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

<table>
<thead>
<tr>
<th>Year</th>
<th>Interval</th>
<th>Year</th>
<th>Interval</th>
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</thead>
<tbody>
<tr>
<td>1361</td>
<td>137y</td>
<td>1498</td>
<td>107y</td>
</tr>
<tr>
<td>1605</td>
<td>102y</td>
<td>1707</td>
<td>147y</td>
</tr>
<tr>
<td>1854</td>
<td>90y</td>
<td>1944/46</td>
<td></td>
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</tbody>
</table>

Philippine Sea Plate

6cm/y

Nankai Trough

32 hours

2 years
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
Slow earthquakes in southwest Japan

Near Nankai Trough

Characteristic time (tc)

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

Shallow Very Low Frequency Earthquake (tc:10 sec)

Accretionary prism

Nankai Trough

Philippine Sea plate
Slow earthquakes in southwest Japan

- **Short-term slow slip**
  - Deep VLF earthquake
    - non-volcanic tremor

- **Long-term slow slip**

**Map Details**:
- **Nankai Trough**
- **Nankai Seismogenic zone**
- **Philippine Sea Plate**: 6cm/y
- **Boso SSE**
- **Tokyo**
- **Shallow VLF earthquake**
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)

- 100 days
- 1 day
- 1000 seconds (1000 sec)
- 10 seconds
- 0.1 seconds

### Observation

Downdip side

- Short-term slow slip event (tc: 2~6 days)
- Deep Very Low Frequency Earthquake (VLF) (tc: 20 sec)
- Deep Low Frequency Tremor (tc: 1.5~5 Hz)

Observation:

- Tiltmeter/strainmeter
- LP seismometer
- SP seismometer

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**Nankai Trough**

**Philippine Sea plate**

**Seismogenic Zone**

**Transition Zone**

**Stable Sliding**

**Short-term SSE VLF Tremor**
Tremor and Low Frequency Earthquake (LFE)

Cross sectional view in western Shikoku

Based on JMA catalog

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)

Precise relocation of LFE in Tokai

Kato et al. (2010)

Visit poster #61
Deep Very Low Frequency (VLF) Earthquake
[Seismograms]

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

[Location and Mechanism]

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

Thrust type mechanism around the plate interface

Ito et al. (2007)
Short-term Slow Slip Event (SSE)

[Tilt change and tremor activity in western Shikoku]

Obara et al. (2004)

Characteristic time scale: 2~6 days

Tilting activity

Tilting

2 years

Tremor activity

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

- Characteristic time (tc)
  - 1000 sec
  - 10 sec
  - 0.1 sec
  - 1 day
  - 100 days

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

Observation:
- GPS

Downdip side

- Long-term Slow Slip Event (SSE)

- Short-term SSE
  - VLF Tremor

- Stable sliding

- Transition zone

- Seismogenic zone

Nankai Trough

Philippine Sea plate

Tokai

Bungo channel
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**

- **1997 episode**
  - East / mm
  - 1997 1998 1999

- **2003 episode**
  - East / mm
  - 2002 2003 2004

- **2010 episode**
  - East / mm
  - 2008 2009 2010

**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

SSE Fault for 2007 episode

1923 Kanto Eq (M7.9)

Tokyo
Boso Peninsula

SSE fault geometry
Slip
Regular earthquake during SSE

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

Cross sectional view of Boso SSE

Boso SSE

<table>
<thead>
<tr>
<th>Year</th>
<th>seismic swarm</th>
<th>Tilt</th>
<th>GPS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1983</td>
<td>O</td>
<td>△</td>
<td>O</td>
</tr>
<tr>
<td>1990</td>
<td>O</td>
<td>△</td>
<td>O</td>
</tr>
<tr>
<td>1996</td>
<td>O</td>
<td>△</td>
<td>O</td>
</tr>
<tr>
<td>2002</td>
<td>O</td>
<td>△</td>
<td>O</td>
</tr>
<tr>
<td>2007</td>
<td>O</td>
<td>O</td>
<td>O</td>
</tr>
</tbody>
</table>

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

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

![Map showing locations of SSE types: Tokai, Boso, Bungo channel]
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 distribution at up- and down dip sides
- Isolated tremor clusters
- Along-dip streaks
Bimodal Tremor coincident with active SSE, VLF

Short-term slow slip event
(Sekine et al. 2010 JGR)

Very low frequency earthquake
(Ito et al. 2009 JGR)
Comparison of tremor catalogs in western Shikoku

Ide (2010)

Downdip edge

Gap

Obara et al. (2010)

JMA-LFE
Space-time distribution of tremor and deep VLF

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

Range of each segment

Average of recurrence interval (month)

2 4 6 8

Shikoku

Tokai

Kii

Nankai trough
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 in minor episodes concentrating at deeper side

within minor episode (shorter than 12 hours)

Tremor distribution in Kii/Tokai

within major episode (longer than 24 hours)

Tremor in major episodes distributed in entire region.

Tremor in minor episodes concentrating at deeper side
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

Inter-ETS tremor is located at deeper side.

Wech et al. (2009 JGR)
Cumulative number of tremor in western Shikoku

- Shallow side – major activity occurs at longer interval
- Deeper side – minor activity occurs frequently at shorter interval
Cumulative number of tremor in central Shikoku

- Shallow 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)

ΔT ~ 450 days               ΔT ~ 80 days
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

Good correlation between GPS and updip tremor activity, which is not burst type, but elevation of the background level.
Tremor location and long-term SSE slip area

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

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

Long-term SSE (~10y interval)
Megathrust seismogenic zone (100y interval)
Deep slow earthquakes (Transition zone)

Shallow VLF

Mantle wedge
Continental lower crust

Short-term SSE with Tremor and VLF (~0.5y interval)
Continuous tremor activity

Gap

Tremors triggered by long-term SSE

Subduction of oceanic plate

Deep slow earthquakes (Transition zone)