Transport properties and its implication of pore pressure change due to frictional heating during 1999 Taiwan Chi-Chi earthquake

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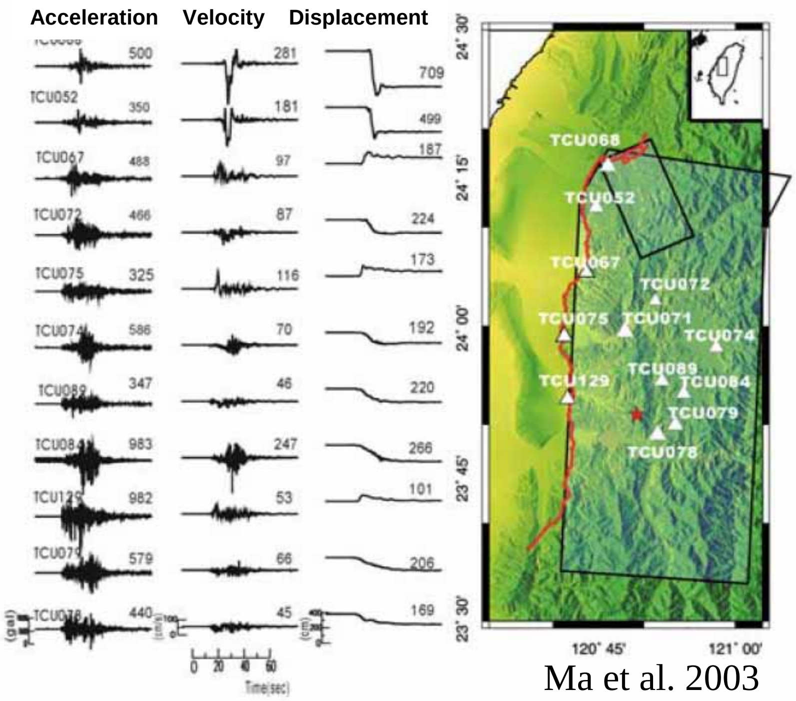
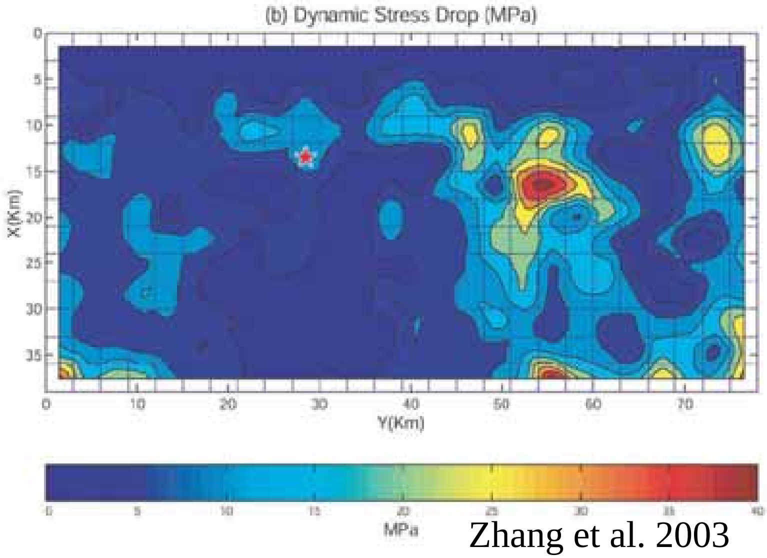
1999 Taiwan Chi-Chi Earthquake

- ◆**September 20, 1999 - Mw 7.6**
- ◆**Rupture of Chelungpu Fault**
- ◆**Propagation from South to North**
- ◆**Remarkable difference between N – S**

	North	**South**
Displacement	**Large -10m**	Small
Velocity	Large – 4.5m/s	Small
Acceleration	Small	Large
High freq. radiation	Low level	
Stress Drop	Large	Small



Ma et al. 2003



Zhang et al. 2003

Question to be Solved

What made the contrast between North and South?

What caused such a large displacement at Northern portion?

Variation of fault rock property and Dynamic fault weakening mechanism

- Melting (Hirose and Shimamoto, 2005) – Psuedotachylyte is rare in fault zones.
- (Elast) hydrodynamic lubrication (Ma et al., 2003) – Fault rocks behaves as viscous?
- Acoustic fluidization (Melosh, 1996) – Difficult how to identify – injection vein?
- Thermal pressurization (Lachenbruch 1980)

Current researches related to the Chelungpu Fault

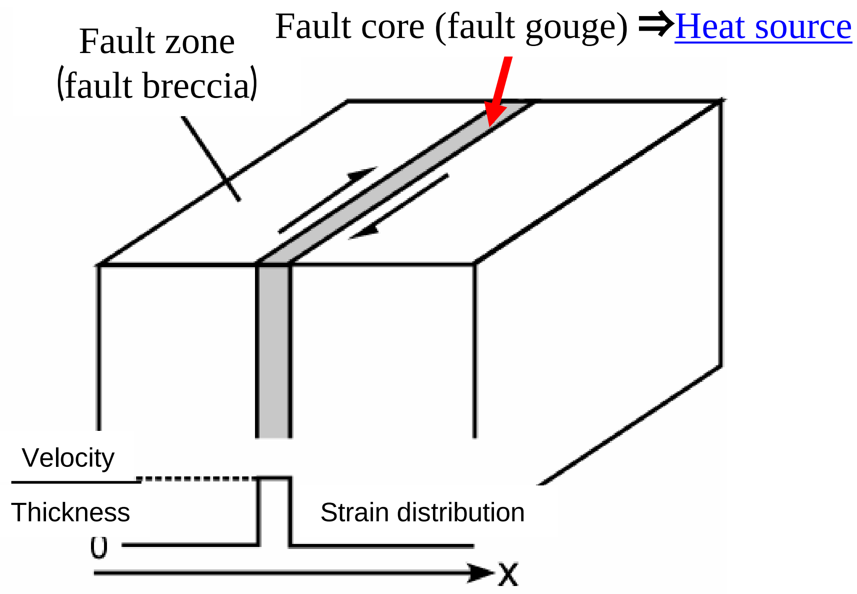
Borehole temperature observation (Kano et al. 2006) - Low friction during slip event

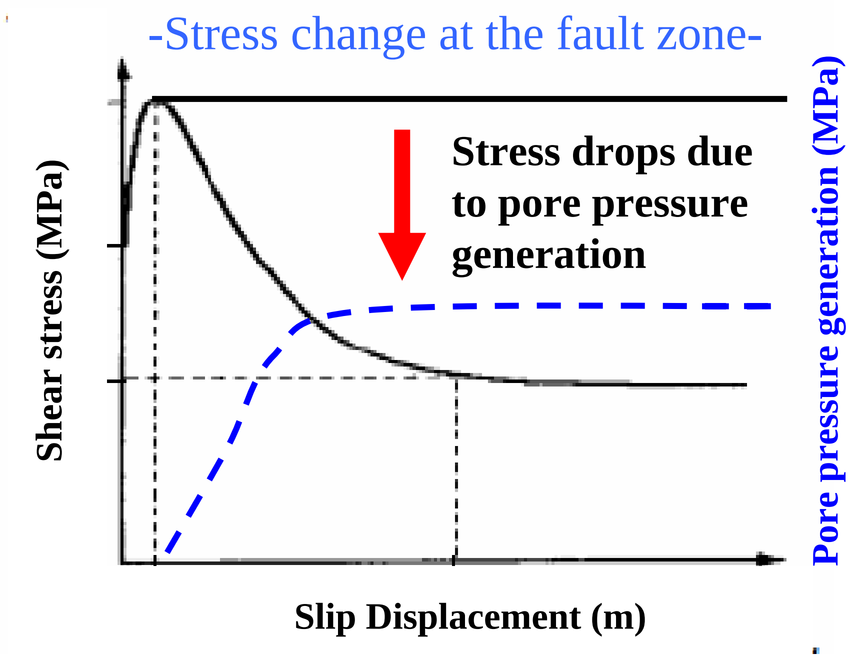
→ Dynamic weakening mechanism effectively occurred?

Core observation (Hirono et al. 2006) - Temperature doesn’t rise to melting point

→ Melt weakening is ineffective?

Concept of Thermal Pressurization




-Stress change at the fault zone-

Frictional Heating (during earthquake)

↓

Thermal expansion of pore water

↓ (Undrained condition)

Pore pressure generation

↓

Reduction of effective pressure

↓

Dynamic fault weakening

↓

Unstable → Large slip?

Critical Parameters for TP

- **Diffusion parameter**
  - Permeability, Specific storage
- **Heat source parameter**
  - Shear strength, Thickness of fault core

Research Area

1)Depth Variation

Chelungpu Fault

Shuangtung Fault

Shuichangliu Fault

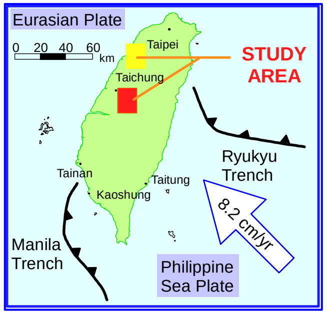
(Stratigraphic cross section, Vitrinite reflectance)

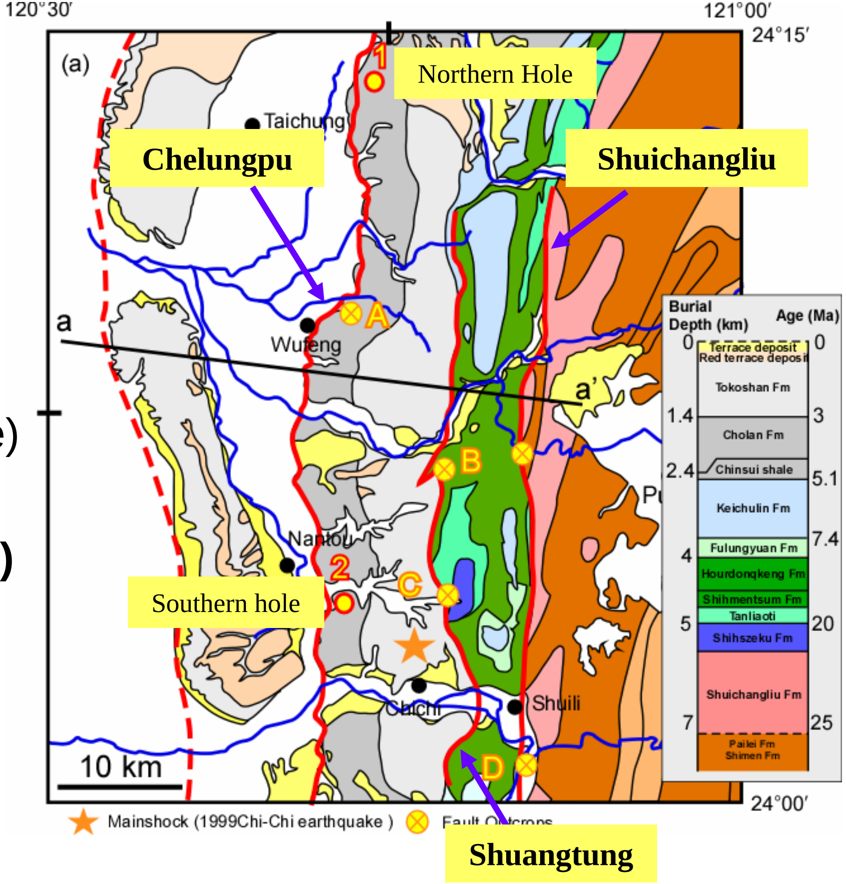
2)Along-Fault Variation (borehole sample)

