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A review of shallow slow earthquakes along the Nankai Trough

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Abstract
Slow earthquakes occur at deep and shallow plate boundaries along the Nankai Trough. Deep slow earthquakes are continuously distributed along the 30–40 km depth contours of the upper surface of the subducted Philippine Sea Plate. In contrast, shallow slow earthquakes occur in limited regions: Hyuga-nada, off Cape Muroto, and southeast off the Kii Peninsula. This review provides an overview of the up-to-date seismological, geodetic, geological, and experimental results in the shallow Nankai area for a unified understanding of the spot-like occurrence of shallow slow earthquakes. Shallow slow earthquakes tend to be distributed in transitional regions between the frictionally locked and stably sliding zones on the plate boundary. Based on geological and experimental studies, the lithology of incoming sediments and their friction coefficients can be variable along the Nankai Trough. Laboratory friction experiments revealed that sediments under shallow plate boundary conditions often exhibit positive ($a-b$) values, while negative ($a-b$) is possible via several processes. Subducted seamounts create complex fracture networks and stress shadows in their surrounding areas; however, not all subducted seamounts are related to shallow slow earthquake activities. This incomplete correlation suggests that alternative factors are required to explain the spot-like distribution of shallow slow earthquakes in the Nankai subduction zone. High pore fluid pressure conditions around shallow slow earthquake zones were interpreted based on seismological structural studies. In addition, ambient noise monitoring revealed temporal changes in seismic velocity structures associated with shallow slow earthquake migrations. This result suggests a close link between pore fluid migration and shallow slow earthquake episodes. Because transient changes in pore fluid pressure can lead to various slip behaviors, the episodic migration of pore fluid around the plate boundary could promote shallow slow earthquake activity along the Nankai Trough.

Keywords Nankai Trough, Shallow slow earthquake, Seismology, Geodesy, Geology, Laboratory experiments

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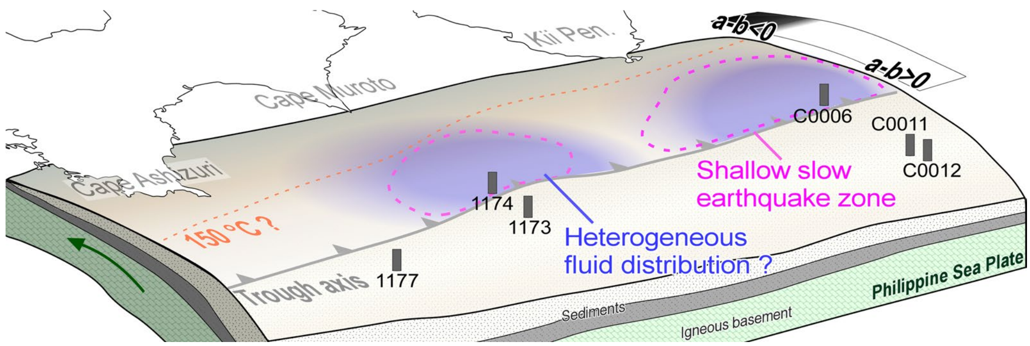
Graphical Abstract



Introduction

Slow earthquakes exhibit intermediate faulting behaviors between ordinary earthquakes and stable sliding. After several pioneering discoveries of slow earthquake phenomena (Hirose et al. 1999; Dragert et al. 2001; Obara 2002; Rogers and Dragert 2003), slow earthquake phenomena have been extensively studied worldwide, particularly in subduction zones (Obara and Kato 2016), to broaden our understanding of slip behaviors on the plate boundary and their effects on the preparation of megathrust earthquakes.

Seismometers can detect signals of low frequency earthquakes (LFEs) in the 1–10 Hz frequency band and very low frequency earthquakes (VLFEs) in the 0.01–0.1 Hz band. Continuous tremor signals are considered successive occurrences of small LFEs (Shelly et al. 2007; Brown et al. 2009; Ide 2021). Global Navigation Satellite System (GNSS) and other geodetic instruments can detect small crustal deformations caused by slow slip events (SSEs; geodetic slow earthquakes) that have a duration of several days to several years. Spatiotemporal correlations between seismic (LFEs, tremors, and VLFEs) and geodetic slow earthquakes (SSEs) are often observed; such events are called episodic tremor and slip (ETS) or slow slip and tremor (SST) (e.g., Rogers and Dragert 2003; Obara et al. 2004). The migration processes and swarms of seismic slow earthquakes during ETSs can be linked to the slip evolution of the accompanying SSEs (e.g., Bartlow et al. 2011; Hirose and Kimura 2020; Itoh et al. 2022). Spatiotemporal correlations between individual tremor/LFE envelopes (i.e., the energy rate function) and VLFE moment rate functions also suggest broadband characteristics of seismic slow earthquakes (Ide et al. 2008). The hypothesis of "broadband slow earthquake" is that tremors/LFEs and VLFEs represent parts of common broadband phenomena, although these high- and low-frequency phenomena are separated by large microseism noises that are typically observed at seismometers. This hypothesis has been confirmed by recent advances in observation and analysis techniques, which enabled us to investigate signals in a microseism frequency band of 0.1–1 Hz (Ide and Yabe 2014; Kaneko et al. 2018; Masuda et al. 2020). The scaled energies and seismic productivities of slow earthquakes have been discussed to further understand their source physics in various regions (e.g., Ito et al. 2009; Takeo et al. 2010; Daiku et al. 2018; Ide and Maury 2018; Frank and Brodsky 2019; Yabe et al. 2021; Passarelli et al. 2021; Baba et al. 2021). The scaled energy is the ratio of the seismic energy of a tremor divided by the seismic moment of the accompanying VLFE. The seismic productivity is the ratio of the cumulative moment of seismic slow earthquakes to the moment of the corresponding geodetic slow earthquake. These values represent the characteristics of dynamics in the faulting processes. The scaled energies of slow earthquakes are almost constant (approximately 10^{-9}–10^{-8}) and 5–6 orders of magnitude smaller than those of ordinary earthquakes (approximately 3×10^{-5}; e.g., Ide and Beroza 2001; Ide 2014). The seismic productivities of ETSs (the ratio of the cumulative moments of detectable seismic slow earthquakes to geodetic slow earthquakes) range from 10^{-4} to 10^{-1}, which is smaller than those of ordinary thrust-type earthquake swarms (Fig. 1 of Passarelli et al. 2021). Because scaled energy and seismic productivity characterize faulting dynamics, these observations suggest that the dynamics of slow and fast (ordinary) earthquakes are qualitatively different. Other basic characteristics of slow earthquakes have been summarized in previous reviews (Schwartz and Rokosky 2007; Beroza and Ide 2011; Ide 2014; Obara and Kato 2016; Obara 2020; Nishikawa et al. 2023).

Slow earthquakes in subduction zones are classified as deep or shallow slow earthquakes. In this review, we classified slow earthquake activity by depth rather than by location relative to megathrust or locked zones. Deep slow earthquakes occur at depths of approximately 30–40 km, corresponding to lower brittle zones. Using the decadal scale (> 10–20 years) and dense inland observations, deep slow earthquakes have been reported in the subduction zones of Ryukyu, Nankai, Japan Trench, Alaska, Cascadia, Mexico, Costa Rica, Chile, and Hikurangi. The temperatures and lithostatic pressures at these depths were approximately 150–500 °C and 0.7–1.7 GPa, respectively (e.g., Peacock and Wang 1999; Syracuse et al. 2010; Behr and Bürgmann 2021). Based on the spatial distributions of deep slow earthquakes and seismic velocity structures, slow earthquake sources are localized within the volume around the plate boundary, which are characterized by low velocity and high Vp/Vs (Vp: P-wave velocity, Vs: S-wave velocity). Because such seismic velocity characteristics are often associated with high pore fluid pressure conditions, the fluid drainage system due to plate subduction is considered one of the most important factors for the occurrence of deep slow earthquakes (e.g., Kato et al. 2010; Audet and Kim 2016; Nakajima and Hasegawa 2016; Chuang et al. 2017; Delph et al. 2018). This was also proposed from a geological perspective based on inland geological structures. Foliation-parallel mineral-filled shear veins were found within accretionary complexes that experienced conditions near the depth where deep slow earthquakes were observed in warm subduction zones, similar to the Nankai Trough (Fagereng et al. 2011; Ujiie et al. 2018). These crack-seal veins are produced by repeated brittle fractures under high fluid pressure conditions, and their formation rate and displacement are comparable to the interval and displacement of the LFEs, which can be observed as a trace of previous tremors (Audet and Bürgmann 2014; Ujiie et al. 2018). Kirkpatrick et al. (2021) proposed that the complex shear-offset structures observed in metamorphic rocks that developed along subduction zones and were located in deep slow earthquake areas served as the source of slow earthquakes. This proposition implies the widespread occurrence of deep slow earthquakes in subduction zones where the temperature–pressure conditions match those of certain metamorphic environments.

In contrast to the widespread occurrence of deep slow earthquakes, observations of shallow (< 10 km) slow earthquakes have been limited to regions such as Ryukyu (e.g., Nakamura and Sunagawa 2015), Nankai (e.g., Asano et al. 2008; Araki et al. 2017; Baba et al. 2020a), Mexican (Plata-Martinez et al. 2021), Costa Rica (e.g., Dixon et al. 2014; Baba et al. 2021), and Hikurangi (e.g., Wallace et al. 2016b; Todd et al. 2018) subduction zones. Along the Japan Trench, slow earthquakes also occur in offshore regions, but their depths are slightly deeper (10–30 km) than other shallow slow earthquakes (e.g., Nishikawa et al. 2019; Tanaka et al. 2019; Baba et al. 2020b; Nishimura 2021). Temperatures and lithostatic pressures at shallow depths are < 150 °C and < 0.2 GPa, respectively (e.g., Peacock and Wang 1999; Saffer and Wallace 2015). Shallow slow earthquakes have been only reported in offshore regions; consequently, the observation and analysis of shallow slow earthquakes remain challenging issues. Thus, our knowledge of shallow slow earthquakes is limited compared to that of deep slow earthquakes.

This review focuses on the Nankai subduction zone. Megathrust earthquakes have occurred repeatedly in this subduction zone at intervals of 100–150 years (Ando 1975). Both shallow and deep slow earthquakes have occurred along the Nankai Trough. Because nationwide inland seismic and geodetic networks were developed after the 1995 Hyogo-ken Nanbu earthquake, deep slow earthquakes have been systematically monitored and studied (e.g., Maeda and Obara 2009; Nishimura et al. 2013; Nishimura 2014; Kobayashi 2017; Takagi et al. 2019; Kato and Nakagawa 2020; Yabe et al. 2023). These monitoring results indicate that deep slow earthquakes are widely distributed at depth contours of 30–40 km on the Philippine Sea Plate, from the Tokai to Kyushu regions (gray symbols in Fig. 2). From seismic structural studies, high Vp/Vs bodies have been confirmed around the plate boundary in regions where deep slow earthquakes actively occur (e.g., Kato et al. 2010; Nakajima and Hasegawa 2016). The fluid supply around the plate boundary is associated with the dehydration of the subducted oceanic crust. Impermeable hanging walls trap pore fluid from the oceanic crust, causing deep slow earthquakes to become more active.

