Gutenberg-Richter law, giant earthquakes and slow events in laboratory experiment

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Laboratory experiments

There are two major reasons for lab experiments.

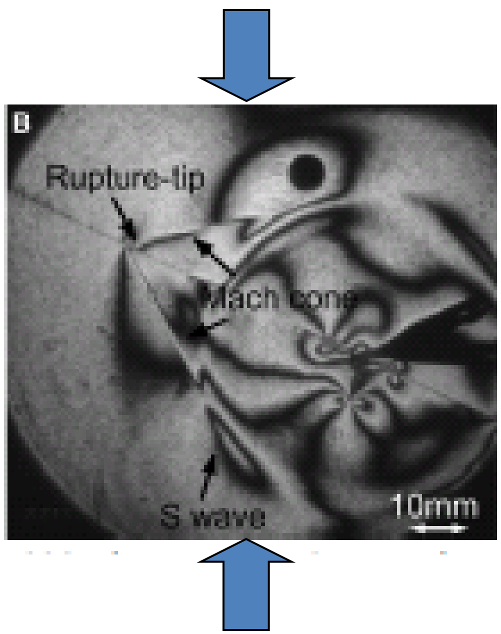
1. Measurement of frictional constitutive law

Dietrich et al. (1978), (1979), Ruina et al. (1983), Marone et al. (1998), …

2. Observation of rupture processes

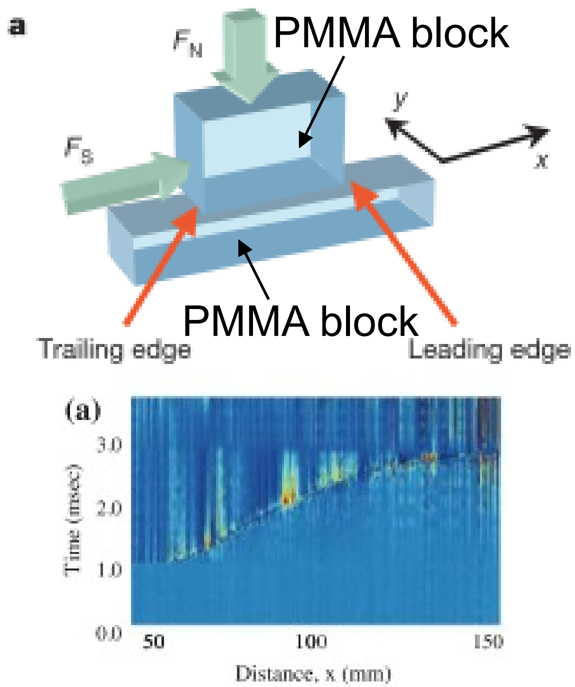
Ohnaka & Shen (1999), Baumberger et al. (2002), Xia et al. (2004), Cohen et al. (2004), Nielsen et al. (2008), …

Supershear rupture



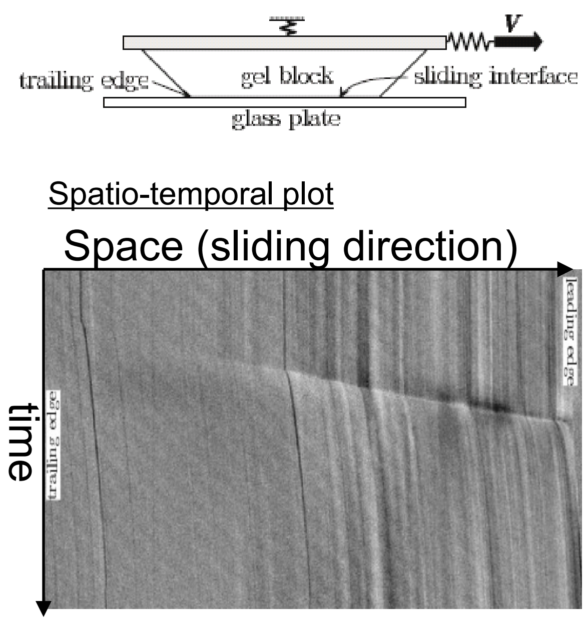
Xia *et al.*, *Science* **308**, 681(2005)

