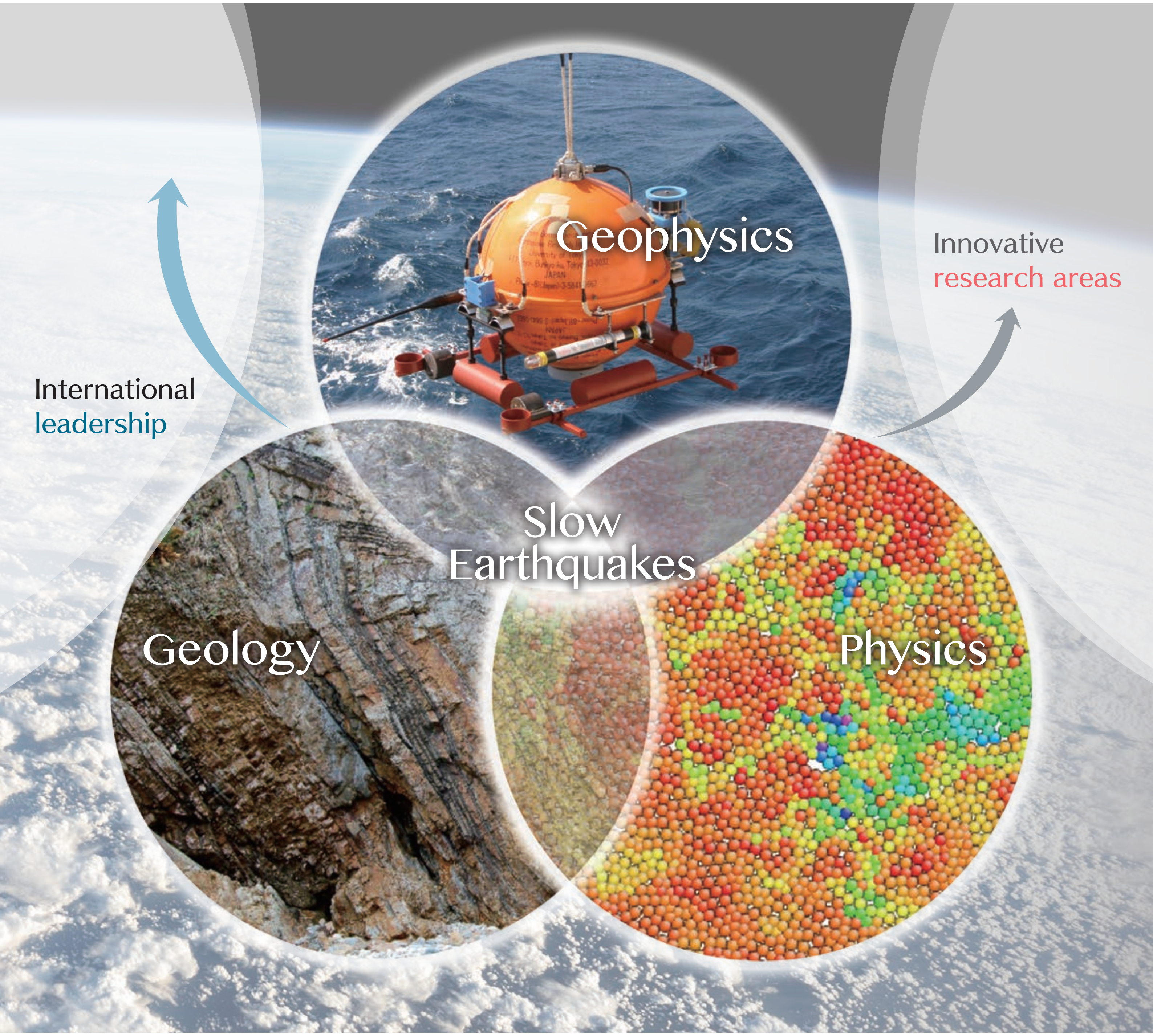
SLOW EARTHQUAKES

Newsletter02



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on Innovative Areas (JSPS KAKENHI No.2804)

INDEX

Introduction to Research in Group A01

Various types of slow earthquakes in the Ryukyu Islands region

Mamoru NAKAMURA, Faculty of Science, University of the Ryukyus

It had been thought that interplate coupling was weak in the Ryukyu Trench, with the Philippine Sea Plate constantly subducting, given the lack of frequent interplate mega-earthquakes. However, recent research has revealed that various types of slow earthquakes are occurring within a predominantly constant subduction setting. Here I explain these various slow earthquakes in the Ryukyu Islands region and consider their meaning.

