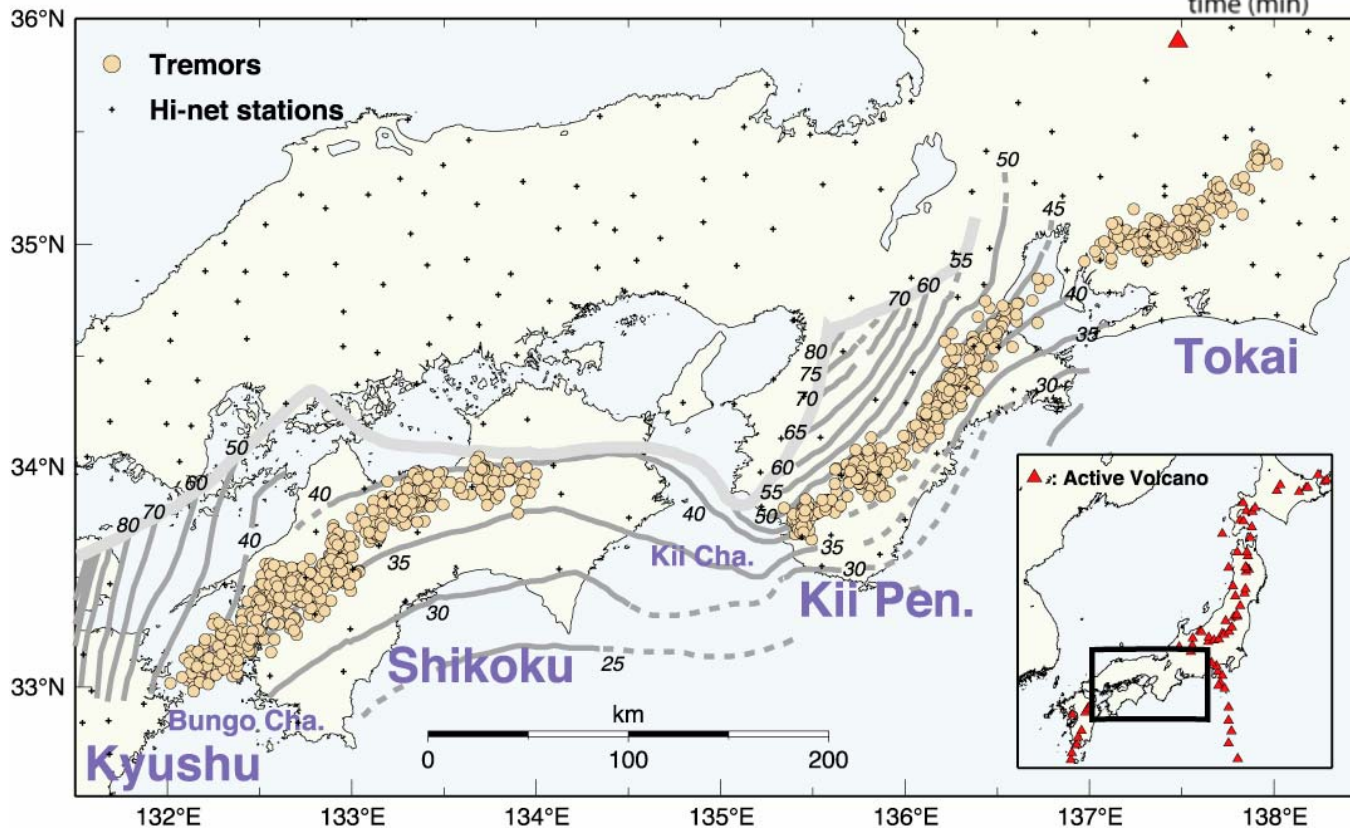
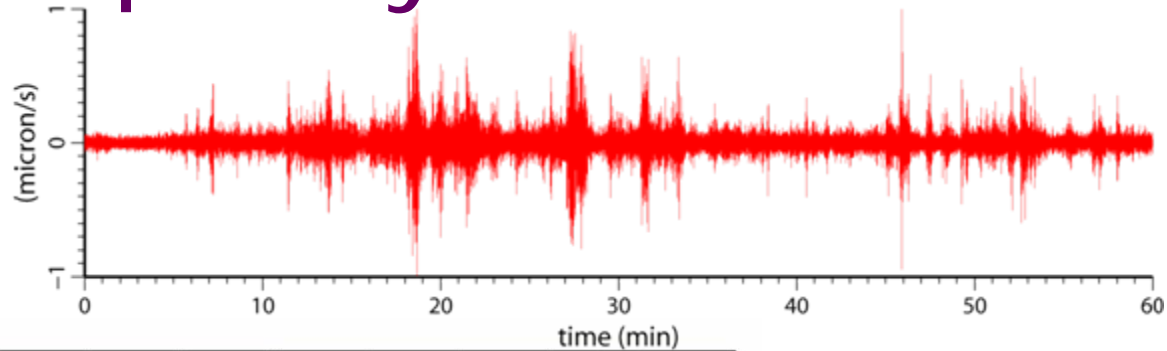


Discussion Seminar: Physics of Slow Slip

Slow Earthquakes Observation and Scaling Relation

Satoshi Ide (EPS, Univ. Tokyo)

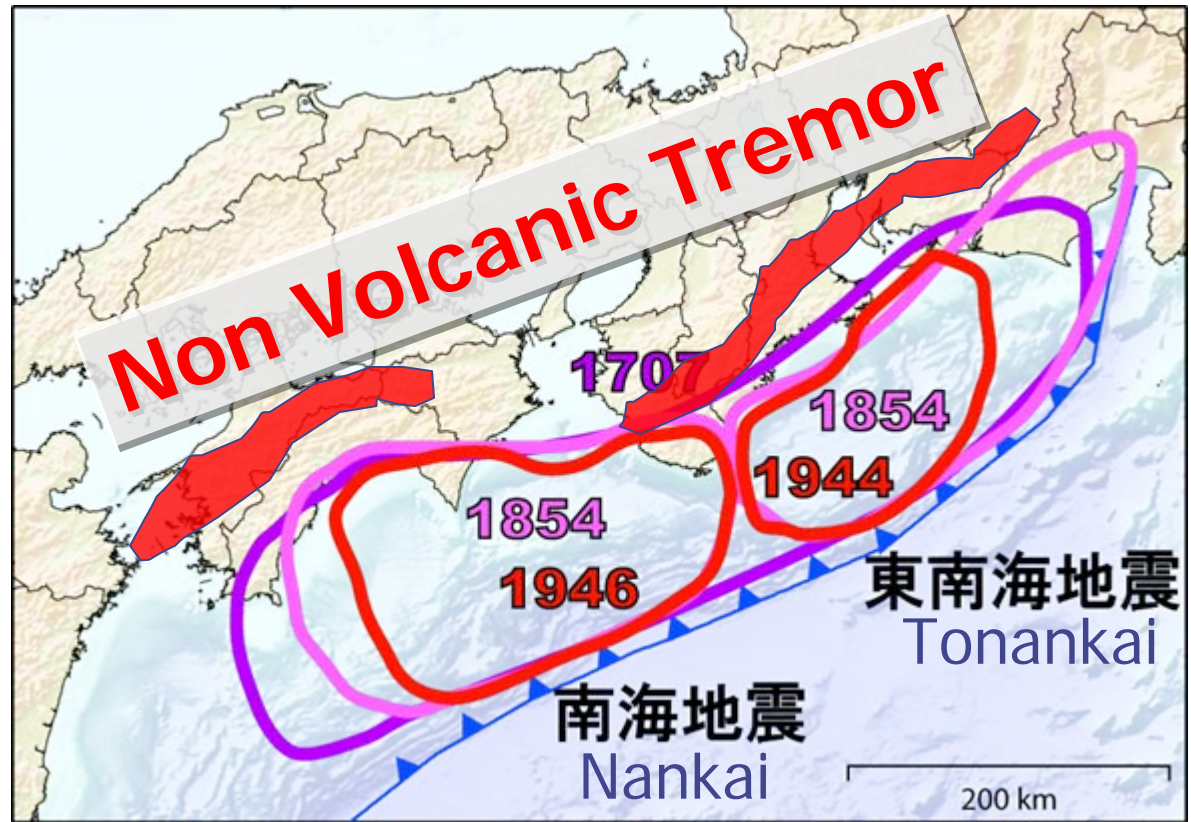
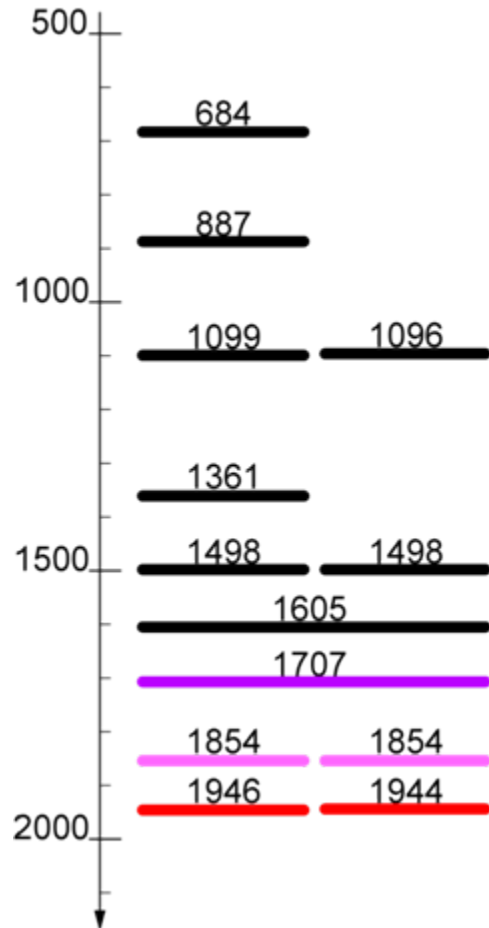
Deep Low Frequency Tremor