Studies of shallow slow earthquakes began in the early 2000s. Ishihara (2003) and Obara and Ito (2005) first recognized surface wave signals caused by shallow VLFE swarms in continuous records of inland broadband seismometers. Because shallow slow earthquakes, except for shallow VLFEs, cannot be sufficiently recognized by inland instruments (Fig. 1a), the initial phase of studies focused on investigating the nature of shallow VLFEs (Ito and Obara 2006a; b; Asano et al. 2008, 2015). The development of permanent and campaign offshore observatories after 2010 enabled the investigation of shallow tremors, VLFEs (Fig. 1b), and SSEs (e.g., Obana and Kodaira 2009; Sugioka et al. 2012; To et al. 2015; Araki et al. 2017; Annoura et al. 2017; Toh et al. 2018; Yokota and Ishikawa 2020). The development of permanent seismic networks in Japan is summarized in Aoi et al. (2020). Consequently, shallow slow earthquakes and tectonic environments along the Nankai Trough have been well studied compared to other subduction zones. Figure 2 shows the spatial distribution of shallow

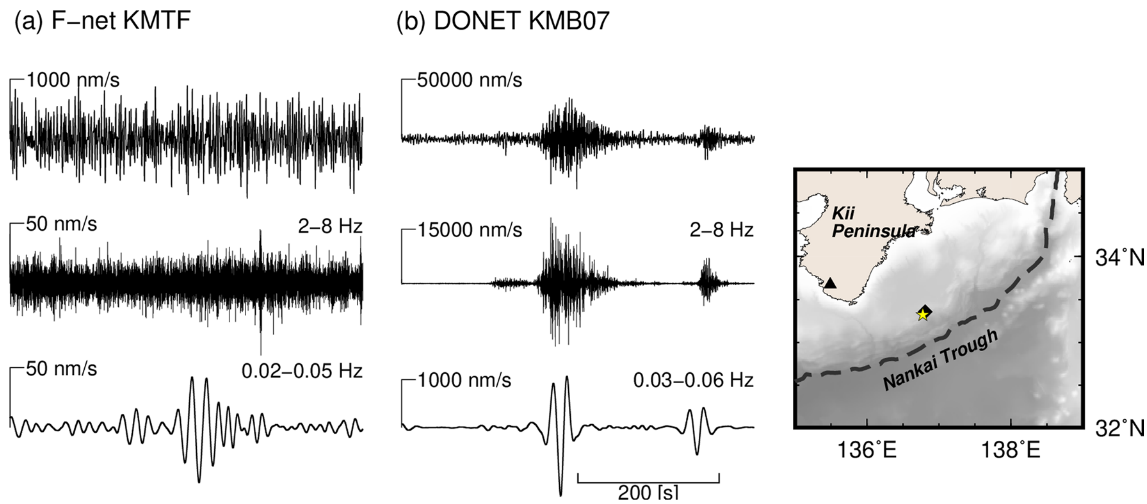


Fig. 1 Example waveforms of a shallow slow earthquake at two stations: **a** inland F-net KMTF and **b** offshore DONET KMB07. Top, middle, and bottom traces are raw (non-filtered), tremor-, and VLFE-band vertical-component seismograms, respectively. Owing to characteristic noise at ocean bottom seismometers (Webb 1998), we selected the 0.03–0.06 Hz frequency band for a shallow VLFE at station KMB07. F-net KMTF, DONET KMB07, and the hypocenter of this event are illustrated by the black triangle, diamond, and yellow star, respectively. An example event occurred on 14:12 December 12, 2020 (JST)

slow earthquakes (shallow tremors, VLFEs, and SSEs) detected by offshore and inland observations from 2004 to 2021. The spatial distributions of shallow VLFEs and SSEs from these observations do not completely coincide because of differences in their detectability (Agata et al. 2019; Takemura et al. 2022a) and the accuracy of location analysis. Nevertheless, in contrast to the belt-like distribution of deep slow earthquakes (gray symbols in Fig. 2), the source locations of the shallow slow earthquakes were concentrated within three specific spots: Hyuga-nada, off Cape Muroto, and southeast off the Kii Peninsula. Along-strike variations in slow earthquake activity have been observed in other subduction zones as well (Nishikawa et al. 2019; Yabe et al. 2021; Baba et al. 2021; Plata-Martinez et al. 2021).

These spot-like occurrences suggest that shallow slow earthquakes cannot be explained simply by depth-dependent temperature and pressure conditions. Toward the understanding of their localized activities and slip behaviors at shallow plate boundaries, we briefly reviewed recent key studies on shallow slow earthquakes in the Nankai subduction zone. Shallow slow earthquakes, heterogeneous subsurface structures, and frictional conditions have been extensively studied. "Characteristics of shallow slow earthquakes along the Nankai Trough" section provides an overview of the observed features of shallow slow earthquakes along the Nankai Trough and their characteristic differences from typical deep slow earthquakes. To further understand which factors control the observed spot-like occurrences of shallow slow earthquakes, we discuss the tectonic environments of shallow slow earthquake zones, such as frictional properties inferred from geodetic and geological studies ("Frictional properties at the shallow plate boundary along the Nankai Trough" section), the topography of the subducted Philippine Sea Plate, and subsurface seismic structures around the plate boundary ("Structural and hydrological factors controlling the spot-like distribution of shallow slow earthquakes" section). "Regional differences in shallow slow earthquake activity along the Nankai Trough" section discusses regional differences in shallow slow earthquake activity along the Nankai Trough. "Conclusions and future perspectives" section provides the conclusions and future perspectives for shallow slow earthquake studies along the Nankai Trough.

Characteristics of shallow slow earthquakes along the Nankai Trough

This section briefly summarizes the observed features of the shallow slow earthquakes along the Nankai Trough. As shown in Fig. 2, shallow tremors, VLFEs, and SSEs were detected using both inland and offshore observations. Figure 2d shows the distribution of interplate moderate-size ordinary earthquakes (Takemura et al. 2020a) and small repeating earthquakes (Igarashi 2020) on the plate boundary. Repeating earthquakes occur in approximately the same source location and nearly identical focal mechanisms. Thus, repeating earthquakes have been monitored as a slip meter on plate boundaries (summarized in Uchida and Bürgmann 2019). Ordinary

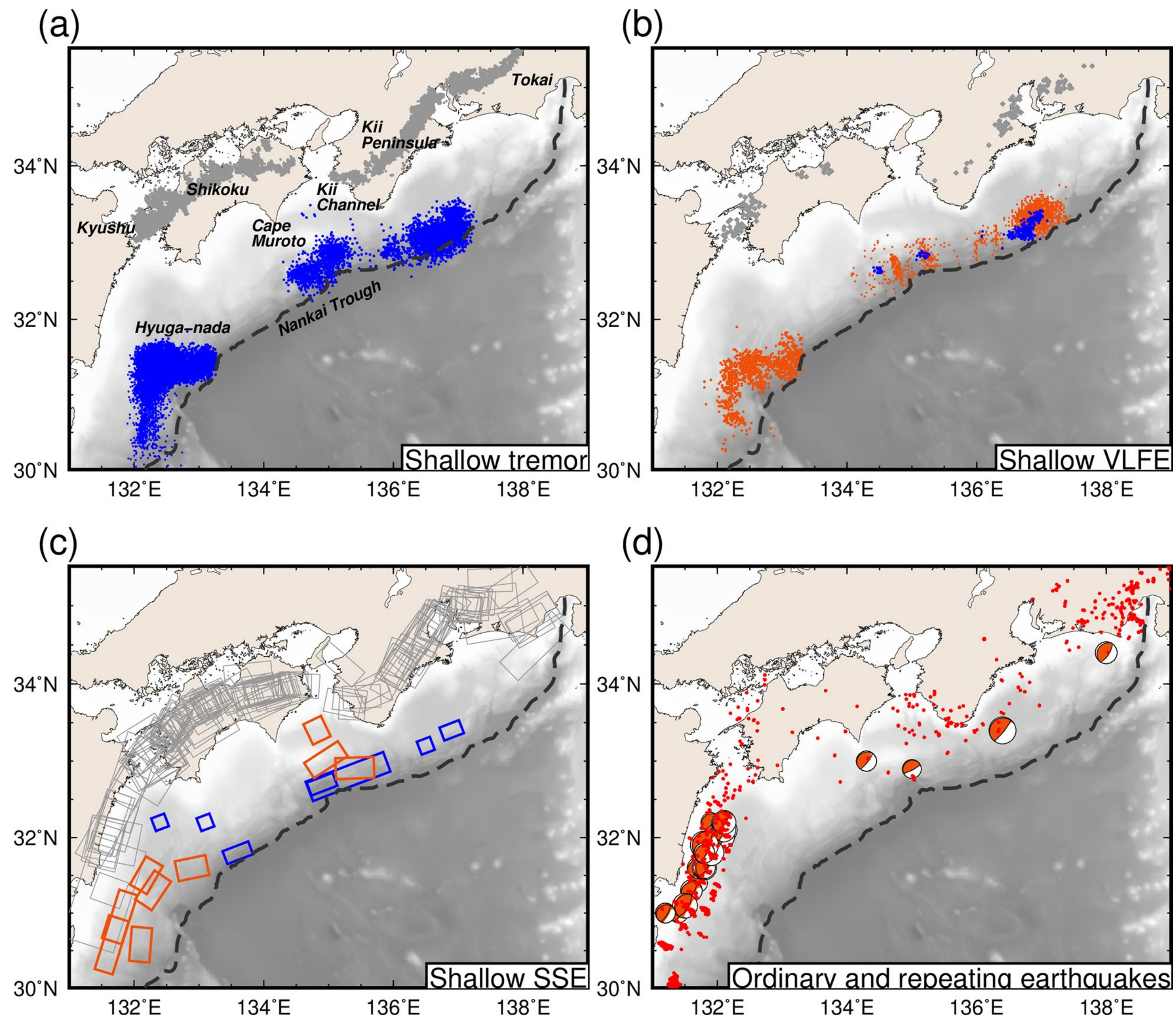


Fig. 2 Spatial distributions of shallow slow earthquakes in Nankai. **a** Shallow tremors (Yamashita et al. 2015, 2021; Tamaribuchi et al. 2022), **b** shallow VLFEs (Asano et al. 2015; Nakano et al. 2018a; Takemura et al. 2022b, c; Yamamoto et al. 2022a) and **c** shallow SSEs (Yokota and Ishikawa 2020; Okada et al. 2022). In **b** and **c**, shallow VLFEs and SSEs detected by inland and offshore instruments are represented by orange and blue symbols, respectively. Gray dots, gray diamonds, and gray rectangles in **a**–**c** are deep tremors (Maeda and Obara 2009; Obara et al. 2010), VLFEs (Ito et al. 2009), and SSEs (Nishimura et al. 2013; Takagi et al. 2016, 2019). Deep SSEs in **c** include both long-term and short-term SSEs. **d** Spatial distribution of moderate-size ordinary interplate earthquakes (Takemura et al. 2020a) and small repeating earthquakes (Igarashi 2020). The catalog of Takemura et al. (2020a) contains ordinary earthquakes with $Mw \geq 4.3$

and slow earthquakes are separately distributed along the Nankai Trough.

