Pore pressure measurements in Kamioka mine

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Pore pressure measurement

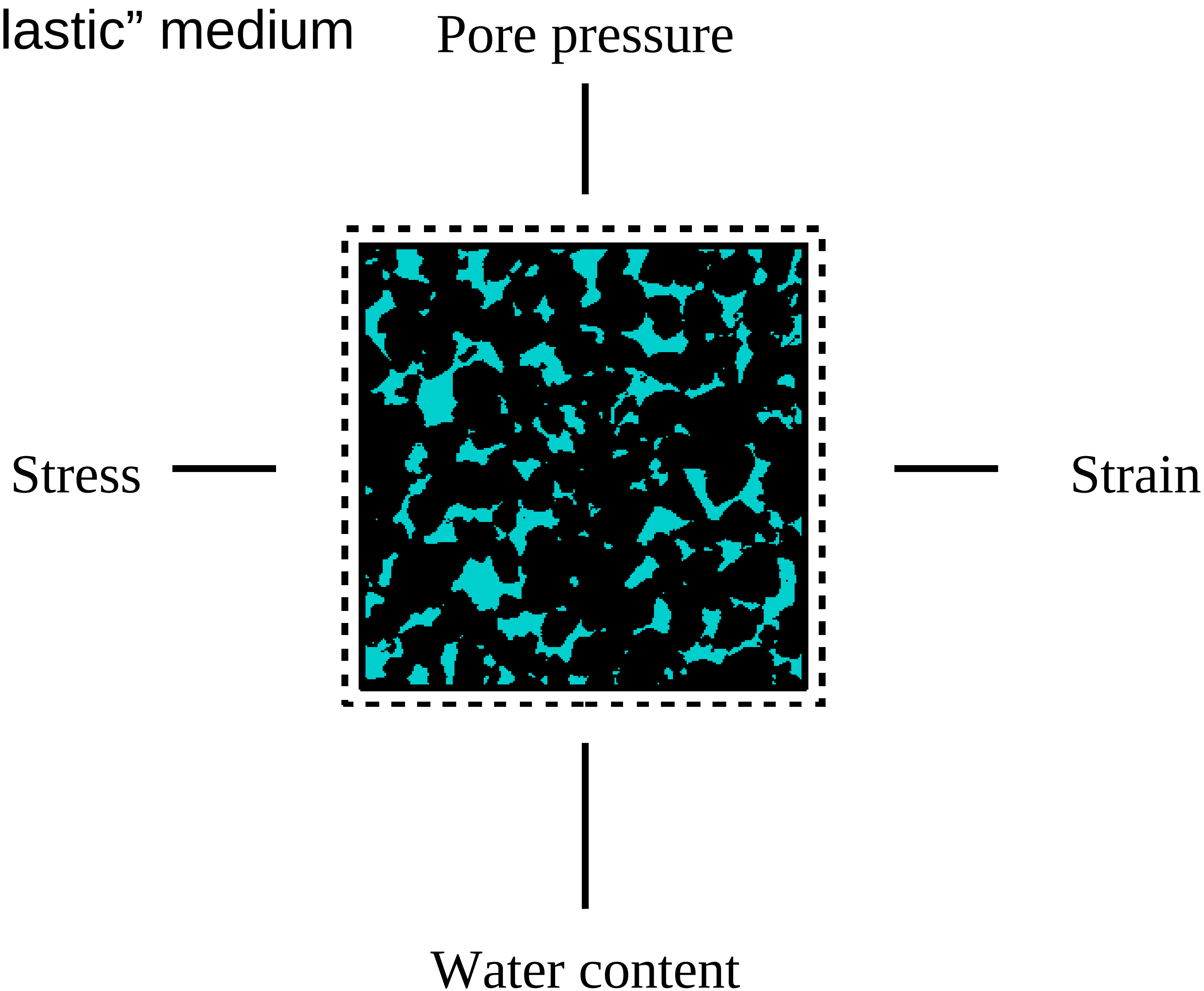
- As proxy of strainmeter
  - Pore pressure is proportional to stress/strain under undained condition (natural amplifier)
  - Evaluation / calibration of response is necessary

- Hydraulic property of an aquifer (fault zone)
  - Tidal/barometric response（1~10 kPa）
  - Pumping/injection test

- Give idea for fluid flow at depth
  - Episodic flow in an aquifer (fault zone) ???
  - Triggering of earthquakes ???

Basics concept of poroelasticity

"Poroelastic" medium



Constitutive equation of poroelasticity

Rice & Cleary (1976)

$$2G\varepsilon_{ij} = \sigma_{ij} - \frac{\nu}{1+\nu}\sigma_{kk}\delta_{ij} + \frac{3(\nu_u - \nu)}{B(1+\nu)(1+\nu_u)} p\delta_{ij}$$

$$m - m_0 = \frac{3\rho_0(\nu_u - \nu)}{2GB(1+\nu)(1+\nu_u)}\left(\sigma_{kk} + \frac{3}{B}p\right)$$

Pore pressure & water content + stress & strain

2 additional constants, such as $\boldsymbol{\nu}_{\mathrm{u}}$ and *B*

Isotropic, linearly elastic, porous medium

Originally developed in the field of soil mechanics

Validity for rock mass should be tested.

Pore pressure vs. strain

Under undrained condition, $m - m_0 = 0$

$$p = -\frac{B}{3}\sigma_{kk} \qquad p = BK_u \varepsilon_{kk}$$

B: Skempton係数

Sensitivity of pore pressure to strain ~ 20 GPa

1 n strain ~ 20 Pa (~ 2 mmH_2O)

Natural amplifier

Fluid flow with poroelastic deformation

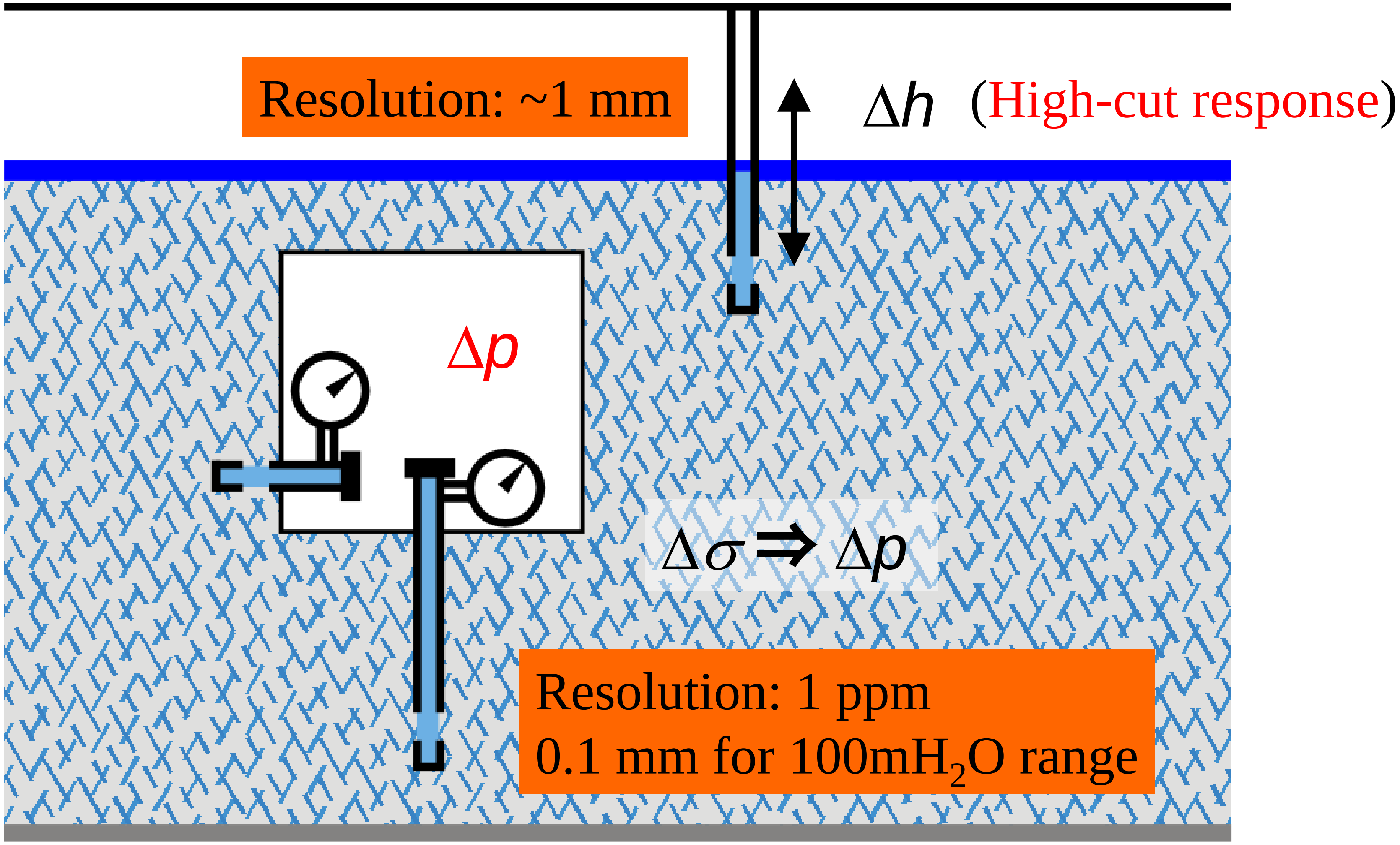
$$c\nabla^2\left(\sigma_{kk}+\frac{3}{B}p\right)=\frac{\partial}{\partial t}\left(\sigma_{kk}+\frac{3}{B}p\right)$$

c : hydraulic diffusivity

Coupled state diffuses

Another frequency dependence: wellbore storage

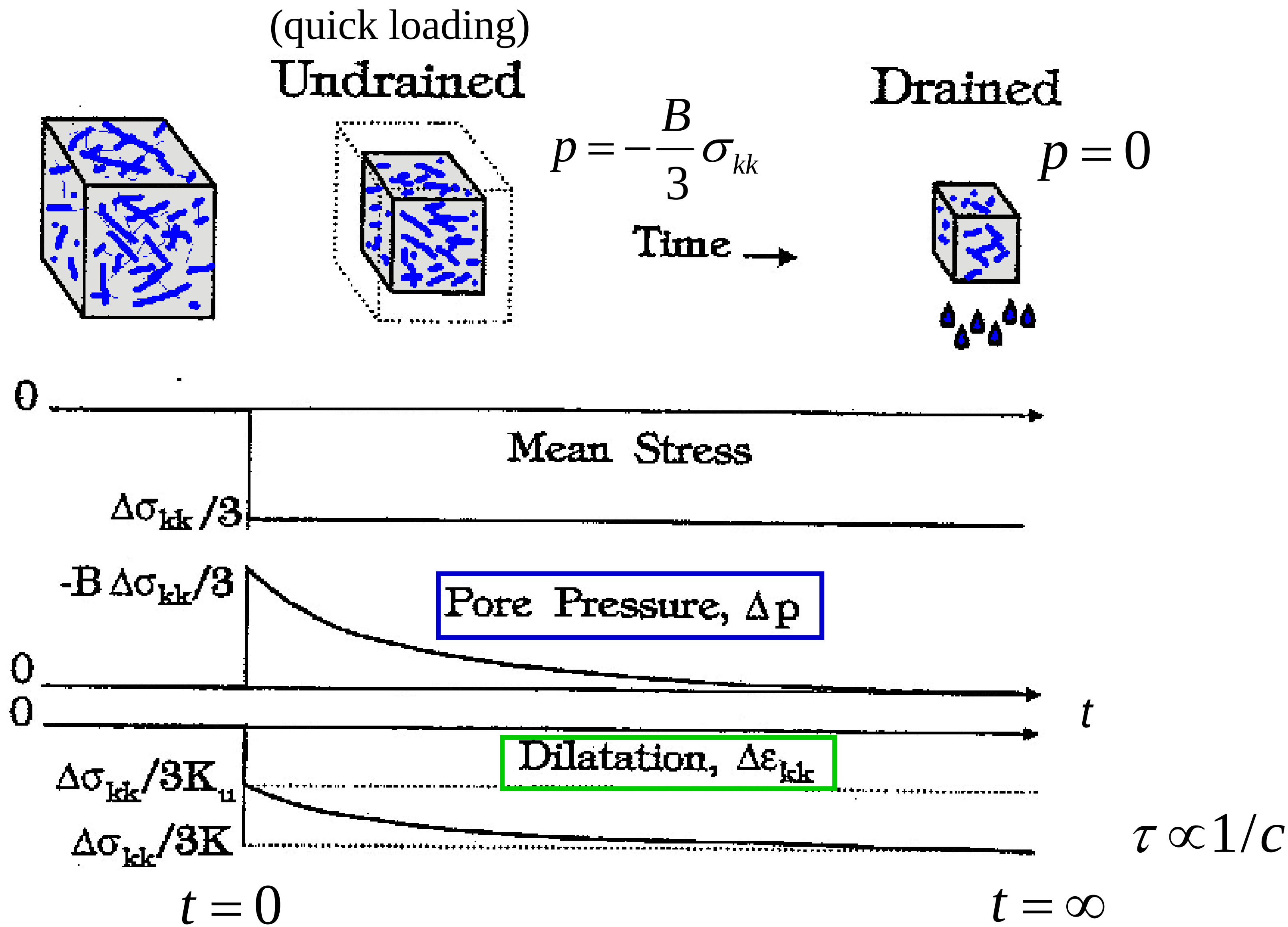
Represent the pore pressure change in the rock mass?