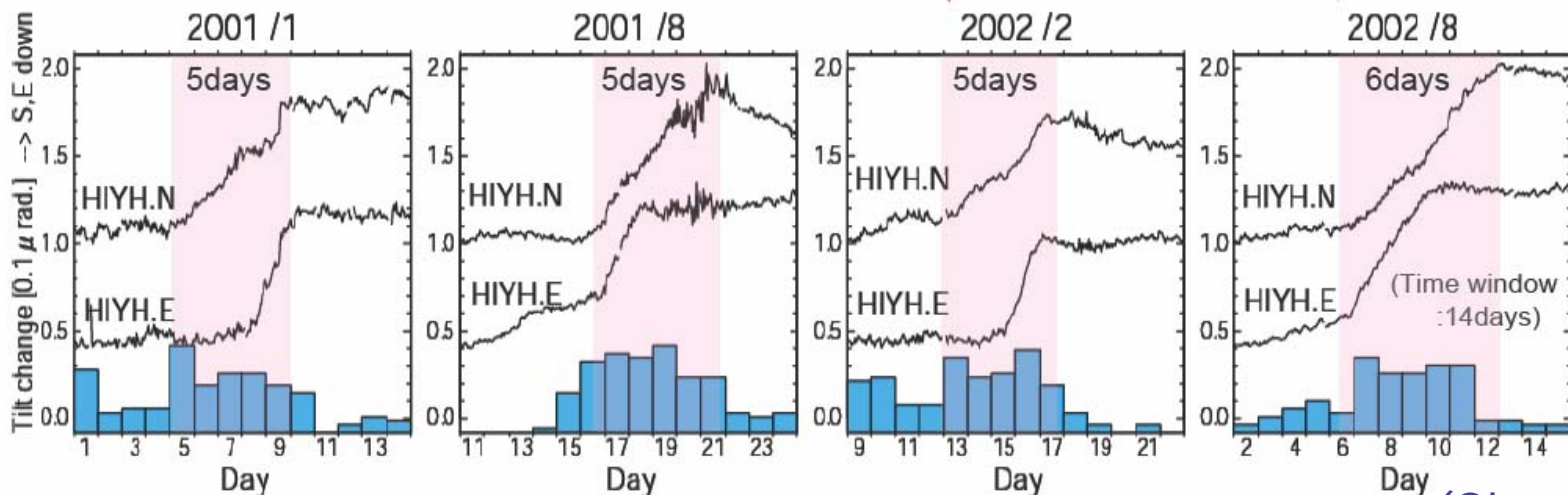
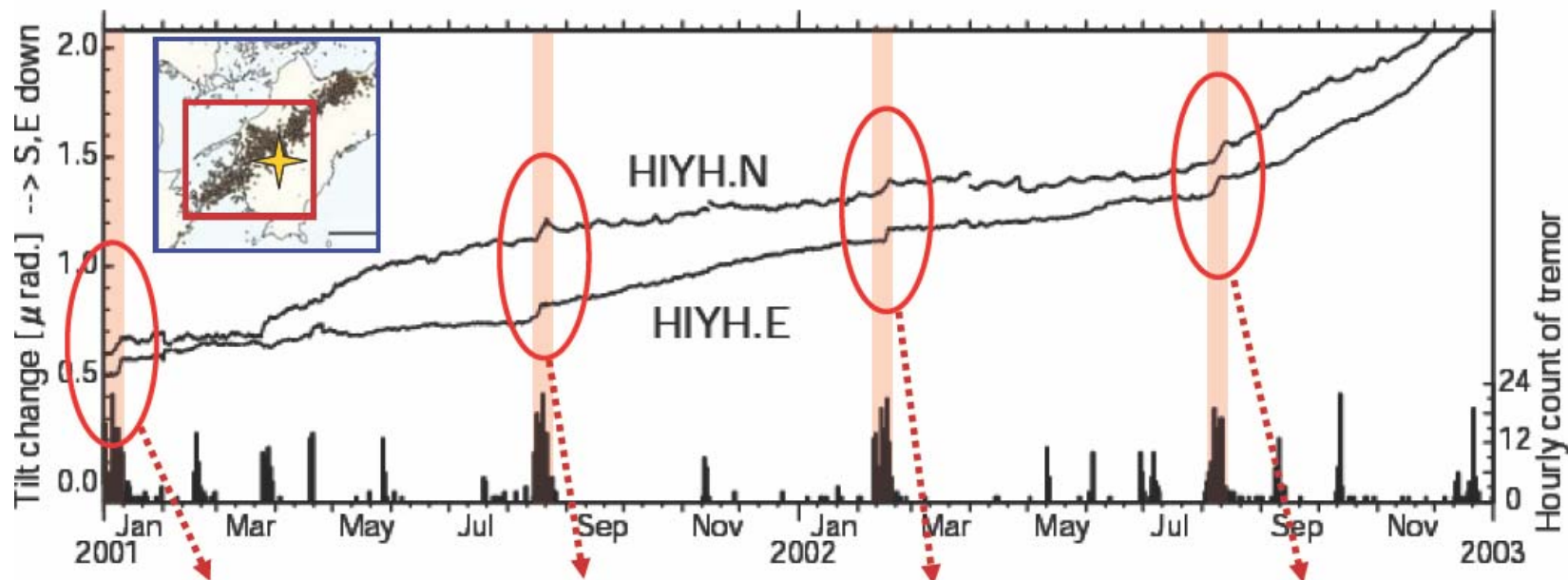
(Obara, Science 2002)

Repeating large (M8) earthquakes

year Nankai Tonankai

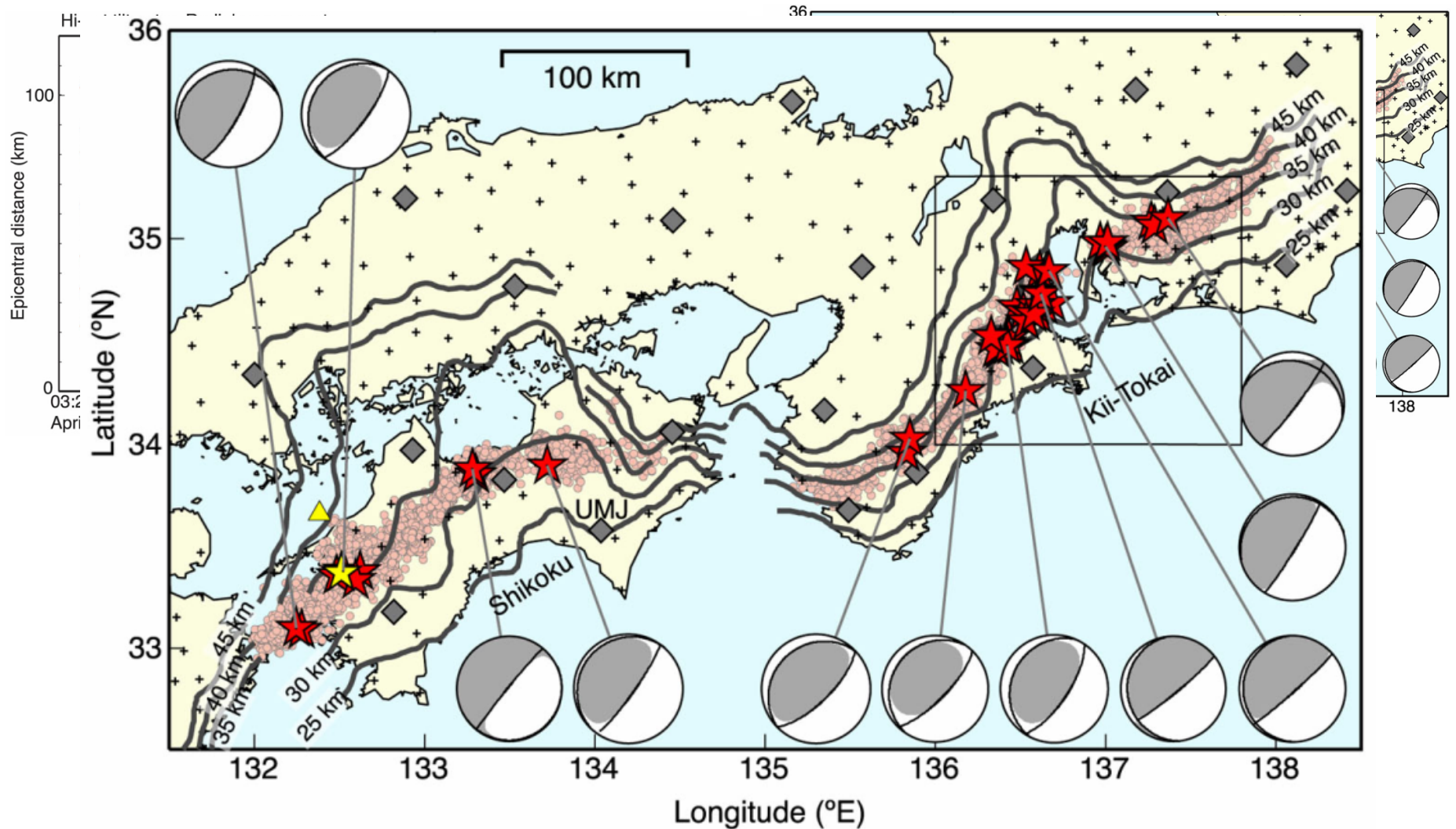


Slow Slip Events and Tremor



(Obara, 2006)

Very Low Frequency EQ (Ito et al., Science, 2007)



