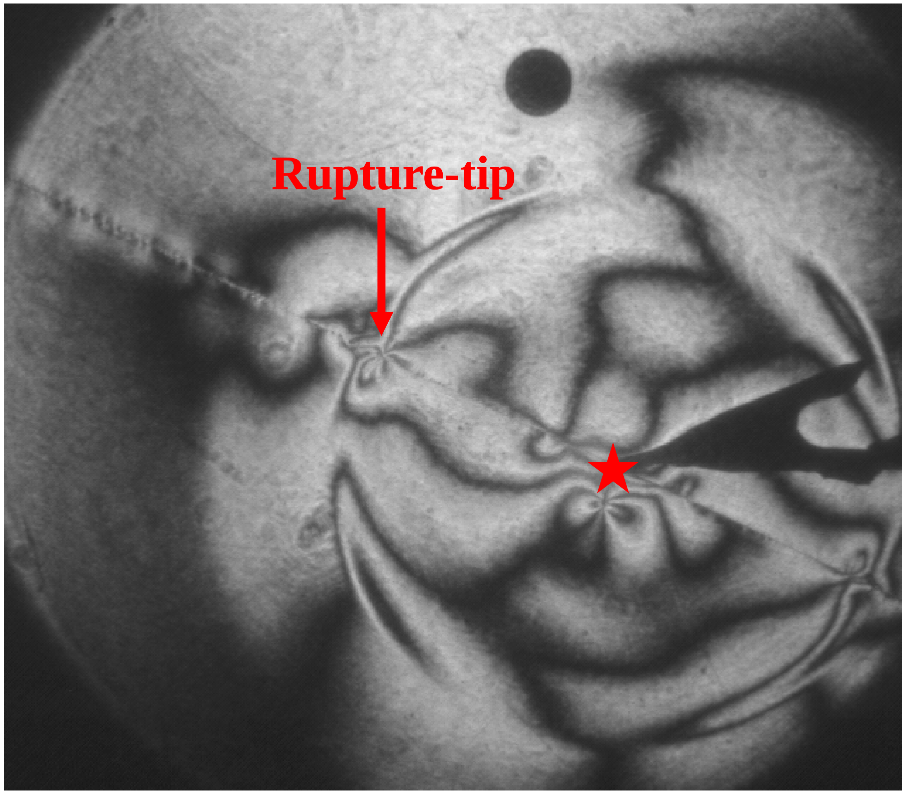


Transition: From Sub-Raleigh to Supershear

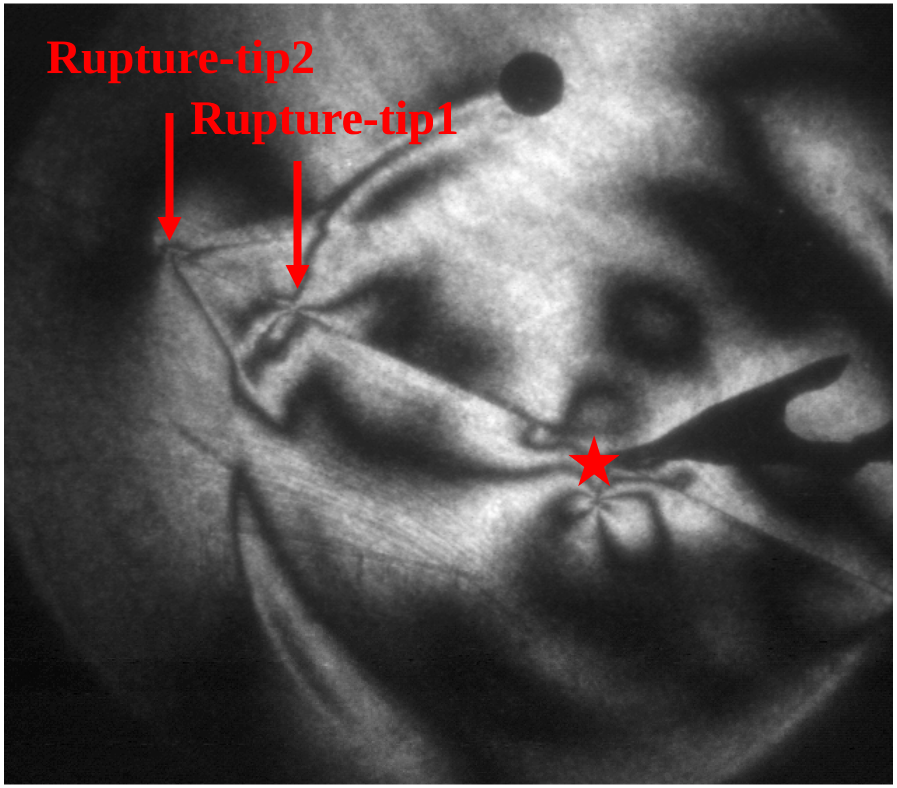
(*Xia, Rosakis and Kanamori, Science 2004*)

Angle=25°, Pressure = 10MPa: transition length L = 20mm

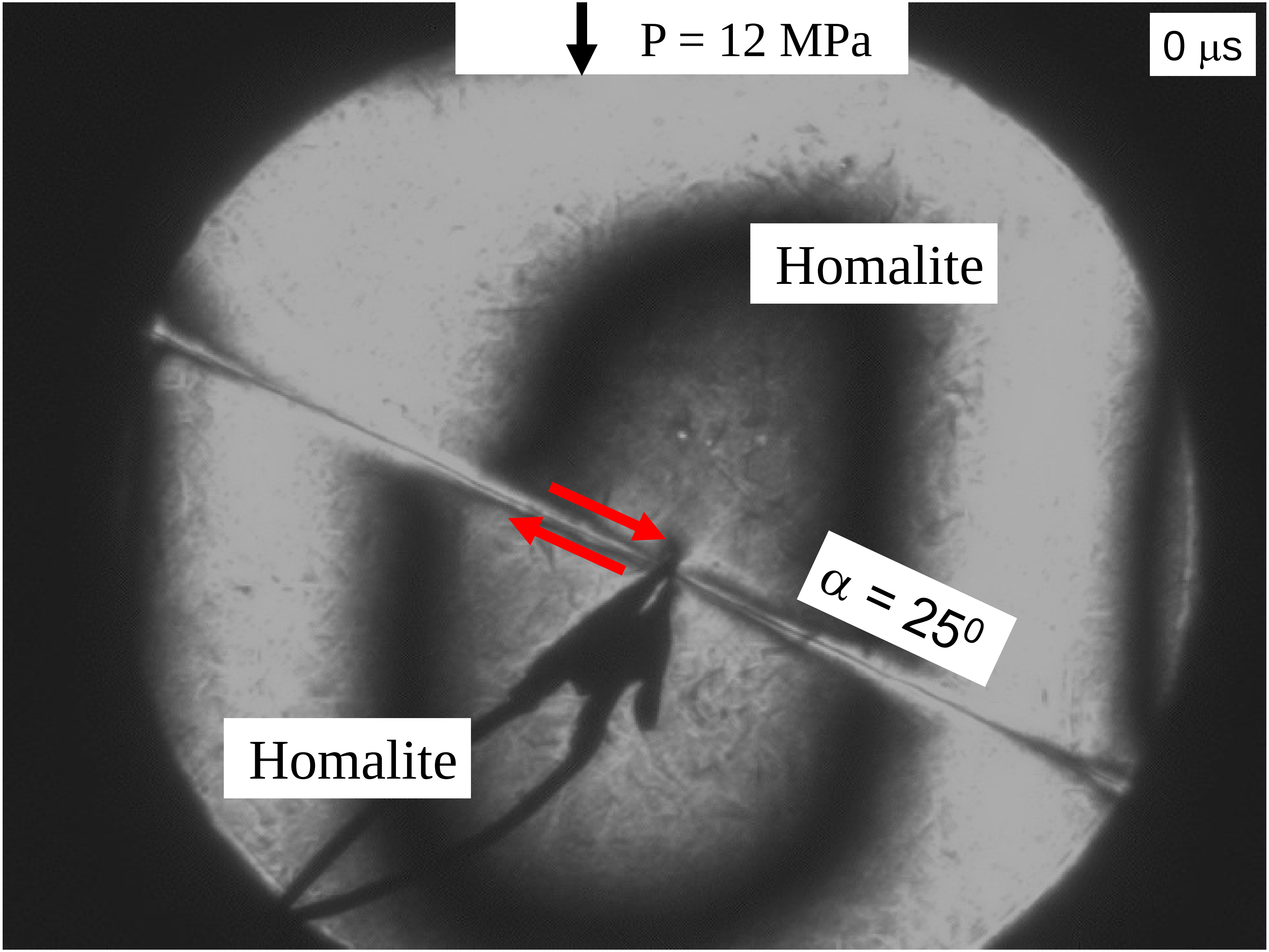
2001 Kunlunshan, Tibet Earthquake: transition length L = 100Km