Precursor event



S. M. Rubinstein *et al.*, *Nature* (2004)

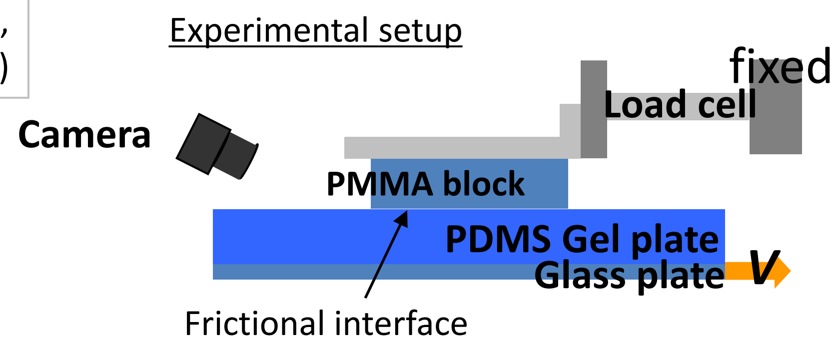
Self-healing slip pulse

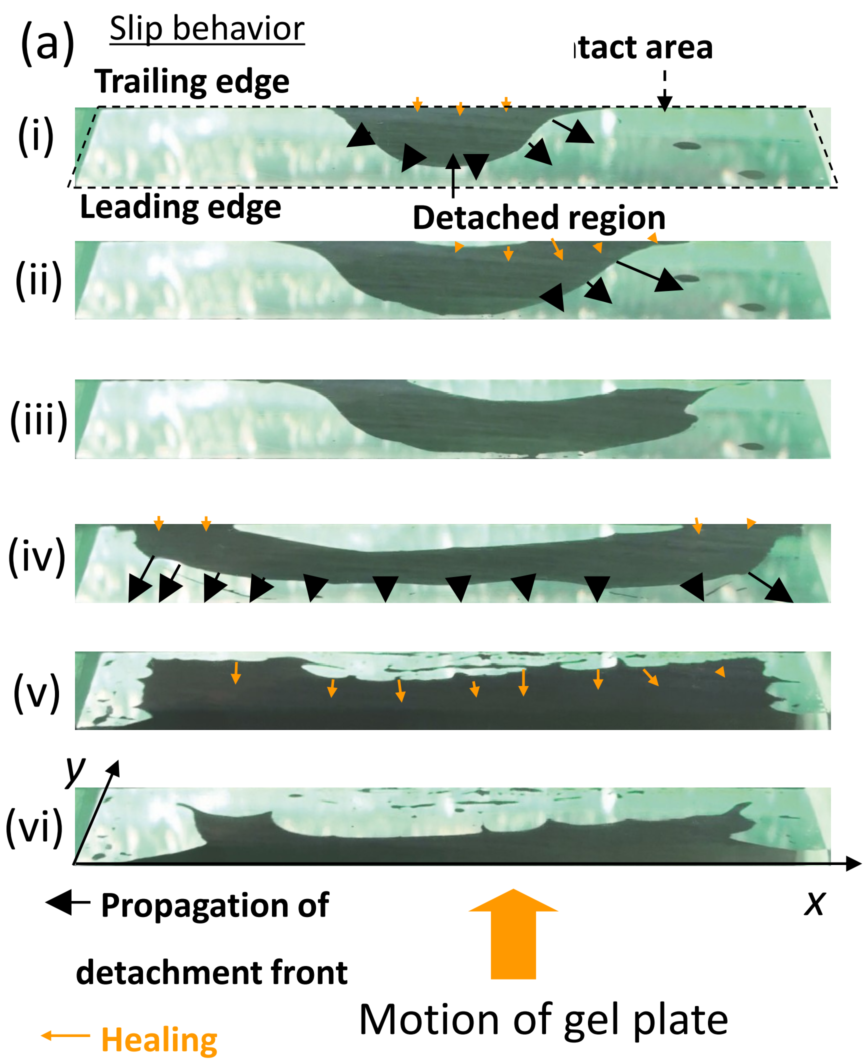


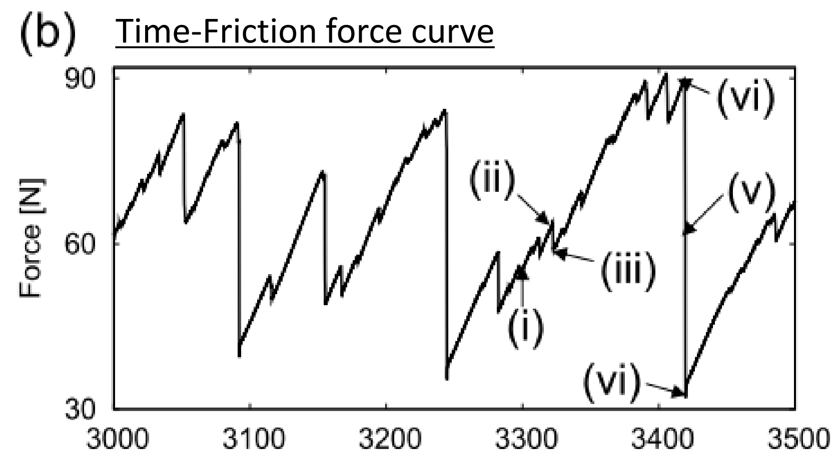
Baumberger *et al.*, *Phys. Rev. Lett.* (2002)

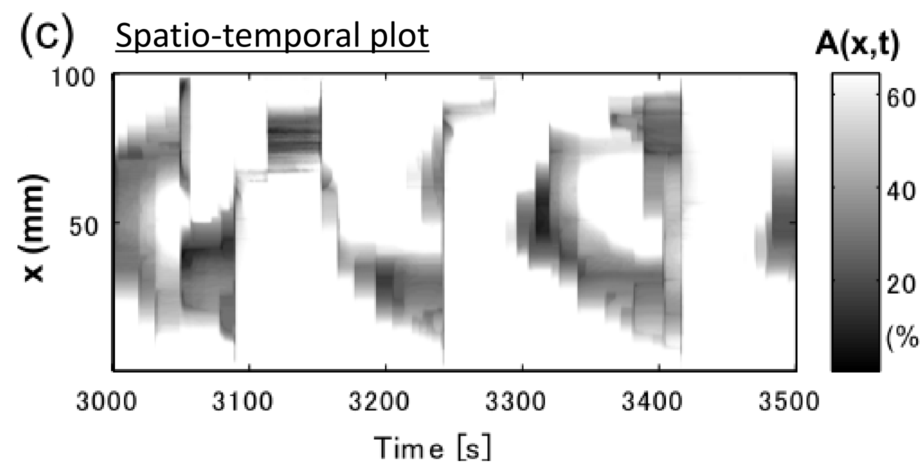
Intermittent Stick-slip Dynamics

T. Yamaguchi, M. Morishita, M. Doi, T. Hori, H. Sakaguchi, J.-P. Ampuero, JGR Solid Earth, 116, B12306 (2011)









Objectives of this study

1. To study the relationship between slip behavior and rheology,

2. To identify the elementary processes of rupture,

3. To measure stress fields, in particular just prior to giant slip events.

"We may just look at different behavior in a different system. If so, it becomes important to check what is similar and what is essentially different !"

Experiment

Material (Silicone gel)

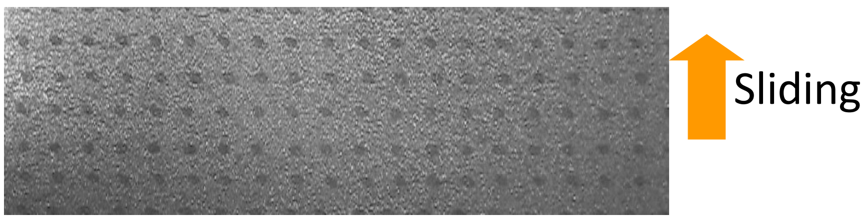
SILPOT 184 (gel) + SE1886 (gel) mixture

(SILPOT 184, SE1886: Toray Dow Corning, Japan)

Measurement of displacement field u(x,y)