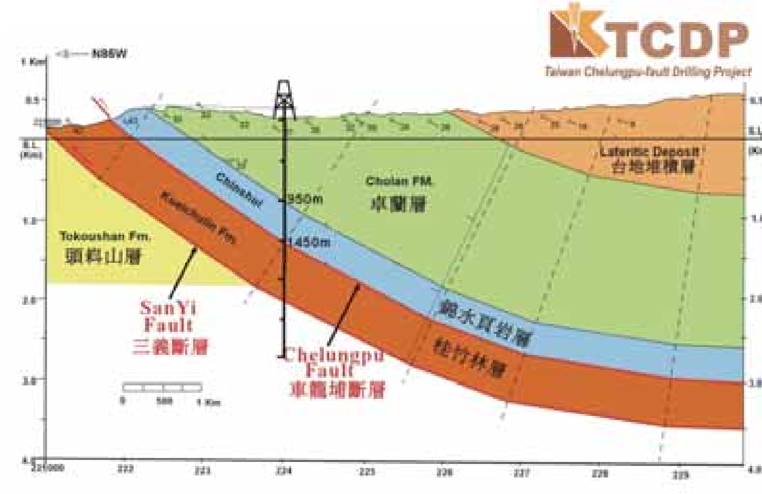
Northern site (Fengyuan 400m)

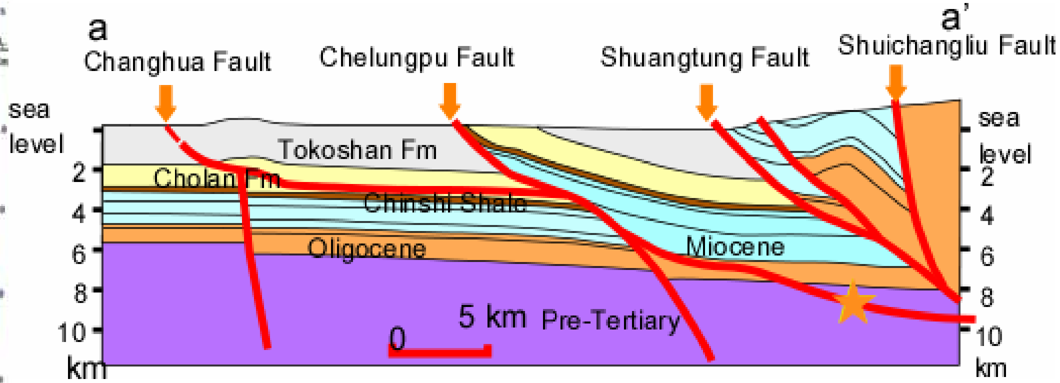
Southern site (Nantou 200m)

TCDP - (Dakeng A:2000m, B:1350m)





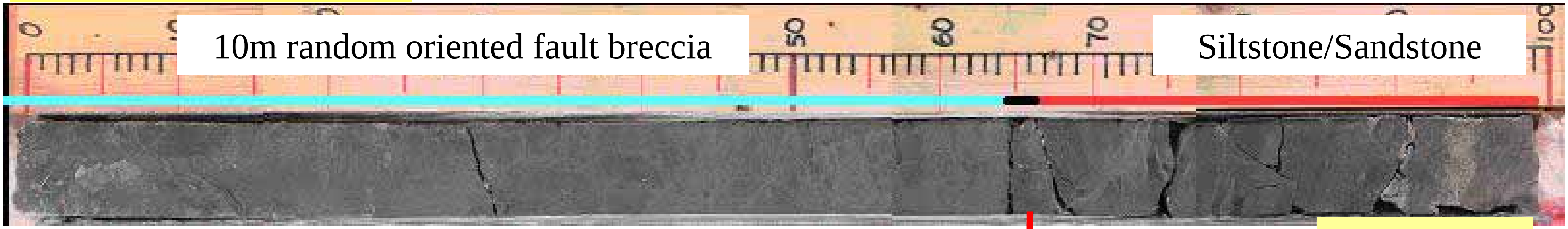




Chelungpu Fault-Northern borehole

3 possible candidates for slip zone - fault zones are developed within siltstone
→Still under discussion which is the best choice!?

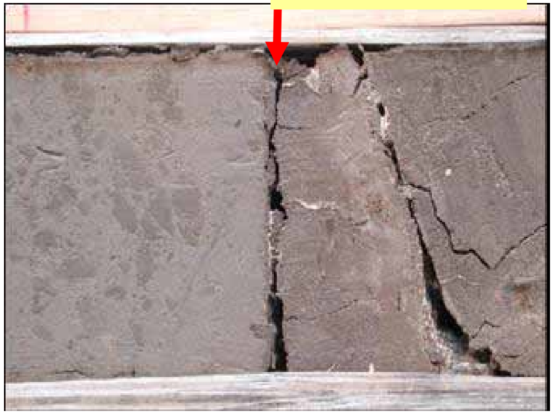
Candidate1(329 - 330 m)



Slip plane?

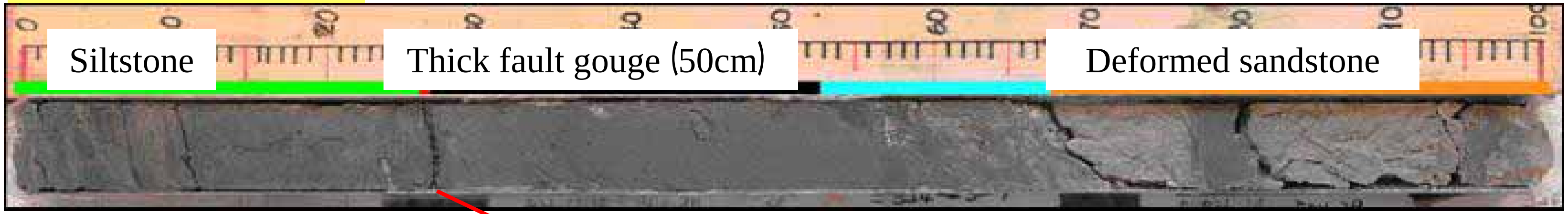
Candidate2 (224.55 – 224.75 m)

No strong shear deformation zone



Thin clayey fault gouge (7 mm)

Candidate3 (405m)



Very thin hard black material (ultra cataclasite?)

Shuangtung Fault-outcrop

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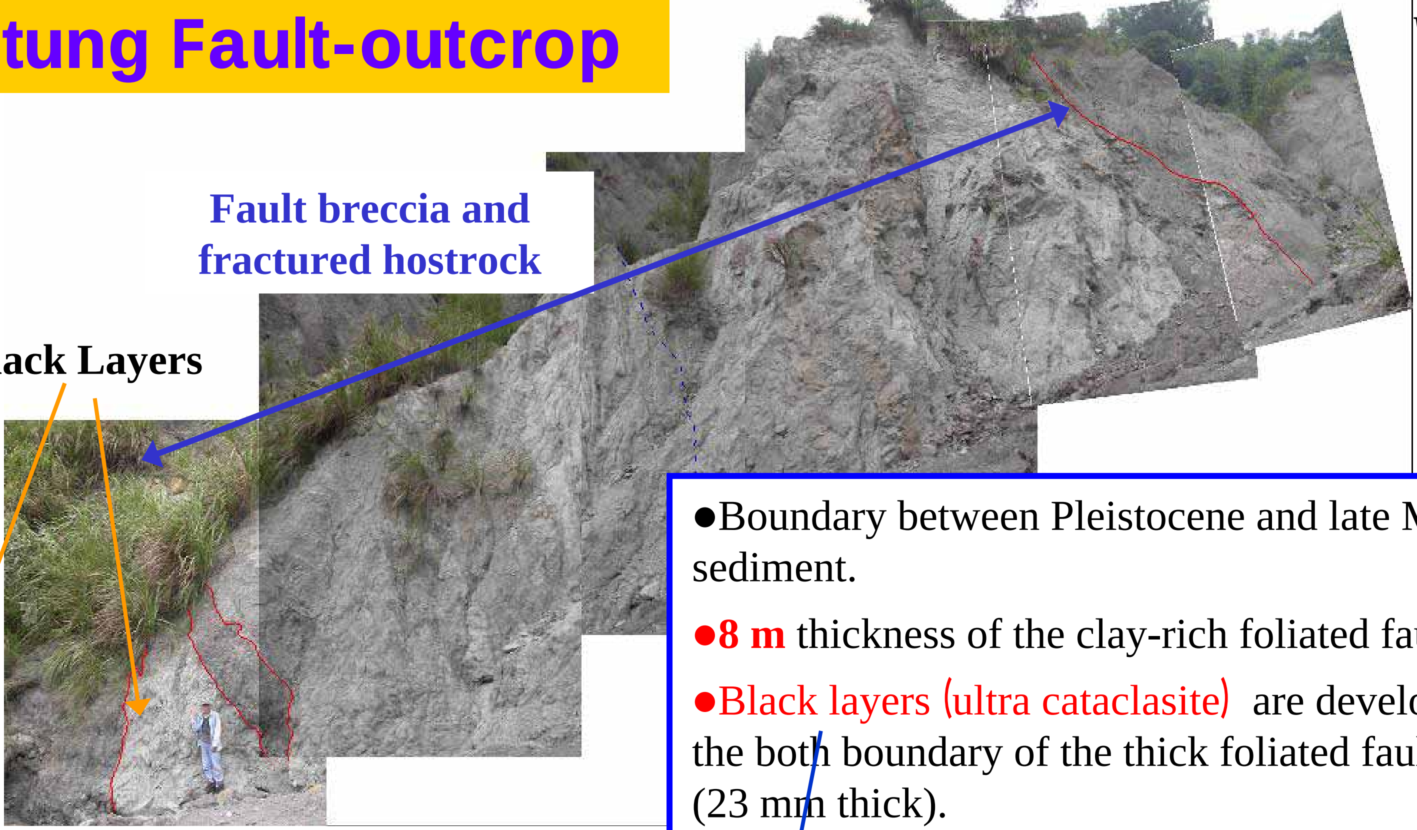
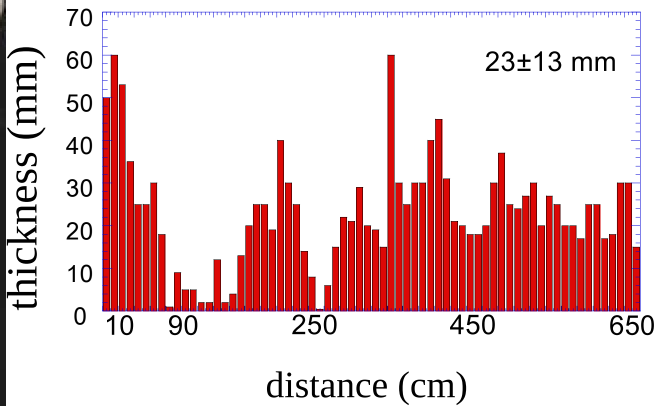


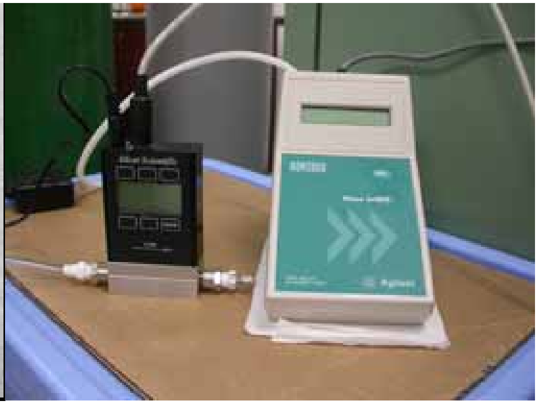
- Boundary between Pleistocene and late Miocene sediment.
- **8 m** thickness of the clay-rich foliated fault gouge.
- Black layers (ultra cataclasite) are developed in the both boundary of the thick foliated fault gouge (23 mm thick).