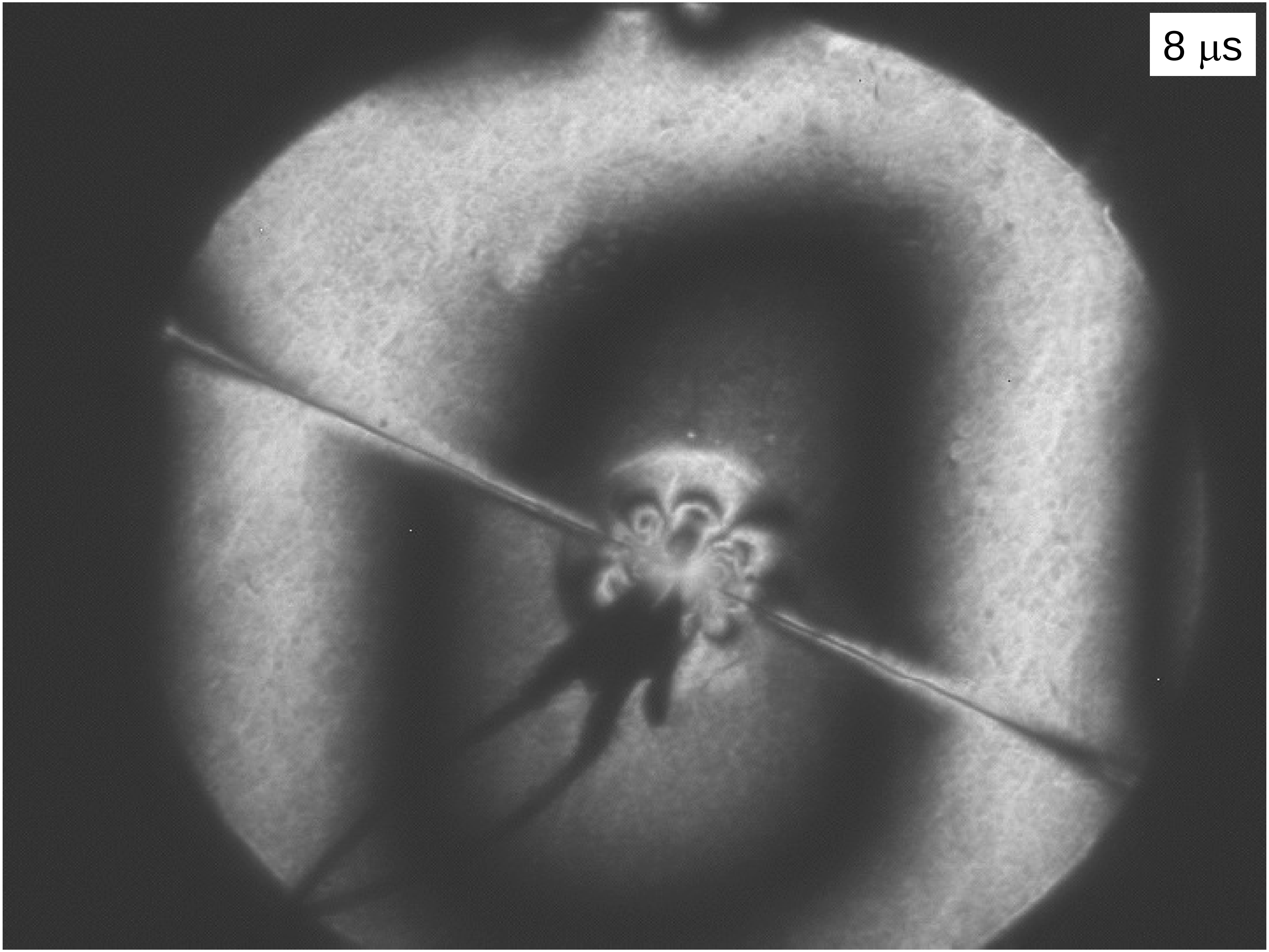


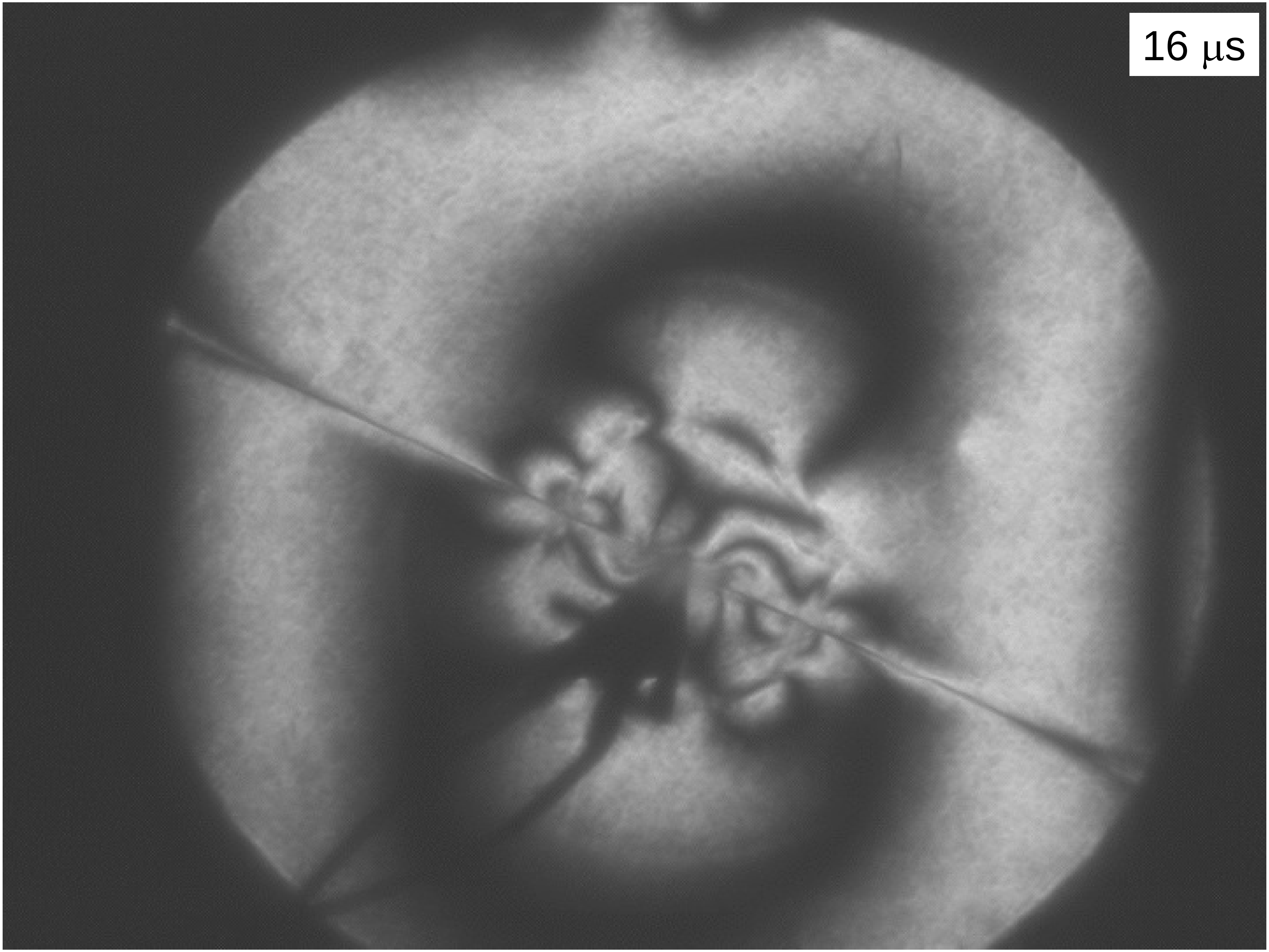
T = 30μs

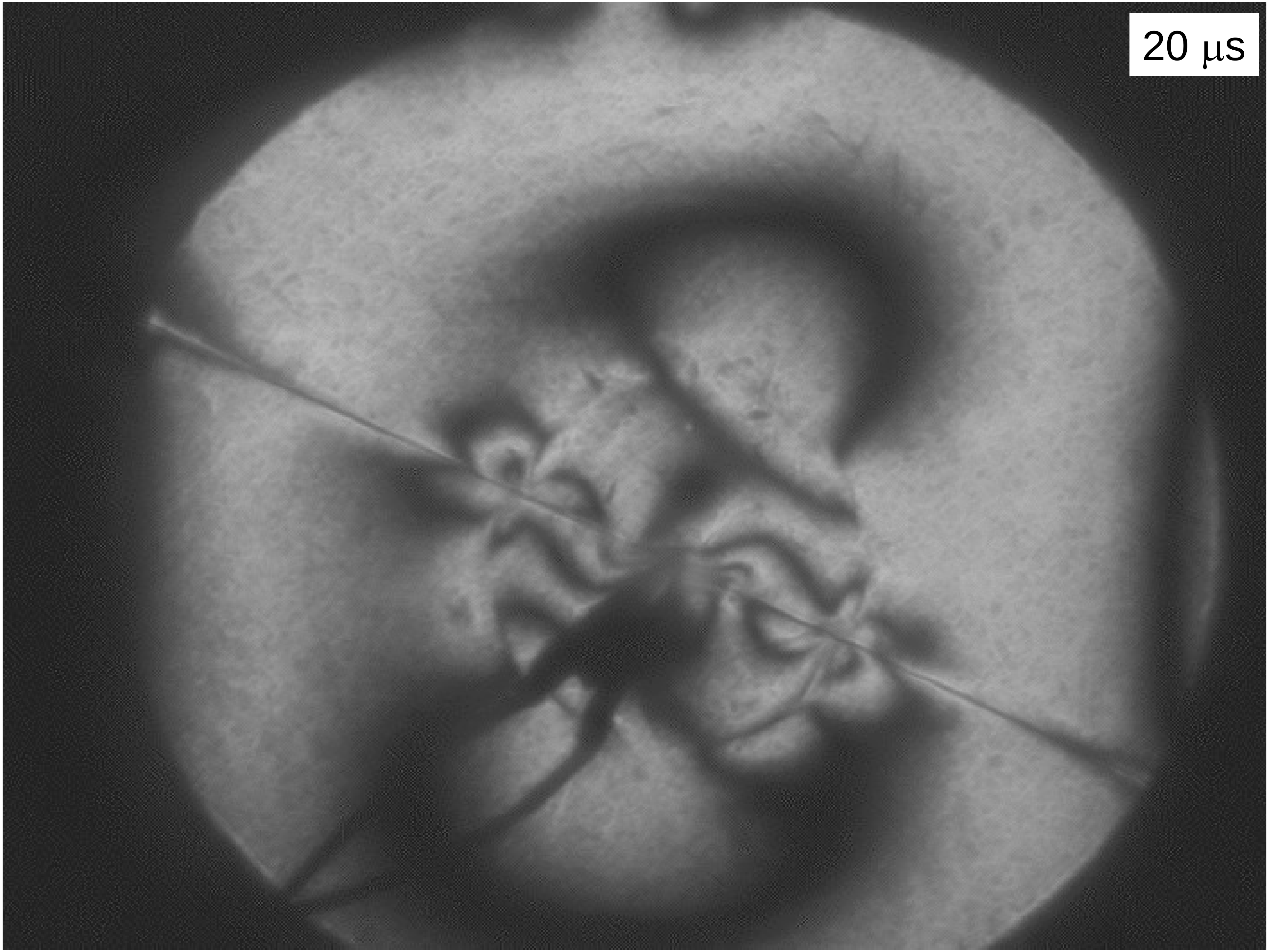


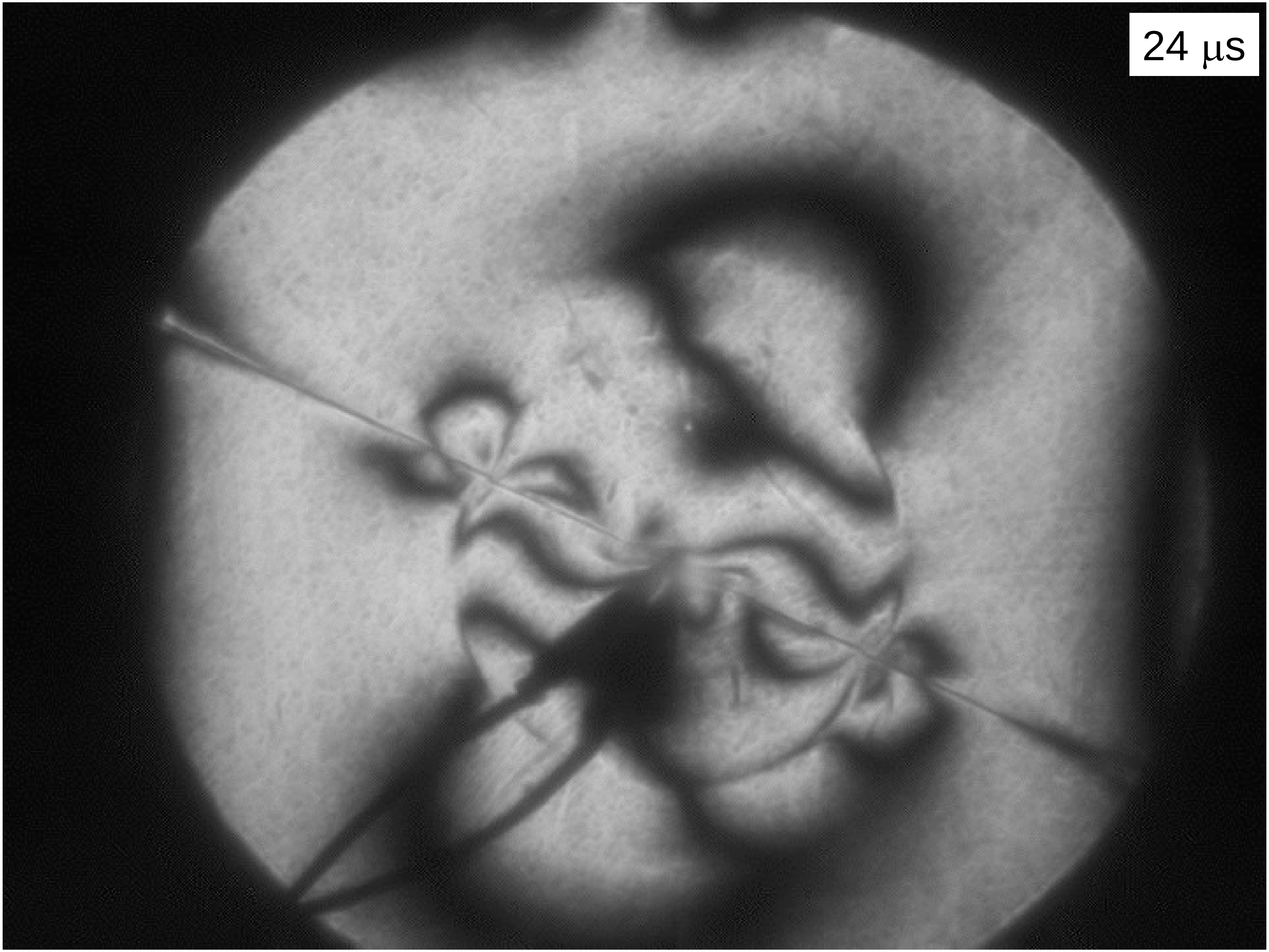
T = 38μs

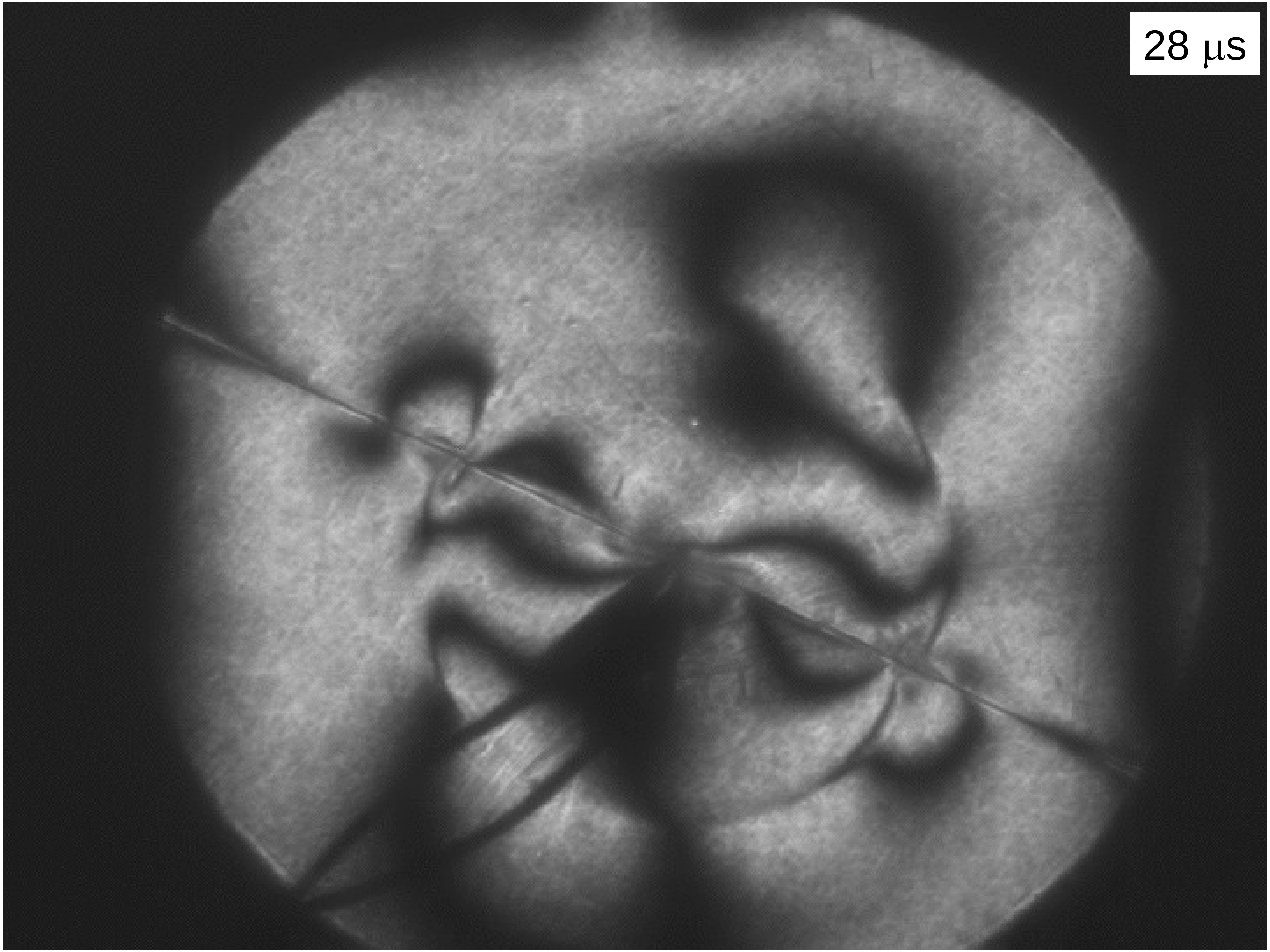

P = 12 MPa
0 μs
Homalite
α = 25⁰
Homalite

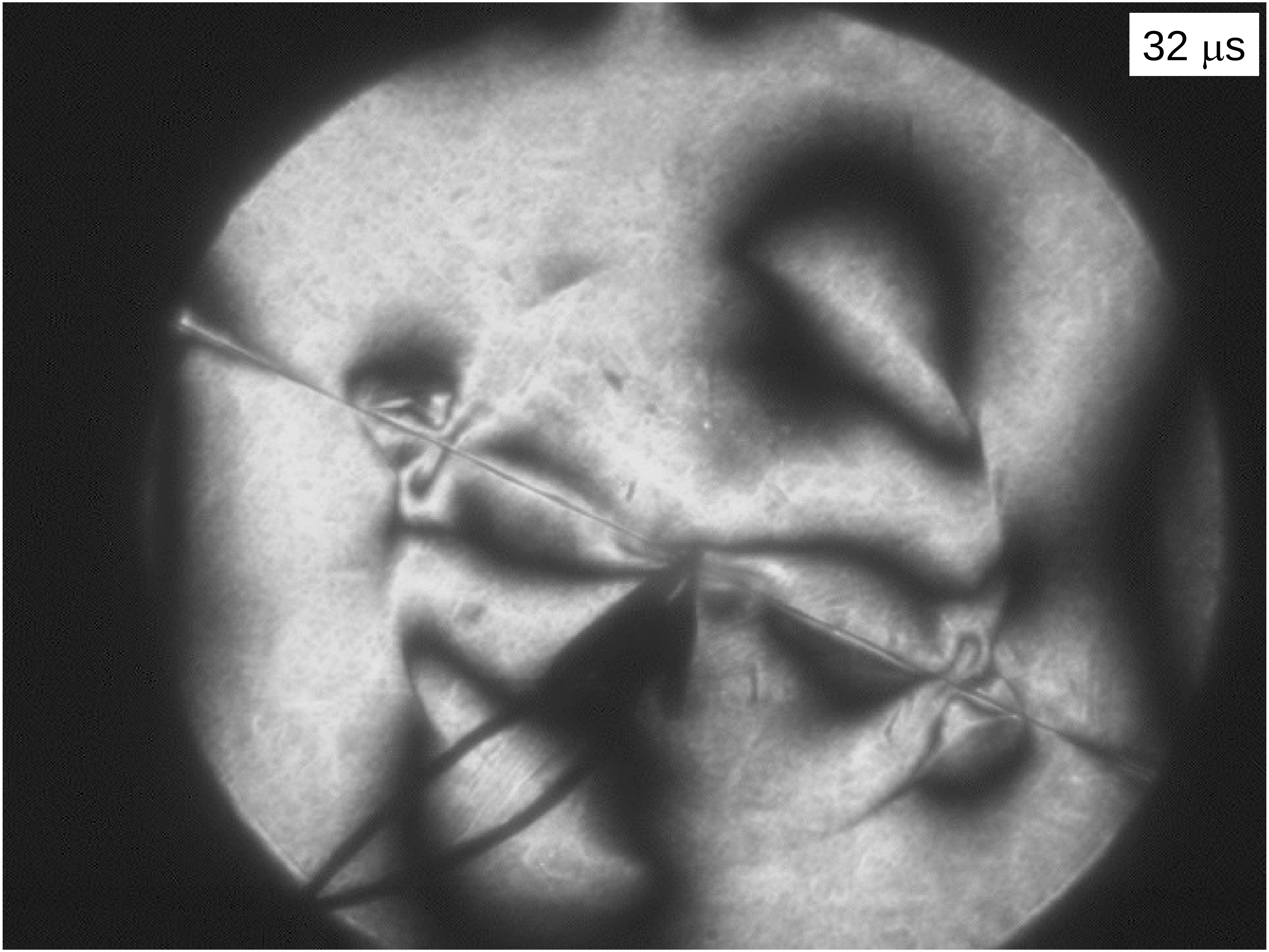

8 µs

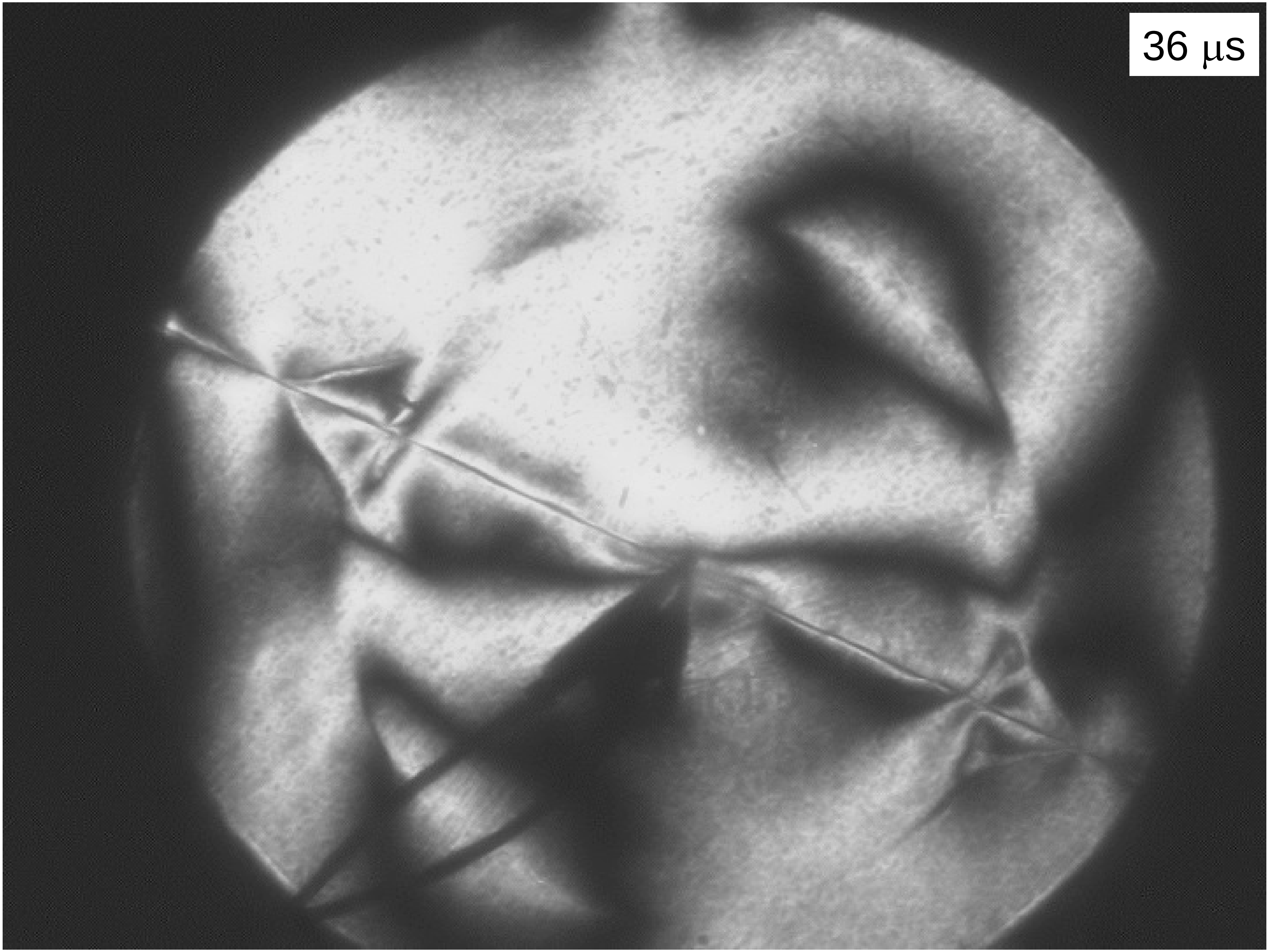

16 μs


20 μs


24 μs


28 μs

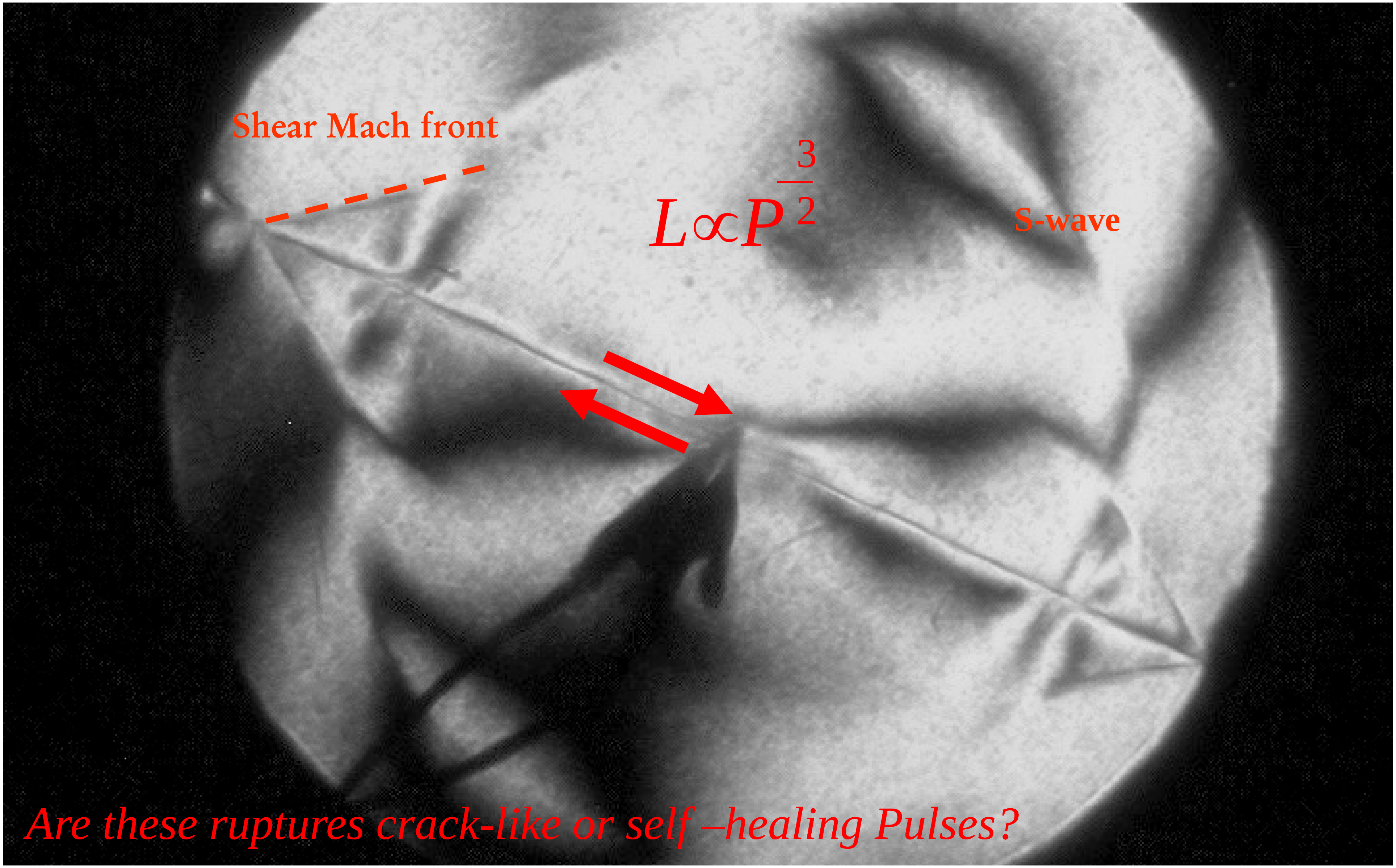

32 μs


36 µs

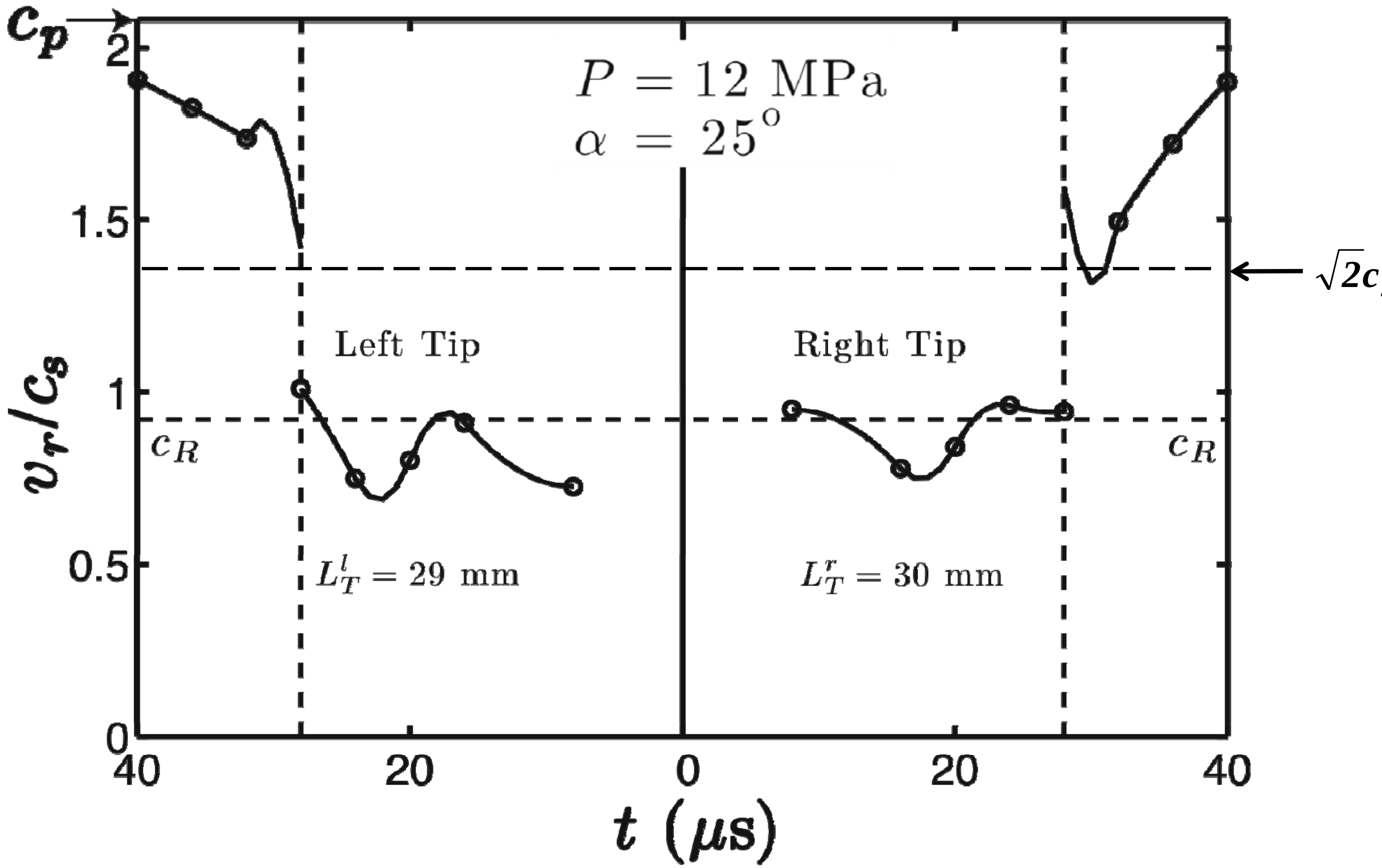
40 μs

Transition: From Sub-Rayleigh to Supershear

(Xia, Rosakis and Kanamori, Science 2004)

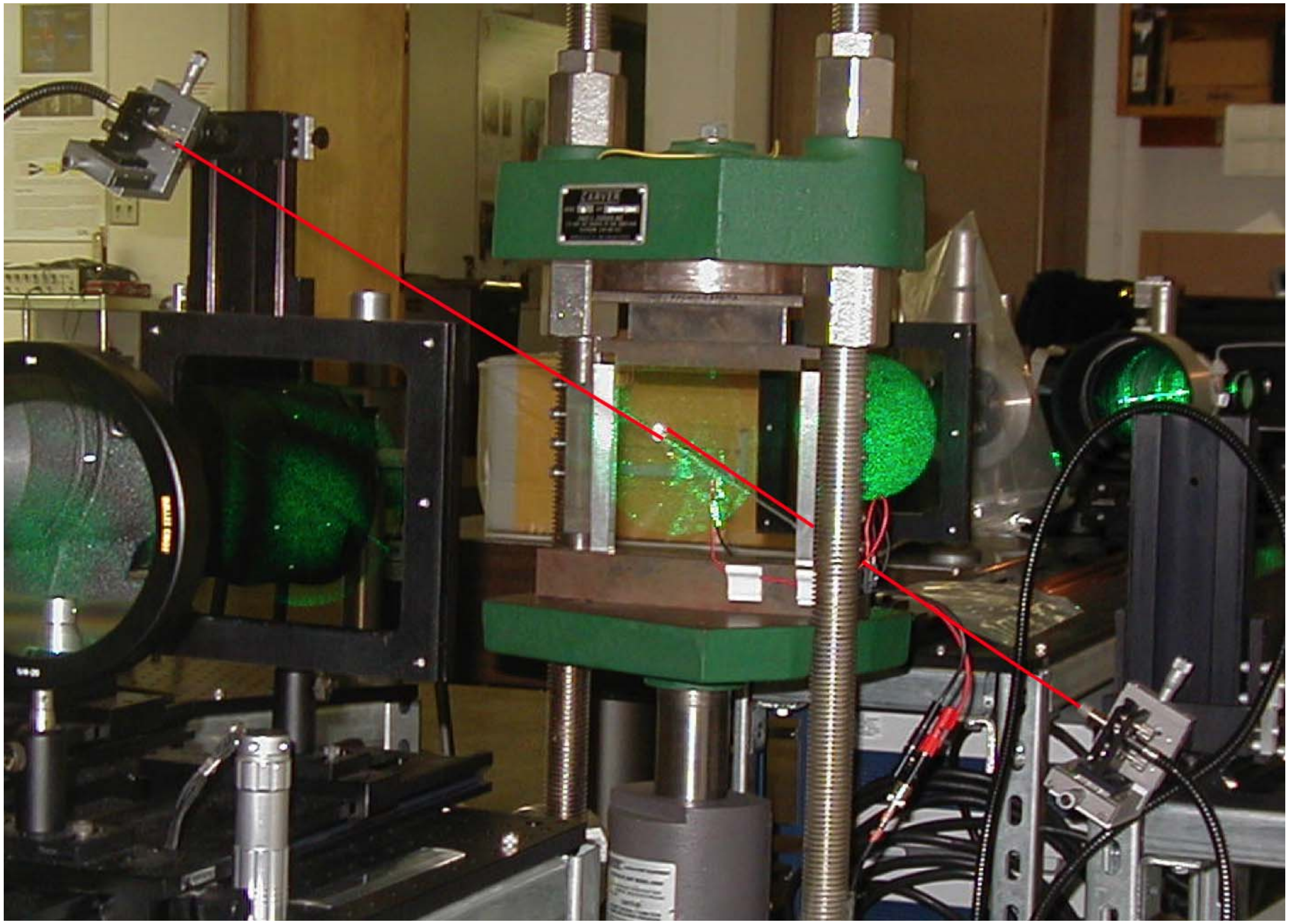


Equi-bilateral Rupture History



Crack-Like v.s Pulse-Like Ruptures: Using laser interferometers for slip Velocity measurements and rupture mode determination.

