Evolution of rupture style with total fault displacement: insight from meter-scale direct shear experiments

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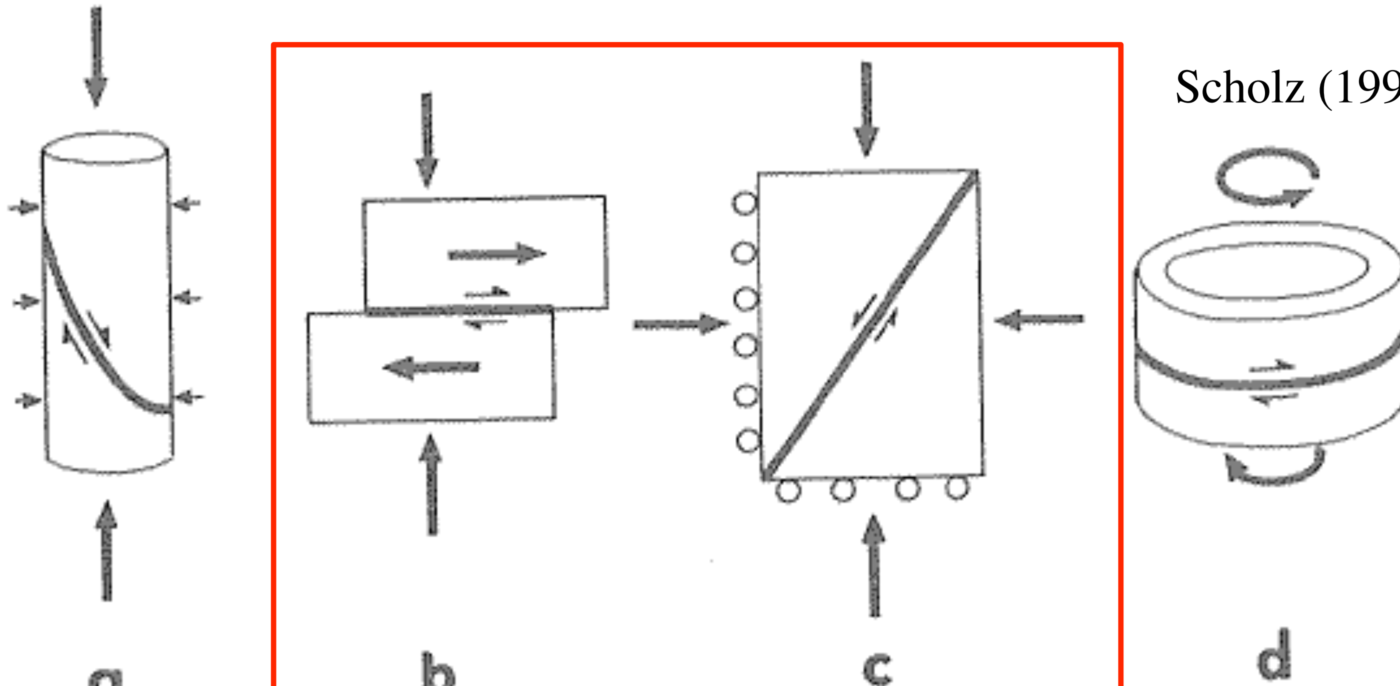
RITSUMEIKAN

NMEM – July 7, 2015 @ Smolenice Castle, Slovakia

Motivations

- Fault zone properties: maturity, roughness, gouge layer thickness, off-fault damage, permeability, etc
- Fault motion styles: stable creep, unstable rupture propagation, conditionally (un)stable motion
- Question: what controls the type of fault motion (loading condition, fault zone properties, etc)
- Focus on how fault rupture style evolves with the total fault displacement (net effect)

Experimental loading configurations



Scholz (1990)

Triaxial compression

Direct shear

Biaxial loading

Rotary shear

high confining pressure

centimeter-scale

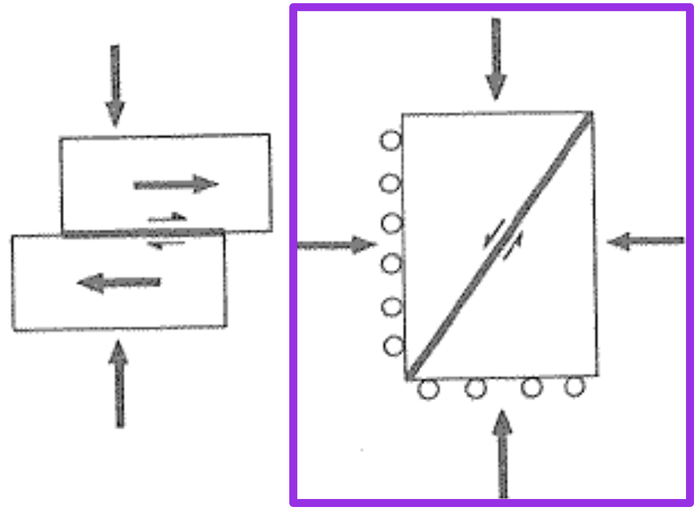
fracture of intact rocks
rupture along pre-cut surface

stick-slip events

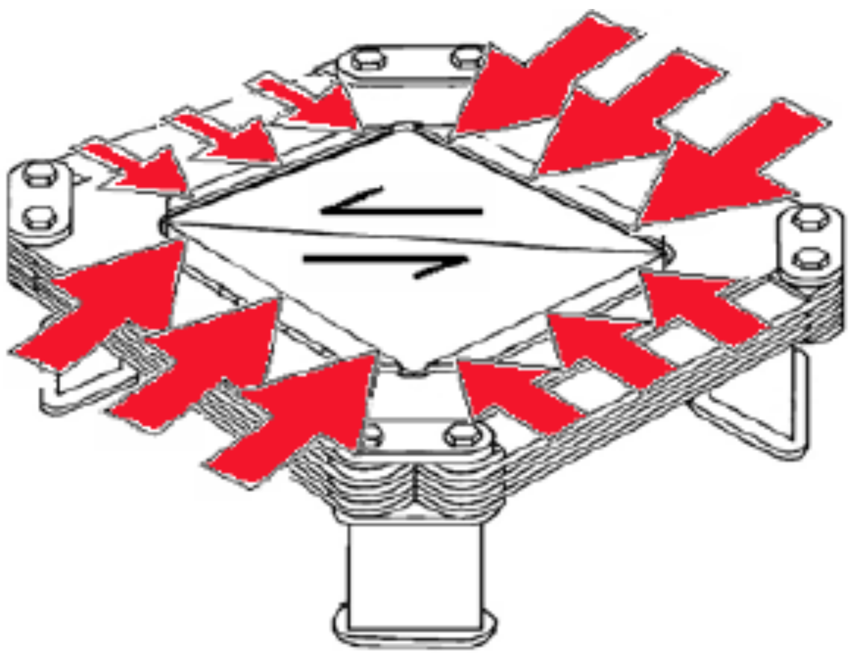
up to meter-scale

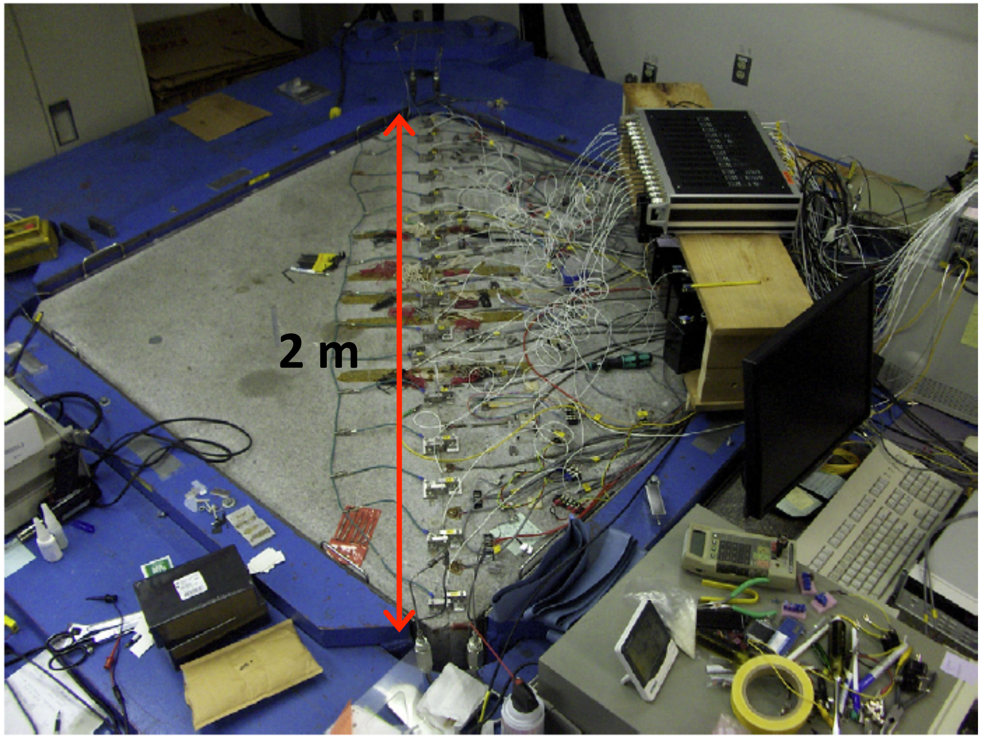
large displacement
up to m/s loading velocity

