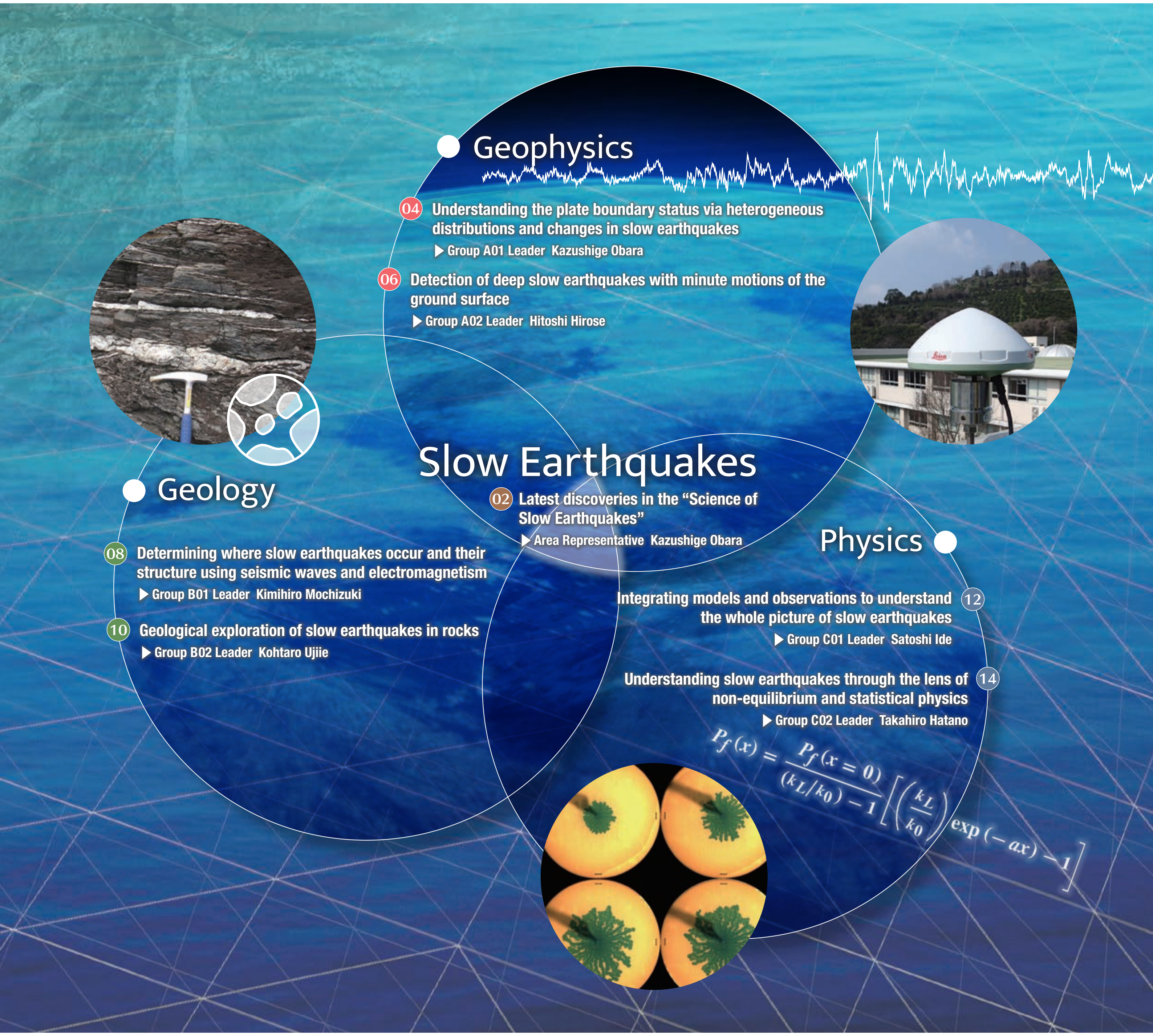
The Impact of SLOW EARTHQUAKES

—Our current understanding—



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SLOW EARTHQUAKES

Latest discoveries in the "Science of Slow Earthquakes"

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1. Introduction

Earthquakes are phenomena caused by faulting to relieve strain in bedrock associated with sliding of rocks on both sides of the fault. Around 2000, a new phenomenon in which faults slip far more slowly than regular earthquakes was discovered in southwest Japan. This is called a slow earthquake. This discovery was made using the seismic and GPS observation networks deployed throughout Japan in the wake of the Great Kobe earthquake. Since then, many slow earthquakes have been detected not only in Japan but also in other parts of the world. Some relationships between slow and huge earthquakes have been noted because the area where slow earthquakes occur is adjacent to the huge earthquake seismogenic zone in subduction zone. In fact, slow earthquakes occurred just before the 2011 Tohoku earthquake, confirming the relationship. However, the study of slow earthquakes has just begun. A comprehensive understanding of slow earthquakes themselves, let alone their relationship to huge earthquakes, remains unclear. To deepen the understanding of slow earthquakes' occurrence modes, environment, and principles, a new project area, "Science of Slow Earthquakes," was launched as part of the Grant-in-Aid for Scientific Research on Innovative Areas in 2016. This research has led to insights into slow earthquakes and the development of models to explain the various characteristics of slow earthquakes from perspectives of geophysics, physics, and geology. This chapter overviews the outcomes obtained in the "Science of Slow Earthquakes".

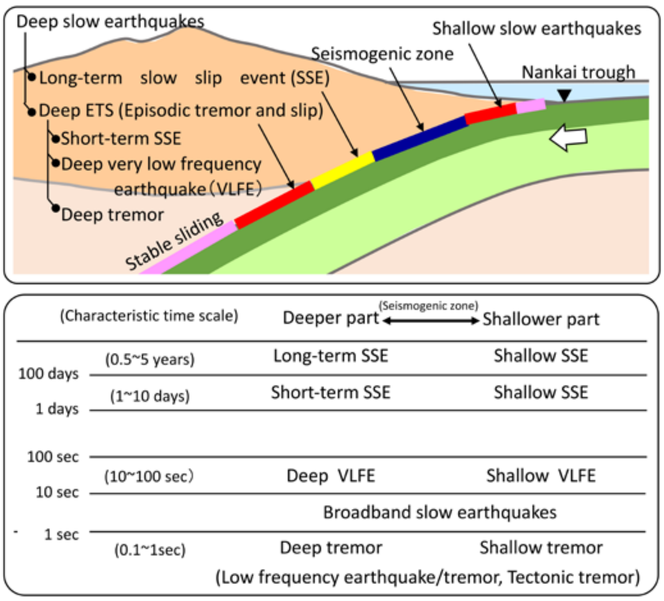


Figure 1
Classification of slow earthquakes in the Nankai Trough

2. Universality of slow earthquakes

Slow earthquakes are classified into several types according to the speed at which the fault slips (**Fig.1**). When a fault slips slowly without producing seismic waves, it is called a slow slip event (SSE), which can be observed as crustal movements by GPS and strain gauges. SSEs are subdivided into short-term SSEs (S-SSEs) and long-term SSEs (L-SSEs) based on their duration. S-SSEs last a few days, while L-SSEs continue for several months to several years. Tremors and very low-frequency earthquakes (VLFEs), which have frequencies of a few Hz and periods of a few tens of seconds, respectively, are types of slow earthquakes that seismographs can capture: high-sensitivity seismographs for tremors and broadband seismographs for VLFEs. Slow earthquakes have a noticeable diversity (heterogeneity) with different combinations of depth, locations and source durations. One of our project outcomes filled the gaps between such discrete facts and elucidated some universal characteristics of slow earthquakes. Based on these findings, we redefined the diversity of slow earthquakes. The following sections introduce the universality of slow earthquakes.

3. Broadband seismic phenomena ranging throughout bands of tremors to VLFEs

This is a research outcome of **Group C01**. For details, please see page 12. In 2002, tremors in the deep part of locked zones were discovered. Then in 2005, shallow VLFEs were discovered in a different place near the Nankai Trough. In 2007, the episodic tremor and slip (ETS), in which tremors, VLFEs, and SSEs coincide in the deep part, was discovered. However, these phenomena were discrete in terms of their frequency contents. In the frequency band between tremors and VLFEs, noise from ocean waves was always dominant, masking the weak seismic signals. **Group C01**, which is led by Professor Ide of The University of Tokyo, confirmed the existence of slow seismic signals by stacking many waveforms and revealed that slow earthquakes are a continuous phenomenon in terms of frequency range from tremors to VLFEs.

4. Commonality between shallow slow earthquakes and deep slow earthquakes

The slow earthquakes that occur in southwest Japan are divided into two groups according to the source depth along the boundary of the subducting Philippine Sea Plate: 1) the deep part of the megathrust seismogenic region and 2) the shallow part in the vicinity of the Nankai Trough. While ETSs and L-SSEs are detected in the deeper side, only VLFEs are detected in the shallower part, indicating different combinations of slow earthquake types.

In recent years, the seismic and crustal movement observation network in the ocean has improved. Similar slow earthquakes occur in both regions.

