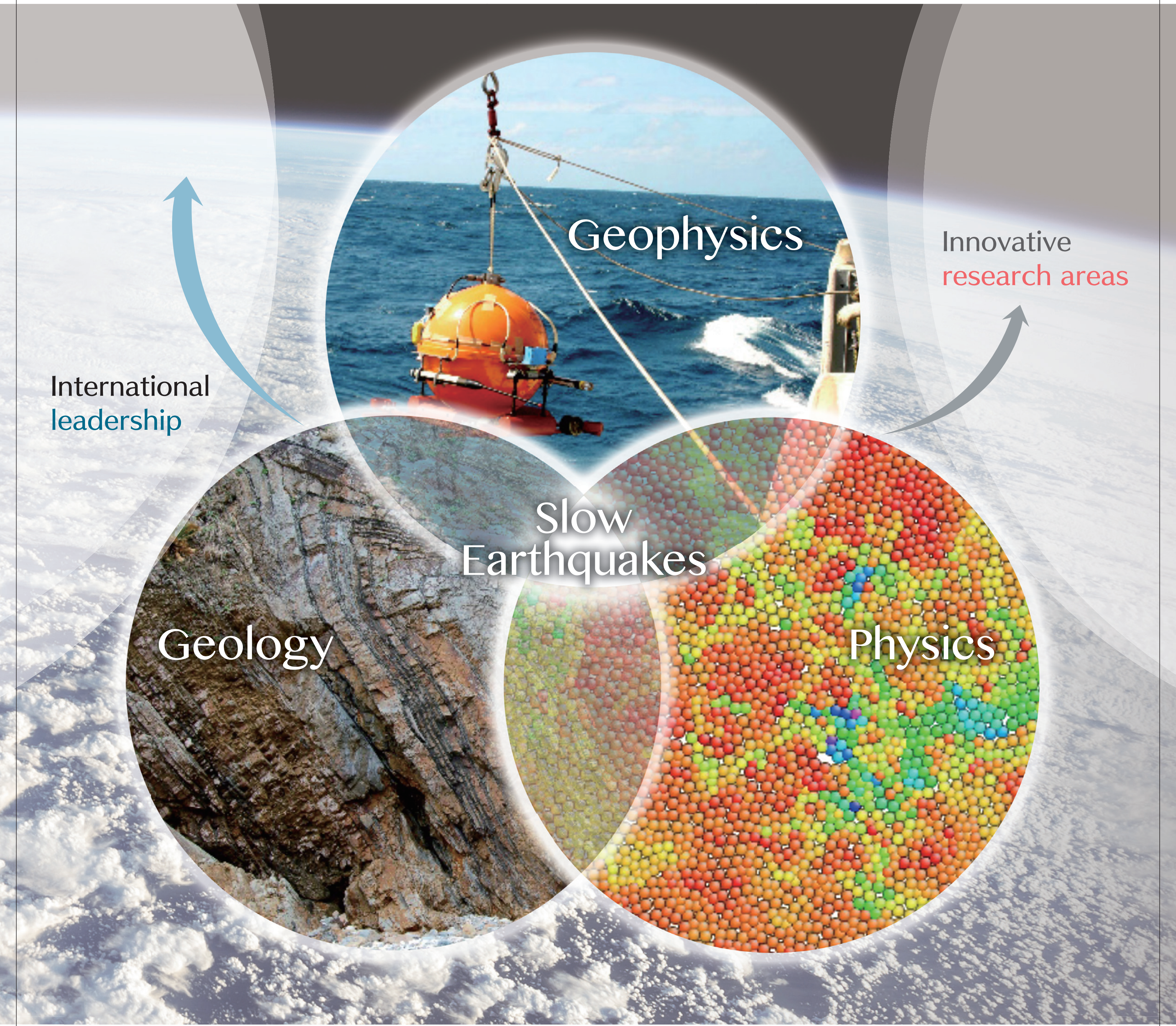
SLOW EARTHQUAKES

Newsletter01



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SLOW

Scientific Research on Innovative Areas

Science of Slow Earthquakes

EARTHQUAKES

How do catastrophic mega-earthquakes occur? Ordinary idea is that the shakings from an earthquake originate from fractures and slips of underground rock. A well-established equation of motion for elastic bodies has elucidated the propagation of the shakings from earthquake rupture reasonably well. However, how is a rock fracture initiated? In addition, how does a small fracture evolve into a mega-earthquake accompanied with frictional slips? Although critical questions, they remain unanswered. Seismologists have been engaged in research focused on the phenomena associated with dynamic rupture for decades, but when reexamining the overall picture of the geologic phenomena associated with earthquakes, these seemingly dramatic ruptur eprocess may not represent the essential nature of earthquakes.

Underground geological faults slip slowly without radiating strong seismic waves. This type of phenomena was suggested in the 20th century, but not frequently observed. Because data are insufficient, such phenomena had been considered rare and even non-existent. However, the monitoring networks for crustal fluctuations and earthquakes deployed all over Japan toward the end of the 20th century spotted many mysterious phenomena. In 1997, a number of GPS monitoring sites around the Bungo Channel moved in almost opposite direction from the ordinary direction over a course of the year; this unique movement pattern was interpreted as a result of slow slip event (SSE) of the subducting plate boundary of the Philippine Sea Plate.

The subsequent discovery of low-frequency tremors, which were the source of very weak seismic waves, reported in *Science* in 2002 was mind-blowing in several aspects. First, weak vibrations that looked like noise were identified as those originating from the underground plate boundary. Second, the vibrations were very frequent events. Finally and most importantly, the source regions of the vibrations delineated the source area of the Nankai megathrust earthquakes, which have caused several catastrophic disasters in Japan. Today, less than 20 years later, similar SSEs and tremors have been observed in Canada, the United States, Mexico, Costa Rica, Ecuador, Peru, Chile, New Zealand, and Taiwan—essentially, around the globe. The phenomena are not rare, but rather, seemingly ubiquitous.

What are SSEs and tremors exactly? Subsequent research has partially answered this question. Both SSEs and tremors are slip motions of a plate boundary just like ordinary earthquakes. They often occur almost simultaneously at the same or an adjacent place. The magnitude of SSEs can be as large as M7 if computed in a similar manner as in ordinary earthquakes. Tremors are considered to be a series of successive small earthquakes below M1, called low-frequency earthquakes. Earthquakes that fall midway between SSEs and low-frequency earthquakes are called very low-frequency earthquakes. All three phenomena are collectively called slow earthquakes. The variations in stress, migration velocity in space, and various kinds of statistical laws of slow earthquakes considerably differ from those of ordinary earthquakes.

While researchers have successfully unraveled one mysterious mechanism of slow earthquakes after another in recent years, the 2011 Tohoku-Oki Earthquake occurred. Afterwards, some labeled seismology as a complete failure since it did not predict this catastrophe caused by the M9 mega-earthquake. This shortcoming demonstrates that our present knowledge about the physical processes initiating earthquakes is limited.

One of the important pieces of this puzzle is the mechanism of slow earthquakes. Slow earthquakes frequently occur in areas just next to a site where a dynamic rupture occurs, and continually change the physical conditions of the surrounding region. Ordinary earthquakes, which are fast slip events, are primed by various types of slow deformations. Slow earthquakes may not even be a factor; they may be a protagonist. This is an important point of view that has been lacking in traditional study of earthquakes. The goal of this research area is to reconstruct the approach of earthquake science based on a unified understanding of slow deformations and fast slips.

The history of slow earthquake research is young. Certainly, there are many unknowns, even in the fundamental modes of occurrence. The occurrence area is deep underground, where neither materials nor physical conditions are known. Moreover, the physical laws governing slow earthquakes apparently differ from those of ordinary earthquakes. There are many unknowns in these laws—even qualitatively, so we can say little about them. To tackle and unravel the mysteries of slow earthquakes, the traditional seismology approach is insufficient; a multi-faceted approach combining geophysics (seismology and geodesy), geology, and physics is necessary. Our basic research strategy, which is aimed at elucidation of the modes, environment, and occurrence mechanisms of slow earthquakes, consists of two different approaches. Using these two approaches we tackle six challenging tasks described here.

