Review

Characteristic activities of slow earthquakes in Japan

By Kazushige OBARA*1,†

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Abstract: Slow earthquakes are a recently discovered phenomenon that mainly occur updip and downdip of the seismogenic zones of great earthquakes along the subducting plate interface. The spatiotemporal activity of various slow earthquakes occurring in the Nankai subduction zone is characterized by along-strike heterogeneity and along-dip systematic changes. Various slow earthquakes are horizontally distributed at their own depths and along-strike segments can be observed with respect to this distribution downdip of the locked zone; however, slow and great earthquakes occur in the same depth range near the Nankai Trough and Japan Trench axes. The frequently observed spatiotemporal interactions between different slow earthquakes can be attributed to their sensitivity and the stress transfer of the surrounding areas. This stress transfer is expected to extend to the adjacent sections in the seismogenic zone. Therefore, precise monitoring of slow earthquakes is important for future evaluations of great earthquakes, which requires the long-term maintenance and continuous improvement of the high-quality observation networks.

Keywords: slow earthquake, subduction zone, tremor, very-low-frequency earthquake, slow slip event

1. Introduction

The term “slow earthquake” is used for various types of fault slip phenomena having longer characteristic times than those of regular earthquakes. Two types of slow earthquakes, i.e., long-term slow slip events (SSEs) and low-frequency tremor (see Table 1), were initially discovered in southwest Japan, just downdip of the seismogenic zone of great earthquakes along the subducting Philippine Sea plate boundary, by Hirose et al.1) and Obara,2) respectively. Subsequently, various types of slow earthquakes have been detected in many tectonic settings around the world, especially the subduction zones along the Pacific Rim (e.g., Cascadia, Mexico, Alaska, New Zealand, Costa Rica, and Chile). Slow earthquakes have also been observed along the strike-slip transform fault systems, such as the San Andreas Fault,3) and along an arc-continent collisional zone, such as beneath the Central Range in Taiwan.4)

Friction experiments5) and thermal modeling studies6) suggest that the source region of the slow earthquake corresponds to the transition zone between the locked and stable sliding zones of the plate boundary fault. This transition zone is also expected updip of the locked zone based on the friction modeling of the subducting plate interface.5) Shallow slow earthquakes have been detected in this shallow transition zone using inland broadband seismograph networks7) and ocean-bottom observation instruments.8) Therefore, slow earthquakes are a phenomenon related to the transition from fast coseismic slip to stable sliding along the subducting plate interface.

This paper presents an overview of the slow earthquake phenomenon in Japan and summarizes the development and deployment of observational networks as the background for the discovery of slow earthquakes. Slow earthquakes are classified into various types based on their characteristic timescale and depth relative to those associated with the seismogenic zone of great earthquakes. Further,
each type of slow earthquake is explained based on its
basic characteristic activity and discovery process.
The spatiotemporal activity patterns used to char-
acterize the various types of slow earthquakes are
also discussed with respect to the along-strike
segmentation and along-dip systematic change.
Finally, the spatiotemporal interactions between
different types of slow earthquakes may be related
to the interactions between slow and great earth-
quakes; hence, the spatiotemporal interactions are
discussed in this study.

2. Discovery of slow earthquakes in Japan

The discovery of slow earthquakes can be related
to the development and deployment of improved
observation networks. The development of two
observation networks in Japan, i.e., the high-
sensitivity seismograph network (Hi-net) operated
by the National Research Institute for Earth Science
and Disaster Resilience (NIED)\(^9\) and the global
navigation satellite system (GNSS) earth observation
network system (GEONET) operated by the Geo-
spatial Information Authority of Japan (GSI),\(^10\)
considerably contributed to the scientific study of
slow earthquakes. Both the aforementioned obser-
vation networks were installed across the Japanese
islands after the Kobe earthquake of 1995, and the
average spacing between two stations was 20–30 km.
Such dense observation networks considerably im-
prove the signal coherency and detection capability
of slow earthquakes. The data are transmitted in
real time and stored on data servers that evolve with
the progress of the data transmission and storage
technology. Each Hi-net seismic station includes a set
of high-sensitivity seismometers and accelerometers
encased in a sensor capsule and installed at the base
of a borehole. The accelerometer serves as a broad-
band seismometer and tiltmeter.\(^11\) The coupling of
such a broad observation window with a high signal-
to-noise ratio (because of the low levels of cultural
noise in deep boreholes) is useful to detect various
types of slow earthquakes having different character-
istic timescales and weak amplitudes.

Two advances in the development of observa-
tional instruments have considerably contributed to
recent discovery of shallow slow earthquakes in
an offshore environment. One is the improvement of
temporarily deployed ocean-bottom observation in-
struments equipped with broadband sensors and
long-life batteries for increasing the spectrum window
and observation time window, respectively. The
second advancement is the construction of a cabled
seafloor observational system, in which the stations
are connected using an optical fiber transmitting
data in real time to an inland data center. The Dense
Ocean floor Network system for Earthquakes and
Tsunamis (DONET), comprising approximately 50
observation points, was constructed by the Japan

| Table 1. Glossary of the terms for slow earthquakes used in this paper |
|---------------------------------|
| **Low-frequency tremor**        |
| Weak seismic vibrations lasting from minutes to days with a predominant frequency of 1–10 Hz, which is lower than that of a regular microearthquake having a comparable amplitude to that of tremor. Tremor comprises swarm activities of LFE. |
| **Low-frequency earthquake (LFE)**        |
| A seismic event radiating a waveform with a predominant frequency of 1–10 Hz, which is lower than that of a regular earthquake having a comparable amplitude. LFEs are mainly distributed in volcanic areas and subducting plate interfaces. The LFEs along the subducting plate interface are considered an elementary process of low-frequency tremor. |
| **Very-low-frequency earthquake (VLFE)**        |
| A seismic event radiating a waveform with a predominant period of 10–100 s associated with very weak amplitudes of high-frequency components. |
| **Slow slip event (SSE)**        |
| A transient slip along the fault plane with no radiation of a seismic wave. |
| **Long-term SSE**        |
| SSEs with a duration ranging from months to years. |
| **Short-term SSE**        |
| SSEs with a duration ranging from days to weeks. |
| **Episodic tremor and slip (ETS)**        |
| Simultaneous occurrence of short-term SSEs, VLFEs, and tremor. |
Agencies for Marine-Earth Science and Technology (JAMSTEC) offshore to the southeast of the Kii Peninsula for evaluating the potential future great earthquakes in Nankai. The seafloor observation network for earthquakes and tsunamis along the Japan Trench (S-net), which comprises approximately 200 seismometers over the entire offshore region to the east of northern Japan (1000 km N–S and 300 km E–W), was constructed by NIED after the Tohoku earthquake in 2011. The development and deployment of such a seafloor observation system contribute to the monitoring of slow earthquakes and forecasting of the strong ground motion and tsunami generated because of great earthquakes.