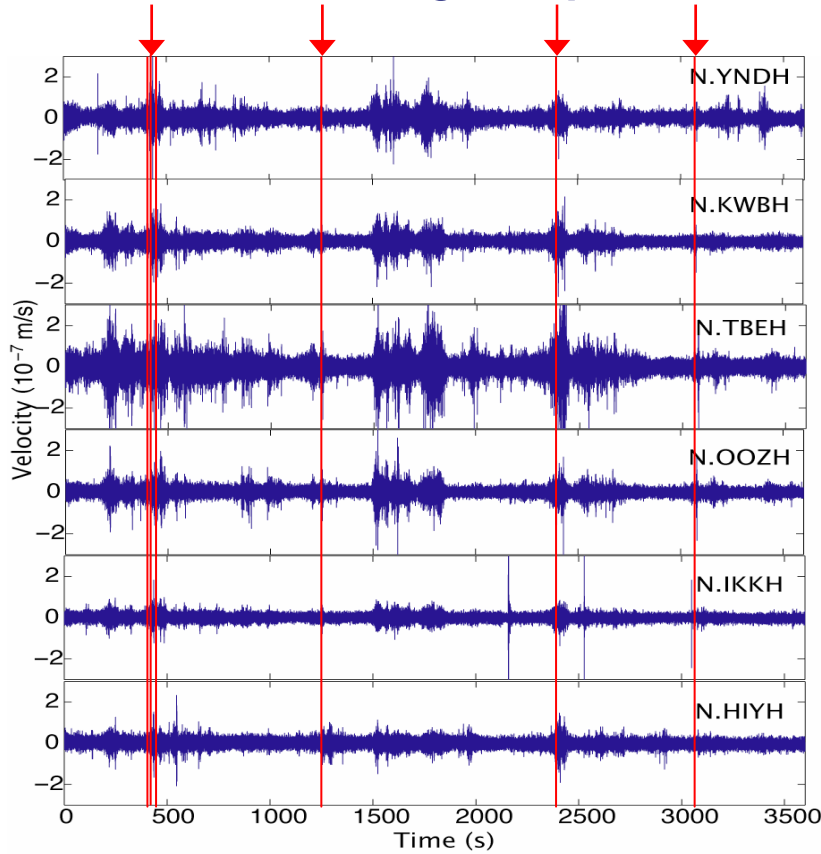
Mechanisms consistent with plate motion

Episodic low frequency tremor and slow slip in western Japan

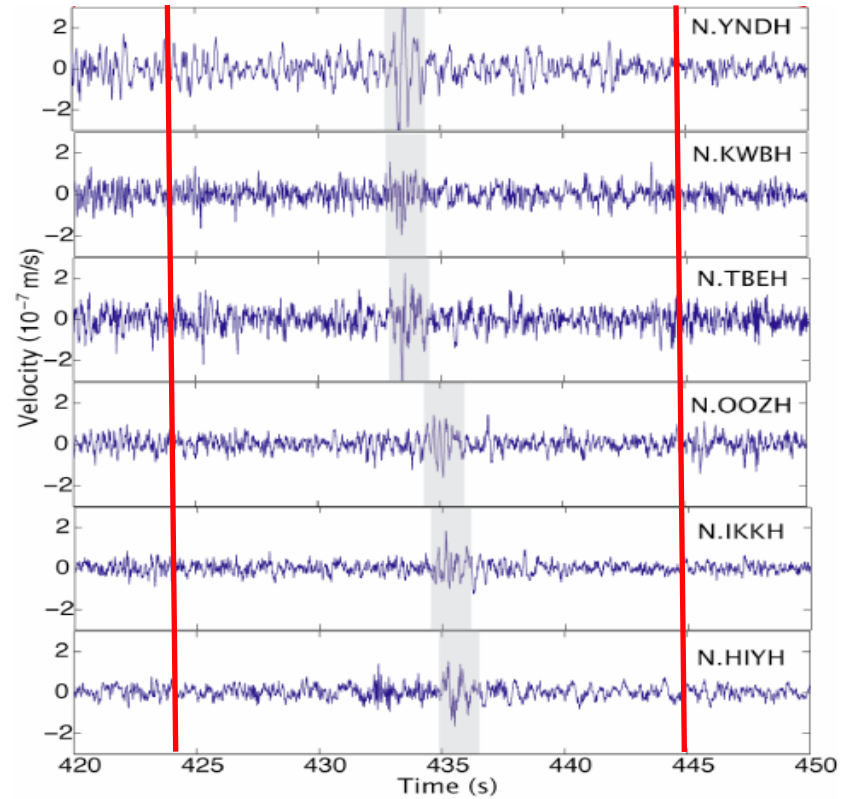
- ◆ Along Nankai trough (Tokai, Kii, Shikoku)
- ◆ Depth 30-35km of subducting plate
Edge of megathrust earthquake sources
- ◆ Recurrence 3-6 month
- ◆ Tremor
 - Amplitude < 1 micron/s, frequency 2-8 Hz
- ◆ Very low frequency earthquake (VLF)
- ◆ Slow slip events (SSE)

Low frequency earthquakes (LFE)

Detected by Japan Meteorological Agency



1 hour



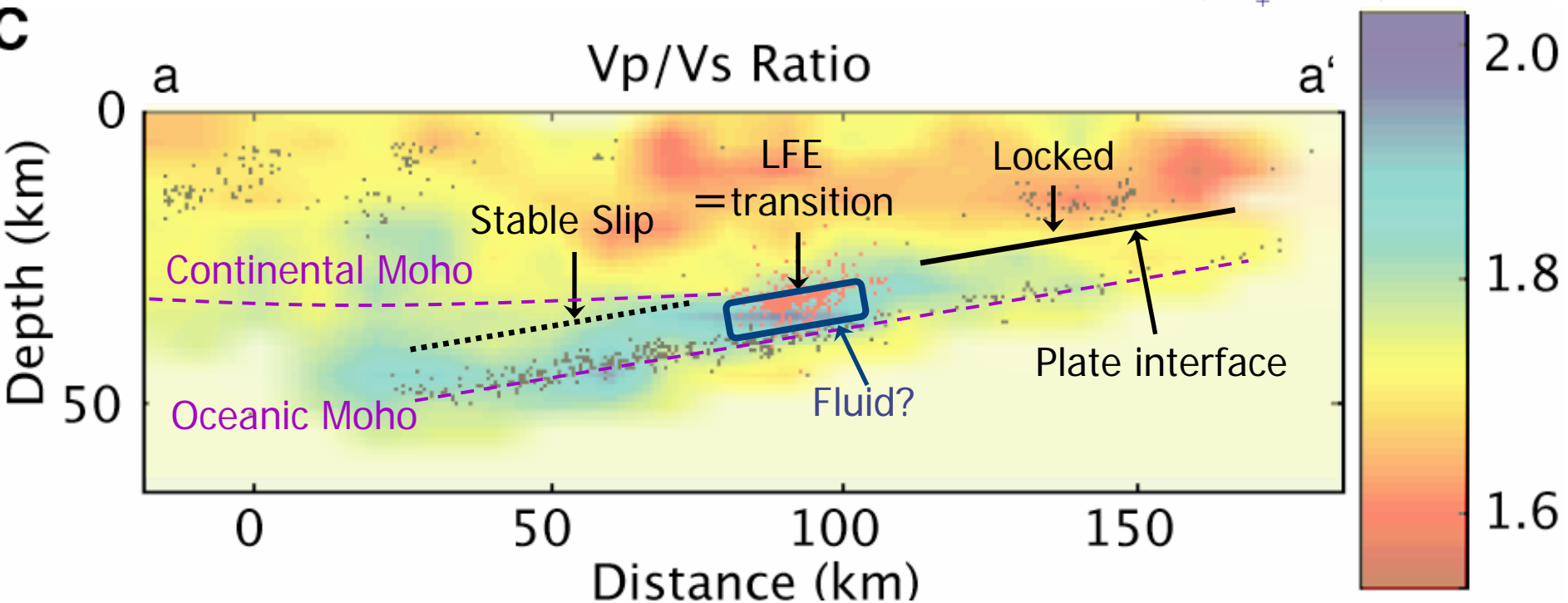
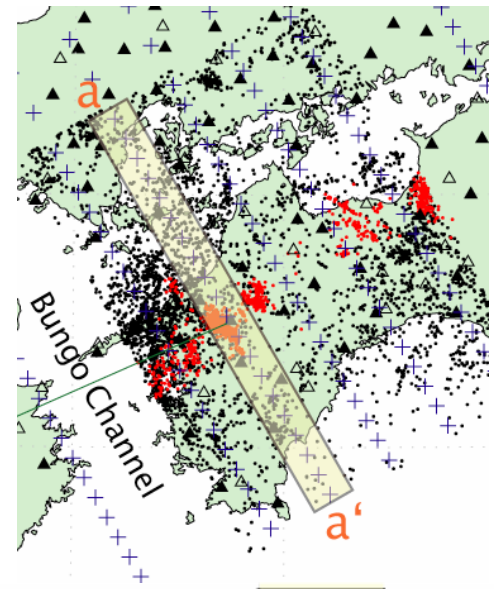
30 sec

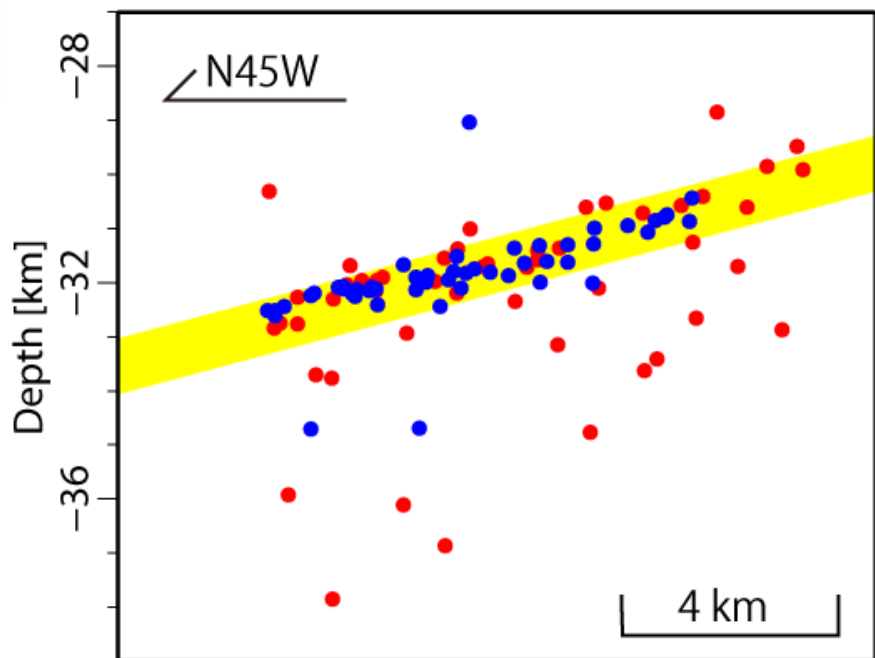
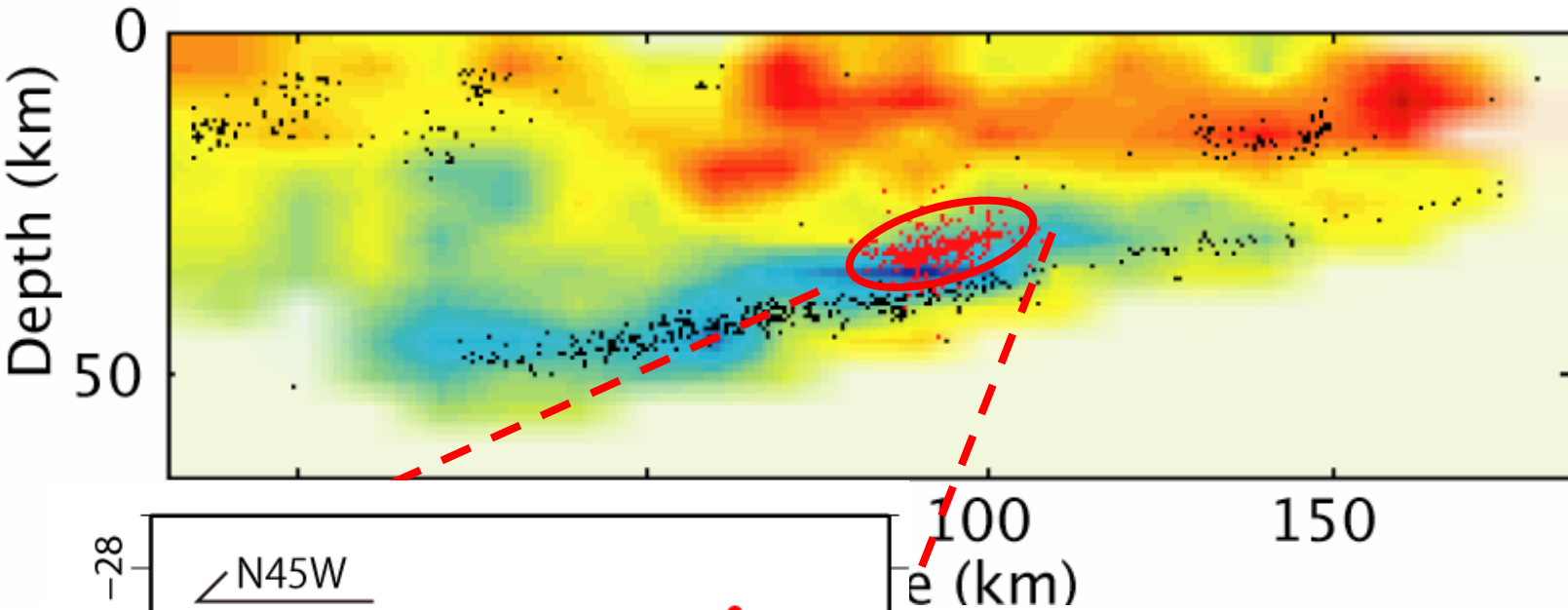
(Shelly et al., Nature, 2006)

