INTERSONIC EARTHQUAKES:
What Laboratory Earthquakes can teach us about real ones

Ares J. Rosakis

Director
Graduate Aeronautical Laboratories (GALCIT)
California Institute of Technology

Astor Public Lecture

Museum Lecture Theatre
Parks Road, Oxford

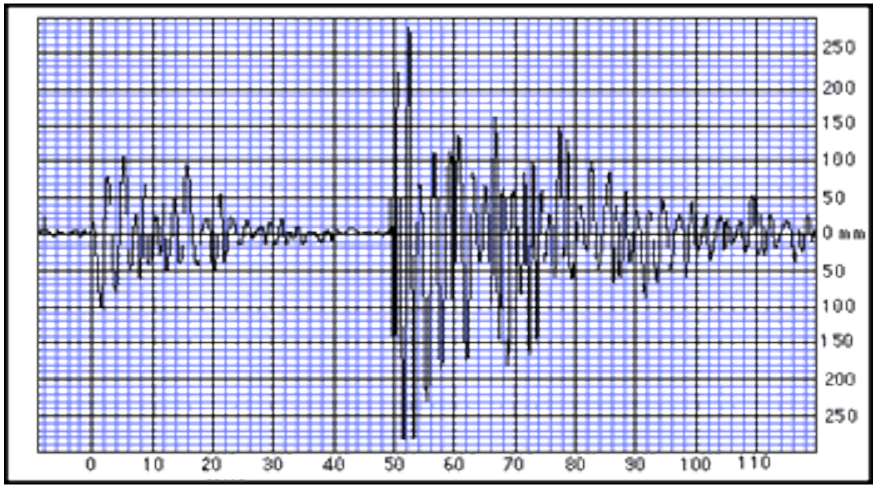
Friday, May 2, 2008

Collaborations:

H. Kanamori, Caltech
J. Rice, Harvard University
K. Xia, University of Toronto
N. Lapusta , Caltech
Xiao Lu, Caltech

Office of Naval Research
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

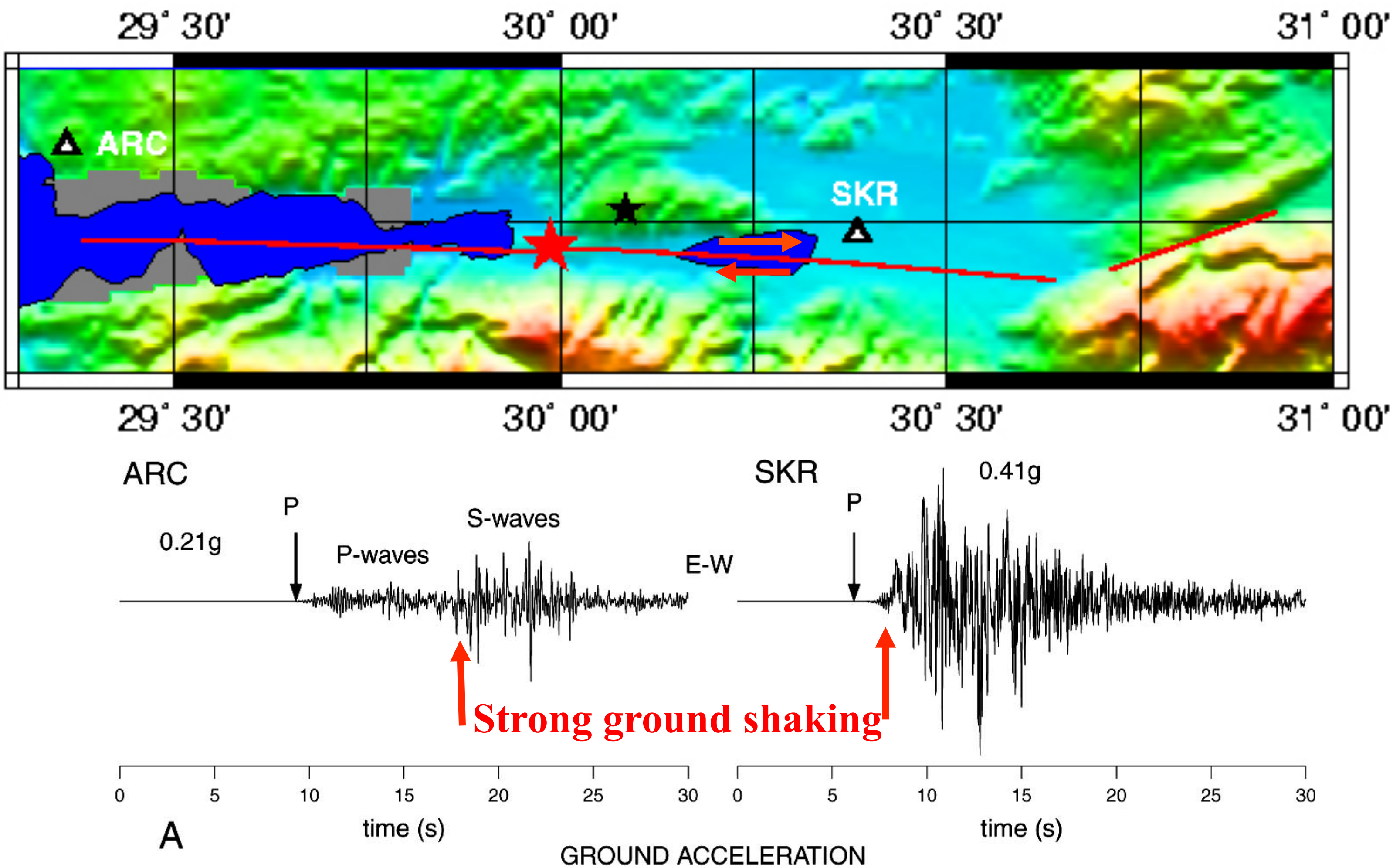
Earthquakes are spontaneous frictional (shear) ruptures occurring along weak planes in the crust :

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

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

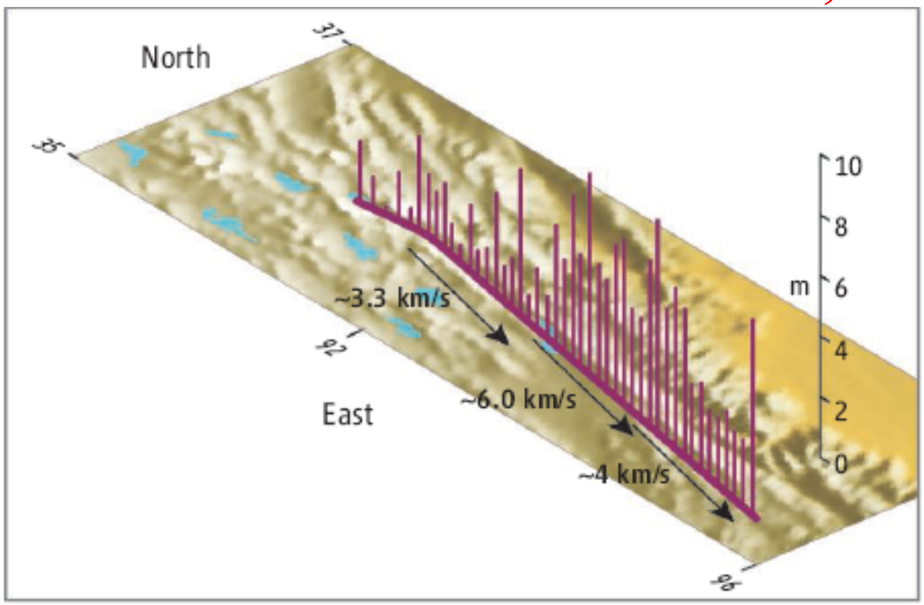
- Evidence of supershear ($C_S < v < C_P$) rupture bursts along fault segments.

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) Robinson, Brough and Das, JGR, 2006, Das, Science, 2007.	2001 Kunlunshan, China (Transition)
• Ellsworth et al., (2004)	2002 Denali, Alaska (Transition)

Personal favorites

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

Bouchon and Vallee,Science,2003, Robinson, Brough and Das, JGR, 2006, Das, Science, 2007.

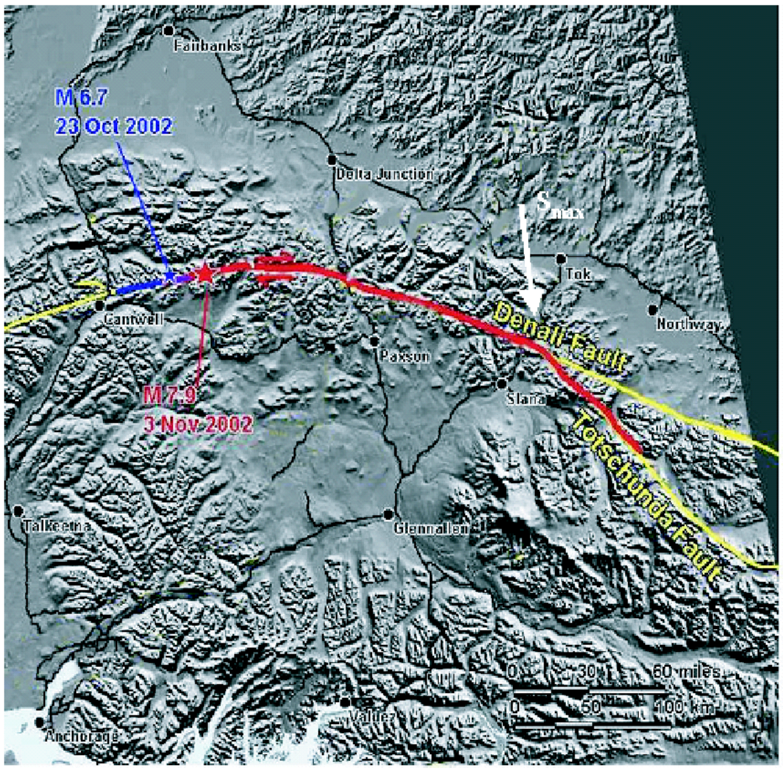


- Unidirectional, left lateral slip occurring over a very long, near-vertical, strike –slip fault segment.(slip:7-8m max)
- Eastward propagation over a 400 km fault segment
- Sub-Rayleigh over first 100 km (2.8-3.3 km/s)
- Transition to supershear (6 km/s ~P-wave speed)

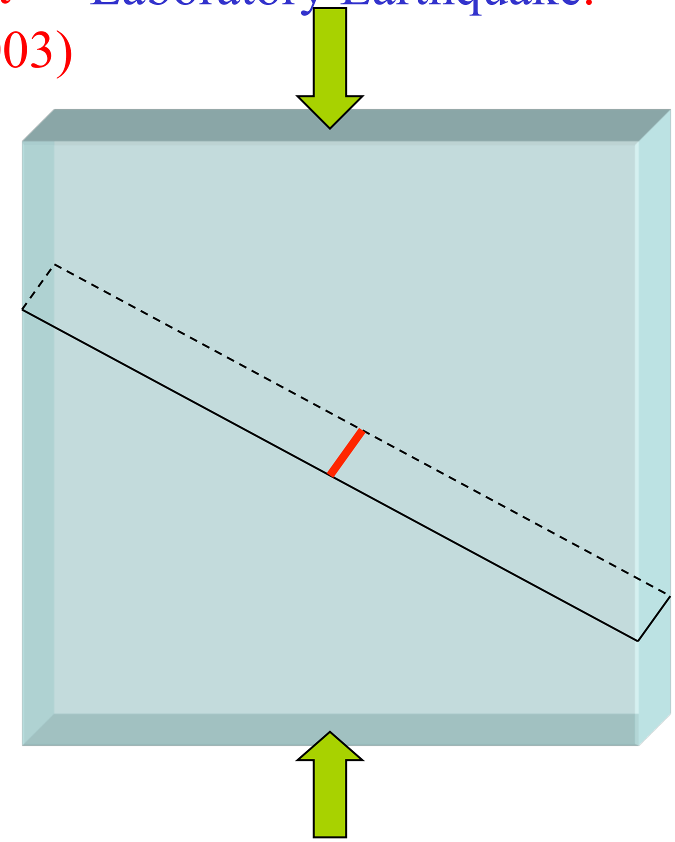
From Real to Laboratory Earthquakes

(*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)



Laboratory Earthquake.



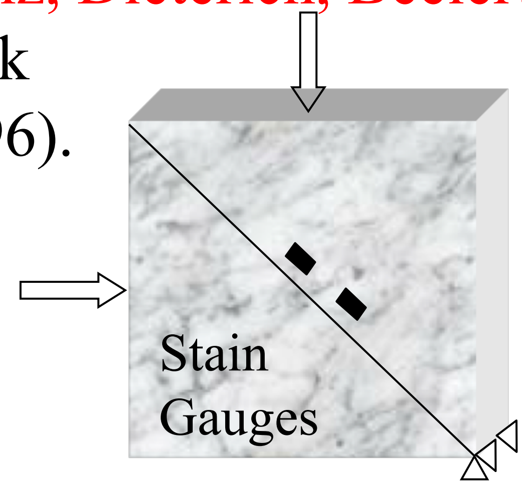
- **Rock** → **Photoelastic Polymer**
- **Fault** → **Inclined Contact Interface**
- **Tectonic stress** → **Far Field Load**
- **Hypocenter** → **Triggering Site**

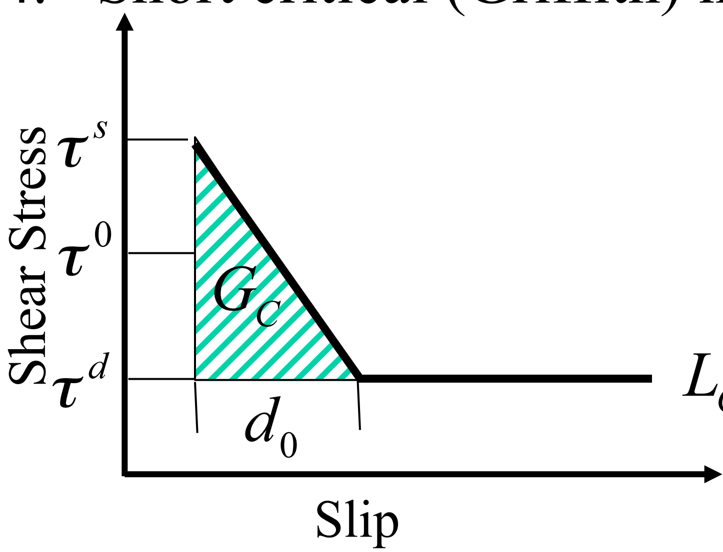
Why Polymer ?

1. Birefringence insures max sensitivity to shear stresses.
2. Good linear-elastic material.
3. Qualitatively Similar frictional properties to rock (Dieterich, 1979, Dieterich @ Kilgore,1994,1996).
4. Short critical (Griffith) initiation length, L_{C}.

Biaxial Loading Model

Scholz, Dieterich, Beeler…





Slip Weakening Law

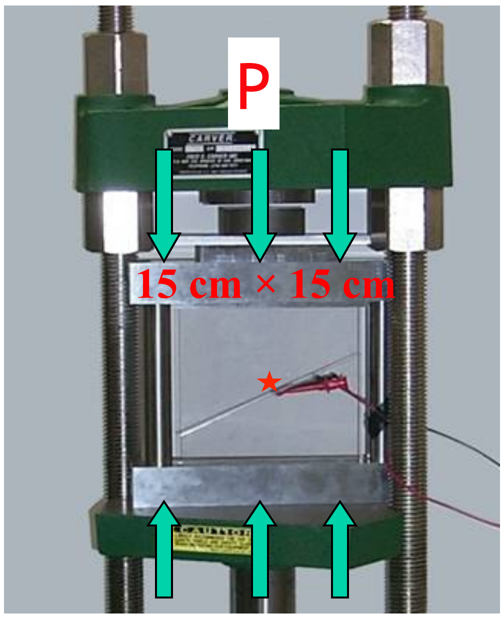
$$s = \frac{\tau^s - \tau^0}{\tau^0 - \tau^d}$$

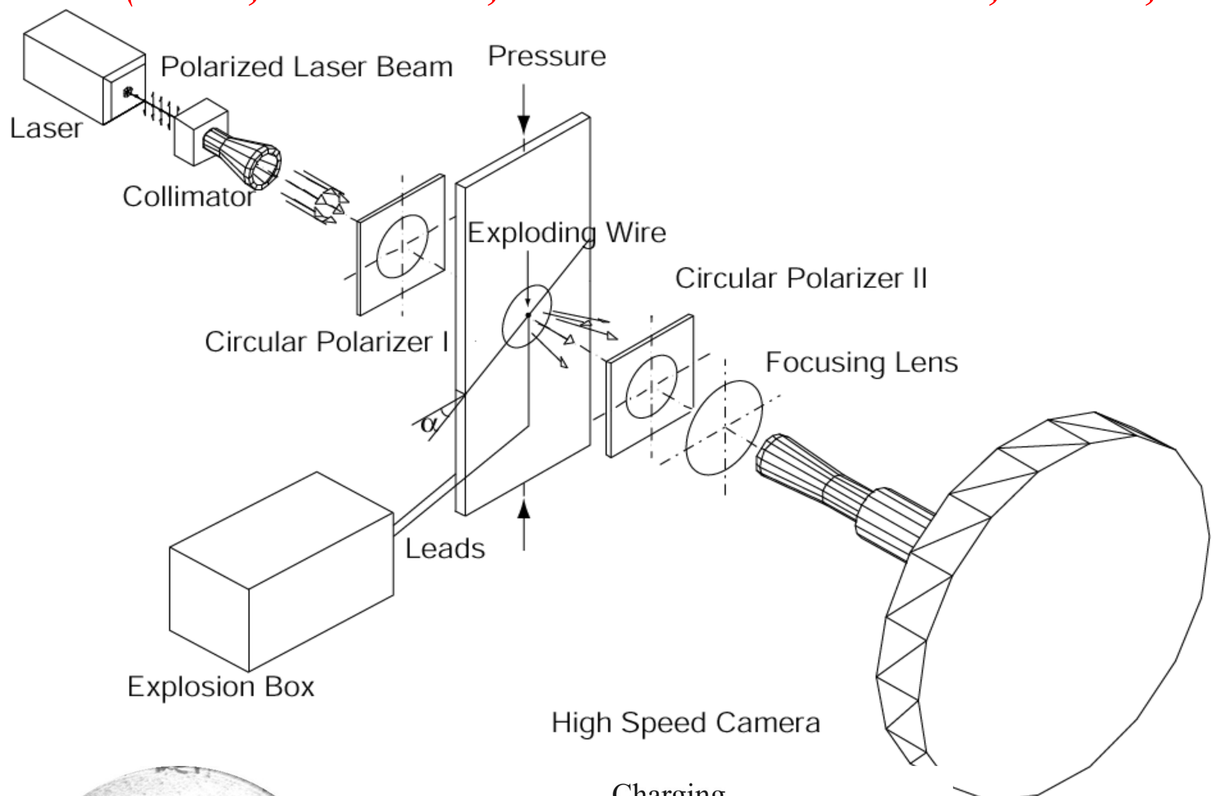
$$L_C = \frac{(1+\nu)}{\pi}\mu\frac{\tau^s - \tau^d}{(\tau^0 - \tau^d)^2}d_0 = \begin{cases} 5mm & \text{Polymer} \\ 135mm & \text{Rock} \end{cases}$$