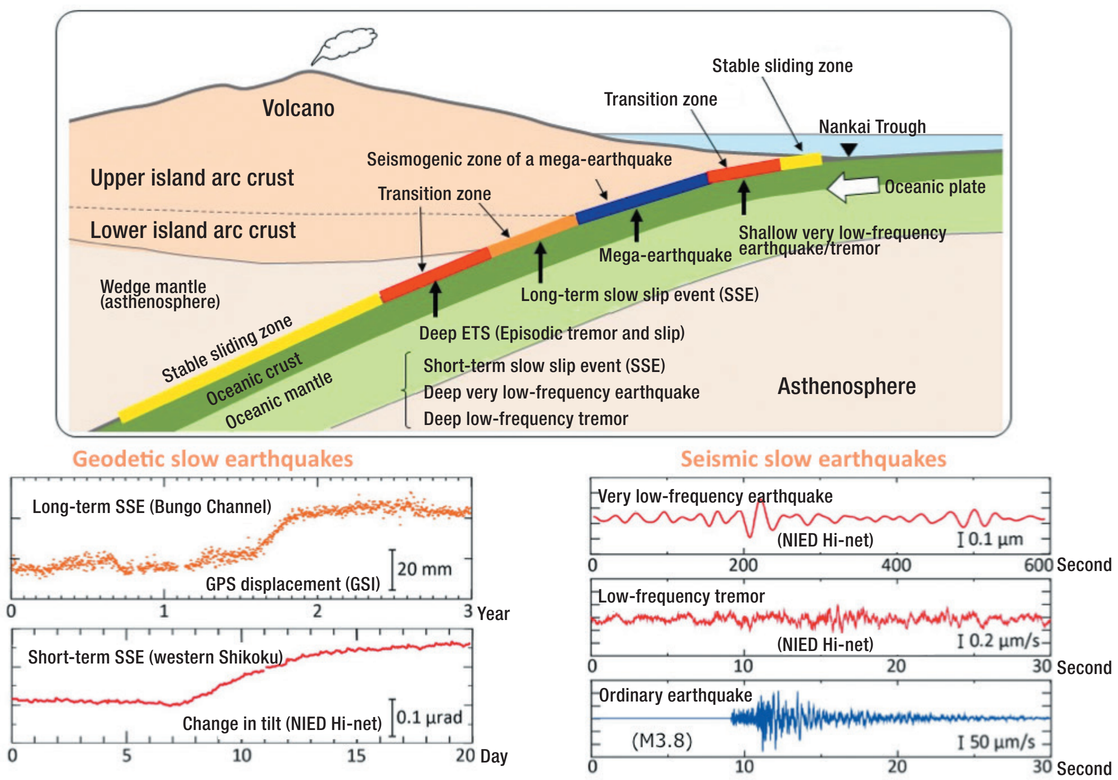


Figure 1. Slow earthquakes in the Nankai Trough

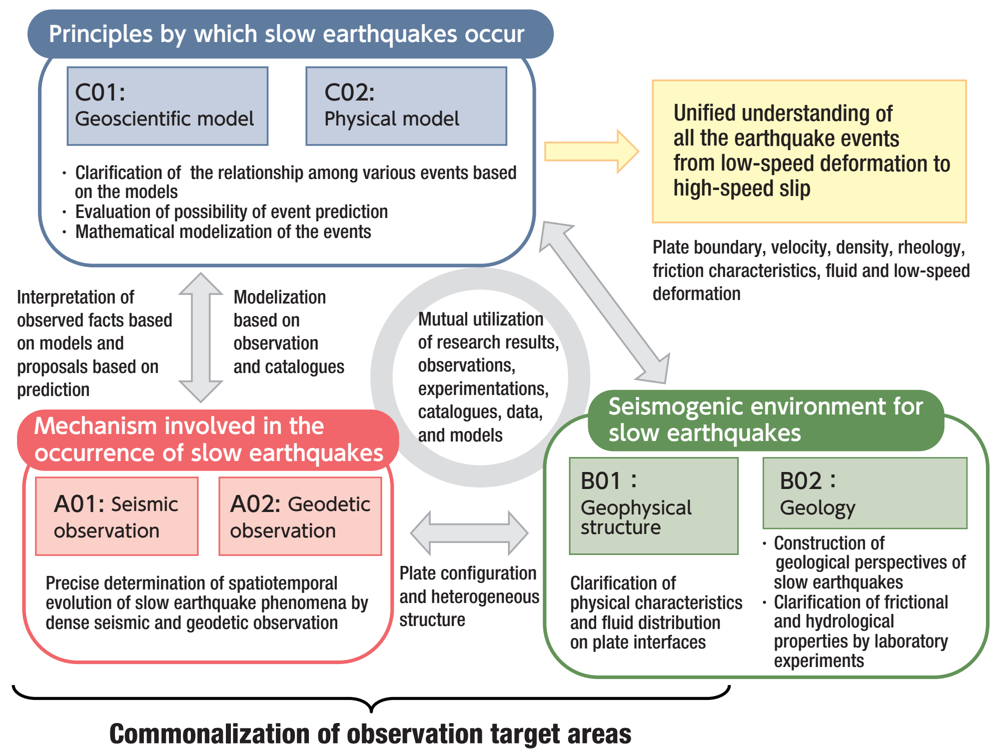


Figure 2. Organizational Chart of "Science of Slow Earthquakes"

Research Topic (A) Elucidation of the Occurrence Style of Slow Earthquakes

This topic implements mobile seismological and geodetic observations in ocean areas as well as on land in southwestern Japan. These data with infrastructural data and advanced data analyses are used to elucidate the occurrence area, magnitude, and spatiotemporal evolution of slow earthquakes with a high precision and high resolution.

This group aims to elucidate the spatiotemporal evolution and interaction of various slow earthquake phenomena (tremor, very low-frequency earthquake, etc.) based on short-period and broadband seismic monitoring as well as the interactions of slow earthquakes with tides and teleseismic waves.

This group strives to reveal the detailed spatiotemporal evolution of SSE by geodetic observations using GNSS, gravimeters, tiltmeters, and strainmeters as well as to elucidate the slip and frictional characteristics of areas where slow earthquakes occur. By comparing SSEs, tsunami earthquakes, and mega-earthquakes, a new image of the source of an earthquake will be captured.

Research Topic (B) Elucidation of the Occurrence Environment of Slow Earthquakes

By comparing the geophysical analyses results of data obtained in various explorations for crustal structures with the results of geologic observations and rock experiments, this topic aims to reveal the underground structures and constituent materials as well as their heterogeneity in areas where slow earthquakes occur.

This group works to elucidate through seismological and electromagnetic surveys and observations the relationship between along-dip variation of the metamorphic processes and the physical properties along the plate interface as well as to determine the distribution of fluids that is considered to affect the strength of interplate coupling.

This group constructs geological perspectives that describe the occurrence of slow earthquakes from observations and analyses of accretionary prisms, metamorphic rocks, etc. formed in areas where slow earthquakes occur. Using experiments with geological and mock samples, this group investigates the frictional and hydraulic properties during the transition process from a slow deformation to a fast slip.

Research Topic (C) Elucidation of the Occurrence Mechanism of Slow Earthquakes

This topic integrates theories of fundamental physics and the results of analog experiments with large-scale numerical simulations to reveal the laws of physics governing slow earthquakes and *in situ* physical conditions.

This group strives to formulate comprehensive geoscientific models that reproduce the physical processes initiating various earthquakes ranging from slow earthquakes to mega-earthquakes, and apply these models to various sites around the globe. The models are used to examine the causes of diversified seismic phenomena that differ by region and to assess the predictability of seismic phenomena.

This group aims to understand the difference between slow and regular earthquakes through spatiotemporal experiments and stability analysis in rheologically heterogeneous fields. Specifically, research is devised to elucidate the interactions of both types of earthquakes from the point of view of cooperative phenomena in nonlinear dynamics.

Research Group A01

Study on the Mechanisms Involved in the Occurrence of Slow Earthquakes Based on Temporal Inland and Offshore Observations

Seismic Observation Group

Slow earthquakes are the phenomena characterized by slow fault ruptures. They have been discovered along subducting oceanic plates in Japan and the Circum-Pan-Pacific since around the end of the 20th century. Slow earthquakes are considered to have some sort of interactions with occurrence of huge earthquakes since slow earthquakes occur in adjacent areas of huge earthquake seismogenic zones. However, the physical process of the phenomena has not been explained well yet. The term slow earthquake is used to collectively express seismic phenomena in which the speed of the fault slip and the rupture propagation are slower than those of regular earthquakes.

Slow earthquakes consist of more than one phenomenon with various time constants. For instance, at a deeper plate boundary than the seismogenic zone of the Nankai megathrust earthquake, the following three types of phenomena occur almost simultaneously at the same place: a short-term slow-slip event (SSE) with a time constant extending over a couple of days, a very low-frequency earthquake (VLFE) with a predominant period of 10 seconds, and a low-frequency tremor with a predominant frequency of a few Hz. In the Bungo Channel, a long-term SSE with a time constant of a few months occurs in a somewhat shallower region of the plate boundary than these slow earthquakes. Slow earthquakes occurring in a deeper region of the plate boundary than the locked zone have been detected in various locations around the world. They are detected even in very shallow regions near troughs around Japan, including the Nankai Trough.

The above-mentioned slow earthquakes sometimes exhibit very clear interactions. For instance, they occur simultaneously or successively in a spatiotemporal distribution. Slow earthquakes are also sensitive to changes in environmental stress. For instance, they are frequently induced by tides and teleseismic waves. Additionally, slow earthquakes exhibit various characteristic activities such as the occurrence period and migration pattern. Precise understanding of occurrence regime, spatiotemporal evolution and causal relationship among the phenomena may lead

