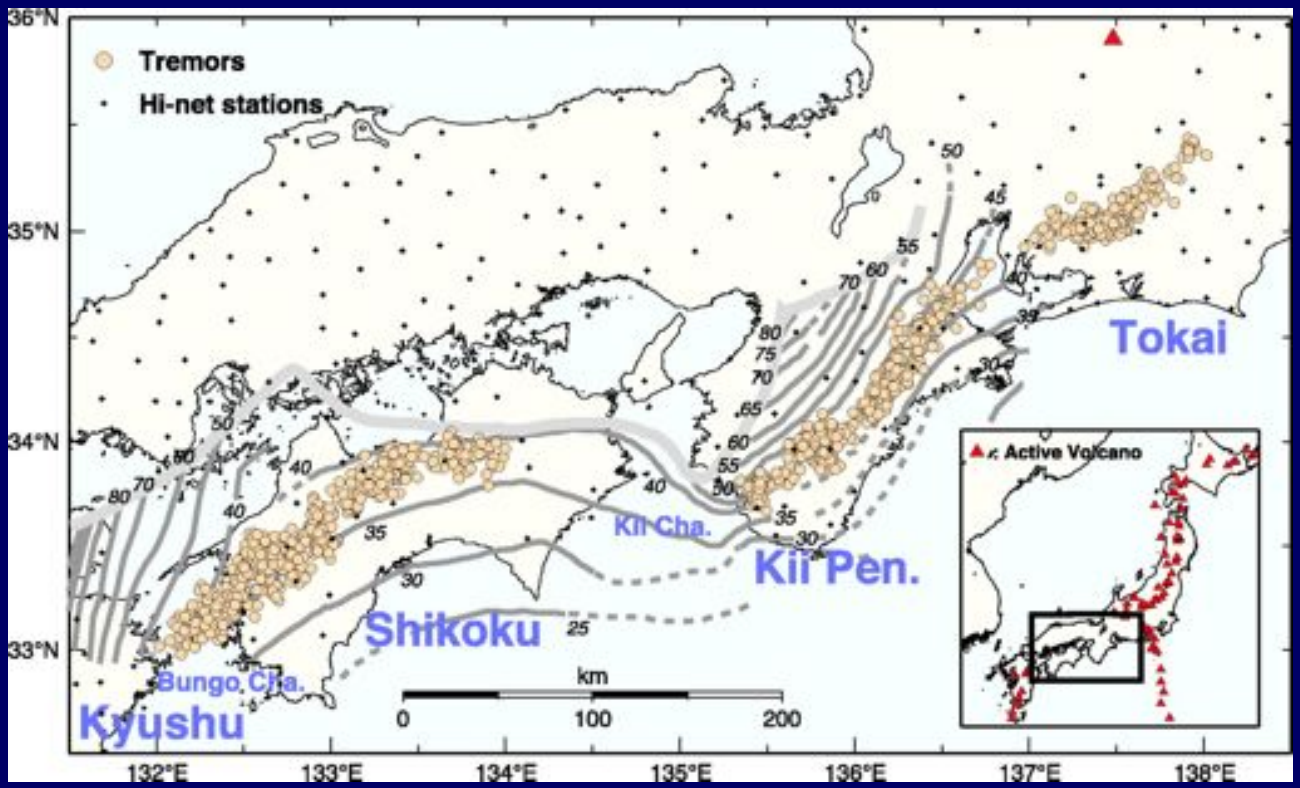
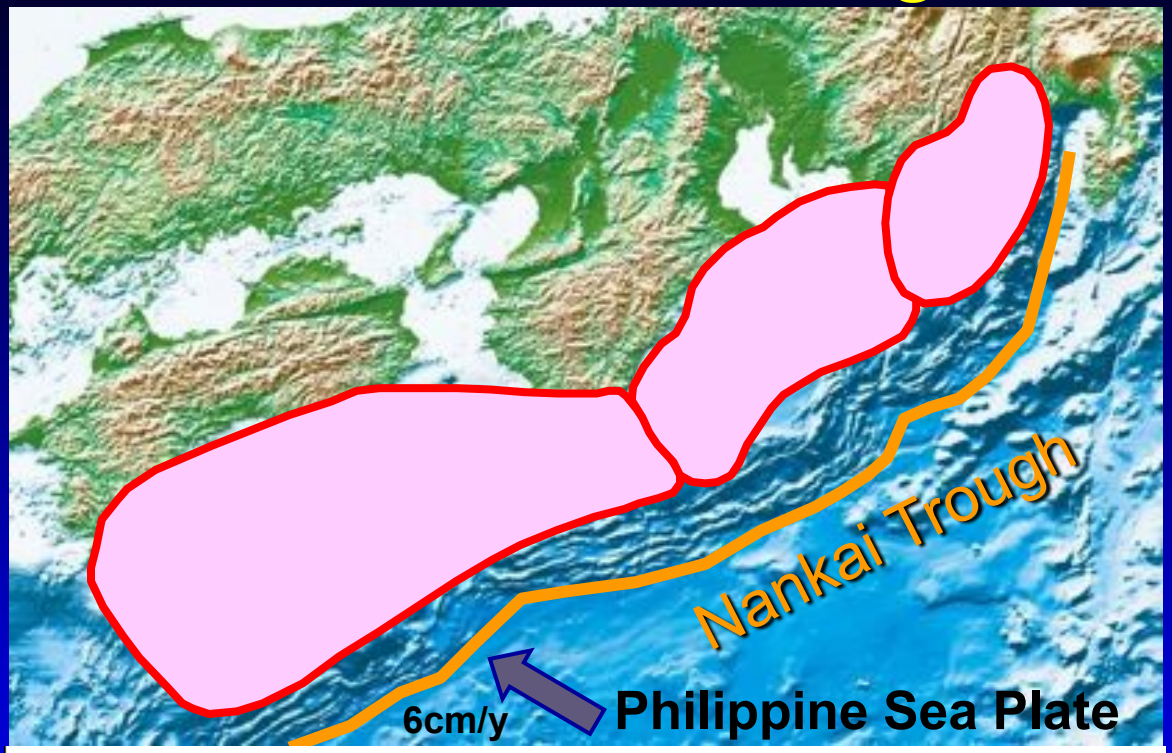
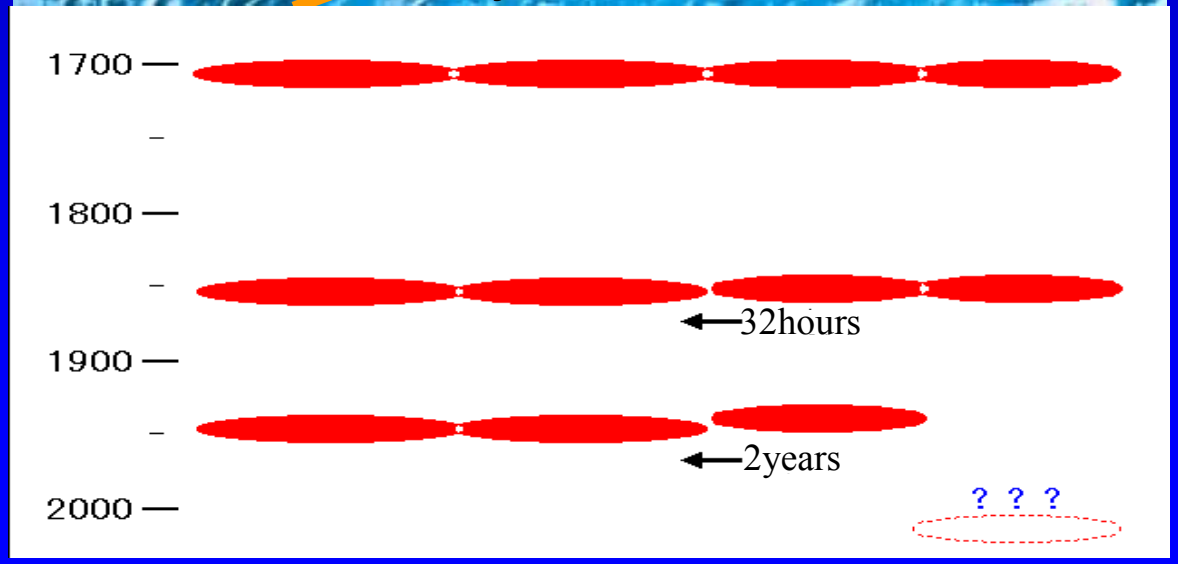
Depth-dependent slip regime on the plate interface revealed from slow earthquake activities in the Nankai subduction zone



Kazushige Obara, ERI, Univ. Tokyo

Recurrence of megathrust earthquake

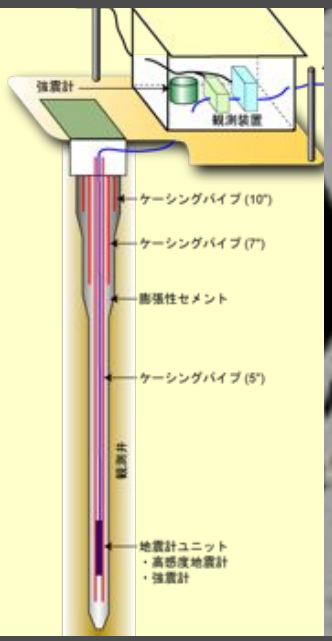




year	interval
1361	
	137y
1498	
	107y
1605	
	102y
1707	
	147y
1854	
	90y
1944/46	

NIED Hi-net

National Research Institute for Earth Science and Disaster Prevention : High-sensitivity Seismograph network



*High S/N ratio (Borehole)

*High density (800 stations at spacing of 30km)

Sensors
- Short-period velocity seismometer
- High-sensitivity accelerometer (tiltmeter, long-period seismometer)

Continuous recording system

GSI GEONET

GeoSpatial Information Authority of Japan : GPS Earth Observation NETwork

Slow earthquakes in southwest Japan

Near Nankai Trough

Characteristic time (tc)

100day

1day

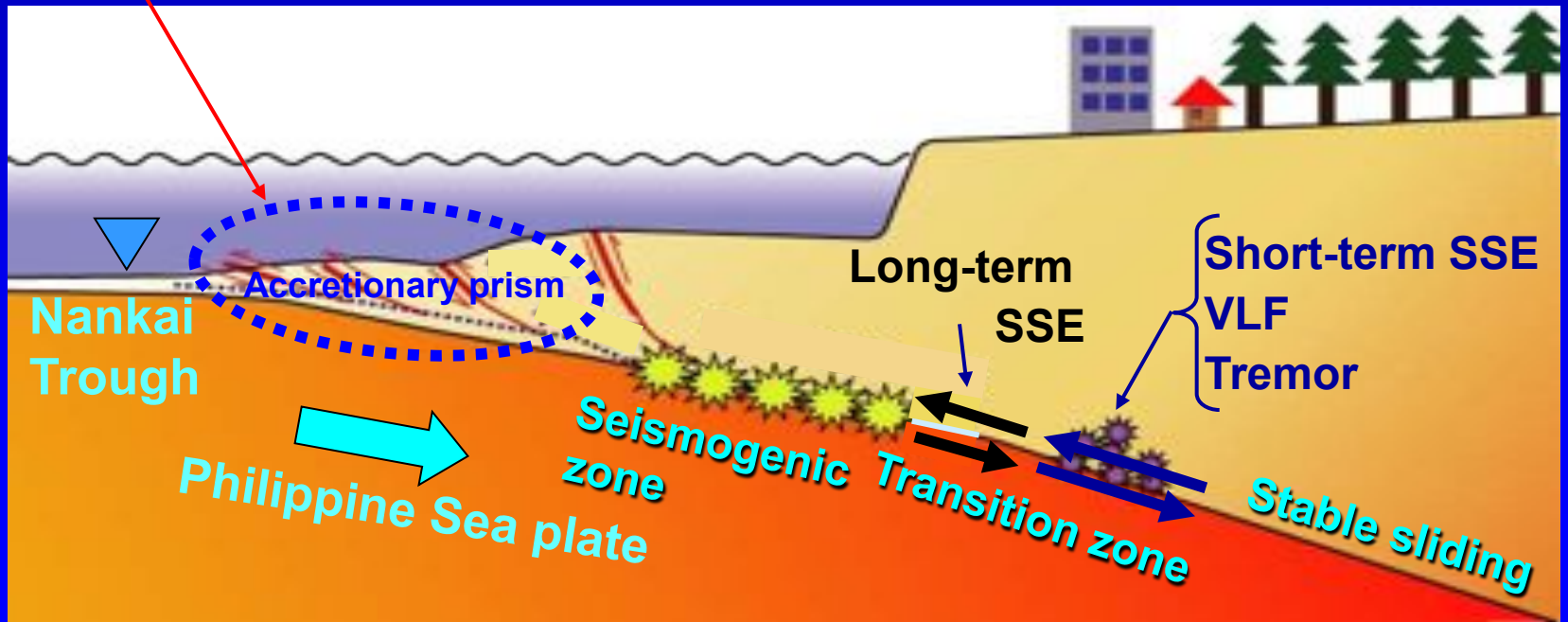
1000sec

10sec

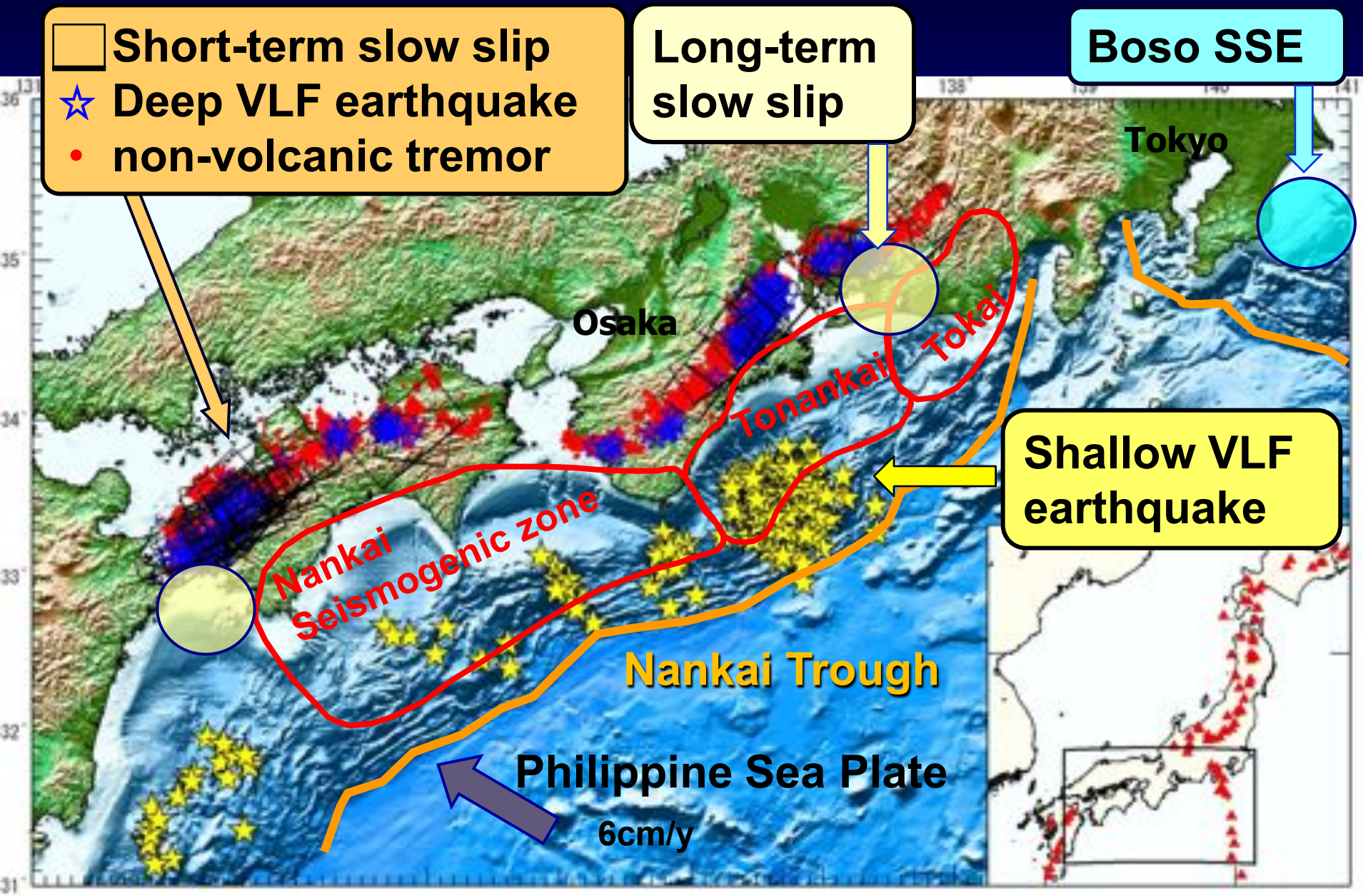
0.1sec

Shallow Very Low Frequency Earthquake (tc:10sec)

Downdip side	Observation
- Long-term slow slip event (tc:0.5~5years)	GPS
- Short-term slow slip event (tc:2~6days)	Tiltmeter/ strainmeter
- Deep Very Low Frequency Earthquake（VLF） (tc:20sec)	LP seismometer
- Deep Low Frequency Tremor (tc:1.5~5Hz)	SP seismometer



Slow earthquakes in southwest Japan



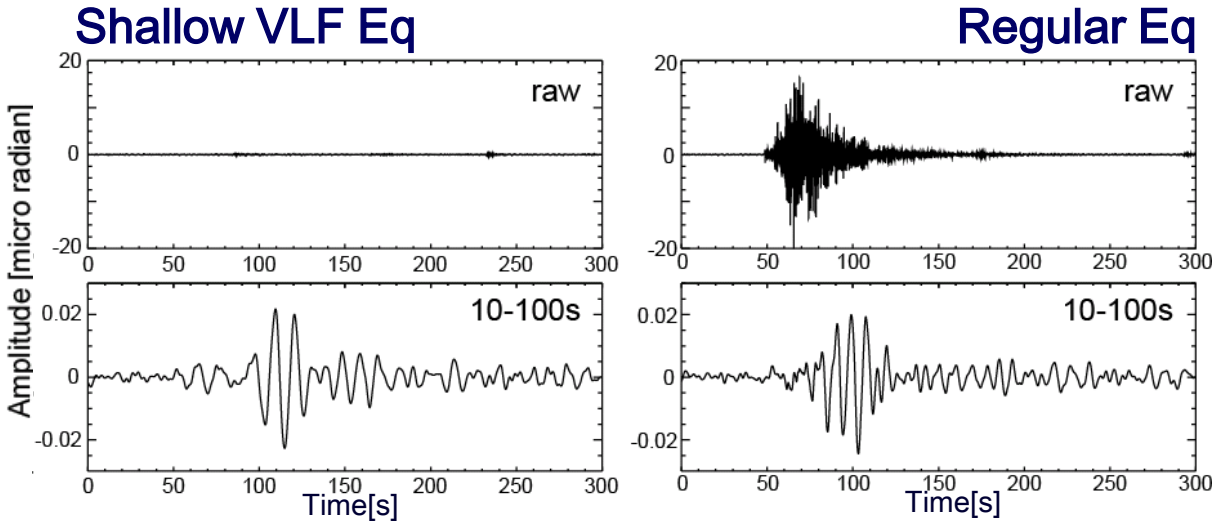
Outline

- Variation of slow earthquakes in SW Japan
  - (Shallow VLF (within accretionary prism))
  - ETS (Tremor and short-term SSE + Deep VLF)
  - Long-term SSE (Tokai and Bungo channel)
  - Long-interval short-duration SSE (Off Boso Peninsula)

- Depth-dependent tremor activity
  - Shallow episodic and deep stable
  - Tremor triggered by updip long-term SSE