Location of LFEs

by tomoDD (Zhang and Thurber, 2003)
(Shelly et al., Nature, 2006)

LFE = Slip on the plate interfaces



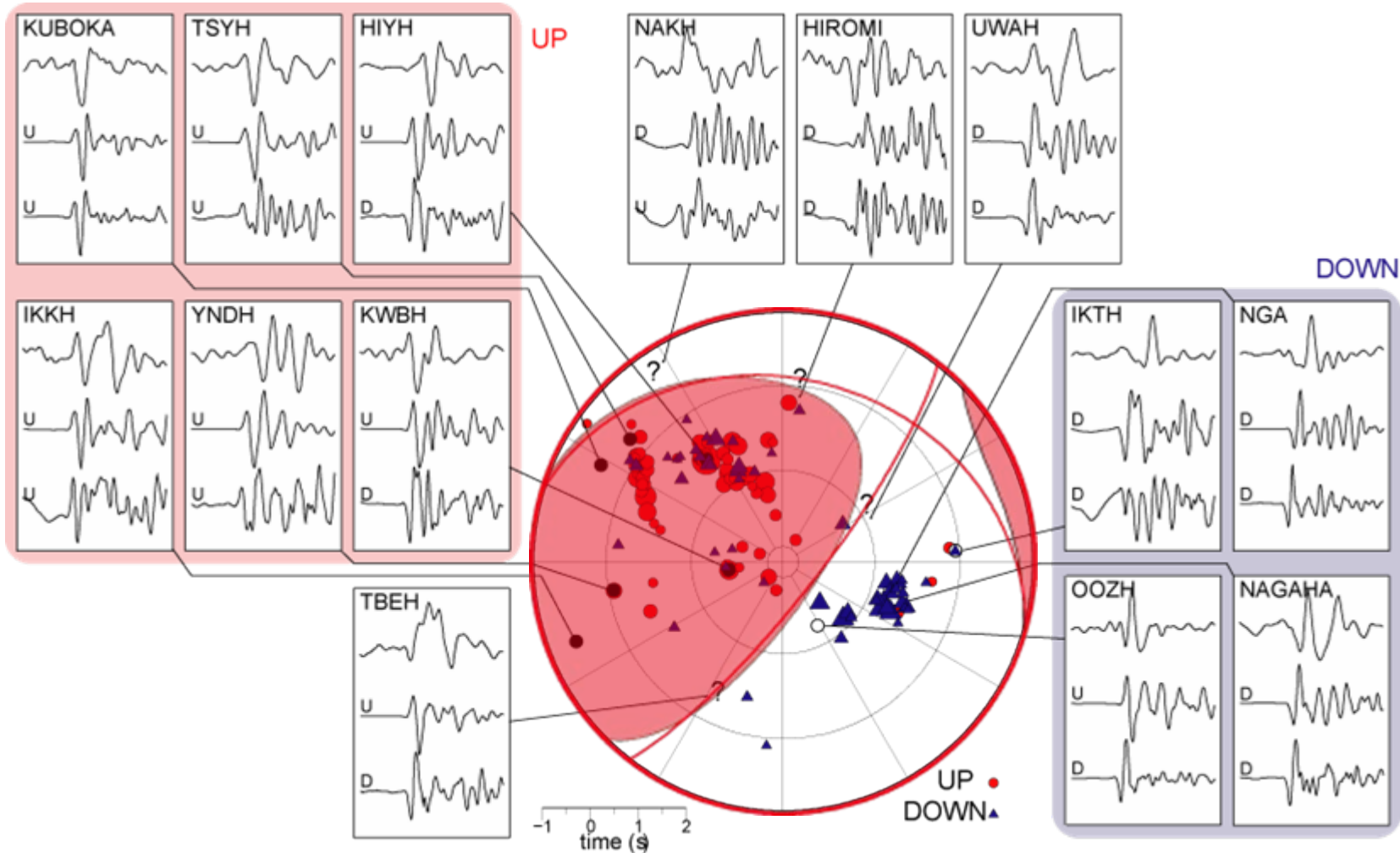


- Shelly et al. (2006)
- Relocated by NCC relocation (Ohta and Ide, 2008)

Within thin (<1km) zone

P wave first motions

Ide et al. (GRL, 2007)



S wave MT inversion

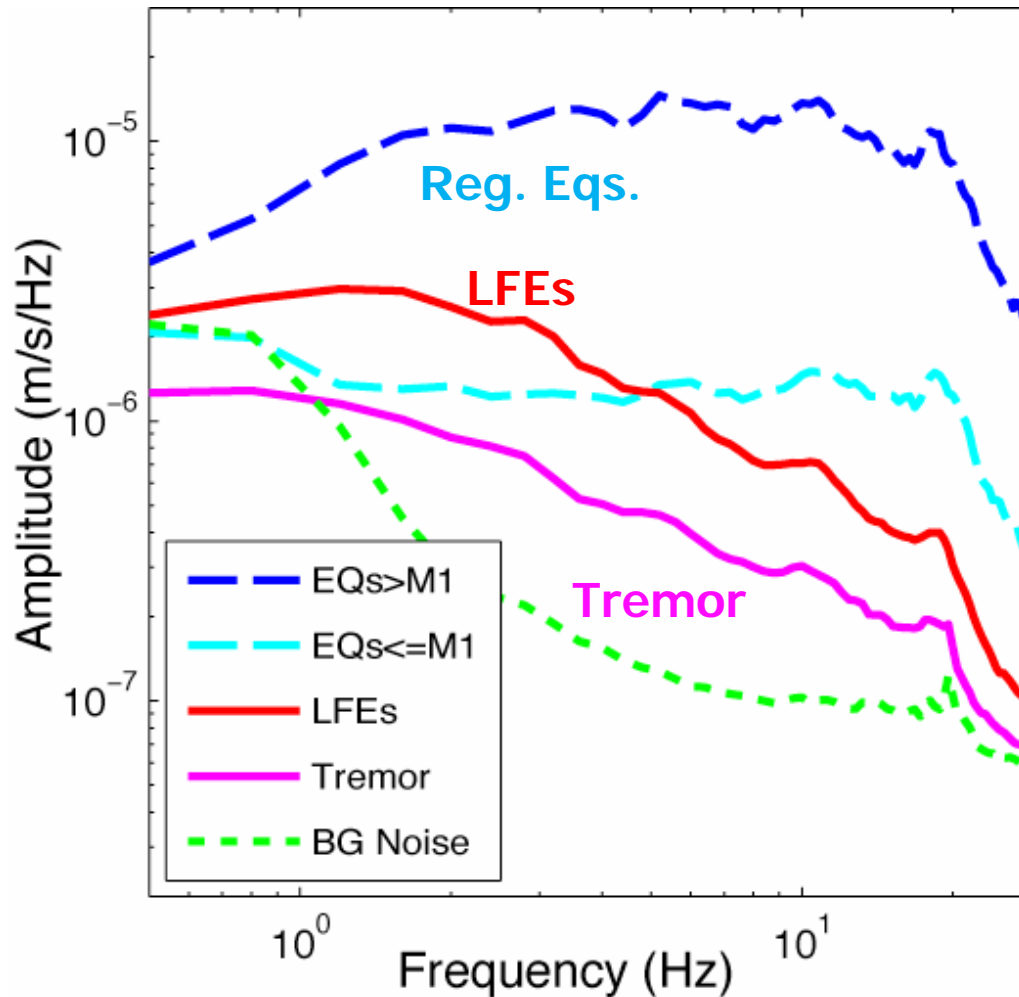
What are LFEs?

- ◆ Location: Plate interface (Shelly et al. 2006)
 - Between stable and unstable region
 - ◆ Mantle-Oceanic Plate interface?
(Hirose et al., 2008; Matsubara et al., 2008)
 - On high V_p/V_s region
 - Very thin zone? (Ohta and Ide, in preparation)
- ◆ Mechanism: Low angle thrust (Ide et al. 2007)
 - Independent evidences from P and S waves