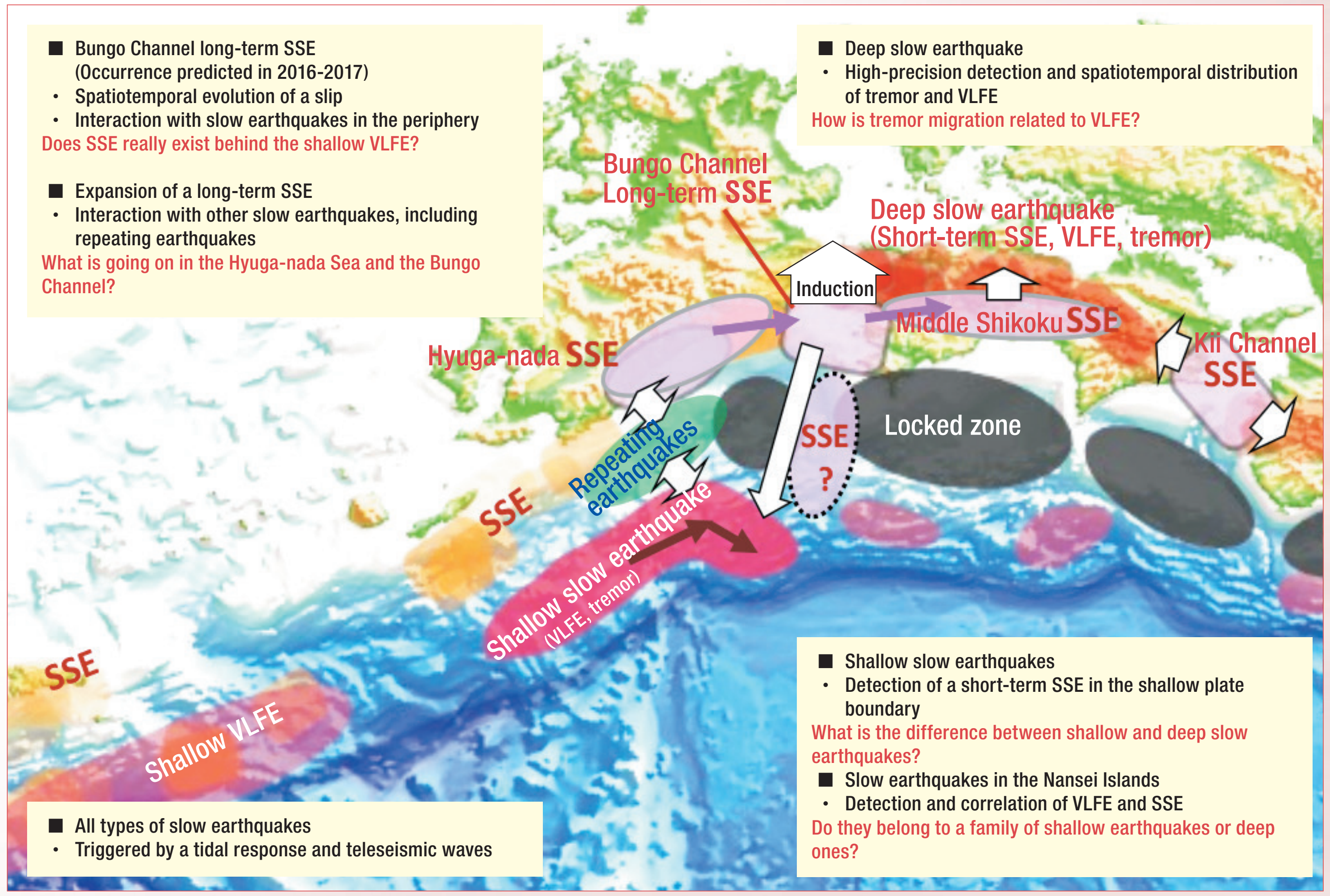


Figure 1. Research area of the observation groups (A01 and A02) of Science of Slow Earthquakes

to clarify the occurrence mechanism of slow earthquakes.

Based on the aforementioned points, this research group focuses on one of the world's most active regions of slow earthquakes, which extends from western Shikoku and the western Nankai Trough to the Ryukyu Islands to determine the occurrence style of slow earthquakes. In particular, we work to answer the following questions:

- **Q Short-term SSEs in the shallow region of a plate boundary—Do they really exist? Do they really occur?**
- **Q Is the occurrence style of shallow slow earthquakes the same as deep slow earthquakes?**
- **Q What factors influence the occurrence style of slow earthquakes? What are the scaling laws of slow earthquakes?**
- **Q Slow earthquakes, repeating earthquakes, and regular earthquakes—How do they interact with each other?**

To date, tremors and very low-frequency earthquakes are identified as shallow slow earthquakes. Their spatiotemporal identities and characteristic migration are extremely similar to those of deep slow earthquakes, which naturally lead us to predict the existence of short-term SSEs behind shallow tremors and very low-frequency earthquakes. Understanding the seismic activity details of these shallow slow earthquakes will allow us to compare the mutual relationships among the contributing factors of slow earthquakes and their activity styles with those of deep slow earthquakes, which will eventually impose restrictions in modeling the source region of slow earthquakes.

Tremors, very low-frequency earthquakes, and short-term SSEs of the deep slow earthquakes have already been identified by permanent earthquake observations. By improving the capability of the spatial resolution, we capture currently undetected smaller events and fast migration phenomena, and reveal the activity style and scaling laws in detail. Incidentally, the activity style of deep tremors, which are affected by the long-term SSEs occurring in the Bungo Channel, is not necessarily similar to that of shallow slow earthquakes. In addition to these slow earthquakes, we clarify the interaction among slow slips and regular earthquakes that may be inferred from repeating earthquakes as well as elucidate the effect of the slip velocity and the extent of asperity in the periphery of the areas on these earthquakes.

These research results will help us understand the entire picture of slow earthquakes. Moreover, these results allow us to model slow earthquakes, which should contribute greatly toward promoting this research field. This research on slow earthquakes will help us achieve the ultimate goal of promoting a unified understanding, which includes regular earthquakes. To be more specific, based on the already-existing infrastructural permanent seismic observations and temporal inland and offshore observations, we conduct research focusing the following types of slow earthquakes:

A Shallow Slow Earthquakes

By conducting temporal ocean bottom observations of earthquakes and pressure changes in the western Nankai Trough, we aim to realize direct geodetic detection of a predicted shallow slow slip event. Specifically, we estimate the spatial distribution of this slip as well as detect a shallow tremor and a shallow very low-frequency earthquake. By conducting temporal broadband seismic observations in the Ryukyu Islands and using the permanent seismic observation data collected in Japan and Taiwan, we investigate the detailed spatiotemporal evolution of the seismic activity of shallow slow earthquakes and the activity style such as tidal response, etc. Moreover, we assess the scaling laws of these phenomena and their mutual relationship.

B Deep Slow Earthquakes

We focus on western Shikoku, which is the most seismically active region in southwestern Japan, and deploy the dense broadband seismometer arrays and the very dense short-period seismometer arrays. Using these instruments, we extract a detailed picture of the spatiotemporal evolution of deep low-frequency tremors and very low-frequency earthquakes, including very fast migrations. Additionally, we examine the applicability of the scaling laws to smaller events of deep very-low frequency earthquakes and understand their interactions. Furthermore, we study the activity style, including phenomena induced by tidal responses and surface waves from remote earthquakes.

C Repeating Earthquakes

In the region extending from the western Nankai Trough to the Ryukyu Islands, we infer from the analysis of repeating earthquakes the slow slip that is predicted to exist behind the repeating earthquakes and elucidate the spatiotemporal evolution. Furthermore, we investigate how a slow slip interacts with shallow slow and regular earthquakes in the periphery of the area of the slow slip.

Finally, we examine the commonalities and differences in the activity styles of shallow and deep slow earthquakes, and how these slow earthquakes interact with repeating earthquakes. Additionally, we assess the effect of long-term slow slip events quantitatively using the fault parameters estimated by A02 geodetic observation group.

Geodetic Observation Group

Research Group A02

Study on Physical Mechanisms of Slow Earthquakes Based on Geodetic Observations

The world's most diversified activities of slow earthquakes can be seen in southwestern Japan in the areas along the Nankai Trough and the Ryukyu Trench. Slow earthquakes are detected as distinct phenomena such as tremors, very low-frequency earthquakes (VLFEs) or slow-slip events (SSEs), according to their waveform characteristics, dominant frequencies, and durations. These types of slow earthquakes exhibit various patterns of activity in each region. One of the prominent characteristic patterns is the simultaneous occurrence, or synchrony, of slow earthquakes, as exemplified by the spatiotemporally synchronous tremors and SSEs. This synchrony is a key phenomenon that can be used to probe the general occurrence mechanism of slow earthquakes. The overall pattern of activity is thought to be controlled by SSEs, which have the largest magnitudes among various types of slow earthquakes. Hence, the elucidation of the occurrence mode of SSEs and factors contributing to the regional characteristics of SSEs should help us understand slow earthquakes in general.

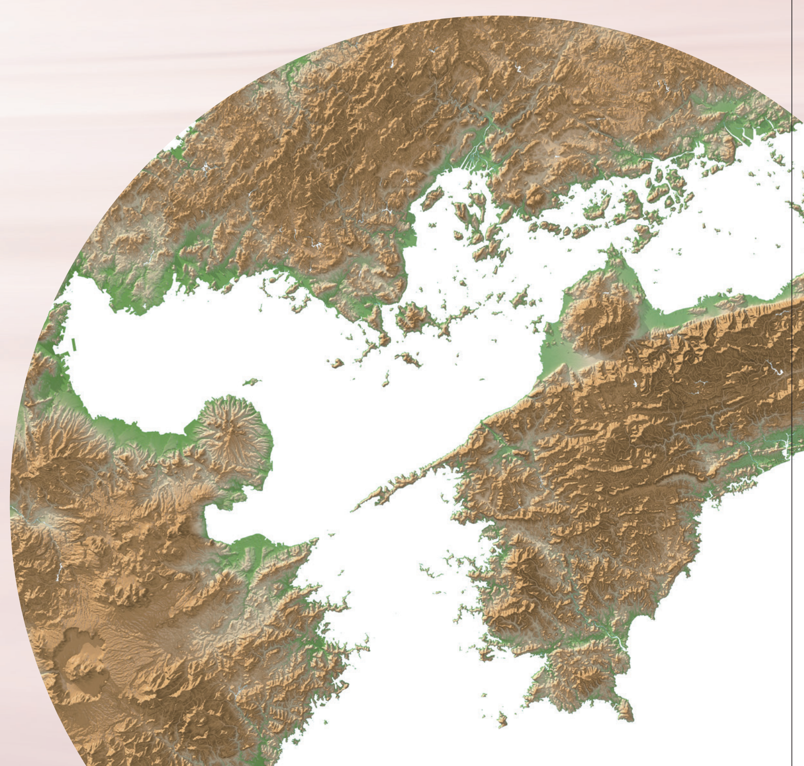
With this mindset, our research group addresses the following three tasks:

1. Determination of the Slip Areas of SSEs and the Understanding of the Interactions among SSEs

Around the Bungo Channel, large SSEs close to magnitude 7 recurs almost regularly every six to seven years (Bungo Channel SSE). In western Shikoku, which is adjacent to the Bungo Channel, smaller SSEs with duration of a week (short-term SSE) repeatedly occur roughly every six months. A change in the repeating pattern of this short-term SSEs has been observed before and after the Bungo Channel SSE, during which the recurrence interval of the short-term SSE becomes shorter than usual. This observation suggests that the activity of the short-term SSEs may be promoted by the larger Bungo Channel SSE. The occurrences of short-term SSEs and longer-duration SSEs are also observed in the Hyuga-nada region, an area across the Bungo Channel, in Kyushu. However, it is unclear if there are connections with the Bungo Channel SSEs.

