Η Καταστροφικής ισχύς των Υπερ-Διατμητικών διαρρήξεων (Super-shear ruptures), όπως αυτή εκδηλώθηκε στον φονικό σεισμό των 7,8 Ρίχτερ , στο Καχραμανμαράς της Ανατολίας , της 6^{ης} Φεβρουαρίου του 2023 :

Ένα κλασσικό μάθημα Μηχανικής.

Mohamed Abdelmeguid, Caltech

ARES J. ROSAKIS

Theodore von Kármán Professor of Aeronautics and Mechanical Engineering, Graduate Aerospace Laboratories (GALCIT), CALTECH, Pasadena CA.

George Gazetas , NTUA, Athens

Ahmed Elbanna, UIUC

Διάλεξη στο Εθνικό Μετσόβιο Πολυτεχνείο, Αθήνα,11 Δεκεμβρίου 2023

Esref. Yalçınkaya Istanbul U.

Chunhui Zhao UIUC

We would like to thank the Turkish Disaster and Emergency Management Presidency (AFAD) for setting up dense near-fault observatories, and for immediately publishing a huge number of openly accessible accelerometers during these trying times for Turkey.

The support of NSF Grant EAR-2045285 and the Caltech's Terrestrial Hazard Observation and Reporting Center (THOR) are also gratefully acknowledged

The Destructive Power of Supershear Ruptures as Observed in the Devastating, Feb 6th 2023 , M_w7.8 Kahramanmaraş /Pazarcik, Türkiye/Syria Earthquake: A classical lesson from Mechanics.

Mohamed Abdelmeguid,
Caltech

Ahmed Elbanna,
UIUC

Chunhui Zhao
UIUC

ARES J. ROSAKIS
Theodore von Kármán Professor of Aeronautics and Mechanical Engineering, Graduate Aerospace Laboratories (GALCIT), CALTECH, Pasadena CA.

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NTUA, Athens

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Istanbul U.

National Technical University of Athens (NTUA)
Athens, Greece, Dec.11th, 2023

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The Feb 6th, 2023 (M7.8) Earthquake in Kahramanmaras ruptured 300 km of the East Anatolian Fault (EAF). ***A second M_w7.7 earthquake occurred 9 hours later on a neighboring fault. Today we concentrate on the first event.***

Hatay province:

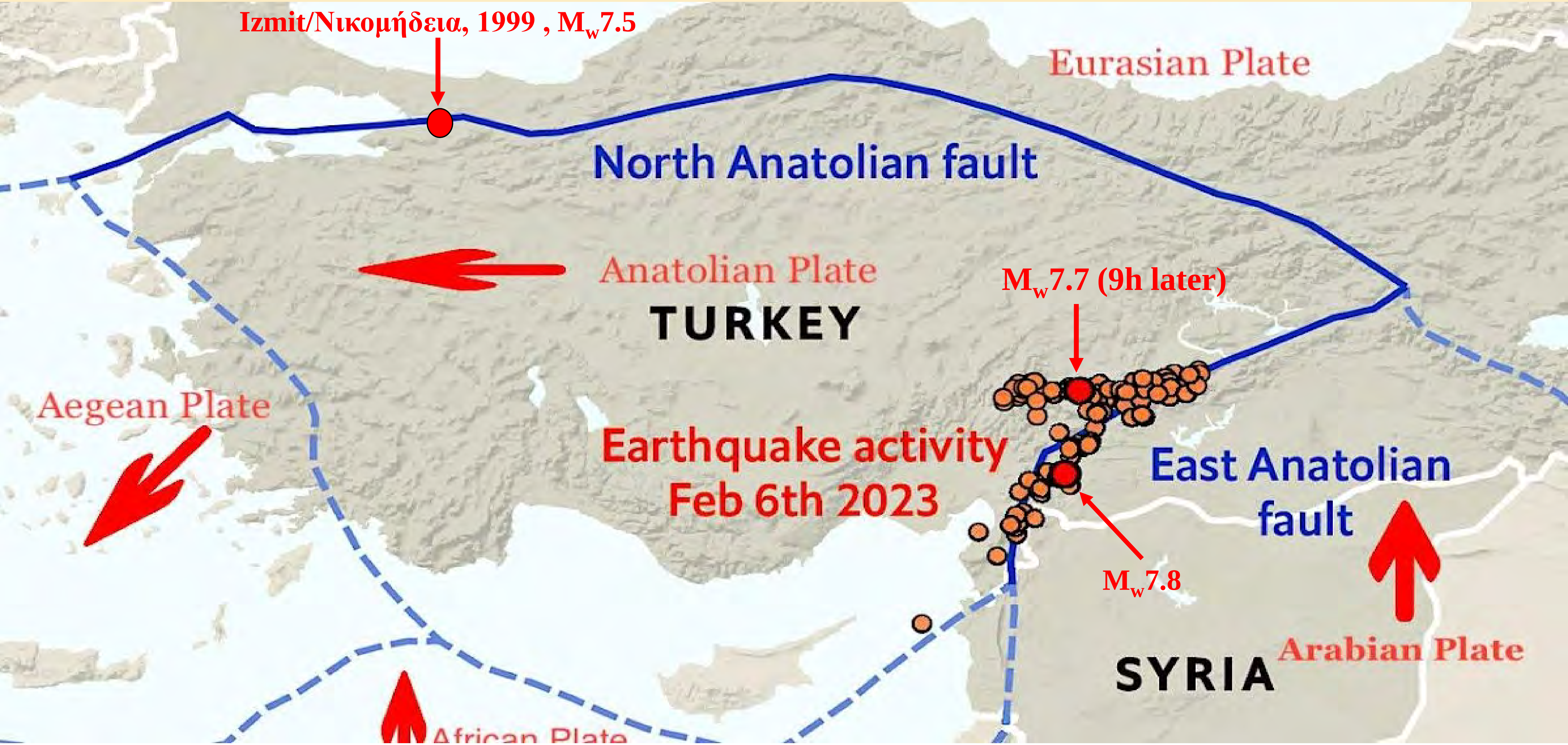
Is this level of destruction expected at 240Km away from Epicenter?

Credit: Anadolu Agency

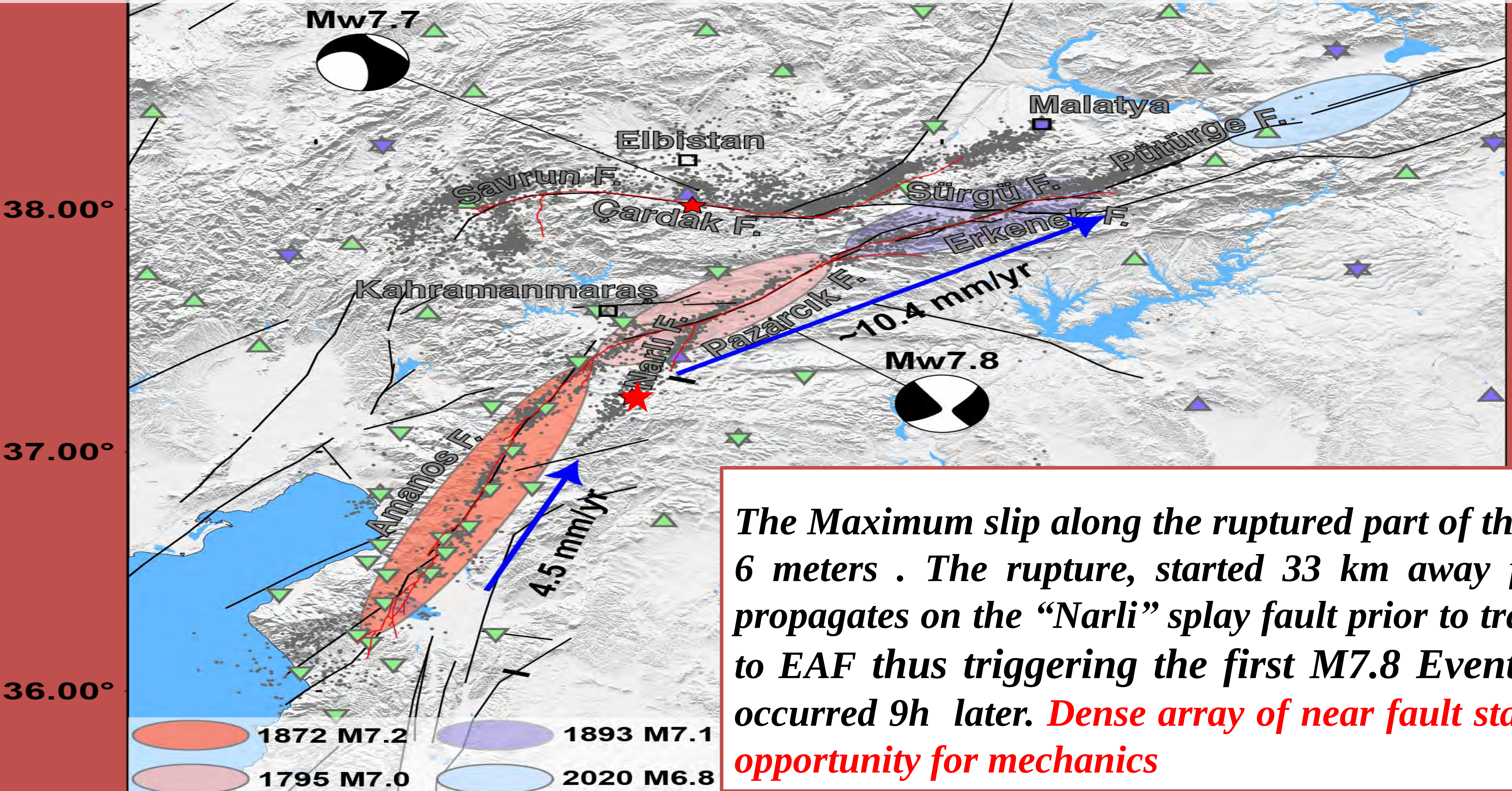
The main shock lasted around 70 second. Overall, the earthquake sequence resulted in horrific human loses, a confirmed death toll of 59,260 people and 1.5 million left homeless, devastating many cities , and making this earthquake the 5th deadliest in the 21st century with total estimated damages exceeding $118.8 Billion. Movie credit: THE INDEPENDENT (Holly Patrick)

The Feb 6th 2023 (M7.8) Earthquake .The Tectonic setting:

WHERE THE ARABIAN MEETS THE ANATOLIAN PLATE



The Fault lines illuminated by aftershocks (gray dots).Many stations exist along the fault line (green triangles)



The Maximum slip along the ruptured part of the fault was 6 meters . The rupture, started 33 km away from EAF, propagates on the "Narli" splay fault prior to transitioning to EAF thus triggering the first M7.8 Event. A Mw7.7 occurred 9h later. Dense array of near fault stations is an opportunity for mechanics

Population distribution in relation to the fault plane is one reason for devastation. ***The rupture, starts 33 km away from EAF, propagates on the "Narli" splay fault prior to transitioning to EAF (USGS)***

Rich heritage lost all over Türkiye and Syria

Volkan Kasik/Anadolu Agency/Getty Images

Gaziantep Castle

Rich heritage lost in Antakya –Türkiye

Habib-i Neccar Mosque

Antioch Greek Orthodox Church

WHAT CAN EXPLAIN THIS LEVEL OF DEVASTATION?

CAN MECHANICS EXPLAIN THIS LEVEL OF DEVASTATION?

SPECIFIC QUESTIONS:

- ***Why was this event so destructive, especially very far from the epicenter?***
- ***Why did the rupture jump to the EAF? Could this level of destruction be associated with super-shear (i.e. rupture tip speeds higher than C_s)?***

-We suspect that the occurrence of supershear and the presence of shear Mach-cones, at fault segments near population centers may have been, at least partially, responsible for the extensive collapse of buildings and the tragic loss of life involved.

-Unlike other major historic earthquakes, this time we have plenty of near-fault records to scrutinize using our past experience in the mechanics of sub-Rayleigh and supershear rupture.

Kahramanmaras, | Altan Adem/AFP , via Getty images

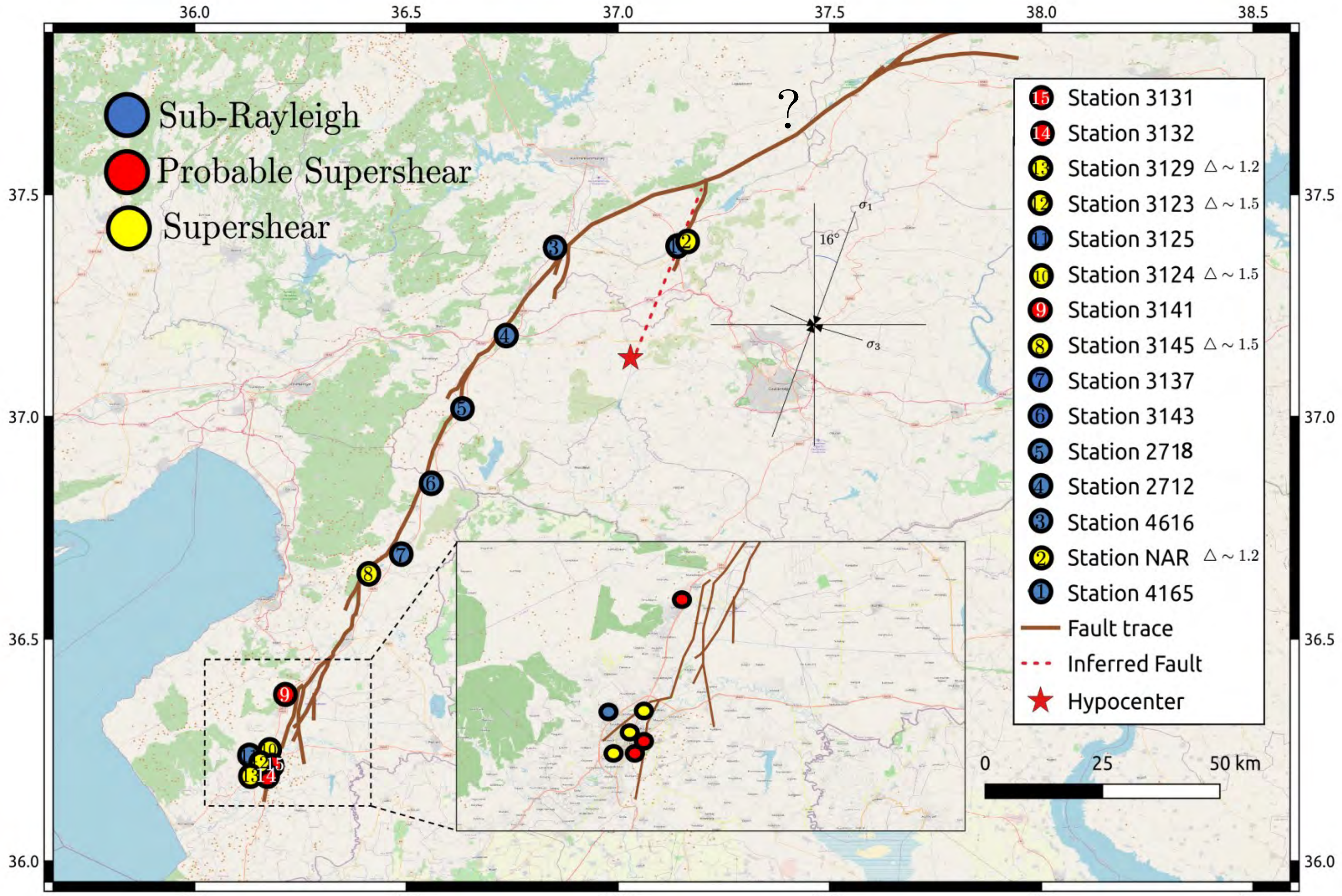
- Rosakis, M Abdelmeguid, A Elbanna, EarthArXiv preprint, 2023 doi: 10.31223/X5W95G "under review" in *Nature Geoscience*
- M. Abdelmeguid, C. Zhao, E. Yalcinkaya, G. Gazetas, A Elbanna, A. Rosakis EarthArXiv preprint Feb. 2023 doi:https://doi.org/10.31223/X5066R

and

Communications of Earth and Environment, Dec. 2023

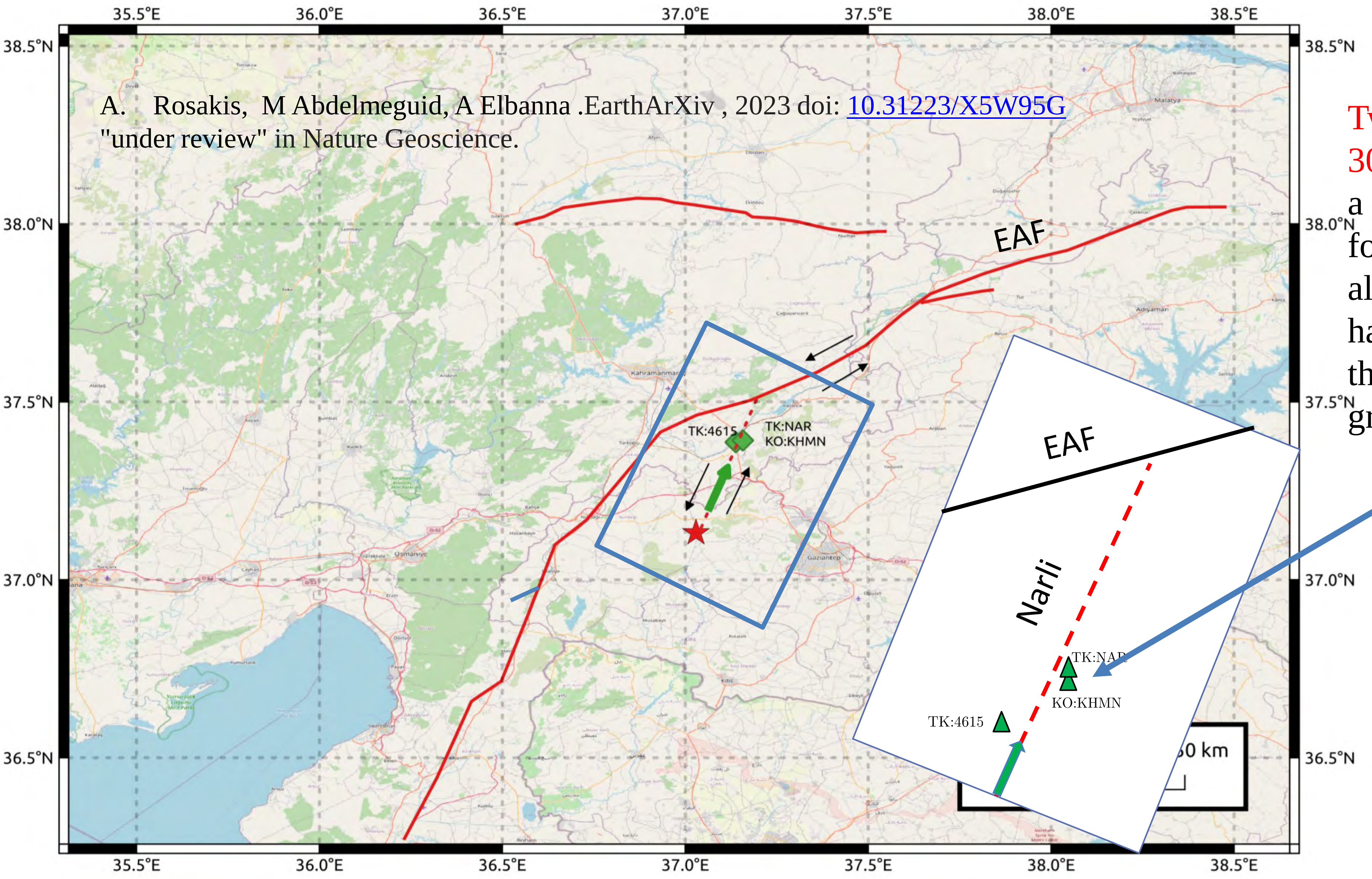
https://doi.org/10.1038/s43247-023-01131-7

Why dynamic rupture mechanics has a chance in helping here:
Very dense array of near fault stations (VERY RARE)



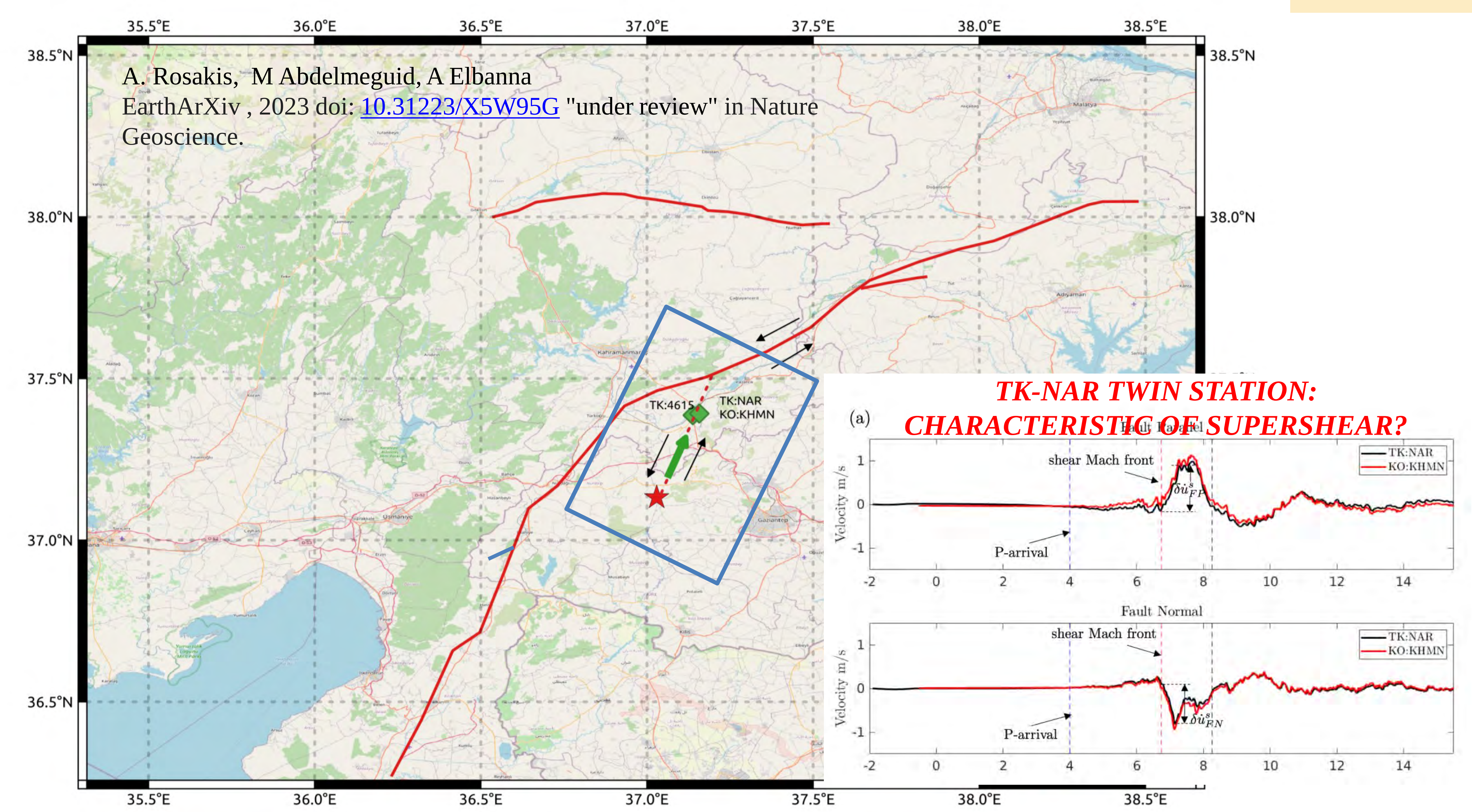
M. Abdelmeguid, C. Zhao, E. Yalcinkaya, G. Gazetas, A Elbanna, EarthArXiv preprint 2023 doi:https://doi.org/10.31223/X5066R , in *Communications of Earth and Environment*, Dec. 2023 https://doi.org/10.1038/s43247-023-01131-7

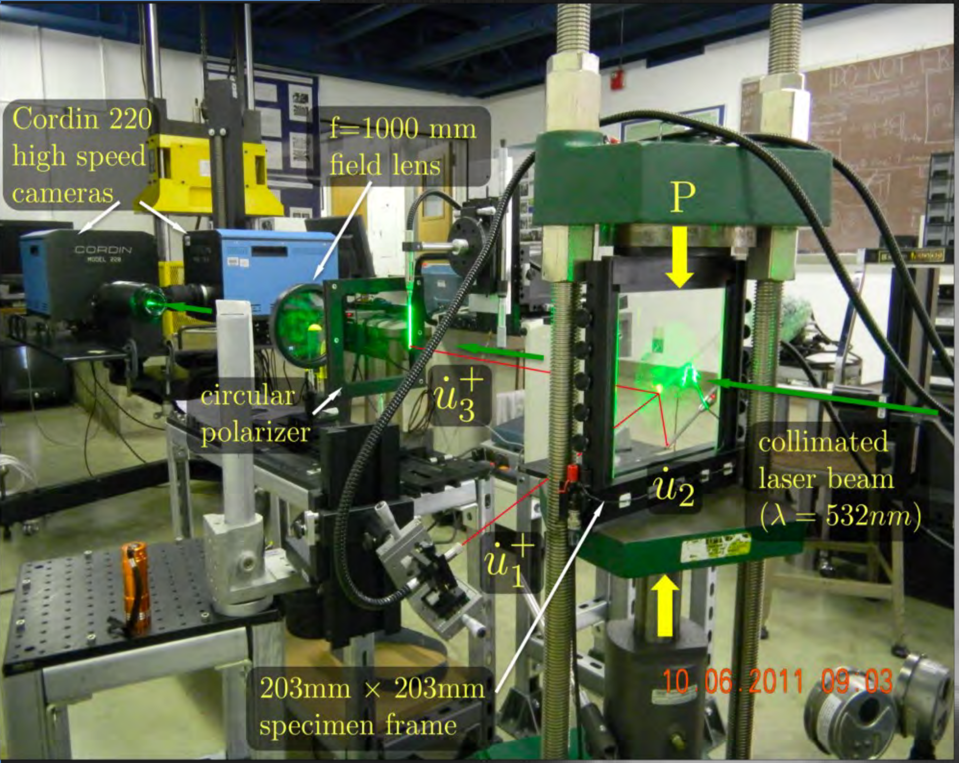
***On-ramp on to the Main Fault highway* : The TK:4615 and the "twin", TK-NAR Stations are located only 1Km from the Narli fault just before its junction with the EAF. The recorded ground velocity signatures are highly uncharacteristic.**

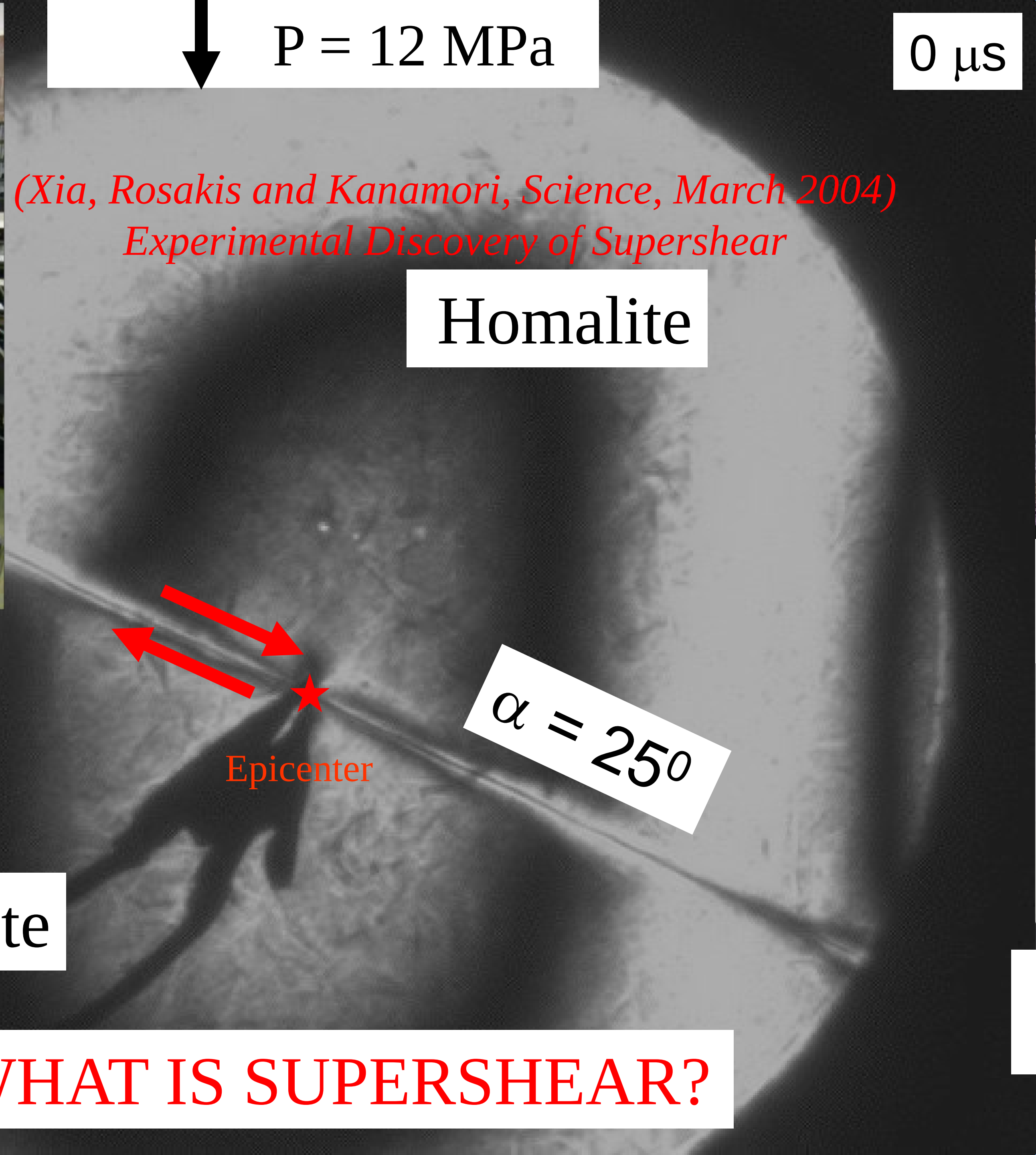


Twin stations 30m apart. This is a very rare and fortuitous situation allowing us to have confidence in the recorded ground shaking

On-ramp on to the Main Fault highway ***: The TK:465 and the "twin", TK-NAR Stations are located only 1Km from the Narli fault just before its junction with the EAF.*** ***The recorded ground velocity signatures are highly uncharacteristic:*** $\delta\dot{u}^s_{FP}$ ***is greater than*** $\delta\dot{u}^s_{FN}$



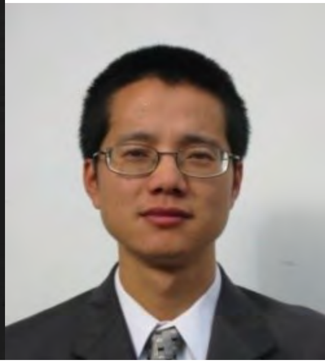




(Xia, Rosakis and Kanamori, Science, March 2004)