LFEs are slip on the plate interfaces

Spectra of LFEs and Tremor

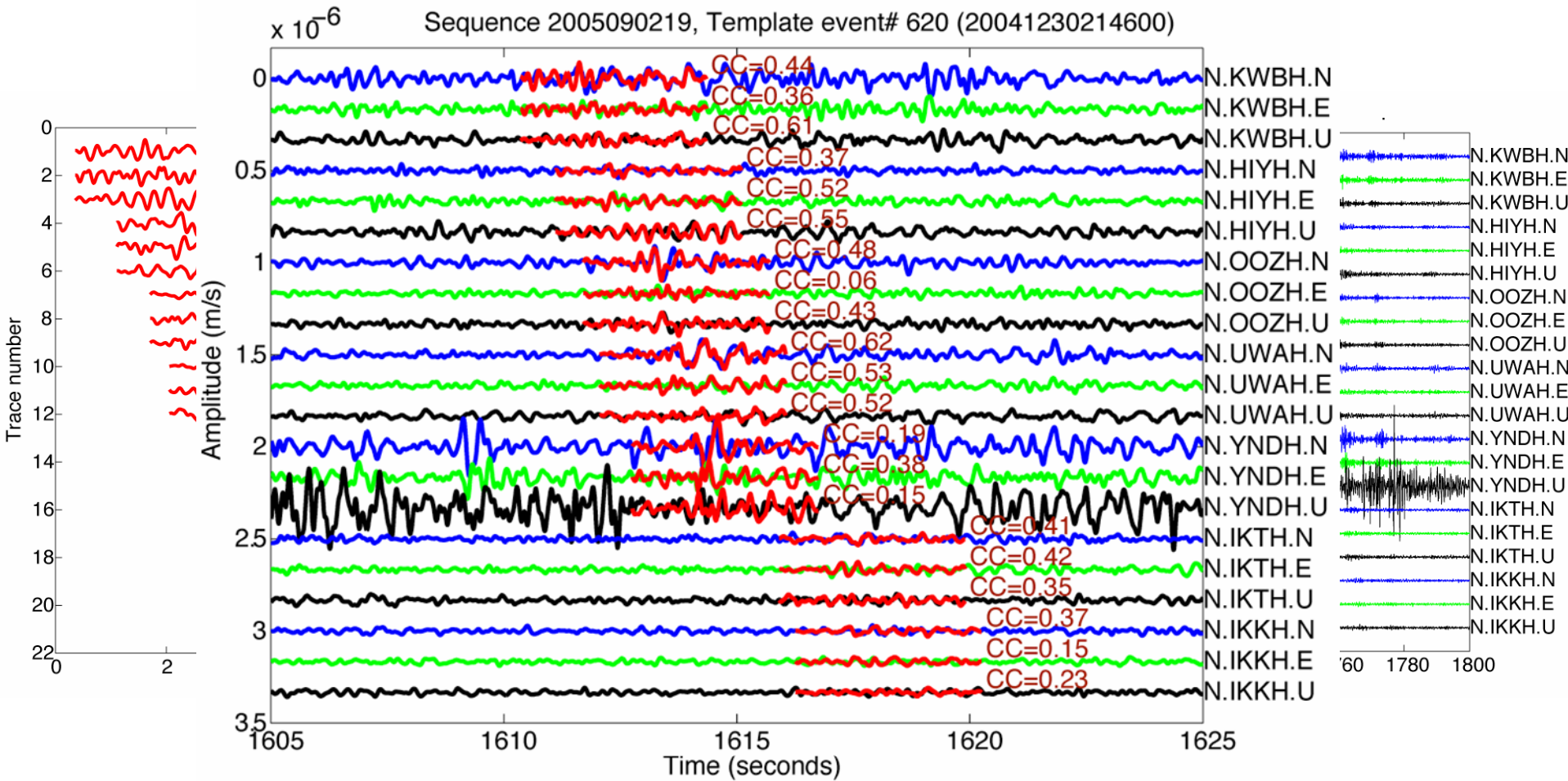
(Shelly et al., Nature, 2007)



Stacked spectra using many stations and events.

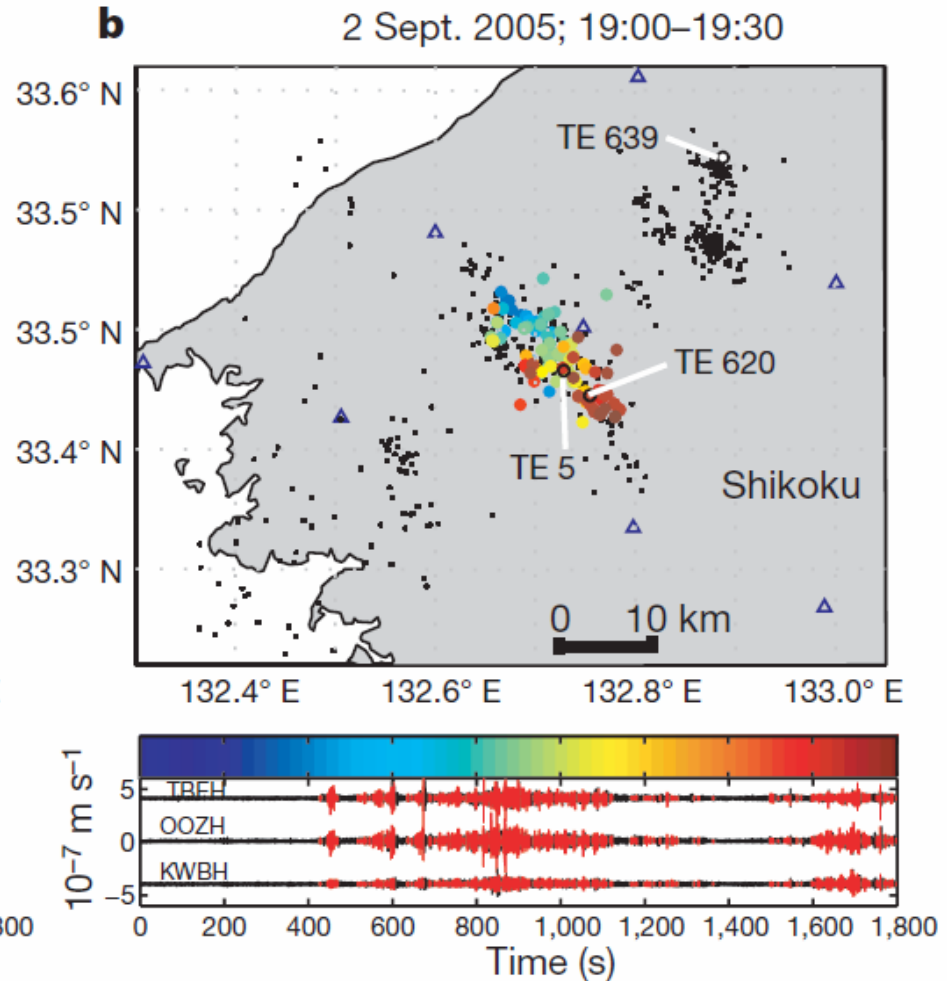
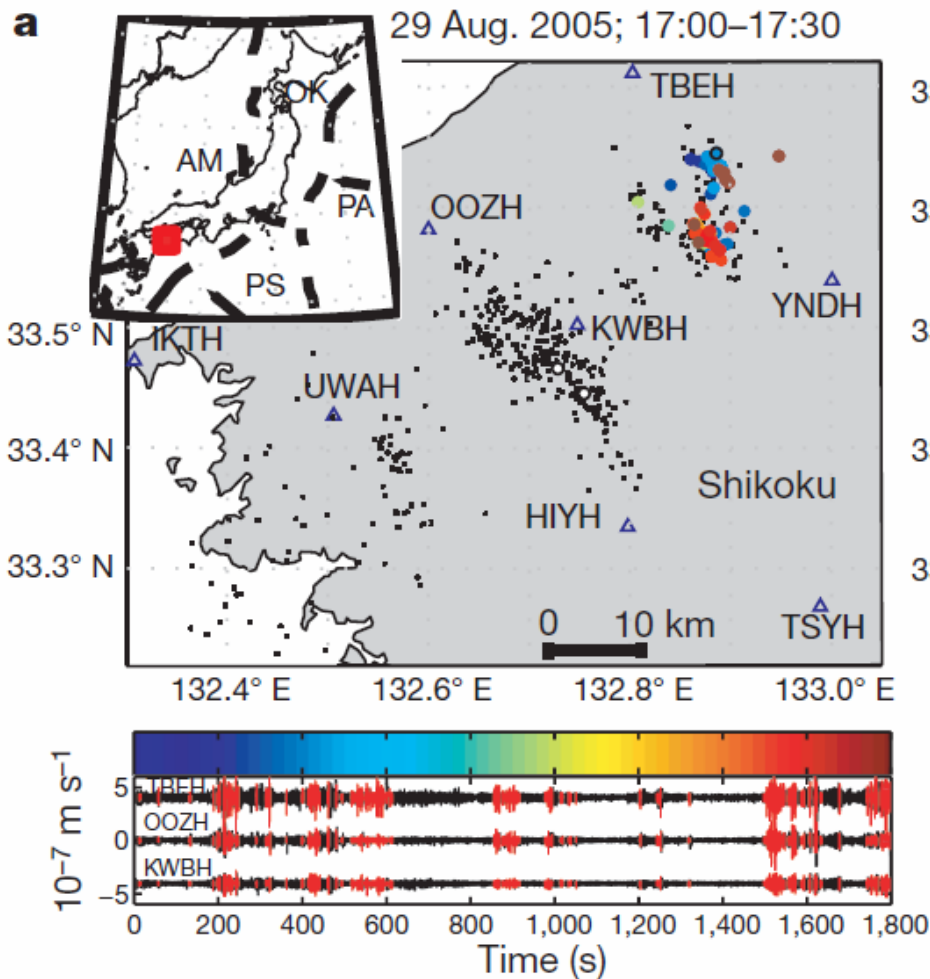
Waves of LFEs = Waves of Tremor

(Shelly et al., Nature, 2007)



Adaptive Filter Analysis

Find a portion of tremor waves that matches to LFE waveforms
677 LFEs -> template events



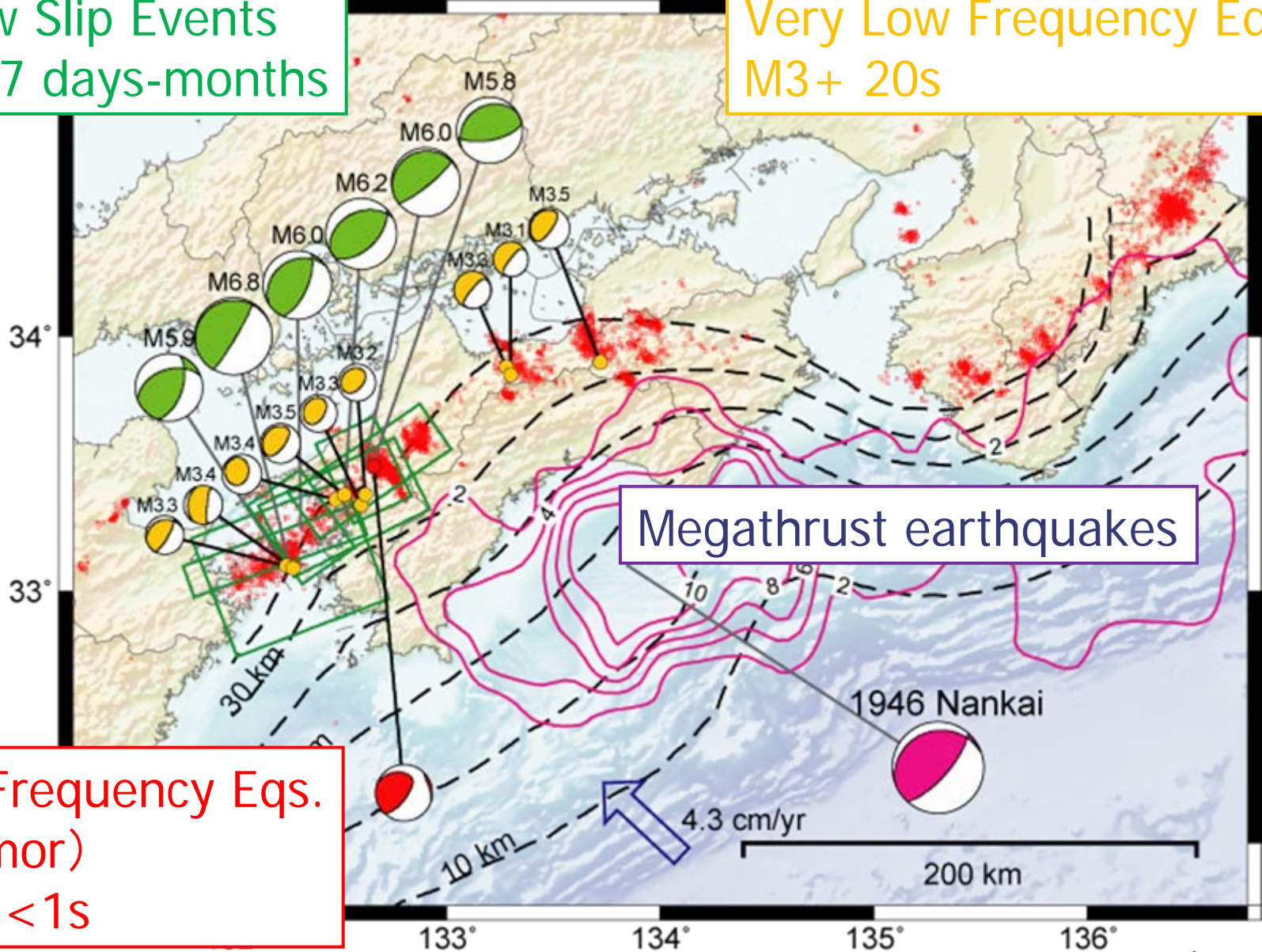
What is low frequency tremor?