Obtain direct measure of pore pressure of the rock mass
Water flow is not necessary to change the pressure in borehole.

Time-dependent respose of poroelastic material

(Roeloffs, 1996)



Time-dependent respose of poroelastic material

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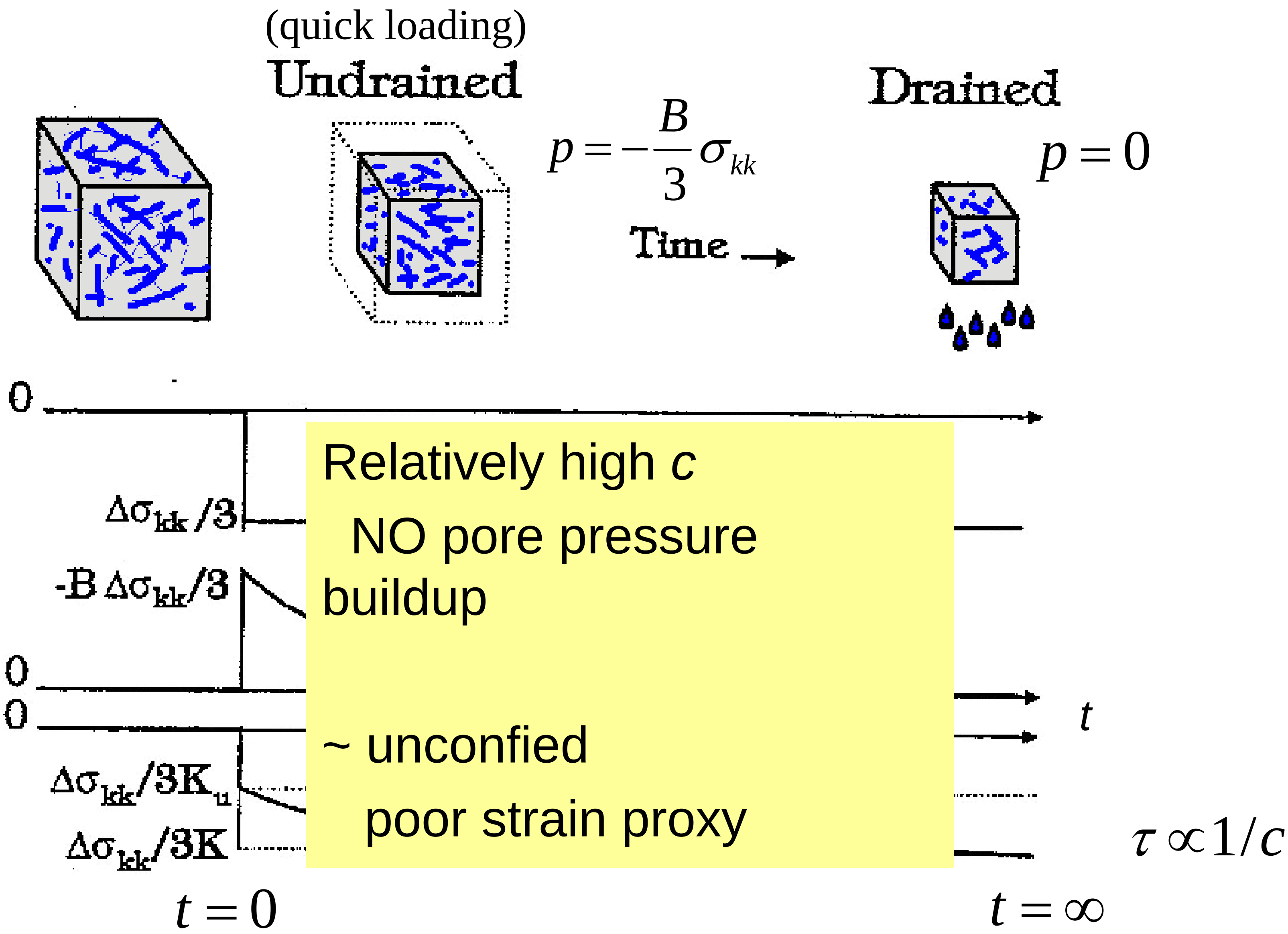


Relatively high *c*

NO pore pressure buildup

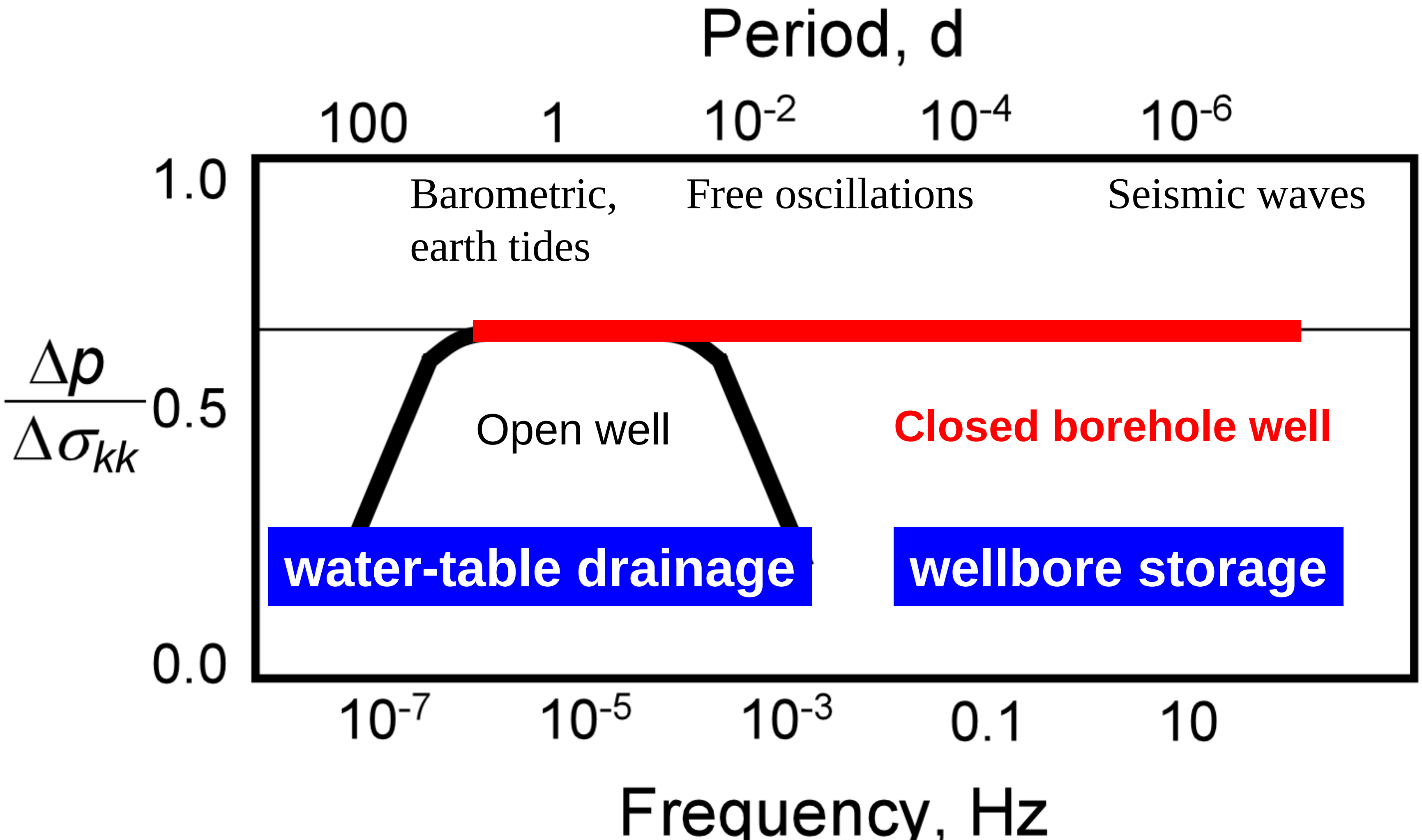
~ unconfied

poor strain proxy

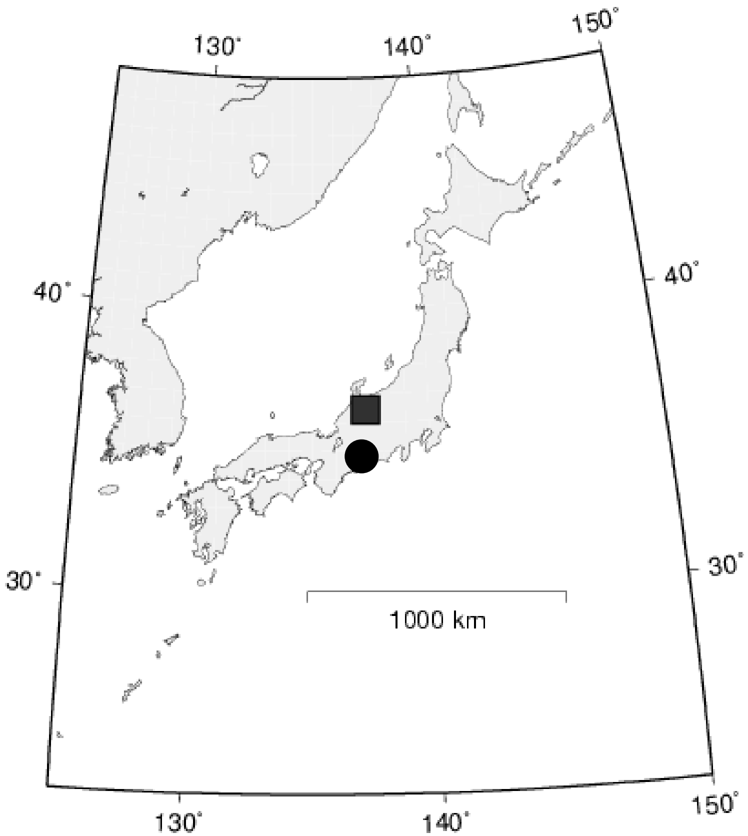
Overall frequency response of closed borehole wells