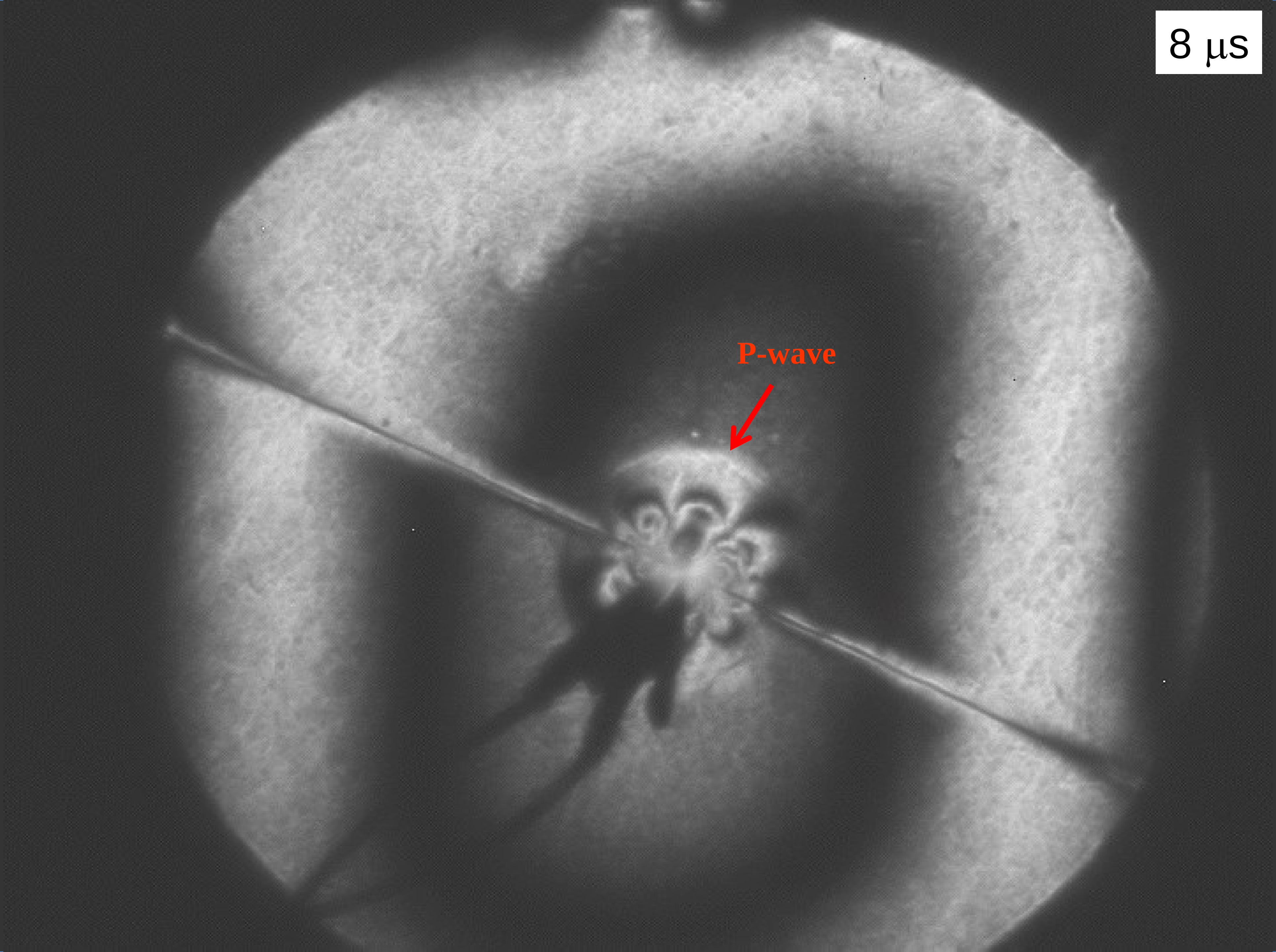
Experimental Discovery of Supershear

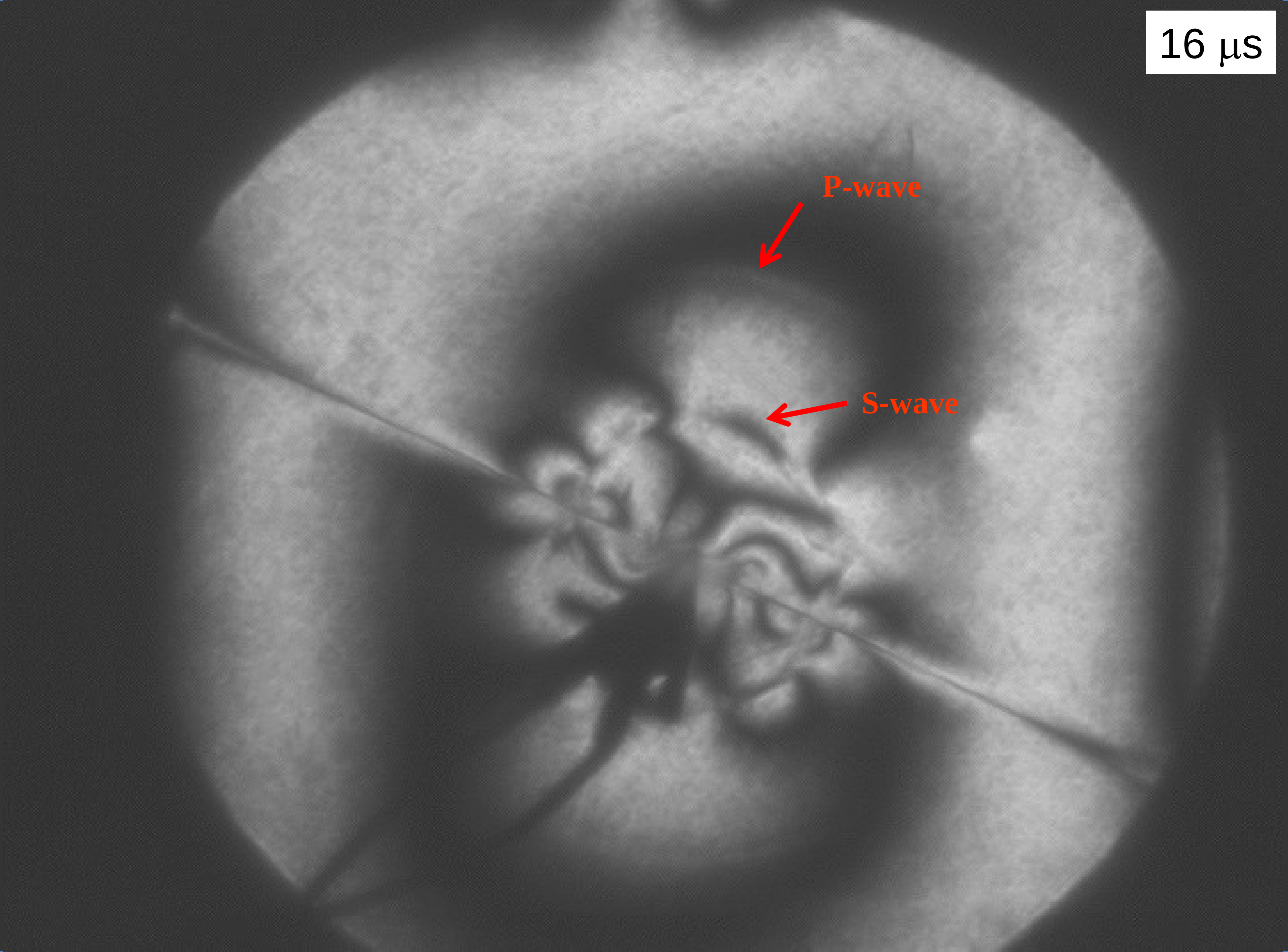
Hiroo Kanamori
Seismo -Lab
Caltech



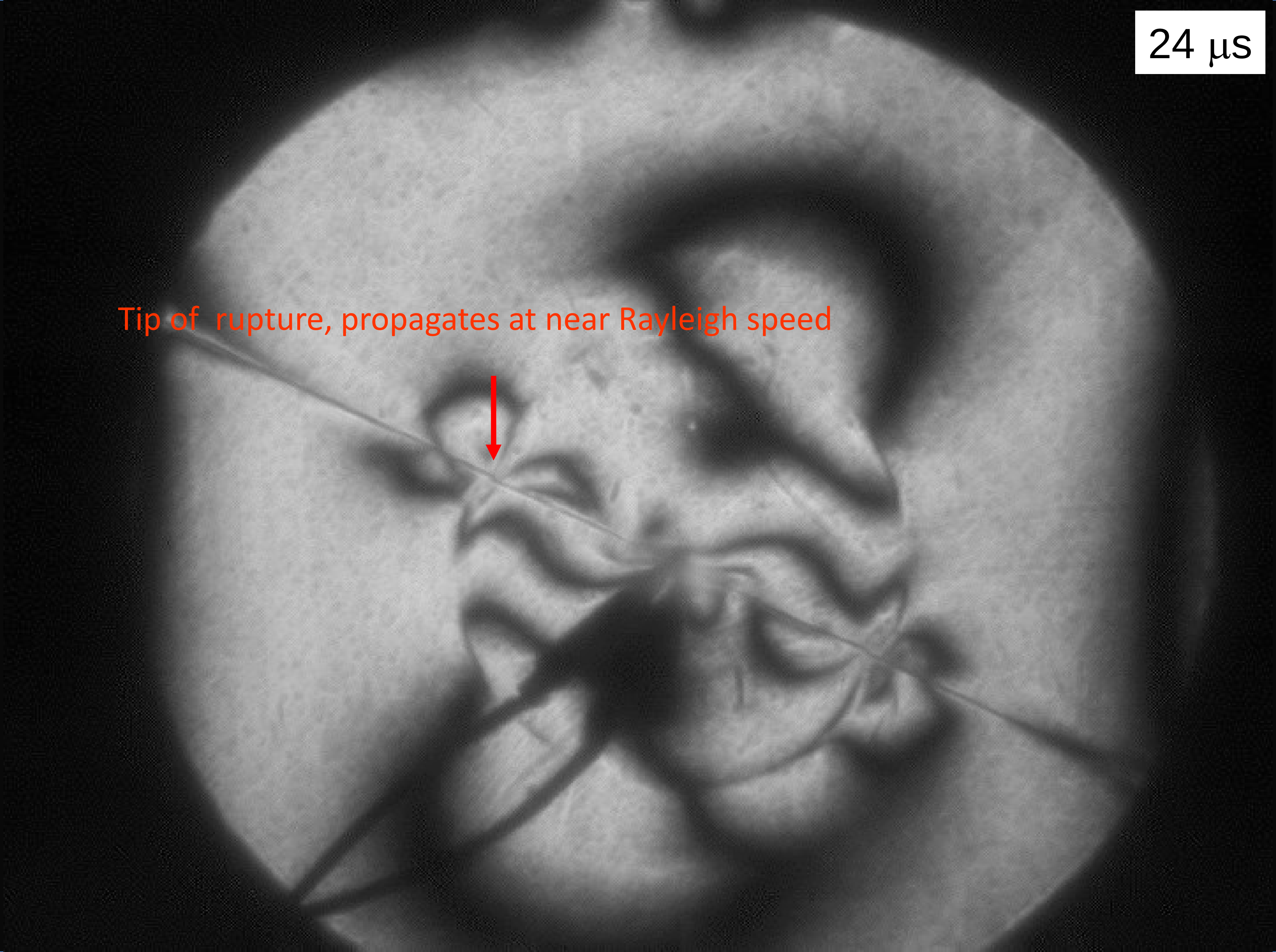
Kaiwen Xia
Univ. of Toronto

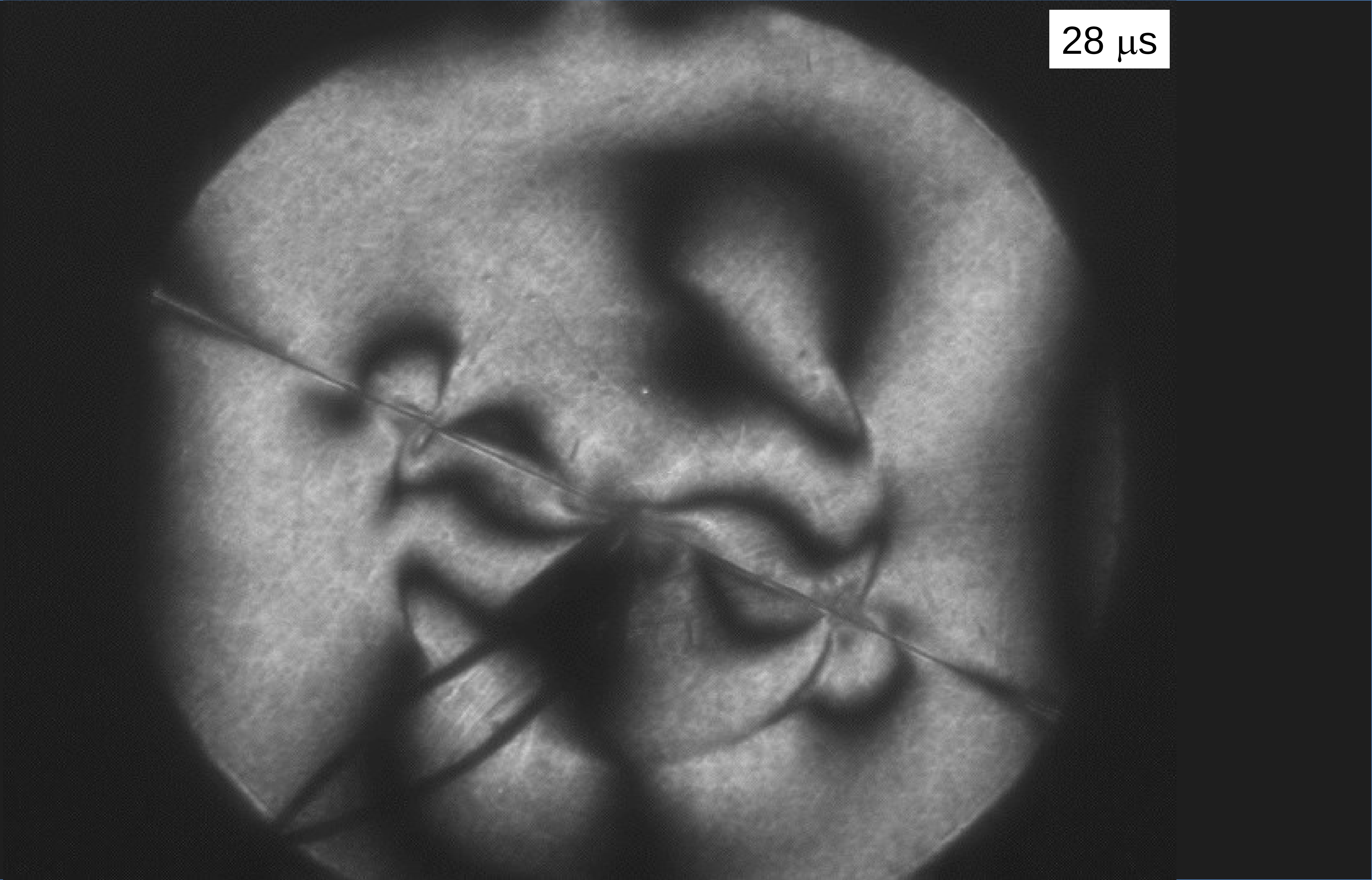
WHAT IS SUPERSHEAR?

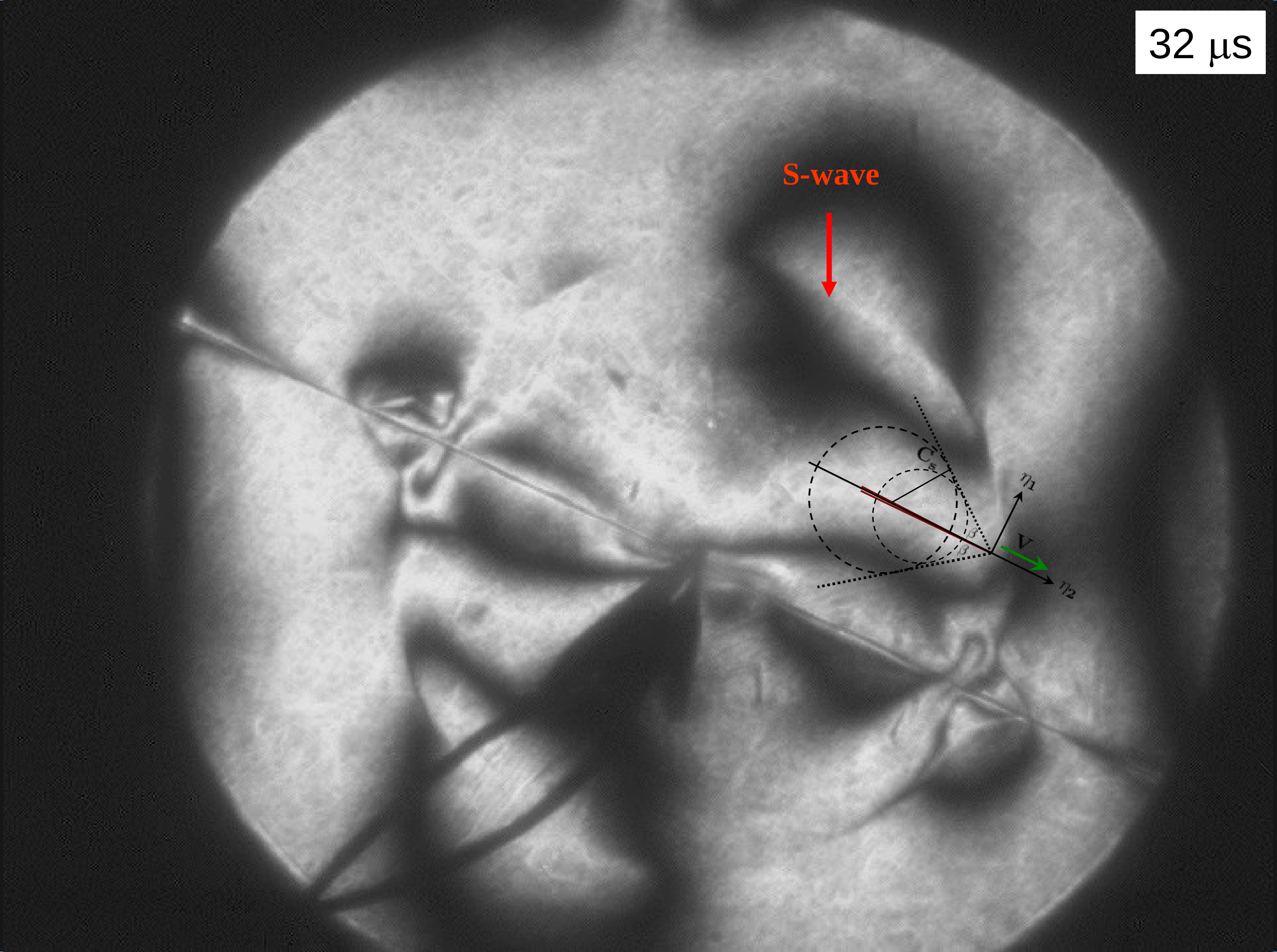

8 μs
P-wave

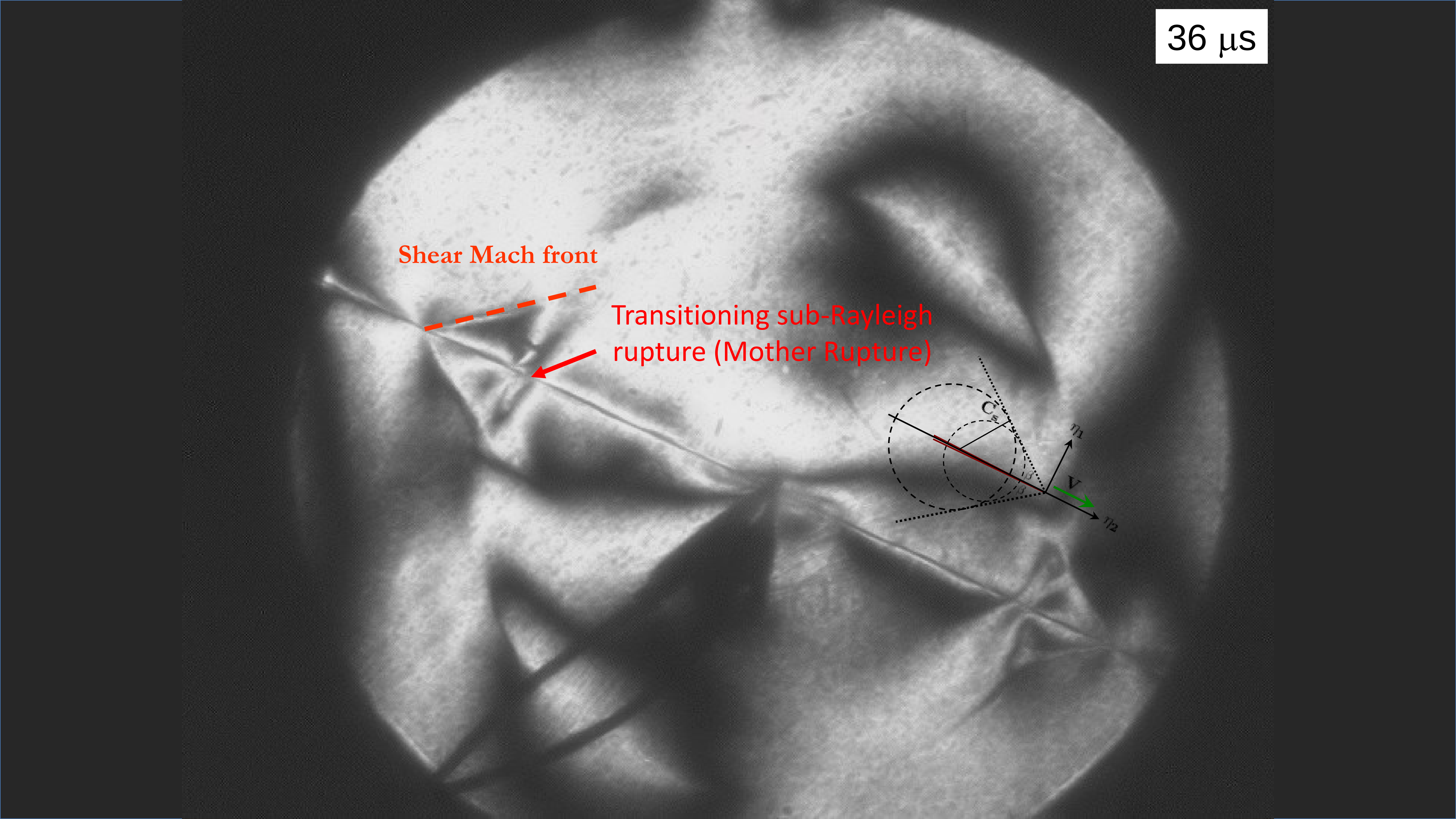

16 μs
P-wave
S-wave


20 μs


24 μs
Tip of rupture, propagates at near Rayleigh speed


28 μs


32 μs
S-wave
V
C_s
η_1
η_2


36 μs
Shear Mach front
Transitioning sub-Rayleigh
rupture (Mother Rupture)
Cs
η1
V
η2

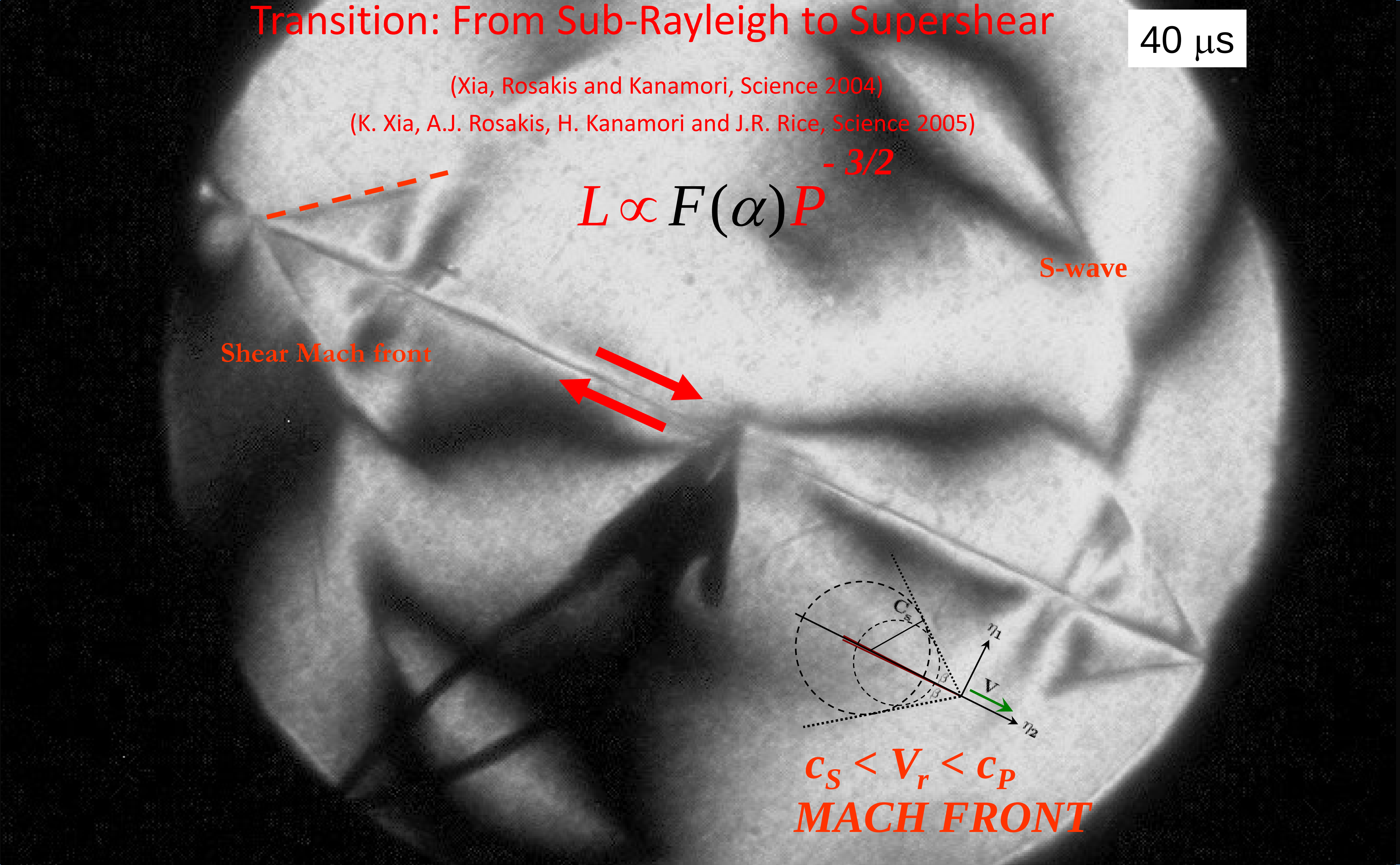
Transition: From Sub-Rayleigh to Supershear

40 μs

(Xia, Rosakis and Kanamori, Science 2004)

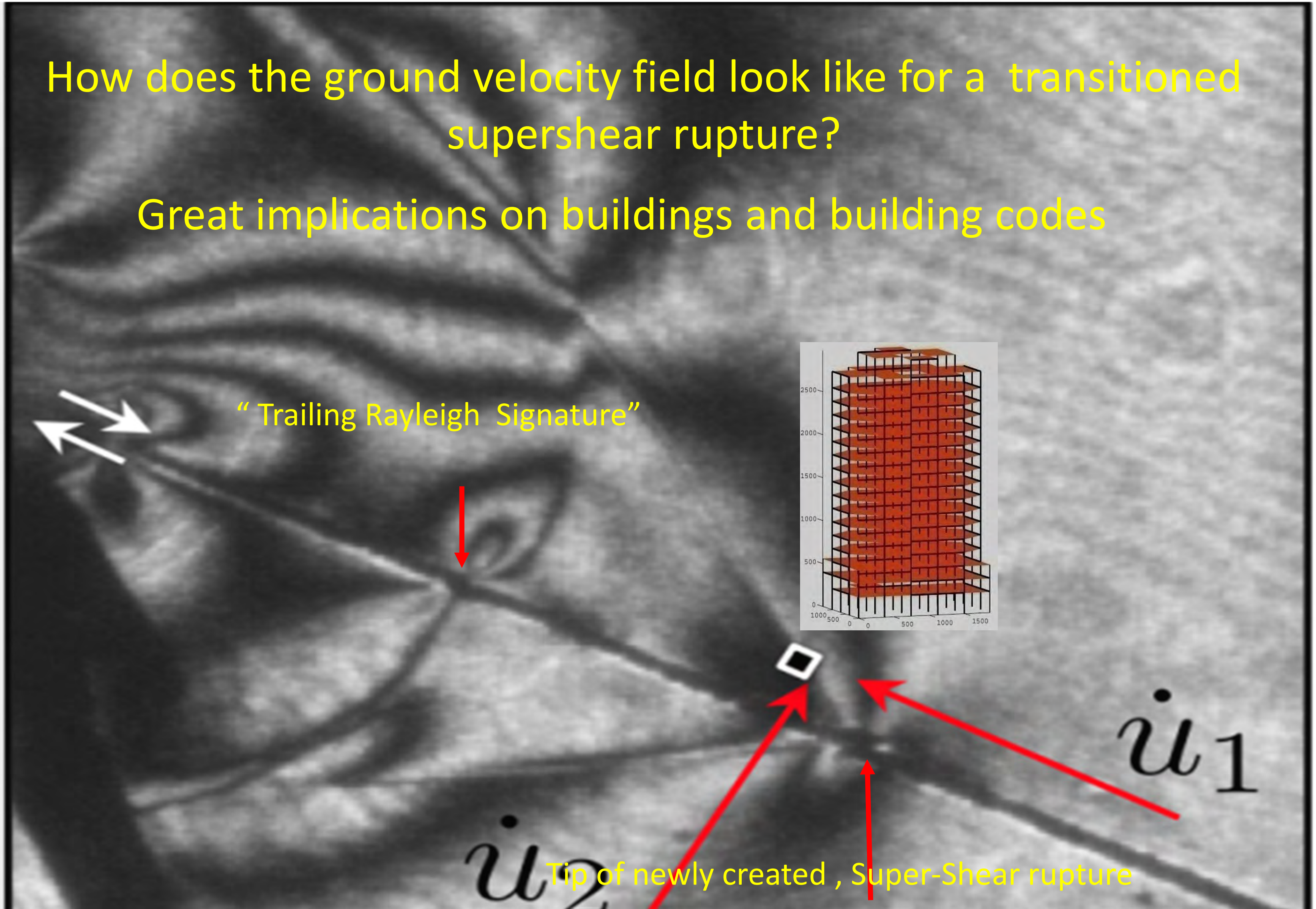
(K. Xia, A.J. Rosakis, H. Kanamori and J.R. Rice, Science 2005)

$$L \propto F(\alpha) P^{-3/2}$$



How does the ground velocity field look like for a transitioned supershear rupture?

Great implications on buildings and building codes

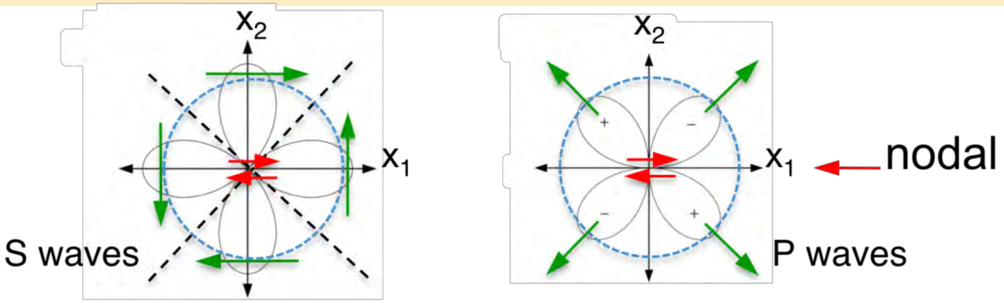


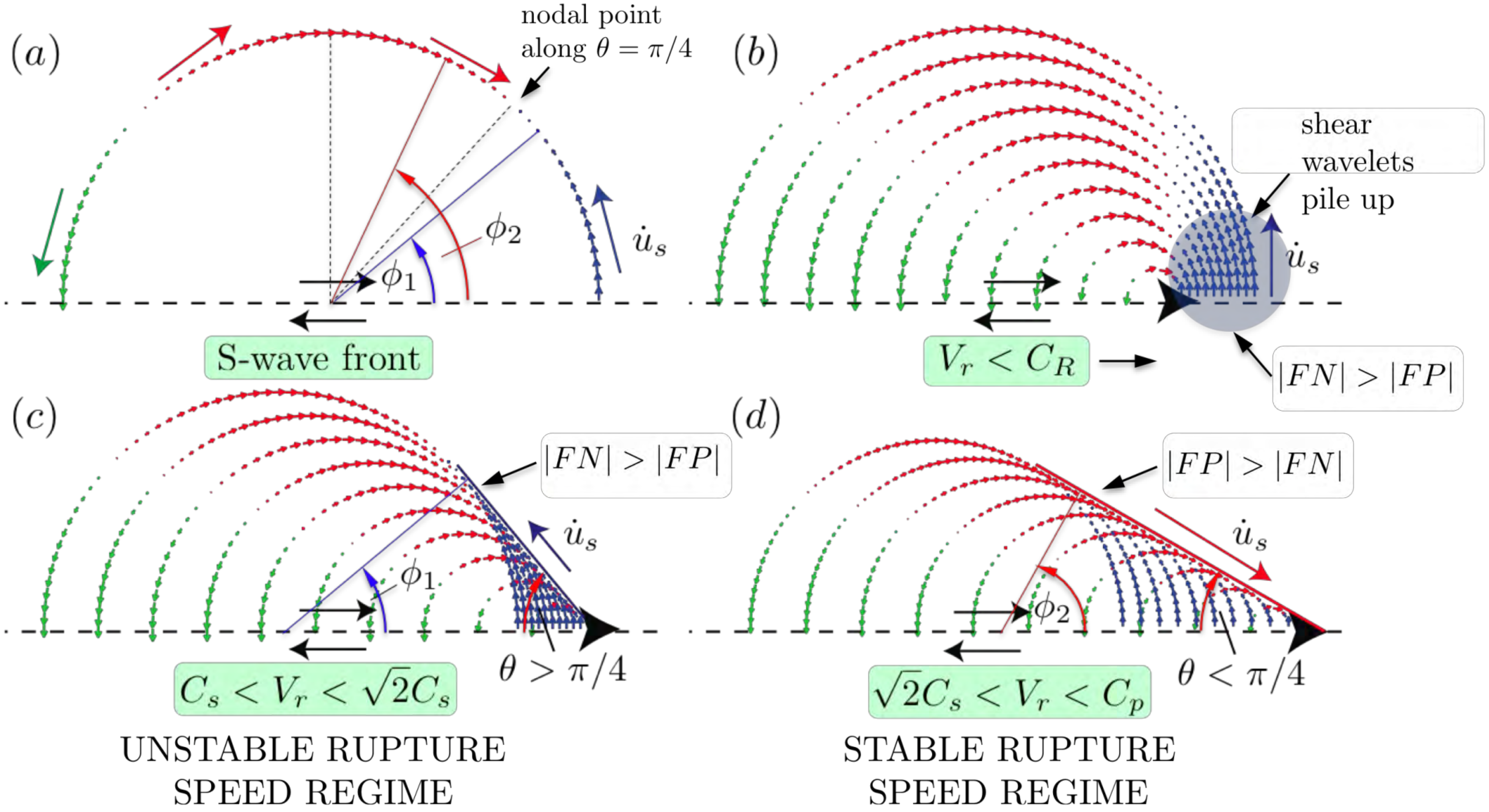
Double-couple in an infinite homogeneous medium

Michael Mello
Caltech

Harsha S. Bhat
INS Paris/ Caltech

Hiroo Kanamori
Seismo -Lab Caltech





Mello, Rosakis, Bhat and Kanamori, Tectonophysics, 2010 and JMPS 2016

Some defining particle velocity signatures as the shear Mach front passes by: (These results hold irrespective of friction law)

- Characteristic soln.... $z_s = x + \beta_s y = C \Rightarrow \quad \tan\theta = |-1/\beta_s| = \frac{1}{\sqrt{V_r^2/C_s^2 - 1}}$
- characteristic lines define Mach fronts: $\theta = \sin^{-1}(C_s/V_r)$
- in the far-field:

$$\delta \dot{u}_x^s \approx \frac{1}{2} sgn(y) \frac{\beta_s^2 - 1}{\beta_s^2 + 1} \Delta \dot{u}_x(z_s)$$

$$\delta \dot{u}_y^s \approx -\frac{1}{2\beta_s} \frac{\beta_s^2 - 1}{\beta_s^2 + 1} \Delta \dot{u}_x(z_s)$$

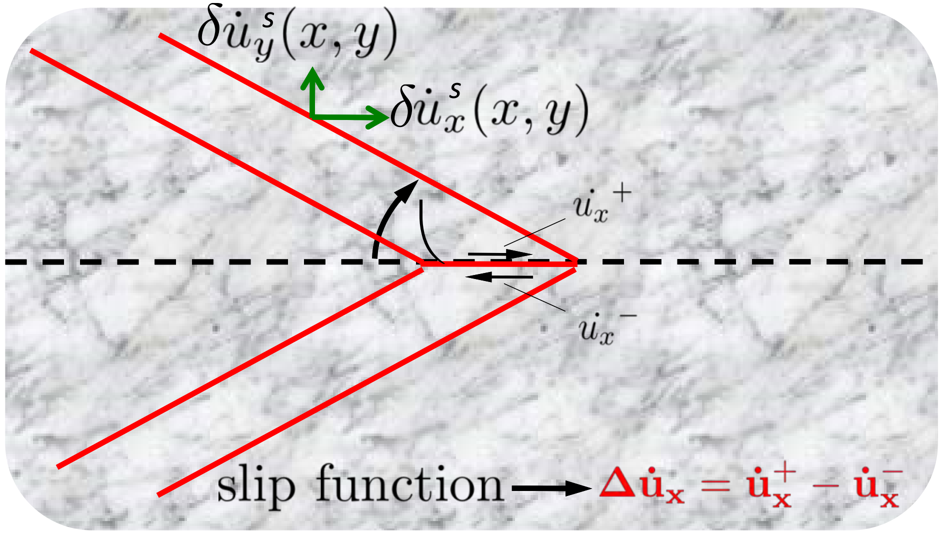
$$\beta_s = \sqrt{\frac{V_r^2}{C_s^2} - 1}$$

Slip function is propagated out along characteristics (Mach fronts)

- along a Mach front:

$$\left| \frac{\delta \dot{u}_x^s}{\delta \dot{u}_y^s} \right| = \beta_s = \cot\theta = \sqrt{\frac{V_r^2}{C_s^2} - 1}$$

Relation dictates which velocity Component is dominant along the Mach front (It depends on Vr/Cs)



Mello, Rosakis, Bhat and Kanamori, Tectonophysics,2010 and JMPS 2016

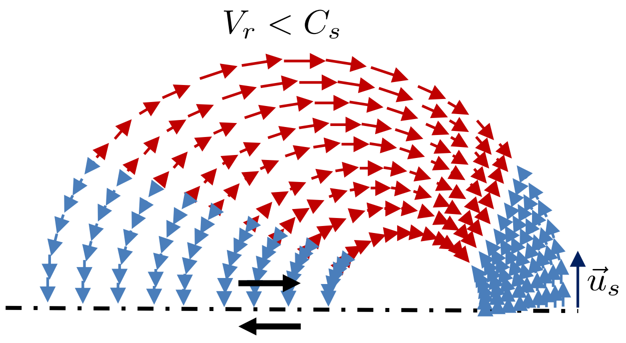
Stable , supershear ruptures: Velocity jumps along the FP direction greater than those along the FN direction

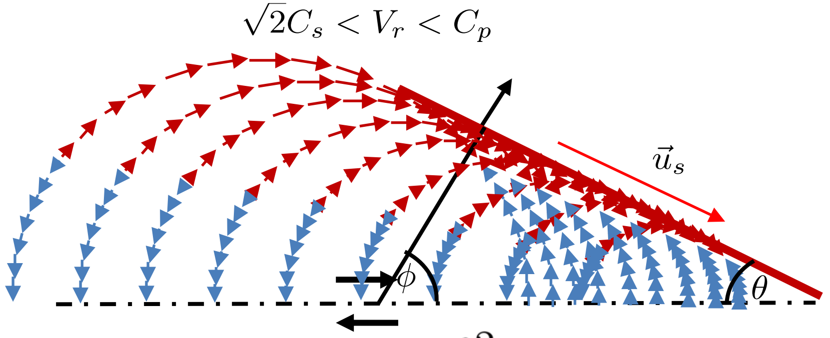
Early numerics agrees with experimental and theoretical analysis

Aagaard and Heaton (2004)

Dunham and Archuleta (2005); Bhat et al., (2007) ;Dunham and Bhat(2008); Mello, Rosakis, Bhat and Kanamori , 2010, 2014 and 2016

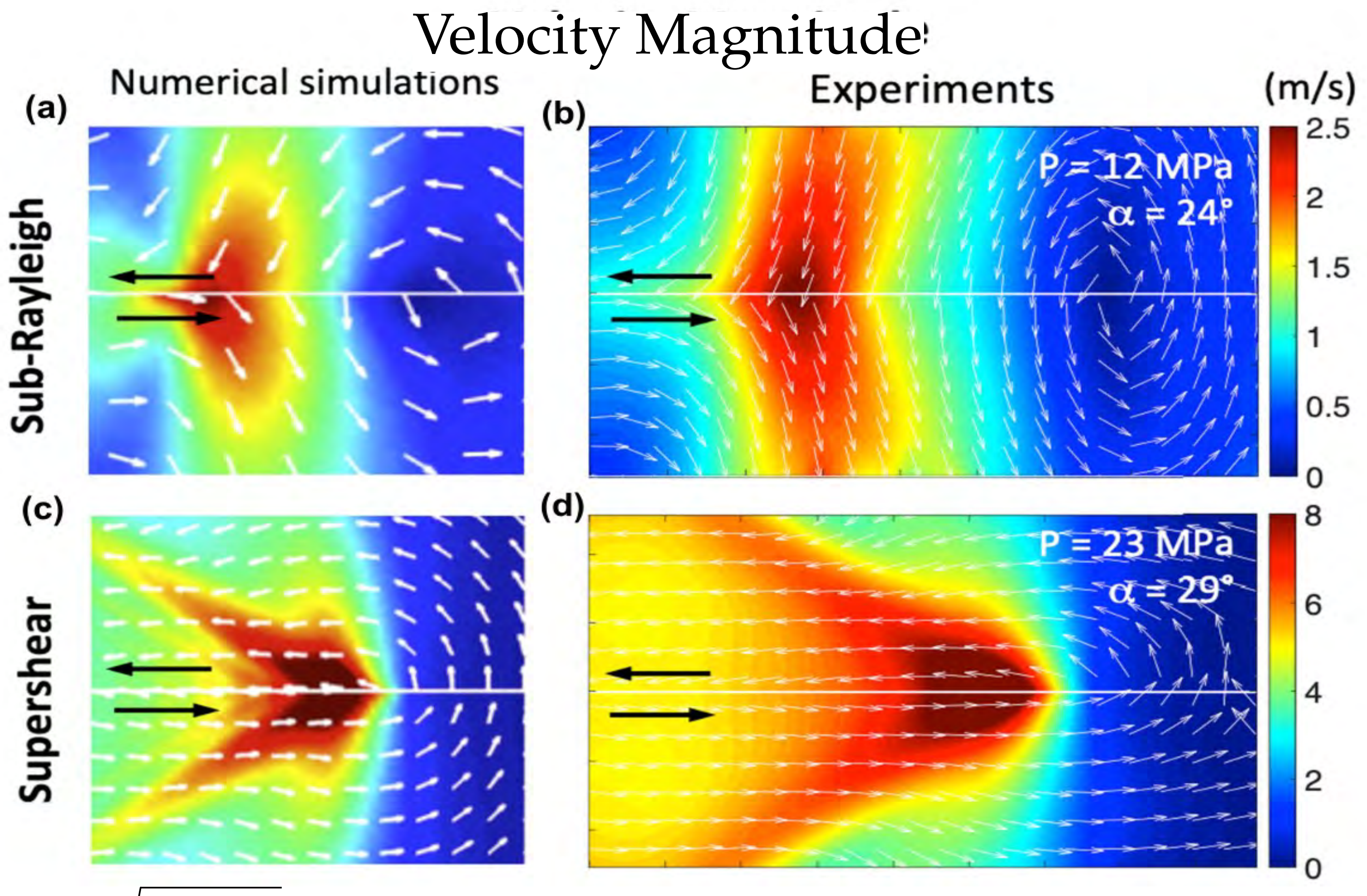
Geometrical Interpretation





$$\delta \dot{u}_x^s \approx \frac{1}{2} sgn(y) \frac{\beta_s^2 - 1}{\beta_s^2 + 1} \Delta \dot{u}_x(z_s)$$

$$\delta \dot{u}_y^s \approx -\frac{1}{2\beta_s} \frac{\beta_s^2 - 1}{\beta_s^2 + 1} \Delta \dot{u}_x(z_s)$$



$$\beta_s = \sqrt{\frac{V_r^2}{C_s^2} - 1}$$

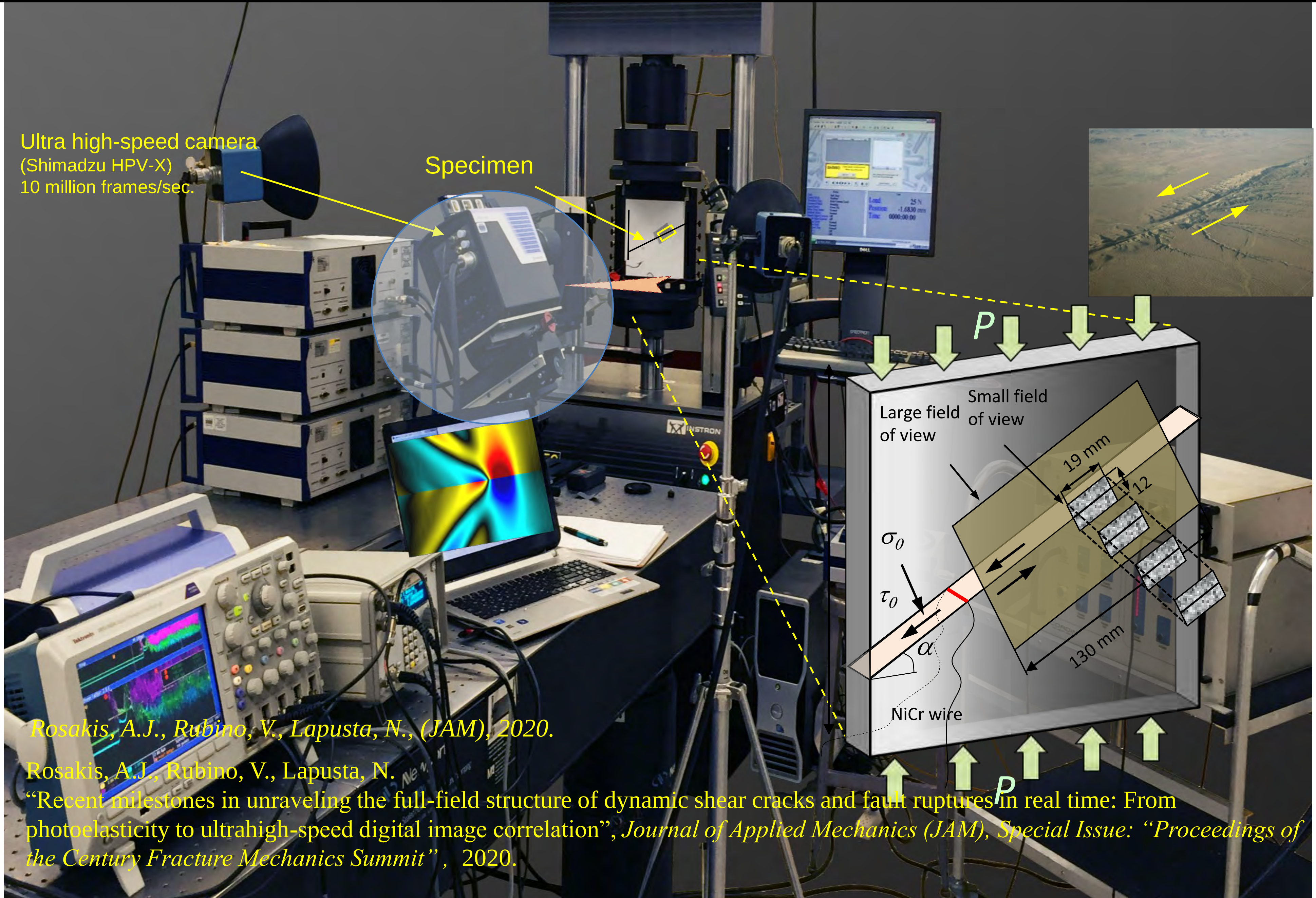
Rubino, Rosakis and Lapusta 2019 JGR:SE

Recent version of the Laboratory earthquake setup

featuring ultra high-speed digital image correlation (DIC) diagnostics

Nadia Lapusta
MCE/GPS
Caltech

Vito Rubino
École Centrale
de Nantes/Caltech

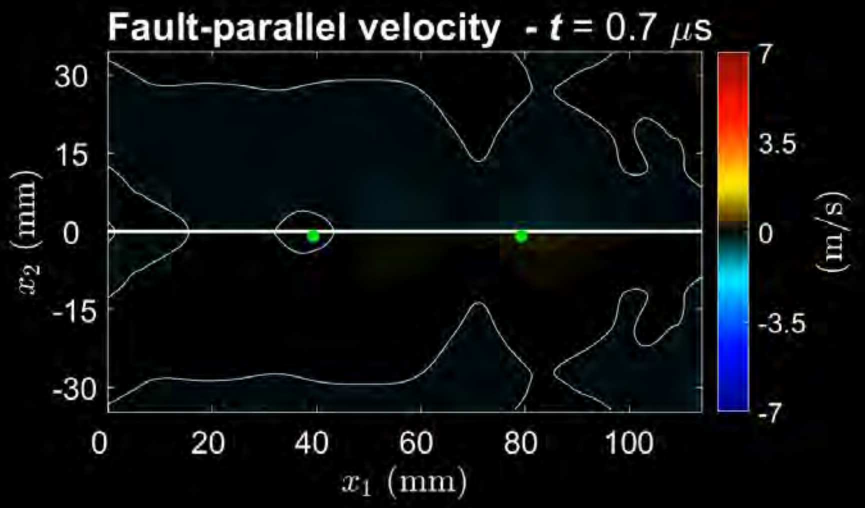


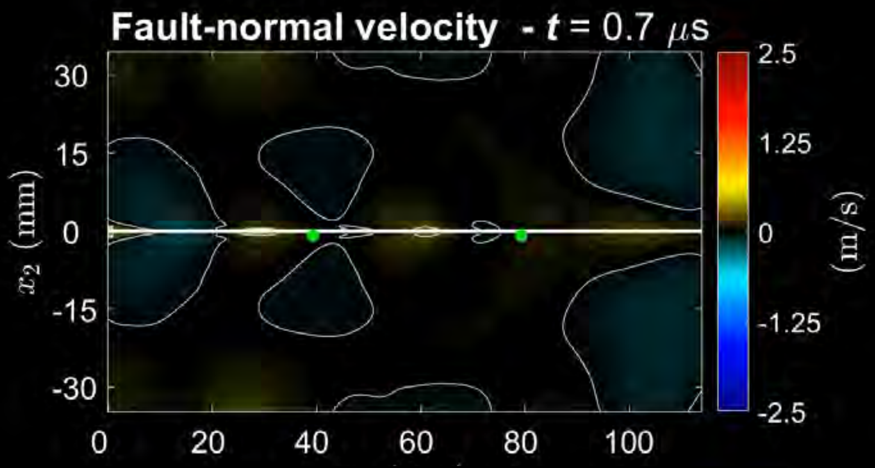
Rosakis, A.J., Rubino, V., Lapusta, N., (JAM), 2020.