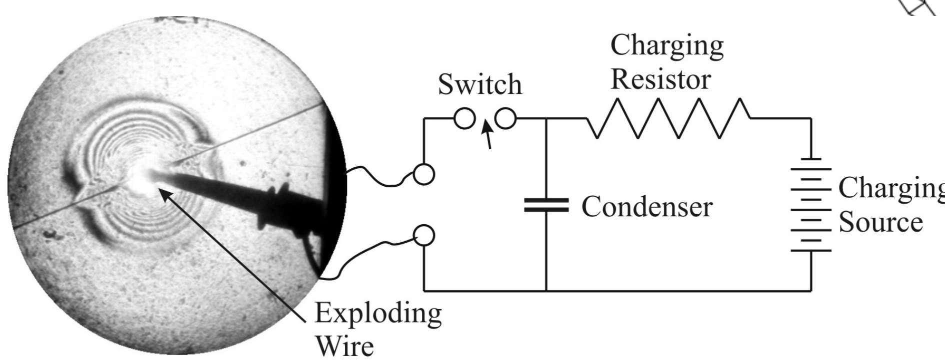
Experimental Setup

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

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

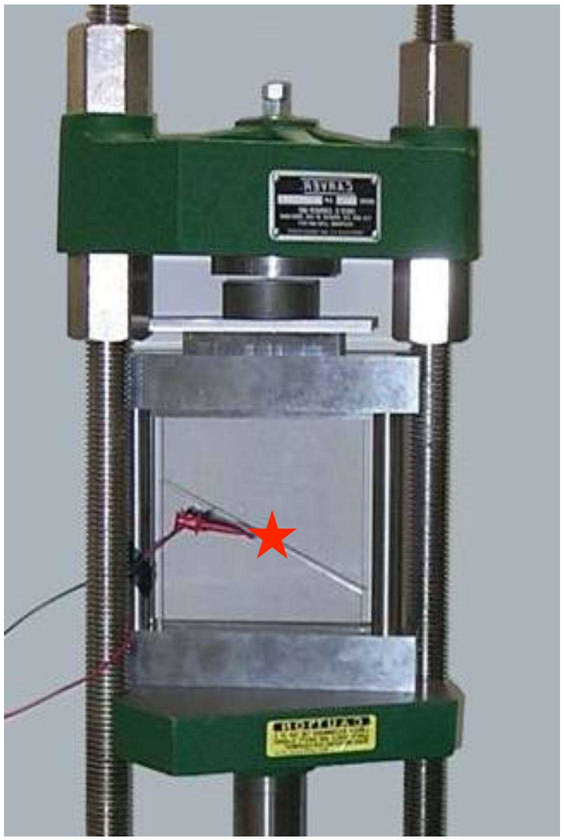


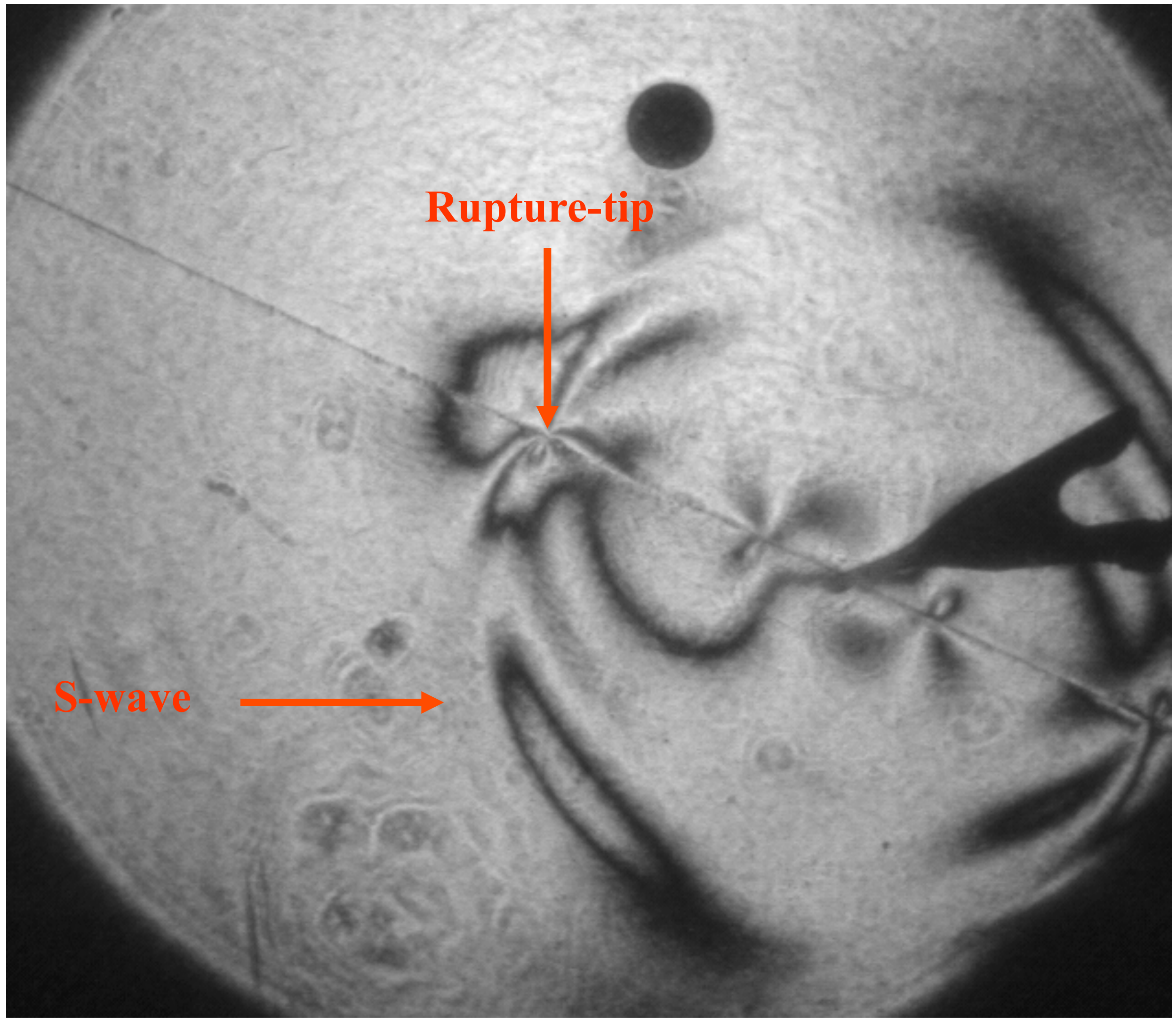




Classical Sub-Rayleigh Rupture
Angle=25°, Pressure=7MPa   T=30μs

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



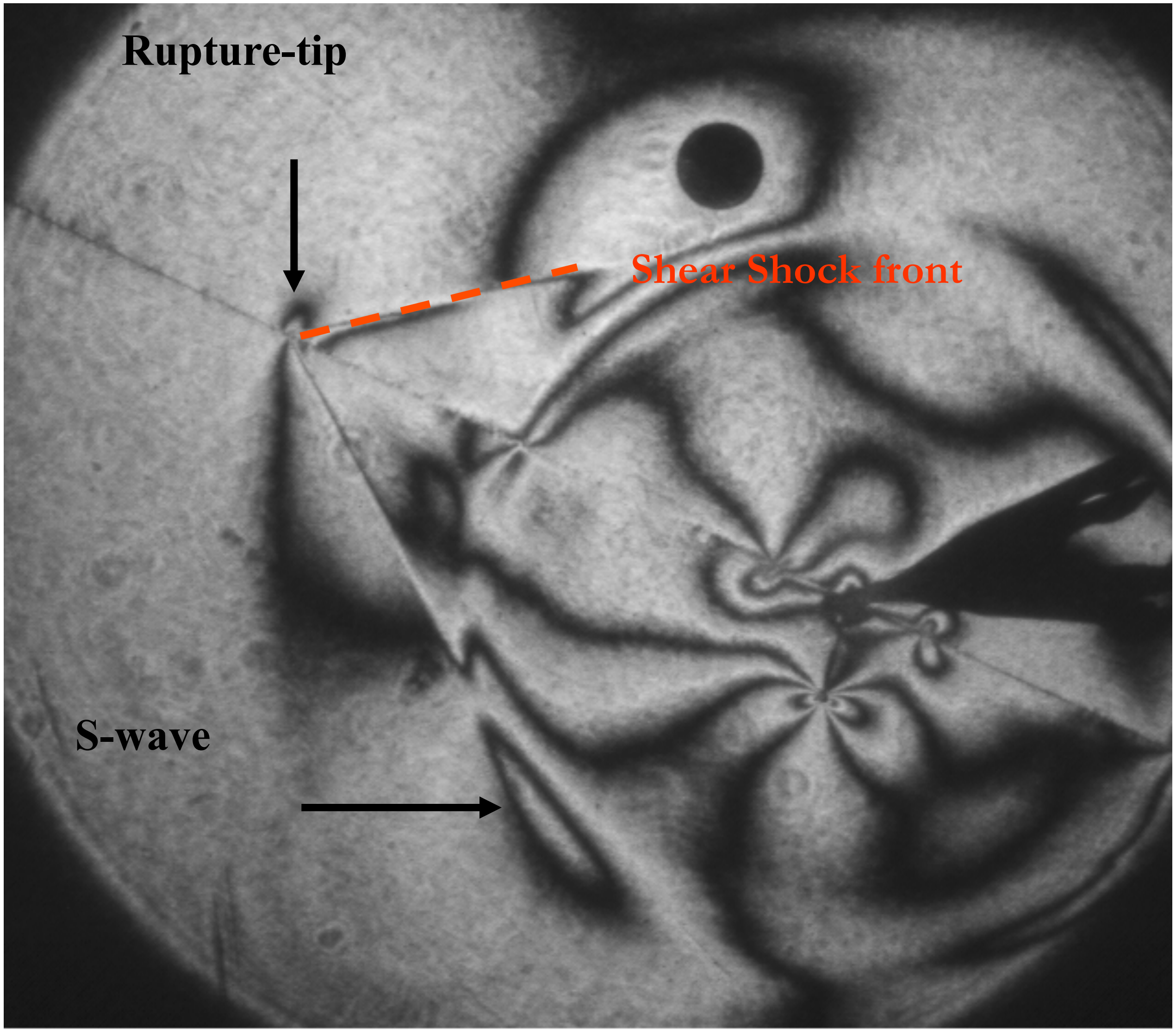


CALIFORNIA INSTITUTE OF TECHNOLOGY 1891

Supershear, or Intersonic, Rupture

Angle=25°, Pressure=13MPa T=30μs

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

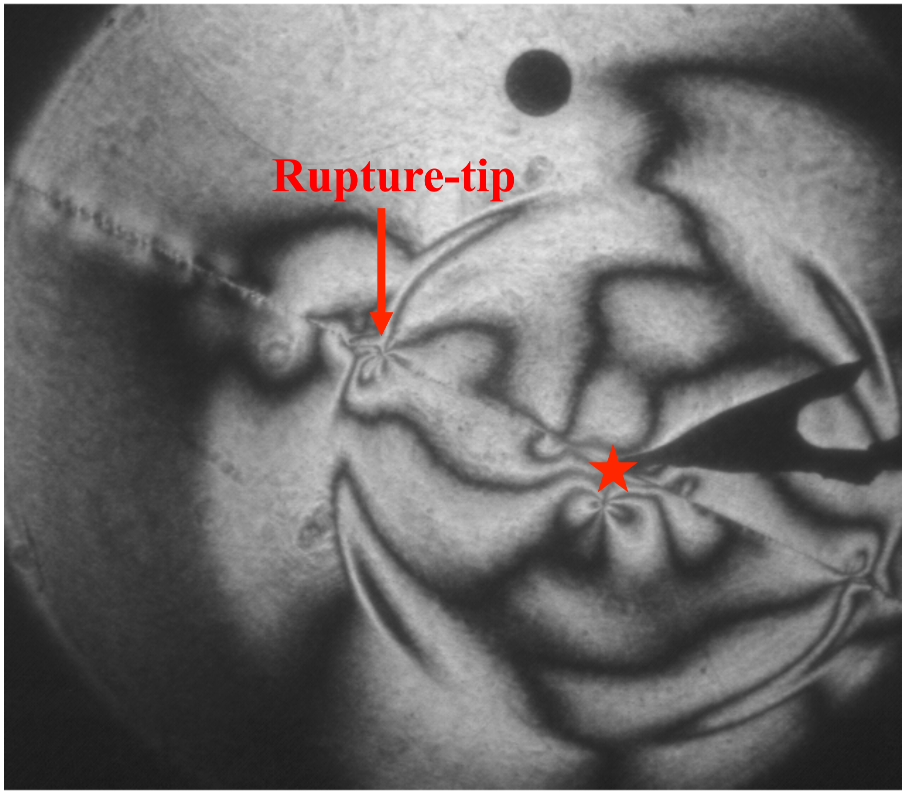


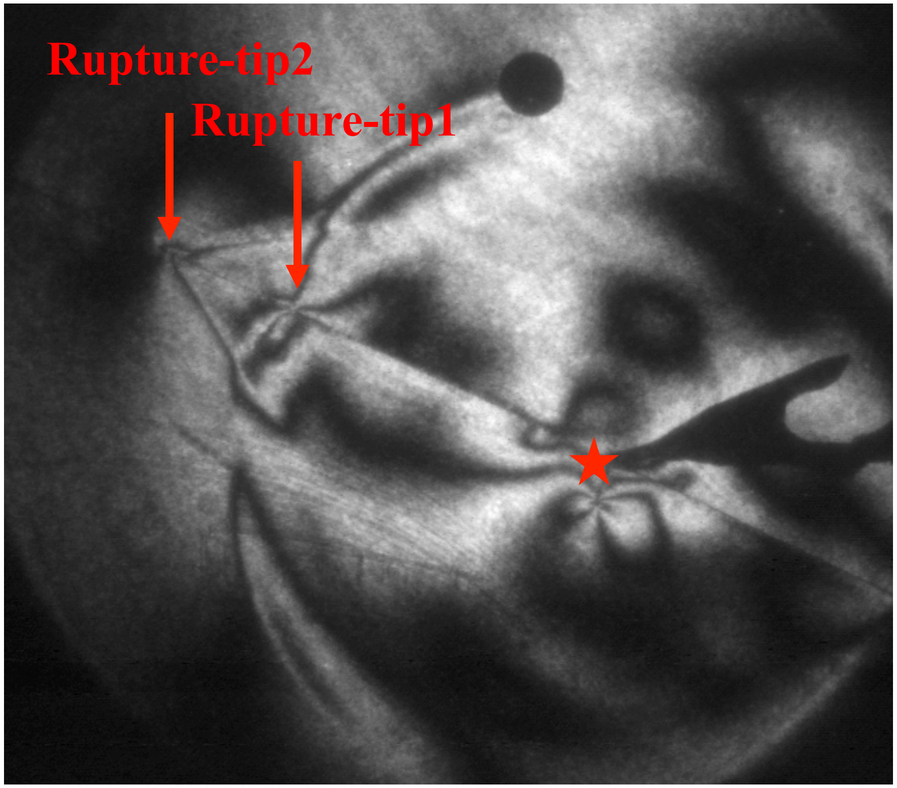
Transition: From Sub-Raleigh to Supershear

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

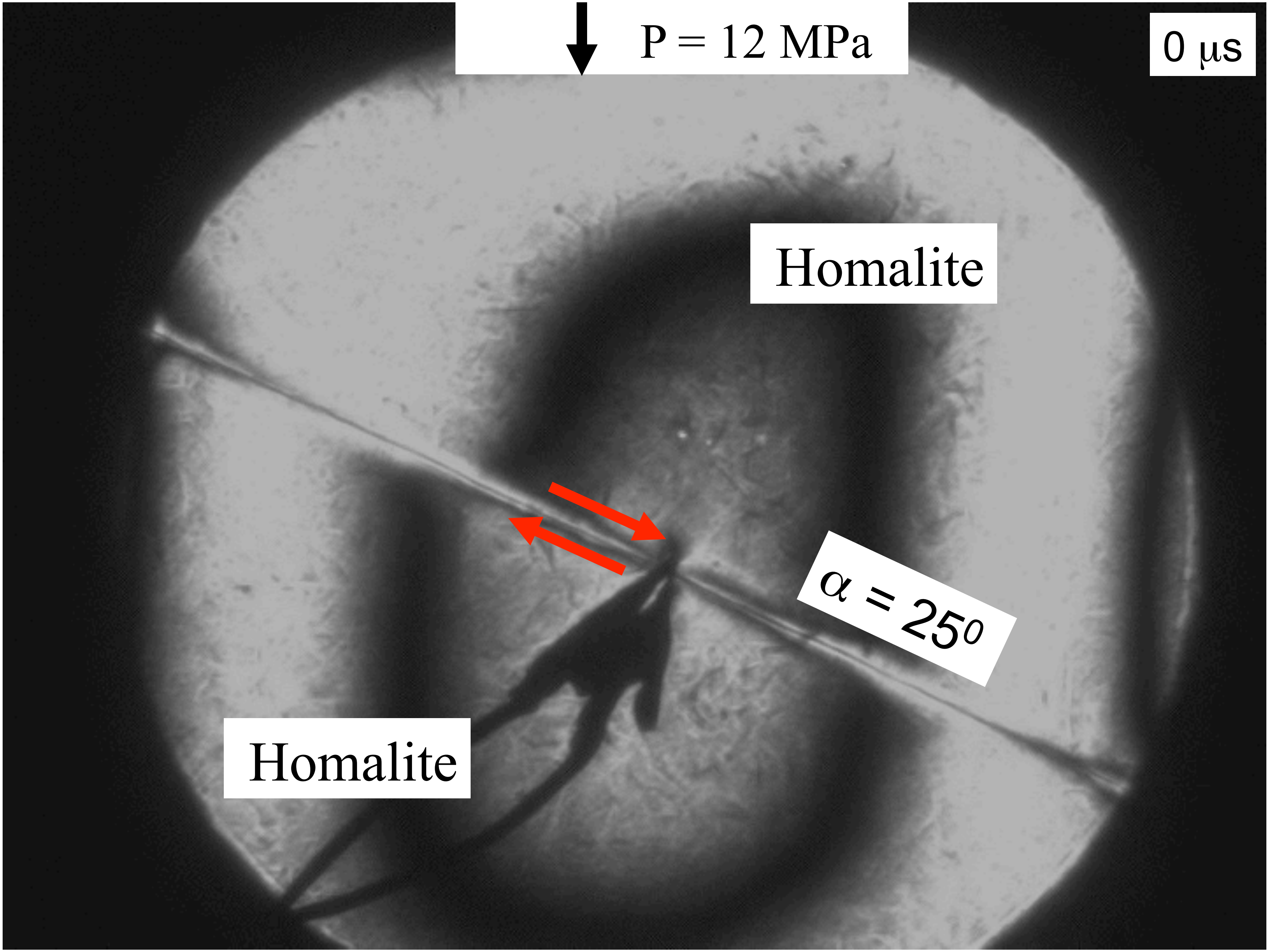
Angle=25°, Pressure = 10MPa: transition length L = 20mm

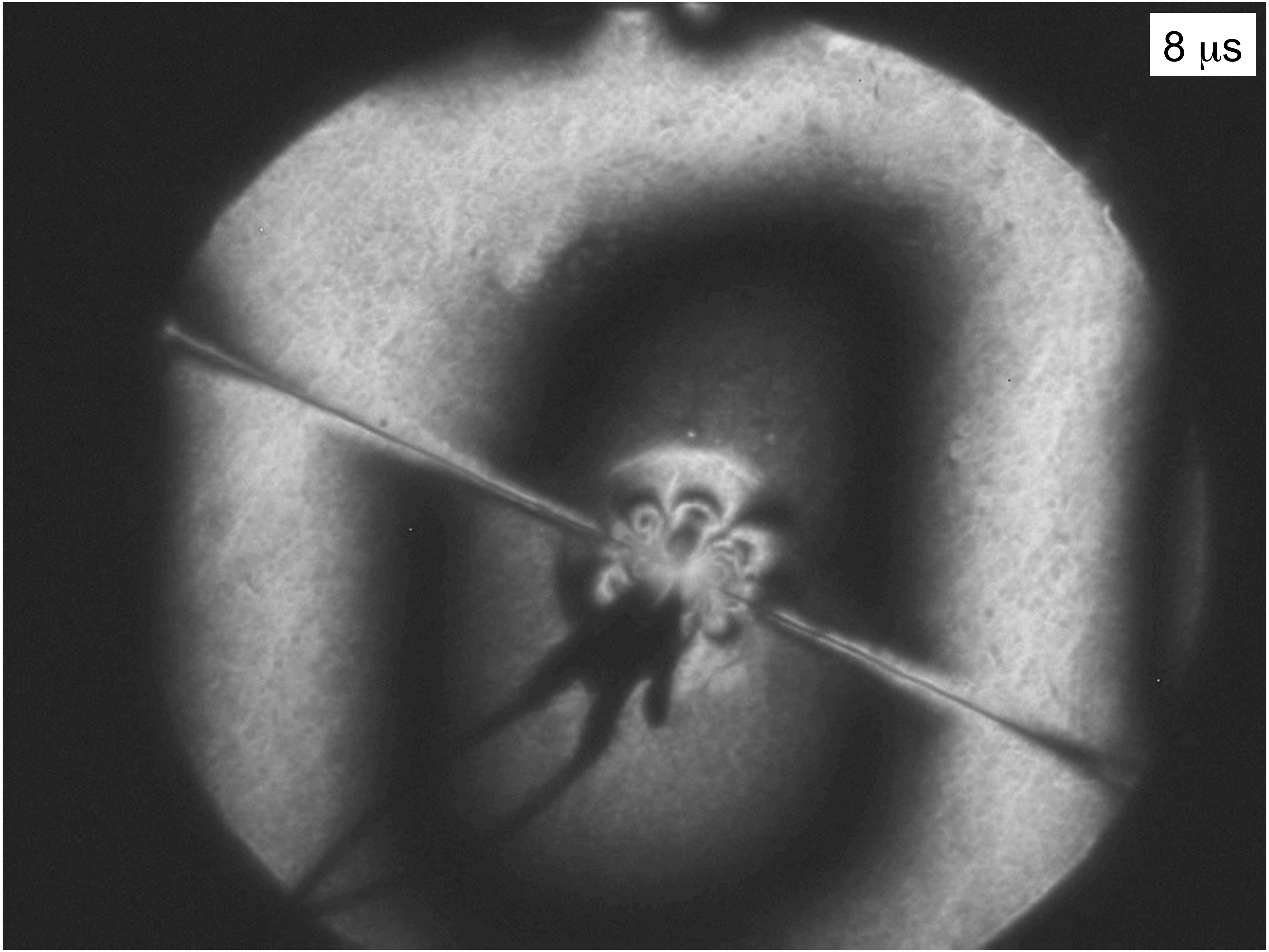
2001 Kunlunshan, Tibet Earthquake: transition length L = 100Km