10 m-thickness clayey foliated fault gouge



Transport Property Test

Cylindrical samples



Flow meter

Experimental condition

Pore Fluid - N2 gas (low viscosity)

Temperature - room temperature

Confining pressure - 0 ~ 200 MPa (12km)

Fluid pressure - 0 ~ 2 MPa

Sample size – ϕ20mm ×Length 10 - 40 mm

Method for measurements

Permeability - steady state gas flow method using accurate gas flow meter (ADM2000, Alicat flowmeter)

Gas permeability is arranged to water permeability using the **Klinkenberg equation**.

Porosity - calculated by the pore pressure change under undrained condition

Specific storage- approximated by **drained pore compressibility** that is estimated from porosity test

$$Ss = \beta_\varphi + \varphi \beta_f$$

$$\beta_\varphi = -\frac{1}{1-\varphi} \frac{\partial \varphi}{\partial Pc}\bigg|_{p=0}$$

Ss: Specific storage (Pa^{-1})

β_f: Fluid compressibility(Pa^{-1})

ϕ : Porosity

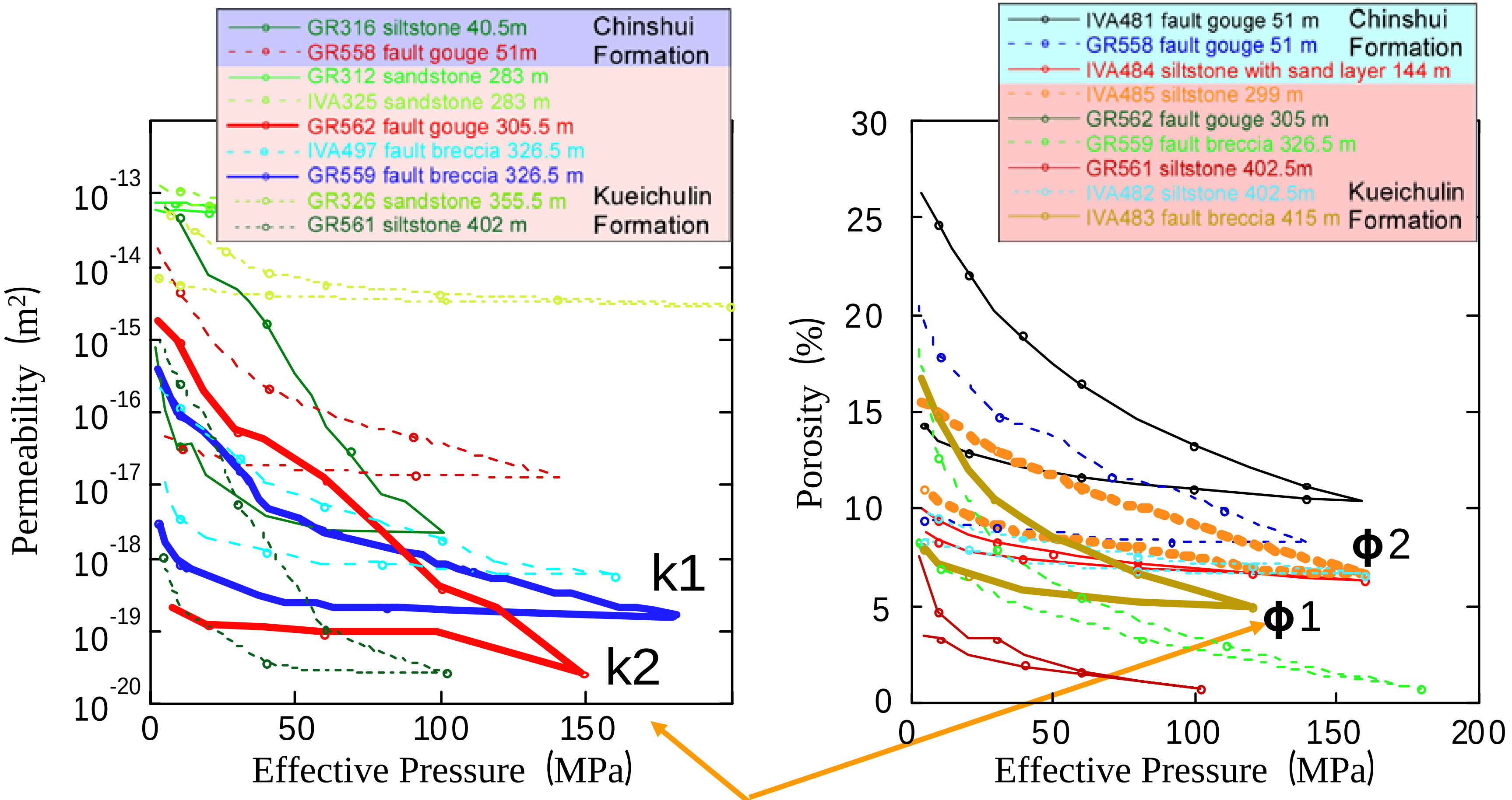
Pc: Confining pressure

p: Pore pressure

Pressure vessel

Example of Experiment – permeability & porosity

Northern Shallow borehole for Chelungpu Fault



Applied for Thermal Pressurization analysis

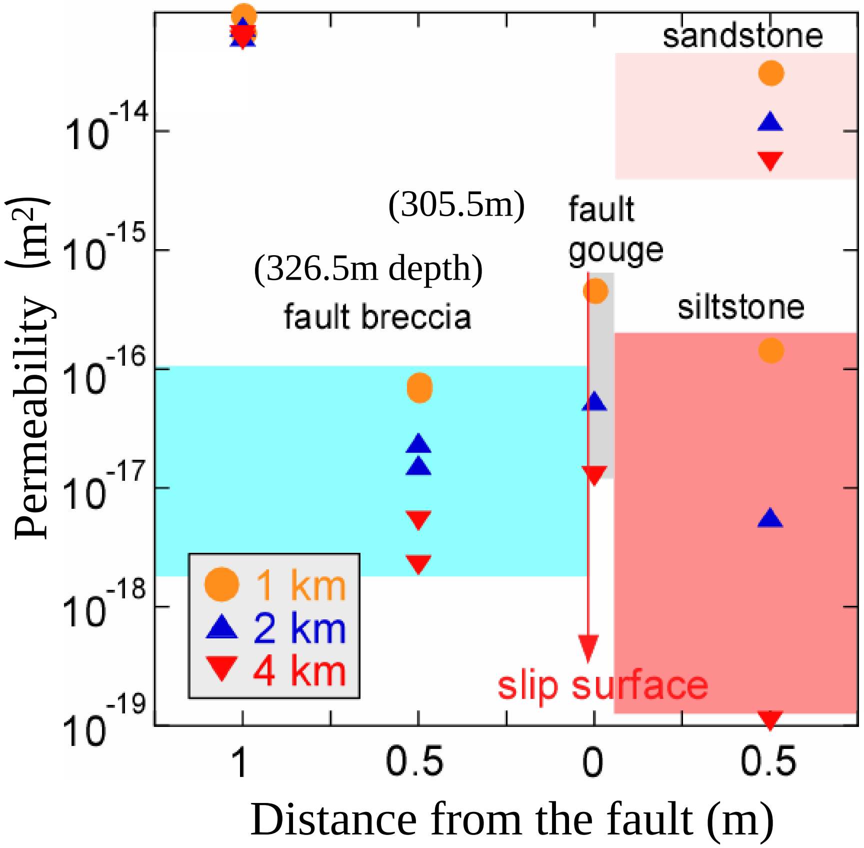
1.Strong sensitivity for effective pressure

2.Elast-plastic behaviors

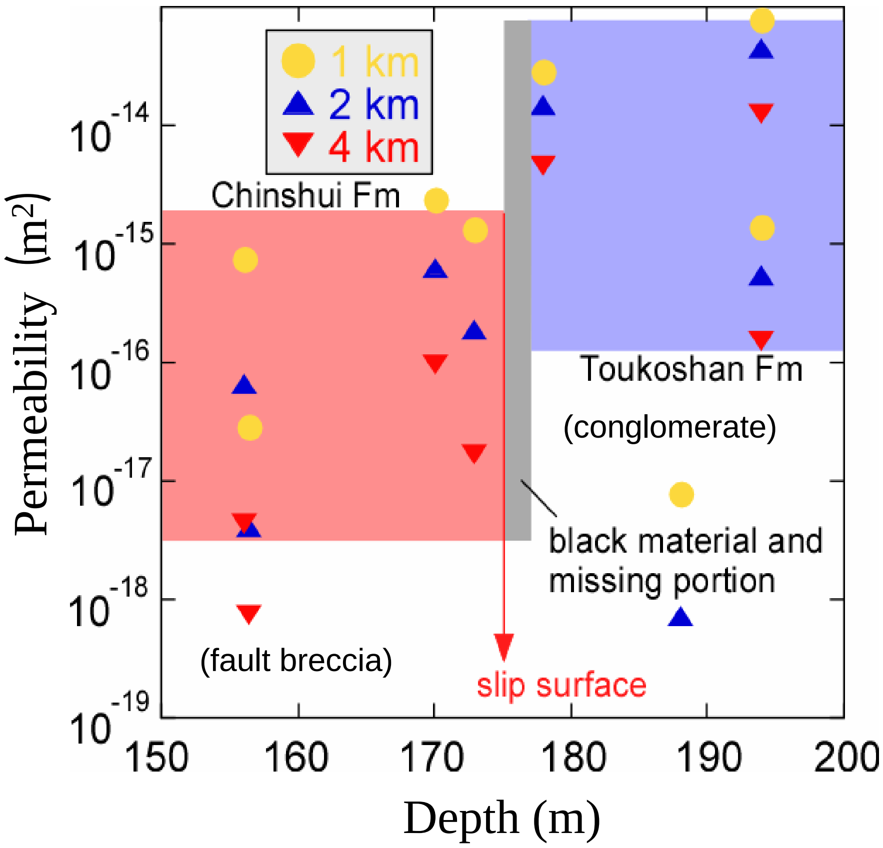
⇨ **Proper description of parameters as a function of pressure is important!**

Permeability Structure Ⅰ - Along Fault Variation

Northern borehole (329m depth)



Southern borehole



◆Permeability for fault rock is larger in Southern site (one order).

◆Permeability for wall rock is larger in Southern site.