Rosakis, A.J., Rubino, V., Lapusta, N.
"Recent milestones in unraveling the full-field structure of dynamic shear cracks and fault ruptures in real time: From photoelasticity to ultrahigh-speed digital image correlation", *Journal of Applied Mechanics (JAM), Special Issue: "Proceedings of the Century Fracture Mechanics Summit"* , 2020.

CAN WE EXPERIMENTALLY CAPTURE WITH DIC THE SIGNATURE OF JUST A TRANSITIONING SUPERSHEAR?

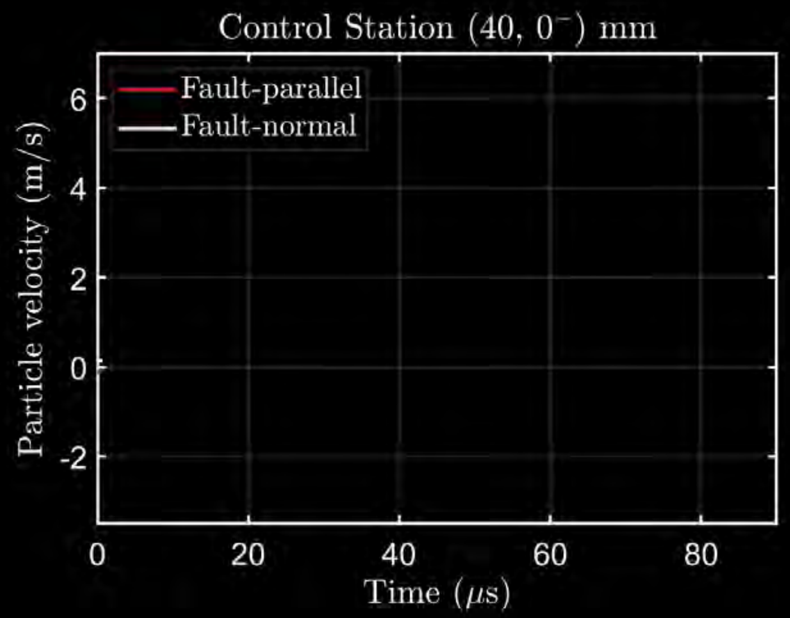
Rosakis, A.J., Rubino, V., Lapusta, N. *(JAM)*, 2020.



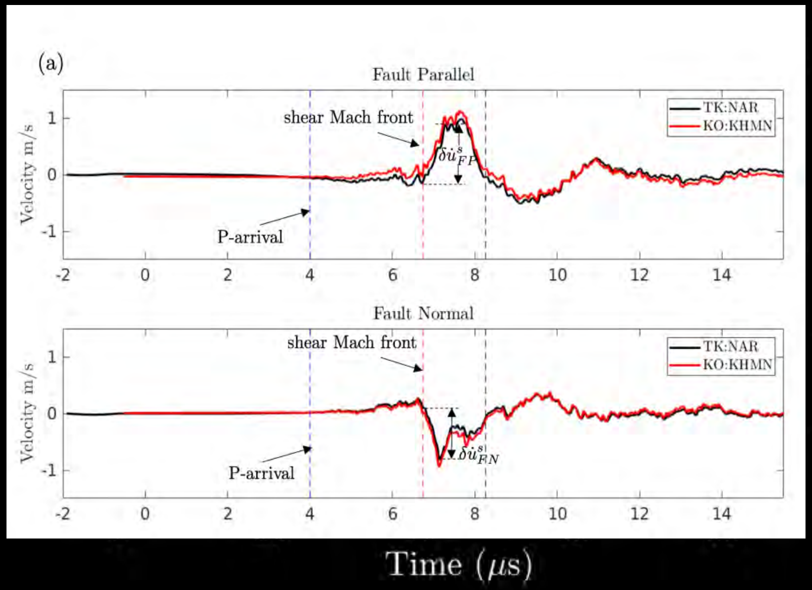


Attilio Lattanzi
Caltech

DIGITAL IMAGE CORELATION

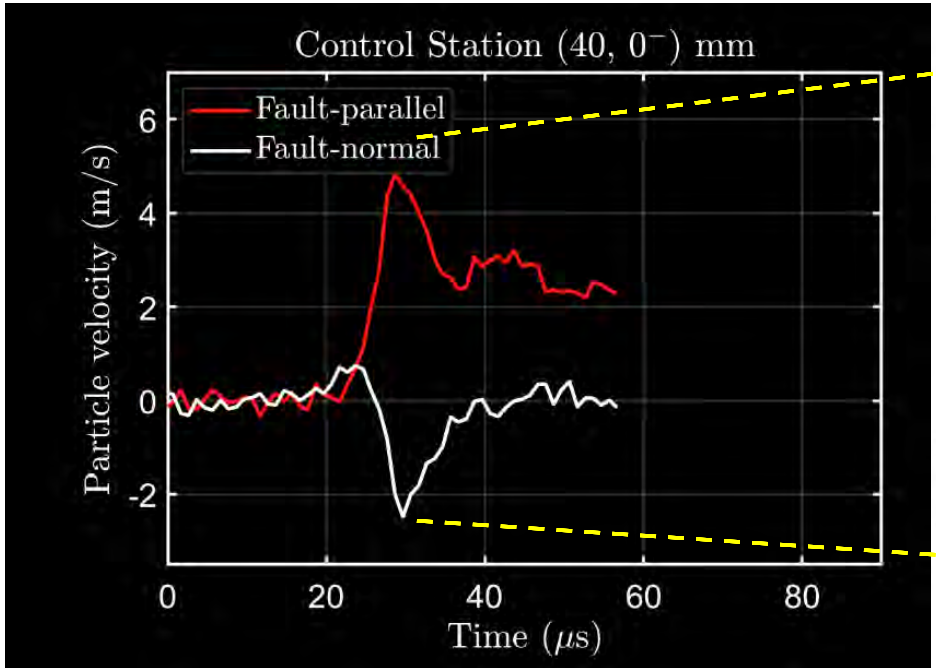


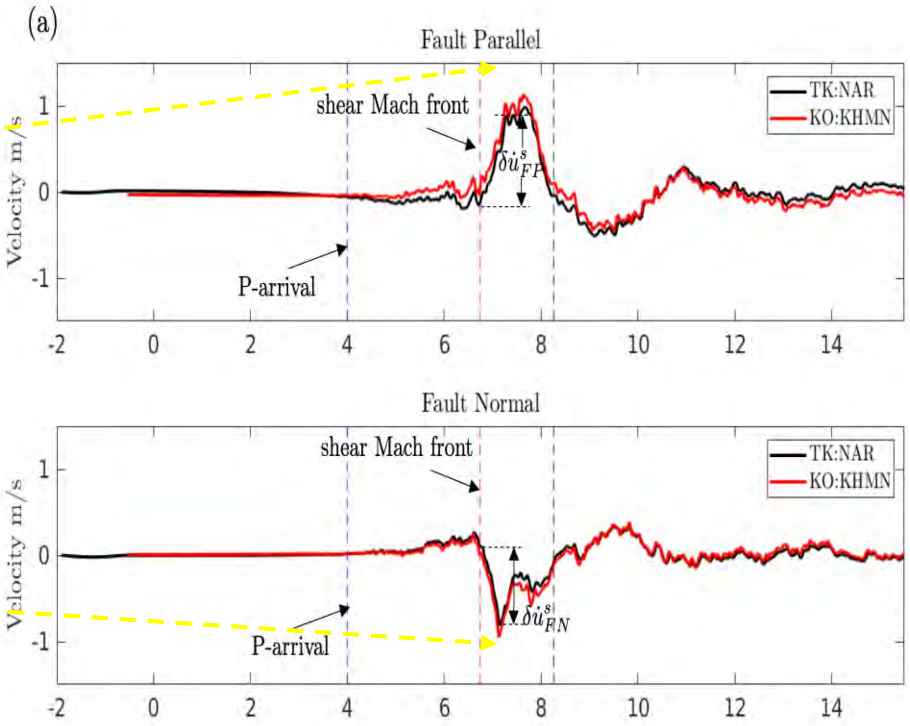
SEISMOMETER



Twin stations (TK:NAR) : Two different stations at almost the same geographical location (30 meters apart) show *characteristic signature of super-shear rupture: FP greater than FN jumps.*

Rosakis, A.J., Rubino, V., Lapusta, N., (JAM), 2020.





Lab Experiment (DIC)

Twin Seismometers

Theory & Experiments: Mello, Rosakis , Bhat and Kanamori, Tectonophysics, 2010 and JMPS 2016.
Numerics &Theory: *Aagaard and Heaton (2004); Dunham and Archuleta (2005) Bhat et al., (2007), Dunham and Bhat, (2008).*

Near fault Twin Stations: The existence of two almost identical recordings from two different instruments 30m apart is fortuitous and provides confidence in the accuracy of recorded motions

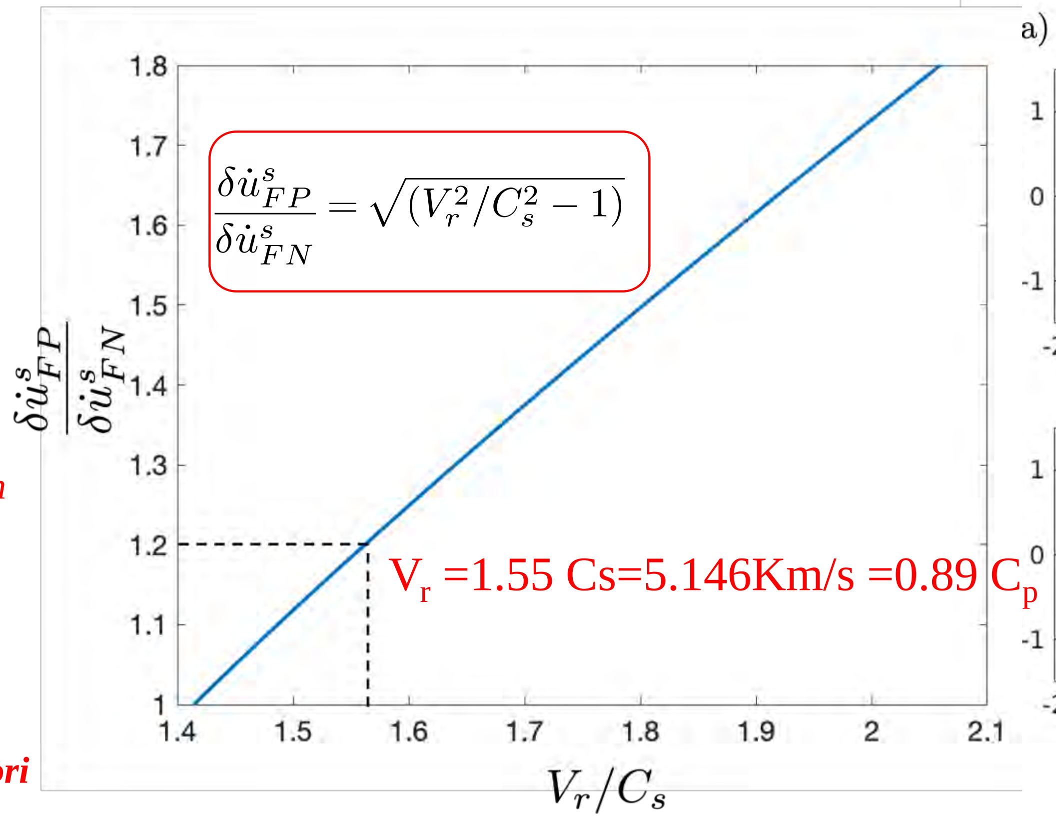
Near fault Twin Stations: Unusual velocity signatures reveal super-shear and enable rupture speed and transition length calculation

Michael Mello
Caltech

Harsha S. Bhat
INS Paris/ Caltech

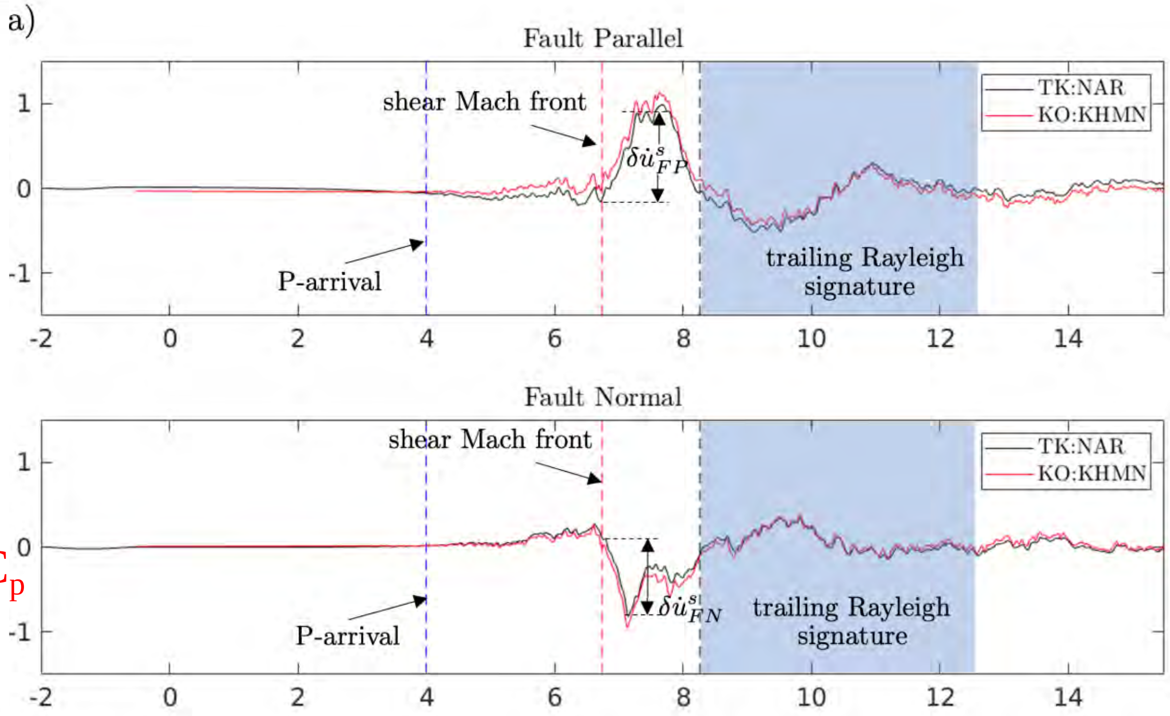
Hiroo Kanamori
Seismo -Lab
Caltech

Theory/Experiment



Field Measurement

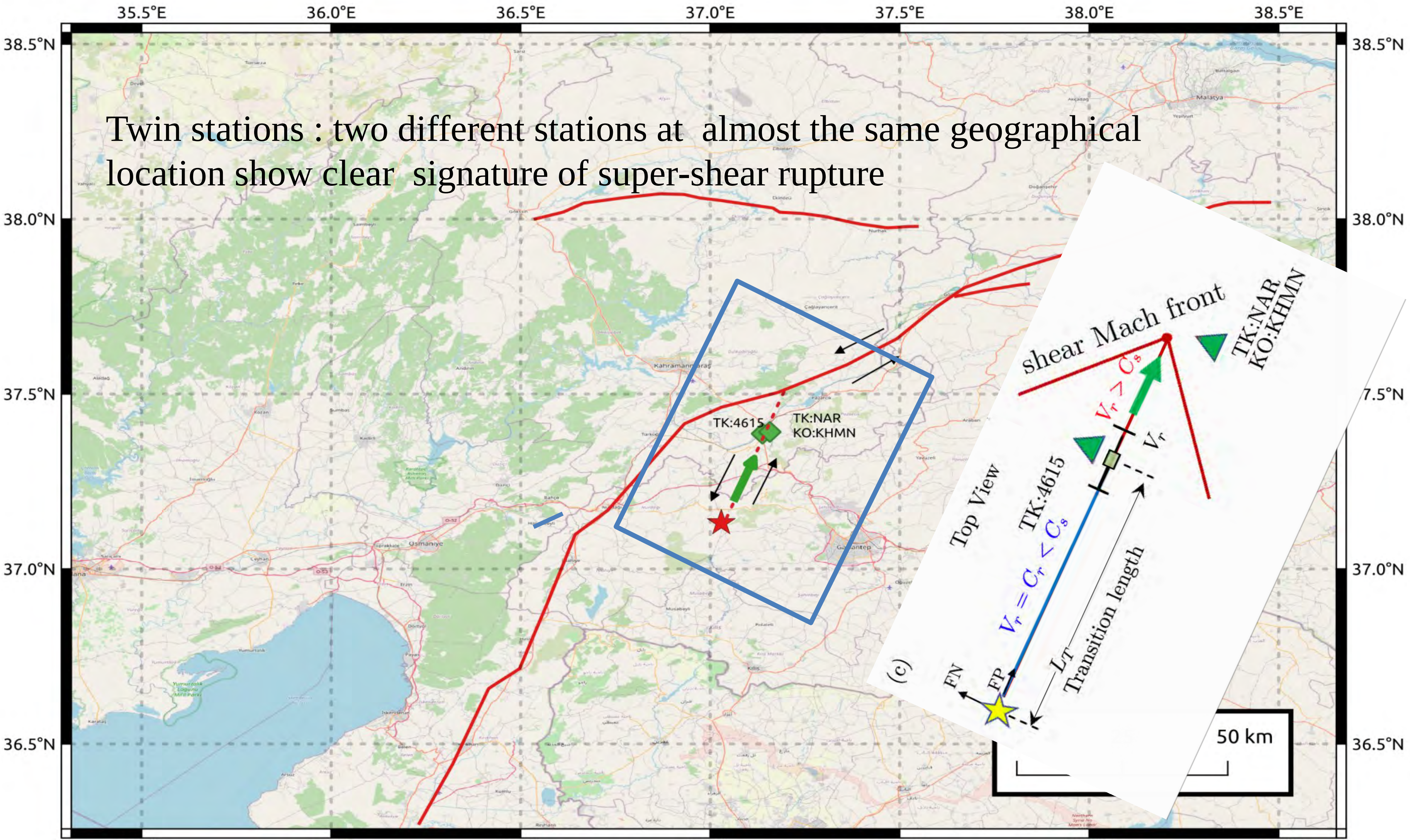
C_s = 3320m/s and C_p =5780m/s



After transition, The speed of the rupture is estimated from ground motion record to be 1.55 Cs=5.146 km/s , based on *Mello, Rosakis , Bhat and Kanamori, Tectonophysics,2010 and JMPS 2016.*

On-ramp on to the main Fault Highway : Early Super-shear Rupture Transition at the small “Narli” fault provides EAF a triggering mechanism ensuring propagation after the junction

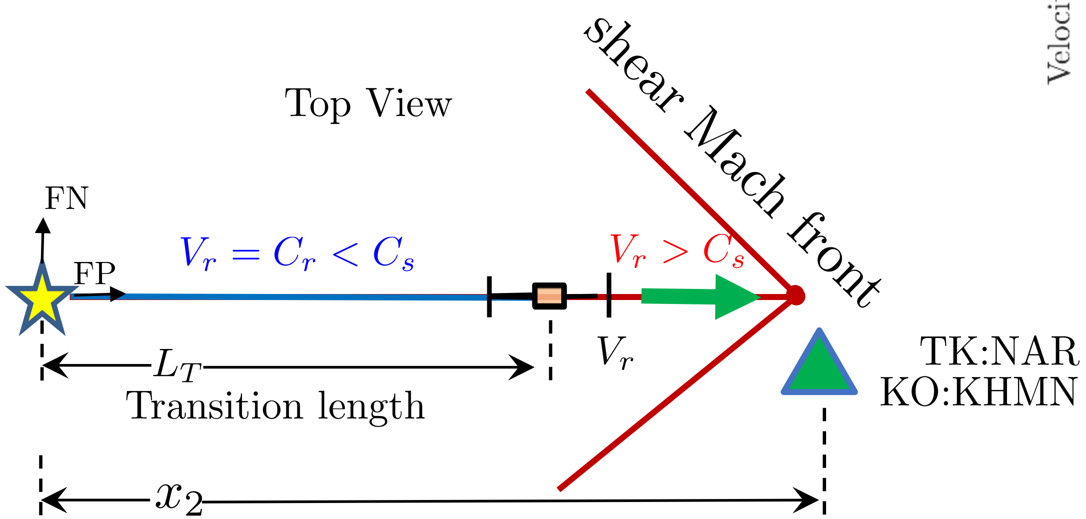
Evidence of Early Supershear Transition in the Mw 7.8 Kahramanmaraş Earthquake From Near-Field Records
A. Rosakis, M Abdelmeguid, A Elbanna , EarthArXiv preprint, Feb. 2023 doi: 10.31223/X5W95G.

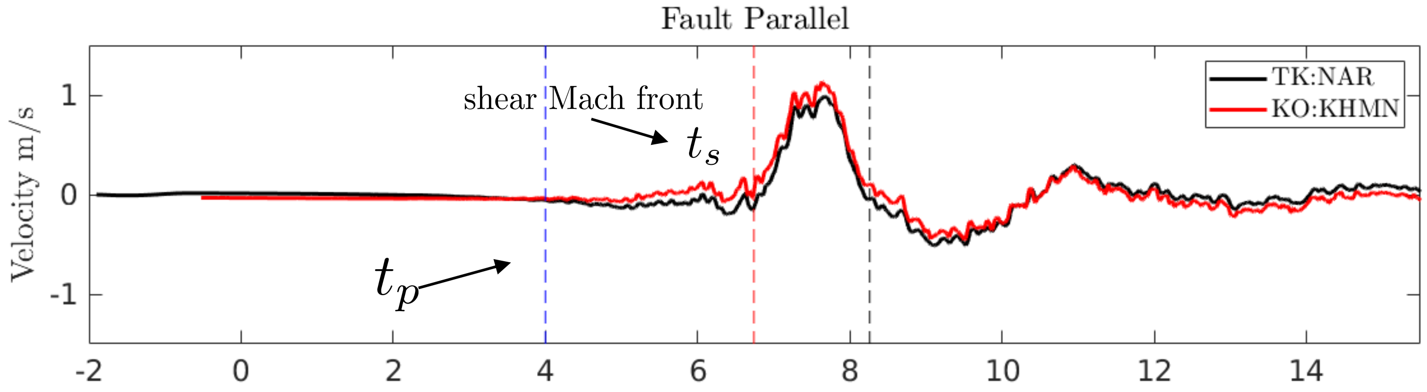


Near fault Twin Stations: Unusual velocity signatures reveal super-shear and enable rupture speed and transition length calculation

Mello, Rosakis , Bhat and Kanamori , Earth & Plan Sc. 2014

t_s : Arrival time of the shear Mach cone to the station





$$t_s = \frac{C_r}{L_T} + \frac{V_r}{(x_2 - L_T)}$$

$$L_T = C_r \frac{x_2 - V_r t_s}{C_r - V_r}$$

x_2 =21km/s V_r =1.55 Cs=5.146Km/s =0.89 C_p

With a known x_2 we compute the transition length $L_T = $ 19.5 km. This estimated transition length is very close to the location of another station TK:4615

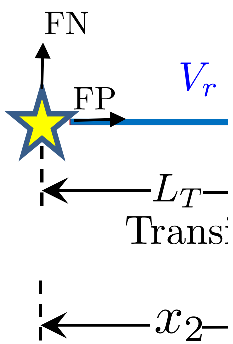
C_s = 3320m/s and C_p =5780m/s

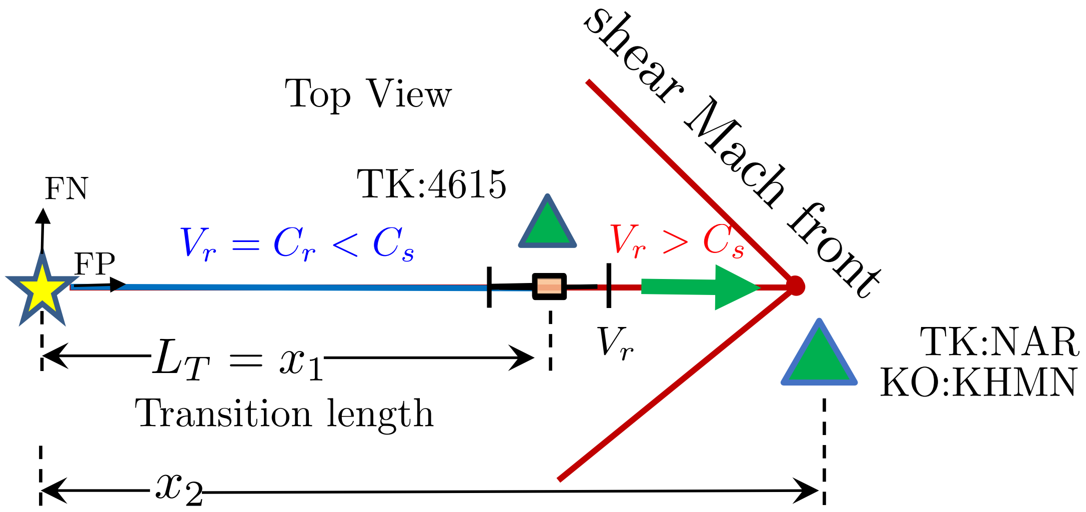
C_r = 3050 m/s

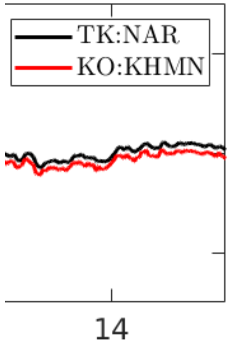
A. Rosakis, M Abdelmeguid, A Elbanna *EarthArXiv preprint, 2023 doi:* 10.31223/X5W95G

Near fault Twin Stations: Unusual velocity signatures reveal super-shear and enable rupture speed and transition length calculation

$$L_T = x_1$$







L_T = 19.5 km.

$\Delta x = x_2 - x_1 = 1.6$Km

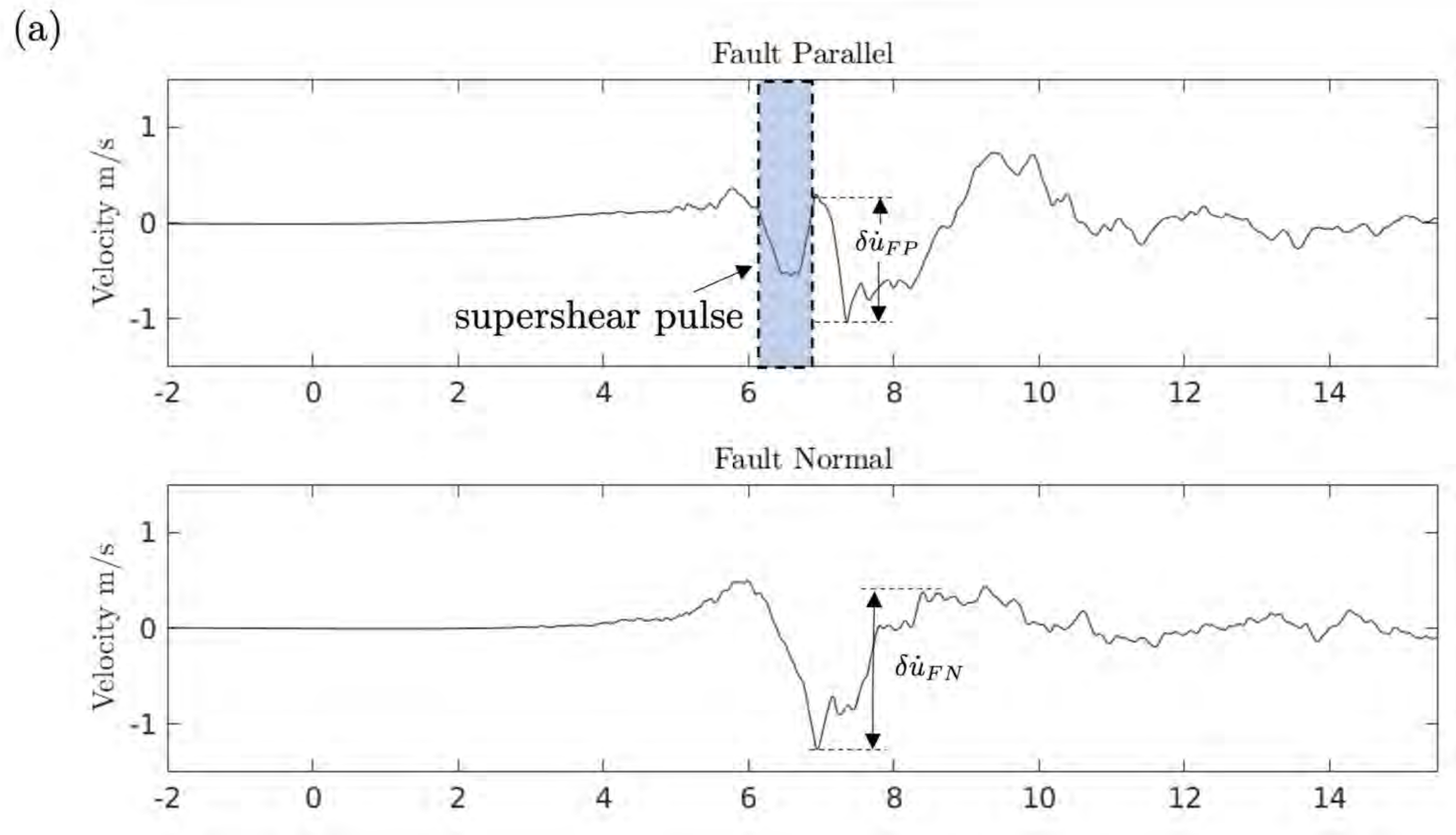
19.5 km.

n of

C_s = 3320m/s and C_p =5780m/s

Third near field station: First recording from a field instrument to ever capture the birth of a super-shear pulse

Through the independent analysis of the transition length, we show that the station TK:4165 is located at the transition point and we do indeed observe the birth of small super-shear pulse forming just ahead of the trailing Rayleigh



THIS IS LUCK!!

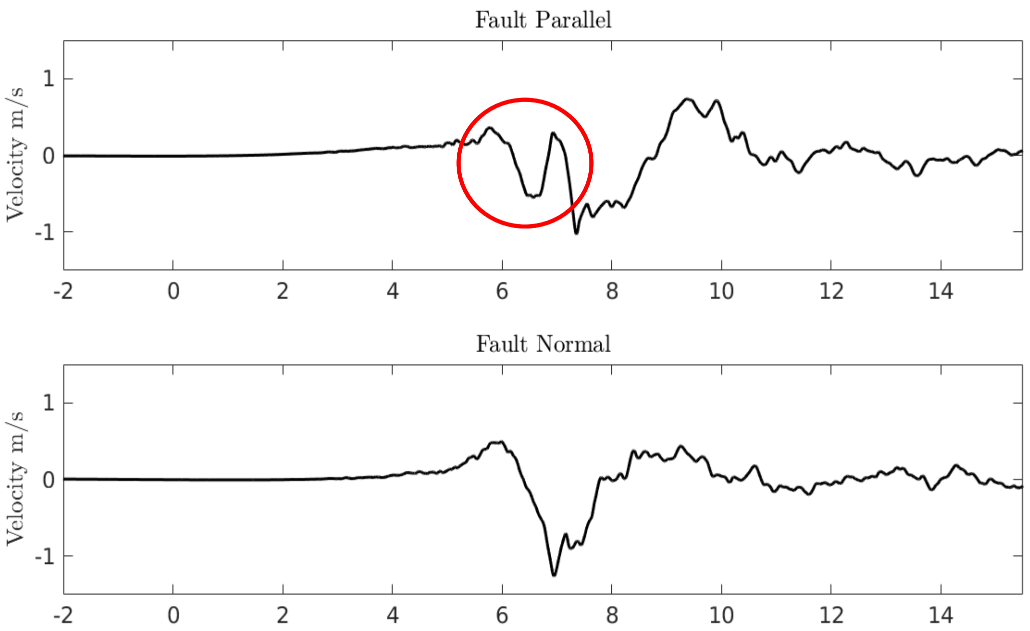
Evidence of Early Supershear Transition in the Mw 7.8 Kahramanmaraş Earthquake From Near-Field Records
A. Rosakis, M Abdelmeguid, A Elbanna , EarthArXiv preprint, Feb. 2023 doi: 10.31223/X5W95G.

Summary of NARLI Conclusions

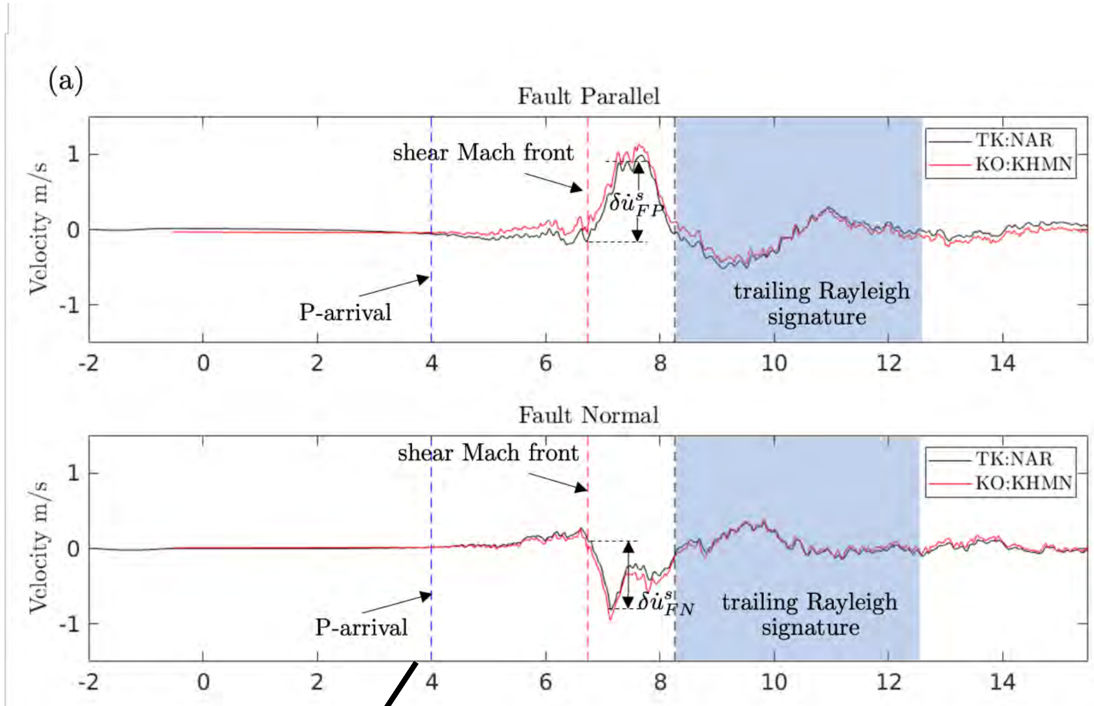
Evidence of Early Supershear Transition in the Mw 7.8 Kahramanmaraş Earthquake From Near-Field Records
A. Rosakis, M Abdelmeguid, A Elbanna , EarthArXiv preprint, Feb 14th 2023 doi: 10.31223/X5W95G

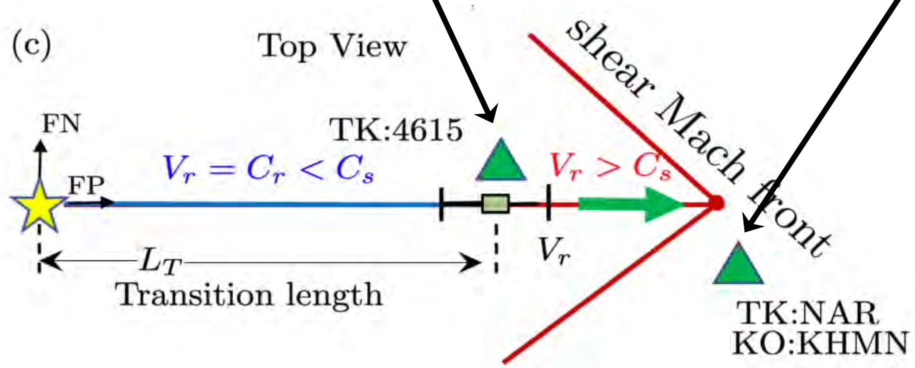
Station TK:4615

Earliest record of the event



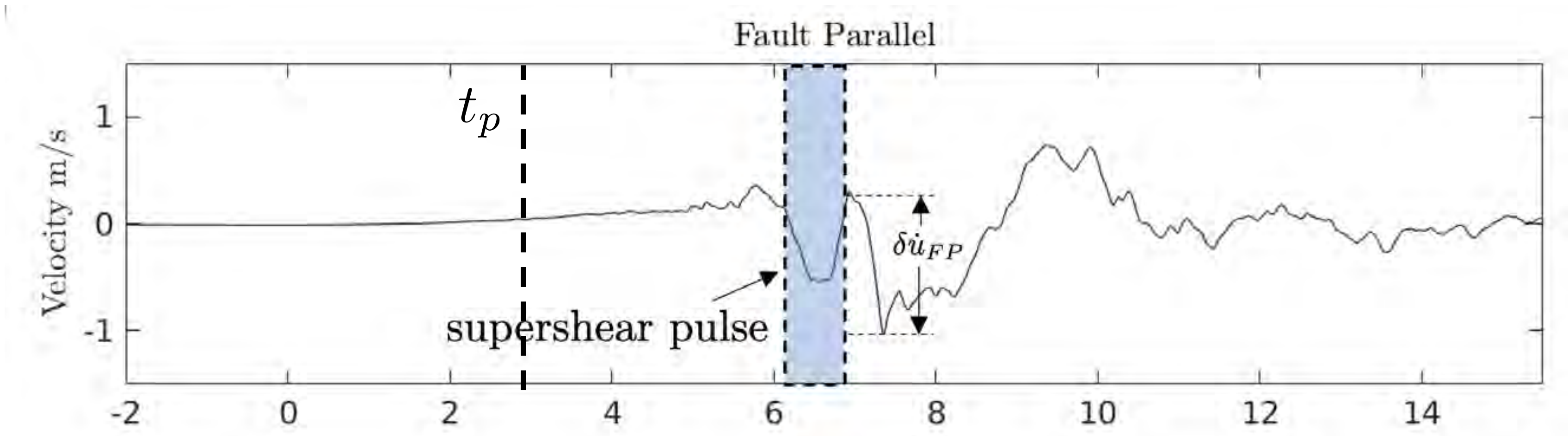
Twin Station TK:NAR

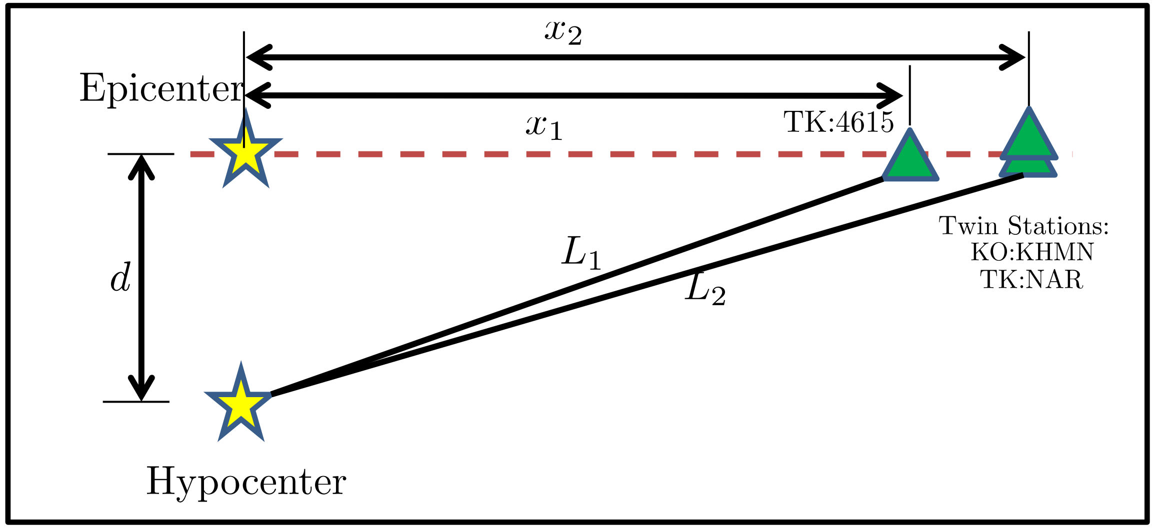




Distance between stations:
$\Delta x = x_2 - x_1 = 1.6$Km

Can mechanics inform Seismology by estimating hypocentral depth?