PIV (particle velocimetry) method

Example of an image



Slip velocity

$$\vec{V} = (V_x(x,y), V_y(x,y))$$

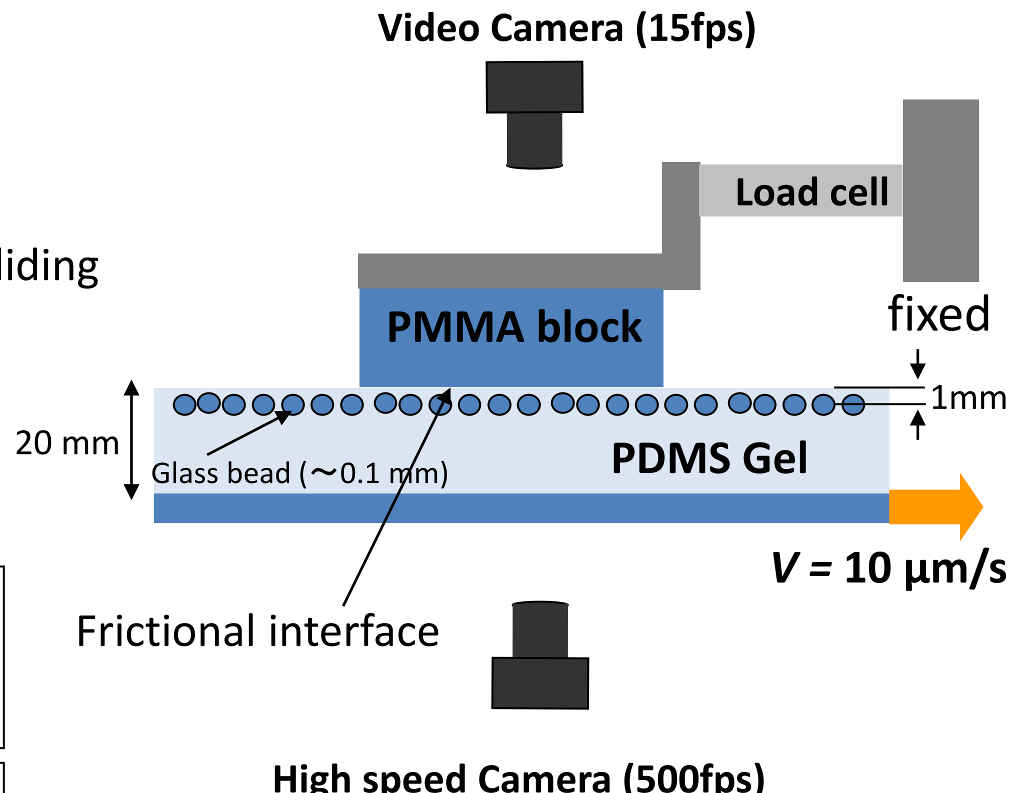
Earthquake moment

$$M_0 = \mu \int_{t_{start,i}}^{t_{end,i}} dt \int_S V_y(x,y)\,dxdy$$

Moment magnitude

$$M_w = (\log M_0 - 9.1)/1.5$$

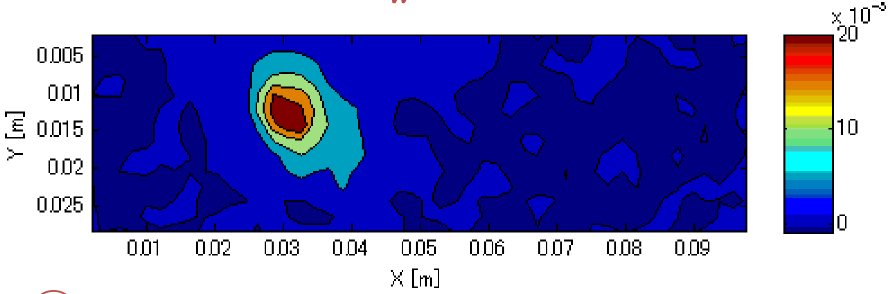
Apparatus



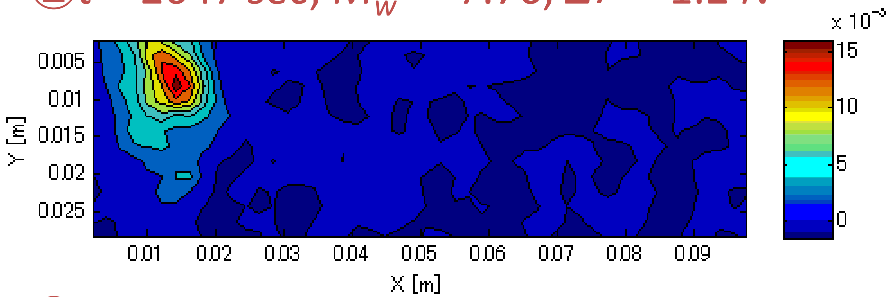
Typical slip events

Gel A

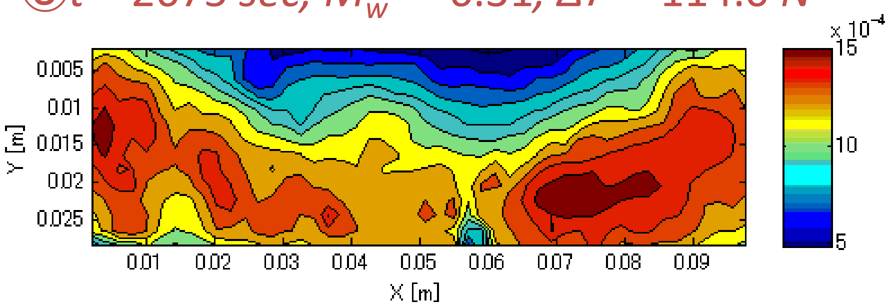
①t = 2646 sec, M_w = -7.65, ΔF = 1.8 N



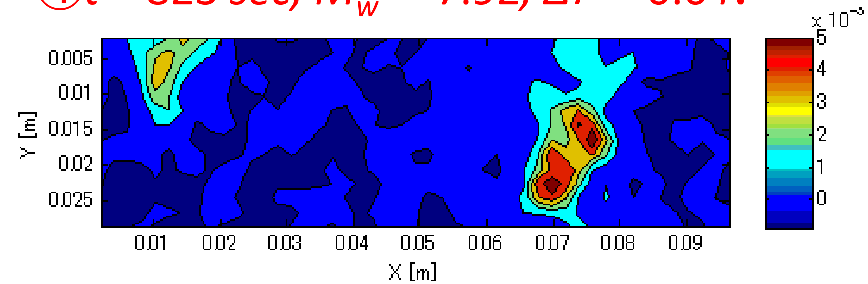
②t = 2647 sec, M_w = -7.76, ΔF = 1.2 N



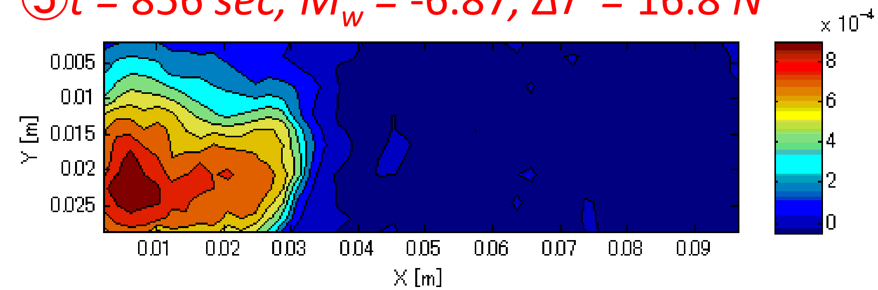
③t = 2675 sec, M_w = -6.31, ΔF = 114.0 N