Permeability Structure II - Depth Variation

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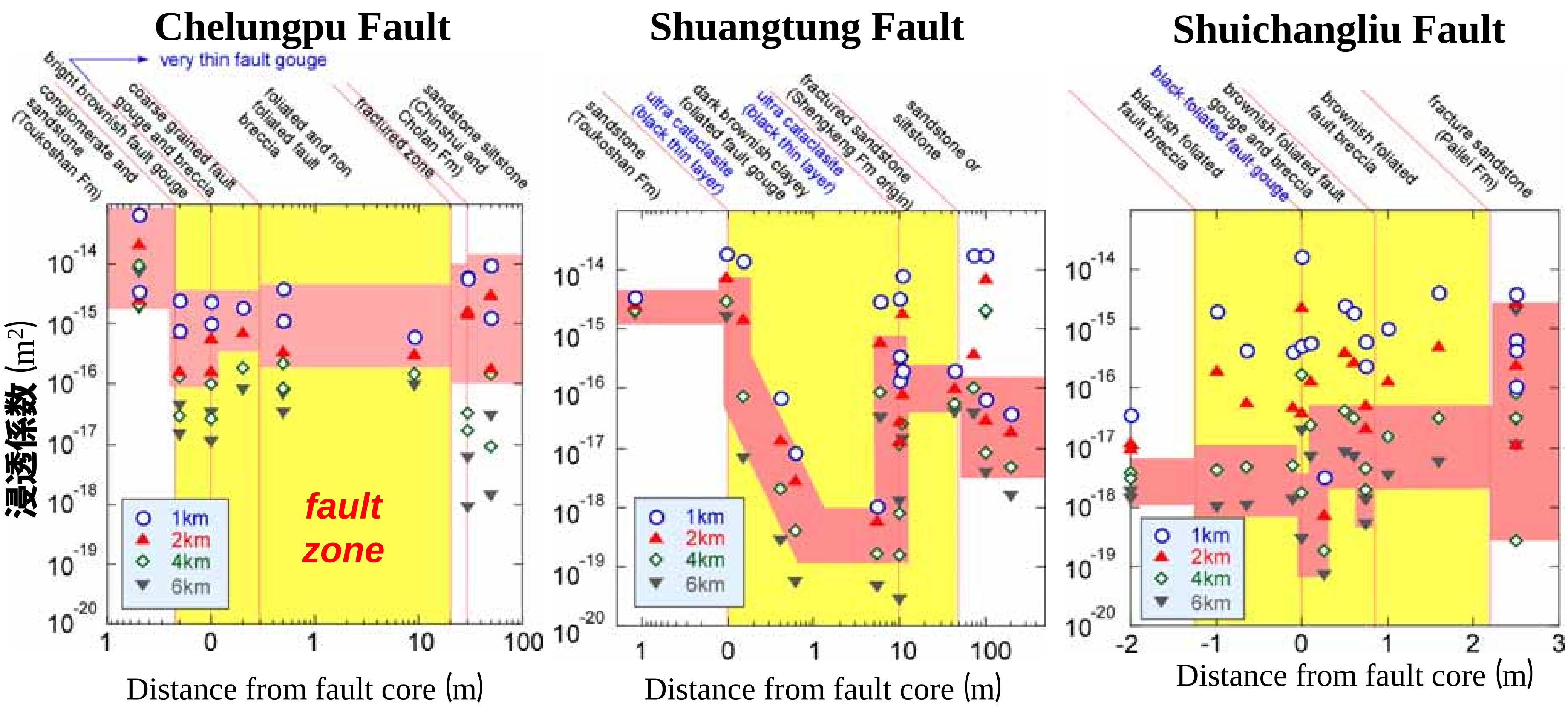
Shallow? → **Deep?**

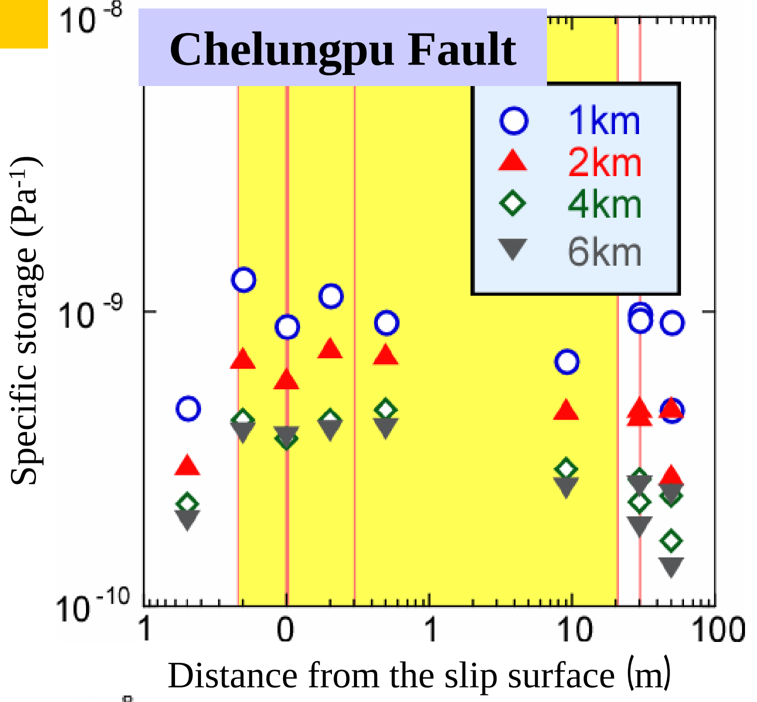


◆Chelungpu Fault < Shuangtung Fault • Shuichangliu Fault

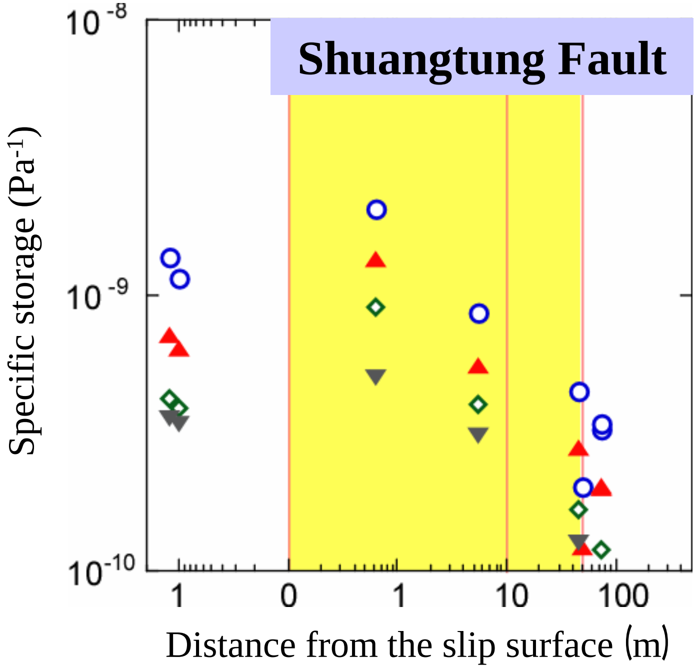
◆Permeability variation within fault zone is small

Specific Storage- Depth Variation

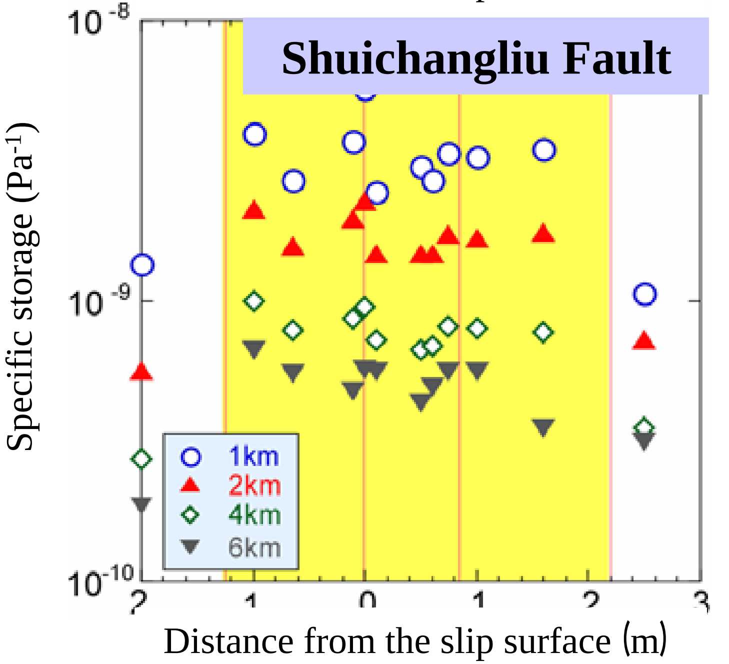
Small difference of specific storage among the faults, within a fault zone, and between fault and host rocks.
Most of them are around **10^{-9} Pa^{-1}**.



Chelungpu Fault



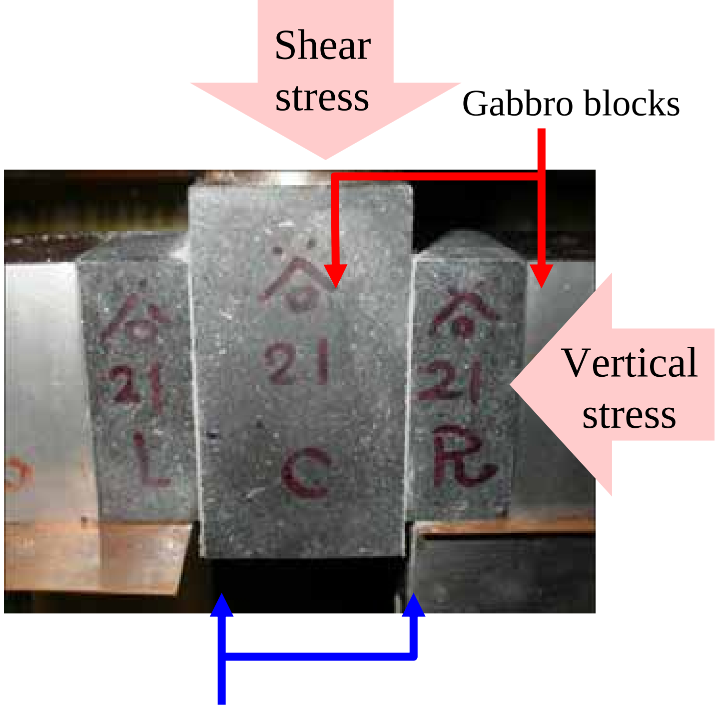
Shuangtung Fault



Shuichangliu Fault

Frictional Property Test

Bi-axial typical frictional test



Shear stress

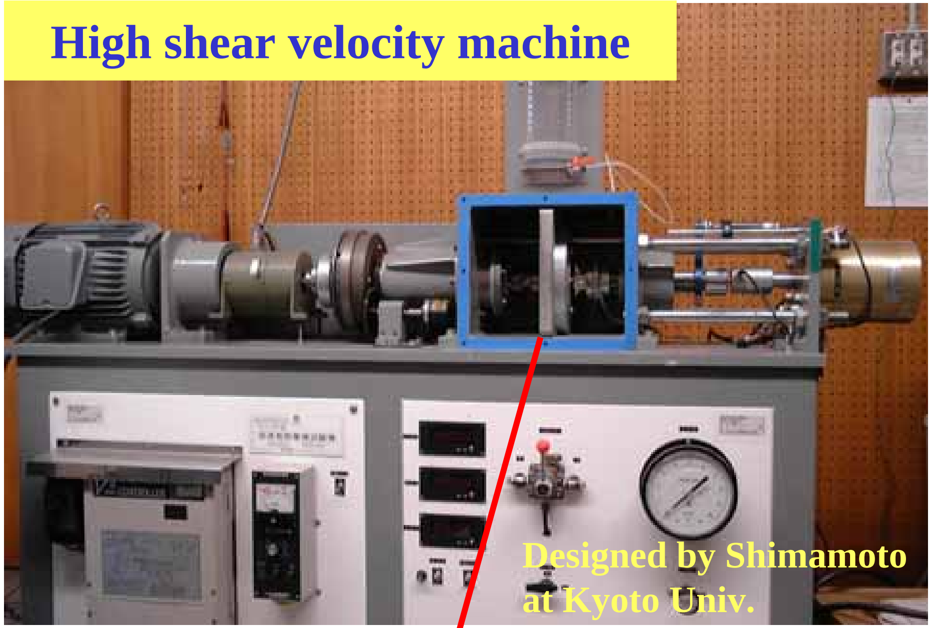
Gabbro blocks

Vertical stress

Gouge material (1.5~2.0 g)

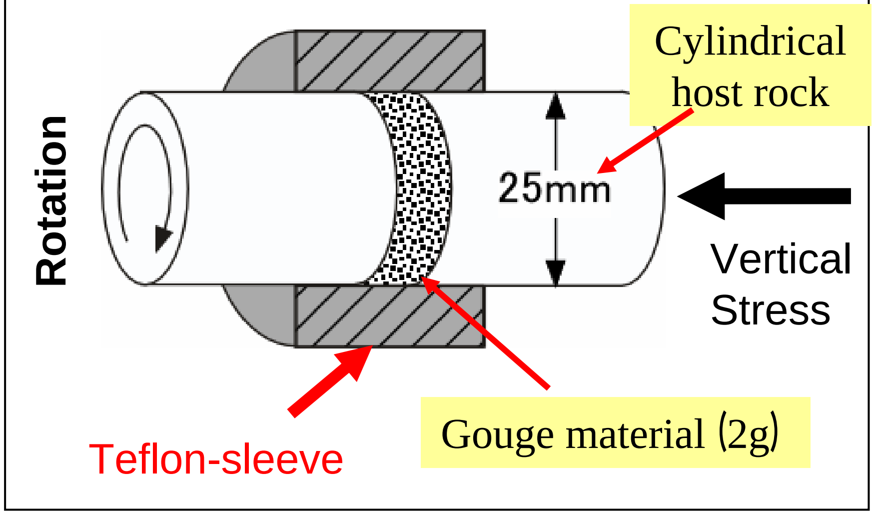
	High Velocity	Low Velocity
Slip velocity	0.1~1 m/s	0.1~100 μ m/s
Vertical stress	1 MPa	0 ~60MPa
Slip distance	∞	20mm

High shear velocity machine



Designed by Shimamoto at Kyoto Univ.