Recently, shallow tremors with durations significantly shorter than typical tremor durations have been observed at a DONET station close to a seismic source (Toh et al. 2023); however, shallow LFEs have yet to be reported. This is because if an LFE occurs at the shallow plate boundary, the observed seismograms in the LFE band (1–10 Hz) are significantly broadened, similar to tremor (spindle-shape) envelopes due to thick low-velocity sediments beneath the ocean bottom seismometers (OBSs) (Takemura et al. 2020b, 2023) and resemble tremor signals such that we cannot distinguish between the two phenomena. The spatiotemporal correlation between shallow seismic and geodetic slow earthquakes (e.g., Nakano et al. 2018a; Ariyoshi et al. 2021; Okada et al. 2022) has been confirmed to be similar to that of deep ETSs, whereas several shallow SSEs occurred without accompanying tremors and VLFE swarms (Araki et al. 2017; Yokota and Ishikawa 2020).

The observed moment rates of shallow VLFEs and the energy rates of shallow tremors range from 10^{12} to 10^{15} Nm/s and 10^2–10^6 J/s, respectively (Yabe et al. 2019, 2021; Nakano et al. 2019; Tamaribuchi et al. 2019, 2022; Baba et al. 2022; Takemura et al. 2022b, c), which are larger than those of typical deep slow earthquakes (Ide and Yabe 2014). The scaled energies of shallow slow earthquakes (10^{-9}–10^{-8}), except those in Hyuga-nada, are 0–1 orders of magnitude larger than those of typical deep slow earthquakes (Yabe et al. 2019, 2021; Tamaribuchi et al. 2019). We note that results from high-frequency seismic waves at OBSs tend to contain larger uncertainties due to strong structural heterogeneities within the accretionary prism (Takemura et al. 2020b, 2023). The seismic productivity of shallow slow earthquakes ranges from 1 to 15% (Takemura et al. 2022b), which is higher than that of deep slow earthquakes (Ito et al. 2009; Takeo et al. 2010). The scaled energies and seismic productivities in these studies suggest that the efficiency of the seismic wave radiation from shallow slow earthquakes may be higher than that from deep slow earthquakes. A combined analysis of shallow tremors and VLFEs revealed that the size distribution of shallow seismic slow earthquakes followed the tapered Gutenberg–Richter law, with a *b*-value of approximately 1 (Figs. 4 and S8 of Nakano et al. 2019). This implies that the expansion of the rupture patch sizes of the shallow tremors and VLFEs is limited. Temporal changes in size distribution during the episode were also observed (Nakano and Yabe 2021).

The observed characteristics of shallow slow earthquakes along the Nankai Trough are summarized in Table 1. The characteristics of typical deep slow earthquakes in this region were obtained from Obara (2011). The durations of shallow ETSs were obtained from the swarms of shallow VLFEs (Baba et al. 2020a; Baba 2022; Takemura et al. 2022b, c) because it is difficult to discuss the durations of shallow SSEs precisely due to their weak signals and the lack of dense offshore geodetic observations in space and time (Yokota and Ishikawa 2020). The variation of the migration speeds during shallow slow earthquake episodes was reported as wider (Yamashita et al. 2015, 2021; Takemura et al. 2022b; Tamaribuchi et al. 2022), although those of typical deep slow earthquakes are approximately 10 km/day. Detailed regional differences in shallow slow earthquakes along the Nankai Trough are discussed later ("Regional differences in shallow slow earthquake activity along the Nankai Trough" section). Figure 3 shows the spatiotemporal distribution of shallow VLFEs and deep tremors around the Kii Peninsula. The duration and recurrence intervals of the shallow ETSs in Fig. 3 are 1–3 months and 3–10 years, respectively. These values are significantly longer than those of the typical deep ETSs (middle column of Table 1). Interestingly, the durations of the observed shallow ETSs (or episodes of seismic slow earthquakes) ranged between short- and long-term SSEs at deep depths.

Frictional properties at the shallow plate boundary along the Nankai Trough

According to local and global earthquake catalogs (e.g., Storchak et al. 2013; Takemura et al. 2020a), the seismicity of observable ordinary earthquakes in the Nankai subduction zone is low. Repeating earthquakes, which are widely used as slip meters on plate boundaries (Nadeau and Johnson 1998; Uchida and Bürgmann 2019), are reported in limited regions, not the whole Nankai

Table 1 Characteristics of deep and shallow slow earthquakes in Nankai (Maeda and Obara 2009; Ito et al. 2009; Takeo et al. 2010; Obara 2011; Ochi and Kato 2013; Ide and Yabe 2014; Yamashita et al. 2015, 2021, 2022; Takagi et al. 2019; Yabe et al. 2019; Baba et al. 2020a; Takemura et al. 2022b, c; Yamamoto et al. 2022a)

	Deep	Shallow
Observed slow earthquake phenomena	LFE, tremor, VLFE, short-term SSE, long-term SSE	Tremor, VLFE, SSE
Segmentation in Nankai	Tokai, Northern Kii, Mid. Kii, Southern Kii, Eastern Shikoku, Mid. Shikoku, Western Shikoku, Kyushu	Southeast off the Kii Peninsula, off Cape Muroto, Hyuga-nada
Episode duration	ETS: 1–7 days L-SSE: 0.4–6 years	ETS: 1–3 months
Recurrent interval	ETS: 70–200 days L-SSE: 2–7 years	Hyuga-nada: 2–5 years Others: 3–9 years
Migration velocity	Main front: 10 km/day RTR: ~ 100 km/day Streak: > 50 km/h	Main front: 1–20 km/day RTR: 10–200 km/day Streak: not observed
Scaled energy	10^{-10}–10^{-9}	Hyuga-nada: 10^{-11}–10^{-8} Others: 10^{-9}–10^{-8}
Seismic productivity (Mo^{VLFE}/Mo^{SSE})	0.1–1%	1–15%

L-SSE is long-term SSE, which is SSE with durations longer than approximately 0.5 years

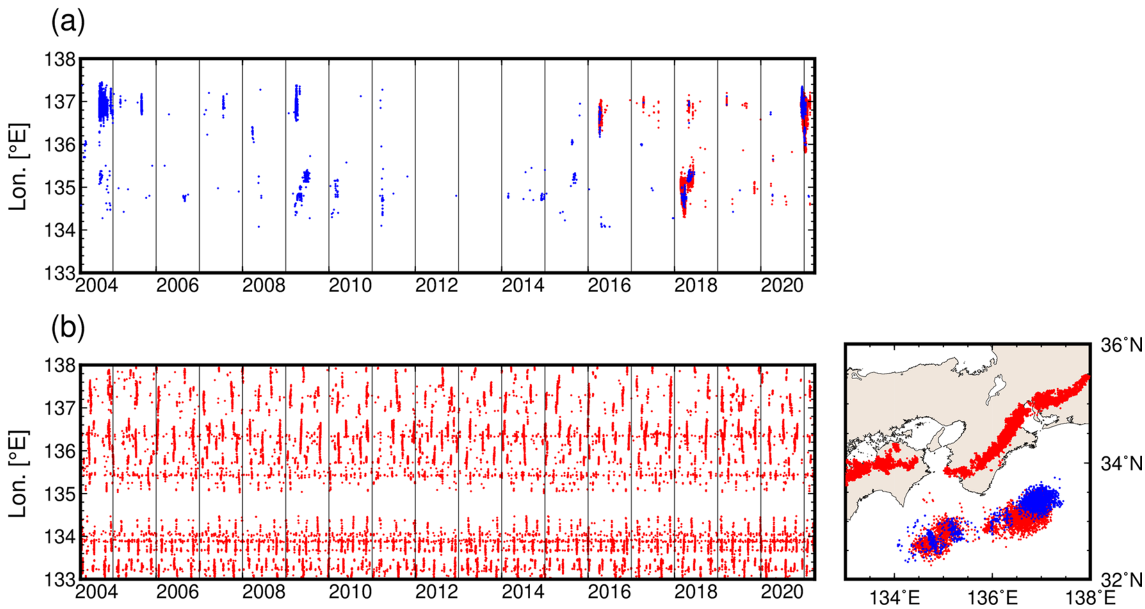


Fig. 3 Slow earthquake activities along the Nankai Trough. **a** Spatiotemporal activity patterns of shallow VLFEs (Takemura et al. 2022b, c) and tremors (Tamaribuchi et al. 2022) southeast off the Kii Peninsula. **b** Spatiotemporal activity patterns of deep tremors beneath the Kii Peninsula (Maeda and Obara 2009; Obara et al. 2010)

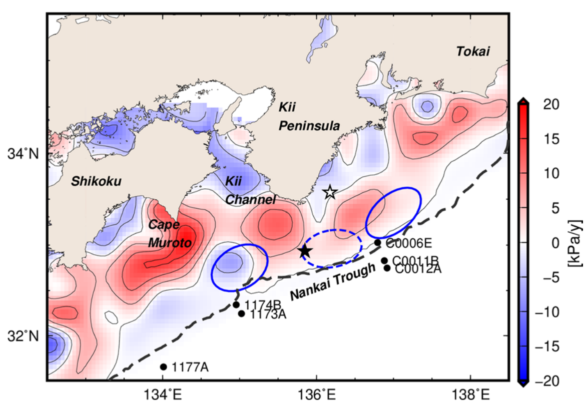


Fig. 4 Comparative plot of shear stress change rate due to the plate subduction (Noda et al. 2018) and shallow slow earthquake regions from Fig. 2. Blue solid ellipses are active shallow slow earthquake zones. The blue dashed ellipse is a region where shallow slow earthquakes were reported but less active (Fig. 3a). The open and filled stars represent the hypocenters of the 1944 Tonankai and 1946 Tokai earthquakes, respectively. The black circles are drilling site locations used in Fig. 5

subduction zone (Fig. 2d; Yamashita et al. 2012; Igarashi 2020). Direct estimations of the rupture patch sizes of shallow slow earthquakes remain difficult because of shallower heterogeneous seismic structures and sparse station coverage. Thus, frictional conditions around the plate boundary can be estimated from GNSS data and laboratory friction experiments using subducted materials. Based on GNSS and laboratory studies, we discuss frictional properties within the regions of shallow slow earthquakes.

