Title: Connecting slow earthquakes to huge earthquakes

Author: Kazushige Obara, Aitaro Kato

Additional information(追加情報)：

 The definitive version was published in Science Vol. 353, Issue 6296, (2016/07/15), doi: 10.1126/science.aaf1512

Connecting Slow Earthquakes to Huge Earthquakes

Kazushige Obara and Aitaro Kato
Earthquake Research Institute, The University of Tokyo

Abstract

Slow earthquakes are characterized by a wide spectrum of fault slip behaviors and seismic radiation patterns that differ from traditional earthquakes. However, slow earthquakes can have common slip mechanisms with huge megathrust earthquakes and are located in neighboring regions of the seismogenic zone. The frequent occurrence of slow earthquakes may help reveal the physics underlying megathrust events as useful analogs. Slow earthquakes may function as stress meters due to their high sensitivity to stress changes in the seismogenic zone. Episodic stress transfer to megathrust source faults leads to increased probability of triggering huge earthquakes if the adjacent locked region is critically loaded. Careful and precise monitoring of slow earthquakes provides new information on the likelihood of impending huge earthquakes.

Introduction

Megathrust earthquakes occurring along the boundary between a subducting oceanic plate and an overriding continental plate may cause devastating damage due to the resulting strong ground motion and possible tsunamis. If we can retrieve a precursory signal prior to a megathrust earthquake, it would be useful for disaster mitigation. While many studies have investigated earthquake prediction, no practical method has been established for the short-term prediction of an impending huge earthquake. Even though long-term changes in *b*-value [which characterizes the magnitude-frequency distribution of seismicity (*1*)] and the tidal sensitivity of regular earthquakes (*2*) were retrospectively observed in the mainshock rupture areas of the 2004 Mw 9.2 Sumatra and the 2011 Mw 9.0 Tohoku earthquakes, we cannot yet come to any conclusion about the quantitative predictive power of these parameters (*3*, *4*).

Slow earthquakes show an intermediate type of fault slip that is transitional between the fast rupture of regular earthquakes and stable sliding along a megathrust fault interface. The deployment of geodetic and seismic observation networks such as GEONET (*5*) and Hi-net (*6*) in Japan have contributed to the discovery of various types of slow earthquakes. Slow earthquakes provide phenomenological evidence for the existence of a transition zone between locked and creeping zones proposed by thermal modeling studies (*7*), and the partial release of slip deficit. In the past two decades, slow earthquakes have been detected in many subduction zones along the Pacific Rim (*8*). The existence of different modes of fault slip is useful for understanding the physics of earthquake phenomena. Furthermore, the characteristic activity of slow earthquakes might be linked to huge earthquakes despite the limited period during which observations of such phenomena have been made. Soon after the discovery of slow earthquakes, it was suggested that slow earthquakes could lead to an increased probability of megathrust events (*9*), although there have been not so many observations to confirm or refute this hypothesis statistically. Based on observations accumulated during the last decade, we focus here on how the study of slow earthquakes can help further our understanding of the earthquake cycle, which should in turn help narrow and focus our ability to improve disaster preparedness for this megathrust earthquake hazards.

Types of slow earthquakes

Slow earthquakes in the Nankai subduction zone are typically categorized as seismic or geodetic events according to their characteristic time-scale (Fig. 1). Geodetic slow earthquakes are characterized as being either long-term slow slip events (SSEs) with durations of months or years, or short-term SSEs with durations of days. Seismic slow earthquakes are characterized by very-low-frequency (VLF) earthquakes at dominant periods of tens of seconds, and low-frequency tremor at dominant frequencies of several Hz. These slow earthquakes are located both shallower and deeper than the seismogenic zone of the 1946 Mw 8.3 Nankai and 1944 Mw 8.1 Tonankai earthquakes (Fig. 2). Deep tremor is nearly continuously distributed within a narrow belt-like zone along the downdip edge of the megathrust seismogenic zone over a length of 600 km and the belt width is several tens of kilometers (10). Tremor episodes usually continue for several days and accompany both short-term SSEs (*11*) and deep VLF earthquakes (*12*). The association of short-term SSEs with tremor was first discovered in Cascadia (*13*, *14*); these coupled phenomena are also referred to as episodic tremor and slip (ETS).

Long-term SSEs occur in southwest Japan, and shift to shallower depths than the deep ETS zone, appearing to fill a gap between tremor and shallower locked zones (*15*). In the Tokai region near the eastern edge of the deep ETS zone, a long-term SSE occurred from 2000 to 2005, releasing a seismic moment equivalent to a Mw 7.1 earthquake (*16*). In the Bungo channel at the western-most part of the deep ETS zone, a Mw 6.8 long-term SSE, with a duration of several months, occurs about every 6 or 7 years, accompanying tremor activity (*17*). On the shallower side of the locked zone, shallow VLF earthquakes are sporadically distributed on the landward side of the Nankai trough (*18*). Data from seafloor seismometers reveal that the intensification of shallow tremor was coincident with shallow VLF earthquake activity off the east coast of Kyushu (*19*). The shallow VLF earthquakes extend to the Ryukyu Islands from off Kyushu (*20*), associated with short-term SSEs (*21*). Another shallow VLF earthquake zone is located east of Hokkaido (*22*), strongly modulated by afterslip following the 2003 Mw 8.1 Tokachi-oki earthquake.

In contrast to ETS observed in the Nankai subduction zone, a series of SSEs of Mw ~ 6.6 located near the Boso Peninsula, central Japan, has consistently accompanied swarms of regular earthquakes on the downdip part of the SSE area (*23*). Each SSE, with a duration of weeks, occurs once every 5 to 7 years.