Off the southeastern coast of the Kii Peninsula, Dr. Araki from the Japan Agency for Marine-Earth Science and Technology (JAMSTEC), a collaborator (Col) of **Group C01**, discovered SSEs synchronized with shallow tremors and VLFEs through borehole observations of pore fluid pressure in 2017. In 2018, Dr. Nakano from JAMSTEC, a co-investigator (CoI) of **C01**, reported that the pore fluid pressure changes due to SSEs and the changes in accumulated seismic moment of VLFEs agree well. This indicates that shallow slow earthquakes occur as ETSs similar to those occurring in deep parts. In 2015, Assistant Professor Yamashita from Kyoto University, a CoI of **A01**, discovered shallow tremors in Hyuga-nada through temporal ocean bottom seismic observations. In 2019, Chief Researcher Tanaka from the National Research Institute for Earth Science and Disaster Resilience, CoI of **A01**, and Assistant Professor Nishikawa from Kyoto University, Col of **C01**, used S-net data to detect shallow tremors near the Japan Trench. They showed that areas where such shallow tremors occurred were separated from the large coseismic slip area of the 2011 Tohoku earthquake. It remains unclear whether SSEs are synchronized with tremors or VLFEs in the Hyuga-nada and off-Tohoku regions. Future observational studies should help resolve this uncertainty.

5. Continuity of the plate running direction of L-SSEs

L-SSEs were the first slow earthquakes to be discovered in 1999. Unlike tremors, which were discovered in 2002 and distributed over 600 km from east to west in southwest Japan, L-SSEs have been detected repeatedly only in the Tokai region and the Bungo Channel. Assistant Professor Takagi from Tohoku University, a CoI of Group **A02**, analyzed the Global Navigation Satellite System data provided by the Geospatial Information Authority of Japan and found that L-SSEs are distributed along the strike of the Philippine Sea Plate. ETSs are distributed parallelly in the deeper part of the L-SSE-distributed areas, while seismogenic zones are distributed in the shallower part, indicating that the phenomenon observed transitions with depth.

6. Diversity of slow earthquakes

With the elucidated universality of slow earthquakes discussed above, we redefined the diversity of slow earthquakes. As described in Section 3, the continuity of slow earthquakes in terms of frequency range from tremors to VLFEs has been established. Currently, only the gap between VLFEs and SSEs remains undetected. Future studies should determine whether a phenomenon fills this gap. For the continuous distribution discussed in Section 5, L-SSEs are lined up in the strike of the plate, but the amount of slips and the intervals between those events are heterogeneous with the spatial variation. This is also true for ETSs that occur at greater depths. In other words, deep slow earthquakes depend on the depth, but the same phenomena are heterogeneously distributed along strike. On the other hand, the commonality mentioned in section 4 found that shallow slow earthquakes occur as the same combination of phenomena as deep slow earthquakes, but alignment of different phenomena along the trough axis differ from deep slow earthquakes in which the same phenomenon is aligned horizontally. In other words, both deep and shallow earthquakes exhibit diversity, and the degree of heterogeneity of the distribution differs. To clarify this difference, it will be necessary to identify the factors that characterize the heterogeneity such as higher resolution subsurface imaging.

7. Modeling of slow earthquakes

In the Project Area “Science of Slow Earthquakes,” various models have been developed to explain the characteristics of slow earthquakes from a wide range of perspectives. Ujiie, Associate Professor of University of Tsukuba, the leader of the **B02 group**, and his colleagues revealed that the quartz veins in outcrops are traces of past slow earthquakes. They successfully determined the interval of slow earthquakes from geological analysis (page 10). Associate Professor Ando of The University of Tokyo, a Col of **C01**, and his colleagues established a model to consider the brittle parts that perform frictional slips and the ductile parts that perform flow deformation after observing hard blocks surrounded by a soft matrix in the surface outcrop at a fault zone. This physical model also accounts for the temperature dependence of the viscosity of ductile materials. As a result, the team reproduced the systematic transition of the occurrence modes with depth, which is observed in deep slow earthquakes. Professor Hatano of Osaka University, the leader of the **C02 group**, and his colleagues performed simulations using a modelled geological structure with bumps, which was inspired by geological excursions. They reproduced the characteristics of slow earthquakes. That is, a higher heterogeneity is more likely to induce slow earthquakes and slow earthquakes tend to precede large earthquakes.

8. Conclusion

The adoption of Science of Slow Earthquakes has realized collaborative research, which integrates geophysics, geology, and physics. These efforts have deepened the understanding of slow earthquakes. Due to space limitations, I cannot cover all the results of this project. Although only of fraction of the results are presented, I hope it gives you a better understanding of slow earthquakes.

Interview on research results of Group A01 (Seismic Observations)

Since the early 2000s, the understanding of slow earthquakes has rapidly progressed. To grasp the overall picture, Group A01 has utilized new observations and data analysis techniques to clarify the occurrence and interaction among tremor, very low-frequency earthquakes (VLFEs), and slow slip events (SSEs), as well as their relationship to mega earthquakes. Advances have highlighted the heterogeneities in the spatial and temporal distributions of slow earthquakes. Such distribution may be used as an indicator of heterogeneous structures at the plate boundaries and the imminence of future mega earthquakes.

Group A01 Leader
Professor
Kazushige Obara
The University of Tokyo

Understanding the plate boundary status via heterogeneous distributions and changes in slow earthquakes

Comprehensive search for VLFEs

VLFEs were first reported in 2005. VLFEs are a type of slow earthquake that produces long period seismic waves with a period of 10 to 100 seconds. This period range lies between low-frequency tremor and SSEs.

Long period shaking can be observed from a distance. Since long period seismic waves hardly attenuate, observation equipment on land can capture a VLFE, even if it induces a displacement in a fault plane as small as a few centimeters beneath the sea floor more than a hundred kilometers away from land.

The High-Sensitivity Seismograph Network (Hi-net) was built after the Great Hanshin-Awaji earthquake. Hi-net connects 800 observation sites across Japan to observe ordinary micro earthquakes (with a period of about one second or less) but is unsuitable for VLFE observations. On the other hand, the Full Range Seismograph Network of Japan (F-net), which is a seismograph network developed and operated by the National Research Institute for Earth Science and Disaster Resilience (NIED) since 1994, can observe earthquakes with longer periods. F-net network was originally launched to monitor the rupture process in source faults of mega earthquakes and to explore deep structures of the Earth. Today, it includes over 70 observation stations. Professor Kazushige Obara from The University of Tokyo, graduate students including Satoru Baba studying at the same University, and their colleagues used F-net to observe VLFEs.

Since VLFE signals are very weak, it is difficult to detect the occurrence of VLFEs by reviewing data with the human eyes. To solve this problem, they used the template matching technique, which has been used in seismology since the late 2000s, to identify VLFE signals from a huge amount of continuous observation data.

For example, from off-Hokkaido to off-Tohoku, 123 virtual grid epicenters were set at plate boundaries on the landward side from the Japan Trench. If a VLFE occurs at a virtual grid, a sequence of phases and amplitudes of seismic waves arriving at the F-net observation points can be calculated. Then the calculated waveform is automatically and exhaustively searched among the continuous observation data accumulated by F-net for more than a decade.

Diversity of VLFE activities reflects plate boundary heterogeneity

Figure 1 shows the result for all detected VLFEs. Dark-colored squares indicate areas where a lot of VLFEs occur. Although Hyuga-nada and off-Tokachi are darker in color, even in areas along the Nankai Trough and the Japan Trench show uneven color, indicating a heterogeneous occurrence of VLFEs.

The contour lines in Fig. 1 indicate the strength of plate boundary locking. The elliptically closed lines found at off-Shikoku and off-Miyagi show the most strongly locked areas, while a weaker locking force occurs far from the

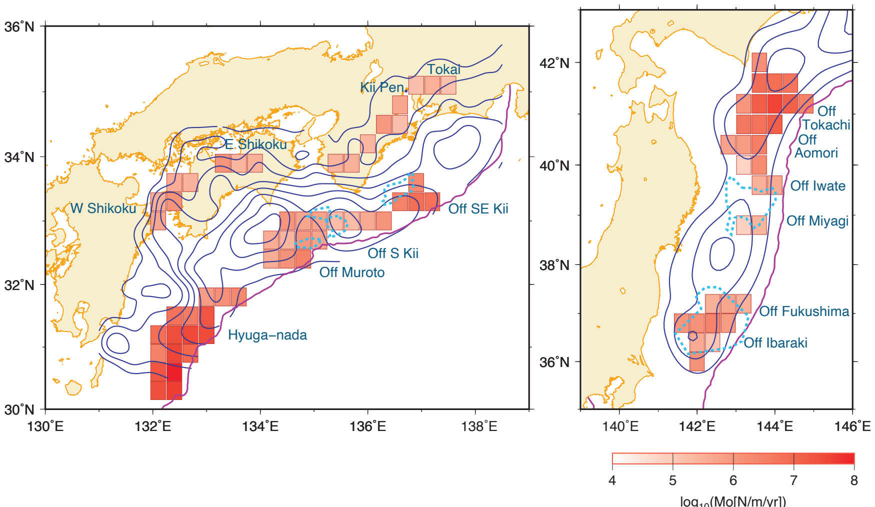


Figure 1
Distribution of very low frequency earthquakes (VLFEs) revealed by a comprehensive study. The darker the shade of red, the more active the VLFEs.

lines. VLFEs rarely occur where the plate boundaries are strongly locked. However, they do occur in other areas.

In the map of southwest Japan, the squares in the deep parts of the plate boundaries (i.e., those underneath Shikoku and the Kii Peninsula) are light-colored with little color variation, while the squares in the shallow part (near Nankai Trough) have a large color variation.

In deeper areas, plate boundary structures are relatively even, resulting in the occurrence of relatively homogeneous VLFEs. On the other hand, plate boundaries with extremely different structures in shallow areas may be located right next to each other. This is thought to be a cause of the observed diversity, in which the occurrence and amplitude of VLFEs differ.