This area already has the GEONET (GNSS: Global Navigation Satellite System) stations of the Geospatial Information Authority of Japan (GSI), Hi-net (tilt) stations of the National Research Institute for Earth Science and Disaster Resilience (NIED), and the Groundwater Monitoring Network (strain) of the National Institute of Advanced Industrial Science and Technology (AIST). In addition, we plan to install a new series of continuous GNSS monitoring sites in Shikoku and Kyushu, and analyze all the data collectively to understand the activity of each SSE in detail. Specifically, we strive to estimate the slip area of each SSE precisely and to clarify the interaction among adjacent SSEs. We also compare the slip velocity and the stress change due to SSEs, and further compare the strains released by SSEs with those accumulated by relative motions between tectonic plates over a longer time span. In this manner, we aim to understand the interplate coupling in the area where slow earthquakes occur as well as reveal the frictional properties near the plate interface.

A direct linkage between slow slip and the activity of shallow VLFEs off Cape Ashizuri in Shikoku, which has been known to increase when a Bungo Channel SSE occurs, has yet to be established. We aim to reveal why this occurs by inferring the activity of SSEs at the shallow plate boundary and interplate coupling from integrated data that we collect using GNSS deployed along the Pacific coast of Kyushu, monitoring of crustal movements with ocean bottom pressure gauges (to be done by the A01 group), and results from the seafloor geodetic measurements along the Nankai Trough.



2. Examination of Environmental Factors Responsible for the Occurrence Mode of SSEs

SSE activity has been observed in several regions along the Ryukyu Trench (**Figure 1**). The SSEs in these regions seem to show isolated activity, unlike those around the Bungo Channel. Among these regions, SSEs are estimated to occur on the shallow plate interface around the Okinawa Island, whereas they are located on the deeper plate interface around the Yaeyama Islands. These activities along the Ryukyu Trench are the results based on the existing GEONET data. Since the number of GEONET sites is limited mainly because the study area is in islands, our discussion about the distribution of the slip areas of these SSEs, especially how the slip is extended in the dip direction of the slab, has been limited.

To improve the detectability of SSEs in these two regions and to simultaneously improve the resolution of the SSE slip distribution and understand the mode of SSE activity such as the recurrence intervals, duration, depth range of slip, we deploy a series of GNSS monitoring sites in remote islands in these regions. We extract the characteristic features of SSE activity in both regions, which along with the activities in other regions, is compared with the underground structures obtained from the geophysical explorations of the **B01 group** as well as the realistic numerical models constructed by the **C01 group**. In this manner, we give constraints on factors determining the slip property at the plate boundary.

3. Detection of Crustal Fluid Migration Associated with SSEs

A supply of water from the slab to the subduction zone is thought to accompany the subduction of an oceanic plate. It is further thought that the existence of such fluids at an plate interface decreases the effective normal stress, thereby contributing to promote slip. This kind of discussion has been addressed not only for slow earthquakes but also to fault slip phenomena in general. For instance, slip of SSEs accompanied with tremors is known to propagate in the strike direction of the plate interface, typically at a speed of about 10 km/day, which is significantly slower than the rupture propagation speed of regular earthquakes. It remains unknown if there is any association between this significantly slow propagation speed and the fluids.

To answer this question, the detection of the migration of crustal fluids by field observations is required. For this purpose, we continuously measure the gravity in areas where SSEs occur using portable superconducting gravimeters to detect temporal gravity changes. Detecting the gravity changes associated with the migration of crustal fluids is itself a challenging task. We try to add quantitative constraints on it, and compare our findings with the time evolution of SSE slips obtained by monitoring the crustal movements such as GNSS. In this manner, we want to understand any association between the occurrence and time-evolution of SSEs and crustal fluids.

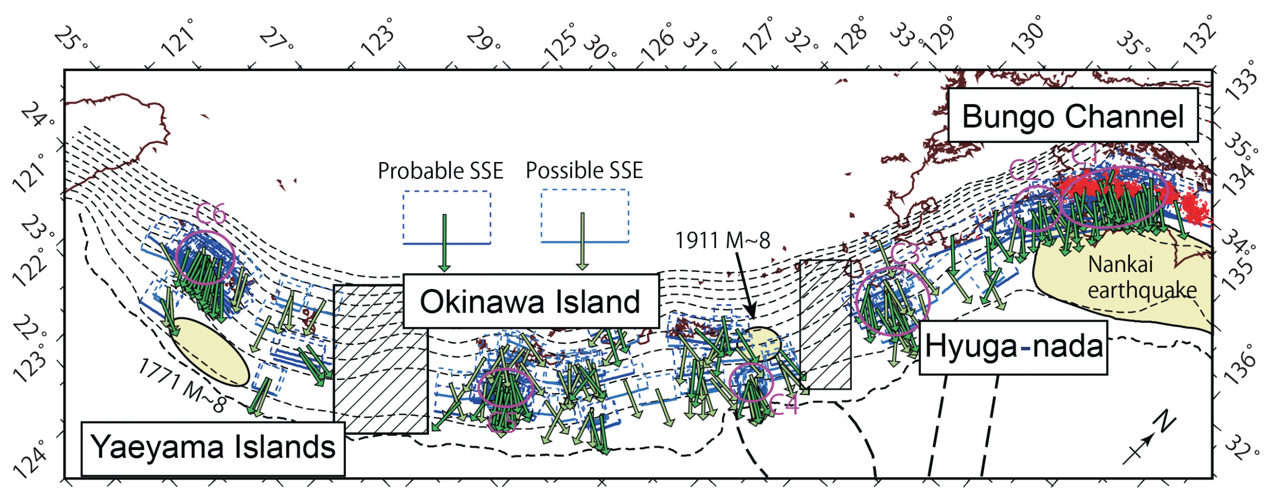


Figure 1. Areas of short-term SSEs occurrence (modified after Nishimura, 2014) and the research areas.

Research Group B01

Study on Seismic and Electromagnetic Subsurface Structure around the Source of Slow Earthquakes

Geophysical Structure Group

The diversified forms of fault slips along the plate interface—from regular earthquakes to slow ones—are attributed to the heterogeneous frictional characteristics of the plate interface, which reflect the structural and environmental factors of the interface such as the geometry, physical properties, and fluid distribution. A lot of research have been conducted on the relationships between fault slips and their structural and environmental factors. However, the structural and environmental factors that account for the diversified forms of the fault slips on the boundary interface are not well understood. In this research group, we primarily focus on the region surrounding the Bungo Channel in Southwest Japan, where the coupling of various fault slips is observed over shallow to deep plate interface. Our challenge is to gain a comprehensive picture of the crustal structure around the plate interface by using all available resources of seismological and electromagnetic methods as well as to capture the changes in the structure associated with the occurrence of fault slips.

It is known that, in the Bungo Channel between Shikoku and Kyushu (**Figure 1**), a slow slip that continues for a couple of months occurs about every six years in almost the same area of the plate interface. In conjunction with this slow slip event, very low-frequency earthquakes are observed along the shallow plate interface adjacent to the trench axis, while low-frequency tremors are observed along the deeper plate interface than the area where slow slips occur. Therefore, these activities may be interpreted as a coupled occurrence of a fault slip sequence, reflecting the frictional characteristics varying along depth. The characteristic scale of these activities is about 50 km, which is a suitable size for geophysical surveys and monitoring. Moreover, the area where long-term slow slips occur is enclosed by Shikoku and Kyushu, facilitating long-term monitoring with a land-based monitoring network surrounding the areas of occurrence.

We believe that marine structural surveys in the region in addition to this land-based monitoring network will elucidate the seamless structure around the plate interface from the trench axis to the onshore area, thereby allowing us to understand the structural factors responsible for each type of characteristic fault slip. The objective of this research group is to reveal the detailed relationship between fault slips and the seamlessly elucidated crustal structure extending from offshore (the shallow plate interface) to onshore (the deep plate interface) regions in the Bungo Channel, which offers an ideal environment for research. Since a long-term slow slip is predicted to occur during the research period of this research group, we aim to capture relevant characteristic fault slips varying along depth, which is coupled with the long-term slow slip event as well as identify minute changes in the structure. By combining obtained results, we will carry on our studies to make contribution to construction of physical models of fault slips.

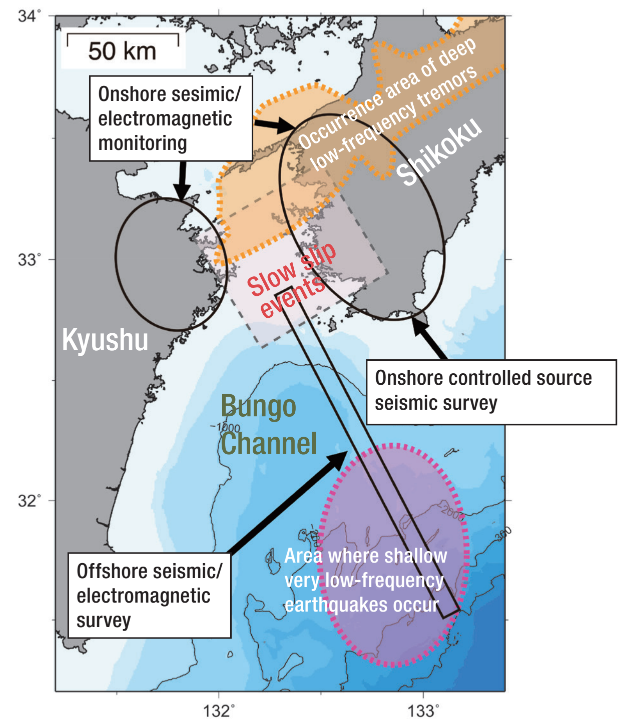


Figure 1. Areas of seismic and electromagnetic surveys, and monitoring in the area surrounding the Bungo Channel, which is the main research target area in this research group.