3. Classification of slow earthquakes

Slow earthquakes include various fault slip phenomena having different characteristic timescales. The combination of different types of slow earthquakes and their associated activity patterns vary along many subduction zones along the Pacific Rim (Fig. 1). Therefore, the different characteristics of slow earthquakes may be used to characterize each subduction system. The Nankai subduction zone in Japan is the region at which most types of slow earthquakes can be observed (Fig. 2). Therefore, the observations obtained from the Nankai subduction zone are used to classify slow earthquakes in this study. Almost all the slow earthquakes are detected at the updip and downdip extensions of the locked seismogenic zone on the subducting plate interface. These slow earthquakes occur over a broad range of characteristic timescales ranging from seconds to years. Therefore, the depth of a given slow earthquake relative to that of the locked zone and the characteristic timescale are used to classify slow earthquakes (Fig. 3). The slow earthquakes are classified as deep or shallow depending on whether they are detected below or above the locked zone. In addition, they are classified as seismic or geodetic based on whether they are seismically detected as ground shaking using seismometers or geodetically detected as crustal deformation using GNSSs, strainmeters, or tiltmeters, respectively. The seismic slow earthquakes are mainly classified as low-frequency tremor, with a predominant frequency of several hertz, and very-low-frequency earthquakes (VLFEs), with a predominant period of several tens of seconds. The geodetic slow earthquakes are mainly divided into long-term SSEs, with a typical duration of several months to years, and short-term SSEs, with a typical duration of some days to weeks (Fig. 4).

3-1. Deep slow earthquakes. In the Nankai Trough region, long-term SSEs are distributed next to the locked zone at the downdip extension of the seismogenic zone. The low-frequency tremor, VLFEs, and short-term SSEs are detected at the deepest section of the deep transition zone. These three phenomena usually occur simultaneously and are termed as “episodic tremor and slip (ETS)” [1]. The Bosso SSEs, which are located at the plate boundary at which the Philippine Sea plate subducts from the Sagami Trough, can be observed at slightly shallower depths when compared with other deep slow earthquakes in the Nankai subduction zone; however, they are defined as deep slow earthquakes because they are located downdip of the Kanto earthquake seismogenic zone.

3-1-1. Low-frequency tremor. Deep low-frequency tremor was initially discovered in 2002 in southwest Japan [2] because of the improved capability of the newly installed Hi-net in detecting weak shaking phenomena. The tremor exhibited a predominant frequency of 1–10 Hz, lasted for minutes to days, and demonstrated no clear P- or S-wave onset. The waveform pattern was similar to that of volcanic tremor; however, this low-frequency tremor was detected in nonvolcanic areas. Therefore, this tremor was originally termed “nonvolcanic tremor” [2]. This tremor has since been termed as “low-frequency tremor” (because it comprises many low-frequency earthquakes (LFEs)) or “tectonic tremor” (because it reflects a large-scale tectonic activity related to plate subduction).

Tremor is a superposition of the swarm activity obtained from many LFEs. The envelope correlation method was developed to locate the tremor source based on the coherent envelope pattern of the tremor at neighboring stations because it is difficult to precisely identify the onset of the tremor owing to the unclear low-frequency onset of the LFEs. Several researchers have improved the envelope-based methods used to estimate the radiation energy and duration. The Japan Meteorological Agency (JMA) has been applying an ordinary hypocenter determination method by selecting onset phases to develop the LFE catalog. A matched filter method in which the waveforms of the previously detected LFEs are considered to be template events is frequently applied to detect tremor. This method has also been used by JMA to detect LFEs since 2018.

The tremor epicenters are distributed along the depth contours of the subducting Philippine Sea.
plate, spanning a zone with an approximate area of 600 km × <50 km from the southern Nagano Prefecture to the Bungo Channel. This belt-like tremor zone is separated into several segments. Generally, a swarm-like tremor activity occurs episodically at an approximately regular recurrence interval in case of...
Such active tremor episodes are associated with short-term SSEs, which are described in the section 3-1-3. The focal mechanism of the tremor is unclear because of the absence of clear onset. However, based on stacking analysis for LFEs, the focal mechanism of the LFEs is consistent with...
reverse faulting along the subducting plate interface.\textsuperscript{20} The tremor episodes usually migrate within each segment at approximately 10 km/day parallel to the strike of the plate geometry,\textsuperscript{21} and the migration rarely extends to the neighboring segments. Other tremor migration modes can also be observed because the active tremor episode associated with along-strike migration at approximately 10 km/day is occasionally accompanied by the along-strike migration of the tremor propagating backward at order of 100 km/day (rapid tremor reversal (RTR))\textsuperscript{21} and the along-dip migration at order of 1000 km/day.\textsuperscript{22,23} 

One of the important characteristics of tremor is that it can be triggered by external stress changes. This suggests that tremor is very sensitive. There are two distinct triggering phenomena. One such phenomenon is triggering by seismic wave originating from other earthquakes. The surface waves propagating from large teleseismic earthquakes frequently trigger tremor.\textsuperscript{24} The tremor bursts triggered by the surface waves are repeatedly activated at an interval of several tens of seconds, which is associated with each phase of the long-period surface waves. The triggered tremor is easier to detect than the ambient tremor because we can focus only on short time windows that include the surface wave packets from teleseismic earthquakes; further, we attempt to estimate the enhancement of the coherent amplitude corresponding to the surface wave phases. Both long-period surface waves and high-frequency body waves trigger tremor. Some tremor bursts are observed approximately 5 minutes after the arrival of the body waves originating from intraslab earthquakes occurring just beneath the triggered tremor activity.\textsuperscript{25} Tidal modulation is another triggering phenomenon. Repeated tremor activation at 12- or 24-h intervals is commonly observed during active tremor episodes associated with short-term SSEs.\textsuperscript{26} 