Assembly of high frictional test for fault gouge



Rotation

25mm

Cylindrical host rock

Vertical Stress

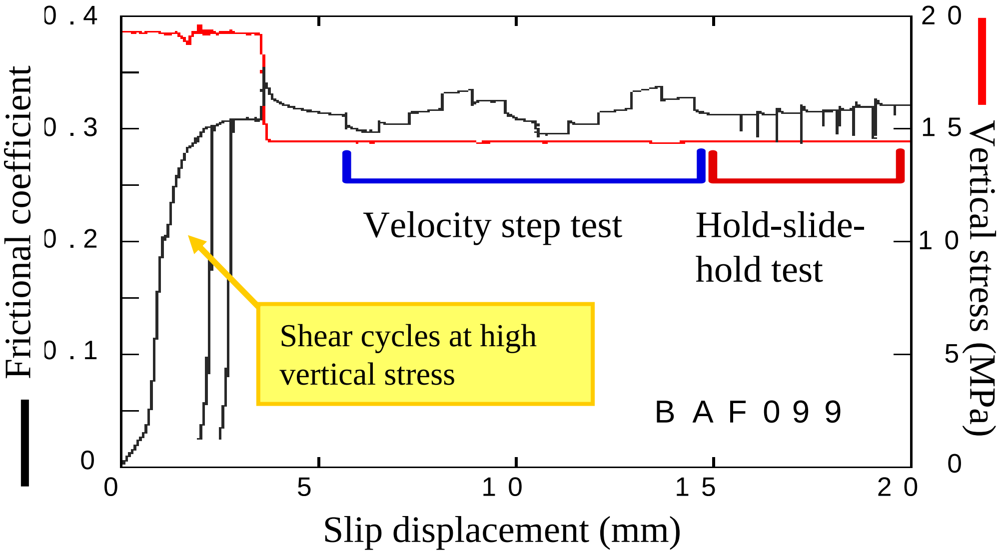
Teflon-sleeve

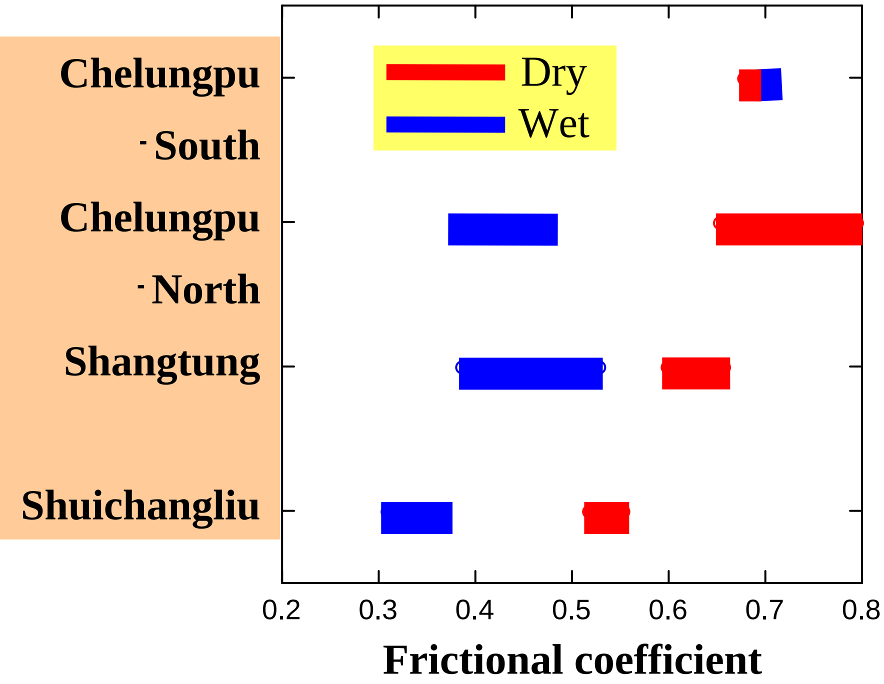
Gouge material (2g)

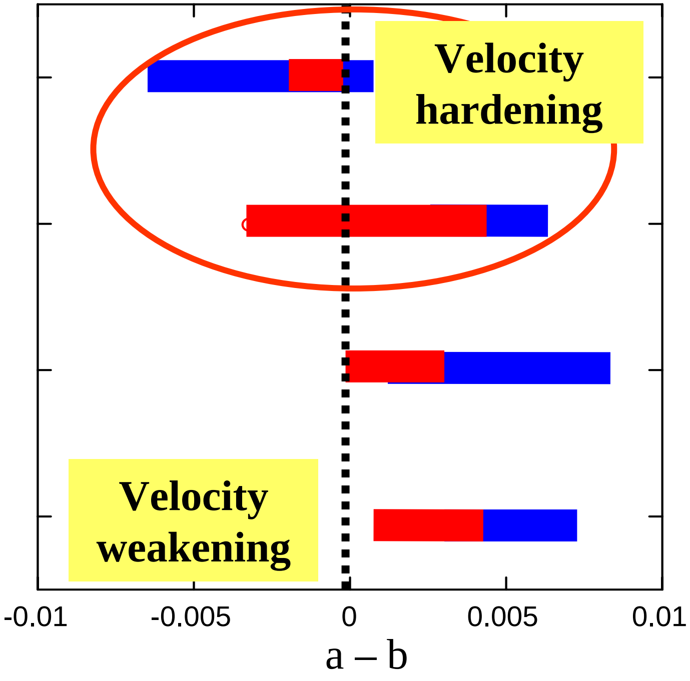
Summery of Low Velocity Friction

- **Stable friction achieved from 10 mm**
- **Chelungpu > Shuangtung > Shuichangliu**
- **Wet gouge < Dry gouge (except South)**
- **South - Velocity weakening**

⇔ North - Velocity hardening

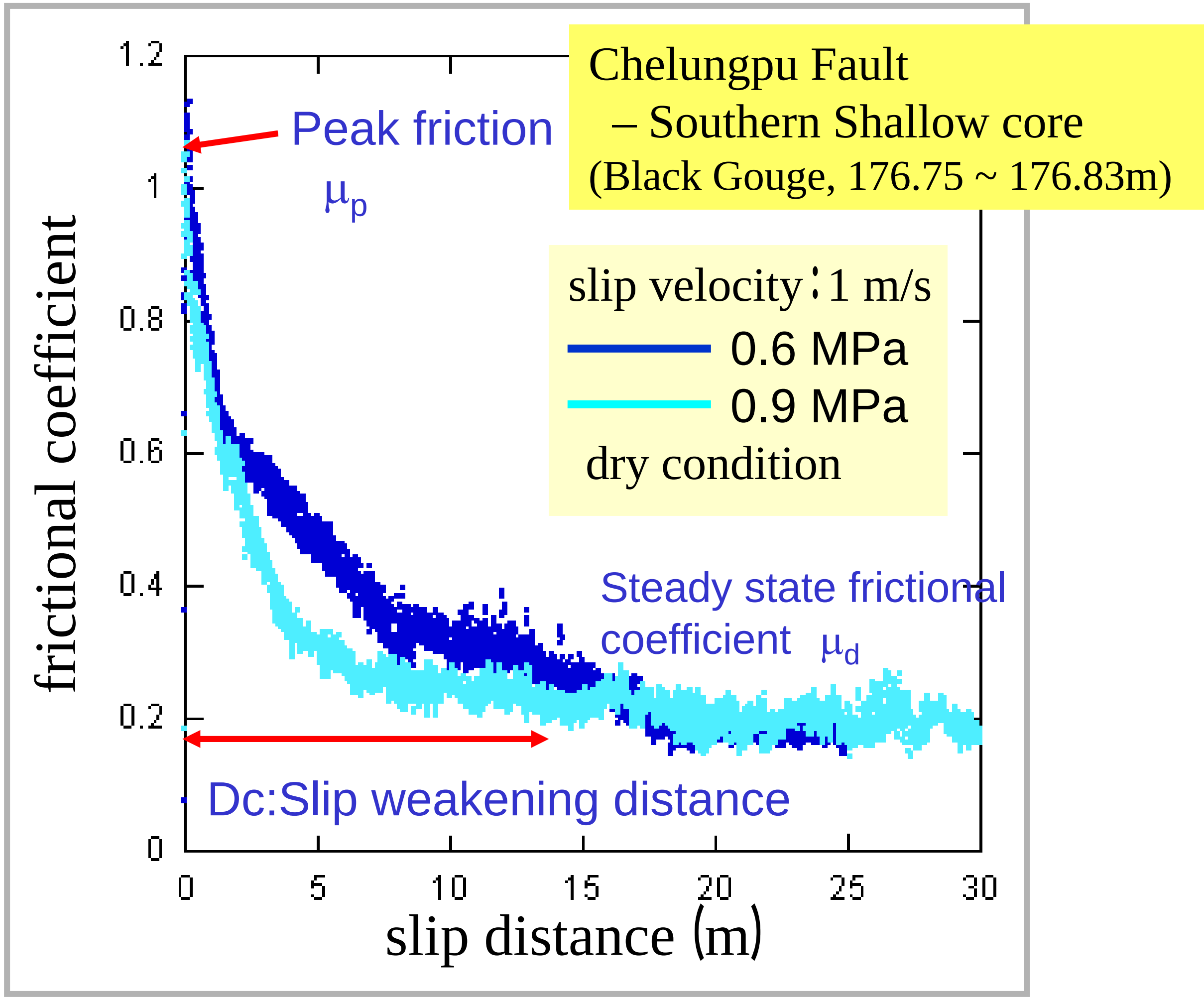






High Velocity Frictional Behavior for FG

→video image



Chelungpu Fault
– Southern Shallow core
(Black Gouge, 176.75 ~ 176.83m)

Temperature rise < 300°C (Mizoguchi 2005) ⇒ Gouge does not melt ⇒ What weakening mechanism?