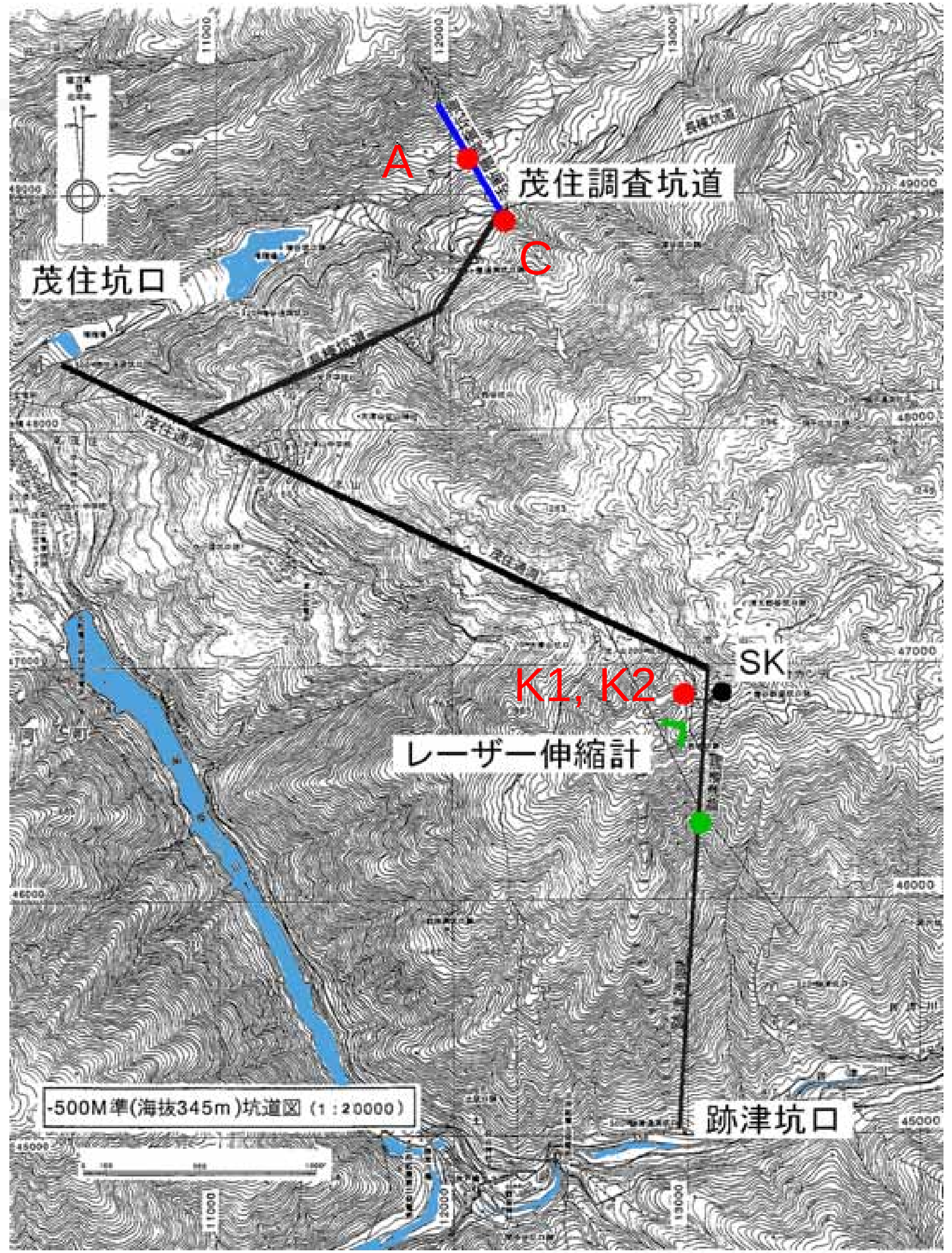
“Sensitivity“ of pore pressure response to mean stress

Observations fit the prediction of poroelasticity

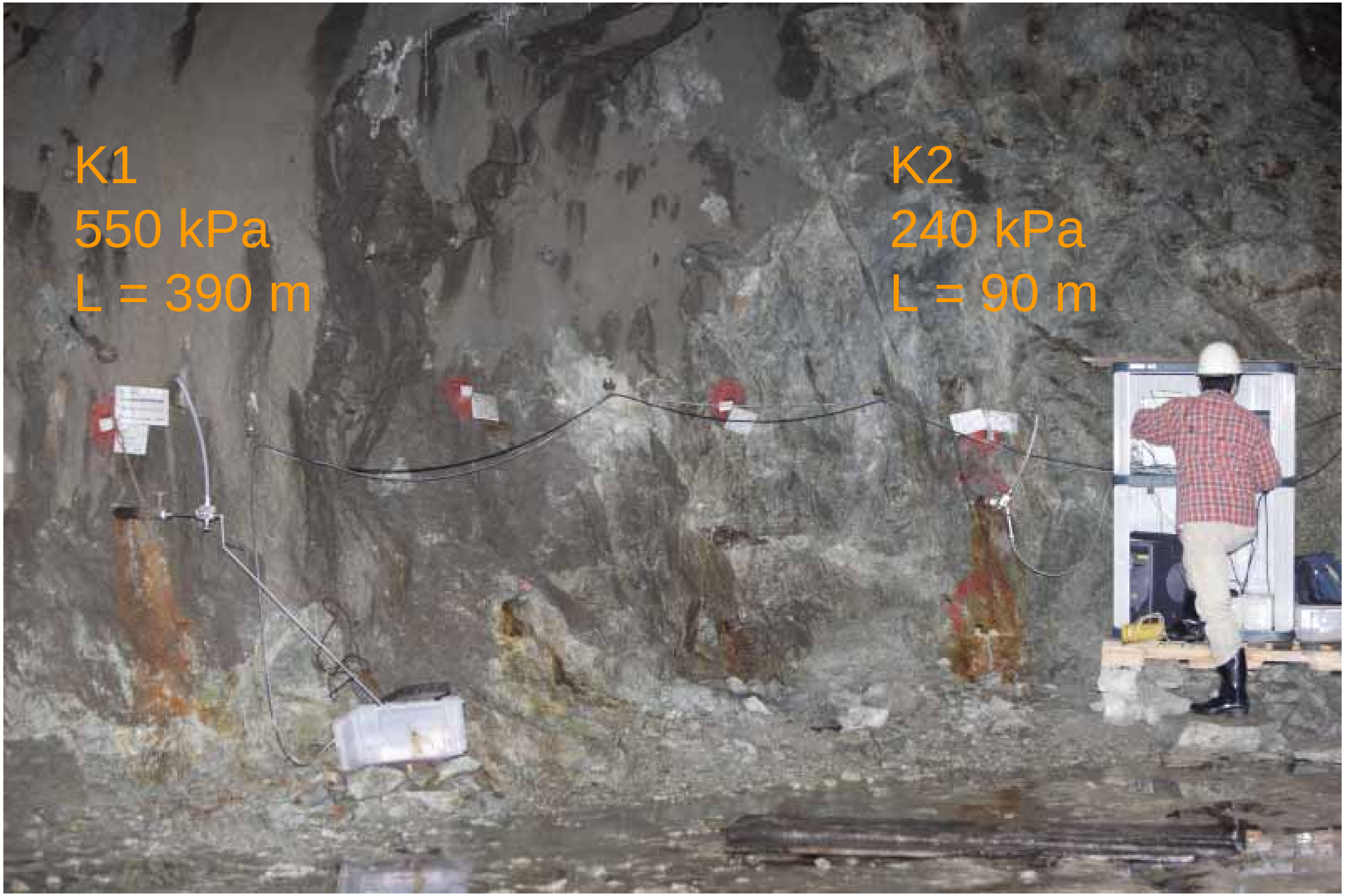


Kamioka mine

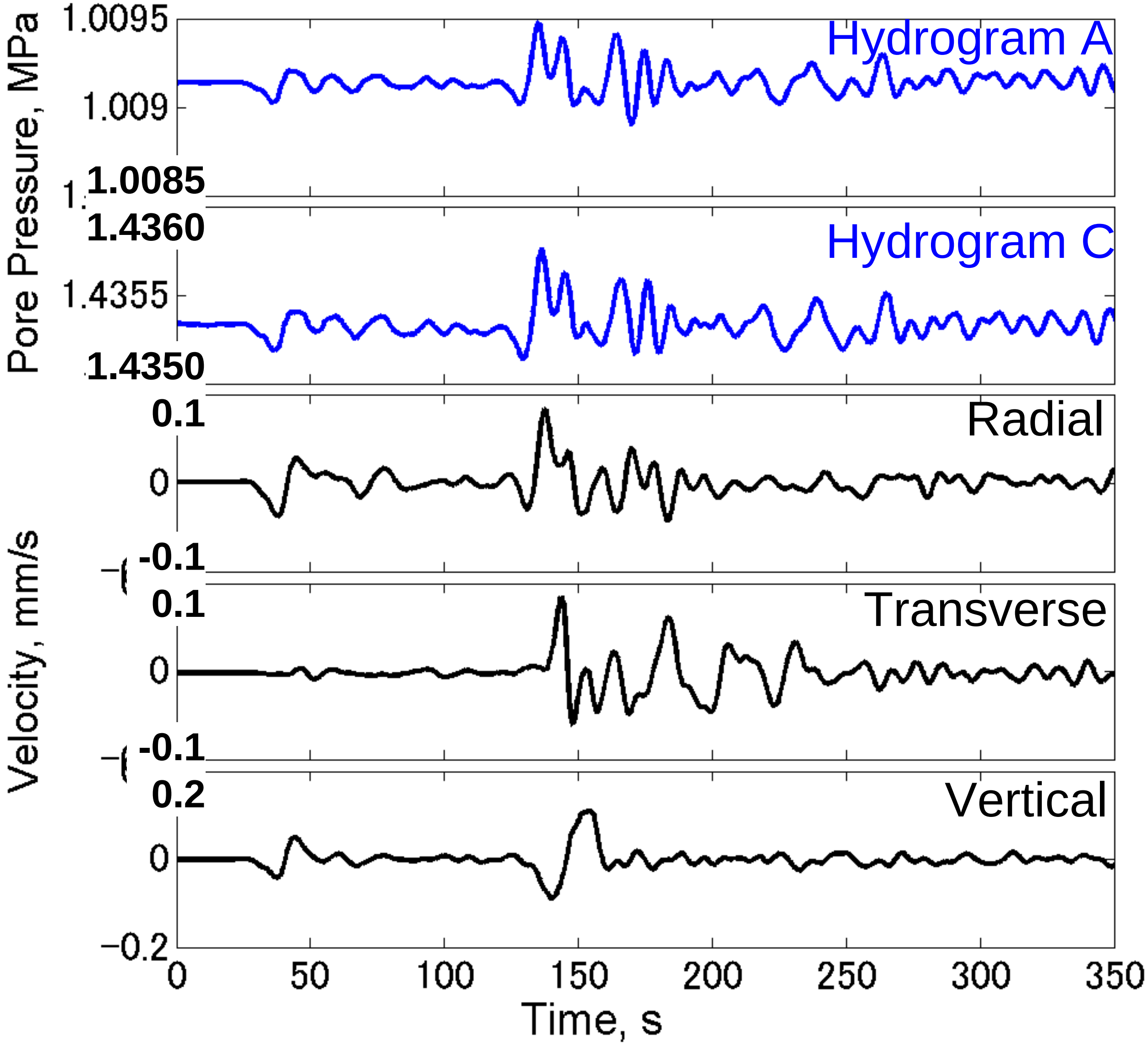




K1 and K2 borehole



Hydroseismogram [Kano and Yanagidani, 2006]