It is speculated that the temperature and topography play roles in this diversity. In shallow areas, plates have just started subducting, so variations in plate temperature and shapes (e.g., seamount) are still maintained. However, as the plates further subduct and pass through locked zones, the temperature increases to 300–400 degrees Celsius and the shape variation becomes smaller. The differences in the activities of VLFEs is thought to reflect such unevenness in the temperature and shapes of plate boundaries.

Major temporal changes before and after the 2011 Tohoku earthquake

Figure 2 shows the change in the occurrence of VLFEs as a function of time. Again, an interesting phenomenon was found. Figure 2(A) shows the time variation of VLFEs occurring within the four squares labeled "off-Iwate" in Fig. 1, and Fig. 2(B) shows the time variation of VLFEs in the two squares labeled "off-Miyagi."

At off-Iwate, the activity level of VLFEs remained low until the occurrence of the Tohoku earthquake in March 2011 (orange dashed line). However, after the earthquake, the number of VLFEs suddenly increased and then gradually decreased again. The opposite is true for off-Miyagi. VLFEs were active to some extent before the mega earthquake, but after the Tohoku earthquake, they barely occurred.

Such a significant difference in the temporal changes between off-Iwate and off-Miyagi is due to the difference in whether they are outside or inside the fault plane, which was displaced significantly during the Tohoku earthquake.

In Figs. 2(C) and (D), the shades of green, which are like an ink wash painting, show the distribution of the slip amount of the faults that caused the Tohoku earthquake. In the darkest areas, faults were displaced by more than 50 m. In Fig. 2(C), the red stars denote the location of the square of off-Iwate, which is outside the area where the fault significantly slipped during the Tohoku earthquake. On the other hand, the square of off-Miyagi, marked with a red star in Fig. 2(D), is located within an area with a significant fault slip.

Figure 2(B), which shows the temporal variations at off-Miyagi, has a stair-step pattern with periods of increased VLFE occurrence and those of no VLFE occurrence before the Tohoku earthquake.

"Before the main shock occurred, plate boundaries seem to have gradually slipped and have become unlocked little-by-little, as reflected in the VLFE activity. The stair-like behavior is a remarkable phenomenon that may reflect the imminence of the occurrence of main shock," said Professor Obara.

The increase in the number of VLFEs at off-Iwate after the Tohoku earthquake probably reflects the after slip, in which areas around the epicenter continue to slip slowly after a major earthquake. The decreased number of VLFEs at off-Miyagi can be attributed to the relieved fault strain after they slipped during the Tohoku earthquake. These behaviors also provide important information for understanding the plate boundary status.

Real-time monitoring of VLFEs to watch plate boundaries

Today, we have a better understanding of the diversity in slow earthquakes: the occurrence locations of VLFEs, tremors, and SSEs are distributed unevenly; such locations tend to move in a certain direction. They also reflect the plate boundary conditions that cause mega earthquakes, providing clues for exploring huge earthquakes.

In the Nankai Trough and the Japan Trench, seafloor seismic observation networks have been increasingly built, allowing us to observe slow earthquakes from more sites closer to the earthquake occurrence sites than ever before. However, such a seafloor observation network is still sparse compared to that on land. Thus, a method that grasps the plate boundary status through VLFEs from a distance on land will continue to be effective.

"The method shown here allows us to monitor changes in VLFEs in real time. I believe it is an important method to study and monitor crustal activities and plate conditions in Japan as a whole," Obara said.

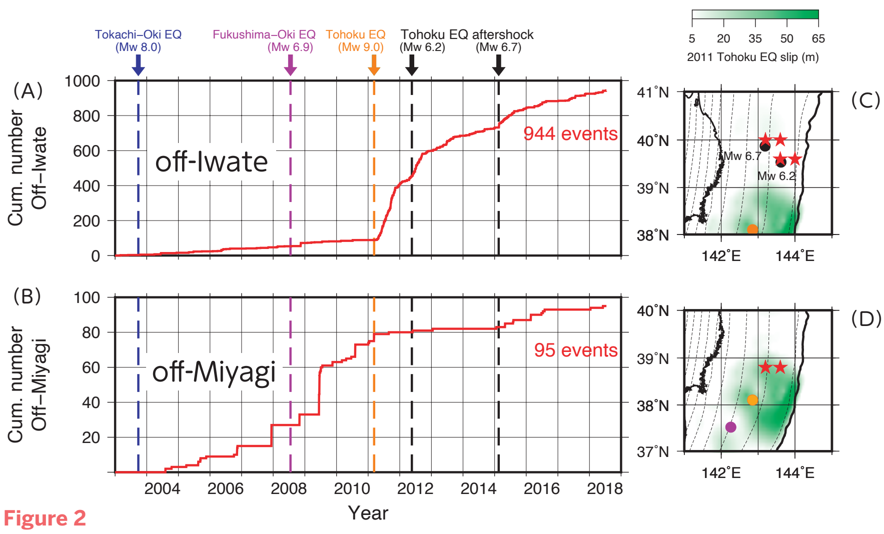


Figure 2

Temporal variation of very low frequency earthquakes (VLFE) occurring off-Iwate (A) and off-Miyagi (B). Locations (red stars) where VLFEs occurred off-Iwate (C) and off-Miyagi (D). Increasingly darker shades of green indicate the amount of fault slippage caused by the Tohoku earthquake.

Interview on research results of Group A02 (Geodetic Observations)

Group A02 aims to capture slow earthquakes occurring in deep areas at plate boundaries utilizing geodetic techniques such as a satellite global positioning system (GPS) and tiltmeters, which detect very small movements in the Earth's surface. The group found that locations where slow earthquakes occur are generally separated from those where mega earthquakes (over magnitude 8) occur, but sometimes slow earthquakes extend into the mega earthquake areas.

Group A02 Leader
Associate Professor
Hitoshi Hirose
Kobe University

Detection of deep slow earthquakes with minute motions of the ground surface

Understanding fault displacements and strains with geodetic techniques

The Nojima Fault Preservation Museum, which is located on Awaji Island in the Hyogo Prefecture, includes the fault that caused the Great Hanshin-Awaji earthquake in 1995 as it is exposed to the ground. During the large earthquake, this fault was displaced as much as 2-m horizontally and about 1-m vertically. The museum also preserves a private house's concrete fence dislocated and broken by the fault movement.

The same kind of fault displacement causes slow earthquakes. However, directly observing such displacements is difficult because they occur deep underground. Associate Professor Hitoshi Hirose from Kobe University and his colleagues use geodetic techniques to infer the size and locations of such displacements from the surface of the Earth. Their research mainly uses a GPS observation network consisting of the Geospatial Information Authority (GSI) of Japan's observation network, the team's own observation stations, and the tiltmeters installed nationwide by the National Research Institute for Earth Science and Disaster Resilience (NIED).

Slow earthquakes displace faults by a few centimeters at plate boundaries tens of kilometers underground. These appear as minute ground motions, for example, a ground tilt change corresponding to a 0.1-mm rise or fall of the ground a kilometer away on the Earth's surface. Using the latest geodetic methodologies, Group A02 captures such ground surface movements and then calculates how faults underground are displaced.

The group investigates where long-term slow slip events (L-SSEs) and short-term SSEs (S-SSEs) occur. In L-SSEs, faults move slowly with durations about a year. Additionally, they study how L-SSEs and S-SSEs are related to the locations where mega earthquakes occur. They aim to elucidate clues that suggest the timing of the next mega earthquake such as whether the underground strain accumulated year-after-year as oceanic plates subduct is relieved by slow earthquakes and how much strain energy remains.

"Habitat differentiation" between slow and mega earthquakes

Can the locations of slow earthquakes and large earthquakes be differentiated? A research team led by Assistant Professor Ryota Takagi at Tohoku University has vividly demonstrated this. The team developed a method to automatically analyze a huge amount of GPS data accumulated by GSI in the past 20 years. They found 24 L-SSEs that occurred in the area from Hyuga-nada in Kyushu to western Shikoku. Eleven had not been documented previously.

They have reported several findings:

Between the area where magnitude 8-class Nankai earthquakes occur once every century or so (locked zone) and areas where tremors are occurring, L-SSEs are observed universally (Fig. 1).

The team also found some patterns in the occurrence of L-SSEs. Off the coast of the Miyazaki Prefecture, SSEs occur at the highest frequency, once every two or three years. Although it was known that SSEs occurred in these areas, the team successfully clarified the cycle using comprehensive analysis.

Furthermore, the team found a chain of L-SSEs. L-SSEs first occurred off-Miyazaki followed by ones at off-Oita and eventually at the western part of Shikoku. Thus, it moved northeastward over a period of three to four years. Such a chain of events occurred 4 times in the 20-year period analyzed. The slow-slip pattern and its changes may reflect changes in the conditions of the locked areas that cause huge earthquakes and should be useful to forecast mega earthquakes.

Slow slips can extend into a locked area where mega earthquakes occur

Assistant Professor Masayuki Kano from Tohoku University and his colleagues used GPS data to understand S-SSEs lasting one to several weeks in western Shikoku.

In S-SSEs, a single fault slip can be detected as a movement of the ground surface by only 1 to 2 mm. Because such a small movement may be hidden in the noise, the team reduced the noise by adding signals from many SSEs to obtain underground fault slip.