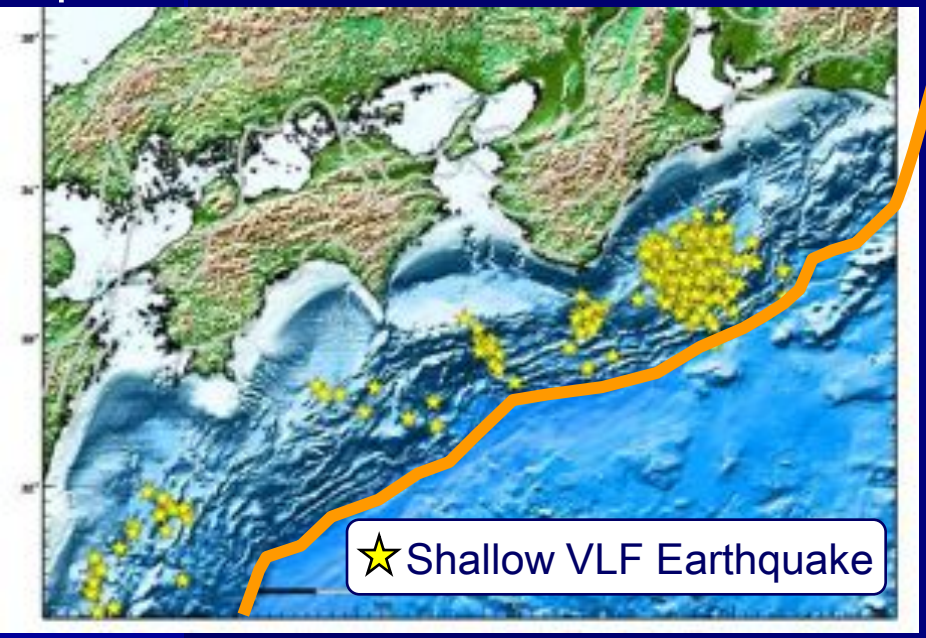
Shallow Very Low Frequency (VLF) Earthquake

Waveform difference

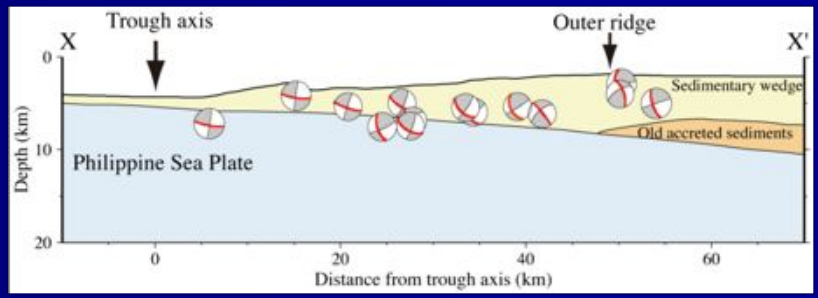


Shallow VLF earthquake	
Mw	around 3.5
Depth	2~10 km
Dominant Frq.	0.1 Hz
Mechanism	Reverse fault
Dip angle	Steeper
Recurrence	unclear

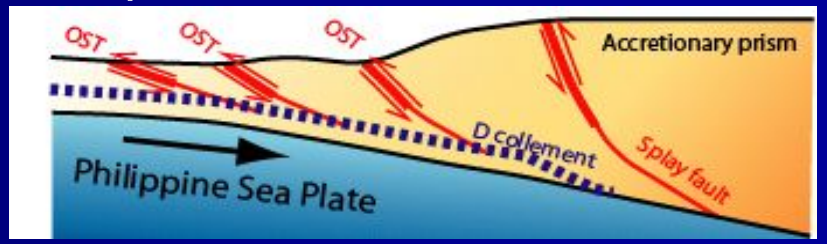
Epicentral distribution



Cross sectional view



Interpretation



Obara and Ito (2005), Ito and Obara (2006)

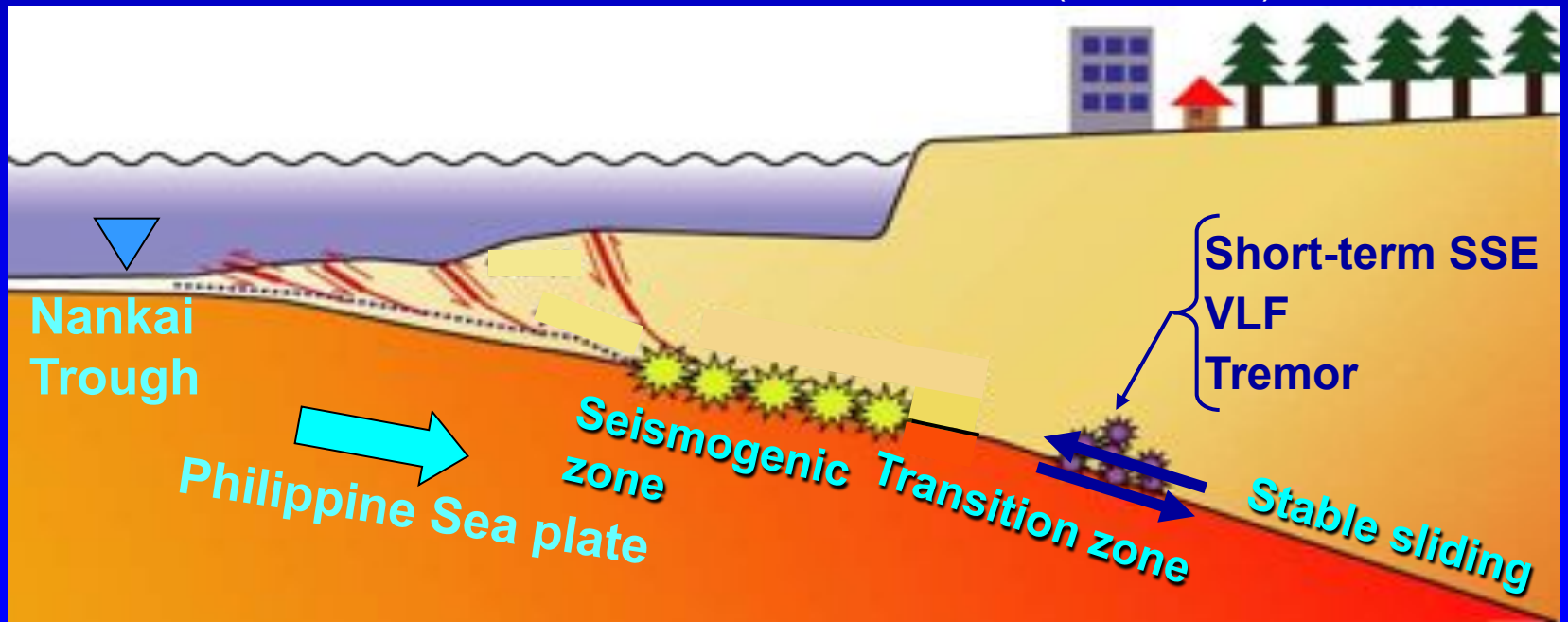
ETS in southwest Japan composed of Tremor (LFE), Short-term SSE, and VLF earthquake

Characteristic time (tc)

100day
1day
1000sec
10sec
0.1sec

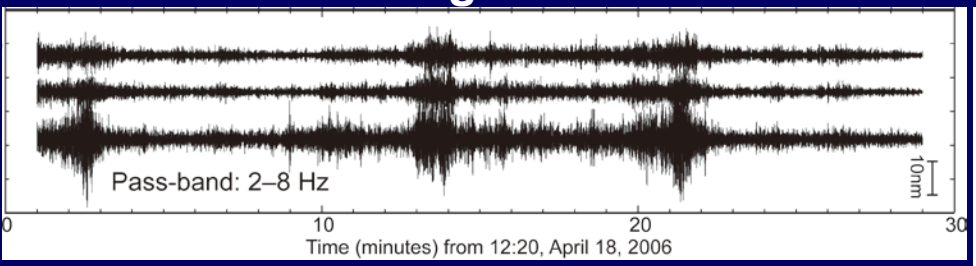
Downdip side

	Observation
- Short-term slow slip event (tc:2~6days)	Tiltmeter/ strainmeter
- Deep Very Low Frequency Earthquake（VLF） (tc:20sec)	LP seismometer
- Deep Low Frequency Tremor (tc:1.5~5Hz)	SP seismometer



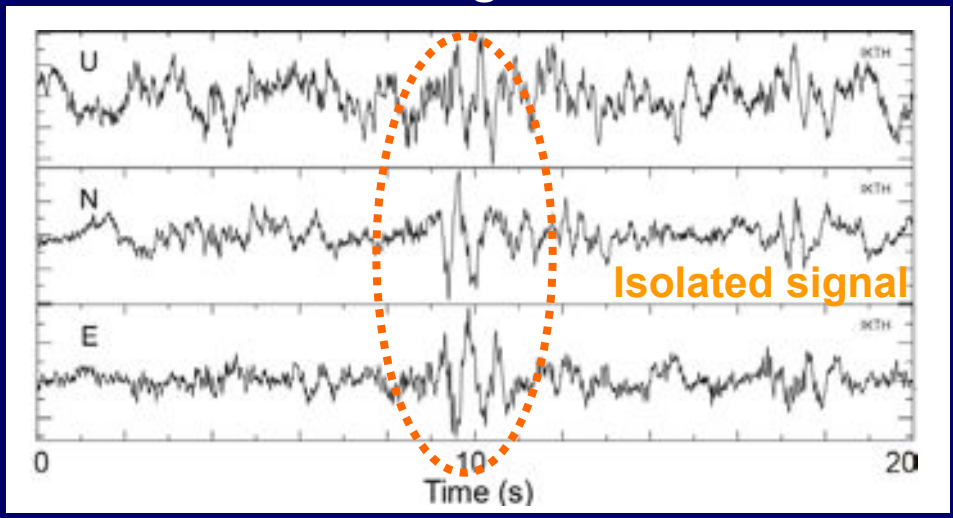
Tremor and Low Frequency Earthquake (LFE)

30 minutes seismogram

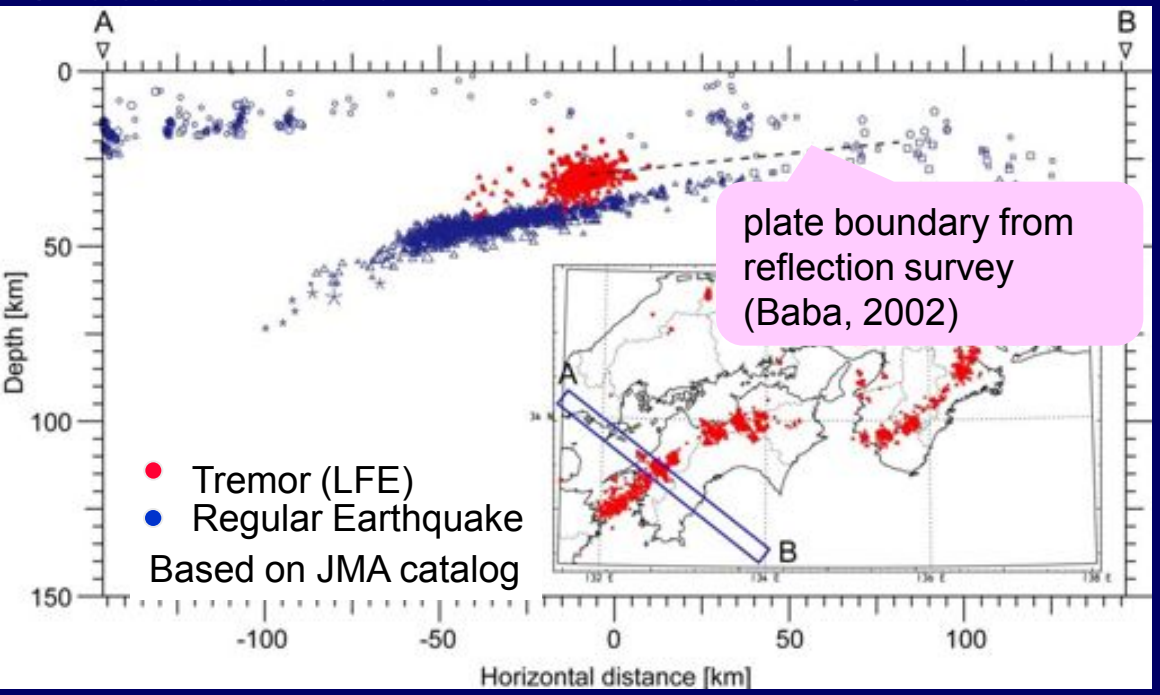


Characteristic time scale:1~10 Hz

20 seconds seismogram



Cross sectional view in western Shikoku

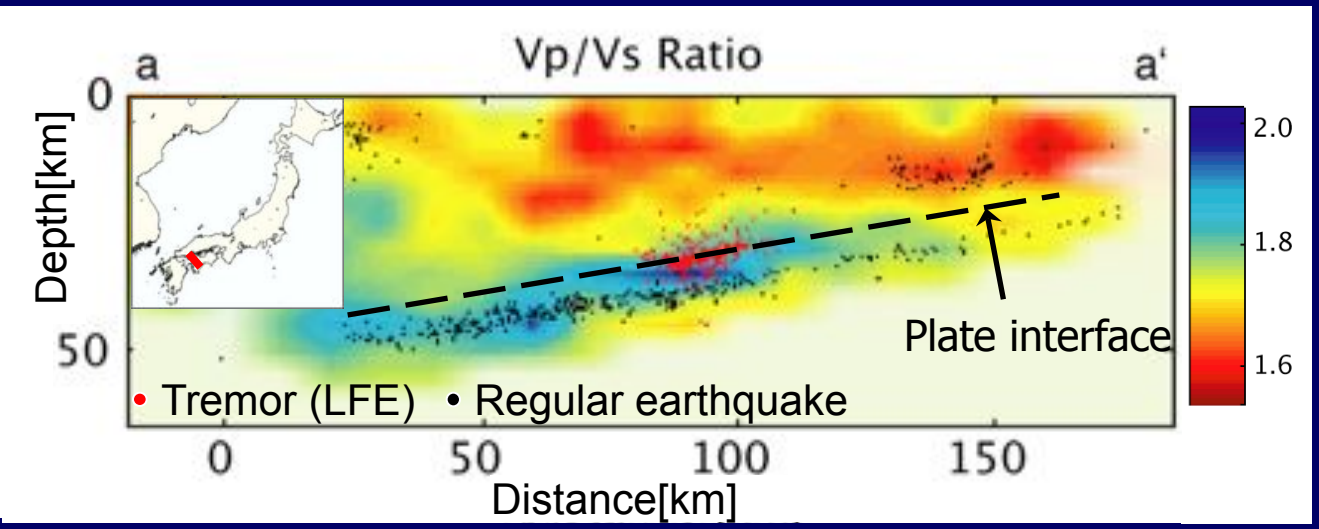


LFE is the element of tremor.

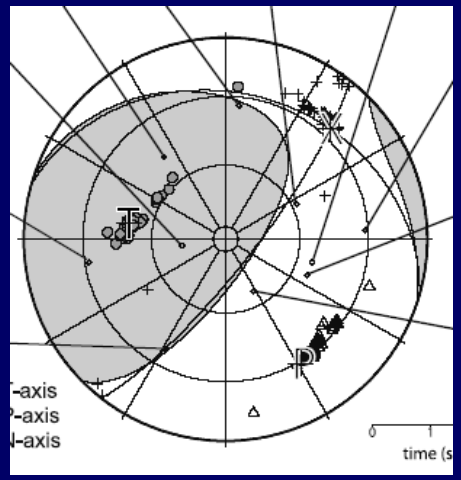
LFE is routinely located by manual phase-picking process by JMA.

Tremor(LFE) on the plate interface

Precise relocation and mechanism of LFE in Western Shikoku

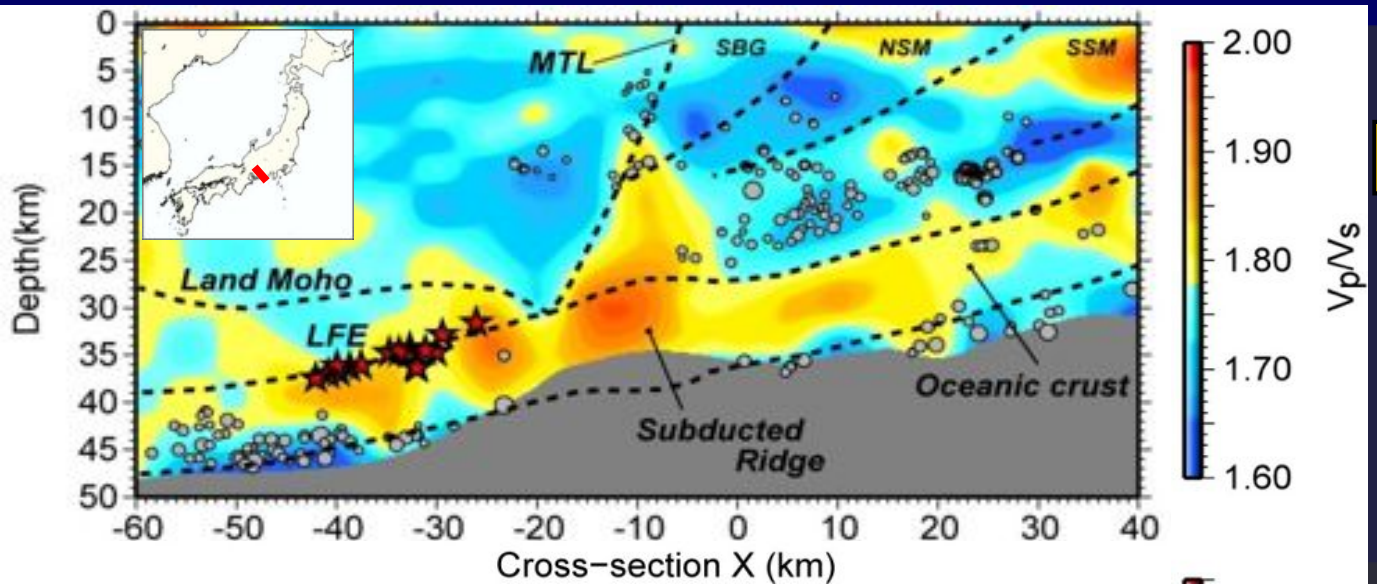


Shelly et al.(2006)



Ide et al.(2007)

Precise relocation of LFE in Tokai



Visit poster #61

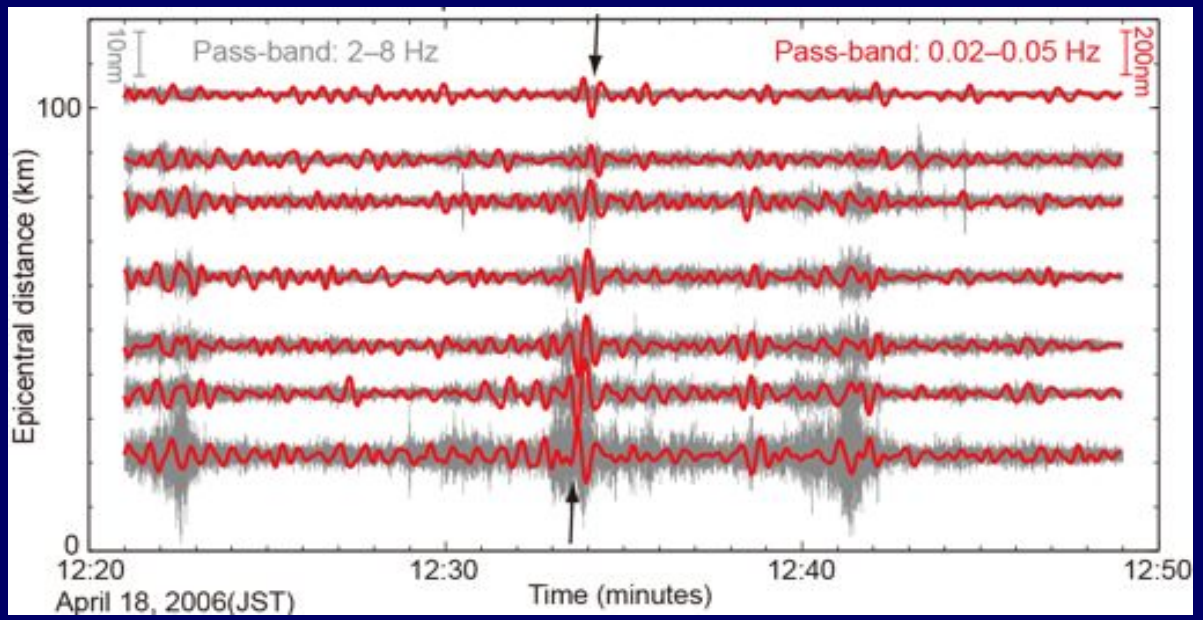
Kato et al. (2010)

Deep Very Low Frequency (VLF) Earthquake

[Seismograms]

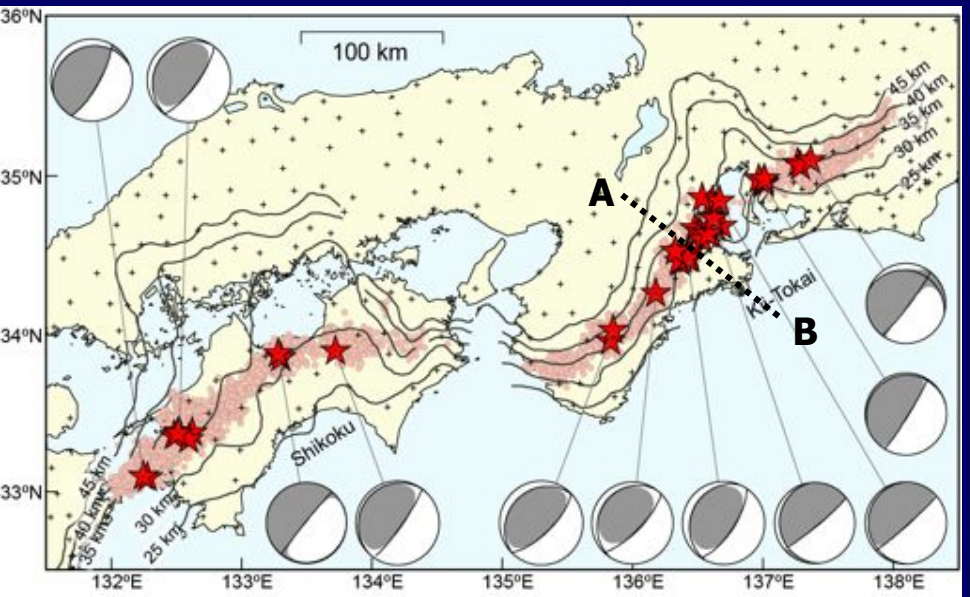
Characteristic time scale : 20sec

VLF signals are usually coincident with large-amplitude wavetrains of tremor (relatively higher-frequency component).