1) Large peak friction~1
2) Rapid reduction with slip ⇒ stable
3) Large weakening distance D_c~10m
4) Low steady state friction μ_d~0.2

↔

Low velocity frictional test
1) D_c 10 μm~1 mm
2) μ_d 0.5 ~ 0.85

Fault Gouge Variation for H-V Friction

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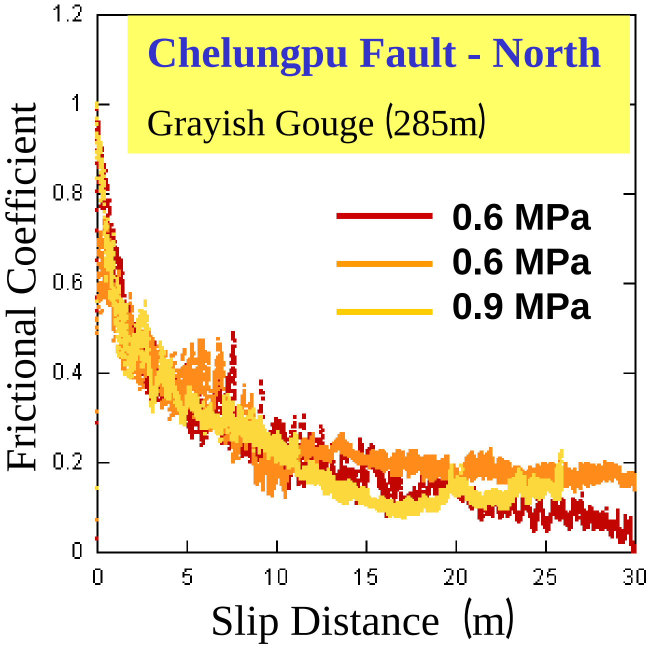
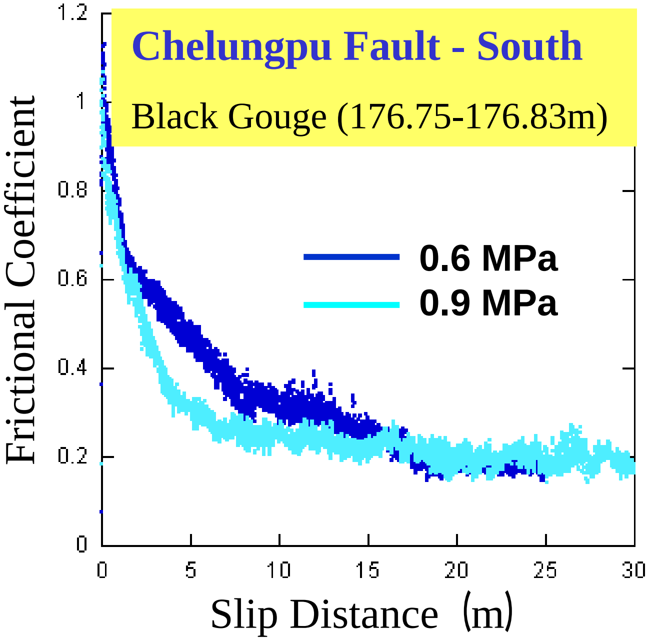
CONDITION

- Slip velocity:1 m/s
- Vertical stress:1MPa
- Room Temperature
- Dry gouge

- All gouges show similar behaviors
- **Dc** ー 6 ~ 13m.
- South is largest

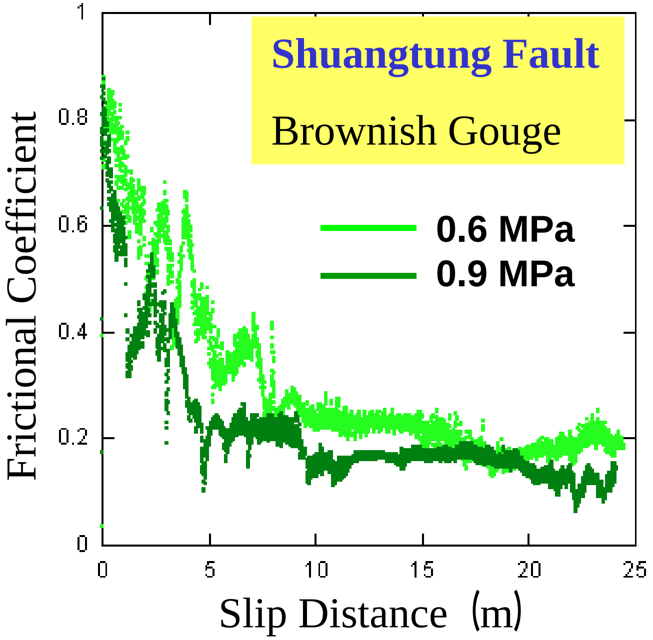


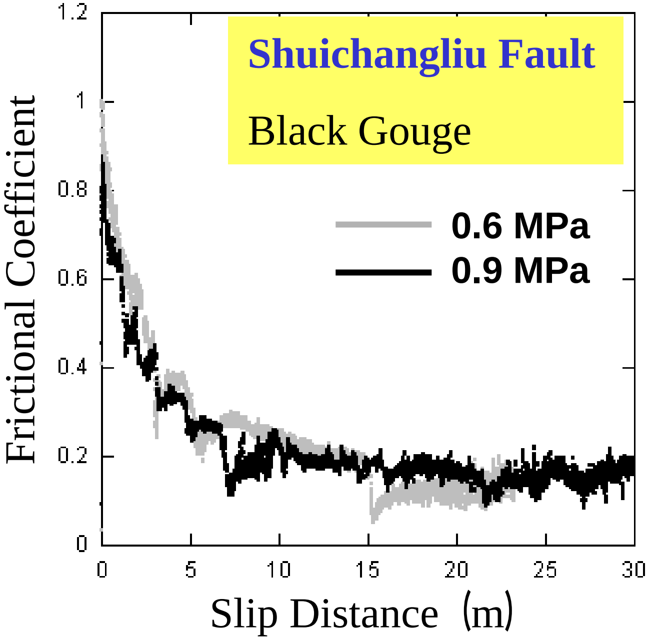


However weakening mechanism is not researched in detail!

→Hydrodynamic lubrication?

→Tribo-chemical reaction with heating?

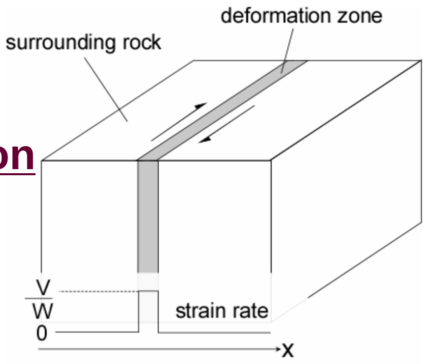




Thermal Pressurization Analysis

1D heat and fluid diffusion equation + High velocity frictional behavior

Lachenbruch (1980)
Mase and Smith (1987)



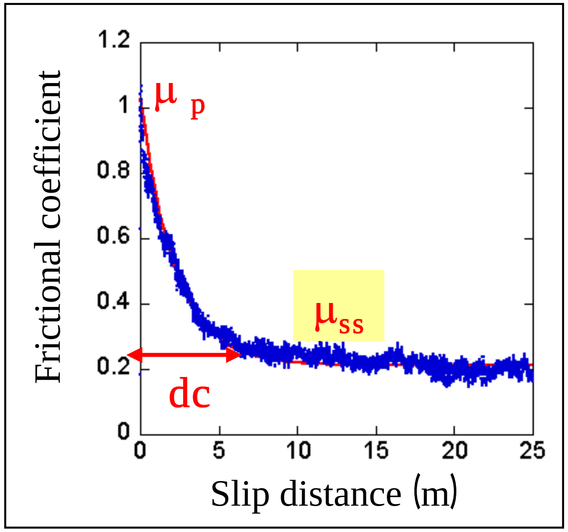
Heat generation and diffusion

$$\frac{\partial T}{\partial t} = \frac{1}{\rho c}\left(A + \kappa \frac{\partial^2 T}{\partial x^2}\right)$$

Heat production rate $A = \mu_d(\sigma - P)\frac{V}{W}$

Fluid flow and Pp generation

$$\frac{\partial P}{\partial t} = \frac{1}{\left(\phi\beta_f + \left(\frac{\partial \phi}{\partial P}\right)_T\right)}\left(\phi(\gamma_f - \gamma)\frac{\partial T}{\partial t} + \frac{\partial}{\partial x}\left(\frac{k}{\mu}\frac{\partial P}{\partial x}\right)\right)$$



$$\mu_d = \mu_{ss} + (\mu_p - \mu_{ss})exp\left(\frac{ln(0.05)\cdot d}{Dc}\right)$$

Laboratory results
(Effective pressure functions)