Shear stress change rate inferred from GNSS observations

To construct possible scenarios for anticipated megathrust earthquakes in the Nankai subduction zone, the spatial distribution of the slip deficit rate or shear stress change rate on the plate boundary was evaluated using inland GNSS and offshore GNSS Acoustic (GNSS-A) data (e.g., Yokota et al. 2016; Nishimura et al. 2018; Noda et al. 2018, 2021; Agata 2020; Saito and Noda 2022). The slip deficit rate, a kinematic manifestation of interplate locking, negatively correlates with shallow slow earthquake activity (Takemura et al. 2019a; Baba et al. 2020a). However, the spatial distribution of the slip deficits does not strictly represent the mechanical properties of interplate locking because the zone of reduced slip rates (pseudo-coupling) appears in the region surrounding frictionally locked zones (e.g., Herman et al. 2018; Lindsey et al. 2021). The shear stress change rate at the plate interface is directly related to the frictional instability because the shear stress increases (accumulates) in frictionally locked zones and eventually is released by an earthquake or other event. The shear stress change rates can be calculated from the estimated slip deficit rates (Hok et al. 2011; Noda et al. 2018, 2021) or directly estimated from geodetic observation data (Xie et al. 2019; Herman and Govers 2020; Saito and

Noda 2022) assuming a continuous elastic medium. Thus, we focused on the spatial distribution of the shear stress change rate at the Philippine Sea Plate boundary. Figure 4 shows the spatial distribution of the shear stress change rate on the Philippine Sea Plate estimated by Noda et al. (2018). In Noda et al. (2018), a spatial distribution of slip deficit rate was estimated assuming the elastic–viscoelastic layered structure model (Table 1 of Noda et al. (2018)), and then shear stress change rate was calculated by using a semi-analytical solution of Fukahata and Matsu'ura (2006). Because of the lack of GNSS-A stations around Hyuga-nada, we focused only on off Cape Muroto and the Kii Peninsula. Several peaks of large shear stress change rates (> 10 kPa/y) were observed, and these regions matched the large slip areas of the 1944 and 1946 megathrust earthquakes (e.g., Sagiya and Thatcher 1999; Kikuchi et al. 2003; Ichinose et al. 2003; Murotani et al. 2015). The 1944 *Mw* 8.2 Tonankai and 1946 *Mw* 8.4 Nankai earthquakes were initiated southeast off and south off the Kii Peninsula (open and filled stars in Fig. 4), respectively. Therefore, these regions with high shear stress change rates can be considered as frictionally locked zones where megathrust earthquakes will occur.

Shallow slow earthquakes (blue ellipses in Fig. 4) are distributed in regions with small-to-intermediate values of shear stress change rate (< 5 kPa/y) adjacent to the peaks (> 10 kPa/y) of shear stress change rates. This spatial relationship suggests that preferable frictional conditions for shallow slow earthquakes may appear in transitional regions between the frictionally locked and stable sliding zones on the plate boundary (Takemura et al. 2019b; Tamaribuchi et al. 2022). Although the occurrence of interplate microearthquakes (< M3) has recently been reported to be close to shallow slow earthquake regions (Yamamoto et al. 2022b), shallow slow earthquakes, moderate (> M3) ordinary earthquakes, and large slip deficit regions are distributed separately (Takemura et al. 2020a). This separation has also been reported at the shallow plate boundaries of other subduction zones (Dixon et al. 2014; Nishikawa et al. 2019; Baba et al. 2021; Plata-Martinez et al. 2021). Based on the above comparisons, the frictional properties within shallow slow earthquake regions are expected to differ from those within zones with high shear stress change rates and ordinary earthquakes.

Geological and experimental observations

The lateral heterogeneity of the shear stress change rate and shallow slow earthquake activity could partially originate from heterogeneity in underthrust sediments. Offshore southwest Japan, sediments deposited on the Shikoku Basin accrete and form an accretionary prism or underthrust along the plate boundary. Figure 5 shows the lithostratigraphy of the frontal accretionary prism and incoming sediments sampled from the Nankai Trough off Shikoku Island and off the Kii Peninsula through deep-sea scientific drilling projects (Mikada et al. 2002; Saito et al. 2010; Henry et al. 2012). Although the sedimentary facies within shallow subduction zones comprised similar lithologies of hemipelagic mud, turbidity currents, and volcaniclastics (Kinoshita et al. 2009; Screaton et al. 2009; Tobin et al. 2020), those lithologies do not show perfectly uniform distribution. The heterogeneous distribution of turbidite along the Nankai Trough may be related to heterogeneous interplate coupling conditions because turbiditic layers are relatively permeable compared to hemipelagic mud and eventually lead to spatial variations in pore pressure and effective pressure conditions (Park and Jamali Hondori 2023). Contents of mineral species are also variable among lithologies, especially for clay minerals, and it has an impact on the frictional strength of the sediment (Ikari et al. 2009, 2013, 2018). Differences in the frictional strength of décollement along the trough are also inferred from the difference in taper angles (Kimura et al. 2007).

Along with frictional strengths, the coefficient of $(a-b)$ associated with the rate-and-state-dependent friction law (Dieterich 1979) is another key component as it indicates the stability of the slip (Ruina 1983; Ranjith and Rice 1999). If $(a-b)$ is negative, i.e., velocity weakening, the fault slip has the potential to become unstable, which could cause ordinary earthquakes considering a balance of the stress state and the stiffness of the surrounding medium (e.g., Rice 1993; Rubin and Ampuero 2005), whereas the fault stably slips when $(a-b)$ is positive, i.e., velocity strengthening. In early experimental studies using the remolded sediments from the Nankai Trough, velocity-strengthening behavior was observed in most cases (Ikari et al. 2009; Ikari and Saffer 2011; Takahashi et al. 2013, 2014). Positive $(a-b)$ values were continuously observed for the cutting samples from the drill hole in the inner accretionary prism (Bedford et al. 2021; Fujioka et al. 2022). On the other hand, recent studies using intact core samples showed velocity weakening (Roesner et al. 2020; Okuda et al. 2021).

These $(a-b)$ values can be influenced by pore pressure and effective normal stress. The shallow décollement, where shallow slow earthquakes occur, is under low effective normal stress and high pore pressure conditions (e.g., Kitajima and Saffer 2012; Tonegawa et al. 2017; Akuhara et al. 2020). In such a situation, the $(a-b)$ values shift to more positive values with increasing pore pressure according to the experiments on the cuttings sample from the inner accretionary prism (Bedford et al. 2021).

Temperature is also an important factor that controls the $(a-b)$ values. Experiments with powdered analog

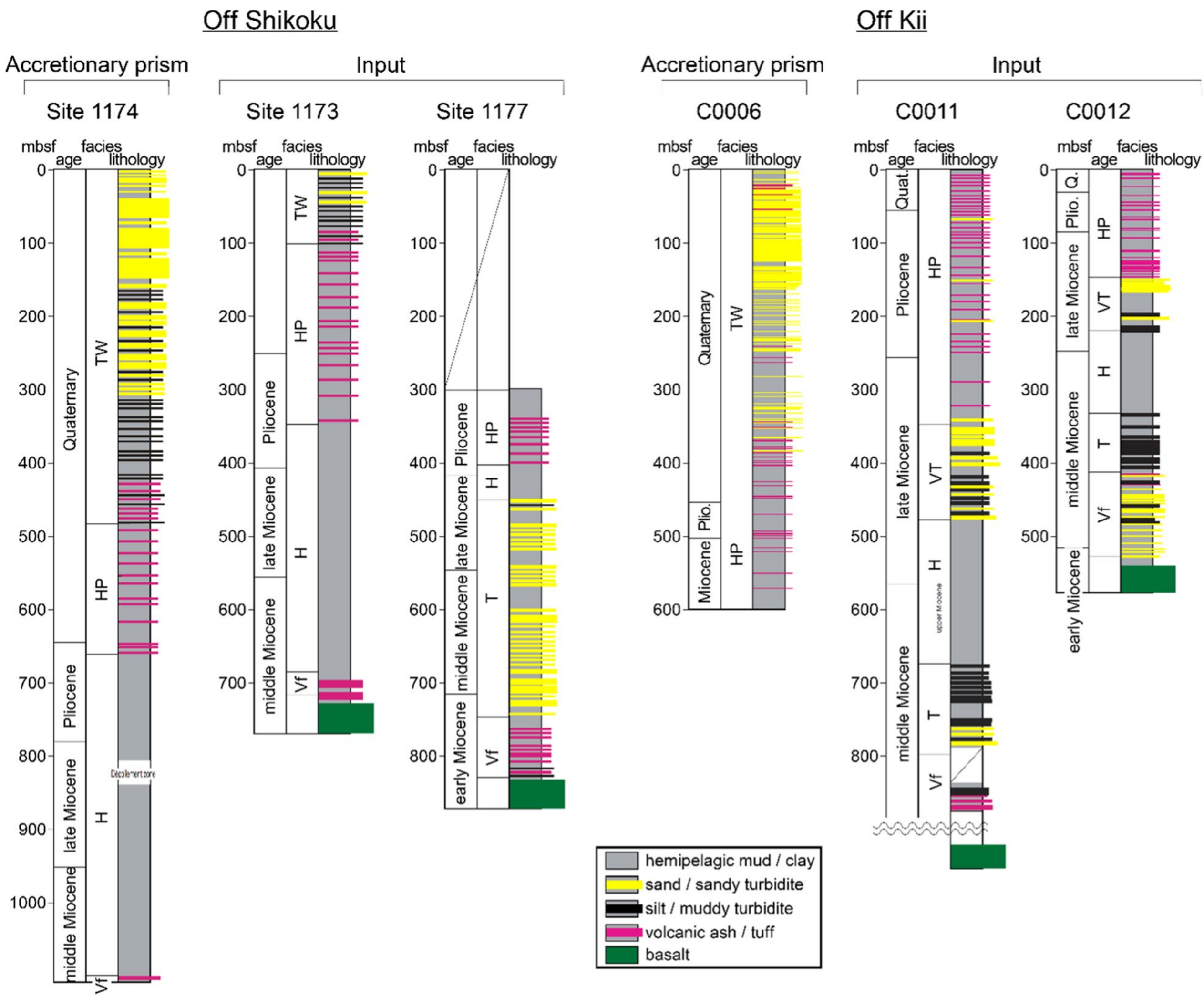


Fig. 5 Lithostratigraphy of the frontal accretionary prism and input sediments of the Nankai Trough off Shikoku Island and Kii Peninsula. The lithology and age are compiled from cruise reports of scientific drillings (Moore et al. 2001; Mikada et al. 2002; Kinoshita et al. 2009; Saito et al. 2010; Henry et al. 2012), and (Hüpers et al. 2015). Drilling site locations are shown in Fig. 4. *TW* trench wedge facies, *HP* hemipelagic pyroclastic facies, *VT* volcanic turbidite facies, *H* hemipelagic facies, *T* turbidite facies, *Vf* volcaniclastic turbidite facies

materials simulating the décollement sediments under various temperature conditions showed that all materials, except illite-rich sediment at over 170 ℃, exhibited positive $(a-b)$ values (den Hartog et al. 2012b; Mizutani et al. 2017; Okuda et al. 2023b). Therefore, unlithified sediments within the region from the trough to approximately 30 km landward, where shallow slow earthquakes occur, are frictionally stable and cannot nucleate an earthquake (Fig. 6), irrespective of pore pressure, temperature, and smectite–illite transition.