(A) Slow Slip Events

Slow slip events (SSEs) with a duration of approximately one month have repeatedly occurred at six- to seven-month intervals beneath Iriomote Island, located in the southwest part of the Ryukyu Islands. The magnitude of these SSEs is Mw 6.7 on average. The SSE rupture process shows that the rupture initiating in the northwest, offshore of Iriomote Island, and propagated to surrounding areas. Short-term SSEs, with durations of a few days, are also observed near the Amami and Okinawa Islands, with magnitudes of Mw<6.4.

(B) Very-low-frequency Earthquakes

Very-low-frequency earthquakes (VLFEs), which consist of exceptional seismic signals with dominant periods of 20–50 s, are widespread from the Hyuga-nada region to the Ryukyu Trench. They occur in clusters, with durations of one to a few days, near the Amami and Okinawa islands and the Yaeyama Islands in the Ryukyu Trench. These events occur in each region at two- to three-month intervals.

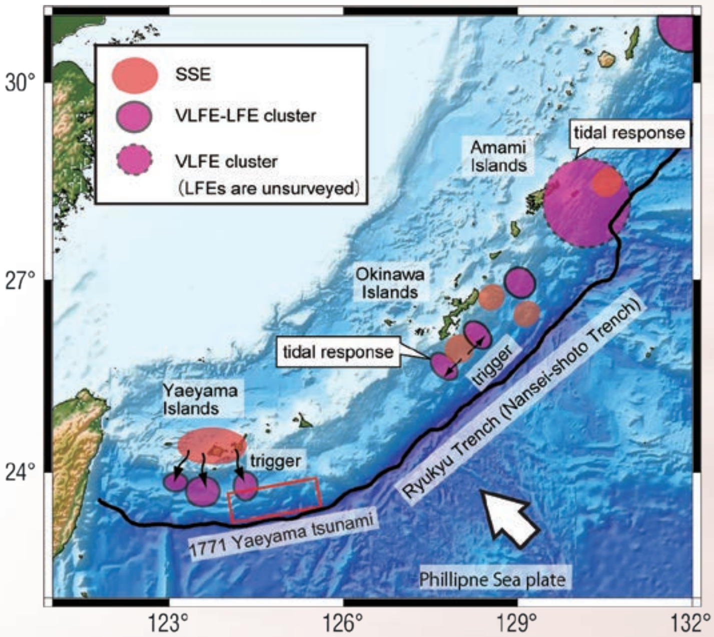

Figure 1. Locations of the various slow earthquakes in the Ryukyu Islands region

These VLFEs are characterized by a tidal response resulting from tidal stress. The seismic activity is greatest at low tide (when the shear stress on the plate is at a maximum). The tidal response is regionally variable, being observed near the Amami and Okinawa islands, but not in the Yaeyama Islands. Furthermore, the tidal response fluctuates with the season and tends to be greater in winter. It is likely to also be sensitive to small stress changes in atmospheric and ocean bottom pressures.

(C) Low-frequency Earthquakes

Low-frequency earthquakes (LFEs) in the Ryukyu Islands are often detected as the high-frequency components of VLFE wave forms when VLFEs are active. Since the magnitudes of these LFEs are in the range of –0.6 to 1.9, it had been believed that these small events would be difficult to detect in the Ryukyu Islands where there is no coverage by the Hi-Net seismic array. However, a short-period seismometer deployed by the Japan Meteorological Agency has unexpectedly detected LFEs.

These LFEs occur in clusters to the south of Okinawa Island and to the south of the islands between Iriomote and Ishigaki. Many of the LFEs detected by the seafloor earthquake observation network along the southwestern part of the Ryukyu Trench occur at the plate interface. These LFEs or low-frequency tremors are sometimes detected with or after the surface waves of teleseismic earthquakes, as observed in other subduction zones.

(D) Discrimination of Slow Earthquakes

It is becoming clear that LFEs, SSEs, and typical reverse fault earthquakes are distinct seismogenic phenomena. This is reflected by the spatial variations in slip conditions along the plate interface. SSEs are often followed by VLFEs and LFEs near Okinawa Island and the Yaeyama Islands, which indicate that the SSE faulting activates the VLFEs and LFEs.