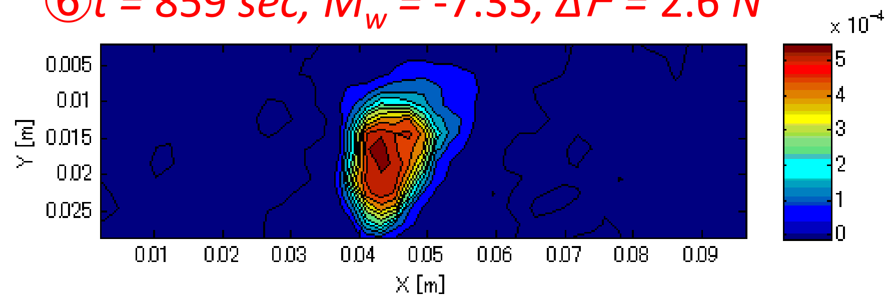
④t = 823 sec, M_w = -7.92, ΔF = 0.6 N



⑤t = 856 sec, M_w = -6.87, ΔF = 16.8 N



⑥t = 859 sec, M_w = -7.33, ΔF = 2.6 N

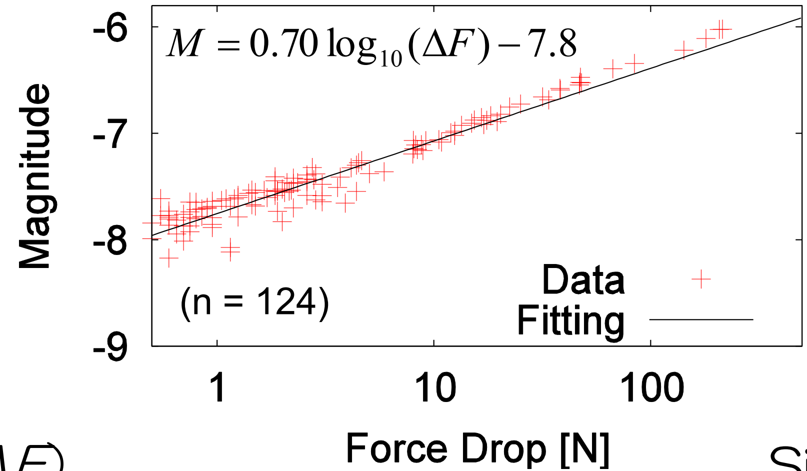


Relationship between *ΔF* and M_w

Force data

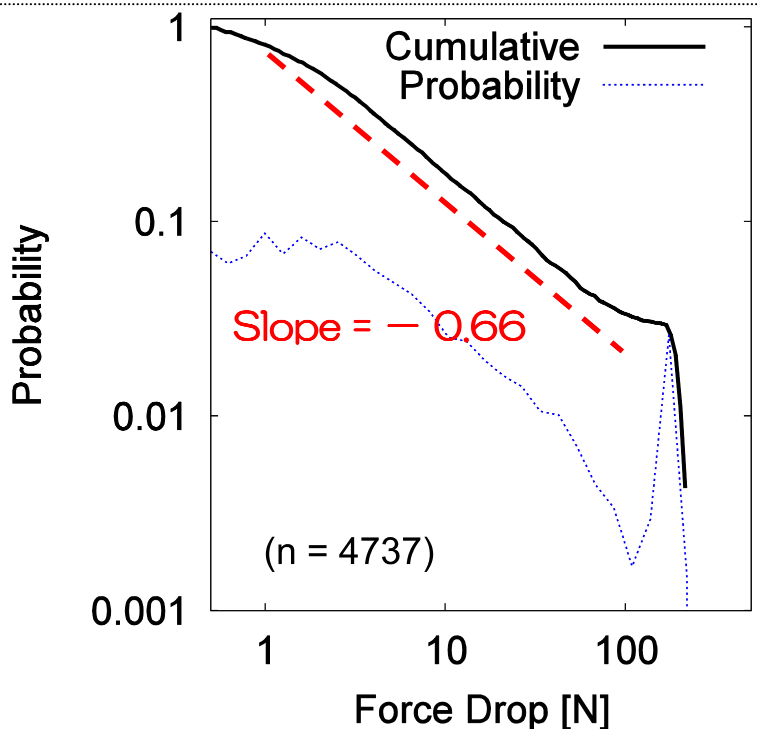
+

PIV analysis

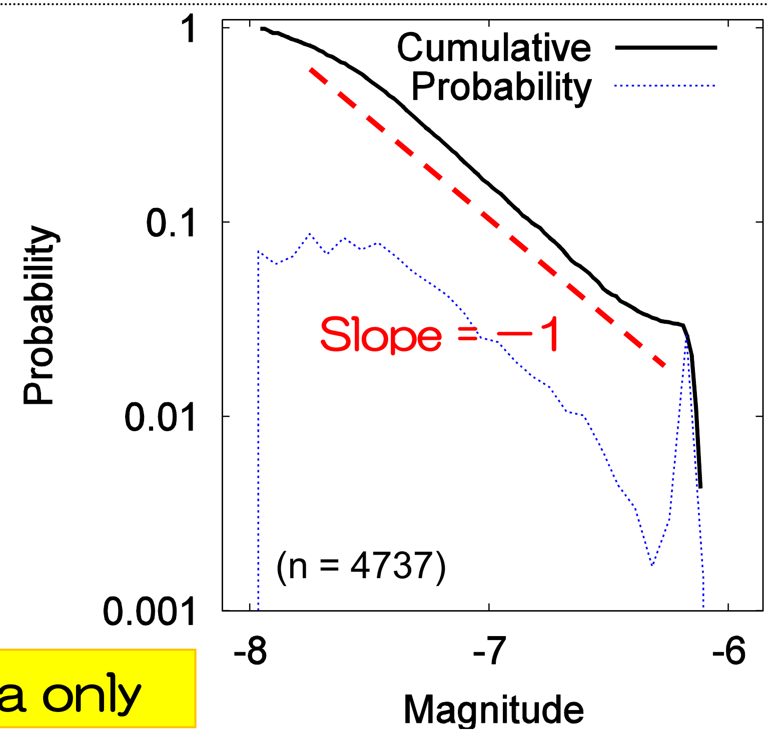


(V = 10 μm/s)

Size distribution（*ΔF*）



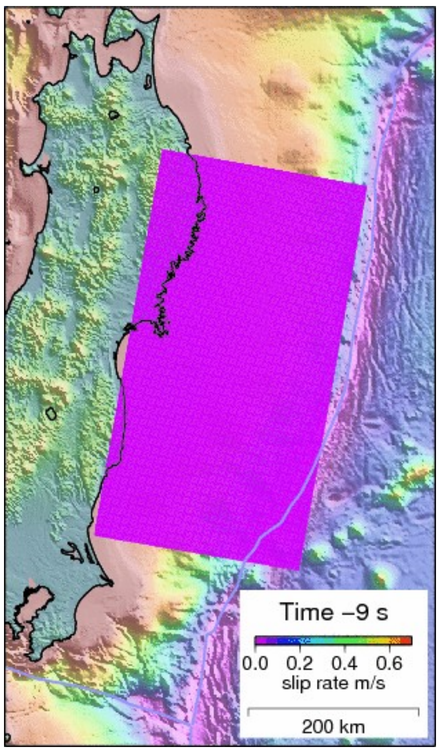
Size distribution（*Mw*）

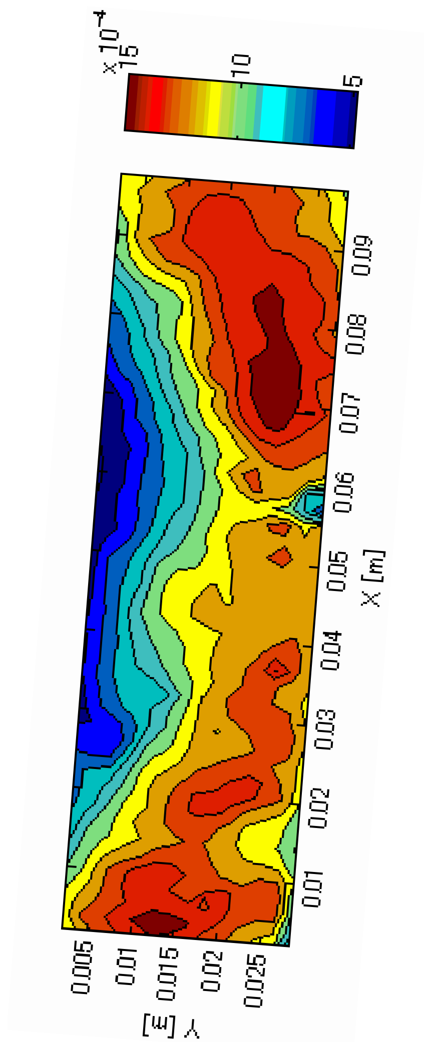


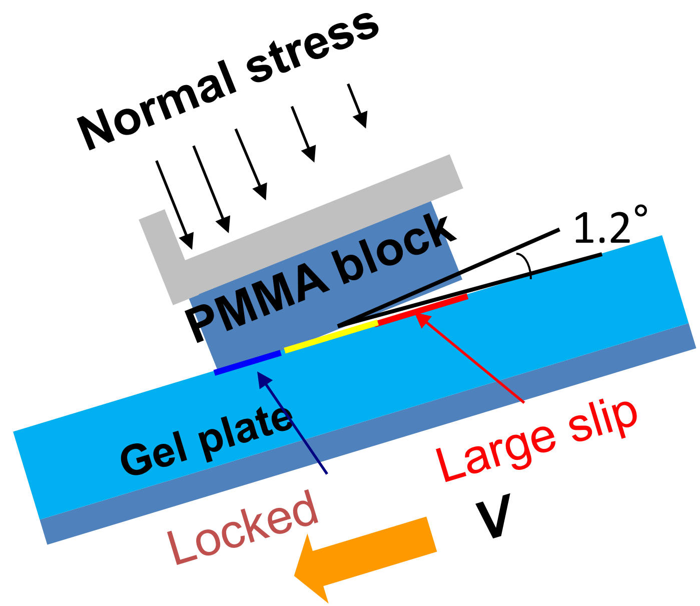
Force data only

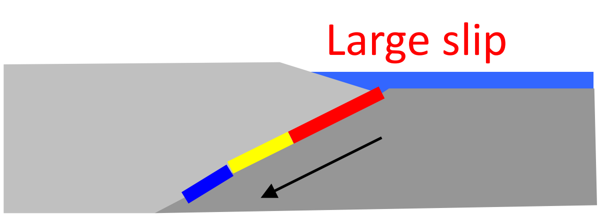
Tohoku-Chiho Taiheiyou-Oki earthquake ($M_w = 9.0$)

S. Ide (U. Tokyo)









Large slip behavior at the edge is similar to one observed close to Japan trench !