Swarm activity of LFEs
= intermittent slip on plate interface

Seismically, no difference has been found
between tremor and LFEs

Slow Slip Events
M6-7 days-months

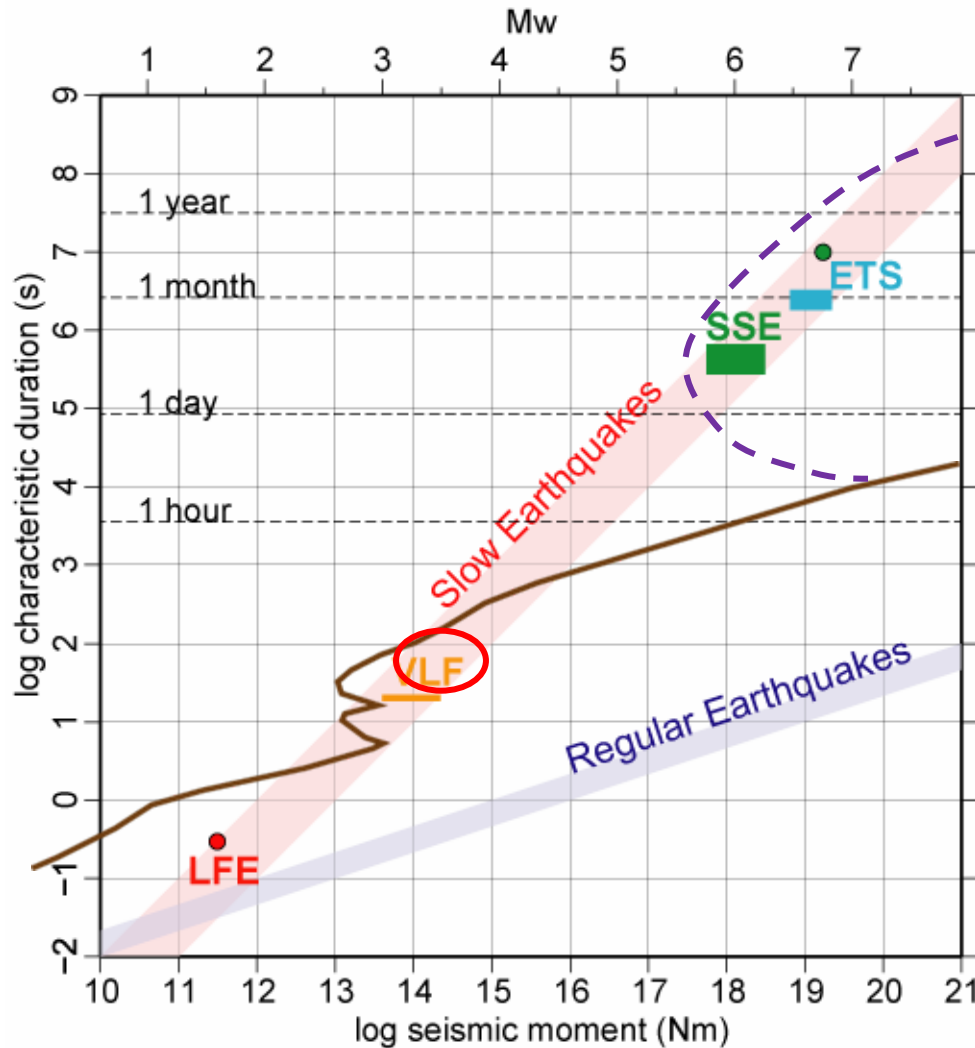
Very Low Frequency Eqs.
M3+ 20s



Low Frequency Eqs.
(Tremor)
M1.5 < 1s

Megathrust earthquakes

Relation between size and time

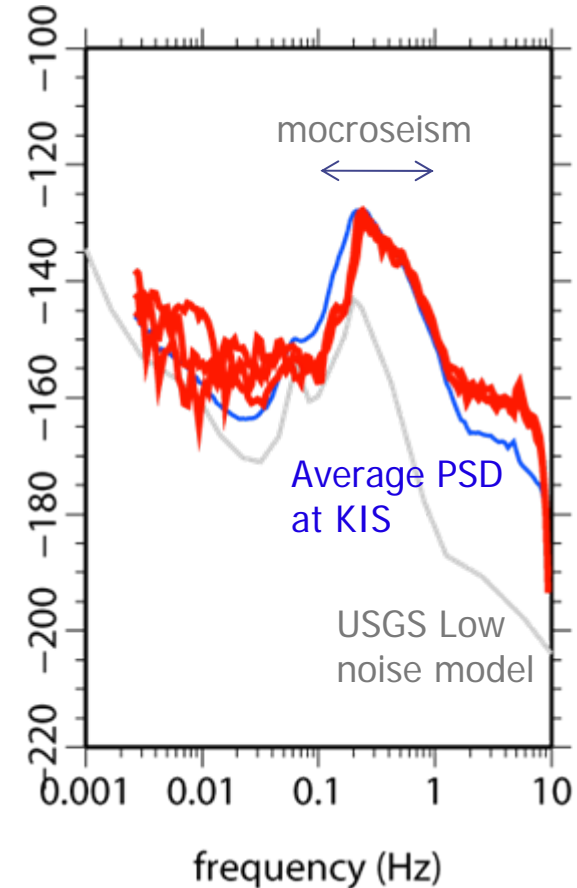
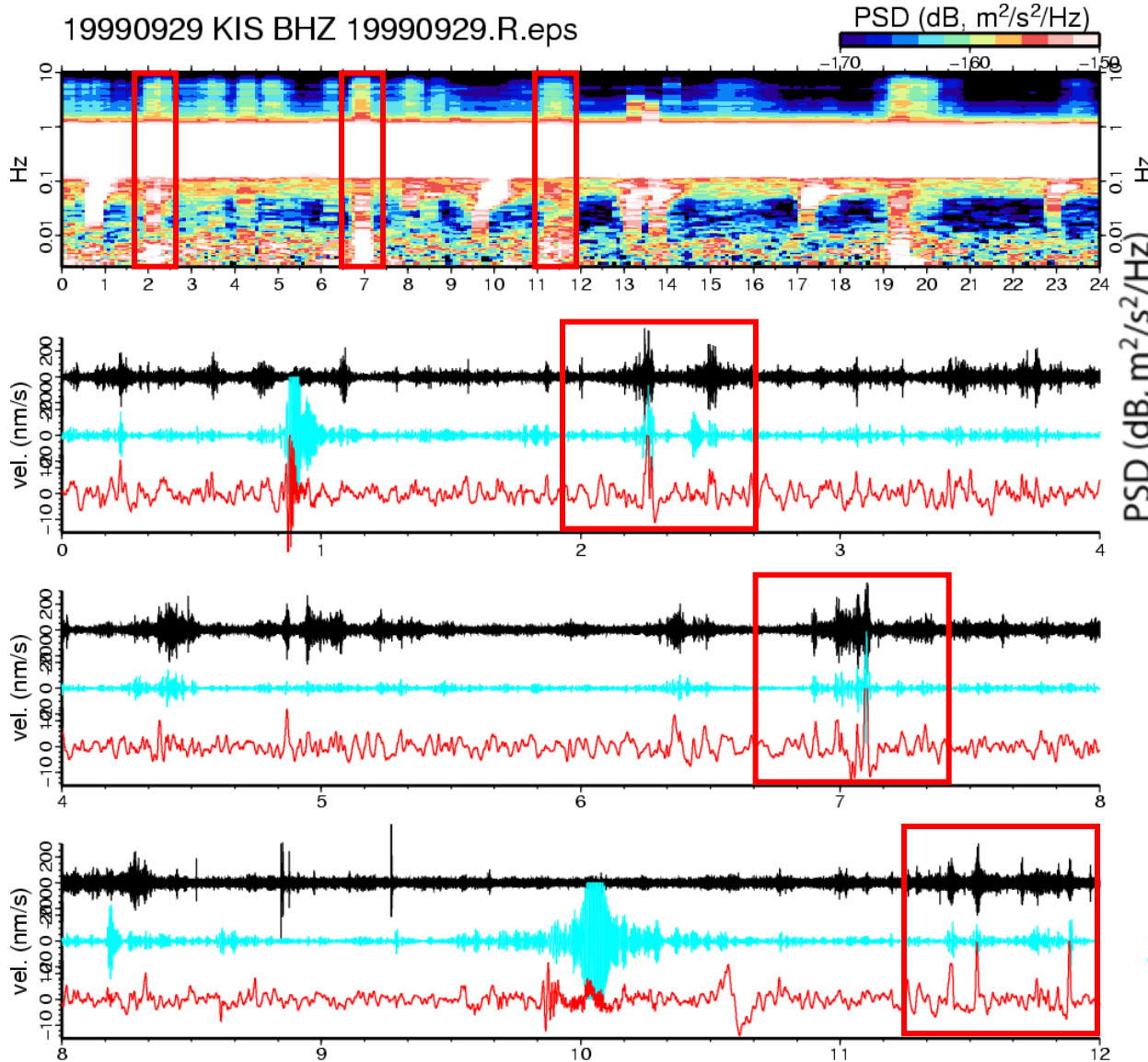


Geodetic Limit???