Still, lithification plays an important role in turning the sediments into velocity weakening, as already mentioned (Roesner et al. 2020). Therefore, the frictional properties of lithified sediments under high temperature and high pore pressure conditions need to be understood. Furthermore, a heterogeneous mixture of materials can also induce velocity-weakening behavior (Bedford et al. 2022), and the velocity-strengthening system can apparently become a velocity-weakening system via local pore pressure build-up (Faulkner et al. 2018). Some studies on both sediment samples and analog samples show slip-weakening behavior that can overcome velocity-strengthening behavior leading to unstable slip (Roesner et al. 2022; Okuda et al. 2023a). These factors may be able to form frictionally unstable patches that can nucleate shallow slow earthquakes. Recent numerical studies reproduced slow earthquakes in shallow depths with velocity-strengthening system through pore pressure

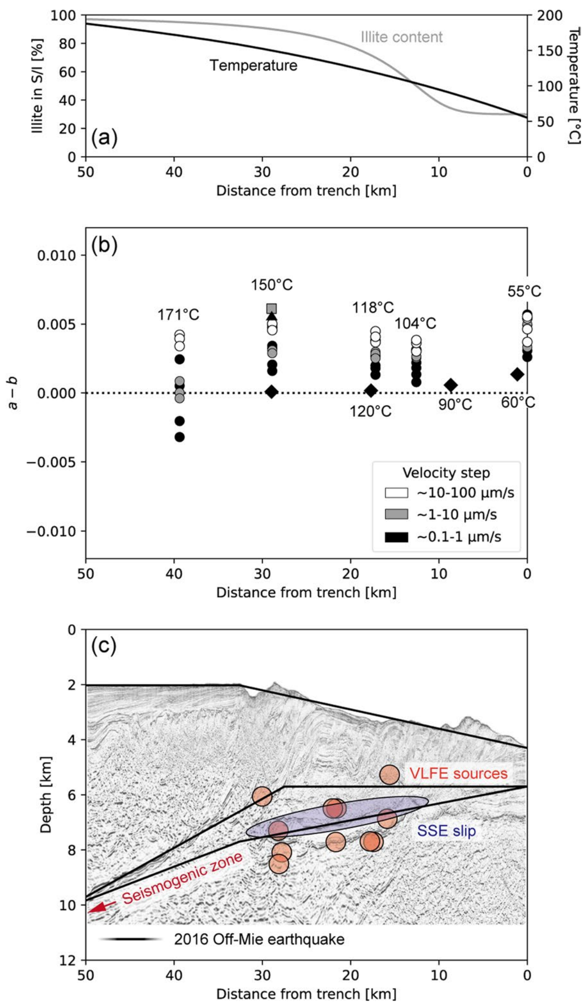


Fig. 6 Laboratory friction experiments of sediments under the shallow plate boundary condition. **a** Temperature condition (black line) and illite content (gray line) along the bottom of underthrust sediment. **b** Variation in ($a-b$) values based on temperature conditions at various locations along the bottom of the accretionary prism. Circle dots; sediments off Kii peninsula (Okuda et al. 2023b); square and triangle: illite shale (den Hartog et al. 2012a; Phillips et al. 2020); and diamond: pure smectite (Mizutani et al. 2017). **c** Locations of very low frequency earthquakes (VLFE), slow slip events (SSE) (Sugioka et al. 2012; Araki et al. 2017; Ariyoshi et al. 2021), and 2016 Off-Mie earthquake (Wallace et al. 2016a; Nakano et al. 2018b; Takemura et al. 2020a)

variations (Perez-Silva et al. 2023), whereas most numerical models are constituted using velocity-weakening system as well as some mechanisms to suppress unstable slip (Shibazaki 2003; Liu and Rice 2007; Segall et al. 2010). The abovementioned experimental results should be tested in numerical models to constrain the frictional property of the plate interface.

From lithological and experimental viewpoints, the heterogeneous distribution of slow earthquakes in shallow plate subduction zones can be partly governed by the distribution of sedimentary facies and their frictional properties. Compared to geophysical observations, however, geological and experimental studies have not yet covered the entire area of the Nankai Trough due to limited coverage of sampling points on the seafloor. Therefore, analyses on materials sampled from various locations along the trough other than the three major transects (Kumano, Muroto, and Ashizuri) for deep-sea drilling projects will be necessary for further quantitative investigation on the linkage between the observed slip behavior and the incoming materials.

Structural and hydrological factors controlling the spot-like distribution of shallow slow earthquakes

In addition to lithological variation and consequence variable frictional properties, other factors control the observed along-strike variations of shallow slow earthquake activity (Figs. 2, 4). Hereafter, we discuss the relationship between shallow slow earthquakes and seismological structural characteristics around the shallow plate boundary along the Nankai Trough.

Subducted seamounts can form heterogeneous fracture networks and stress conditions in their surrounding regions (e.g., Wang and Bilek 2011, 2014; Ruh et al. 2016; Sun et al. 2020; Chesley et al. 2021); consequently, they are considered to be a factor of heterogeneous seismicity, including slow earthquakes. Indeed, complicated distributions of small ordinary and slow earthquakes have been confirmed around subducted seamounts (e.g., Mochizuki et al. 2008; Todd et al. 2018; Shaddox and Schwartz 2019; Kubo and Nishikawa 2020; Yamaya et al. 2022). Figure 7 shows the spatial distribution of shallow slow earthquakes and subducted seamounts along the Nankai Trough. Shallow slow earthquakes actively occurred around the paleo-Zenisu and Kyushu-Palau ridges (e.g., Yamashita et al. 2015, 2021; Toh et al. 2018, 2020; Tonegawa et al. 2020; Baba et al. 2022; Takemura et al. 2022c); shallow slow earthquakes also occurred in areas without these seamounts. Although detailed three-dimensional configurations of the paleo-Zenisu and Kyushu-Palau ridges have not been sufficiently resolved, dense geophysical survey data have resolved the detailed configuration of the upper surface of the Philippine Sea plate off Cape Muroto (Nakamura et al. 2022). Individual small-scale subducted seamounts (blue enclosed regions in Fig. 7) were not spatially correlated with shallow slow earthquakes. Southeast off the Kii Peninsula, the spatial correlation between oceanic crust ridges and shallow VLFE swarms was confirmed in Shiraishi et al. (2020) and Hashimoto et al. (2022); however, shallow slow earthquakes were also distributed in regions without oceanic

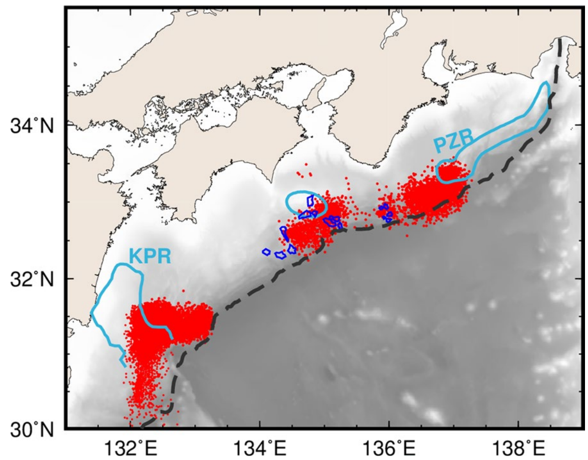


Fig. 7 Comparative plots of shallow slow earthquakes and subducted seamounts. Areas enclosed by light blue lines are locations of subducted seamounts (Kodaira et al. 2000; Park et al. 2004; Yamamoto et al. 2013). Off Cape Muroto, the revisited analysis (solid blue lines) was conducted by Nakamura et al. (2022). Red dots are shallow tremors (Yamashita et al. 2015, 2021; Tamaribuchi et al. 2022). KPR and PZR are abbreviations for the Kyushu-Palau Ridge and the Paleo-Zenisu Ridge, respectively

crust ridges. Because of the accuracy of source locations in the catalogs (Fig. 2a of Yamamoto et al. (2022a)) and the resolutions of the used structural models, the relationship between seamounts and slow earthquakes remains an open question for future research.