Among the various slow earthquake types observed along the Pacific Rim (Fig. 3), Cascadia ETS behavior is similar to that seen in Nankai; however, the scale of activity is much larger in Cascadia, where the ETS zone extends for 1200 km along the strike of the subducting plate and is divided into several segments (*24*). Recently, deep VLF earthquakes were detected (*25*); however, no accompanying long-term SSEs or shallow slow earthquakes were observed. In Mexico, long-term SSEs with Mw > 7 were detected first, followed by tremor in the downdip portion of the long-term SSE source area (*26*). Slow earthquakes around the North Island of New Zealand show more complicated behavior (*27*). That is, SSEs with durations of weeks occur at intervals of a few years along the shallow interplate zone of the Hikurangi margin accompanying regular earthquakes, similarly to the Boso SSEs. Recently, seafloor pressure gauge observations revealed that the slip area of the SSE extends close to the trench (*28*). At depths of 20 ~70 km, long-term SSEs occur with durations of a couple of years, and minor tremor activity has been detected near the SSE-generating fault.

Tremor occurs not only in subduction zones but also along the transform plate boundary setting, at the deep extension of the San Andreas Fault (*29*). Tremor associated with teleseismic surface waves has also been detected in the zone of collision between the Pacific and Eurasian plates in southern Taiwan (*30*).

Slow earthquakes as analogs of megathrust earthquakes

Megathrust earthquakes are characterized by their variability in size and recurrence interval (*31*). Nankai megathrust earthquakes seem to occur repeatedly; however, the rupture area and recurrence interval are highly variable. On the other hand, some slow earthquakes are characterized by their regular, periodic occurrence. Typical recurrence intervals of slow earthquakes range from months to years, much shorter than those of megathrust earthquakes. Therefore, the repetitious nature of slow earthquakes may be useful for improving our understanding of rupture styles and recurrence cycles of megathrust earthquake.

Among the various types of slow earthquakes, episodic tremor and slip (ETS) is analogous to megathrust earthquakes, as both exhibit recurrent activity and rarely rupture multiple fault segments. An ETS zone at the deeper extension of the seismogenic zone along a plate interface can be separated into segments (Fig. 4) based on recurrence interval, which ranges from 3 to 6 months in southwest Japan (*11*) and from 10 to 19 months in Cascadia (*24*). This recurrence interval is more regular than those for megathrust earthquakes, although the interval and rupture area for each episode are variable. ETS events usually migrate within each segment, and rarely propagate to adjacent segments. For example, tremor episodes occur independently at six-monthly intervals in the Kii and Tokai segments, separated by a gap at Ise Bay (Fig. 2). However, during the 2006 ETS episode, slow slip events (SSEs) continuously propagated from the Kii to the Tokai segments through the Ise Bay gap, without any excitation of tremor (*12*). The continuous propagation of minor slow slip without tremor has also been observed at Cascadia (*32*). The gap zone does not always host tremor, allowing smooth migration of tremor on other occasions. These observations suggest that frictional properties may change over space and time at the gaps that characterize segment boundaries. ETS migration that extends to an adjacent segment is analogous to multi-segment rupture during huge earthquakes. Consequently, ETS zone segment-boundaries play an important role in controlling rupture termination.

Interestingly, for the 2003 and 2010 episodes the Bungo channel long-term SSE recurred with almost identical slip parameters, including moment magnitude, slip area, and duration of SSE (*33*). This SSE seems to be a characteristic earthquake, which is a unique earthquake rupturing at approximately the same source with a regular interval. On the other hand, moment magnitude and slip area of each Boso SEE were not always identical, based on the longest observed repetition history of any SSE, almost 30 years. The three most recent SSEs detected by GNSS (Global Navigation Satellite System) occurred in 2002, 2007, 2011, and 2014, indicating a gradual shortening of the recurrence interval, possibly due to stress transfer related to the 2011 Tohoku earthquake (*23*, *34*). Alternatively, this shortening may signal a stress-state change caused by an approaching large earthquake, as seen in numerical simulations (*35*), as discussed below. On the other hand, a small SSE was detected by seismological means immediately after the 2011 Tohoku earthquake (*36*). If we take this small SSE hidden by substantial afterslip following the Tohoku earthquake into account, the recurrence interval shows a more complex pattern, and the entire recurrence history must be reconsidered.

Slow earthquakes as stress meters

Slow earthquakes are sensitive to external stress perturbations because of fault weakness. During episodic tremor and slip (ETS), tremor is usually modulated by stress variations associated with Earth tides (*37*). On the other hand, during inter-ETS periods, triggered tremor is often associated with the propagation of surface waves from distant, large earthquakes (*38*). The sensitive nature of tremor means that slow earthquakes may play an important role as stress meters, and reflect stress accumulation at strongly locked sections of the megathrust adjacent to slow earthquake regions.

At Parkfield, California, U. S. A., two possible changes in tremor activity along the San Andreas Fault have been recognized prior to the 2004 Mw 6.0 Parkfield earthquake. One is an increase in tremor seismicity beginning approximately 3 weeks before the earthquake (*39*). This foretremor might have been caused by preslip at the mainshock nucleation point, as indicated by an elevation in tremor seismicity that decays gradually after the earthquake, consistent with afterslip (*40*). Another change is a characteristic migration pattern of seismicity revealed by precise event catalogs (*41*). Tremor usually migrates in both directions along the fault; however, during the 3 months before the Mw 6 earthquake, all tremor events migrated unilaterally in a southward direction towards the rupture initiation point of the Mw 6 earthquake. This change in migration direction might indicate stress accumulation around the rupture initiation point.