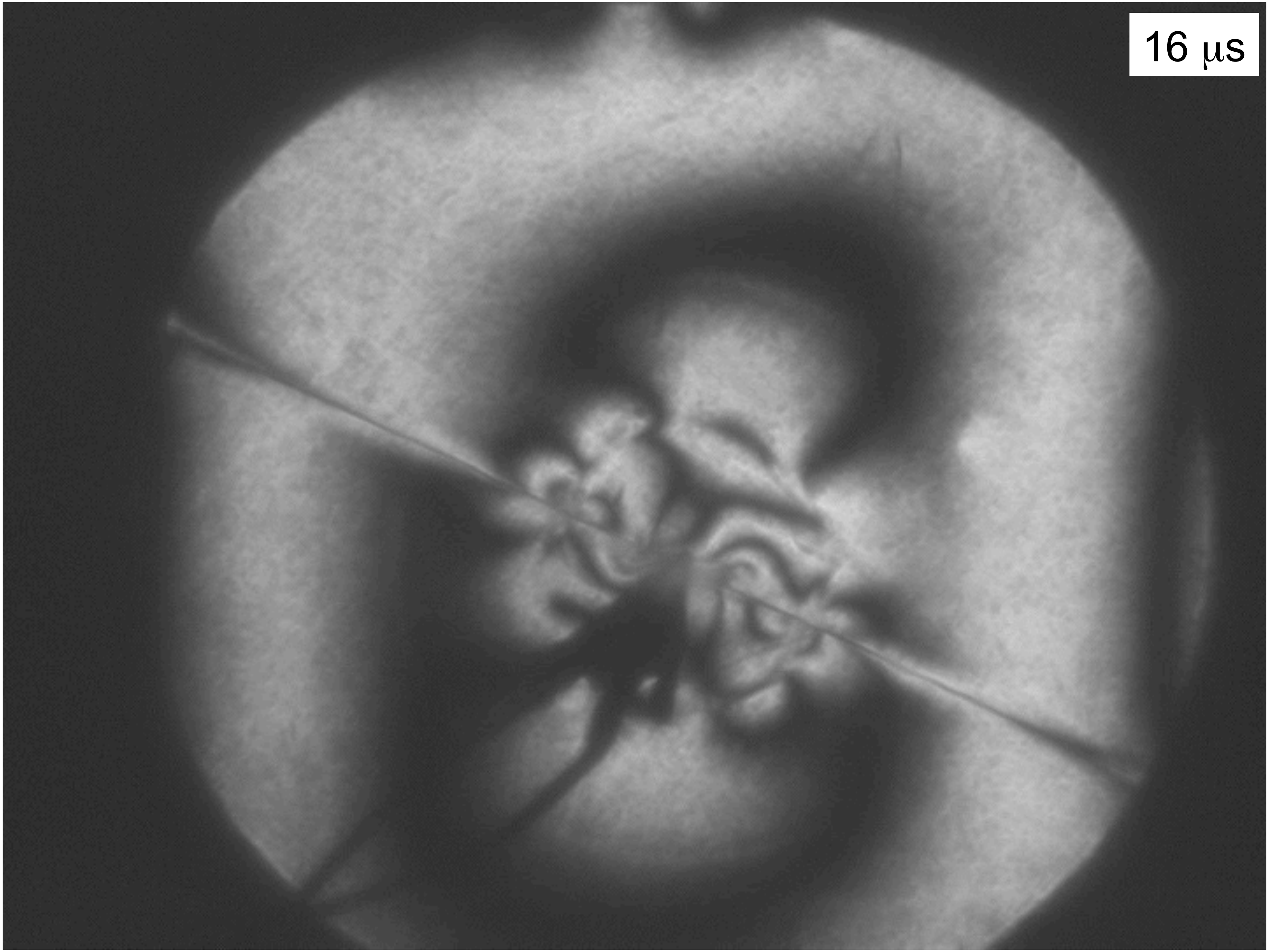


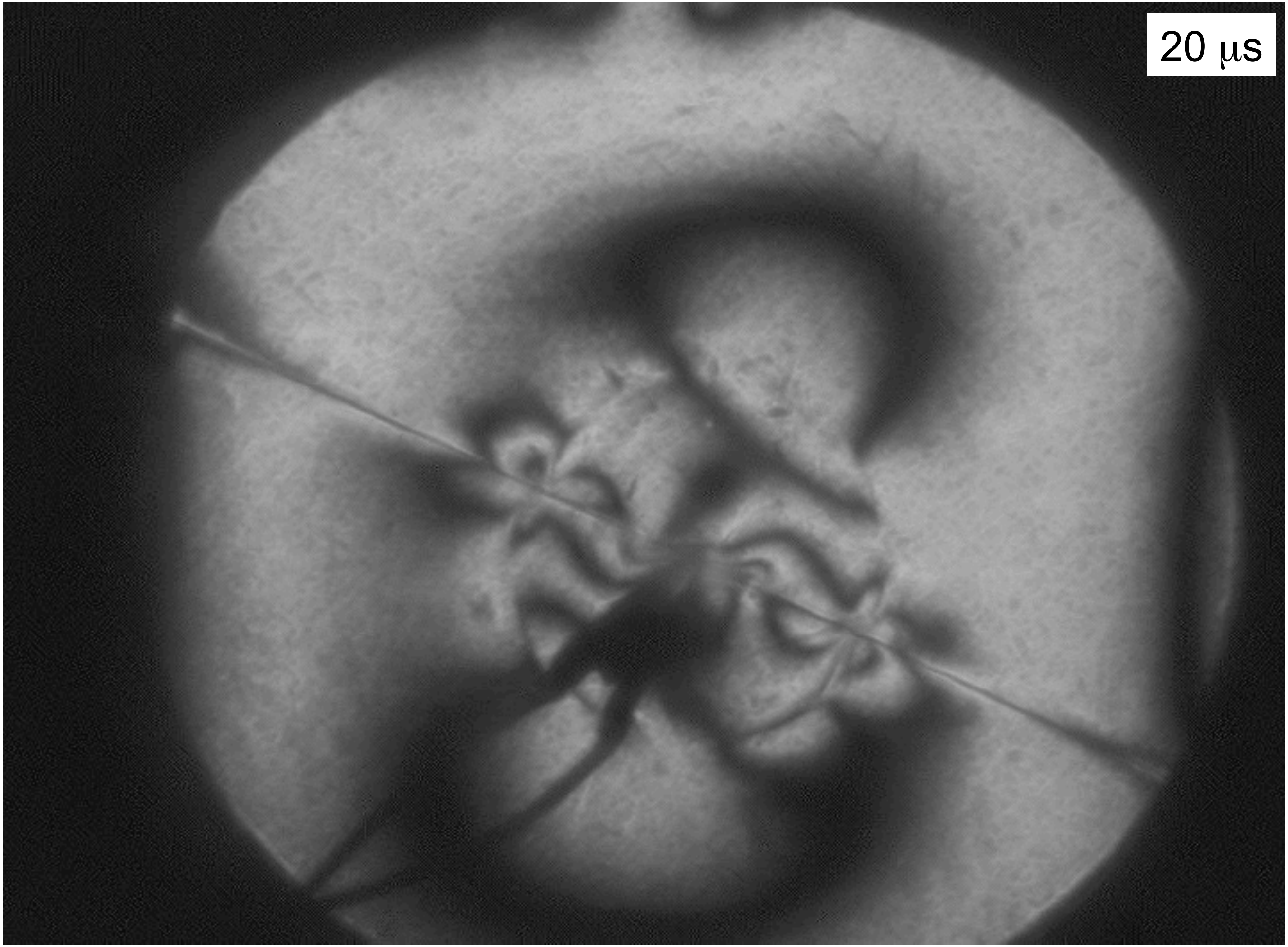


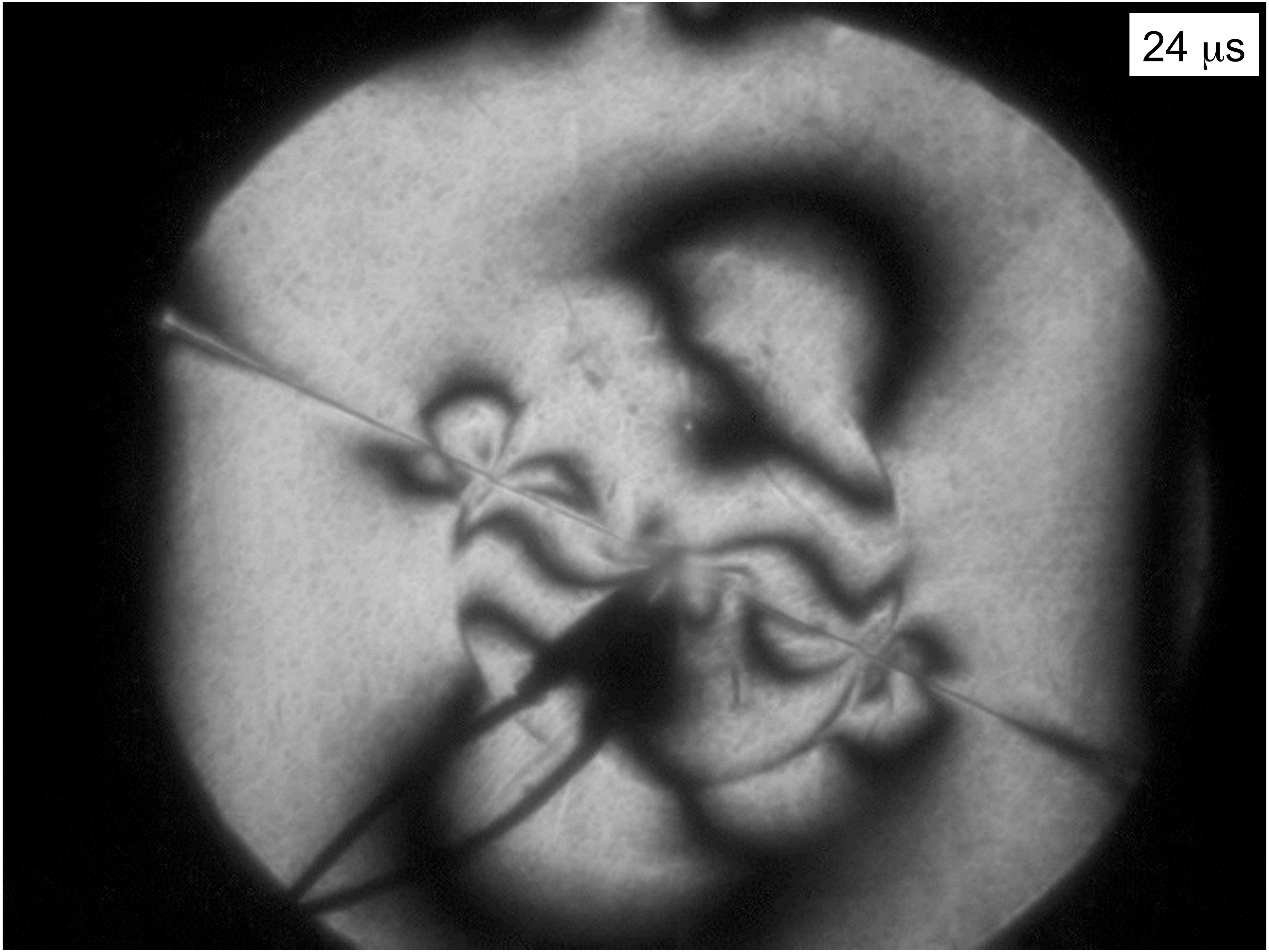
T=30μs **T=38μs**

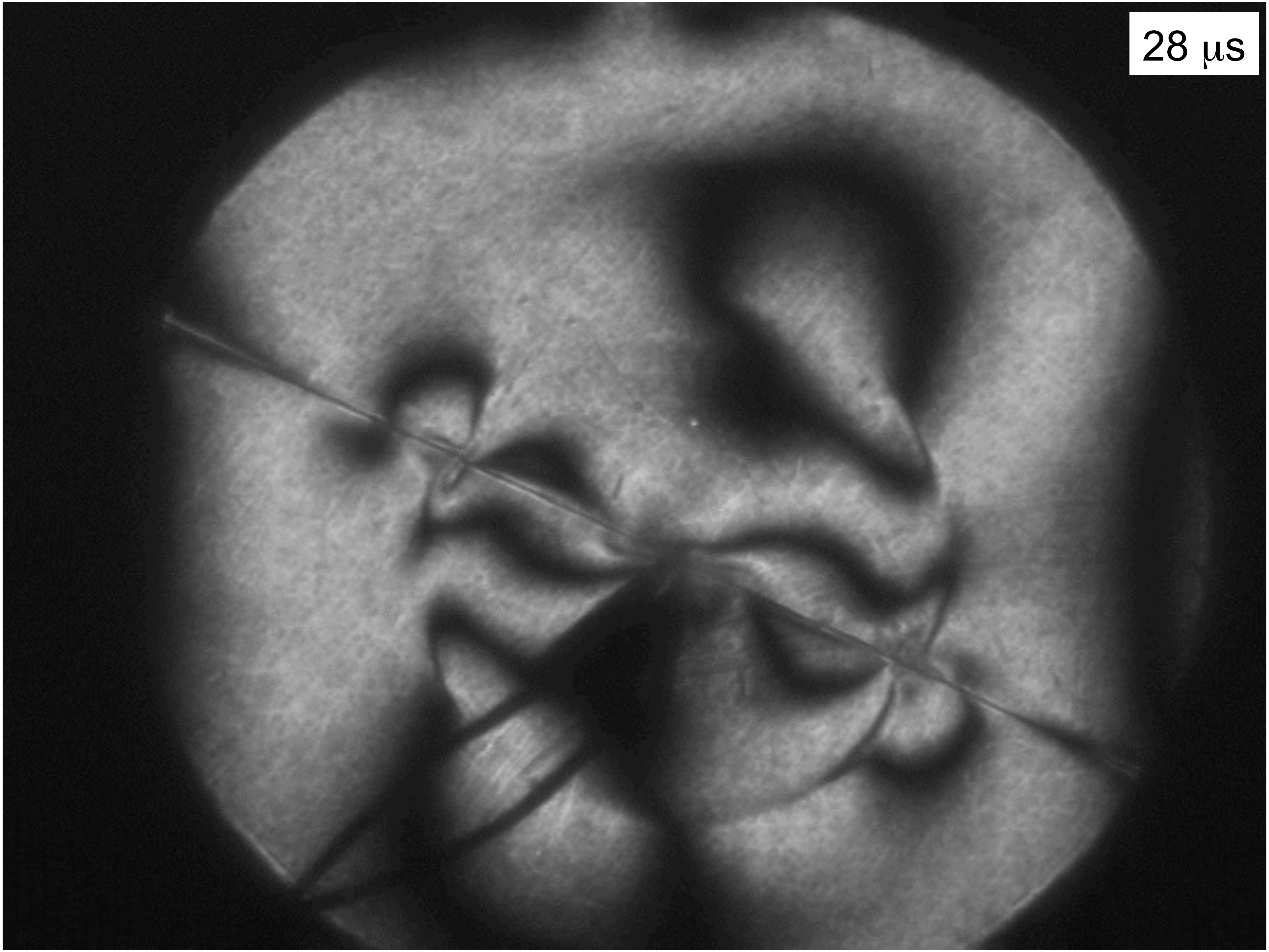

P = 12 MPa
0 μs
Homalite
α = 25⁰
Homalite

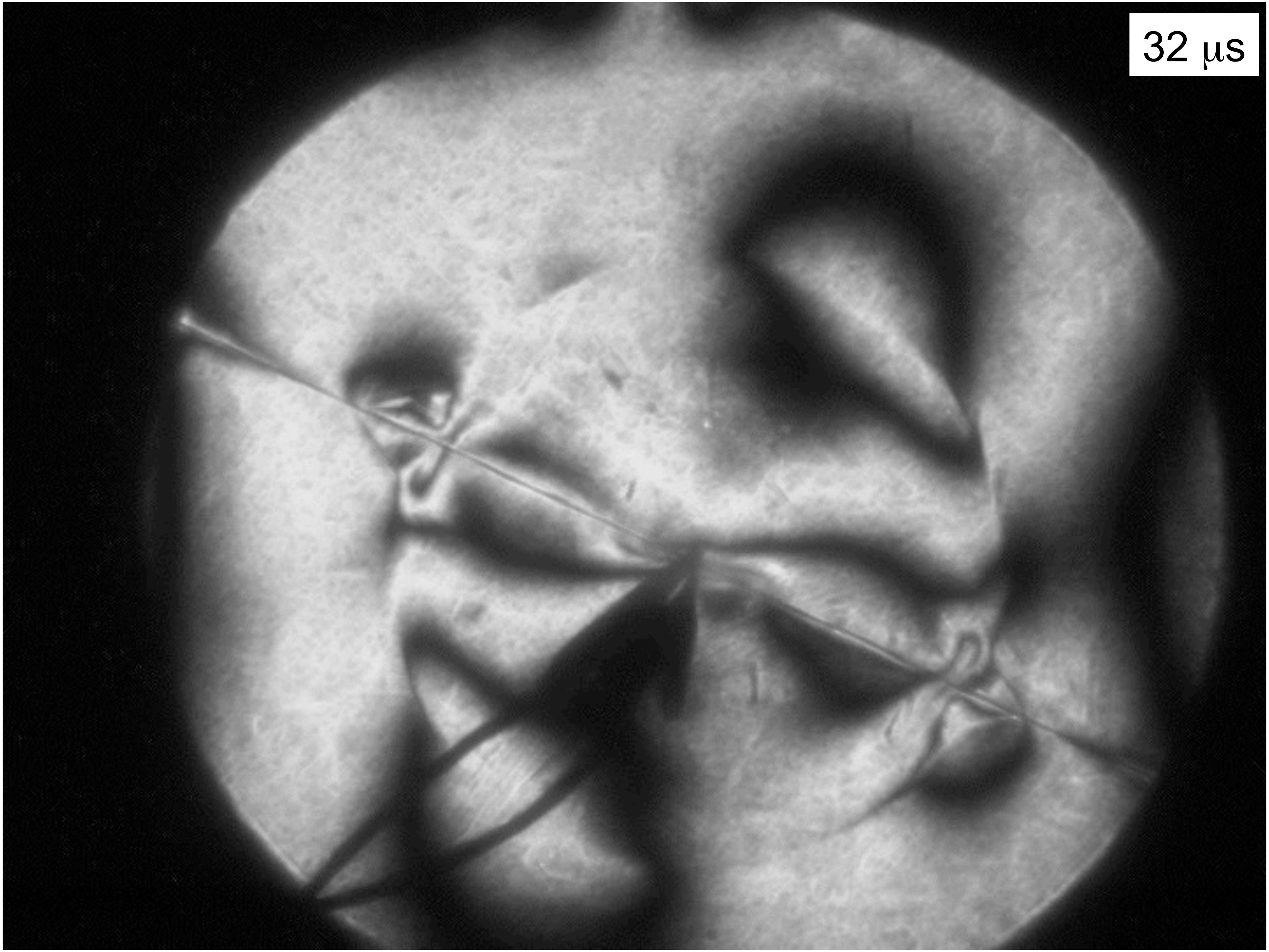

8 μs

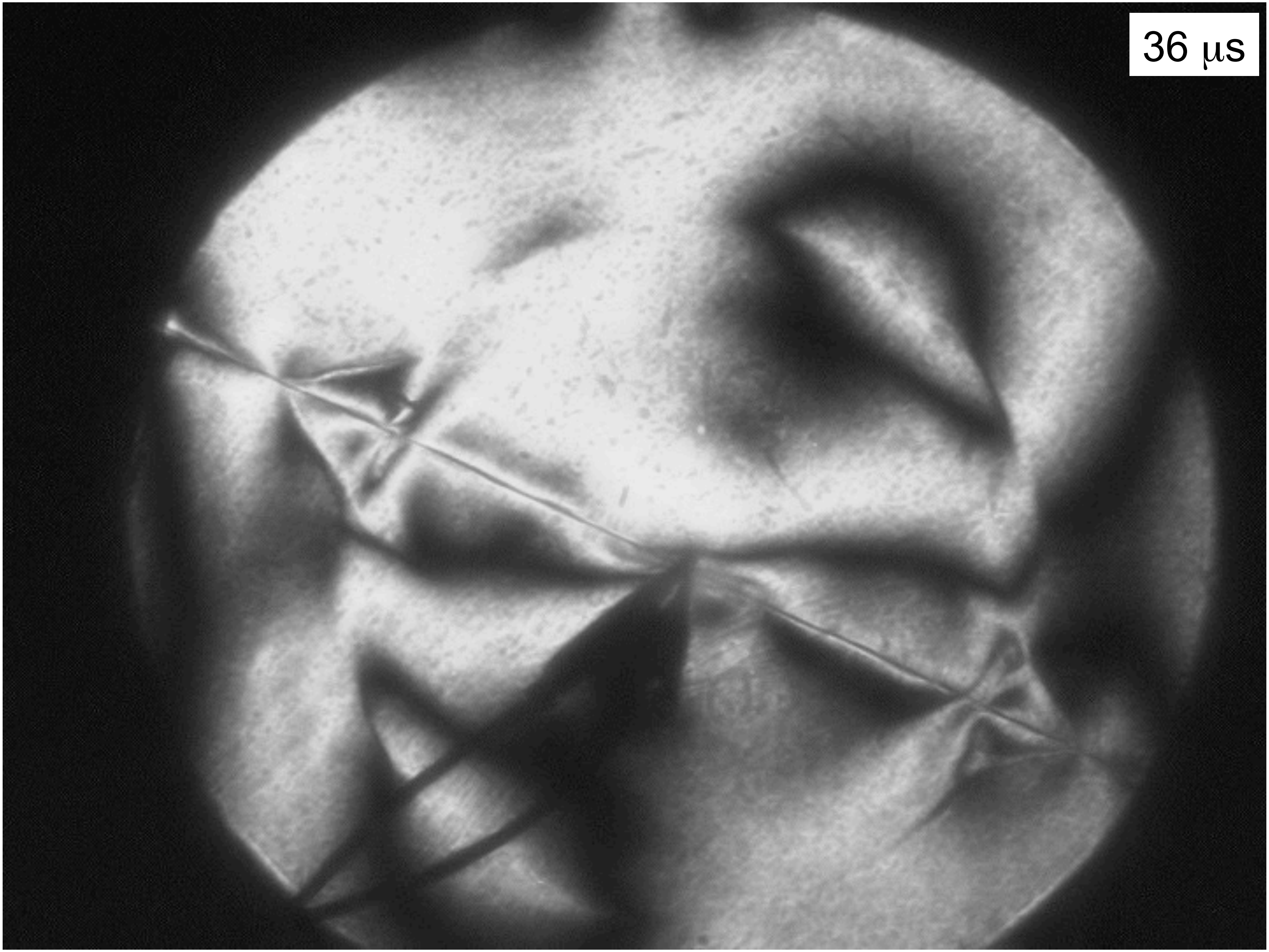

16 μs


20 μs


24 μs


28 μs

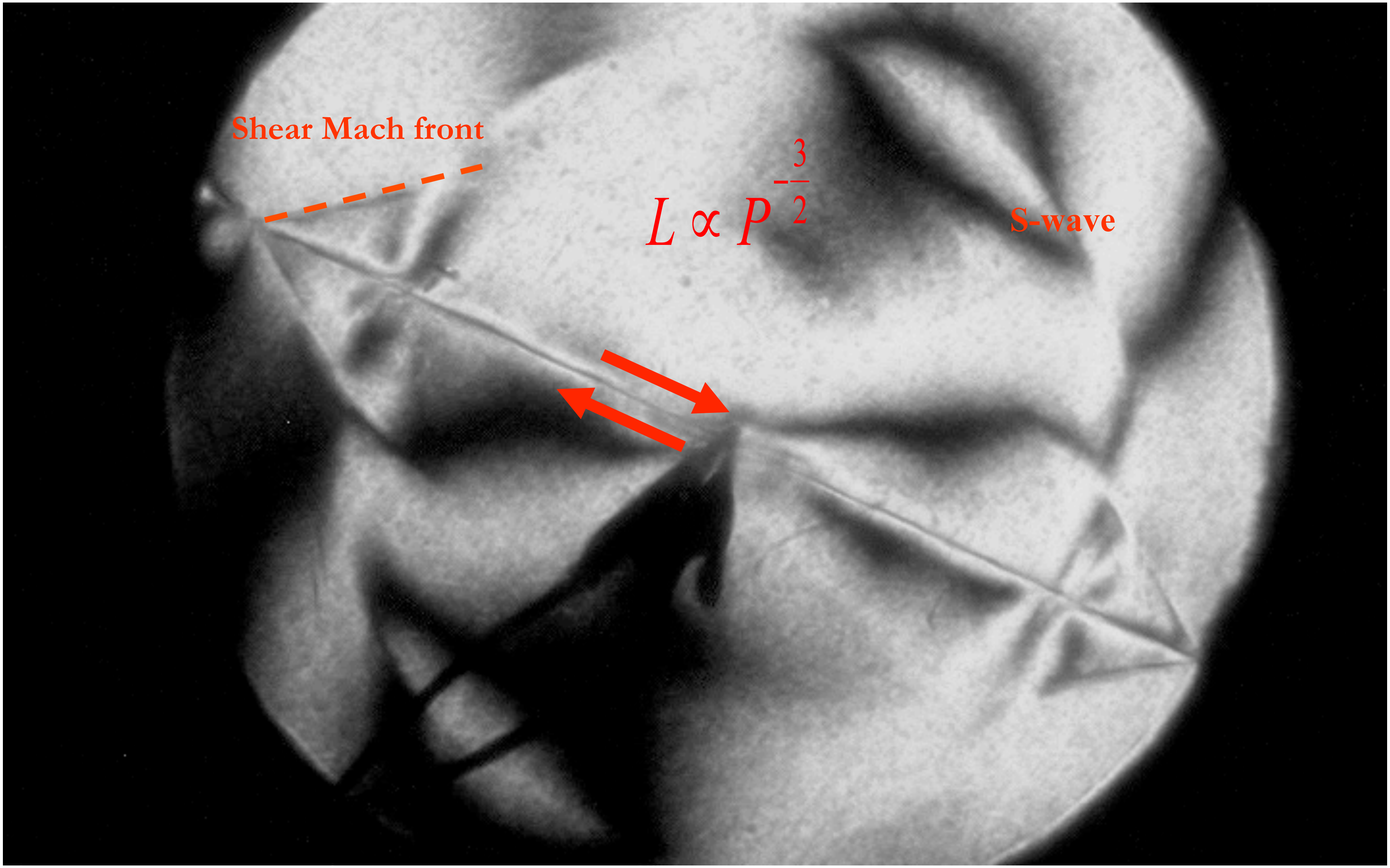

32 μs


36 μs

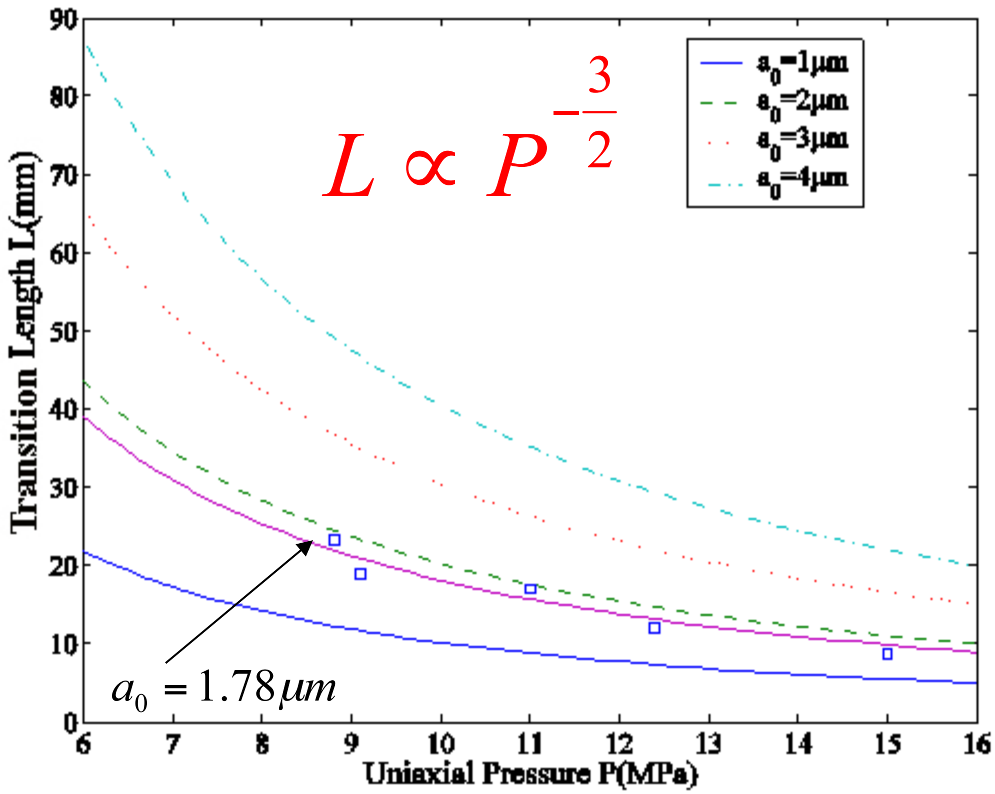
40 μs

Transition: From Sub-Raleigh to Supershear

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



From Lab to real earthquakes (Pressure Dependent d_0)



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

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

d_o ~ 1m .FIELD

a_0… average asperity radius. Angle = 25**deg**

d_o ~ 10 μm.LAB

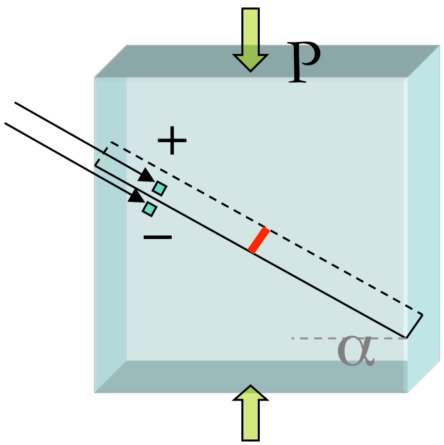
$$\boxed{L = f[s(\alpha)]\frac{1+\nu}{\pi}\mu\frac{f^s - f^d}{[\sin(\alpha) - f^d\cos(\alpha)]^2}2c\left(\frac{f^s - f^d}{f^s}\right)^M \sqrt{H}\, a_0 P^{-\frac{3}{2}} \cos^{-1}(\alpha)}$$

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

→ *L* ~ 80km (Kunlun (100 km), Denali (70km))

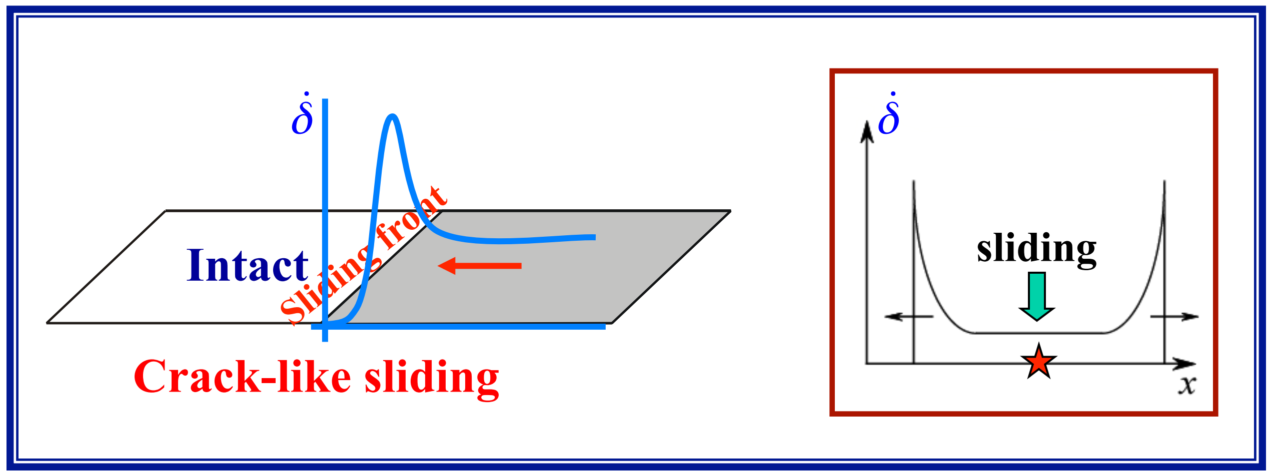
Using particle velocimeters to determine rupture mode

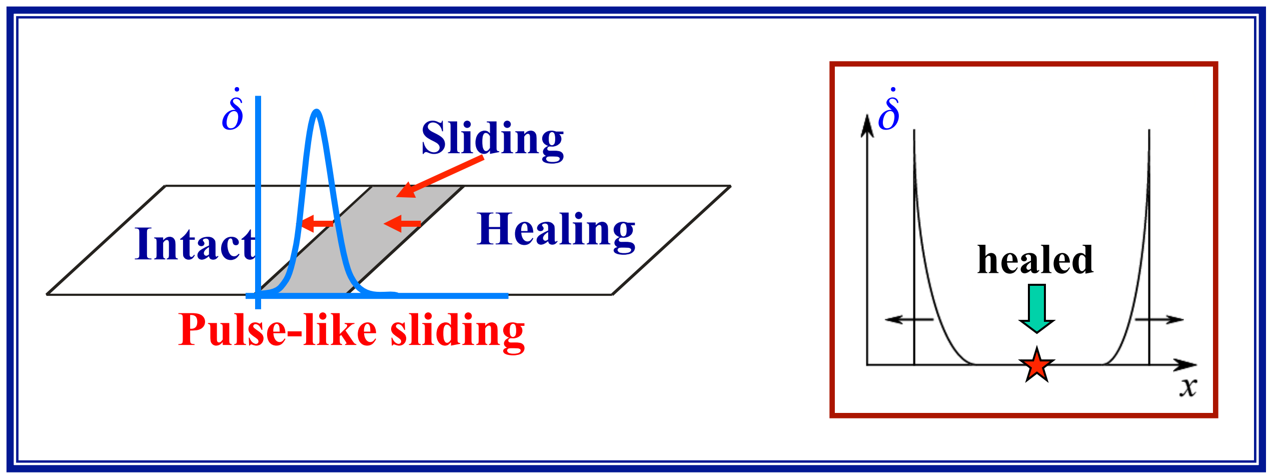
X . Lu, N. Lapusta A.J. Rosakis, PNS 2007.



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

crack-like and pulse-like

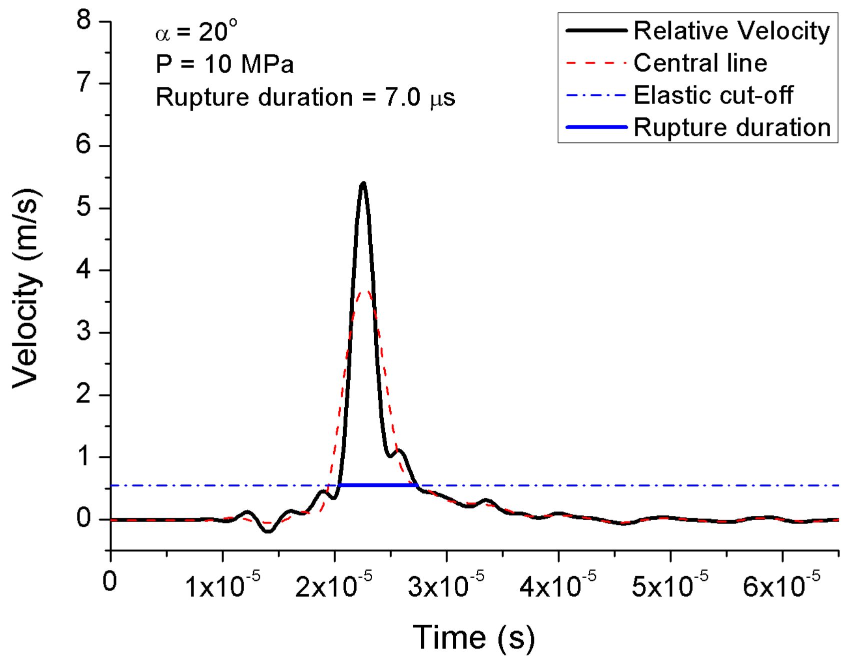




Earthquakes often occur as pulses of slip (e. g., Heaton, 1990)

Observing pulse-like rupture (narrow pulses)

Alpha = 20 degrees, P = 10 MPa, measured at 20 mm



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

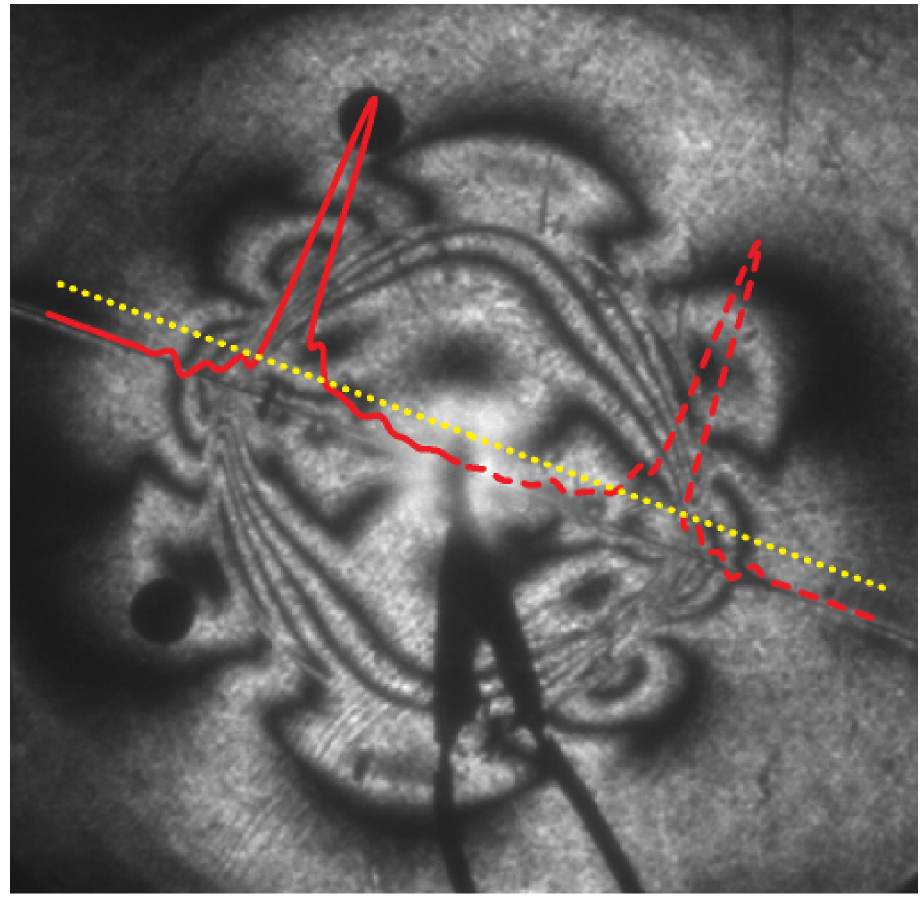
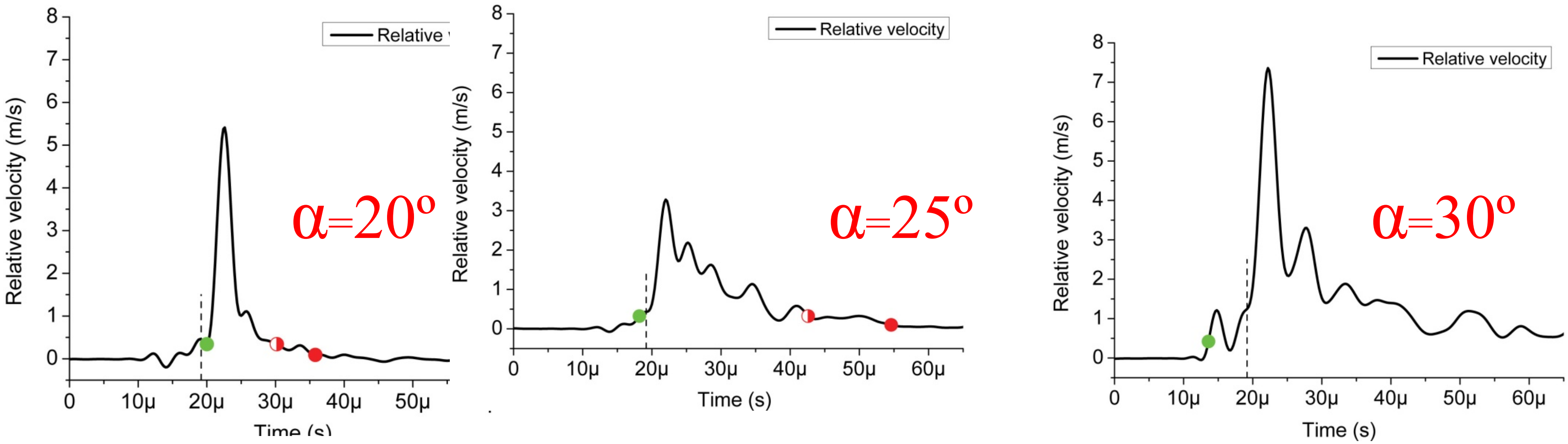
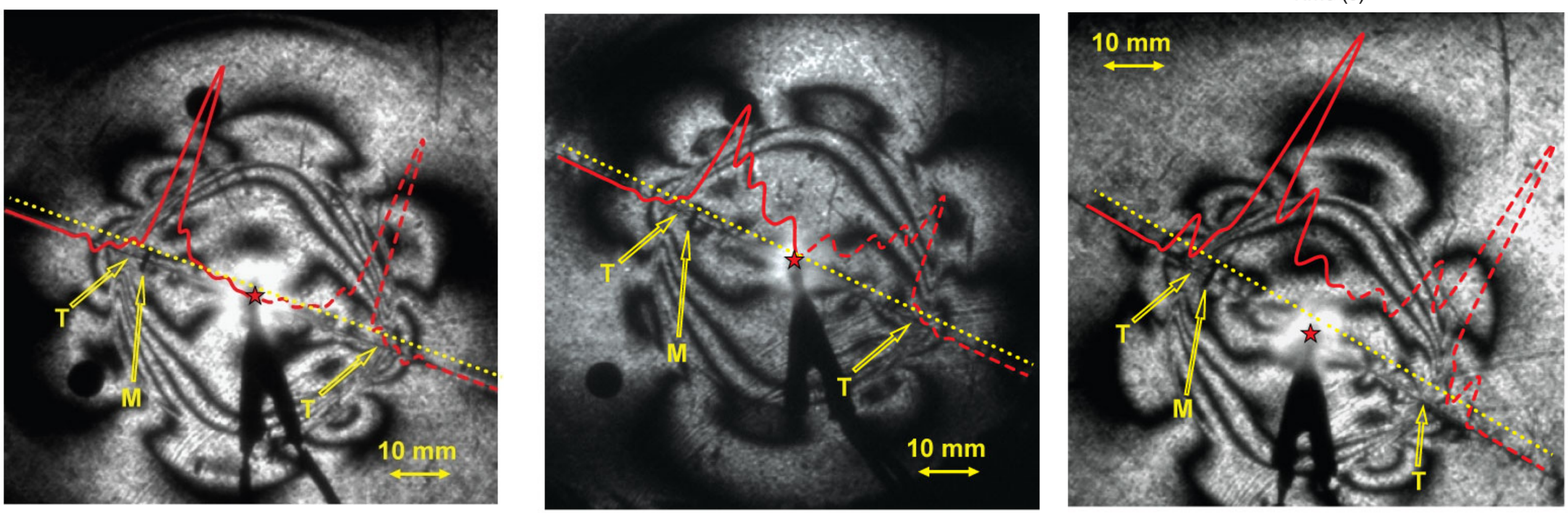


Image captured at 22 μs

Transitioning from Pulses to Cracks (P=10 MPa)

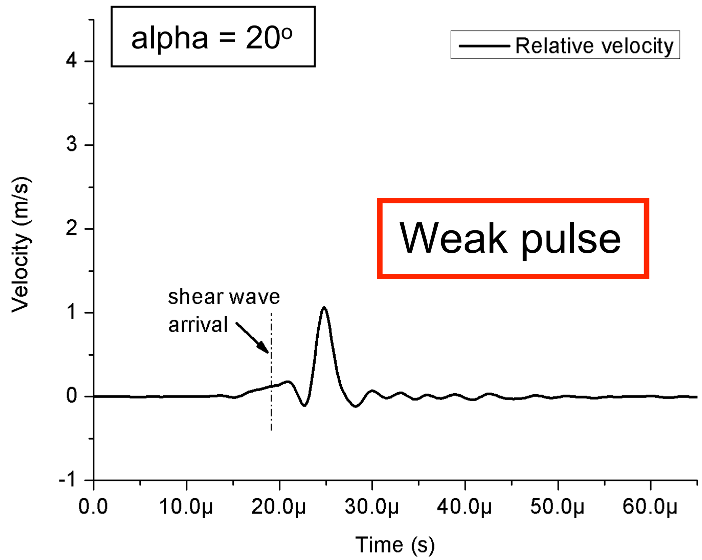
X . Lu, N. Lapusta A.J. Rosakis, PNS 2007.

