Heat Signature on the Chelungpu Fault Associated with the 1999 Chi-Chi, Taiwan Earthquake

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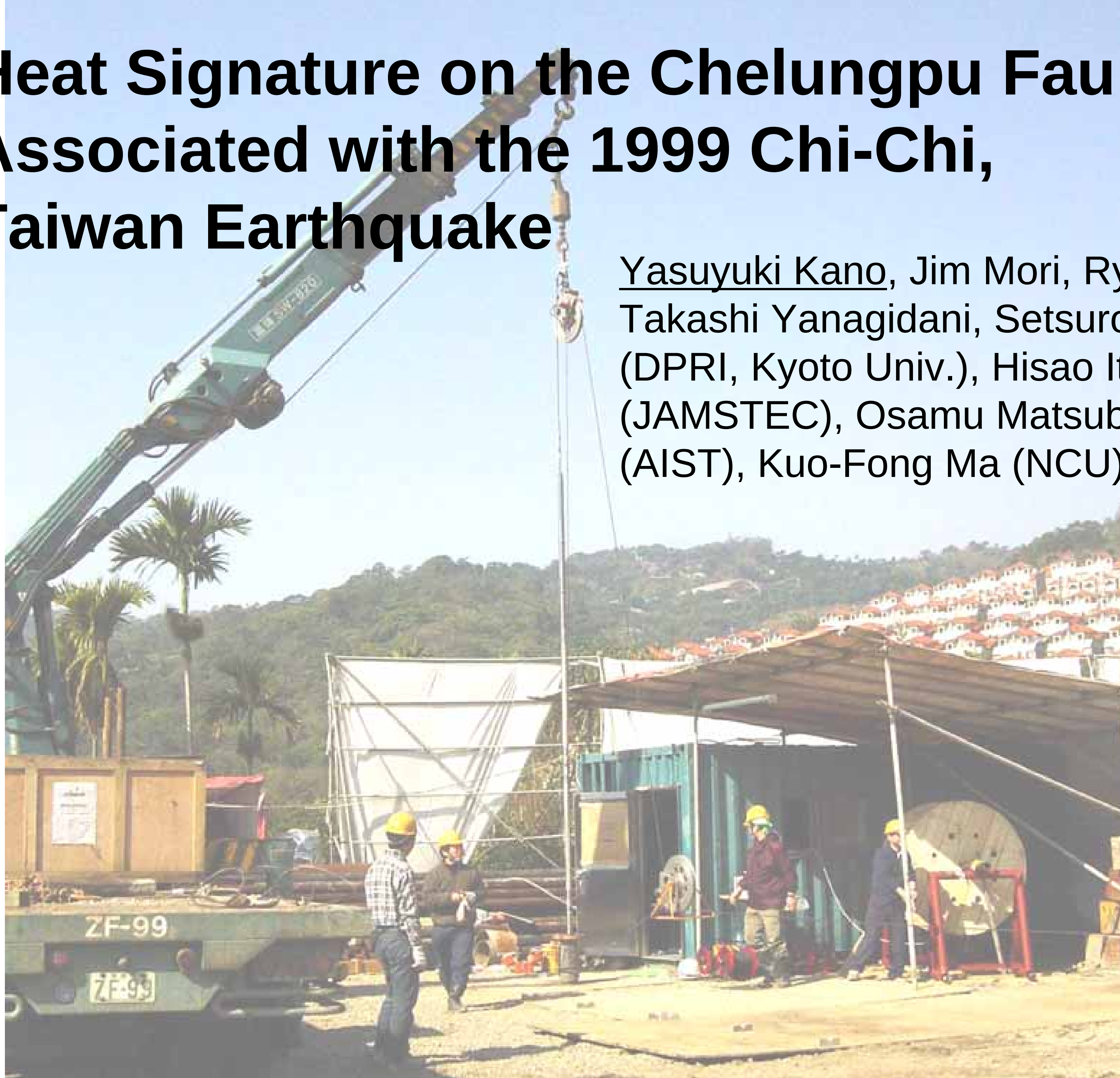


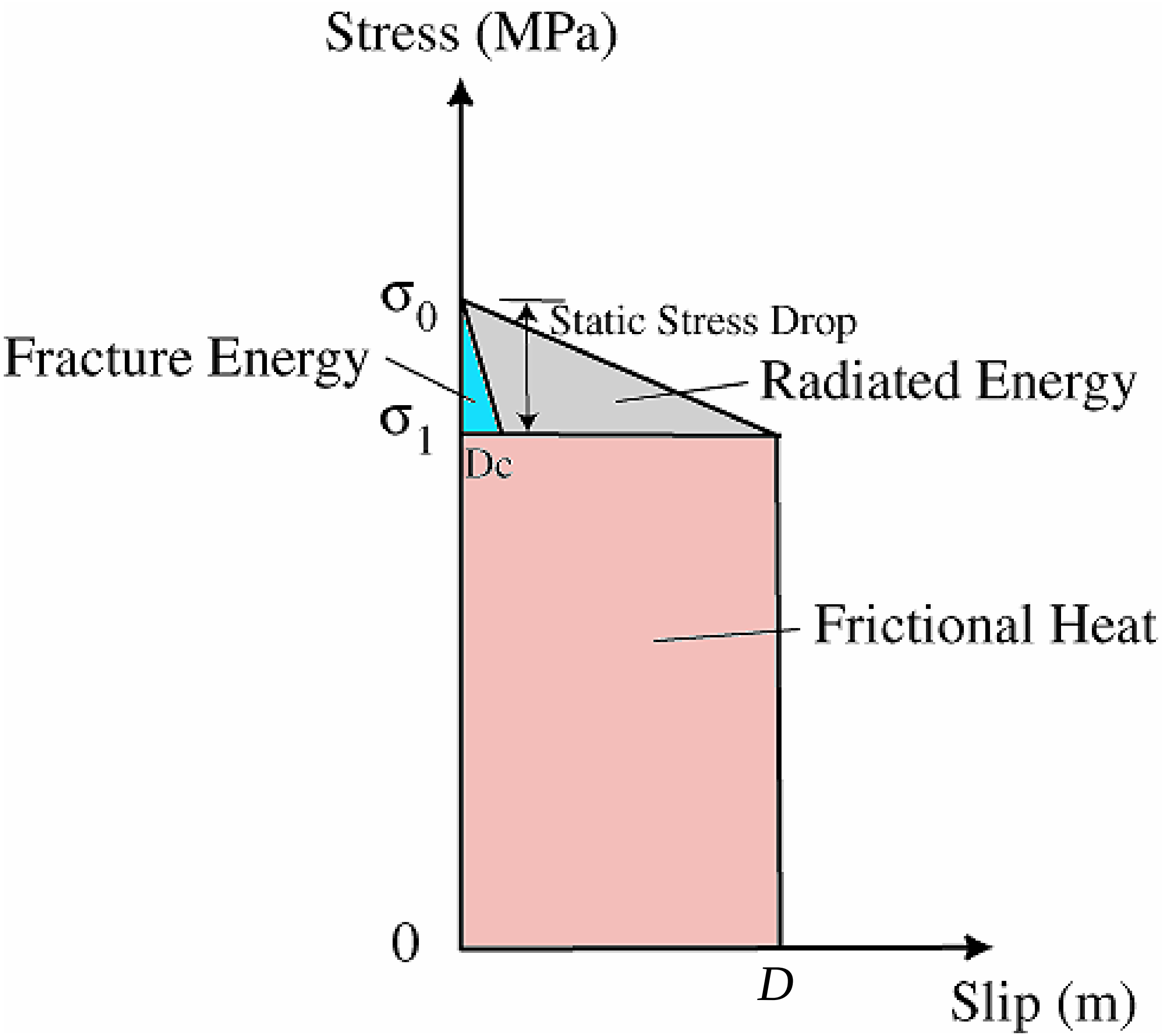
Energy budget for an earthquake

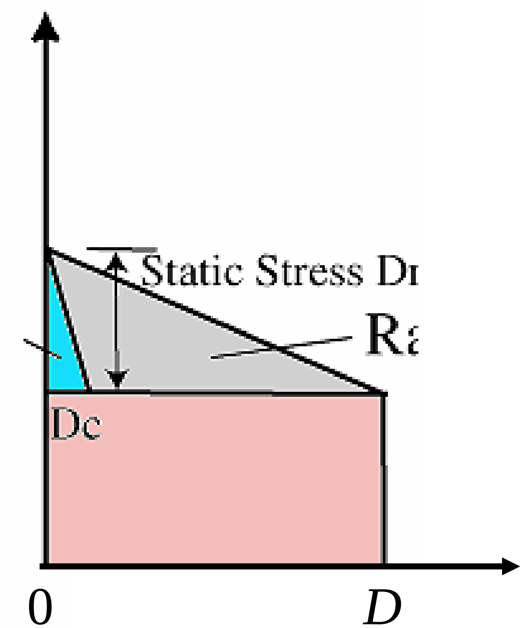
$$W = E_H + W_0 \qquad W_0 = E_R + E_G$$

$$W = \frac{\sigma_0 + \sigma_1}{2} DS$$

$$E_H = \sigma_1 DS$$

$$W_0 = \frac{\sigma_0 - \sigma_1}{2} DS$$





Goal of the talk

Target: Temperature (heat) signature of the earthquake

We observed temperature signature around the fault zone along the Chelungpu fault (September, 2005)