USGS NLNM
Seismological Limit

Example of 100 s Signals

Ide et al.
(GRL, 2008)



2-8 Hz Tremor & LFE Band

20-50 s VLF Band

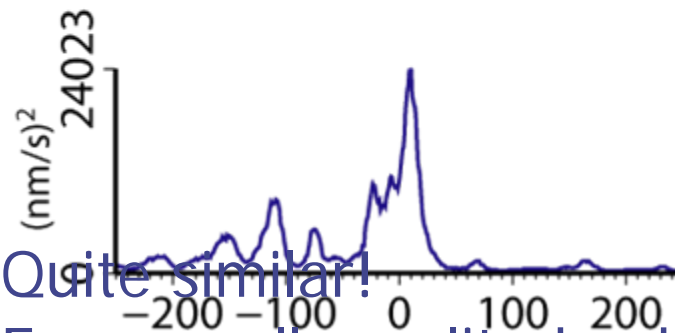
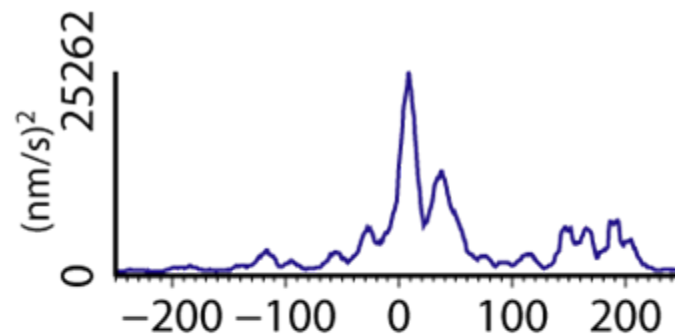
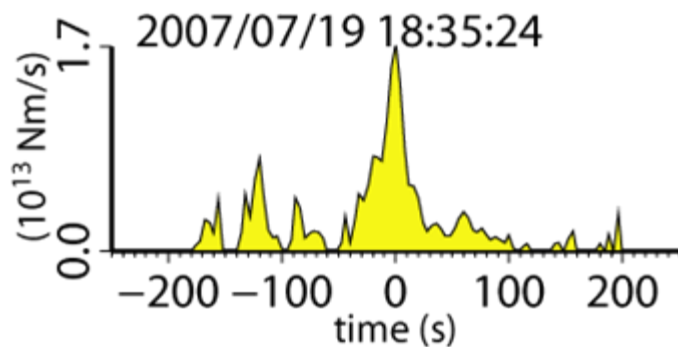
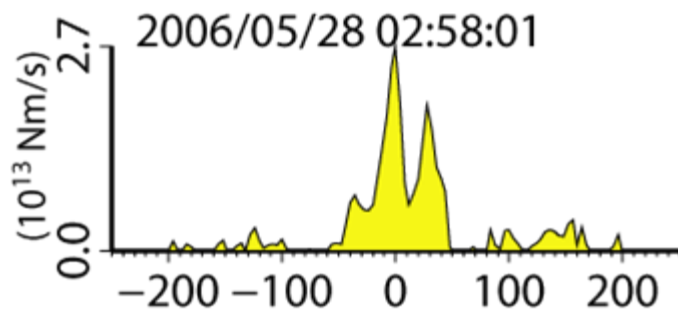
50-300 s

Mo rate and squared velocity

Ide et al. (GRL, 2008)

Moment rate function
 0.005-0.05 Hz (20-200 s)
 Determined by Inversion

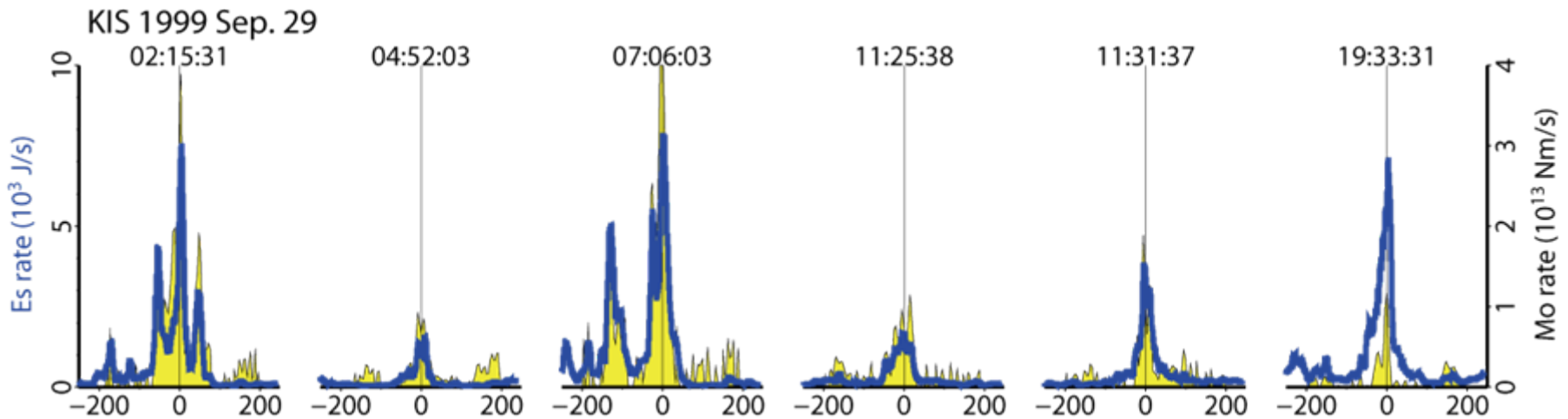
Squared Velocity
 Bandpassed, 2-8 Hz (~ tremor)
 Smoothed, 10 s



Quite similar!
 Even small amplitude phases

Seismic Energy Radiation in Tremor Frequency Band (2-8 Hz)

$$\begin{aligned} \dot{E}_s^{2-8} &= 4\pi\rho\beta r^2 \overline{\left(\dot{u}^{2-8}(t)\right)^2} \\ &= 0.23 \cdot \overline{\left(\dot{u}^{2-8}(t)\right)^2} \quad (\text{nm/s})^2 \end{aligned}$$



Constant

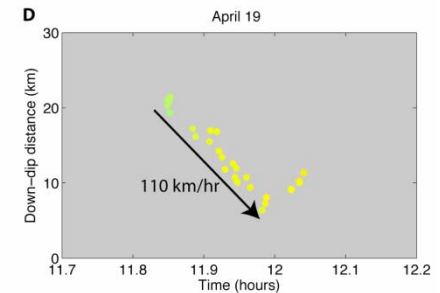
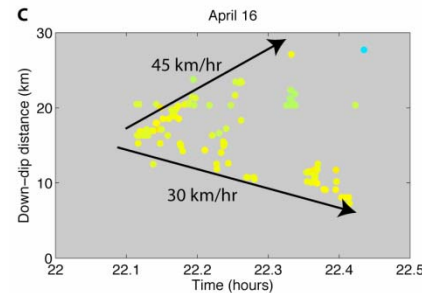
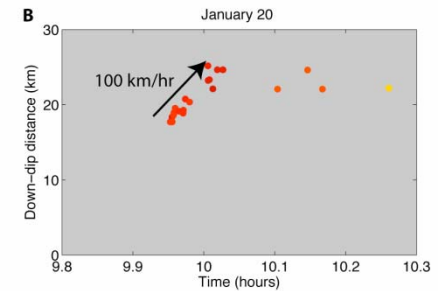
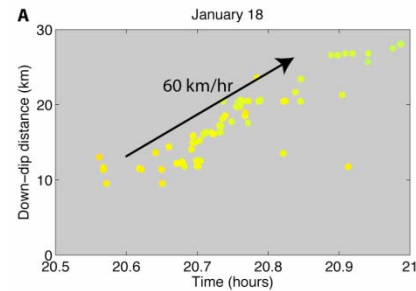
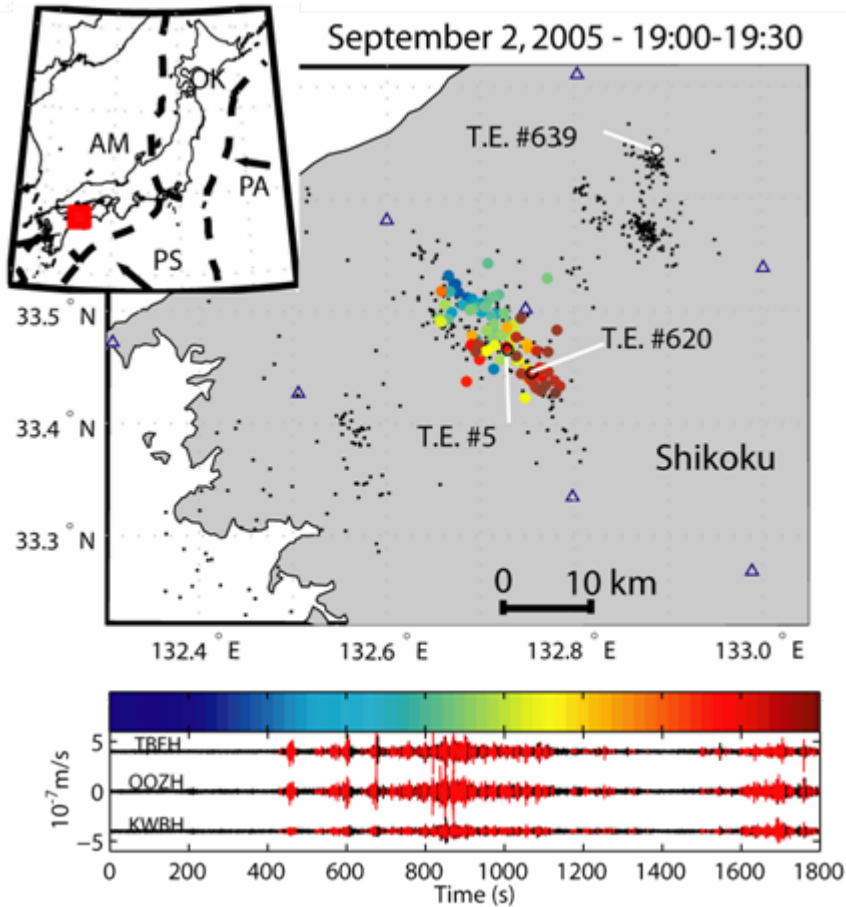
Es/Mo (Scaled Energy) $10^{-10} \sim 10^{-9}$
 (Apparent Stress 10 Pa)

Slow earthquakes and scaling

- ◆ Swarm activity of LFE = Tremor
Long tremor activity \rightarrow VLF \rightarrow SSE
Different names from different observation windows
- ◆ Constant seismic moment rate
 $M_0/T \sim 10^{12.5} \text{ Nm/s}$
from M1 to M7
- ◆ Constant scaled energy
 $E_s/M_0 \sim 10^{-9.5}$
from M3 to M4, to M6?