Relative changes in shear stress at depth can be inferred from temporal changes in the recurrence interval of tremor along the San Andreas Fault. The tremor pattern regularly oscillated at doubled recurrence intervals of 3 and 6 days for many years, but was disrupted by the 2004 Parkfield earthquake (*42*). Period-doubling tremor can be modeled as regular slip in slow and fast ruptures using physics-based modeling (*43*). Sudden changes, and gradual recovery, of the recurrence intervals can be explained by temporal changes in shear stress driven by a rise in pore pressure following the Parkfield earthquake.

Slow earthquakes, and their relationship to huge earthquakes, have been well studied using numerical simulations (*35*, *44*). Matsuzawa *et al*. (*35*) modeled a locked zone with high effective normal stress and a downdip ETS zone with high pore fluid pressure on the dipping interface, adopting a rate- and state-dependent friction law with cutoff velocities. Allowing lateral variations of fluid pressure in the ETS zone, they reproduced the recurrence interval of short- and long-term slow slip events (SSEs), and the depth-dependent behavior of ETS. The recurrence intervals of long- and short-term SSEs gradually become shorter as the huge earthquake approaches. The shortening of recurrence interval is caused by stress accumulation due to a gradual unlocking near the edge of the strongly locked region. After the earthquake, the recurrence intervals return to larger values. This result suggests that shortening of recurrence intervals may indicate an impending huge earthquake. We are unsure if this result is real, as it may result from the simplicity of the model. However, if the modeling results are correct, they point to the possibility that precursory changes in slow earthquake activity may be indicative of an upcoming huge earthquake. Integrating monitoring with slow earthquake simulation will not only deepen our understanding of this connection, but also potentially allow us to evaluate the timing of events from a long-term perspective. The best-case scenario might be an improvement in the estimation of the probability of earthquake hazard, as slow earthquakes provide a different type of information that is not yet being utilized.

One of the striking properties of slow earthquakes is the interaction between different types of such events. These interactions are explained by stress transfer from larger slow earthquakes to triggered slow earthquakes, as discussed in the next section. On the other hand, differences in the type of slow earthquake activity that is triggered may reflect shear strength or stress level variations therein. During the 2003 and 2010 long-term SSEs in the Bungo channel, shallow very-low-frequency (VLF) earthquakes were triggered (*17*) as well as deep tremor (Fig. 4). The association of shallow VLF earthquakes with shallow tremor activity was also seen in seafloor observations for the 2013 shallow slow earthquake episode (*19*). If we compare the 2010 and 2013 shallow slow earthquake episodes, both are seen to initiate at the southern part of the zone and both migrate in the same direction northwards. In 2013, the shallow slow earthquake activity terminated at the point where the Nankai trough bends; however, during the 2010 long-term SSE, the shallow slow earthquake episode propagated around this bend (*45*). We interpret this process of overcoming bends as a weakening of interplate coupling due to the long-term SSE.

Possible stress transfer from slow to huge earthquakes

Understanding the interactions between huge earthquakes and other phenomena would very valuable for evaluating the potential of an impending huge earthquake. So far, we have observed a few kinds of interaction: 1) between different slow earthquakes; 2) between slow earthquakes and smaller earthquakes; and 3) between slow earthquakes and larger earthquakes. The most obvious interaction between slow earthquakes occurs during the long-term slow slip event (SSE) in the Bungo channel when, for a few months, minor tremor activity intensifies in the updip part of the tremor zone closest to the SSE source fault. However, the rate of deeper tremor activity is constant, regardless of SSE activity (*17*). The tremor response to the SSE clearly depends on distance from the SSE source fault. Therefore, the long-term SSE seems to occur spontaneously and triggers tremor in the adjacent downdip region (Fig. 4). A similar interaction between long-term SSEs and tremor is observed in Mexico. During the 2006 SSE in this region tremor occurred on the shallower side of the SSE, even though deeper tremor was more persistent (*46*). In contrast, the long-term SSE in Tokai lacks any concurrent, sharp increase in tremor count like that seen in the Bungo channel, even though the relative distance between tremor and SSE source fault is almost the same. The degree of interaction is roughly dependent on the slip velocity of the long-term SSE; slip velocity in the Bungo channel (~3 cm/month) is six times that at Tokai (~0.5 cm/month), resulting in greater production of tremor.

Recently a series of small long-term SSEs has been detected in the gap between the Nankai earthquake rupture area and the tremor zone (*47*). These SSEs appear to migrate eastward along the gap adjacent to the Bungo channel SSE. Tremor count at the updip part of the deep tremor zone shows a slight increase due to a downward stress loading by these migrating SSEs. The front of the increase in tremor activity propagates quite slowly (~25 km/year). This slow-migrating SSE seems to be a kind of afterslip that is enhanced by the Bungo channel long-term SSE, as afterslip following the 1946 Nankai earthquake occurred in the same region. It is possible that the gap zone is weakly locked, thereby facilitating afterslip in response to neighboring large slip events.

The Boso SSE is a typical example of a large-magnitude SSE driving a swarm of small earthquakes downdip of the major slip patch of the SSE (*23*). The moment magnitude of the SSE and the largest triggered earthquake are generally Mw 6.6 and Mw 5.3, respectively. The duration of the SSE and the triggering of downdip events resemble the behavior observed during the long-term SSE in the Bungo channel.