The signature can be interpreted as the frictional heat caused by fault slip at the time of the 1999 Chi-Chi earthquake

Evaluate other cause of the temperature anomaly

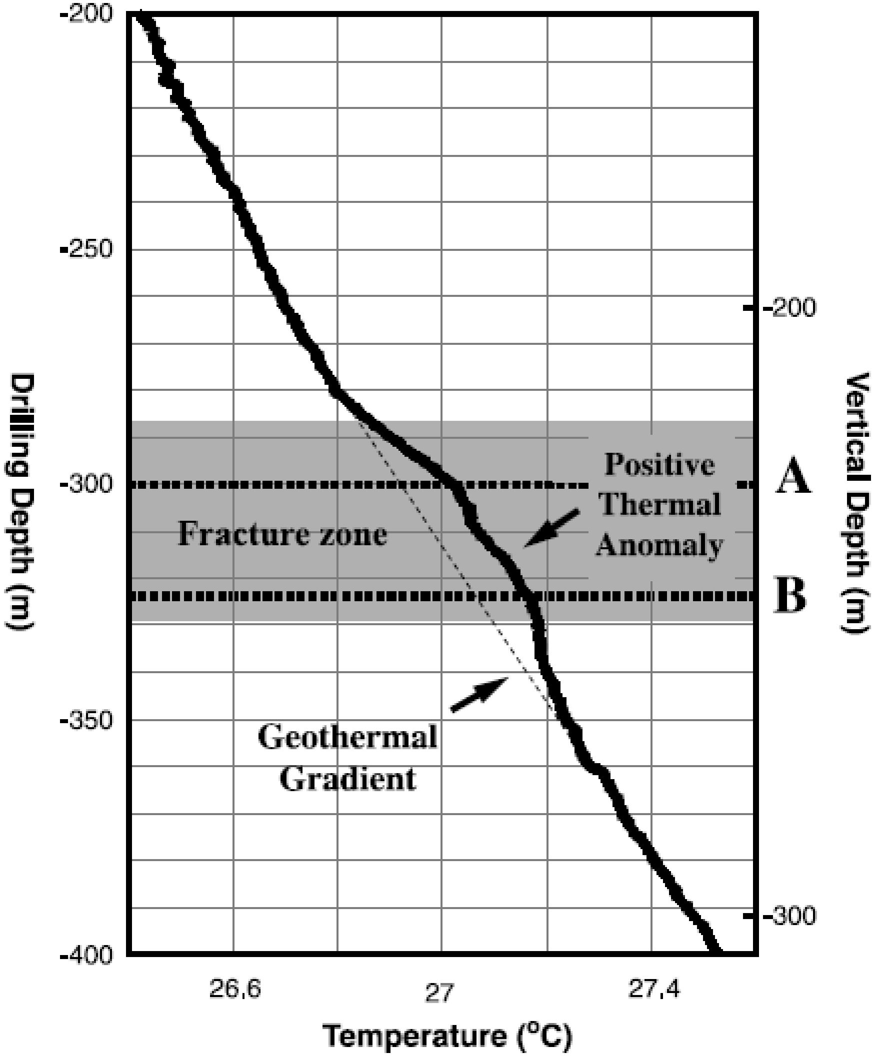
(1) Spatial variation of material thermal conductivity

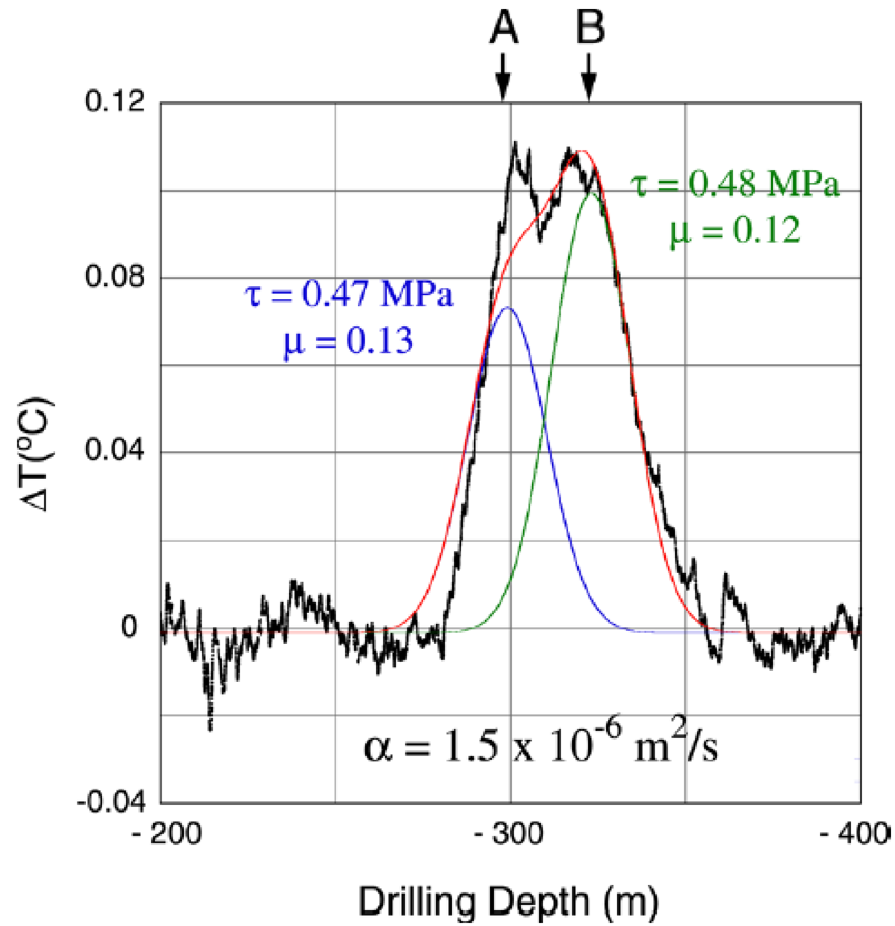
Estimate “noise level” and obtain upper bound of heat strength

(2) Water flow

Calculate the temperature anomaly affected by 1-dimensional water flow

Shallow borehole (Tanaka et al., 2006)