However, a gap is found in the spatial relationship between the SSE faults and areas of LFE occurrence. Near Okinawa Island, the LFEs occur near the SSE faults. However, in the vicinity of the Yaeyama Islands, the LFEs occur immediately beneath the islands, quite far from the SSE faults. It is currently unclear as to what causes this gap.

Although many questions remain on the mechanism of these activities, it is becoming clear that the various slow earthquakes occurring along the Ryukyu Trench influence each other. These slow earthquakes and their associated processes will influence the shallow plate boundaries near the trench axes, as well as the reallocation of interplate stress. For example, the source fault of the 1771 Great Yaeyama Earthquake and Tsunami triggered a mega-tsunami up to ~30 m high across the Yaeyama Islands. As mentioned above, the interplate coupling is weak in the Ryukyu Trench. In the southwest Ryukyu Trench, mega-tsunamis have occurred approximately every 600 years.

It is important to assess the impact of the various slow earthquakes in the surrounding areas on the Ryukyu Islands region. Clarification of the styles of occurrence, mutual interactions, and the key parameters of various slow earthquakes, as derived from observations and numerical simulations, may show how these mega-tsunamis are generated.

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Science of Slow Earthquakes

Activity report

Jan. 13, 2017

Observation group

Activities of observation groups

The first meeting for observation groups was held at the Earthquake Research Institute, The University of Tokyo on January 13th, 2017. It mainly consists of members of Groups **A01**, **A02** and **B01** among which target regions are overlapped. We will hold the meeting on an annual basis to share each group's individual observation methods, as well as observation plans and backgrounds. We believe that inter-field information sharing and cooperation with data analysis groups may bring the better outcomes of our study.

May 20-25, 2017

JpGU-AGU

JpGU-AGU Joint Meeting 2017

JpGU-AGU Joint Meeting 2017 was held from May 20th to 25th at Makuhari Messe, Chiba. Our project took a part in the session "Subduction zone dynamics from regular earthquakes through slow earthquakes to creep." We had 24 oral presentations including invited speakers from overseas (Jessica Hawthorne, Lisa McNeill, Donna Shillington, Matt Ikari, William Frank, Eric Dunham, Onno Oncken). We had 65 poster presentations, the largest number in the Meeting. Global development of the study is expected in the future.

Introduction to Research in Group A02

Detection of shallow SSEs by an onland borehole strain observation network

Satoshi ITABA, Geological Survey of Japan, National Institute of Advanced Industrial Science and Technology (AIST)

1. Introduction

It is known that slow earthquakes occur in both the deeper and shallower regions around the locked zone along the Nankai Trough. The deep slow earthquakes consist of tremors and very low frequency earthquakes (VLFEs) that are detectable by seismological observation methods, short-term slow slip events (SSEs) that are detectable by geodetic observation methods and have durations of up to a few days, and long-term SSEs that have durations of a few months or more. On the contrary, it is obvious from shallow slow earthquakes that tremors and VLFEs occur, but no SSE (herein referred to as "shallow SSE") had been detected until recently due to the difficulty of conducting high-precision geodetic observations in ocean settings.

As of 2017, the AIST has been conducting strain, groundwater, and earthquake observations at 17 drilled wells in the Tokai, Kii Peninsula, and Shikoku regions. The main purpose of the observation network is to understand in detail the activities of deep slow earthquakes that occur beneath the observation network, and we are also conducting detailed monitoring of short-term SSEs using a high-sensitivity borehole strainmeter.