3-1-2. Deep VLFEs. Deep VLFEs, with a predominant period of several tens of seconds, were discovered in 2007 based on their association with active ETS\textsuperscript{27} by applying the GRiD-MT (Grid-based Realtime Determination of Moment Tensors) method.\textsuperscript{28} Further, the focal mechanism of VLFEs was estimated via centroid moment tensor analysis and the geometry and motion of the subducting Philippine Sea plate. This is one of the key lines of evidence that prove that ETS is an interplate shear-slip phenomenon. VLFEs are mainly events with $M_W < 4$. Deep VLFEs are heterogeneously concentrated within areas in the belt-like tremor source zone,\textsuperscript{29} and tremor is homogeneously distributed across this zone.\textsuperscript{18} The stacking analysis of broadband seismograms with reference to the tremor time revealed that the VLFE distribution, including weak-amplitude events, covered the entire tremor source zone.\textsuperscript{30} Deep VLFEs have been comprehensively detected in western Shikoku, and long-term temporal variations have been observed with respect to the VLFE seismicity\textsuperscript{31} via matched filter analysis based on the synthetic waveforms calculated from the focal mechanisms of deep VLFEs.\textsuperscript{30} 

3-1-3. Short-term SSEs. SSEs were discovered in Cascadia in 2001 using the regional GPS network,\textsuperscript{32} and an association between SSEs and tremor episodes was discovered in 2003.\textsuperscript{13} The discovery of ETS in Cascadia resulted in the expectation that similar SSEs associated with tremor would occur in southwest Japan, and ETS was discovered at western Shikoku in 2004.\textsuperscript{19} Finally, a tiny crustal deformation was detected in southwest Japan using tiltmeters.\textsuperscript{11} These SSEs had durations ranging from some days to a week and were associated with active tremor episodes. The slip parameters were estimated to denote reverse faulting along the upper boundary of the subducting Philippine Sea plate,\textsuperscript{19} which is the same focal mechanism as that of the interplate megathrust earthquakes. The duration was considerably less than those of the previously discovered SSEs in the Bungo Channel,\textsuperscript{1} which are mentioned in the next section. Therefore, the SSEs associated with tremor have been termed “short-term SSEs” and the Bungo Channel SSEs have been termed “long-term SSEs”\textsuperscript{33} to distinguish between SSEs with different timescales. The short-term SSEs in southwest Japan were initially detected using the Hi-net borehole tiltmeter because of the smaller magnitude of these SSEs compared with those in Cascadia. Subsequently, they were detected using borehole strainmeters operated by JMA and the National Institute of Advanced Industrial Science and Technology. Short-term SSEs have since been detected by GEONET after the development of a refined detection method and achieving improvements in solving the coordinate value.\textsuperscript{34} 

The estimated source fault of short-term SSEs approximately corresponds to the tremor distribution for each episode. Short-term SSEs occur periodically at a nearly constant recurrence interval associated with the tremor episode at each ETS segment. The SSEs in western Shikoku occur at an approximately 6-month interval, with these approximately $M_W 6$ events resulting in 1–2 cm of slip.\textsuperscript{19} The spatial
distribution of SSEs usually migrates with tremor.
The spatiotemporal evolution analysis of short-term
SSEs indicates that the tremor epicenters are well
collocated with the peaks in slip distribution.\textsuperscript{35} This
observation is similar to that in Cascadia.\textsuperscript{36} Therefore,
tremor is caused by a seismic failure at small
seismic patches embedded on the short-term SSE
fault plane because of stress loading by the surrounding
transient slip. This model suggests that the
migration of the tremor may reflect the propagation
of the short-term SSE rupture front\textsuperscript{36} and supports
that tremor is a proxy for SSEs.\textsuperscript{37} Tremor is the
easiest slow earthquake to detect among the ETS
phenomena because of its properties and detectability
in observational networks; therefore, tremor is
frequently treated as a proxy for ETS.

3-1-4. Long-term SSEs. Long-term SSEs were
discovered in the Bungo Channel\textsuperscript{4} and Tokai
region\textsuperscript{38} shortly after the deployment of GEONET
in Japan. Long-term SSEs have since been detected
at other locations, including the Kii Channel,\textsuperscript{39}
central Shikoku,\textsuperscript{40,41} northern Miyazaki Prefecture,\textsuperscript{42,43}
and southern Miyazaki Prefecture.\textsuperscript{44}
These long-term SSEs are commonly observed
between the locked and ETS zones along the
subducting plate interface in southwest Japan.

Each long-term SSE has its own unique property
(recurrence interval, duration, and size) in each
region. The M\textsubscript{W} 6.8-class long-term SSEs in the
Bungo Channel have a duration of six months and a
recurrence interval of 6–7 years (1997, 2003, and
2010). A similar-sized SSE could be observed in 2019;
however, two small SSEs occurred in 2014 and 2016
during this inter-SSE period. Therefore, these small
SSEs may release a small amount of accumulated
stress, delaying the occurrence of large SSEs.

A M\textsubscript{W} 7-class long-term SSE was observed from
mid-2000 to mid-2005 near Lake Hamana in the
Tokai region by GEONET.\textsuperscript{45} The crustal deformation
owing to the long-term SSE was detected using the
tiltmeter installed at the Mikkabi station. A similar
ground tilting was previously observed at the
same tilt station from 1989 to 1991.\textsuperscript{46} Furthermore,
a small-sized long-term SSE occurred in the
same region from 2013 to 2015.\textsuperscript{47} Therefore, the
recurrence behavior of the long-term SSEs in Tokai
is irregular.