Measurement of Stress field

H. Delanoë-Ayari et al. (2008), A. Chateauminois et al. (2008)

- Green's tensor

$$\begin{bmatrix} u_x(x,y) \\ u_y(x,y) \end{bmatrix} = \begin{bmatrix} G_{xx} & G_{xy} \\ G_{yx} & G_{yy} \end{bmatrix} \begin{bmatrix} F_x(0,0) \\ F_y(0,0) \end{bmatrix}$$

$$G_{xx} = \frac{3}{4\pi E}\left(\frac{1}{r} + \frac{x^2}{r^3}\right)$$

$$G_{xy} = G_{yx} = \frac{3}{4\pi E}\frac{xy}{r^3}$$

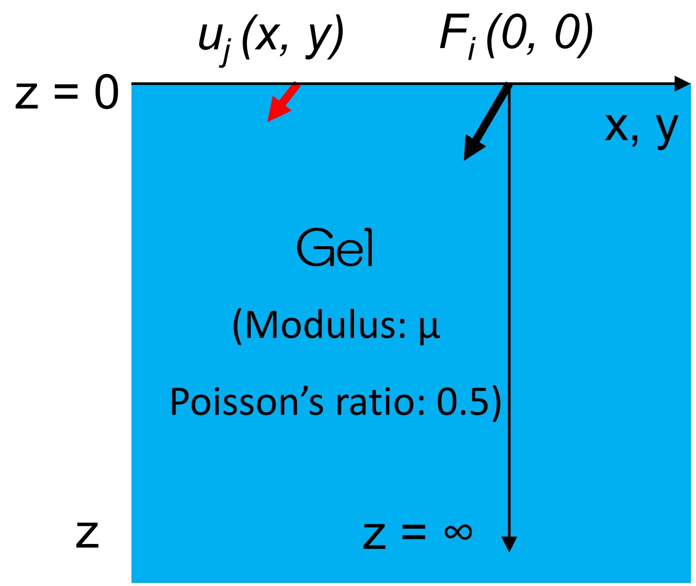
$$G_{yy} = \frac{3}{4\pi E}\left(\frac{1}{r} + \frac{y^2}{r^3}\right)$$

- Stress-Displacement relation

$$\vec{u}(x,y) = \int dr\, G(x-x', y-y')\,\vec{\sigma}_z(x', y')$$

Known

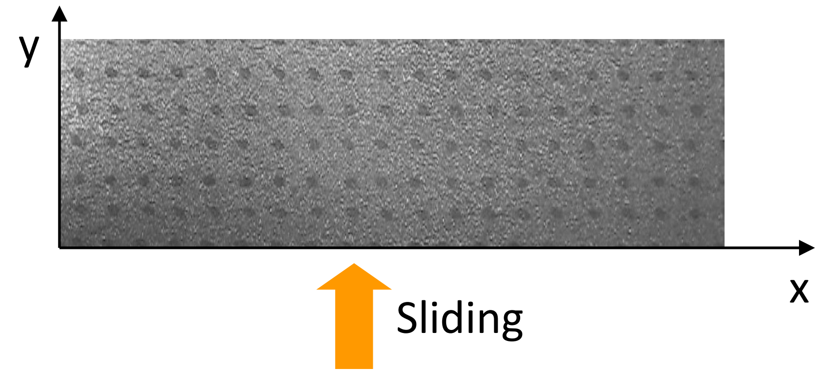
Unknown

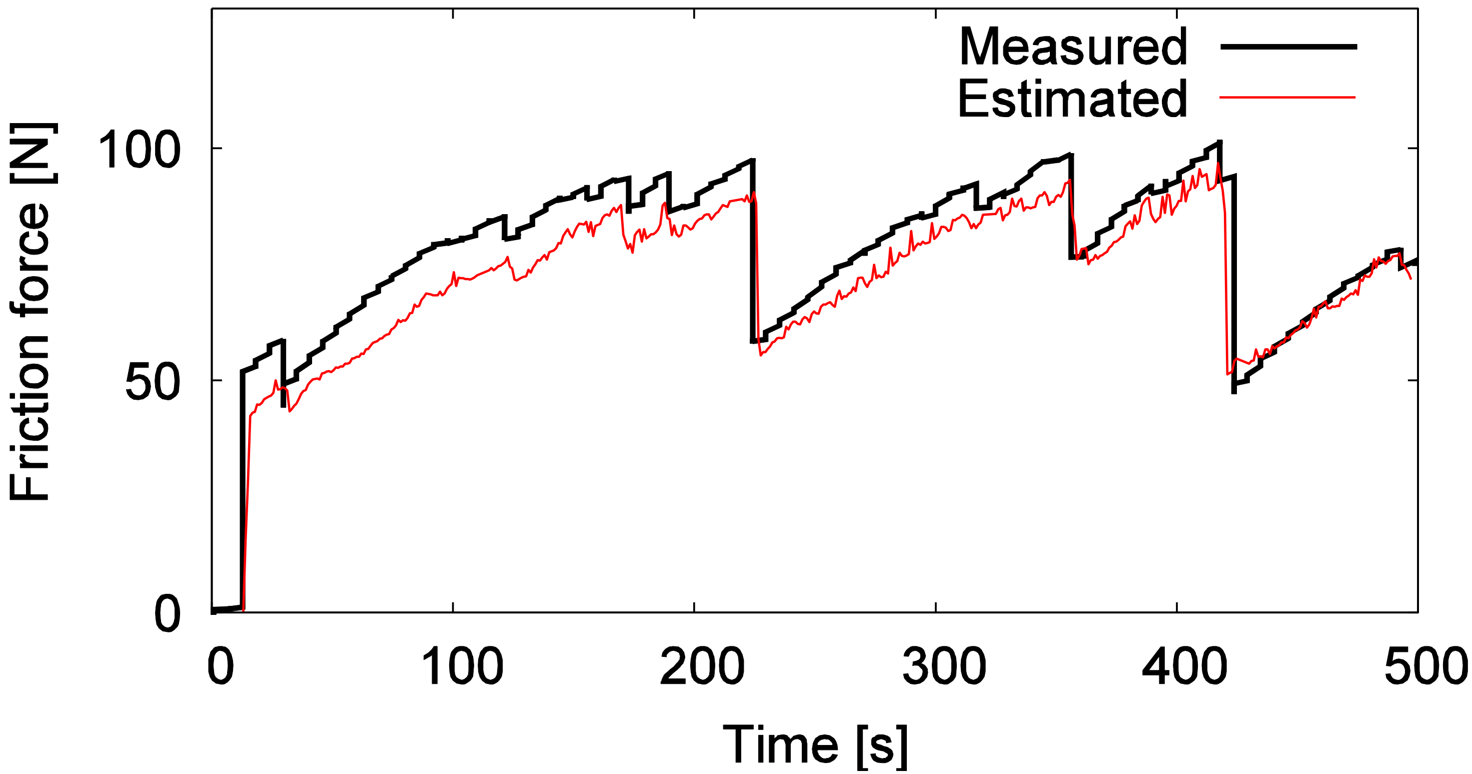


Characterization of stress field

Friction force

$$F(t)=\iint_{L,W}\sigma_{zy}(x,y,t)\,dxdy$$

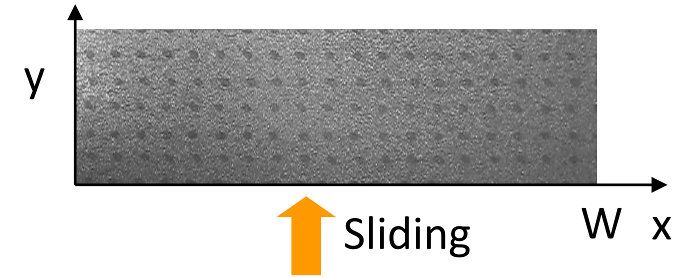




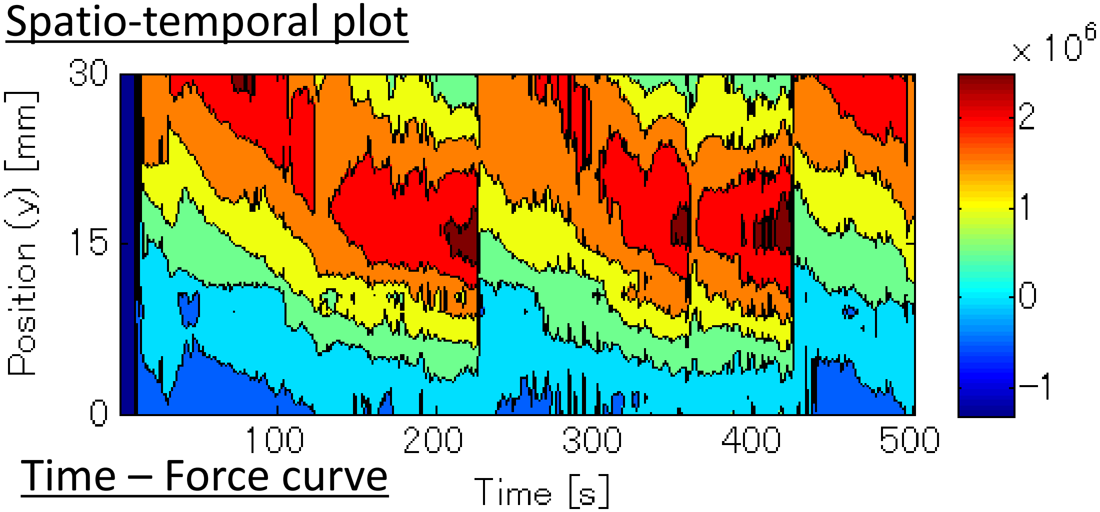
Characterization of stress field (2)