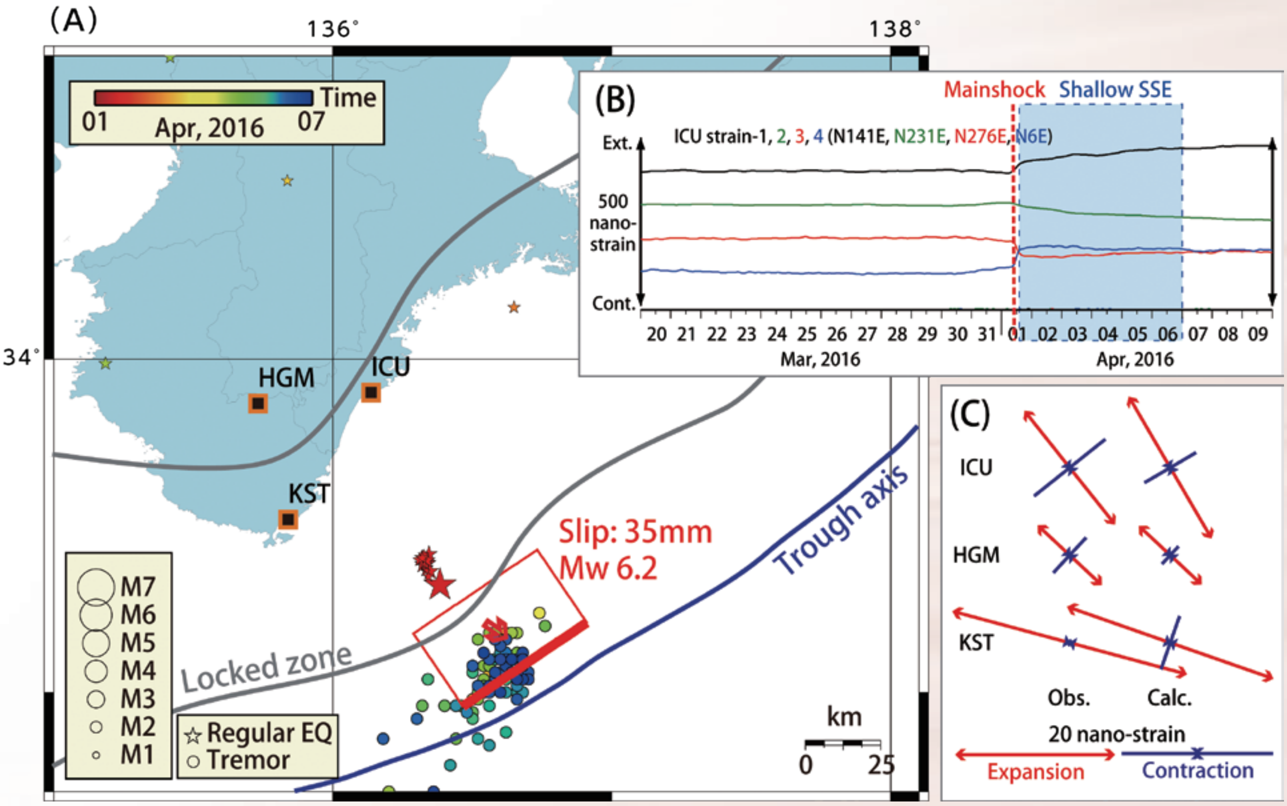

Figure 1.
(A) Map of the estimated fault planes of the shallow SSE observed from April 1 to 6, 2016 (red rectangle), epicenter distribution of shallow tremors (white circles) and regular earthquakes (stars), and locations of the strain observatories used in the analyses. The epicenters of the shallow tremors are from Annoura *et al*. (2017), and the epicenters of the regular earthquakes are from the Japan Meteorological unified catalog. The colors of the epicenters indicate the times when shallow tremors/regular earthquakes occurred, as indicated by the color bar.
(B) Four horizontal strain observation results at ICU before/after the occurrence of shallow SSEs.
(C) Comparison of the observed principal strains at three observatories and the calculations derived from shallow SSE fault models. The estimated fault planes are well able to explain the observed strain changes.

2. Detection of shallow SSEs off the Kii Peninsula

On April 1st, 2016, a M6.5 earthquake (herein referred to as the "mainshock") occurred on the plate interface off the Kii Peninsula. Step-like changes (static strain change) at the time of the earthquakes, followed by slow changes, were observed at three strain observatories within the above-mentioned observation network (Figure 1 (B)). Analysis of these slow strain changes showed that the shallow SSEs had occurred immediately after the mainshock and were also located off the Kii Peninsula (Figure 1 (A)). This is the first detection of shallow SSEs in the region by an onland observation station. According to Annoura *et al*. (2017), the shallow tremor activity at 20–40 km to the southeast (shallow side) of the epicenter of the mainshock were most active. The shallow tremor activity seems to have been triggered by the mainshock, with temporal gaps of 2 days and spatial gaps of ~20 km. However, the above-mentioned shallow SSEs started immediately after the main shock. The slip range extended from the area of shallow tremor activity to the neighboring area of the mainshock, and included both the temporal and spatial gaps between the mainshock and shallow tremors. Hence, it is presumed that the mainshock triggered the shallow SSEs and that they both triggered the shallow tremor. In the introduction to the research plan presented by the A02 geodetic observation team in this newsletter, the spatiotemporal synchrony of tremors and SSEs is expressed as "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 the various types of slow earthquakes." This phenomenon, verified off the Kii Peninsula, is a prime example of SSEs controlling shallow tremor activity.