Therefore, the mechanism enabling the Boso SSE to drive earthquake swarms might be similar to that which drives tremor related to the Bungo channel SSE. However, these SSEs differ in their source depth; the Boso SSE source fault is up to 20 km deep, which is shallower than that of the Bungo channel SSE, and so the thermal regime in Boso is colder than that in Bungo. The different thermal regime in the two cases might affect the type of slip seen in the triggered events.

Before the 2011 Tohoku earthquake, with the exception of afterslip, no slow earthquakes had been reported off Tohoku. However, precise studies using data retrieved by on-land networks and offshore seafloor instruments subsequently revealed that slow earthquakes with various time scales in and around the rupture area of the Tohoku earthquake had loaded the mainshock fault. A decade-long SSE took place in the deepest part of the Tohoku mainshock rupture area, and accelerated over time (*48*). Near the mainshock rupture initiation point, SSEs were detected geodetically by seafloor pressure gauges in 2008 and 2011 in the vicinity of the high-slip area of the mainshock rupture zone (*49*). During the foreshock sequence lasting 23 days before the Tohoku earthquake, two sequences of SSE migrated toward the mainshock rupture initiation point (*50*). In addition, shallow tremor was detected by seafloor seismometers during the foreshock sequence (*51*). These observations indicate that the plate interface near the mainshock initiation point had been locally unlocked by these slow earthquakes during the foreshock sequence.

Similar slow earthquakes preceding huge earthquakes have been observed in Mexico and Chile. The Mw 7.3 Papanoa (Mexico) earthquake of 18 April 2014 was clearly triggered by an SSE that started in February 2014 in the region neighboring the earthquake source fault (*52*). Before the 2014 Mw 8.2 Iquique earthquake in northern Chile, an SSE lasting about 2 weeks occurred prior the mainshock. The SSE was located near a strongly locked section of the megathrust, as revealed by both seismicity analysis and geodetic slip inversion of GPS data recorded near the coastline (*53*). The spatio-temporal evolution of intense foreshocks indicates that the SSE migrated towards the rupture initiation point of the mainshock, as also seen before the Tohoku earthquake (*54*, *55*). Of course, accumulated stress on the strongly locked area is required to be close to a critical level for SSEs to prompt unstable dynamic rupture of the mainshock. When an SSE migrated near the strongly locked area, the locked area did not always rupture dynamically, which suggests that forecasts of an impending earthquake cannot rely solely on a migrating pattern of SSEs.

A combination of repeating earthquake analysis and crustal deformation analysis has revealed quasi-periodic slow slip behavior that is widely distributed across the off Tohoku megathrust zone (*56*). The recurrence interval of the slow slip transients ranges from one to six years and often coincides with, or precedes clusters of large interplate earthquakes (i.e., M > 5), including the 2011 Tohoku earthquake. These periodic slow slip events cause periodic stress loading onto the plate boundary fault, and modulate the recurrence time of large earthquakes.

Conclusion

Slow earthquakes have been frequently detected in regions neighboring megathrust seismogenic zones. Some types of slow earthquakes have somewhat similar occurrence styles to those of megathrust earthquakes. The study of slow earthquakes as an analog to megathrust earthquakes is expected to improve our understanding of the megathrust rupture cycle. Furthermore, a better understanding of the various slow earthquake types may deepen our knowledge of the tectonic framework required for the formation of subduction systems, including the rupture style of huge megathrust earthquakes. Slow earthquakes have the possibility of playing a role as stress meters or in stress transfer. Frequent loading might eventually trigger failure of the megathrust, although the stress transfer due to each slow earthquake episode will be very small. However, we should recall that many slow earthquakes don’t lead directly to megathrust earthquakes because the final rupture of the megathrust earthquake depends on the areal extent of the megathrust fault that is close to failure and how close the critical area is to failure in the seismogenic zone (*57*). The most important and useful information for evaluating seismic potential would be an estimate of the degree of criticality within the seismogenic zone adjacent to slow earthquake source region. Long-term monitoring of slow earthquakes is required so that a reliable picture of these phenomena can be built over all timescales, and so that physics-based numerical simulations that reproduce the observed plate boundary faulting behavior can be developed.