Do Currently Accepted Structural Models Appropriately Account for the Occurrence of Tremors?

We start with a fundamental question. Are the models designed for the occurrence of tremors that are considered appropriate *really* appropriate? The relationship between the occurrence of tremors and the dehydration reaction inside the subducting plate has been a subject of debate, especially the presence of serpentine produced by a metamorphic process in the hanging wall above the plate interface in the area of occurrence of tremors. Comparison of the properties of materials found in the hanging wall immediately above the plate interface along tremor observed areas extending from Kanto to Kyushu indicate no markedly abnormal values in the seismic wave velocity, Vp/Vs ratio, seismic wave attenuation, or the magnitude of anisotropy in the tremor observed areas. In contrast, the characteristic features such as low seismic wave velocity and substantial attenuation of seismic wave have been observed in non-tremor observed areas. These results suggest that the plate interface in tremor-observed areas possesses a property that impedes the percolation of water produced in the dehydration reaction to the hanging wall. Hence, structural models contrary to traditional ones have been proposed to account for the relationship between the tremor-observed areas and the metamorphic process in the hanging walls. Therefore, it is necessary to elucidate the detailed structure around the plate interface and investigate the factors responsible for the diversified forms of fault slips.

Seismological Structure around the Plate Interface

Among the seismological approaches to investigate the structure around the plate interface that exhibits diversified forms of fault slips is receiver-function analysis. The extraction of P-to-S converted waves at the plate interface where the seismic wave velocity or material density is discontinuous in the depth direction allows us to map the geometry of the plate boundary. Investigations of the P-to-S conversion efficiency also allow us to infer the property of the materials around the plate interface. The environmental conditions for seismological observations at the seafloor used to pose an obstacle for application of receiver-function analysis to waveforms recorded by ocean bottom seismometers, but a recently developed analysis method has removed such obstacles, allowing us to map the entire plate interface extending from the offshore to the onshore areas under study with the receiver functions. This should help elucidate the dehydration reactions associated with plate subduction.

Controlled Source Seismic Structural Survey

A structural survey using controlled seismic sources of airgun arrays towed behind a vessel or those of dynamite explosion help find the P-wave velocity structure in the crust down to the periphery of plate interface. Additionally, investigating the amplitude intensity distribution of the reflected waves from the plate interface allows us to infer the heterogeneous property of a material along the plate interface. In this research group, offshore and onshore structural surveys using controlled seismic sources are scheduled in the fourth and fifth year of the program, respectively (**Figure 1**). The objective for the onshore survey is to elucidate the changes in the property of the materials from the shallow to the deep part along the plate interface. In the onshore survey, the planar deployment of shot points and receiving points (receivers) helps find the heterogeneous property of the materials along the plate interface.

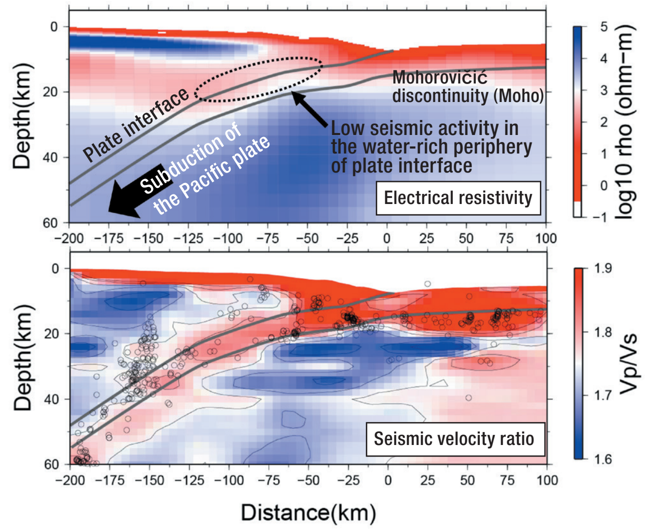


Figure 2. Electrical resistivity structure (above) and the seismic velocity ratio structure (bottom) in the crust along a profile normal to the Japan Trench off the coast of Tohoku. The diagram indicates a low seismic activity in the periphery of the plate interface where a rich water content is estimated from the resistivity structure.

Detection of the Fluid Distribution in the Crust and the Fluid Movement Associated with Slow Earthquakes by Electromagnetic Monitoring

Using ocean bottom electromagnetometers (OBEM) installed in the Bungo Channel and a land-based electromagnetic monitoring network surrounding them, we elucidate the three-dimensional resistivity structure in the crust, which is an indicator of how the crustal fluids are distributed (**Figure 2**). Additionally, we attempt to detect the fluid movement associated with slow earthquakes by monitoring the natural electric potential. Furthermore, by detecting the spatiotemporal changes in the resistivity structure, we extract information about the changes in the distribution of the pore water and the structure connecting pores. Successful detection, which has yet to be reported anywhere in the world, is a real challenge, but very important as it will contribute greatly toward constructing physical models that are expected to reproduce the occurrence of slow earthquakes.

Eventually, we will establish a comprehensive and integrative interpretation of all the results obtained in the above-mentioned tasks and elucidate the structural and environmental factors that account for the diversified forms of fault slips along the plate interface.

Geology Group

Research Group B02

Study on Geological Perspectives, Frictional and Hydrological Properties of Slow Earthquakes

Research in this program is conducted based on: 1 geological survey and sample analyses of accretionary prisms and metamorphic rocks formed at depths where slow earthquakes occur, 2 deep ocean drilling into the slow slip area, and 3 friction and permeability experiments using geological samples.

1 Geologic Surveys and Sample Analyses of Accretionary Prisms and Metamorphic Rocks Formed at Depths Where Slow Earthquakes Occur

Seismic and geodetic monitoring have revealed that slow earthquakes occur in two areas of a plate boundary: in the region shallower than the region deeper than the seismogenic zone of plate boundary earthquakes. In the Shimanto accretionary complex and the Sanbagawa and Nagasaki metamorphic rocks distributed in the Japanese archipelago, we can observe the rocks exhumed from the source area of slow earthquakes in subduction zones (**Figure 1**). We conduct geological survey and analyses of samples taken from the field to elucidate the materials, deformation features, and deformation mechanisms responsible for slow earthquakes.

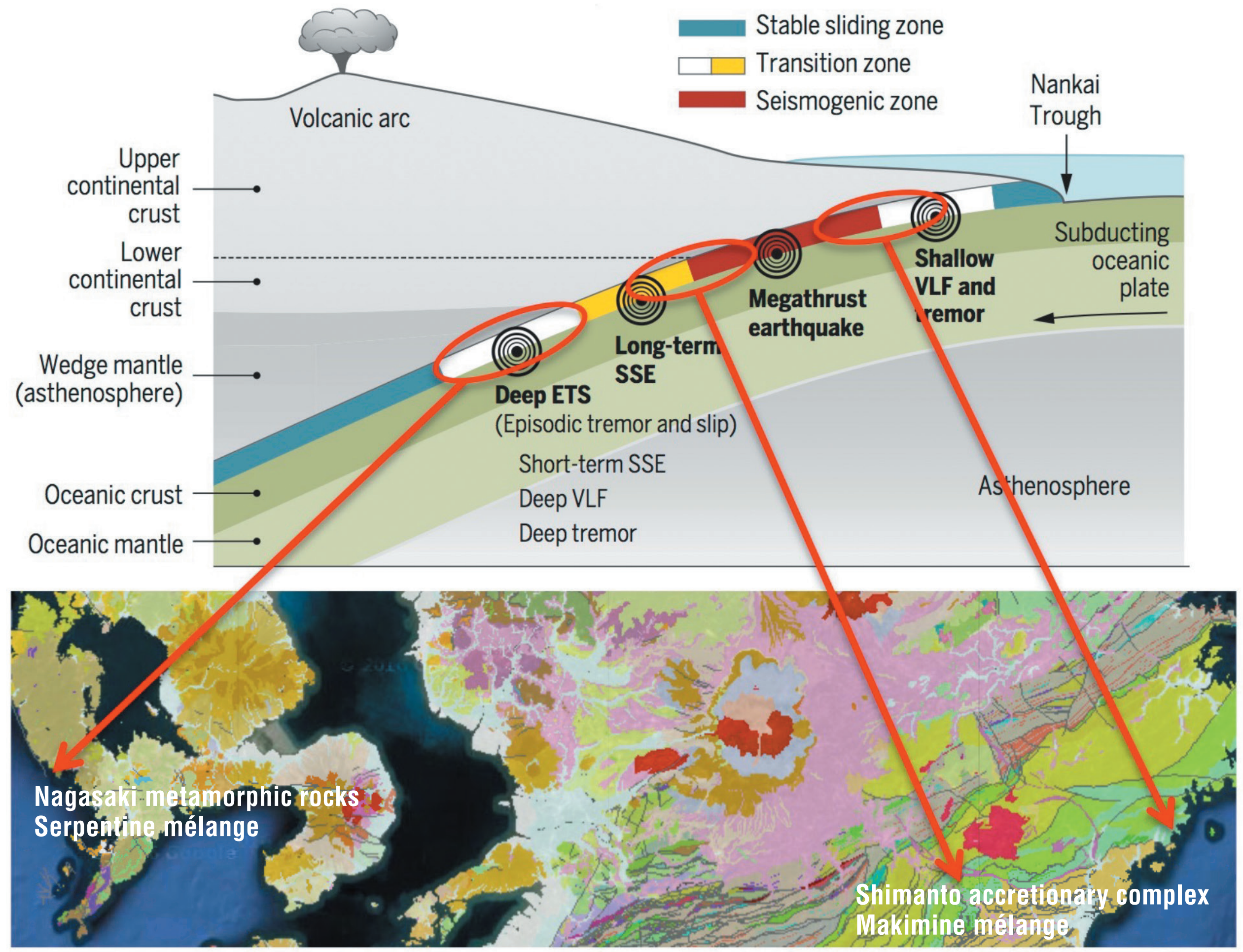


Figure 1. (Above) Various types of slow earthquakes in the subduction zone (Obara and Kato, 2016). (Bottom) Exposed accretionary prisms and metamorphic rocks in Kyushu, which were formed at the depth where slow earthquakes occur (Geologic Map Navi).