centimeter-scale
steady-state or transient frictional response



USGS at Menlo Park

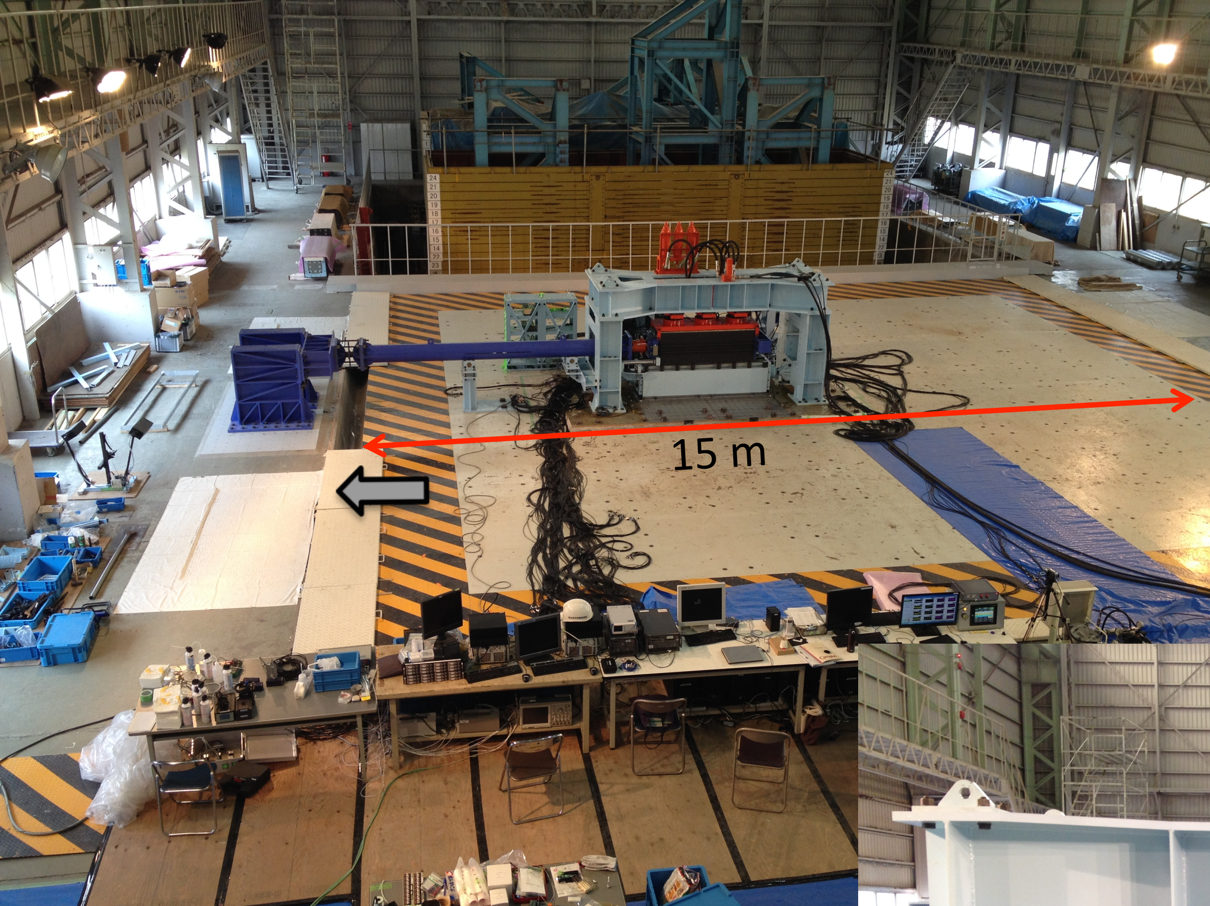


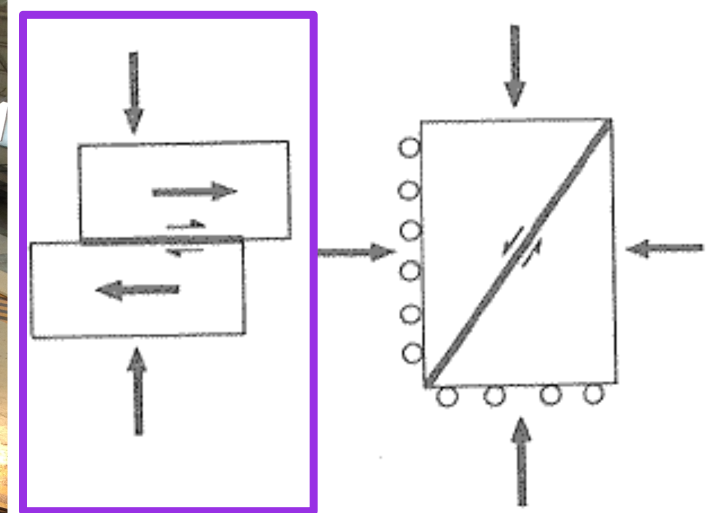


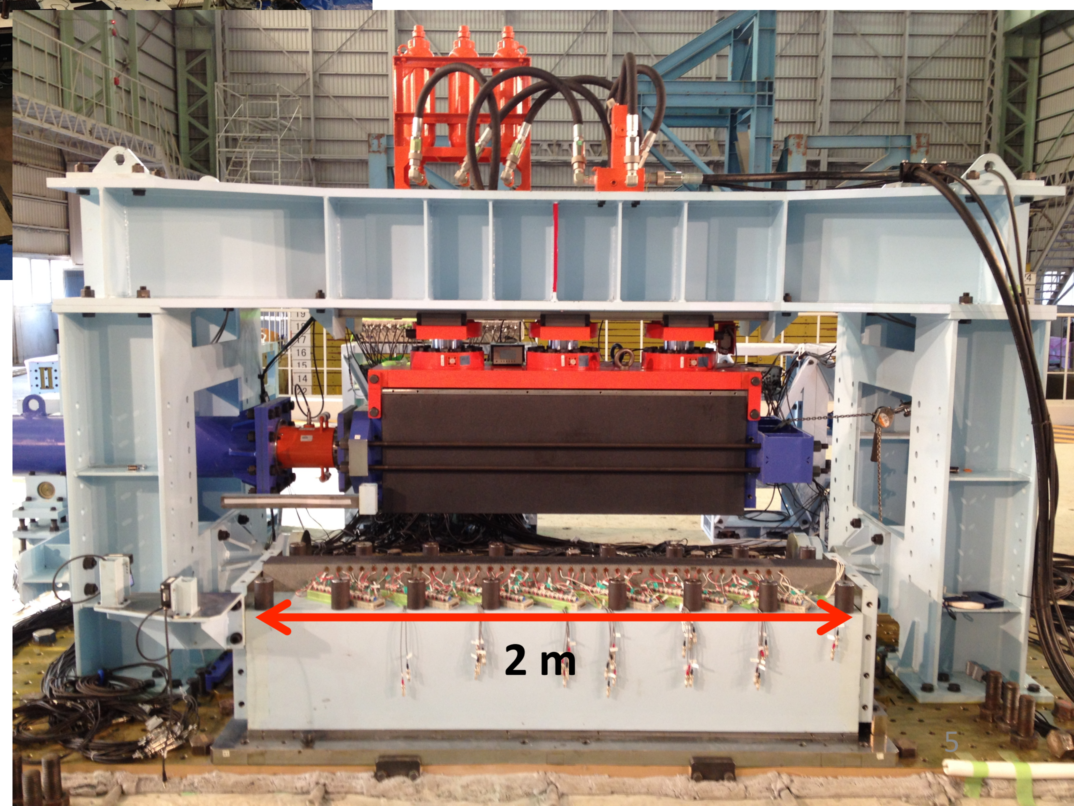
Small displacement (~ cm)
Slow loading rate
Cannot check the fault surface condition

Photos courtesy of McLaskey and Beeler

NIED, Tsukuba, Japan





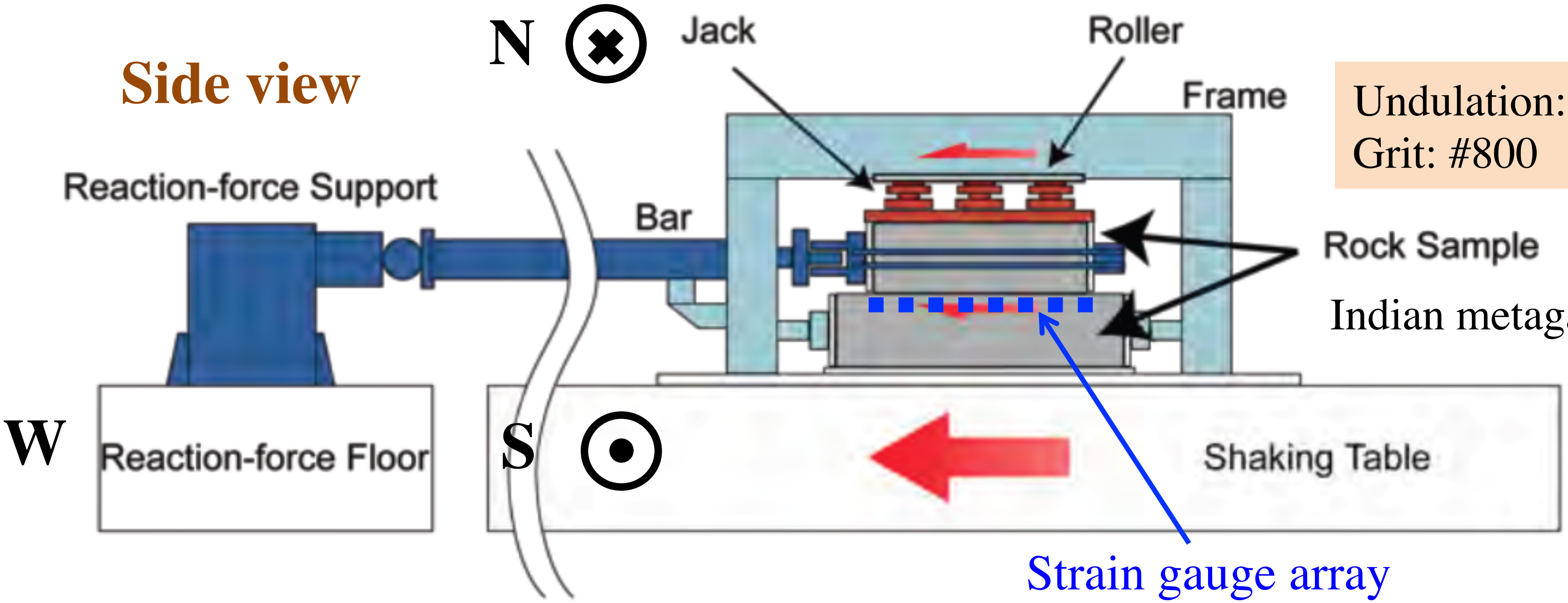


Up to 0.4 m displacement per run

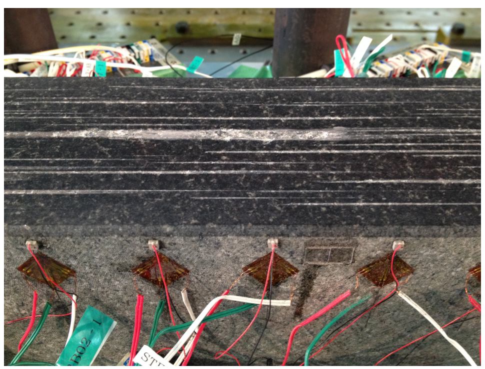
Both slow and fast loading rate

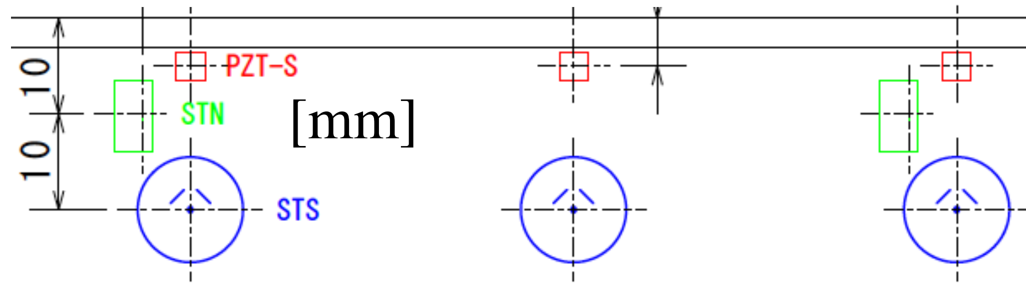
Can check the fault surface condition after each run

Side view



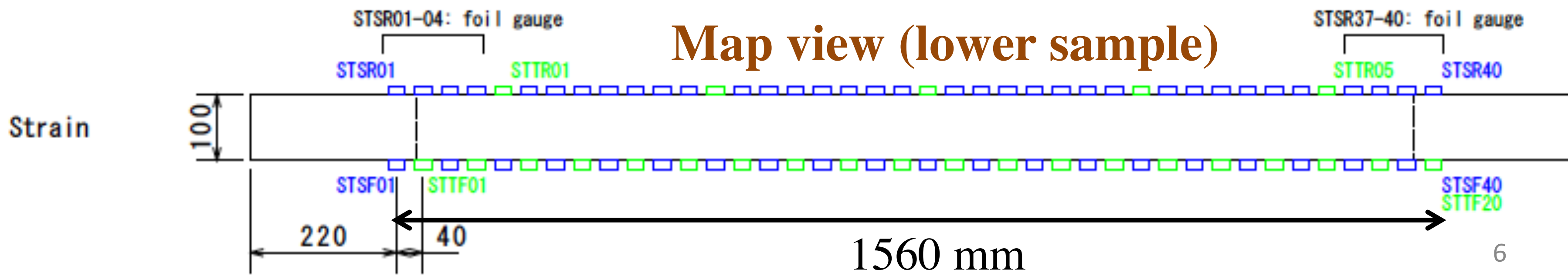
Undulation: <10 μm
Grit: #800

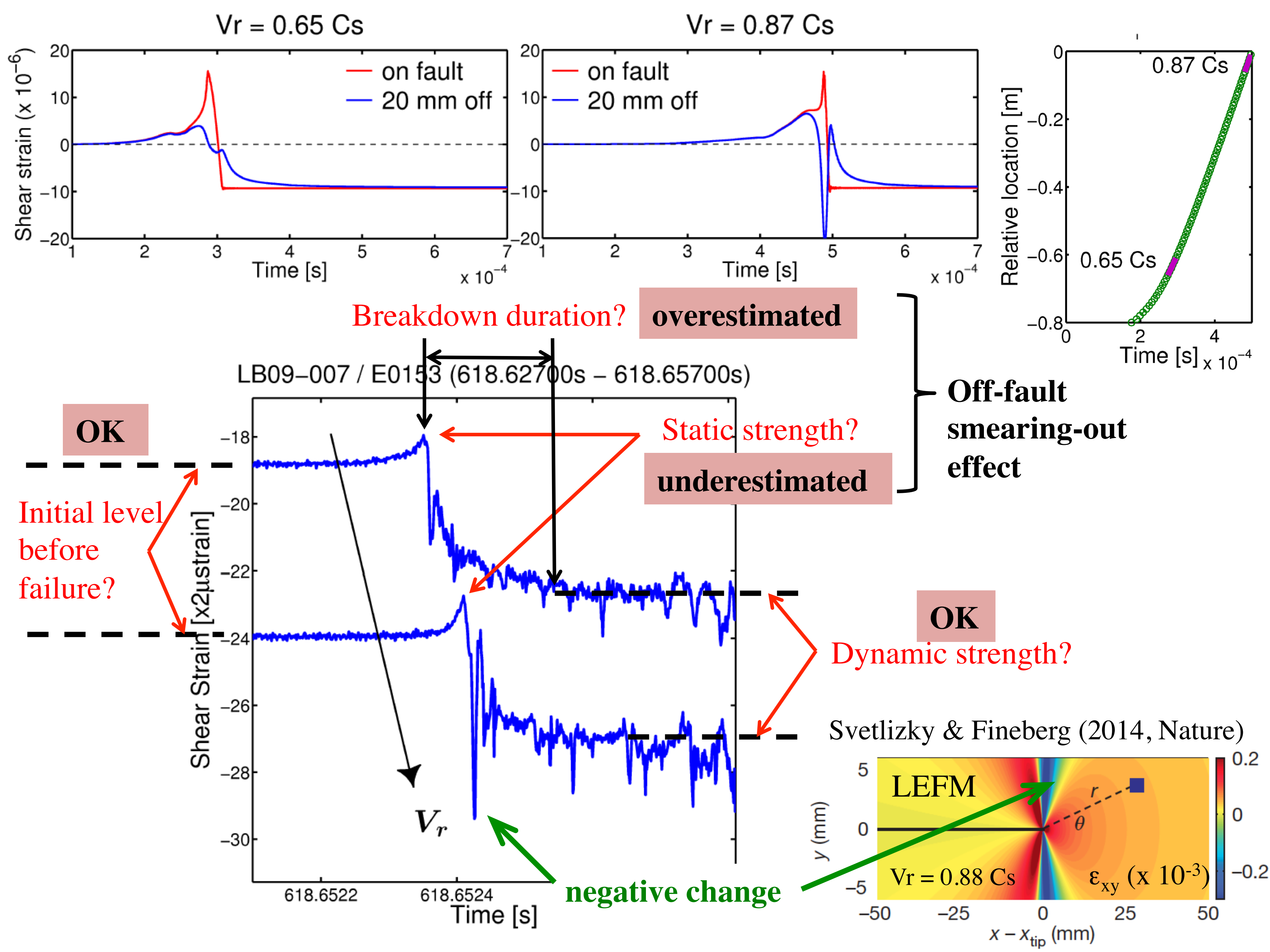




Sampling rate: 1 MHz

Map view (lower sample)