Xiao Lu, Nadia Lapusta, and Ares Rosakis, *PNAS*, 104(48), 2007



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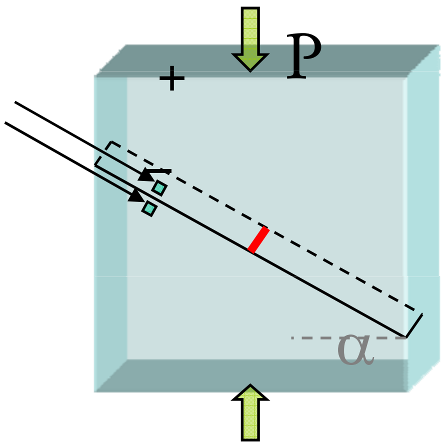
Simultaneous Pair of Fault Parallel Velocity Measurements just above and below the fault line

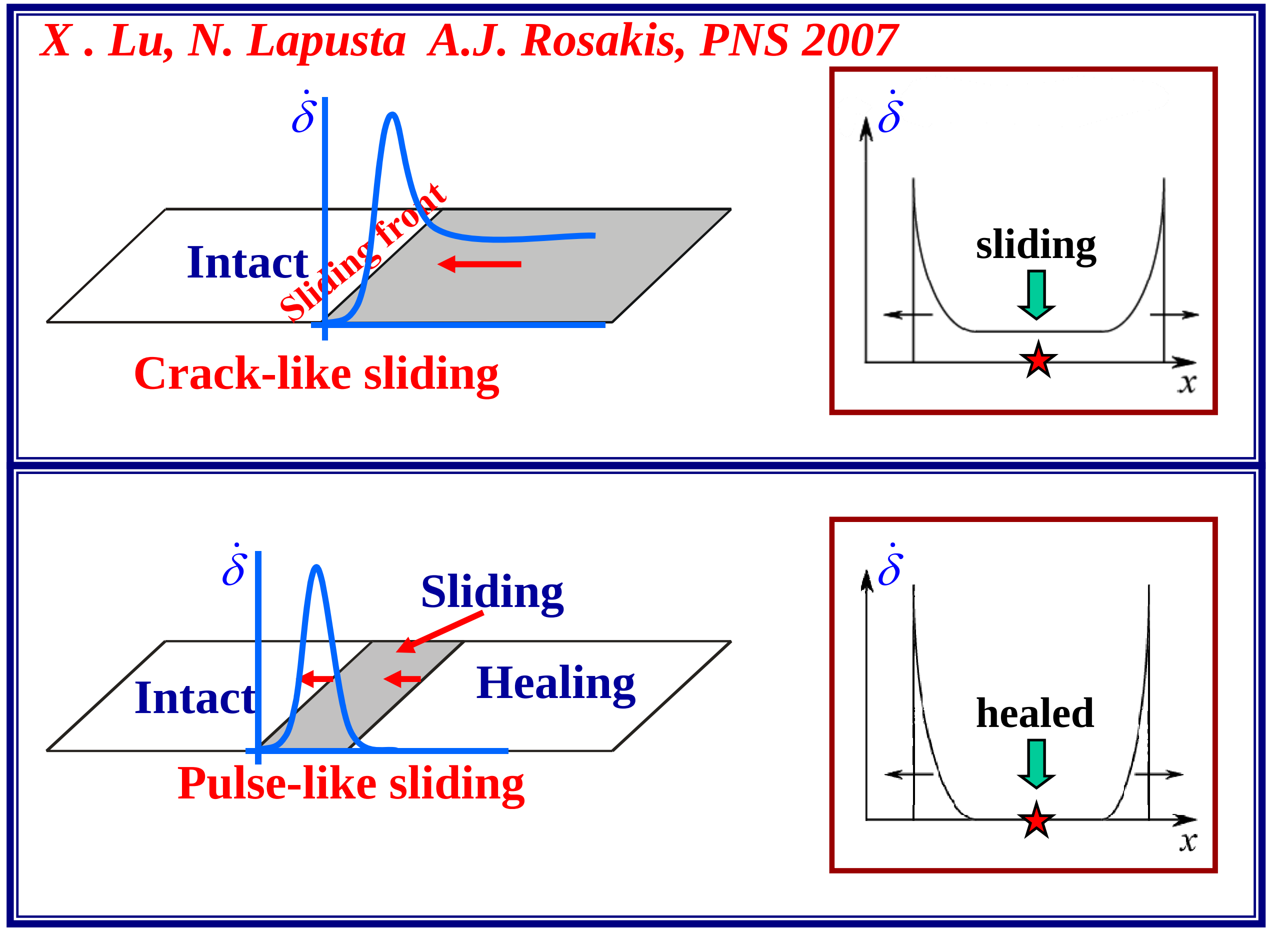
Using particle velocimeters to determine rupture mode

Earthquakes often occur as pulses of slip, called WEERTMAN or HEATON PULSES

crack-like and pulse-like



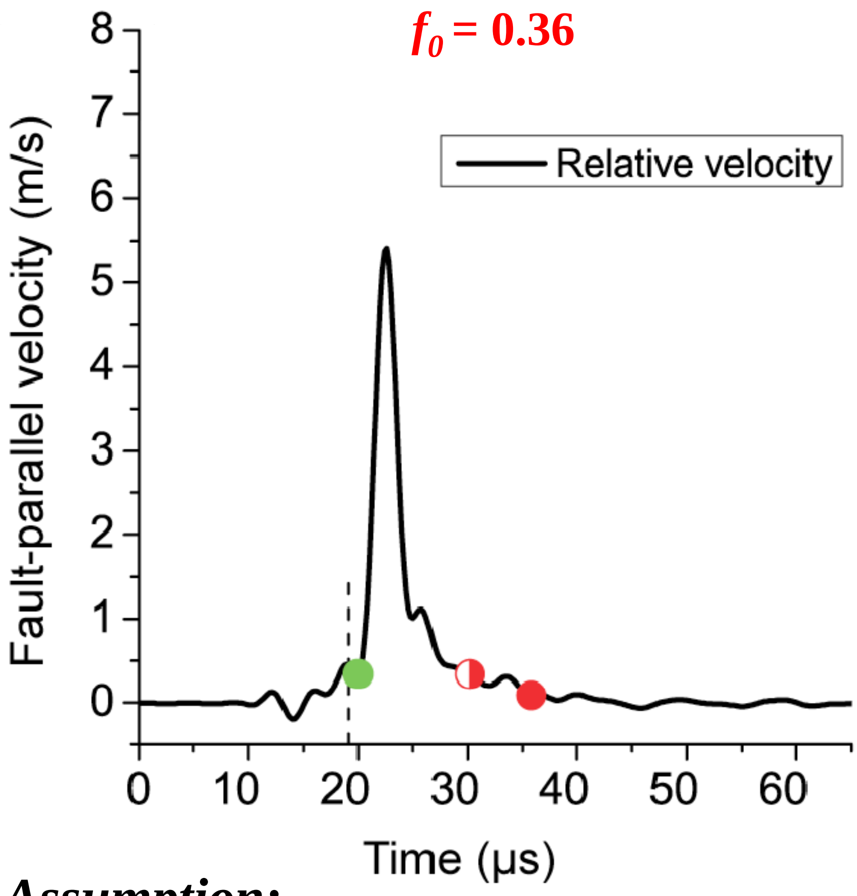
$$\dot{\delta} \equiv \dot{u}_1^+ - \dot{u}_1^-$$

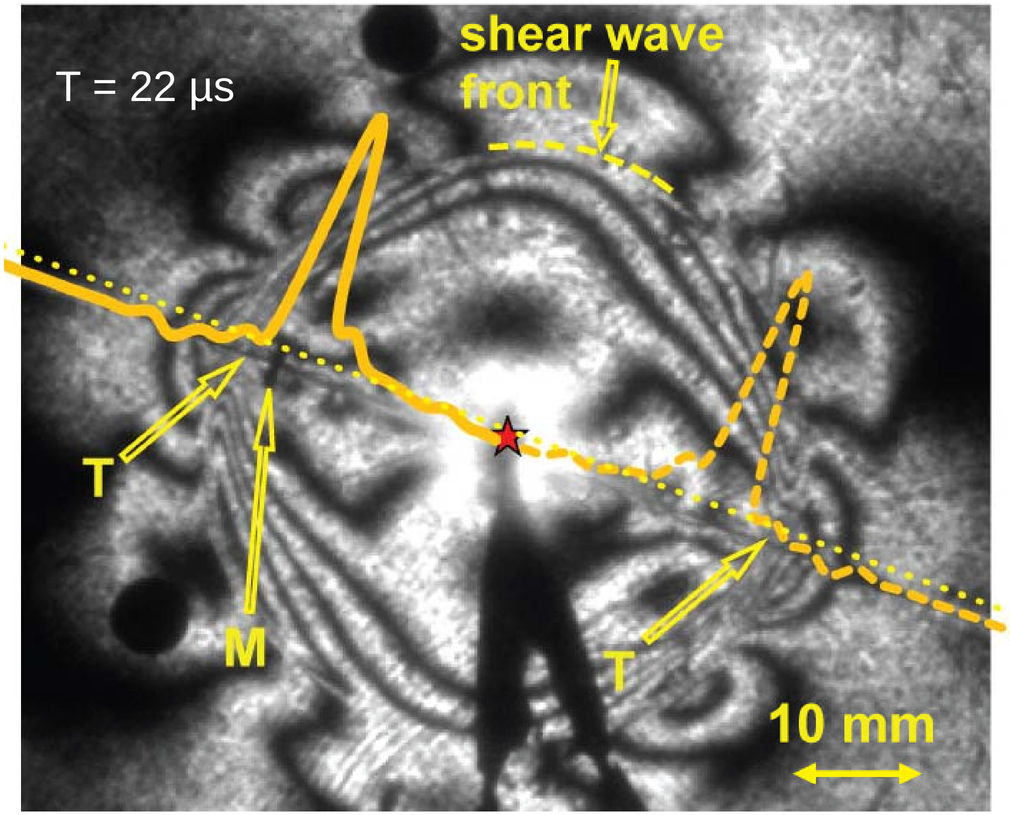


- Several proposed explanations for pulse-like rupture
  - Velocity-weakening friction (eg. Heaton, 1990, Perrin et al. 1995, Zheng and Rice, 1998)
  - Interaction with fault geometry and local heterogeneities (eg. Day, 1982, Johnson, 1992)
  - Normal stress variation, in particular due to bi-material effect (eg. Weertman 1980, Andrews and Ben-Zion, 1997)

First experimental observation of pulse-like rupture (Narrow pulse) on pre-stressed faults

α = 20 degrees, P = 10 MPa, velocity measured at 20 mm





Assumption:

Rupture propagates with Rayleigh wave speed (1155 m/s)

X. Lu, N. Lapusta, and A. Rosakis, *PNAS*, 104 (48), 2007

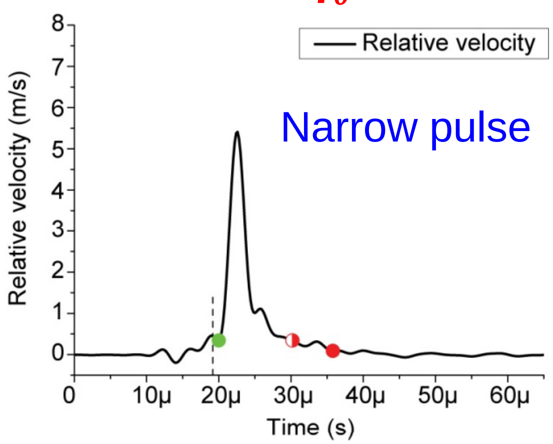
Non-dimensional shear prestress $= \tau_0 / \sigma_0 = f_0 = \tan\alpha$

Transitioning from Pulses to Cracks (P=10 MPa)

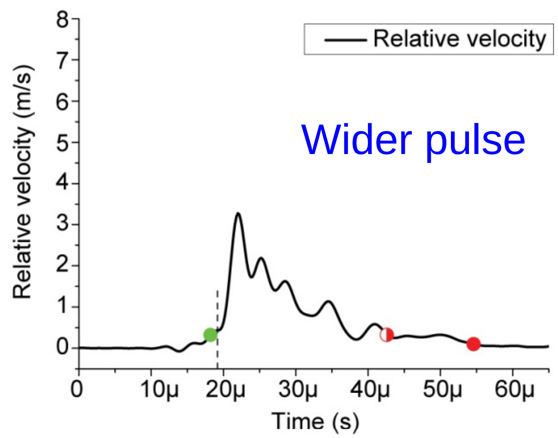
X . Lu, N. Lapusta A.J. Rosakis, PNS 2007

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

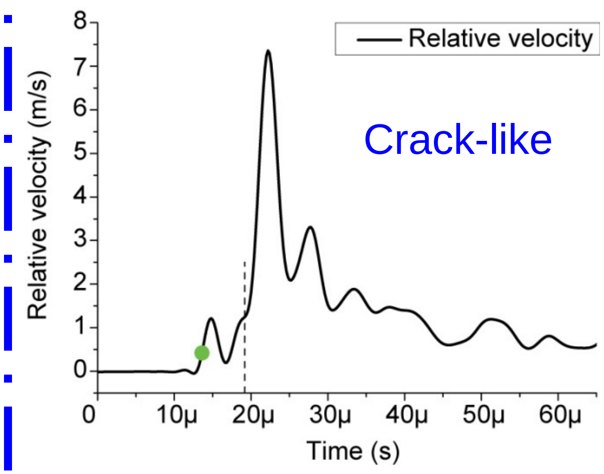
$\alpha = 20^0$, $f_0 = 0.36$

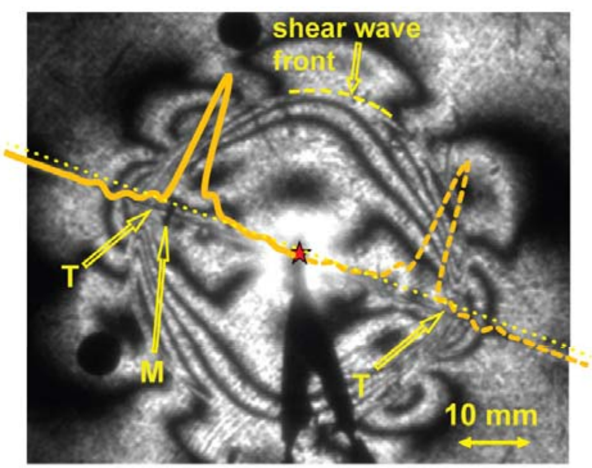


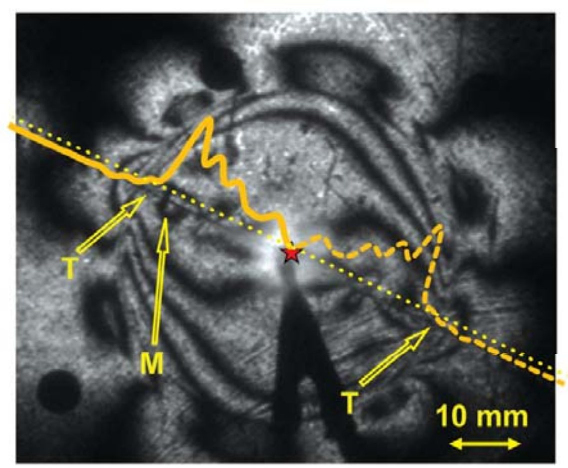
$\alpha = 25^0$, $f_0 = 0.47$

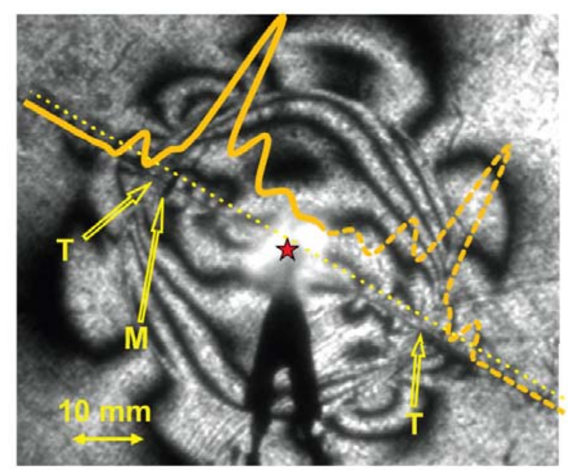


$\alpha = 30^0$, $f_0 = 0.58$





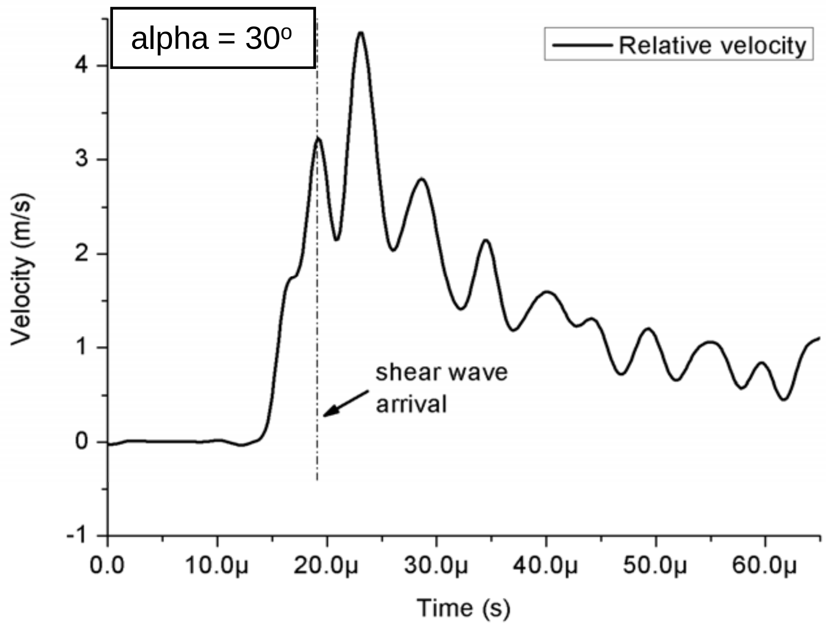




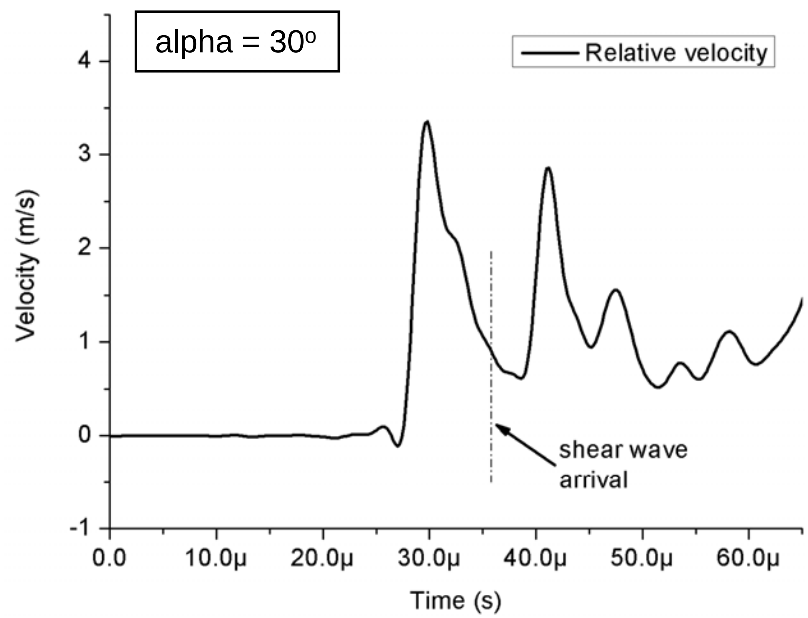
Consistent with velocity weakening friction analysis of Zheng and Rice, BSSA,1998