2 Deep Ocean Drilling into the Slow Slip Area

Deep ocean drilling into the slow slip area is planned in offshore Hikurangi, New Zealand by the U.S. scientific drilling vessel *JOIDES Resolution* (Figure 2). We will join in this drilling program and elucidate the role of fluids in the area where slow slips occur. Namely, we plan to investigate physical properties, stress state, materials, deformation features, and effects of fluids on slow slip.

3 Friction and Permeability Experiment Using Geological Samples

Using the samples taken from accretionary prisms and metamorphic rocks described in 1 and the core samples recovered from the slow slip area described in 2, we plan to conduct friction and permeability experiments to reveal frictional and hydrological properties in a wide range of slip rates and pore fluid pressure. Comparing the samples after the experiments with natural ones in 1 and 2, we will reveal factors controlling the slow deformation and the high-speed slip.

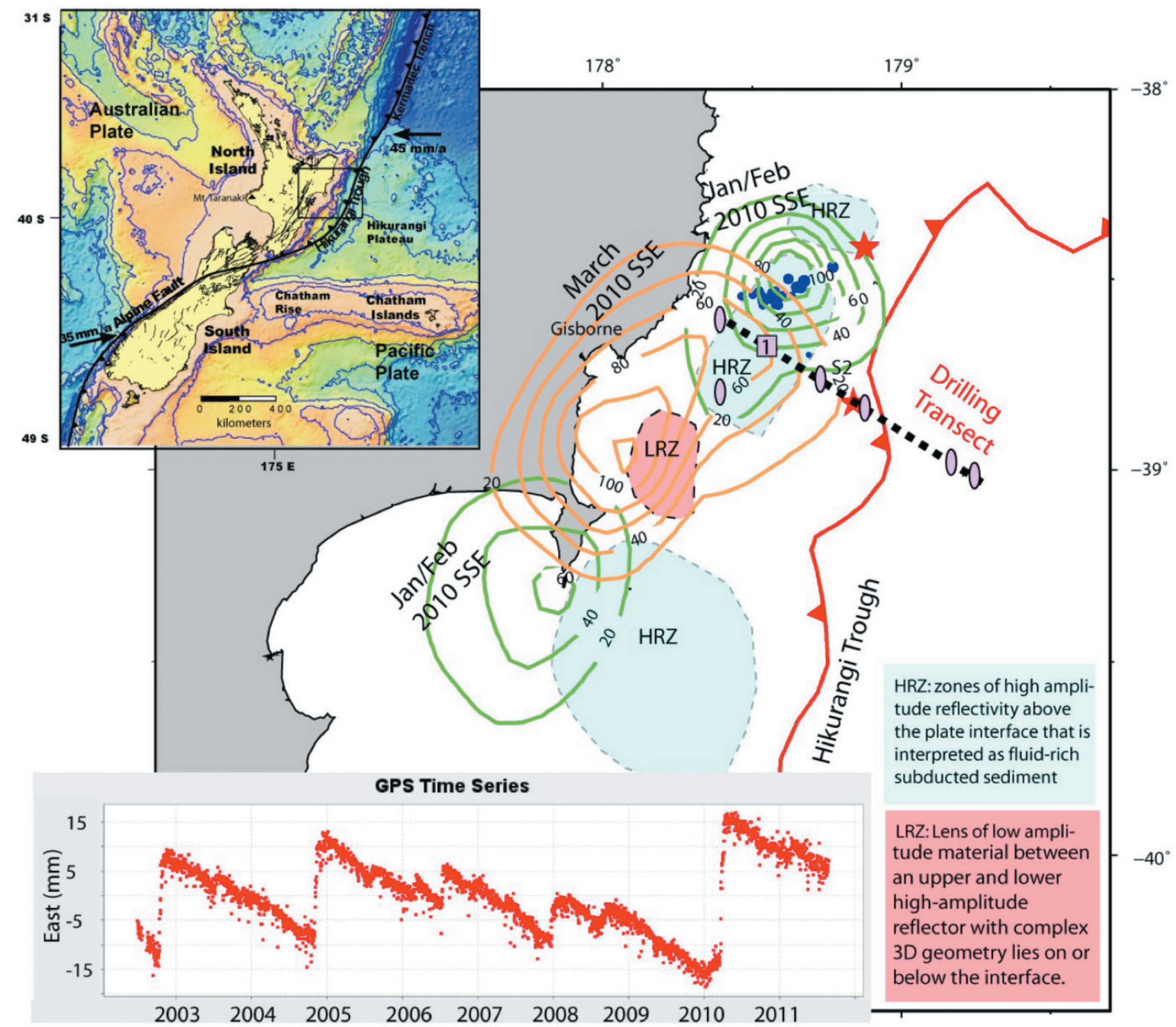


Figure 2. Scheduled drilling sites in the slow slip area offshore Hikurangi, New Zealand. A slow slip occurs every two years in offshore Hikurangi (IODP Drilling Proposal 781A-Full).

Geoscientific Modeling Group

Research Group C01

Study on Geoscientific Modeling of Earthquake Phenomena from Low-speed Deformation to High-speed Slip

In this research group, we employ large-scale simulation methods and data analysis to understand the mechanism of slow earthquakes and related phenomena. We include the word "geoscientific" in our research topic, as one of the two research groups dedicated to modeling studies in this research area. We emphasize that all theoretical and numerical models considered in this group have to be realistic to some extent and reflect some phenomena observed in the interior of the Earth.

Model research is multifaceted, and we focus on the following three categories: 1 the spatiotemporal relationship among slow earthquake phenomena, 2 realistic systems of plate movement, and 3 predictability of mega-earthquakes and tectonic plate motion. Examples of research programs in each category are presented below.

1 The Spatiotemporal Relationship among Slow Earthquake Phenomena

Phenomena collectively called slow earthquakes are primarily slip on the plate boundary, which include various phenomena with different characteristic time constants, ranging from short-period fracture events that generate seismic waves to slow slips that are detectable only with long-term crustal deformation. Many phenomena occur in the periphery of the seismogenic zones of ordinary earthquakes, whereas preslips and afterslips of large earthquakes occur almost within the seismogenic zones of ordinary earthquakes; that is, slow earthquakes occur over an extensive region from the shallow to the deep part of subduction zones. We must understand the spatiotemporally diversified picture of slow earthquakes as well as the underlying principle responsible for such diversification.

To conduct numerical simulations, we intend to develop several kinds of models specifically including the different spatial distribution of the friction laws at a plate boundary. Examples of the models include a model to help determine whether slow slips are spontaneous or generated under the influence of external factors, a model to account for the change in the size and frequency of small repeating earthquakes near slow earthquakes, and a model to reproduce the occurrence of various earthquakes from tremors and slow slips to ordinary earthquakes with a spatial distribution of slip weakening and strengthening zones.

In the meantime, we quantitatively research the diversity of slow earthquakes. We construct a catalog of slow earthquakes around the world by collaborating with other research groups, and we ultimately plan to quantify different types of slow earthquakes in each region using the physical indices such as the seismic moments, seismic energy, and event duration. Our research target regions include Japan (Tokai, Kii, Shikoku, Kyushu, and Okinawa), Taiwan, New Zealand, Canada, the United States, Mexico, and Chile. We will expand our research target regions through international collaborations.

2 Realistic Tectonic Plate Motion Systems

Many numerical models are developed based on rather simple settings. To fill the gap between simplified theories and complex real world phenomena, it is essential to study models that can accommodate as many complex real world phenomena as possible. Numerical models that accommodate plate geometries fairly close to real plates have been under development in various regions, including the Nankai Trough (Figure 1). This research intends to give a thrust (hopefully, a megathrust!) to the development of these models.

One of the real-world parameters that has yet to be incorporated in the models is tidal stress, which is about one thousandth of the stress change observed in ordinary earthquakes but is comparable to the stress change observed in slow earthquakes. In fact, tremors and slow slips are greatly affected by the tides. Thus, we are factoring in the disturbance of tidal stress as well as the change in stress due to long-term plate tectonic motion to the models under development. These models will be used to investigate the behavior of tectonic plates. Concurrently with model development, we will use crustal fluctuation data to infer the friction law at a plate boundary from the relationship between tidal stress and slow earthquakes. The results will be fed back into the model design.

Although it is well known that the temperature impacts the conditions of the occurrence of slow earthquakes, the actual temperature distribution at a realistic plate boundary is not well known. In this research, we formulate models for the thermal structure assuming a three-dimensional geometry of the tectonic plate in the subduction zones in Japan, Mexico, New Zealand, etc.

3 Predictability of Mega-earthquakes and the Tectonic Plate Movement

The relationship between slow and mega-earthquakes is an important research subject for this entire new research area. In this research group, the predictability of tectonic plate movement, which includes mega- and slow earthquakes, is examined based on the results obtained from various developed numerical models, data analyses, and rock experiments.

In recent years, we found the increase of seismicity just before the occurrence of several large earthquakes, near its hypocenter. It has been suggested that they are a type of preslips. In our studies, we use sophisticated data analysis to detect precursory seismic activities and elucidate the statistical properties of their behavior. In this manner, we investigate the occurrence probability of preslips and the scaling laws. We also conduct data analysis focused on the behavior of the seismic activity during the transition process from the preslip to the early rupture process of large earthquakes to elucidate their relationship. Preslip-like phenomena are also observed in rock experiments. We conduct friction experiments using large rock samples to investigate the conditions for slow slips.