$\Delta x = x_2 - x_1 = 1.6$Km

$$L_T = x_1$$

$$d = \sqrt{L_1^2 - x_1^2} = \sqrt{L_1^2 - L_T^2}$$

$$L_1 = t_p C_p$$

With some uncertainty due to P-wave arrival time and C_p ,we can estimate the depth entirely by setting the location of the TK:4615 to be at the transition length.

$$d \approx 10.9 \text{ km}$$

Can mechanics inform Seismology by estimating hypocentral depth?

Evidence of Early Supershear Transition in the Mw 7.8 Kahramanmaraş Earthquake From Near-Field Records
A. Rosakis, M Abdelmeguid, A Elbanna, EarthArXiv preprint, Feb 14th 2023, doi: 10.31223/X5W95G "under review" in Nature Geoscience

Original depth estimate 02/13

Contributed by US 2 last updated 2023-02-13 05:09:58 (UTC)

✓ The data below are the most preferred data available
✓ The data below have been reviewed by a scientist

Details Phases Magnitudes

Magnitude uncertainty	7.8 mww ± 0.1
Location uncertainty	37.166°N 37.042°E ± 6.3 km
Depth uncertainty	17.9 km ± 3.3

Updated depth estimate 02/19

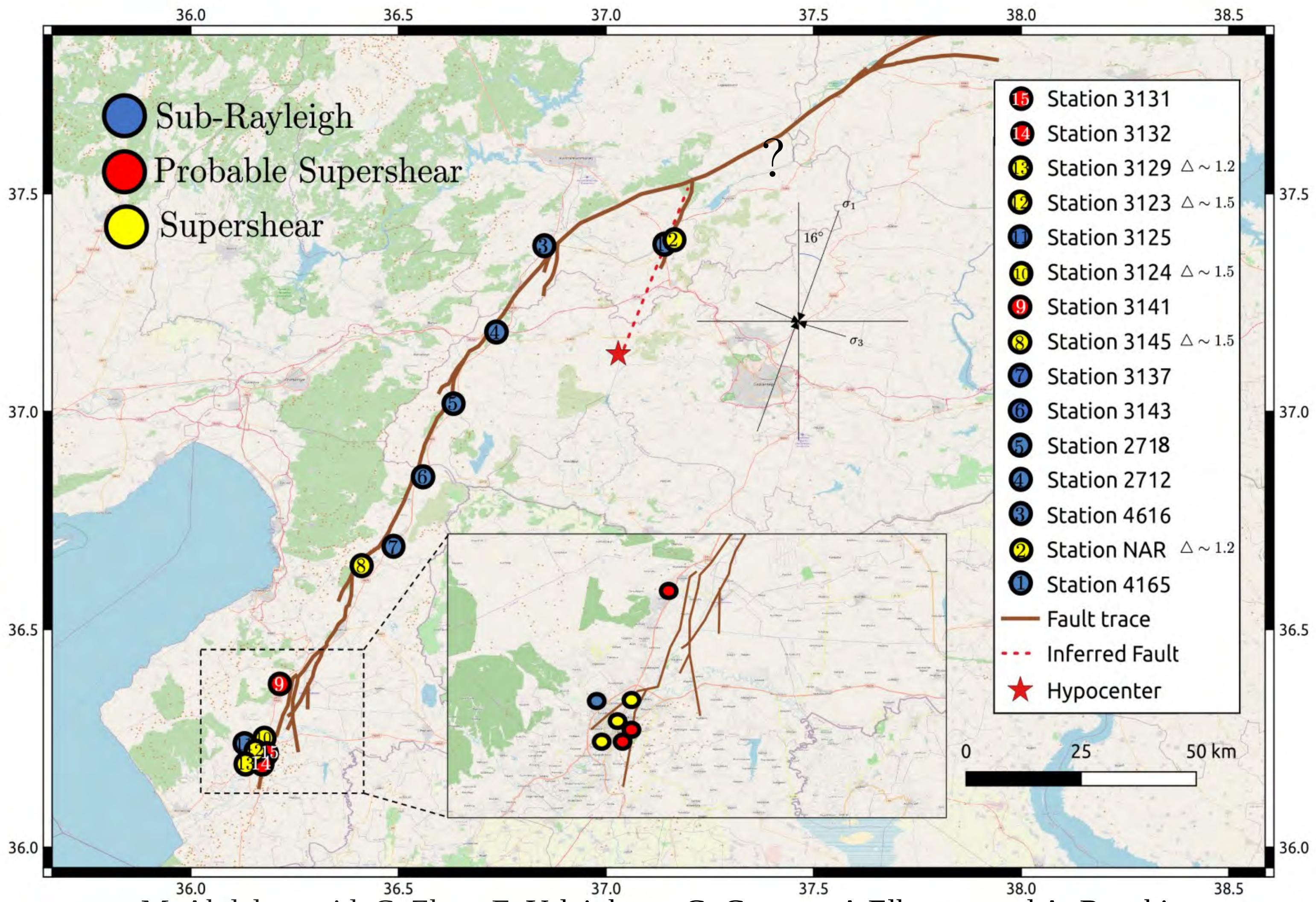
Contributed by US 2 last updated 2023-02-19 06:04:32 (UTC)

✓ The data below are the most preferred data available
✓ The data below have been reviewed by a scientist

Details Phases Magnitudes

Magnitude uncertainty	7.8 mww ± 0.1
Location uncertainty	37.225°N 37.021°E ± 5.2 km
Depth uncertainty	10.0 km ± 1.8

We analyze the bigger picture by using a similar methodology to Narli, but for all near-fault records along EAF. Here we offer a complementary , fracture mechanics-based, approach to inversions

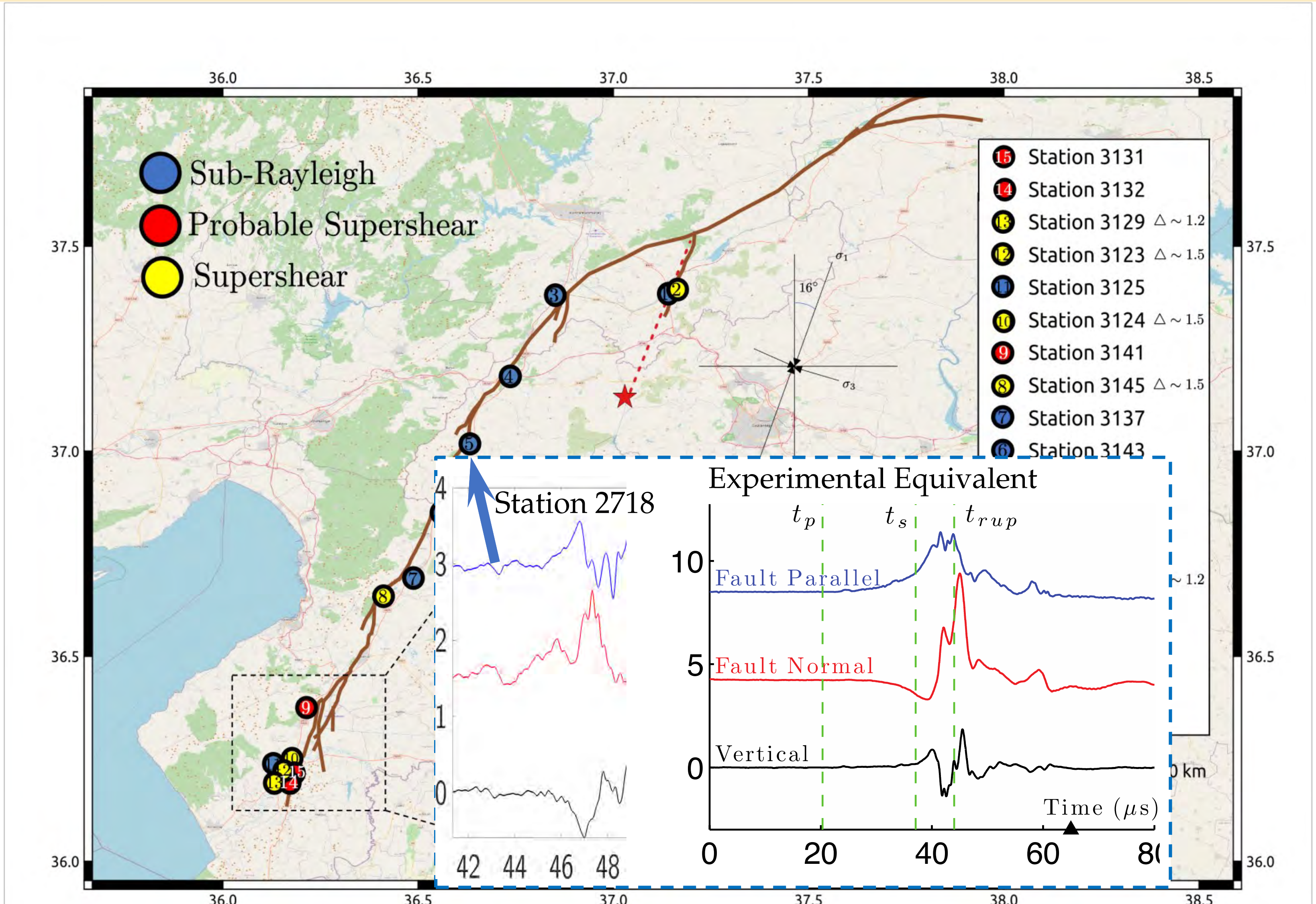


M. Abdelmeguid, C. Zhao, E. Yalcinkaya, G. Gazetas, A Elbanna, and A. Rosakis,

Dynamics of episodic supershear in the 2023 M7.8 Kahramanmaraş/Pazarcik earthquake, revealed by near-field records and computational modeling.

EarthArXiv preprint Feb 2023 doi:https://doi.org/10.31223/X5066R , *Commun Earth Environ* **4**, 456 (Dec. 2023) https://doi.org/10.1038/s43247-023-01131-7

The bigger picture:
Similar methodology for the whole earthquake

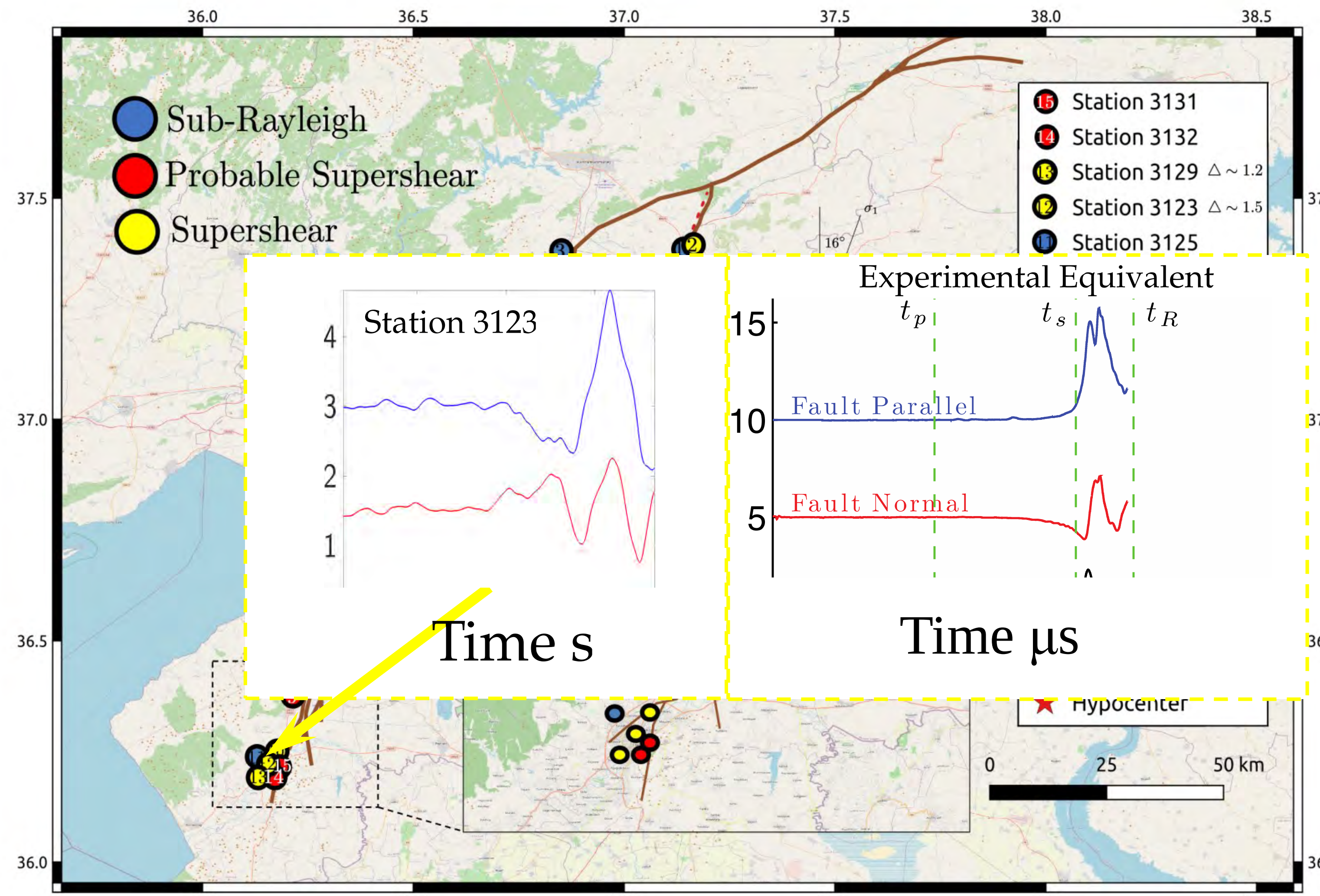


Ground velocity signatures from experiments simulating the 2002, M_W 7.9, Denali Earthquake: Mello, Rosakis ,Bhat and Kanamori, Earth & Plan Sc. 2014

The bigger picture:
Similar methodology for the whole earthquake

Early Personal communication by G. Gazetas who cites unusual ground motion records:
"Notice in particular $(PGV_{FP}) = 1.9\ (PGV_{FN})$ in station 3129 in Antakya, where the city was truly devastated."

Also see: E. Garini and G. Gazetas (2023). **The two earthquakes of Februrary 6th 2023 in Turkey.** Preliminary Report, NTUA, Greece.

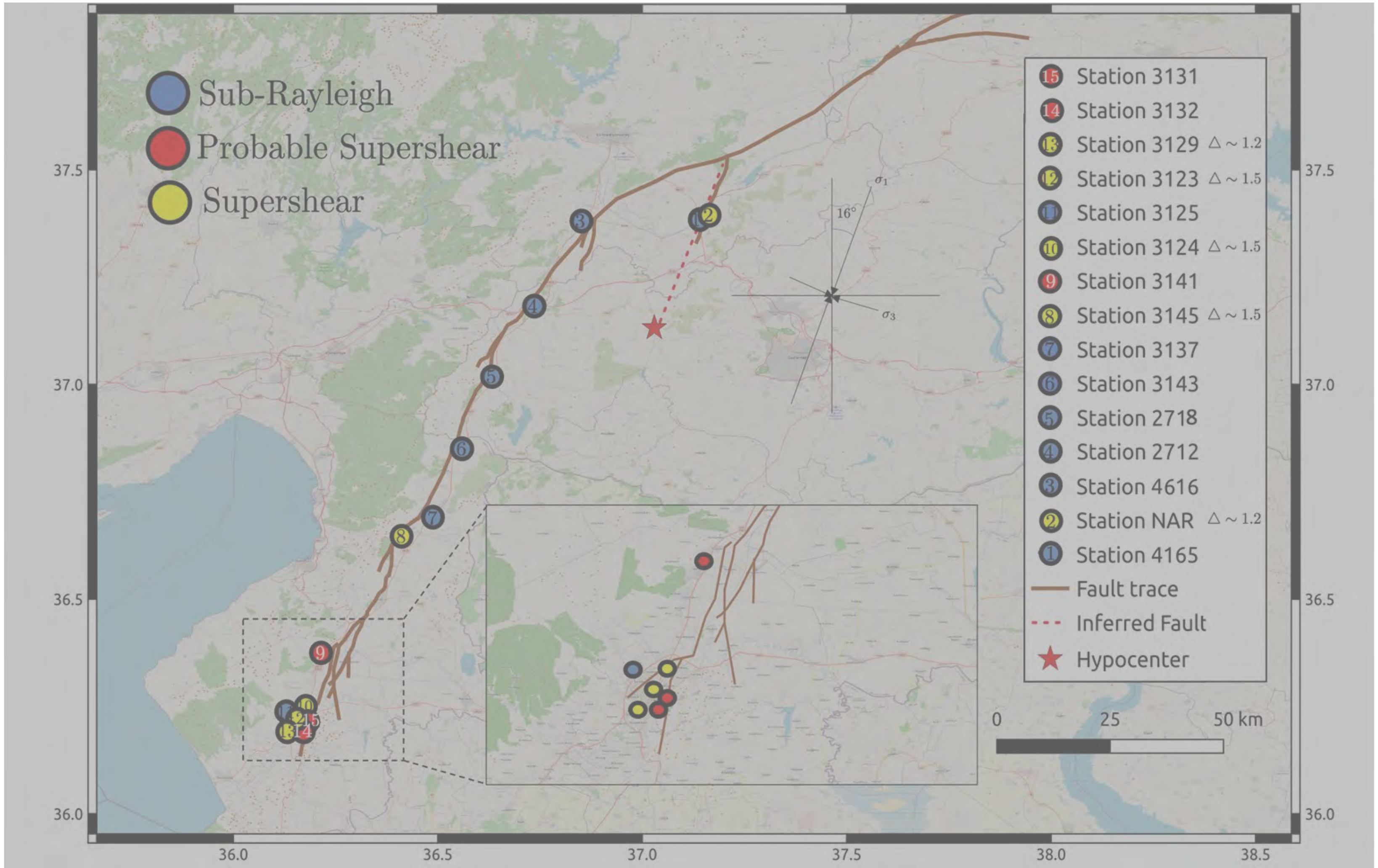


After studying the nucleation mechanism and having constrained the rupture speed at discrete locations, can we fill the rupture history gaps for the entire earthquake?

Can we now use rupture mechanic to reproduce the entire event?

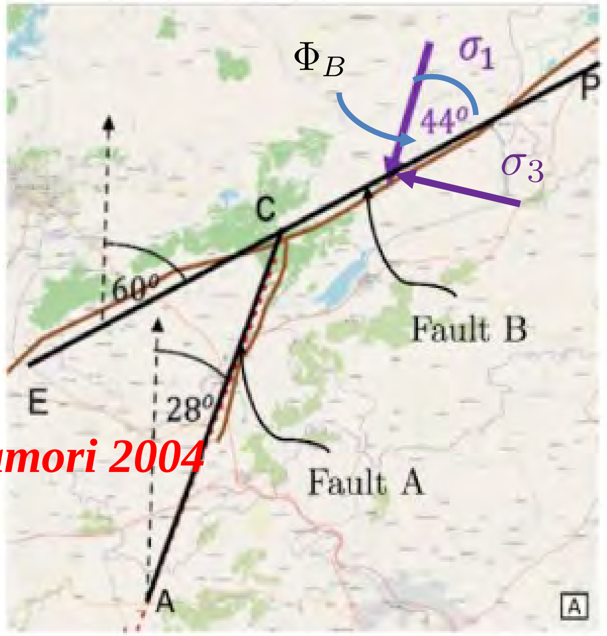
After studying the nucleation mechanism and having constrained the rupture speed at discrete locations, can we fill the rupture history gaps for the entire earthquake?

-To do this we start with the junction-



THE SPLAY FAULT ON-RUMP
CONSTRAINING THE UNKNOWN FRICTION ON THE NARLI

WE CHOOSE THE PARAMETERS OF FRICTION ON THE NARLI TO BE SUCH THAT THE INCOMING RUPTURE TRANSITIONS AT 19,5Km AFTER NUCLEATION AND THEN, PROPAGATE AT 1.55 C_S UNTIL THE JUNCTION.



Acarel, Diğdem, et al. "Seismotectonics of Malatya Fault, Eastern Turkey." Open Geosciences 11.1 (2019): 1098-1111.

Rupture length required for supershear transition.

Theory: Andrews 1985; Experiment: Xia, Rosakis and Kanamori 2004

$$L_T = \mathcal{F}(S) L_c$$

$\mu_s = 0.7$

μ_d , D_c are varied to control S and ultimately L_T while keeping L_c fixed

$$\sigma_1/\sigma_3 = 0.25$$

Linear slip weakening Friction

Where S is the strength parameter:

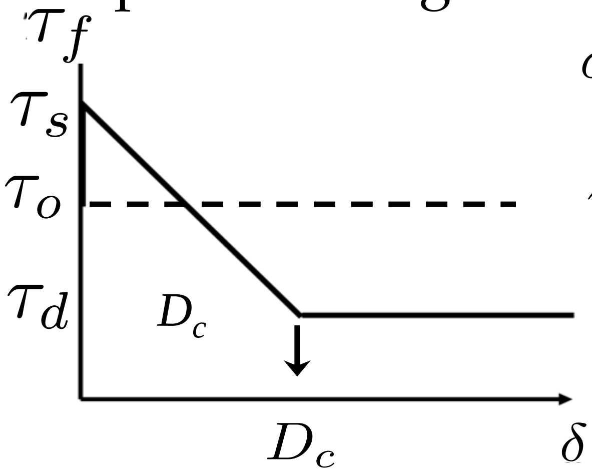
$$S = \frac{\tau_s - \tau_o}{\tau_o - \tau_d}$$

And L_c is the nucleation length:

$$L_c = \mu D_c/(\tau_s - \tau_d)$$

$$\tau_s = \mu_s \sigma_o$$

$$\tau_d = \mu_d \sigma_o$$

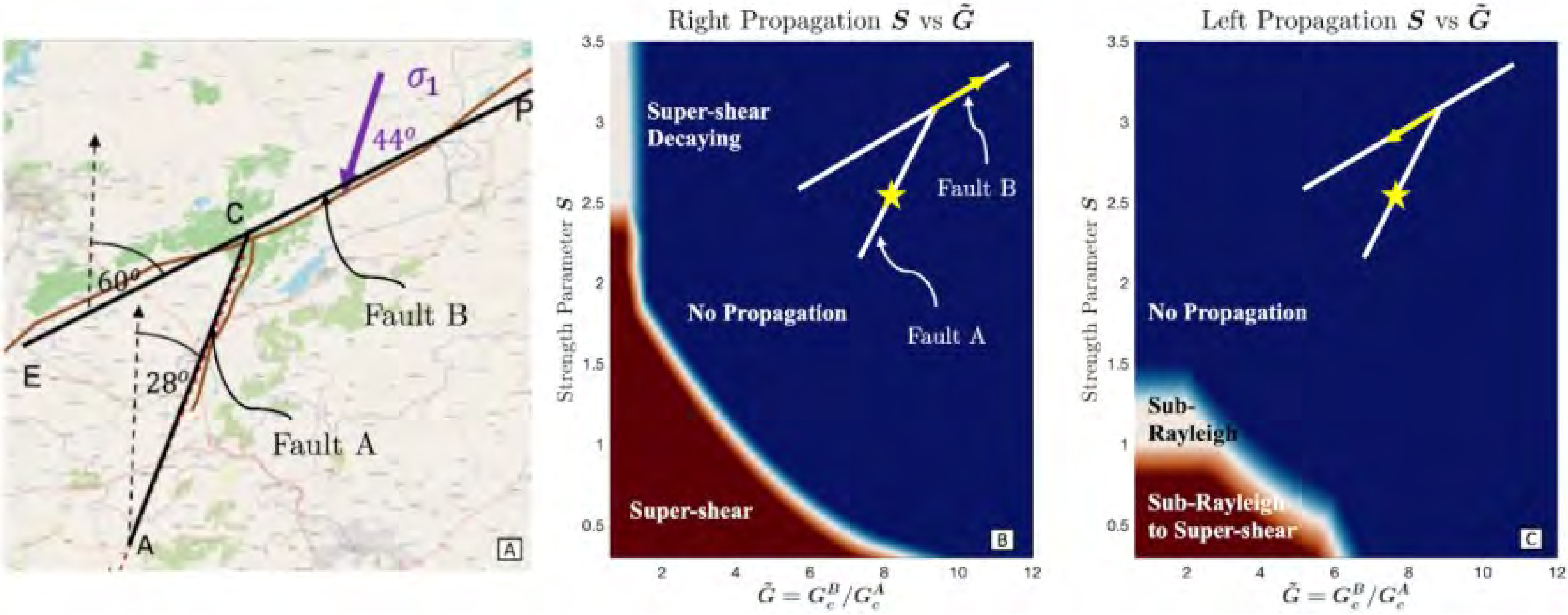


$$\sigma_o = \sigma_1 \sin^2(\Phi) + \sigma_3 \cos^2(\Phi)$$

$$\tau_o = (\sigma_1 - \sigma_3)\sin(\Phi)\cos(\Phi)$$

$$G = \frac{1}{2} D_c(\tau_s - \tau_d)$$

CONSTRAINING THE UNKNOWN FRICTION ON THE EAF

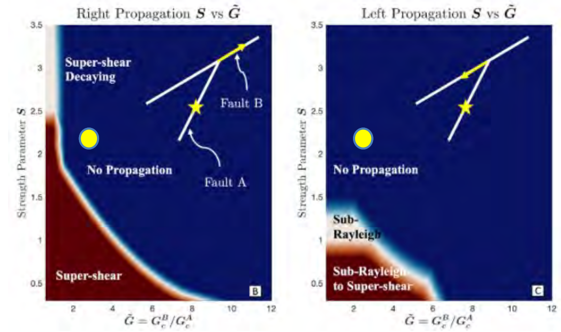


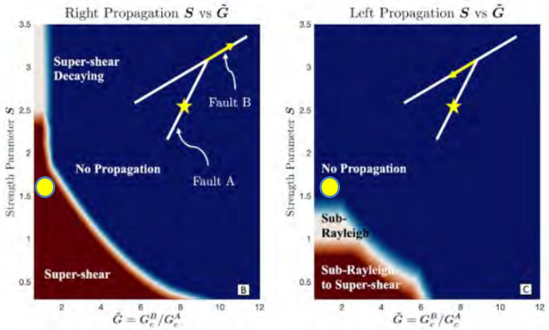
After fixing fault A (Narli Fault), we explore the friction parameter space for fault B (EAF) such that we get bilateral propagation after the junction. ***Approximately 100 simulations are conducted with various frictional parameters.***

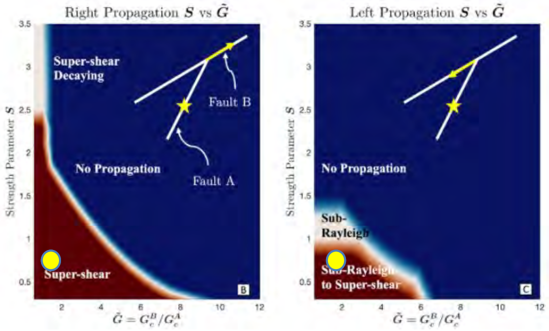
CONSTRAINING THE UNKNOWN FRICTION ON THE EAF:

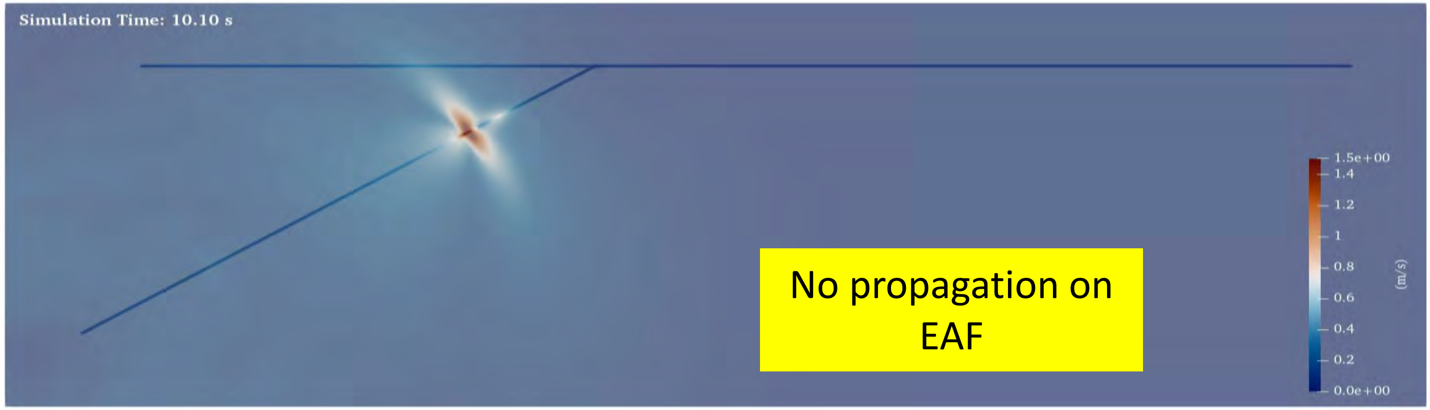
WE CHANGE THE FRICTIONAL PARAMETERS ON THE MATURE EAF AND RUN SIMULATIONS OF THE TRANSITION. WE CHOOSE THE PARAMETERS RESULTING IN BILATERAL GROWTH AND AGREEING WITH RECORDED ARRIVAL TIMES

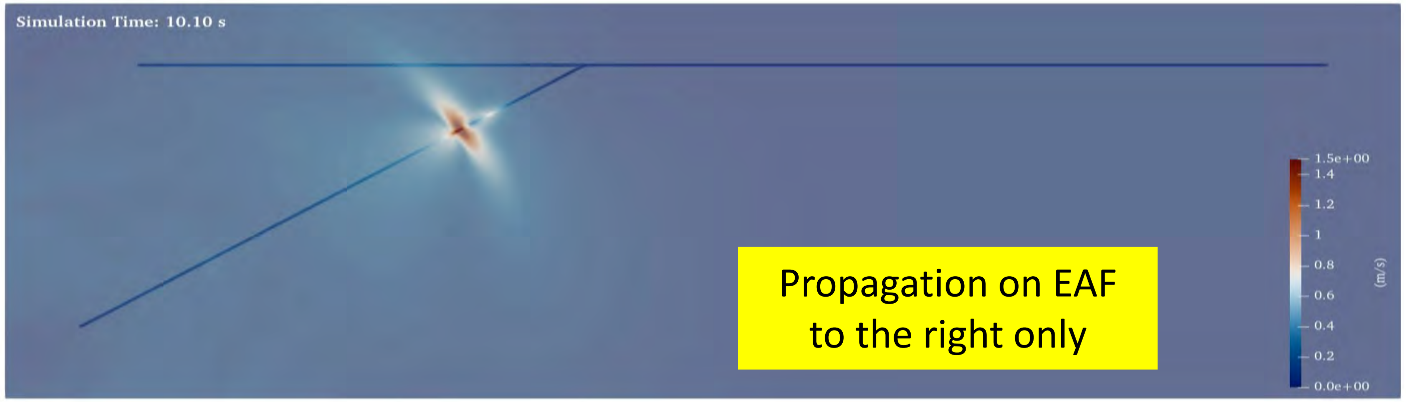
μ_s, μ_d, D_c are varied to control S and G while keeping L_c fixed

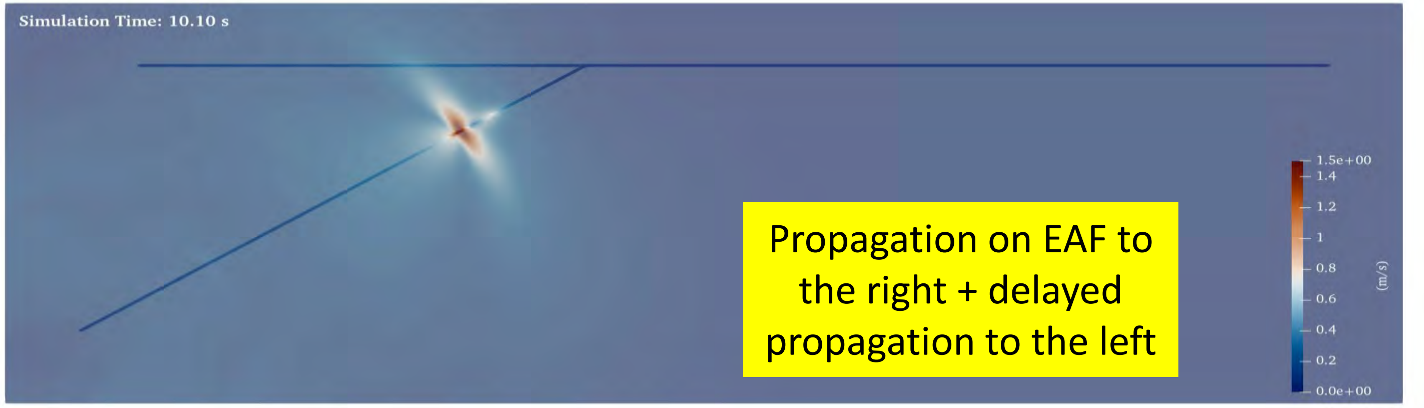




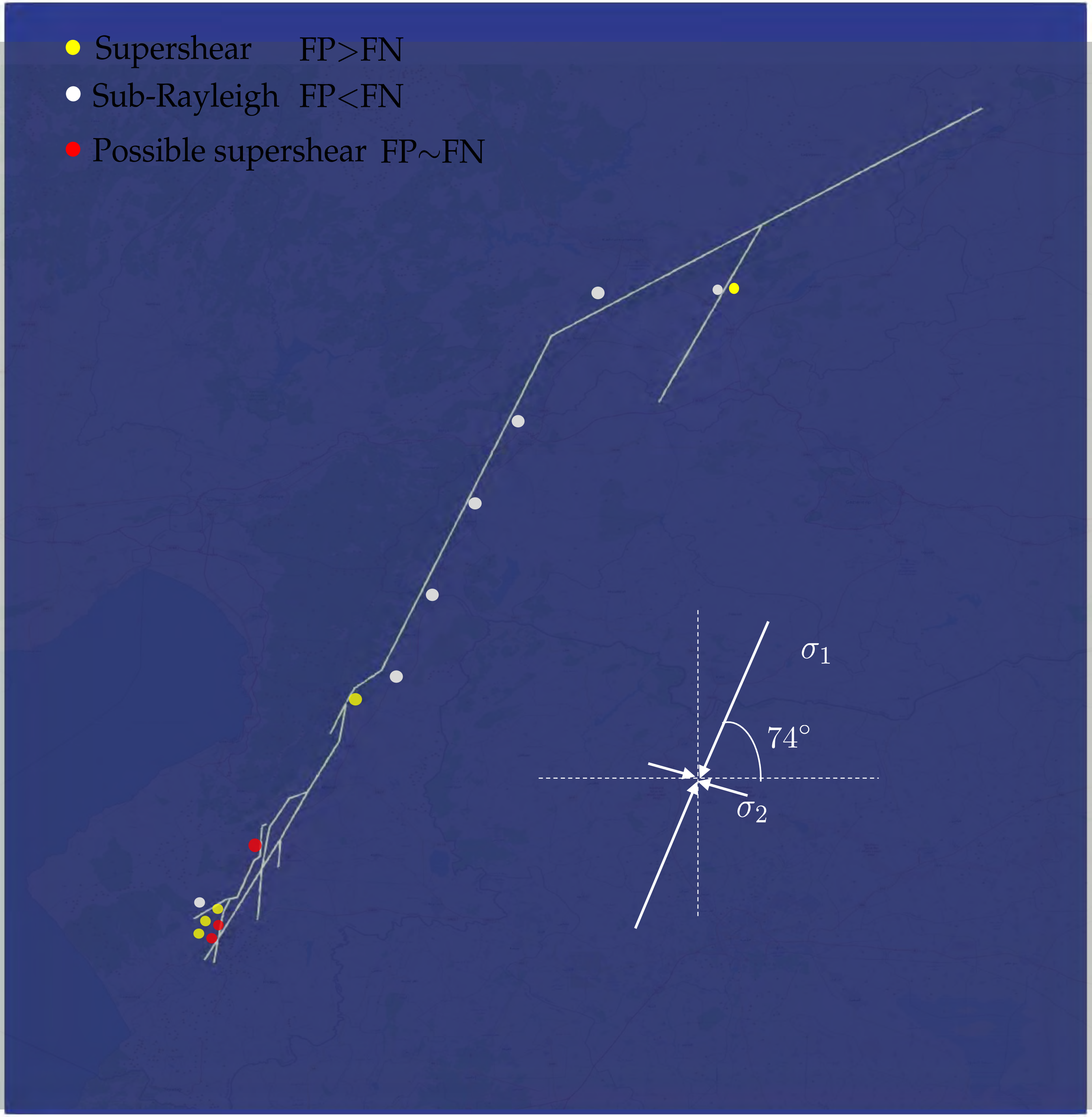


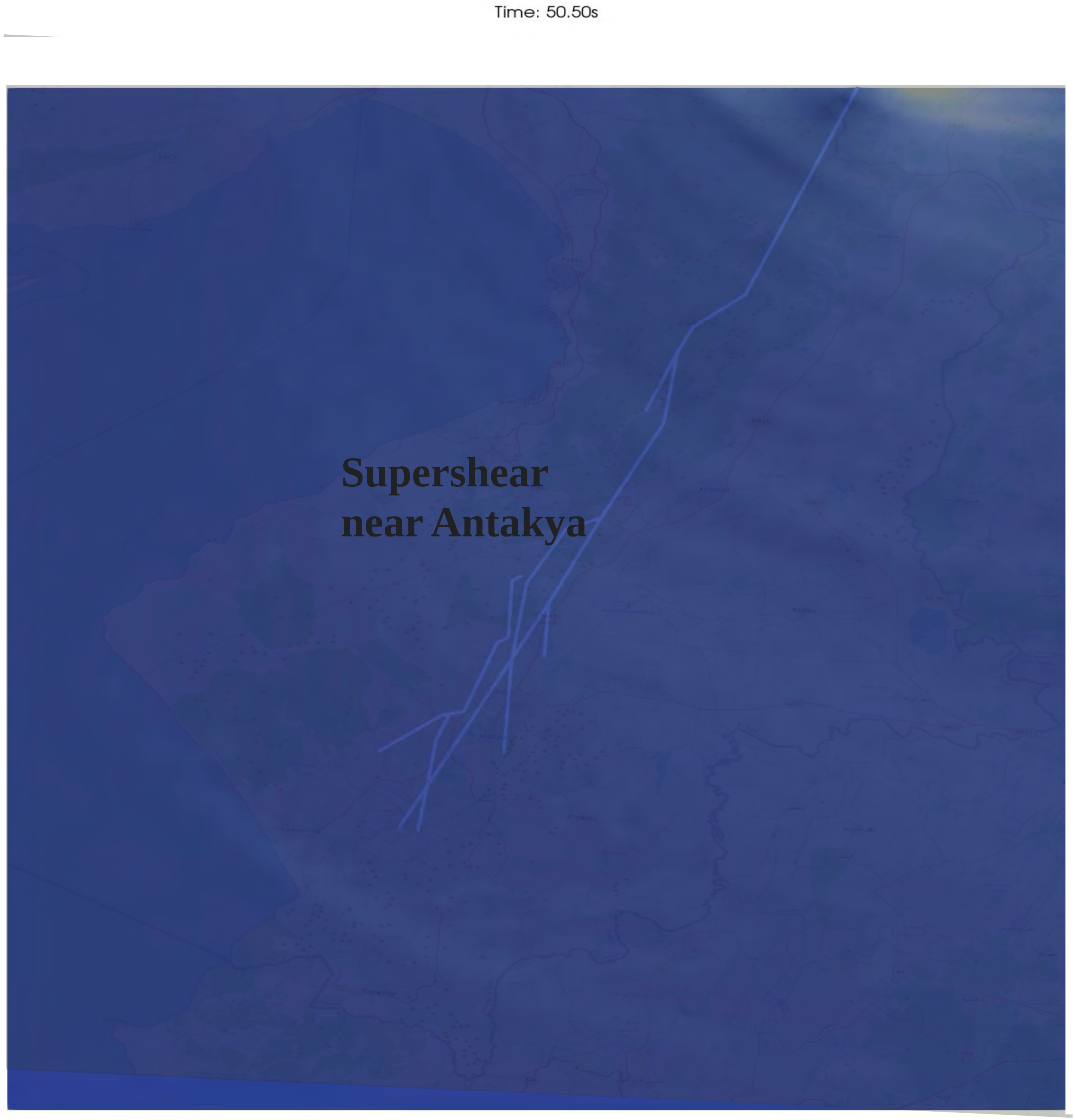


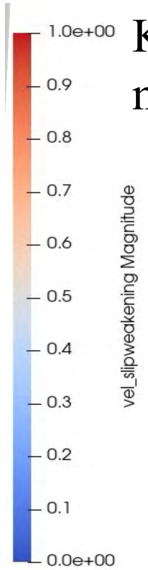




Can we reproduce station observations with forward dynamic models constrained by our knowledge of the incoming Narli rupture behaviour at the junction, fault geometry and independent estimates of tectonic state?