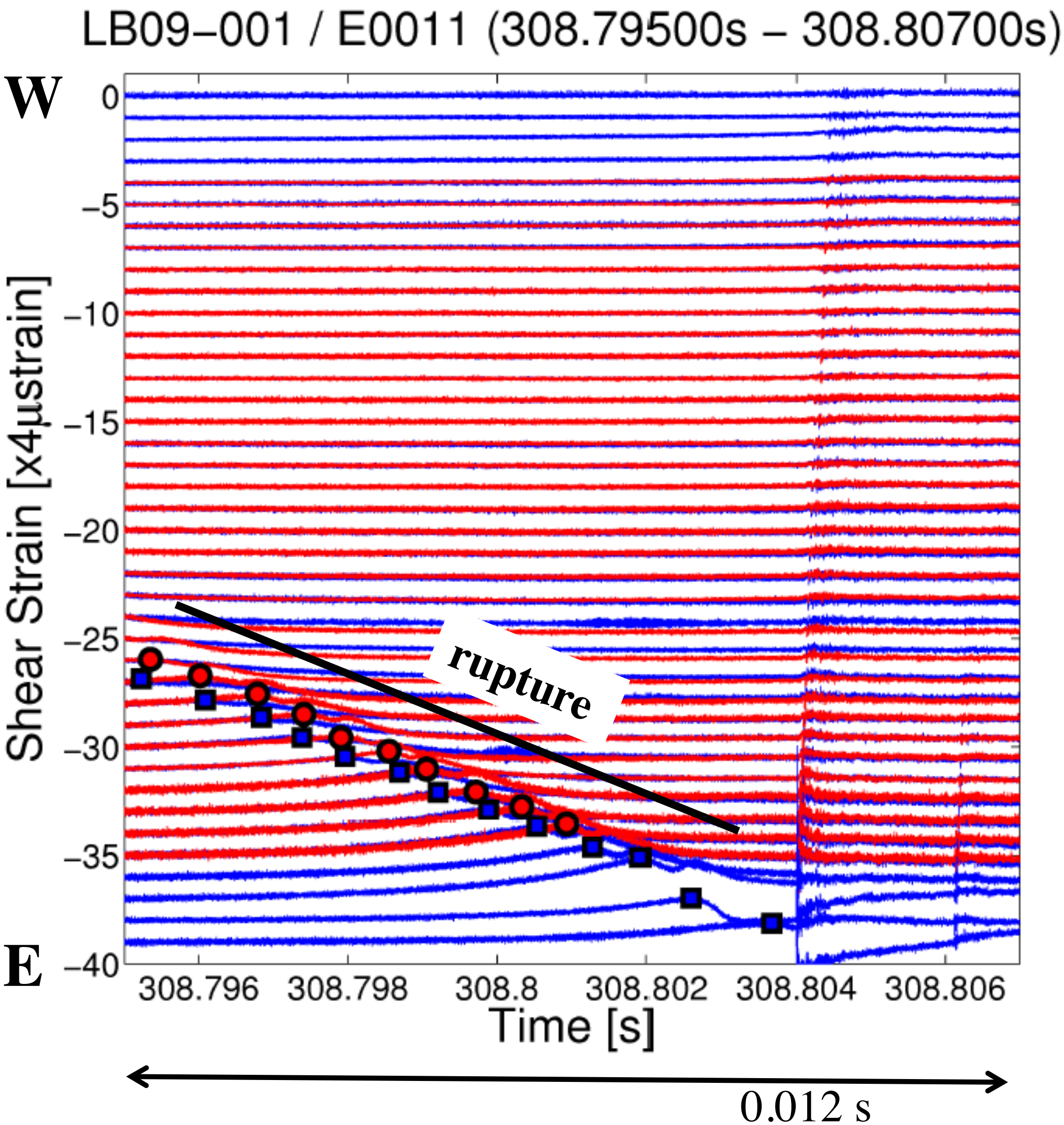
Vr = 0.65 Cs
Vr = 0.87 Cs
on fault
20 mm off
Shear strain (x 10^-6)
Time [s]
x 10^-4
Relative location [m]
0.87 Cs
0.65 Cs
Breakdown duration?
overestimated
LB09−007 / E0153 (618.62700s – 618.65700s)
OK
Static strength?
underestimated
Off-fault smearing-out effect
Initial level before failure?
Shear Strain [x2μstrain]
OK
Dynamic strength?
Svetlizky & Fineberg (2014, Nature)
LEFM
Vr = 0.88 Cs
εxy (x 10^-3)
y (mm)
x − x_tip (mm)
Vr
negative change

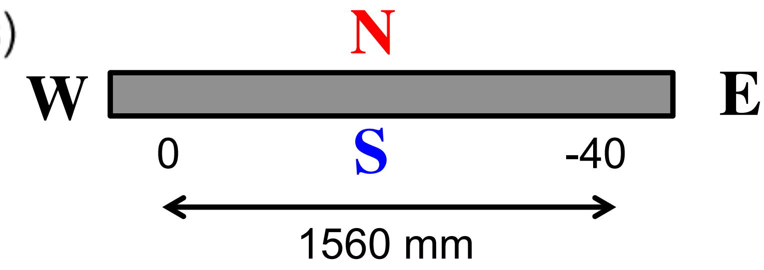
LB09-001 (in 2014)

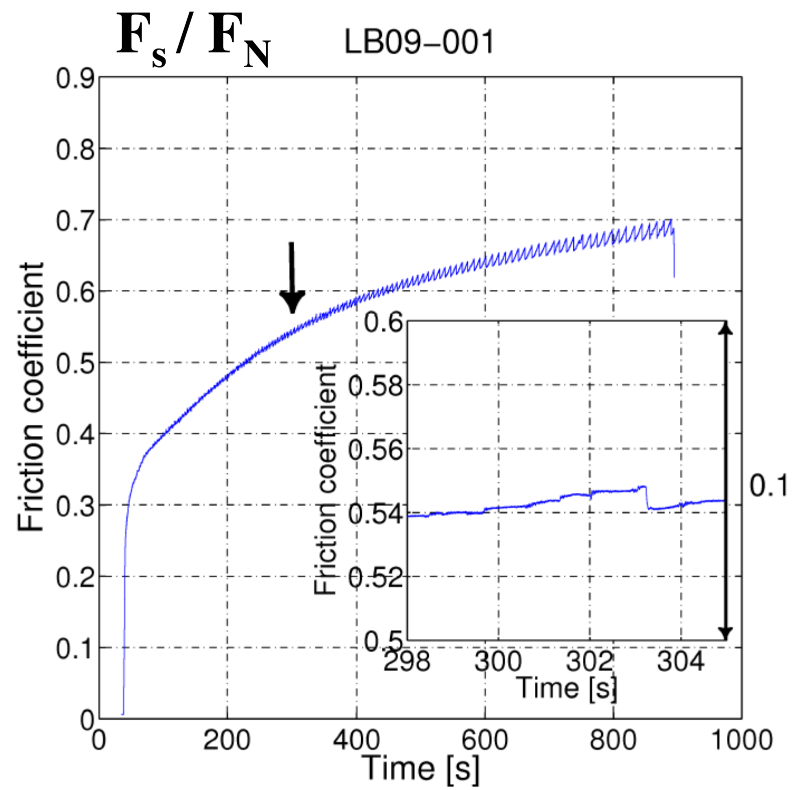
- Normal stress: 6.7 MPa
- Loading rate: 0.01 mm/s
- Incremental displacement: **6.9 mm**
- Cumulative displacement: **6.9 mm**

Yamashita-type (100mm/gabbro)

	normal stress(MPa)	loading vel (mm/s)	max. disp(mm)	strain mode	AE sensors	ACC	Conducted date
LB09-001	6.7	0.01	6.9	shear only	P-mode, 64ch	NIED,3Comp	4/7
LB09-002	6.7	0.01	6.1	shear only	S-mode, 64ch	NIED,3Comp	4/7
LB09-003	6.7	0.1	36.2	shear only	S-mode, 64ch	NIED,3Comp	4/8
LB09-004	6.7	1	396.0	shear only	S-mode, 64ch	none	4/8
LB09-005	6.7	0.1/0.01	22.2	shear only	S-mode, 64ch	NIED,3Comp	4/9
LB09-006	6.7	0.1/0.01	34.4	shear only	P-mode, 64ch	NIED,3Comp	4/9
LB09-007	6.7	0.1/0.01	35.5	shear only	S-mode, 64ch	NIED,3Comp	4/9



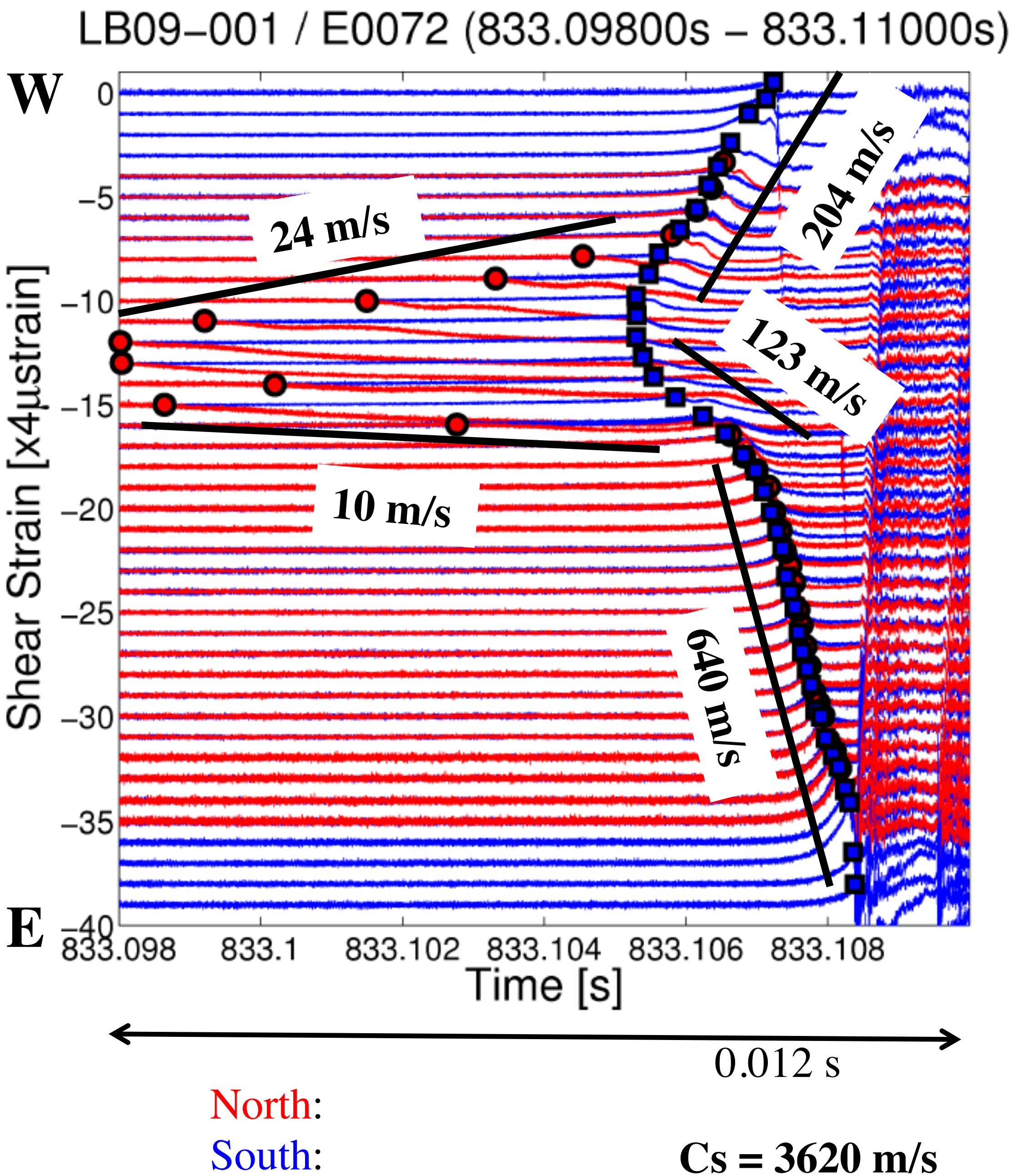


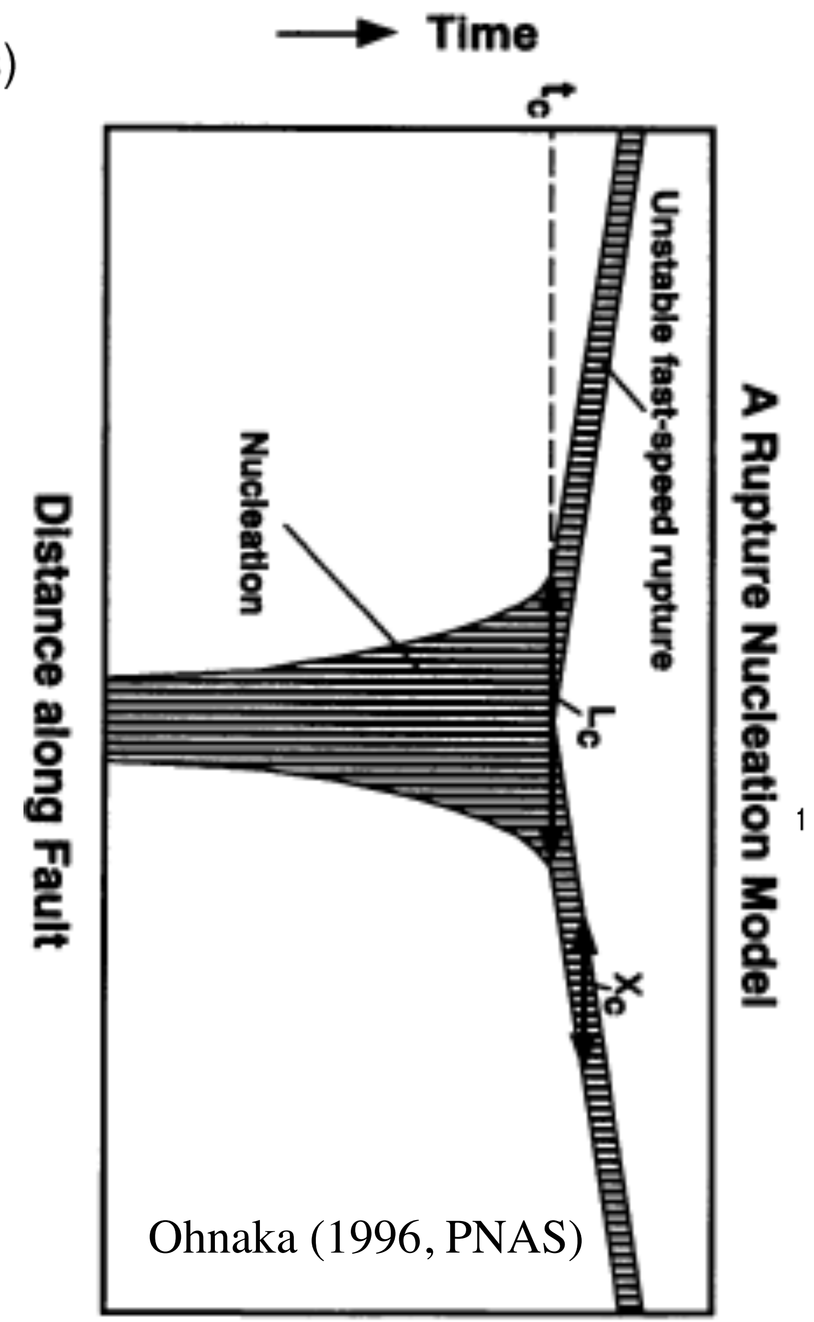


North: **65 m/s**

South: **60 m/s**

Cs = 3620 m/s


LB09−001 / E0072 (833.09800s − 833.11000s)
W
E
Shear Strain [x4μstrain]
Time [s]
24 m/s
204 m/s
123 m/s
10 m/s
640 m/s
0.012 s
North:
South:
Cs = 3620 m/s