Figures

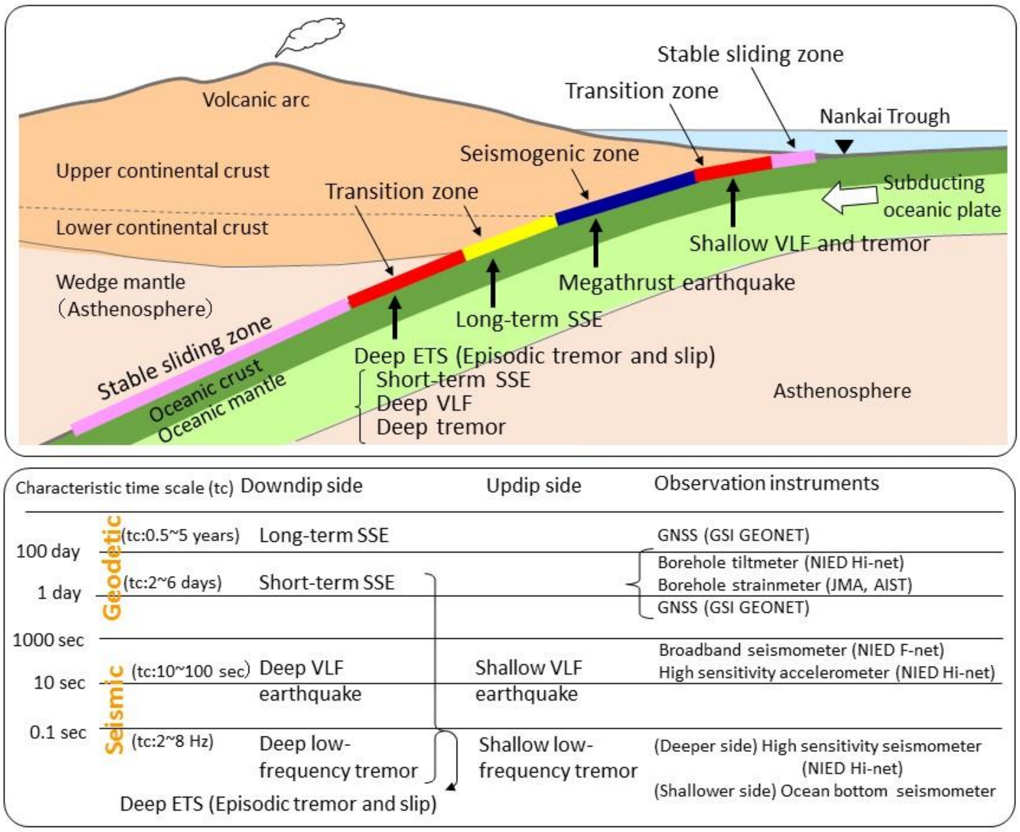

Figure 1: Cross-section of a subduction zone showing the occurrence of various types of slow earthquake and summarizing the instruments used for slow earthquake detection and monitoring based on the Nankai subduction zone. Key to acronyms: SSE (Slow Slip Event); VLF (Very Low Frequency); ETS (Episodic Tremor and Slip); GSI (The Geospatial Information Authority of Japan); NIED (National Research Institute for Earth Science and Disaster Resilience); Hi-net (High Sensitivity Seismograph Network of Japan); F-net (Full Range Seismograph Network of Japan); JMA (Japan Meteorological Agency); AIST (The National Institute of Advanced Industrial Science and Technology).

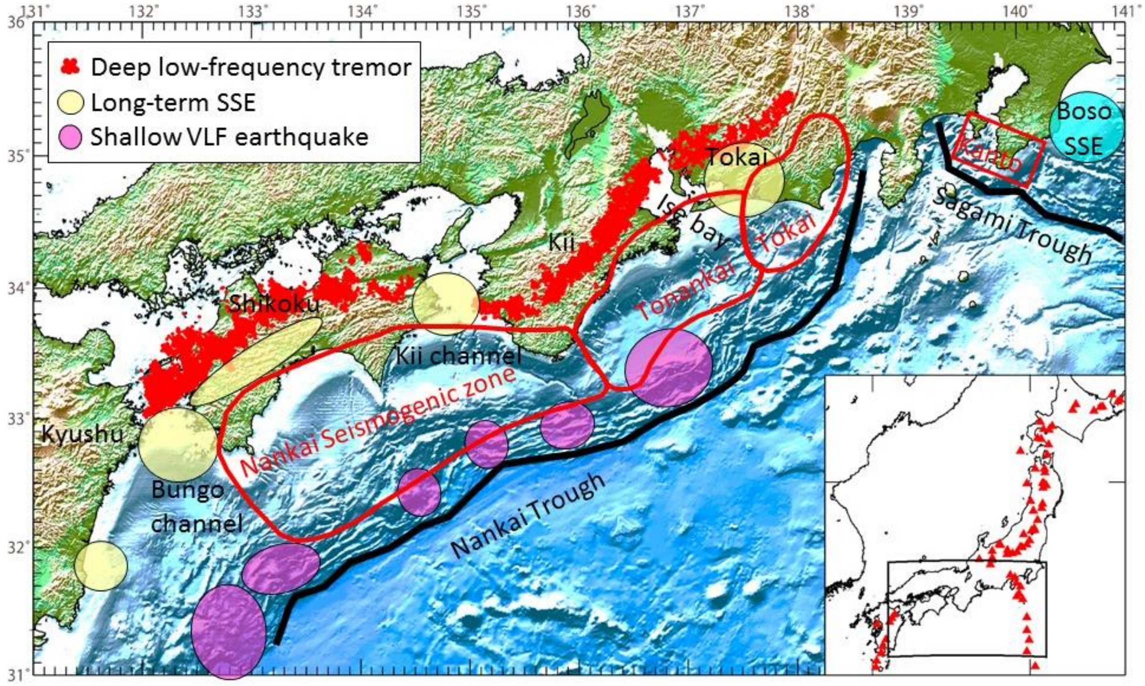

Figure 2: Distribution of slow earthquakes in southwest Japan. Deep low-frequency tremor is denoted by red symbol. Locations where long-term SSEs, and shallow VLF earthquakes occur are indicated by the yellow and pink shaded areas, respectively. The megathrust seismogenic zones along the Nankai subduction zone are outlined in red. The inset map shows the regional setting of the area of interest; active volcanoes are denoted by red triangles.