ARTICLE

Dynamics of episodic supershear in the 2023 M7.8 Kahramanmaraş/Pazarcik earthquake, revealed by near-field records and computational modeling

M. Abdelmeguid, C. Zhao, E. Yalcinkaya, G. Gazetas,
A. Elbanna, and A. Rosakis,

EarthArXiv preprint Feb. 2023
doi:https://doi.org/10.31223/X5066R
and
Commun Earth Environ **4**, 456 (Dec. 2023)
https://doi.org/10.1038/s43247-023-01131-7

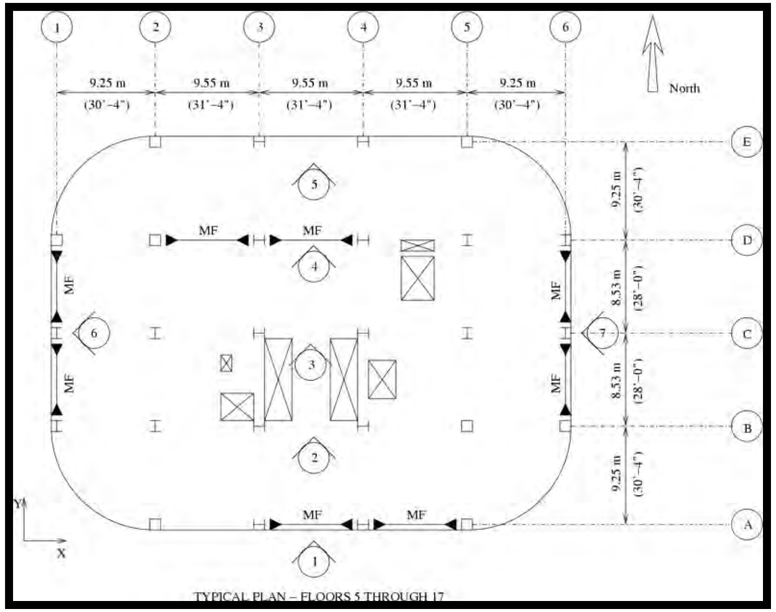
IN MANY CITIES SUCH AS ANTAKYA OR MALATYA , SUPERSHEAR CAN PERHAPS PARTIALLY EXPLAIN THIS LEVEL OF DEVASTATION

TO EMPHASIZE THIS POINT : *Choose an existing building in LA with Asymmetric placement of Moment Frames (Center of resistance and Center of Mass don't coincide)*

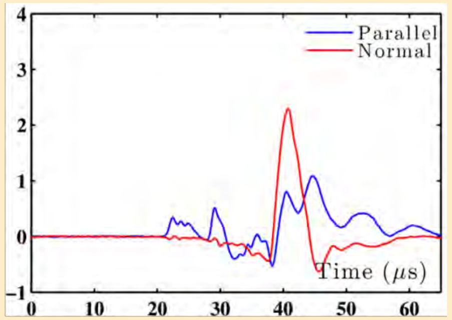
Building Studied : Existing steel moment-frame building of the 20-story class

- 3D Finite Element simulations using FRAME3D
- Developed at Caltech by Professor Swaminathan Krishnan

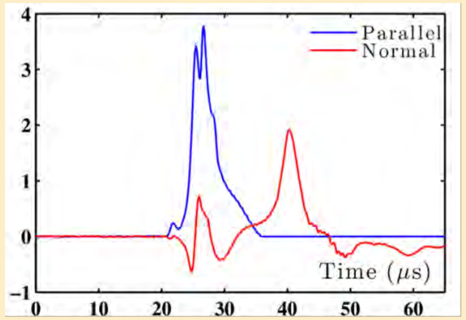
Swami Krishnan



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



Sub-Rayleigh Earthquake Rupture

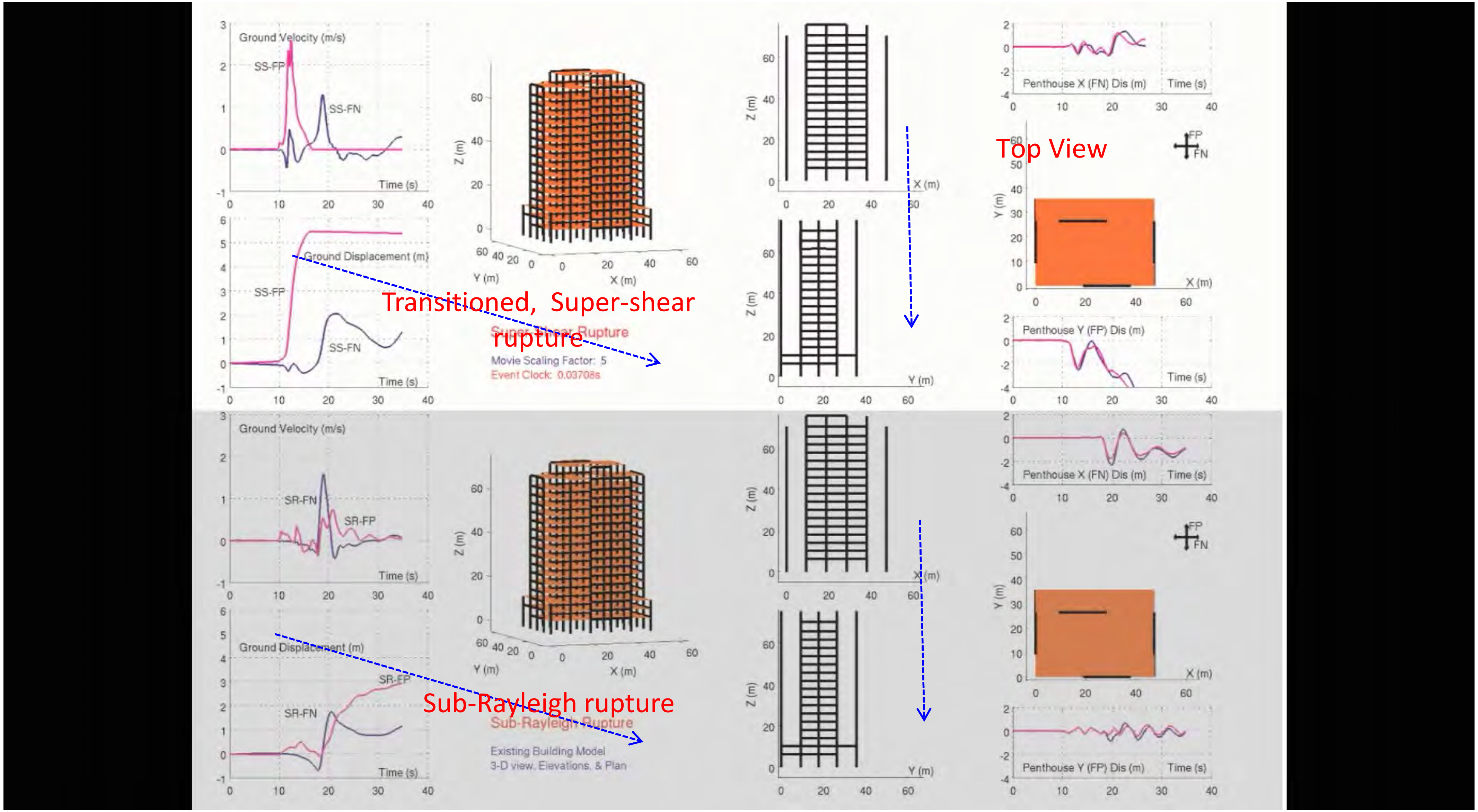


Super-shear Earthquake Rupture

Scaled Ground velocity signatures from experiments simulating the 2002, M_W 7.9, Denali Earthquake: Mello, Rosakis ,Bhat and Kanamori, Earth & Plan Sc. 2014

***TO EMPHASIZE THIS POINT* : Identical Buildings at 3Km from the fault were subjected to excitation from *Super-shear* or *Sub-Rayleigh* ruptures**

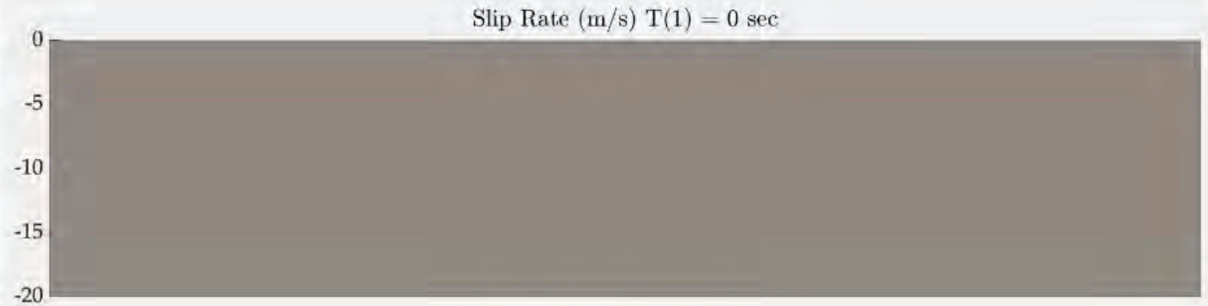
Swami Krishnan



WORK IN PROGRESS: Are 2-D theories enough? What are the ground motion characteristics in real 3-D Faults with velocity structure and geometric complexity?

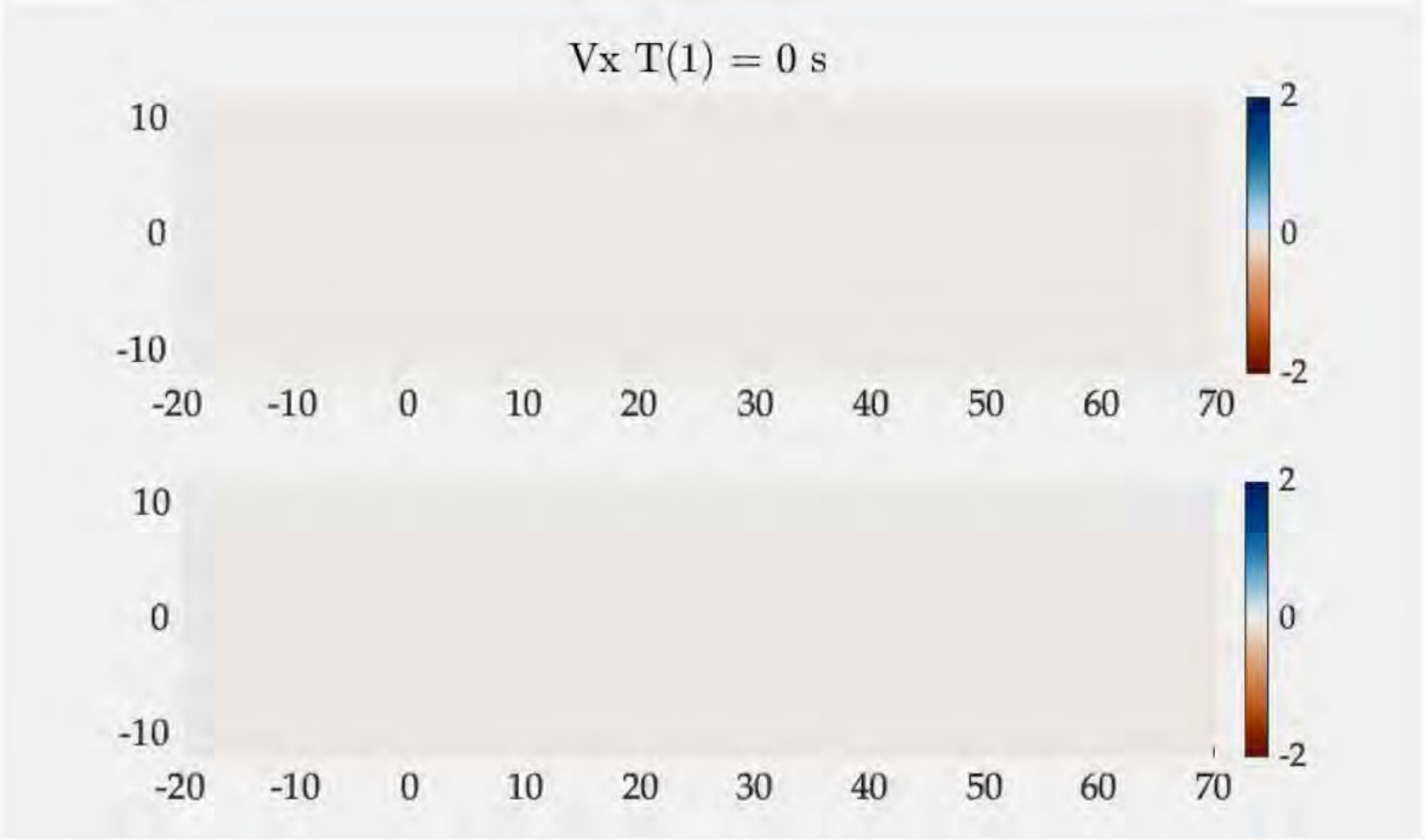
Mohamed Abdelmeguid, Caltech

Slip rate at depth



FP

FN



Rate and state friction with flash heating

ΣΑΣ ΕΥΧΑΡΙΣΤΩ !!!!

Traditional kinematic inversions cannot accurately resolve speeds on the Narli fault. They also seem to produce contradictory rupture speed results regarding the main EAF fault

Sub- and super-shear ruptures during the 2023 *Mw* 7.8 and *M*...
earthquake doublet in SE Türkiye

D. Melgar[1,*], T. Taymaz[2], A. Ganas[3], B.W. Crowell[4], T. Öcalan[5], M. Kahraman[6], ...
Yolsal-Çevikbilen[2], S. Valkaniotis [8], T.S. Irmak[9], T. Eken[2], C. Erman[2], B. Özkan[2] ...
Altuntaş[5]

The M7.8 event is sub-shear throughout!

Multi-scale rupture growth with altern... ...tions in complex fault network during the 2... ...n-eastern Türkiye and Syria earthquake d...ublet

Ryo Okuwaki[1], Yuji Yagi[1], Tuncay Taymaz[2], Stephen P. ...

The M7.8 event is super-shear throughout!

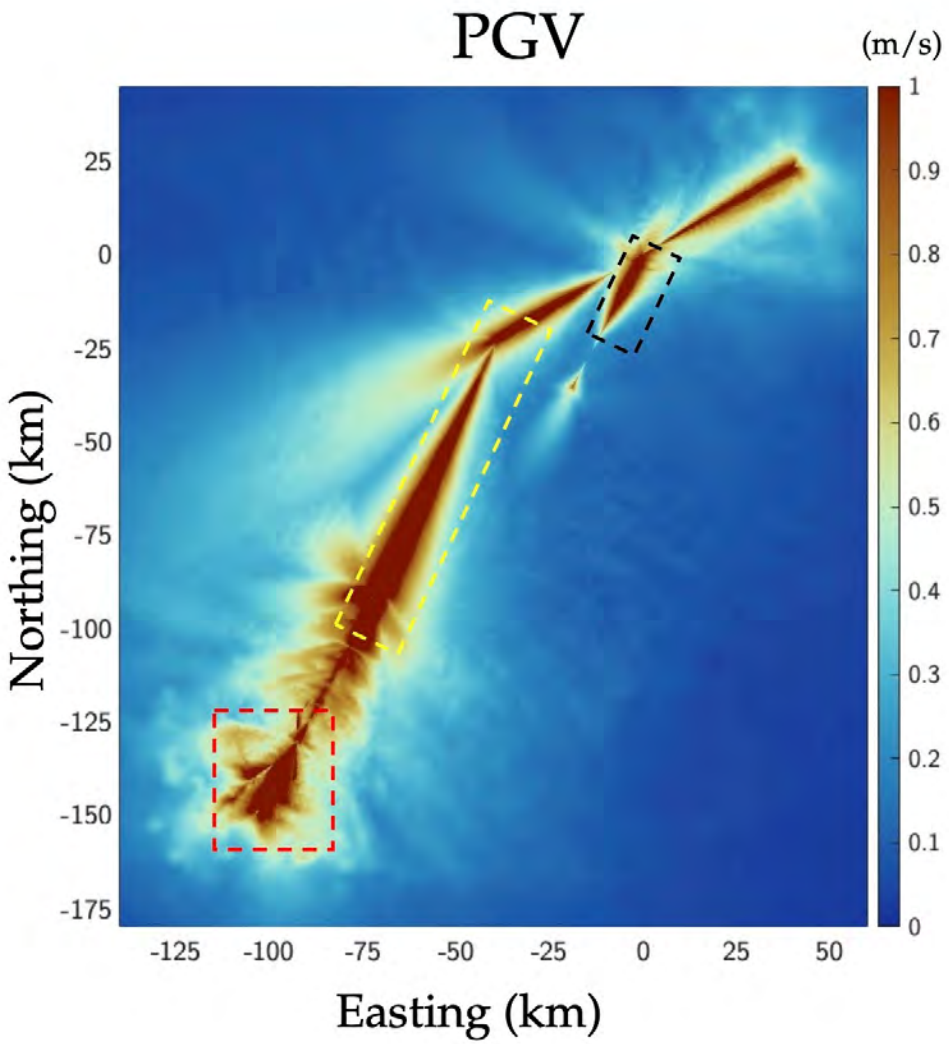
Kinematic rupture model of the February 6th 2023 Mw7.8 Tu... earthquake from a large set of near-source strong motion r... combined by GNSS offsets reveals intermittent supersh...

Bertrand Delouis[1], Martijn van den Ende[1], and Jean-Paul Ampuero[1]

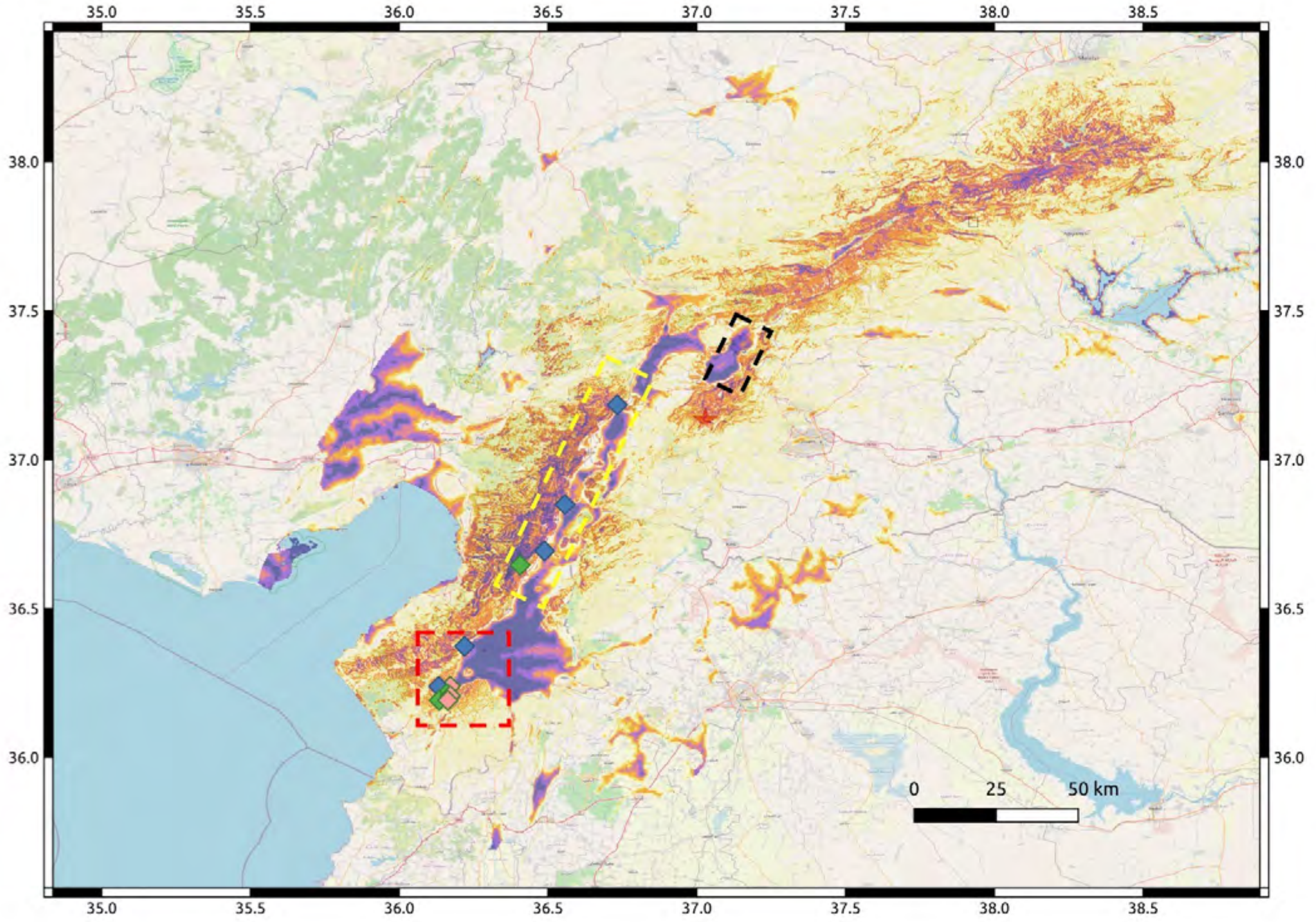
The M7.8 event is intermittently supershear!

And many many more ..

Geo-hazards correlate, to first order, with the spread and magnitude of peak ground velocity

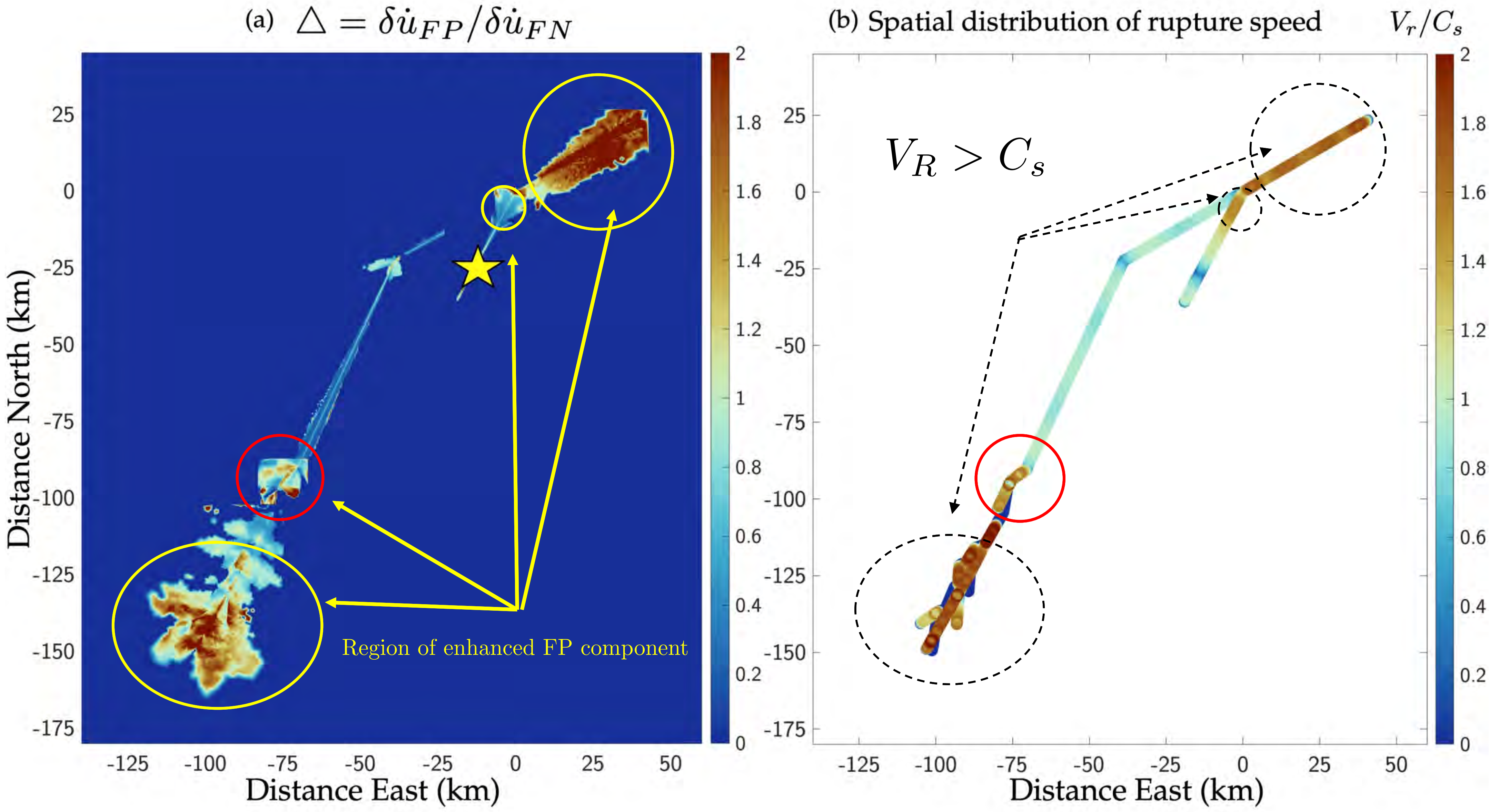


PGV map obtained from the dynamic rupture model



Ground failures (e.g., liquefaction and slope failures predicted by USGS and later confirmed by reconnaissance studies.

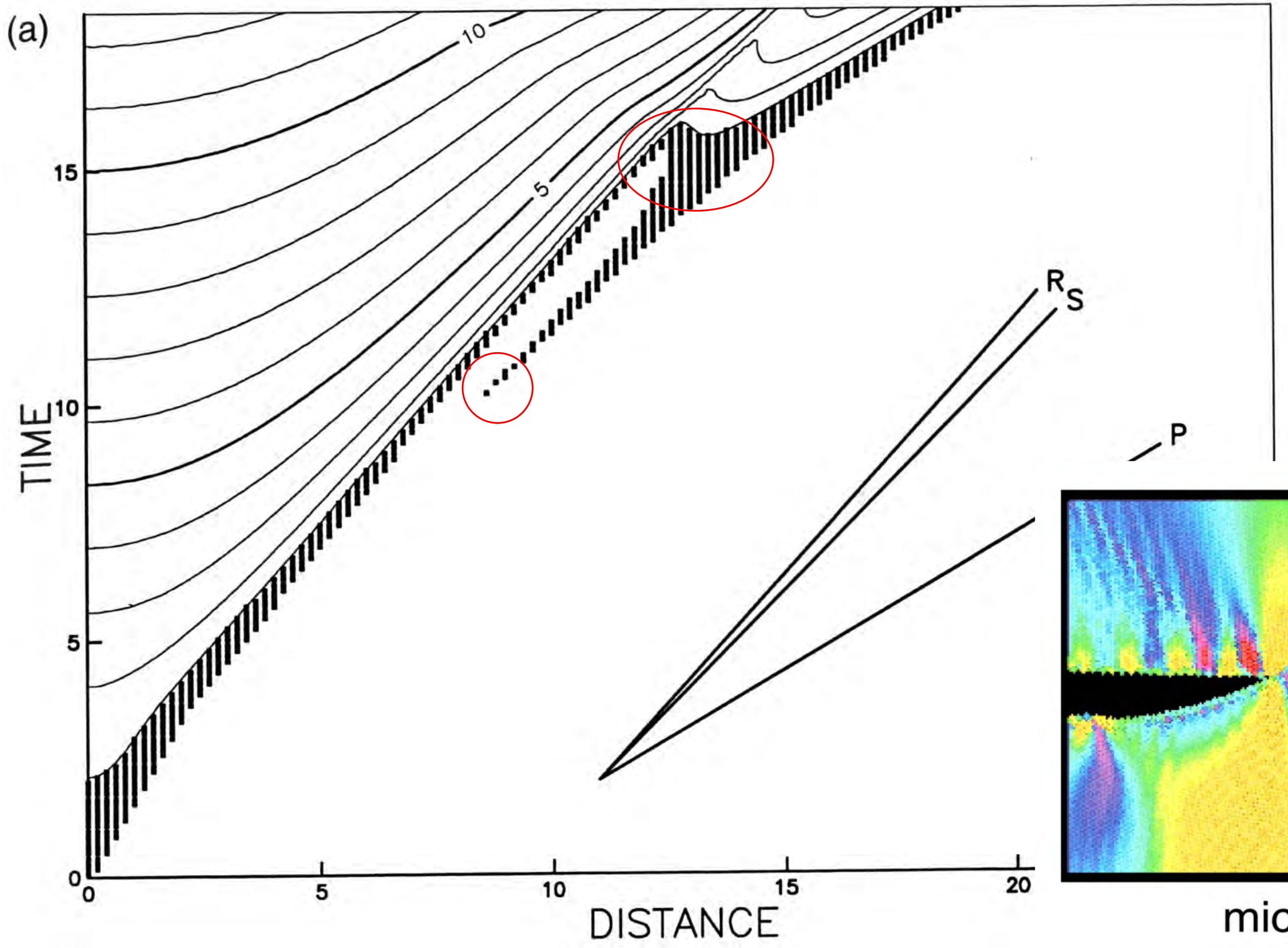
Correlation: ***Ratios of FP to FN velocity jumps (Left) correlate well with rupture speeds (Right) and agrees with seismic records during the event***



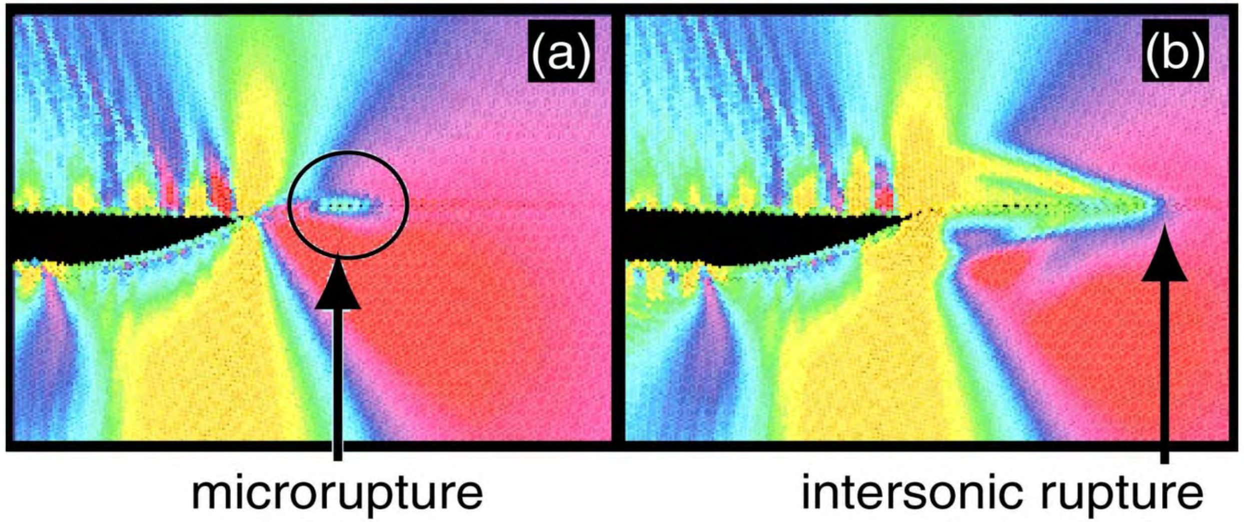
Transition Mechanism at the Nanoscale

(Theory: ***Burridge 73, Burridge, Conn &Freund 79, Andrews 1985; Gao &Abraham, 2000; Experiment: Xia Rosakis and Kanamori 2004& Xia, Rosakis and Kanamori 2005, Liu and Lapusta (2008), Lu, Lapusta &Rosakis, 2009.*** **)**

Supershear is persistent across scales (10^{-9}m to 10^{2}m)



Gao &Abraham, 2000



- μ_s , μ_d , D_c are varied to control S and G while keeping L_c fixed

Θα ήθελα ευχαριστήσω ιδιαίτερα για την συμβολή τους για την αναγόρευσή σου):

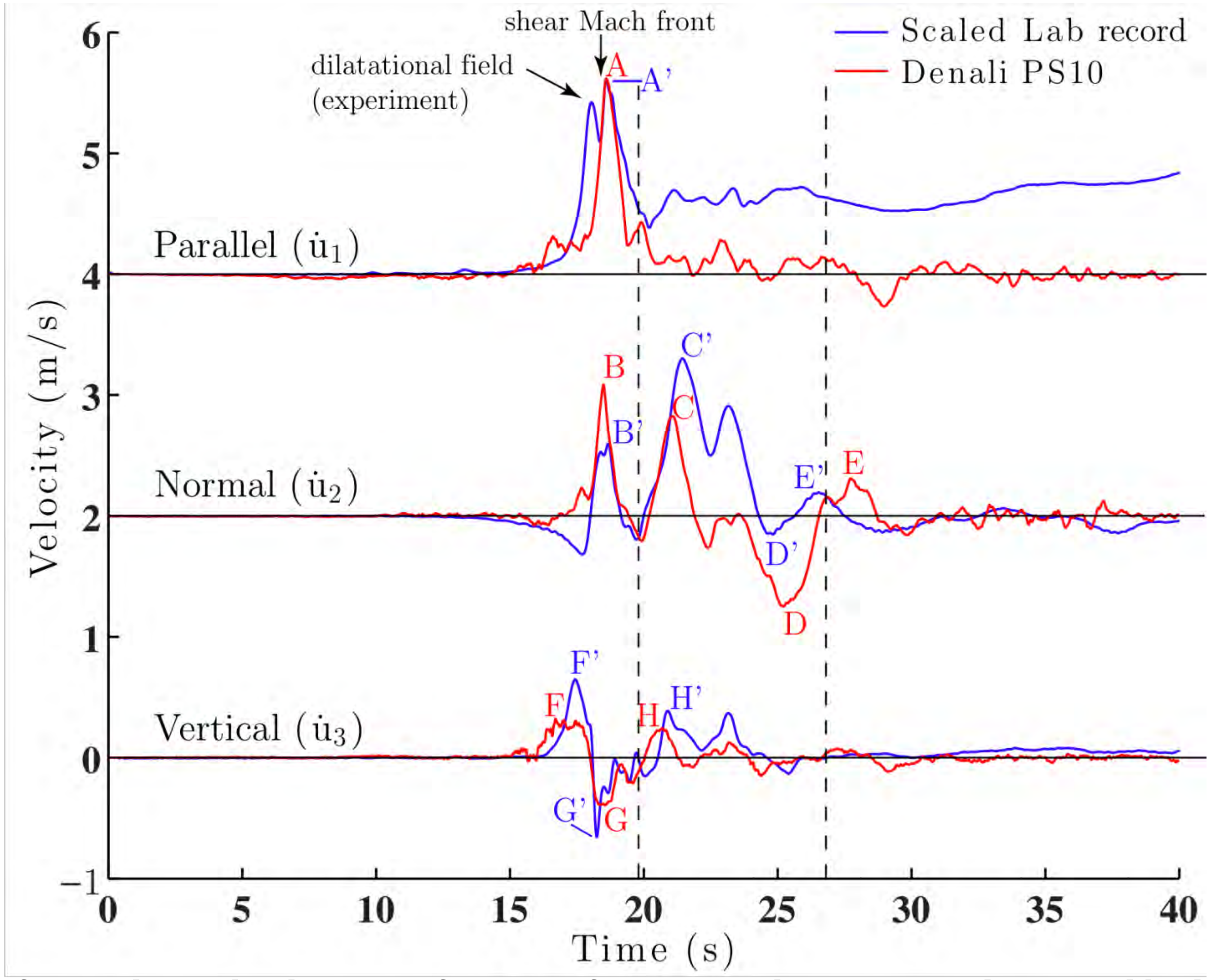
1) προς τον Πρύτανη Καθηγητή κ. Χατζηγεωργίου,
2) << τέως Πρύτανη κ. Μπουντουβή,
3) << τα μέλη της Συγκλήτου,
4) << Κοσμήτορα της Σχολής Εφαρμοσμένων Μαθηματικών & Φυσικών Επιστημών κ. Ράπτη,
5) << τέως Κοσμήτορα της Σχολής κ. Κουρκουλή,
6) << τα μέλη του Τομέα Μηχανικής και της Σχολής Εφαρμοσμένων Μαθηματικών & Φυσικών Επιστημών,

και, βεβαίως, προς όλους τους παρισταμένους "για την παρουσία τους".