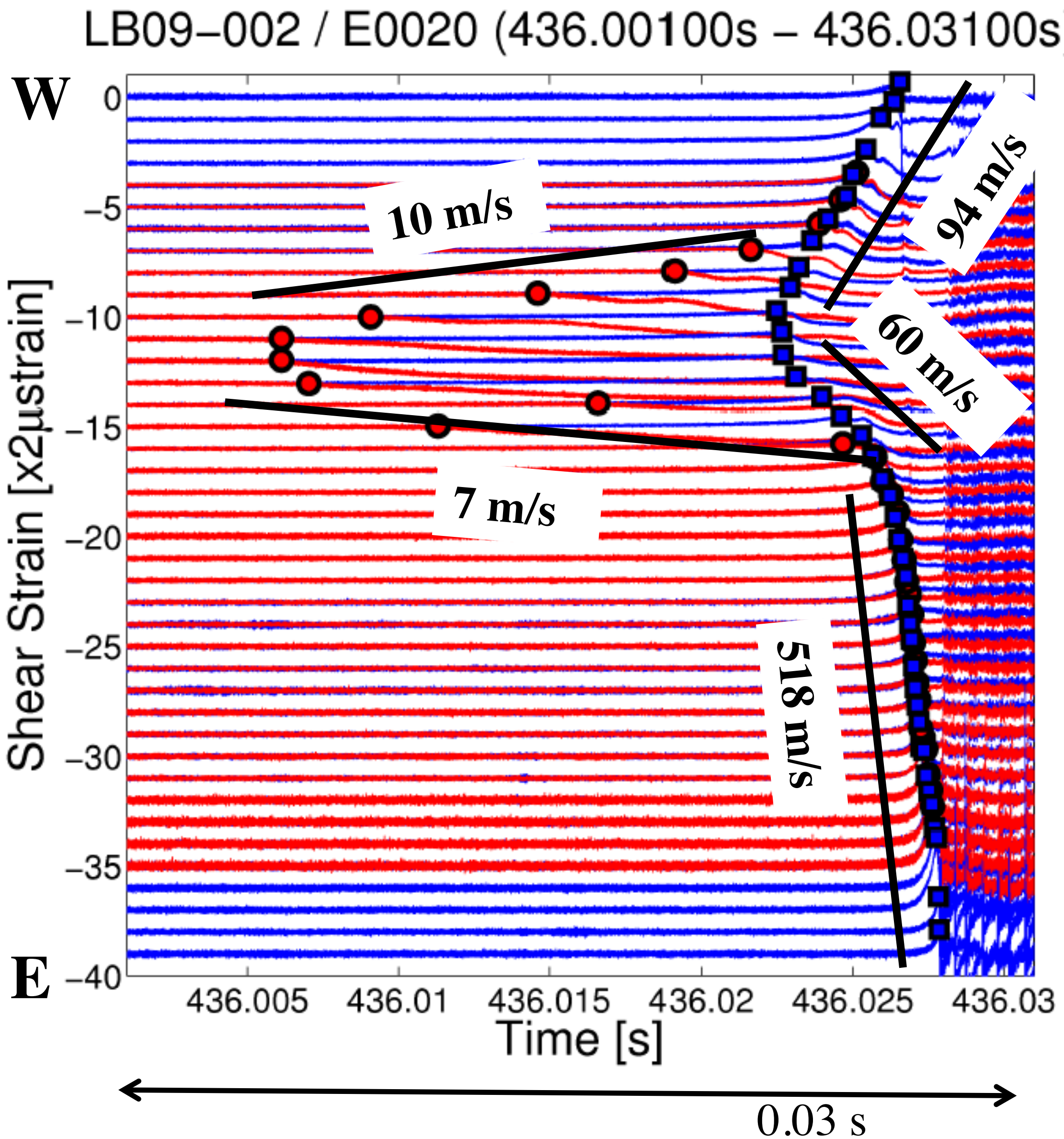

Time
A Rupture Nucleation Model
Distance along Fault
Unstable fast-speed rupture
Nucleation
Ohnaka (1996, PNAS)

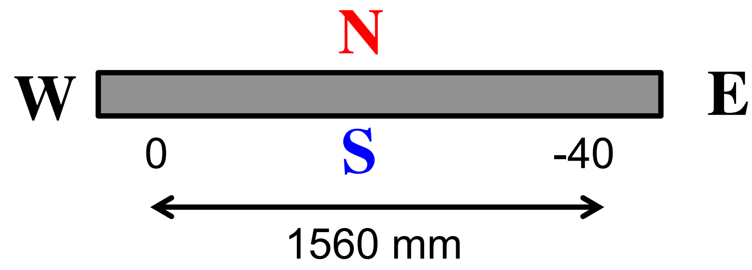
LB09-002 (in 2014)

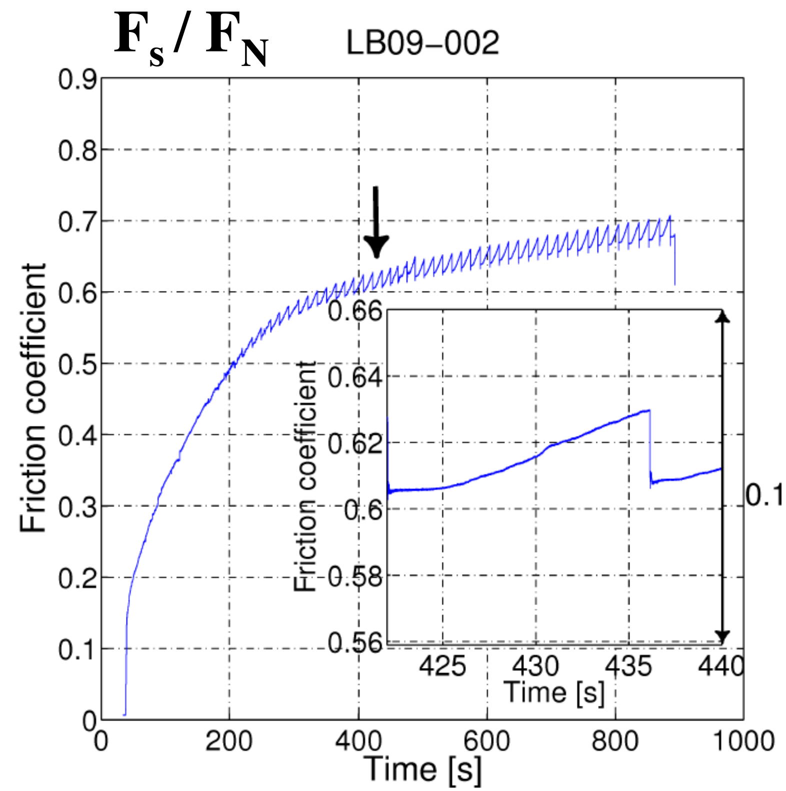
- Normal stress: 6.7 MPa
- Loading rate: 0.01 mm/s
- Incremental displacement: **6.1 mm**
- Cumulative displacement: **13.0 mm**

Yamashita-type (100mm/gabbro)

	normal stress(MPa)	loading vel (mm/s)	max. disp(mm)	strain mode	AE sensors	ACC	Conducted date
LB09-001	6.7	0.01	6.9	shear only	P-mode, 64ch	NIED,3Comp	4/7
LB09-002	6.7	0.01	6.1	shear only	S-mode, 64ch	NIED,3Comp	4/7
LB09-003	6.7	0.1	36.2	shear only	S-mode, 64ch	NIED,3Comp	4/8
LB09-004	6.7	1	396.0	shear only	S-mode, 64ch	none	4/8
LB09-005	6.7	0.1/0.01	22.2	shear only	S-mode, 64ch	NIED,3Comp	4/9
LB09-006	6.7	0.1/0.01	34.4	shear only	P-mode, 64ch	NIED,3Comp	4/9
LB09-007	6.7	0.1/0.01	35.5	shear only	S-mode, 64ch	NIED,3Comp	4/9



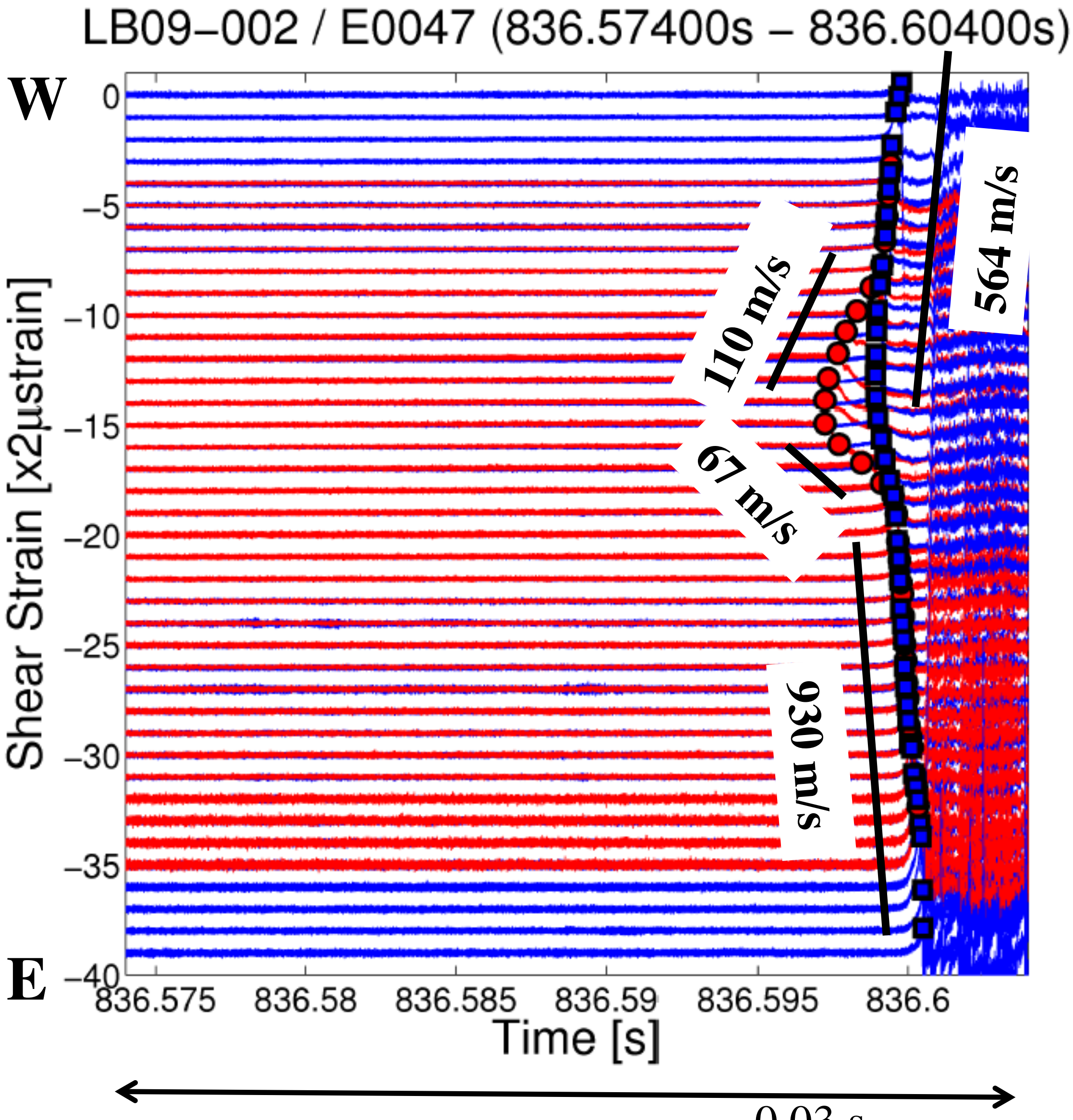


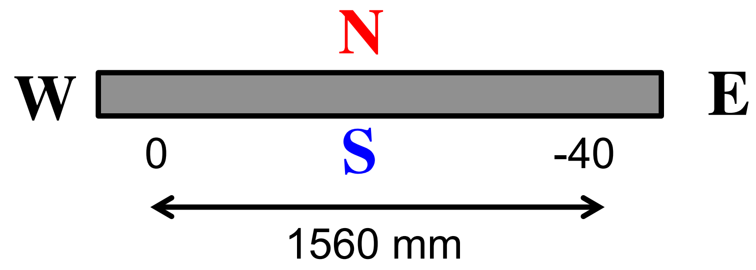


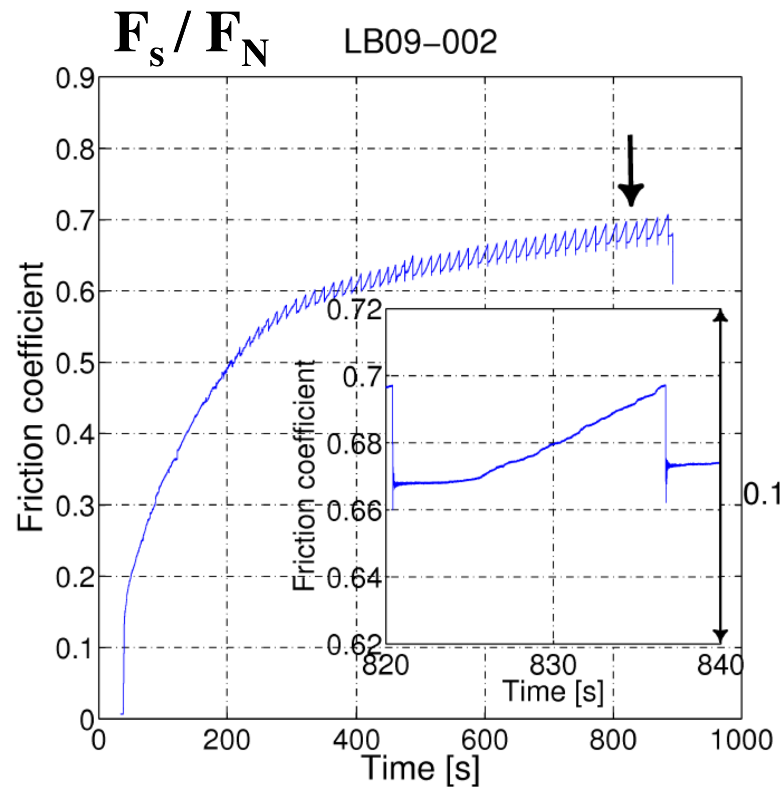
North:

South:

Cs = 3620 m/s







North:

South:

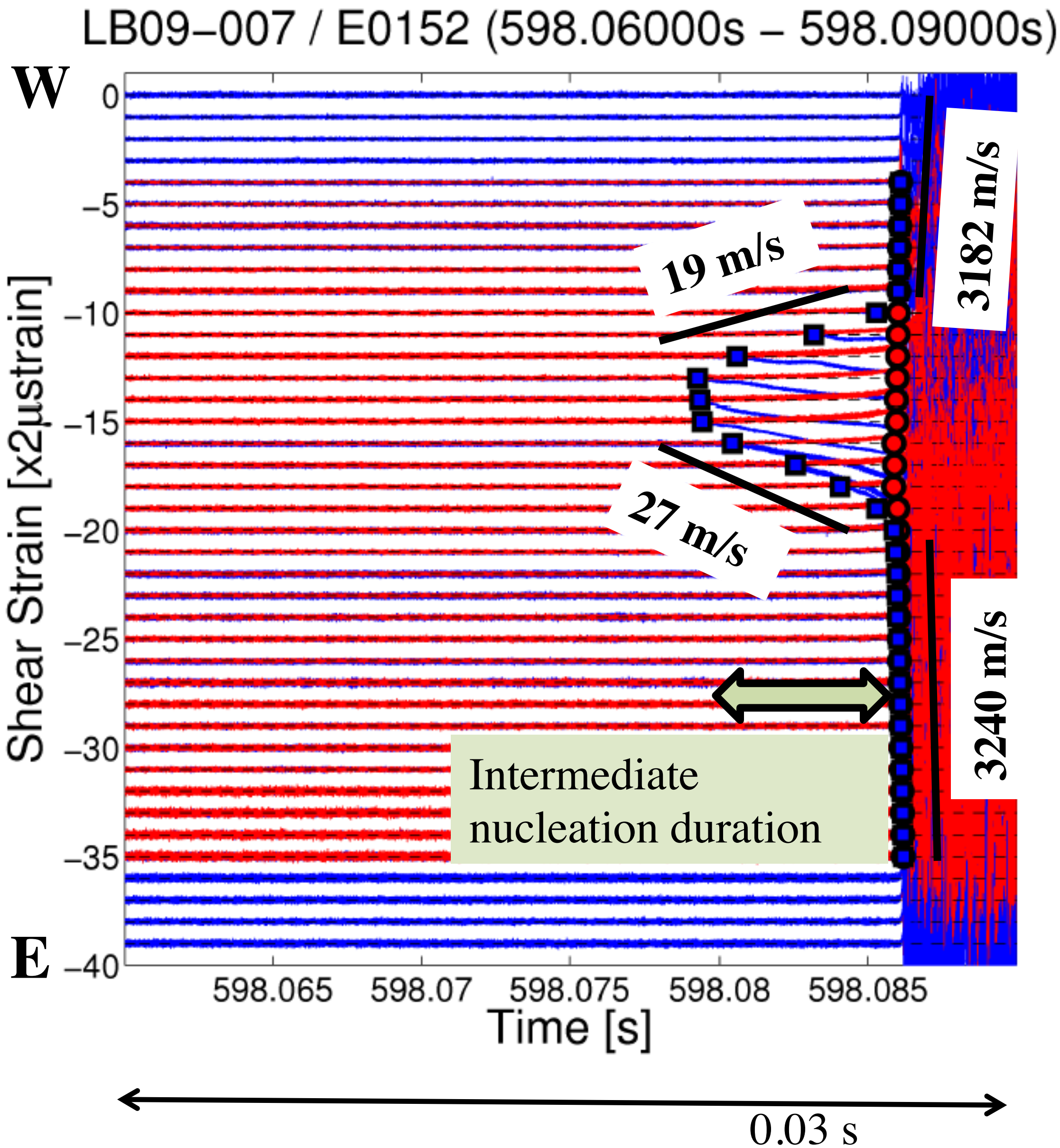
Cs = 3620 m/s

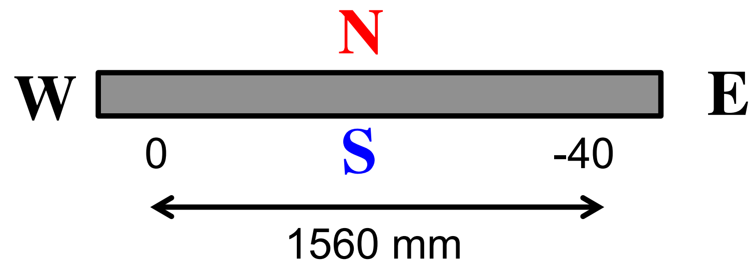
LB09-007 (in 2014)

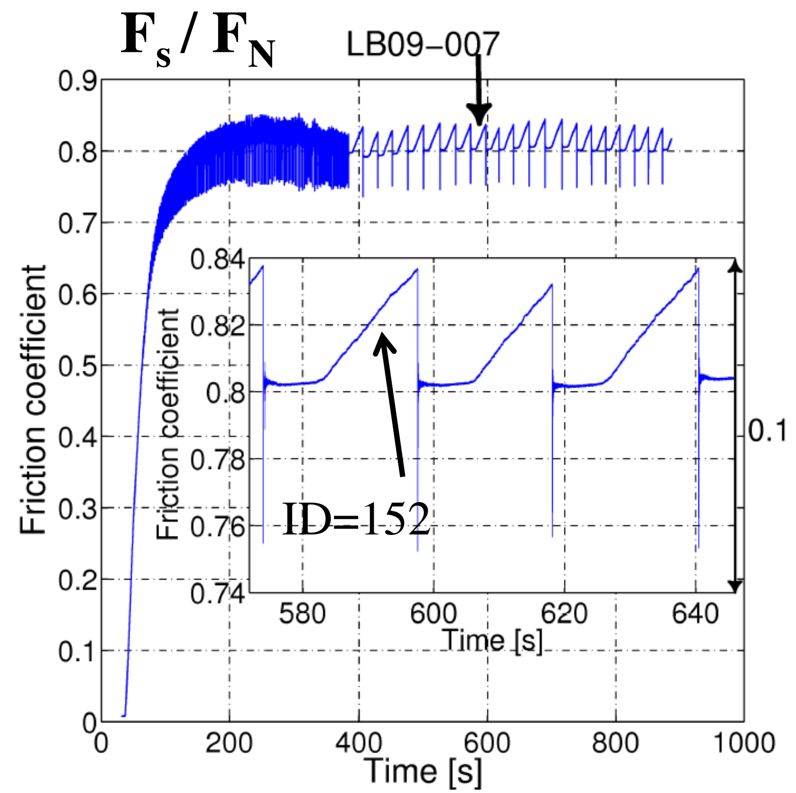
- Normal stress: 6.7 MPa
- Loading rate: 0.1 mm/s , then 0.01 mm/s
- Incremental displacement: **35.5 mm**
- Cumulative displacement: **537.3 mm**

Yamashita-type (100mm/gabbro)

	normal stress(MPa)	loading vel (mm/s)	max. disp(mm)	strain mode	AE sensors	ACC	Conducted date
LB09-001	6.7	0.01	6.9	shear only	P-mode, 64ch	NIED,3Comp	4/7
LB09-002	6.7	0.01	6.1	shear only	S-mode, 64ch	NIED,3Comp	4/7
LB09-003	6.7	0.1	36.2	shear only	S-mode, 64ch	NIED,3Comp	4/8
LB09-004	6.7	1	396.0	shear only	S-mode, 64ch	none	4/8
LB09-005	6.7	0.1/0.01	22.2	shear only	S-mode, 64ch	NIED,3Comp	4/9
LB09-006	6.7	0.1/0.01	34.4	shear only	P-mode, 64ch	NIED,3Comp	4/9
LB09-007	6.7	0.1/0.01	35.5	shear only	S-mode, 64ch	NIED,3Comp	4/9



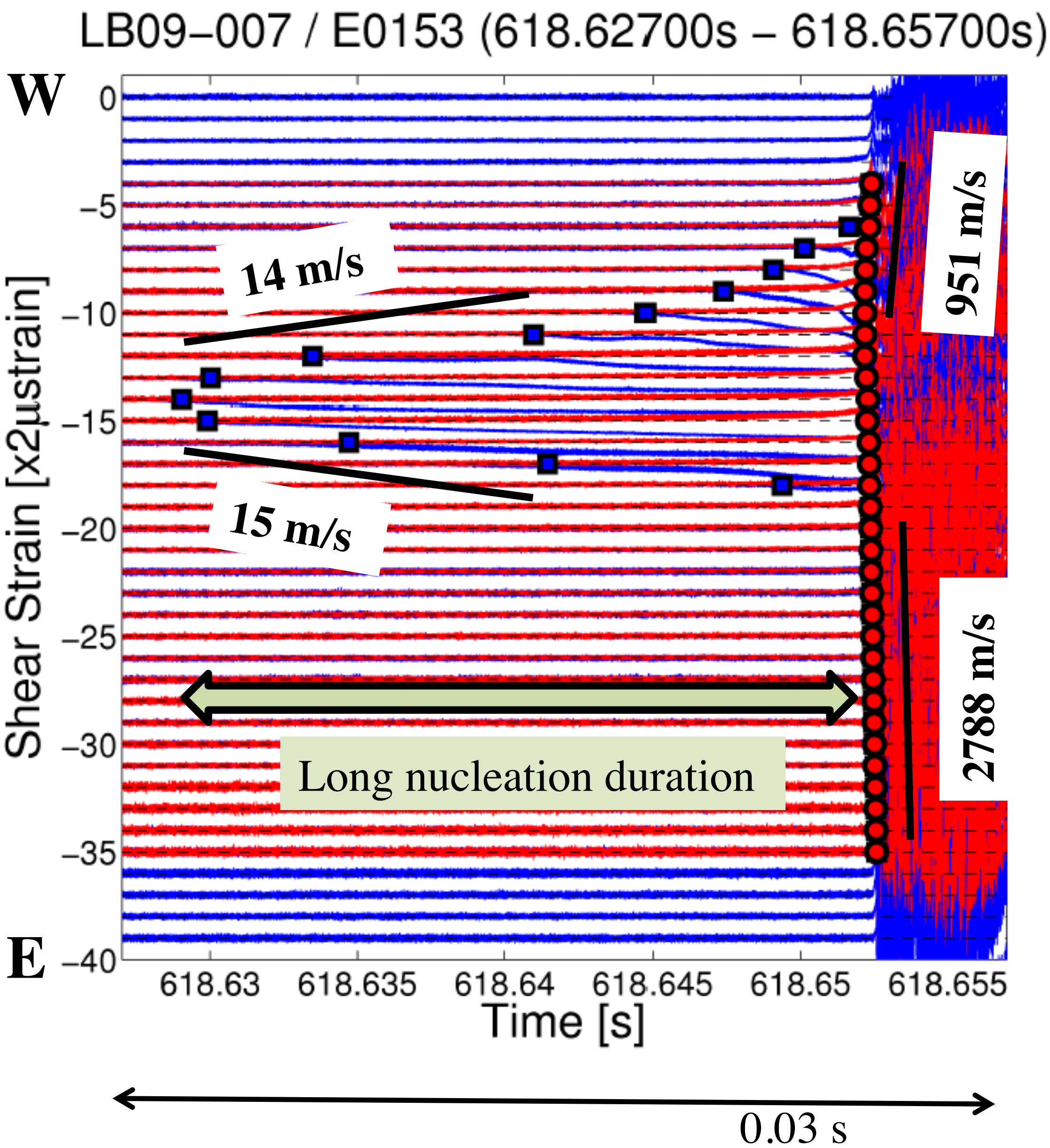


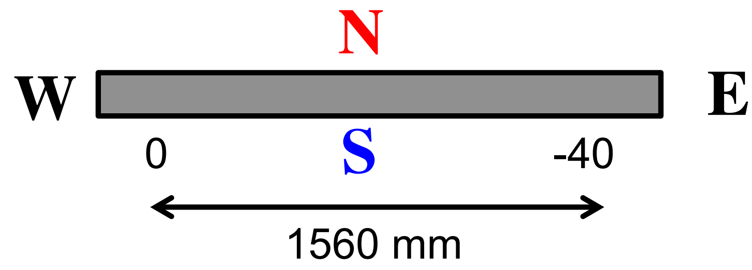


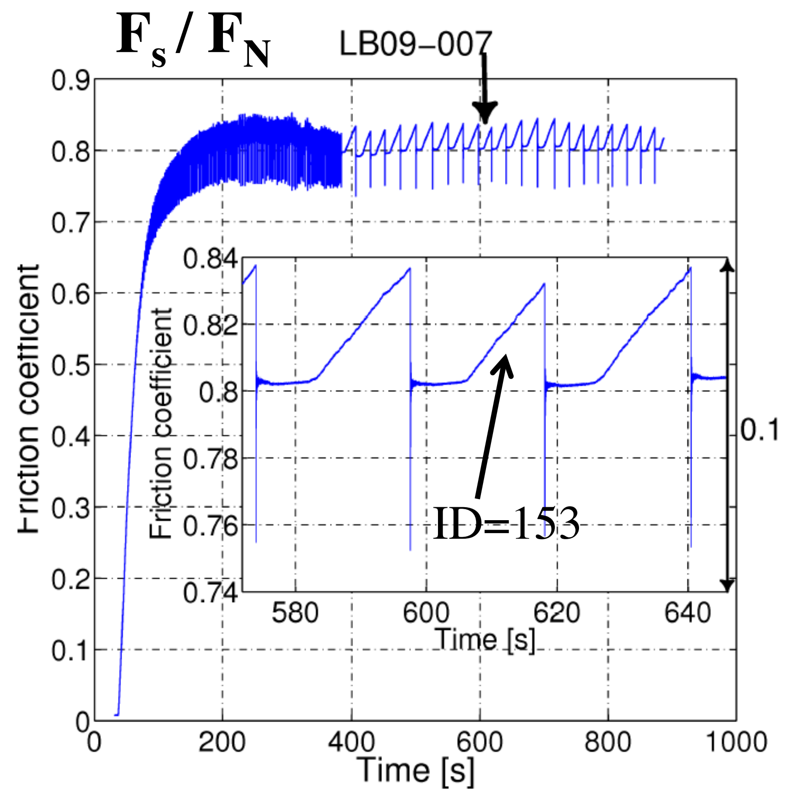
North:

South:

Cs = 3620 m/s



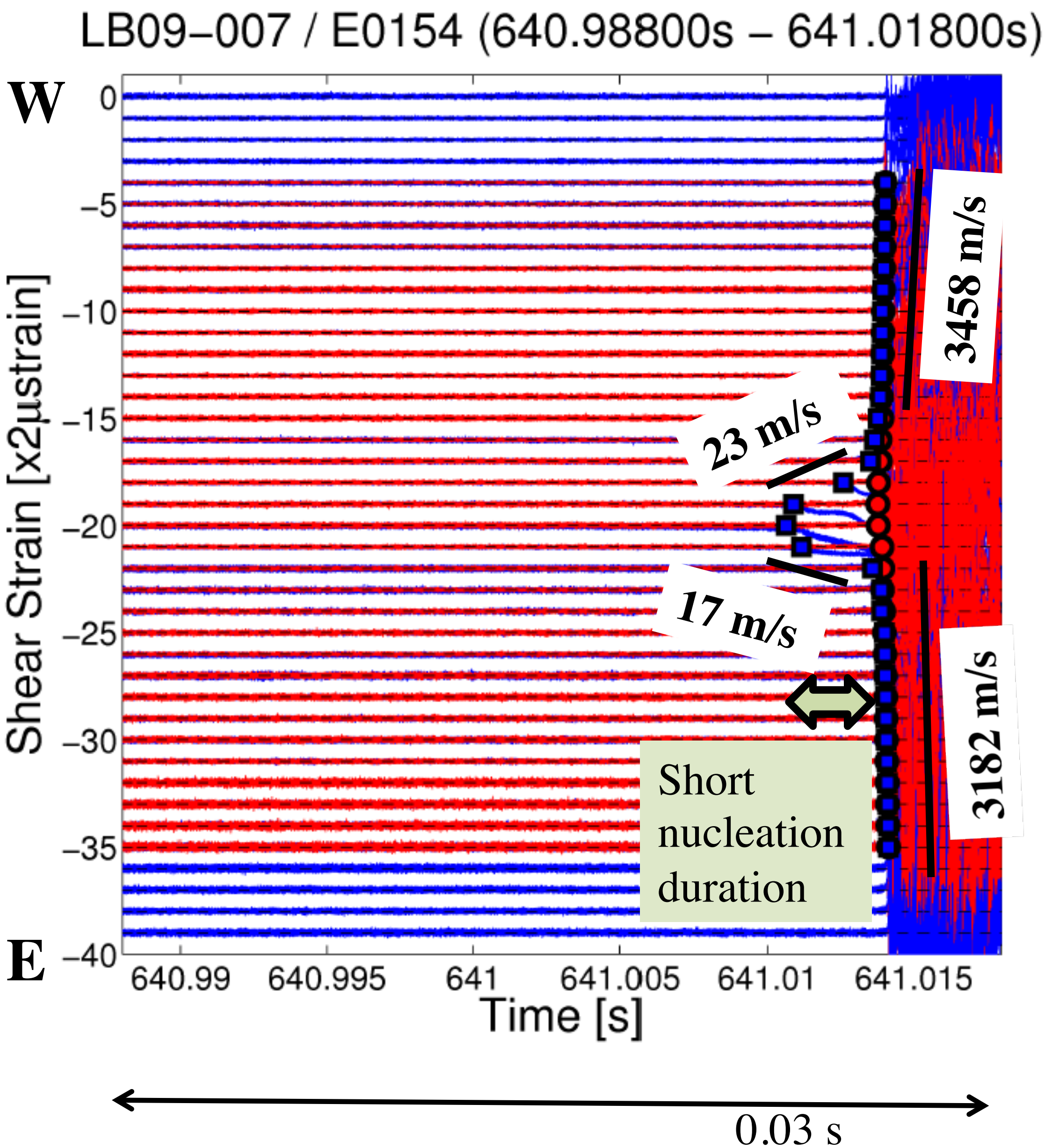


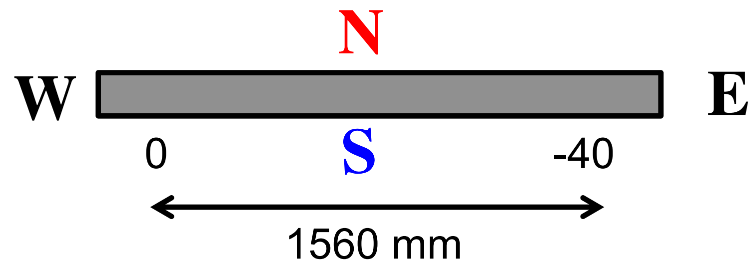


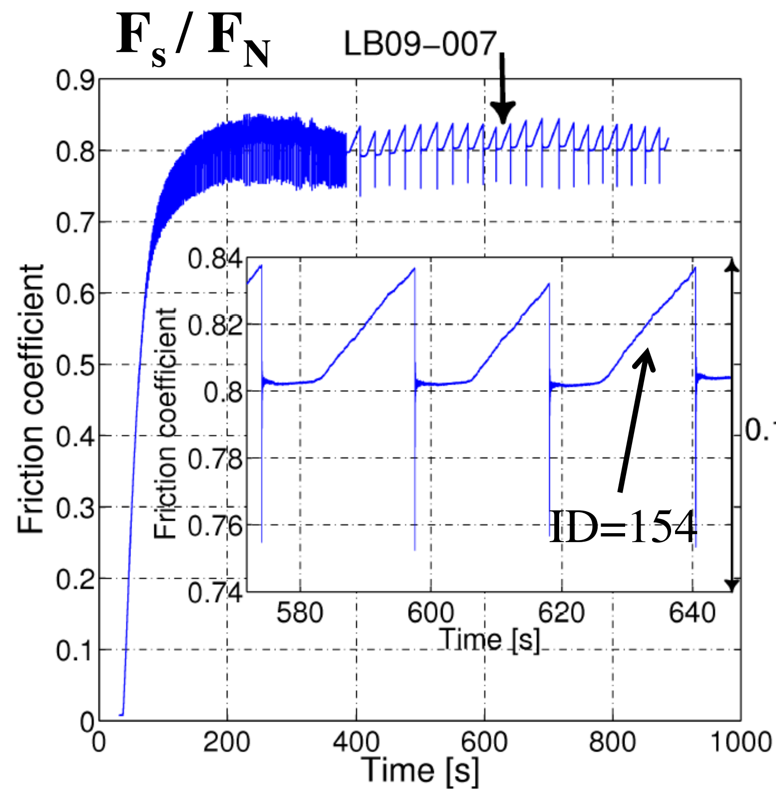
North:

South:

Cs = 3620 m/s





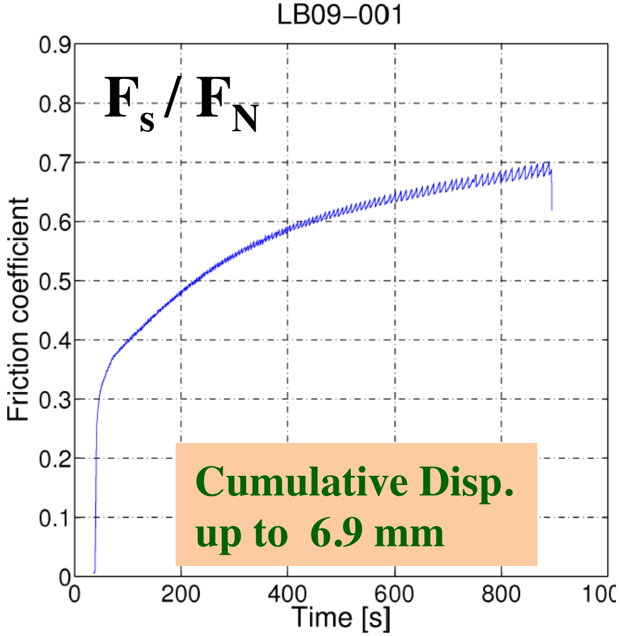


North:
South:

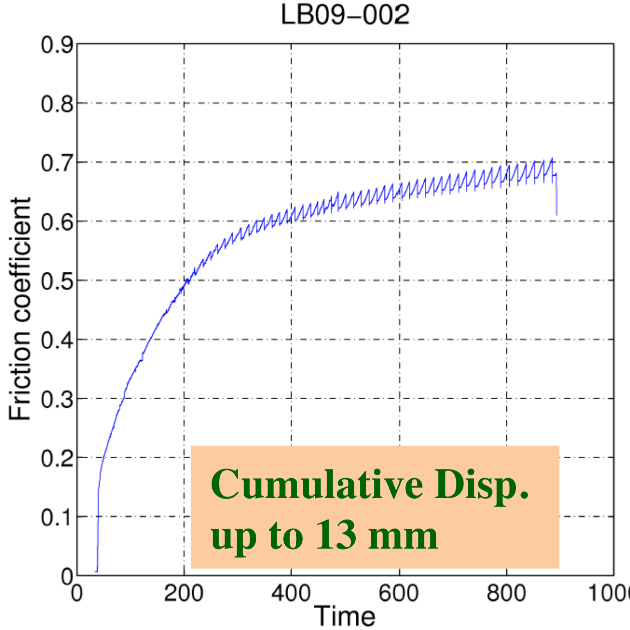
Cs = 3620 m/s

Fault rupture style – Cumulative displacement – Damage pattern

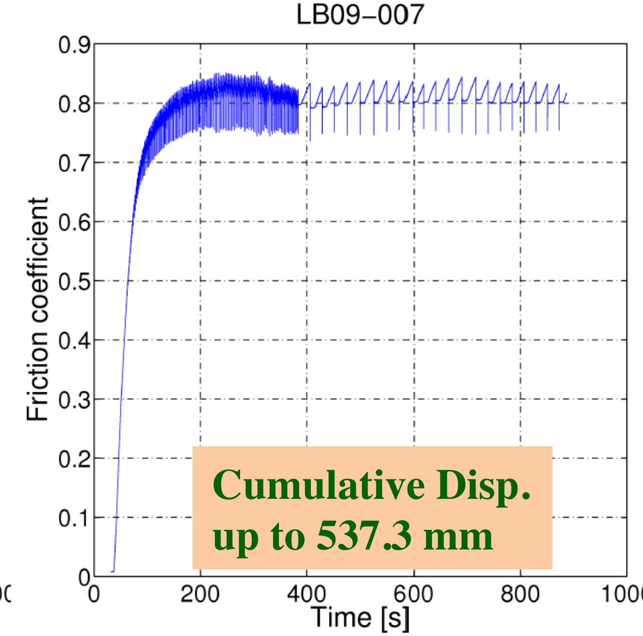
Vr: 10s to 100s m/s



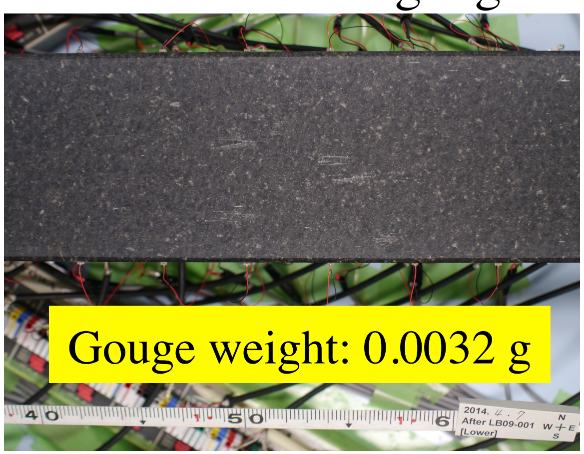
Vr: 100s to ~ 1000 m/s

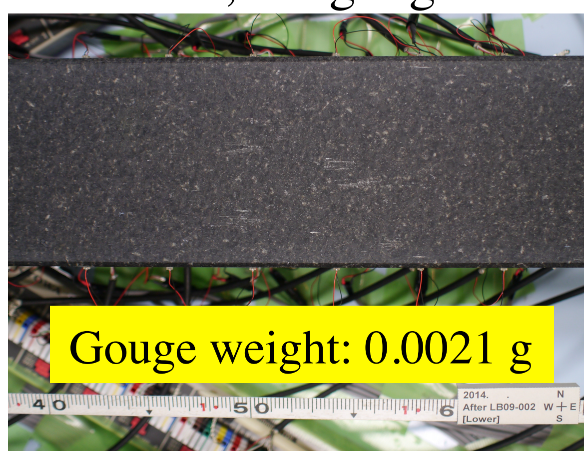


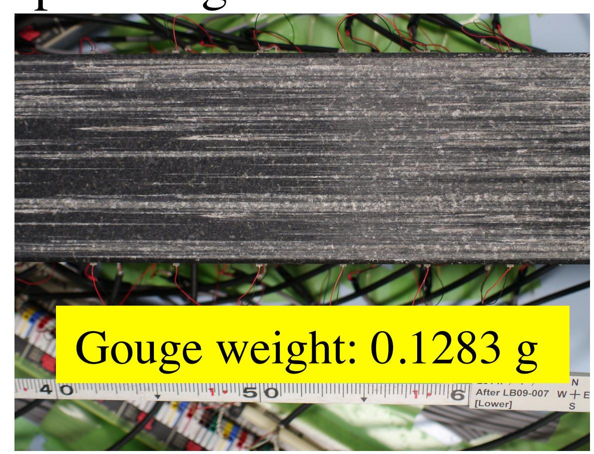
Vr: comparable to Cs (km/s)