X-averaged shear stress

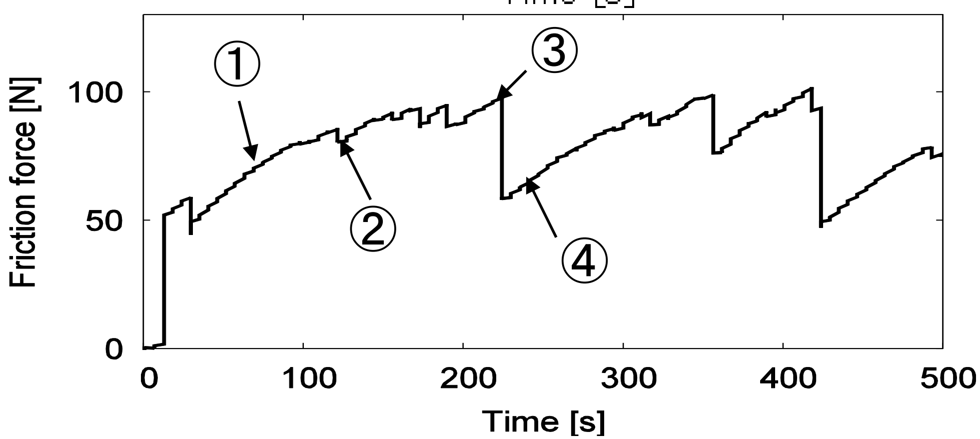
$$\sigma_{zy}(y,t) = \int_0^W \sigma_{zy}(x,y,t)\,dx$$