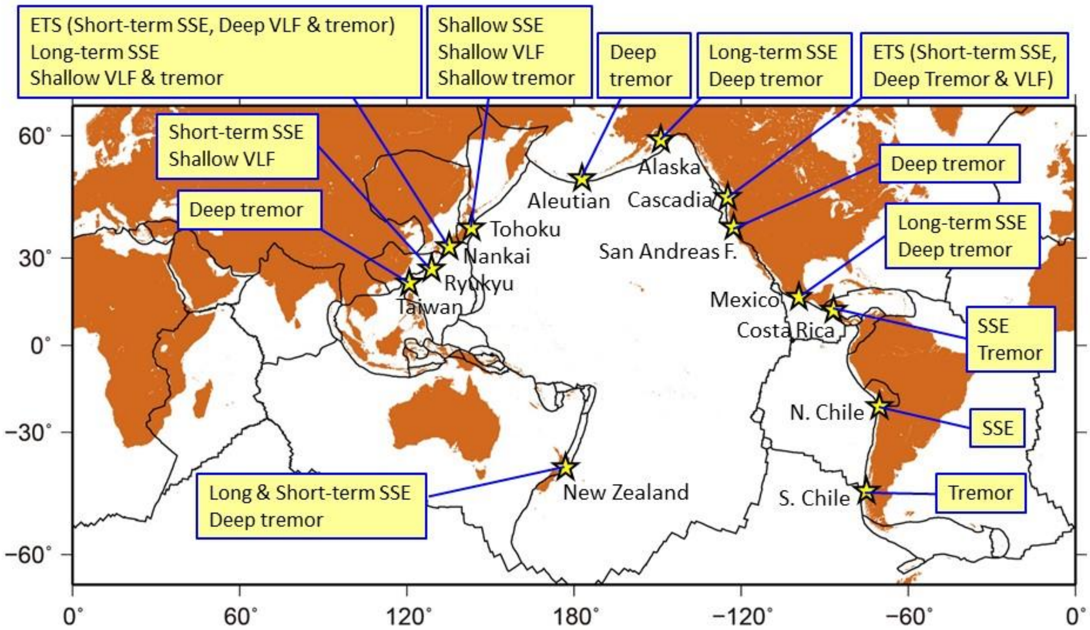

Figure 3: Global distribution of slow earthquakes.

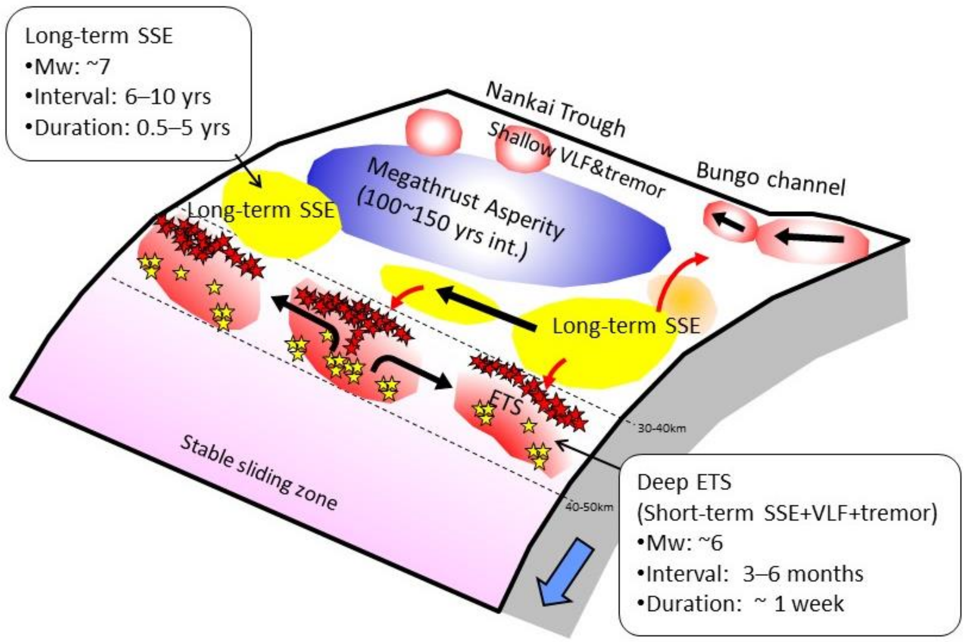

Figure 4: Schematic view of the heterogeneous distribution of various types of slow earthquakes in the Nankai subduction zone. Arrows indicate interactions between the long-term SSEs and other slow earthquakes on the interface of the subducting Philippine Sea plate in southwest Japan. Red and yellow circles indicate tremor at updip

and downdip parts within deep ETS zone, respectively.

References

1. K. Nanjo, N. Hirata, K. Obara, K. Kasahara, Decade-scale decrease in b value prior to the M9-class 2011 Tohoku and 2004 Sumatra quakes, Geophys. Res. Lett., 39, L20304, doi:10.1029/2012GL052997, 2012.
2. S. Tanaka, Tidal triggering of earthquakes prior to the 2011 Tohoku-Oki earthquake (Mw 9.1), Geophys. Res. Lett., 39, L00G26, doi:10.1029/2012GL051179, 2012.
3. T. Tormann, B. Enescu, J. Woessner, S. Wiemer, Randomness of megathrust earthquakes implied by rapid stress recovery after the Japan earthquake, Nat. Geosci., 8, 152–158, doi:10.1038/ngeo2343, 2015.
4. W. Wang, P. M. Shearer, No clear evidence for localized tidal periodicities in earthquakes in the central Japan region, J. Geophys. Res. Solid Earth, 120, 6317–6328, doi:10.1002/2015JB011937, 2015.
5. T. Sagiya, A decade of GEONET: 1994-2003 –The continuous GPS observation in Japan and its impact on earthquake studies–, Earth Planets Space, 56, xxix–xli, 2004.
6. Y. Okada *et al*., Recent progress of seismic observation networks in Japan –Hi-net, F-net, K-NET and KiK-net-, Earth Planets Space, 56, xv–xxviii, 2004.
7. R. D. Hyndman, K. Wang, M. Yamano, Thermal constraintso n the seismogenicp ortion of the southwestern Japan subduction thrust, J. Geophys. Res., 100, 15,373–15,392, 1995.
8. Z. Peng, J. Gomberg, An integrated perspective of the continuum between earthquakes and slow-slip phenomena, Nat. Geosci., 3, 599–607, doi:10.1038/ngeo1940, 2010.
9. S. Mazzotti, J. Adams, Variability of Near-Term Probability for the Next Great Earthquakeone, Bul. Seis. Soc. Am., 94, 1954–1959, 2004.
10. K. Obara, Nonvolcanic deep tremor associated with subduction in southwest Japan, Science, 296, 1679–1681, 2002.
11. K. Obara, H. Hirose, F. Yamamizu, K. Kasahara, Episodic slow slip events