Another candidate for the spot-like shallow slow earthquake distribution is patchy high pore pressure areas. Based on the high-resolution two-dimensional *P*-wave structures southeast off the Kii Peninsula (e.g., Park et al. 2010; Kamei et al. 2012), shallow VLFE sources (Sugioka et al. 2012) are typically located within low *P*-wave velocity bodies. Based on the empirical relationships among the physical parameters from laboratory experiments, these low *P*-wave velocity bodies indicated the presence of high pore fluid pressure zones (Kitajima and Saffer 2012; Tsuji et al. 2014). After 2011, continuous seismic records from the permanent OBS network of DONET enabled us to investigate the *S*-wave velocity structures around the plate boundary, which are more sensitive to pore fluids. Figure 8 shows comparative plots of the subsurface structures and shallow slow earthquakes off Cape Muroto and off the Kii Peninsula. Strong negative *S*-wave perturbations above the plate boundary (Tonegawa et al. 2017) appeared around the shallow slow earthquake active zones (Fig. 8a). Such low *S*-wave velocity conditions suggest that pore fluid pressure is high around the active zones of shallow slow earthquakes. Using high-frequency receiver functions southeast off the Kii Peninsula, Akuhara et al. (2020) found a high-Vp/Vs body

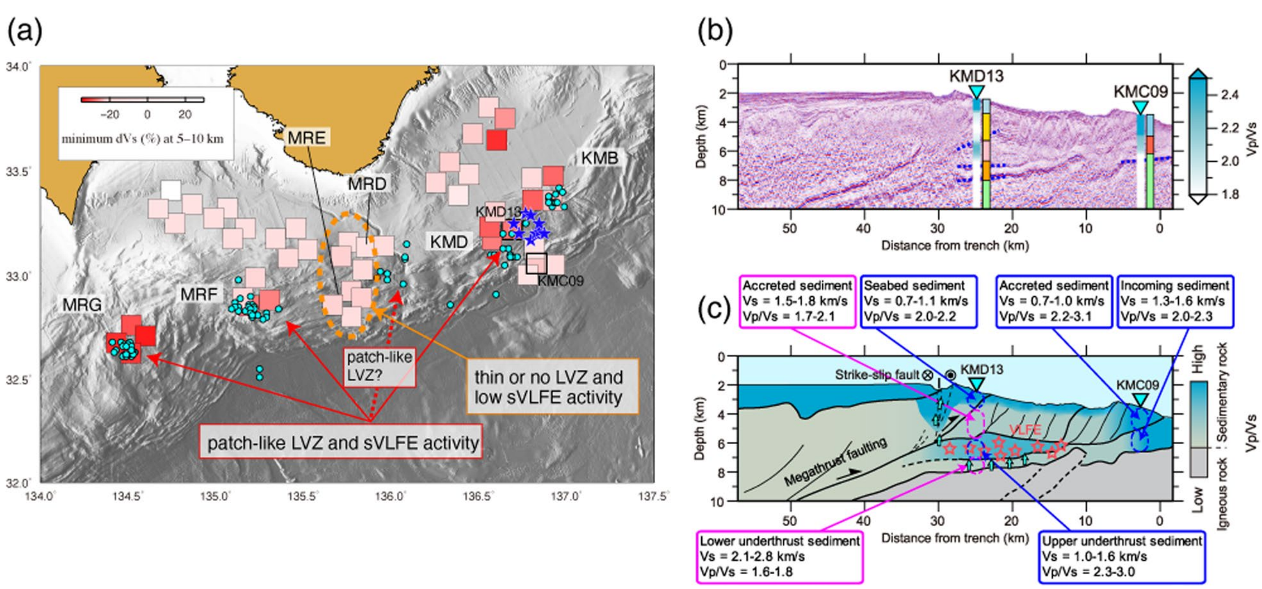


Fig. 8 Relationship between shallow slow earthquakes and subsurface seismic structures. **a** *S*-wave velocity perturbations 5–10 km below sea level beneath the DONET stations (Tonegawa et al. 2017). **b** Cross-section of reflection profile (Tsuji et al. 2014) and high-resolution receiver function image southeast off the Kii Peninsula (Akuhara et al. 2020). c Schematic figure from the interpretation of Akuhara et al. (2020). We modified Fig. 3 of Tonegawa et al. (2017) and Fig. 4 of Akuhara et al. (2020). Colored dots and stars in **a** and **c** are hypocenters of shallow VLFEs (Sugioka et al. 2012; Nakano et al. 2018a). Light blue, yellow, pink, orange, red, and light green layers in **b** represent seabed sediment, accreted sediment, upper underthrust sediment, lower underthrust sediment, incoming sediment, and oceanic crust, which are interpretations of velocity structures from receiver function images. Locations of KMC09 and KMD13 are shown in **a**

within the shallow VLFE source region just above the décollement (Fig. 8b). These high-resolution velocity structures are limited southeast off the Kii Peninsula. However, the clear correlation between slow earthquakes and high Vp/Vs bodies suggests the importance of pore fluids for slow earthquake occurrence at shallow plate boundaries.

Based on the framework by Rice (1992) and physical conditions at shallower parts of the Nankai subduction zone (Moore et al. 2009), Kaneki and Noda (2023) incorporated the effects of smectite dehydration and fluid leakage through the splay fault (a branching fault within the accretionary prism that is isolated from the plate boundary) to quantitatively investigate the cause of the local reduction of effective normal stress on the shallow plate boundary. They concluded that neither smectite dehydration nor fluid leakage through the splay fault could create a local reduction in the effective normal stress on the shallow plate boundary. However, if a local impermeable condition is introduced, a local reduction in the effective normal stress due to the trapped fluid can occur at the depths of shallow slow earthquakes (5–10 km). Similarly, impermeable hanging wall conditions are considered important for deep slow earthquake activity in the Nankai subduction zone (e.g., Kato et al. 2010; Nakajima and Hasegawa 2016).

The fluid drainage associated with slow or repeating earthquakes has been observed in various subduction zones (e.g., Nakajima and Uchida 2018; Warren-Smith et al. 2019; Gosselin et al. 2020; Kita et al. 2021). Around the pathways of the pore fluid, the structural or stress conditions could temporarily change due to fluid migration. Such structural or stress condition changes can typically be monitored using the waveforms of ordinary earthquakes or ambient noise monitoring techniques (e.g., Nakata et al. 2019). Unfortunately, the intraslab seismicity beneath shallow slow earthquake zones is not high. The spatiotemporal resolution of ambient noise monitoring using DONET is limited by noise properties and station coverage. In addition, owing to low-velocity oceanic sediment, the sensitivities of ambient noise monitoring for structural or stress changes are restricted to shallower depths (< 1–2 km from the seafloor). However, Tonegawa et al. (2022) found spatiotemporal changes in seismological structures associated with shallow slow earthquakes beneath the DONET stations (Fig. 9). Figure 9a shows the spatiotemporal distributions of scattering coefficient changes (Δg) southeast off the Kii Peninsula, resolved by 1-month stacking of coda parts

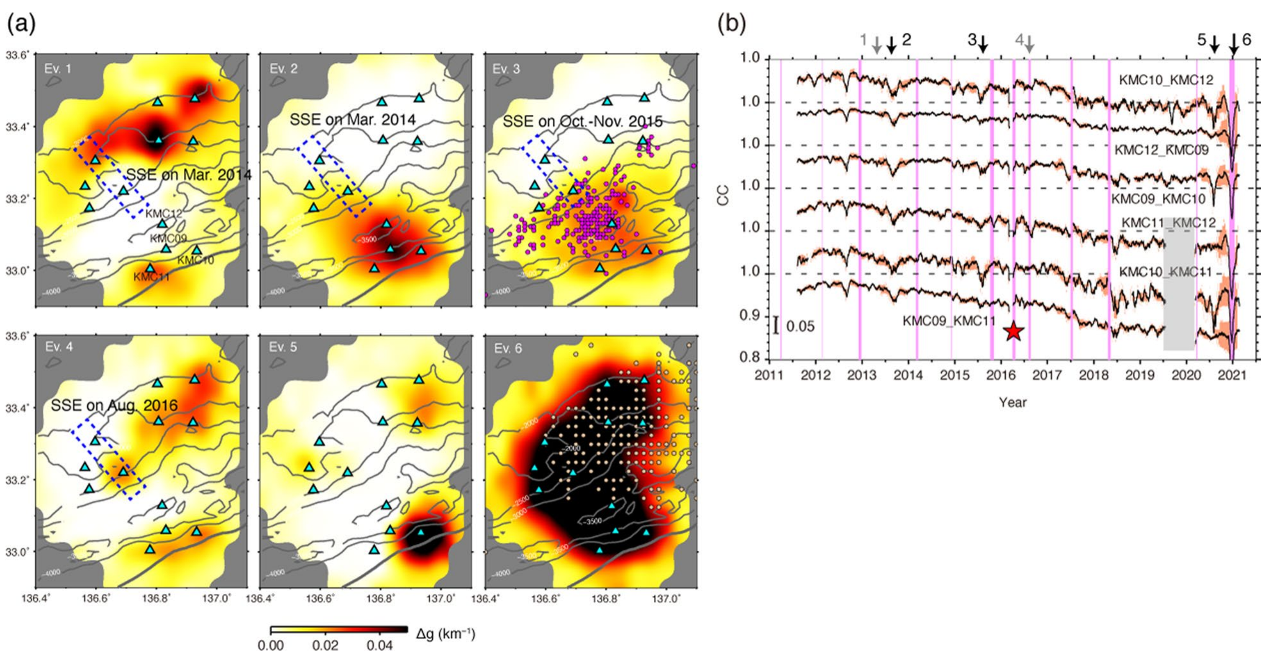


Fig. 9 Spatiotemporal change of subsurface structure associated with shallow slow earthquakes southeast off the Kii Peninsula (Tonegawa et al. 2022). **a** Spatiotemporal variations of scattering coefficient change (Δg), which is related to subsurface structure changes beneath DONET stations. Dashed blue boxes represent the regions of shallow SSEs detected by Araki et al. (2017). Purple and light-brown circles during Events 3 and 6 are shallow VLFEs (Nakano et al. 2018a; Takemura et al. 2022c). **b** temporal change in cross-correlation coefficient (CC) for KMC-node. Black and gray arrows represent the CC reductions observed around KMC-node and other regions. Pink regions represent the periods of shallow SSEs (Araki et al. 2017; Ariyoshi et al. 2021) and large shallow slow earthquake episode from December 2020. Gray regions are data gaps. The red star in **b** indicates the 2016 off Mie earthquake which was an *Mw* 6 interplate earthquake. Names of station-node are added in **a**

of cross-correlation functions (CCFs) (Obermann et al. 2013). The decorrelation of the CCF at each DONET station pair were obtained by calculating the cross-correlation coefficients between CCFs at a certain time and that at the reference time. Thus, the decorrelation represents a temporal change of subsurface structure around the propagation path between a certain station pair (Fig. 9b). The Δg in Fig. 9a represents the change in scattering coefficient, which is typically considered as a result of temporal change in small-scale (a few kilometers) fluctuations of seismic velocity structure from those at the reference time. Tonegawa et al. (2022) confirmed that based on numerical simulations of seismic wave propagation, localized small velocity reductions at shallower depth can be imaged as the spatial distribution of scattering coefficient change and interpreted that such observed velocity fluctuations are induced by fluid migration. Structural changes (temporal changes in seismic velocity fluctuations) were observed around the shallow SSE faults in SSEs during Event 1 (March 2014) and Event 4 (August 2016) (Araki et al. 2017). Shallow tremors and VLFEs were not detected during these SSEs. However, during the shallow ETSs (Events 3 and 6; April 2016 and December 2020), changes in seismic velocity structure appeared within the regions of shallow VLFEs (Nakano et al. 2018a; Takemura et al. 2022c). All changes (decorrelation/small velocity fluctuation) appeared 0–9 months before shallow slow earthquake activity (Fig. 9b). These observations also suggest that pore fluid migration and spatiotemporal changes in pore fluid pressure around shallow plate boundaries are important for the occurrence and migration of shallow slow earthquakes.