Sub-shear crack transitioning to supershear crack
Angle=30°, Pressure=14 MPa

X . Lu, N. Lapusta A.J. Rosakis, PNS 2007

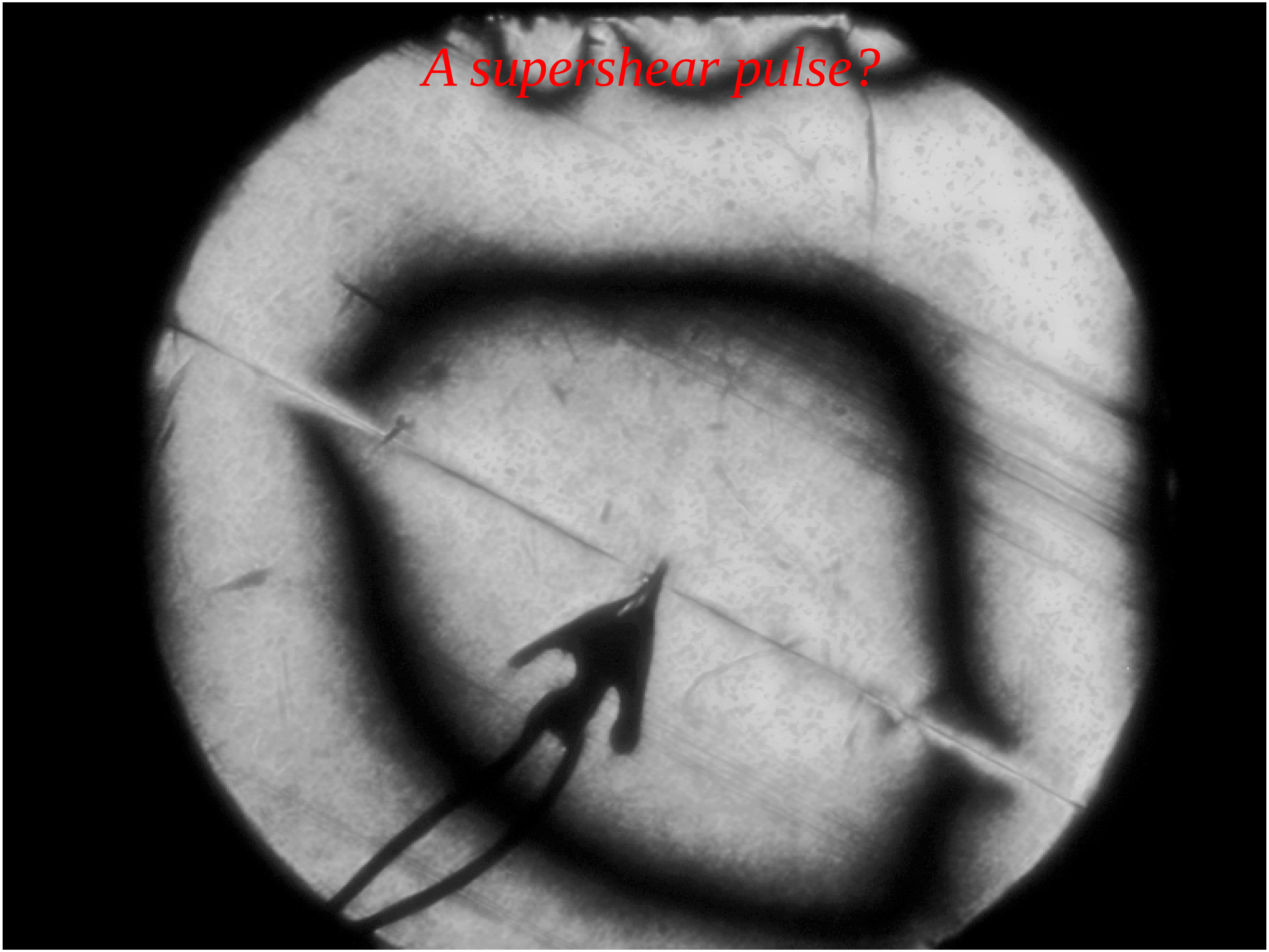


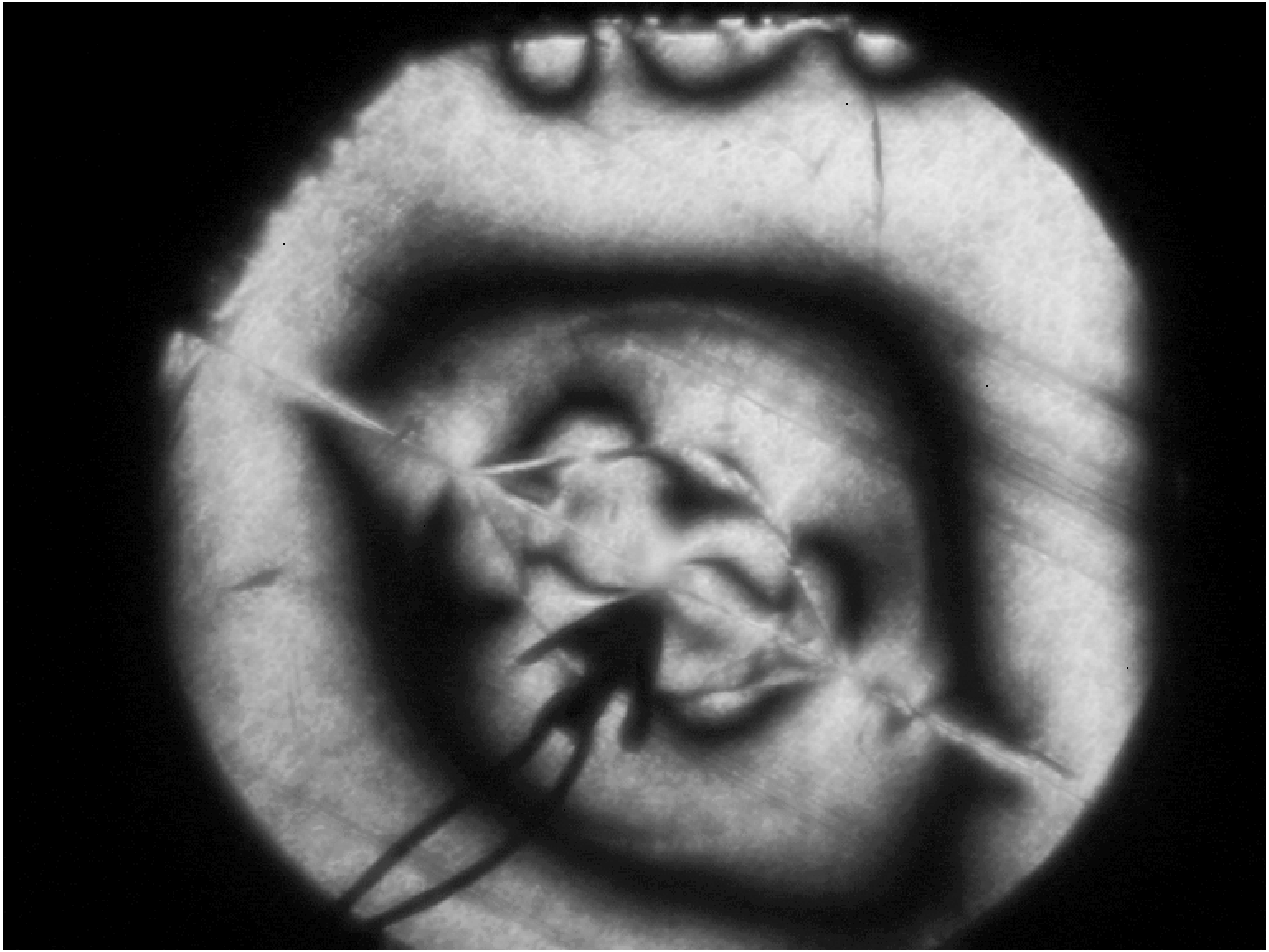
Velocity measured at **20** mm

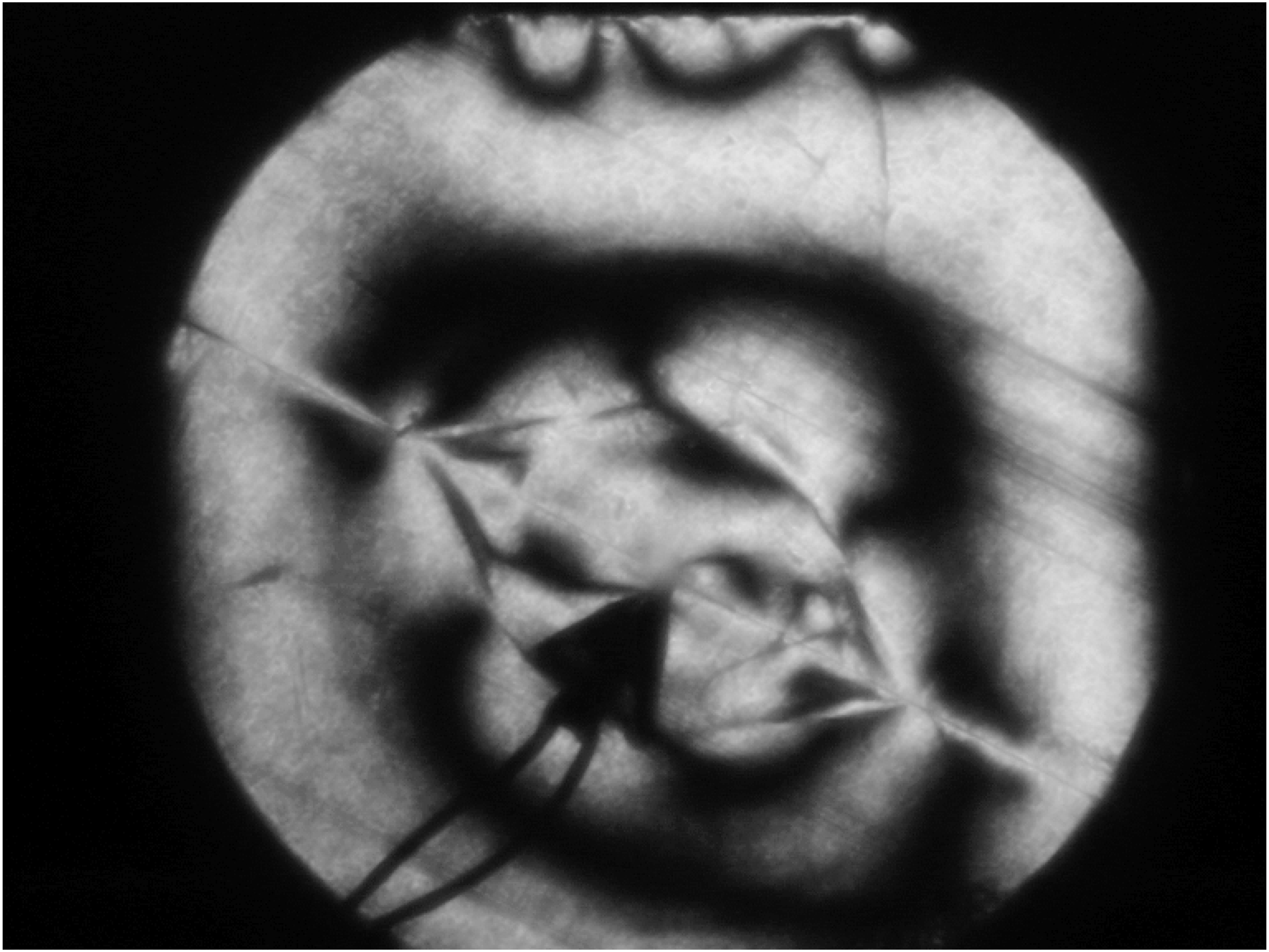


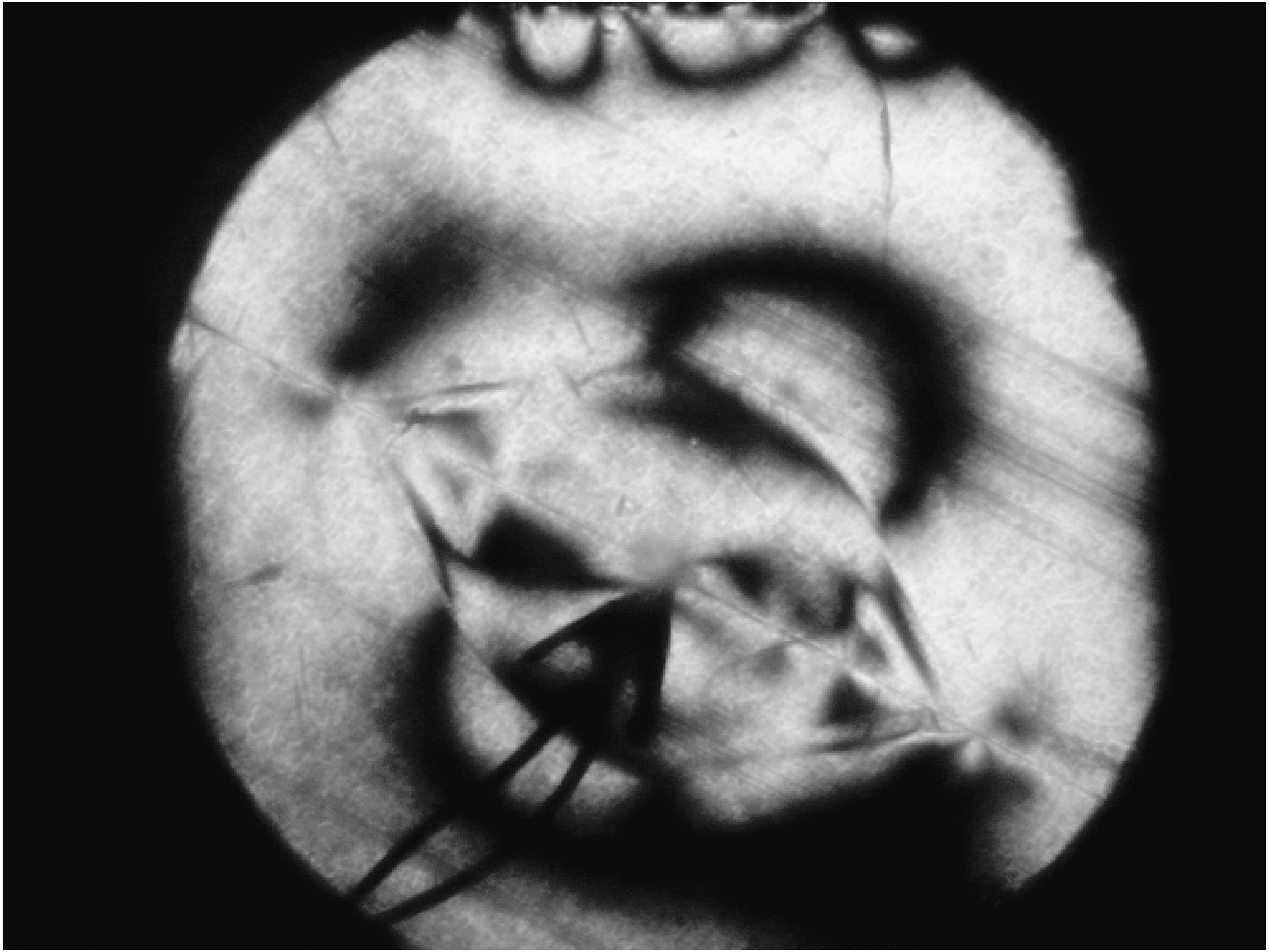
Velocity measured at **40** mm

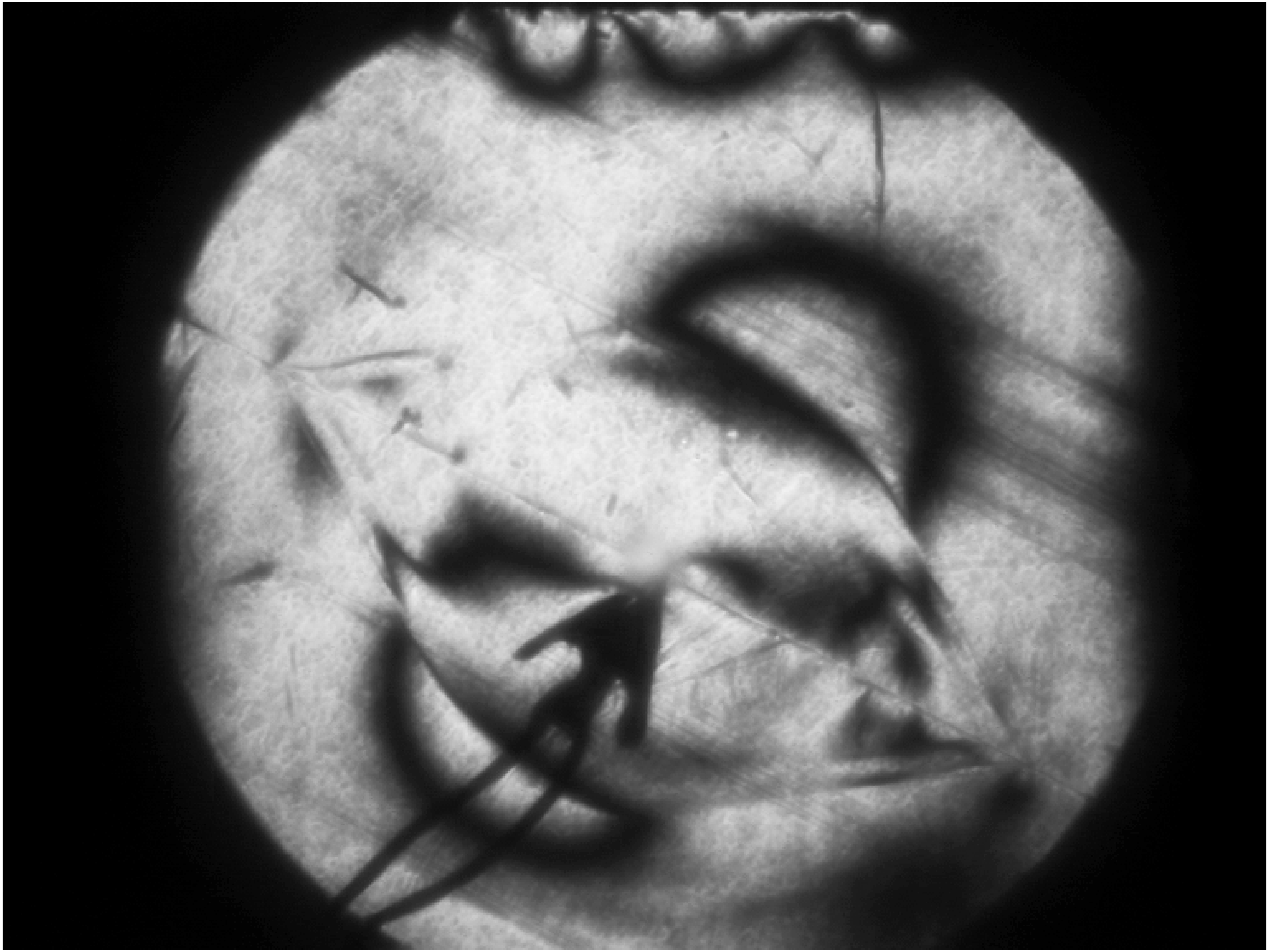
Do super-shear PULSES exist?

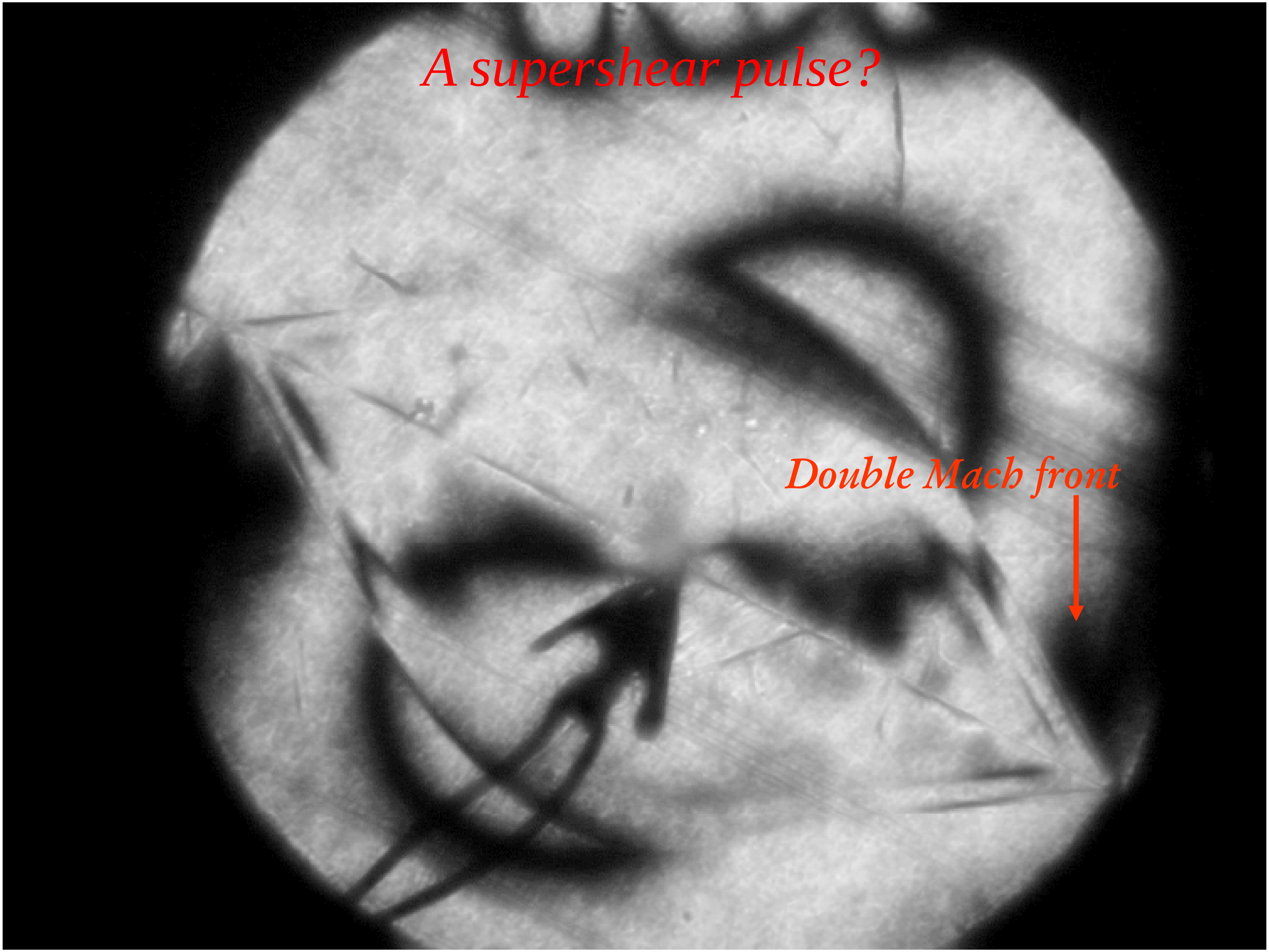

A supershear pulse?