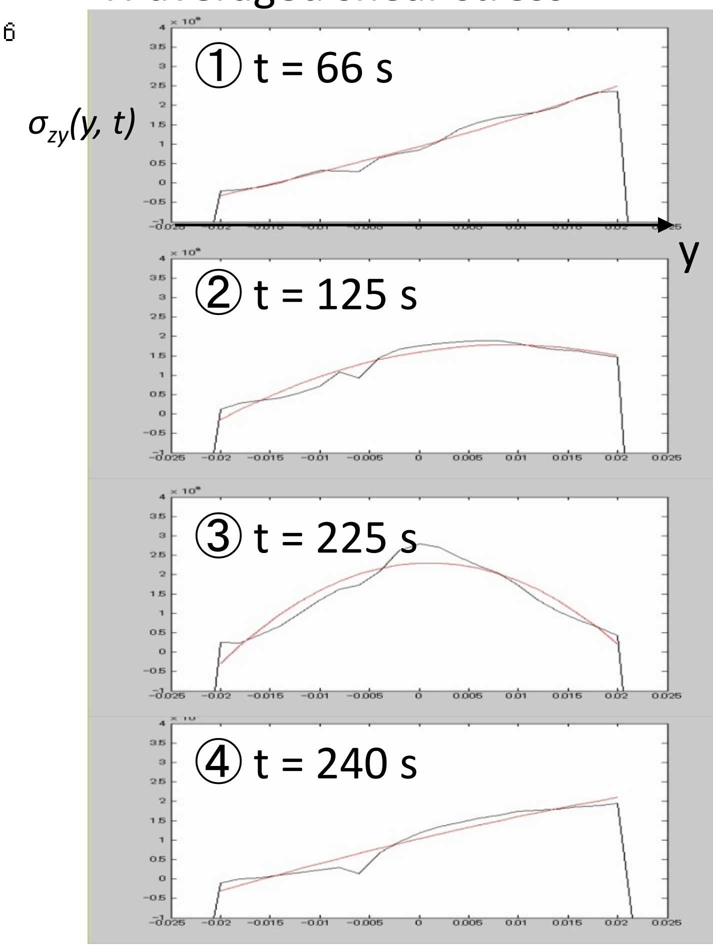
Spatio-temporal plot



Time – Force curve



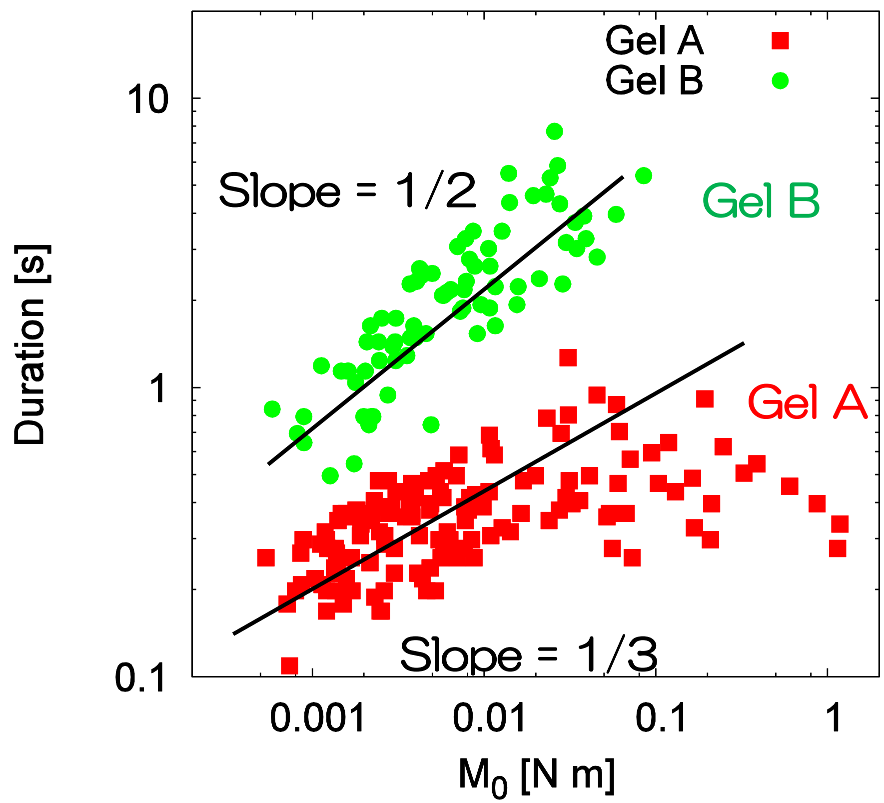
X-averaged shear stress



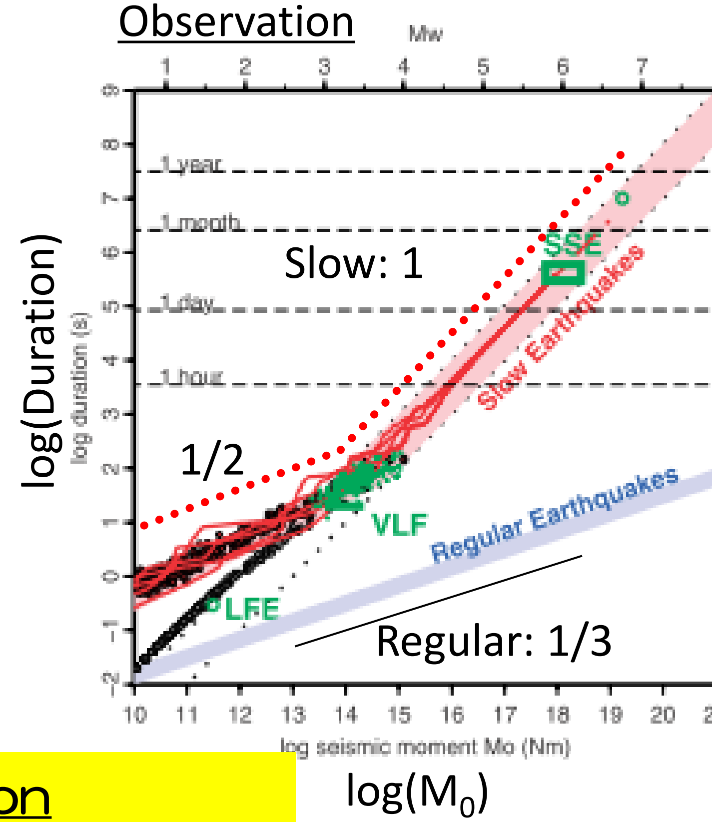
Scaling of duration

$$T \sim M_0^{\alpha} \quad (M_0 = \mu DS = \mu D L_x L_y)$$

Experiment



Observation



Slope = 1/2 ⇒ $M_0 \sim T^2$

Slope = 1/3 ⇒ $M_0 \sim T^3$

Question
Contribution of each parameter ?

S. Ide *et al.*, *Nature* (2007)

S. Ide, *Geophys. Res. Lett.* (2008)

Size-duration relation for regular earthquakes

Regular earthquake

$$\boxed{T \sim M_0^{1/3}}$$

T: Duration

$M_0 = \mu DS$: Earthquake moment

μ: Rigidity (shear modulus)

D: Slip

S = L^2: Rupture area

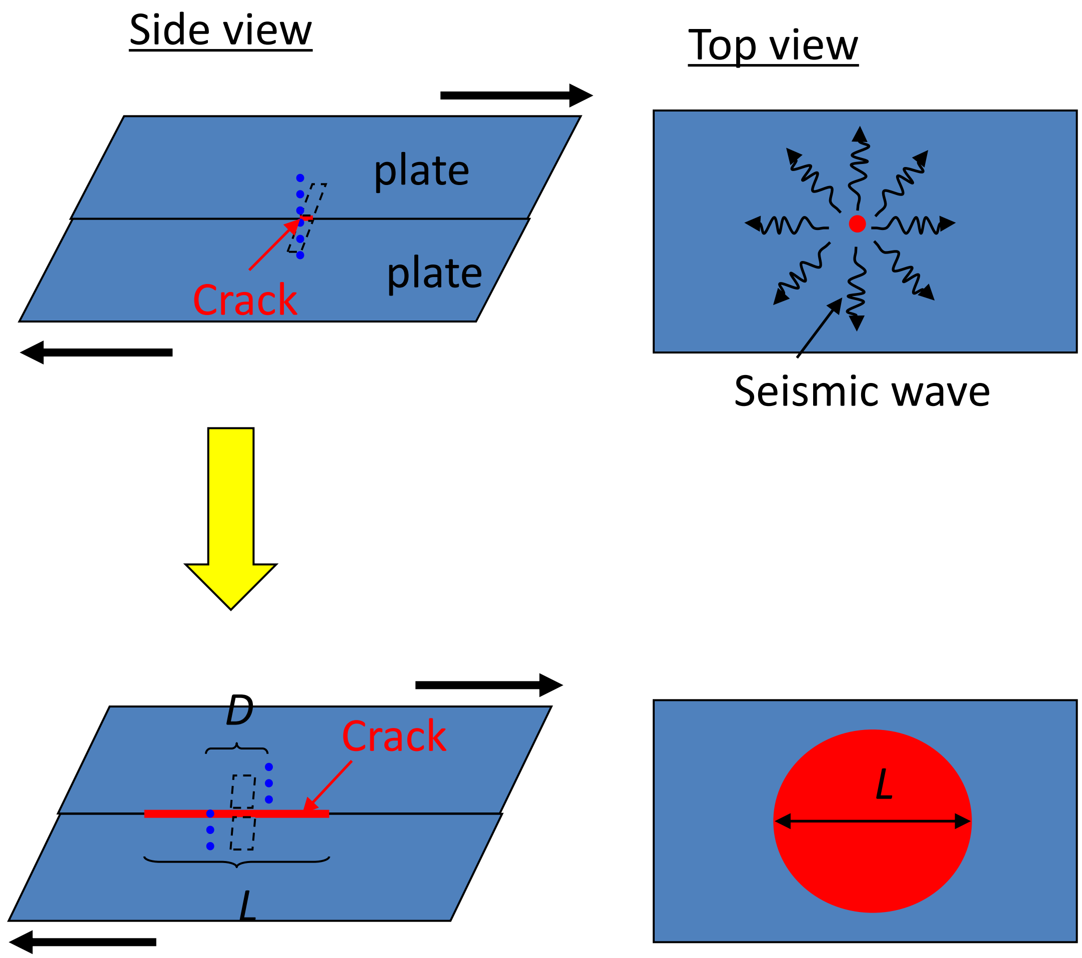
L = c T (c: propagation velocity)

$S \propto L^2 \propto T^2$

$D \propto L \propto T$ (Δγstrain drop = const.)

(Kanamori & Anderson, 1975)

$$\Rightarrow \quad M_0 \sim T^3$$

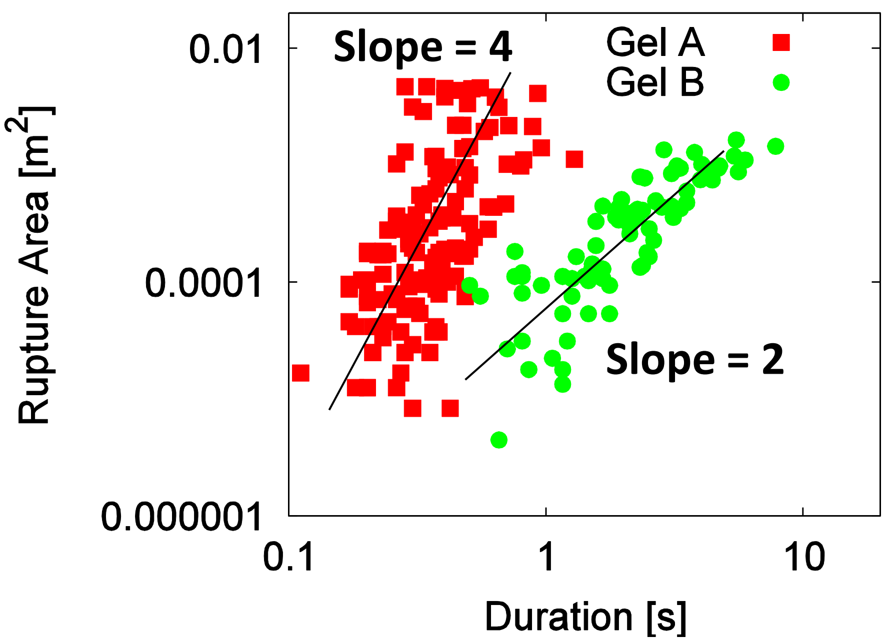


- How is slow earthquake explained ?
- Is it possible to reproduce these behaviors in laboratory experiments ?