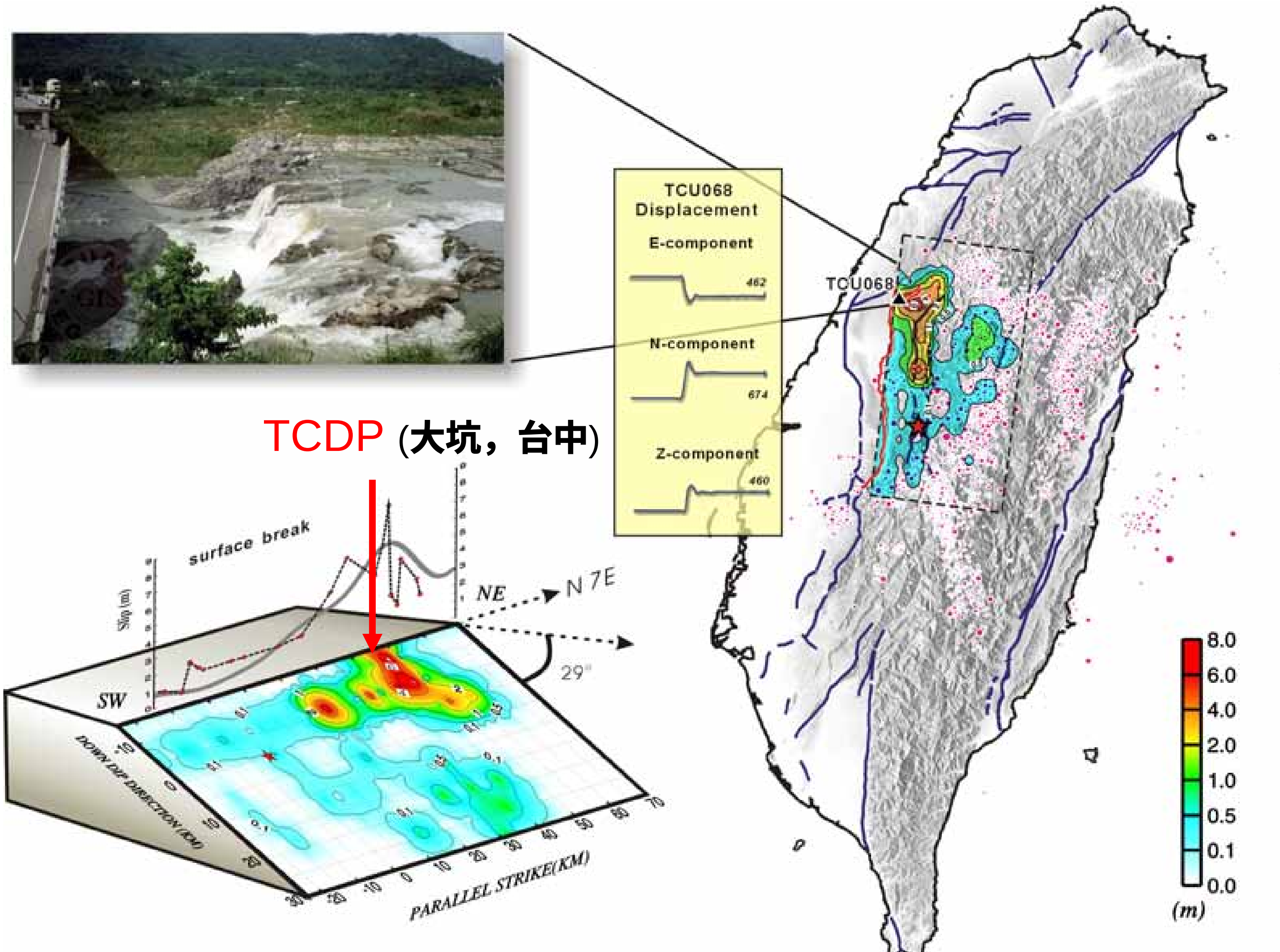


Deeper and stable measurement!

Relatively broad anomaly: affected by shallow ground water flow?

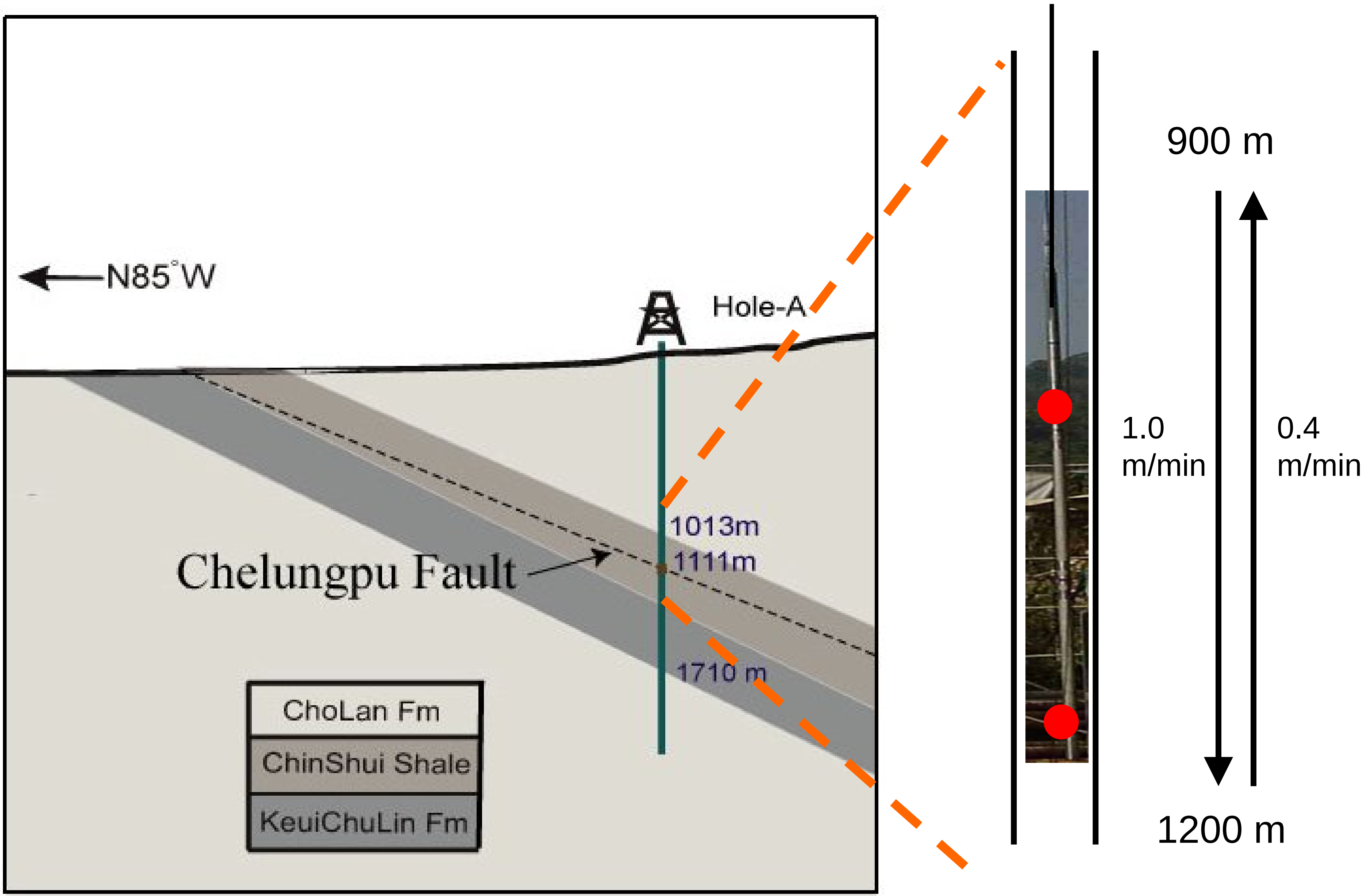
Mesurement right after drilling: drilling effect

1999 Chi-Chi earthquake and TCDP site



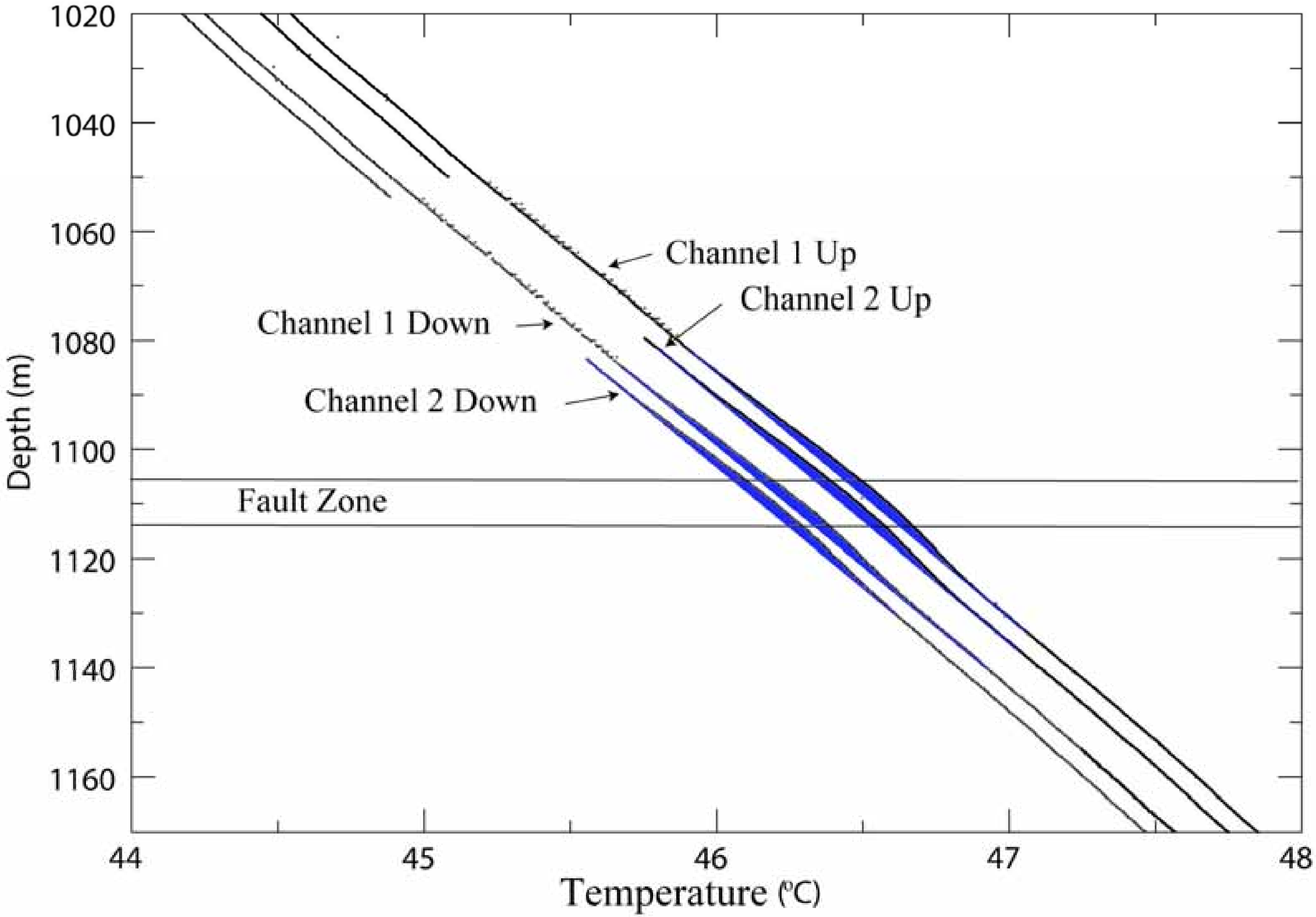
[Ma et al, 2002]