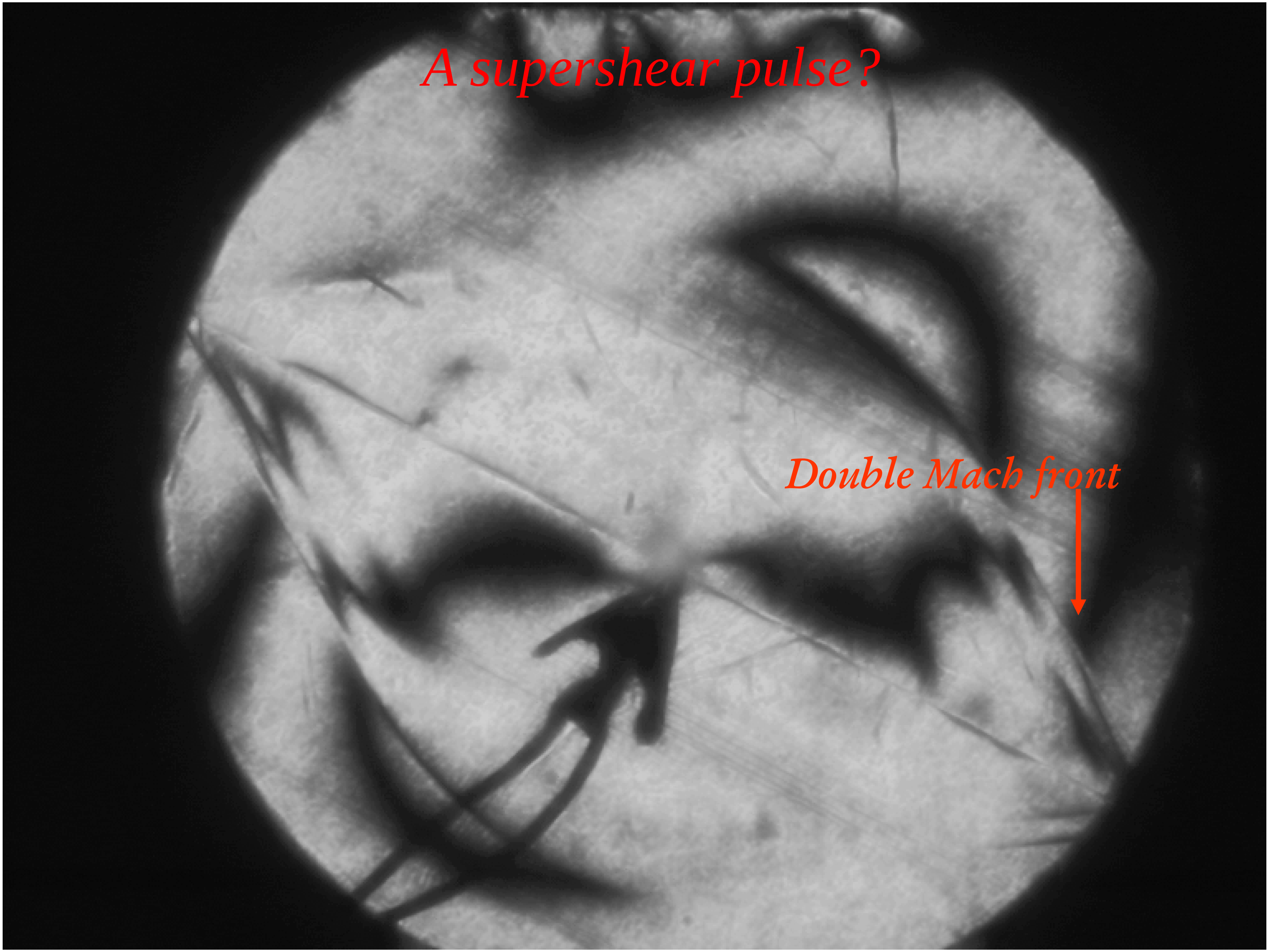








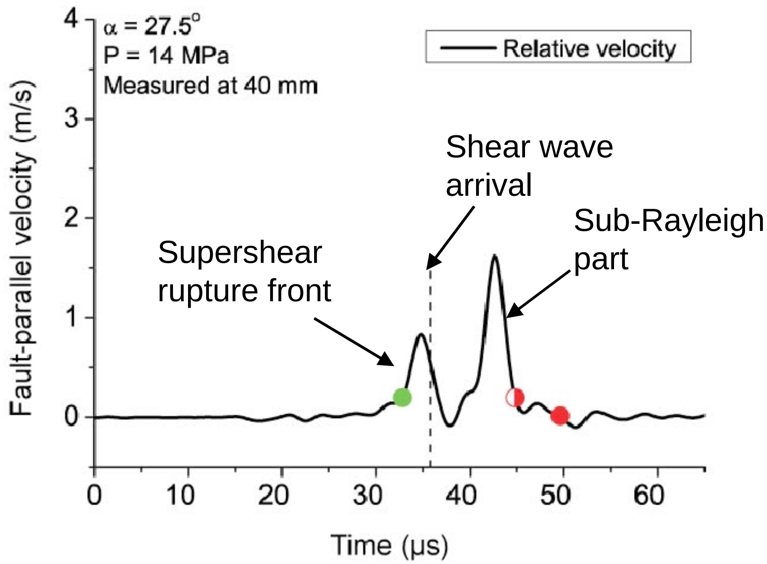

A supershear pulse?
Double Mach front

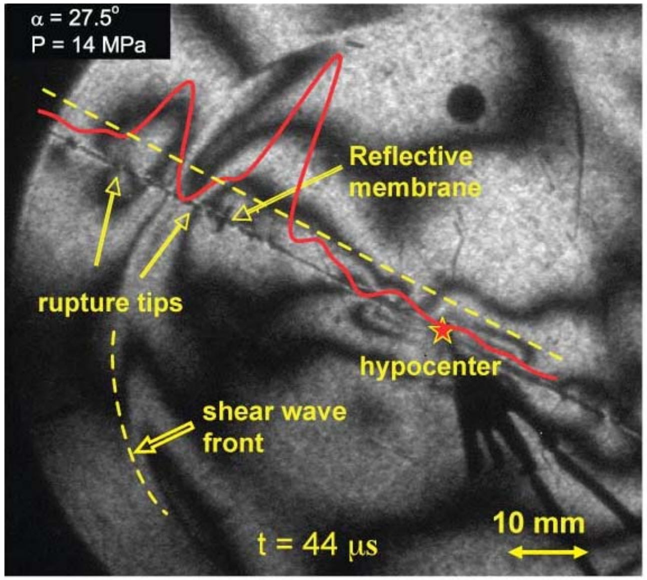

A supershear pulse?
Double Mach front

Lab Observations of supershear pulses and cracks

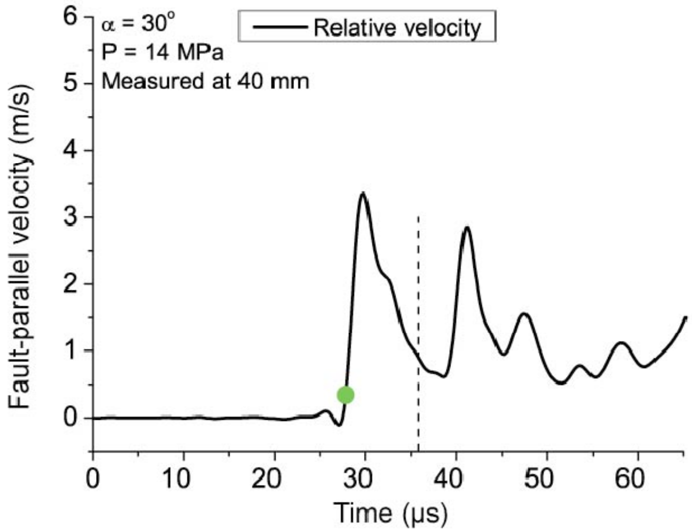
Pulse to Pulse

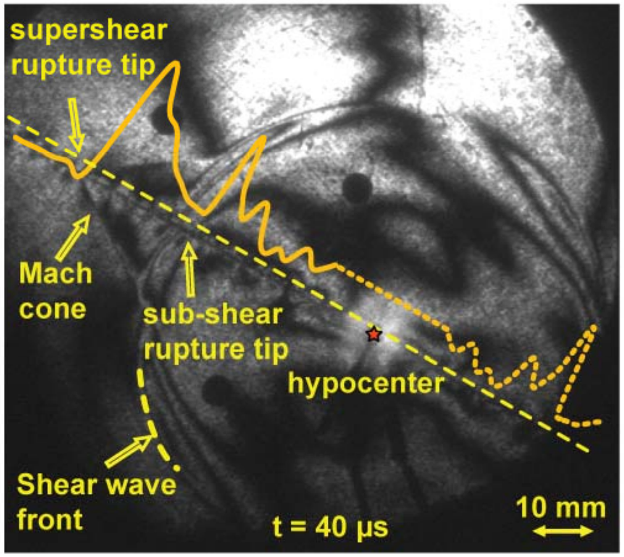
(Like M_w 7.8 2001Kunlunshan, Tibet & M_w 7.9 2002 Denali, Alaska Earthquakes?)



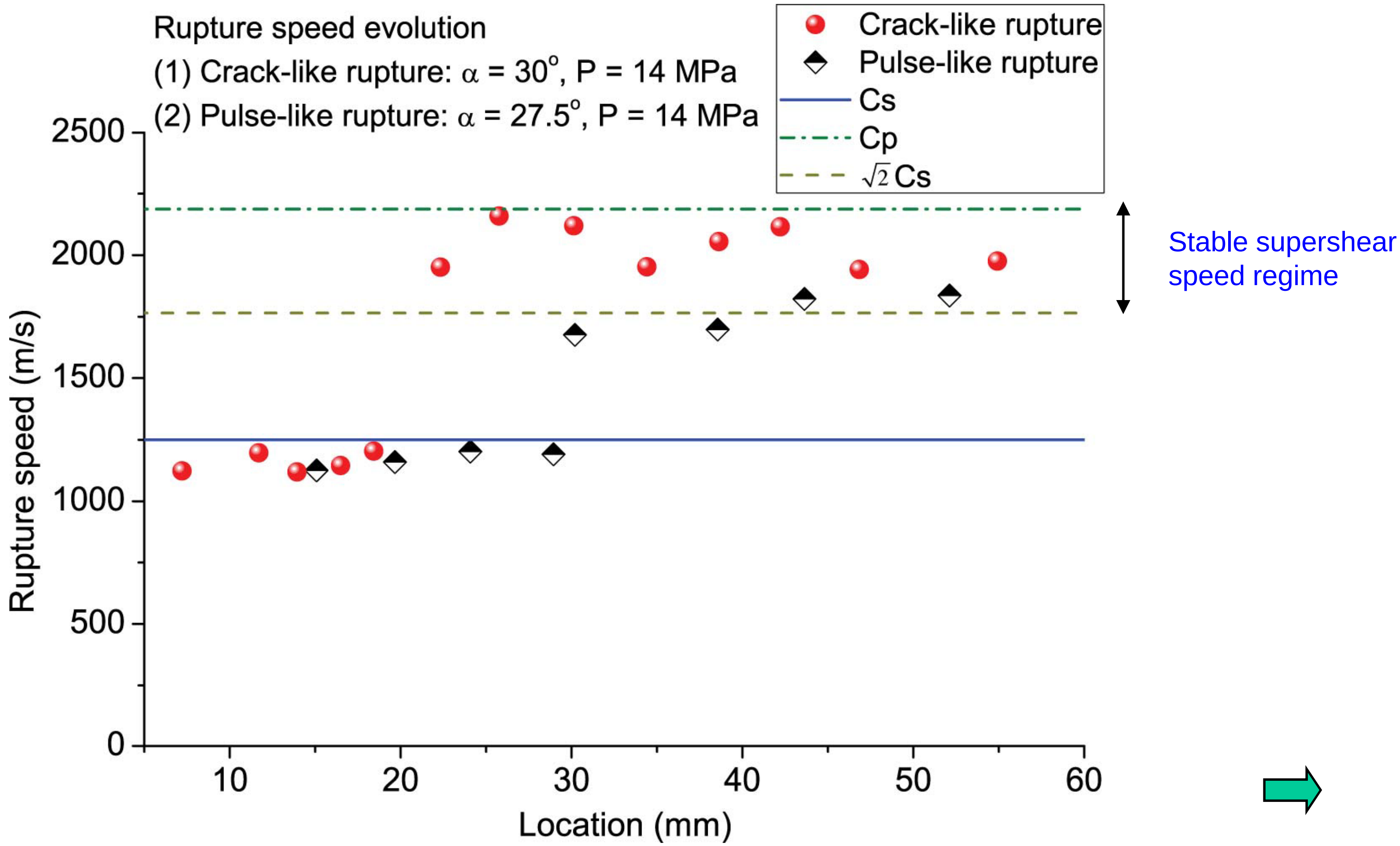


The Burridge-Andrews Mechanism
Crack to Crack





Evolution of rupture speed for supershear ruptures



The inferred speeds are consistent with the theoretical study of velocity-weakening interfaces (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 supershear speeds

Particle velocity fields for steady state singular elastic solution

$$\dot{u}_1^d = AV_r \frac{\sin(q\theta_d)}{r_d^q} \qquad \dot{u}_1^s = -AV_r sgn(\xi_2) \frac{\hat{\alpha_s}^2 (2 - \frac{V_r^2}{C_s^2}) \sin(\pi q)}{2\hat{\alpha_s}(|\xi_1 + \hat{\alpha_s}\xi_2|)^q} H(-\xi_1 - \hat{\alpha_s}|\xi_2|)$$

$$\dot{u}_2^d = -AV_r \alpha_d \frac{\cos(q\theta_d)}{r_d^q} \qquad \dot{u}_2^s = AV_r \frac{(2 - \frac{V_r^2}{C_s^2}) \sin(\pi q)}{2\hat{\alpha_s}(|\xi_1 + \hat{\alpha_s}\xi_2|)^q} H(-\xi_1 - \hat{\alpha_s}|\xi_2|)$$

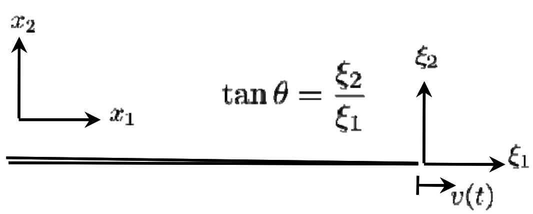
$$\dot{u}_1 = \dot{u}_1^s + \dot{u}_1^p$$

$$\dot{u}_2 = \dot{u}_2^s + \dot{u}_2^p$$

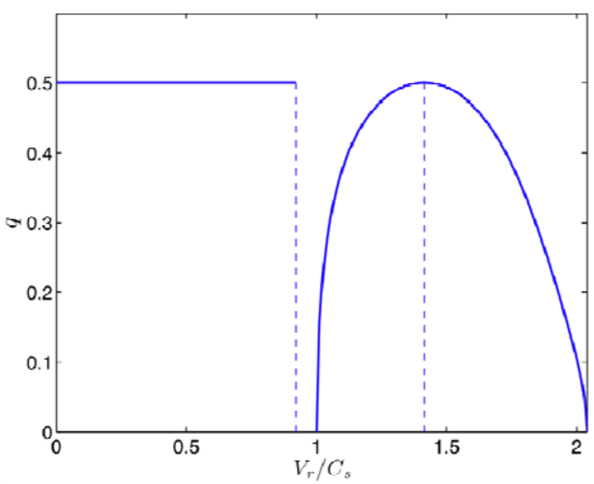
$$\dot{u} = \sqrt{\dot{u}_1^2 + \dot{u}_2^2}$$

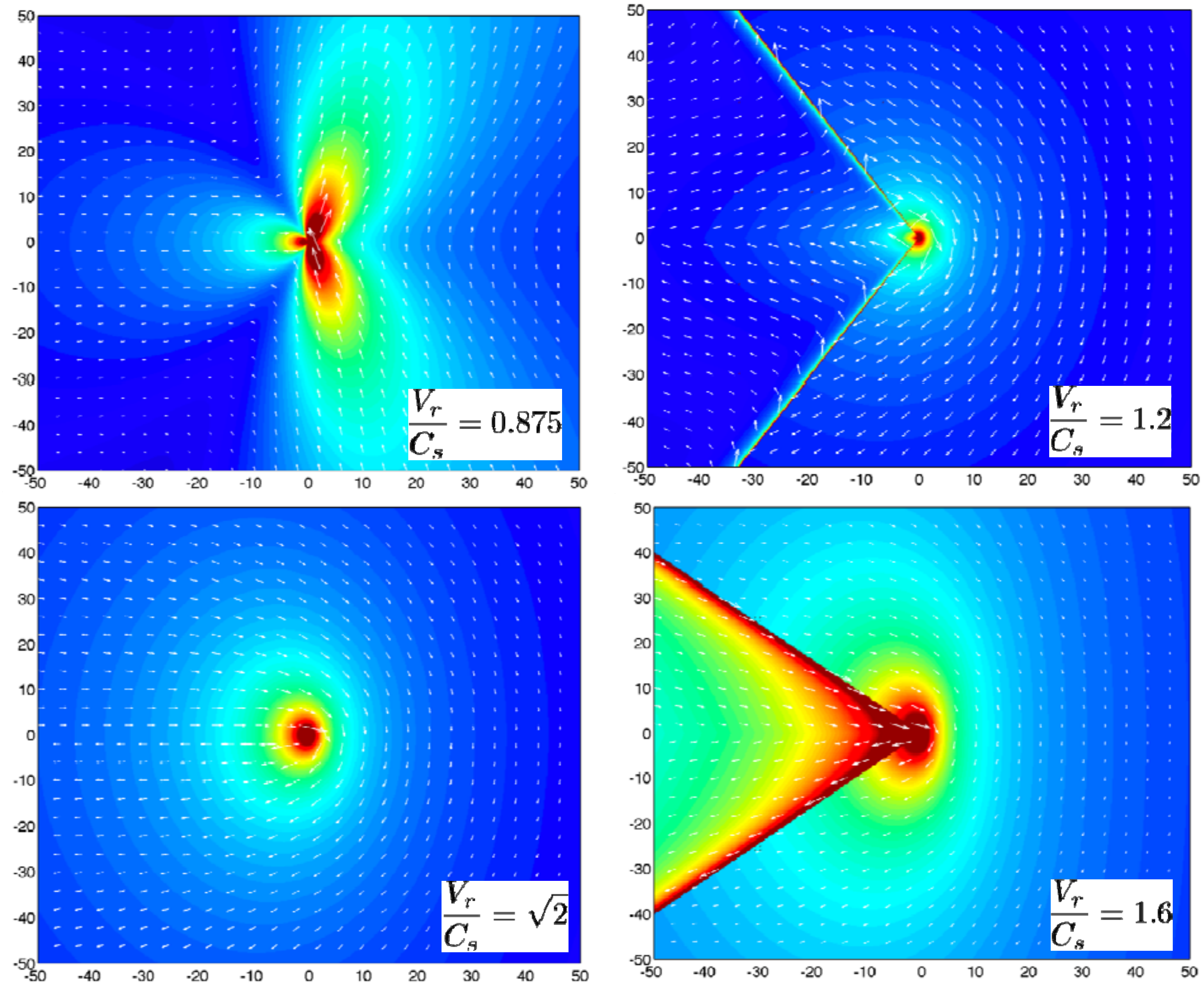
$$\hat{\alpha_s} = \sqrt{\frac{V_r^2}{C_s^2} - 1} \qquad q = \frac{1}{\pi} \tan^{-1}\left(\frac{4\hat{\alpha_s}\alpha_d}{2 - \frac{V_r^2}{C_s^2}} \right)$$

$$\alpha_d = \sqrt{1 - \frac{V_r^2}{C_d^2}} \qquad \tan\theta_d = \alpha_d \tan\theta$$



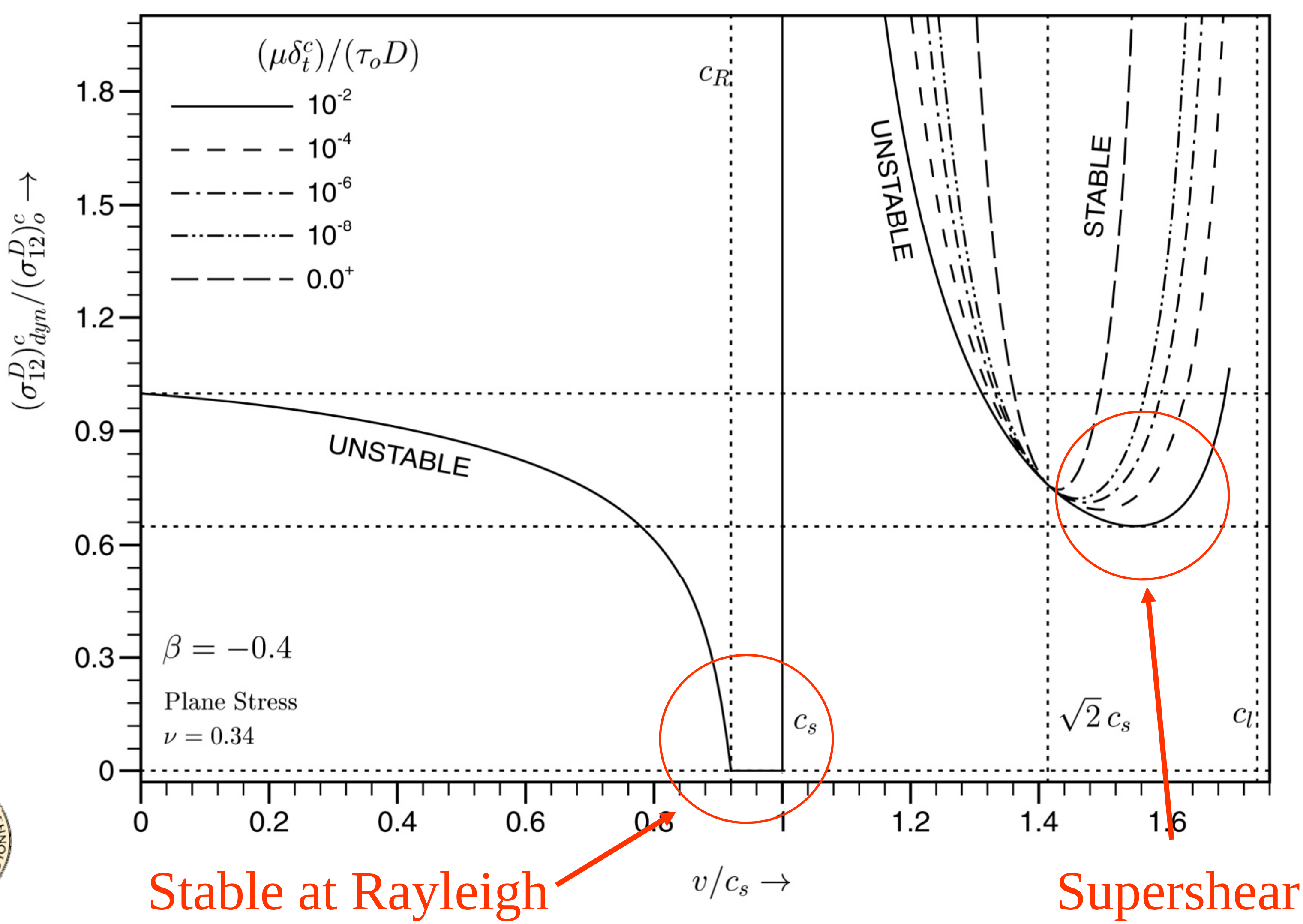
$$\tan\theta = \frac{\xi_2}{\xi_1}$$





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

(*Samudrala, Huang and Rosakis, JGR 2002*)



Experimental Results and Seismological Questions

- ***Small loads or angles: SUBRAYLEIGH RUTPURES (PULSES)***
- ***Large load or angle: SUPERSHEAR RUPTURES (CRACKS)***
- ***Sub-shear to supershear and mode transitions are observed for both cracks and Pulses.***
- ***The speed transition length increases with decreasing load and angle.***
- ***Experiments support the presence of strong velocity weakening .***

X . Lu, N. Lapusta A.J. Rosakis, PNS 2007

What are the special , ground shaking , signatures of a super-shear earthquake?

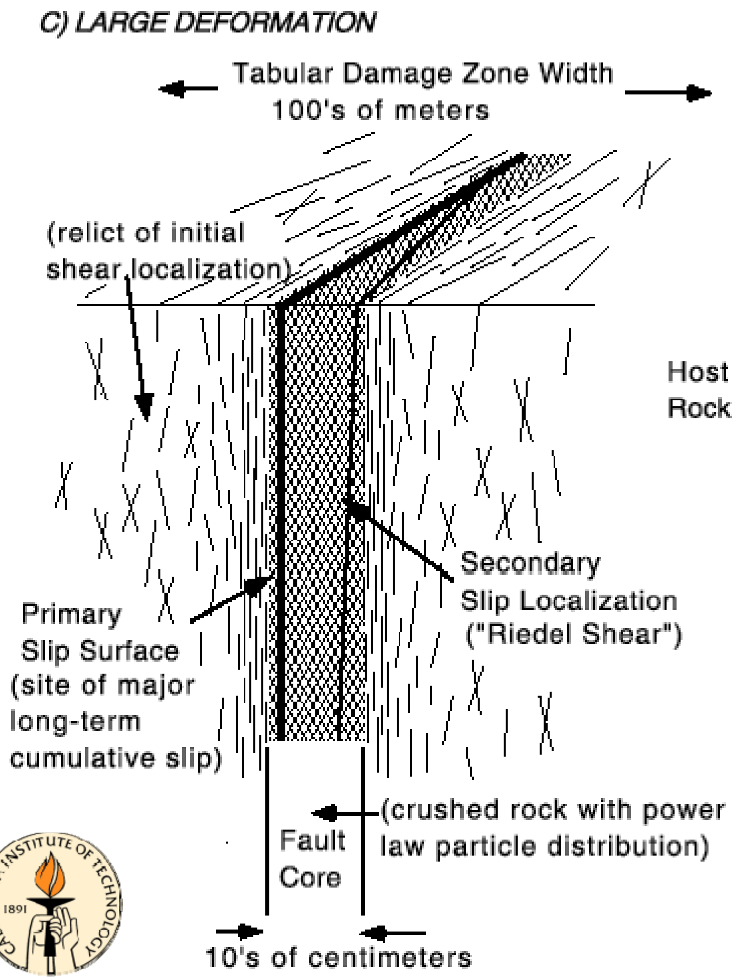
What are the implications for building safety and Seismic hazard?