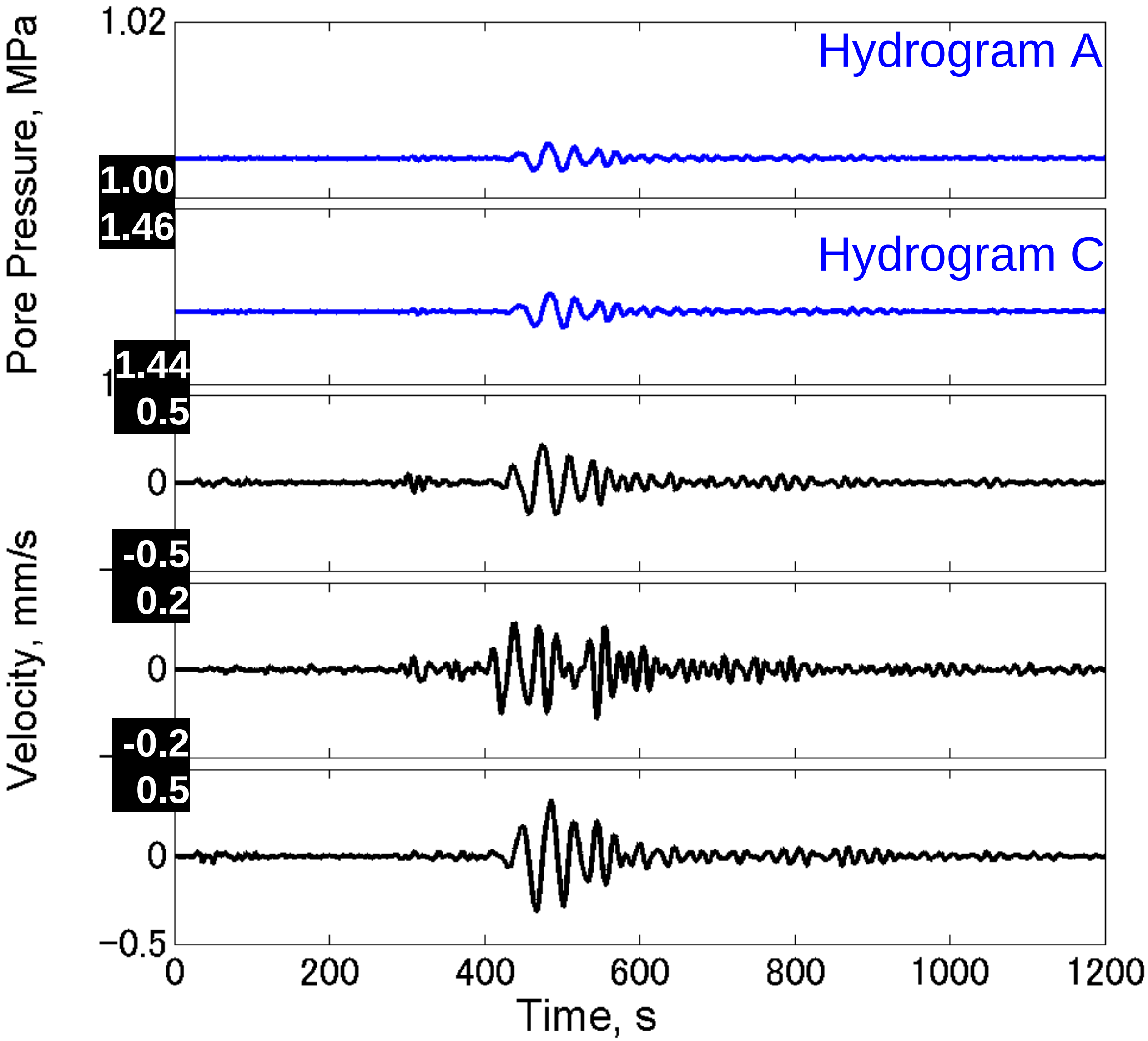
Vladivostok(Mw7.3), 2002-06-29, Δ= 9^{o}, Depth= 565 km,

Seismogram

KTJ STS-1, 0.1 Hz , low-pass-filtered

P ＝ Vr （radial） × (poroelastic const.) × (ray parameter)r

Hydroseismogram (2) (surface wave)



ydrogram

Rayleigh wave o

Love wave x

Mariana(Mw7.1)

2002-04-27

$\Delta = 24^o$

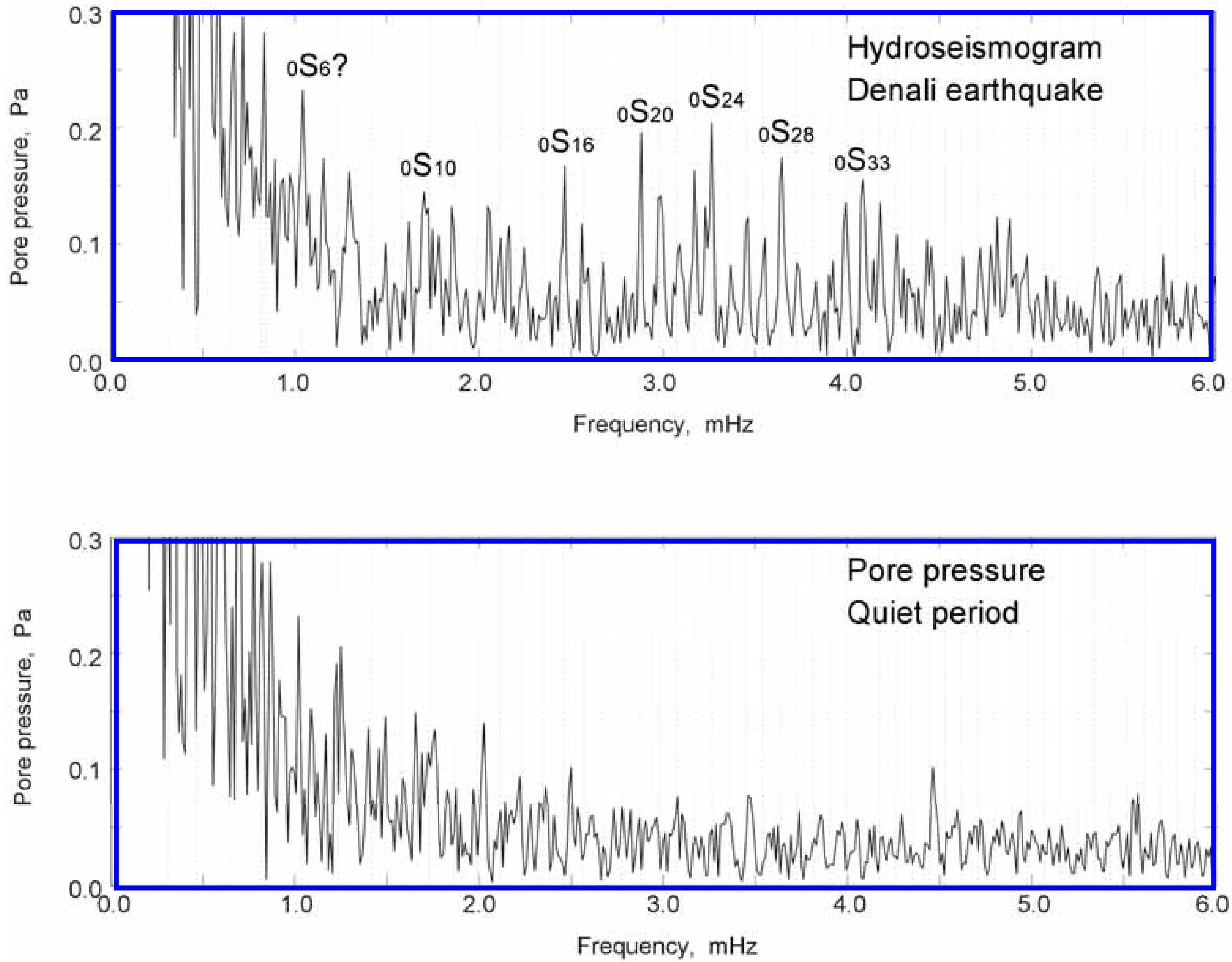
Depth= 55 km

KTJ STS-1

0.1 Hz

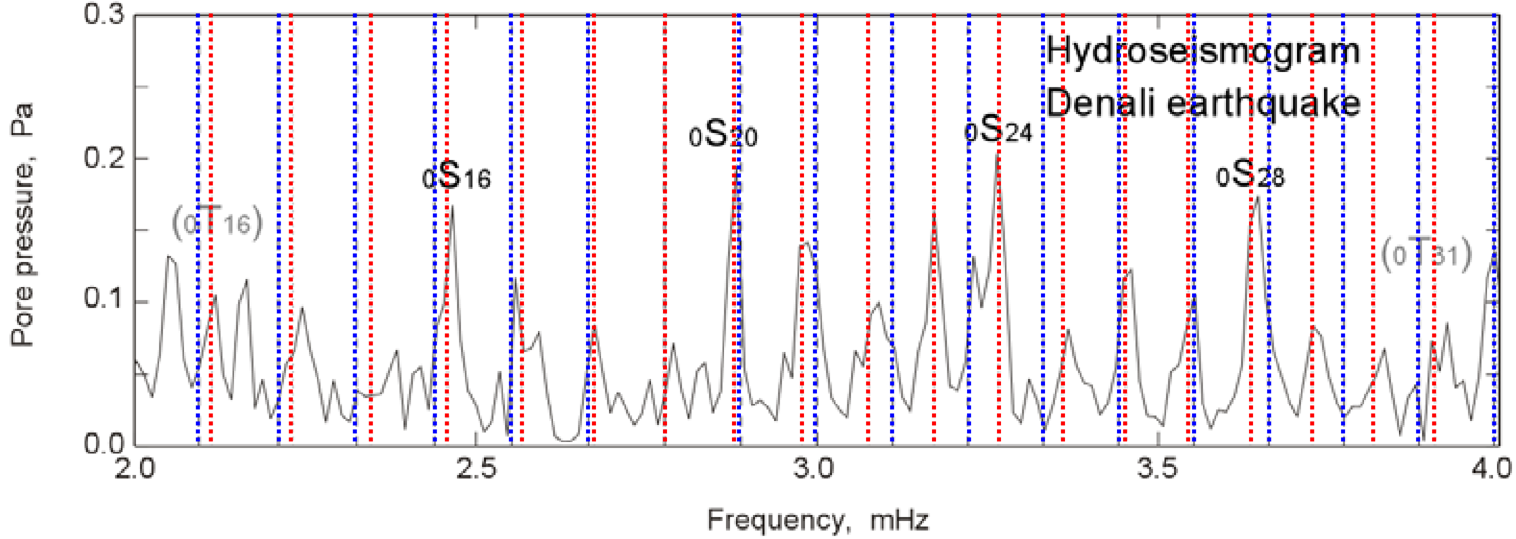
low-pass-filtered

Sensitive to small signal



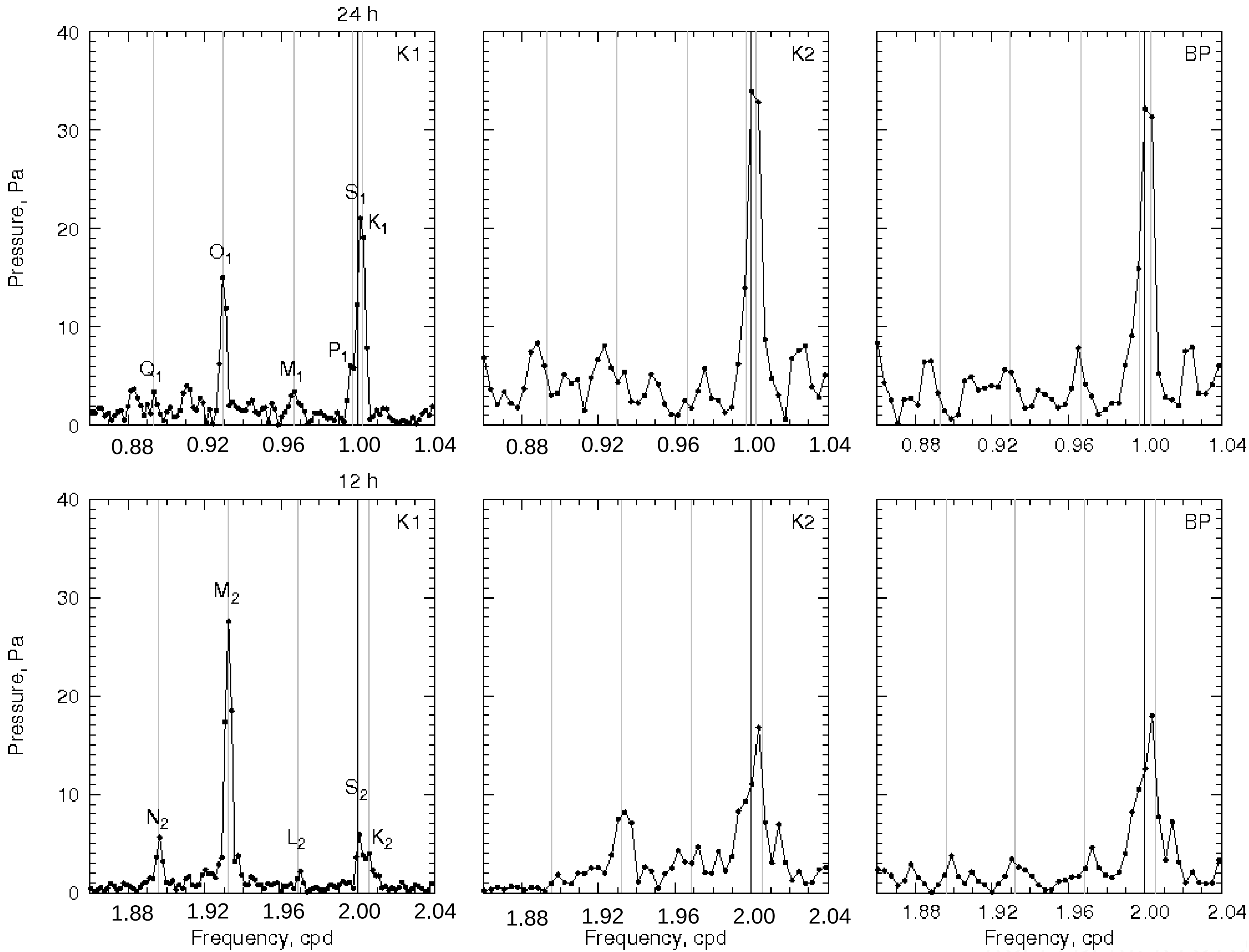
2002 Denali, Alaska earthquake

Spheroidal v.s. Troidal modes



No troidal (shear) response !