Detailed mechanisms of high-fluid pressure conditions and shallow slow earthquakes are still an open question. Thus, continuous monitoring of fluid migration around plate boundaries is critical for a more quantitative understanding of shallow slow earthquake mechanisms in the future.

Regional differences in shallow slow earthquake activity along the Nankai Trough

Observed regional differences of shallow slow earthquake activity

Based on seismic, geodetic, geologic, and experimental results, localized pore fluids and their migration (transient changes in pore fluid pressure) can promote shallow slow earthquake activity along the Nankai Trough. There are regional differences in the migration patterns and recurrent intervals of ETSs along strike of the Nankai Trough (Baba et al. 2020a; Baba 2022; Takemura et al. 2022b). Takemura et al. (2022b) investigated the scaling law of shallow VLFE swarms in regions off Cape Muroto to southeast off the Kii Peninsula (Fig. 10). Detailed migration patterns are illustrated in previous studies (Figs. 2 and 3 of Takemura et al. (2019b) and Fig. 6 of Takemura et al. (2022c)). Because seismic slow earthquake (i.e., LFE, tremor, and VLFE) swarms reflect the characteristics of the corresponding slips caused by SSEs (e.g., Bartlow et al. 2011; Itoh et al. 2022), the scaling laws of seismic slow earthquake swarms are important for understanding fault slips in slow earthquake regions (e.g., Frank and Brodsky 2019; Aiken and Obara 2021; Passarelli et al. 2021). The areas of shallow VLFE swarms (Fig. 10a) approximately follow a scaling law similar to that for ordinary earthquakes and deep SSEs (e.g., Kanamori and Brodsky 2004; Gao et al. 2012) and exhibit no obvious regional differences. This observation suggests that the stress drops of the shallow VLFE swarms (slips due to background shallow SSEs) should be similar, irrespective of the region. Shorter-duration VLFE swarms migrate faster (Fig. 10d), as is commonly observed in other regions (Fig. 1b of Gombert and Hawthorne (2023)). However, slower and longer migration swarms occurred only off Cape Muroto (red symbols in Fig. 10b–d). The apparent spreading speed of the shallow VLFE migration (along-strike distance/duration) off Cape Muroto was one order of magnitude smaller than that southeast off the Kii Peninsula. Regional differences were also found in the temporal changes in the seismic velocity structures associated with shallow slow earthquakes (Tonegawa et al. 2022) (Fig. 11). The structural changes associated with shallow slow earthquakes off Cape Muroto occurred during the ETSs. In contrast, those southeast off the Kii Peninsula started 2–9 months prior to the shallow slow earthquakes (SSEs).

Possible causes of observed along-strike variations of shallow slow earthquake activity

These regional differences could be partially explained by lateral variations of lithology and frictional property ("Geological and experimental observations" section). Along-strike variations in pore fluid pressure (or effective normal stress) around the shallow plate boundary may have also caused these regional differences (Fig. 11a, b). Laboratory experiments revealed that a small change (~0.1) in the ratio of the pore fluid pressure to the normal stress on the fault can induce a large (1–2 orders of magnitude) change in the rupture velocity (Passelègue et al. 2020). In practice, negative *S*-wave perturbations around the plate boundary were relatively strong off Cape Muroto (Fig. 8a), where high pore fluid pressure patches with radii of several hundred meters were found (Hirose et al. 2021). The Vp/Vs ratio within the hanging wall (Audet and Bürgmann 2014) and effective normal stress (Liu and Rice 2007; Hirose et al. 2022) can affect the recurrent intervals of the SSEs. Baba et al. (2020a) and

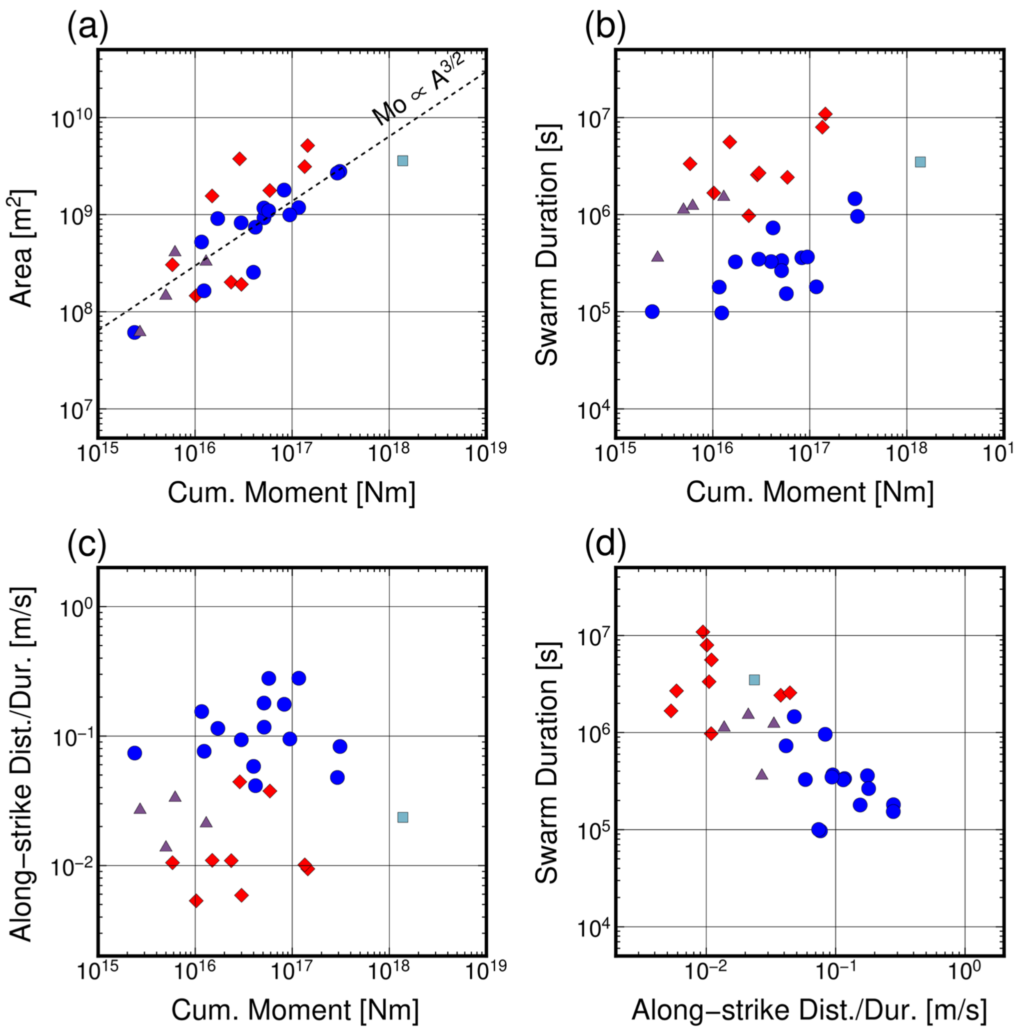


Fig. 10 Regional differences in shallow VLFE swarms in Nankai. We modified Fig. 4 of Takemura et al. (2022b). Blue circles, purple triangles, and red diamonds are the resultant values in regions southeast off the Kii Peninsula, south off the Kii Peninsula, and off Cape Muroto, respectively. The light blue square represents a shallow VLFE swarm that started on September 6, 2004, which can be considered a triggered VLFE swarm owing to the *Mw* 7.4 intraslab earthquake. Cumulative moments versus **a** swarm activity areas, **b** swarm durations, and **c** apparent spreading speeds. We added **d** apparent spreading speeds versus swarm durations. The apparent spreading speed was evaluated by dividing the along-strike distance by the duration of each shallow VLFE swarm. The data of shallow VLFE swarms can be downloaded from https://doi.org/10.5281/zenodo.5824418

Baba (2022) found regional differences in the recurrence intervals of shallow slow earthquake episodes throughout the Nankai subduction zone. They found that the recurrent intervals in Hyuga-nada were approximately four times shorter than those off Cape Muroto and southeast off the Kii Peninsula and could be explained by regional differences in Vp/Vs within the hanging wall or effective normal stress conditions around the plate boundary.

Other factors, such as geometry and convergence rate of the Philippine Sea Plate, may also affect shallow slow earthquake activity. Based on numerical simulations, the segmentation of shallow SSEs in the Hikurangi subduction zone can be explained by incorporating along-strike changes in the fault geometry and the convergence rate of the subducting oceanic plate (Perez-Silva et al. 2022). The plate convergence rate is roughly correlated with the deep tremor activity rate along the Nankai Trough (Annoura et al. 2016). Because the plate configuration and convergence rate along the Nankai Trough also varies laterally (Seno et al. 1993; Hirose et al. 2008), they may also explain the observed regional differences in the activity patterns of shallow slow earthquakes.