3-1-5. Boso SSEs. SSEs occur at an approximately 6-year interval along the eastern coastline
and offshore area of the Boso Peninsula, central part
of Japan. They usually have a size of M\textsubscript{W} 6.5 with a
duration of approximately one week. The SSE fault is
located at a depth of approximately 10–20 km. One
of the most characteristic phenomena of the Boso
SSEs is their association with regular earthquake
swarms, usually including M 4–5-class earthquakes
and repeating earthquakes at the downdip edge of
the Boso SSE source fault region.\textsuperscript{48} Therefore, the
occurrence of M 4–5-class medium-sized earthquakes
during swarm activity can be predicted immediately
after the detection of the initiation of the Boso SSEs.
The recurrence interval of the Boso SSEs decreased
gradually before the Tohoku earthquake in 2011;
however, the recurrence interval was reset by the
Tohoku earthquake.\textsuperscript{49} Repeated earthquakes were
detected during the active aftershock period of the
Tohoku earthquake in March 2011 even though there
was no meaningful geodetic signal owing to the large
coseismic slip and afterslip.\textsuperscript{49} Thus, a small SSE
may have occurred during the Tohoku earthquake
sequence in 2011. Boso SSEs substantially occurred
in November 2011, January 2014, and June 2018, and
the recurrence interval was observed to gradually
increase after the Tohoku earthquake. Precise
spatiotemporal evolution analysis revealed that the
migration of the earthquake swarms was associated
with slip propagation and that the 2014 SSE was
preceded by slow slip acceleration that began one
month before the rapid acceleration of the SSE.\textsuperscript{50}

3-2. Shallow slow earthquakes. Various slow
earthquakes were detected between the updip edge
of the seismogenic zone of great earthquakes and the
Nankai Trough axis. Shallow slow earthquakes were
also detected along the Japan and Kuril trenches
and near the Ryukyu Islands. The detection of these
shallow slow earthquakes in several offshore regions
over the previous decade can be attributed to the
recent development of the seafloor observation
technology and the deployment of the seafloor
observation instruments.

3-2-1. Shallow VLFEs. Shallow VLFEs were
initially reported in 2003 in the offshore region in
southwest Japan using the NIED F-net broadband
continuous seismograph data,\textsuperscript{51} and several spatio-
temporal clusters of shallow VLFEs could be
observed in the landward section of the Nankai
Trough axis via back-projection analysis using the
continuous waveform data obtained from the Hi-net
high-sensitivity accelerometers.\textsuperscript{7} The discovery of
shallow VLFEs led to the discovery of deep
VLFEs.\textsuperscript{37} Subsequently, shallow VLFEs have been
detected at the Nankai Trough, Ryukyu Islands,\textsuperscript{52}
offshore Tokachi,\textsuperscript{53} and Japan Trench.\textsuperscript{54} The focal
mechanism of the shallow VLFEs offshore to the
southeast of the Kii Peninsula was estimated to denote a reverse fault solution with a steep dip angle compared with that of the plate interface near the trench axis. This was interpreted as a slow rupture along a spray fault and/or out-of-sequence thrust fault within the accretionary prism.\textsuperscript{55) }

The aforementioned research results were derived using inland broadband observation networks. Recently, shallow VLFEs have been observed using temporal and permanent seafloor observation networks. The shallow VLFEs offshore to the southeast of the Kii Peninsula detected by closely deployed ocean-bottom broadband seismometers indicated reverse fault mechanisms with nearly horizontal fault planes.\textsuperscript{56) }Thus, shallow VLFEs are shear-slip phenomena along the decollement or plate boundary. Many shallow VLFEs and tremor have been detected using the DONET cabled seafloor observation system.\textsuperscript{57) }One of the important results obtained using DONET is the discovery of slow earthquakes with a predominant period of 1–10 s.\textsuperscript{58) }This period corresponds to a spectrum gap between tremor and VLFEs owing to the large amplitude of the microseisms; however, such new events were only observed after conducting a stacking analysis of many tremor and VLFEs activated after the April 2016 M\textsubscript{W} 6-class interplate earthquake. This proves that slow earthquakes involve continuous spectrum components.

A matched filter analysis in which the synthetic template events obtained based on the plate geometry and motion has enabled the comprehensive detection of shallow VLFEs in the Japan Trench region.\textsuperscript{59) }They revealed temporal activation and inactivation immediately after the 2011 Tohoku earthquake in the afterslip and coseismic slip regions, respectively. The cumulative number of shallow VLFEs in the afterslip region of the 2003 Tokachi-oki earthquake was similar to the crustal deformation pattern that can be attributed to the afterslip.\textsuperscript{53) }These observations suggest that the shallow VLFE activity reflects an interplate transient slip.

Shallow VLFEs are occasionally triggered by other phenomena such as nearby major earthquakes, like as triggered deep tremor. For example, shallow VLFEs were activated in Hyuga-nada after the 2003 Tokachi-oki earthquake and offshore to the southeast of the Kii Peninsula after the occurrence of a M\textsubscript{W} 7.5 intraslab earthquake in the same area.\textsuperscript{53) }However, the shallow VLFE seismicity in the Ryukyu Islands was tidally modulated, denoting maximum activation during low tide and a tidal response exhibiting regional and seasonal dependence.\textsuperscript{60) }

3-2-2. Shallow tremor. The predominantly high-frequency composition of tremor indicates that it is strongly attenuated with the increasing distance. Consequently, \textit{in situ} offshore observations are required to detect shallow tremor even though the long-period seismic signal from shallow VLFEs efficiently propagates to distant inland broadband seismic stations. Shallow tremor near the trench axis was initially discovered in 2009 offshore to the southeast of the Kii Peninsula by temporarily deploying ocean-bottom seismometers,\textsuperscript{61) }and there was no clear evidence with respect to the collocation of the shallow tremor and VLFEs. An active shallow tremor episode lasting for one month was detected based on the temporary offshore seismic observations in Hyuga-nada.\textsuperscript{59) }This shallow tremor episode was spatiotemporally consistent with the shallow VLFE activity detected by the inland broadband observation network. This is the first result indicating the coincident occurrence of shallow VLFEs and tremor.

Furthermore, the shallow tremor episode included two migration modes with different speeds based on the very precise hypocentral location of the shallow tremor because of the \textit{in situ} observation area. One is northward migration at approximately 20 km/day, which is similar to the along-strike migration of the deep tremor at approximately 10 km/day. The other is faster migration that propagates backward at order of 100 km/day, which is similar to the RTR detected during deep tremor episodes.\textsuperscript{21) }The common characteristics associated with the coincident occurrence of VLFEs and tremor and the existence of multiscale migration modes observed in the shallow and deep sections suggest that seismic slow earthquakes are associated with SSEs in the shallow section, similar to the relation between the seismic slow earthquake phenomenon and short-term SSEs in the deeper section.