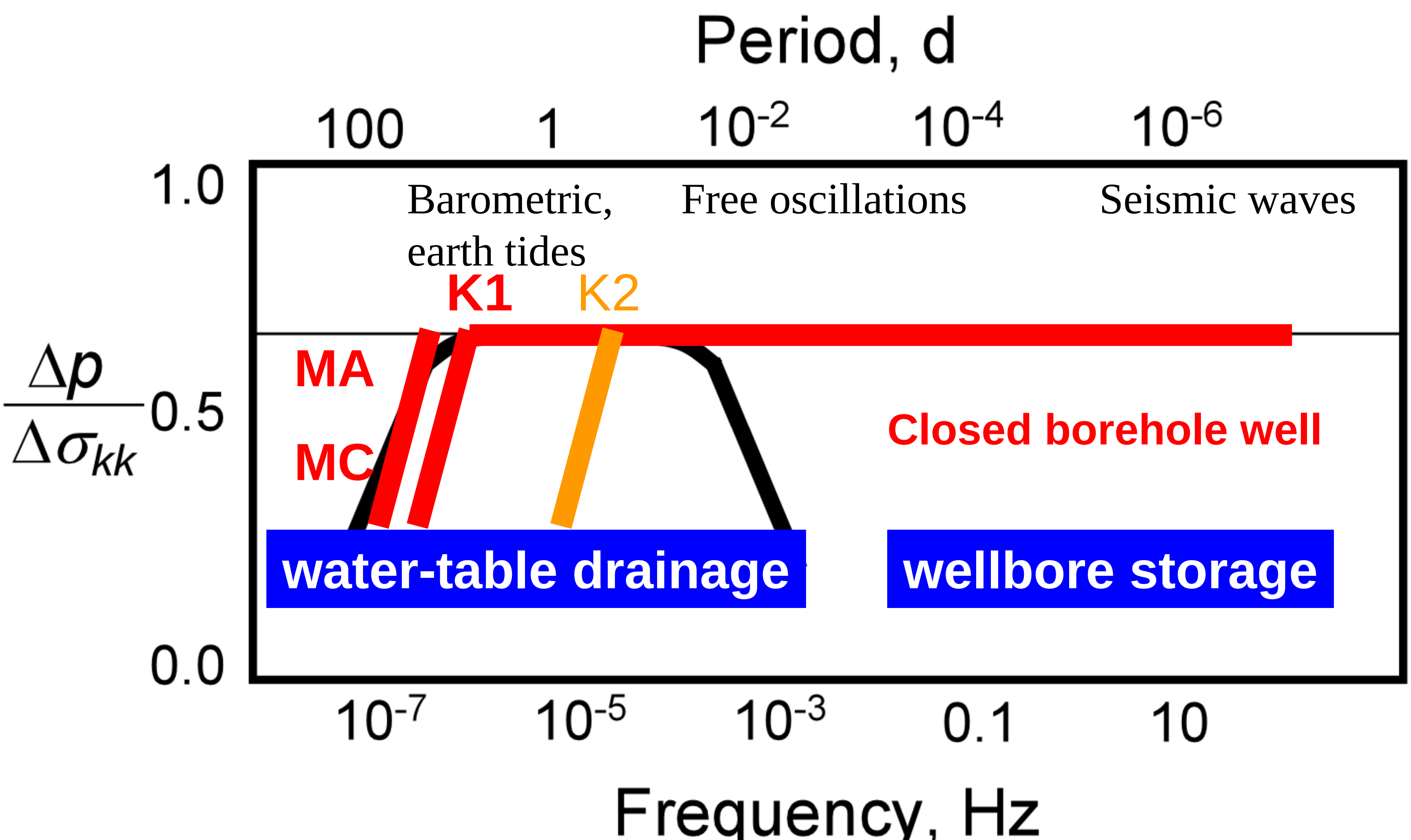
Tidal / Barometric response of K1 and K2



Overall frequency response of closed borehole wells

“Sensitivity“ of pore pressure response to mean stress

Observations fit the prediction of poroelasticity



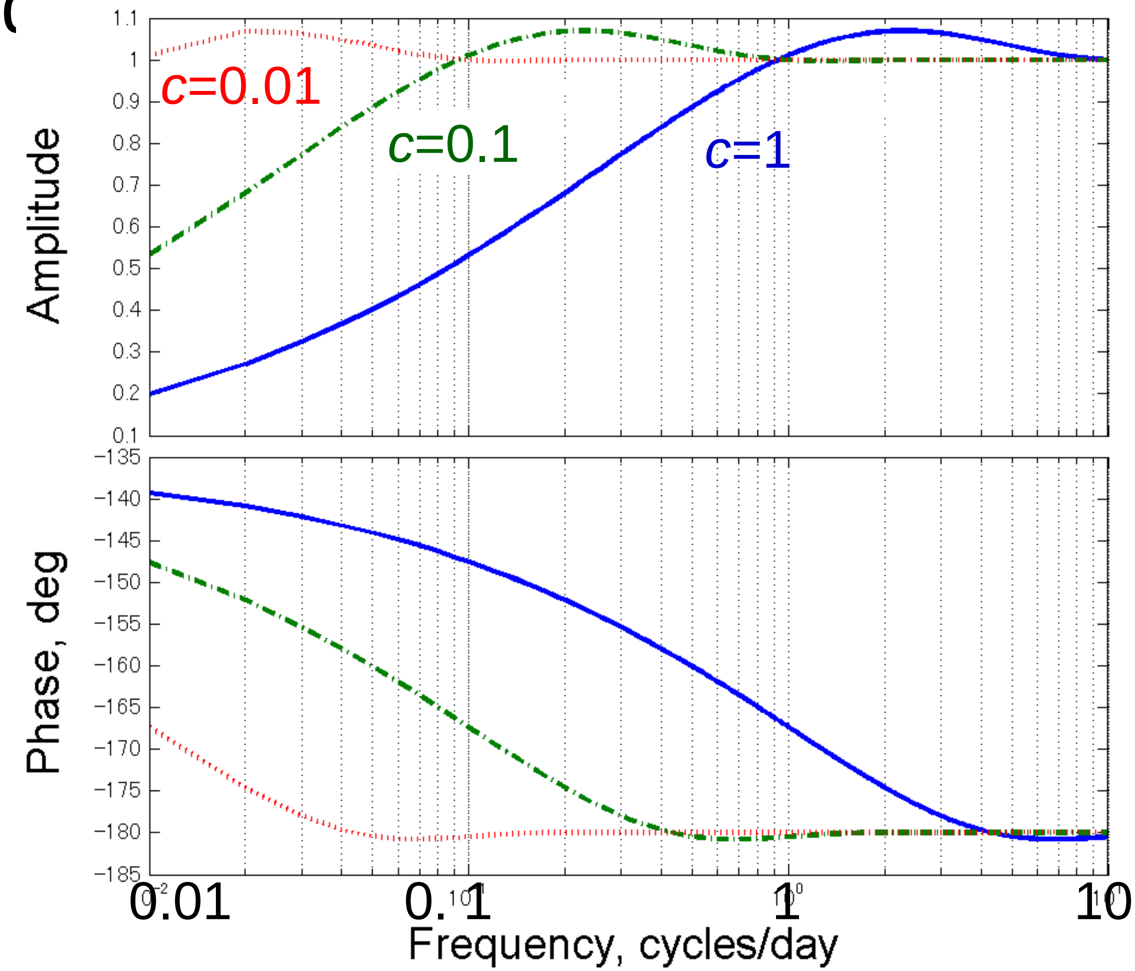
Effect of water flow

Low-cut response depending on diffusivity, c

(calcurated base

Water-table dranage

Tidal response band



$$c = \frac{k}{\mu S}$$

k : permeability

μ: viscosity

S: specific storage

Tidal response

Summary: Kamioka

Closing the well is effective to measure the pore pressure of rock mass, especially for higher frequency bands.

Closed borehole well is a broadband sensor for crustal deformation including not only barometric pressure and earth tides but also free oscillations and seismic waves.

Validity of the linear isotropic poroelasticity for the rock mass (different from soil) is confirmed by in situ measurement especially for higher frequency bands.

-> strain/stress (change) proxy

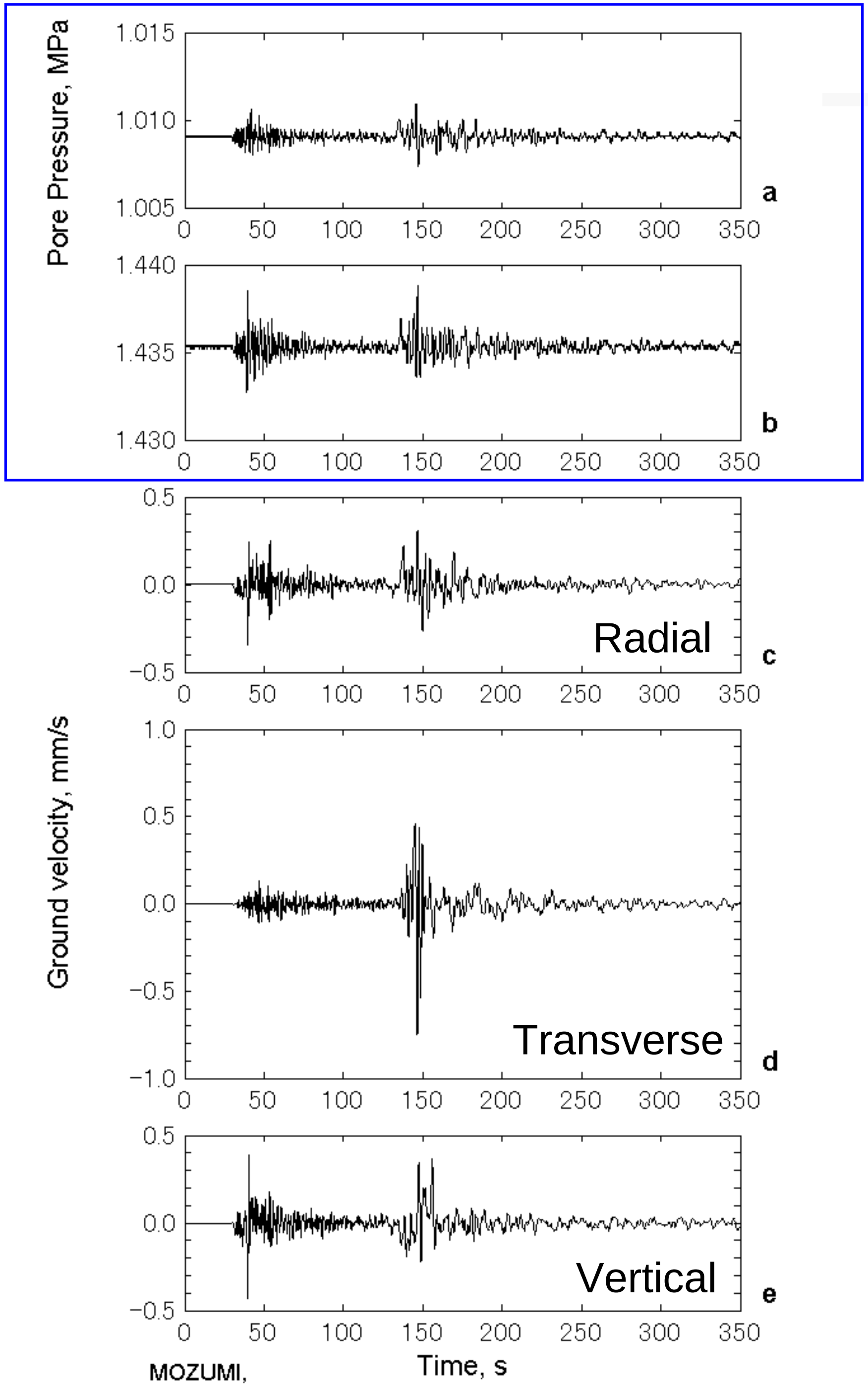
Pore pressure measurement

- As proxy of strainmeter
  - Pore pressure is proportional to stress/strain under undained condition (natural amplifier)
  - Evaluation / calibration of response is necessary -> slow event?