Measurement



Quartz thermometer

Temperature profile using Quartz thermometer

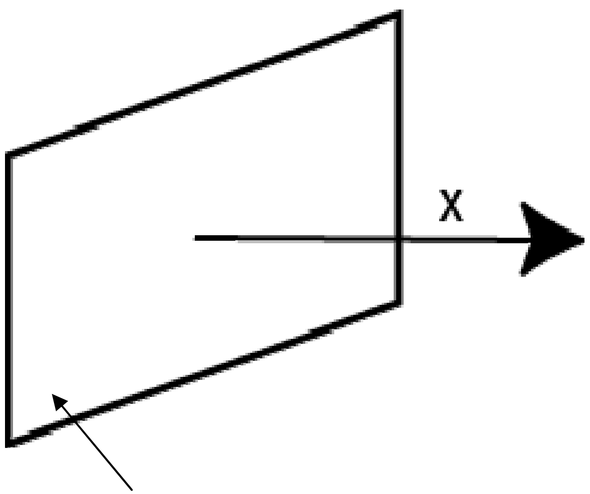


(Kano et al., 2006, GRL)

Spatio-temporal variation of the temperature signature

One-dimensional heat conduction

$$T(x,t) = \frac{S}{2\sqrt{\pi \alpha t}} \exp\left(-\frac{x^2}{4\alpha t} \right)$$ (Officer, 1974)



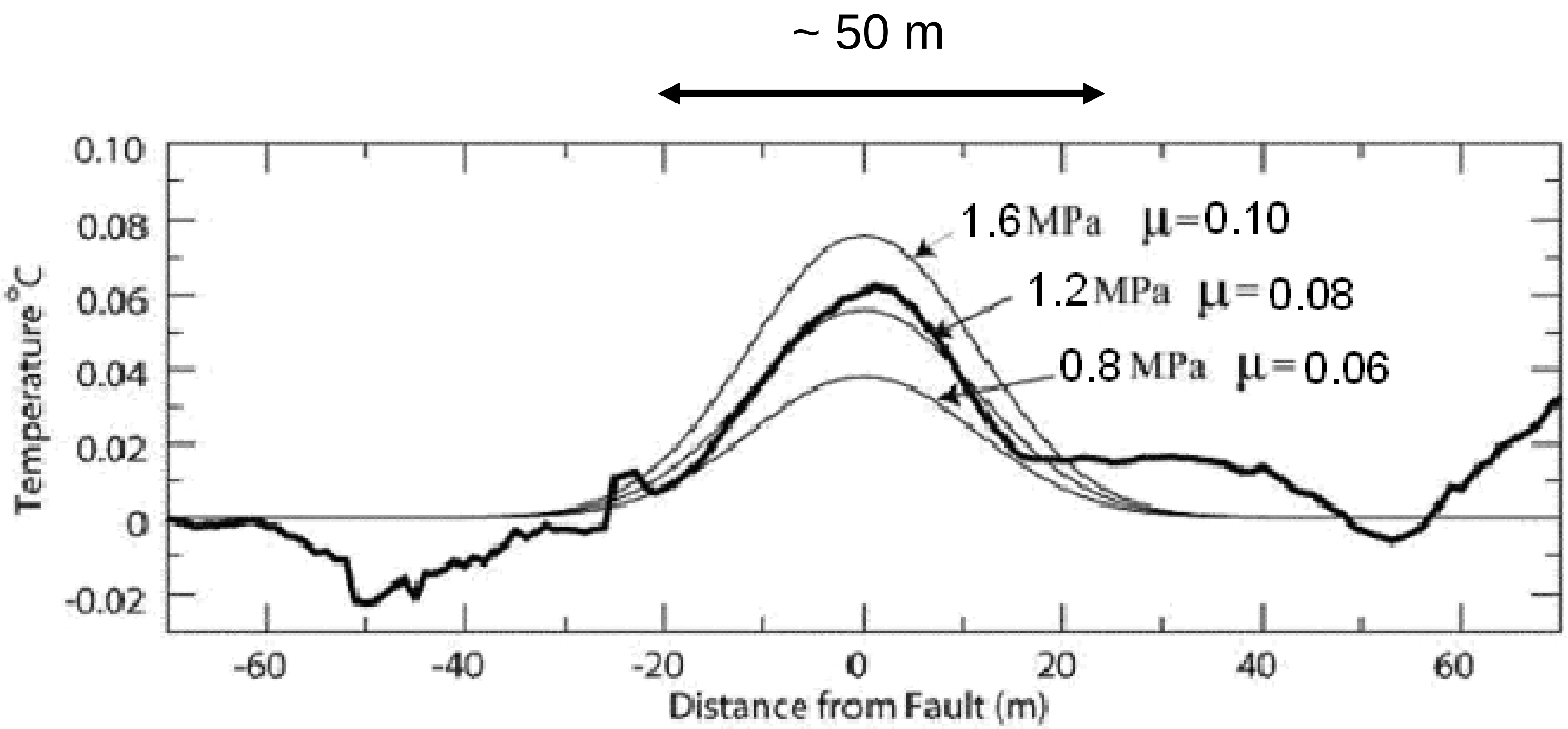
Plane Heat Source = S

S: strength of source, ºCm

α : thermal diffusivity,

Temperature anomaly
Transient: Friction, ….
Stable: Geothermal gradient
+ thermal property

Temperature anomaly



Remove linear temperature gradient

Average of 4 profiles

4 m slip, 6 years, $\boldsymbol{\alpha}$ = 3.4 x 10^{-7} m^2/s

(Kano et al., 2006, GRL)