Shallow tremor was detected by the ocean-bottom seismometers temporarily deployed near the Japan Trench region before the Tohoku earthquake in 2011.\textsuperscript{62) }The S-net seafloor cabled observation system, operated by NIED, has considerably contributed to the detection of the shallow tremor along the Japan Trench.\textsuperscript{63) }\textsuperscript{64) }The properties of the shallow VLFEs are similar to those of deep tremor because shallow tremor is associated with shallow VLFEs and indicates clear along-strike migration.

3-2-3. Shallow SSEs. The ocean-bottom pressure gauges detected two shallow SSEs with respect to the rupture area of the Tohoku earthquake in 2008 and 2011, before its occurrence.\textsuperscript{65) }Furthermore, two
foreshock sequences that occurred one month and two days before the 2011 Tohoku earthquake were associated with migration toward the initial rupture area of the Tohoku earthquake. These two foreshock sequences included repeating earthquakes, such that the shallow SSEs occurred as a background foreshock process. The repeating migration sequences of the SSE slip front may have resulted in additional stress with respect to the initial rupture area of the Tohoku earthquake in 2011, triggering the great earthquake rupture.

Borehole pore-pressure gauges were installed offshore to the southeast of the Kii Peninsula, and detected the pressure changes associated with the occurrence of shallow VLFEs and tremor observed by DONET. These pressure changes indicate shallow SSEs with reverse faulting near the Nankai Trench axis. Furthermore, the pressure-change time series is consistent with the cumulative seismic moment of shallow VLFEs, indicating that shallow SSEs and VLFEs can be attributed to a common slip process on the same fault plane.

The heterogeneous distribution of interplate coupling in the offshore region of the Nankai Trough was estimated based on the results of a widely deployed seafloor acoustic GNSS network. Furthermore, transient seafloor displacement was observed near the Kii Channel region at a couple of acoustic GNSS stations from 2018 to 2020, and the SSE fault plane was estimated at the Nankai Trough. A similar long-term shallow SSE was observed in 2009 in the same region.

SSEs with an approximate $M_W$ of 6.7 were initially detected at Iriomote Island in the Ryukyu Islands between Kyushu and Taiwan. These SSEs usually last for approximately one month and have an interval of six months. Furthermore, many short-term SSEs with an approximate $M_W$ of 6.4 and a duration of several days have been detected near the Okinawa and other nearby islands. Many SSEs in the Ryukyu Islands are classified as deep slow earthquakes; however, some SSEs may be classified as shallow slow earthquakes because they are located near the Ryukyu Trench and denote interactions with shallow VLFEs.

4. Characteristic spatiotemporal activity and interaction of slow earthquakes

Each type of slow earthquake in the Nankai subduction zone is mainly distributed horizontally along the strike of the subducting plate geometry at nearly the same depth and is usually segmented. These slow earthquakes are characterized by along-dip systematic changes and along-strike heterogeneities. Thus, each phenomenon is controlled by a unique frictional property at the specified geophysical and/or geological condition. The slow earthquakes in the Nankai subduction zone are mainly separated into shallow and deep phenomena relative to the depth of the seismogenic zone of great earthquakes. This bimodal depth distribution is consistent with the depth-dependent frictional properties along the subducting plate interface, corresponding to the existence of a conditionally stable field representing the transition between unstable and stable regions in the shallow and deep sections of the seismogenic zone. In this section, the characteristic properties of slow earthquakes, especially those in the Nankai subduction zone, are reviewed by considering the spatiotemporal interaction between slow earthquakes.

4-1. Along-strike heterogeneity of deep slow earthquakes.

4-1-1. Segmentation of deep ETS. ETS, which is the deepest interplate slow earthquake phenomenon been recognized to date and is well observed in the Nankai and Cascadia subduction zones, shows an along-strike variation roughly characterized by two different scale lengths: segment scale and subsegment scale.

The spatiotemporal properties of ETS are characterized by its segmentation and periodicity even though the scales vary in both space and time. The along-strike extensions of the ETS zone are 600 and 1,200 km in Nankai and Cascadia, respectively. However, the entire ETS source region is mainly divided into segments with different recurrence intervals similarly for both subduction zones. Each segment group includes some small segments, where-in ETS occurs at a similar recurrence interval but with different timing. There are three main segment groups in Cascadia, with 14-, 19-, and 11-month recurrence intervals in Vancouver Island and northern Washington, southern Washington and Oregon, and northern California, respectively. The ETS in southwest Japan is also divided into three segment groups, with 6-, 3-, and 6-month recurrence intervals in western Shikoku, eastern Shikoku and western Kii Peninsula, and northeastern Kii Peninsula and Tokai, respectively.

The ETS behavior may be controlled by the hanging wall structure. Brudzinski and Allen proposed that the three segment groups of ETS in Cascadia correspond to different geologic terranes.
The recurrence interval and elevation of the large-scale upper plate topography are negatively correlated. However, there is no such relation between the large-scale topography and segmentation of ETS in southwest Japan. Audet and Burgmann recently assembled a global compilation of the Vp/Vs ratio with respect to the hanging wall just above the ETS zone and demonstrated that the ETS recurrence interval was proportional to Vp/Vs. Nakajima and Hasegawa investigated the relation between the tremor location and the three-dimensional seismic velocity structure around the subducting Philippine Sea plate boundary in southwest Japan. They revealed that the P-wave velocity at the bottom of the upper plate was normal just above the tremor region; however, it was low above the tremorless region. This low-velocity body on the hanging wall just above the tremorless region is interpreted as the metamorphism related to fluid enrichment from the subducting slab. Tremor actively occurs just beneath the unmetamorphosed overriding plate because of the impermeable plate interface and enhanced pore fluid pressure.