30 minutes-seismogram of VLF

[Location and Mechanism]



Thrust type mechanism around the plate interface

The location of VLF corresponds to the belt-like tremor source area.

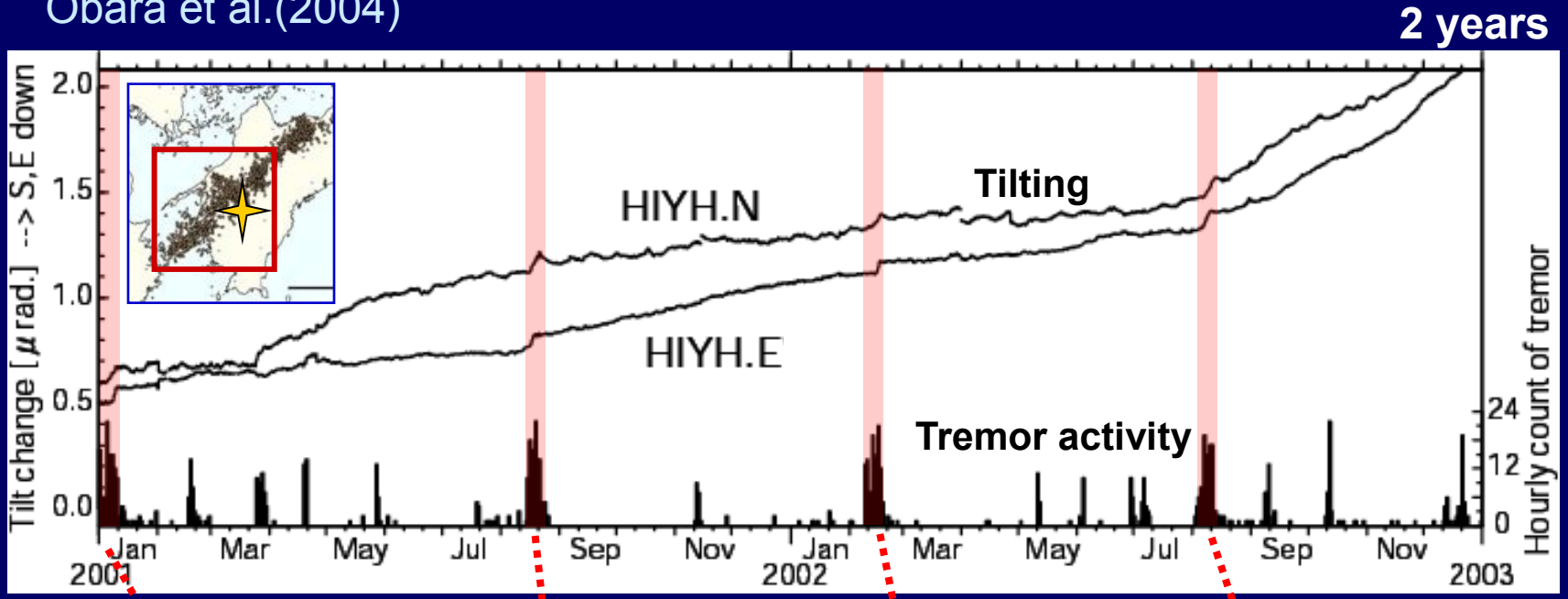
Ito et al.(2007)

Short-term Slow Slip Event (SSE)

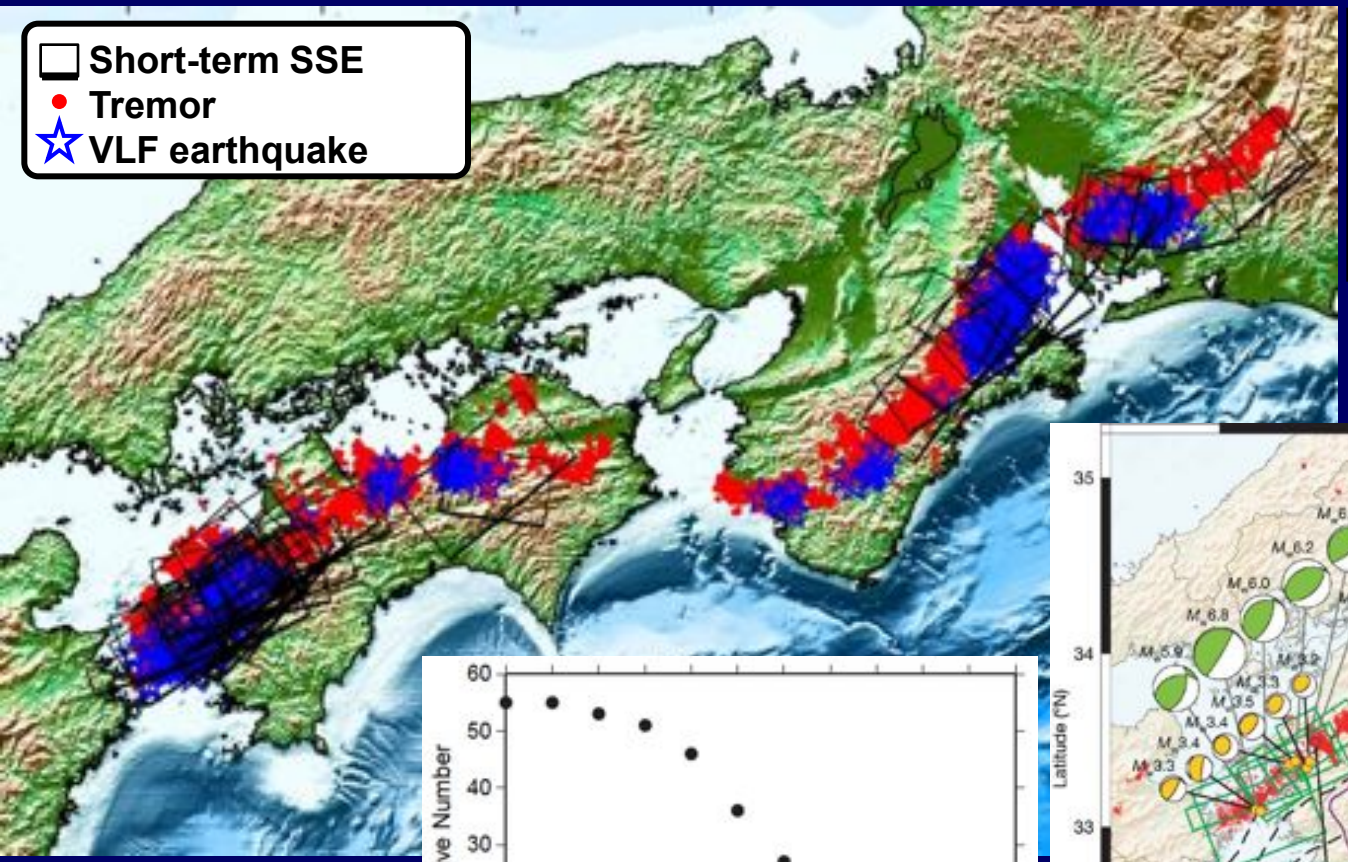
Characteristic time scale:2~6days

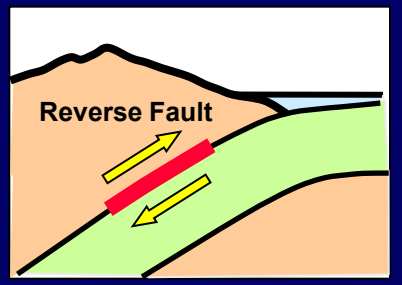
[Tilt change and tremor activity in western Shikoku]

Obara et al.(2004)

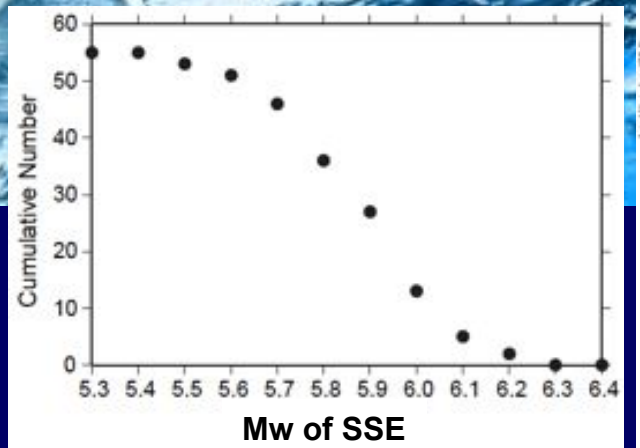


ETS in southwest Japan composed of Tremor (LFE), Short-term SSE, and VLF earthquake are all interplate shearing phenomena.

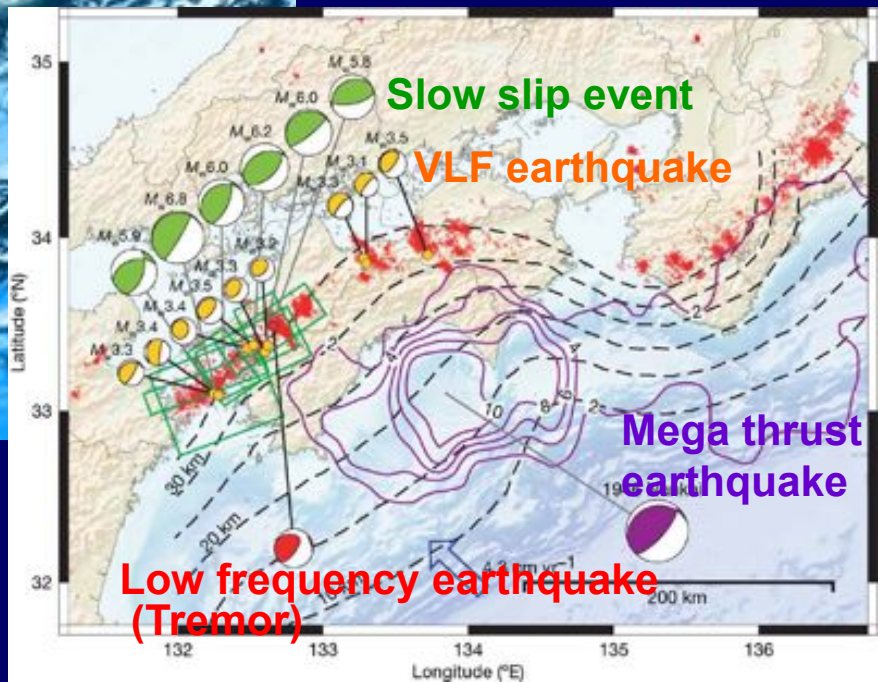




Ide et al.(2007)



Sekine et al.(2010)



Long-term Slow Slip Event (SSE)

Characteristic time (tc)

100day

1day

1000sec

10sec

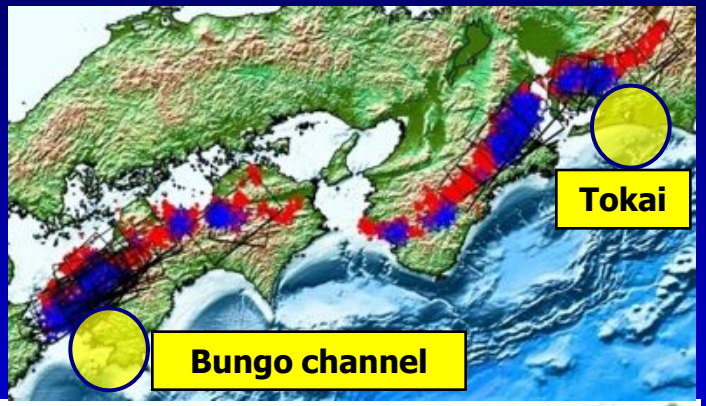
0.1sec

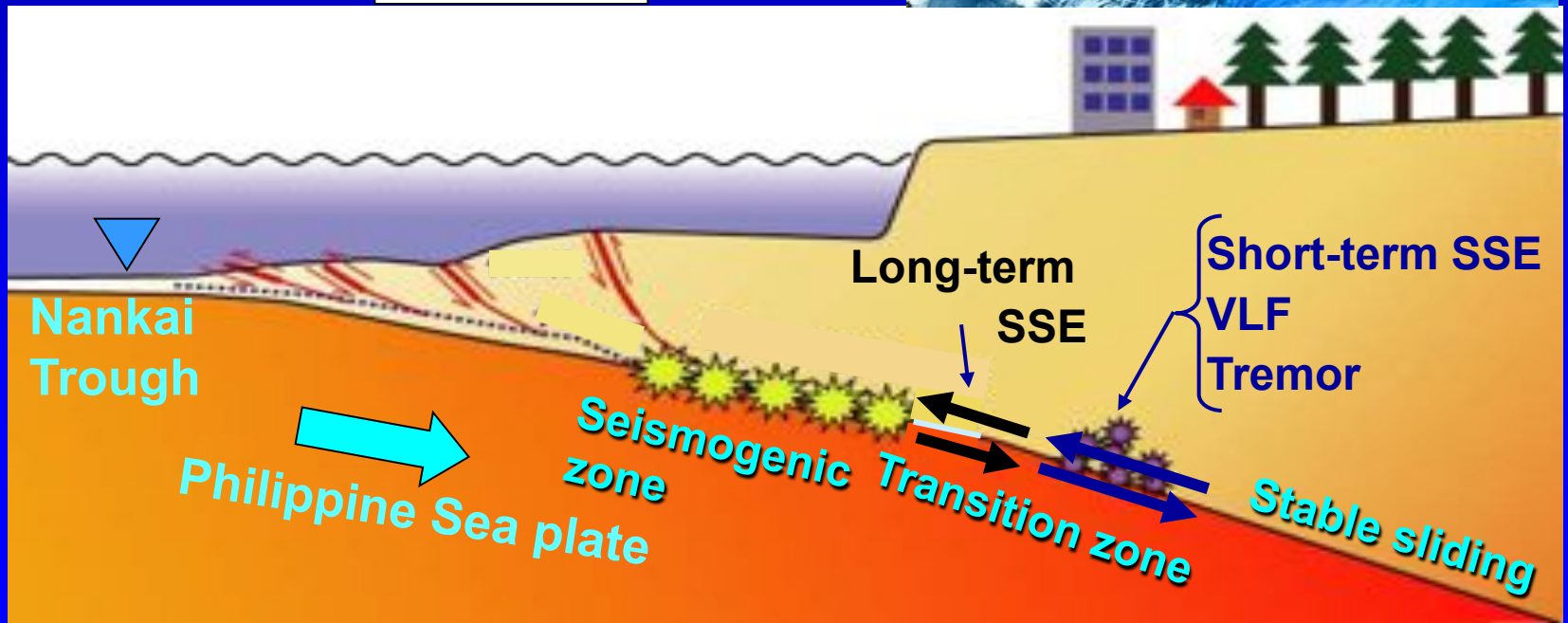
Downdip side

Observation

- Long-term slow slip event (tc:0.5~5years)