3. Future directions

Recent sub-ocean-bottom pore pressure monitoring from borehole monitoring systems at two drilling points, installed by the International Ocean Discovery Program, found that shallow SSEs have occurred repeatedly off the Kii Peninsula (Araki *et al*., 2017). As for the event in April 2016, a pore pressure change was observed at one drilling point (monitoring was not being undertaken at the other point at that time), which indicated that the shallow SSEs occurred approximately one and half days after the main shock. In the future, I will actively integrate both the onland (strain, tilt, and GNSS) and ocean observations, such as sub-seafloor pore pressure observations. A key goal will be to clarify the detailed occurrence pattern of these deep and shallow SSEs, and also the interrelation between tremor, VLFEs, and SSEs.

References:
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Science of Slow Earthquakes
Activity report

2017
Overseas researches

Overseas research reports

Three researchers developed their studies abroad in 2017. Saeko Kita, a project assistant professor at Hiroshima University, did researches on relationship between seismic velocity/attenuation structure of Japanese islands and slow earthquakes and occurrence interval of slow earthquakes with Dr. Donna Eberhart-Phillips at University of California, Davis and Professor Heidi Houston at University of Washington from March 4th to 20th. Ryo Kurihara, a D1 student at the Earthquake Research Institute, The University of Tokyo, did researches on tremors triggered by surface waves with Professor Zhigang Peng and Dr. Kevin Chao at Georgia Institute of Technology. Satoshi Katakami, a D1 student at Kyoto University, stayed at Miami University and University of California, Riverside. At Miami University, he discussed engineering issues such as possibility of low frequency tremors triggered by oil mining as well as physical issues with Dr. Mike Brudzinski.

Ryo Kurihara with Professor Zhigang Peng

Introduction to Research in Group B01

Low-frequency earthquake activity on undrained megathrusts

Junichi NAKAJIMA, Department of Earth and Planetary Sciences, School of Science, Tokyo Institute of Technology

The discovery of various types of slow earthquakes or slow slips in a number of subduction zones since the 1990s has advanced our understanding of the universality and diversity of slow-slip phenomena. The deep low-frequency tremors, or low-frequency earthquakes (LFEs), discovered in southwest Japan occur down-dip of the source areas of megathrust earthquakes. These LFEs tend to be triggered by small stress fluctuations caused by either the surface waves of distant earthquakes or earth tides. It is believed that the shear strength of faults is quite low along megathrusts where tremors occur, given the small effective normal stress caused by enhanced pore-fluid pressure, the mechanism of which remains poorly understood. In this report, the correlation between the heterogeneous seismic wave structure and distribution of LFEs reported by Nakajima and Hasegawa (2016) is briefly described, and a model is proposed to explain the enhanced pore-fluid pressure along megathrusts.

Nakajima and Hasegawa (2016) estimated the seismic velocity, attenuation, and anisotropy structures around the megathrust of the Philippine Sea slab, where LFEs occur along a band-shaped area with an along-arc length of ~1000 km, extending from Kanto to Kyushu. The obtained heterogeneous structure was then compared with the locations of the LFEs determined by the Japan Meteorological Agency. Nakajima and Hasegawa (2016) revealed a clear spatial correlation between the heterogeneous megathrust structure and LFEs, where: (1) average or slightly elevated seismic velocities and low attenuation are observed above the megathrust where the LFEs are active, and (2) reduced seismic velocities and higher attenuation are observed in the Kii channel, Ise Bay, Kanto, Izu, and Kyushu, where no, or limited, LFE activity is observed (Figure 1). These results show a marked correlation between the heterogeneity of the overlying plate and the distribution of LFEs that cannot be explained by a conventional