Consequently, they detected fault slip of S-SSEs in the same areas where tremors occur. This was unsurprising since it was previously known as the episodic tremor and slip (ETS), in which the tremor coincides with SSEs. However, it was noteworthy that slip of the S-SSEs also occur in much shallower areas on the plate boundary, almost overlapping with the locked areas generating mega earthquakes (Fig. 2).

Previously, it was thought that areas where short-term SSEs occur are clearly separated from the locked areas of faults causing mega earthquakes. Their research revealed that slow slip also occurs within locked fault areas.

"Our achievement found that when a slow slip occurs in a deep area, the fault may also slightly slip in shallow areas, near locked areas. Thus, SSEs may affect huge earthquakes. This is a surprising result," said Hirose.

Successful observations of water movement

Geodetic methods other than GPS and tiltmeters have also yielded results. The research team of Yoshiyuki Tanaka, Associate Professor at The University of Tokyo, is using a device called the absolute gravimeter to explore underground structures. A special mirror is dropped within a vacuum tube, and the distance it falls is measured by a laser, while the time it takes to fall is measured by an atomic clock to determine the gravity value of the site. Although dropping an object seems like a simple method to measure gravity, it is extremely accurate and can detect changes in gravity values as small as about one part per billion. This change reflects variations in the density and distribution of materials beneath the observation site.

With this device, Assoc. Prof. Tanaka's team has studied how gravity changes during slow slips that occur intermittently near the expected source area of the Tokai earthquake for more than 20 years. Their three observation sites are Omaezaki and Kakegawa in the Shizuoka Prefecture, near the Suruga Trough, where the Philippine Sea Plate is subducting, and Toyohashi in the Aichi Prefecture, near the center of an actual slow-slip area. Two SSEs have occurred at the plate boundary about 30-km underground. One was in 2001–2006 and the other in 2013–2017. Observations showed that the change in gravity is small during those SSEs, while the gravity value increases during periods without SSEs.

The change in gravity can be explained by thinking about when an SSE begins water seeps into the rocks underground and moves to shallower areas along the fault. "We found this by observing the relationship between earthquakes and water. This finding should be useful for understanding the effect of water on fault movements, not only in slow earthquakes but also in normal ones," said Hirose.

Aiming to understand long-term changes

After the Great Hanshin-Awaji earthquake in 1995, GPS and tiltmeters were rapidly deployed across Japan. The GSI and NIED installed about 1,300 GPS receivers and about 800 tiltmeters, respectively, nationwide. Such a high-density observation network is one of the strengths of Japan's earthquake research.

The Philippine Sea Plate and the Pacific Plate are subducting at a rate of several centimeters per year deep beneath the landward plate. GPS signals recorded at stations on islands, including Kitadaito Island, which is located on the Philippine Sea Plate, allow us to see how the islands are approaching Japan in near real time. "Using geodetic methods to study earthquakes is appealing because you can feel how the plates are slowly moving," says Hirose.

When Assoc. Prof. Hirose was a doctoral student, the GSI was in its third or fourth year of GPS observations, and the accumulated GPS data was just beginning to be usable. Taking advantage of this, Assoc. Prof. Hirose reported the first slow slip near the Bungo Channel in 1999.

By analyzing GPS and tiltmeter data for more than 20 years, he found that some phenomena did not appear in the first 10 years but have started to appear in the last 10 years. "No one knows what will happen in the next ten years. When a huge earthquake is imminent, we may see different phenomena. I would like to know how the occurrence of slow earthquakes will change in the long run," said Hirose.

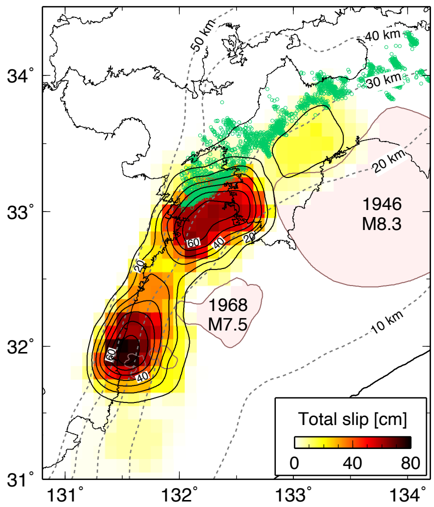


Figure 1

Locations where L-SSEs occur

L-SSEs occurred between the locked areas generating huge earthquakes (1946 Nankai and 1968 Hyuga-nada earthquakes) and the area where tremors are occurring (green dots). The darker the color (yellow to red), the greater the amount of the accumulated slip.

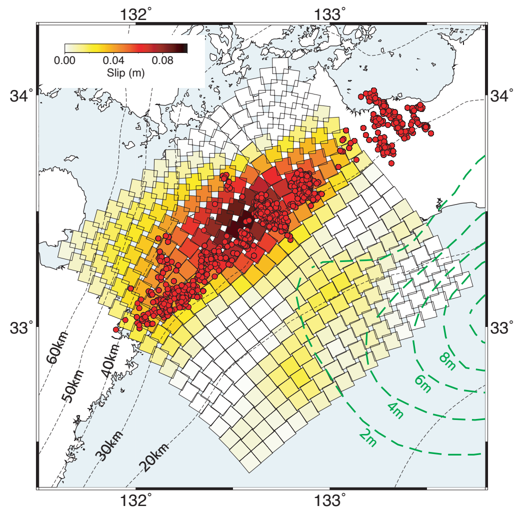


Figure 2

Location of short-term SSEs

Some SSEs in yellow are within part of the locked area generating the Nankai earthquake as indicated with the green dotted lines. Red dots indicate areas where tremors occur.

Interview on research results of Group B01 (Geophysical Structures)

When a fault slips, sometimes it causes a megathrust earthquake but other times it causes slow earthquakes such as slow slip events (SSEs) or tremors. Where does this difference come from? **Group B01** combines multiple observation techniques that use seismic waves and electromagnetism to explore plate interface structures in which fault slips occur. They found that heterogeneously distributed water along plate interfaces may contribute to the occurrence patterns of slow earthquakes and megathrust earthquakes.

Group B01 Leader
Associate Professor
Kimihiro Mochizuki
The University of Tokyo

Determining where slow earthquakes occur and their structure using seismic waves and electromagnetism

Intensive observations of the plate interface beneath the Bungo Channel

The Bungo Channel, which is located between Shikoku and Kyushu islands, connects the Seto Inland Sea and the Pacific Ocean. It has beautiful ria coastlines on both sides. The shortest route across the Channel is about 30-km long, which is from Cape Sata in Ehime Prefecture to Saganoseki in Oita Prefecture. The area centered on the Bungo Channel is now the world's most advanced research site for slow earthquakes.

In an area with a depth of 20–40 km beneath the ocean floor at the Bungo Channel, there is an interface between the Eurasian Plate and the Philippine Sea Plate. Shikoku and Kyushu islands sit on the Eurasian Plate, while the Philippine Sea Plate is subducting beneath the Eurasian Plate. Recently, it has been clarified that megathrust earthquakes such as the 1946 Nankai earthquake (magnitude 8.0) and the 1968 Hyuga-nada earthquake (magnitude 7.5) and various types of slow earthquakes such as tremors and SSEs occur in this area.

The Philippine Sea Plate is subducting a few centimeters per year into the Nankai Trough south of Shikoku. This causes the strain accumulation and various fault slips across shallow to deep portions along the plate interface. Such a fault slip generates a megathrust earthquake, a SSE, or a tremor. The event type depends on the environment of the plate interface, which changes with the depth of the plate interface. **Group B01**, led by Associate Professor Kimihiro Mochizuki from The University of Tokyo, aims to clarify the environmental characteristics. The advantage of conducting research in the Bungo Channel is that observations can be performed from the sea as well as on land in western Shikoku.

When examining a human body, computed tomography using X-rays, magnetic resonance tomography, and ultrasound tomography are generally used together to make a diagnosis. Analogously, earthquake research uses a variety of means to explore subsurface structures, including the transmission of seismic waves and electromagnetic waves. The tomography accuracy of the human body can be improved by detecting signals from 360 degrees around the organ of interest. Unfortunately, observations of subsurface structures cannot be performed in the same way. Information about the upper surface of the plate interface can only be detected from tens of kilometers away.

"This is a large-scale study that aims to examine slips at plate interfaces by many researchers getting together and applying different methods. I believe that no other site in the world has been studied using so many techniques in such a detailed manner," said Mochizuki.

Clarifying the relationship between water and slow earthquakes

Group B01 created a cross-sectional diagram of the subsurface structure beneath the seafloor by analyzing seismic reflected waves generated from a research vessel using compressed air. Specifically, the research team deployed ocean bottom seismographs at 2-km intervals to determine where the speeds of seismic waves change. An ocean bottom device to measure differences of the electric potential was also used to evaluate the heterogeneity of the subsurface structure. The team identified areas where electricity can and cannot be transmitted easily.

As a result, the team has started to grasp the three-dimensional structure of the Philippine Sea Plate, the Eurasian Plate, and the mantle sandwiched between them. In areas where the rocks contain a lot of water, the propagation speed of the seismic waves are slow. Electrical conductivity is also high in areas where the rocks contain more water. By combining and interpreting these results, the team has clarified that tremors occur more frequently when more water is present (**Fig. 1**).

Tremor occurrence may increase in areas with more water. A mantle containing water transforms into a soft rock called serpentine. Serpentine is softer and more slippery than rocks that exist in the solidified part of a normal plate interface. This condition may cause tremors.