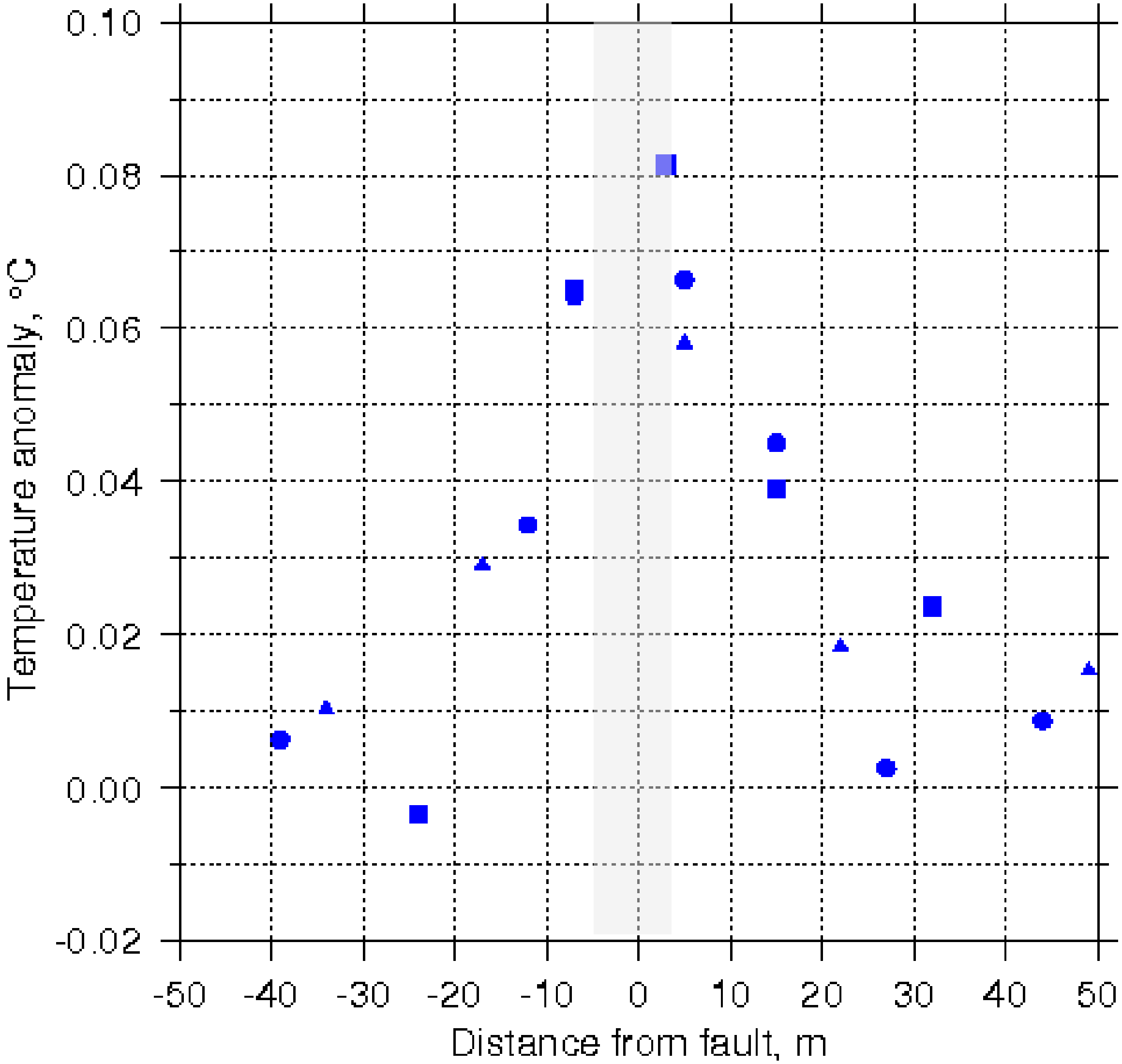
Estimated parameters

- Heat diffusivity $\boldsymbol{\alpha} \sim 0.3 \times 10^{-6}$ m^2/s
  ($k \sim 0.9$ Wm^{-1}K^{-1})
- Strength of source $S \sim 1$ ^{o}Cm
  ↓ ($Q \sim 4 \times 10^6$ J/m^2)
  Shear stress $\boldsymbol{\tau} \sim 0.6$ MPa
  ↓
  Frictional coefficient $\boldsymbol{\mu} \sim 0.04$

- Upper limit of shear stress $\boldsymbol{\tau} \sim 1.7$ MPa
  ↓
  Frictional coefficient $\boldsymbol{\mu} \sim 0.1$

Pt-RTD thermometer

Temperature anomaly using another thermometer (Pt-RTD)



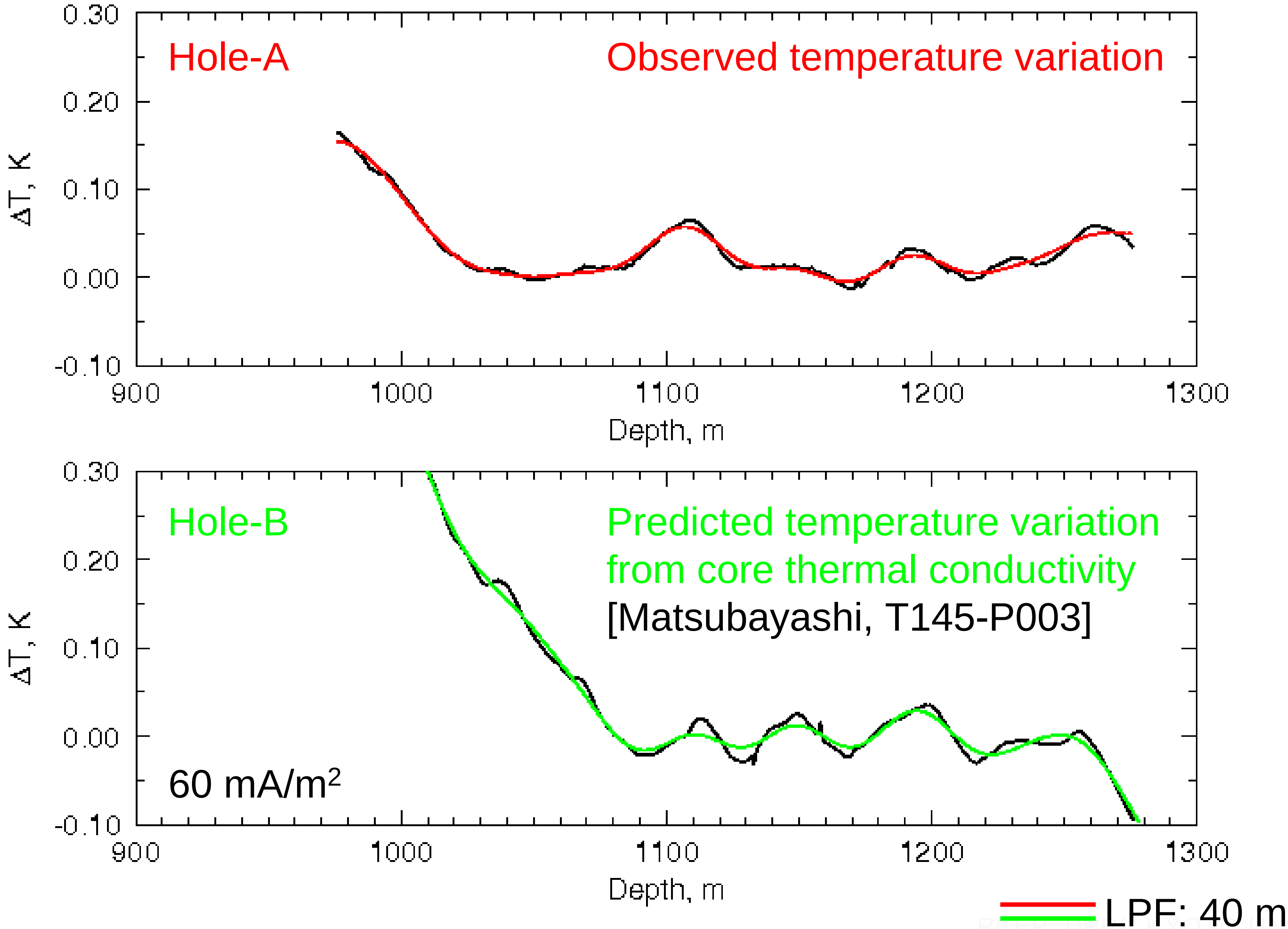
Shear stress and frictional heat

$$q = \kappa \frac{dT}{dz}$$

q : Heat flow
κ : Thermal conductivity
T : Temperature
z : depth

Temperature gradient (-> temperature structure) is affected by variation of thermal conductivity under constant heat flow.

Temperature observation and core measurement



Effect of water flow

$$\alpha \frac{\partial^2 T}{\partial x^2} - \frac{n\rho_w c_w}{\rho c} v \frac{\partial T}{\partial x} = \frac{\partial T}{\partial t}$$

(Domenico and Schwartz, 1997)