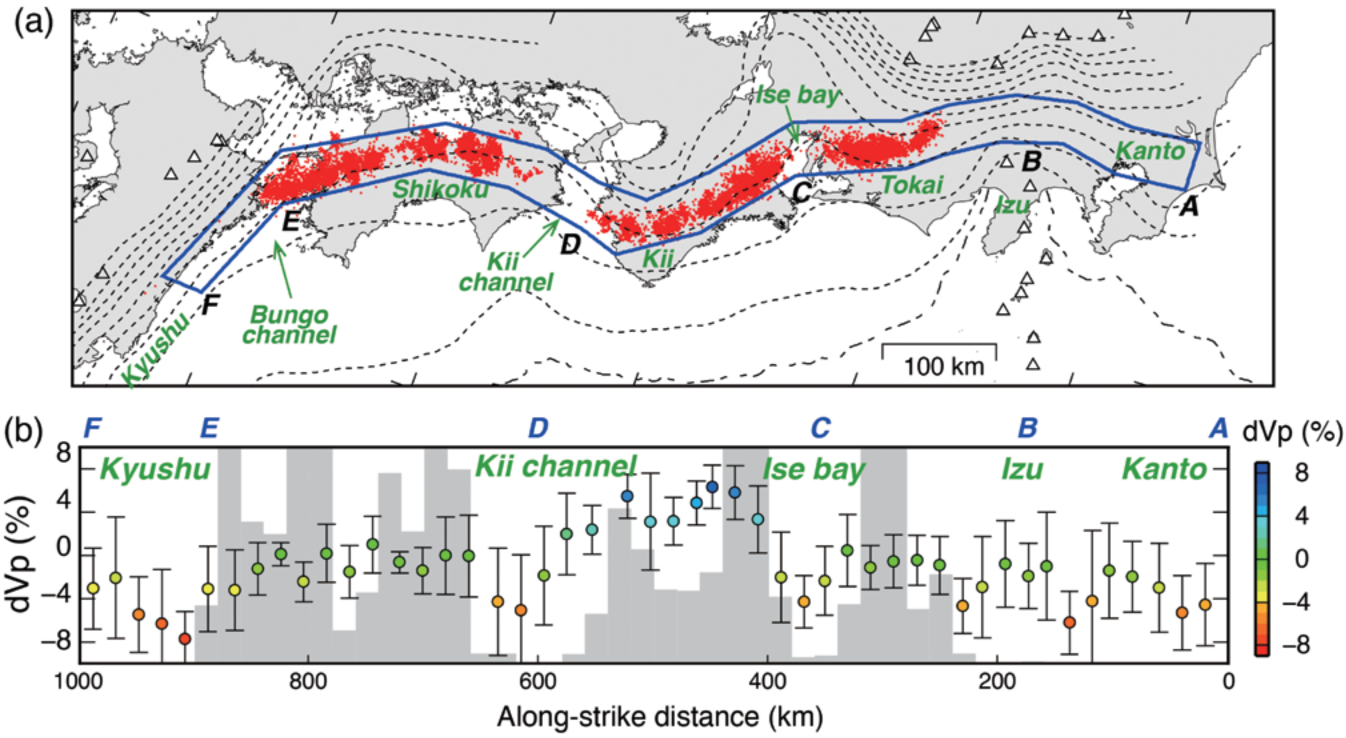


Figure1.
(a) Map of the study area. The epicenters of the LFEs are denoted by red dots. The broken lines denote the depth contours of the upper surface of the Philippine Sea slab, with an interval of 10 km. The seismic wave heterogeneities in the area outlined in blue were calculated and compared with the LFE distribution. (b) Mean value and one standard deviation of the P-wave velocity perturbations (dVp) over the layer located 1–4 km above the megathrust. The values indicate deviations from the average velocity at each depth.

model that links LFE activity along the megathrust to the serpentinized regions of the overlying plate.

Here we propose another model, where the spatial correlation between the heterogeneous structure in the overlying plate and LFE activity is determined by the draining condition above the megathrust, which may be related to the permeability of the overlying plate. No LFE activity occurs along a well-drained megathrust, because there is no build-up of pore-fluid pressure along the megathrust due to the high permeability of the overlying plate. It is therefore likely that the draining fluid metamorphoses the overlying plate, resulting in the observed low-velocity and high-attenuation anomalies (Figure 2b). The movement of fluid into the overlying plate is probably associated with the observed earthquake activity in the overlying plate, below which no, or limited, LFE activity occurs. However, in areas where the megathrust is undrained, the fluid is effectively provided to the megathrust, with little, if any, fluid permeating into the overlying plate. This process may cause LFE activity due to the elevated pore-fluid pressure at the megathrust and the consequent reduction in shear strength of the fault (Figure 2a).