Electrical conductivity is low in the southern part of the Bungo Channel, near the plate interface where the Hyuga-nada earthquake occurred. On the other hand, in an area west of the Hyuga-nada earthquake area, where SSEs occur, the electrical conductivity is high (**Fig. 2**).

It is presumed that water is present in areas where electricity is easily transmitted. However, electricity is not easily transmitted in areas where strong earthquakes such as the Hyuga-nada earthquake occurred.

The team has proposed a mechanism, which differs from serpentinization for tremor generations. In regions where electricity cannot be transmitted easily, that may be related to the occurrence of megathrust earthquakes.

"A key word is water. We are beginning to grasp the relationship between the existence of water and the occurrence of slow and megathrust earthquakes from shallow to deep areas along plate interfaces," said Mochizuki.

Structural changes before a slow earthquake

In addition to the Bungo Channel, **Group B01** conducts research at other plate interfaces in Japan and abroad including: one that runs from Shikoku Island to the Kii Peninsula, the Japan Trench in the Tohoku region, and one in New Zealand. In these sites, they also have found that earthquakes are affected by water migratoin and the structure formed with a seamount that subducts along the plate interface.

A submarine seismic observation network (DONET: Dense Oceanfloor Network System for Earthquakes and Tsunamis) is located on the seafloor off the Kii Peninsula to study earthquakes in the Nankai Trough. It has been fully operational since the 2011 Tohoku-Oki earthquake. These observations have identified a relationship between temporal changes in the subsurface structure and slow slips.

The seafloor seismographs used at the Bungo Channel have a built-in battery. Shortly after an observation, they float to the sea surface for data collection. On the other hand, DONET seismographs, which are connected to submarine cables, continuously collect data in real time over a period of years. The team analyzed such data from DONET.

Comparing the data from several submarine seismographs of DONET, the group found that the subsurface structure changes 2–9 months before a slow slip occurred. Here, it is speculated that water may be responsible. When water accumulates at a plate interface, it is detected by the ocean bottom seismograph as a change in the subsurface structure. As more water accumulates, slow slips are induced.

"Such structural changes have also been observed in New Zealand. By examining these changes, we may be able to explain the relationship between the structural change and water migration," explained Mochizuki.

Appeal of researching earthquakes from the sea

Associate Professor Mochizuki specializes in marine seismology. Each year, he spends about a month aboard a university-owned or other research vessel to study earthquakes from the sea.

The electromagnetic method, which is used in marine surveys from the off-Bungo Channel to Hyuga-nada, has been effective on land and the seafloor far away from land. However, implementing this method on the seafloor close to land is challenging because the seafloor has much weaker electromagnetic signals compared to land. The uneven and complex topography of the seafloor further complicates the electromagnetic field near land. Analysis methods developed by research members of the Science of Slow Earthquakes have overcome these challenges. **Group B01** was one of the first to reveal the 3-D electrical conductivity near a plate interface near the offshore-onshore boundary.

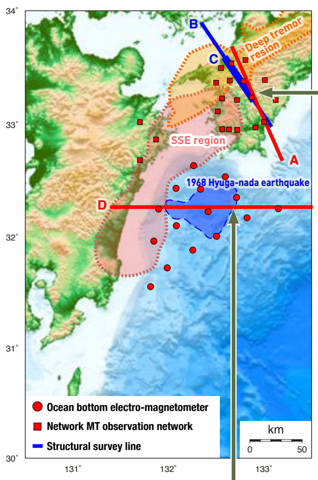
Ocean bottom seismographs have technical limitations when detecting a long period ground motion such as that in a slow earthquake. On land, seismographs are securely fixed to the ground at locations where the ground is firm. In contrast, seismographs on the seafloor simply land on the soft sediment of the ocean floor. It is difficult to fix them firmly to the seabed because they must be raised to the surface once the observation is finished.

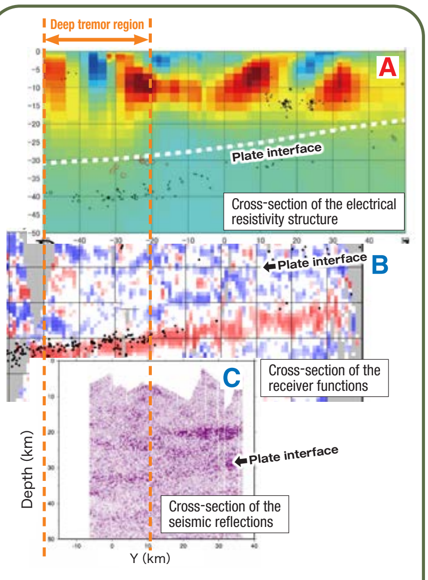
"To explain simply, it's like observing earthquakes on tofu," said Mochizuki. The oceanic environment contains a lot of unique noises. For seismographs, which measure tremors with a high sensitivity, even tiny waves generated on the sea surface become large noises.

Despite these challenges, there is a great deal of appeal in observing earthquakes from the sea. The secrets of plate interfaces that **Group B01** aims to elucidate exist too deep and too far away from land. "From the sea, observation equipment can be placed close to the area of interest, providing high-resolution information. There are still many fields where we can contribute to the study of slow earthquakes," Mochizuki explained.

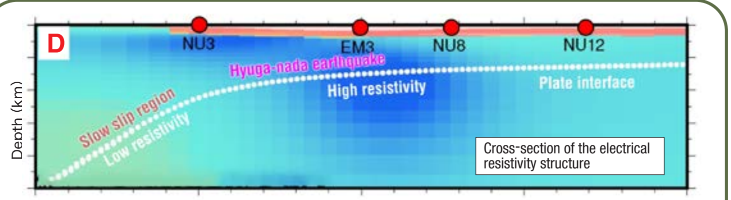
Figure 1

Three different analysis methods are used along each section profile on the map.





(A) electromagnetic analysis results. (B) and (C) Subsurface structure cross-sections obtained by seismic wave analyses. Lines A to C on the map indicate the cross-section profiles. The combination of three analysis methods reveals that deep tremors occur in areas where water is abundant.



Cross-section across the Hyuga-nada earthquake area (red line (D) on the map). The electrical conductivity near the plate interface differs between the regions where the Hyuga-nada earthquake occurred and that where slow slips occur. This difference is also attributed to water content.

Interview on research results of Group B02 (Geology)

What kinds of rocks cause slip events in slow-earthquake-producing faults? Why are the slips so slow compared to those producing mega earthquakes? Group B02 geologists strive to elucidate the detailed mechanism of slow earthquakes by observing real faults from outcrop to microscopic scale. The team has developed a powerful model to explain the slow earthquake mechanism by studying an actual site exposed on land on the east coast of Kyushu Island, Japan, which hosted a slow earthquake.

Group B02 Leader
Associate Professor
Kohtaro Ujiie
University of Tsukuba

Geological exploration of slow earthquakes in rocks

Examining a fault surface that caused earthquakes

Plate boundaries causing earthquakes are often depicted as simple single lines in diagrams. Ground surface observations (i.e., seismographs or global positioning systems) can indirectly elucidate what is happening on these "lines." However, can faults that are deep underground be seen and touched directly?

In 2013, Associate Professor Kotaro Ujiie from Uniersity of Tsukuba and his colleagues studied the plate boundary that caused the 2011 Tohoku-Oki earthquake by drilling the boundary with Chikyu, a deep-sea drilling vessel. They dug about 200 kilometers east of the Oshika Peninsula in Miyagi Prefecture and 820 meters from the seabed to a depth of 6,900 meters. A lot of clay was observed on the fault surface that slipped, revealing that the frictional heat generated by the fault slip thermally expanded the water in the fault, resulting in a very large fault slip that triggered a huge tsunami.

What is the difference between a fault that causes a slow earthquake and one that causes a giant ground motion and a catastrophic tsunami?

White quartz veins

Unfortunately, areas causing slow earthquakes (tremor or slow slip) cannot be studied by digging because such they are even deeper underground than the rupture area of mega earthquakes. Assoc. Prof. Ujiie's team began by characterizing a site where an ancient plate boundary was exposed on land due to uplifting over time.

"If we compare an earthquake to a disease, drilling is like an endoscopic operation that can address only one site, while examining faults exposed on land is like a postmortem examination that can thoroughly dissect a large area. By observing such faults, we can examine past earthquakes, although they are no longer active," said Ujiie.

An area on the Pacific coast between the Oita and Miyazaki prefectures formed uplifted rocks near a plate boundary around 70 to 80 million years ago. This area was thought to form by a plate with the same characteristics as the Nankai Trough. Additionally, the uplifted rocks were formed under the same temperature and pressure conditions where slow earthquakes occur. Consequently, the site seemed ideal to explore "fossils" of slow earthquakes.

Figure 1
Slow earthquake (episodic tremor and slip) occurrence area exposed on land. Many layers of white mineral veins composed of quartz developed in metamorphic rocks.