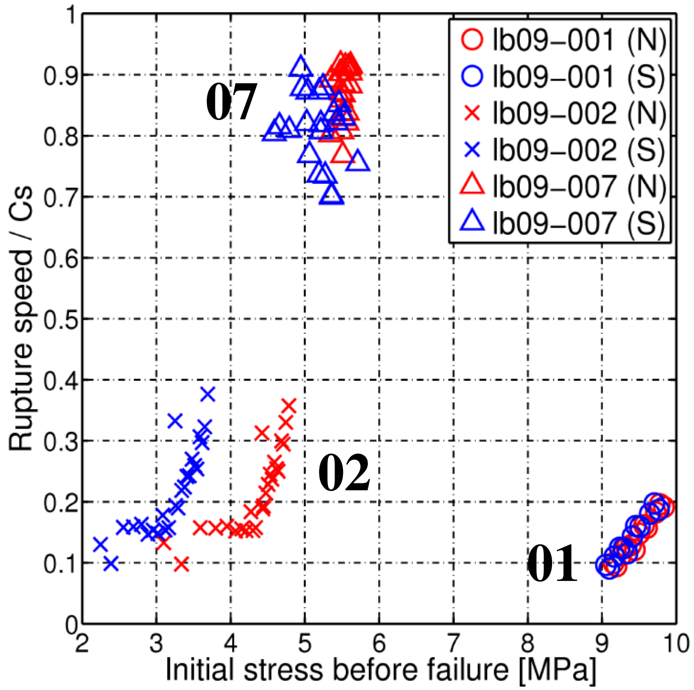


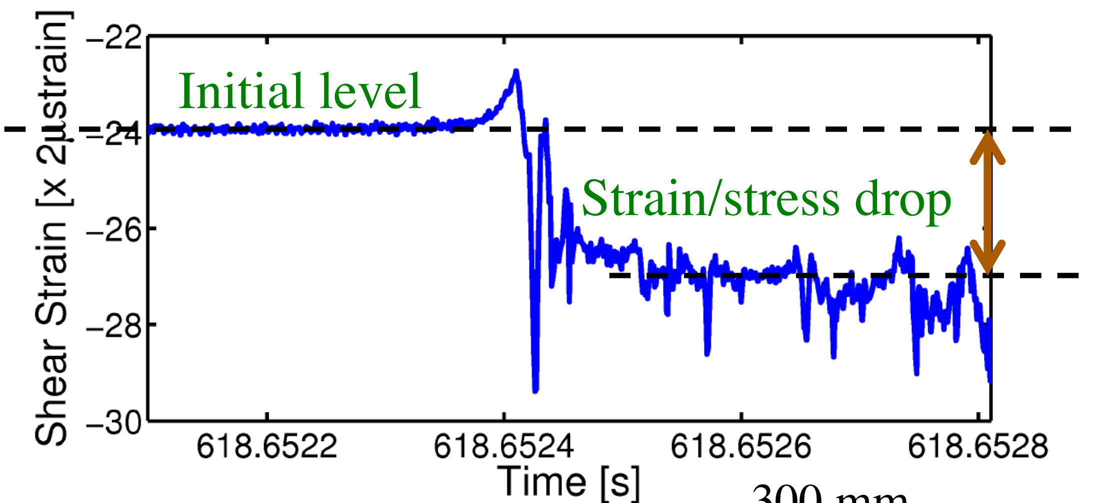
We collect gouges after each run, but gouges were kept during each run

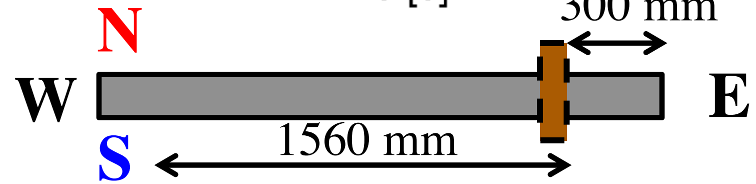


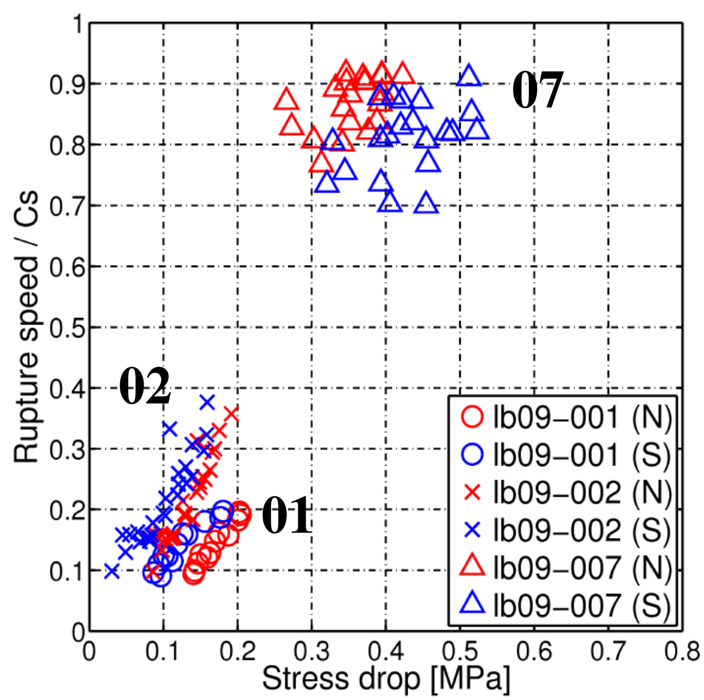




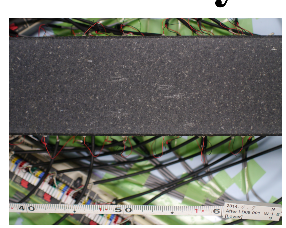


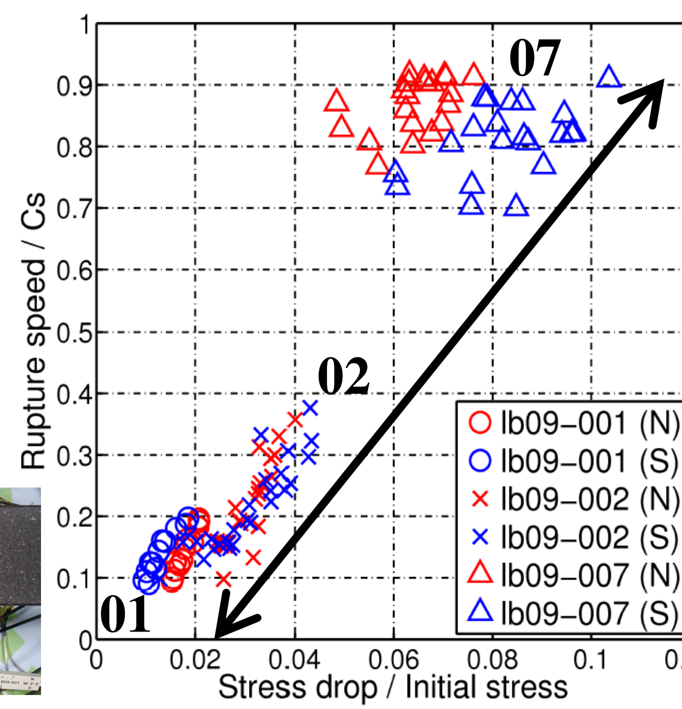




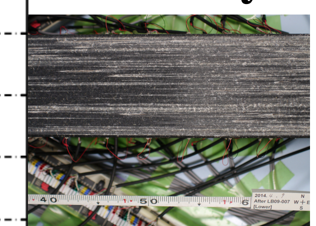


Low efficiency

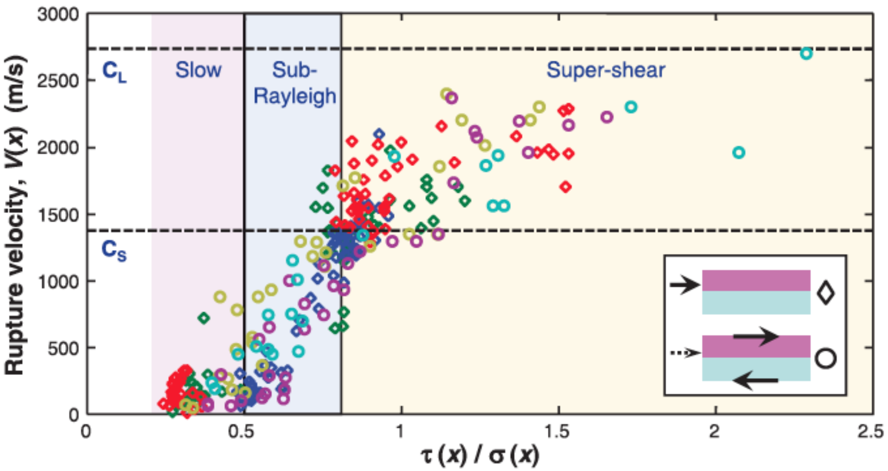




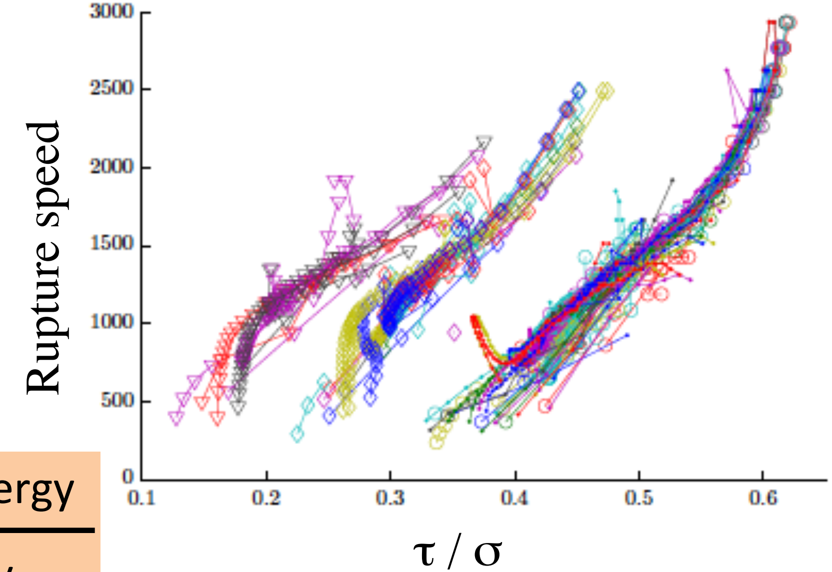
High efficiency



What determines rupture speed



Ben-David et al. (2010, Science)



Stored strain energy

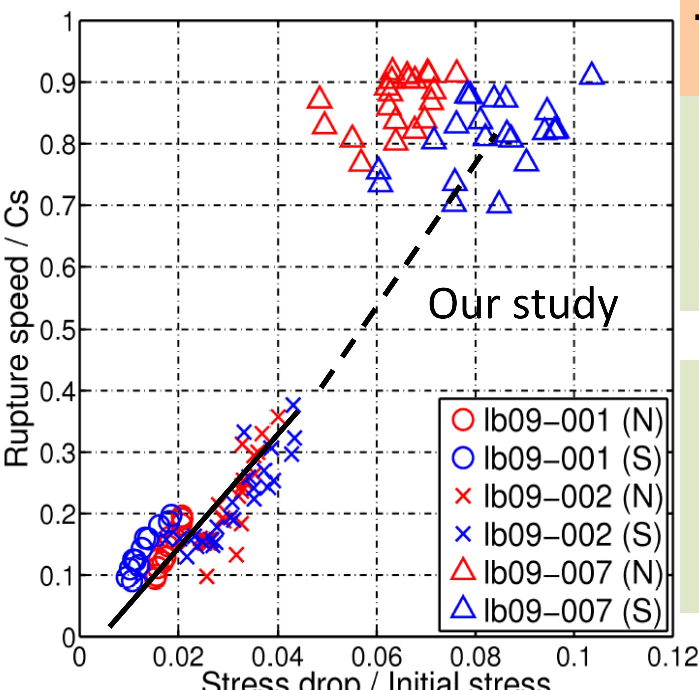
Fracture energy

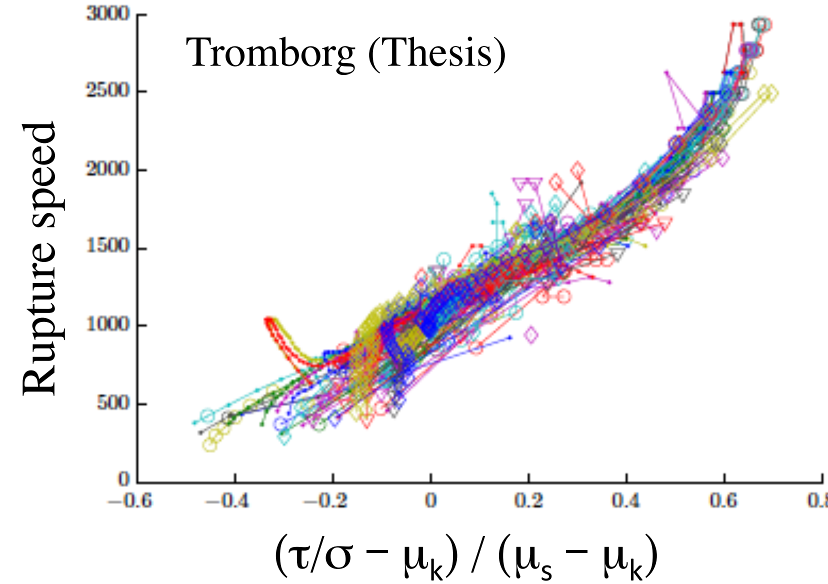
Das and Aki: S

$$S = \frac{\tau_s - \tau_0}{\tau_0 - \tau_d}$$

Madariaga and Olsen: κ

$$\kappa = \frac{\tau_0^2}{\mu \tau_s} \frac{L}{D_c}$$

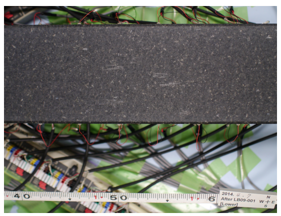




Proposed localization model

Patches with locally high normal and shear stress – high coupling, high work rate and wear rate