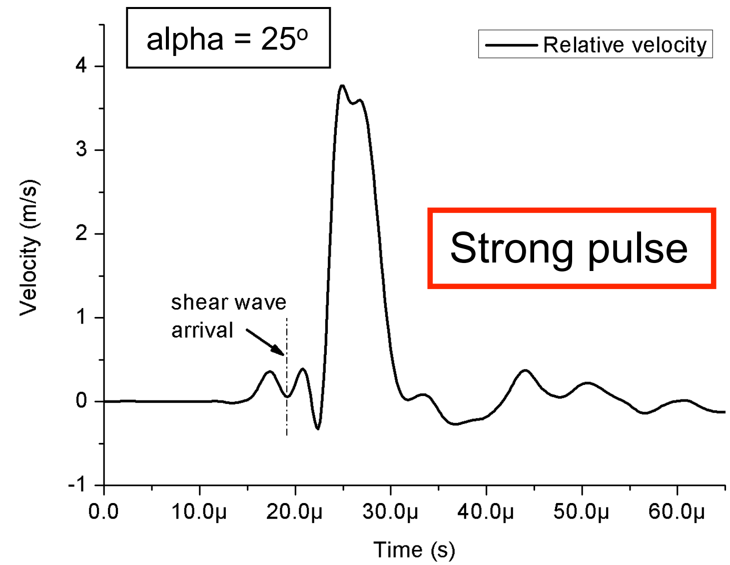


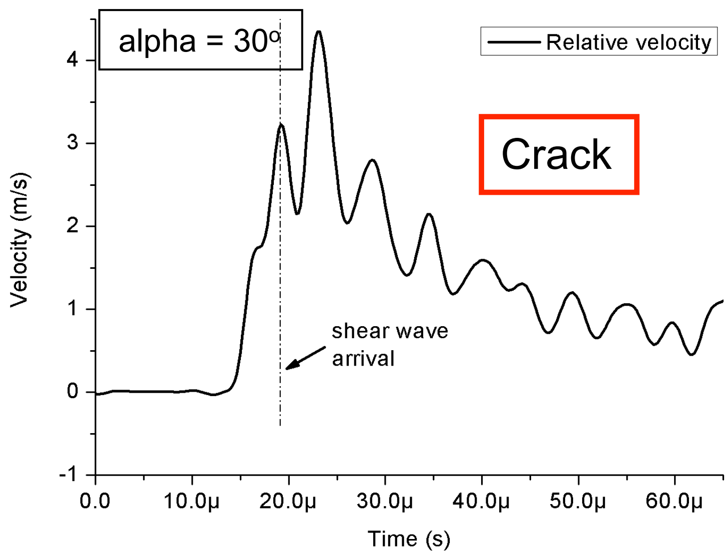


Rupture mode changes by increasing interface angle

Pressure=14 MPa (From Cracks to Heaton Pulses)







Velocity measured at ***20 mm*** away from epicenter

Prediction:

alpha = 20° ⇒ dying pulse or nothing

alpha = 25° ⇒ pulse

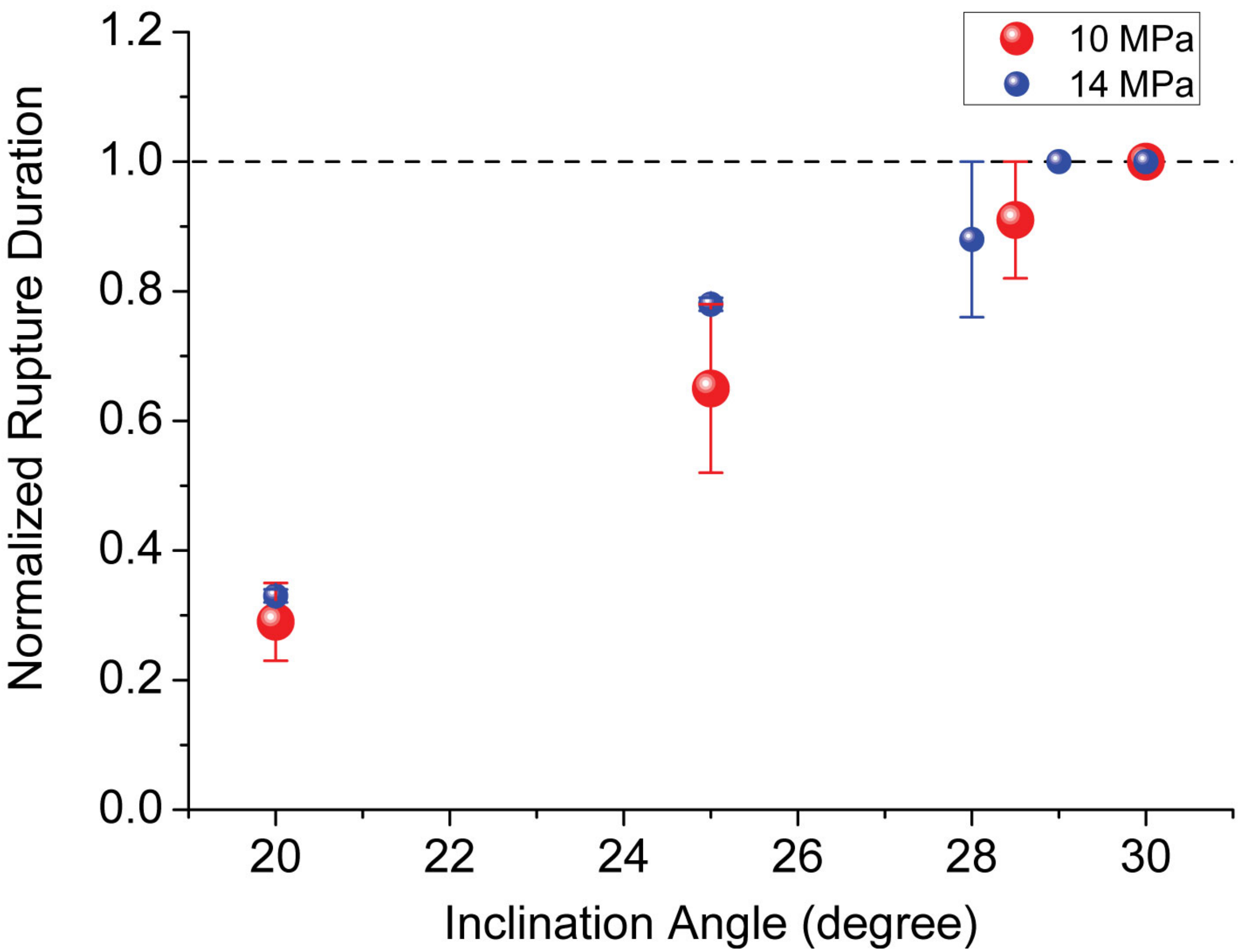
alpha = 30° ⇒ crack

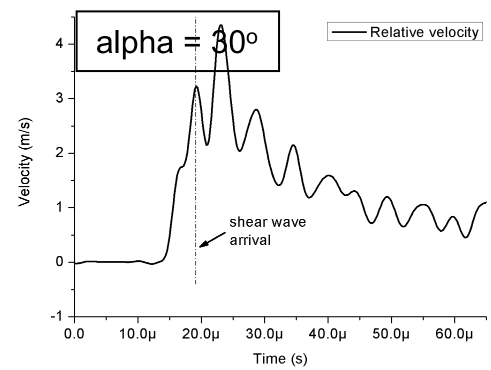
(***Theory: Zheng and Rice, BSSA, 1998***)

CALIFORNIA INSTITUTE OF TECHNOLOGY 1891

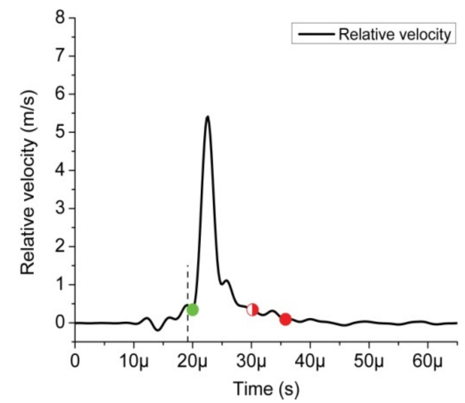
Mode Transition:

From Pulses (0) to Cracks (1)





Crack-Like



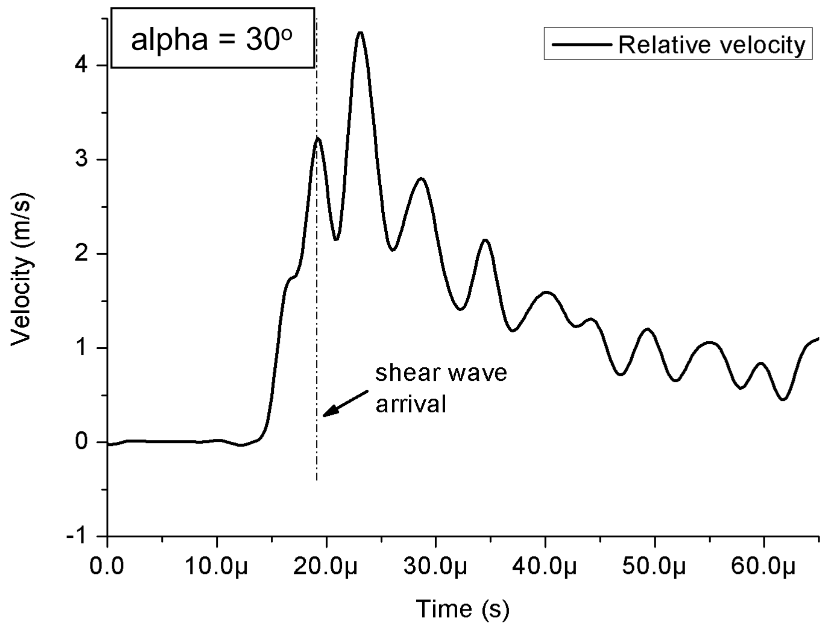
Pulse-Like

Sliding duration normalized by the maximum potential sliding time

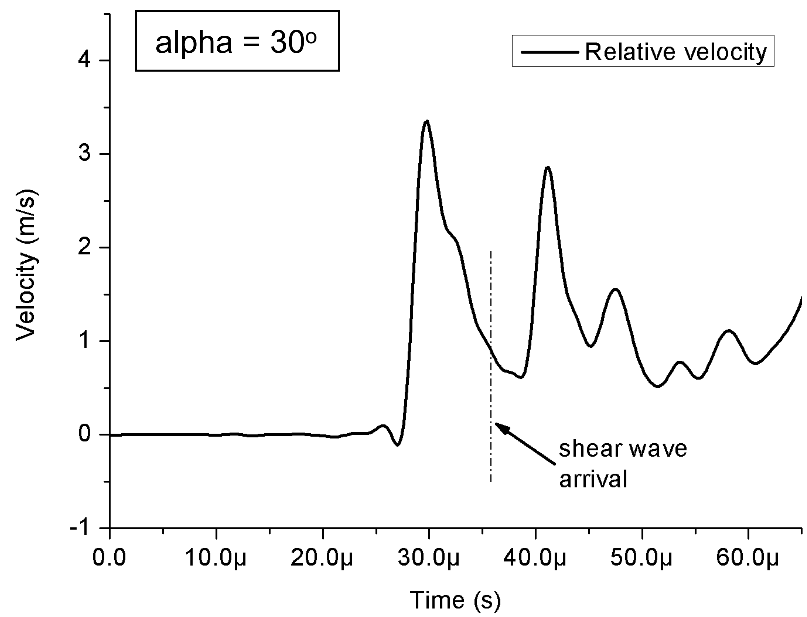
Consistent with Zheng and Rice, BSSA, 1998

Sub-shear crack transitioning to supershear crack

Angle=30°, Pressure=14 MPa



Velocity measured at **20** mm



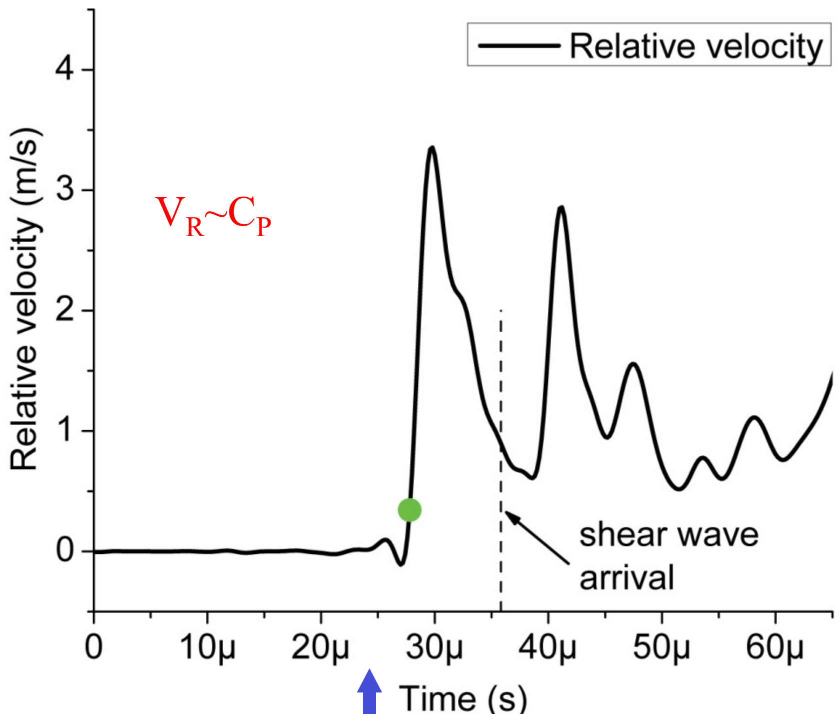
Velocity measured at **40** mm

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

Transition to Supershear:

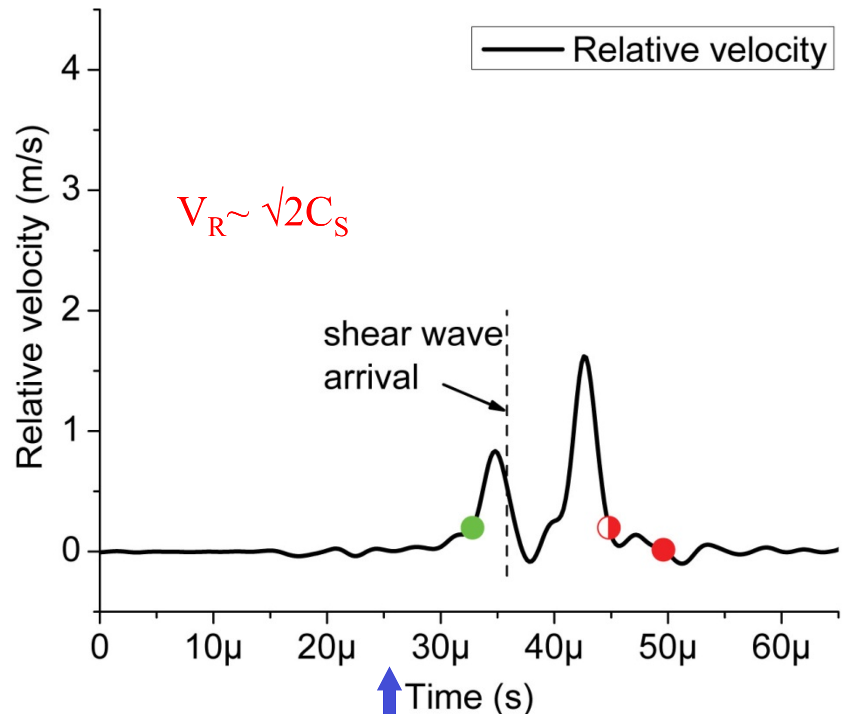
Crack to Crack or Pulse to Pulse?

P = 14 MPa, α=30º

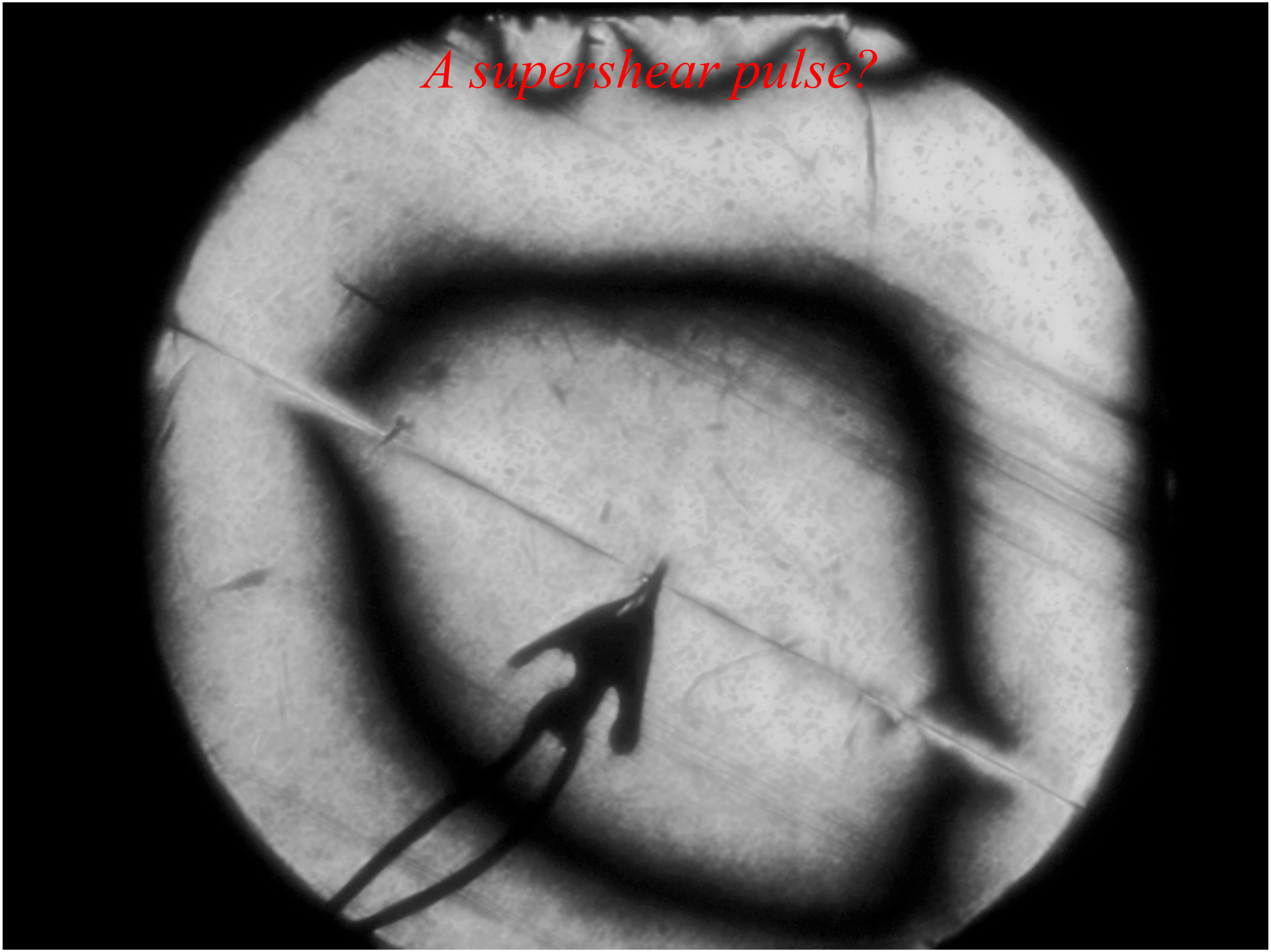


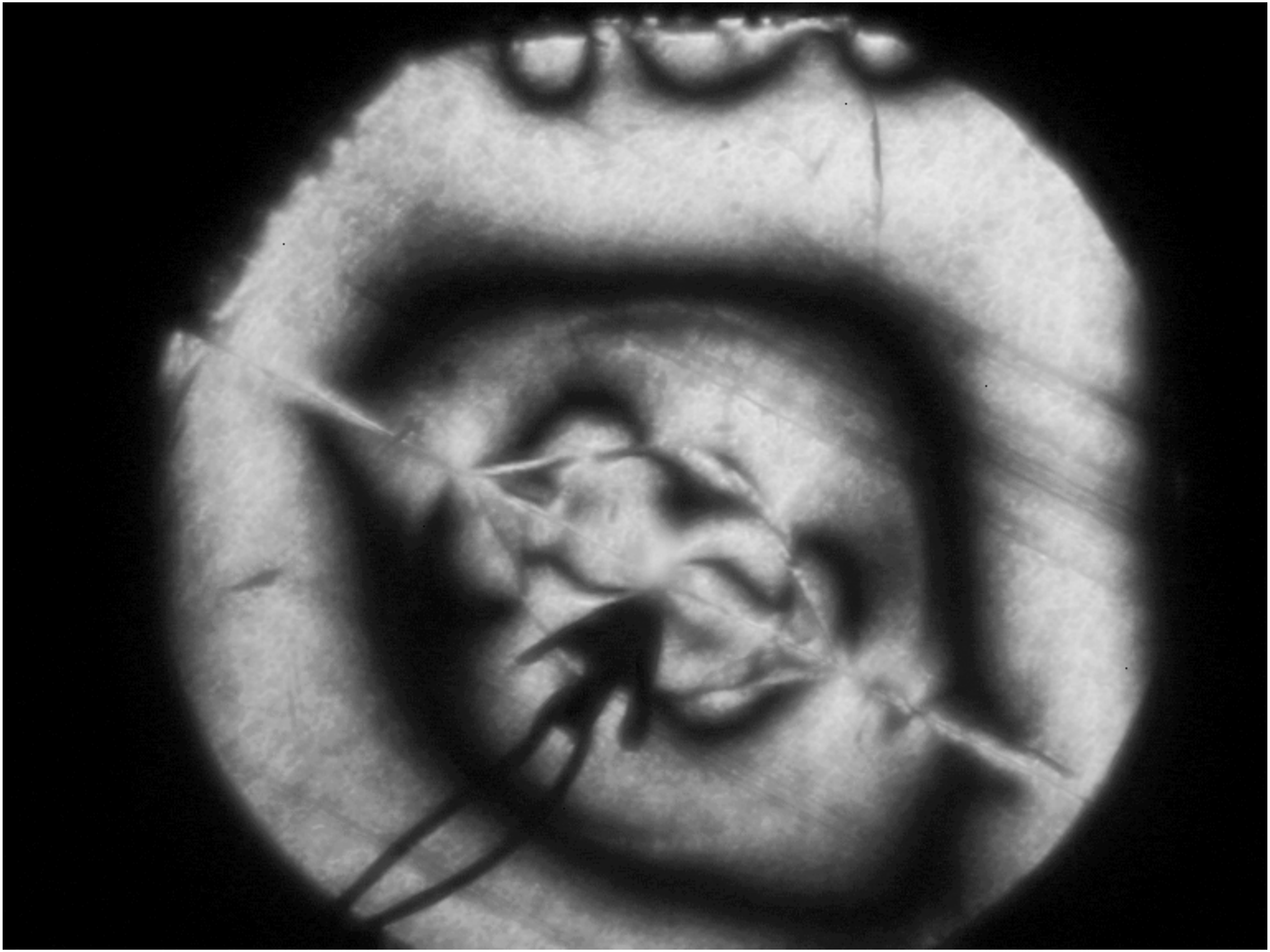
The Burridge-Andrews Mechanism
Crack to Crack