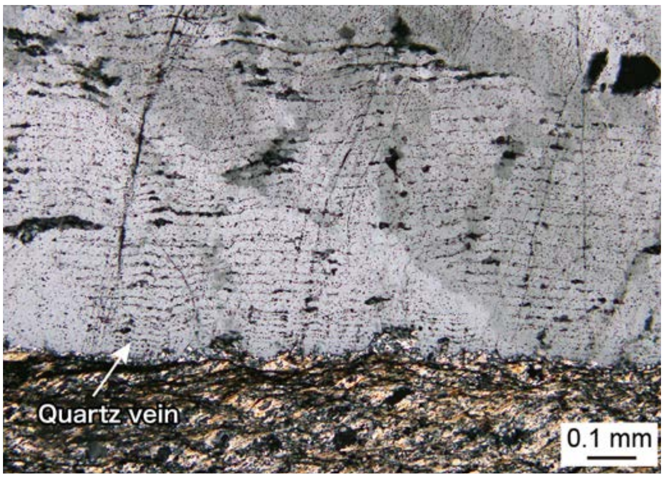


Figure 2
Stripe pattern found in quartz veins showing repeated fracture and quartz precipitation.

The first clue was water. Research on the transmission of seismic waves revealed that water was somehow involved in the occurrence of slow earthquakes. Hence, traces of water should be present at sites where slow earthquakes occur.

Ujiie and his colleagues focused on the white quartz veins running through metamorphic rocks (**Fig. 1**). Sometimes mineral veins are said to be fossils of fluids. When silica contained in water seeps into rock cracks and its solubility drops for some reason (*e.g.*, decreased pressure), then silica precipitates in the cracks and forms quartz mineral veins. Ujiie explains, “It’s like a hot spring pipe gradually becoming clogged with the compounds contained in the hot spring water.”

Each vein was about 1 to 10 m long and less than a few centimeters thick. They were concentrated in an area about 60-m thick and more than 100-m long. Such a mineral-vein concentration area emerged as a strong candidate where a slow earthquake occurred.

Records of slow earthquakes

Faults during a mega-earthquake are dislocated at a speed of about 1 m/s. Traces of heat generated by such dislocations on fault surfaces provide evidence that the fault caused earthquakes. However, this approach cannot be used for slow earthquakes because the fault movement is too slow. Therefore, other evidence is needed to demonstrate that a site with concentrated mineral veins caused past slow earthquakes.

Major characteristics of slow earthquakes are:

1) They are caused by a low-angle reverse fault movement;
2) The fault slips with a very weak force;
3) They occur under high fluid-pressure conditions; and
4) They occur repeatedly every less than several years.

His team examined whether mineral veins satisfied these four conditions. Such veins adhere to 1)–3). For 4), the mille-feuille-like stripe pattern observed in mineral veins with microscopy provided a clue (**Fig. 2**). This stripe pattern indicated that fracture and quartz precipitation repeatedly occurred. The team calculated the time interval at which these processes repeated using the quartz precipitation reaction rate. The calculation results also agreed with the characteristics of slow earthquakes.

This examination provided evidence that sites with concentrated veins were actual sites of past slow earthquakes. This idea started to attract much attention as a promising geological model. The simultaneous occurrence of tremor and slow slip can be explained by tremor due to the serial destruction of multiple mineral veins and slow slip due to the flow deformation of metamorphic rocks surrounding the veins. These processes differ greatly from those of mega earthquakes, where a thin layer slides at high speed all at once. This research triggered a series of similar reports from overseas, including Italy and New Zealand.

Another promising model is called the block-in-matrix, in which hard blocks (rock blocks) are surrounded by a soft matrix (substrate). In this model, hard rock blocks fracturing causes tremor and low-frequency earthquakes, while the flow of the soft matrix is observed as a slow slip.

Not only is Ujiie’s team working on this model, but they are also studying where the water comes from, which is critical to understand slow earthquakes. When different types of rocks come into contact deep underground, chemical reactions may generate water. Additionally, when a plate subducts and has an increased temperature and pressure, the water contained in rocks may be discharged. The team is currently investigating whether the water produced contributes to rock failure or slipping faults that cause slow earthquakes.

Unlocking the power of geology

When an oceanic plate such as the Philippine Sea Plate subducts, sediments on top of the plate are scraped-off and accreted to the overriding plate. This is called an accretionary prism. Some accretionary prisms are uplifted and exposed on land. Recently, it was recognized that such prisms contain former plate boundary faults.

The maximum temperature reached by an accretionary prism is between 150 to 300 °C. This temperature range is consistent with that at a plate boundary in which a mega earthquake occurs. Accordingly, geologists postulated that the accretionary prisms might contain earthquake rupture area.

Associate Professor Ujiie earned his doctorate in 1998 for research on the accretionary prism formation process, but his thesis had nothing to do with earthquakes. In early 2000s, the relationship between accretionary prisms and mega earthquakes was just beginning to be understood. He thought, “If I choose to study accretionary prisms, my research theme should be earthquakes. Specifically, I want to elucidate earthquake occurrence processes and mechanisms from accretionary prisms.” Since then, research on slow earthquakes has progressed rapidly, and the environmental conditions of plate boundaries where slow earthquakes occur are becoming clearer. “These conditions should also be recorded in the rocks,” Ujiie thought. Thus, he focused on areas deeper than accretionary prisms and found mineral veins.

A different approach is needed to track earthquake phenomena occurring in a very short time because traditional geological methods are effective at long time scales. A new physicochemical method needs to be adopted. His team is partnering with researchers in other fields working on geophysics and earthquake modeling to explain actual earthquake phenomena from a geological viewpoint. “I like exciting research rooted in intellectual curiosity. This is why I love slow earthquake research,” says Ujiie.

Interview on research results of Group C01 (Geoscientific Modeling)

Group C01 explores the principles of slow earthquakes through geoscientific modeling. To date, they have realized three major achievements. First, they confirmed that slow earthquakes are a single inseparable broadband phenomenon through observations and devised a model that can mathematically explain them. Second, they realized numerical calculations of the temperature and water to explain the diversity of slow earthquakes. Third, they reproduced and observed "pre-slips," which is a kind of slow slip, using a large experimental facility. Their research has clarified the conditions in which slow earthquakes occur.

Group C01 Leader
Professor
Satoshi Ide
The University of Tokyo

Integrating models and observations to understand the whole picture of slow earthquakes

Slow earthquakes are an inseparable broadband phenomenon

Previously, it was unclear if tremors, low-frequency earthquakes (LFEs), and very low-frequency earthquakes (VLFEs), all of which were identified as types of slow earthquakes, were distinct phenomena or aspects of a single phenomenon.

Professor Satoshi Ide from The University of Tokyo and his colleagues confirmed that the latter was correct through observations. They named the overarching phenomenon "broadband slow earthquakes" and developed a mathematical model, the "two-dimensional diffusive stochastic process model," to explain the nature of the entire phenomena from tremors to VLFEs.

Previously, detecting broadband slow earthquakes was challenging because observations at a certain frequency band were difficult due to the noise from microseisms, or the constant small shaking of the Earth. Using the seismographs of the Dense Ocean-floor Observatory Network for Earthquakes and Tsunamis (DONET), Professor Ide and his colleagues detected a variety of slow earthquakes from locations closer to the epicenters, confirming that the different types of slow earthquakes were components of an inseparable phenomenon. DONET is submarine cabled real-time seafloor surveillance infrastructure, which began full-scale operations off the Kii Peninsula in 2011.

Figure 1 plots the relationship between the duration and seismic moment. Similar to normal earthquakes (fast earthquakes), broadband slow earthquakes show a linear relationship. The vertical axis shows the duration of each earthquake, and the horizontal axis shows the seismic moment (the magnitude of the earthquake energy). Here, LFE, VLFE, and slow slip event (SSE) can be plotted in an almost straight line. Prior to their research, the signal of slow earthquakes in the region between the LFE and VLFE had not been confirmed. Not only does it exist, but it connects the LFE and VLFE as phenomenon. That is, the broadband slow earthquake.

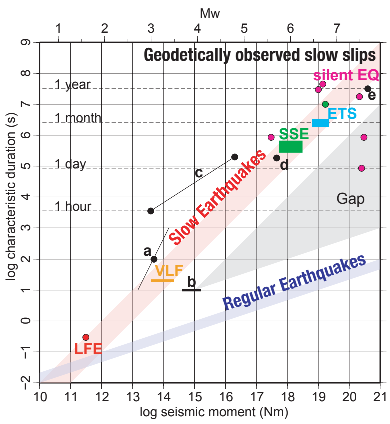


Figure 1
Slow earthquake signals are found between LFE and VLFE, indicating that they are connected broadband slow earthquakes.

Figure 1 also shows that there is a linear relationship between the duration and seismic moment for normal earthquakes (fast earthquakes). Namely, an earthquake of magnitude 7 lasts longer than that of magnitude 3. However, the slopes for the straight line of slow earthquakes and fast earthquakes drastically differ "because although both slow earthquakes and fast earthquakes involve ruptures and slips, they are distinct phenomena with different principles for fault rupture propagation," explains Ide.

Fault slips caused by fault rupture propagate rapidly as waves in fast earthquakes. In fast earthquakes, seismic waves generated by a rupture induce another rupture in the neighboring area of the fault in a serial manner. On the other hand, seismic waves in slow earthquakes are not coupled with ruptures. In the case of slow earthquakes, ruptures propagate relatively slowly, as a diffusion phenomenon. Namely, when a fault ruptures and slips, the surrounding area does not hold, and it slips again. Thus, the slip is slowly transmitted to the surrounding area like spontaneous wrinkle formation.

In a paper published in Nature (2007), Professor Ide presented this idea and a prototype of the graph to describe such phenomena. This paper significantly impacted the field of science of slow earthquakes. In the last five years, the discovery of broadband slow earthquakes and the establishment of a diffusion-based mathematical model to explain them have provided additional evidence to support Professor Ide's conclusions.