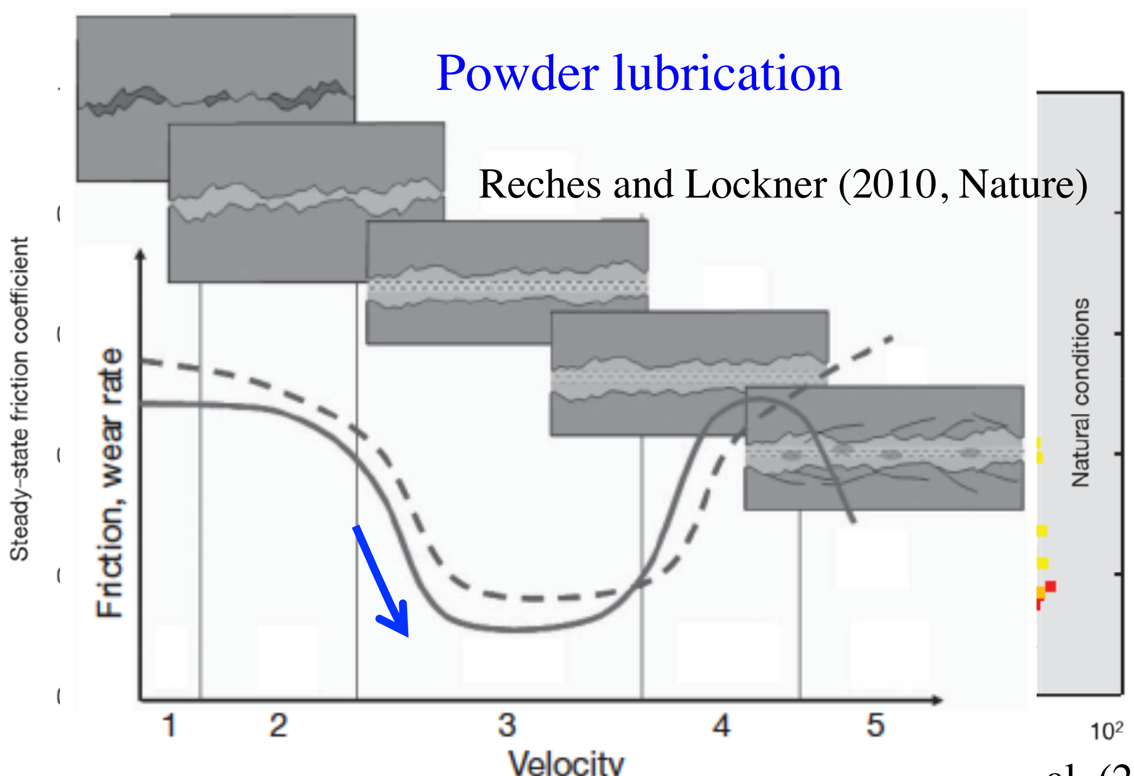
Low efficiency



Slow speed

01

02

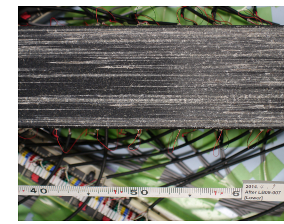


Reches and Lockner (2010, Nature)

al. (2011, Nature)

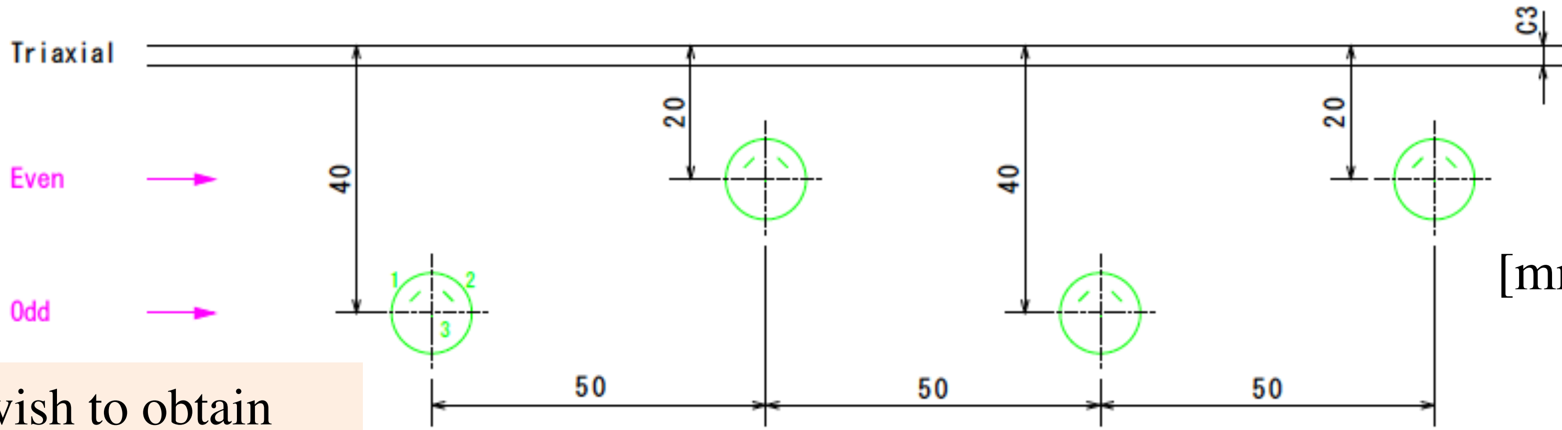
High efficiency

07

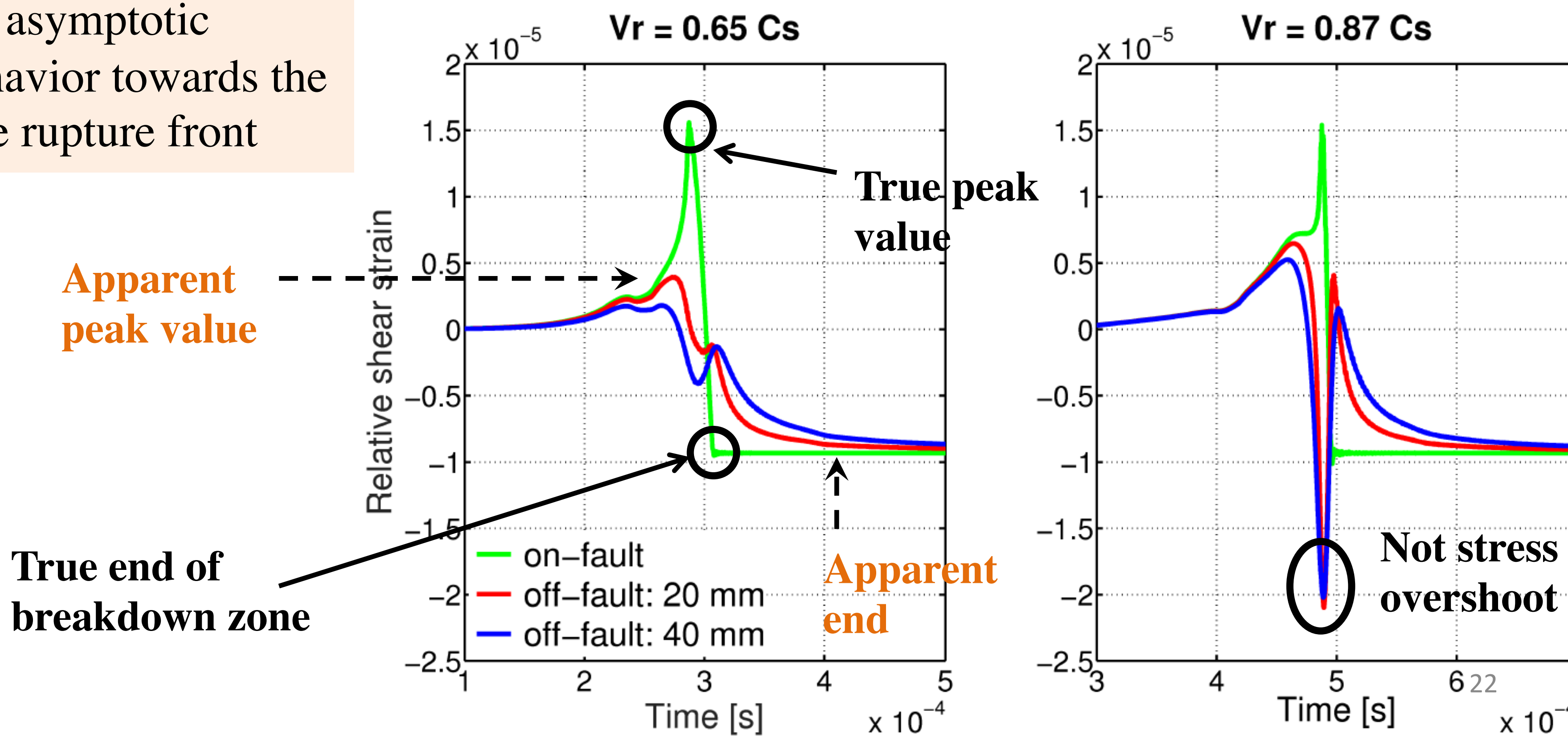


Fast speed

Some improvement in 2015

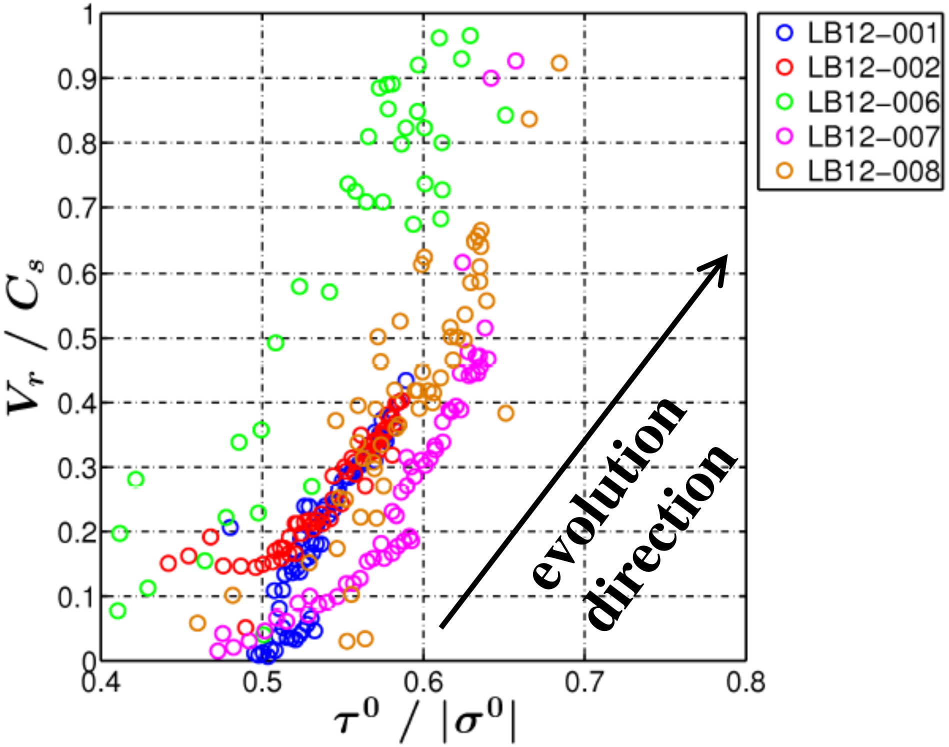


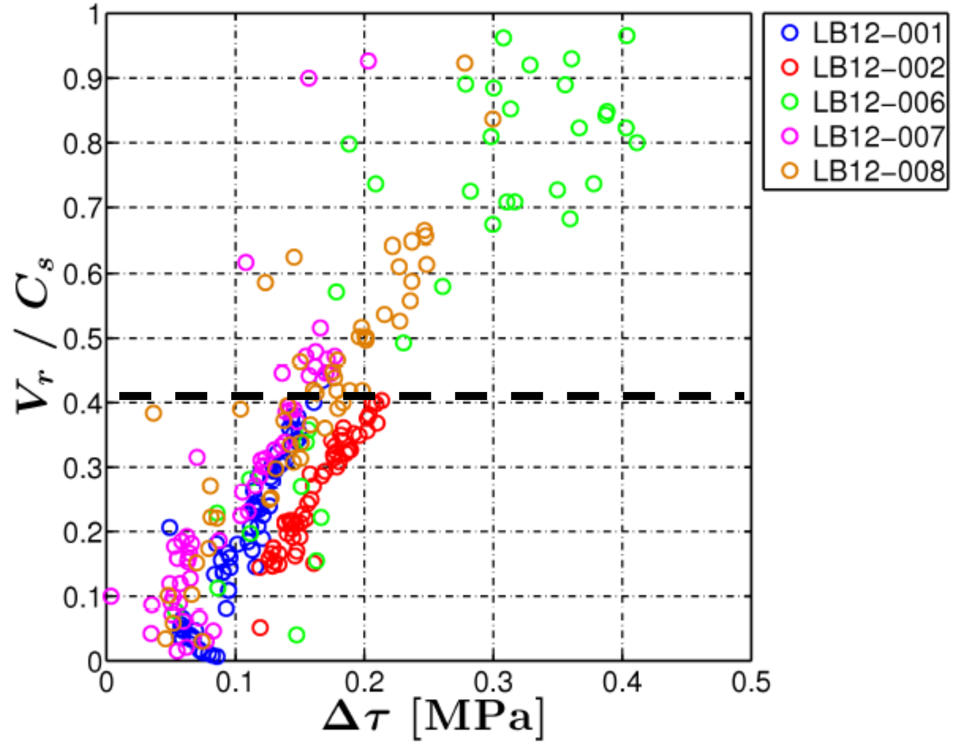
We wish to obtain the asymptotic behavior towards the true rupture front



Data from LB12 series

6.7 MPa
0.01 mm/s





LB12-001
LB12-002
} Cumulative displacement < 50 mm

LB12-006
LB12-007
LB12-008
} Cumulative displacement > 400 mm

Conclusions

- With the accumulation of total fault displacement under direct-shear loading, rupture style along the synthetic fault changes from slow propagation to fast propagation.

- Evolution of the fault surface properties are responsible for the above change of rupture style.

- Developed fault heterogeneities (grooves and gouges) facilitate strain localization, encouraging more efficient release of the stored strain energy (e.g. gouge lubrication) and faster rupture propagation.

- Natural faults are more heterogeneous and span a wider range of scales. We should care about the local/macroscopic description, and the scale-dependency.

THANK YOU