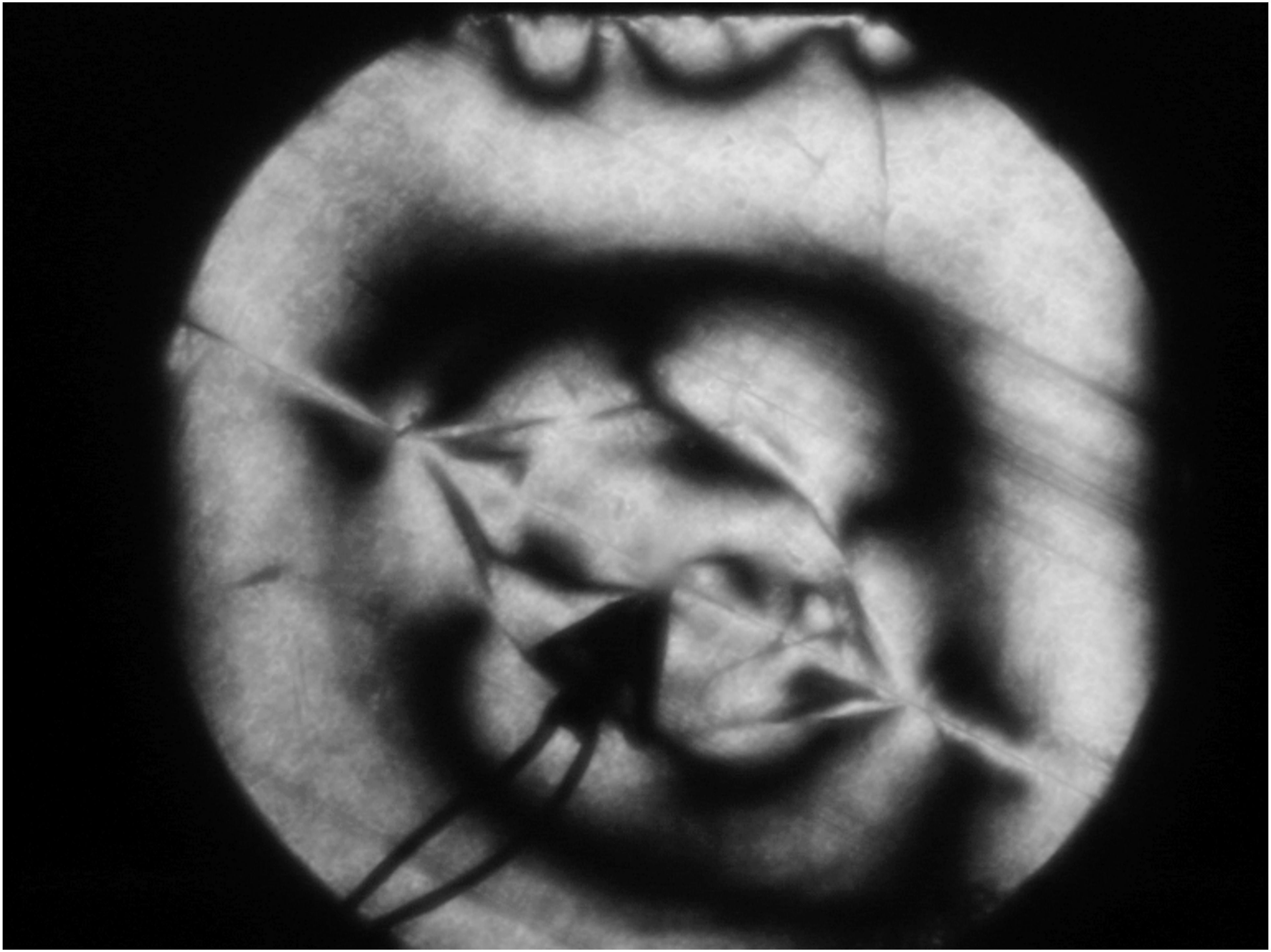
P = 14 MPa, α=27.5º

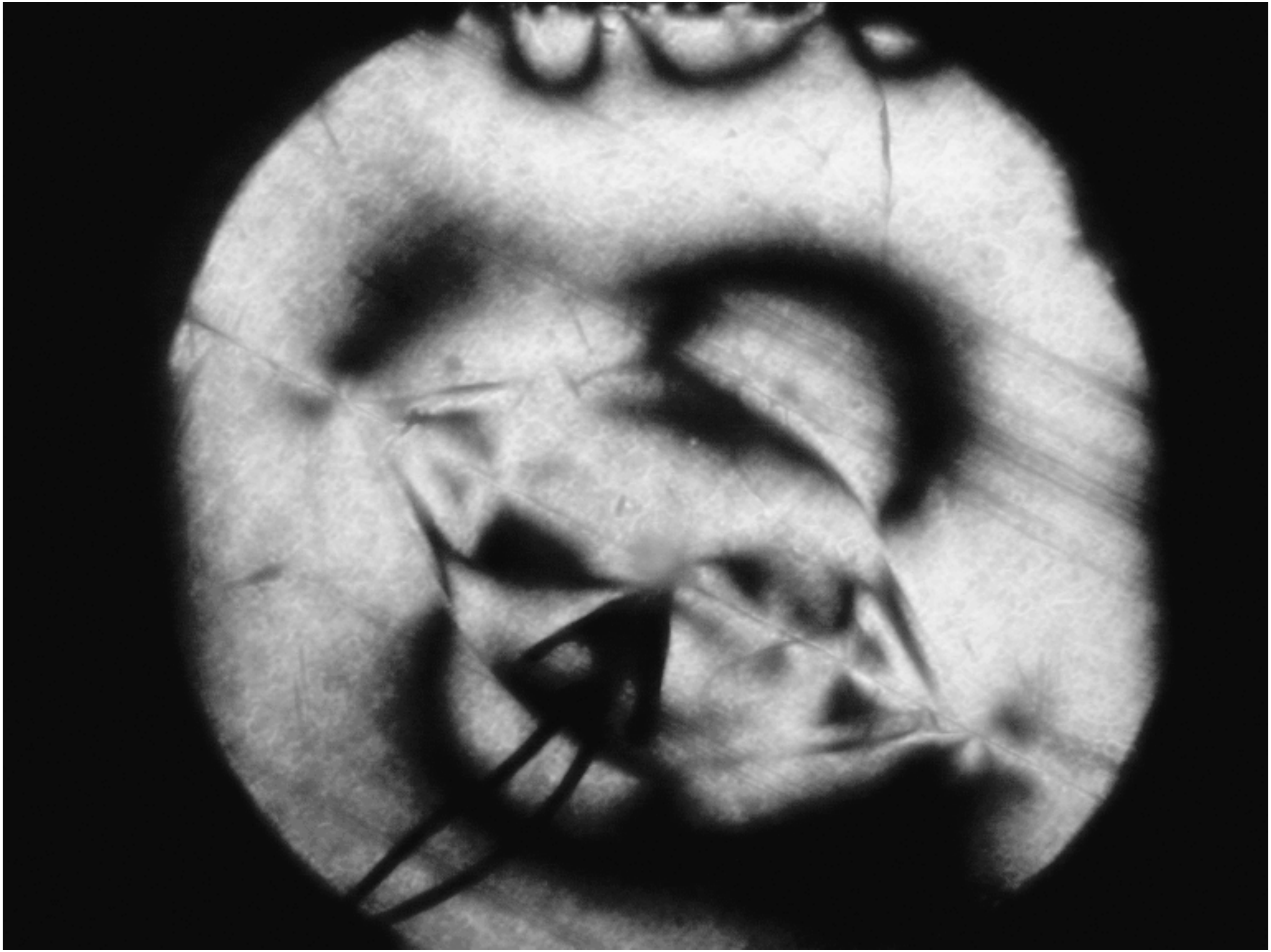


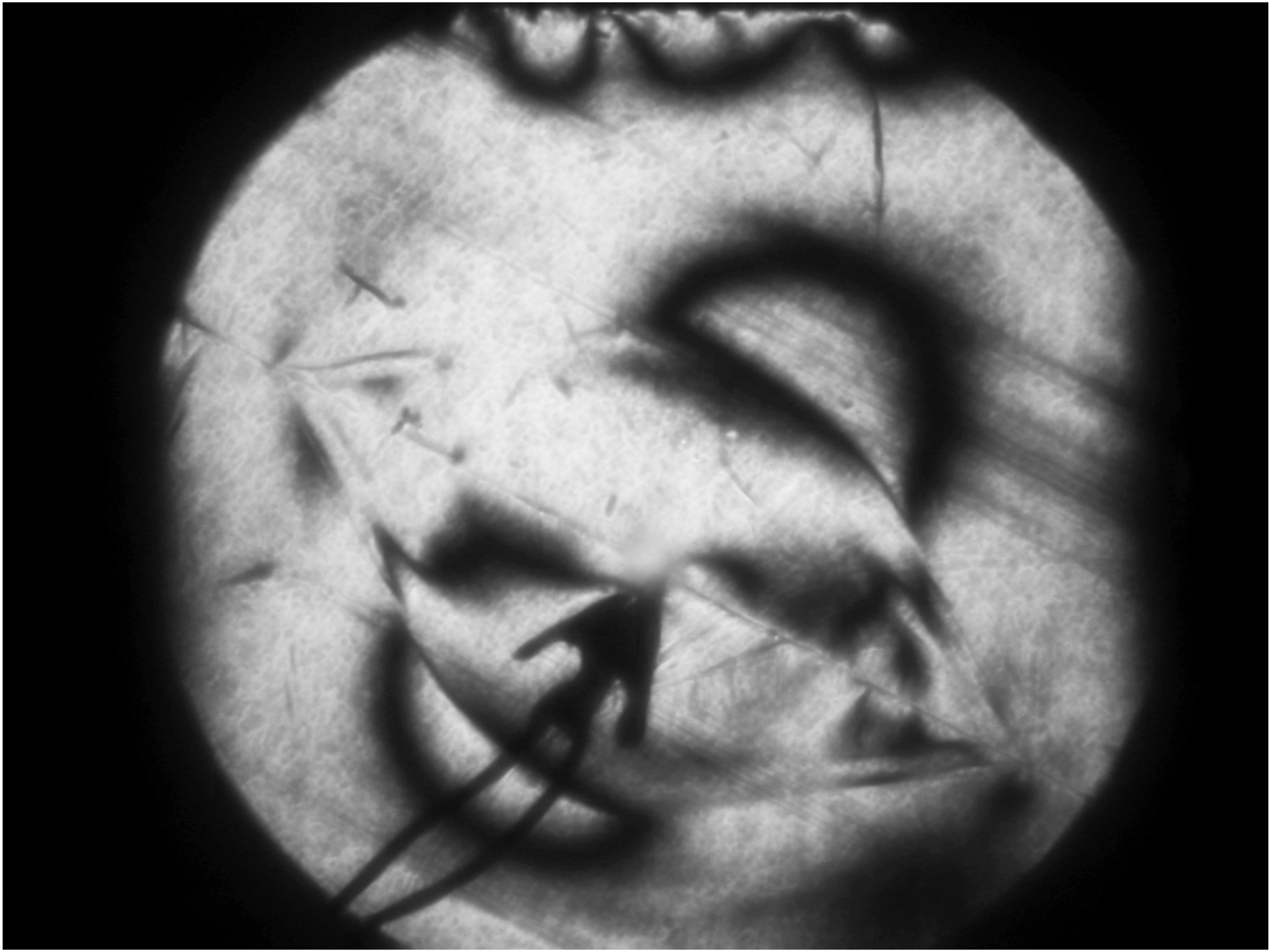
Pulse to Pulse

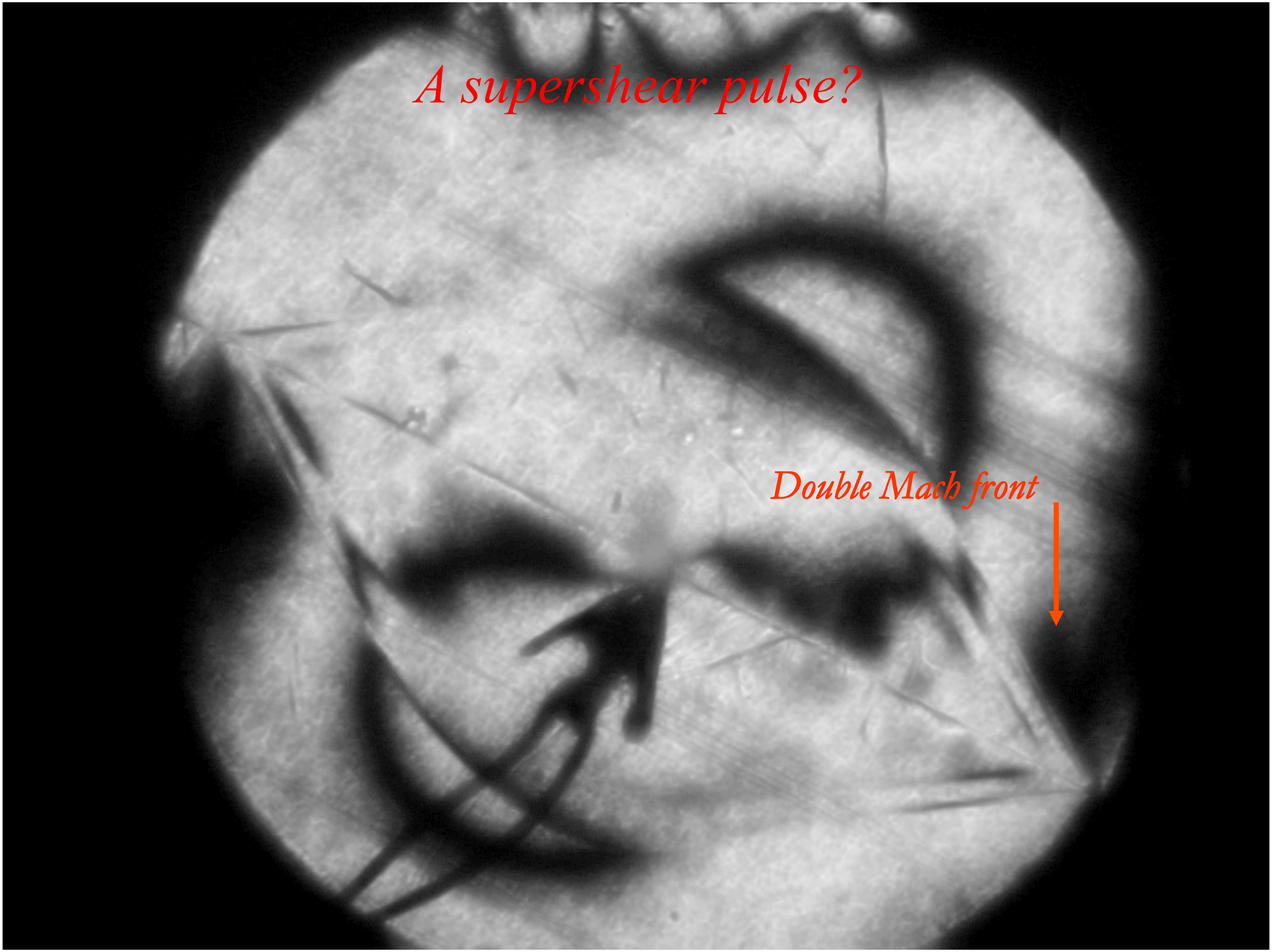

A supershear pulse?










A supershear pulse?
Double Mach front


A supershear pulse?
Double Mach front

Results and Questions from the Homogeneous Case

RESULTS:

- 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.

QUESTIONS:

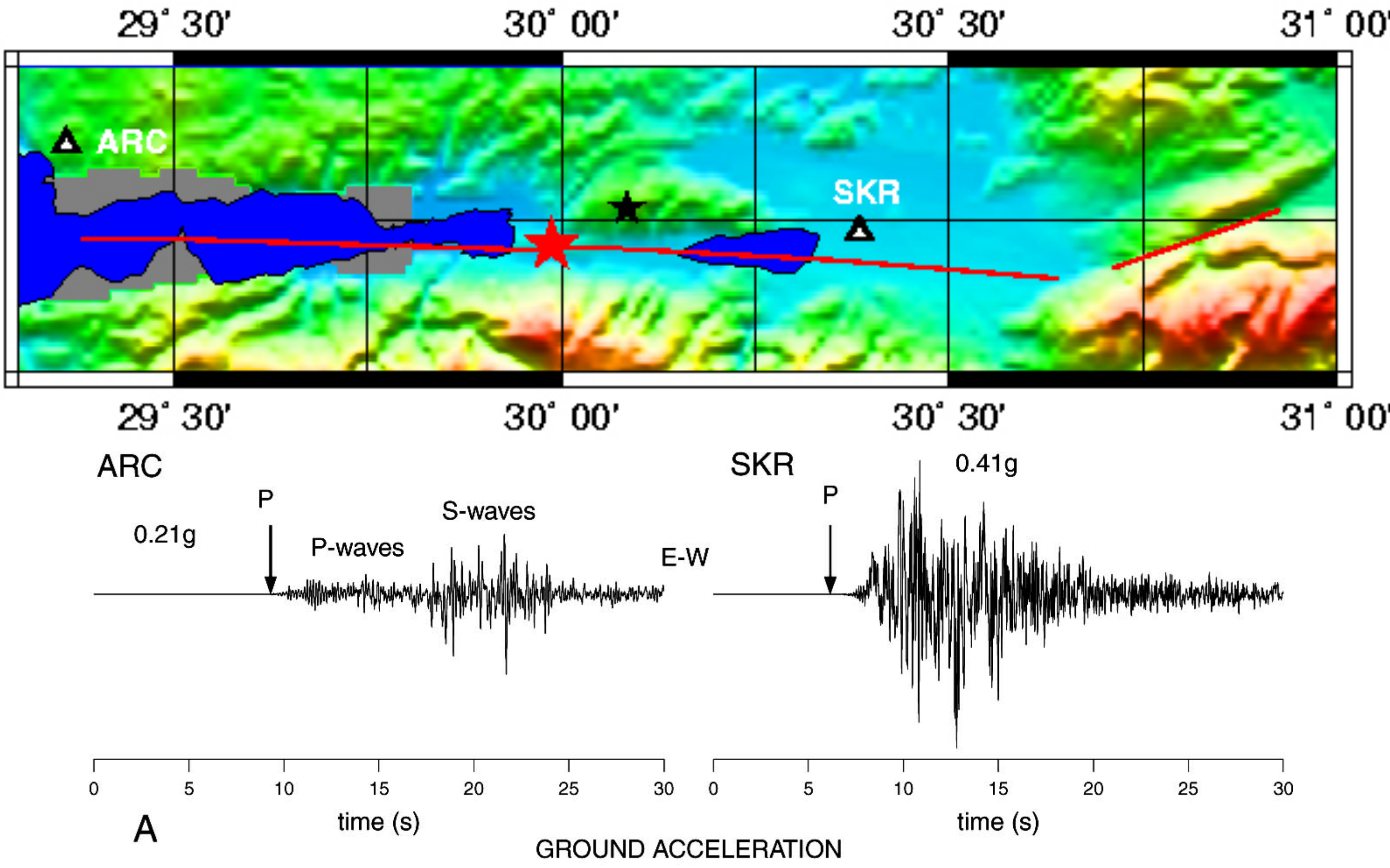
- What would happen if all faults were perfectly uniform, straight and infinite? Would all ruptures eventually transition to supershear?
- Is there a connection between LARGE earthquakes and super shear rupture? A large earthquake event is one whose rupture continues for a long time.

Explaining the Rupture speed ASYMMETRY

(The N. Anatolian fault near the sea of Marmara has bimaterial structure)

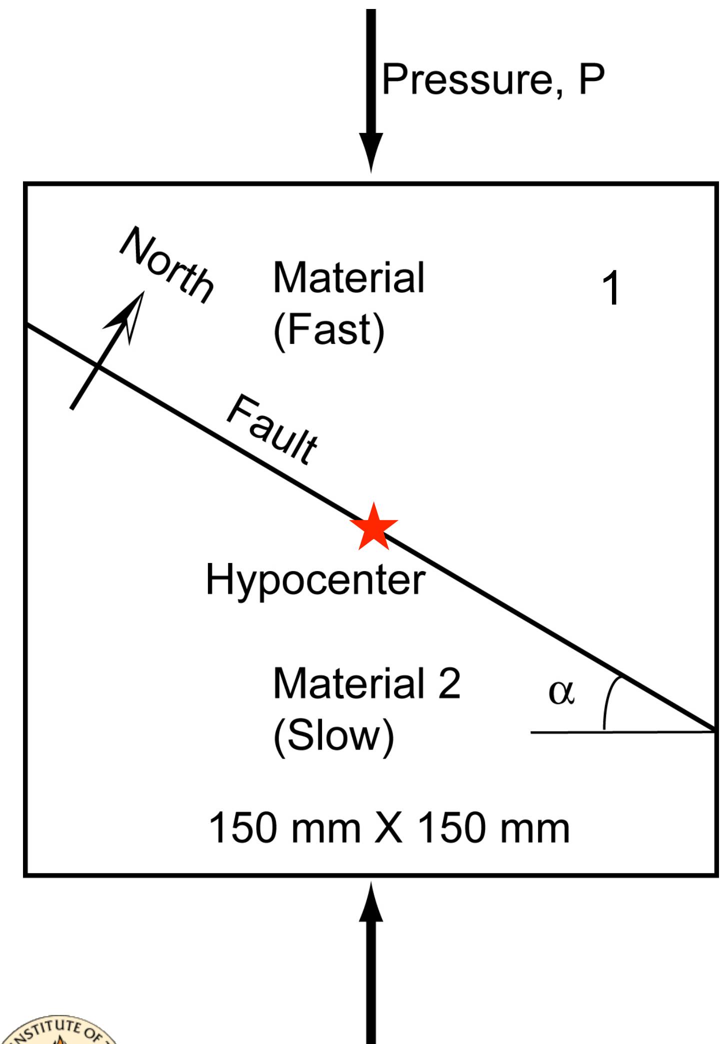
Le Pichon, Chamot-Rooke, Rangin and Sengor. J.G.R. 2003.

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

⇩

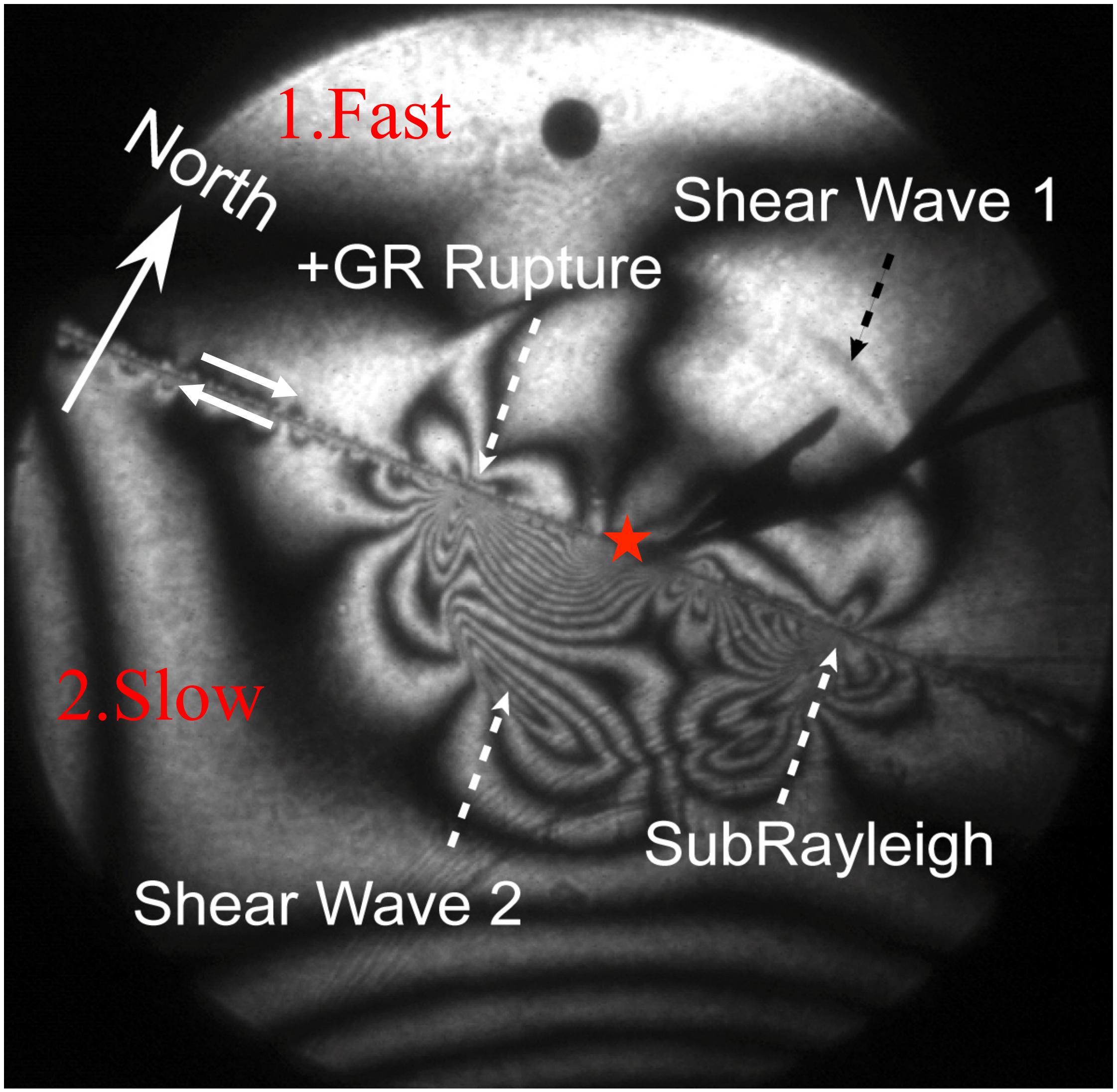
- Shear wave difference: 25%
- The generalized Rayleigh wave speed: 950 m/s

<u>Generalized Rayleigh (GR) wave speed:</u> Propagation speed of sliding in frictionless contact.

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

POSITIVE:

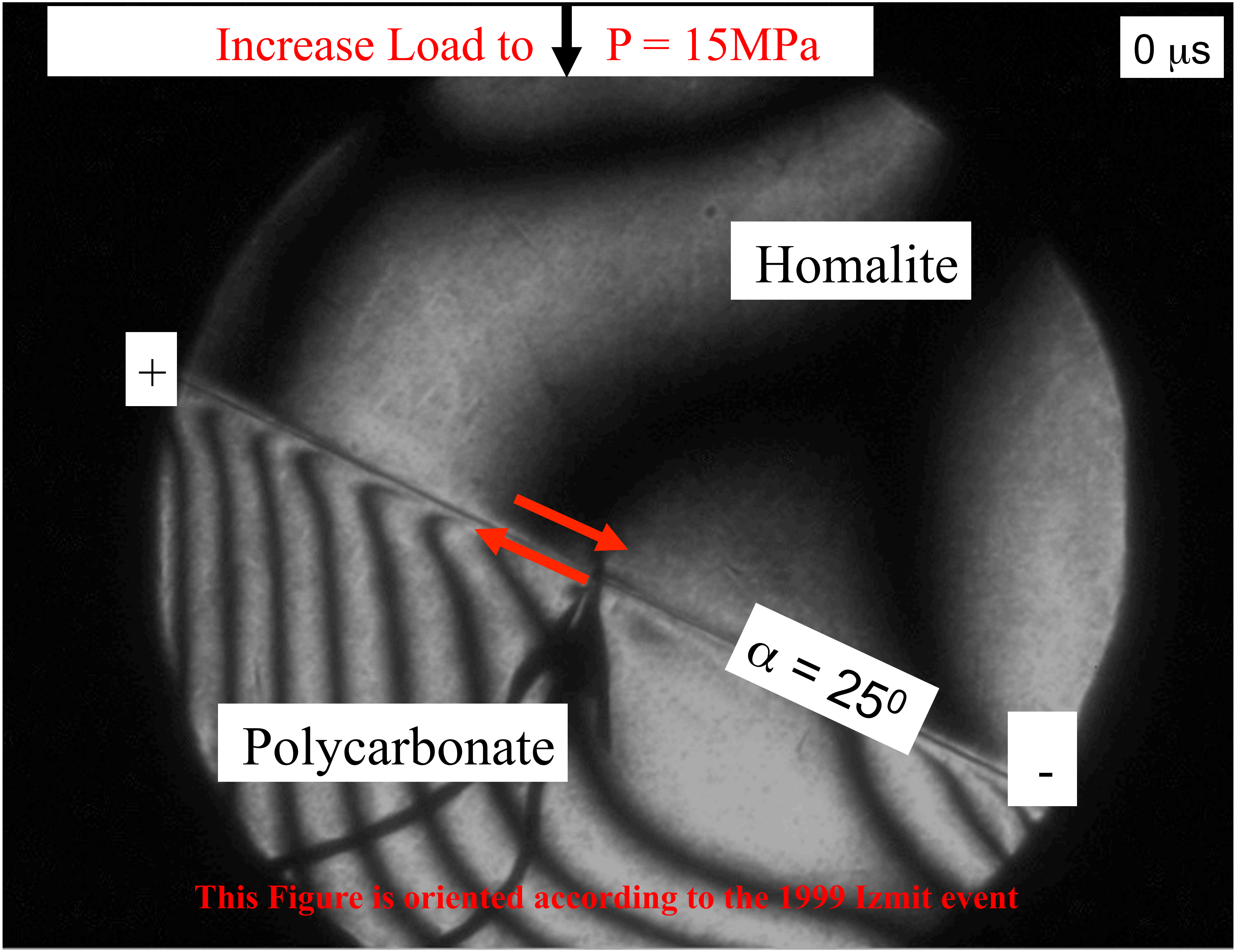
Rupture direction same as direction of slip of the lower velocity side
$V= +C_{GR}$



(Small P)

<u>Generalized Rayleigh (GR) wave speed:</u> Propagation speed of sliding in frictionless contact.