Duration – Slip area relation

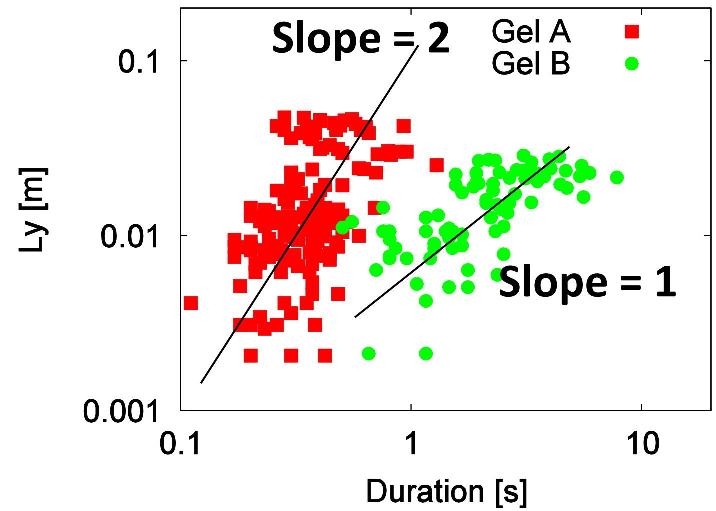
Duration-Rupture Area relation

$$S = L_x L_y \sim \begin{cases} T^4 & \text{Gel A} \\ T^2 & \text{Gel B} \end{cases}$$

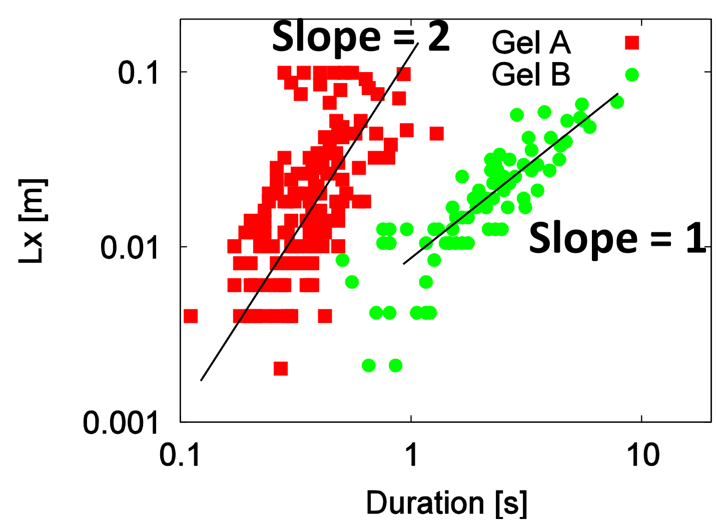


Isotropic expansion of rupture area !

T - *Ly* (siding direction)

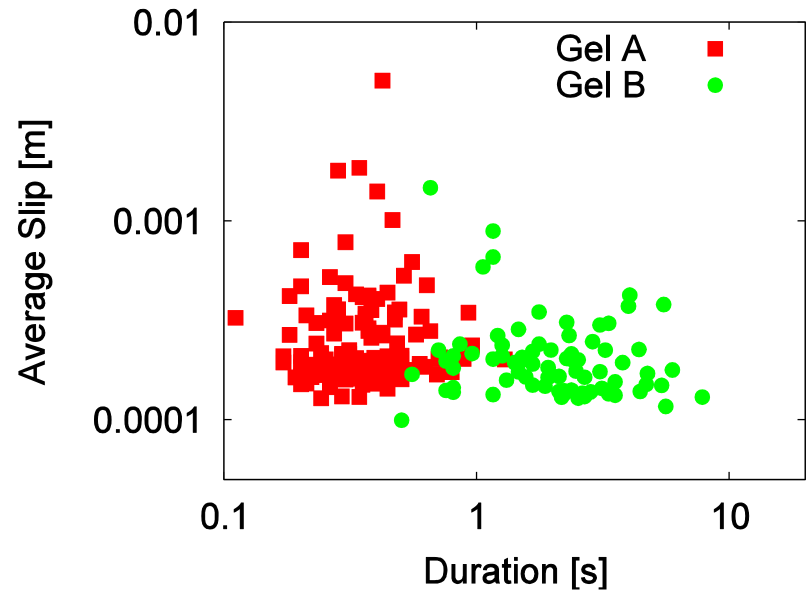


T - *Lx* (perpendicular)

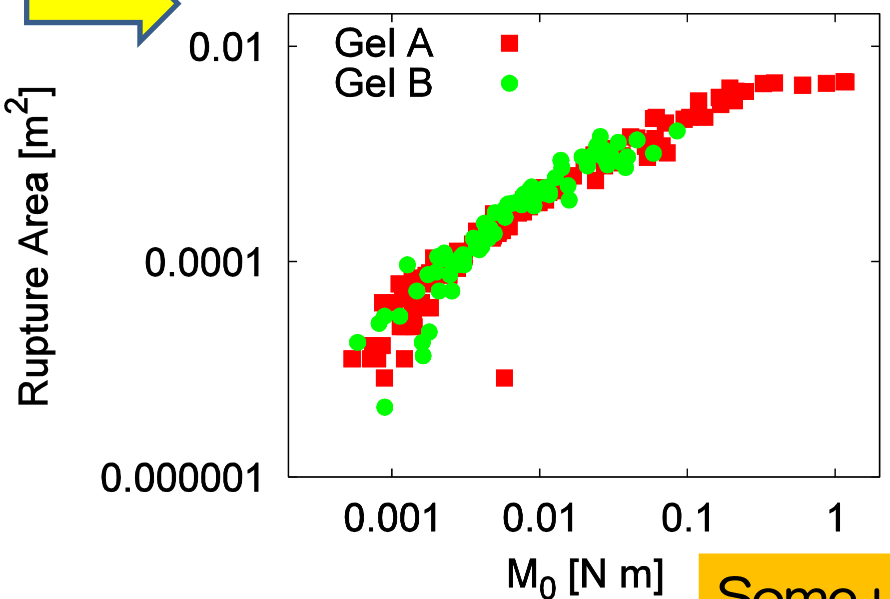


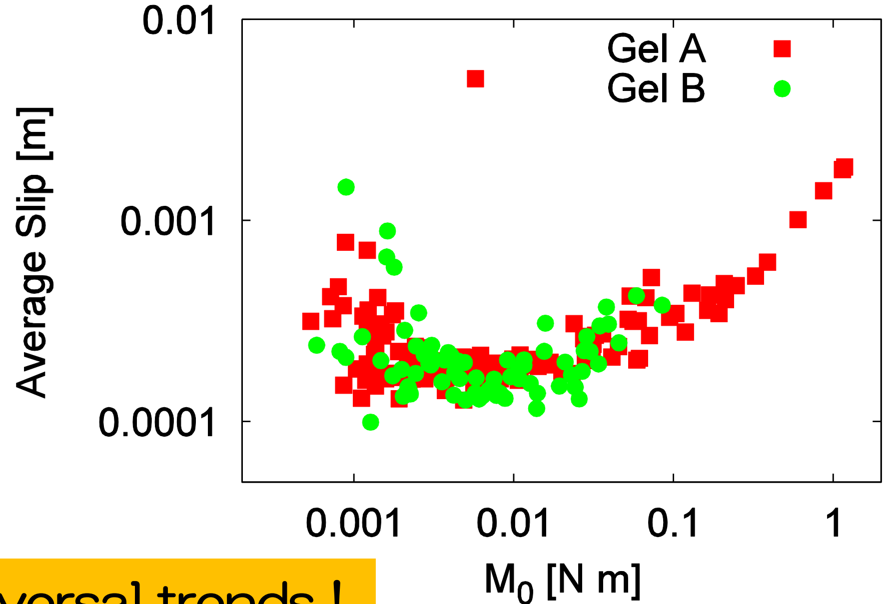
Duration – Slip distance relation

$$D_{ave} \sim T^0$$



Rupture area and slip distance against Earthquake moment





Some universal trends !

Summary

◆ We introduced PIV method to analyze

- Displacement field,
- Moment magnitude, and
- Shear stress distribution.

◆ We found a large enhancement of the slip due to the crack acceleration at the trailing edge. This behavior looks similar to what is observed for Tohoku-Chiho Taiheiyo-Oki earthquake.

◆ We found a significant difference in the shear stress fields during the small slip phase and just before the large slip phase.

◆ We reproduced scaling relations for slow earthquakes, and found a universal behavior.