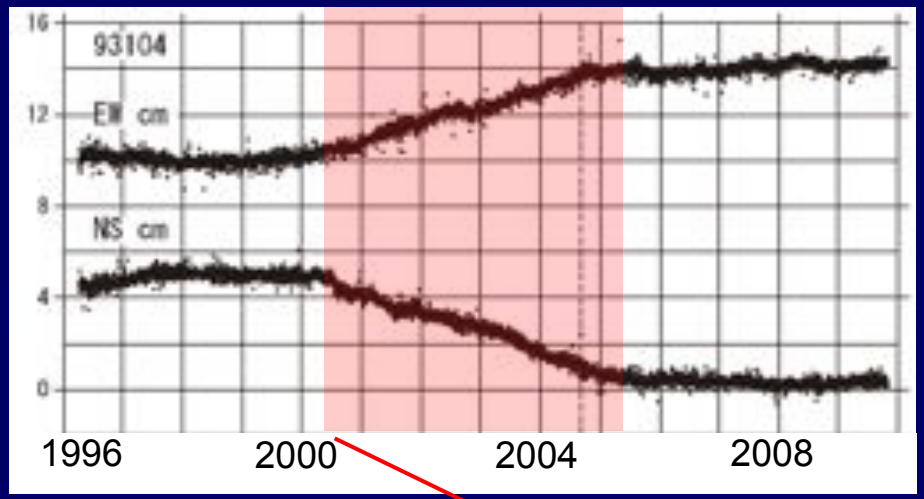
GPS



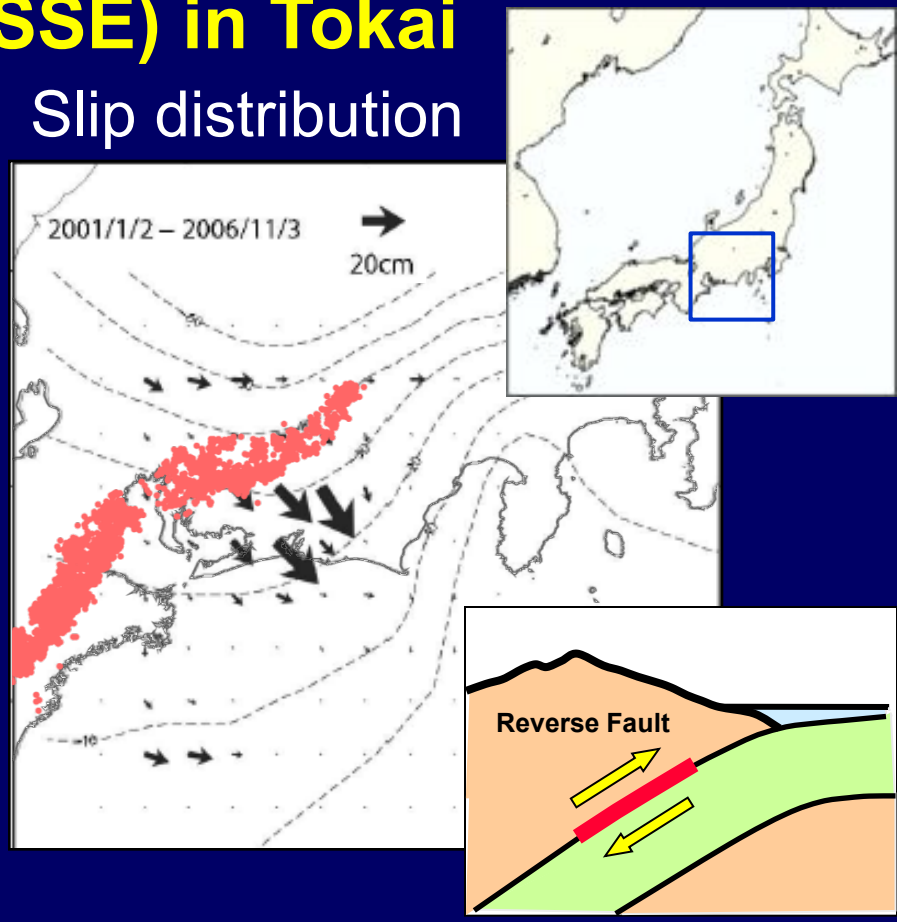


Long-term Slow Slip Event (SSE) in Tokai

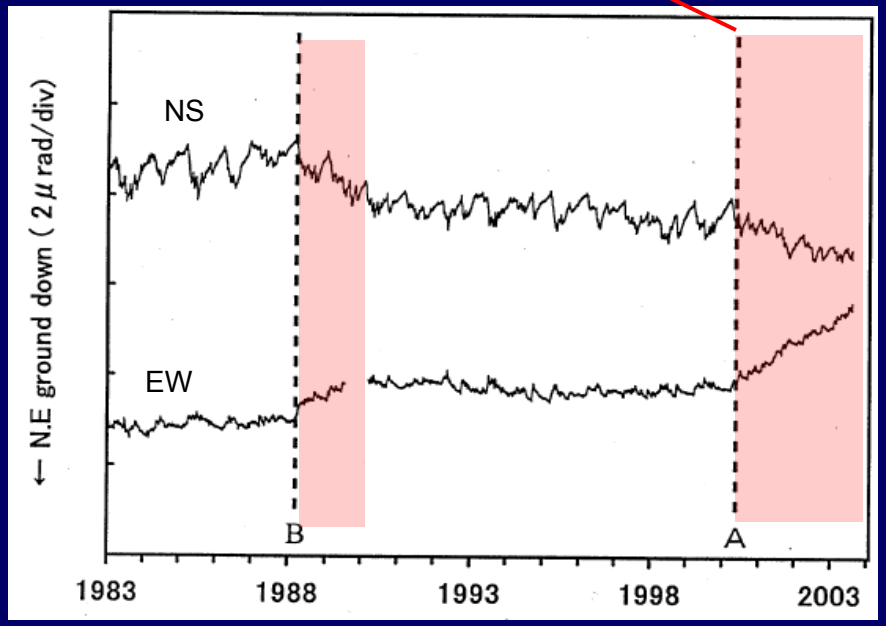
GEONET GPS displacement



Slip distribution



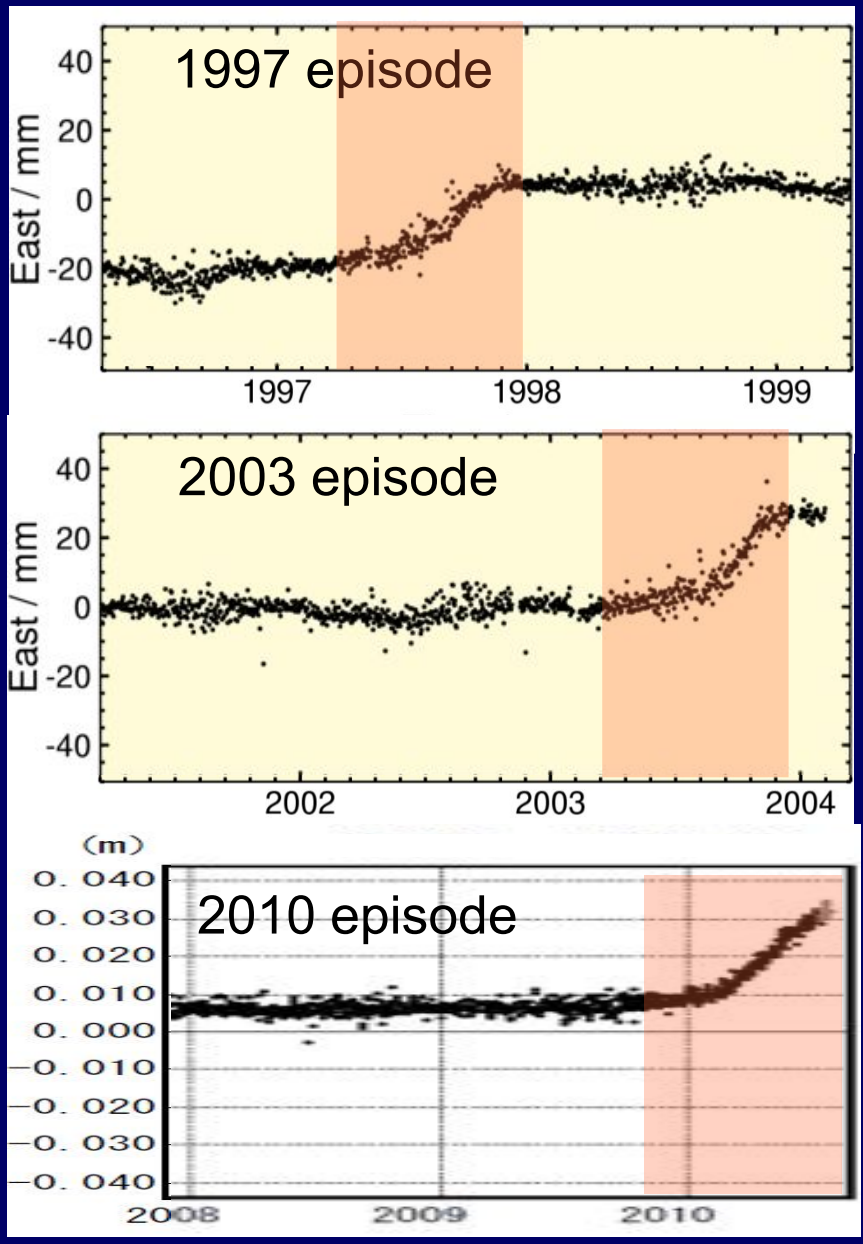
NIED Tilt change



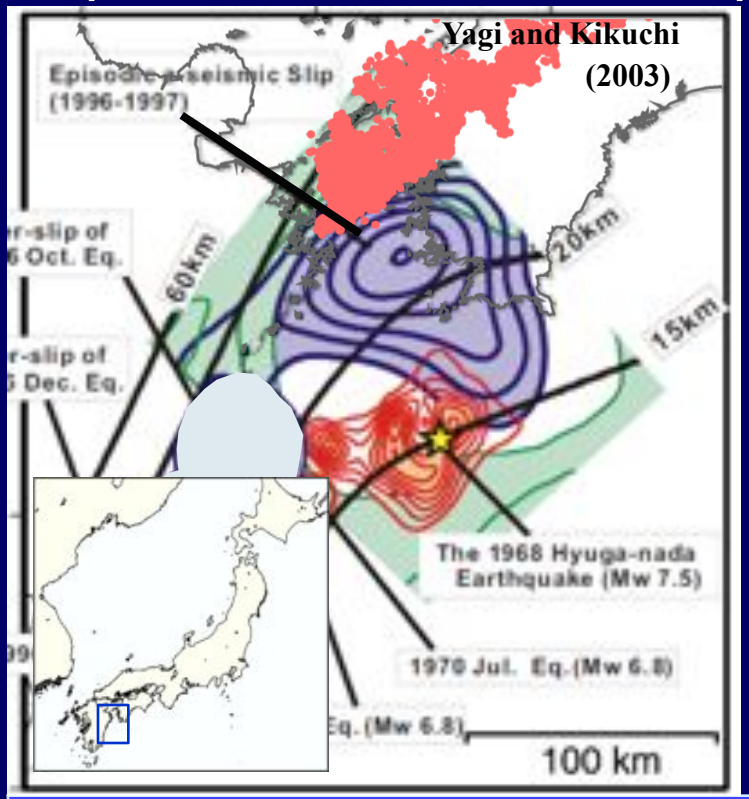
Tokai long-term SSE	
Mw	7.1 (2000~2005)
Depth	20~30 km
Slip length	25 cm
Duration	2~5 years
Recurrence	10 years

Long-term Slow Slip Event (SSE) in Bungo channel

GEONET GPS displacement

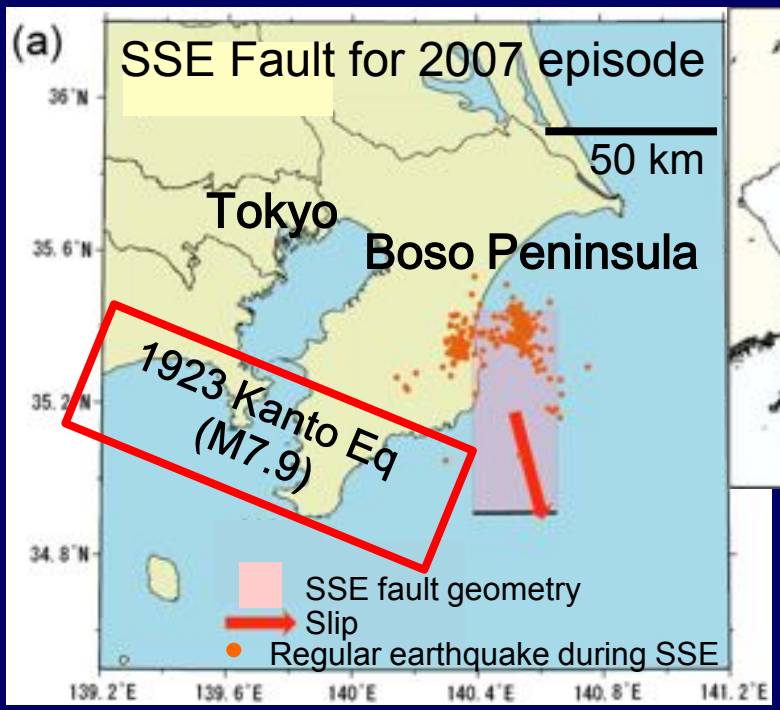


Slip distribution of 1997 episode



Bungo channel long-term SSE	
Mw	6.7~6.8
Depth	15~35 km
Slip length	11~18 cm
Duration	0.5~1 year
Recurrence	6 years

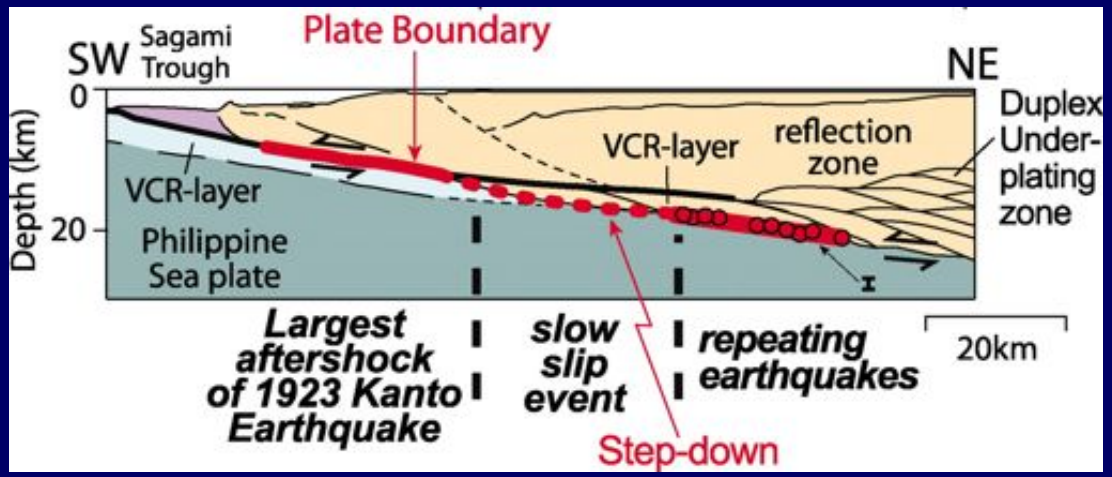
Long-interval, short-duration SSE in Boso Peninsula



	seismic swarm	Tilt	GPS
1983	○	△	
1990	○	△	
1996	○	△	○
2002	○	△	○
2007	○	○	○

Depth shallower than other Nankai SSE/tremor
Associated with seismic swarm (not tremor)

Cross sectional view of Boso SSE

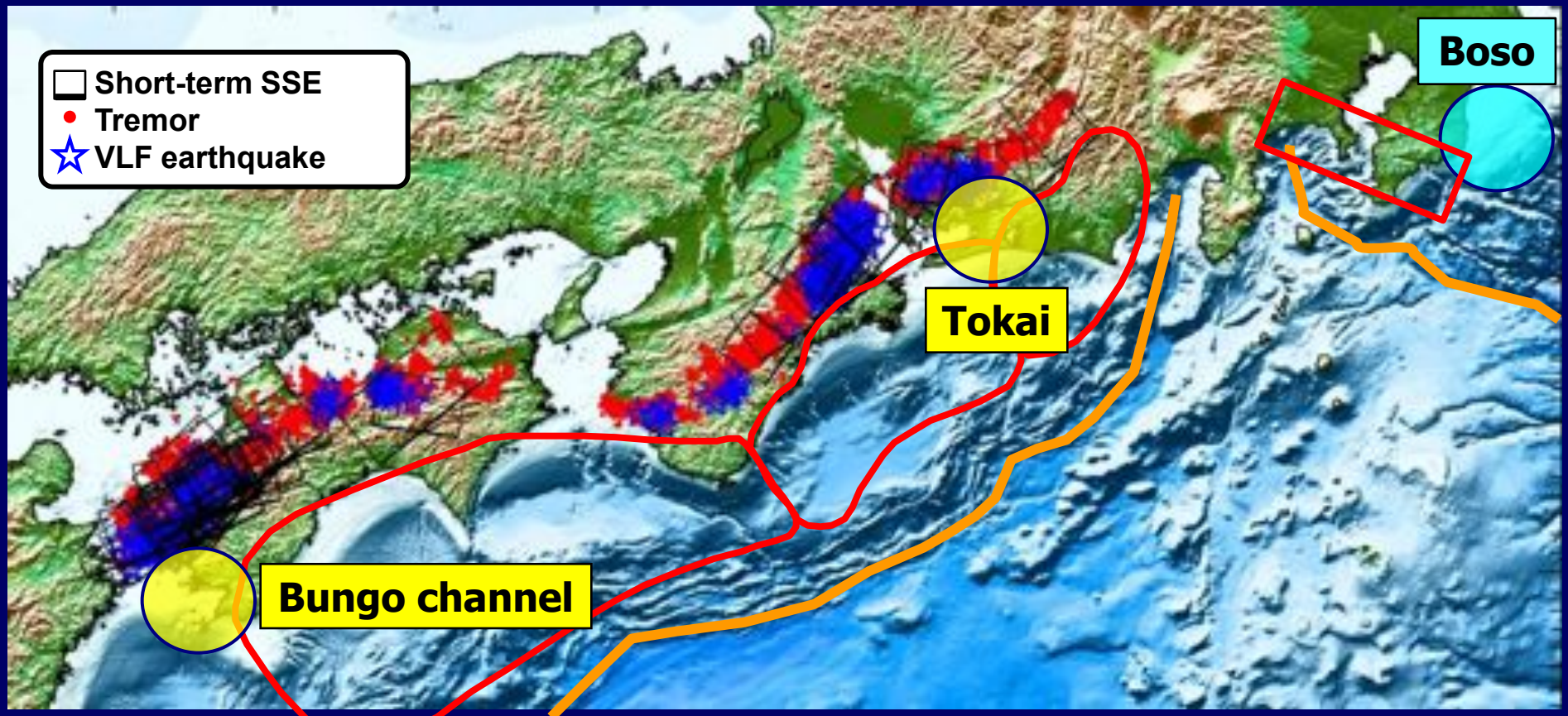


Boso SSE	
Mw	6.4
Depth	10~20 km
Slip length	10 cm
Duration	10 days
Recurrence	6 years

H. Kimura et al., Science 329, 210-212 (2010)

Long-term and Short-term Slow Slip Event (SSE)

SSE Type	Mw	Depth	Duration	Recurrence	Tremor
Short-term SSE	5.5~6.2	30~45 km	2~6 days	3~6 months	Strong coupling
Tokai long-term SSE	7.1	20~30 km	2~5 years	10 years	Triggering
Bungo channel long-term SSE	6.7~6.8	15~35 km	0.5~1 year	6 years	Triggering
Boso SSE	6.4	10~20 km	10 days	6 years	No, but earthquake

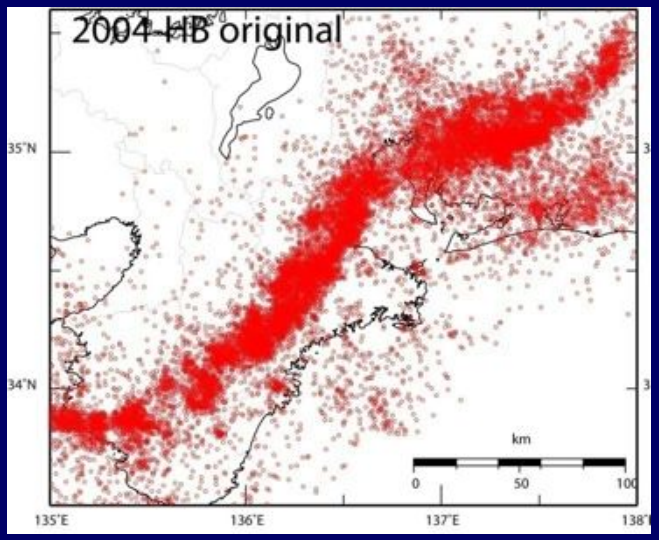


Construction of new tremor catalog

Hybrid method (Maeda and Obara, 2009)

= Measurement of time lag by envelope correlation
+ Spatial distribution of envelope amplitude

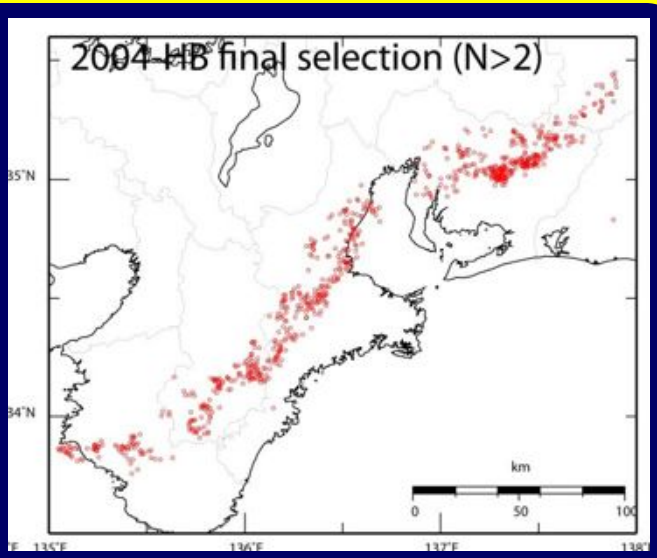
- Locate tremor source at every one minute with pinning at the plate interface (Shiomi et al., 2008)
- Select well located data with high VR