This Figure is oriented according to the 1999 Izmit event



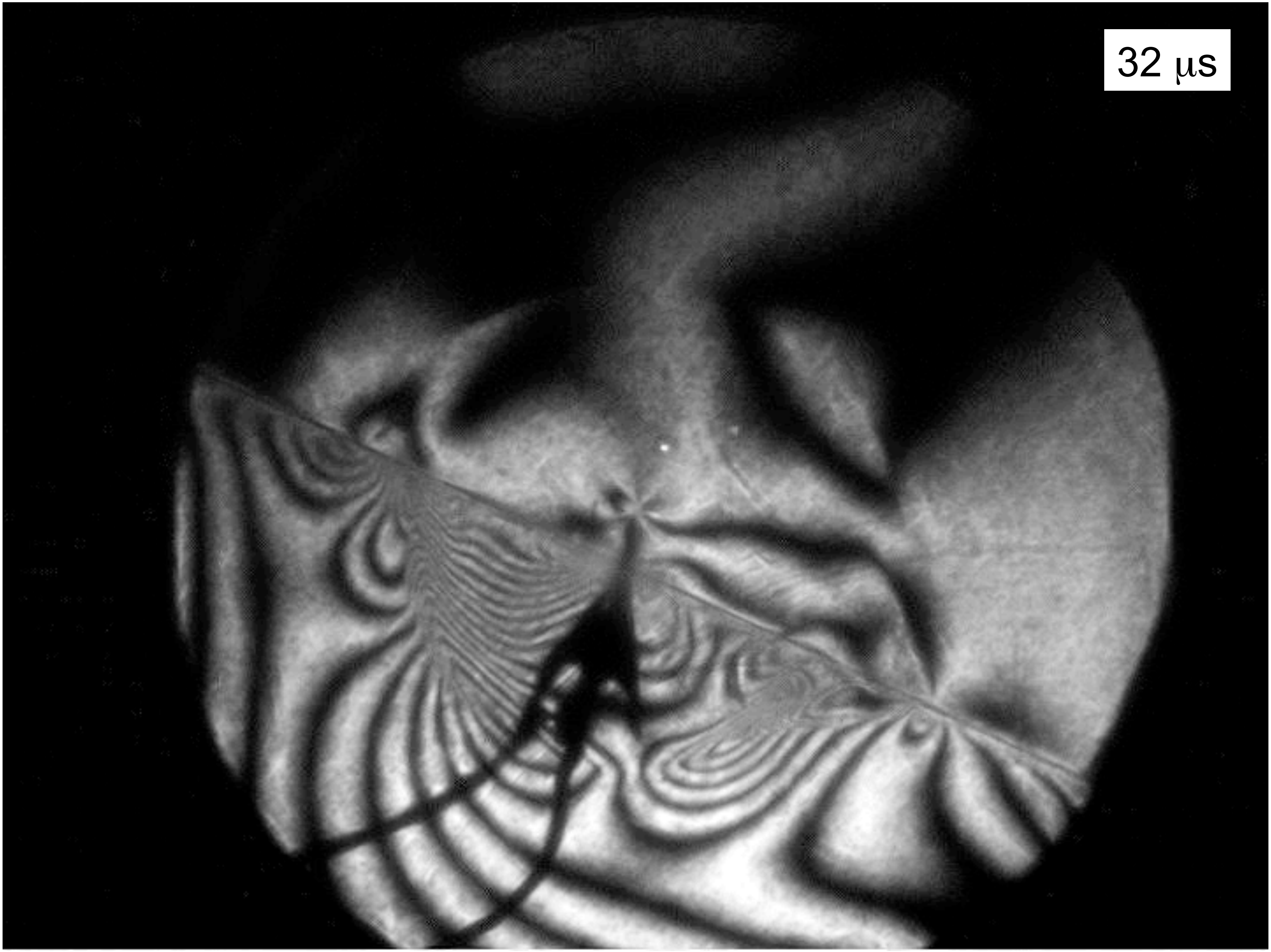
Increase Load to P = 15MPa
0 μs
Homalite
+
α = 25o
Polycarbonate
-
This Figure is oriented according to the 1999 Izmit event


16 μs

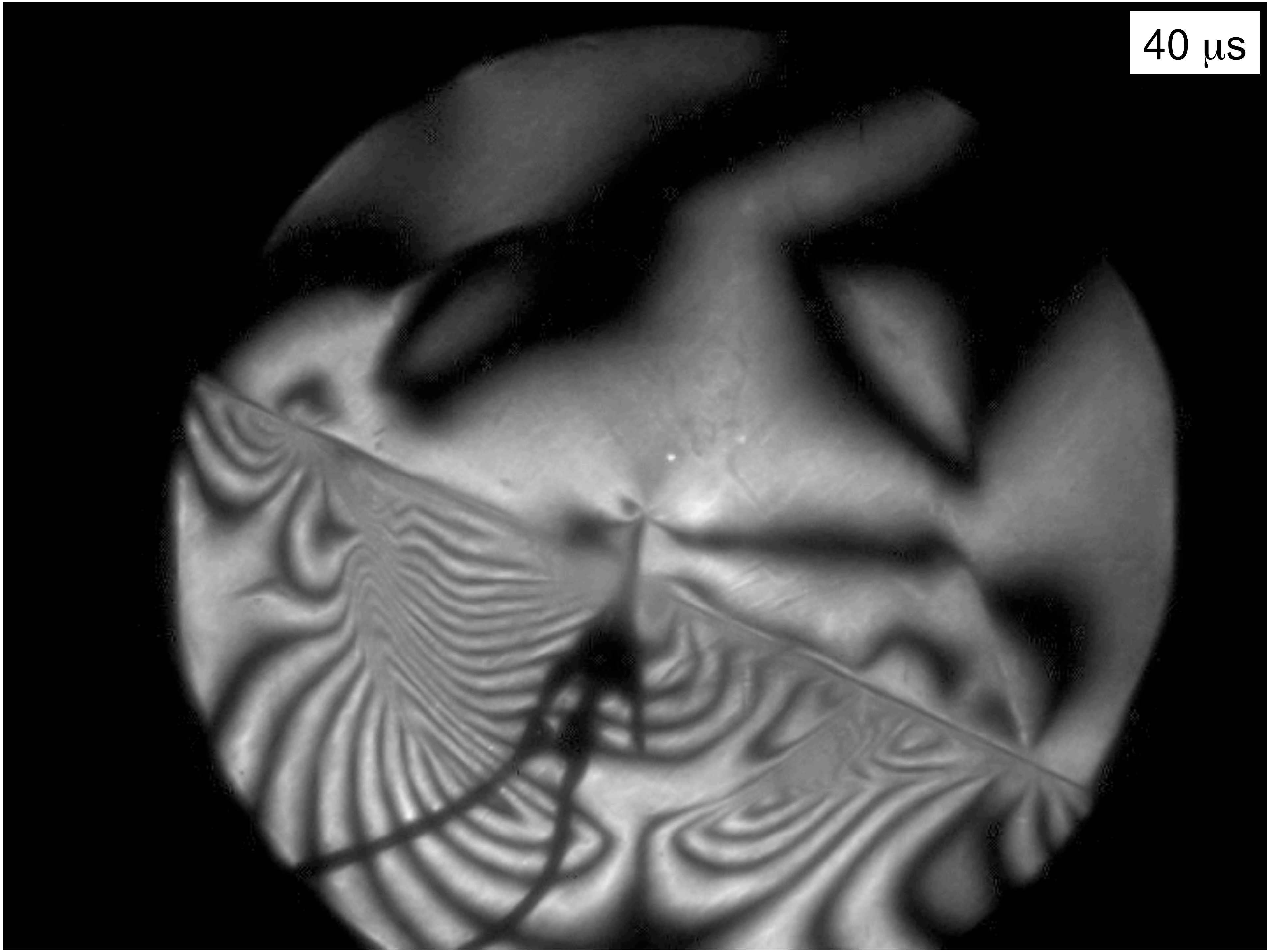

20 μs


24 μs


28 μs

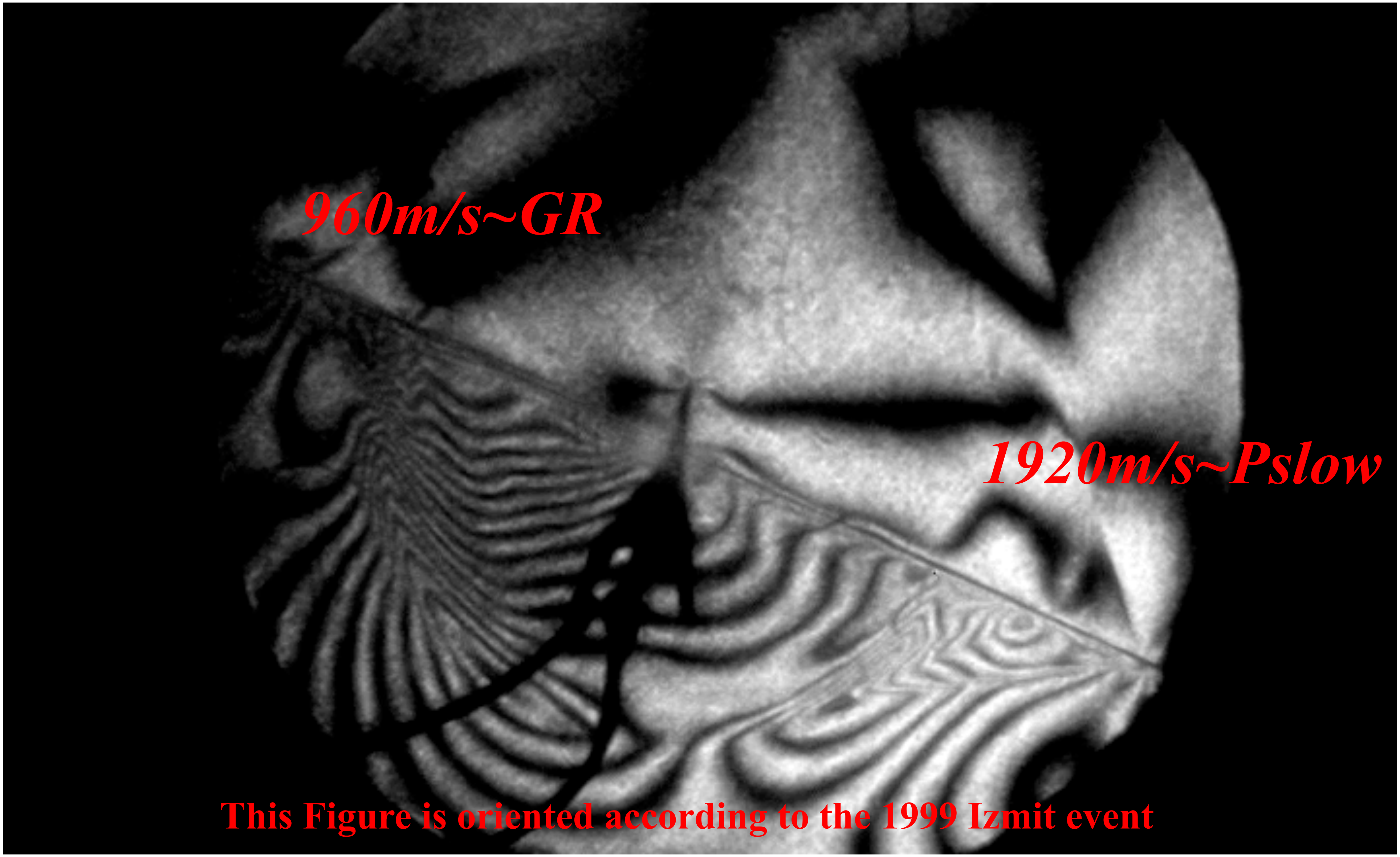

32 μs

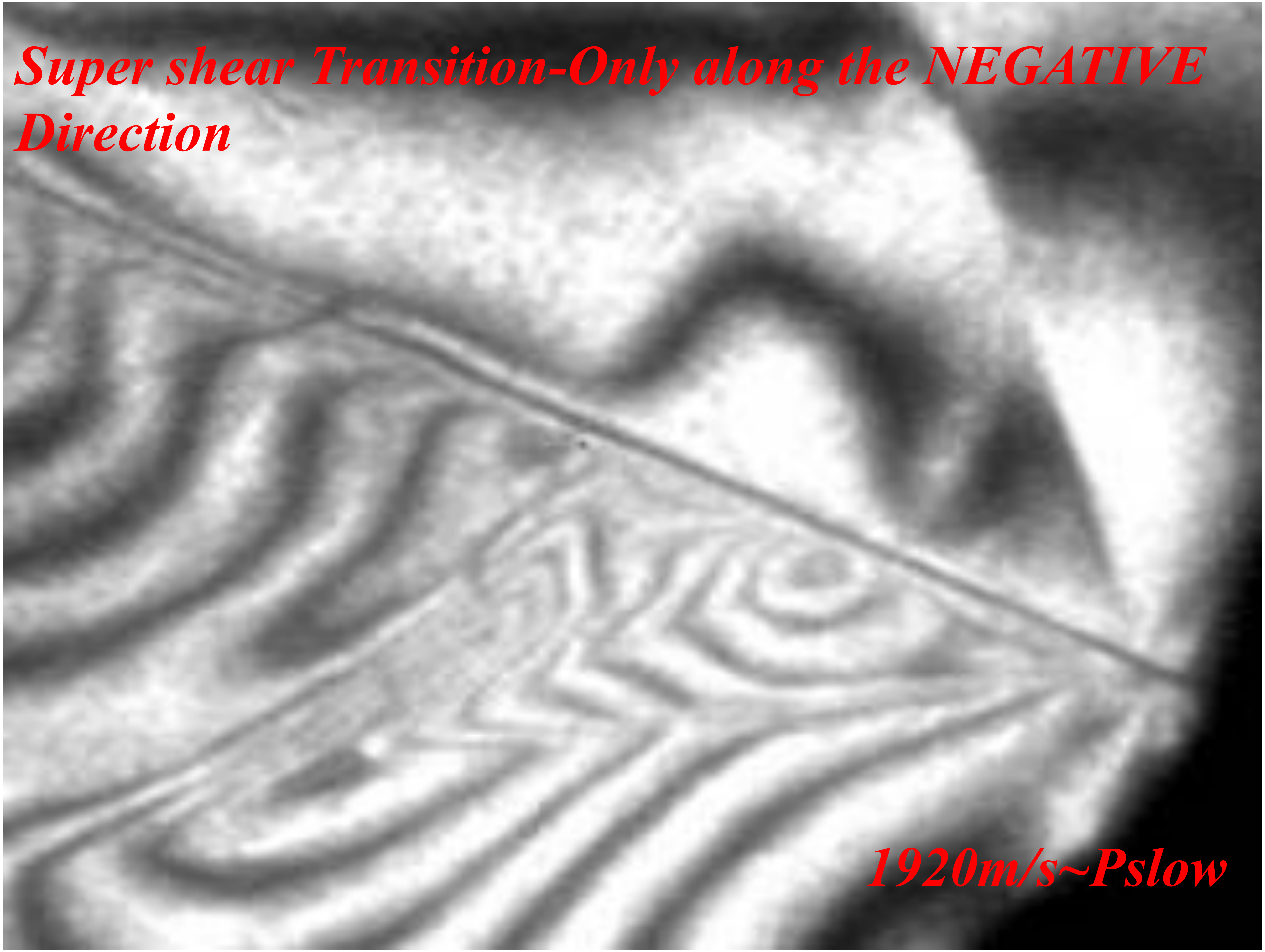

36 μs


40 μs

44 μs

GR (POSITIVE DIRECTION)& $-P_{SLOW}$ (NEGATIVE DIRECTION)



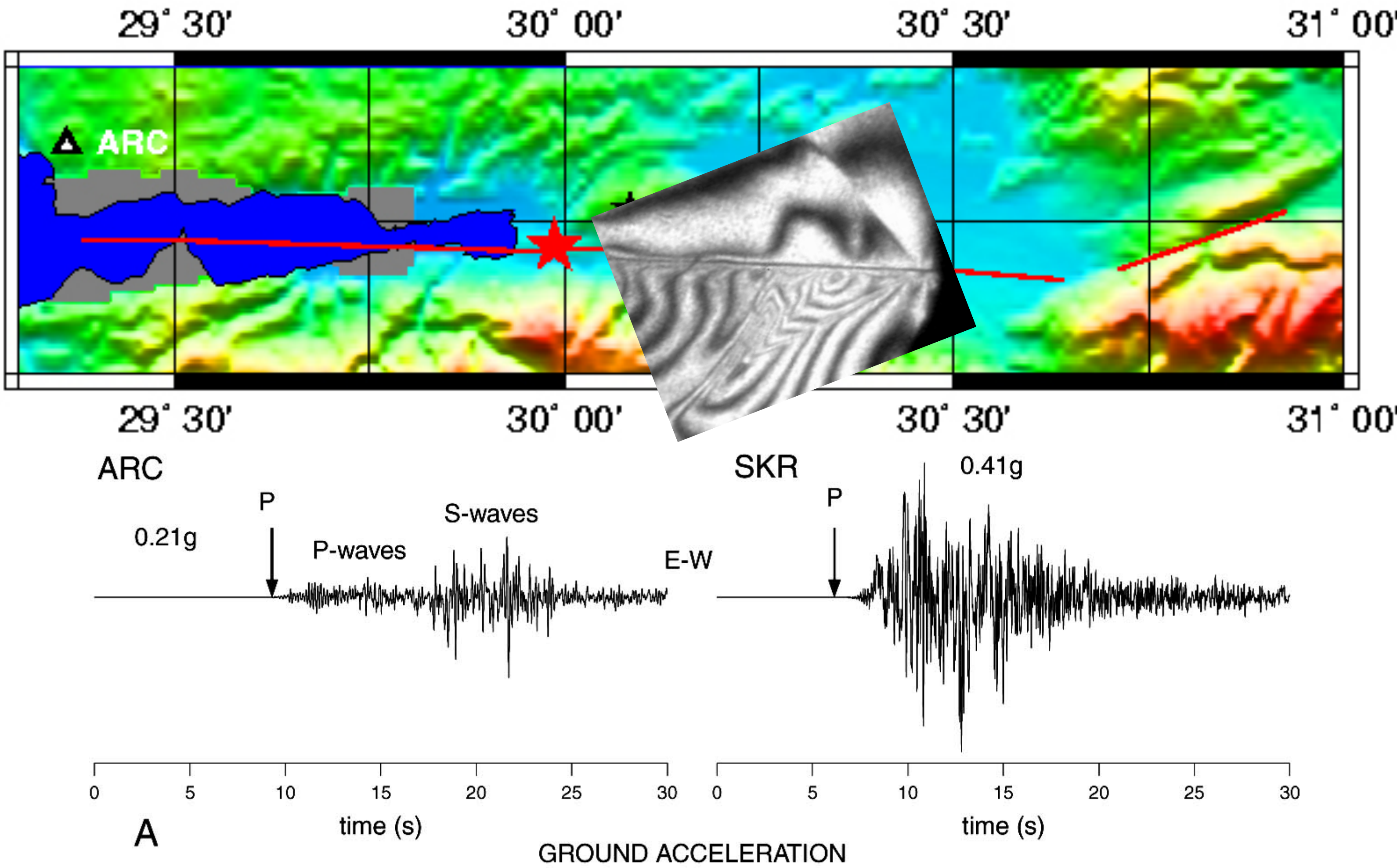

Super shear Transition-Only along the NEGATIVE Direction
1920m/s~Pslow

Explaining the Rupture speed ASYMMETRY

(The N. Anatolian fault near the sea of Marmara has bimaterial structure)

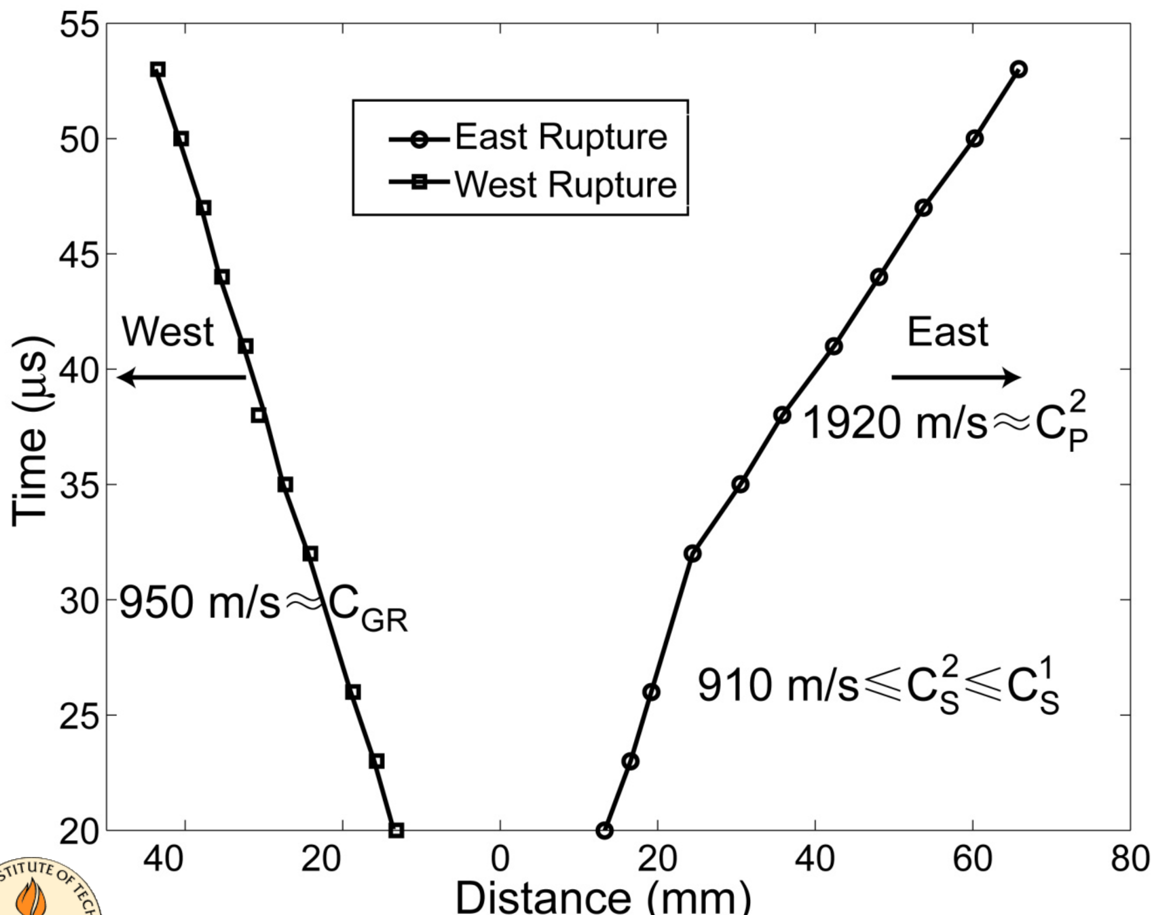
Le Pichon, Chamot-Rooke, Rangin and Sengor. J.G.R. 2003.

Softer material to the South

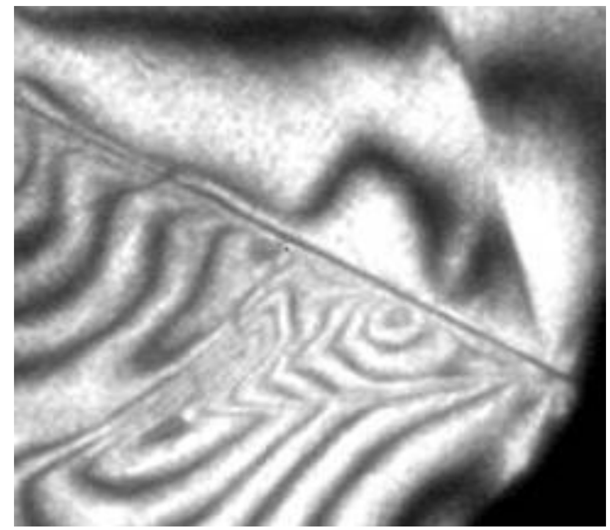


Supershear Transition-Only along the NEGATIVE Direction

(Angle=25°, Pressure=13MPa)

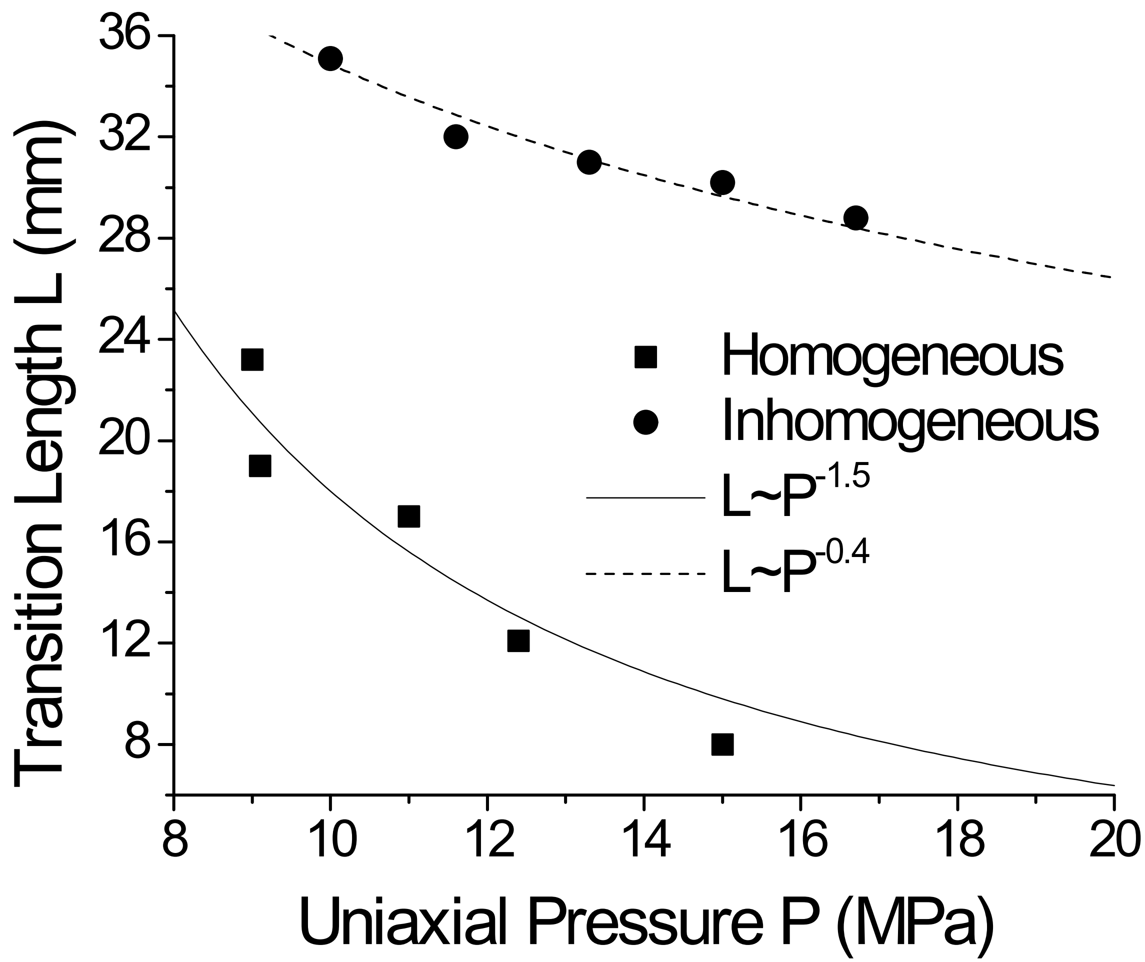


(Intermediate P)



Equivalent observations in terms of increasing angle

Transition Length as a Function of load P for Both Homogeneous and Bimaterial Systems



For the same load, it takes longer propagation distance in bimaterials to transition to super shear

Summary of Experimental Results

- *All ruptures are bilateral. No preferred direction observed.*
- *The rupture in one direction (POSITIVE) always propagates at the generalized Rayleigh wave speed $+C_{GR}$.*
- *Depending on loading, the rupture in the NEGATIVE direction is either sub-shear or supershear.*
- *For large enough P or α (small s), rupture in the NEGATIVE direction eventually transitions to supershear*

  ($V= -P_{SLOW}$)

- *Suggested 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 being PREFERABLE**

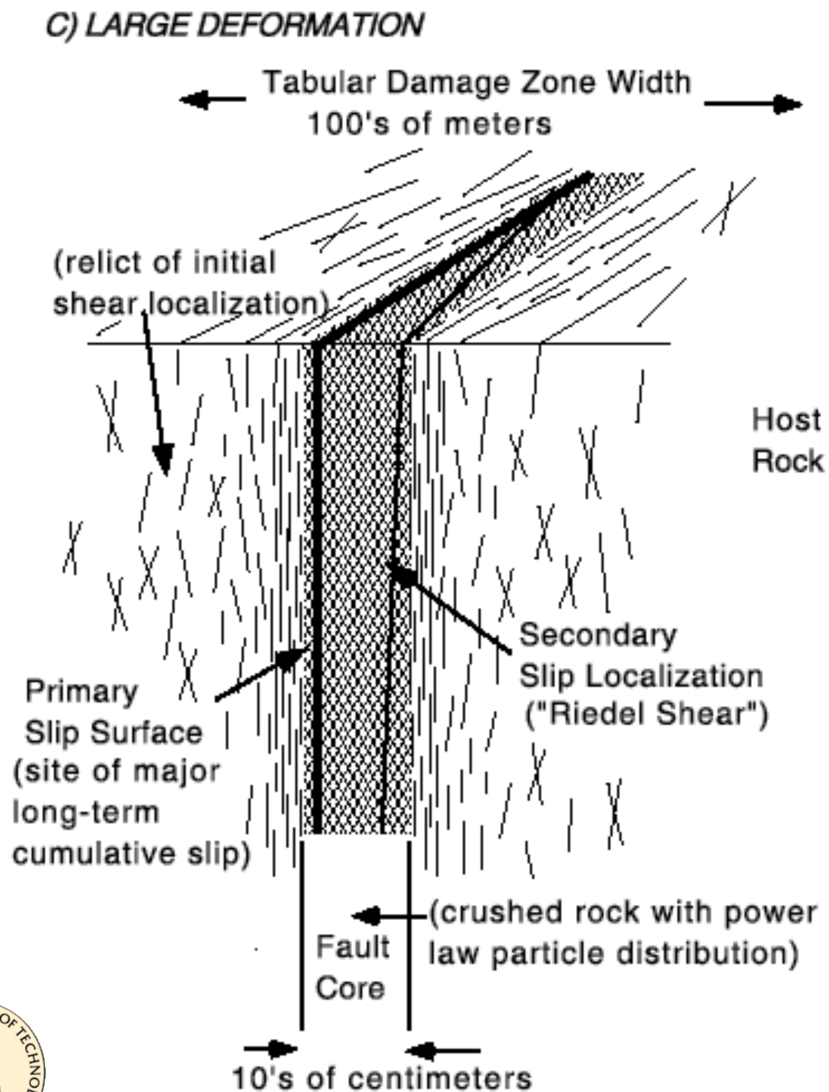
Weakening frictional laws: (*Harris &Day, 1999-2D, 2005-3D*)