accompanied by non-volcanic tremors in southwest Japan subduction zone, Geophys. Res. Lett., 31, L23602, doi:10.1029/2004GL020848, 2004.

12. Y. Ito, K, Obara, K, Shiomi, S. Sekine, H. Hirose, Slow earthquakes coincident with episodic tremors and slow slip events, Science, 315, 503–506, 2007.
13. H. Dragert, K. Wang, T. S. James, A silent slip event on the deeper Cascadia subduction interface, Science 292, 1525–1528, 2001.
14. G. Rogers, H. Dragert, Episodic tremor and slip on the Cascadia subduction zone: the chatter of silent slip, Science, 300, 1942–1943, 2003.
15. A. Kobayashi, A long-term slow slip event from 1996 to 1997 in the Kii Channel, Japan, Earth, Planets and Space, 66:9, doi:10.1186/1880-5981-66-9, 2014.
16. H. Suito, S. Ozawa, Transient crustal deformation in the Tokai district—The Tokai slow slip event and postseismic deformation caused by the 2004 off southeast Kii Peninsula earthquake (in Japanese), Jishin,61, 113–135, 2009.
17. H. Hirose *et al*., Slow earthquakes linked along dip in the Nankai subduction zone, Science, 330, 1502, 2010.
18. K. Obara, Y. Ito, Very low frequency earthquake excited by the 2004 off the Kii peninsula earthquake: A dynamic deformation process in the large accretionary prism, Earth Planets Space, 57, 321-326, 2005.
19. Y. Yamashita *et al*., Migrating tremor off southern Kyushu as evidence for slow slip of a shallow subduction interface, Science, 348, 676–679, doi:10.1126/science.aaa4242, 2015.
20. M. Nakamura, N. Sunagawa, Activation of very low frequency earthquakes by slow slip events in the Ryukyu Trench, Geophys. Res. Lett., 42, 1076–1082, doi:10.1002/2014GL062929, 2015.
21. T. Nishimura, Short-term slow slip events along the Ryukyu Trench, southwestern Japan, observed by continuous GNSS, Progress in Earth and Planetary Science, 1–22, doi:10.1186/s40645-014-0022-5, 2014.
22. Y. Asano, K. Obara, Y. Ito, Spatiotemporal distribution of very-low frequency earthquakes in Tokachi-oki near the junction of the Kuril and Japan trenches revealed by using array signal processing, Earth, Planets and Space, 60, 871–875,

2008.

23. H. Hirose, H. Kimura, B. Enescu, S. Aoi, Recurrent slow slip event likely hastened by the 2011 Tohoku earthquake, Proc. Natl. Acad. Sci. U.S.A., 109(38), 15,157–15,161, doi:10.1073/pnas.1202709109, 2012.

24. M. R. Brudzinski, R. M. Allen, Segmentation in episodic tremor and slip all along Cascadia, Geology, 35, 907-910,doi:10.1130/G23740A.1, 2007.

25. A. Ghosh, E. Huesca-Prez, E. Brodsky, and Y. Ito, Very low frequency earthquakes in Cascadia migrate with tremor, Geophys. Res. Lett., 42, 3228–3232, doi:10.1002/2015GL063286, 2015.

26. J. S. Payero *et al*., Nonvolcanic tremor observed in the Mexican subduction zone. Geophys. Res. Lett. 35, L07305, doi:10.1029/2007GL032877, 2008.

27. L. M. Wallace, J. Beavan, Diverse slow slip behavior at the Hikurangi subduction margin, New Zealand. J. Geophys. Res. 115, B12402, doi:10.1029/2010JB007717, 2010.

28. L. M. Wallace *et al*., Slow slip near the trench at the Hikurangi subduction zone, New Zealand, Science, 352, 701–677, doi: 10.1126/science.aaf2349, 2016.

29. R. M. Nadeau, D. Dolenc, Nonvolcanic tremors deep beneath the San Andreas Fault, Science, 307, 389, doi:10.1126/science.1107142, 2005.

30. Z. Peng, K. Chao, Non-volcanic tremor beneath the Central Range in Taiwan triggered by the 2001Mw 7.8 Kunlun earthquake, Geophys. J. Int., 175, 825–829, 2008.

31. K. Satake, Advances in earthquake and tsunami sciences and disaster risk reduction since the 2004 Indian ocean tsunami, Geoscience Lett., 1–15, 2014.

32. A. G. Wech, N. M. Bartlow, Slip rate and tremor genesis in Cascadia, Geophys. Res. Lett., 41, 392–398, doi:10.1002/2013GL058607, 2014.

33. S. Ozawa, H. Yarai, T. Imakiire, M. Tobita, Spatial and temporal evolution of the long-term slow slip in the Bungo Channel, Japan, Earth, Planets and Space, 65, 67–73, 2013.