The segment boundary of ETS illuminated by the multisegment rupture of ETS may be affected by the spatial frictional heterogeneity similar to the relation between the along-strike variation of the fault friction and earthquake faulting. Tremor migration usually occurs within each segment; however, this migration rarely extends to the neighboring segments. The ETS migration pattern is unique for each segment. The tremor episode usually begins from the edge of the tremor gap at Ise Bay and propagates southwestward and eastward in Kii and Tokai, respectively. Such a tremor gap is generally used to define the segment boundary. There are three tremor gaps in southwest Japan, i.e., Ise Bay, Kii Channel, and between the eastern and middle parts of Shikoku. These tremor gaps are always seismically quiet; however, tremor migration can continue smoothly along both sides of a gap. For example, a 2006 tremor episode began in central Kii Peninsula and migrated northeastward, ending at Ise Bay, whereas another tremor episode propagated eastward through the Tokai segment. Both the tremor migration pathways are smoothly connected by a single regression line. These migrating tremor episodes are usually associated with short-term SSEs. Generally, the SSE source faults are estimated based on the spatiotemporal distribution of tremor. However, the SSE source faults can also be estimated in the aseismic portion at Ise Bay, indicating that the tremor patch was not homogeneously distributed on the SSE fault plane, with no or few tremor patches at Ise Bay. The smooth migration of tremor can be frequently observed along both sides of the tremor gap between eastern and middle Shikoku. There is no geodetic evidence to prove the occurrence of short-term SSEs in the gap; however, SSEs may propagate smoothly along the plate interface, and the tremor gap can be attributed to the absence of a tremor patch on the plate interface.

### 4-1-2. Subsegment-scale heterogeneity of ETS

4-1-2. Subsegment-scale heterogeneity of ETS. The ETS comprising tremor, VLFEs, and short-term SSEs does not occur uniformly within each segment; however, it indicates an along-strike variation, which can possibly denote the spatial heterogeneity in the plate boundary zone. The tremor migration is rather homogeneous even though a heterogeneous distribution of VLFEs and short-term SSE faults can be observed in some areas. Similarly, improvements of the tremor detection method, including the estimation of the radiation energy, provide a more heterogeneous distribution similar to that observed in case of VLFEs. The along-strike profiles of the tremor radiation energy and VLFE moment are similar and consistent with the total slip distribution of the short-term SSEs estimated via GNSS analysis, including some discrepancies in the relation between SSEs and seismic slow earthquakes. The general consistency between SSEs and seismic slow earthquakes supports an interpretation for the occurrence of seismic slow earthquakes modulated by aseismic slow slips.

The clear difference in the tremor activity pattern in the western Shikoku region may suggest the along-strike heterogeneity of the tremor patch strength based on the energy information of the tremor catalog. The radiation energy is larger and the occurrence number is smaller than those in the inland region for the offshore Bungo Channel region. Furthermore, many tremor events have been initiated in the offshore Bungo Channel region that has diffusively migrated eastward. The tremor migration velocity is proportional to the radiation energy. The aforementioned observational results are explained using a model in which the tremor patch associated with the spatially heterogeneous strength distribution ruptures in a chain via the stress diffusion process. This model indicates that strong and weak tremor patches are distributed in the offshore and inland regions, respectively.

### 4-1-3. Segmentation of long-term SSEs

Long-term SSEs, which exhibit considerably longer
The along-strike distribution of long-term SSEs is segmented similar to ETS, although the distribution pattern is different. ETS is distributed from the southern Nagano Prefecture to the Bungo Channel and includes some gaps; however, the long-term SSE distribution is considerably heterogeneous, and isolated occurrences from Lake Hamana and continuous occurrences from the Kii Peninsula to the Bungo Channel; however, the tremor activity along the updip part of the tremor zone does not develop into an active episode associated with along-strike propagation. Such a depth-dependent recurrence behavior is explained by the upward stress transfer model proposed by Wech and Creager. The frictional strength is expected to become weaker with increasing depth because of the systematic change in temperature and/or pore fluid pressure. Minor ETS episodes can be readily observed at the downdip edge of the ETS zone because of stress accumulation at the boundary between ETS and stable sliding zones. The frequent occurrence of minor ETS events is initiated in the deep section. Subsequently, the loading of stress onto the shallower section is gradually initiated, and propagation of major ETS episodes to the updip edge can be observed.

4-2-2. Interaction between ETS and long-term SSEs. The long-term SSEs occurring at the updip part from ETS may trigger ETS tremor activity. This triggering effect is considerably dependent on the distance between these slow earthquake phenomena. Obvious interactions can be observed between the long-term SSEs and ETS in the Bungo Channel. The tremor activity along the updip section of the tremor zone, which is the adjacent downdip section of the long-term SSE source fault, is only activated when long-term SSEs occur in the Bungo Channel; however, the tremor activity along the downdip section of the tremor zone is stable and unrelated to the occurrence of long-term SSEs. If the magnitudes of the slow earthquake phenomenon interacting with each other are compared, then the long-term SSE and tremor must be the master and slave events, respectively. The activation of the tremor along the updip part of the tremor zone does
not increase smoothly but comprises many step-like increases, although the GNSS displacement changes that represent the occurrence of the long-term SSEs are smooth. Each small step indicates a small tremor burst, suggesting the occurrence of a minor short-term SSE not detected geodetically. The short-term SSEs are triggered to reach the slip caused by long-term SSEs under the displacement continuum condition at the boundary section.

The two small long-term SSEs in the Bungo Channel in 2014 and 2016 clearly show a distance-dependent interaction during the 2010–2019 period when there were no large long-term SSEs. These small long-term SSEs exhibit slightly different slip areas. The SSEs during 2014 and 2016 are located in the northern and southern parts of the Bungo Channel, respectively, and the differences in their slip locations indicate considerably different tremor activities. An obvious tremor activity was observed during the long-term SSE in 2014, whereas no tremor activity was associated with the long-term SSE observed in 2016. The difference in tremor behavior can also be explained by the difference in the distances between the master and slave phenomena.

The long-term SSE observed in 2014 was located in the northern section close to the tremor zone, whereas that in 2016 was located far from the tremor zone. Deep VLFEs were triggered by the Bungo Channel long-term SSEs. Baba et al. detected deep VLFEs in western Shikoku using the matched filter method and revealed a rapid increase in VLFE seismicity with respect to the long-term SSEs observed in 2010 and 2014. The number and activated area of the triggered VLFEs during the SSE in 2010 were larger than those of the SSE in 2014 because of the larger moment of the former.

The interaction between long-term SSEs and tremor has also been observed in Tokai and Mexico, although the interactions are not so clear. Further, the interactions are considerably affected by the distance of the master long-term SSE from the slave tremor. The slip velocity of the master event may affect the degree of the triggered phenomenon. Conversely, annual-scale interactions between tremor activity and long-term SSEs have been observed in western and central Shikoku. The eastward migration of long-term SSEs has been observed twice after the Bungo Channel long-term SSEs in 2003 and 2010 along the gap zone between the ETS and seismogenic zones. The tremor activity pattern migrates eastward at 50 km/year, which is similar to the eastward migration of long-term SSEs.