These regional differences provide clues for understanding the mechanisms of shallow slow earthquakes and slip behaviors on plate boundaries. More

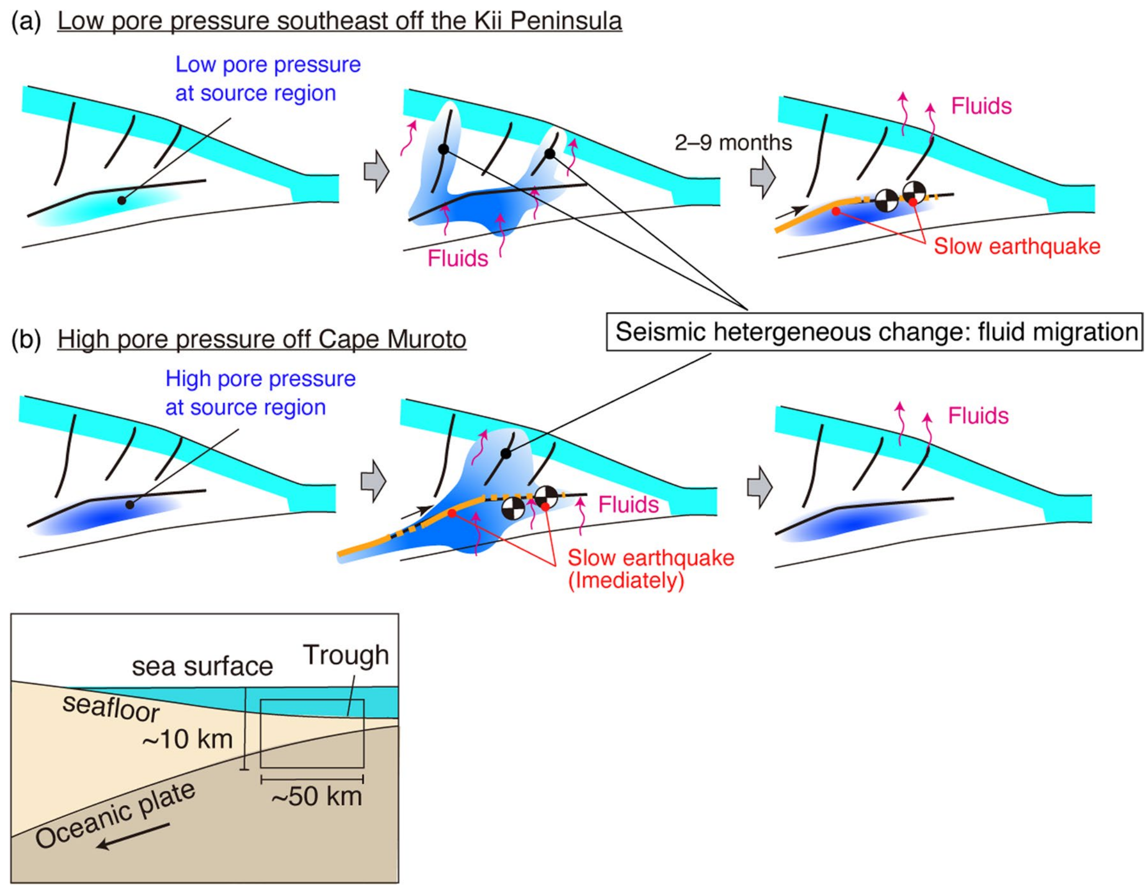


Fig. 11 Spatiotemporal relationship between fluid pressure conditions and slow earthquakes, in which dark blue indicates relatively high pore pressure. **a** Slow earthquake generation and fluid conditions in the source region for low pore pressure (southeast off the Kii Peninsula). Beach balls and orange lines show VLFEs and SSEs. Magenta arrows indicate fluid flow. **b** Same as **a**, but for high pore pressure (off Cape Muroto). We modified Fig. 5 of Tonegawa et al. (2022)

quantitative and physical approaches to shallow slow earthquakes will be required for a deeper understanding in future studies.

Conclusions and future perspectives

Conclusions

Obara and Kato (2016) mainly reviewed seismological findings of slow earthquakes in the world. They showed the spatial distribution of slow earthquakes in the Nankai subduction zone, but for shallow slow earthquakes, shallow VLFEs based on inland observations were only illustrated. This is because catalogs of shallow slow earthquakes based on offshore observation were not sufficiently developed in 2016. In our review, we reviewed characteristics of shallow slow earthquakes listed in the updated catalogs using both inland and offshore observations. In addition, for a unified understanding of shallow slow earthquakes, we also provided an overview of the up-to-date structural, geological, and experimental results at shallower depths of the Nankai Subduction zone.

In the Nankai subduction zone, in contrast to the continuous belt-like distributions of deep slow earthquakes, shallow slow earthquakes are concentrated in limited regions, such as Hyuga-nada, off Cape Muroto, and southeast off the Kii Peninsula. These regions correspond to those surrounding the stress accumulation peaks expected from the geodetic observations. This spatial relationship suggests that the preferable frictional conditions for shallow slow earthquakes may be satisfied in the transitional regions between the frictionally locked and stably sliding zones on the plate boundary. However, laboratory friction experiments on sedimentary materials from various locations along the Nankai Trough under the temperature–pressure–mineral conditions of shallow slow earthquake zones revealed that the $(a-b)$ values are positive in most cases, although there are some processes proposed to make the $(a-b)$ negative.

Previous studies have proposed a relationship between shallow slow earthquakes and subducted seamounts. Although subducted seamounts create complex fracture networks and stress shadows in their surrounding areas and may affect the activity of nearby shallow slow earthquakes, not all subducted seamounts on the Philippine Sea Plate are related to shallow slow earthquake activities. This incomplete correlation leads to alternative factors explaining the spot-like distribution of shallow slow earthquakes along the Nankai Trough. According to seismic structural studies in the Nankai subduction zone, high pore-fluid pressure conditions around shallow slow earthquake zones were inferred from low *S*-wave velocities or high Vp/Vs volumes. In addition, ambient noise monitoring revealed a spatiotemporal correlation between changes in seismic velocity structures and shallow slow earthquake migrations. This correlation suggests pore fluid migration during shallow slow earthquake episodes. Transient changes in the pore fluid pressure can lead to various slip behaviors, such as creep and unstable slip. The studies summarized in this paper suggest that spot-like high pore fluid pressure conditions and their drainage may explain preferable locations for shallow slow earthquakes. The episodic migration of pore fluid around the plate boundary may have promoted shallow slow earthquake activity along the Nankai Trough. The conclusions are summarized in Fig. 12. The areas with temperatures greater than 150 °C are almost corresponding to the expected source regions of future Tonankai and Nankai earthquakes (available at http://www.jishin.go.jp/main/chousa/01sep_nankai/index.htm).

Future perspectives

Along the Japan Trench (Nishikawa et al. 2019, 2023), slow earthquakes and the large slip area of the 2011 Tohoku earthquake are spatially separated within the same depth range (10–20 km). They interpreted that slow earthquake zones in the Japan Trench could be the barriers against the rupture of the 2011 Mw 9.0 Tohoku earthquake. On the other hand, recent microstructural investigations of drilling core samples near the Nankai Trough (Kimura et al. 2022) have suggested that the plate boundary fault has experienced both fast ruptures and slow slips, implying that fast coseismic rupture can occur in the same regions as shallow slow earthquakes. Coseismic ruptures near trenches can cause large vertical seafloor deformations and destructive tsunamis. For disaster mitigation of future megathrust earthquakes in the Nankai subduction zone, it is important to determine whether fast coseismic ruptures can propagate to shallow slow earthquake zones and generate large tsunamis. Another key problem is the interaction between slow and megathrust earthquakes. Although some observational and simulation studies tried to investigate the interaction between slow and megathrust earthquakes (e.g., Kato et al. 2012, 2016; Vaca et al. 2018; Voss et al. 2018; Luo and Liu 2019; Ohtani et al. 2019), it is not fully understood whether a slow earthquake can trigger a megathrust earthquake.

In the future, integration of greater numbers of seismological, geodetic, geological, and experimental studies will be indispensable to address these issues.

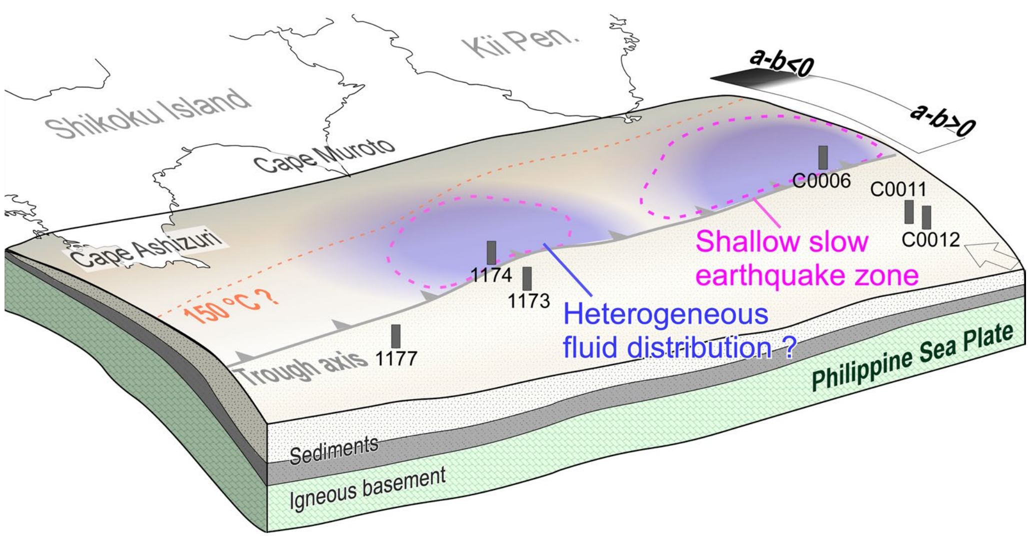


Fig. 12 Schematic image of the shallow slow earthquake zone of the Nankai Trough off Shikoku Island and Kii Peninsula. Gray bars represent the drilling points used in Fig. 5. Thin open arrow indicates the convergence direction of the Philippine Sea Plate. The areas with temperatures greater than 150 °C are almost corresponding to the expected source regions of future Tonankai and Nankai earthquakes (available at http://www.jishin.go.jp/main/chousa/01sep_nankai/index.htm)

Abbreviations

DONET Dense Oceanfloor Network for Earthquakes and Tsunamis
ETS Episodic tremor and slip
F-net Full-range seismograph network
GNSS Global Navigation Satellite System
GNSS-A Global Navigation Satellite System Acoustics
JAMSTEC Japan Agency for Marine-Earth Science and Technology
LFE Low-frequency earthquake
NIED National Research Institute for Earth Science and Disaster Resilience
SSE Slow slip event
SST Slow slip and tremor
VLFE Very low frequency earthquake
Vp P-wave velocity
Vs S-wave velocity

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Author contributions

ST and YH conducted informal seminars on shallow slow earthquakes along the Nankai Trough. ST and YH drafted the first version of the manuscript. ST created Figs. 1, 2, 3, 4, 7, and 10. YH created Figs. 5 and 12. ST reviewed the seismological observations of shallow slow earthquakes. AN and YO reviewed geodetic views of plate motion and slow earthquakes on the Philippine Sea plate. TA and TT reviewed the seismological structures around fault zones of shallow slow earthquakes. TT created Figs. 8, 9, and 11. YH provided the geological features of the input to Nankai. HO and KO considered the observed slow earthquakes and frictional behaviors based on the results of laboratory experimental studies. All authors have drafted, read, and approved the final manuscript.

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Availability of data and materials

We used F-net and DONET data from the NIED (National Research Institute for Earth Science and Disaster Resilience 2019a; b). The images were drawn using Generic Mapping Tools (Wessel et al. 2013). We downloaded the catalogs of slow earthquakes at the shallow plate boundary along the Nankai Trough and repeating earthquakes from the "Slow earthquake database" http://www-solid.eps.s.u-tokyo.ac.jp/~sloweq/ (Kano et al. 2018) and the NIED website https://hinetwww11.bosai.go.jp/auth/?LANG=en.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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