- Hydraulic property of an aquifer (fault zone)
  - Tidal/barometric response（1~10 kPa）
  - Pumping/injection test

- Give idea for fluid flow at depth
  - Episodic flow in an aquifer (fault zone) ???
  - Triggering of earthquakes ???

A borehole



- How can we measure good hydroseismograms?

- What kind of information can we extract from hydroseismograms?

  In-situ poroelastic parameter

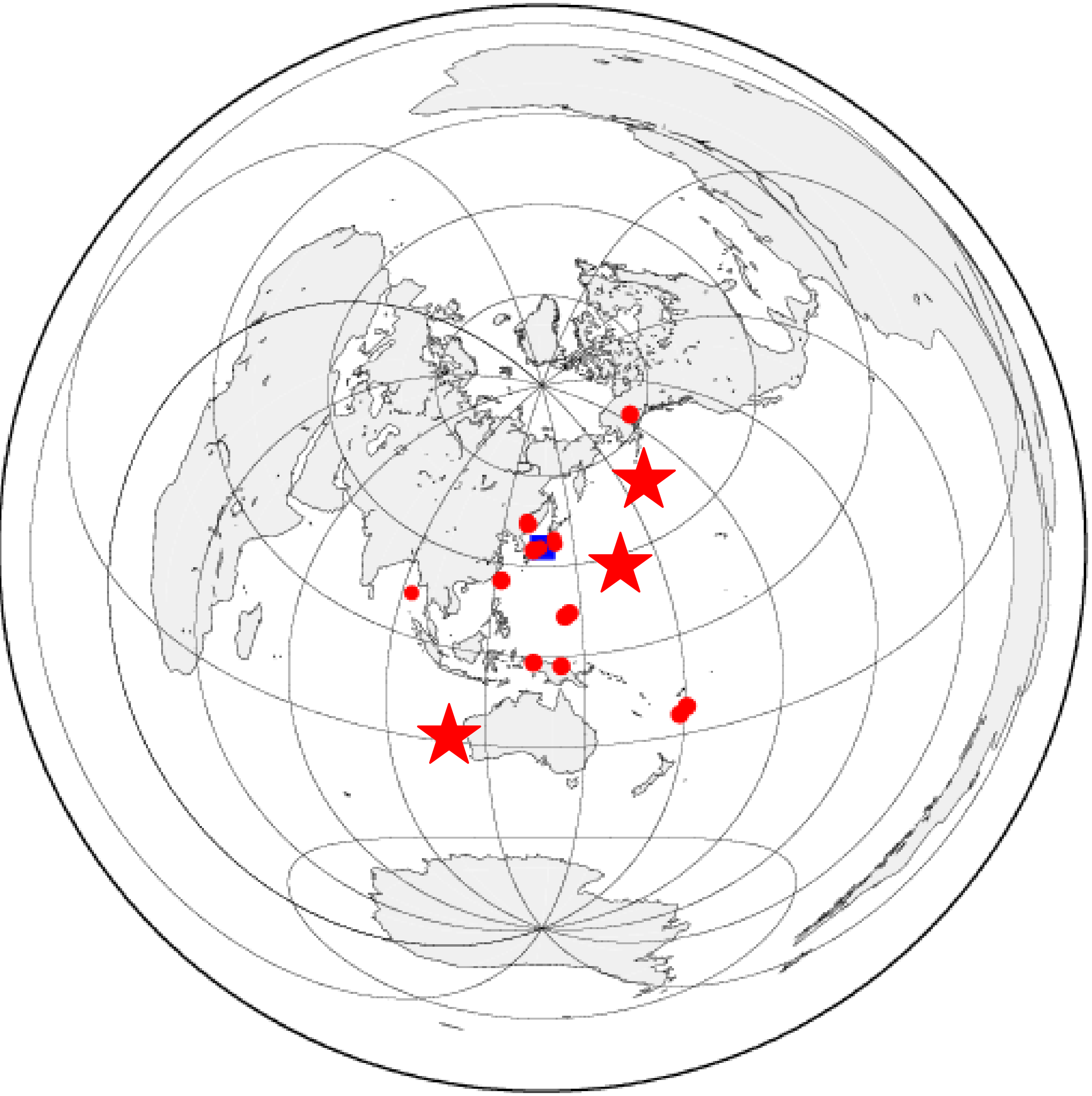
Vladivostok(Mw7.3), 2002-06-29,

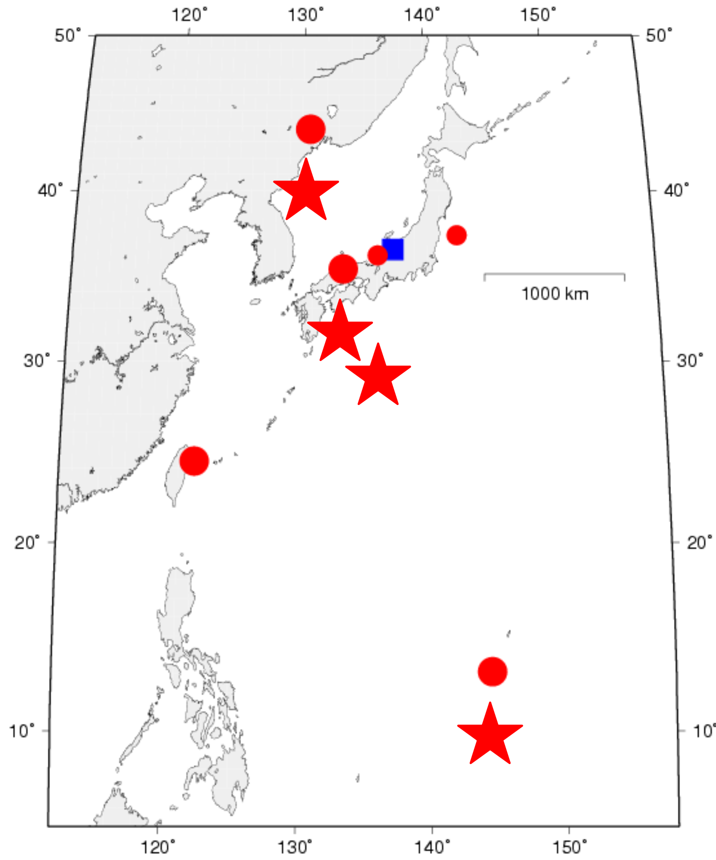
Δ= 9^o, Depth= 565 km,

KTJ STS-1

0.1 Hz , low-pass-filtered