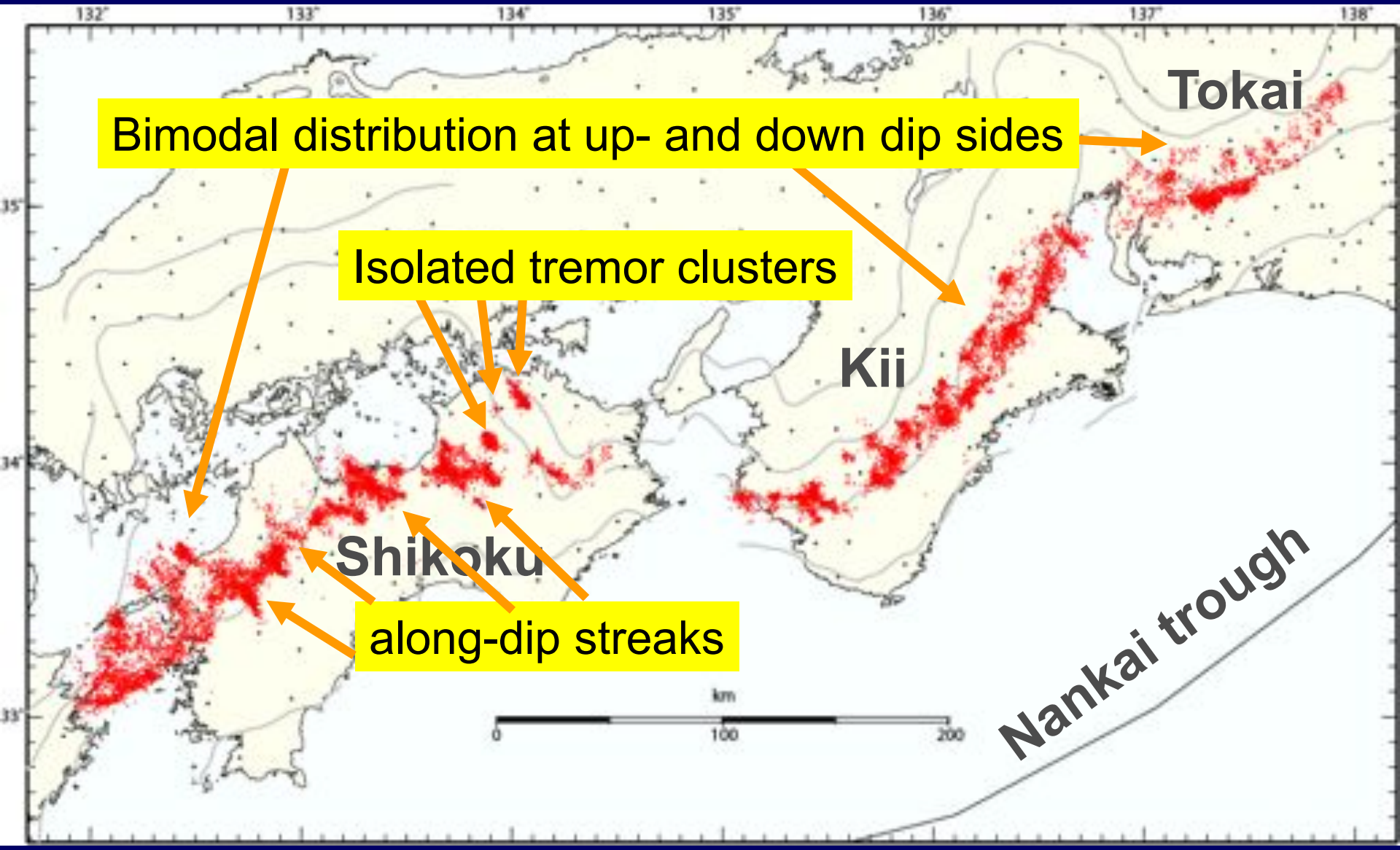
Including of regular earthquake and noises

Clustering process (Obara et al., 2010)

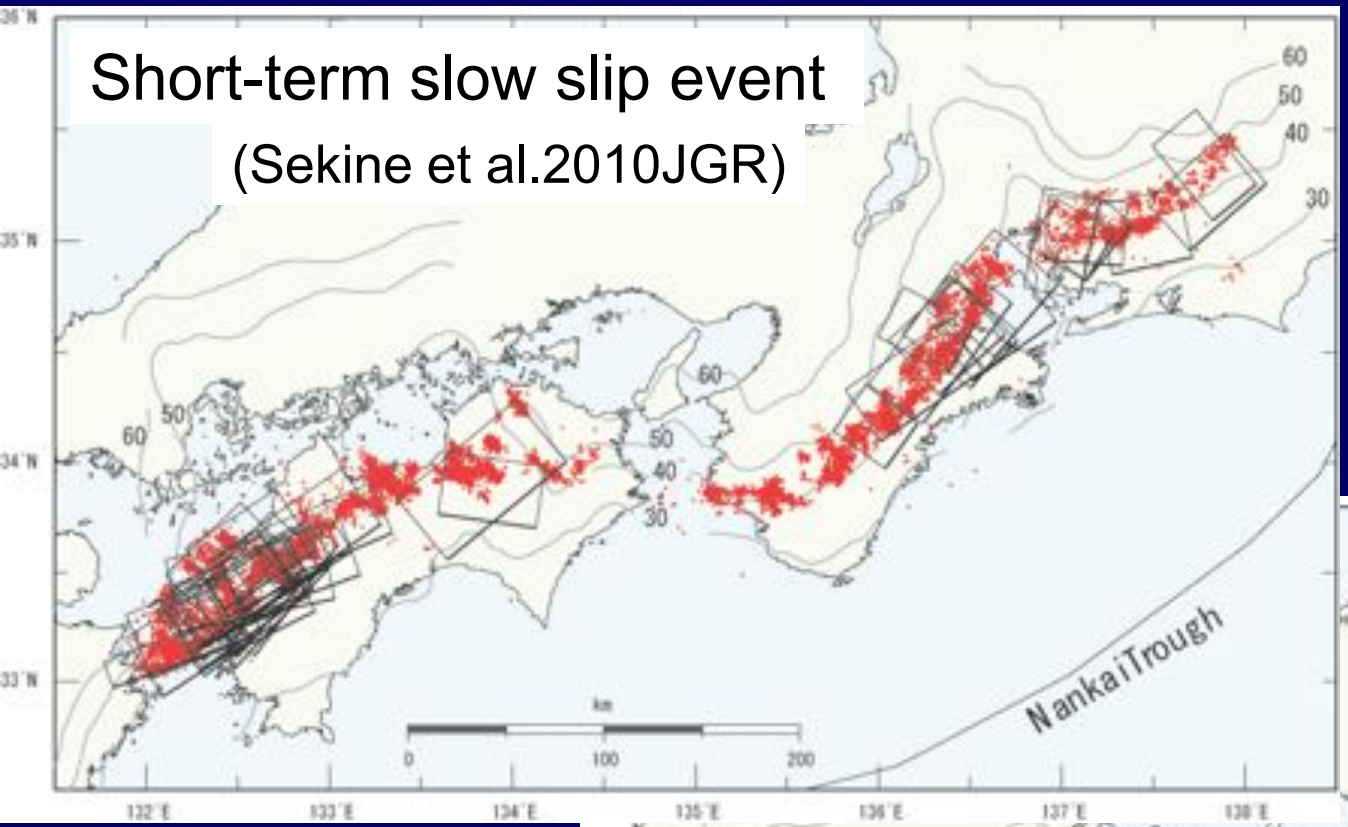
- Estimate centroid location from neighbor tremors every one hour
- Select centroid composed of more than three original tremor sources as the final data

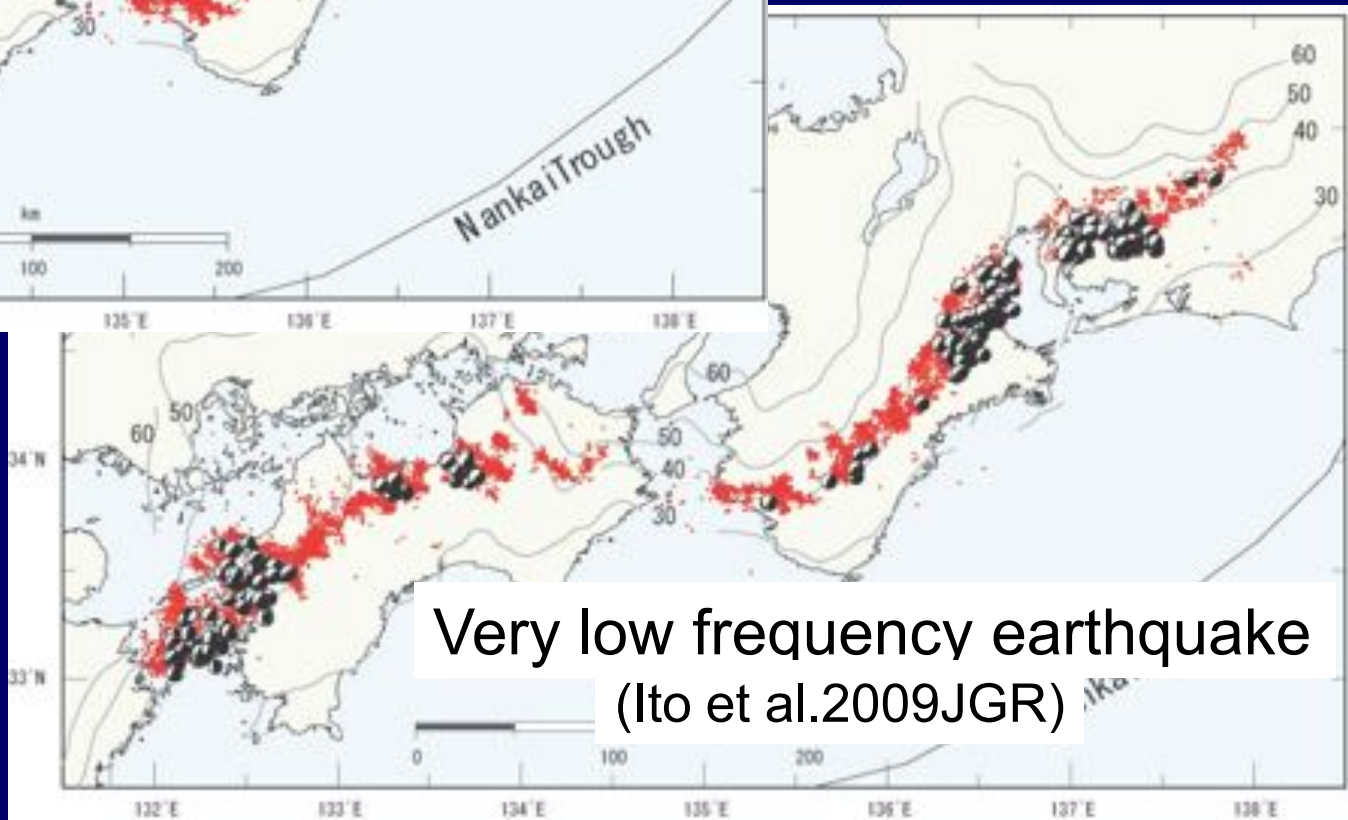


Epicentral distribution of tremor(2001-2009)