4-2-3. Controlling the difference between ETS and long-term SSEs based on the structural environment.

Different frictional regimes that can be attributed to different geological materials may result in slow earthquakes with different slip velocities. Long-term SSEs and ETS (short-term SSEs) located next to each other in the Bungo Channel may be controlled by different hanging wall materials, i.e., the mantle wedge and continental lower crust, respectively. Kato et al. investigated a high-resolution subsurface structure in the Tokai region via tomography and receiver function analyses of the seismic data obtained from a temporally deployed linear array above both the ETS and long-term SSE source region. Further, they concluded that the long-term SSEs and ETS were separated by the continental Moho discontinuity; thus, the long-term SSEs and ETS were located at the base of the continental lower crust and the forearc mantle wedge, respectively. Holtkamp and Brudzinski estimated the interplate coupling along the subducting plate interface in Cascadia based on the GPS data and revealed that the ETS region at the base of the mantle wedge was considerably coupled, whereas the region beneath the continental lower crust was weakly coupled because of the geological material, which is governed by the flow law. The interplate slip properties in the zone between the ETS and locked zones may be affected by the viscoelastic nature of the lower crust even though long-term SSEs have never been detected in Cascadia.

4-2-4. Interaction between the long-term SSE and shallow VLFEs. In the Bungo Channel, long-term SSEs may interact with the shallow VLFEs near the Nankai Trough because of a possible SSE between them near the western margin of the large rupture area owing to the Nankai earthquake. Hirose et al. observed that the long-term SSEs in the Bungo Channel interacted with the deep tremor activity along the updip section of the ETS zone and shallow VLFEs near the Nankai Trough in 2003 and 2010. The correlation pattern slightly differed in case of deep tremor and shallow VLFEs. The activated deep tremor continued for several months corresponding to the duration of long-term SSEs; however, the shallow VLFEs were activated for several days, which coincided with the beginning of the GPS displacement changes that can be attributed to long-term SSEs. Although the detailed triggering mechanisms may differ, both the deep tremor and shallow VLFEs were likely triggered by long-term SSEs because of the reproducibility of coherent observa-
tions in 2003 and 2010. However, the source location of the activated shallow VLFEs was >100 km away from the estimated source fault of the long-term SSEs. Both the source locations were estimated based on the inland observation, although the poor resolution of the inland GPS network limited the estimation of the offshore slip distribution. The relation between the long-term SSEs and deep tremor suggested that shallow VLFEs may be triggered by the slow slip occurring near the shallow VLFE source region. The activation of shallow VLFEs would be explained if the long-term SSE source fault extended southward near the trough axis. If such an extended slip distribution exists for long-term SSEs, then different types of slow earthquakes should align in the along-dip direction; further, the alignment of slow earthquakes corresponds to the western boundary of the coseismic rupture associated with the Nankai earthquake that occurred in 1946. Such a slow earthquake alignment may act as a barrier to high-speed coseismic rupture.

Uchida et al. reinvestigated the relation between shallow VLFEs, deep tremor, and long-term SSEs in addition to the repeating earthquake activity. They reported the northward migration of the slow earthquake activity from the southern extent of the shallow VLFE source region in Hyuga-nada to the deep tremor region in western Shikoku through the updip section of the repeating earthquake region and long-term SSE fault areas in the Bungo Channel. Although this denotes an opposite migration pattern when compared with that proposed by Hirose et al., various types of slow earthquakes may mutually interact with each other over a wide region from the shallow to deep sections in the Hyuga-nada and Bungo Channel regions.

Nakamura and Sunagawa revealed an interaction between shallow VLFEs and repeating long-term SSEs in the southwestern Ryukyu Trench at a depth of 30–50 km beneath the southern Ryukyu arc. The VLFE seismicity peaked 10–20 days after the onset of the long-term SSEs.

4-3. Interactions between shallow slow earthquakes. The plate interface at shallow depths near the trench axis is considerably heterogeneous, including a strongly coupled section containing coseismic ruptures because of great earthquakes and a weakly coupled section in which slow earthquakes occurred. The acoustic GNSS observations have revealed a contrast in coupling strength along the Nankai Trough axis and indicated that shallow VLFEs are distributed across the weakly coupled section. A shallow tremor was not detected within the large coseismic rupture area of the Tohoku earthquake in 2011 along the Japan Trench. How do these seismic slow earthquakes along the shallow section interact with the geodetic slow earthquakes? The short-term SSEs detected by a borehole pore-pressure gauge were clearly correlated temporally with the shallow VLFE and shallow tremor seismicity detected by DONET offshore to the southeast of the Kii Peninsula. Conversely, the shallow VLFE seismicity in the Tokachi offshore region was very coherent with the crustal deformation caused by the afterslip from the Tokachi-oki earthquake in 2003. Similarly, the shallow VLFE seismicity was activated because of the afterslip sequence in the northern and southern sections of the large coseismic rupture zone of the Tohoku earthquake in 2011. These shallow VLFEs were activated by a transient slip with a long characteristic timescale. However, only some long-term SSE observations are available. Long-term SSEs with a duration in the range of years may be detected in 2009 and 2018 in the Kii Channel offshore region near the Nankai Trough axis. These long-term SSEs have been associated with the migrating shallow VLFE episodes.

5. Discussion

The slow earthquake activity in southwest Japan is roughly characterized by a zone-like distribution associated with the along-strike heterogeneity at different depth ranges, although the slip behaviors may vary in two dimensions on the subducting plate interface (Fig. 5). Long-term SSEs were initially detected in only two regions, Tokai and Bungo Channel in the early 2000s, and the gap between the ETS and locked zones was filled by long-term SSEs. Therefore, the long-term SSEs and tremor systematically share the megathrust plate boundary at each depth and are horizontally distributed, including their separation into small segments. This suggests that different types of slow earthquakes occur along the deep section of the Nankai subduction zone. However, each type of slow earthquake has a different along-strike extension. The long-term SSEs are distributed beneath both Kyushu and Shikoku, although there is no ETS activity beneath Kyushu, except the minor and localized tremor activity in southeastern Kyushu.