D_c

Scaled Laboratory Earthquake Record vs. Denali Pump Station 10

Mello, Rosakis , Bhat and Kanamori , Earth & Plan Sc. 2014



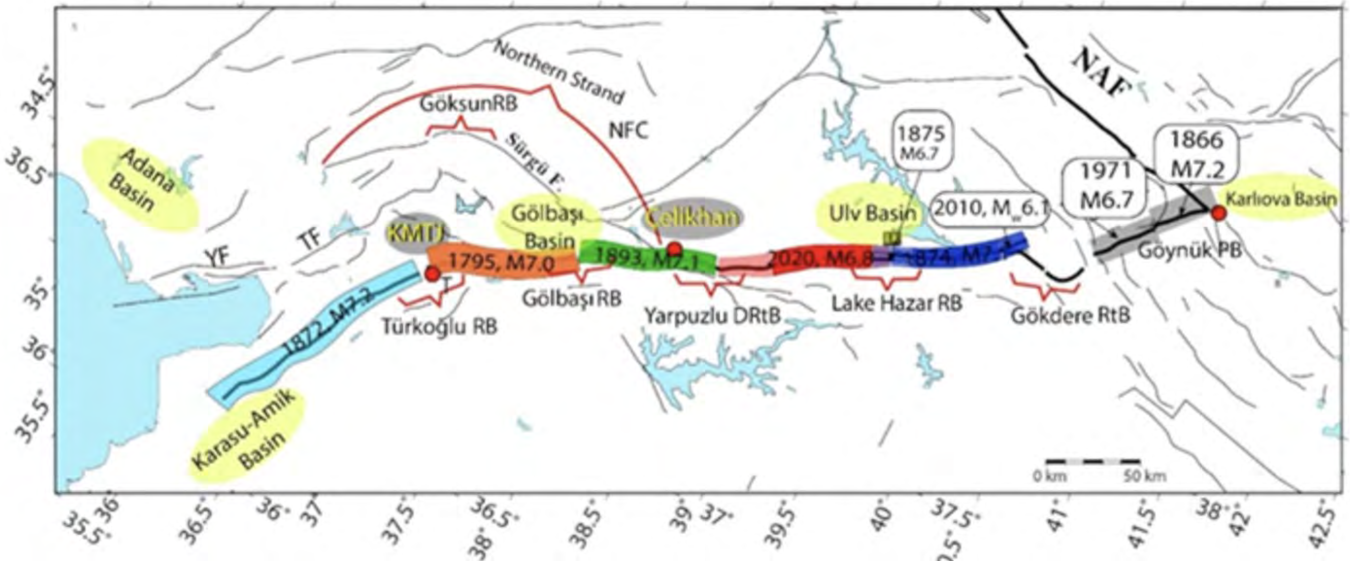
✧After Scaling , the dominant features of 2002 Denali PS10 record captured by laboratory record

Similarities with California

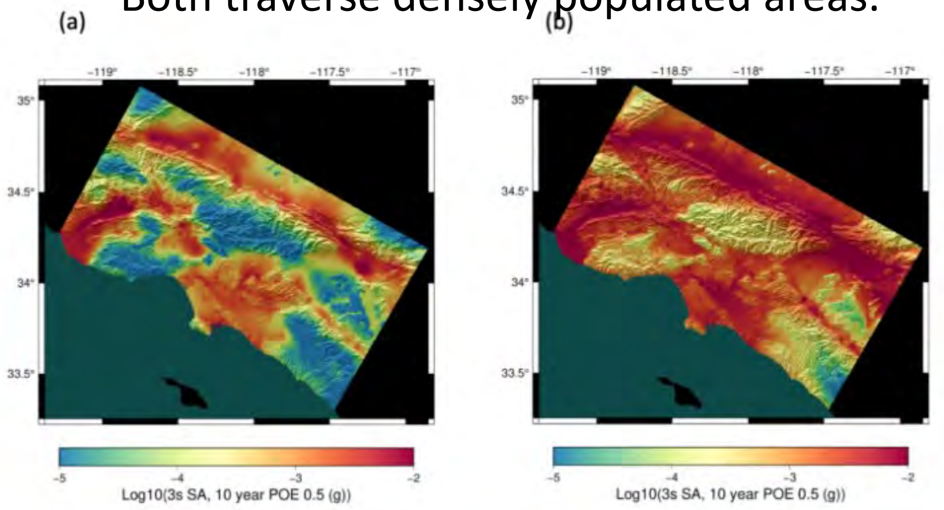
Elbanna , Milner and Ben-Zion: https://www.scec.org/article/1003

San Andreas Fault , Wallace 1990

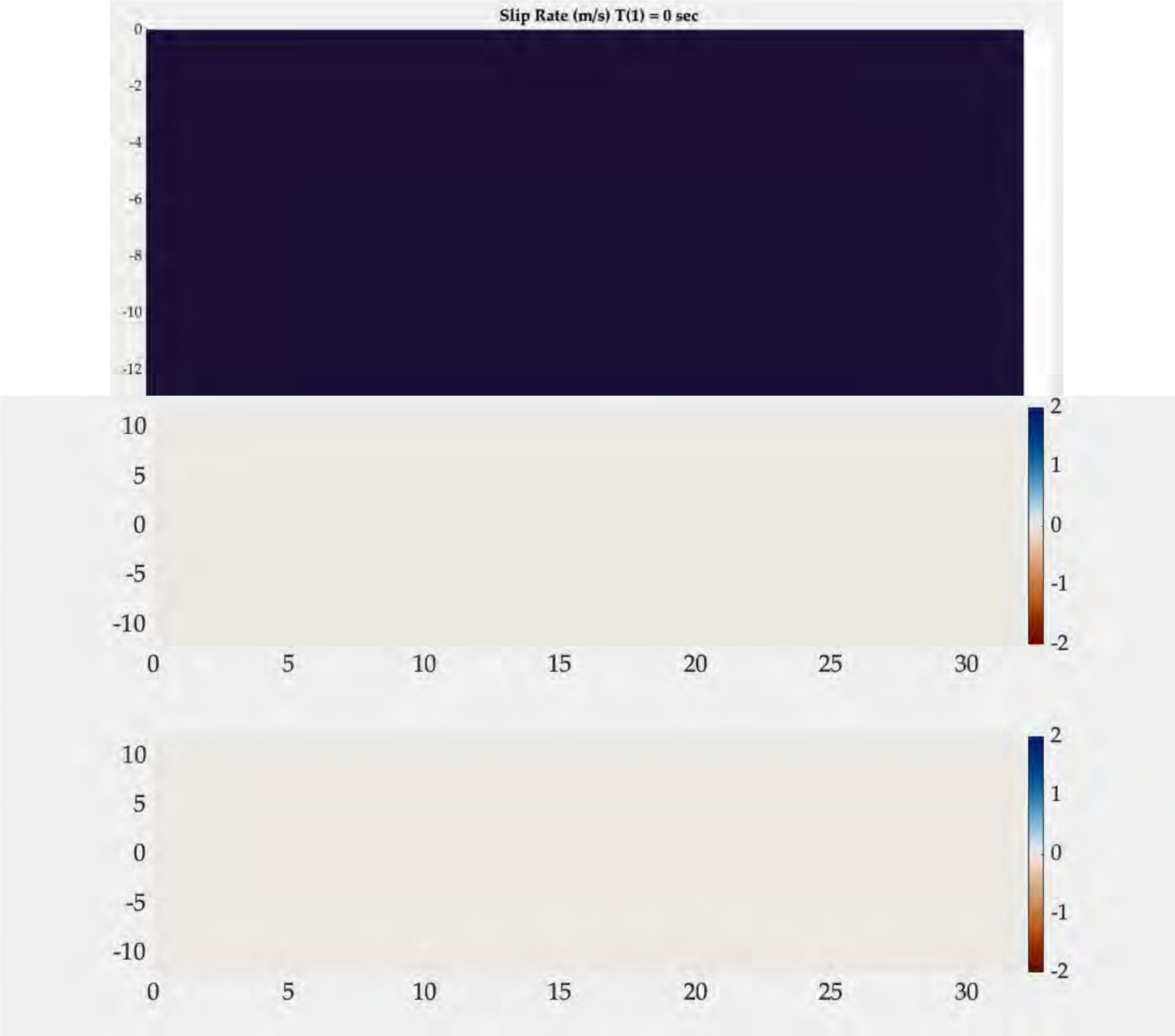
- The geometry is fairly similar (length and features).
- Both are mature faults that have hosted large historic earthquakes on individual segments
- The probability of intense ground shaking (exceeding 0.5g and even reaching 1g) is quite large for the LA region.
- Both have long fault segments that can potentially host supershear propagation
- Both traverse densely populated areas.



EAF, Güvercin et al. 2022

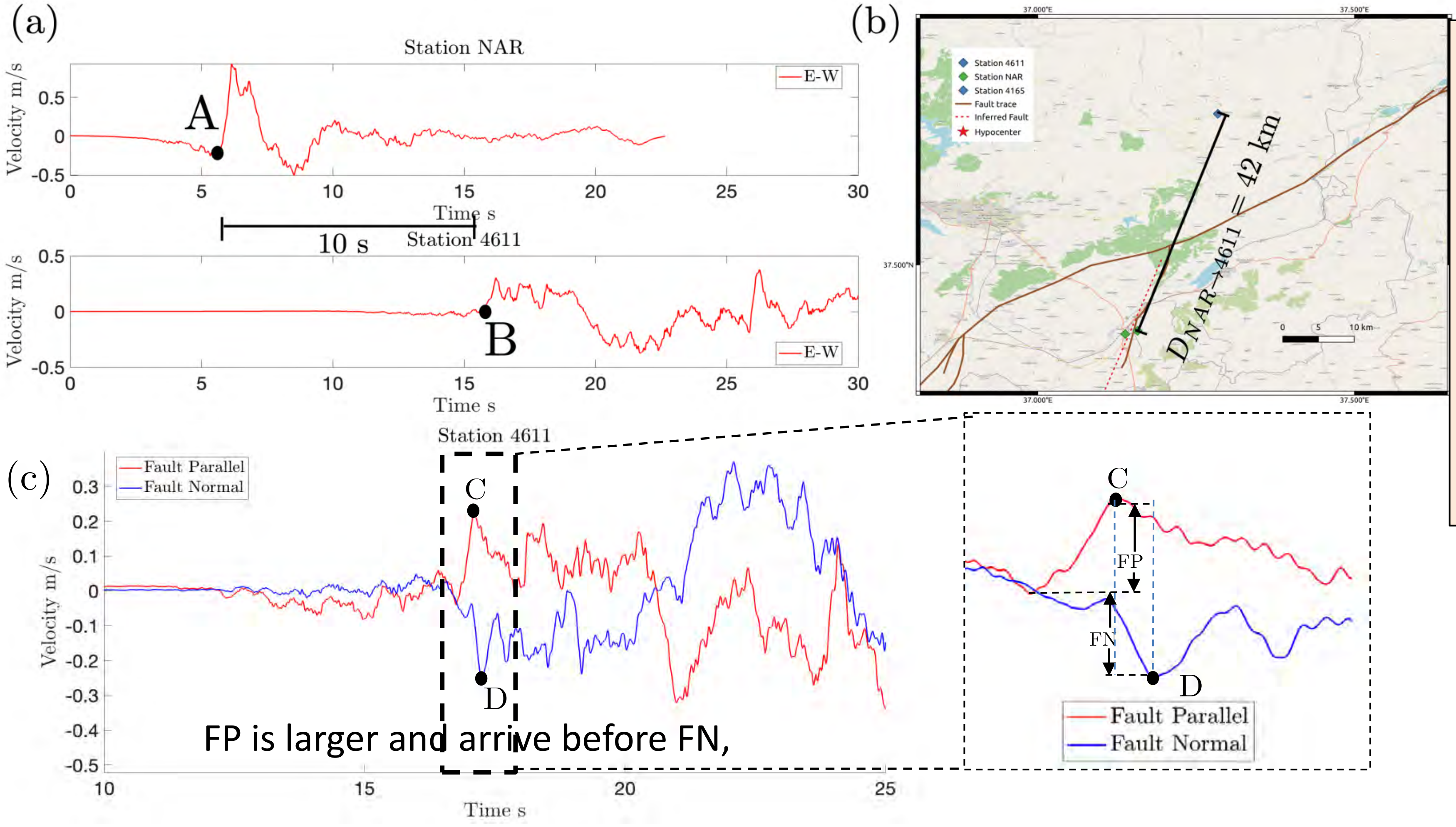


Probability of intense ground shaking (*exceeding 0.5g of 3 second pseudospectral acceleration)* along LA region



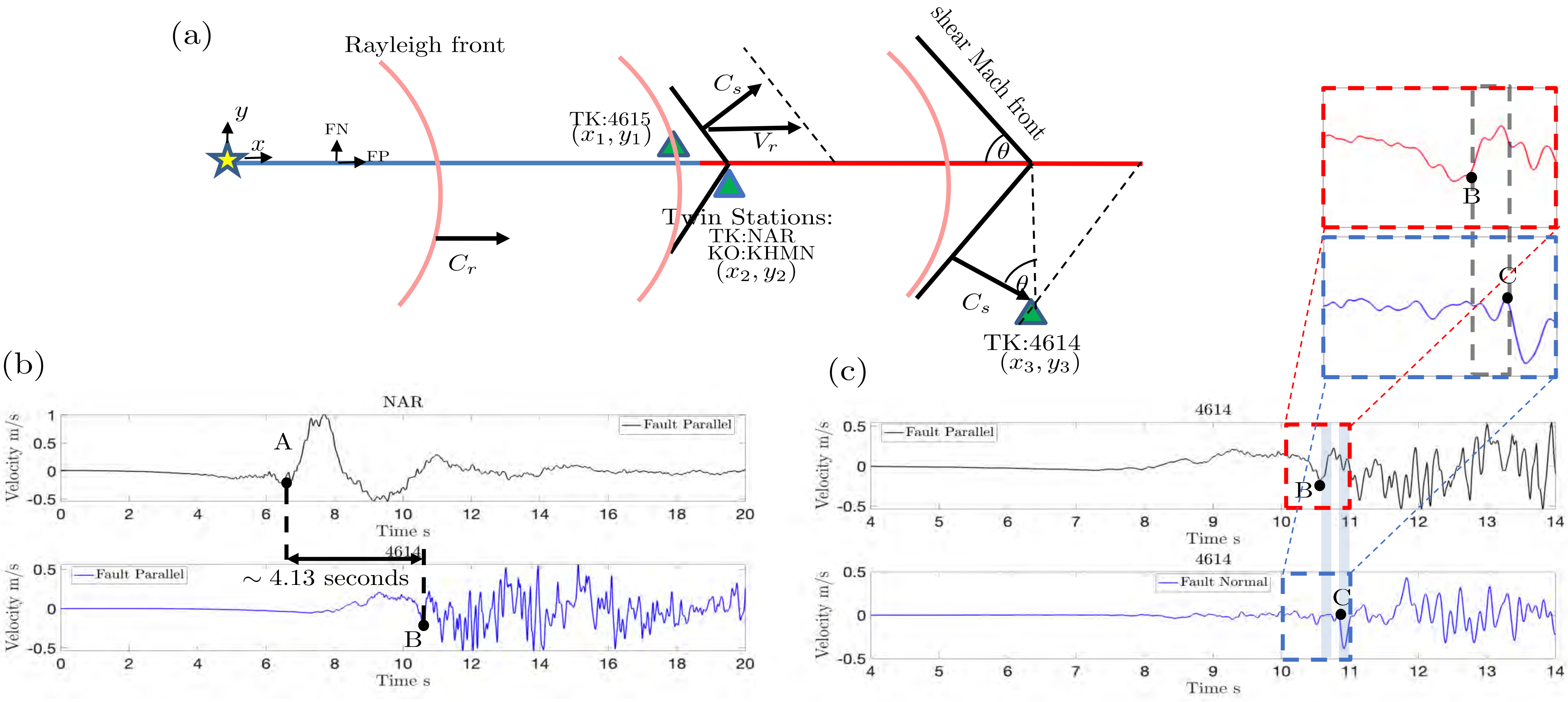
Slip Rate (m/s) T(1) = 0 sec
0
-2
-4
-6
-8
-10
-12
10
5
0
-5
-10
0
5
10
15
20
25
30
2
1
0
-1
-2

Additional Evidence for supershear transition along the Narli Fault

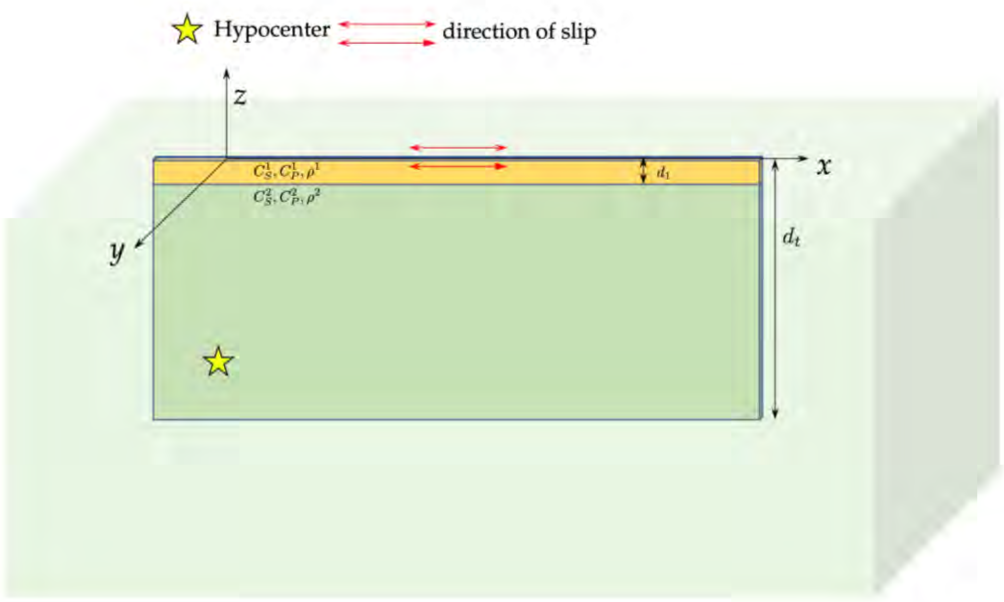


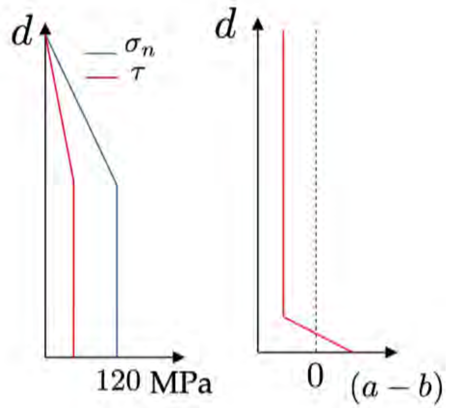
“At locations within a few kilometers of the rupture, the time histories of the polarization of the horizontal motion provide a better diagnostic with which to gauge the rupture speed than the orientation of the peak motion. Subshear ruptures are associated with significant fault-perpendicular motion *before* fault-parallel motion close to the fault; supershear ruptures are associated with fault-perpendicular motion *after* significant fault-parallel motion.” Aagaard and Heaton 2004

Additional Evidence for supershear along the Narli Fault



16 kms away from NAR rules out subshear propagation





$$f(V,\Psi) = a\,\mathrm{archsinh}\left(\frac{V}{2V_o}e^{\frac{\Psi}{a}}\right)$$

$$f_{ss} = f_w + \frac{f_{LV} - f_w}{[1+(V/V_w)^8]^{1/8}}$$

$$f_{LV} = f_o - (b-a)\ln(V/V_o)$$

$$\dot{\Psi} = -\frac{V}{L}[\Psi - \Psi_{ss}]$$

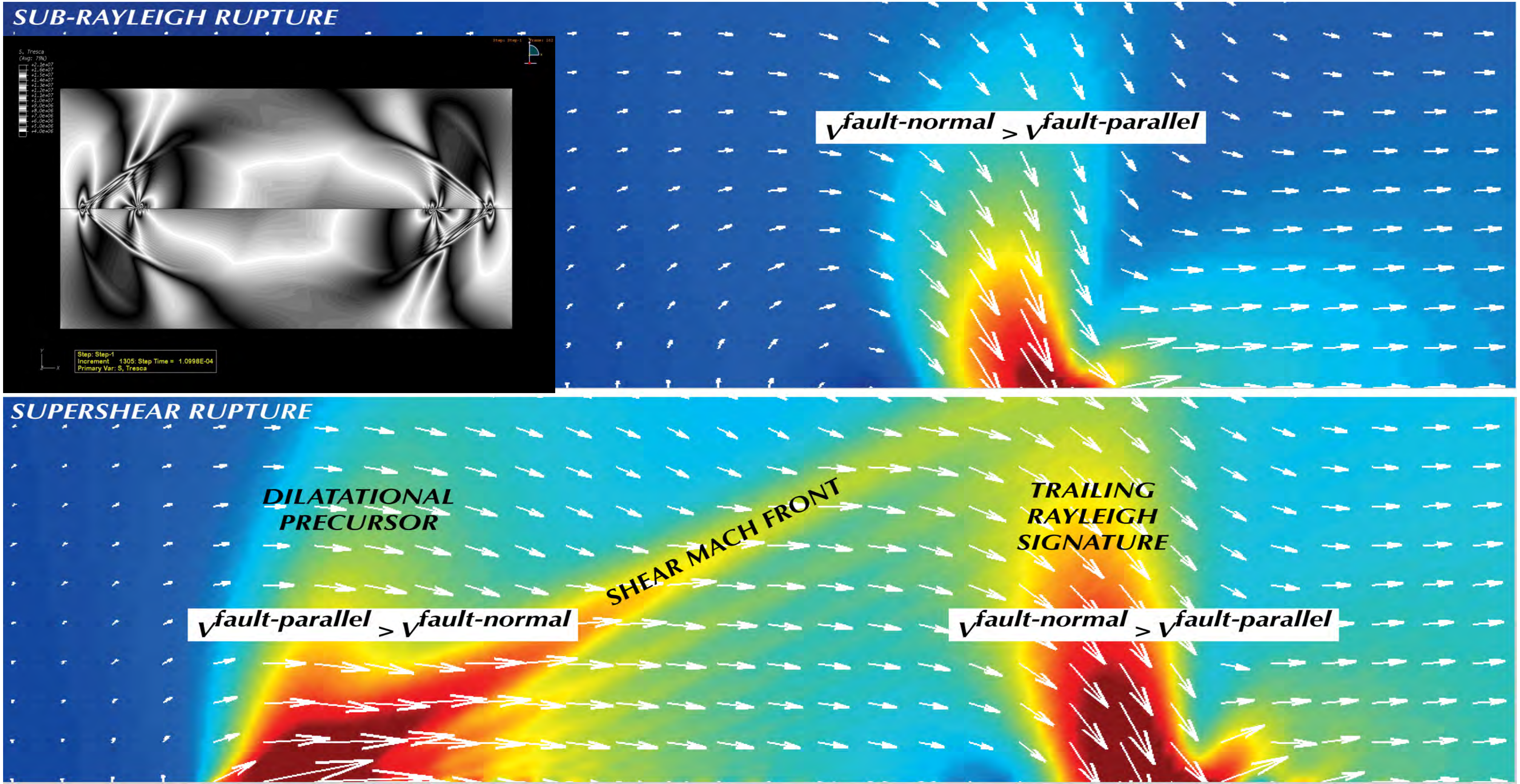
$$C_s^1 = C_s^2 = 3464 \text{ m/s}$$
$$C_p = 6000 \text{ m/s}$$

$$\Psi_o = 0.55$$

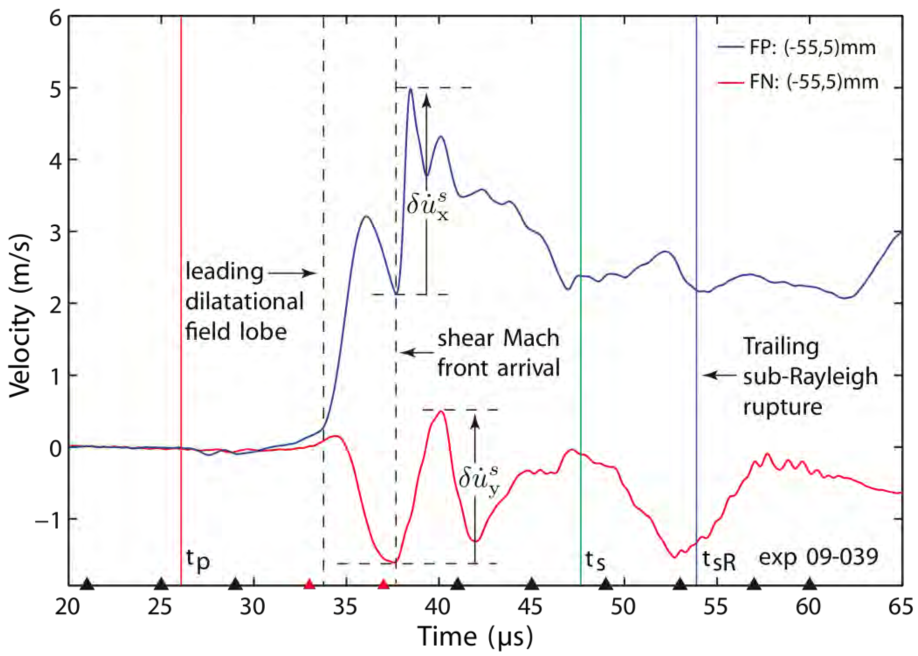
Rich heritage lost all over Türkiye and Syria

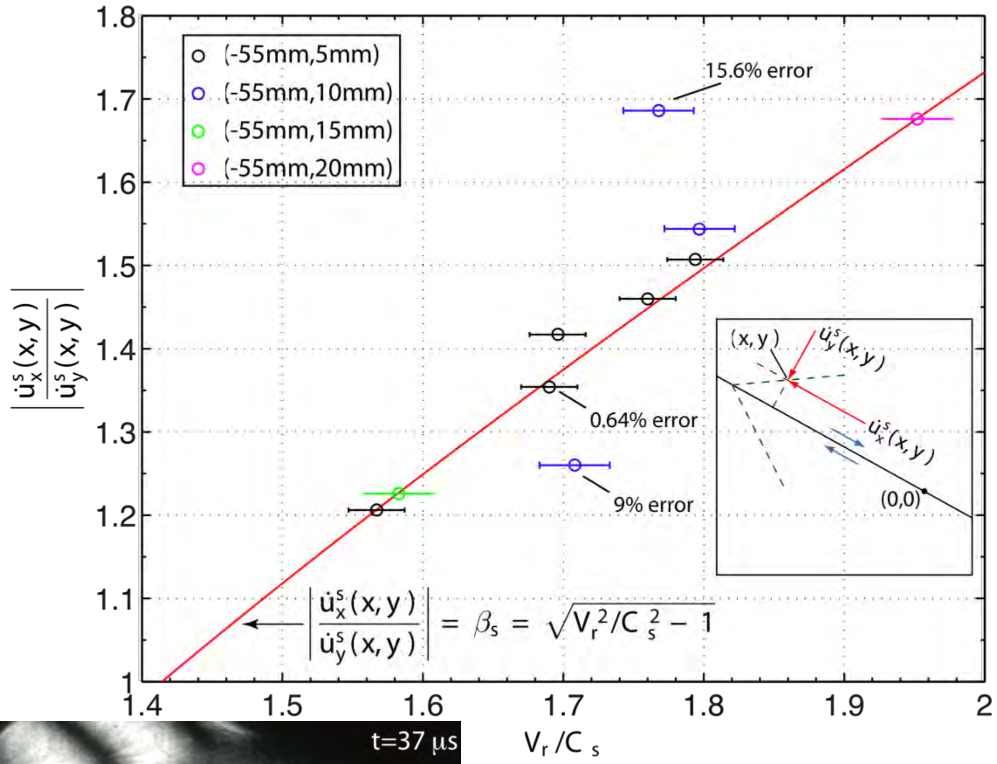
Gaziantep Castle (Ἀντιόχεια τοῦ Ταύρου)

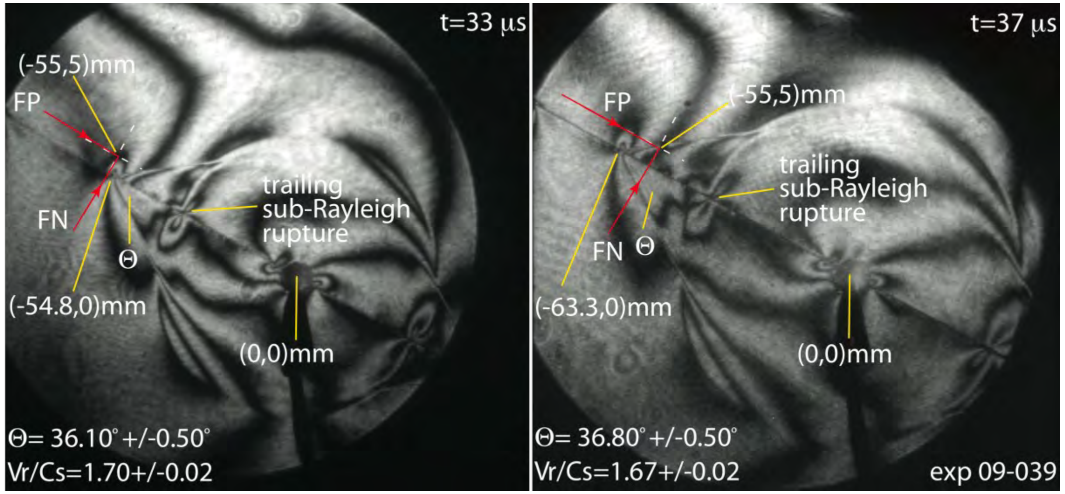
Velocity Signatures of Sub-Rayleigh and Super-shear Ruptures



Examination of the ratio: $\beta_s = |\delta \dot{u}_x^s(z_s)| / |\delta \dot{u}_y^s(z_s)|$ along a shear Mach front



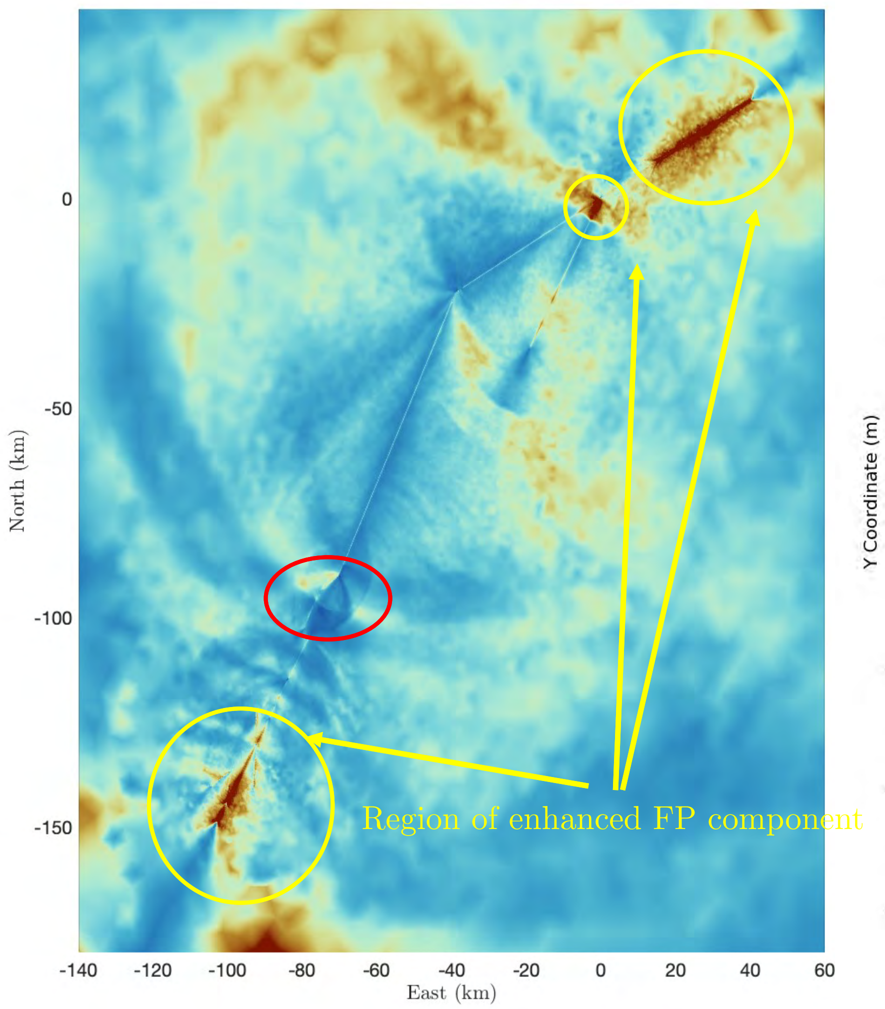




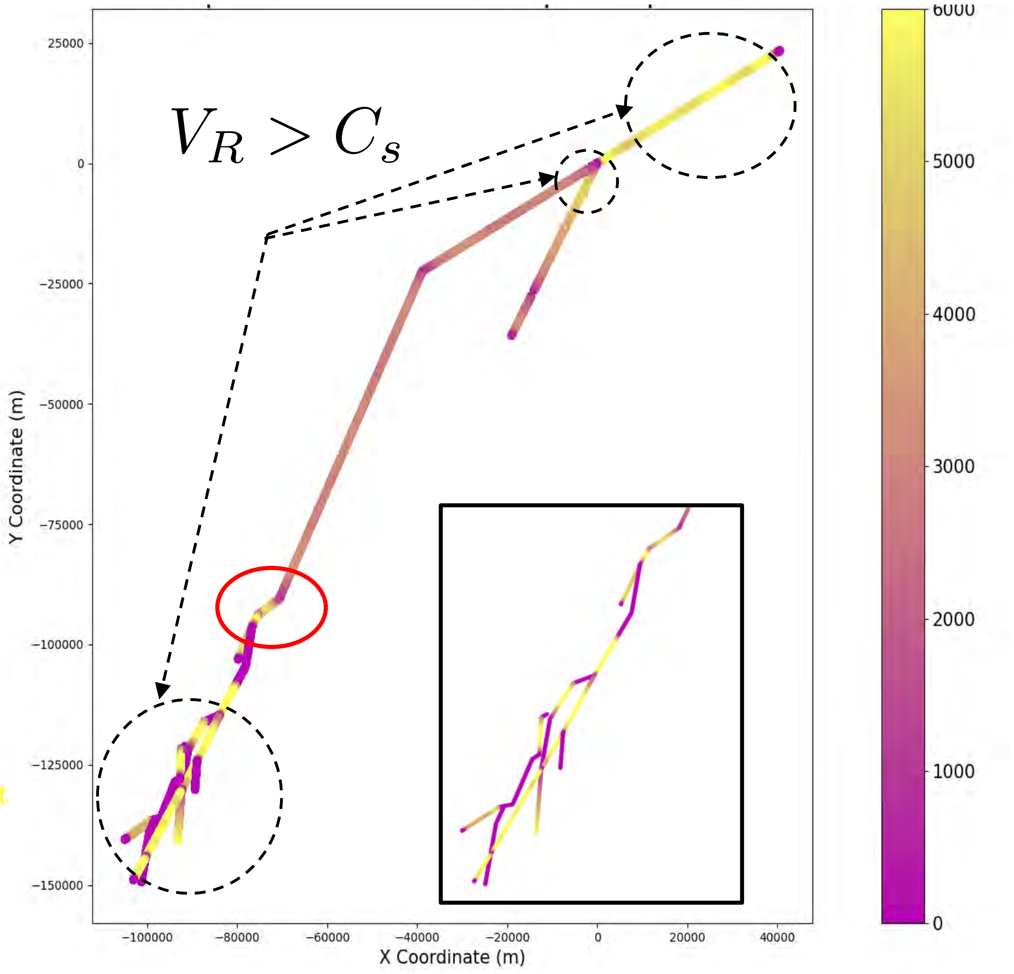
FP vs FN enhancement during rupture propagation

Spatial Distribution of Rupture Speed

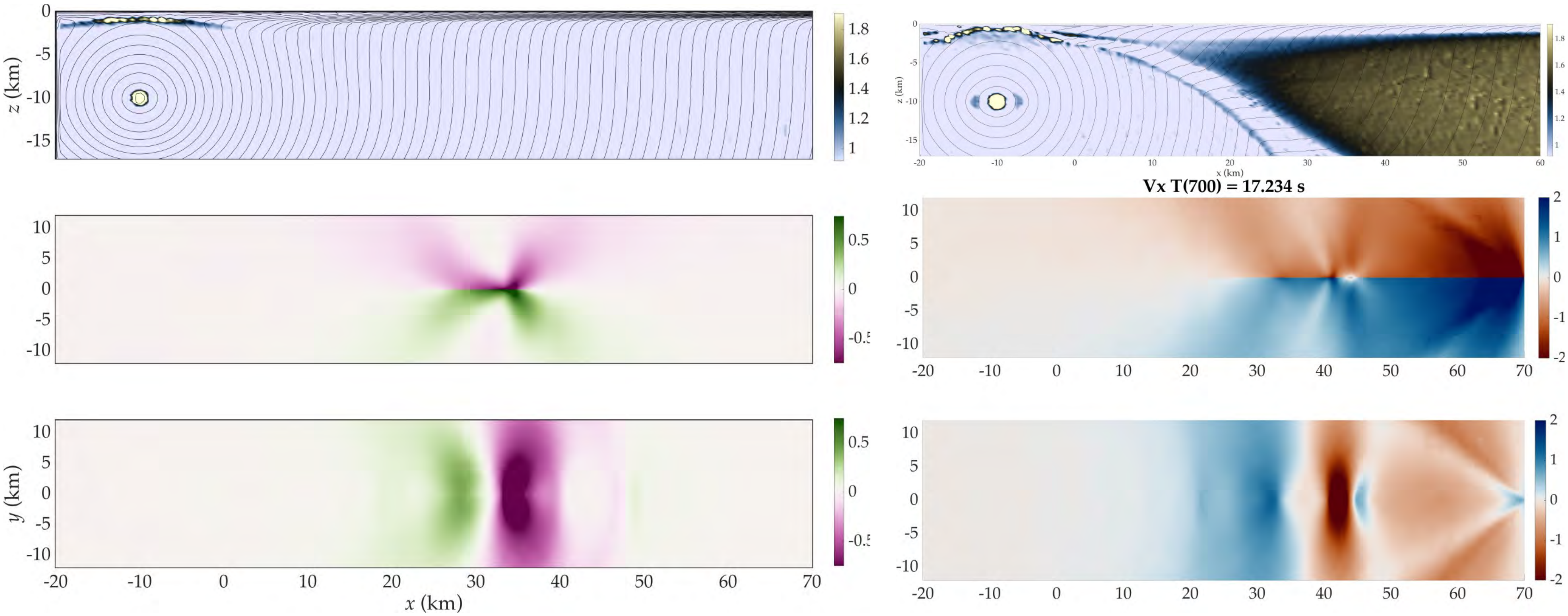
$\max|\dot{u}_{FP}|/\max|\dot{u}_{FN}|$



V_R

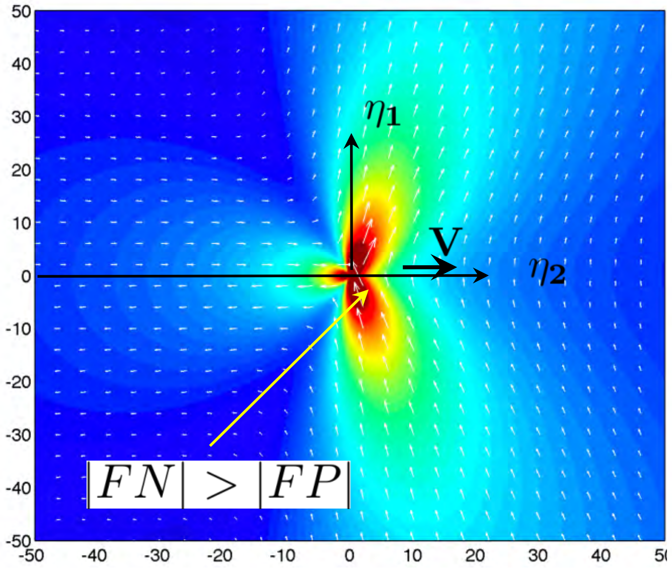


Similarities with California

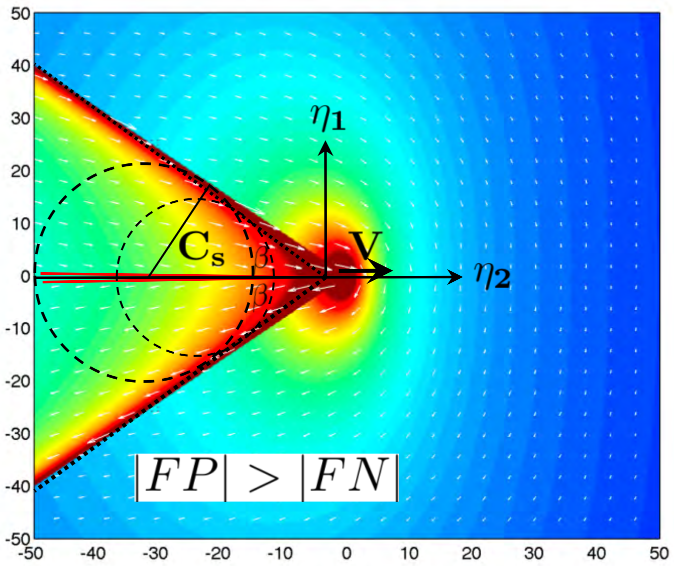


Classification of Earthquakes: Ground motion signatures of steady-state, Sub-Rayleigh and Super-shear Ruptures