34. S. Ozawa, Shortening of recurrence interval of Boso slow slip events in Japan, Geophys. Res. Lett., 41, 2762–2768, doi:10.1002/2014GL060072, 2014.

35. T. Matsuzawa, H. Hirose, B. Shibazaki, K. Obara, Modeling short‐ and long‐term slow slip events in the seismic cycles of large subduction earthquakes, J. Geophys. Res., 115, B12301, doi:10.1029/2010JB007566, 2010.
36. A. Kato, T. Igarashi, K. Obara, Detection of a hidden Boso slow slip event immediately after the 2011 Mw 9.0 Tohoku-Oki earthquake, Japan, Geophys. Res. Lett., 41, 5868–5874, doi:10.1002/2014GL061053.2014.
37. J. L. Rubinstein, M. La Rocca, J. E. Vidale, K. C. Creager, A. G. Wech, Tidal modulation of nonvolcanic tremor, Science, 319, 186–189, DOI: 10.1126/science.1150558, 2008.
38. K. Chao *et al*., A Global Search for Triggered Tremor Following the 2011 Mw 9.0 Tohoku Earthquake, Bull. Seism. Soc. Am., 103, 1551–1571, 2013.
39. R. M. Nadeau, A. Guilhem, Nonvolcanic tremor evolution and the San Simeon and Parkfield, California earthquakes, Science, 325, 191–193, doi:10.1126/science.1174155, 2009.
40. F. Brenguier *et al*., Postseismic Relaxation Along the San Andreas Fault at Parkfield from Continuous Seismological Observations, Science, 321, 1478–1481, DOI: 10.1126/science.1160943, 2008.
41. D. R. Shelly, Possible deep fault slip preceding the 2004 Parkfield earthquake, inferred from detailed observations of tectonic tremor, Geophys. Res. Lett., 36, L17318, doi:10.1029/2009GL039589, 2009.
42. D. R. Shelly, Periodic, chaotic, and doubled earthquake recurrence intervals on the deep San Andreas Fault, Science, 328, 1385–1388, doi: 10.1126/science.1189741, 2010.
43. D. M. Veedu, S. Barbot, The Parkfield tremors reveal slow and fast ruptures on the same asperity, Nature, 532, 361–365, doi:10.1038/nature17190, 2016.
44. K. Ariyoshi *et al*., Migration process of very low-frequency events based on a chain-reaction model and its application to the detection of preseismic slip for megathrust earthquakes, Earth, Planets and Space, 64, 693–702, 2012.
45. Y. Asano, K. Obara, T. Matsuzawa, H. Hirose, Y. Ito, Possible shallow slow slip events in Hyuga-nada, Nankai subduction zone, inferred from migration of very

low frequency earthquakes, Geophys. Res. Lett., 42, 331–338, doi:10.1002/2014GL062165, 2015.

46. W. B. Frank *et al.*, Using systematically characterized low-frequency earthquakes as a fault probe in Guerrero, Mexico, J. Geophys. Res. Solid Earth, 119, 7686–7700, doi:10.1002/2014JB011457, 2014.
47. R. Takagi, K. Obara, T. Maeda, Slow slip event within a gap between tremor and locked zones in the Nankai subduction zone, Geophys. Res. Lett., 43, 1066–1074, doi:10.1002/2015GL066987, 2016.
48. Y. Yokota, K. Koketsu, A very long-term transient event preceding the 2011 Tohoku earthquake, Nature Commun., 6, 5934, doi:10.1038/ncomms6934, 2015.
49. Y. Ito *et al.*, Episodic slow slip events in the Japan subduction zone before the 2011 Tohoku-Oki earthquake, Tectonophysics, 600, 14–26, doi:10.1016/j.tecto.2012.08.022, 2013.
50. A. Kato *et al.*, Propagation of Slow Slip Leading Up to the 2011 Mw 9.0 Tohoku-Oki Earthquake, Science, 335, 705–708, doi: 10.1126/science.1215141, 2012.
51. Y. Ito, R. Hino, S. Suzuki, Y. Kaneda, Episodic tremor and slip near the Japan Trench prior to the 2011 Tohoku-Oki earthquake, Geophys. Res. Lett., 42, 1725–1731, doi:10.1002/2014GL062986, 2015.
52. M. Radiguet *et al*, Earthquake triggering by slow earthquake propagation: the case of the large 2014 slow slip event in Guerrero, Mexico, T51J, American Geophysical Union Fall Meeting, San Francisco, Calif., 18 December, 2015.
53. S. Ruiz *et al.*, Intense foreshocks and a slow slip event preceded the 2014 Iquique Mw 8.1 earthquake, Science, 345, 1165–1169, DOI: 10.1126/science.1256074, 2014.
54. A. Kato, S. Nakagawa, Multiple slow-slip events during a foreshock sequence of the 2014 Iquique, Chile Mw 8.1 earthquake, Geophys. Res. Lett., 41, 5420–5427, doi:10.1002/2014GL061138, 2014.
55. A. Kato, J. Fukuda, T. Kumazawa and S. Nakagawa, Accelerated nucleation of the 2014 Iquique, Chile Mw 8.2 Earthquake, Scientific Reports, 6, 24792, doi:10.1038/srep24792, 2016.

56. N. Uchida, T. Iinuma, R. M. Nadeau, R. Burgmann, R. Hino, Periodic slow slip triggers megathrust zone earthquakes in northeastern Japan, Science, 351, 488–492, doi: 10.1126/science.aad3108, 2016.

57. H. Kanamori, E. E. Brodsky, The physics of earthquakes, Physics Today, 54(6), 34–40, 2001.