Temperature and water related to slow earthquakes: comparing subduction zones around the world

The mechanisms of slow earthquakes in eastern and western Japan differ. In western Japan, slow earthquakes occur in shallow and deeper parts of the plate boundary, but fast earthquakes occur at intermediate depths. This layered segregation is clear. On the other hand, a clear segregation does not exist in eastern Japan. In some cases, slow earthquakes and fast earthquakes appear to be mixed.

The Philippine Sea Plate, which subducts into the Nankai Trough in western Japan, is about 20 million years old, whereas the Pacific Plate, which subducts near the Japan Trench in eastern Japan, is about 130 million years old. It is speculated that the environments near the plate boundaries differ in terms of temperature, water content, and sinking speed.

Shoichi Yoshioka, a professor at Kobe University, and his colleagues have conducted numerical calculations of the heat and water distribution produced by subducting plates not only in Japan but also in North America (Cascadia Subduction Zone), South America (Chilean Subduction Zone), and New Zealand (Hikurangi Subduction Zone). His team created a model that explains the temperature data measured at each plate boundary. “With this model, we can now generalize the environment in which slow earthquakes occur in subduction zones and discuss the effects of temperature, water structures, and the shape of plate boundaries in subduction zones around the world,” says Ide.

For example, the question “why are there so few slow earthquakes in Ise Bay?” can be explained with this model. Among the areas along the Nankai Trough, the Tokai region and the Kii Peninsula have experienced many slow earthquakes. However, in Ise Bay, which lies between the two, there are many places where slow earthquakes are hardly observed. Professor Yoshioka and his colleagues explain that the temperature near the plate boundary in Ise Bay differs from that in the surrounding areas. This leads to different temperature and pressure conditions for mineral components, which contain water. Under such different conditions, water is discharged in different ways below the seabed. This may result in conditions that are inconducive for slow earthquakes.

Reproducing slow slips at a large friction testing facility

Futoshi Yamashita, Chief Researcher at the National Research Institute for Earth Science and Disaster Resilience (NIED), and his colleagues are conducting fault-slip experiments using a large shaking table at the Institute. The shaking table, which is the second largest in the world, measures 15-m long and 14.5-m wide. The shaking table was originally built to test the earthquake resistance of buildings. It can shake quickly and significantly even with a heavy load. Utilizing this high capacity, experiments can be conducted using large rocks on the order of meters in size. Experiments involving such a large rock are rare. Increasing the rock size can better reproduce the conditions for friction in the actual environment.

Rocks were piled vertically on the shaking table to reproduce a 1.5-m long fault (**Fig. 2-1**). The lower rocks move with the table, while the upper rocks are fixed outside the shaking table so that they do not move. The team measured the displacements of both rocks with strain gauges embedded below the reproduced fault surface at 12-cm intervals. They were the first in the world to observe two-dimensionally the rupture process of a fault.

When applying a force to slip the fault by moving the lower rocks, a preslip begins at a point on the fault plane. This is followed by fast slips in an accelerated wider area. Preslips are a kind of slow slip that precedes fast slips (fast earthquakes). Dr. Yamashita investigated the conditions in which a preslip is likely to occur.

When the fault slip speed on the shaking table is slow, the preslip is clearly visible. However, as the speed increases, a high-speed slip suddenly occurs and the preslip is no longer visible (**Fig. 2-2**). Although the numerical model predicted this behavior, the group experimentally confirmed it. “Roughly speaking, if a plate subducts too fast, preslips cannot be observed. In contrast, preslips can be observed if it subducts slowly.” says Ide.

As the fault surface becomes rougher, the duration of a preslip increases, but its reproducibility decreases. With rough surfaces, it is difficult to know when a fast slip will occur because the preslip duration is unknown, making it difficult to predict.

Approaching the core of slow earthquake occurrences

Preslip propagation occurs under the appropriate circumstances, which diffuse rupture and wave motion. Although water, viscoelastic deformation, and other candidate elements have been proposed, their roles are not well understood. The experiments on the large shaking table did not consider water-related or other ambient conditions. Additionally, it is believed that places that normally cause fault slips of slow earthquakes may sometimes slip fast due to ambient conditions, inducing a mega earthquake. “Such a mechanism has yet to be elucidated. It is also possible that ordinary earthquakes are a mixture of fast and slow earthquakes. As elucidating such processes may lead to the understanding of fast and giant earthquakes, it is a major issue for the future,” Ide said.

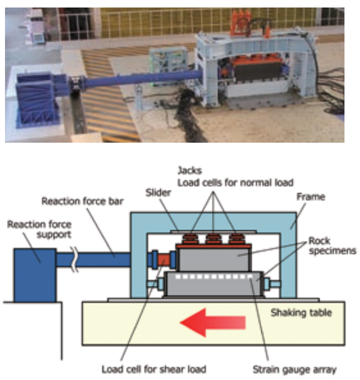
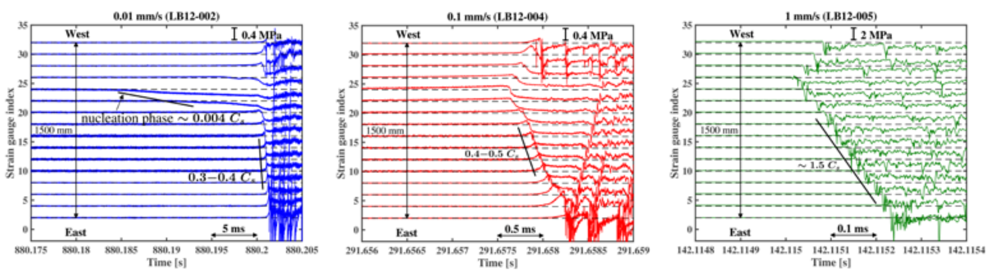


Figure 2-1
Experimental device to move large rocks on a shaking table.



(a) If the shaking table moves slowly, preslips appear.

(b) A little faster: preslips remain.

(c) Even faster: suddenly fast slips occur.

Figure 2-2 Preslip appearance depends on the speed at which the fault slips.

Interview on research results of Group C02 (Physical Modeling)

The C02 (Physics) Group approaches the true nature of slow and mega earthquakes from the perspectives of physics, especially nonequilibrium and statistical physics, which have yet to be applied to seismological research. The group discovered how heterogeneity such as the unevenness of fault surfaces and the presence of water generates diversity of fault slips. They also “export” their rich knowledge of seismology to other fields, since such knowledge may be applicable to other phenomena that occur in heterogeneous environments.

Group C02 Leader
Professor
Takahiro Hatano
Osaka University

Understanding slow earthquakes through the lens of non-equilibrium and statistical physics

Universal description of earthquakes from a perspective different from seismology

In 1880, the Seismological Society of Japan was founded. The first members were international researchers who came to Japan at the invitation from the Meiji government. Subsequently, the Seismological Society began to research earthquakes in Japan by developing a seismometer, which recorded waves of the ground shaking. Since then, research on earthquakes has mainly focused on what is happening underground based on seismic waves. Therefore, most traditional seismologists focus on areas of physics that deal with waves. However, these areas constitute only a small part of physics.

Professor Takahiro Hatano from Osaka University, the leader of Group C02, is not a seismologist in the narrow sense but a physicist who specializes in nonequilibrium physics and statistical physics. He explains his research field as “a field that aims to derive a universal theory to connect various phenomena at different scales and to describe these connections with mathematical equations.”

As a physicist, he aims to find a law that can universally describe phenomena from friction of millimeter-order powders in experiments to real massive earthquakes that involve displacement of faults over hundreds of kilometers. “One of the key words is heterogeneity,” he says.

The types of rocks and minerals at plate boundaries, which cause slow or mega earthquakes, depend on the location. The types of minerals present create faults with different properties when they deform or slip. Additionally, the water content and temperature conditions vary, resulting in a heterogeneous fault environment.

Elucidating the overall behavior of faults with such a miscellaneous collection of different properties using only conventional methodologies of seismology is difficult. Hence, the team has paved a path to apply methodologies developed in other areas not related to earthquakes such as statistical physics.

Demonstrating behaviors caused by uneven surfaces through simulations and experiments

One manifestation of heterogeneity is unevenness. Faults that cause slow earthquakes do not have even or smooth surfaces. Characteristic uneven surfaces are found when measuring outcrops of faults, which are suspected to induce previous earthquakes and appear on the surface of the earth over a long period of time with various measuring devices. The team mathematically reproduced these characteristic surfaces with a computer (Fig. 1-1) and clarified how faults would slip.

If the size of the unevenness is very small and the surface is almost flat, the fault slip accelerates at an early stage, becoming even faster. This results in ordinary (fast) earthquakes.

A greater unevenness results in more local slow slips. Preliminary slow and long-duration slips occur over a larger area as the size of unevenness becomes greater. By changing the degree of unevenness, the team successfully demonstrated that faults could slip fast like ordinary earthquakes or slip slowly for a long time like slow earthquakes.

The group also expressed the degree of unevenness using a single parameter. Such calculations are computationally expensive, and the cost increases as the load applied to a fault increases when the surface is curved. Professor Hatano’s group made full use of techniques to speed up the calculations, and they made it possible to track the time course of the slip.

Experiments have shown the diversity of slippage

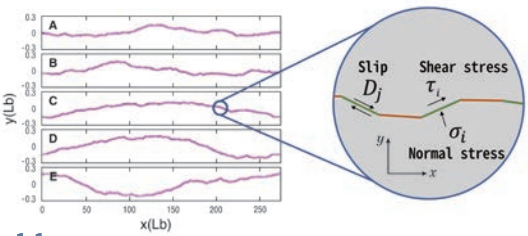


Figure 1-1
Simulation of a fault slip by quantifying the unevenness of the fault surface.