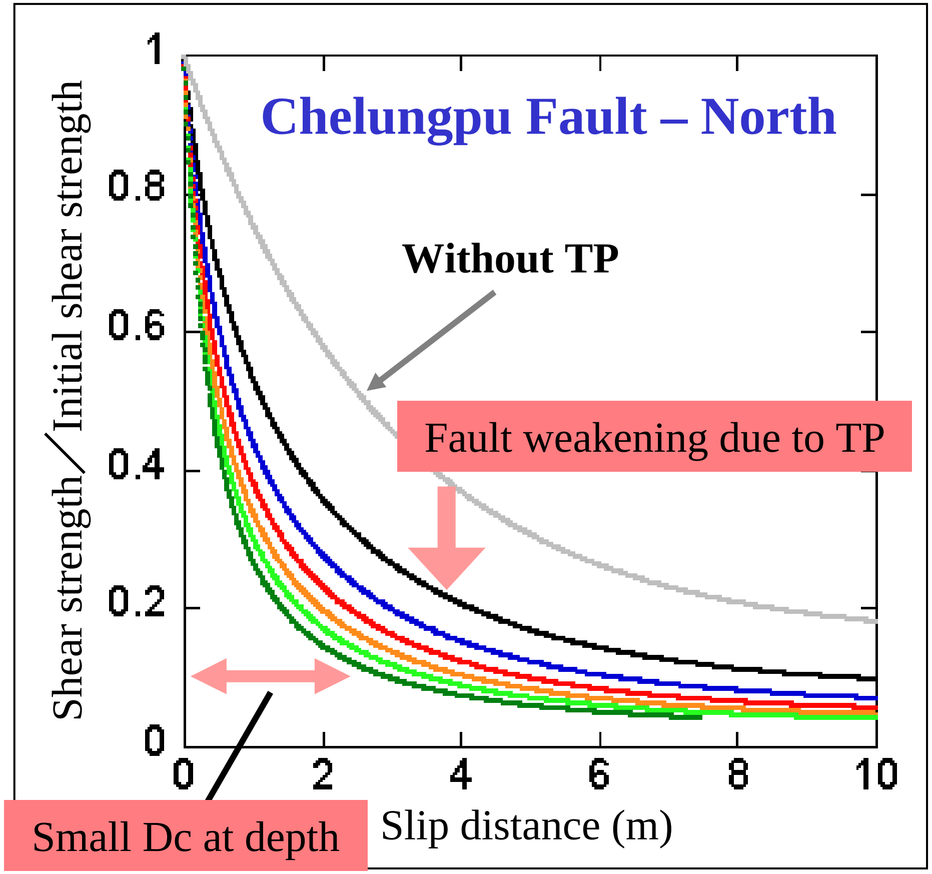
Shear Stress Change

$\tau = (Pc - Pp) \times \mu_d$

TP Result Ⅰ - Pp Generation Ⅰ

Slip Velocity－1 m/s

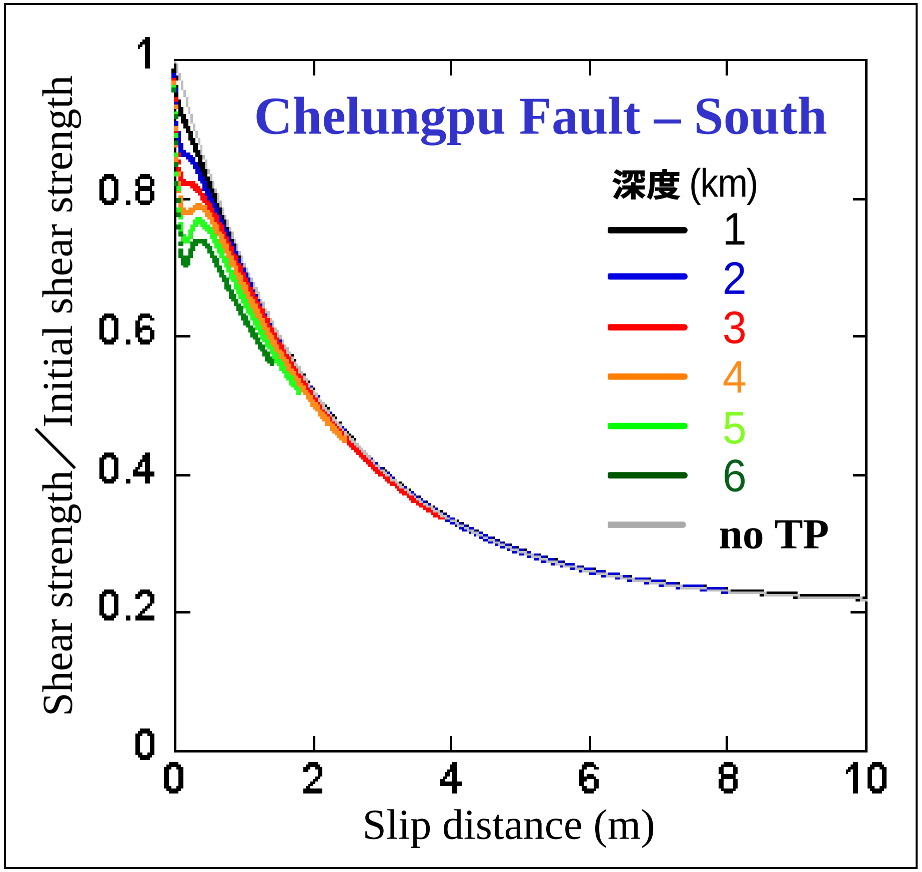
Thickness of fault－20 mm



Without TP

Fault weakening due to TP

Small Dc at depth



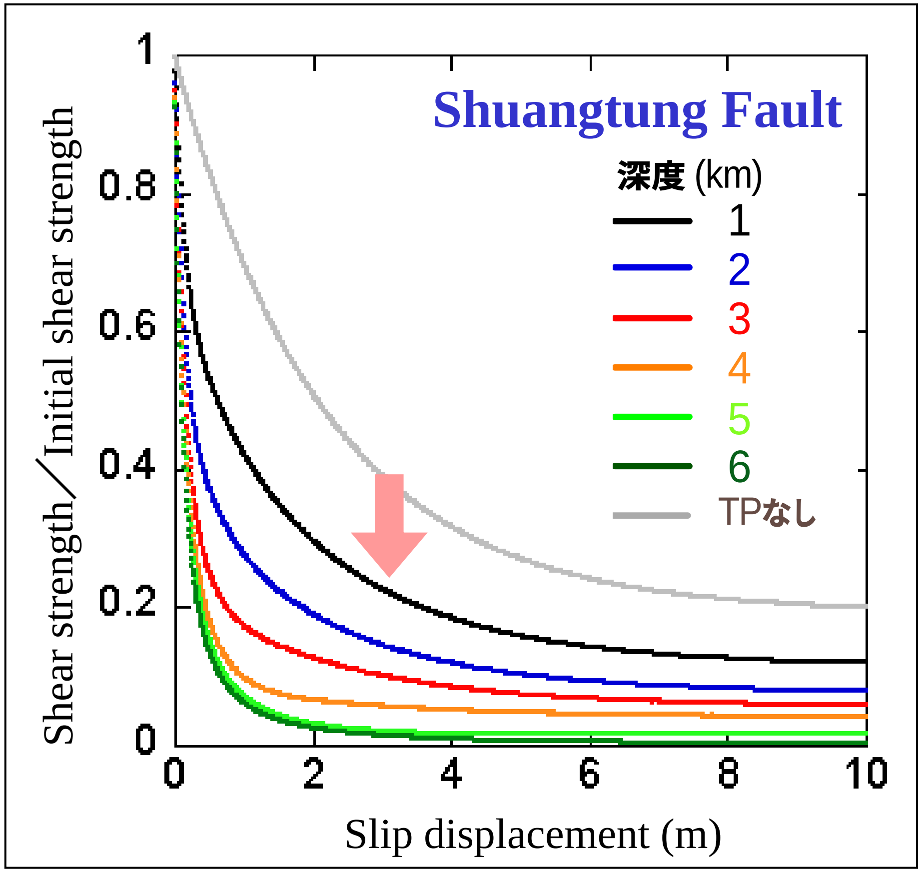
TP is effective!! ⇒ Weakening is accelerated with depths.

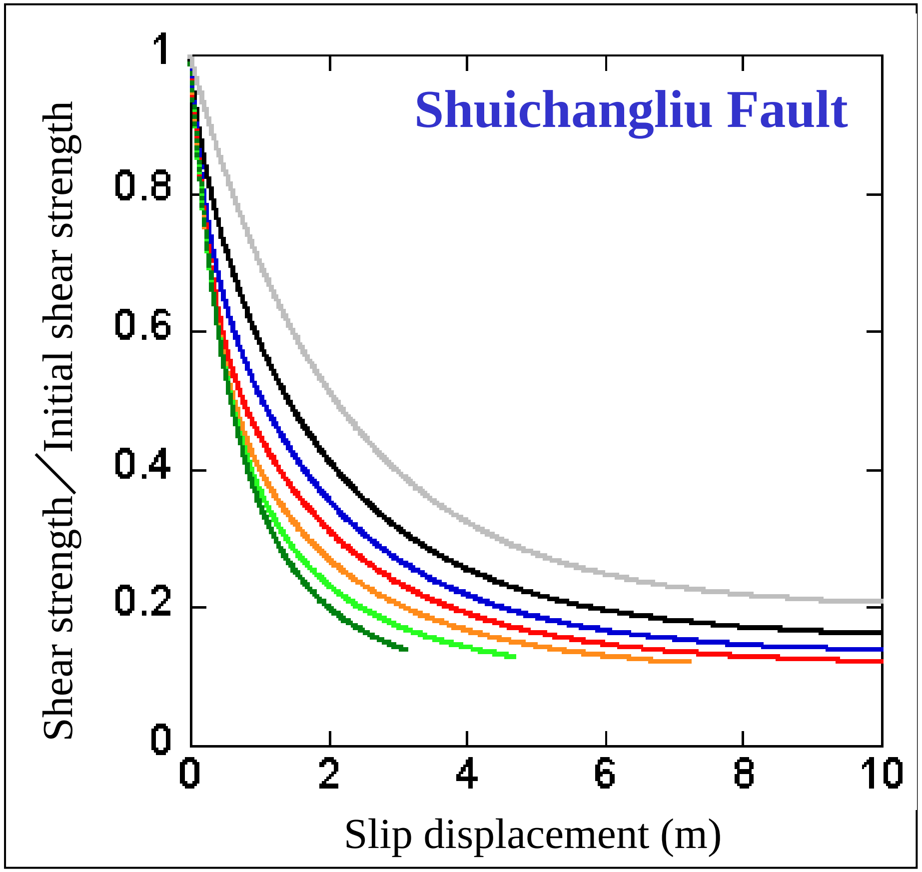
TP is ineffective!! ⇒ Weakening is due to high velocity (mechanical?) weakening

TP Result Ⅱ-Pp Generation Ⅱ

Slip Velocity ー1 m/s

Thickness of fault ー20 mm





TP is much effective !!

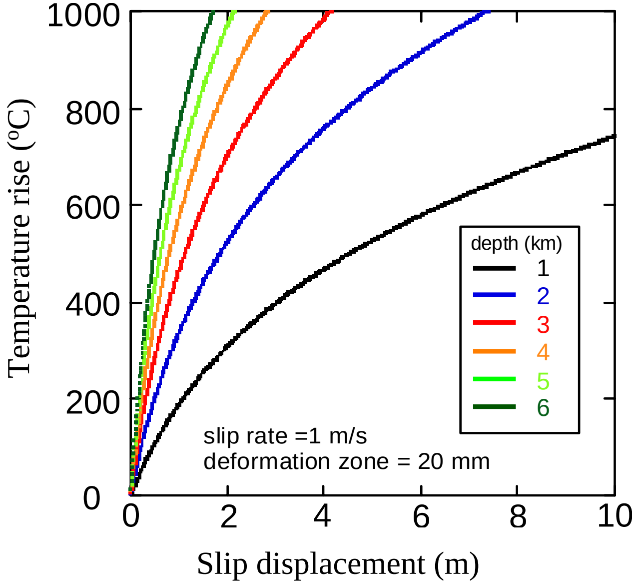
TP is relatively effective (Similarity to Northern Chelungpu Fault)

TP Result III - Temperature Rise

TP effective regime

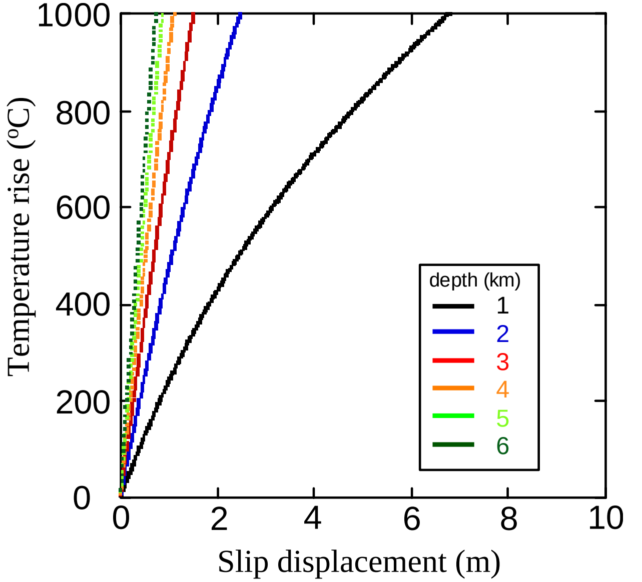
Reducing shear strength of fault. Low, and relatively low temperature rise in Shuangtung, and Northern Chelungpu Faults .

Chelungpu Fault – North



slip rate =1 m/s
deformation zone = 20 mm

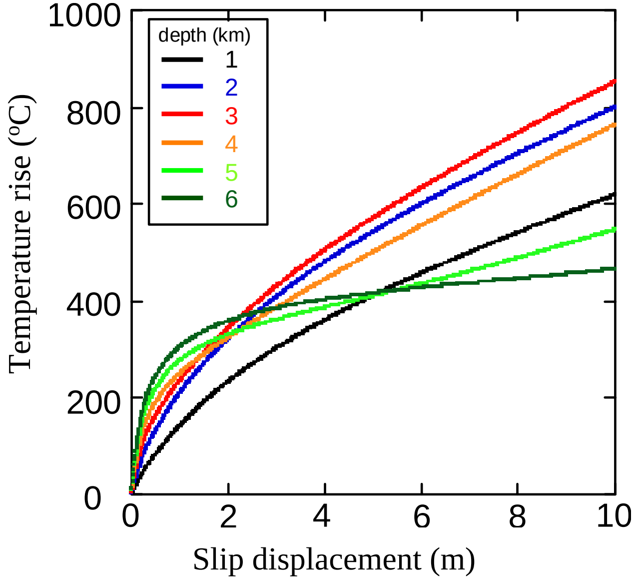
Chelungpu Fault – South



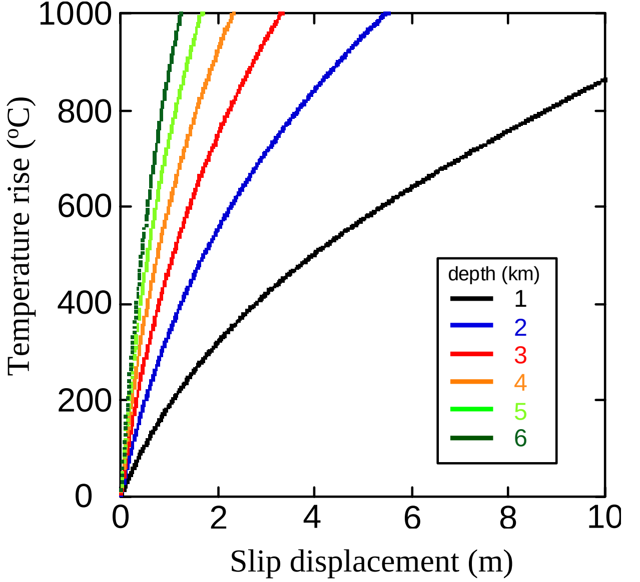
TP ineffective regime

Rapid temperature rise easily reaches to melting point.