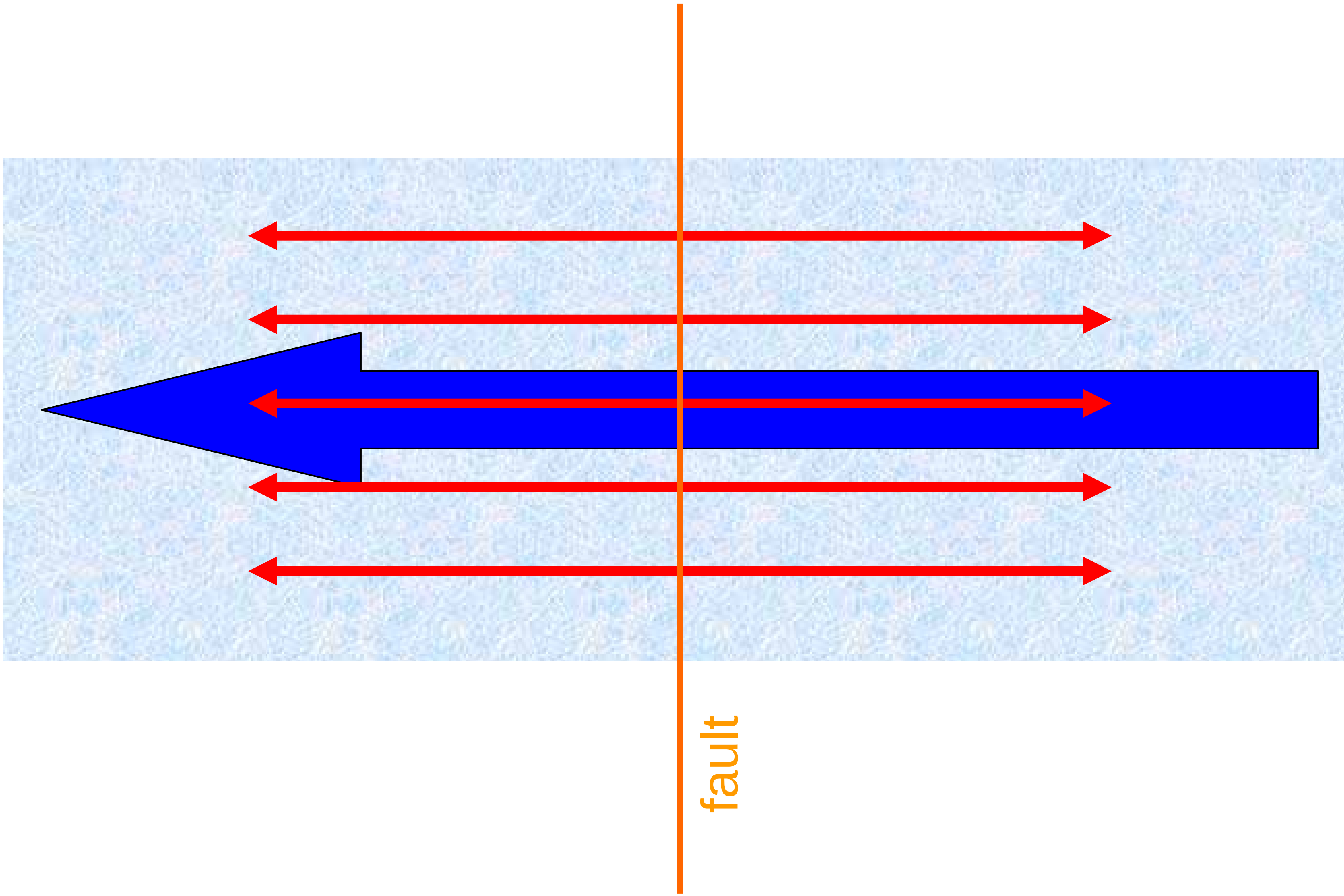
v : flow rate

n : porosity

ρ_w: density of water

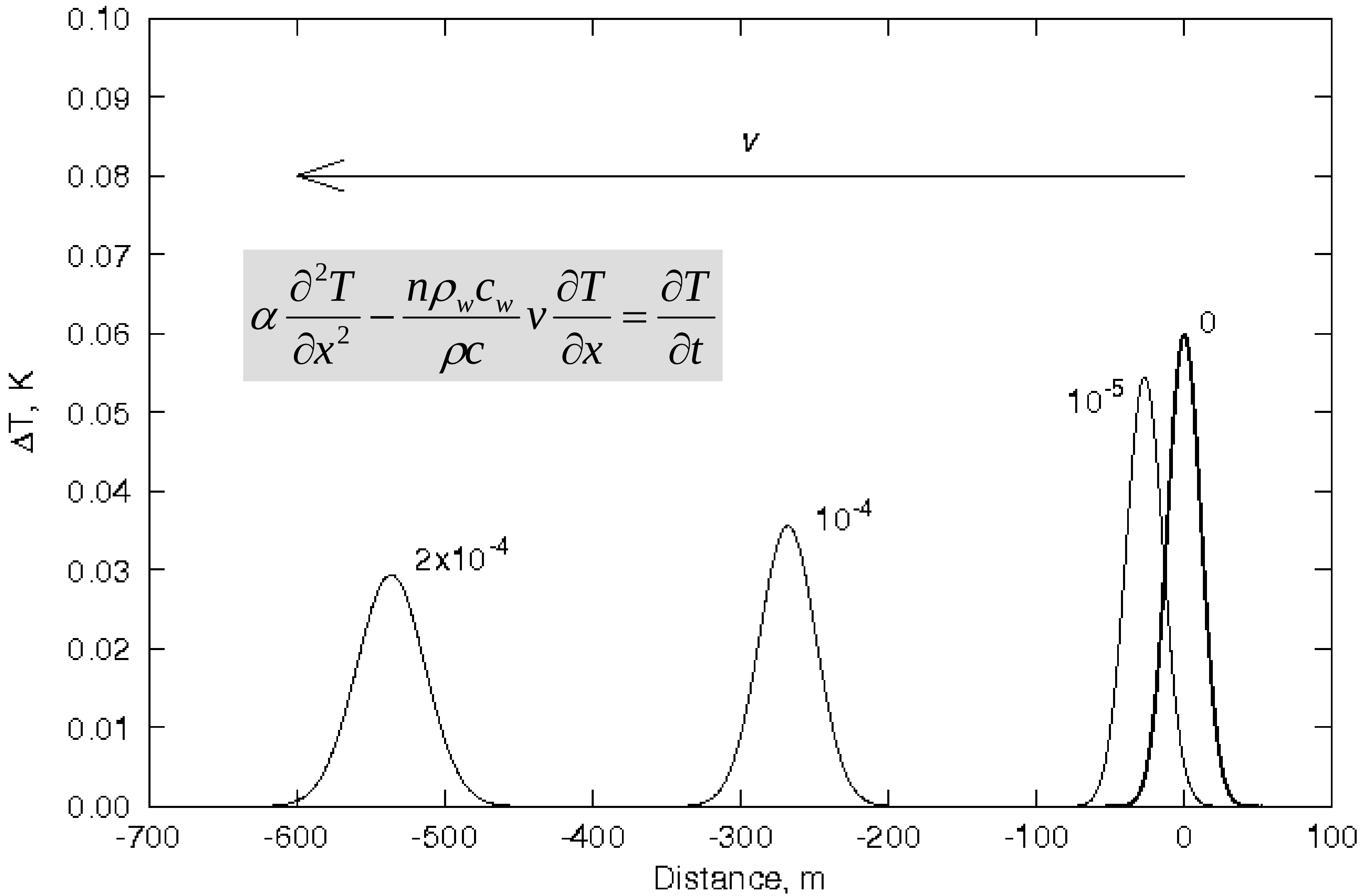
c_w : specific heat of water.

Effect of water flow



Effect of waster flow

(Kano et al., 2006, GRL)

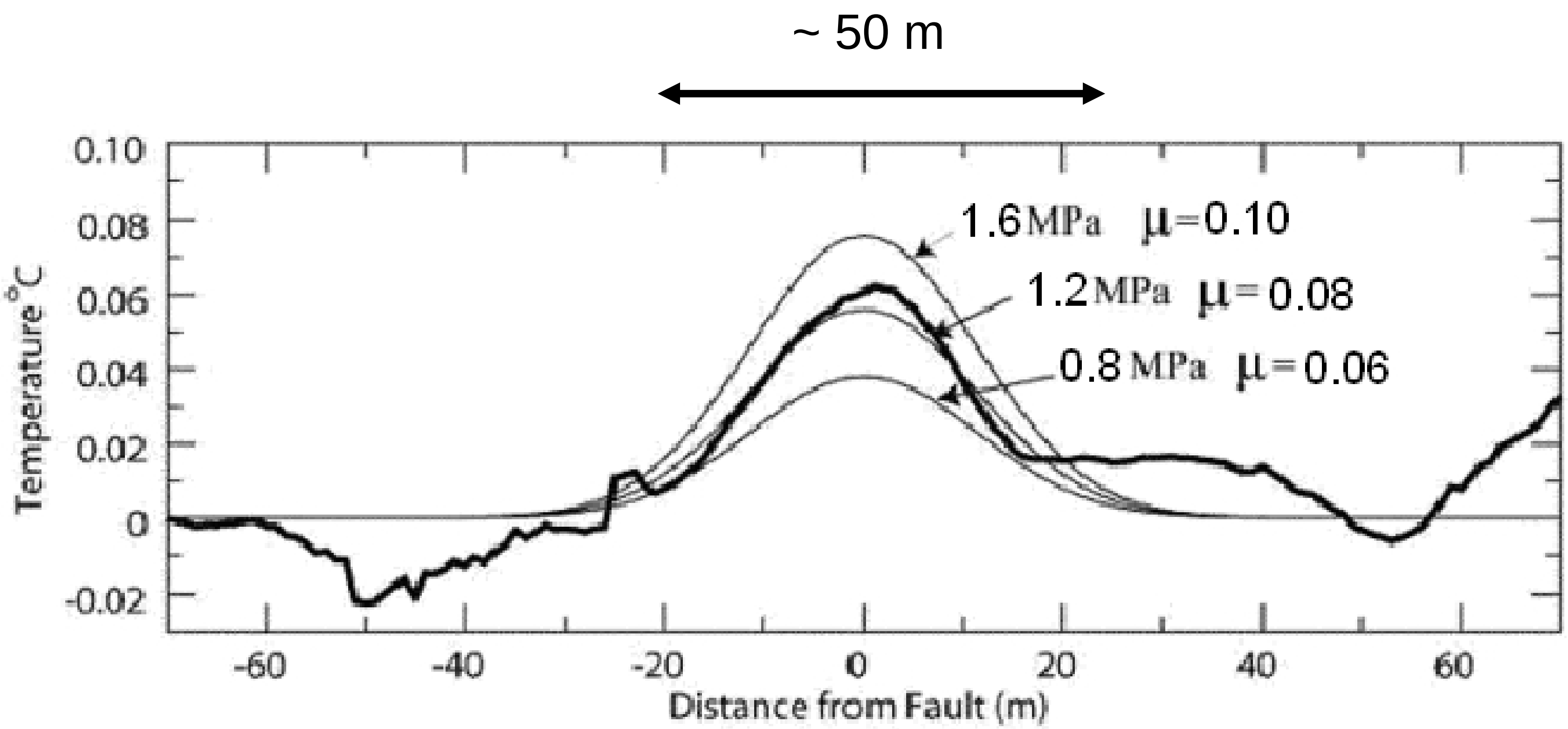


The effect of the water flow: (1) move the anomaly downstream in position

(2) broaden its shape

Temperature anomaly

(Kano et al., 2006, GRL)