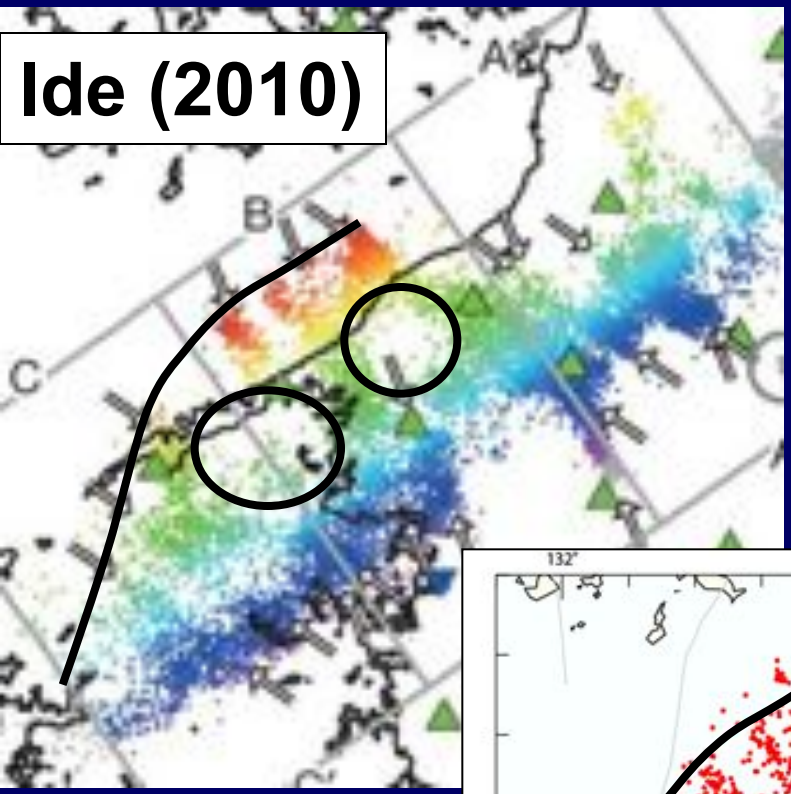


Bimodal Tremor coincident with active SSE, VLF



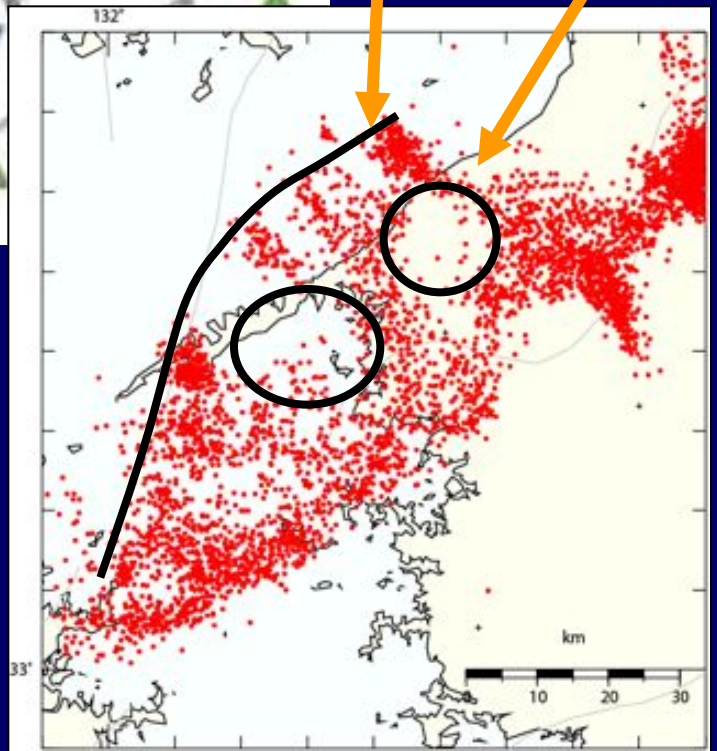


Comparison of tremor catalogs in western Shikoku

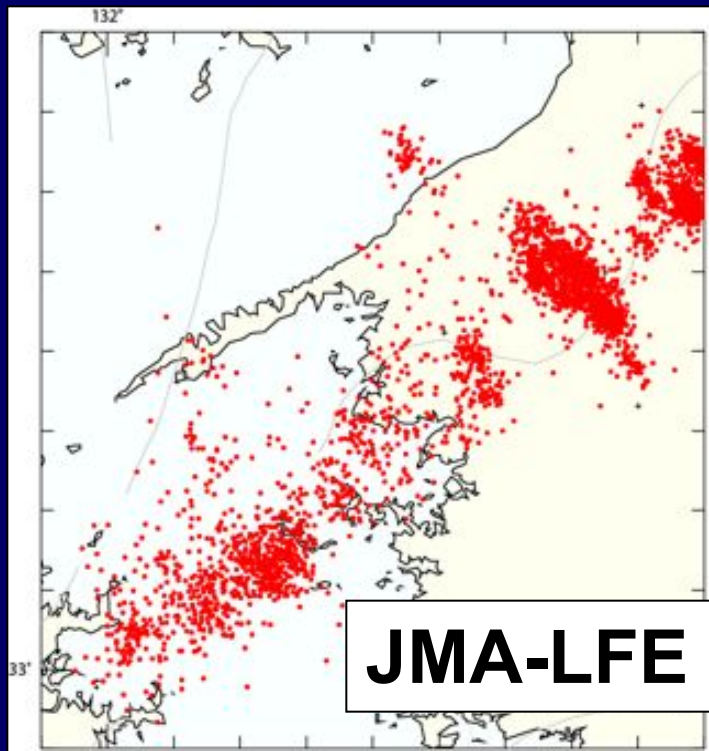


Downdip edge

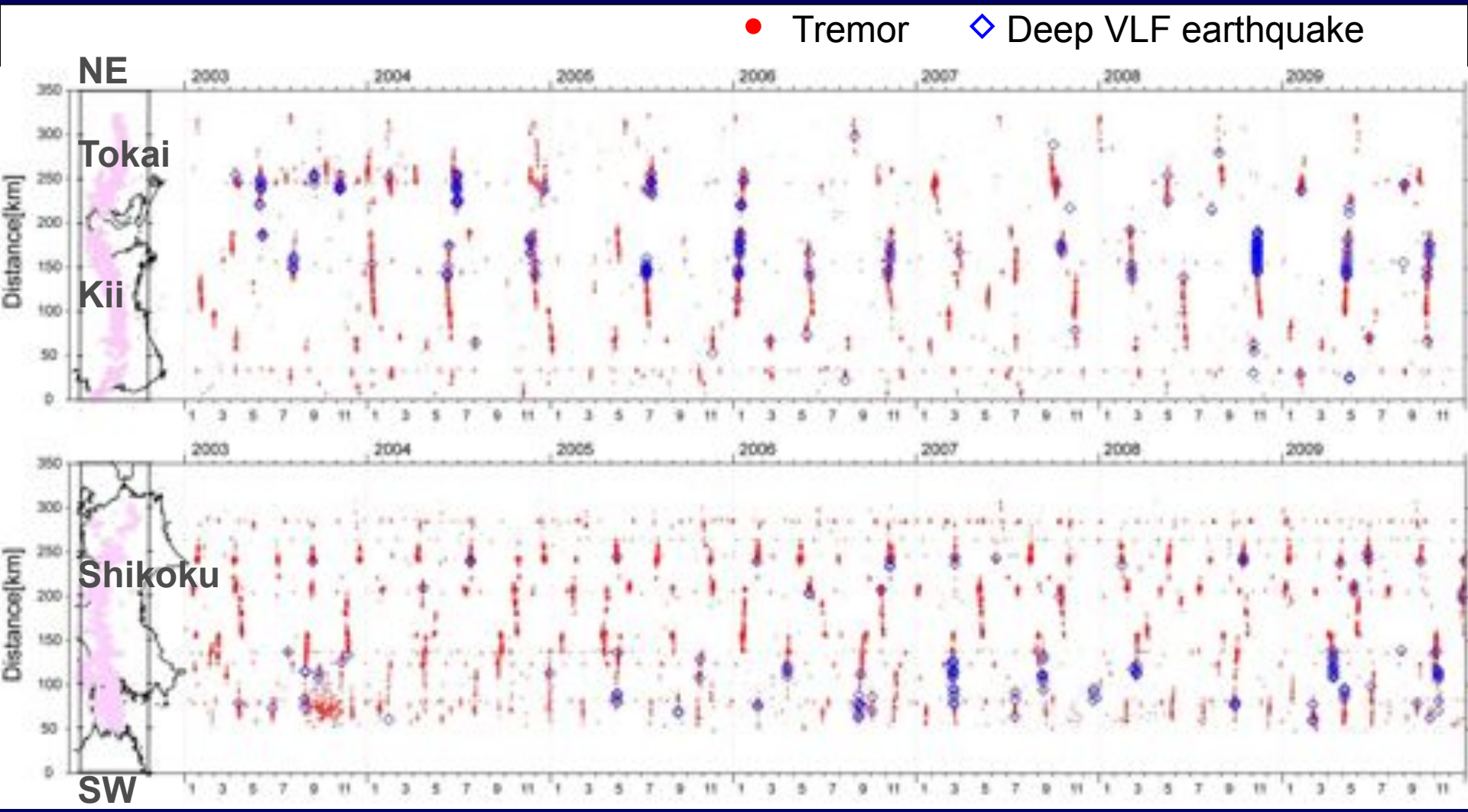
Gap



Obara et al. (2010) ⟶

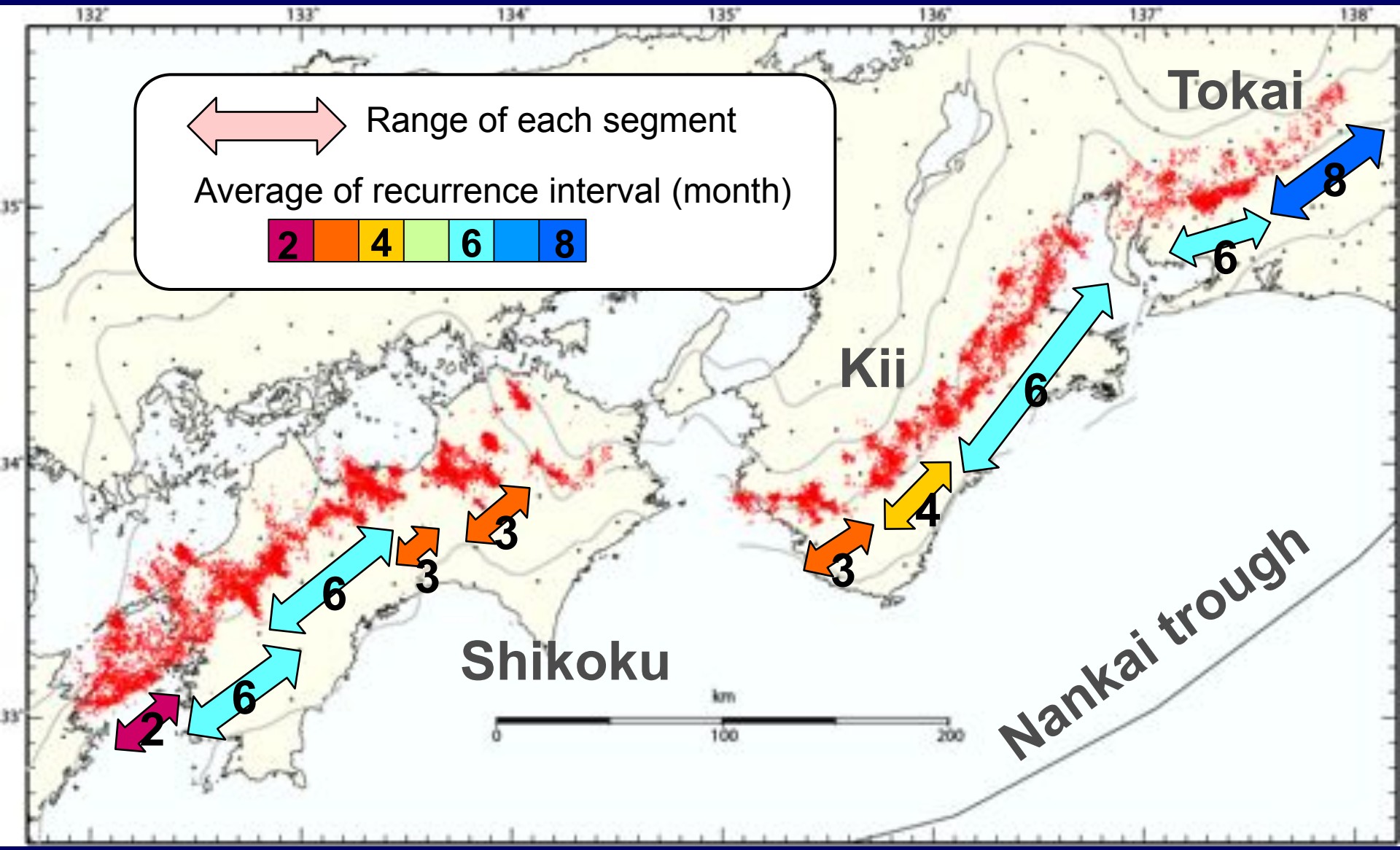


Space-time distribution of tremor and deep VLF

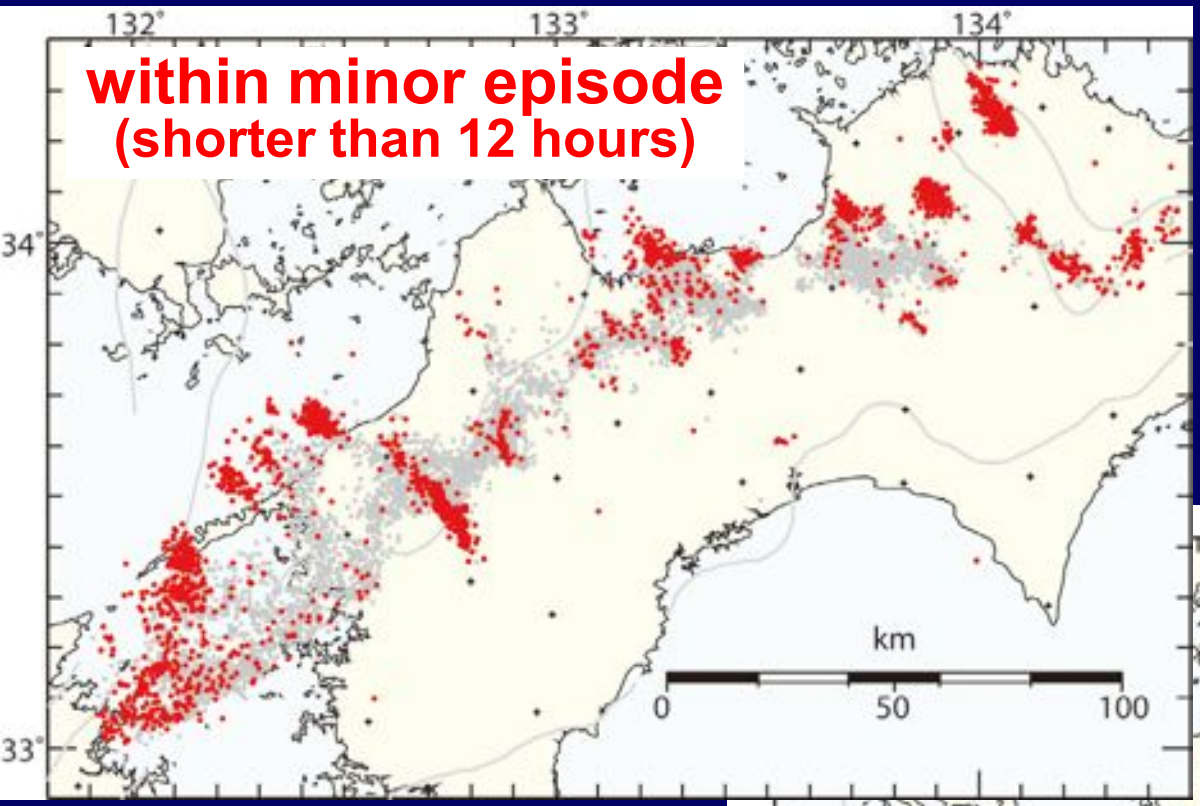


- Clear segmentation with regular interval
- Continuous activity in small isolated clusters

Segmentation and recurrence interval

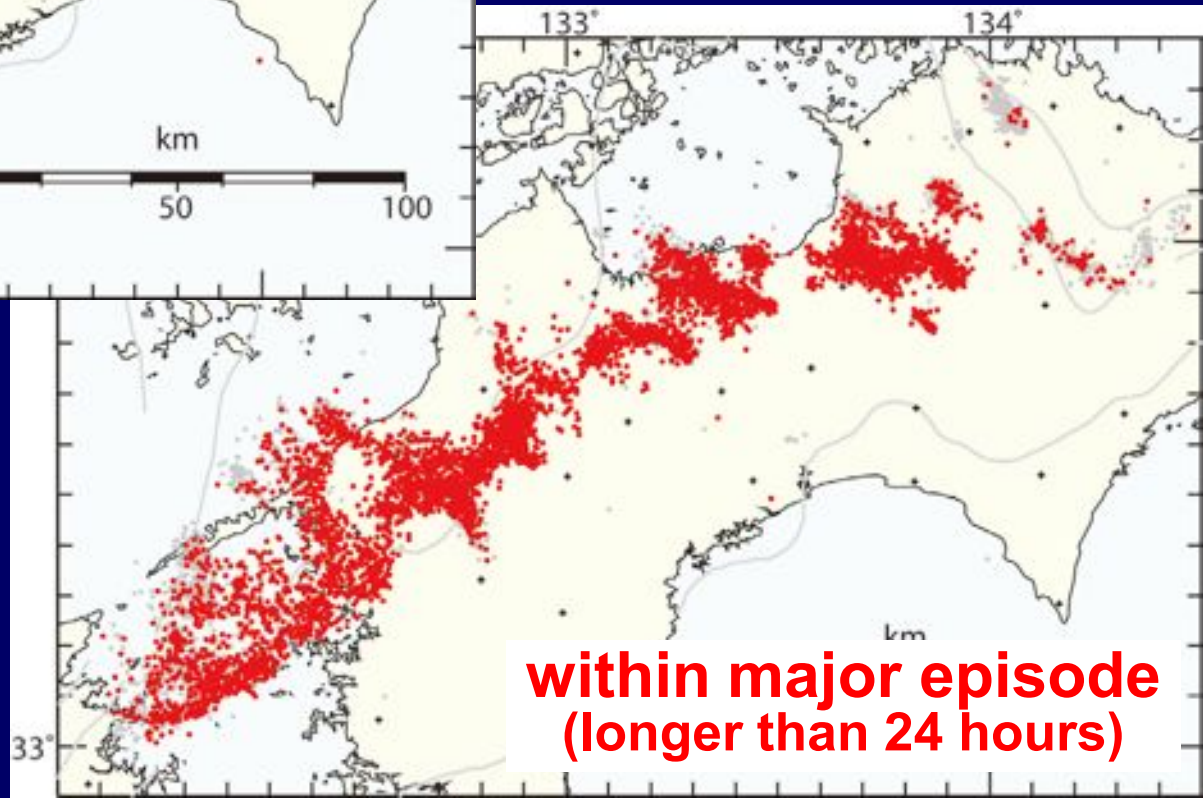


Tremor distribution in Shikoku



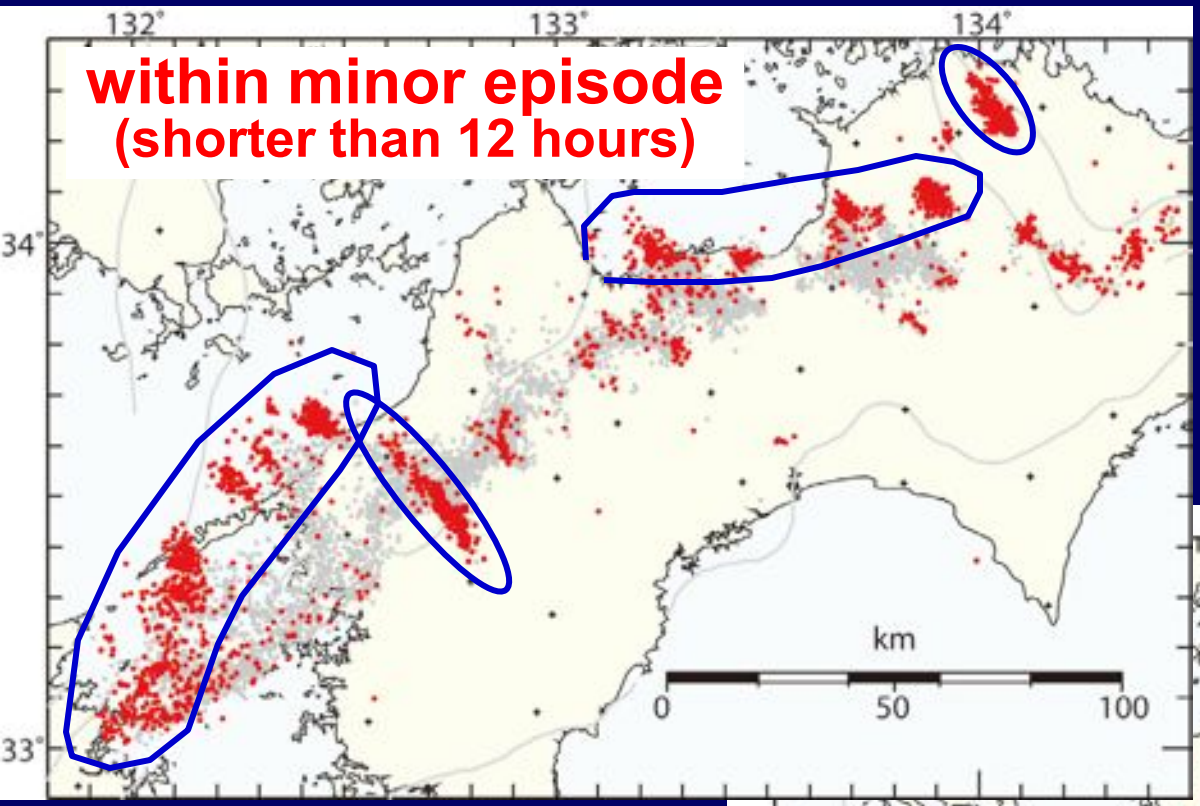
within minor episode
(shorter than 12 hours)

Tremor in major episodes distributed in entire region.



within major episode
(longer than 24 hours)

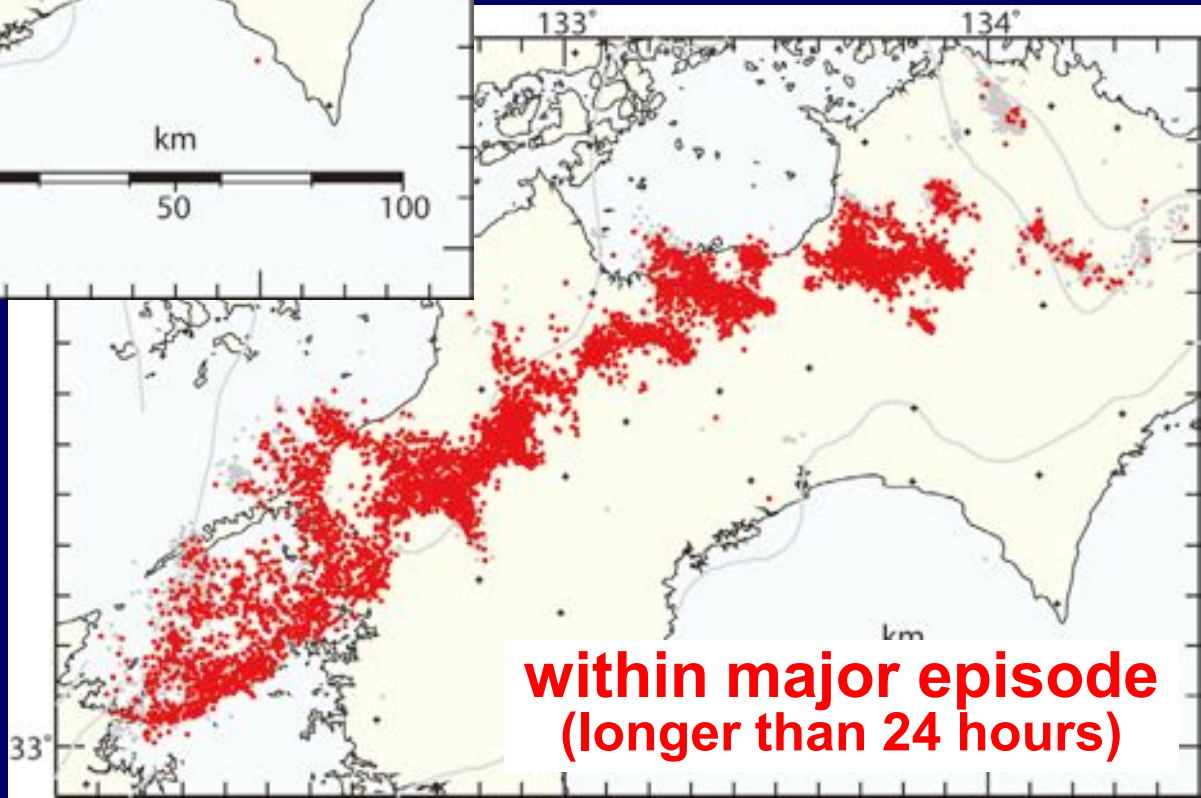
Tremor distribution in Shikoku



within minor episode
(shorter than 12 hours)

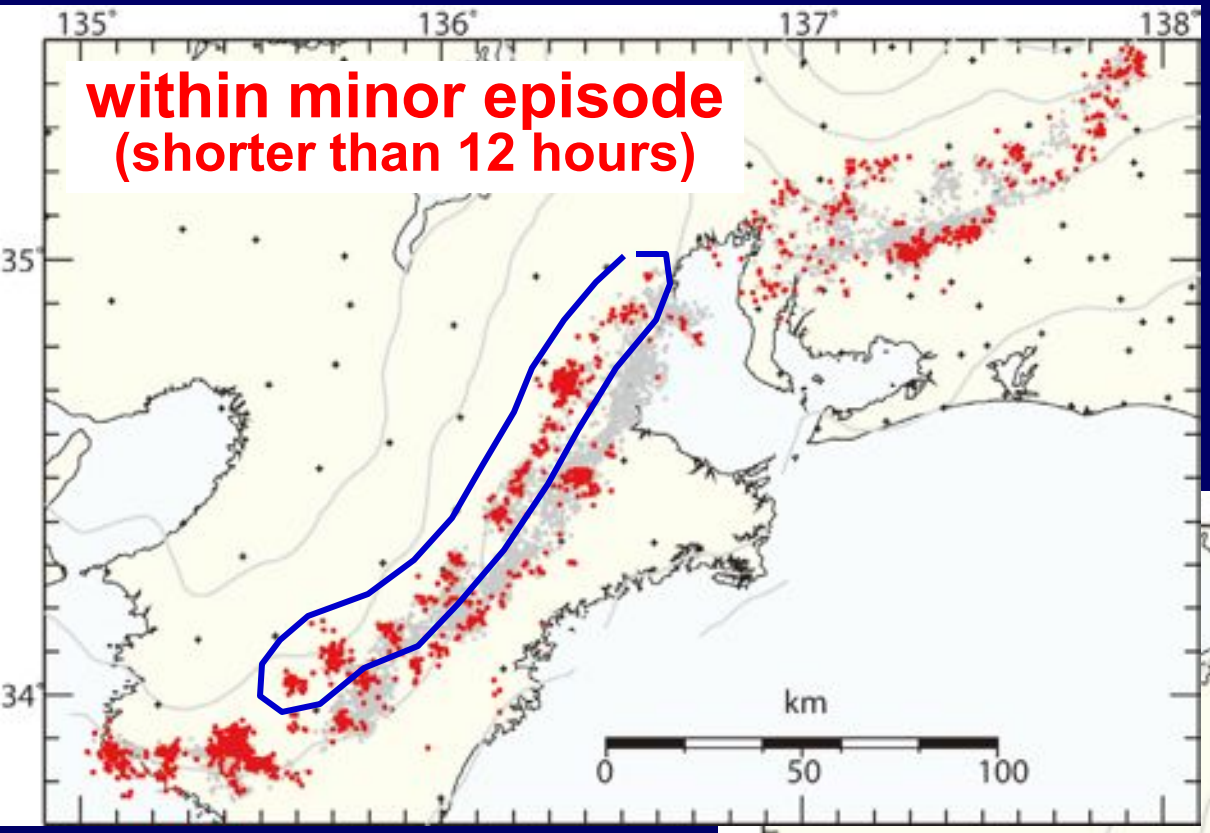
Tremor in minor episodes concentrating at deeper side

Tremor in major episodes distributed in entire region.