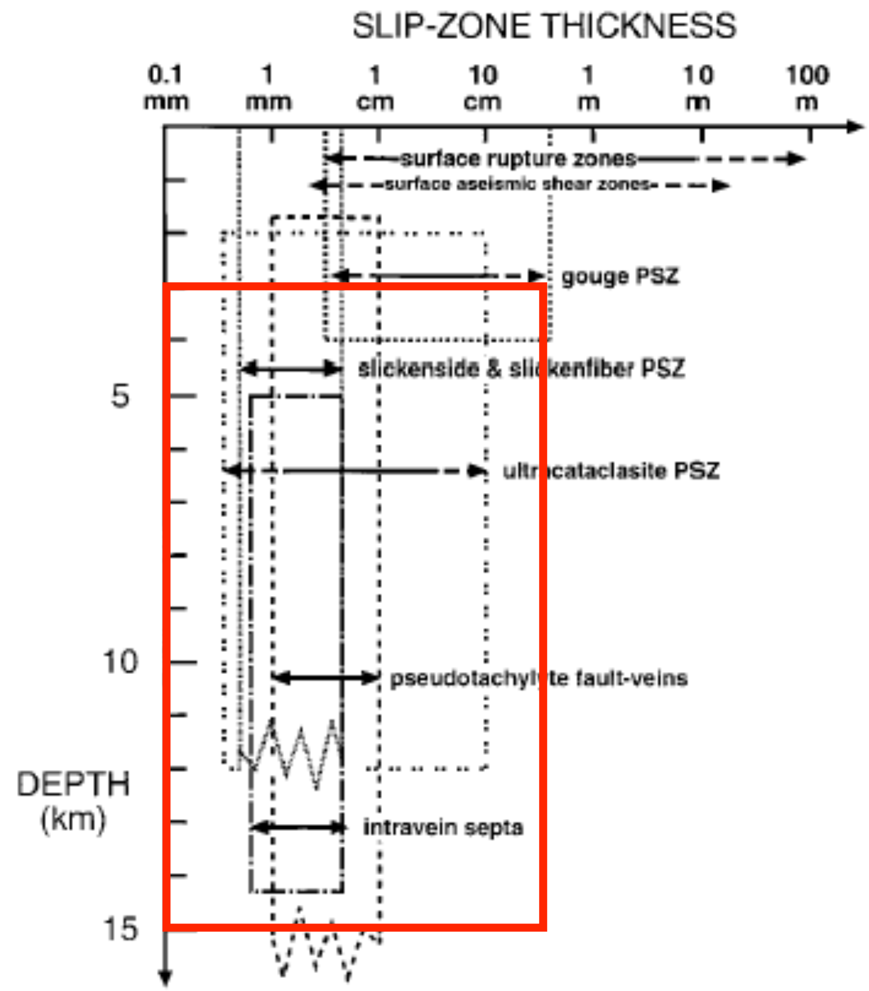
- **Only bilateral ruptures**
- **Both $+C_{GR}$ and $-P_{SLOW}$ modes observed**

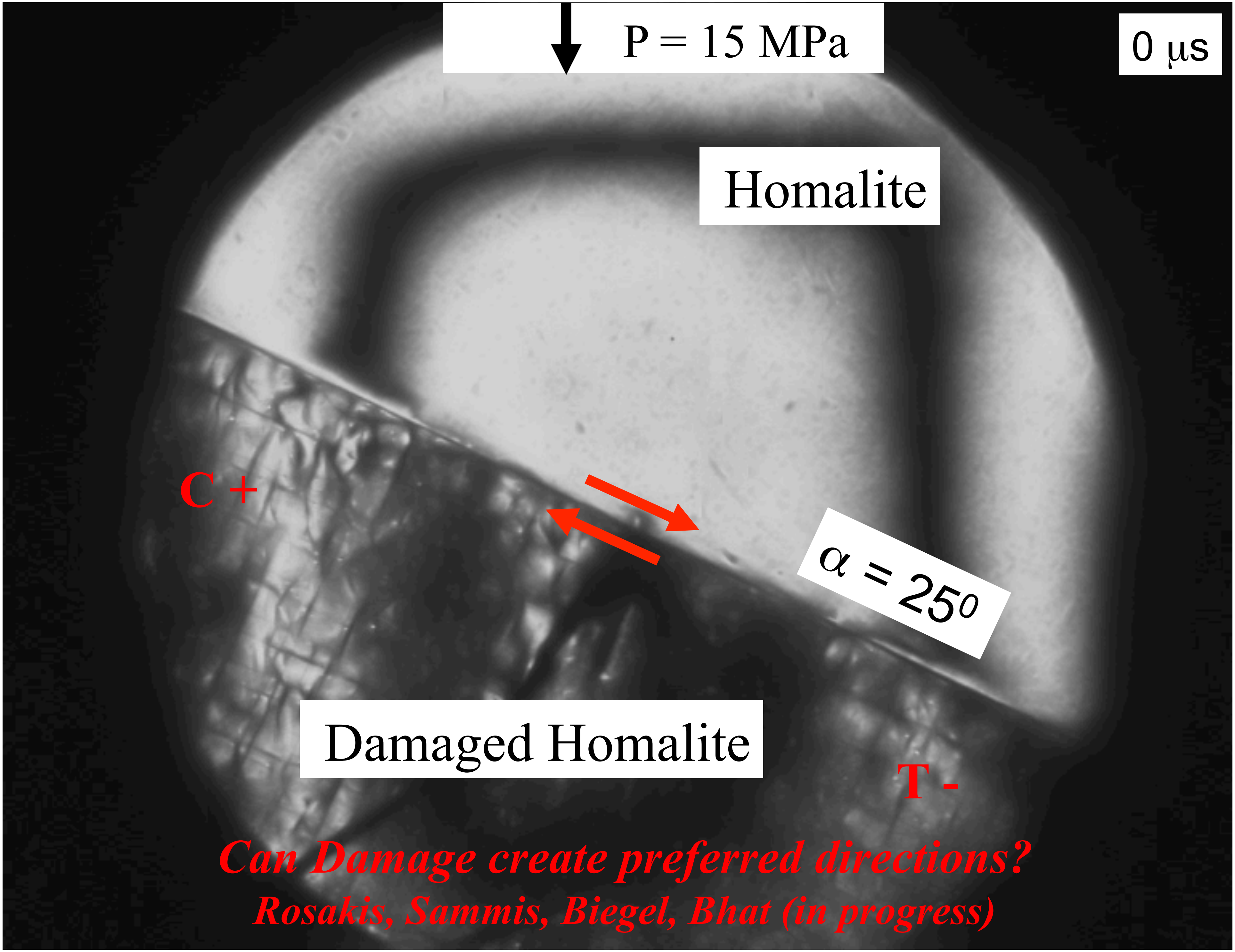
New parametric studies by Shi & BenZion 2006 and by Rubin and Ampuero , 2006.

Structure of Geological Faults

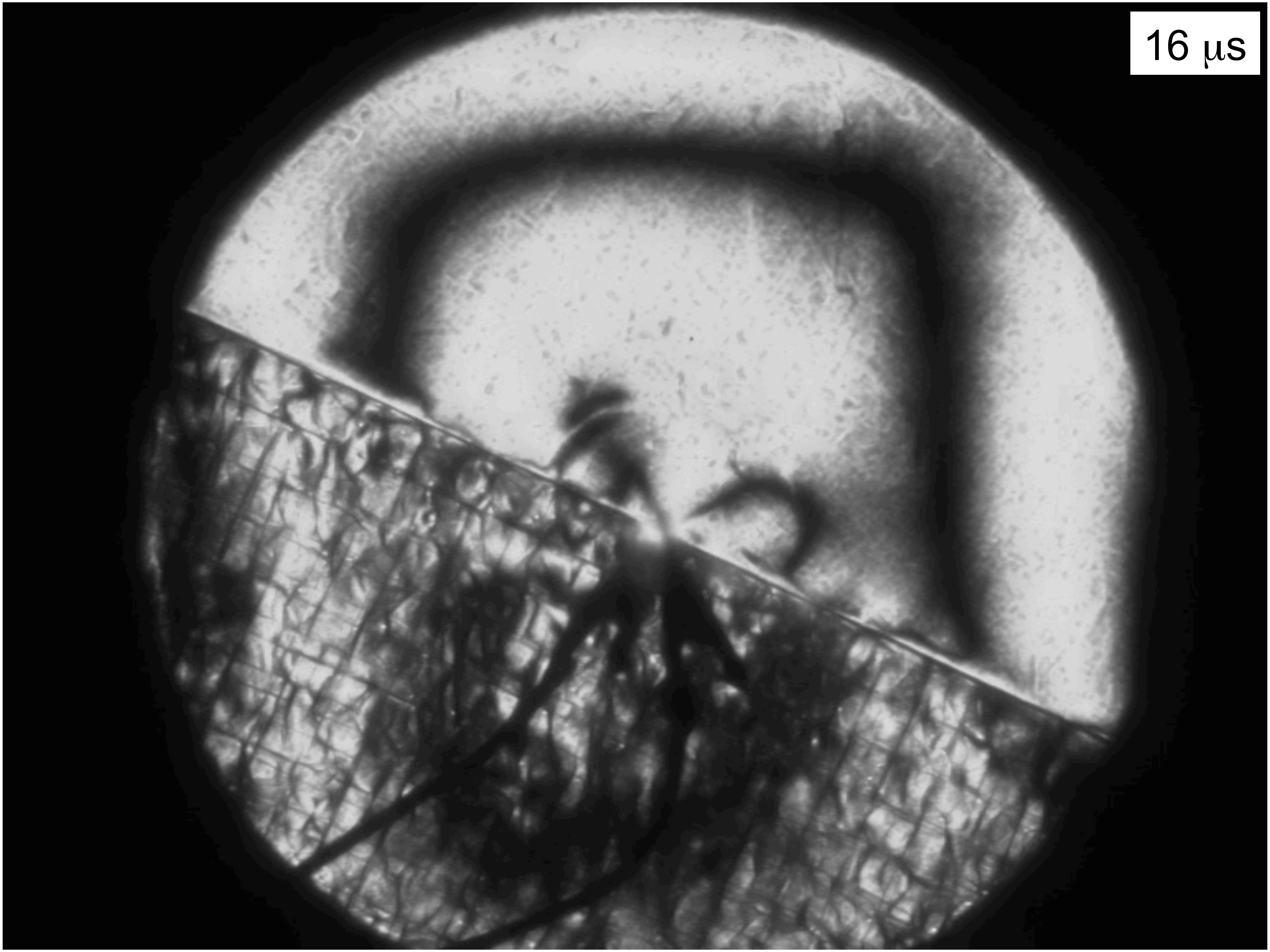
(Ben-Zion and Sammis, PAGEO 2003; Sibson, BSSA 2003)

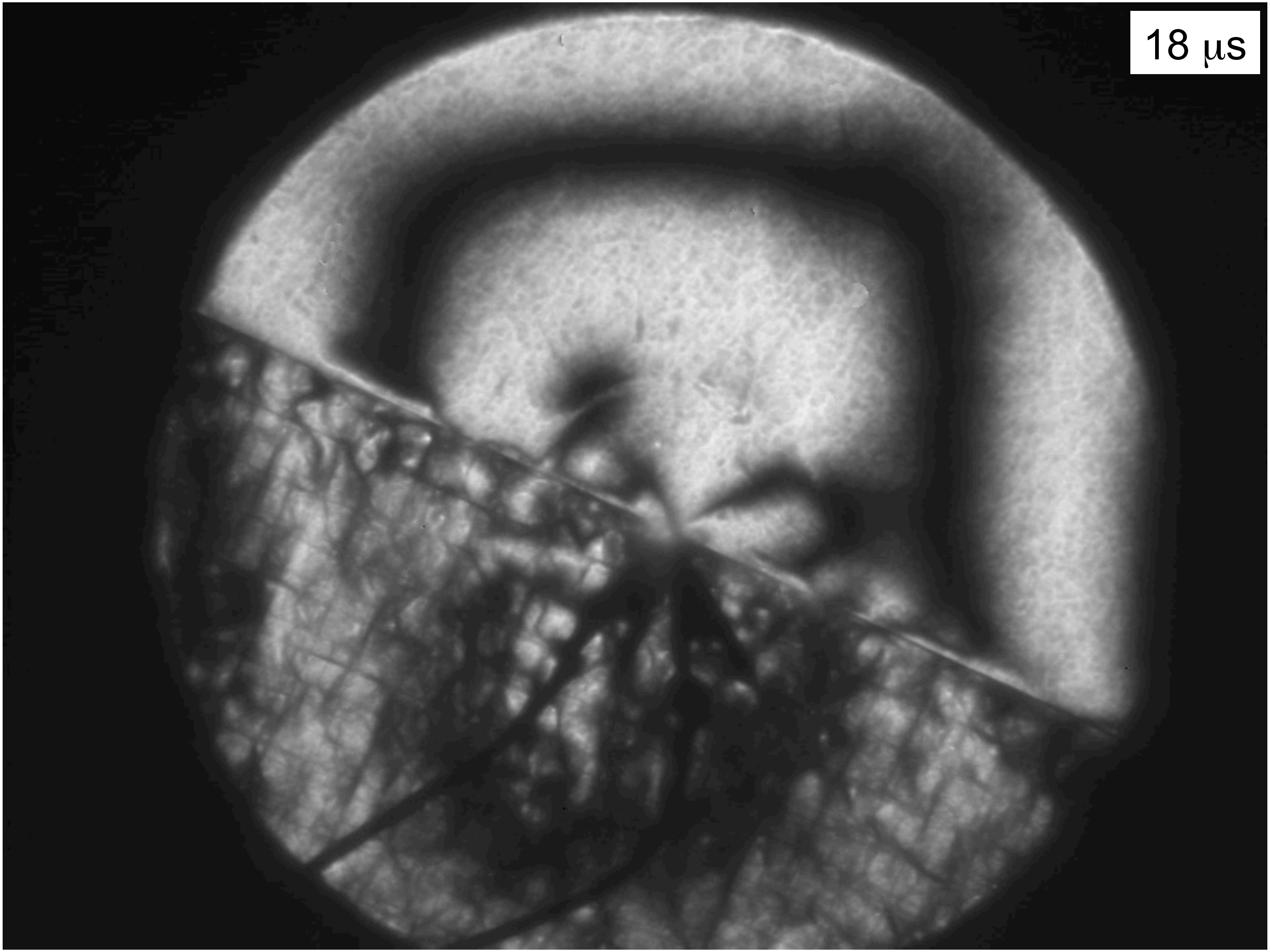


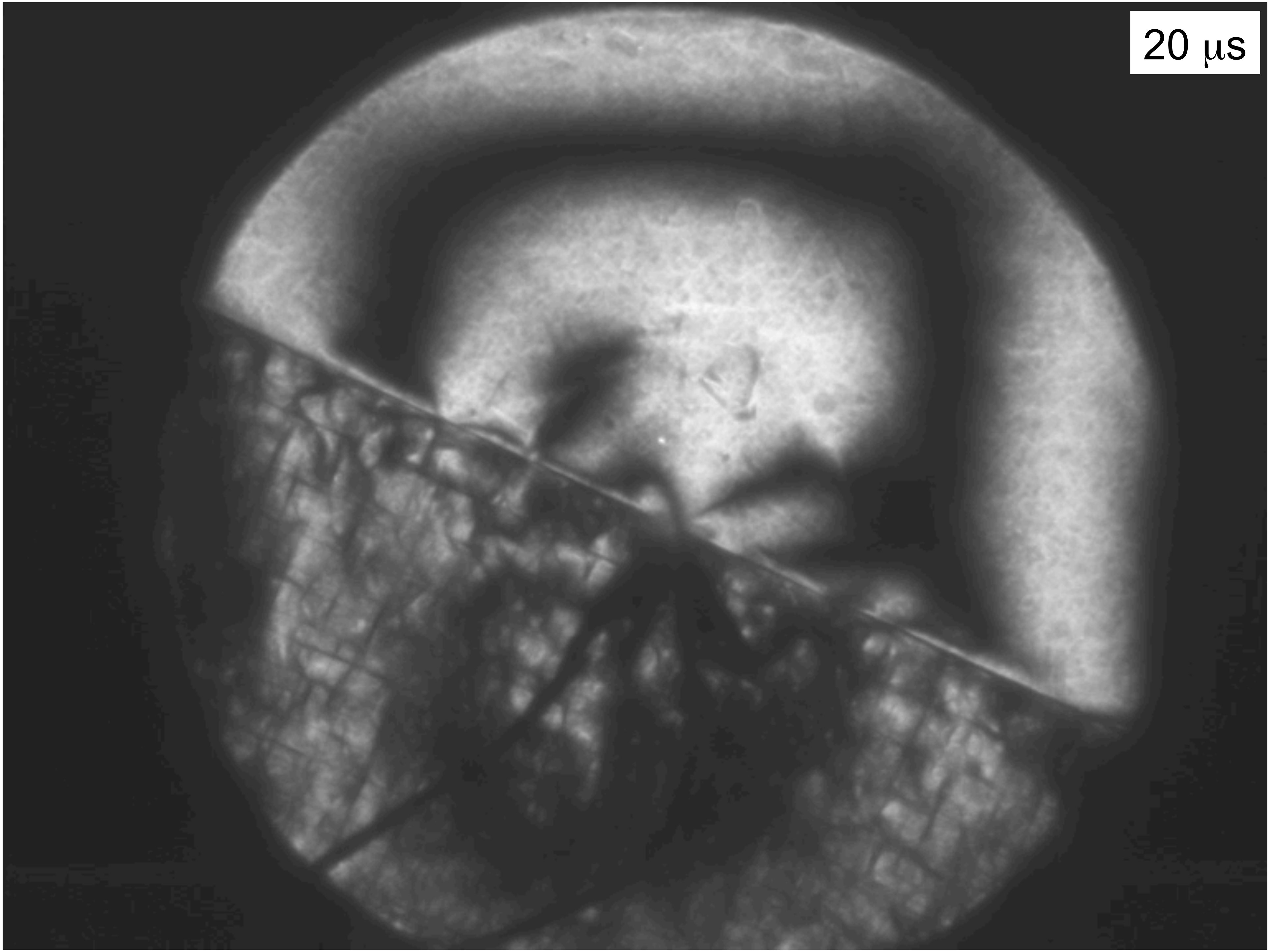


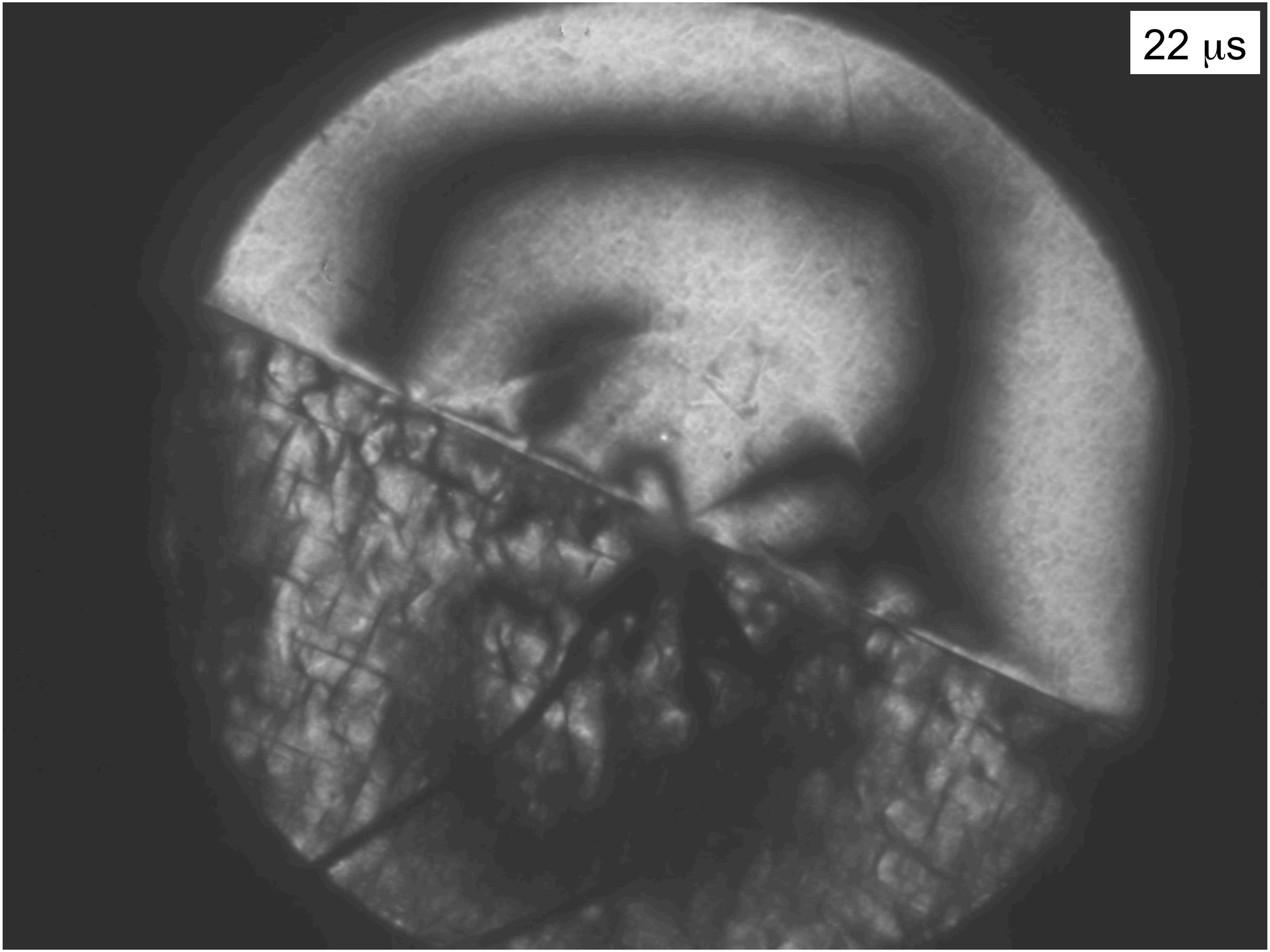


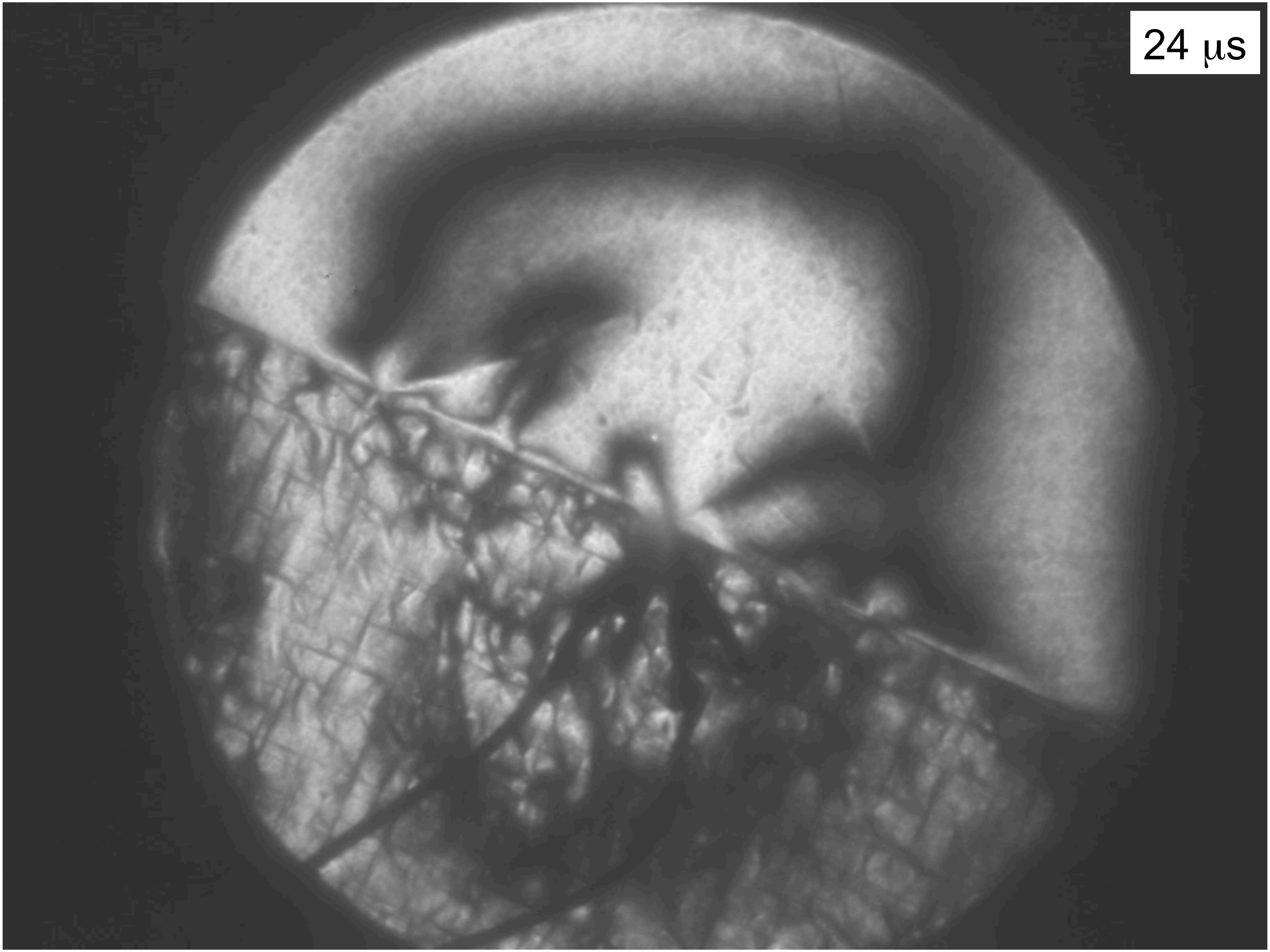
P = 15 MPa
0 μs
Homalite
C +
α = 25⁰
Damaged Homalite
T -
Can Damage create preferred directions?
Rosakis, Sammis, Biegel, Bhat (in progress)