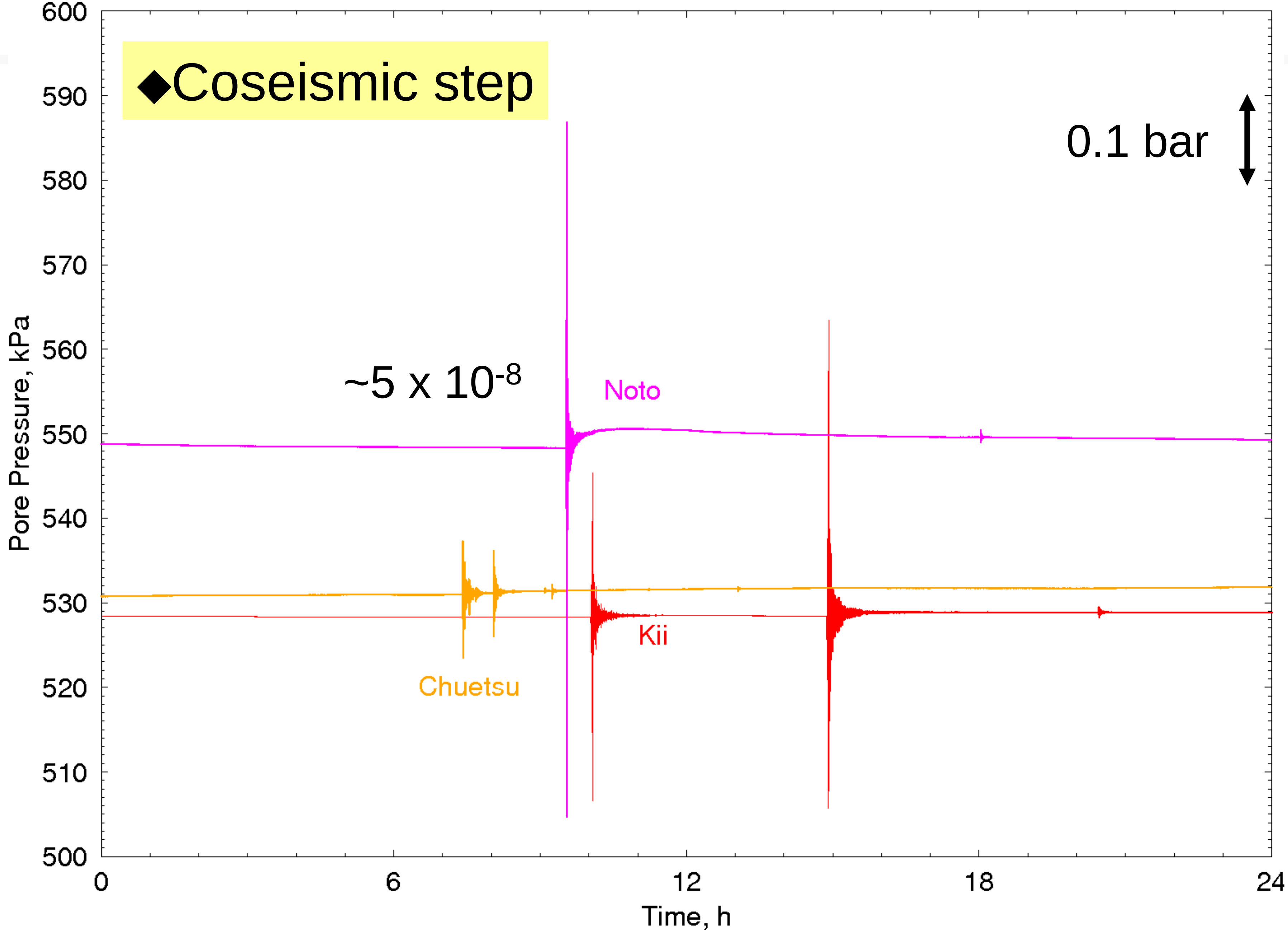
Earthquakes recorded at Kamioka



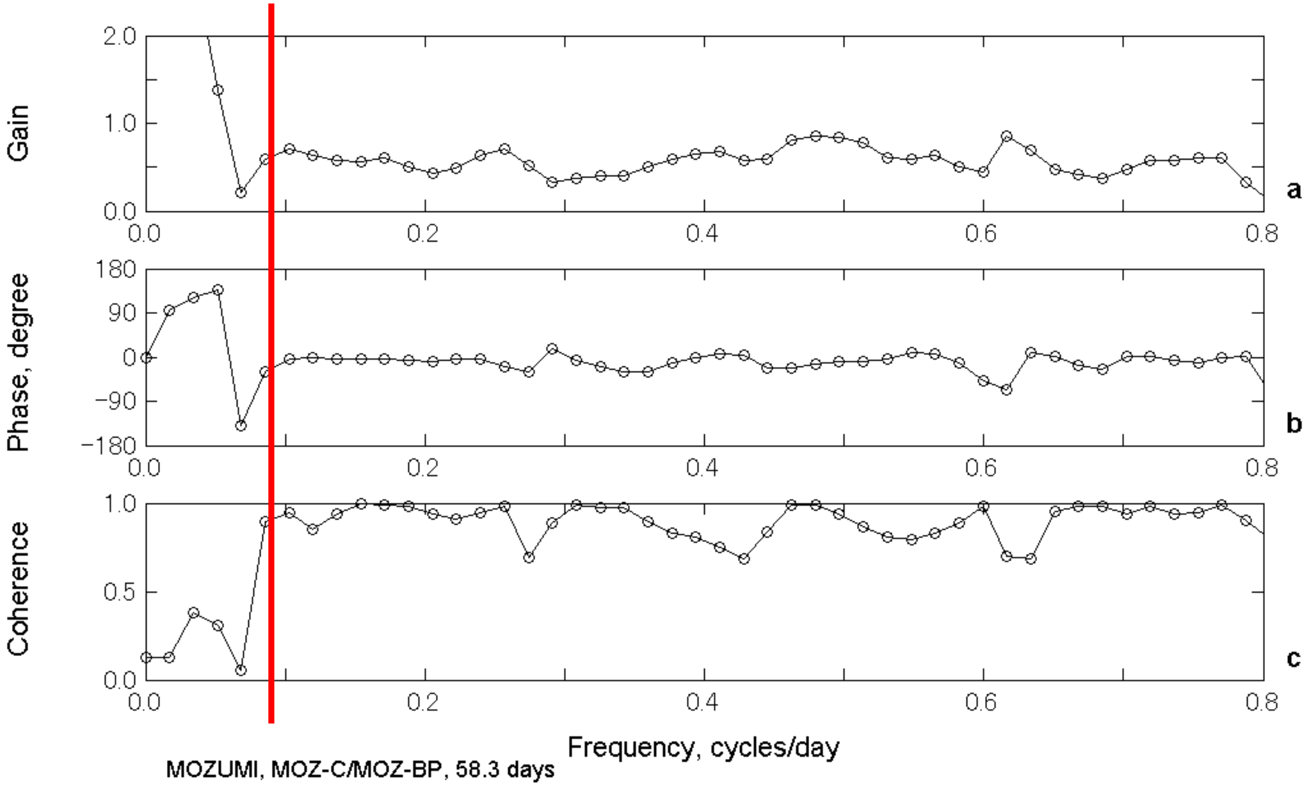


No azimuth dependenth - Isotropic

◆Coseismic step



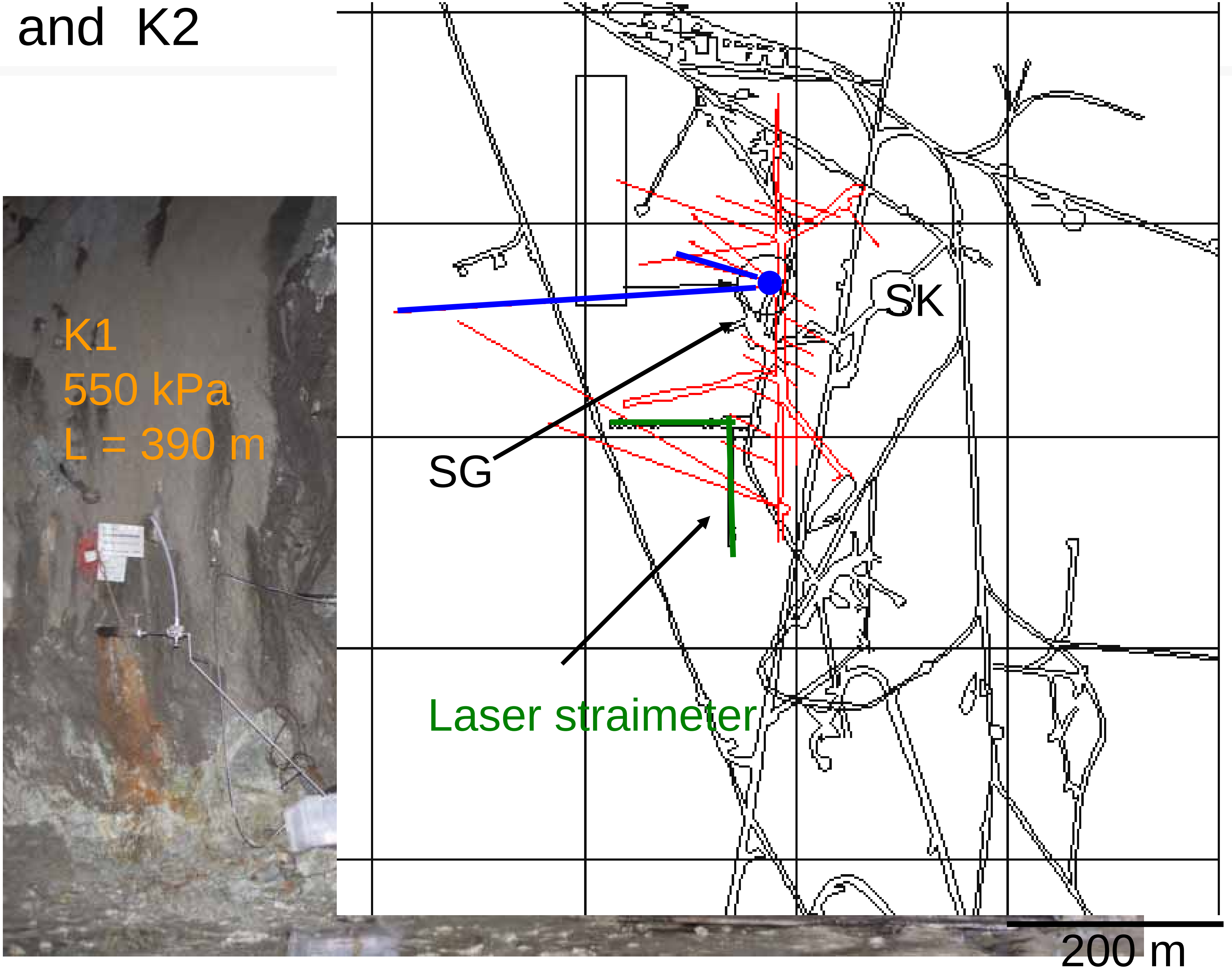
Spectrum of pore pressure and barometric pressure



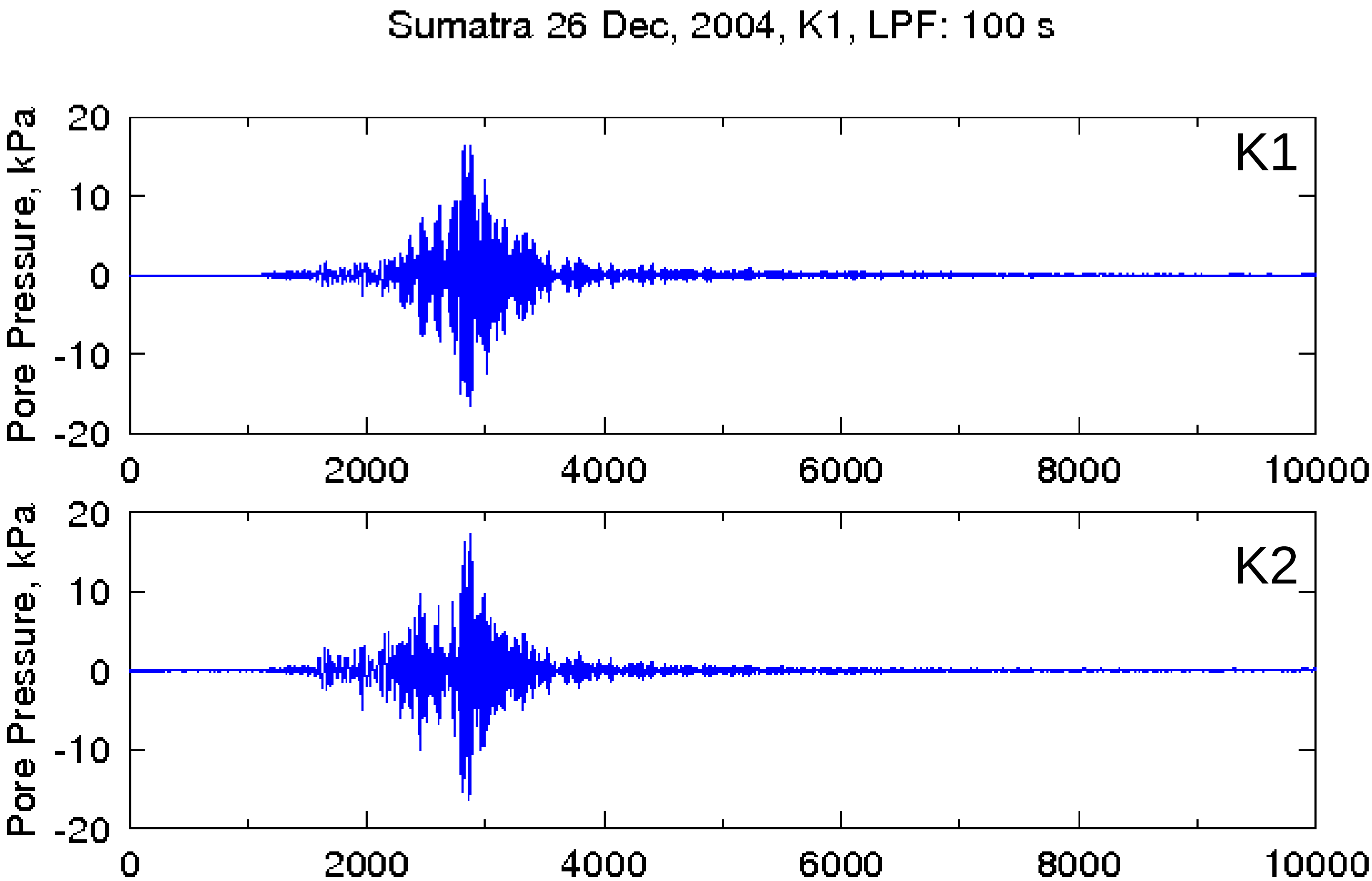
Cutoff -> c ~ 0.1m^2/s (0.01 m2/s from core sample)

58.3 days

K1 and K2

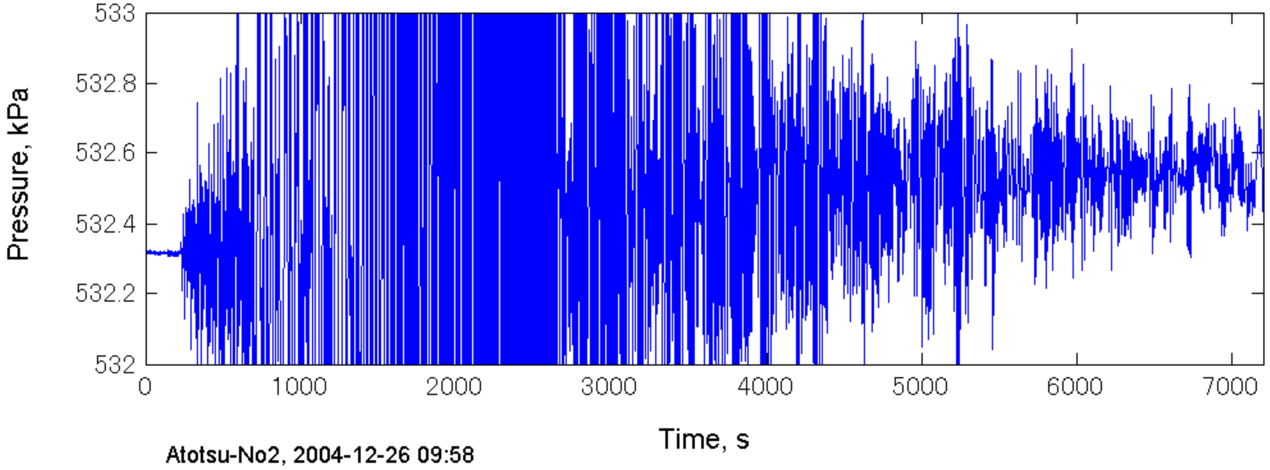


Hydroseismogram of the Sumatra earthquake

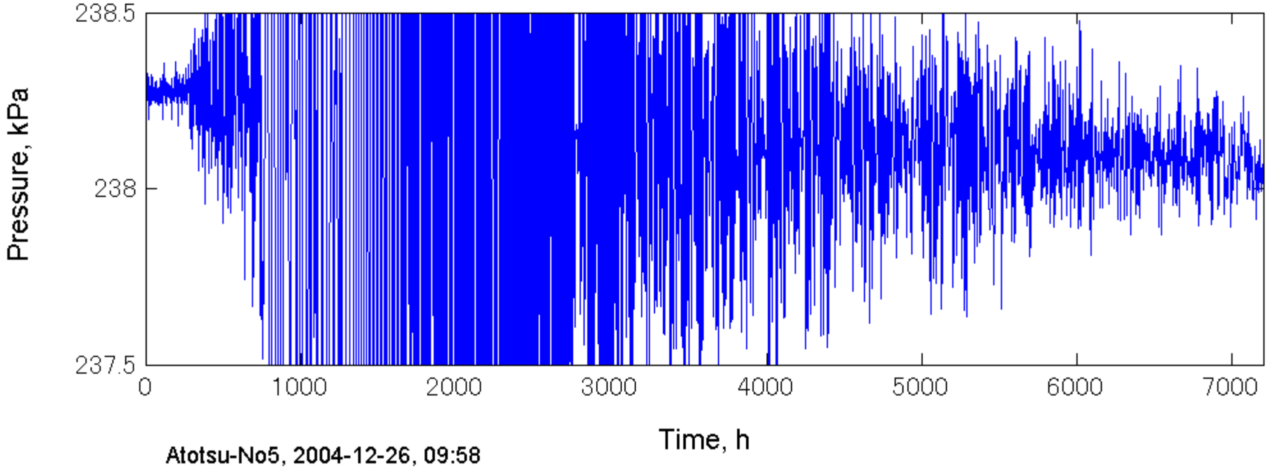


Hydroseismogram of the 2004 Sumatra earthquake

K1: increase, K2: decrease   different polarity!