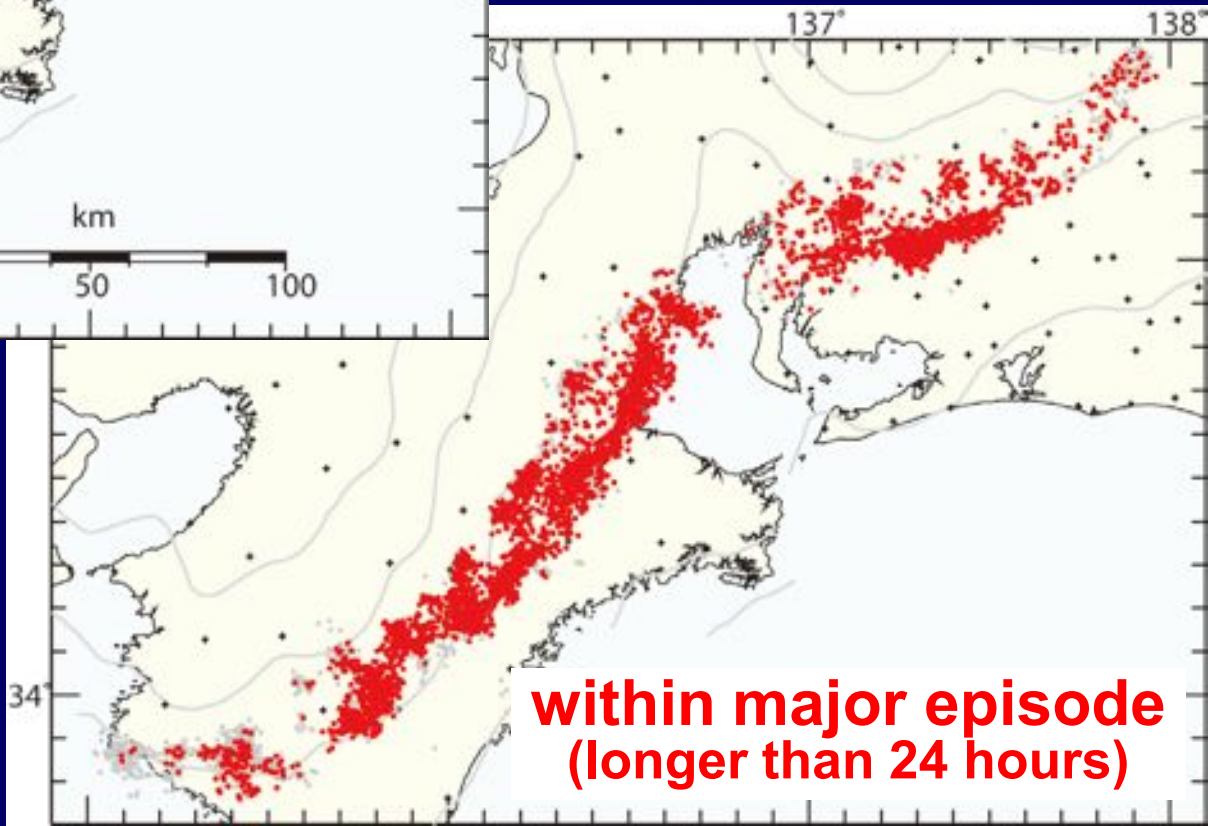
within major episode
(longer than 24 hours)

Tremor distribution in Kii/Tokai



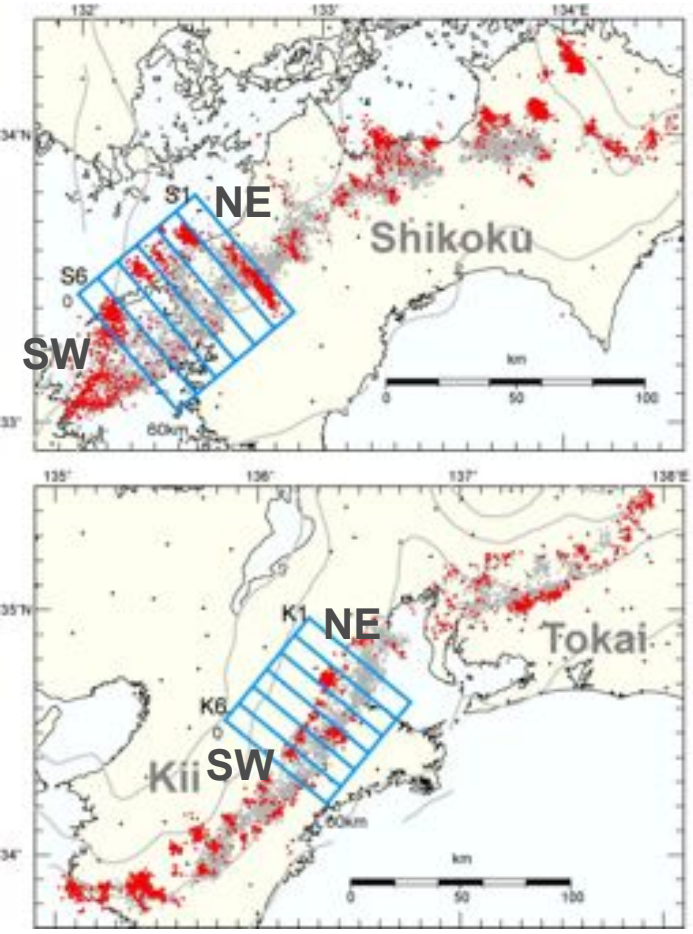
Tremor in minor episodes concentrating at deeper side

Tremor in major episodes distributed in entire region.

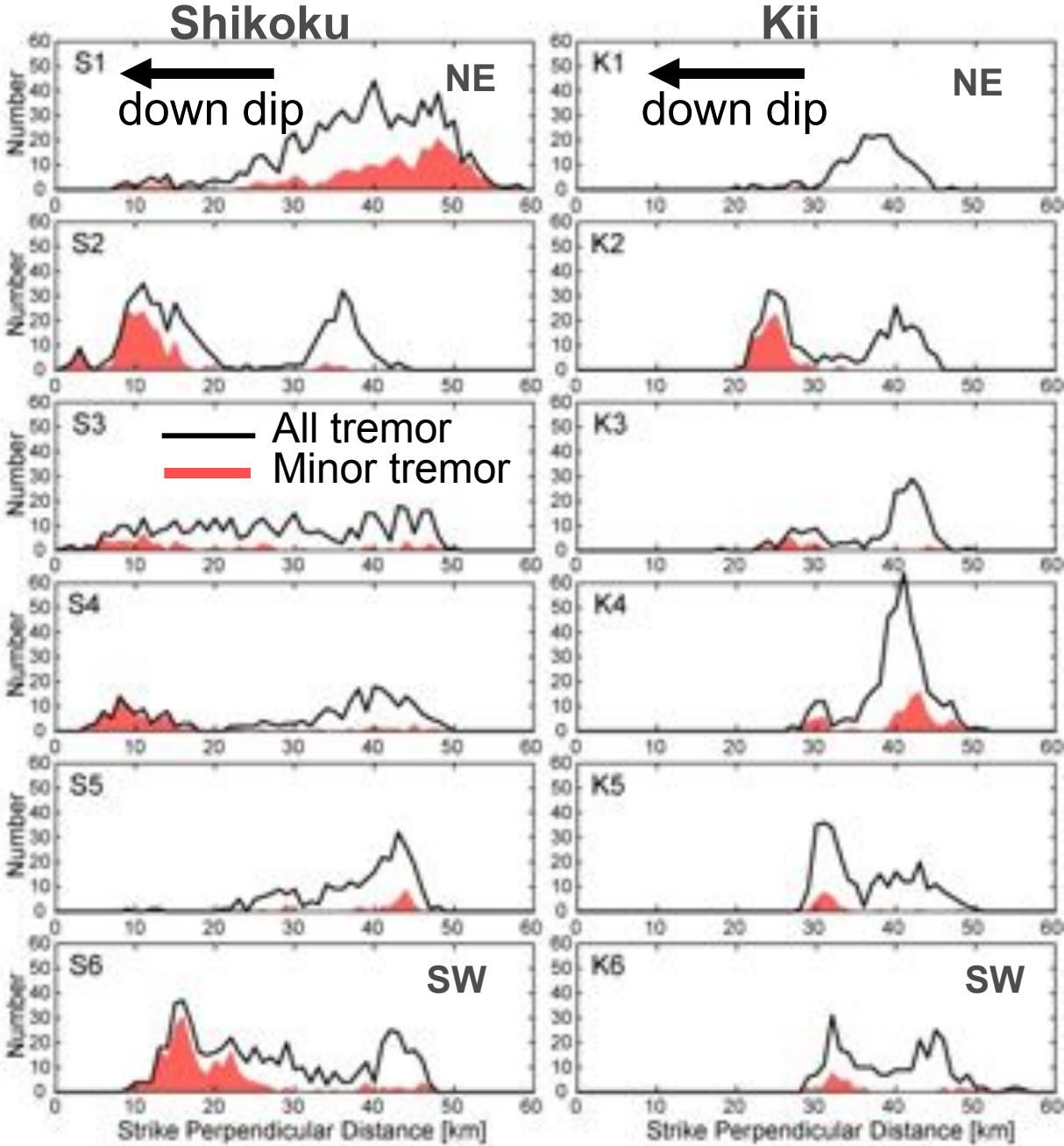


Frequency distribution of tremor along dip direction

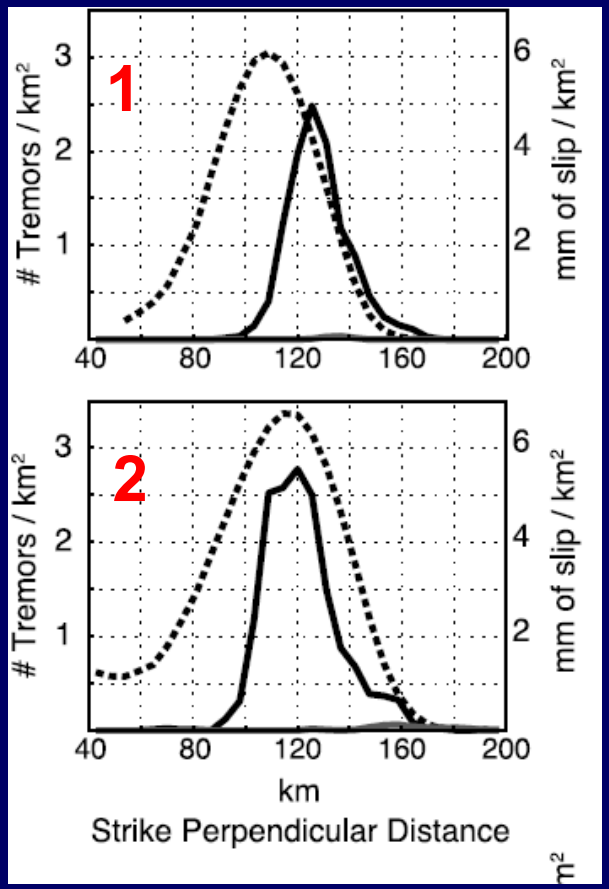
- **Tremor within minor episode (shorter than 12 hours)**



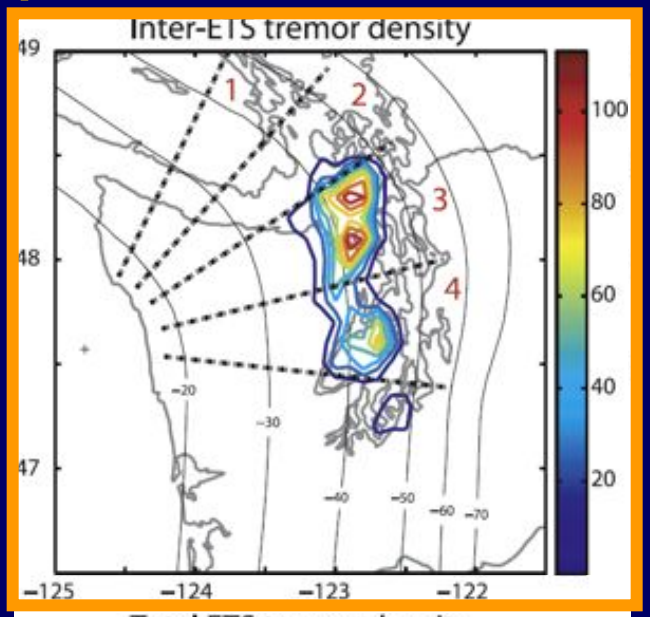
Shallow – burst with SSE
Deep -- stable

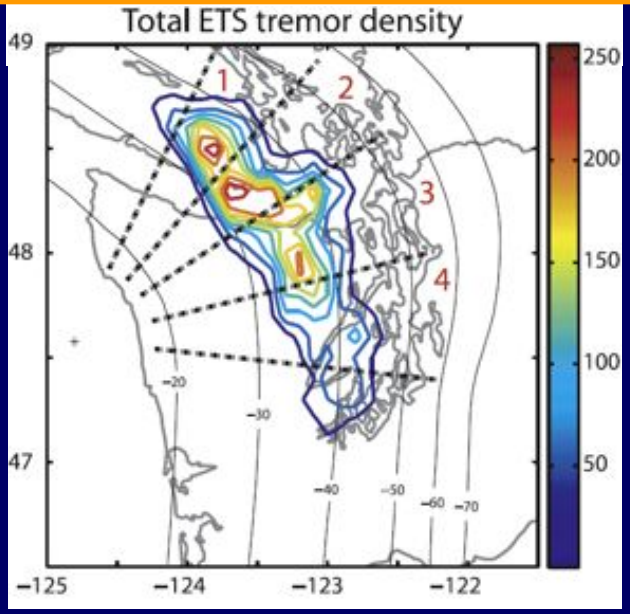


ETS/Inter-ETS tremor along dip in Cascadia



Down dip

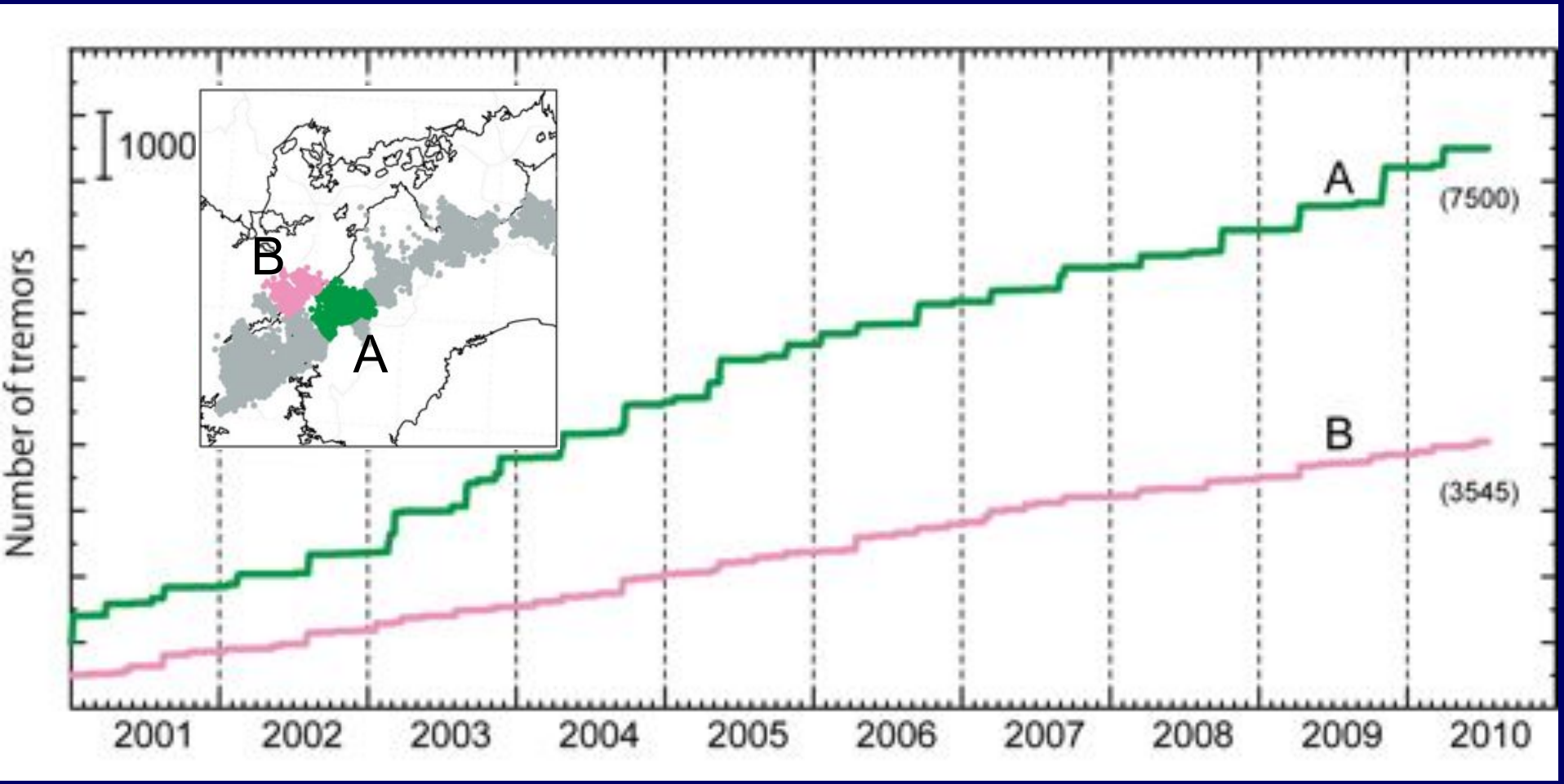




Inter-ETS tremor is located at deeper side.