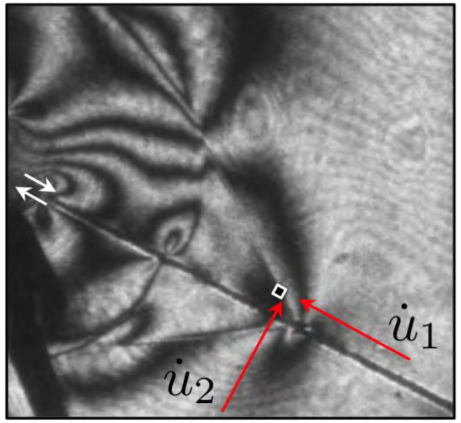
Ben Freund
Brown university

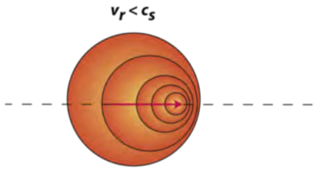
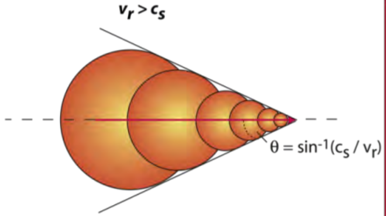


$$\frac{V_r}{C_s} = 0.875$$



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



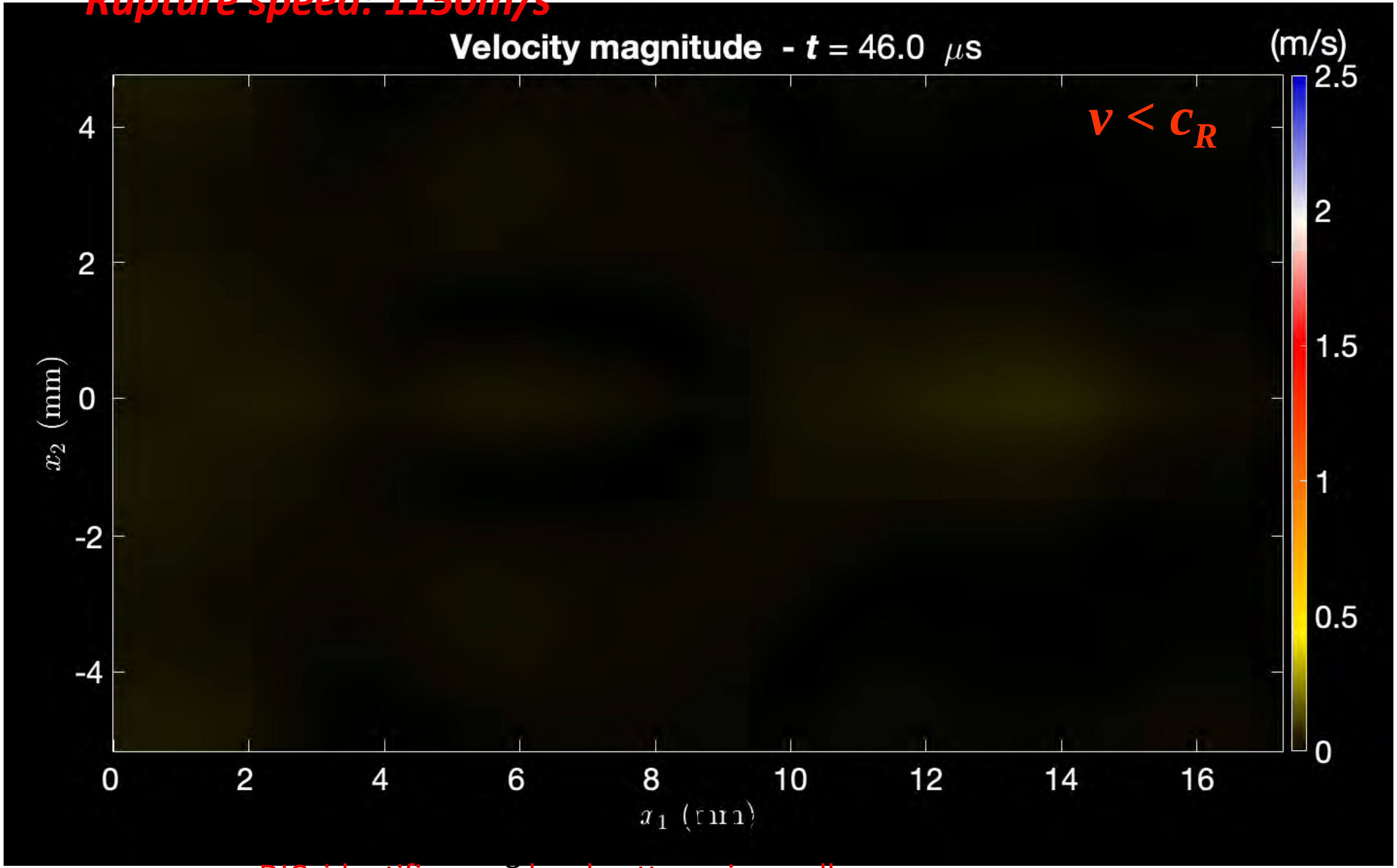
$V_r < C_R$	$\sqrt{2}C_s < V_r < C_p$
	
$\left\|\frac{\dot{u}_{2_{max}} - \dot{u}_{2_{min}}}{\dot{u}_{1_{max}} - \dot{u}_{1_{min}}}\right\| > 1$	$\left\|\frac{\dot{u}_{1_{max}} - \dot{u}_{1_{min}}}{\dot{u}_{2_{max}} - \dot{u}_{2_{min}}}\right\| > 1$

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

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

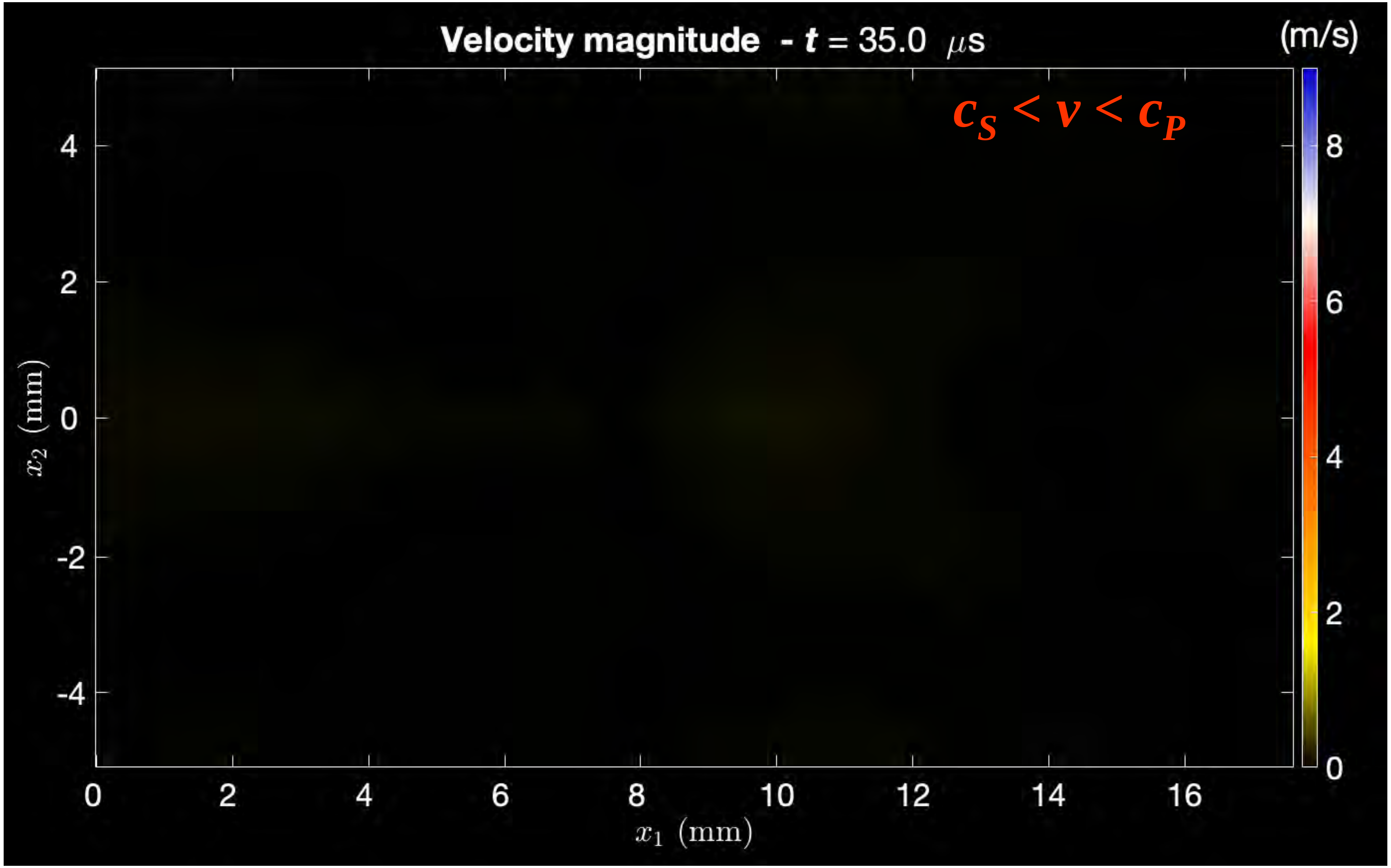
Classical Sub-Rayleigh, sliding "Rice-Heaton" pulse (Zheng & Rice)

Rupture speed: 1150m/s

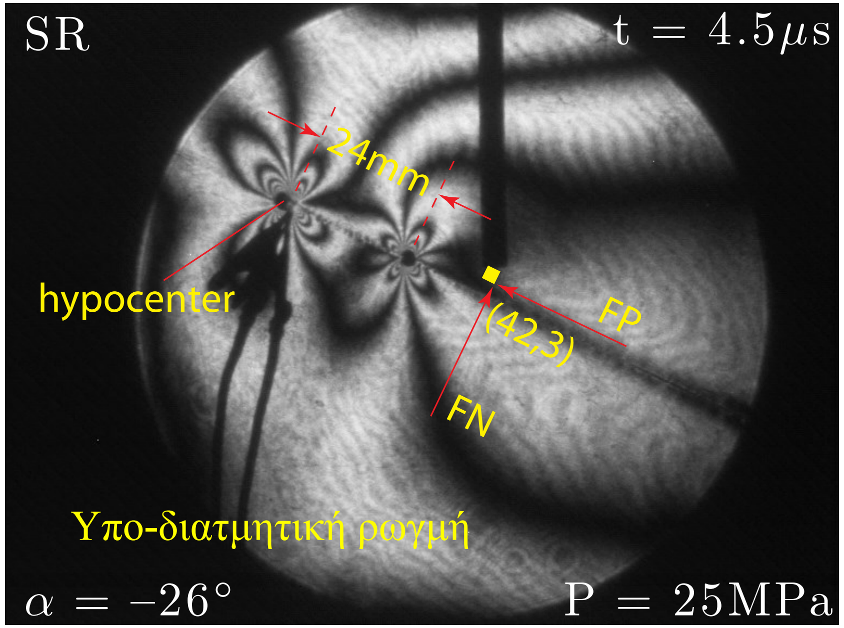


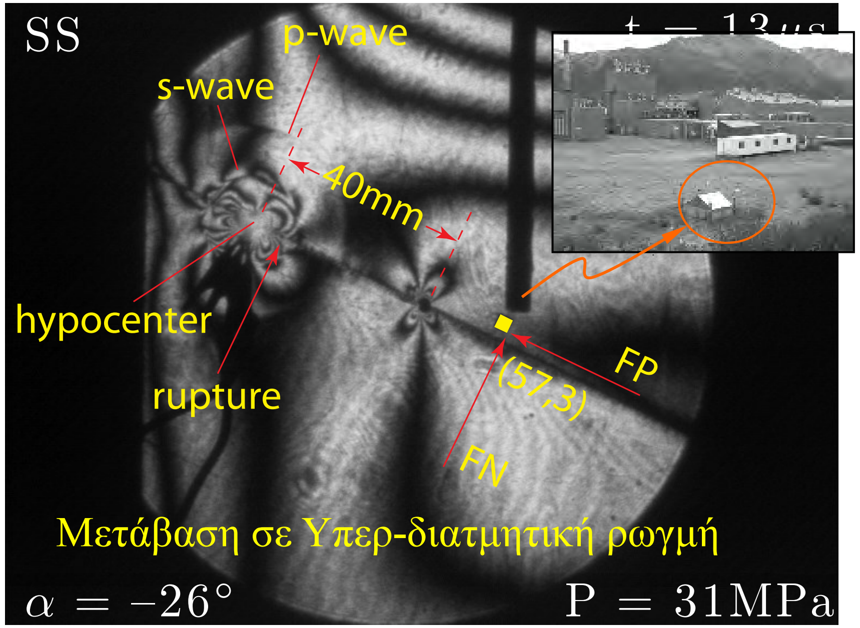
DIC identifies gray level patterns in small **pixel subsets** and tracks their motion during deformation

Supershear crack, Rupture speed: 2368m/s

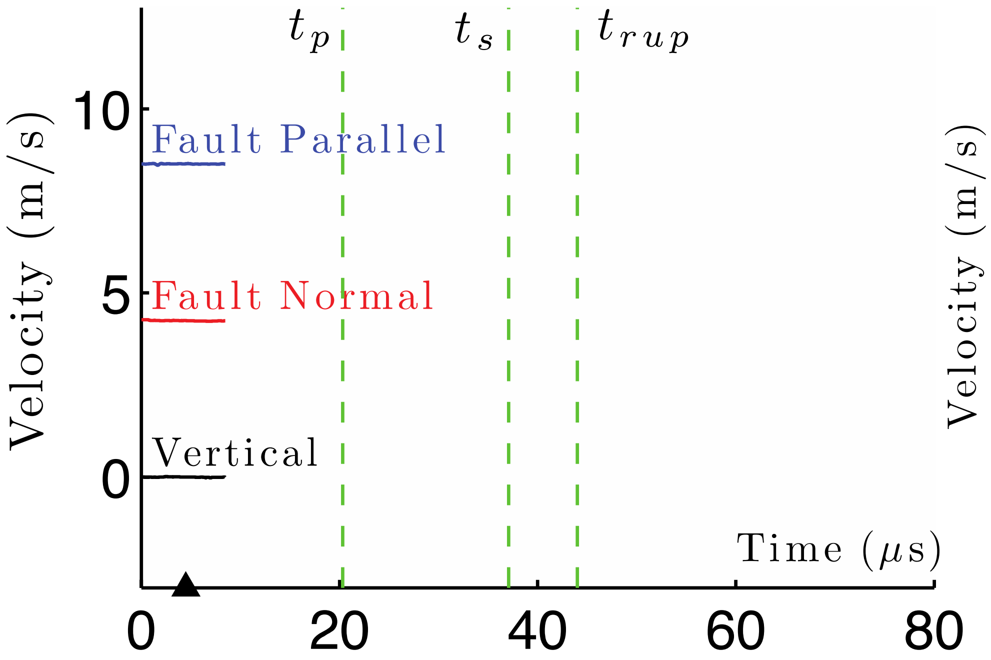


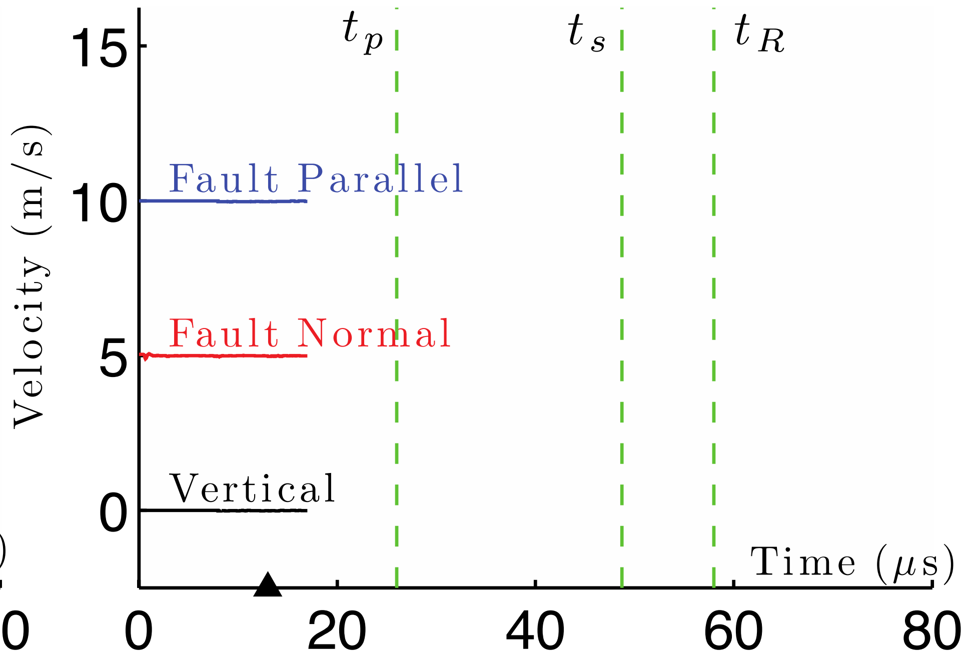
DIC identifies gray level patterns in small
pixel subsets and tracks their motion during deformation

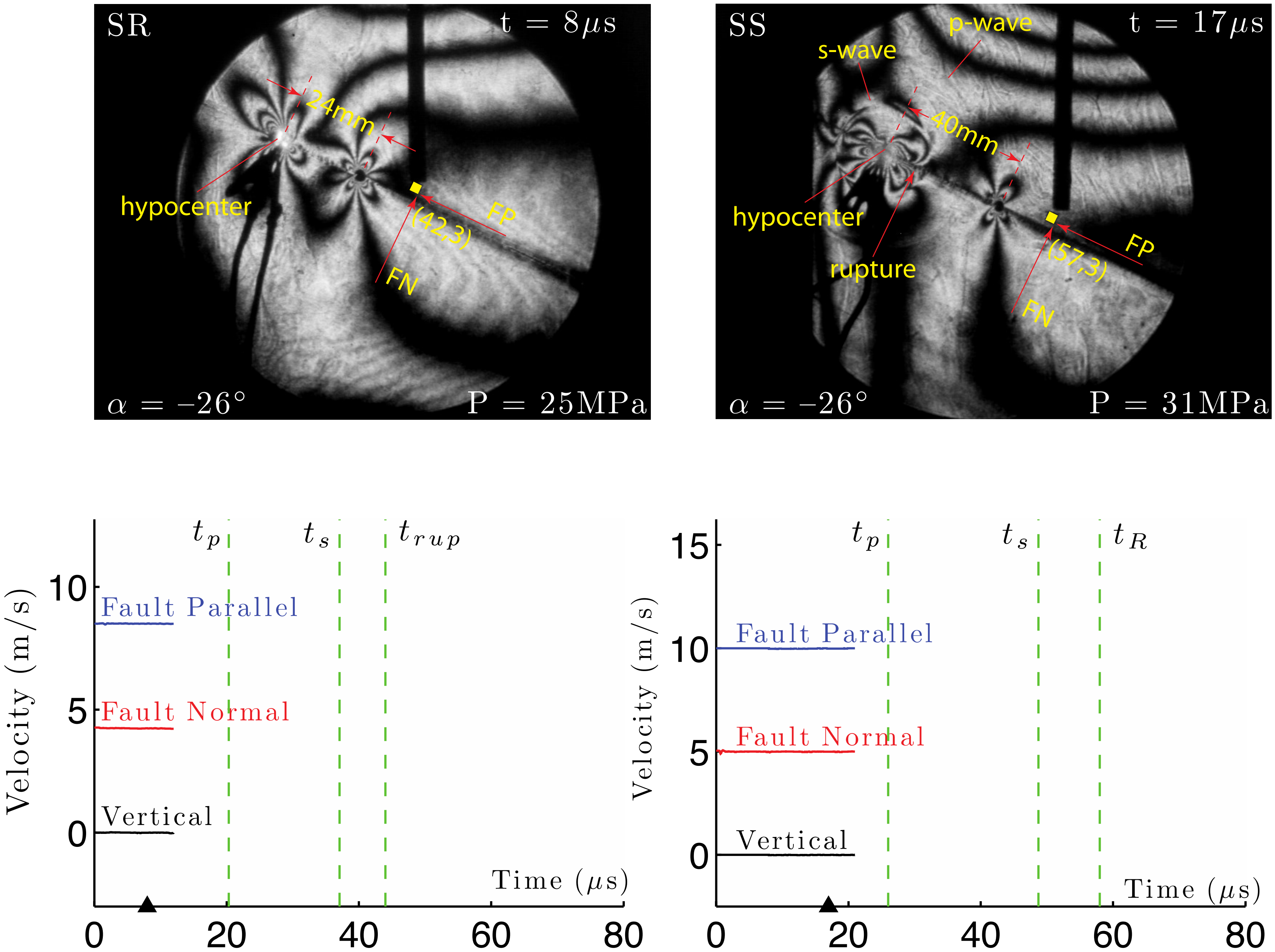




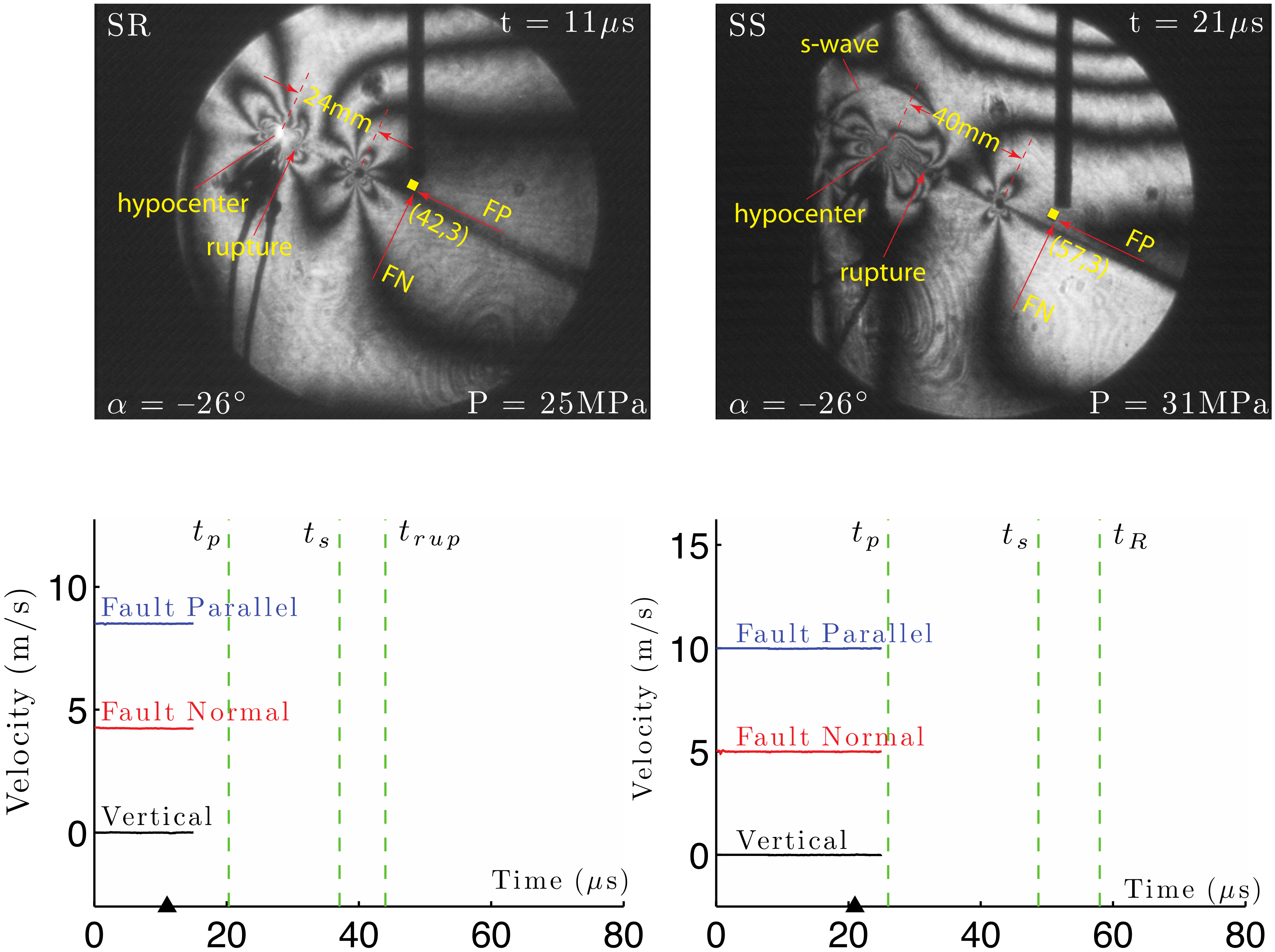
• Reproducing Denali in the Laboratory . Measurement N/E of the epicenter and 3mm North of the Fault.



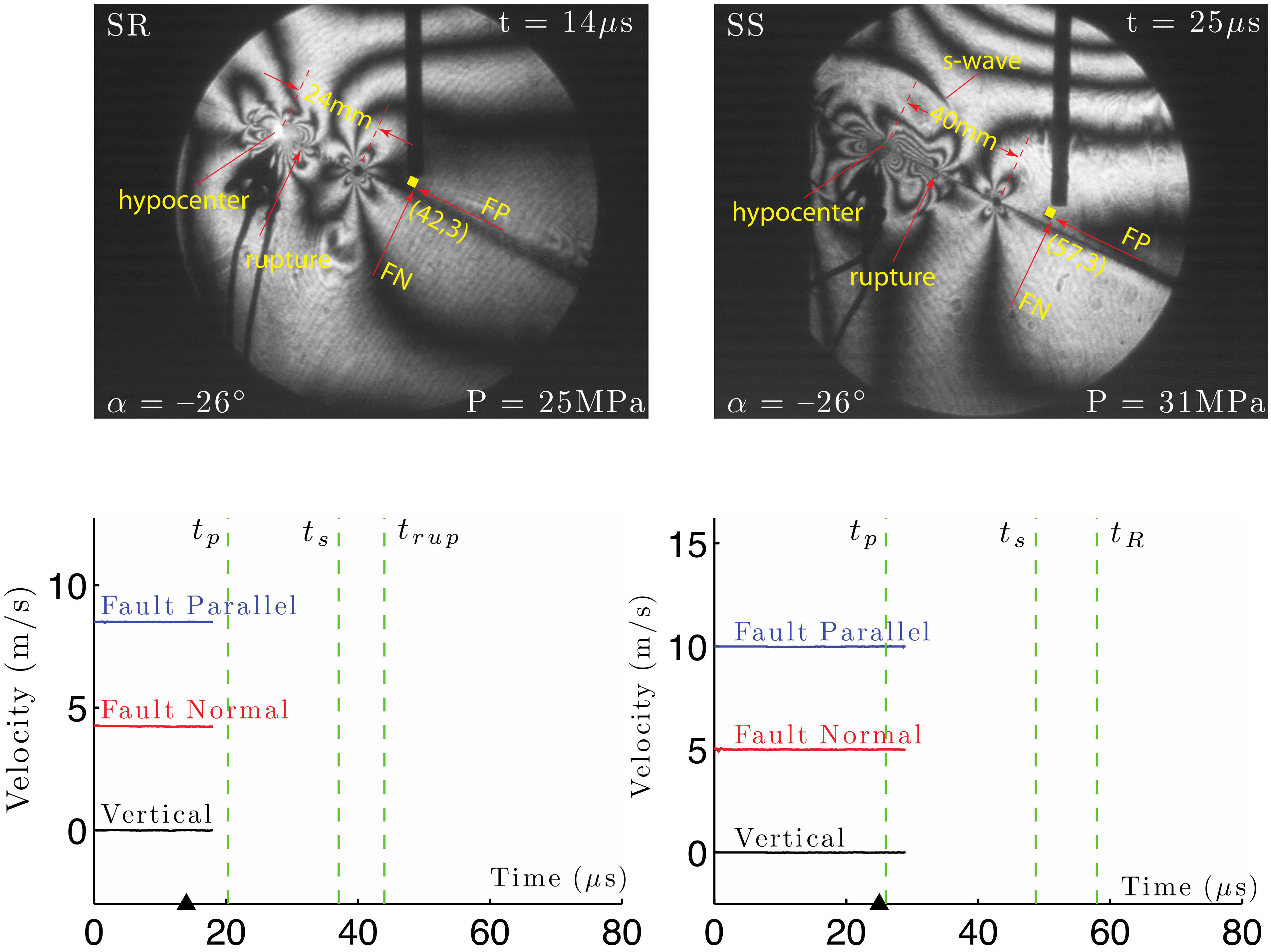




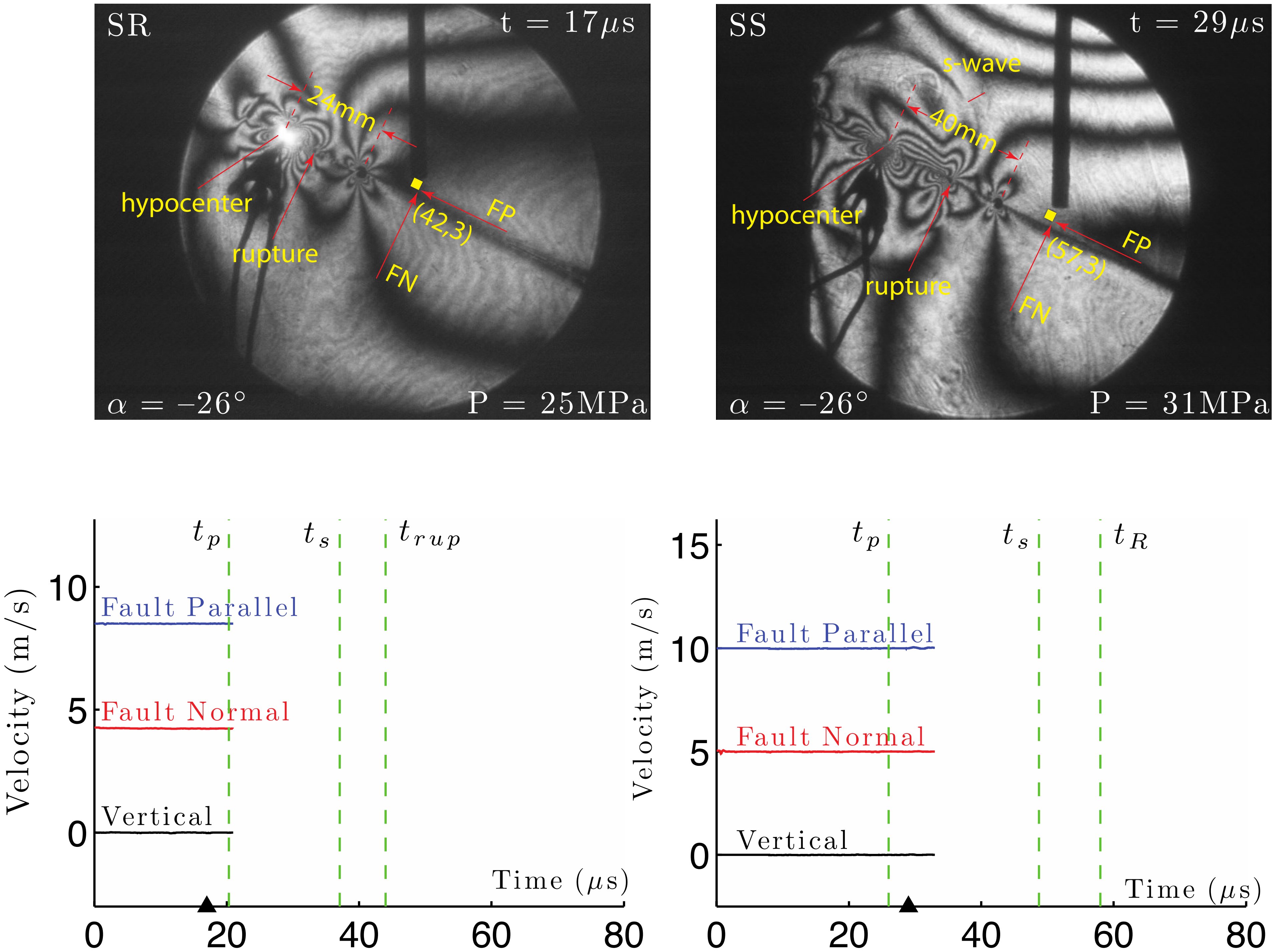
SR
t = 8μs
24mm
hypocenter
(42,3)
FP
FN
α = −26°
P = 25MPa
SS
t = 17μs
p-wave
s-wave
40mm
hypocenter
rupture
(57,3)
FP
FN
α = −26°
P = 31MPa
Velocity (m/s)
Fault Parallel
Fault Normal
Vertical
t_p
t_s
t_{rup}
t_R
Time (μs)
0
5
10
15
20
40
60
80



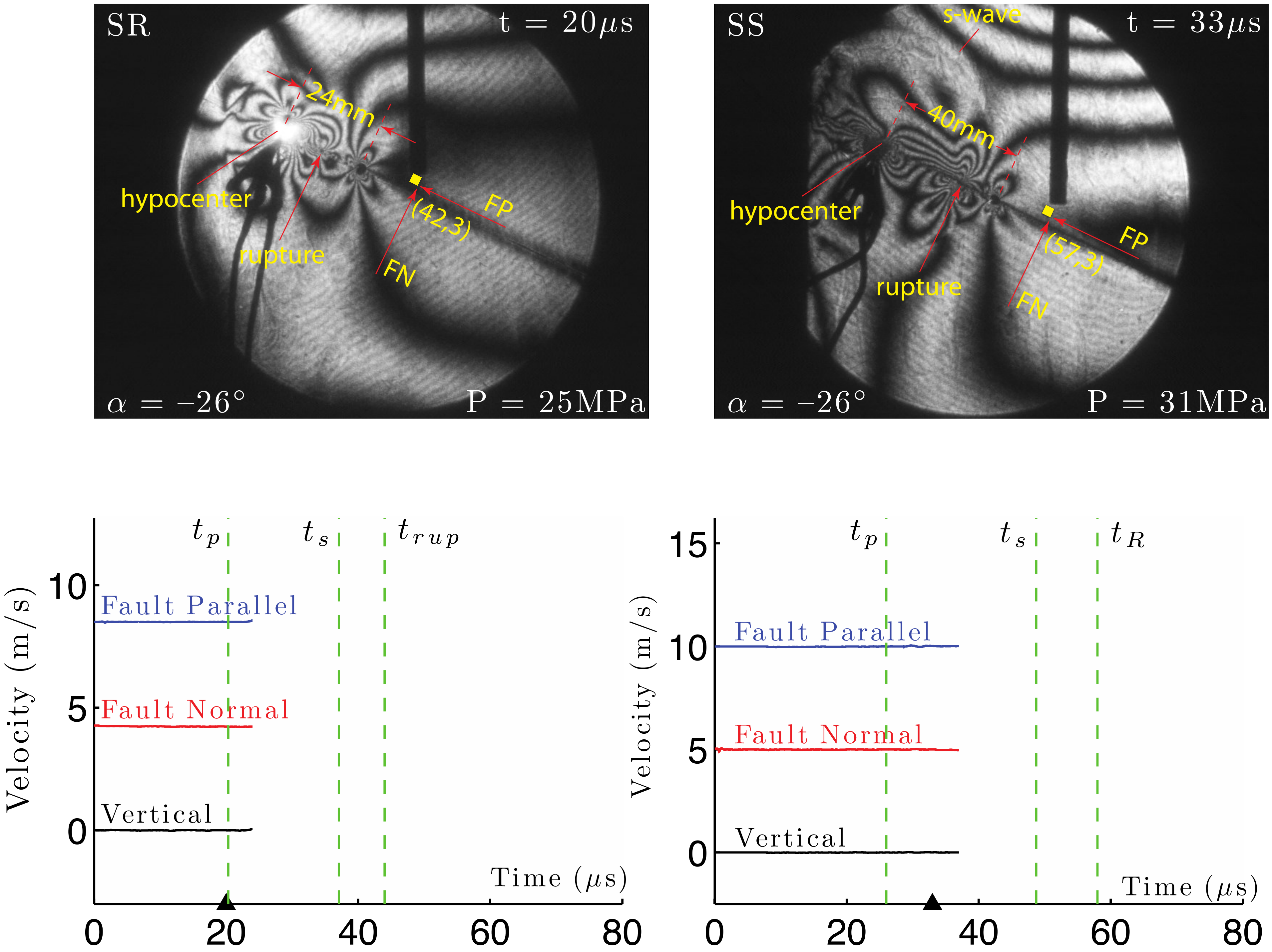
SR
t = 11μs
24mm
hypocenter
rupture
(42,3)
FP
FN
α = −26°
P = 25MPa
SS
t = 21μs
s-wave
40mm
hypocenter
rupture
(57,3)
FP
FN
α = −26°
P = 31MPa
Velocity (m/s)
Fault Parallel
Fault Normal
Vertical
t_p
t_s
t_{rup}
Time (μs)
0
5
10
0
20
40
60
80
Velocity (m/s)
Fault Parallel
Fault Normal
Vertical
t_p
t_s
t_R
Time (μs)
0
5
10
15
0
20
40
60
80



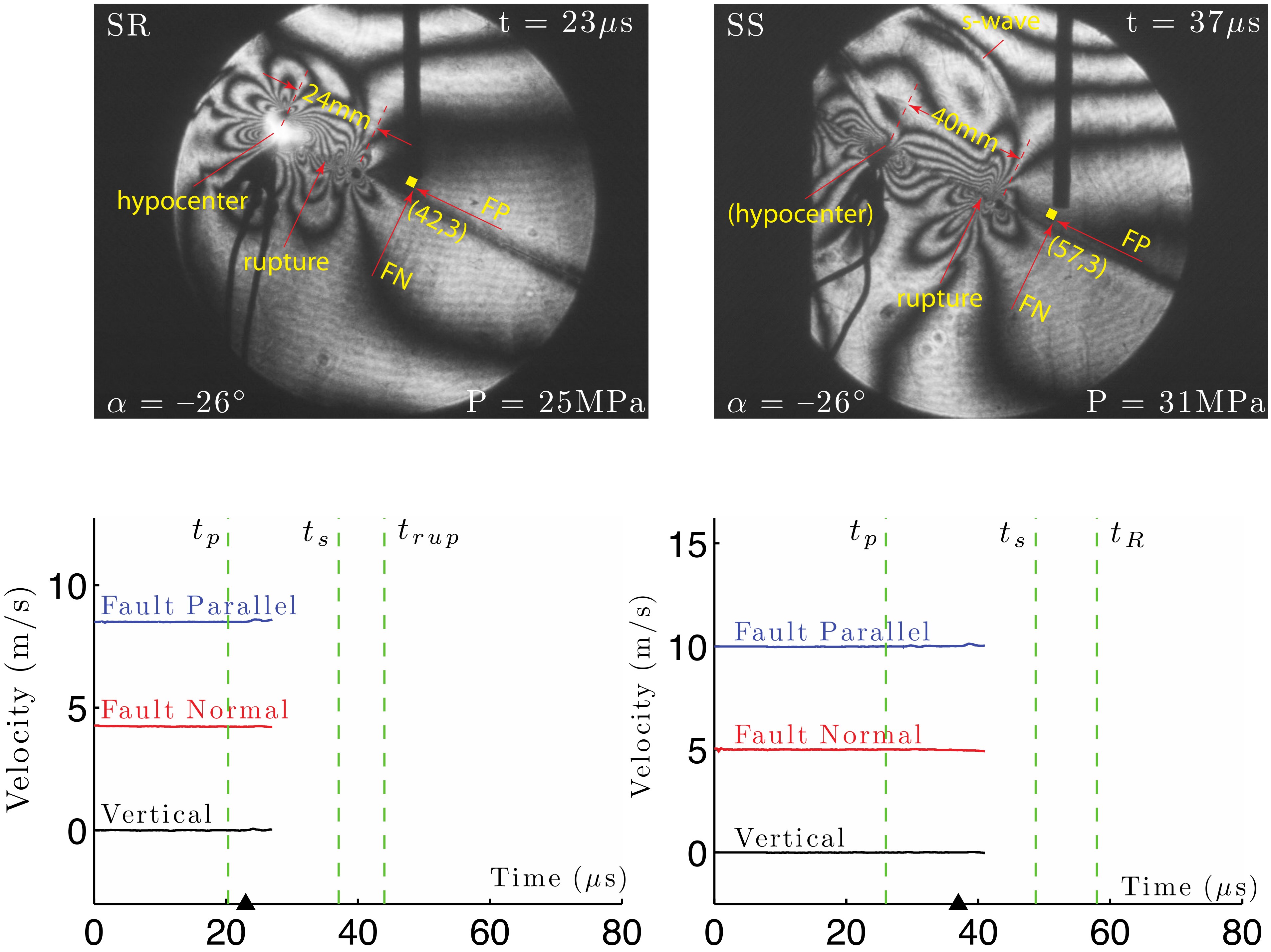
SR
t = 14μs
24mm
hypocenter
rupture
(42,3)
FP
FN
α = −26°
P = 25MPa
SS
t = 25μs
s-wave
40mm
hypocenter
rupture
(57,3)
FP
FN
α = −26°
P = 31MPa
Velocity (m/s)
Fault Parallel
Fault Normal
Vertical
t_p
t_s
t_{rup}
Time (μs)
0
5
10
0
20
40
60
80
Velocity (m/s)
Fault Parallel
Fault Normal
Vertical
t_p
t_s
t_R
Time (μs)
0
5
10
15
0
20
40
60
80