K1



K2

Possible cause of pore pressure unbalance

(1) Unclogging [Brodsky et al, 2003]

caused by shaking induces water flow

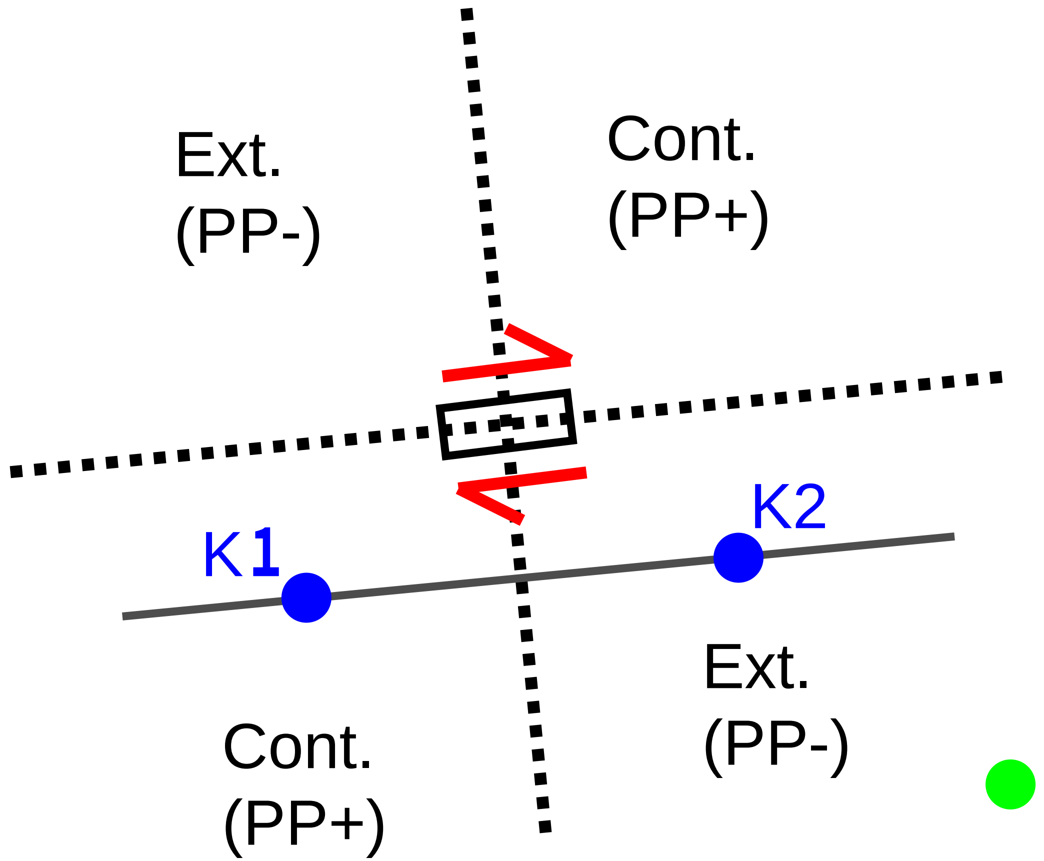
Not the case: the pore pressure is higher in K1

K1: +
K2: -

(2) Local slip

causes static contraction/extension field and consequently pore pressure increase/decrease

Static strain change caused by local slip



Initial condition

Static strain field caused by local slip event

Calculated using Okada (1991) code

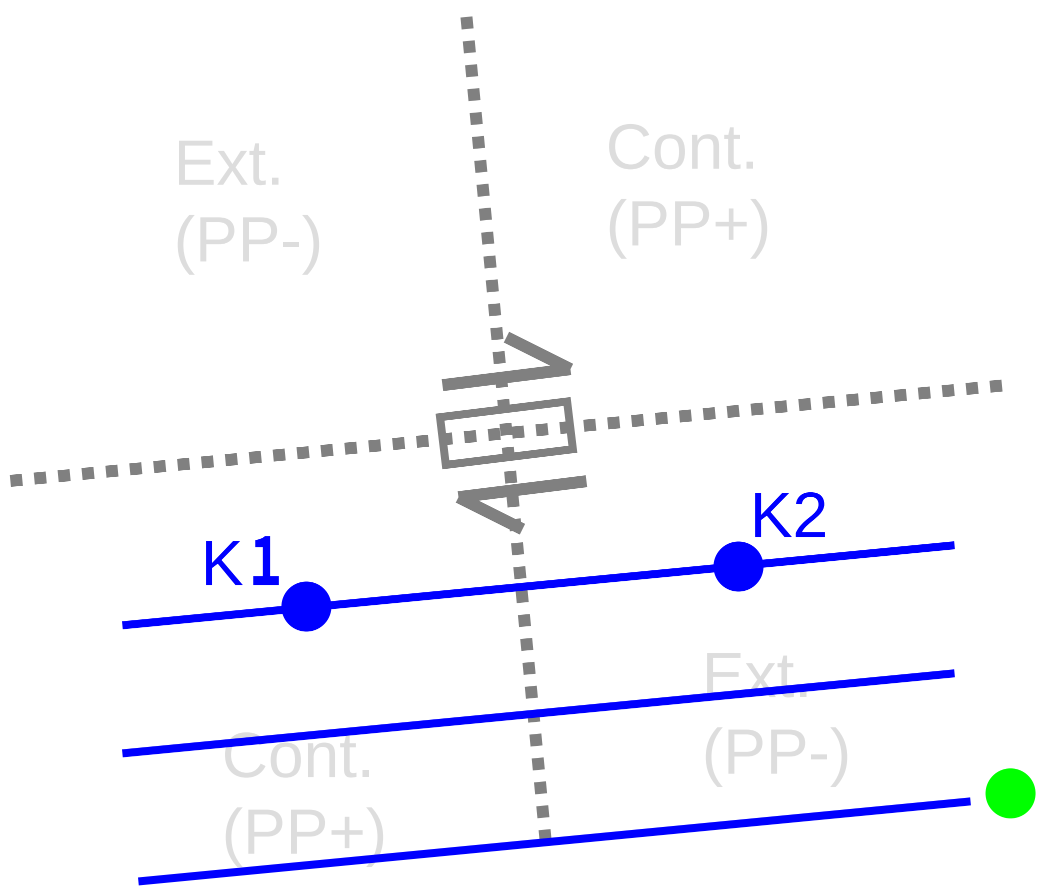
20 m x 20 m, 0.05 m slip

Mo = 30 GPa

x 20 m x 20 m x 0.05 m

~ 6 x 10^{11} Nm

Re-equilibrium of pore pressure unbalance caused by local slip



1-dimensional fluid flow
(poroelastically coupled)

$$c\nabla^2\left(\sigma_{kk} + \frac{3}{B}p\right) = \frac{\partial}{\partial t}\left(\sigma_{kk} + \frac{3}{B}p\right)$$

Water flow only along the
crack (fault) systems

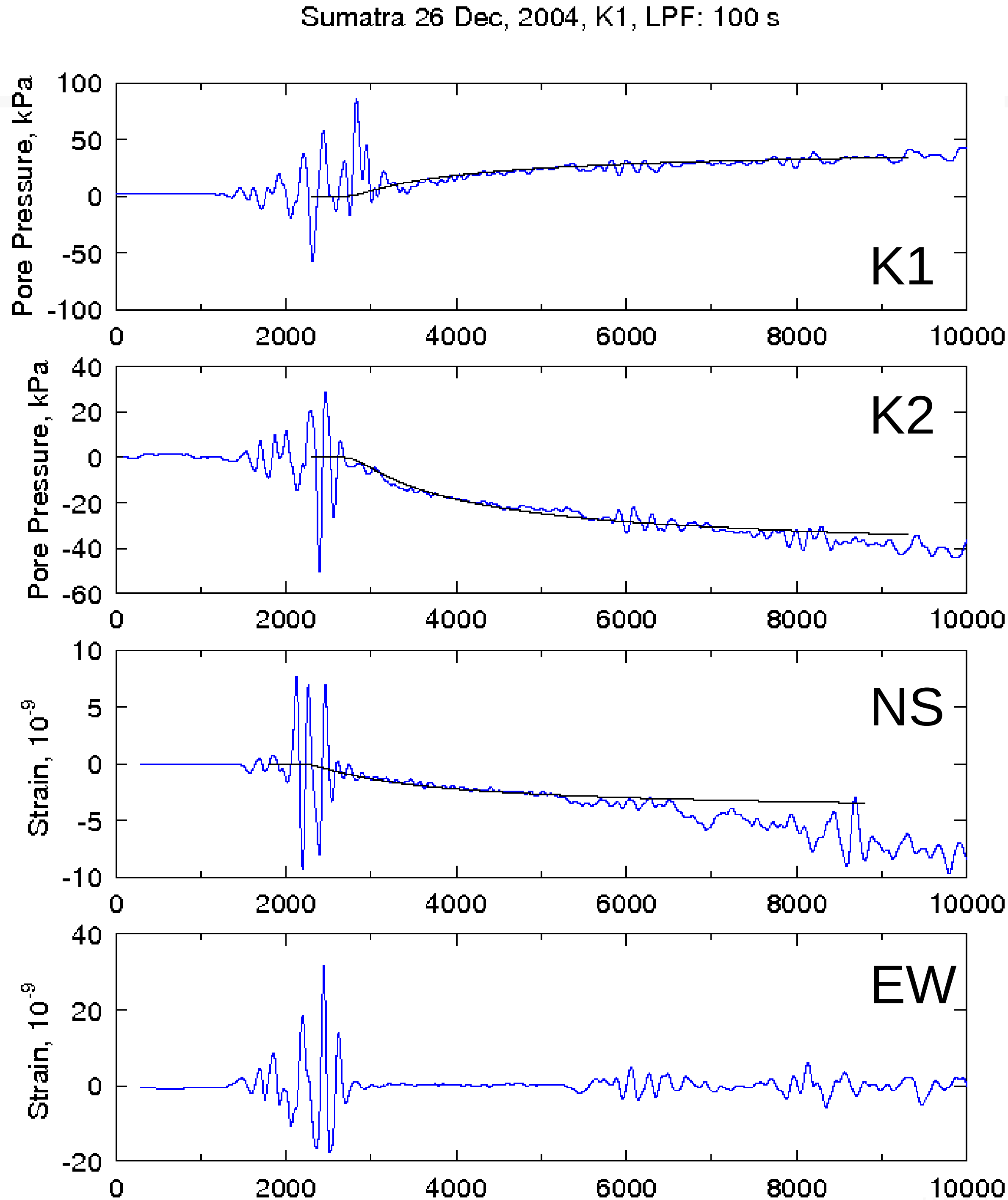
c = 0.1 m^2/s

B = 0.8

K1 and K2 : 90 m, +- 10 m

Laser strainmeter:

200 m, +200 m


Sumatra 26 Dec, 2004, K1, LPF: 100 s
Pore Pressure, kPa
100
50
0
-50
-100
K1
0
2000
4000
6000
8000
10000
Pore Pressure, kPa
40
20
0
-20
-40
-60
K2
Strain, 10^-9
10
5
0
-5
-10
NS
Strain, 10^-9
40
20
0
-20
EW