Migration of Slip (short range)

10 km – 10 min (10 m/s)

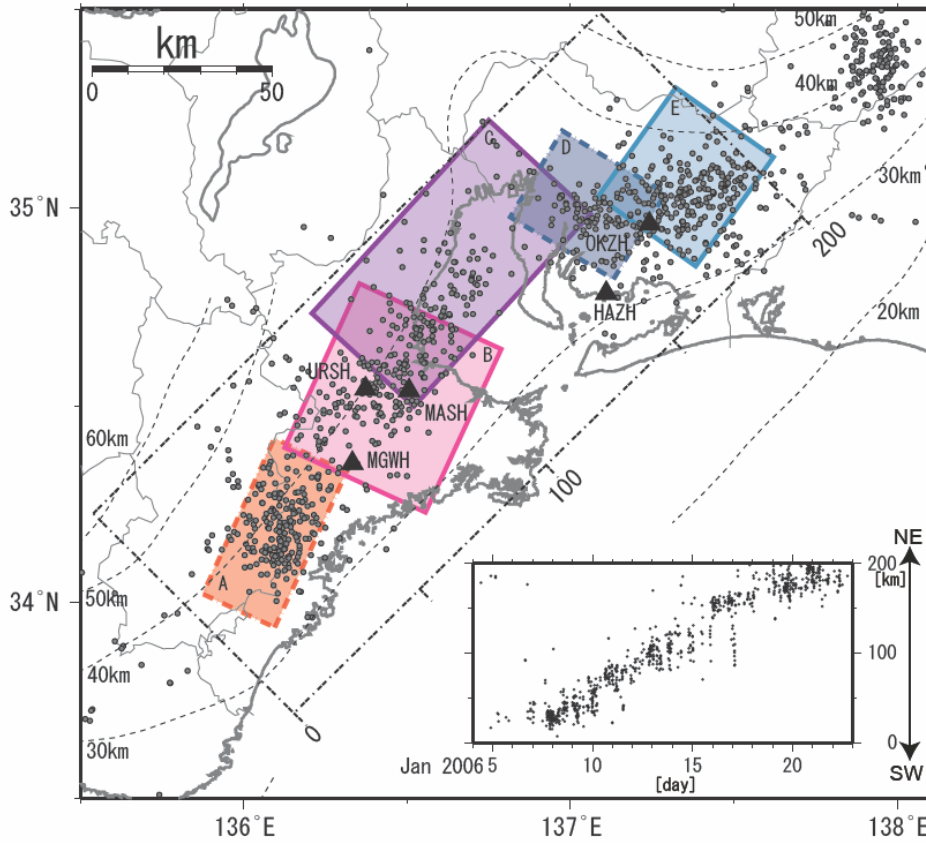


10 km/10 min
(~10 m/s)

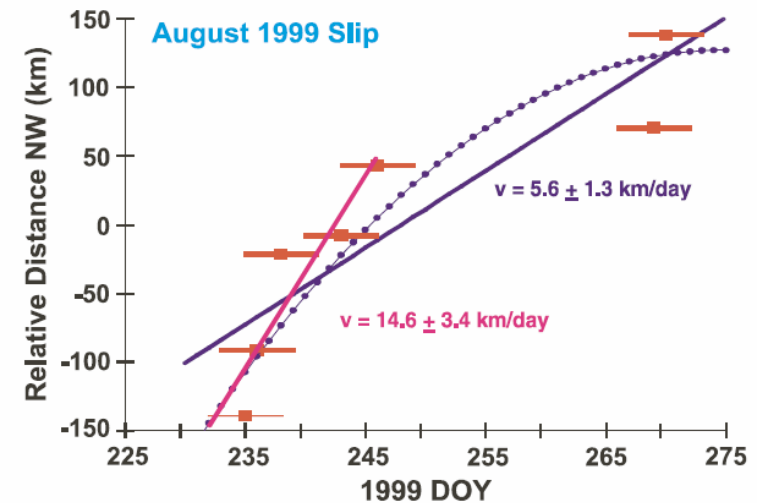
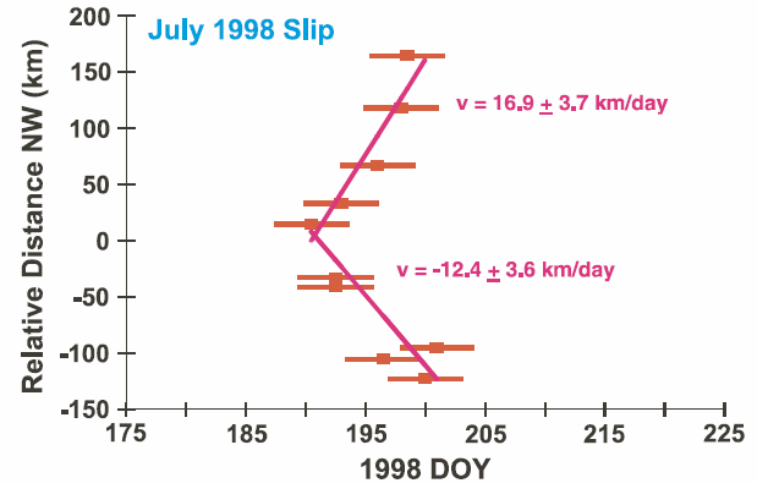
Shelly et al. (Nature, 2007 & G-cubed, 2007)

Migration of Slip (long range)

100 km — 10 day (0.1 m/s)

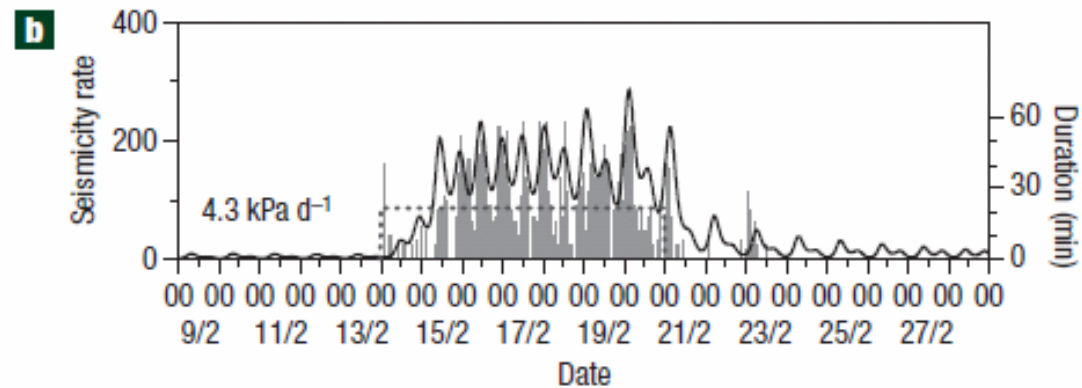
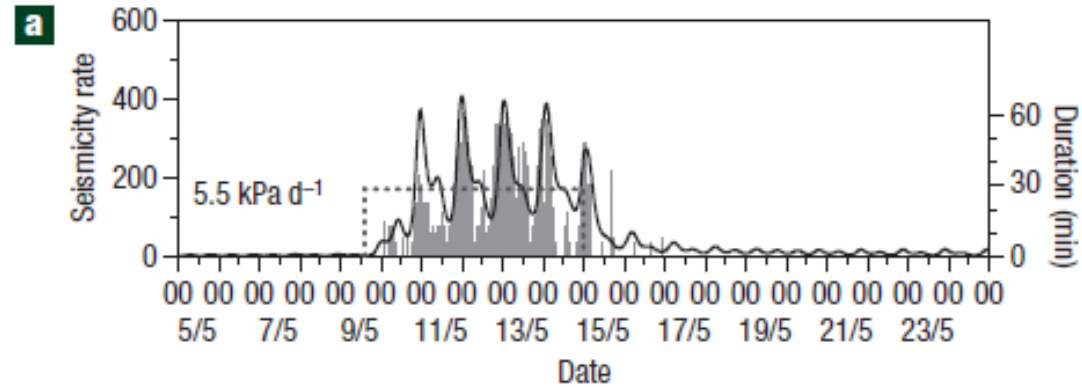
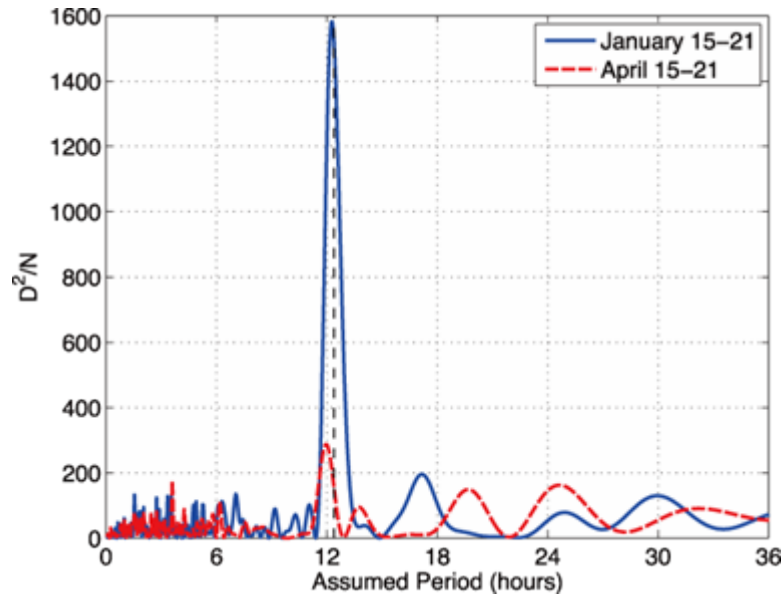


Tokai (NIED, 2006)



Cascade (Dragert et al., 2004)

Triggering



Triggering

Tidal stress

Shelly et al. (2007), Nakata et al. (2008)

Surface waves of large Eqs

Miyazawa and Mori (2005)

What should be explained

◆ Scaling laws

- Constant Mo rate, $10^{12.5}$ Nm/s
- (Probably) constant Es/Mo, $10^{-9.5}$

◆ Recurrence time (3-6 months)

◆ Migration

- Short range (10 km at 10 min, ~ 10 m/s)
- Long range (100 km at 10 day, 0.1 m/s)

◆ Triggering

◆ Variation of world similar phenomena