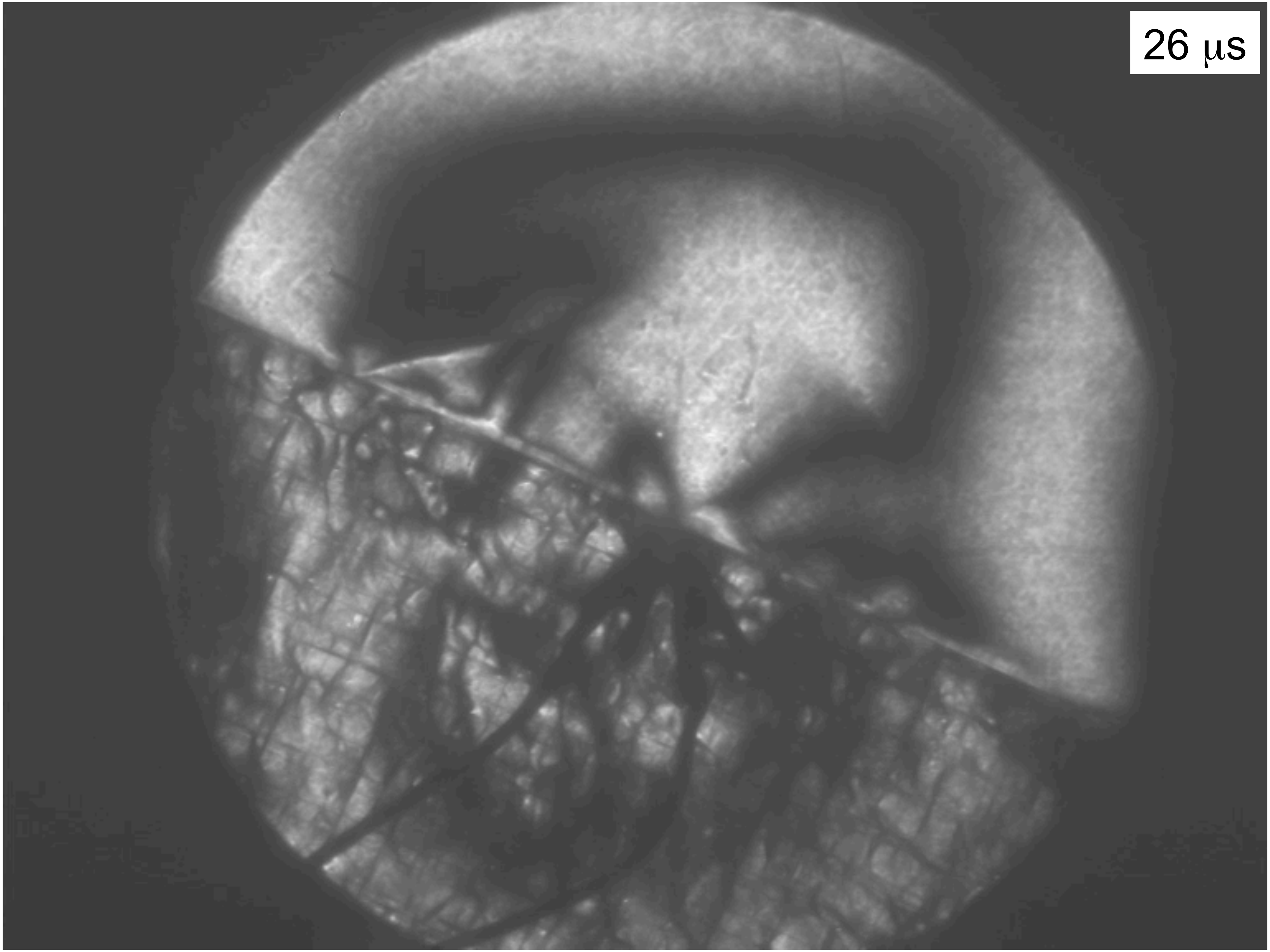

16 μs

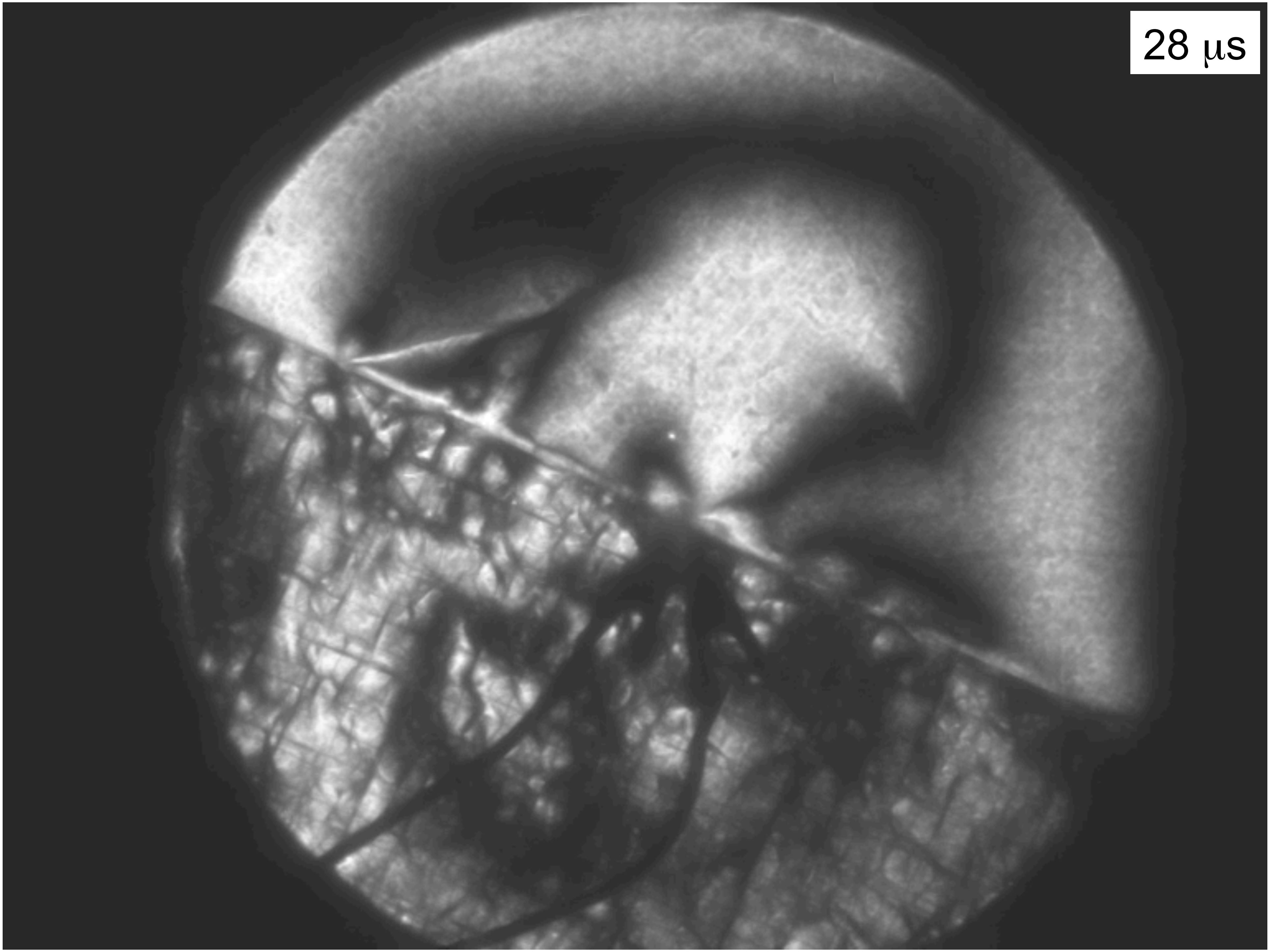

18 μs

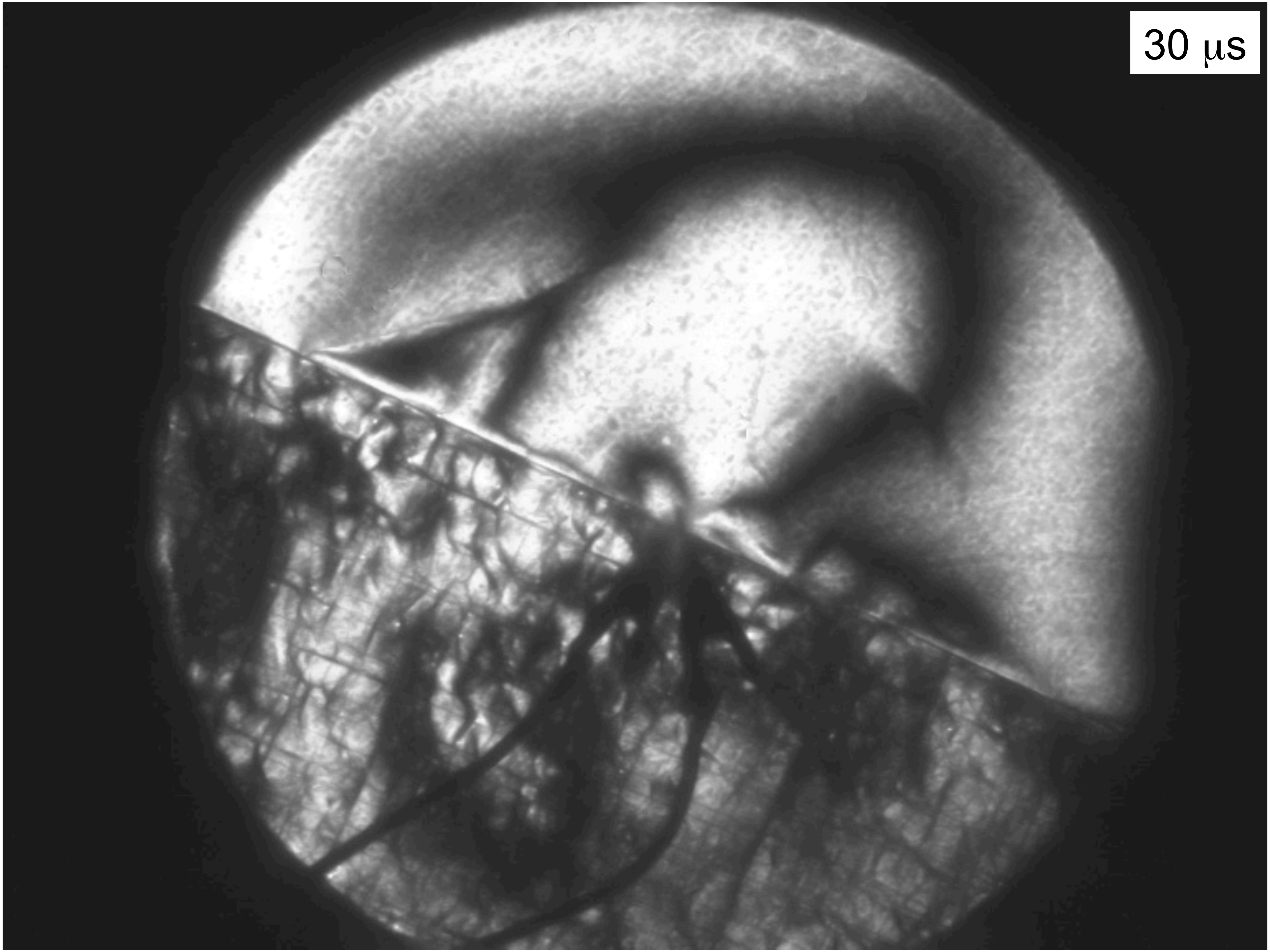

20 μs


22 μs


24 μs


26 μs

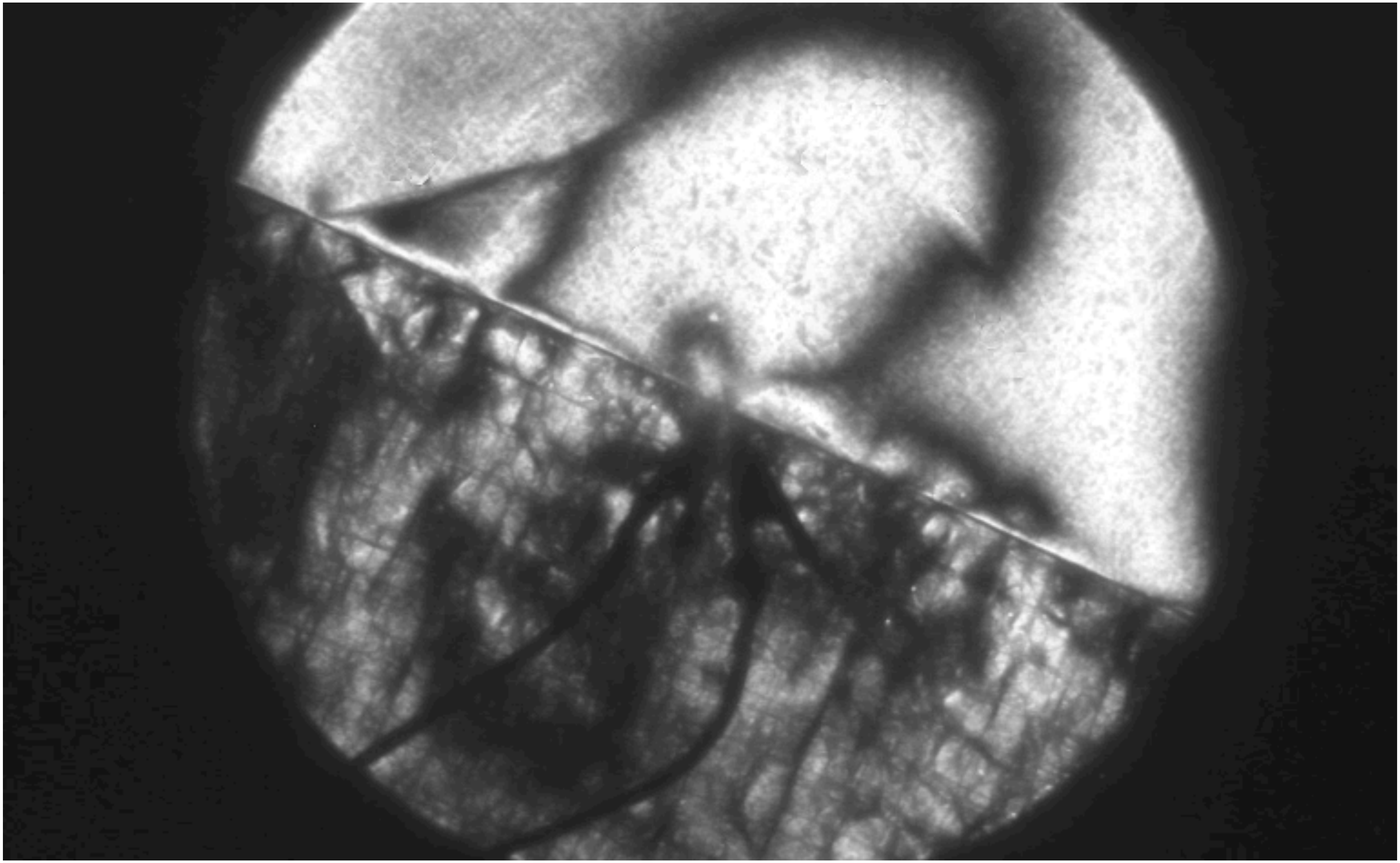

28 μs


30 μs

32 μs

Can Damage create preferred directions?

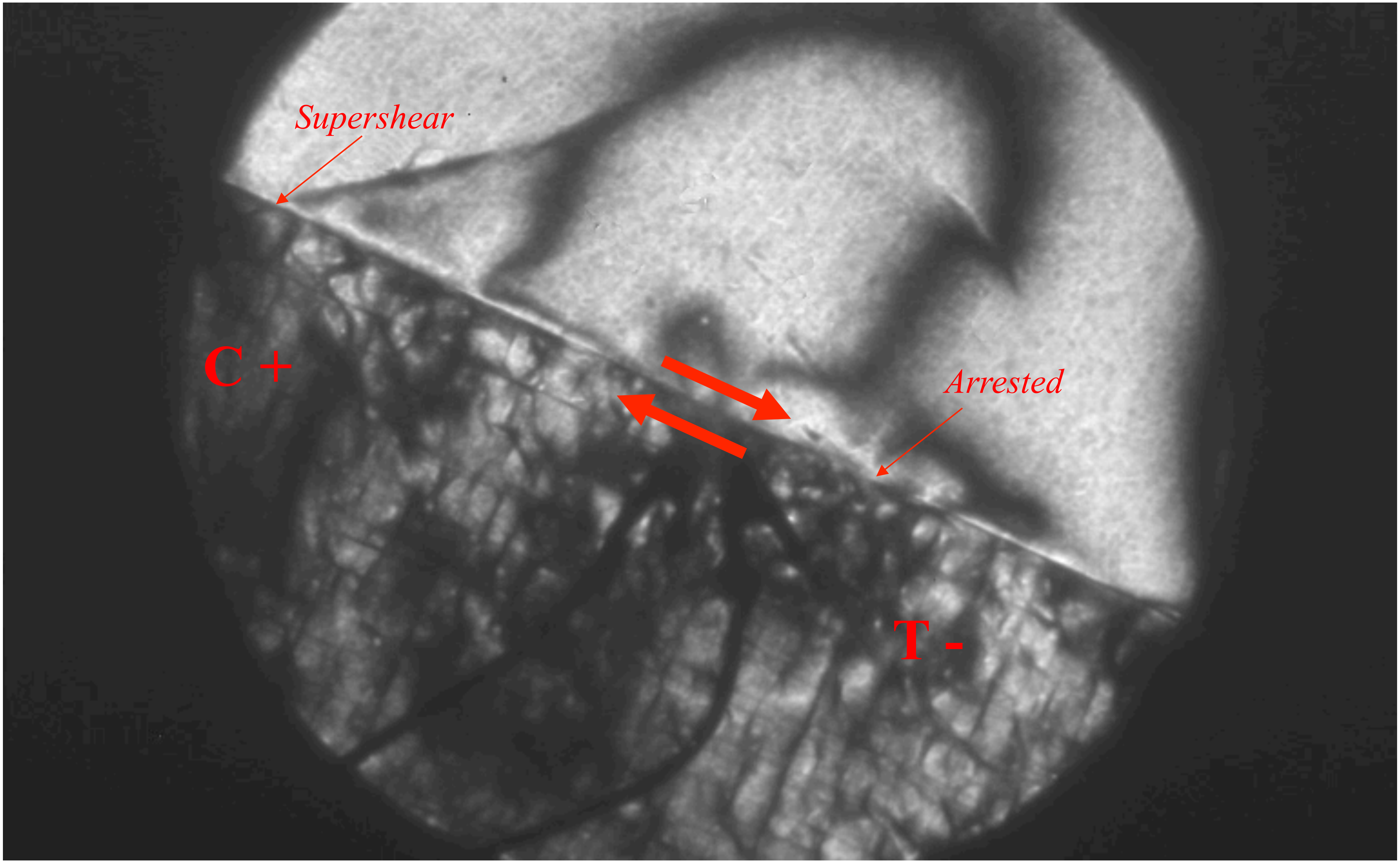
Rosakis, Sammis, Biegel, Bhat (in progress)



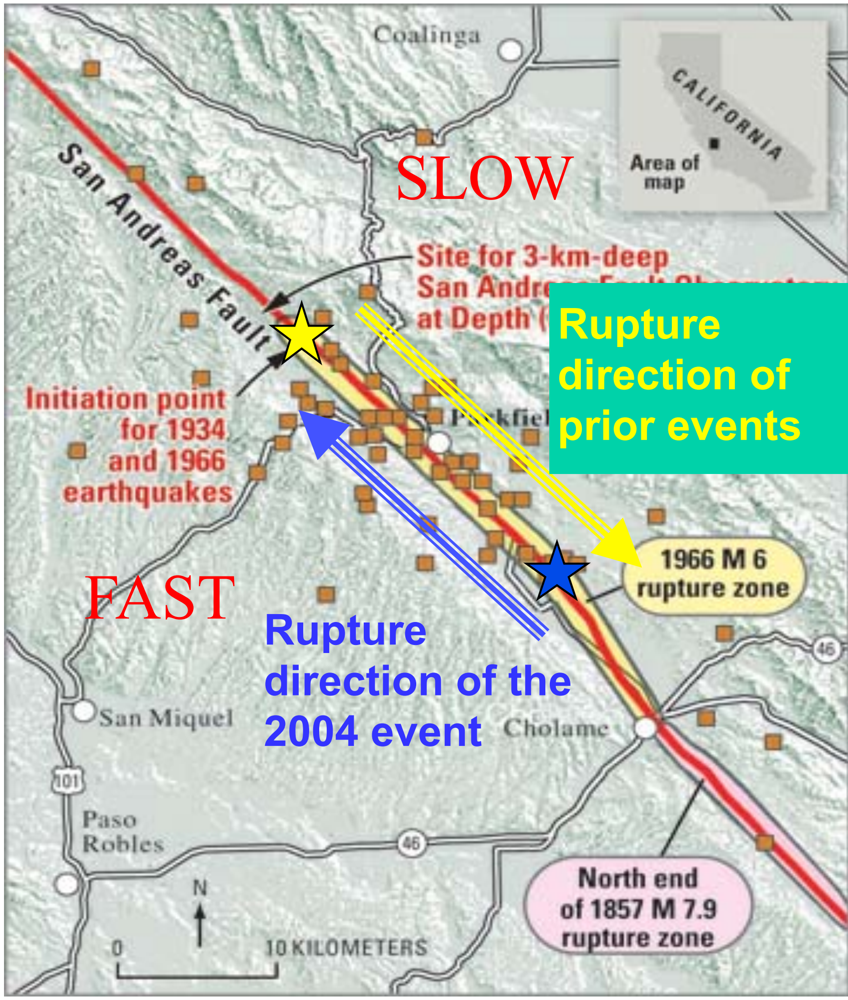
Can Damage create preferred directions?

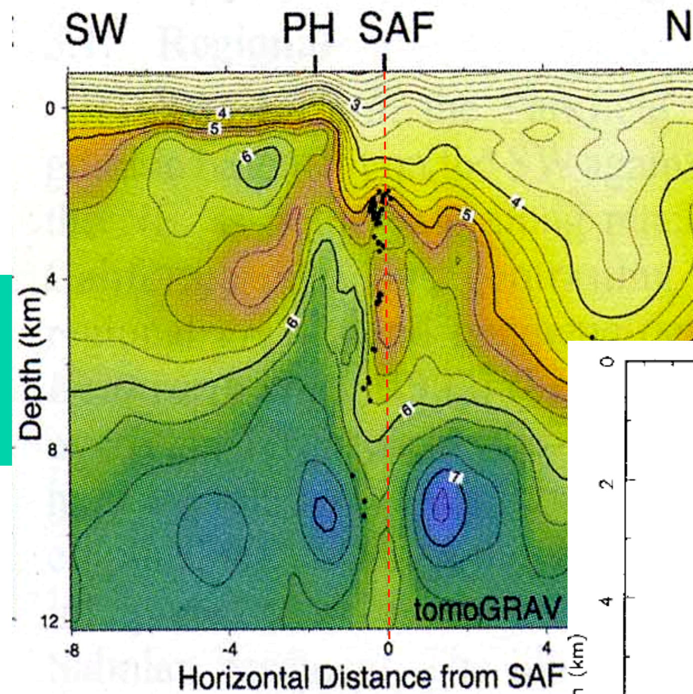
Rosakis, Sammis, Biegel, Bhat (in progress)

34 μs

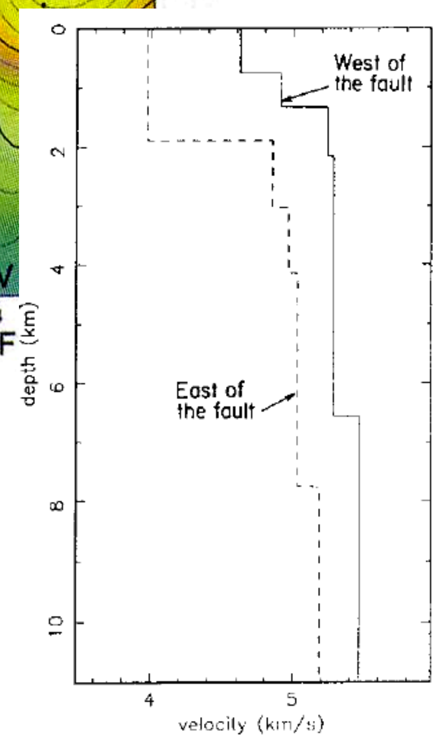


Bimaterial Crust Structure at Parkfield
-Evidence Against an Exclusive Direction-





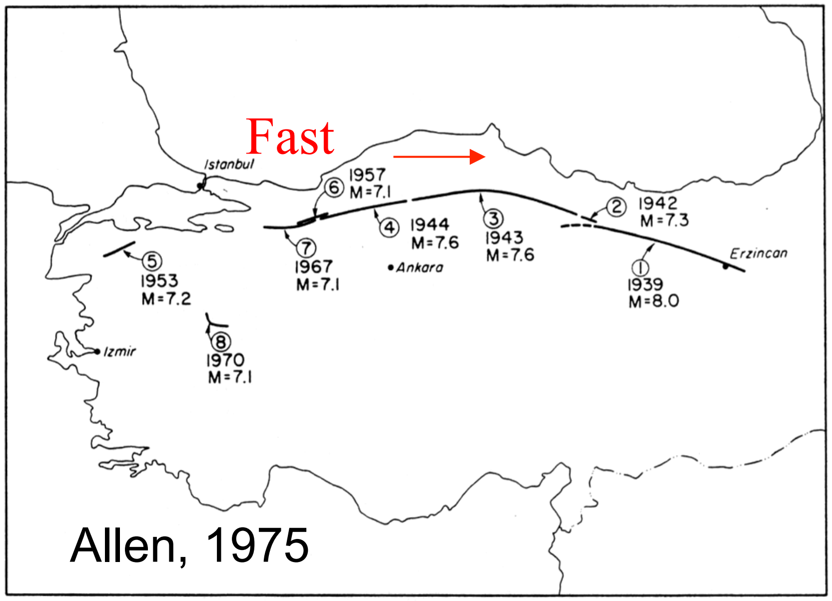
Thurber et al. (2004)



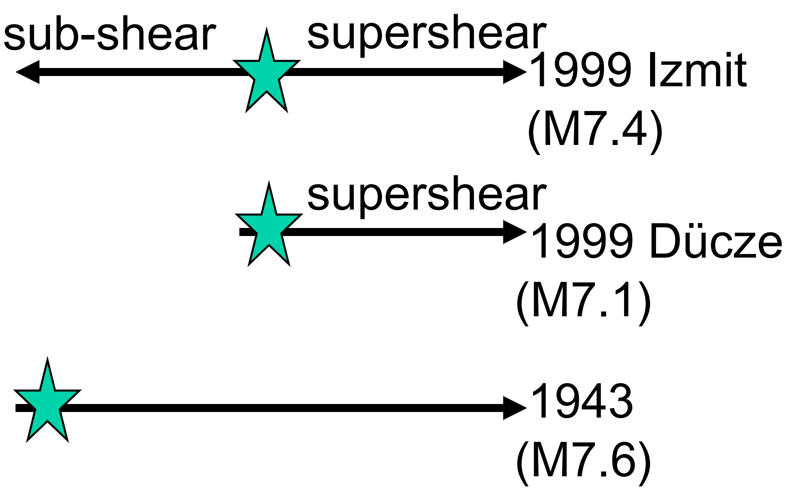
(Ben-Zion et al., 1992)

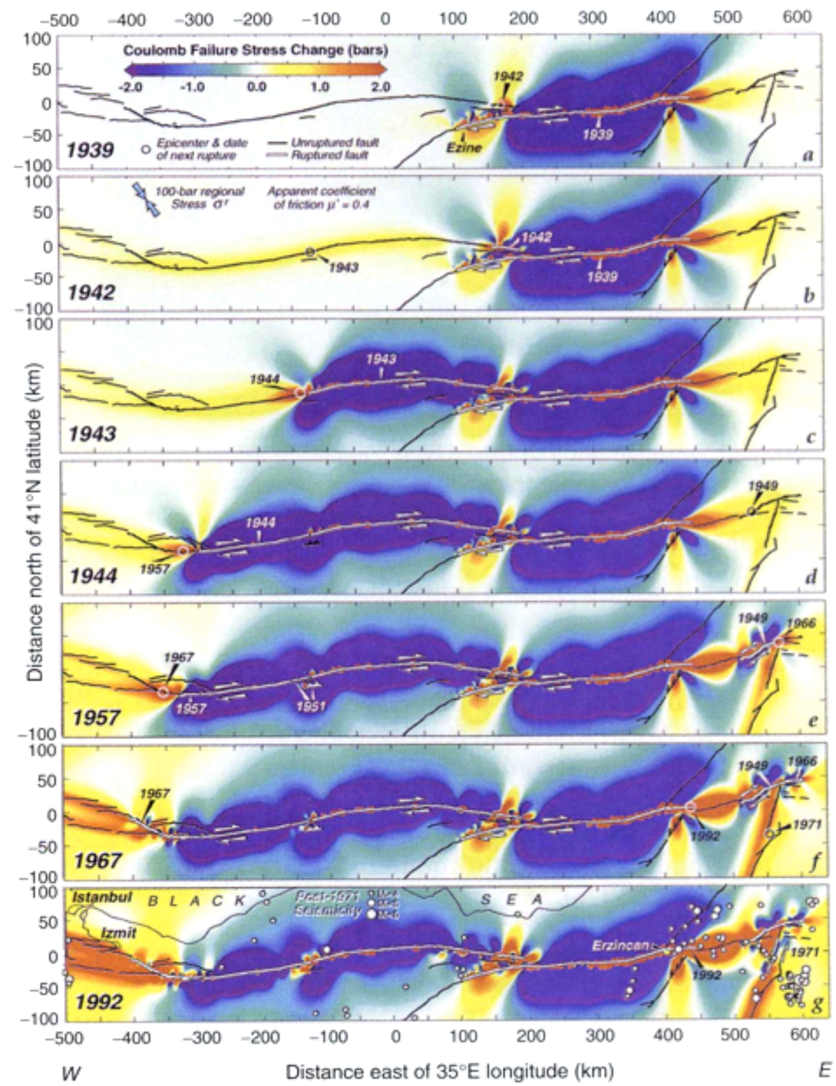
At depth 3-8 km, shear wave speed contrast is 10-20% with east side being slower.

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



Allen, 1975





Stein et al., 1997