Remove linear temperature gradient

Average of 4 profiles

Observed temperature signature is located right at the location of the fault

Summary

(1) Spatial variation of material thermal conductivity
may cause noise in data

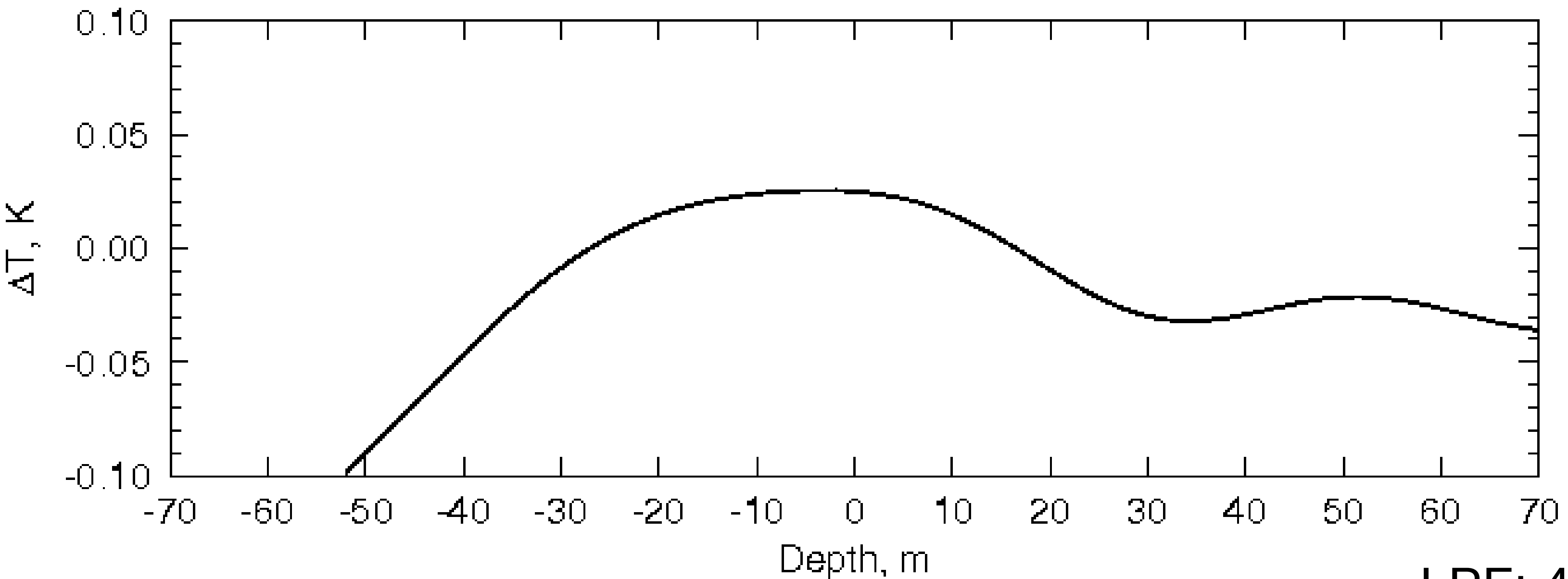
Our observation gives upper bound of heat strength (still low friction)

(2) Minimal effects from fluid flow
in our observed temperature signature

(3) Small heat signature indicates a low level friction
on the fault during earthquake

Shear stress: 2 MPa

Temperature observation and core measurement



LPF: 40 m

Observed temperature variation (Hole-A)

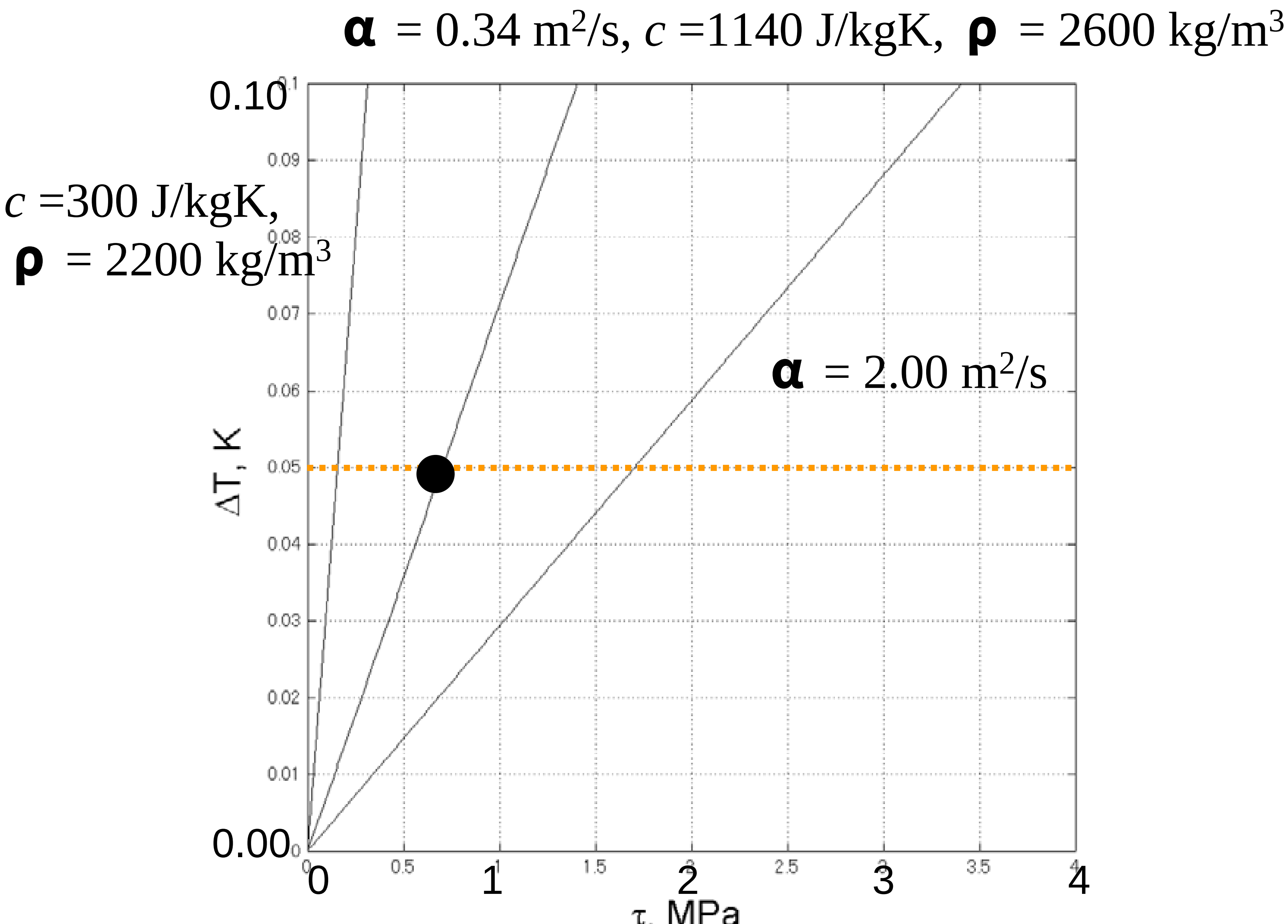
– Predicted temperature variation (Hole-B)

Correct background temperature gradient

- Depth correction (Hole-A vs Hole-B)
- Appropriate filter

Our estimate give upper bound of temperature anomaly

Upper limit of the shear stress



Motivation

Find the temperature signature associated with the 1999 Chi-Chi, Taiwan earthquake

Amount of frictional heat (~ Level of shear stress)

- Key unknown values of important parameter for understanding the physics of earthquake rupture
- Cannot be determined by seismic observation

Residual heat

- Can be observed as temperature anomaly along the fault

Precise temperature measurements

Development of thermometers

- Quartz thermometer (0.003 °C)
- Pt-RTD thermometer (0.001 °C)

No water flow in the borehole

- Cased borehole

No drilling disturbance

- A half year from the end of drilling

Quartz thermometer

Pt-RTD thermometer

Estimation

Assumption

- Transferred to frictional heat
- One-dimensional heat conduction
- Constant background thermal gradient

$$\Delta T(x,t) = \frac{\Delta S}{2\sqrt{\pi \alpha t}} \exp\left(-\frac{x^2}{4\alpha t}\right)$$

$$\tau = S\,\frac{c \cdot \rho}{u}$$

$$\mu = \frac{\tau}{\sigma_n - p}$$

$\boldsymbol{\sigma}_{\mathrm{n}}$: normal stress
(Sibson, 1974)
p : pore pressure
hydrostatic

Summary

Precise temperature measurement reveals

- Temperature anomaly of ~ 0.05 °C
- Temperature distribution at depth comparable to core measurement

Low shear stress

- Low dynamic friction
- Mechanism such as super-hydrostatic pore pressure or lubrication

Future works

- Temperature anomaly caused by spatial variation of thermal property
- Sensor calibration (transfer function of instruments)
- Repeated measurement (Hole-B ?)