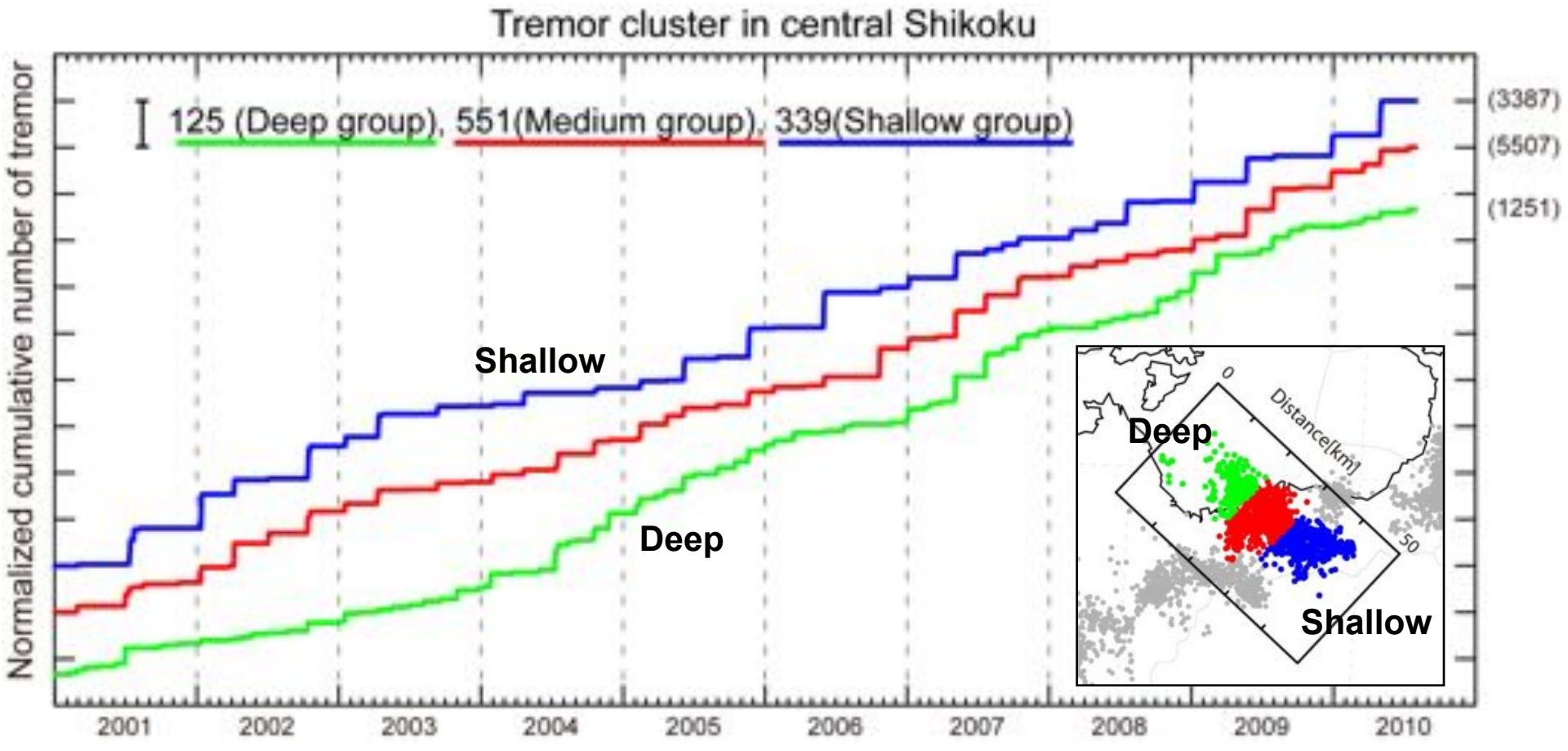
Wech et al.(2009 JGR)

Cumulative number of tremor in western Shikoku



- Shallower side – major activity occurs at longer interval
- Deeper side – minor activity occurs frequently at shorter interval

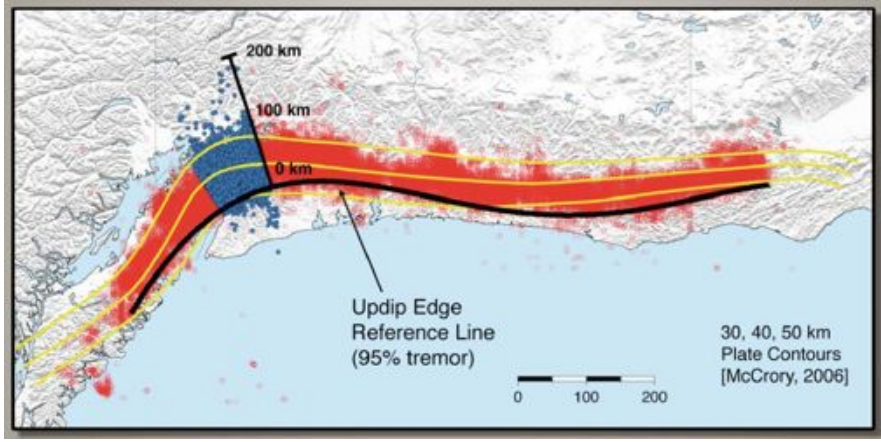
Cumulative number of tremor in central Shikoku

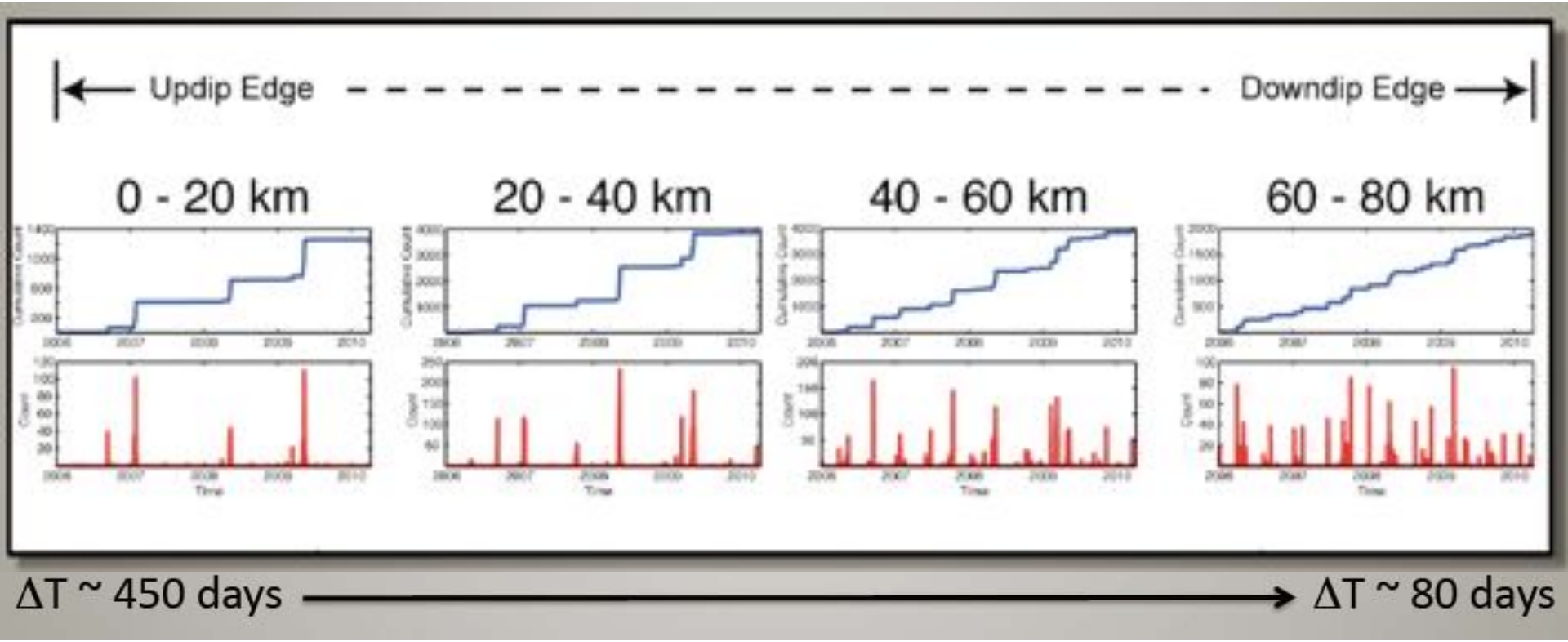


- Shallower side – major activity occurs at longer interval
- Deeper side – minor activity occurs frequently at shorter interval

Depth dependency of tremor recurrence in Cascadia

Wech（2010）





Observation

Depth dependency of tremor activity

- Bimodal distribution in some regions
- **Recurrence interval:** shorter according to depth
- **Updip activity:** modulated by episodic SSE
- **Downdip activity:** continuously

Consistent with Cascadia and SAF

Interpretation

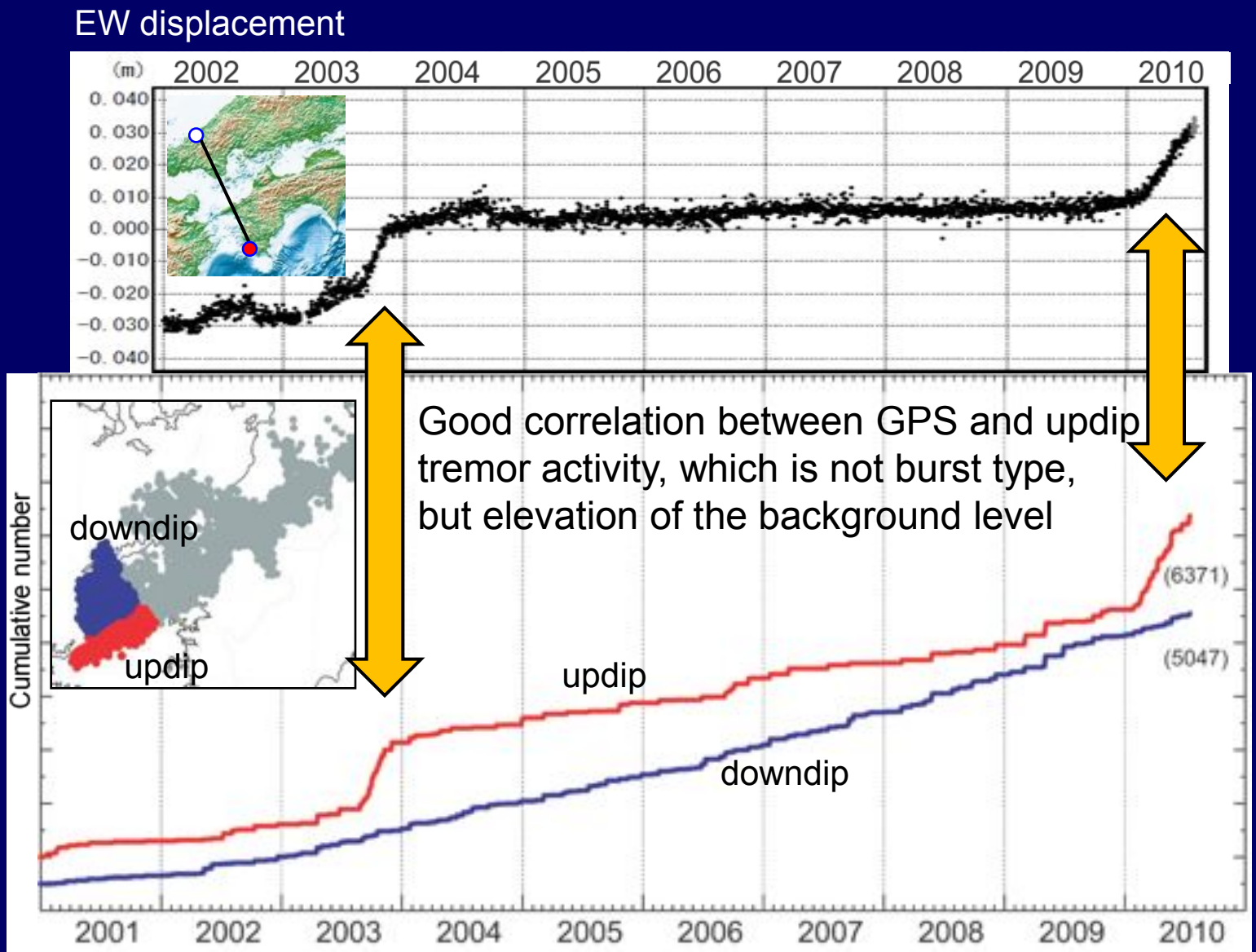
-frictional property weakening with depth and temperature

- pore fluid pressure increasing with depth

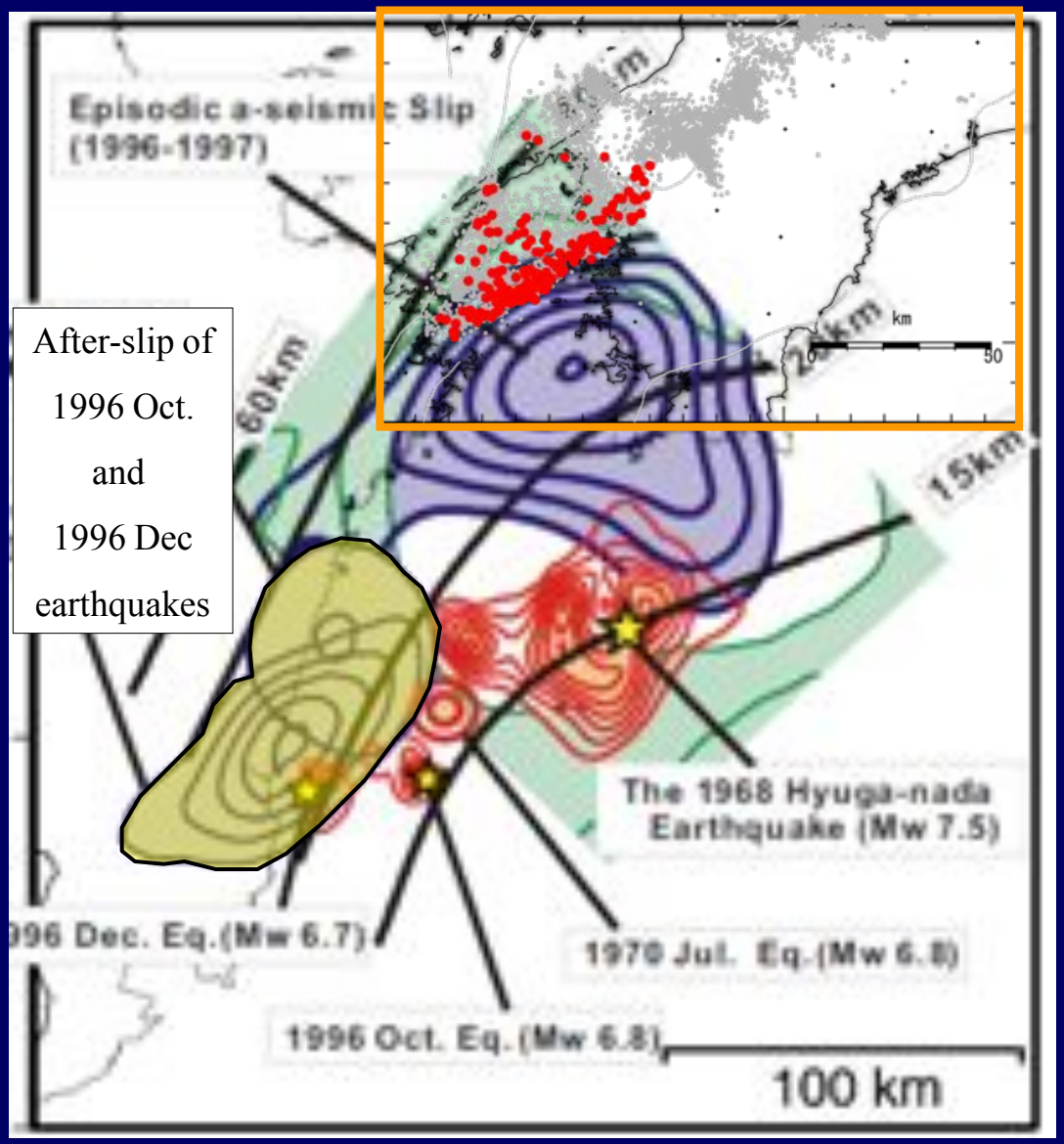
On-going Long-term SSE and tremor in Bungo channel

GPS

Tremor



Tremor location and long-term SSE slip area



Yagi and Kikuchi (2003)

- Tremor epicenters during 2003/9/3-11/1

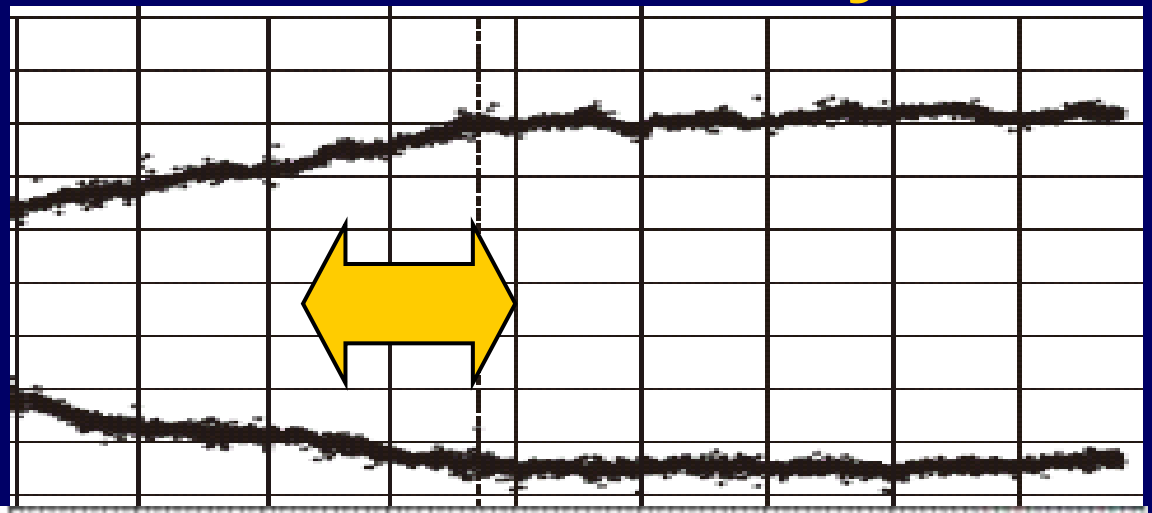
Slip distribution of 1997 long-term SSE (Yagi and Kikuchi,2003)

Updip tremor aligned on the downdip edge of long-term SSE

--> Both source areas are neighbor each other.

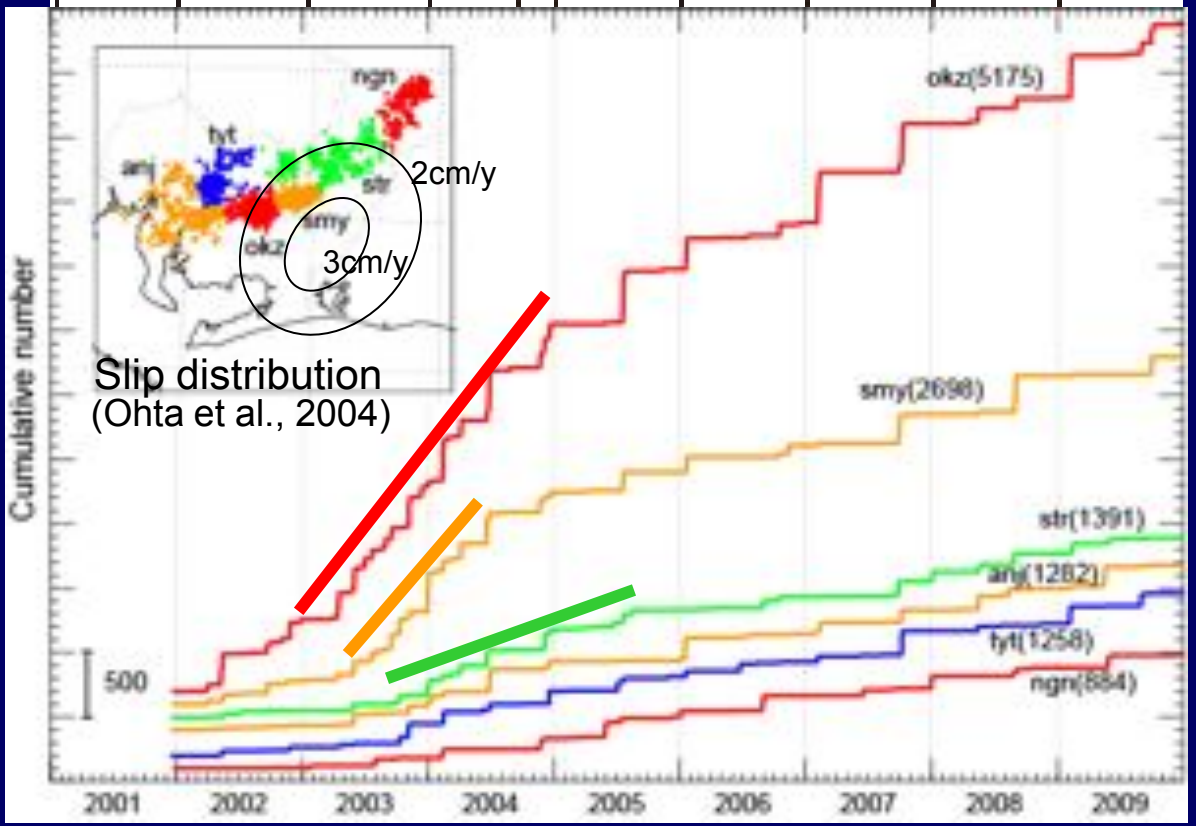
The long-term SSE triggers nearest tremor.

Tremor activated by Tokai long-term SSE



GPS

accelerated in 2003~04



Tremor

Updip tremor groups of smy and okz are well activated during acceleration of SSE.

Summary

- Depth-dependency of recurrence interval
  - Megathrust earthquake ~ 100 years
  - Long-term SSE ~ 10 years
  - Short-term SSE with tremor ~ 0.5 years
- Within tremor zone
  - Recurrence becomes shorter according to depth.
  - Updip tremor occurs with longer interval.
  - Downdip activity is continuous with shorter interval.
- Long-term SSE triggers neighbor tremor.

Summary model

Various slip regime on plate interface