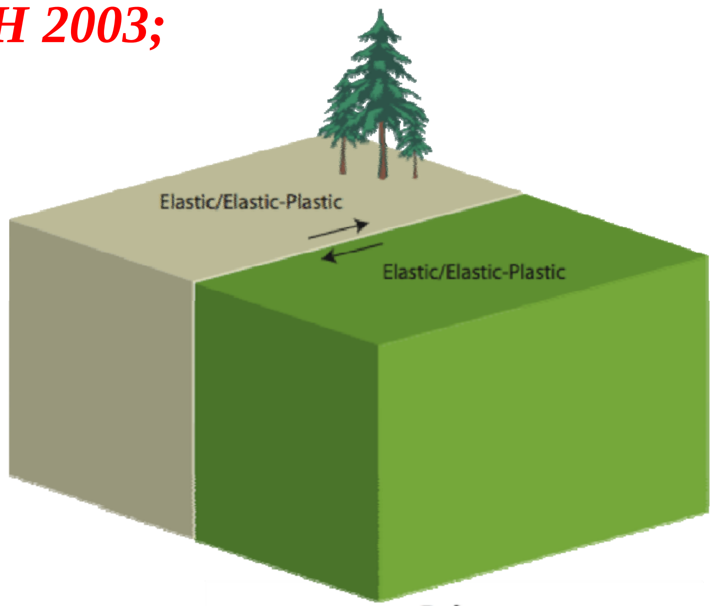
Mello, Bhat, Rosakis and Kanamori, 2010

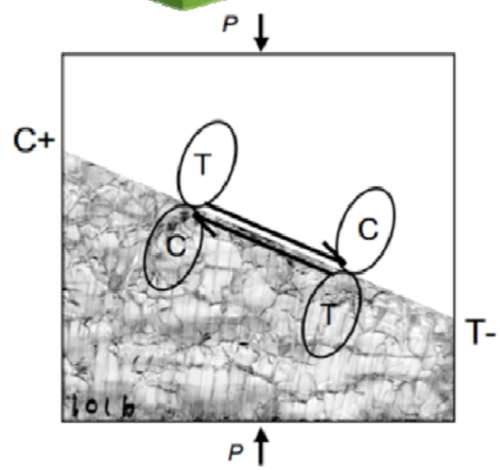
FAULT ZONES FEATURE BOTH BULK ELASTIC AND DAMAGE MISMATCH

Chester and Logan 1986 *Chester et al., 1993, 2004*

Ben-Zion and Sammis, PAGEOPH 2003;
Sibson, BSSA 2003







Charlie Sammis
Earth Sciences, USC

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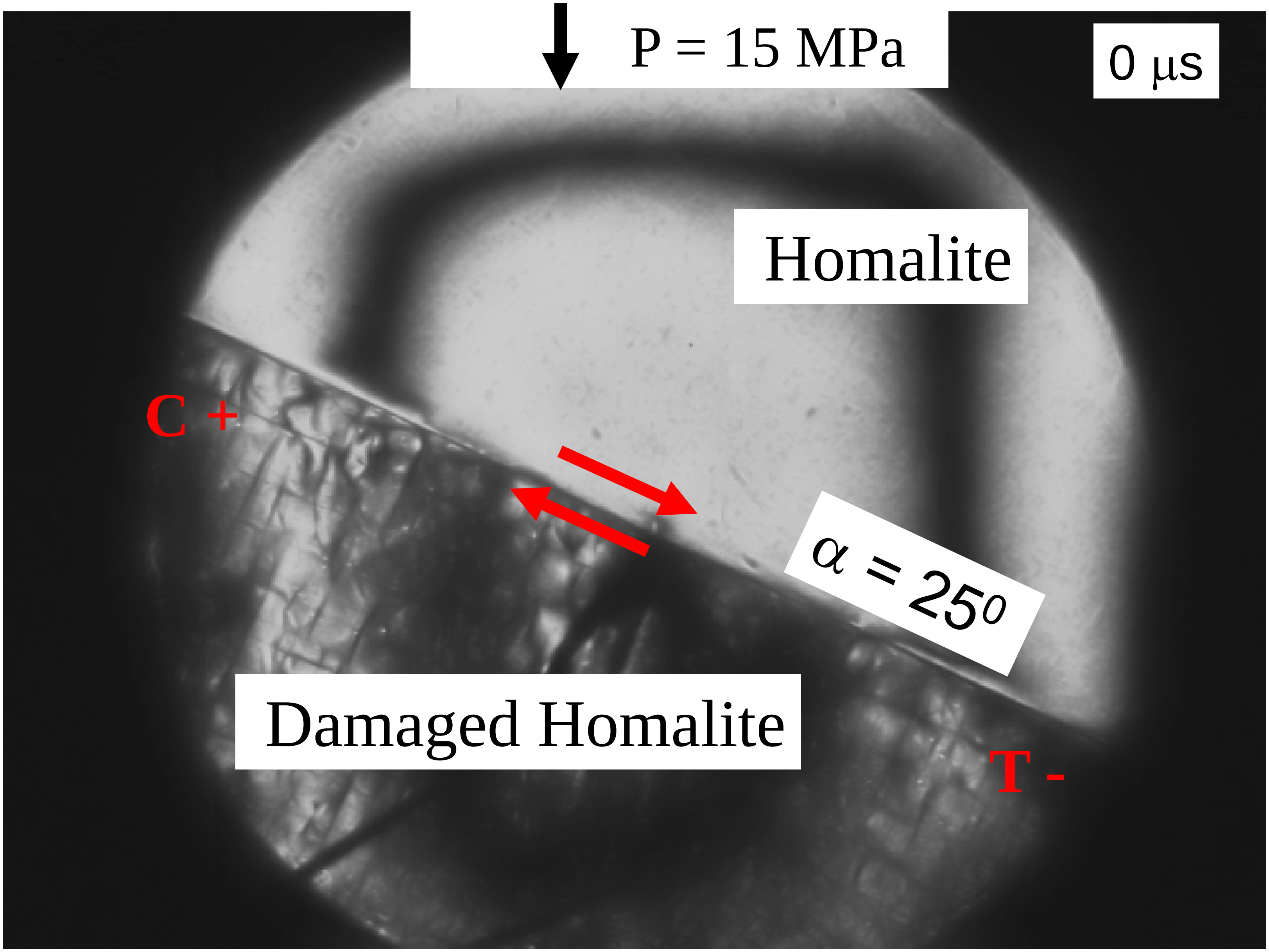
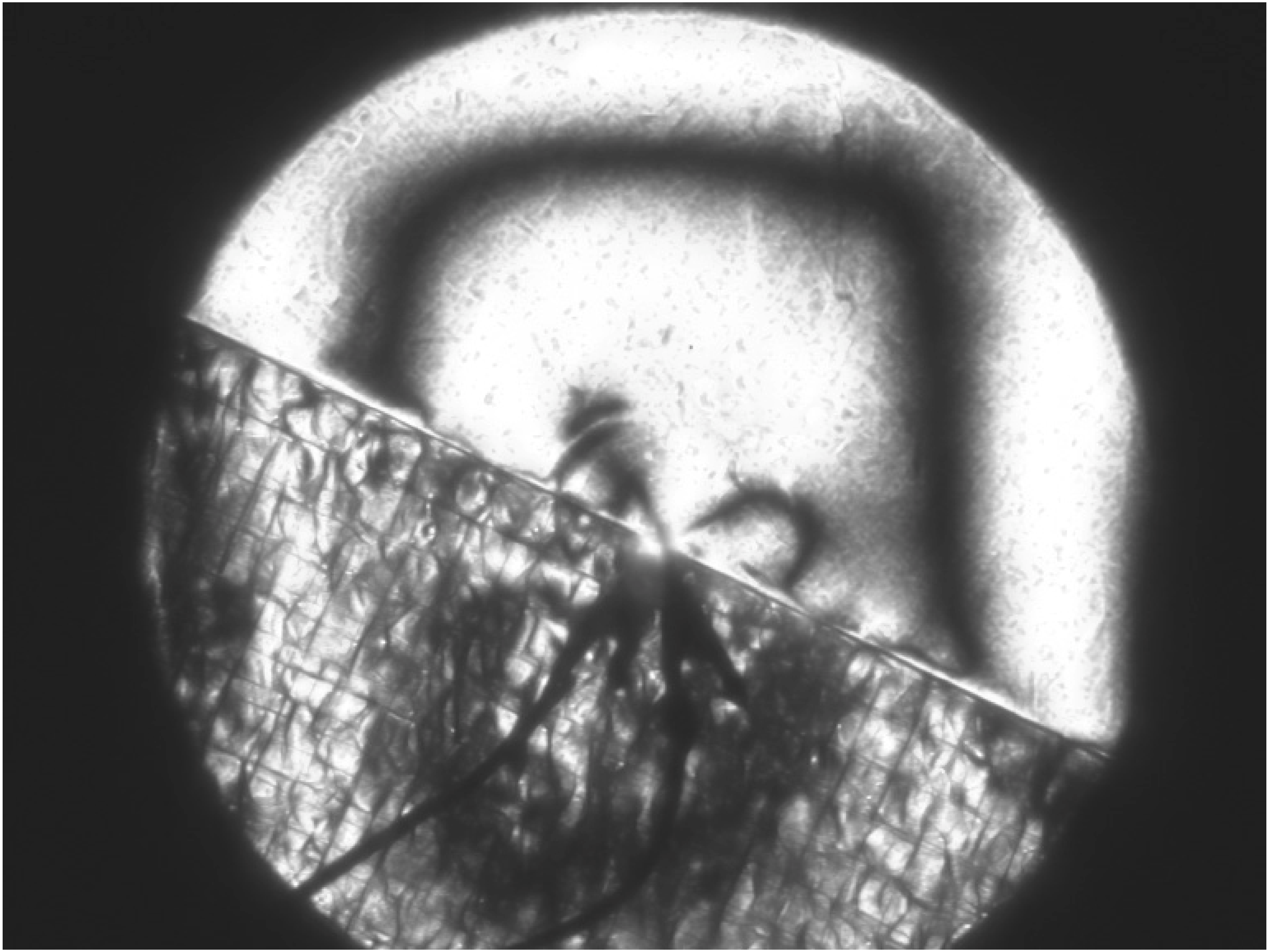
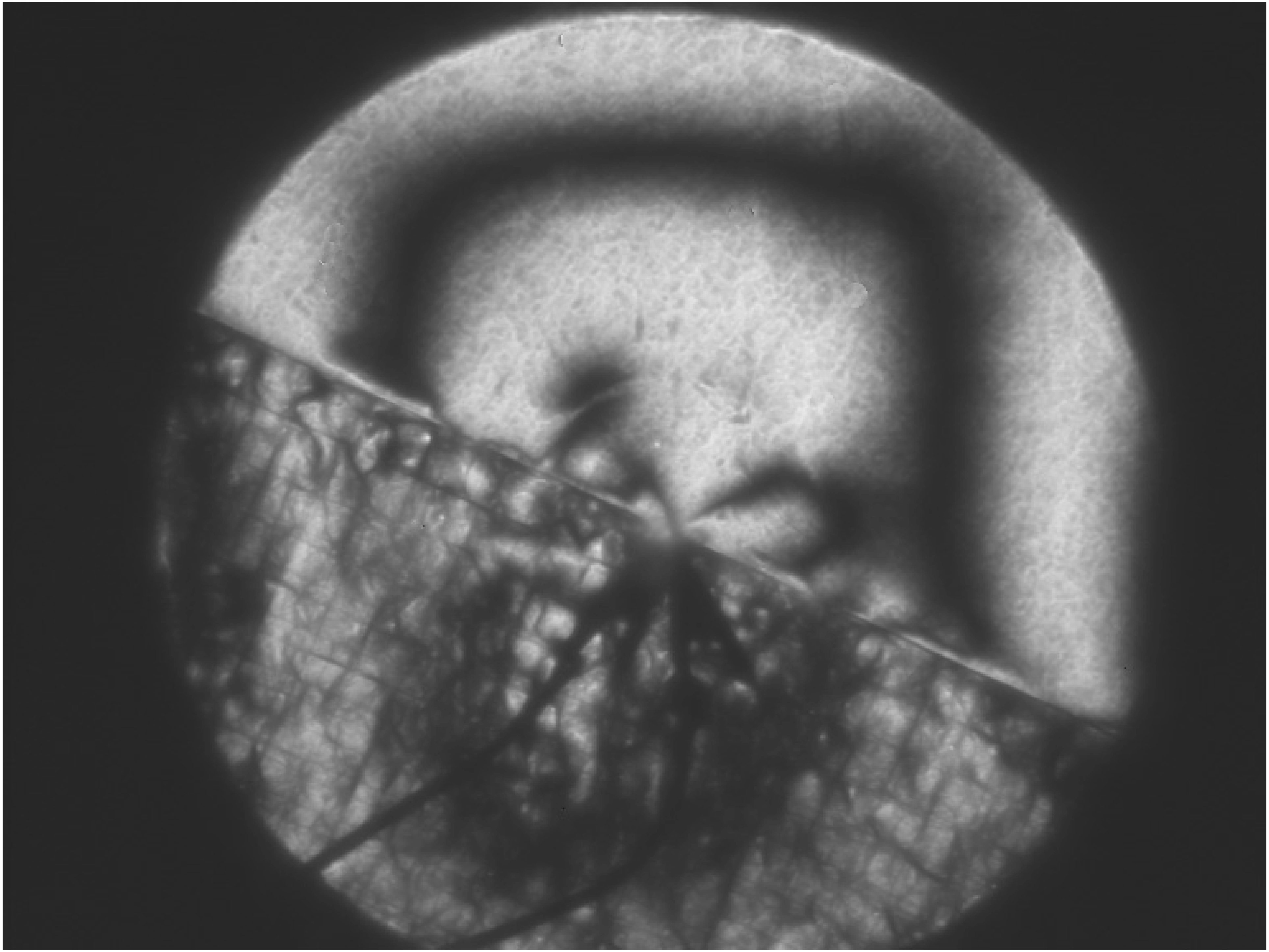
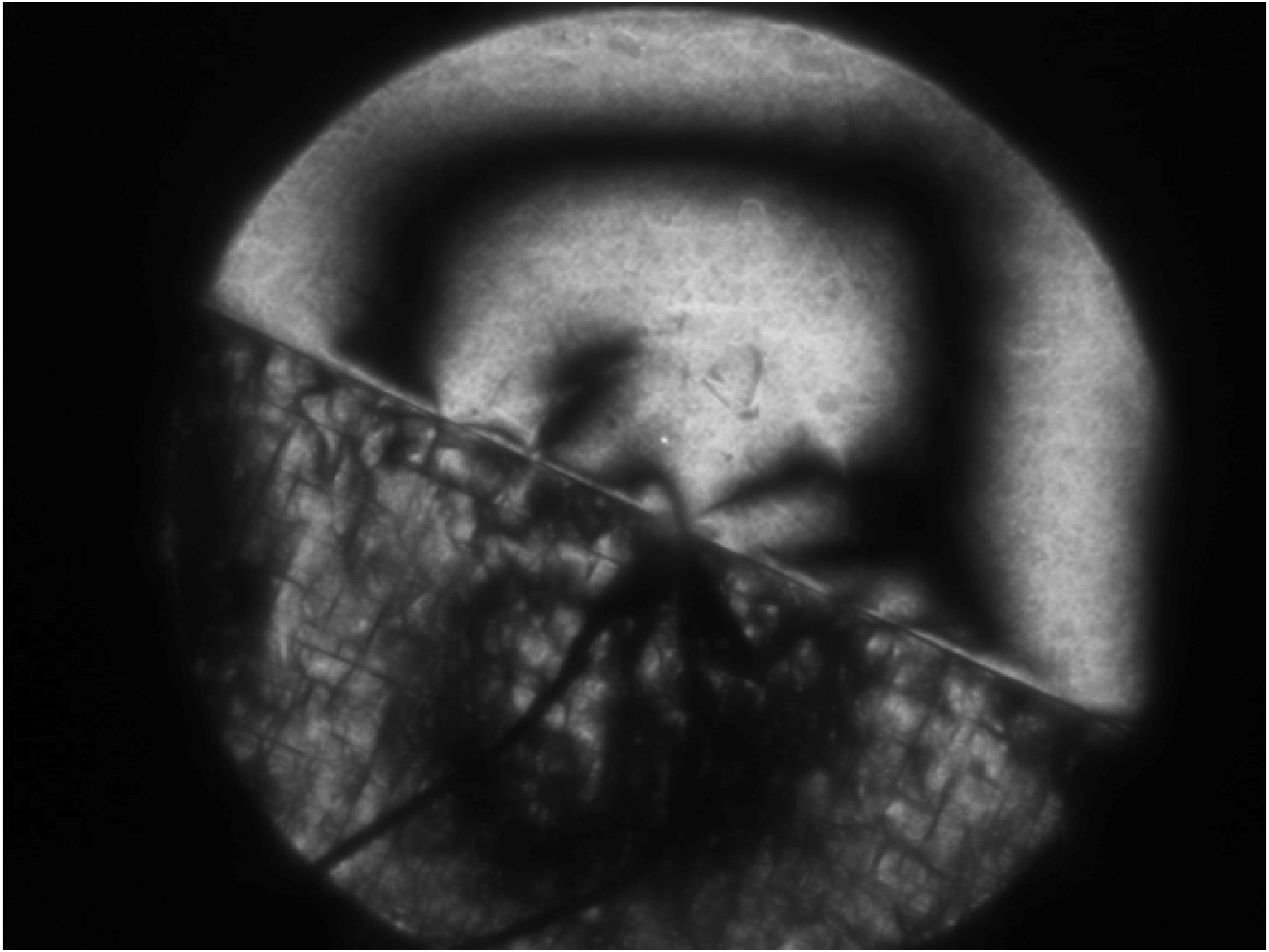
GALCIT, Caltech, USC

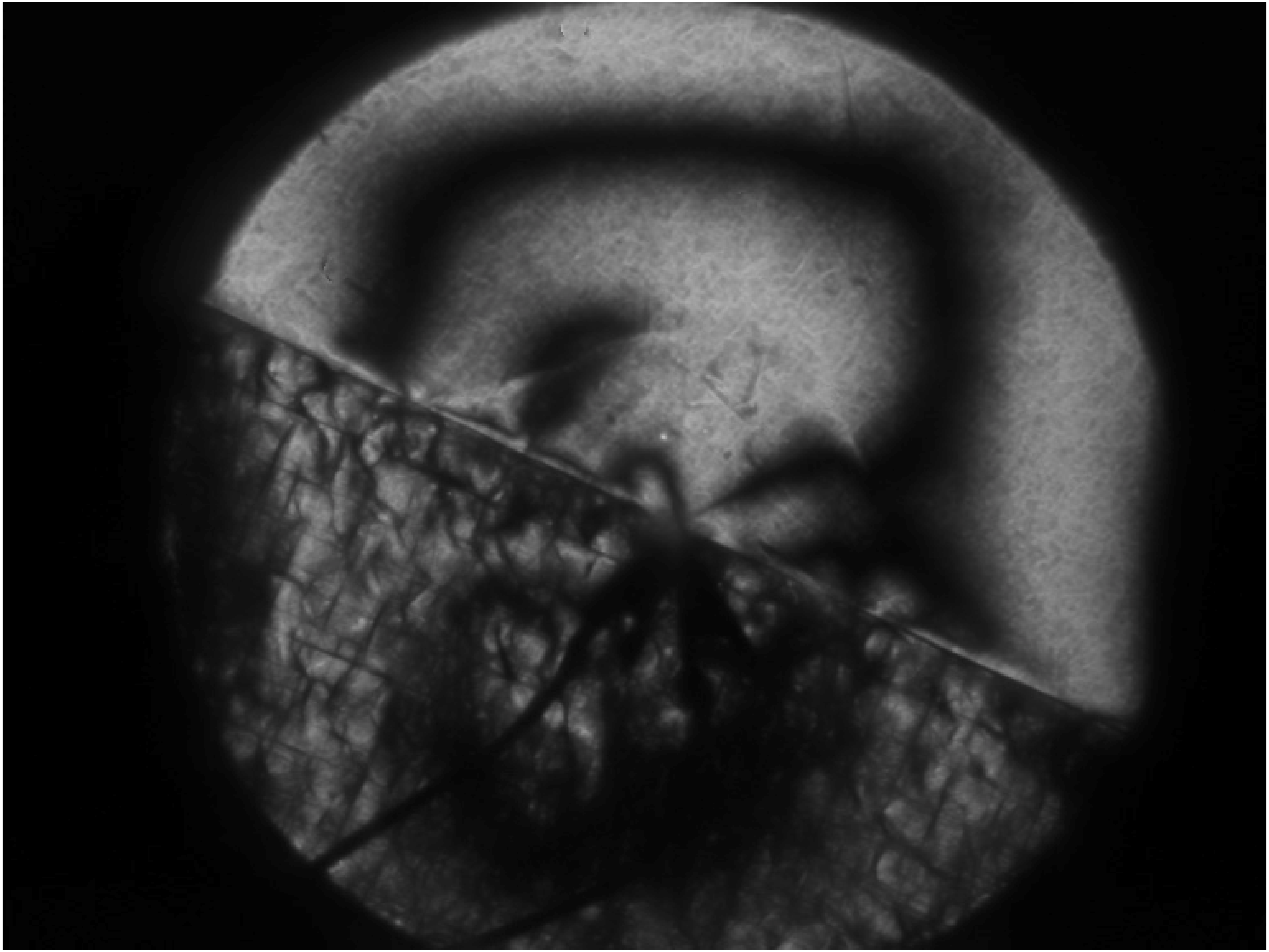
NO BULK ELASTIC MISMATCH;
Can Damage create preferred directions?