Shuangtung Fault



Shuichangliu Fault

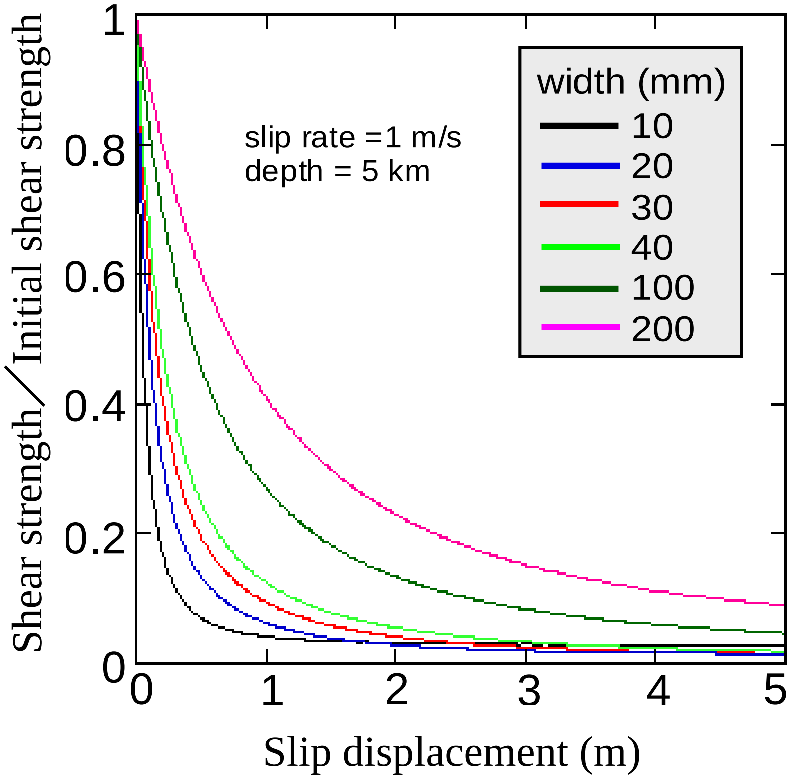


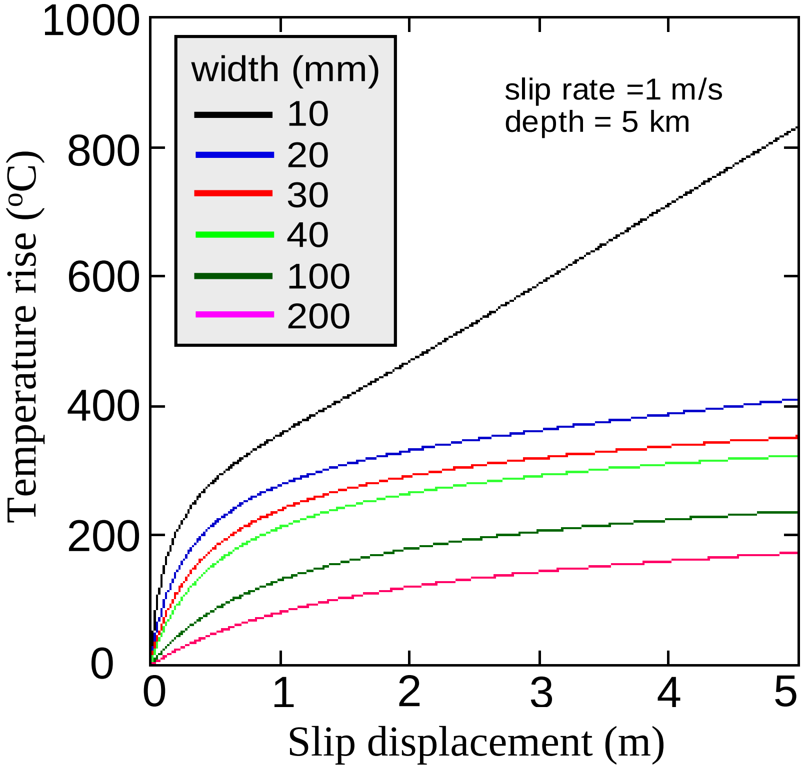
TP Result Ⅳ - Importance of Width

Width of the fault core is directly related to heating rate, and identification of the shear zone is important (though it is difficult).

TCDP-Hole B 1194m

BM disk（20mm thickness）





Summery Ⅰ - fault variation

		North	**South**	**Depth**	**Remark**
Permeability（m^2）		10^{-16}~10^{-17}	10^{-15}~10^{-16}	10^{-16}~10^{-18}	North < South
Specific storage（Pa^{-1}）		Small difference among faults（10^{-9} Pa^{-1}）			
High velocity friction		Similar behavior（exponential decay curve，Low steady state friction，Large initial friction）			Relatively large frinction in Southern Chelungpu Fault
TP analysis		Relatively effective	Ineffective	Effective	Possible existence of overpressure at depth might be negative influence for TP.
Low velocity friction	**μ dry**	0.7	0.7	0.5 ~0.6	Reduction in 50% at wet condition
	a-b	+	−	+	

Permeability variation ⇒ TP variation ⇒ Explain the difference between N-S?

TP might be effective at depths（Overpressure can not be neglected）.

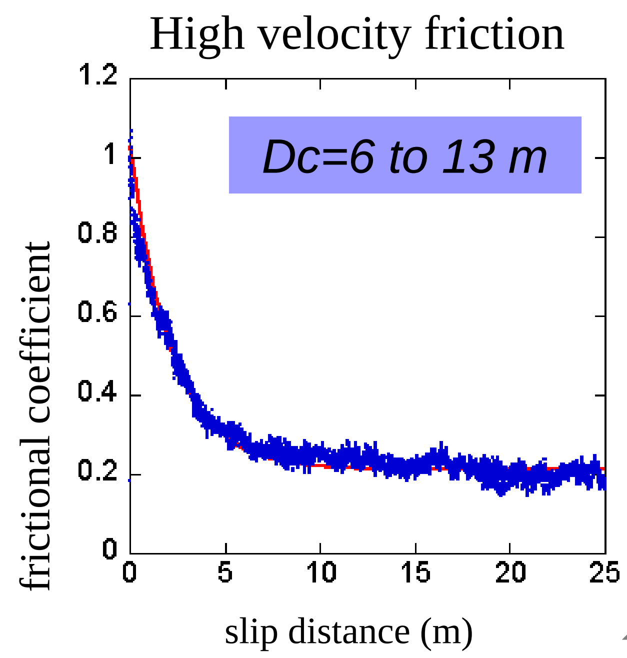
South is unstable ⇒ Consistent with initiation of EQ from the south?

Summery Ⅱ -TP vs Seismic Data

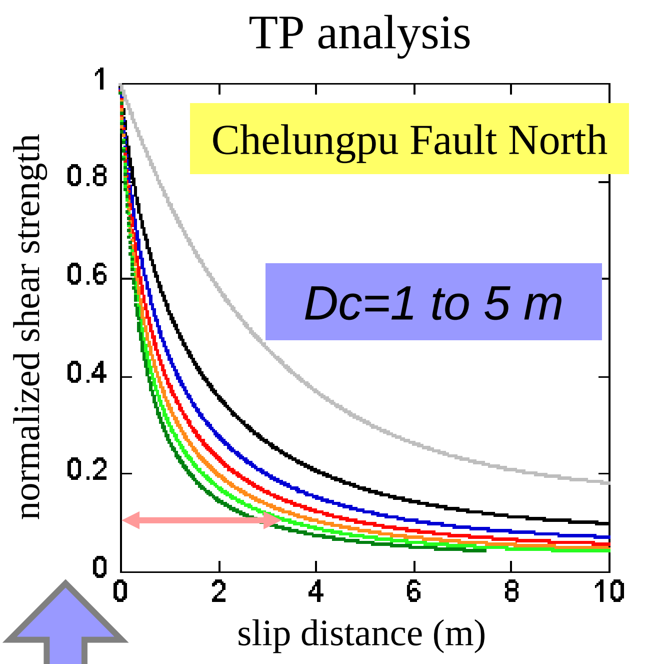
1.Weakening distances,Dc, evaluated from TP analysis are similar order to that evaluated from seismic inversion analysis.

2. Without thermal pressurization, we can account for the Dc from High velocity behavior.

3.Stress drop between TP and seismic data has gap.


High velocity friction

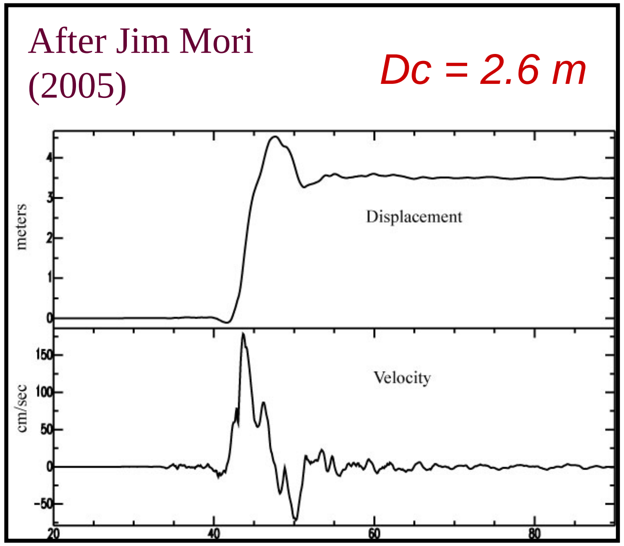
Dc=6 to 13 m


TP analysis

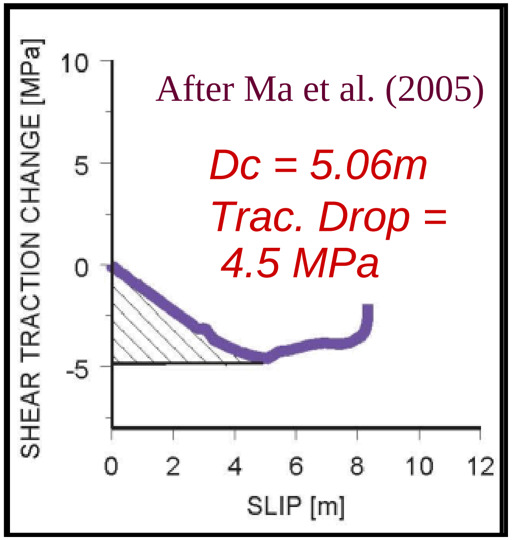
Chelungpu Fault North

Dc=1 to 5 m

Inversion analysis (several cm to 10 m)

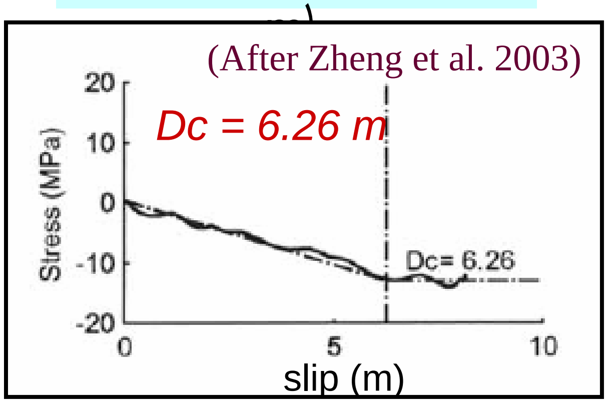

After Jim Mori (2005)

Dc = 2.6 m


After Ma et al. (2005)

Dc = 5.06m

Trac. Drop = 4.5 MPa


(After Zheng et al. 2003)

Dc = 6.26 m