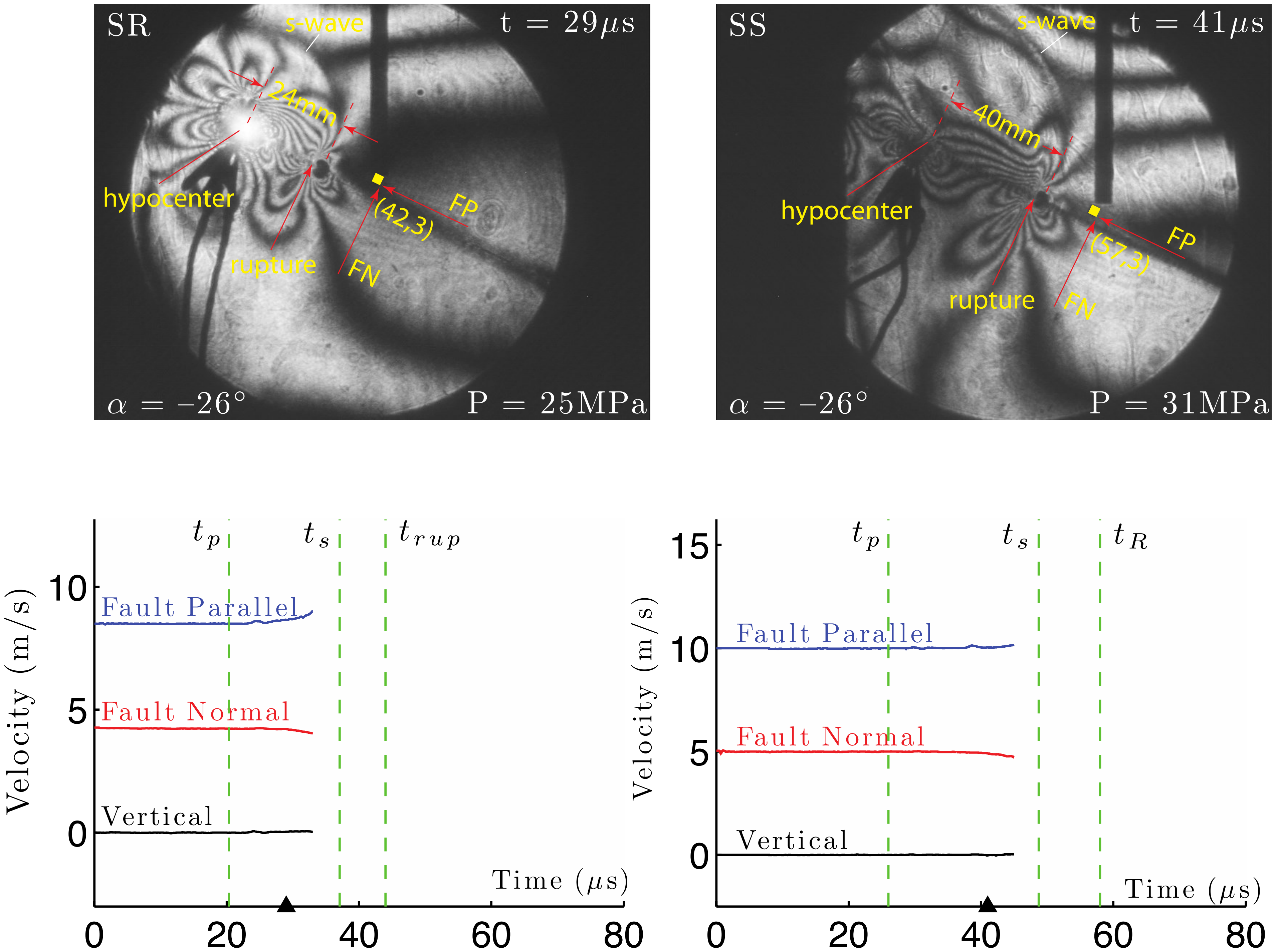
SR
t = 17μs
24mm
hypocenter
rupture
(42,3)
FP
FN
α = −26°
P = 25MPa
SS
t = 29μs
s-wave
40mm
hypocenter
rupture
(57,3)
FP
FN
α = −26°
P = 31MPa
t_p
t_s
t_rup
Fault Parallel
Fault Normal
Vertical
Velocity (m/s)
Time (μs)
0
5
10
0
20
40
60
80
t_p
t_s
t_R
Fault Parallel
Fault Normal
Vertical
Velocity (m/s)
Time (μs)
0
5
10
15
0
20
40
60
80



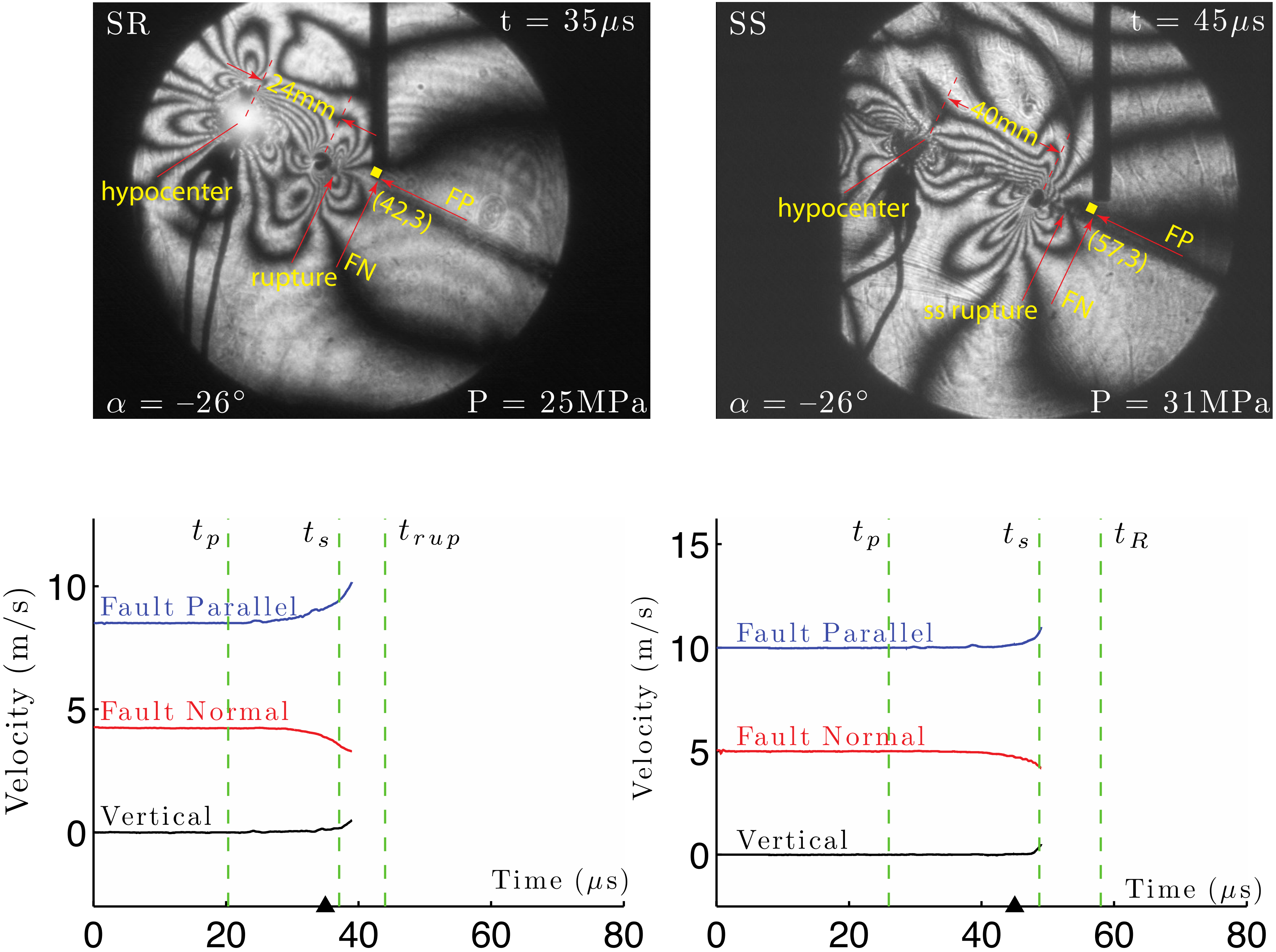
SR
t = 20μs
24mm
hypocenter
rupture
(42,3)
FP
FN
α = −26°
P = 25MPa
SS
t = 33μs
s-wave
40mm
hypocenter
rupture
(57,3)
FP
FN
α = −26°
P = 31MPa
t_p
t_s
t_{rup}
Fault Parallel
Fault Normal
Vertical
Velocity (m/s)
Time (μs)
t_p
t_s
t_R
Fault Parallel
Fault Normal
Vertical
Velocity (m/s)
Time (μs)



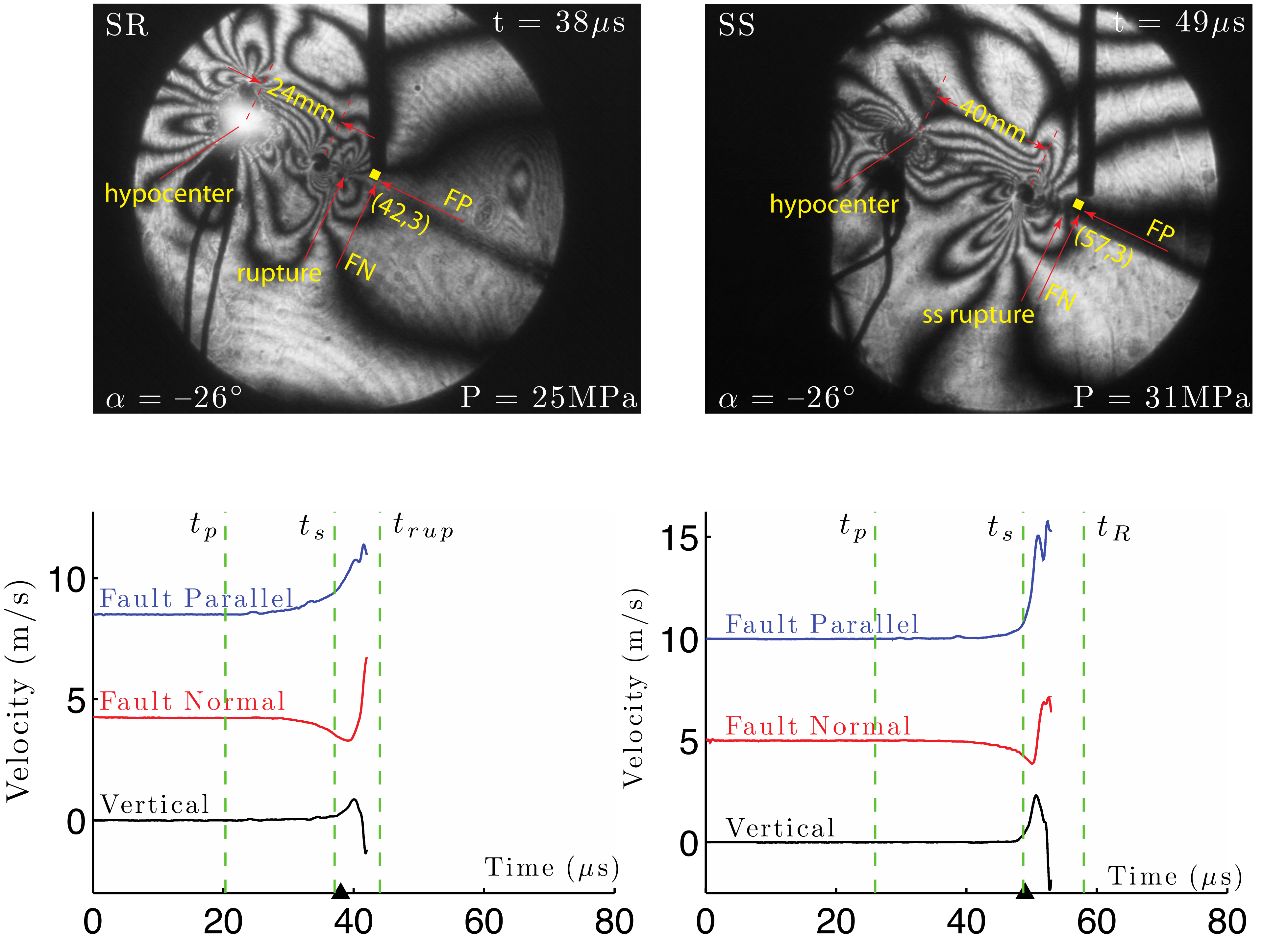
SR
t = 23μs
24mm
hypocenter
rupture
FP
FN
(42,3)
α = −26°
P = 25MPa
SS
t = 37μs
s-wave
40mm
(hypocenter)
rupture
FP
FN
(57,3)
α = −26°
P = 31MPa
Velocity (m/s)
Time (μs)
Fault Parallel
Fault Normal
Vertical
t_p
t_s
t_{rup}
t_R
0
5
10
15
20
40
60
80



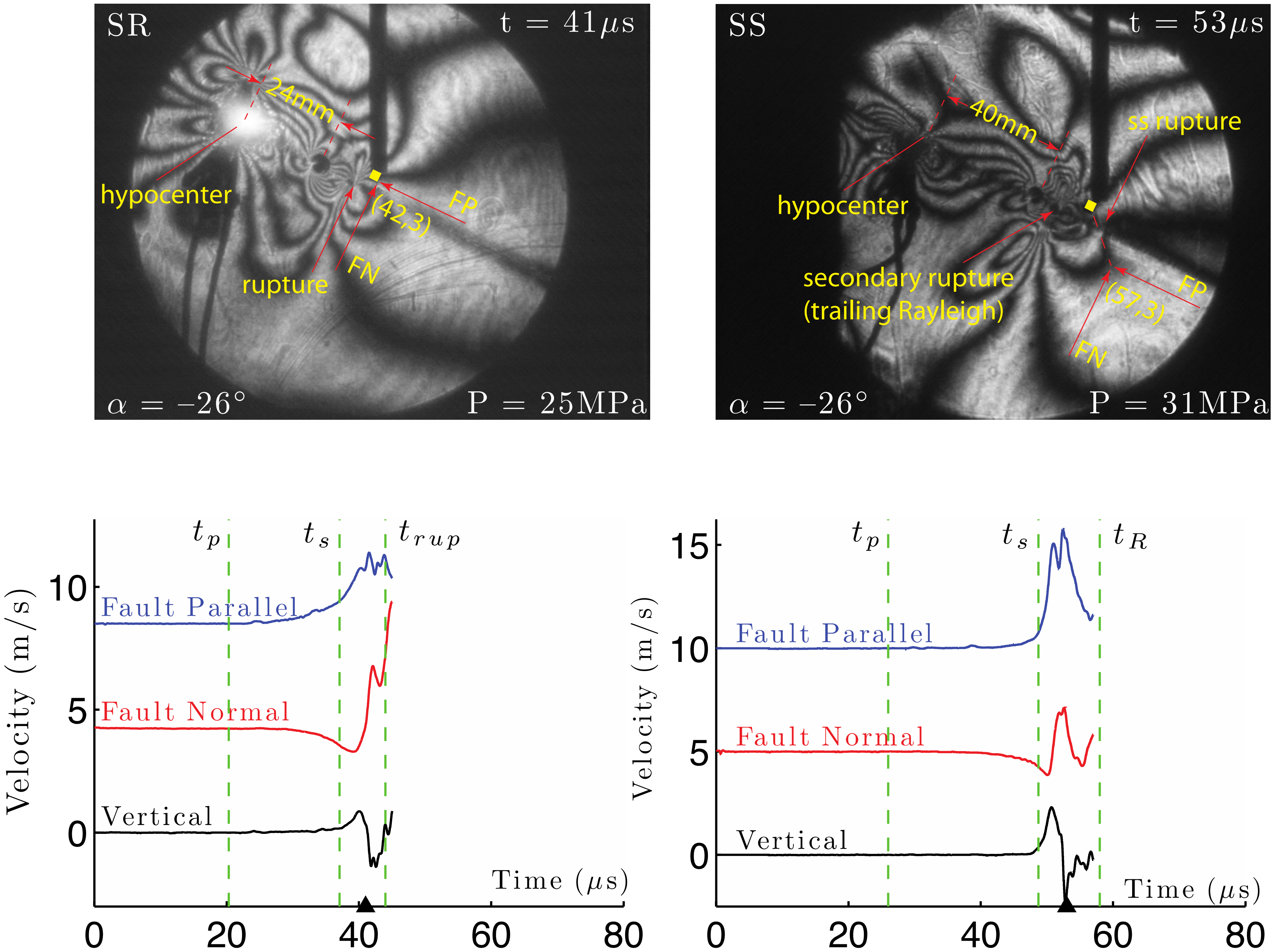
SR
s-wave
t = 29μs
24mm
hypocenter
rupture
FP
FN
(42,3)
α = −26°
P = 25MPa
SS
s-wave
t = 41μs
40mm
hypocenter
rupture
FP
FN
(57,3)
α = −26°
P = 31MPa
Velocity (m/s)
Fault Parallel
Fault Normal
Vertical
Time (μs)
t_p
t_s
t_{rup}
t_R
0
20
40
60
80
5
10
15



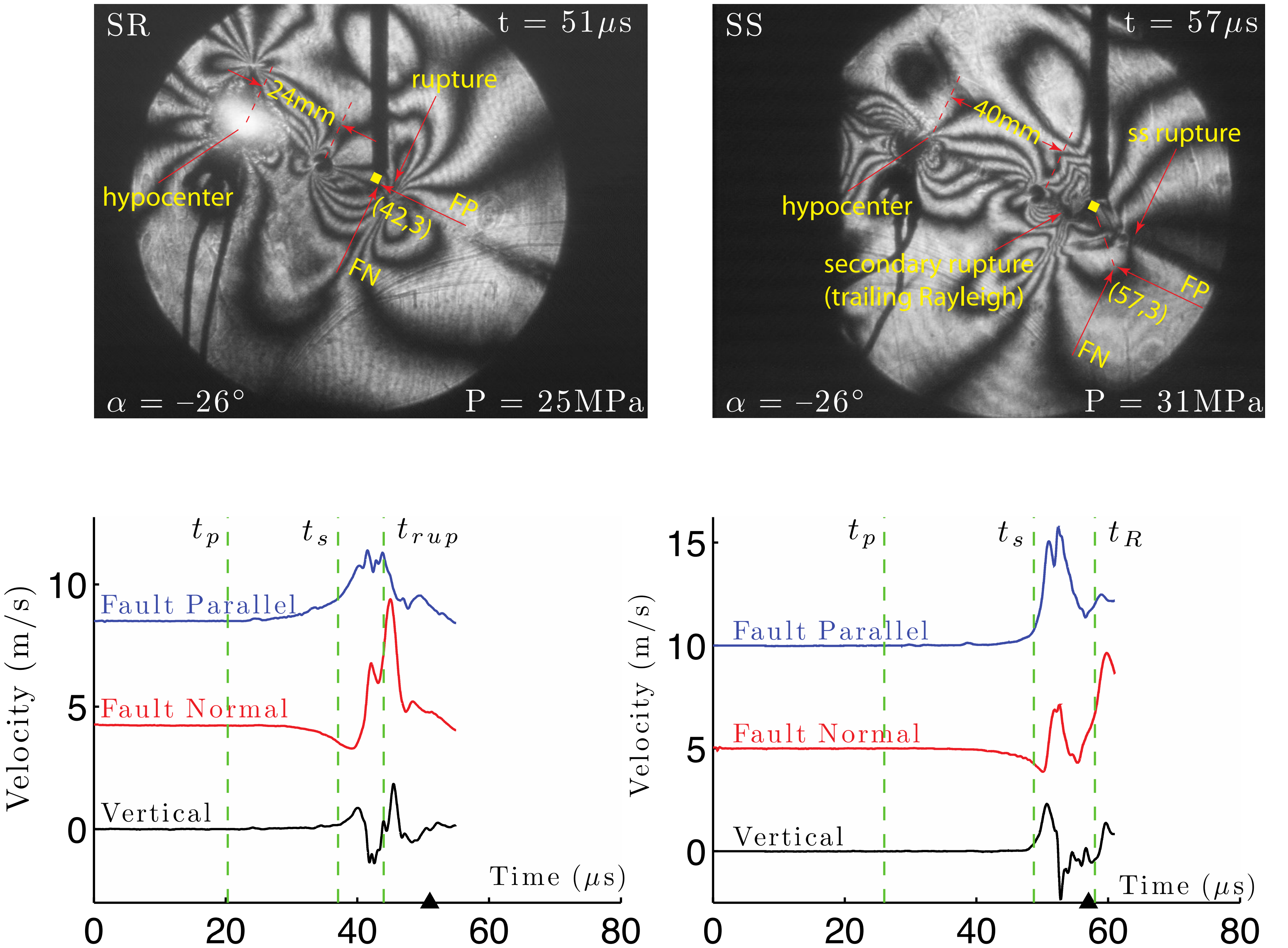
SR
t = 35μs
24mm
hypocenter
rupture
FN
FP
(42,3)
α = −26°
P = 25MPa
SS
t = 45μs
40mm
hypocenter
ss rupture
FN
FP
(57,3)
α = −26°
P = 31MPa
Velocity (m/s)
Time (μs)
Fault Parallel
Fault Normal
Vertical
t_p
t_s
t_{rup}
t_R
0
5
10
15
20
40
60
80

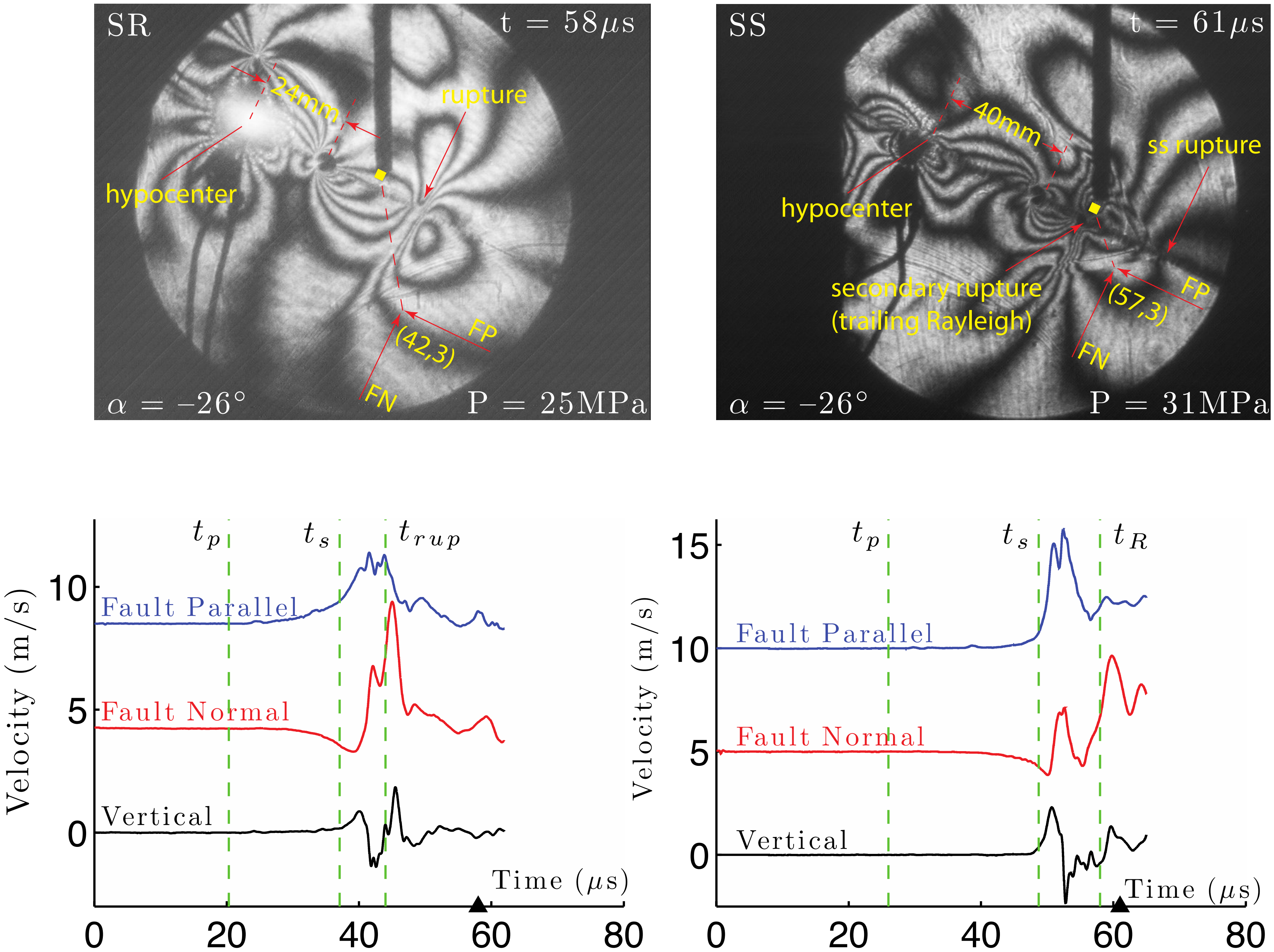


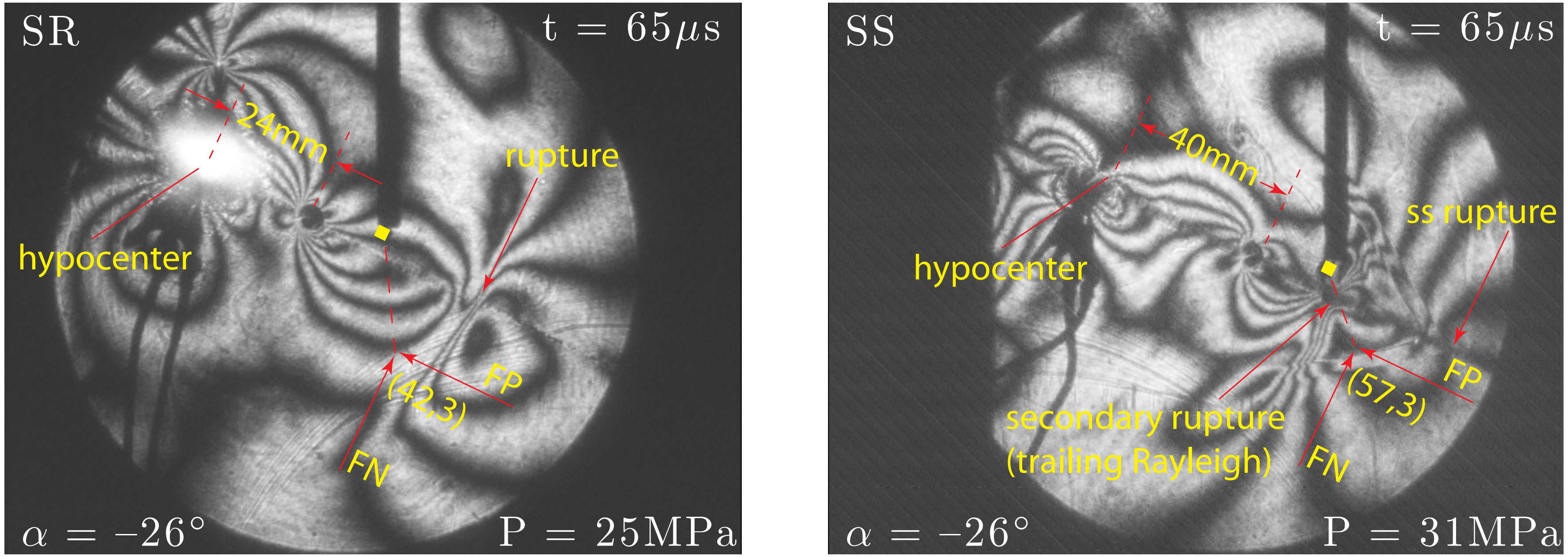
SR
t = 38μs
24mm
hypocenter
(42,3)
FP
FN
rupture
α = −26°
P = 25MPa
SS
t = 49μs
40mm
hypocenter
(57,3)
FP
FN
ss rupture
α = −26°
P = 31MPa
Velocity (m/s)
t_p
t_s
t_{rup}
Fault Parallel
Fault Normal
Vertical
Time (μs)
0
5
10
0
20
40
60
80
Velocity (m/s)
t_p
t_s
t_R
Fault Parallel
Fault Normal
Vertical
Time (μs)
0
5
10
15
0
20
40
60
80



SR
t = 41μs
24mm
hypocenter
(42,3)
FP
FN
rupture
α = −26°
P = 25MPa
SS
t = 53μs
40mm
ss rupture
hypocenter
secondary rupture
(trailing Rayleigh)
(57,3)
FP
FN
α = −26°
P = 31MPa
t_p
t_s
t_{rup}
Velocity (m/s)
Fault Parallel
Fault Normal
Vertical
Time (μs)
0
5
10
0
20
40
60
80
t_p
t_s
t_R
Velocity (m/s)
Fault Parallel
Fault Normal
Vertical
Time (μs)
0
5
10
15
0
20
40
60
80

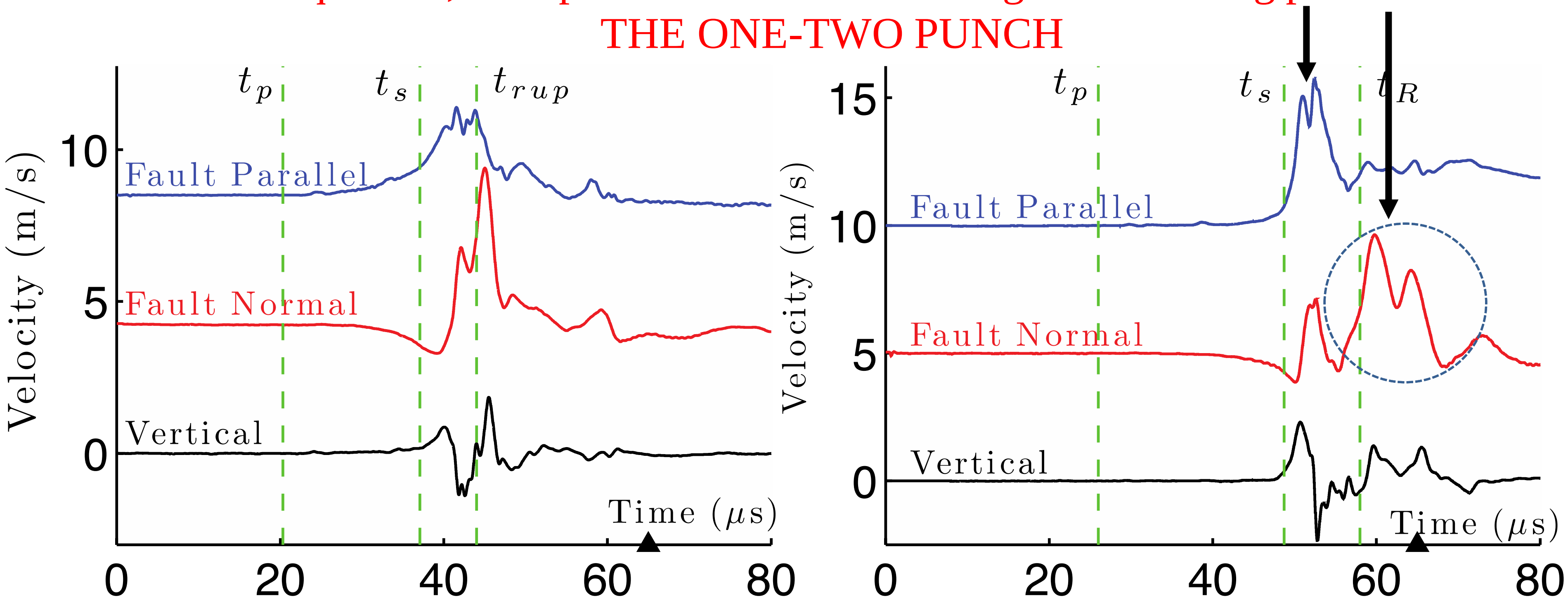

SR
t = 51μs
24mm
rupture
hypocenter
FP
(42,3)
FN
α = −26°
P = 25MPa
SS
t = 57μs
40mm
ss rupture
hypocenter
secondary rupture
(trailing Rayleigh)
(57,3)
FP
FN
α = −26°
P = 31MPa
Velocity (m/s)
Fault Parallel
Fault Normal
Vertical
Time (μs)
t_p
t_s
t_{rup}
t_R
0
5
10
15
20
40
60
80


SR
t = 58μs
24mm
rupture
hypocenter
FP
(42,3)
FN
α = −26°
P = 25MPa
SS
t = 61μs
40mm
ss rupture
hypocenter
secondary rupture
(trailing Rayleigh)
(57,3)
FP
FN
α = −26°
P = 31MPa
t_p
t_s
t_{rup}
Fault Parallel
Fault Normal
Vertical
Velocity (m/s)
Time (μs)
t_R



Sequential, fault parallel and fault normal ground shaking peaks.

THE ONE-TWO PUNCH



Particle velocity fields for steady state singular elastic solution

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

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

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

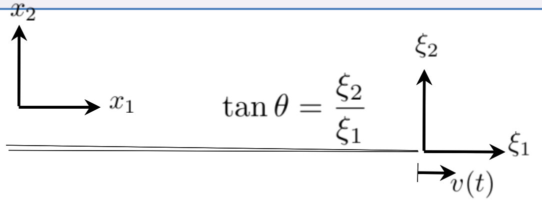
$$\dot{u}_2 = \dot{u}_2^s + \dot{u}_2^p$$

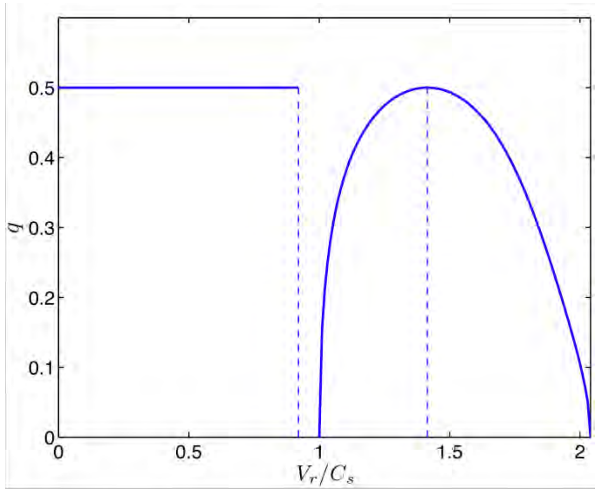
$$\dot{u} = \sqrt{\dot{u}_1^2 + \dot{u}_2^2}$$

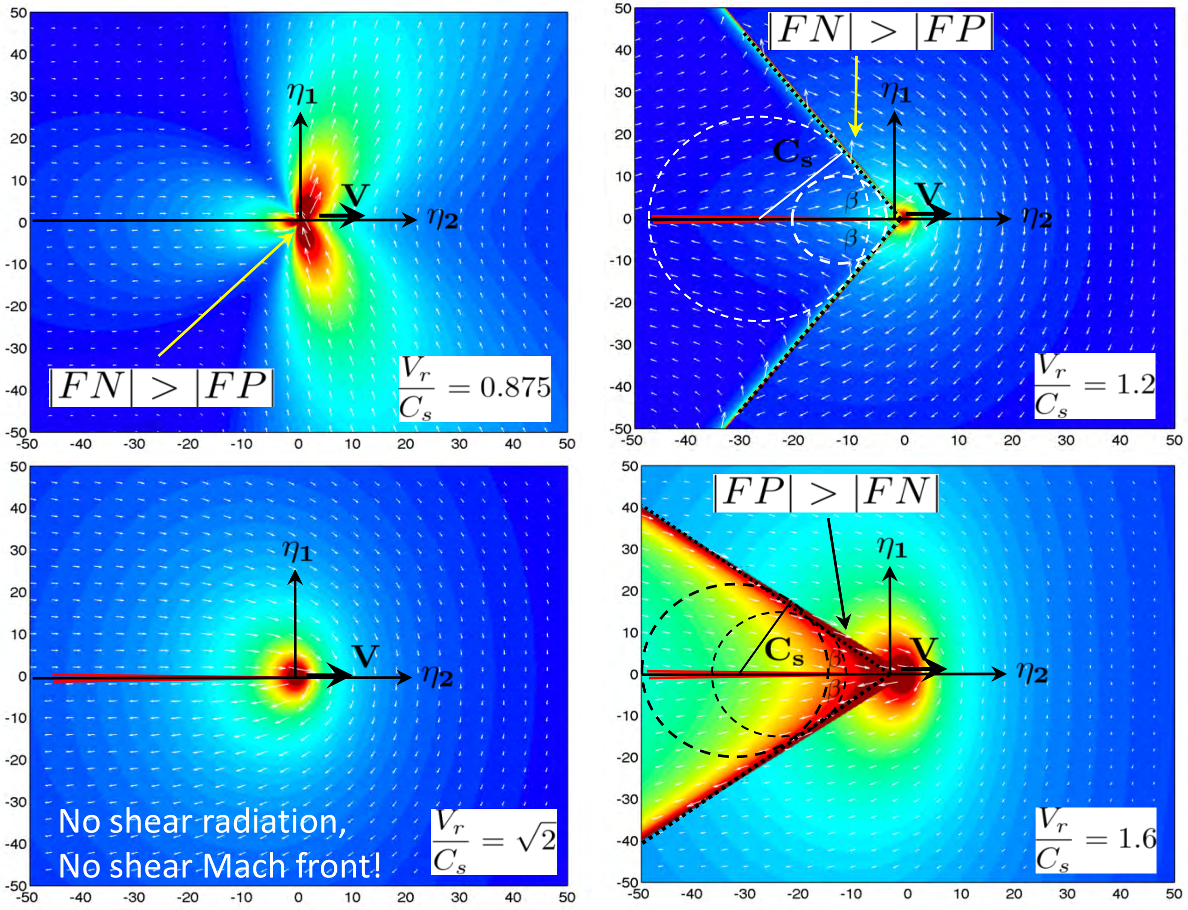
Freund JGR (1979)&Freund (1990)

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

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







D_c

$\delta\dot{u}^s_{FP}$

$\delta\dot{u}^s_{FN}$

$\delta\dot{u}^s_y$

$\delta\dot{u}^s_x$

$\left|\frac{\delta\dot{u}^s_x}{\delta\dot{u}^s_y}\right|$

$\left|\frac{\delta\dot{u}^s_{FP}}{\delta\dot{u}^s_{FN}}\right|$

$=$

Detailed observations of transition to Supershear (images 4μs Apart)

llo
Caltech

Harsha S. Bhat
NS Paris/ Caltech

Hiroo Kanamori
Seismo -Lab
Caltech

Mello, Rosakis, Bhat and Kanamori, Tectonophysics, 2010 and JMPS 2016