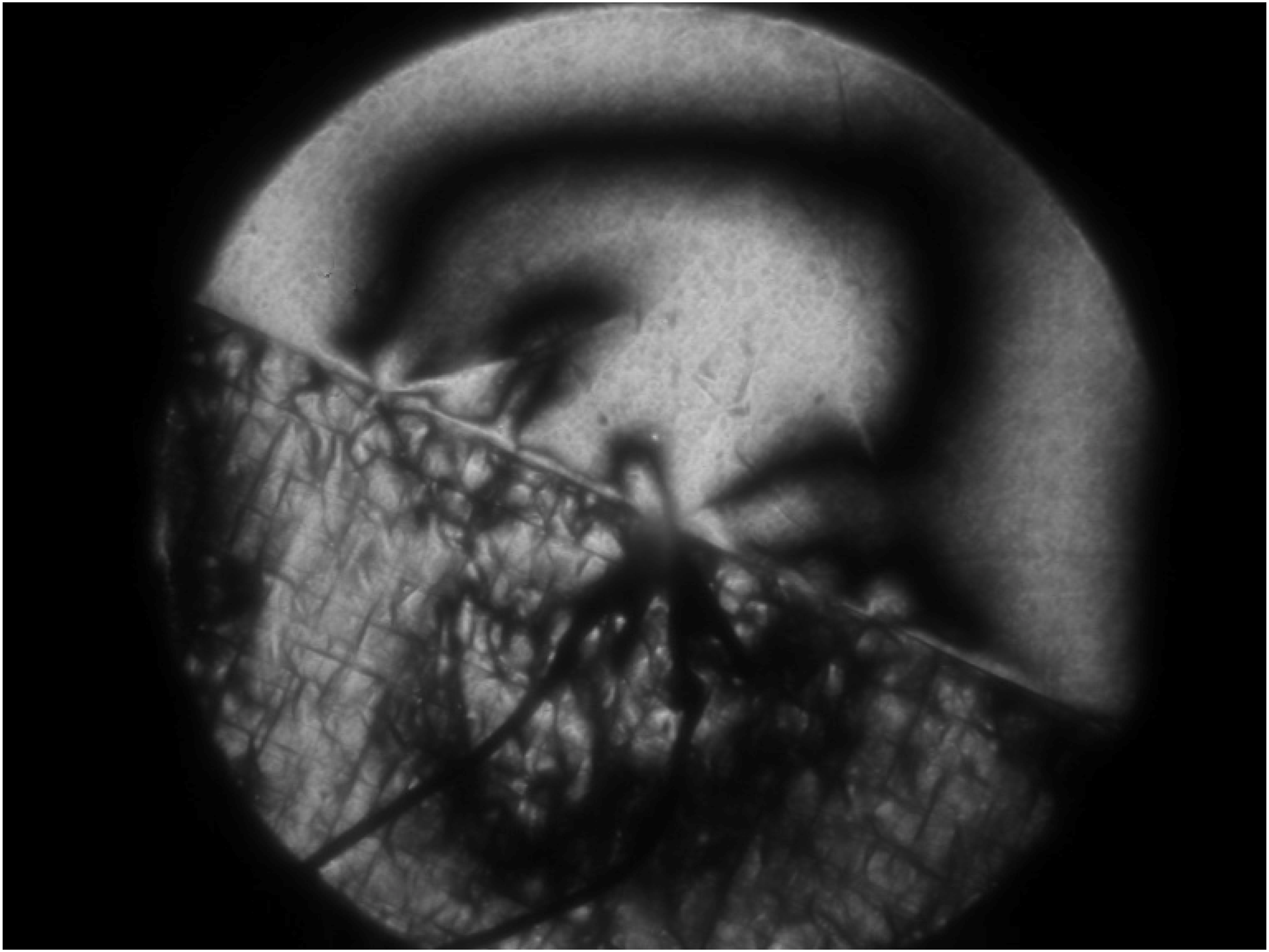


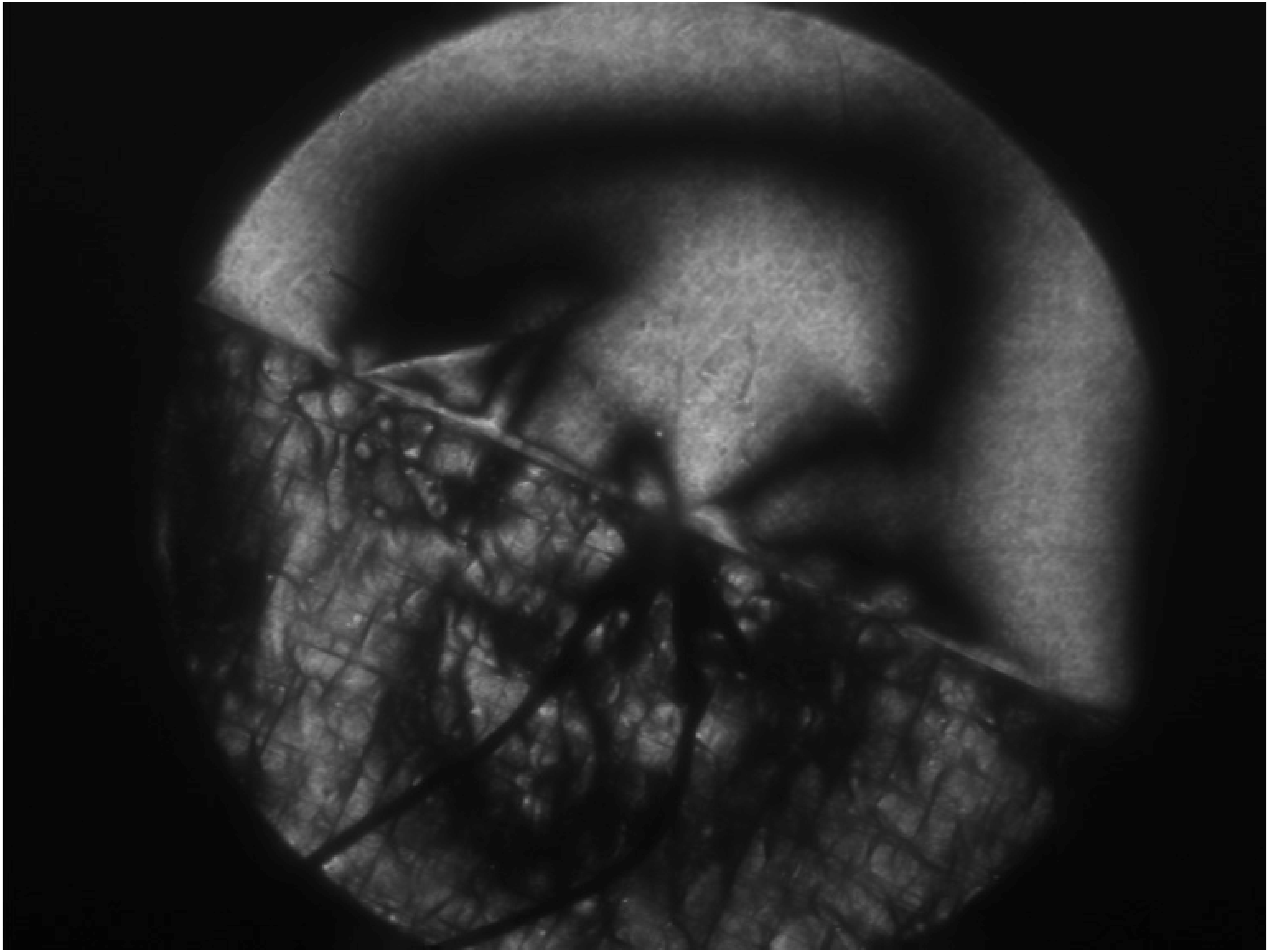


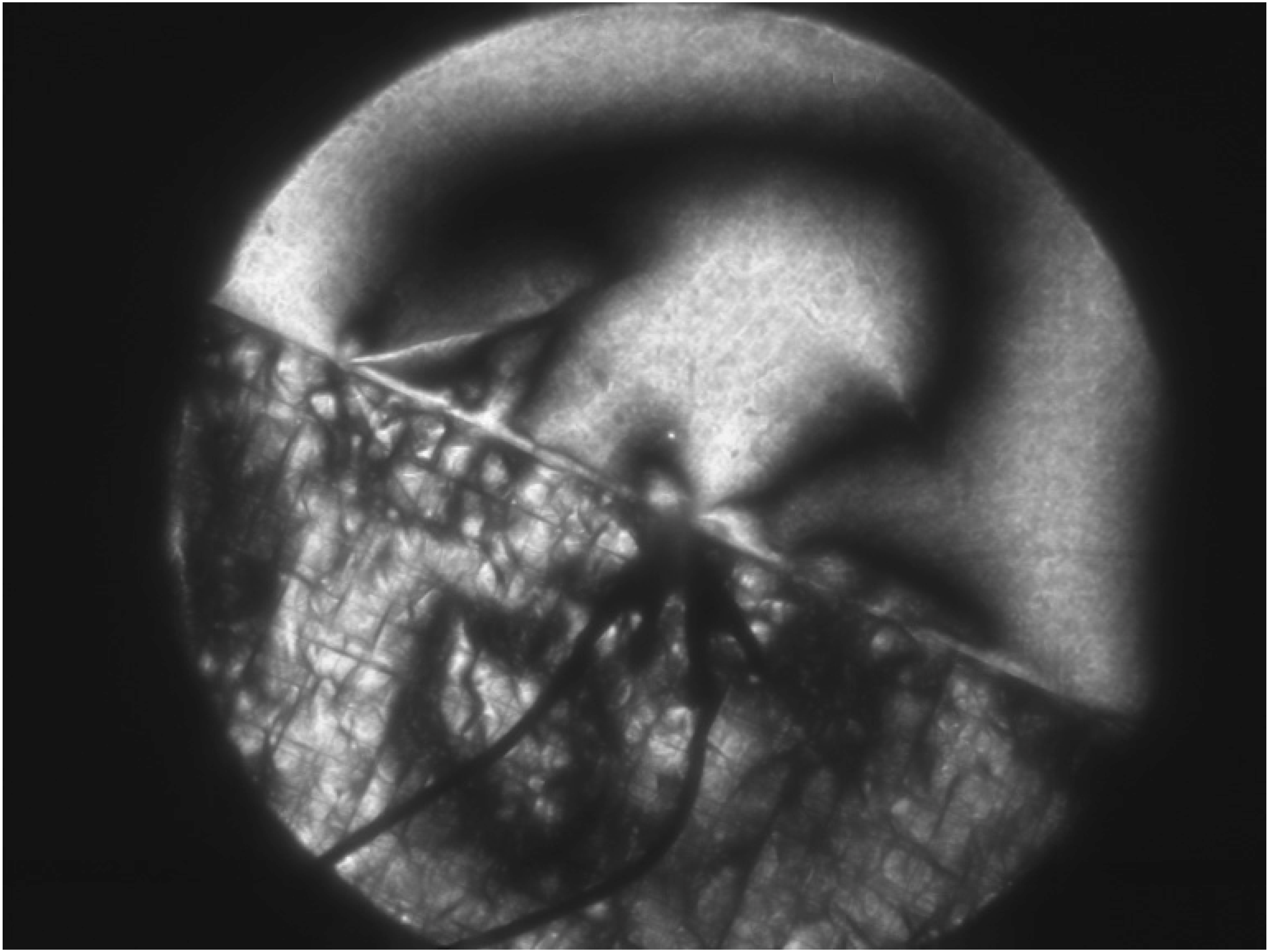


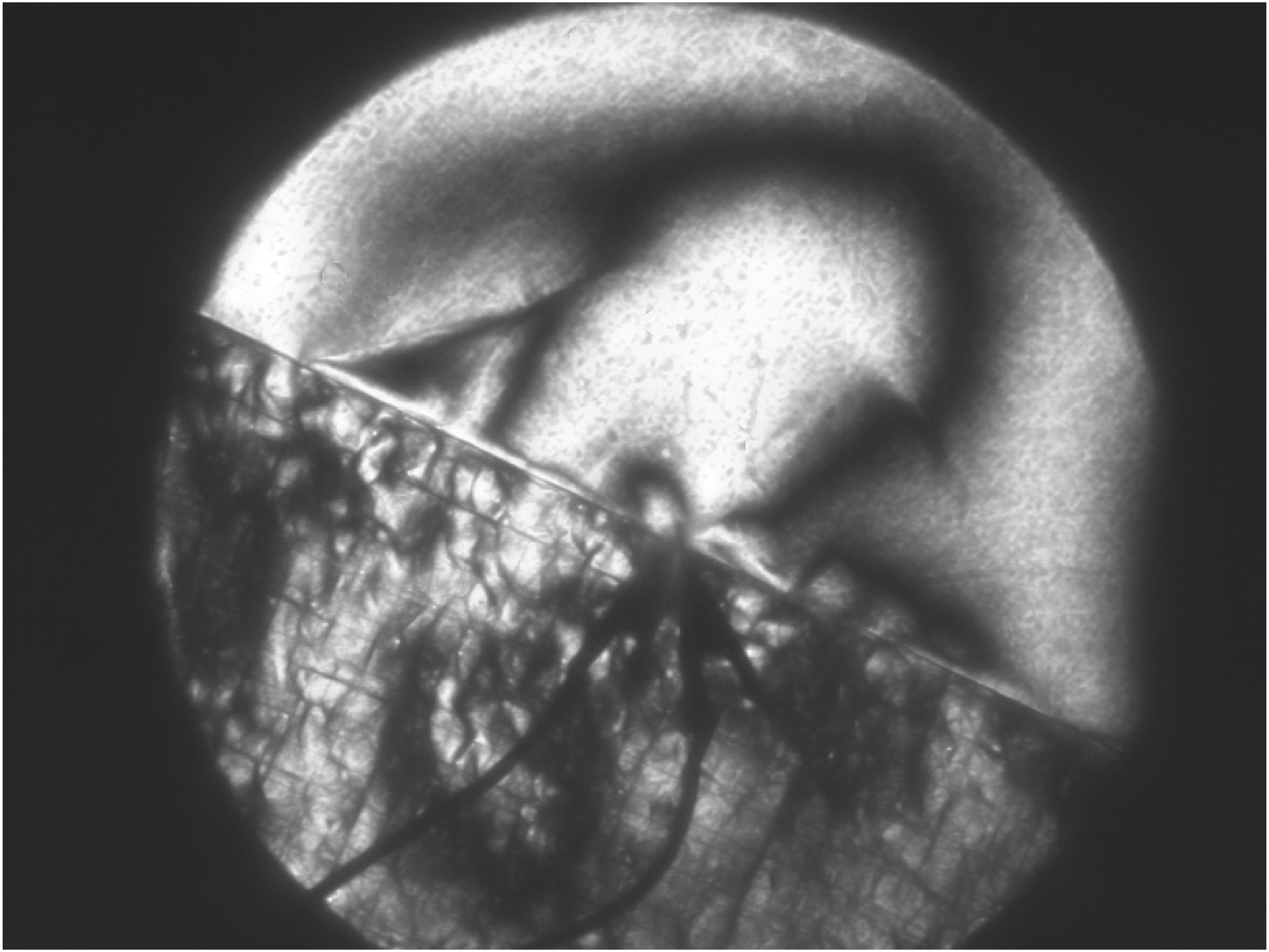


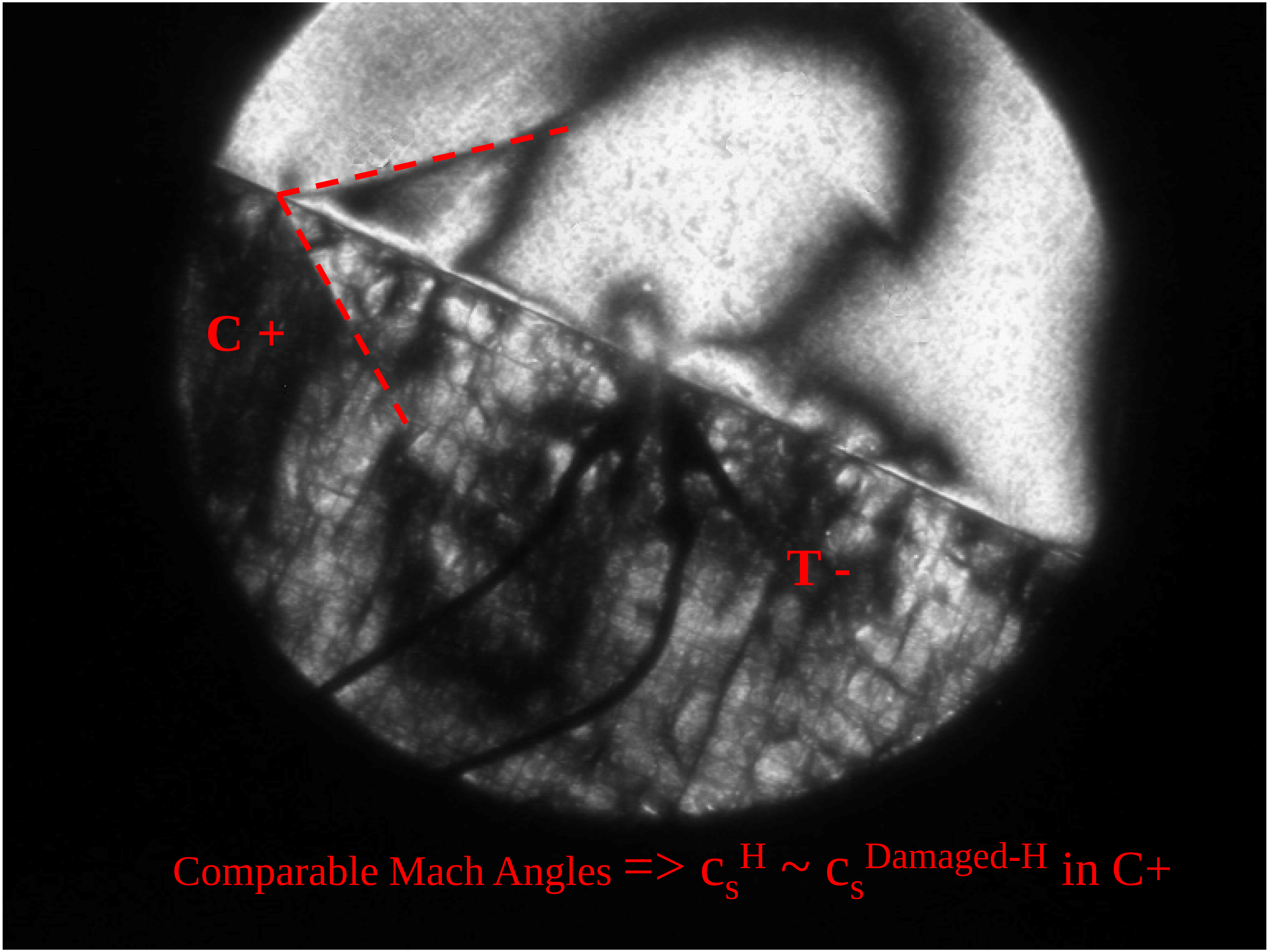


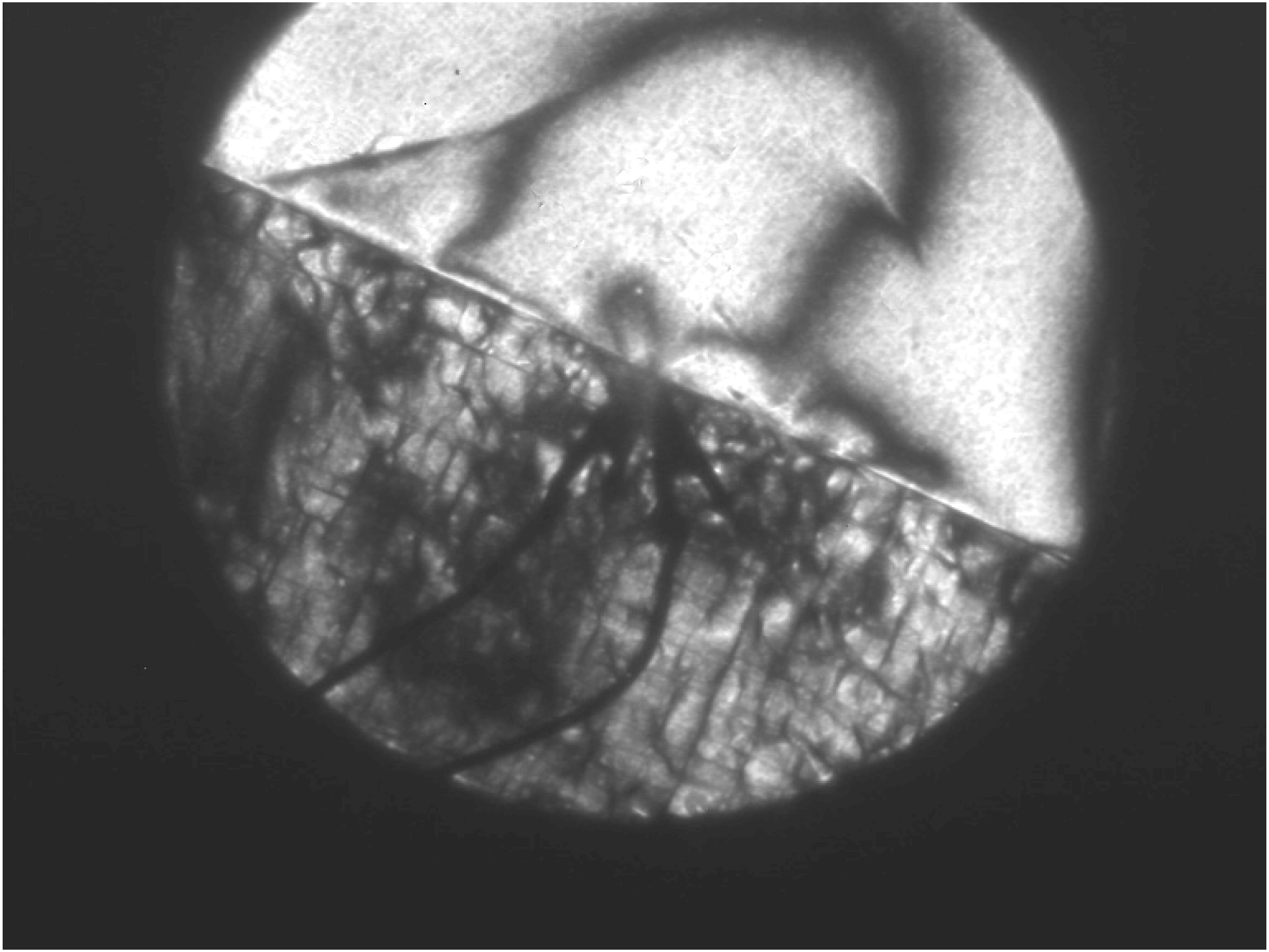


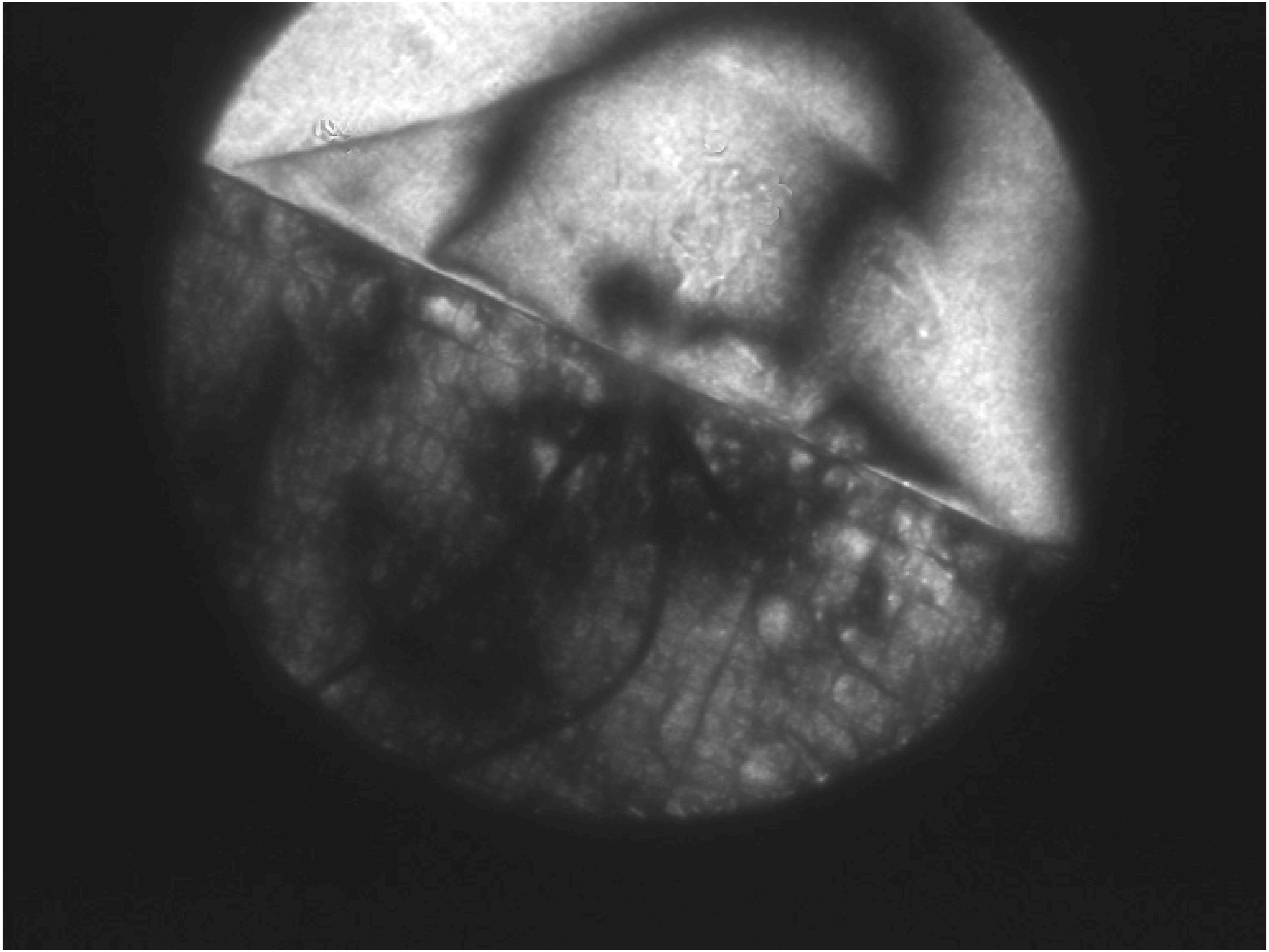


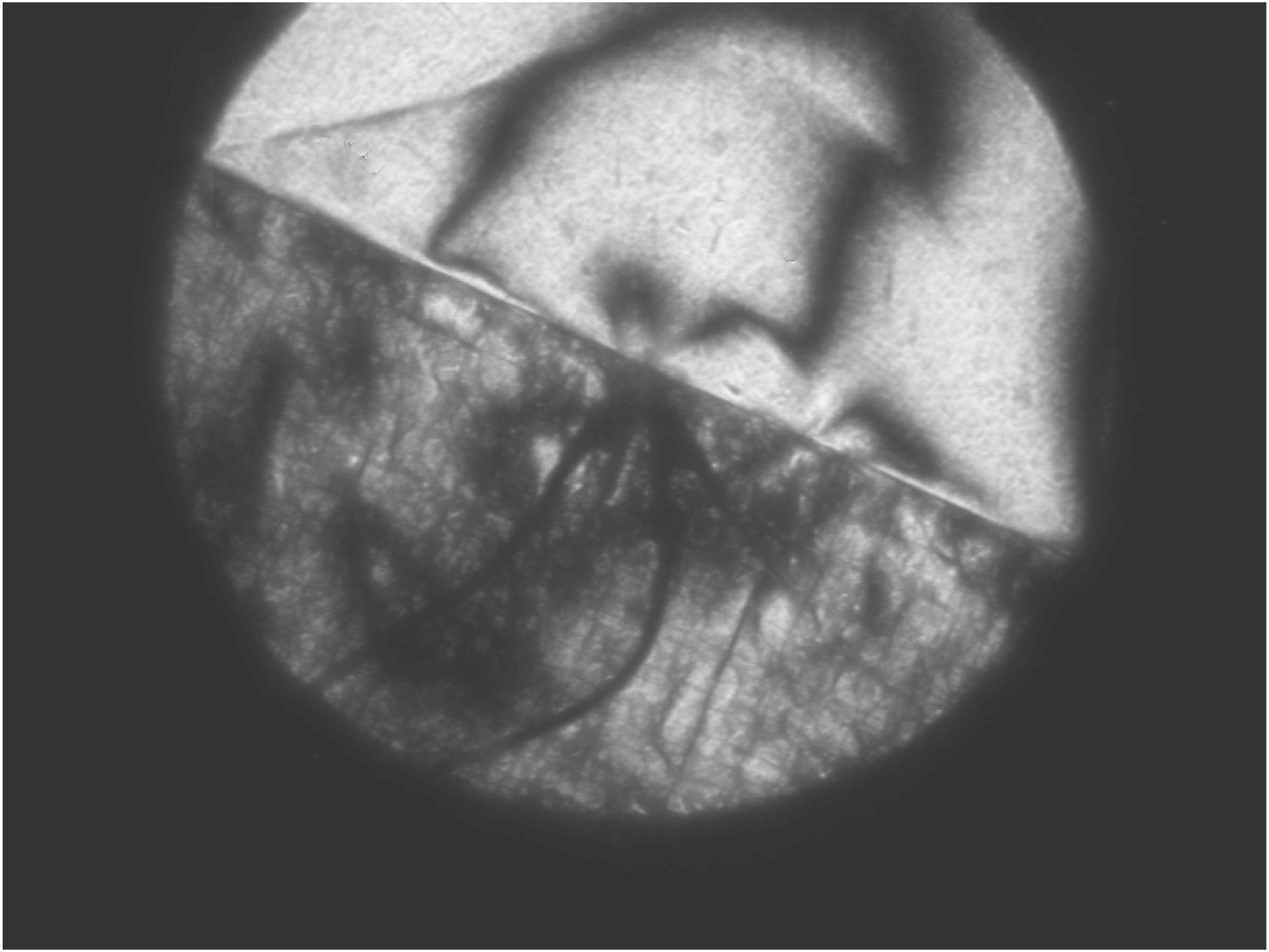


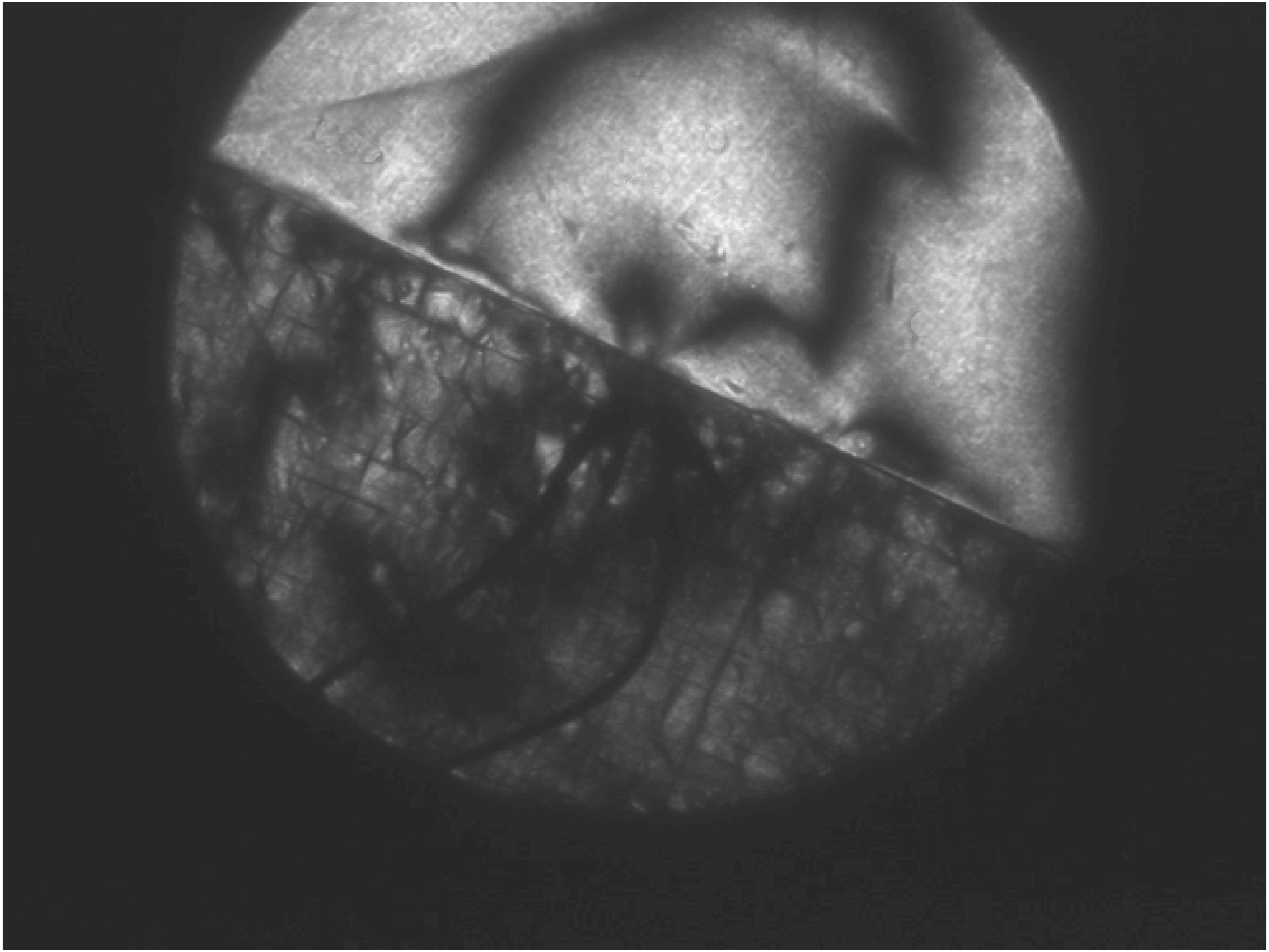


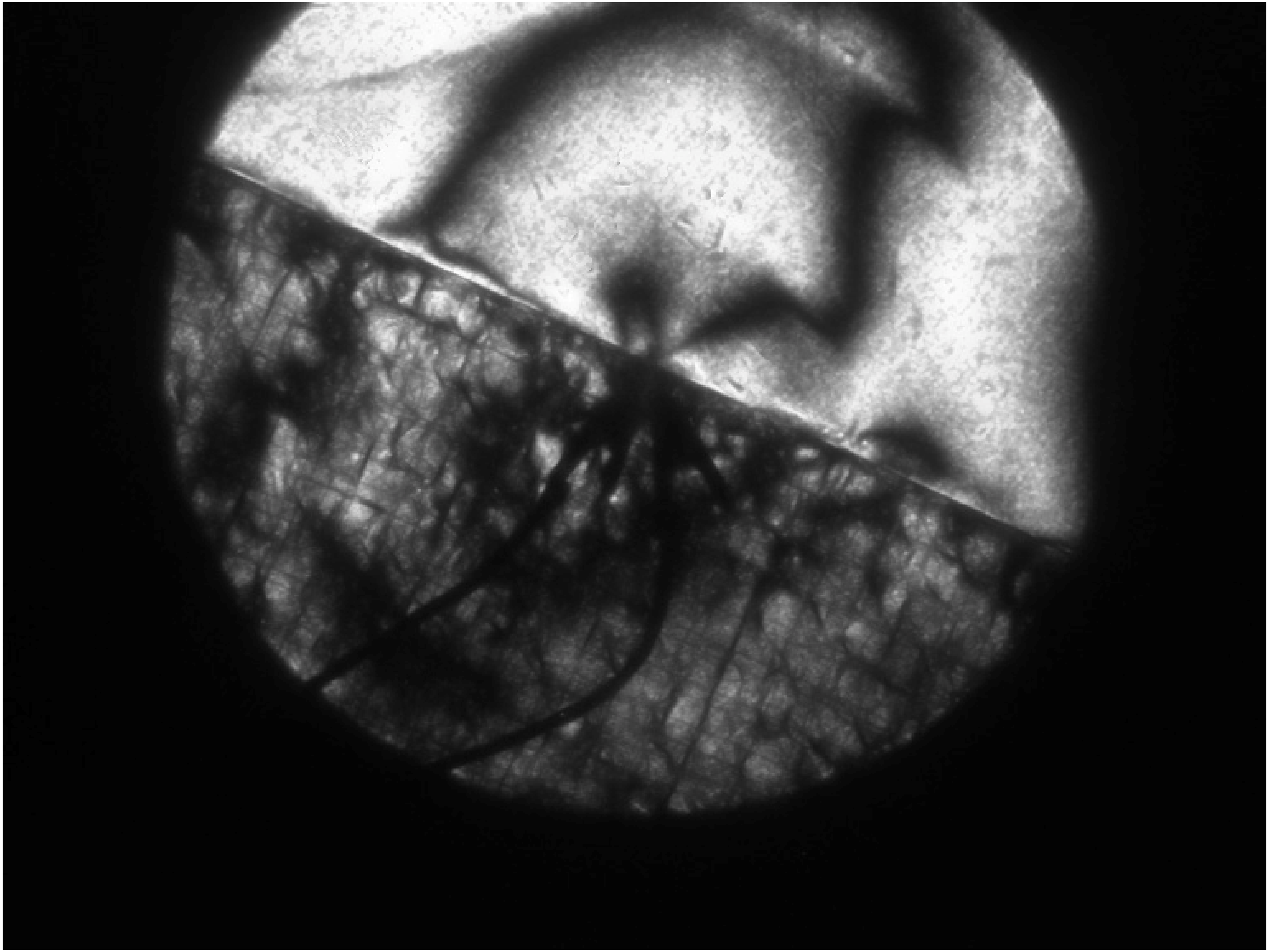

C +
T -
Comparable Mach Angles => $c_s^H \sim c_s^{Damaged\text{-}H}$ in C+

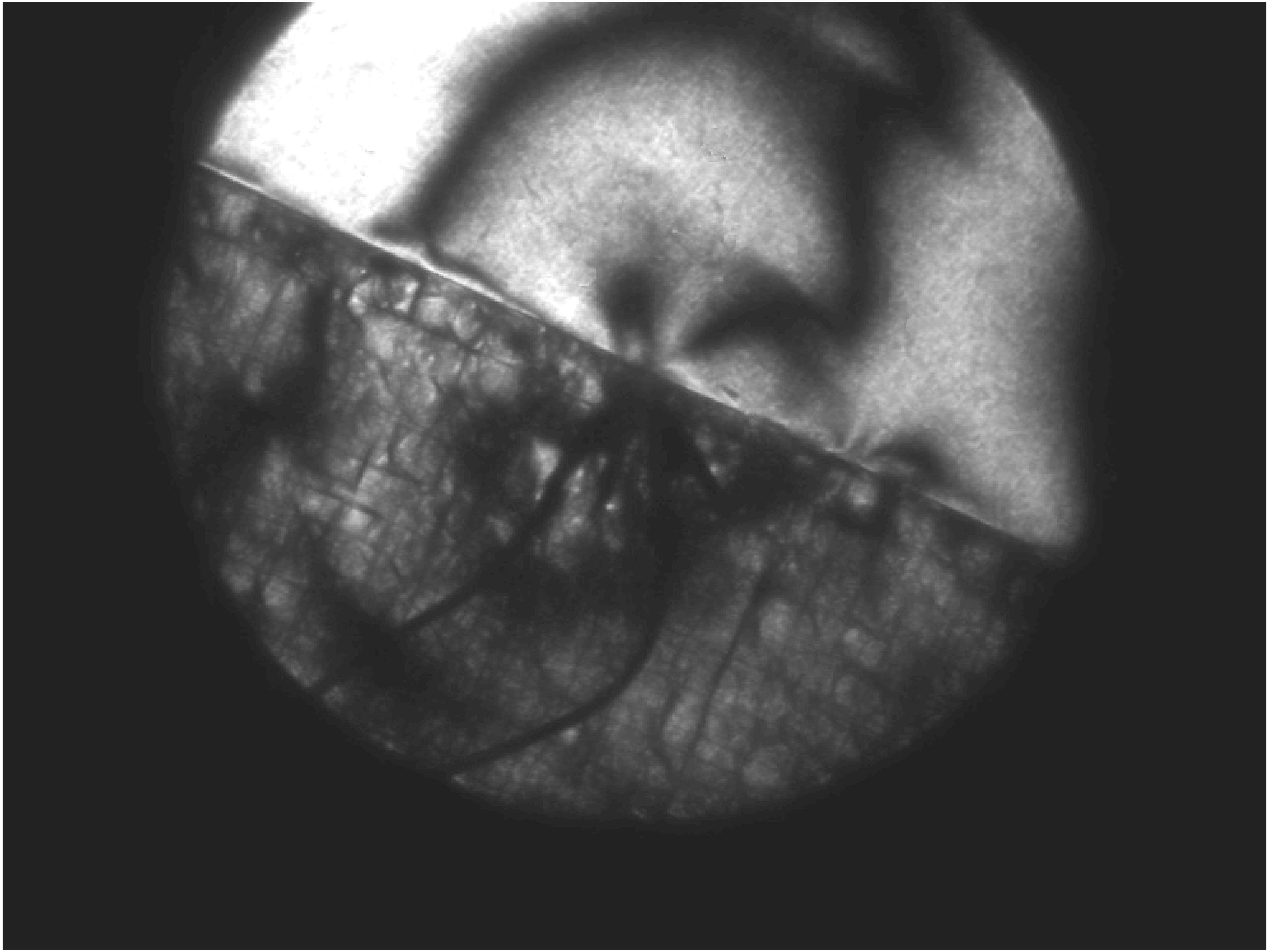


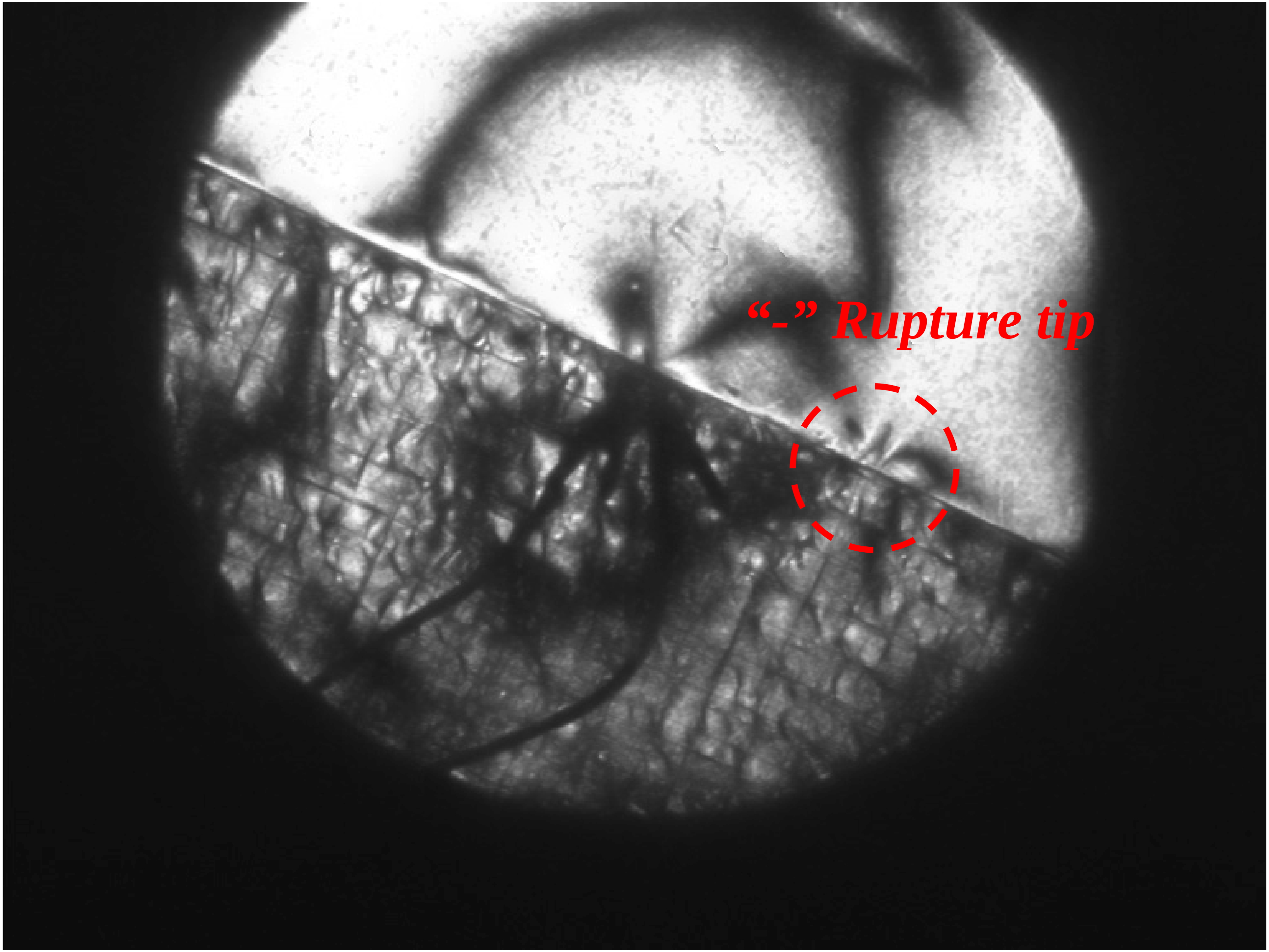






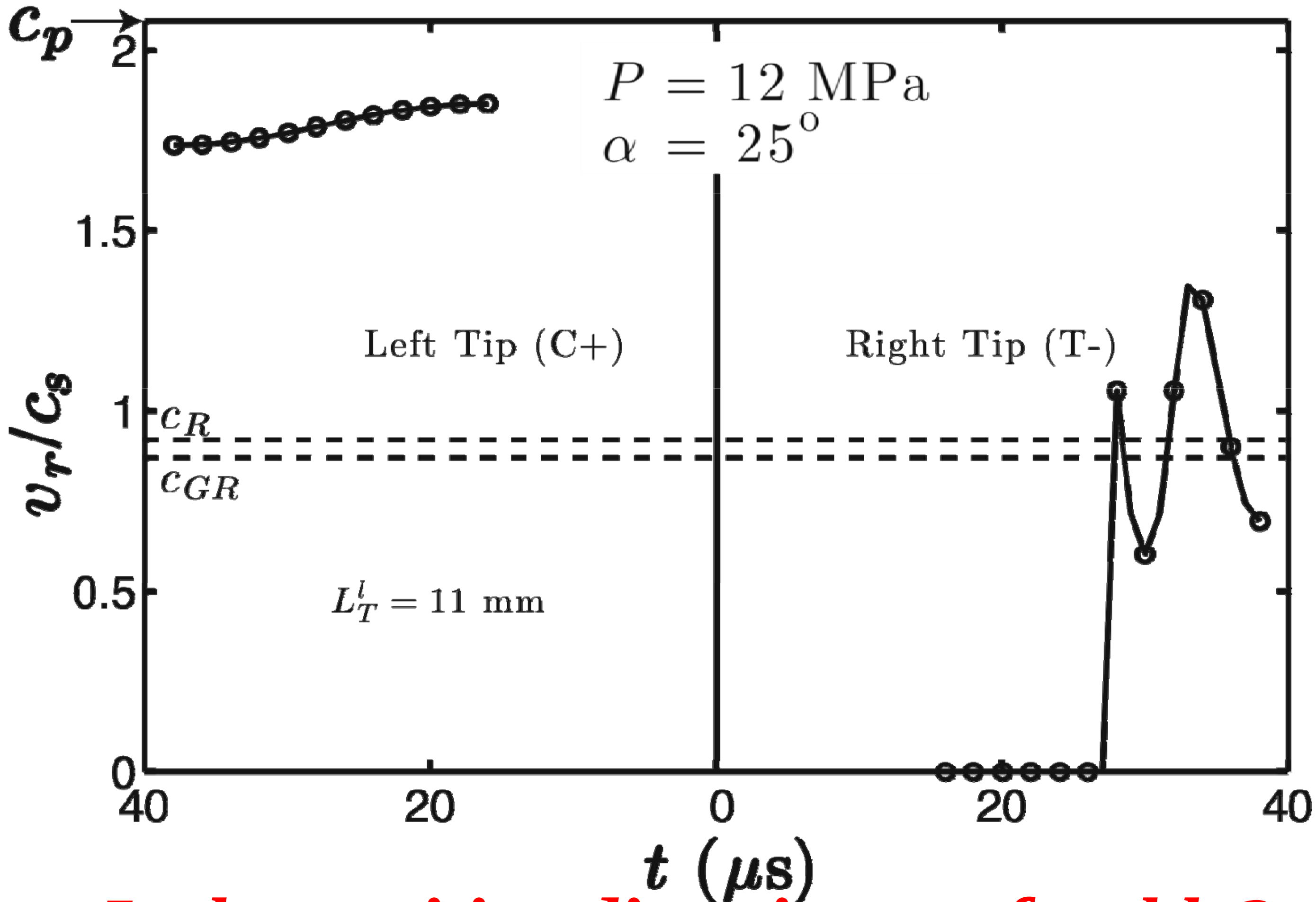





"-" Rupture tip

Rupture Velocity: Retardation in the "-" side

Biegel, Bhat, Sammis and Rosakis, Part-I, Tectonophysics , Special volume on super-shear (2010).



Is the positive direction preferable?

Proposed White Light Experiment

- Opaque plates , held in frictional contact.
- Constant intensity illumination (sun)
- Collimated White light , light scattering.
- Single square-array of detectors or existing High-speed cameras capable of recording reflected light intensity field changes due to wave-induced surface slope changes (imitating a Sun-synchronous orbit).
- Various materials systems and “ground” surface preparations.

White Light Experiment Design

- Use remote sensing principles and numerical Seismo-mechanics calculations to determine:

1)Intensity of constant white light source (surrogate Sun)

2)Detection characteristics.

3) Framing rate and Exposure times of Existing High speed cameras

4) Acceptable levels of Surface roughness and variability.

5) Length-scale of material in-homogeneities interfering with wave and image coherence

Perform Experiments designed (as described above) to ultimately validate on the ground the metrology solution proposed for Space measurement.

MUCH LESS EXPENSIVE