Another important objective of this research is to examine the feasibility of probabilistic forecasting of earthquakes based on these findings. The occurrence of slow earthquakes or some other external factors that are possibly behind slow earthquakes such as tides may alter the occurrence probability and the development of earthquakes. An example is the change in the statistics of earthquake frequency due to tides published recently **(Figure 2)**. As our research progresses, we will incorporate more data in our research, and by quantifying this change in probability, assess the predictability of our models.

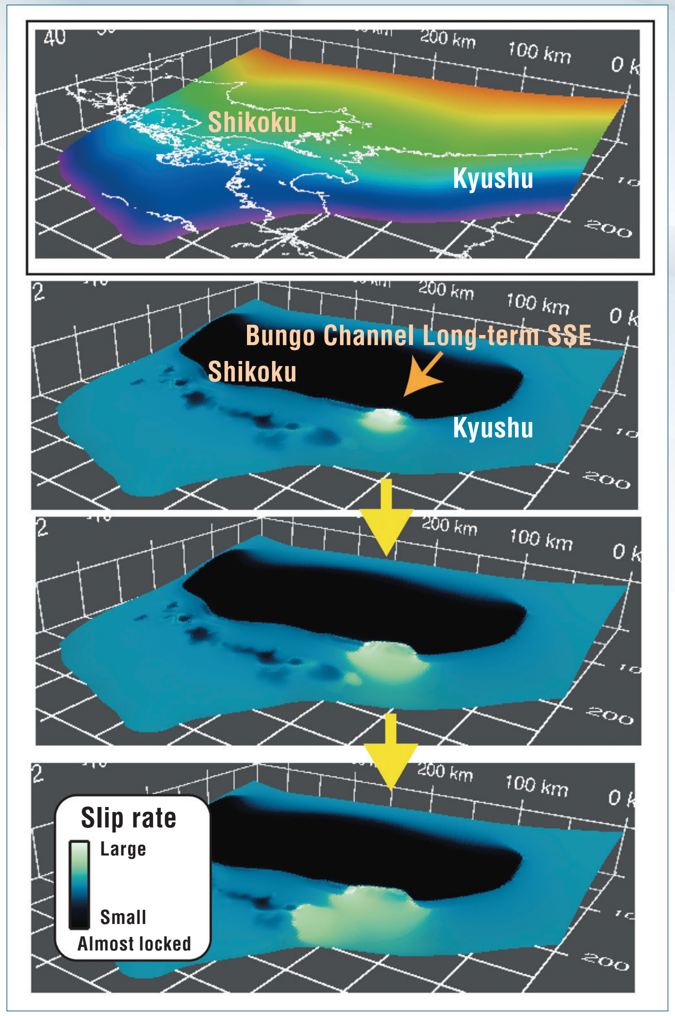


Figure 1. Realistic slow earthquake model in western Japan

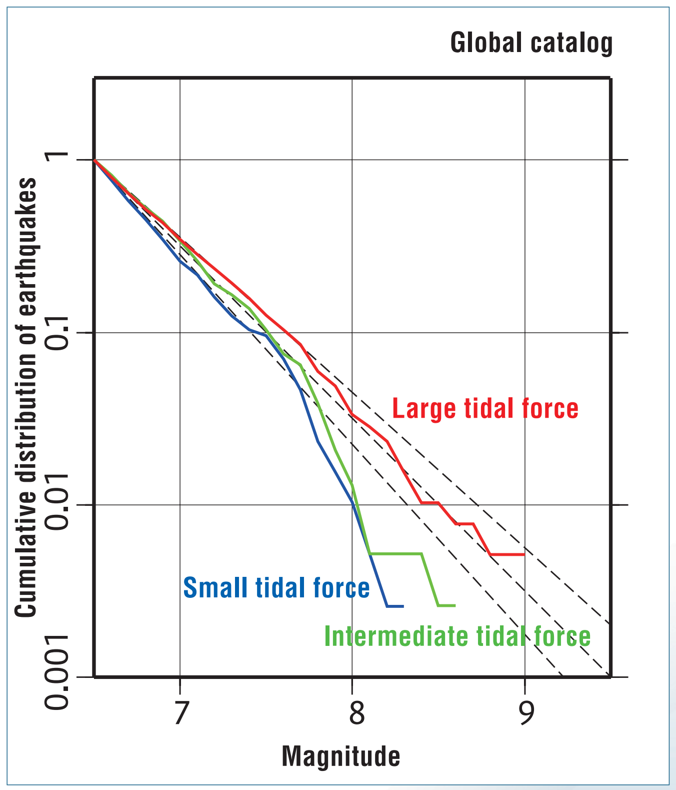


Figure 2. Change in the statistics of earthquake frequency due to tidal stresses.

Physical Modeling Group

Research Group C02

Unified Understanding of Slow and Regular Earthquakes from Nonequilibrium Physics Point of View

More than 15 years have passed since the discovery of tremors. Although the excitement of this discovery has slowly stepped out of the spotlight, the pursuit of understanding the mechanism has emerged as the star of research on slow earthquakes. Perhaps seismologists around the world have already jump-started their research, seeking a unified theory that explains all earthquake phenomena from slow deformations to fast slips.

On the other hand, in nonequilibrium physics, which we believe is foreign to seismologists, is a new approach to understand various forms of friction phenomena. For instance, *in situ* observations in a laboratory friction experiment using a transparent elastic body led to the discovery of complex spatiotemporal dynamics quite similar to slow earthquakes. Moreover, slow slips precede unstable slips; this fact reminds us of slow earthquakes, which precede a mega-earthquake. This kind of switching between slow and fast motions is observed not only in elastic bodies but also in fluid systems. For instance, in the interfacial motion of viscoelastic fluids, fast fracturing motion competes with slow viscous motion. These experimental systems are not identical to slips at the plate boundary, but since elastic bodies and fluids do not have characteristic length constants, an analogy between the experimental systems and a large system may be drawn, in principle.

On the other hand, the laws of friction are an important physics principle for slip phenomena in general. The characteristic length constants may sneak into such phenomena through the surface topography, for example. Although experiments to investigate the friction of rocks have been conducted since the field of geoscience was first established, presently there is no logic available to extrapolate the experimental results from the laboratory scale to the fault scale. In order to apply the results of laboratory friction experiments to a geoscientific scale, we must elucidate the scale dependence of laboratory experimental results, including the laws of friction. With all the aforementioned points duly taken into consideration, we address primarily the following three tasks in this research group (also see **Figure 1**):

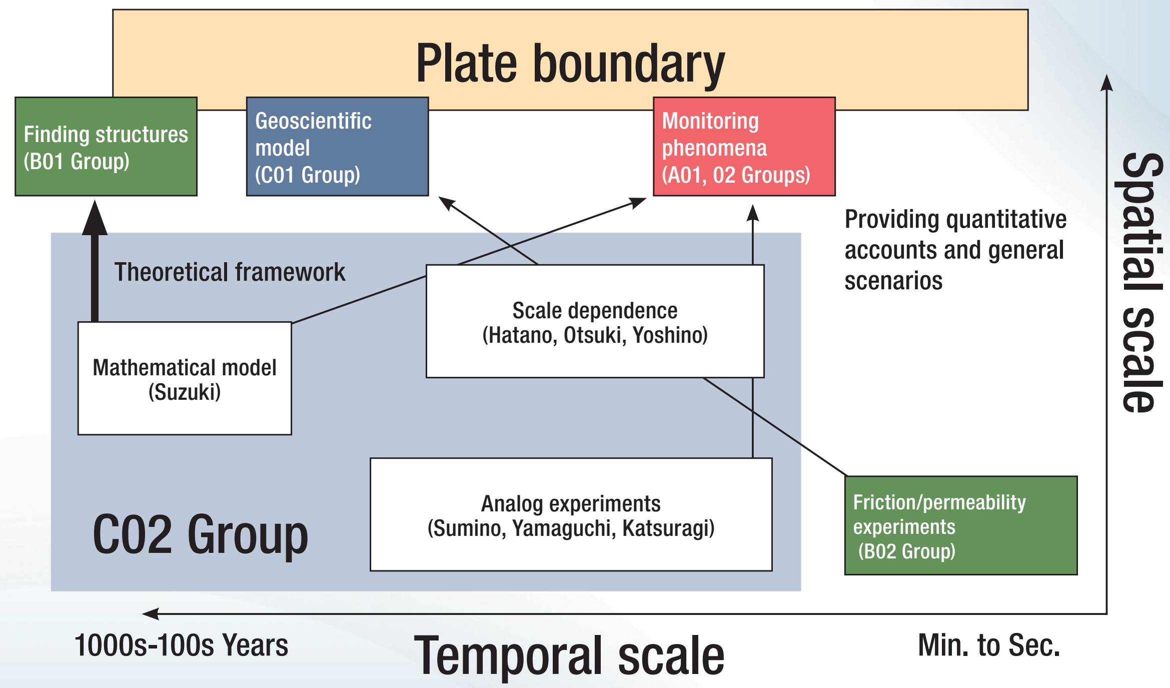


Figure 1. Flowchart of the research collaborations between the C02 group and others.

1 Interaction between Slow and Regular Earthquakes: Laboratory Analog Experiments

Here, the plate boundary is regarded as a system where more than one motion mechanism coexists and/or competes. Each mechanism has a unique time constant (stability). An experimental system with the same characteristics as the plate boundary is constructed. Laboratory experiments allow us to manipulate the parameters of the material property and boundary conditions at will. Taking advantage of laboratory experiments, we elucidate the emerging process of plural motion mechanisms and their competing and/or cooperative phenomena. Examples of such experiments include slip experiments with transparent elastic bodies and interfacial evolution experiments of viscoelastic fluids. Both types of experiments involve *in situ* observations of interfacial motions. These experiments characterize the switching and ramification mechanisms of fast and slow slips quantitatively.

Furthermore, by constructing mathematical models of experimental systems, we strive to extract a universal mechanism that is common to systems where various modes of motion with different time constants or stability compete and/or interfere each other. The goal is to reveal knowledge beyond the analog experiments; that is, to understand the general theory of complex slip dynamics through a mathematical interpretation of various phenomena.