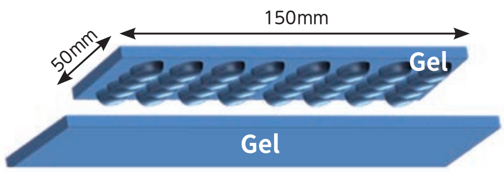


Figure 1-2
Simulated fault composed of vertically coupled soft polymer solids (gels). Experiment observed how the friction and slip are altered when the size of the bumps on the solid surfaces is changed.

caused by unevenness. The group created pieces of a soft polymeric solid (gel) with bumps on their surface, coupled two pieces vertically, and rubbed them together to simulate a fault slip (Fig. 1-2). The changes in the size of the bumps altered the nature of the frictional force.

In faults with small-sized bumps, an increased slip speed leads to increased frictional force. In this case, when a fault that has started to slip accelerates further, the increased friction force stops the slip, reducing the likelihood of an earthquake and causing the fault slip to become slimy. This is similar to the mechanism of a slow earthquake. On the other hand, in a fault with large-sized bumps, when the slip becomes faster the braking force becomes weaker. In this case, the fault slips fast for a certain distance and then stops. This process is repeated. This is similar to the mechanism for an ordinary earthquake. As described above, the group has successfully demonstrated that even if faults are made of the same material, the mechanism for earthquake occurrence can completely differ just by changing the bumps.

Model in which unevenly distributed water transmits repeated fault slips

Another important factor related to heterogeneity is water.

A variety of observations, including seismic waves, the Global Positioning System (GPS), electromagnetic waves, and gravity observations, have provided an increasing amount of data supporting the idea that the uneven distribution of water contributes to the occurrence of slow earthquakes. Professor Hatano and his colleagues have proposed the following model to explain the relationship between water and earthquakes.

The lower row of Fig. 1-3 shows the time evolution of water pressure distribution on fault planes. The red sections are filled with water at high pressure, while others are filled with water at low pressure, creating an uneven water distribution. Sections with high-pressure water can easily slip. When the water pressure reaches a certain value in a given section, the section slips and discharges water to an adjacent section. This section, which receives the water, can easily slip due to increasing water pressure. In this model, the starting point is the heterogeneity of the water. The heterogeneity creates a flow where water moves from section to section, as those sections slip due to increasing water pressure. The upper row of Fig. 1-3 shows the cumulative distribution of slips, and how it becomes more complicated with time.

With this model, the group examined how a slip propagates over time. They successfully reproduced a large part of the behavior of slow earthquakes. The energy characteristics (power spectrum) of slow earthquakes and those calculated by the model are very similar to each other. The simulation result for the relationship between the duration of a single slow earthquake and the amount of moment (earthquake energy) released by that earthquake was similar to the actual earthquake data.

"Our important achievement is that we are now able to reproduce observed facts with a very simple model," said Hatano.

"Export" of rich data and insight in seismology to other fields

The group has applied the perspective of physics to seismology. Simultaneously, they are studying how to "export" the outcomes of seismological research to other fields.

"Seismologists love the Earth very much. Thus, they tend to have a narrowed view of it. In the field of seismology, there is a wealth of interesting phenomena. By abstracting such phenomena and looking at them from a generalized perspective, our studies can impact change in other fields," says Hatano. He says that abstracting and generalizing are one of the roles of physics. This is another stage of the physics group.

For example, a model or theory that explains the behavior of an object like a fault causing slow earthquakes, which is a mixture of something that deforms slimy (i.e., matrix) and something that breaks (i.e., rock grains), may also explain the deformation of a combination of wood and metal.

When wooden parts are assembled with screws, reinforced with metal fittings, or joined with adhesives, applying a force to the assembly causes the metal parts like a screw to bend slowly. On the other hand, the wooden parts do not deform much. Instead, they break at a certain point. Understanding how two materials with different deforming properties behave when applying force seems to have something in common with how slow earthquakes occur (Fig. 2). Such an understanding may be useful to build or reinforce robust wooden houses.

"In the field of seismology, observational techniques are advancing rapidly, and a great amount of observational data is being accumulated. However, researchers in other fields of physics remain unaware of these advances. Consequently, this field is a treasure trove of interesting materials to be discovered," said Hatano.

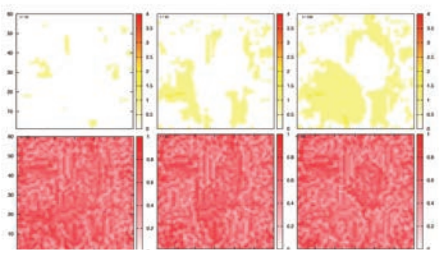


Figure 1-3
Model in which unevenly distributed water interacts with the slip and is transferred, which, in turn, promotes another slip. (Upper row: time evolution of the cumulative slip distribution, lower row: time evolution of the stress field)

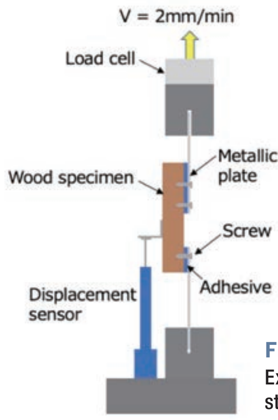
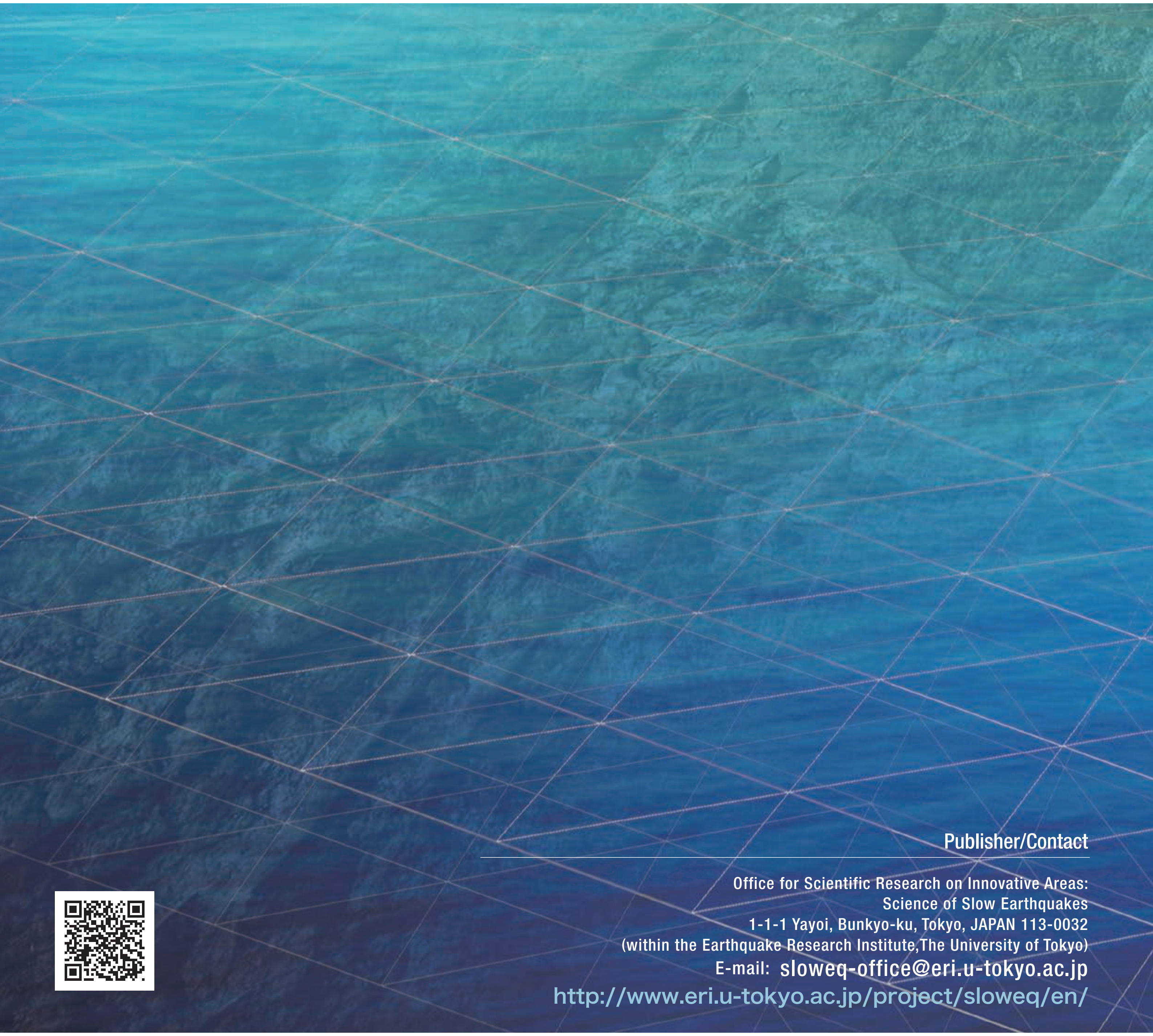


Figure 2
Experiment to investigate the strength of a structure made of wood and screws.



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Science of Slow Earthquakes

The Impact of SLOW EARTHQUAKES

—Our current understanding—

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