Conversely, shallow tremor occurred along the Japan Trench in the offshore region of northeast Japan at the same depth as that of the great
earthquake coseismic rupture area along the subducting Pacific plate boundary. The shallow slow earthquake activity along the Japan Trench exhibited no systematic pattern but indicated strong along-strike heterogeneity, including the fast-speed coseismic rupture of regular earthquakes. Such along-strike heterogeneity was observed in the shallow VLFE distribution and interplate coupling distribution along the Nankai Trough.

Slow earthquakes occur on the updip (shallower) and downdip (deeper) sections of the seismogenic zone in southwest Japan. The ETS activity and a couple of different tremor migration modes are commonly observed in both the depth sections even though the pressure and temperature environments are considerably different. However, the detailed activity pattern of slow earthquakes is slightly different. For example, the occurrence of slow earthquakes is periodic in the deeper section compared with that in the shallower section. The shallow tremor migration velocities were 20 km/day and 100 km/day for the two migration modes observed in Hyuga-nada, which were a few times higher than the deep tremor migration velocities. Such minor differences in activity patterns may be useful for resolving the frictional properties via experimental studies. The observations of various slow earthquakes in the offshore area should be considered to resolve these properties.

The slow earthquakes and interplate great earthquakes are related since the initial discovery of deep tremor in the Nankai subduction zone because of their neighboring spatial geometries. Obara and Kato proposed three key aspects with respect to the connection between slow and great earthquakes. The slow earthquakes are initially considered to be an analog for great earthquakes because of their similar activity patterns. Both the slow and great earthquakes are characterized by a periodic recurrence behavior, and large fluctuations can be observed in each segment (Fig. 6). Therefore, frequent slow earthquake observations will be useful to obtain the occurrence model of great earthquakes based on their large recurrence interval. A slow earthquake is subsequently considered to be a stress meter for monitoring the stress changes in the locked section because of its sensitive nature, as suggested from triggering by teleseismic waves and tidal modulation. Although there is no example to indicate that the slow earthquake activity changes as a function of stress based on the accumulated stress in the locked section in southwest Japan, there are a couple of examples demonstrating changes in slow earthquake activity prior to the occurrence of historical large earthquakes around the world. The occurrence of slow earthquakes is also expected to transfer the stress to the surrounding region, including the locked portion. The remainder of this section will discuss stress transfer based on the recent research results.

The migration of slow earthquakes toward the initial rupture of the Tohoku earthquake in 2011 is a typical example of the stress transfer phenomenon. A similar slow earthquake migration sequence was observed before the Iquique earthquake in 2014 in northern Chile. Although the amount of stress transferred from a given slow earthquake sequence is likely to be considerably small for triggering the rupture of a great earthquake, the frequent occurrence of slow earthquakes may result in stress accumulation, gradually approaching the critical rupture level. Takagi et al. revealed the northward migration of long-term SSEs along the subducting Philippine Sea plate, where the long-term SSEs migrated from the weakly coupled region in southeastern Kyushu to the firmly locked zone beneath Shikoku. Thus, a long-term SSE may load additional stress to the locked zone over a characteristic timescale of years. The ETS activity along the deepest section of the transition zone indicates upward stress transfer within the ETS zone, as previously discussed, which may cause stress accumulation at the updip section. If the plate boundary toward the updip side of the ETS zone is in contact with the continental lower crust in the hanging wall, then the updip stress transfer may relax because of the viscous properties of the hanging wall. However, if the ETS zone is in direct contact with the locked zone, then the updip stress loading may result in the accumulation of additional stress in the locked zone. Kano et al. revealed that the small slip along the downdip portion of the locked zone was associated with the ETS episodes in western Shikoku. They interpreted that the ETS episode ruptured the impermeable seal at the top of the mantle wedge such that the fluid pressure could propagate upward along the plate interface to the downdip portion of the locked zone through the base of the continental lower crust, which is the source region of long-term SSEs. Thus, ETS may enable stress transfer to the locked section in both the cases even if the continental lower crust does not exist in the hanging wall.
6. Summary

The slow earthquakes along the subducting plate interface are classified into various seismic and geodetic phenomena exhibiting different characteristic timescales at different depths. The segmentation and large fluctuations in recurrence intervals are common properties associated with the slow earth-
quakes detected at the downdip edge of the seismogenic zone; however, shallow slow earthquakes also occur near the locked zones containing high-speed coseismic rupture zones. The frequently observed interaction between different types of slow earthquakes may extend to the neighboring seismogenic zone. The stress accumulation in the locked section may change the activity patterns of the neighboring slow earthquakes. Therefore, precisely monitoring slow earthquakes is important for evaluating great earthquakes in future, which is dependent on the long-term maintenance and continued improvement of the high-quality observation networks.

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Profile

Kazushige Obara was born in 1959 in Sendai, Miyagi Prefecture. After he received his master’s degree from Tohoku University in 1985, he served the National Research Institute for Earth Science and Disaster Prevention (NIED) as a government researcher of the Prime Minister’s Office of Japan. His work was related to the maintenance and data analysis of the deep borehole seismic observatories in the Tokyo metropolitan area and Kanto–Tokai crustal activity observation network. He received his PhD degree in 1992 from Tohoku University for his study on scattering of seismic wave propagation and worked as a visiting research fellow at MIT for one year in 1993. After the Kobe earthquake in 1995, he participated in the project for constructing a nationwide high-sensitivity seismograph network (Hi-net). He was appointed as the head of the Hi-net management laboratory in 2001 and the director of the seismic observation data center in 2006. When working on Hi-net data, he discovered some types of slow earthquakes: low-frequency tremor, very-low-frequency earthquakes, and short-term slow slip events. In 2010, he moved to the Earthquake Research Institute (ERI), the University of Tokyo, as a professor and was elected as the Director of ERI from 2015 to 2019. He is the leader of the project ‘Science of Slow Earthquakes’ funded for five years from 2016 via the Japan Society for the Promotion of Science, Grant-in-Aid Scientific Research on Innovative Areas. For his accomplishment, he received the Ministry of Education, Culture, Sports, Science and Technology (MEXT) Commendation in 2003, Inoue Award in 2008, American Geophysical Union (AGU) Fellow in 2013, AGU Gutenberg Lecturer in 2015, and Seismological Society of Japan (SSJ) Prize in 2015. He is currently the President of SSJ.