2 Theoretical Research to Fill the Gap between Laboratory and the Plate Boundary.

The existence or nonexistence of characteristic length constants in friction phenomena and the scale dependence are investigated. In particular, the transformation rules to apply the results of both laboratory analog experiments as mentioned above and friction/water-permeability experiments conducted by the **B02 group** to a geoscientific scale are examined theoretically to reveal the relationship between the phenomena observed in the laboratory and those at the plate boundary. This work also provides a foundation in physics and scale dependence of the laws of friction assumed in the geoscientific models developed by the **C01 group**, contributing toward an organic connection among the research groups in this research area.

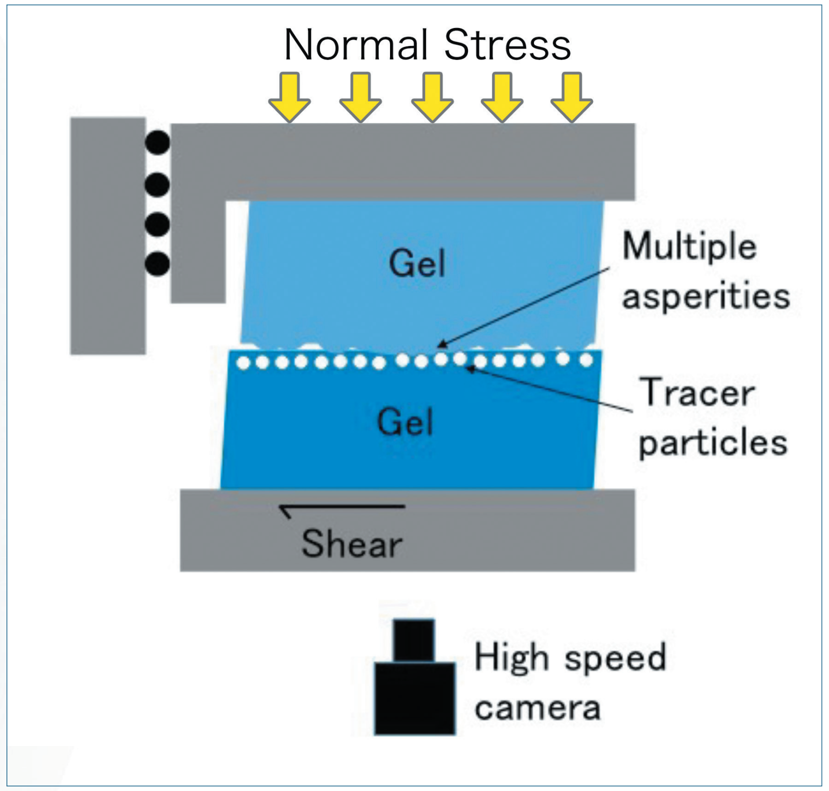


Figure 2. A slip experiment of elastic bodies. Elastic bodies made of a transparent gel allows *in situ* observations of the spatiotemporal dynamics of the slip. The material also facilitates modifications of friction surfaces.

3 Construction and Analysis of a Minimal Mathematical Model Adapted for Actual Physical Conditions at a Plate Boundary

A minimal mathematical model is being developed. The model assumes only three physical parameters: frictional heat due to a slip, formation of microcracks, and fluid movements. The dynamic interaction of these parameters determines the slip velocity in the model. By analyzing the model, we ultimately aim to elucidate a unifying mechanism that governs various earthquakes ranging from slow earthquakes to regular ones. In the meantime, we execute simulations up to a geologic time scale and provide a foundation in physics for the geologic (seismologic and hydraulic) structures determined by the **B02 group** and the rheological structures assumed by the **C01 group**. In this way, we contribute to the goal of this research area.

Our research project is characterized by a somewhat distanced approach from the plate boundary; we emphasize our abstract and mathematical approach. Generally speaking, the closer our model is to reality, the more complex it becomes, leading to difficulties in systematic investigations of, for example, the dependence on parameters. We are caught in a dilemma. Our group makes an effort by going in the opposite direction. By removing as many details as possible, we want to reveal more general dynamics independent of the details.

This kind of abstraction will lead to an emphasis on laboratory analog experiments. People today, however, tend to ignore laboratory experiments in geoscience because the difference in scales makes laboratory experiments seem unreliable. However, if we can elucidate the scaling property through a mathematical understanding of the experimental results, we can raise laboratory experiments to the status of a general model. The theory of physics has evolved through a process of thinking about how the phenomena respond to changes when their scale is enlarged. Transplanting the methodology of physics for the scale dependence to geoscience and establishing a new methodology that connects laboratory experiments to the scale of the Earth will greatly change the future of geoscience.

In the future, we hope to create an interdisciplinary research domain beyond the scope of traditional geoscience. For instance, suppose that the **B02 group** discovers new geologic properties. Further examination of these properties by our **C02 group** from the perspective of condensed matter physics may lead to the development of a material with noble frictional characteristics.

Earthquake-like phenomena are also known in social and economic systems such as stock market and income distribution. Are these phenomena like a slow earthquake? Elucidation of the general dynamics in this research area may lead to an emphasis on the perspective by focusing on the competition between slow and fast events in phenomena from social and economic contexts. Physics is one principle. Geoscientists do not need to be bounded by the Earth.

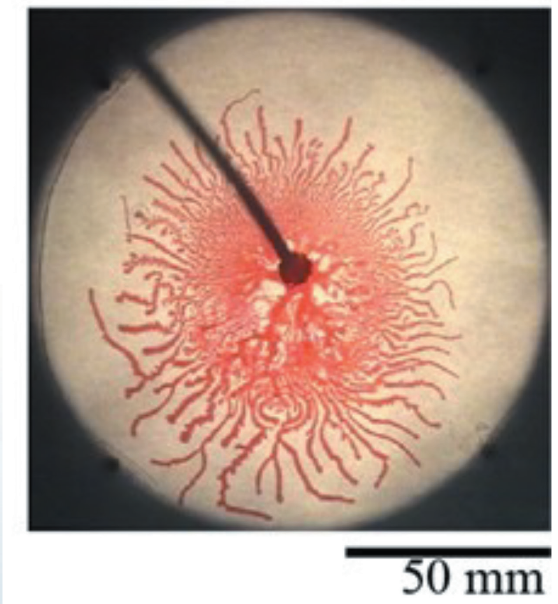


Figure 3. An experiment showing the interfacial evolution of a viscoelastic body. When a viscoelastic body is blown into the interior of a transparent thin quasi two-dimensional cell using a tube, both slow and fast motions evolve simultaneously.

Science of Slow Earthquakes **Activity Report**

09.13 ▶ 09.15
Joint Workshop

Joint Workshop on Slow Earthquakes

A joint workshop on slow earthquakes was held from September 13 to 15, 2016. Various presentations and discussions were held, involving visiting researchers from abroad. At the kickoff meeting held on September 13, leaders of the research groups outlined their projects, which are presented on pages 2–17 in this newsletter. For details of this workshop, visit the website of this research project (http://www.eri.u-tokyo.ac.jp/project/sloweq/). The website also contains introductions of the members in each research project group. We hope you will find our website useful.

Chile-Japan Academic Forum 2016 at Patagonia

Satoshi Ide
(School of Science, The University of Tokyo, C01 Group Leader)

11.07 ▶ 11.11
Patagonia

The Chile-Japan Academic Forum 2016 was held in Patagonia, Chile (South America) from November 7 to 11, 2016. The forum was co-hosted by The University of Tokyo, Universidad de Chile and Universidad Católica. The two-day seismology workshop provided an opportunity for intense discussions about mega-earthquakes, tsunamis, and slow earthquakes. Additionally, the forum provided an excursion opportunity to see a glacier (photograph). Chile is one of the most ideal places to study the relationship between mega-earthquakes and slow earthquakes. A sophisticated research environment has been rapidly organized for seismology researches. For instance, a new seismic observation network has been installed recently. We used this forum as an opportunity to develop future collaborative projects with researchers abroad, and in the domain of Scientific Research on Innovative Areas, various projects are presently in the pipeline.

Report on the Kickoff Excursion

11.11 ▶ 11.13
Mugi, Tokushima

Takahiro Hatano
(Earthquake Research Institute, The University of Tokyo, C02 Group Leader)

The kickoff excursion to the Mugi mélange exposed along the coastline extending from Mugi Town to Minami Town of Tokushima Prefecture was held from November 11 to 13, 2016. The name "Kickoff Excursion of the Science of Slow Earthquakes" may be inappropriate as the 14 participants were mainly members of the **B02**, **C01**, and **C02 groups**. However, if we follow the advice I received multiple times when I took a new post in the Earthquake Research Institute after a career in statistical physics, "Researchers must visit and become familiar with actual sites—especially, those involved in mathematical research!", perhaps members from the **C01** and **C02 groups** should be the first to visit. For some of the participants from the **C02 group**, this was their first encounter of a fault outcrop, which seemingly left a strong impression.

The outcrop that we visited was full of shear structures. We closely examined various geologic structures, including different types of fold structures associated with ductile deformation, pseudotachylites associated with fast deformation, and intrusion of gorges into veins. Personally, it was a great experience to examine dozens of nonplanar structures in the fault ranging from a few centimeters to a few meters. This trip was labeled as the "kickoff" excursion as many other trips are planned in the future. I highly encourage those who could not join this time to participate in the next one. The excursion was also a camping trip, providing a wonderful opportunity for discussions day and night.

Group Photo: Snapshot of all the members on this excursion taken in front of an outcrop of pseudotachylite.

Snapshot of Excursion 1: Intense discussion of the excursion members in front of a fault outcrop that recorded fluidization.

Snapshot of Excursion 2: The C02 group leader, Hatano, climbing a cliff with a rope to closely examine pseudotachylite.

Science of Slow Earthquakes

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