Shear stress and frictional heat

$$S = \frac{\tau \cdot u}{c \cdot \rho}$$

$$E_H = \sigma_1 D S$$

S : Strength of source, °Cm

τ : Shear stress, MPa

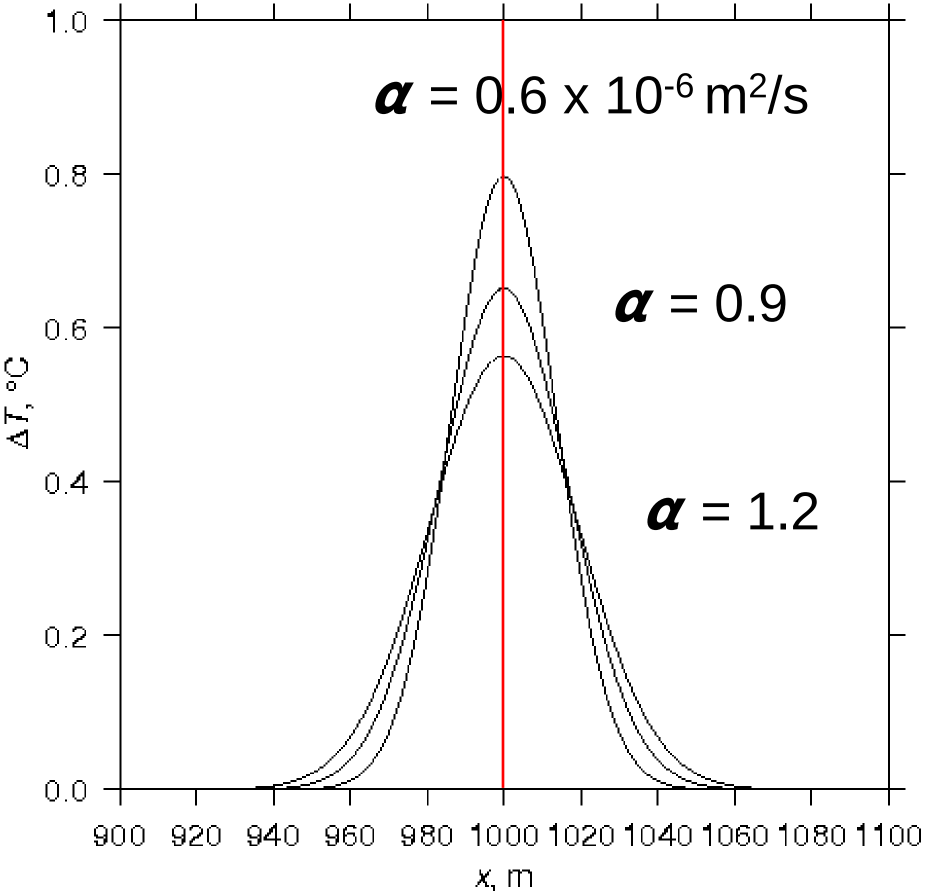
u : Slip, m

c : Heat capacity, 1140 J Kg^{-1} $^{o}C^{-1}$

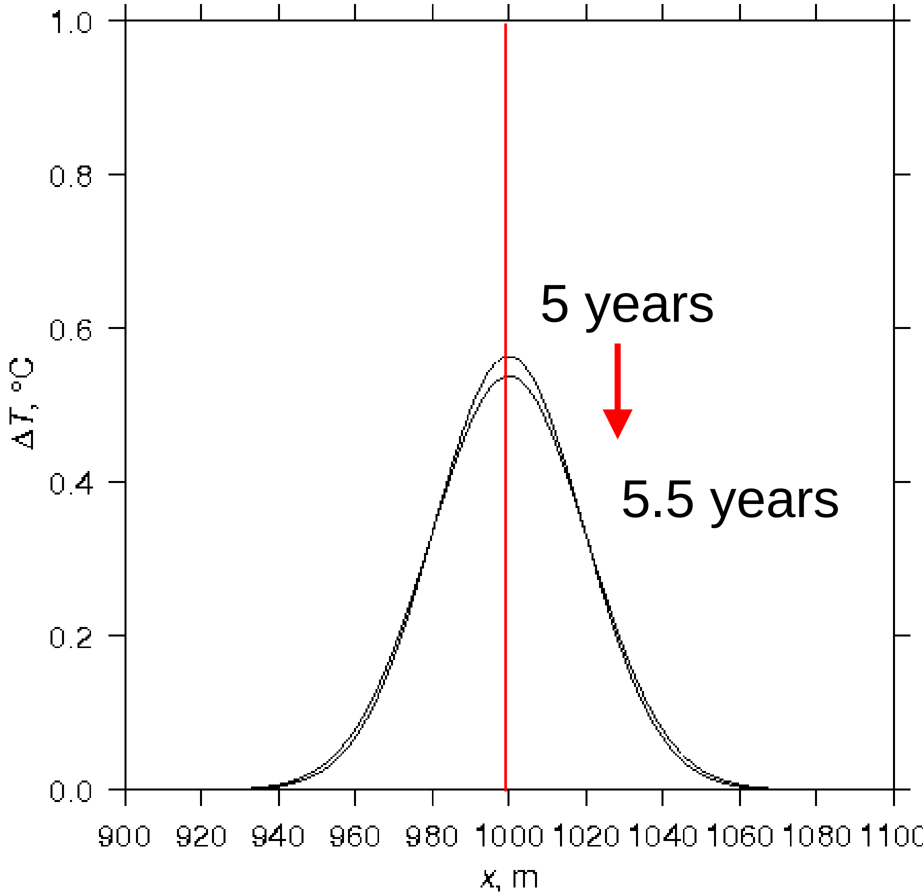
ρ : Density, 2600 Kg/m^3

Expectation

Depth 1 km, Slip 8 m, frictional coefficient 0.6 (S ~50 °Cm)

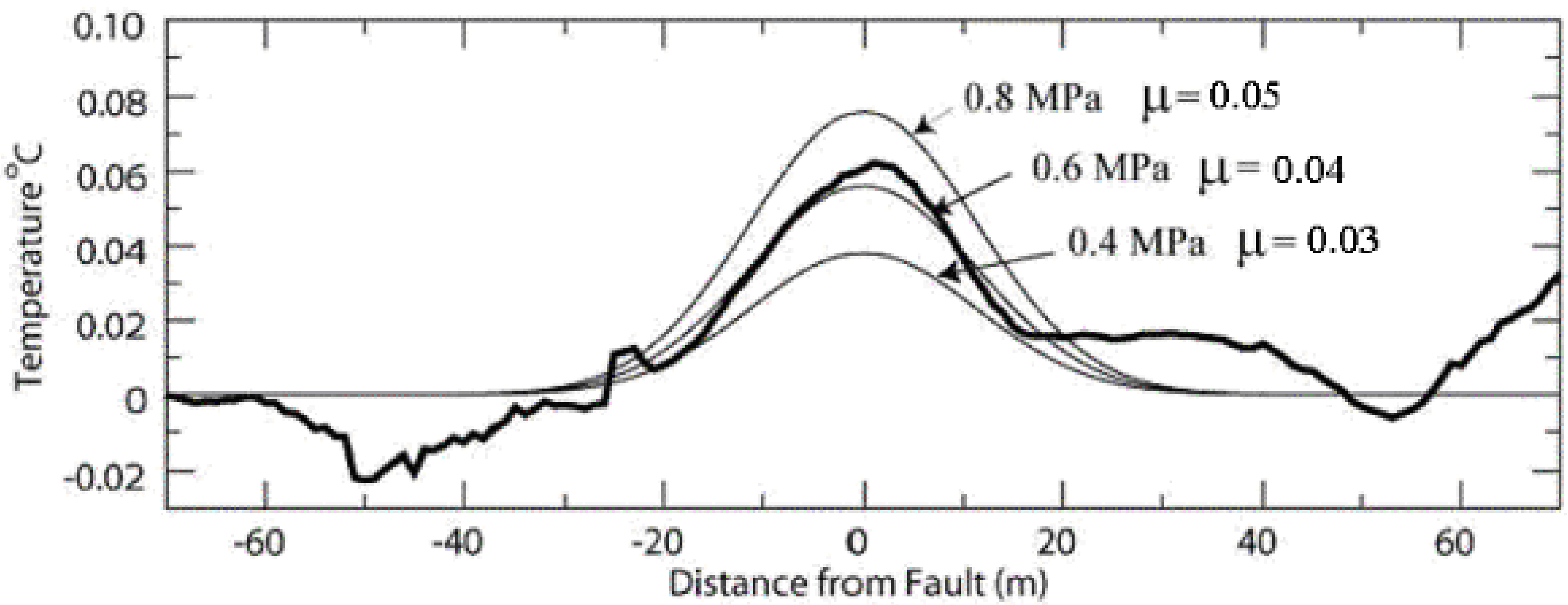


5 years



$\alpha = 1.2 \times 10^{-6}$ m^2/s

Temperature anomaly



Remove linear temperature gradient

Average of 4 profiles