The condition of fluid leakage controlling the pore-fluid pressure does not require certain metamorphic reactions, such as serpentinization of the overlying plate and silica precipitation. Therefore, this model would also explain LFEs (tremors) that are discovered along shallow megathrusts and transform faults. However, the model introduced here hypothesizes that heterogeneous seismic structures result from metamorphism, that the rate of fluid leakage does not vary along the strike of an island arc over geological time scales, and that all the fluid permeating into the overlying plate contributes to metamorphism. Furthermore, the factors that control the drained or undrained conditions at the megathrust are not understood. More detailed structural analyses along the megathrust and quantification of fluid flow at the plate interface are therefore essential to validate the model presented by Nakajima and Hasegawa (2016). Further research on the physical mechanisms of slow earthquakes will be conducted in the future.

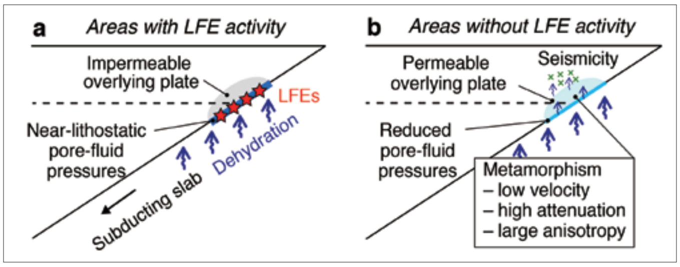


Figure2.
(a) Model of enhanced pore-fluid pressure along the megathrust under undrained conditions. (b) Model of reduced pore-fluid pressure along the megathrust and enhanced metamorphism of the overlying plate under well-drained conditions.

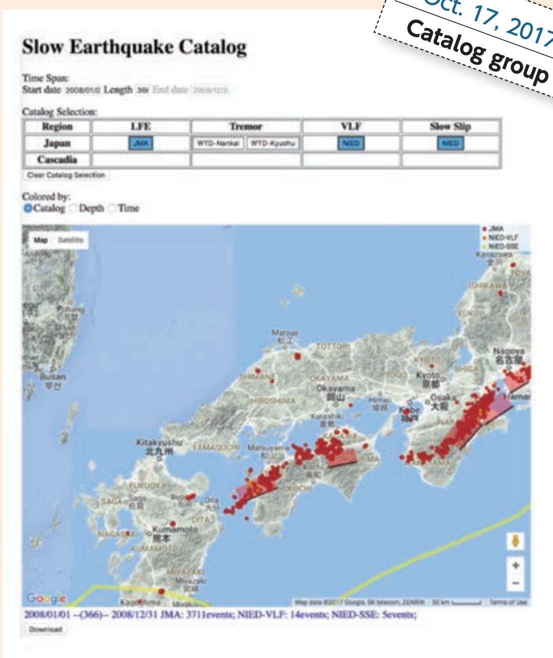
References:
Nakajima, J. & Hasegawa, A., Tremor activity inhibited by well-drained conditions above a megathrust, *Nat. Commun.* **7**, 13863, doi: 10.1038/ncomms13863, 2016.

Science of Slow Earthquakes
Activity report

Activities of the catalog group

"Working group for sharing/releasing slow earthquakes catalog" was organized. Its main purpose is that various slow earthquakes catalogs created by institutions and researchers to be easily compared/downloadable by other researchers.

After the kick-off meeting on October 17th, 2017, website creation was started. Catalog is now available on our website.



Oct. 17, 2017
Catalog group

Introduction to Research in Group B02

Role of slow slip in megathrust earthquakes

Yoshihiro ITO, Disaster Prevention Research Institute, Kyoto University

What impact does slow slip have on the occurrence of massive earthquakes? Examples from recent observations indicate that slow slip has two primary effects on the occurrence of massive earthquakes, as follows: (1) the temporal acceleration of stress accumulation velocity on asperities due to the occurrence of slow slip around the asperities, which triggers earthquakes (i.e., triggering); and (2) the slow slip causes friction weakening on the fault (i.e., acceleration). Previous studies have reported on the effects of (1), whereas little has been done to explore the effects of (2). However, the mechanism of (2) should be carefully examined, because the rupture area at the time of the 2011 Tohoku-Oki earthquake overlapped the area where slow slip had been occurring prior to the massive earthquake. Here we report the results of an investigation of the acceleration of slow slip obtained from a friction experiment using plate boundary material retrieved from 820 m below the sea floor by the Integrated Ocean Drilling Program, Japan Trench Fast Drilling Project, conducted in the Tohoku region (Ito and Ikari, 2015; Ito *et al.*, 2016).

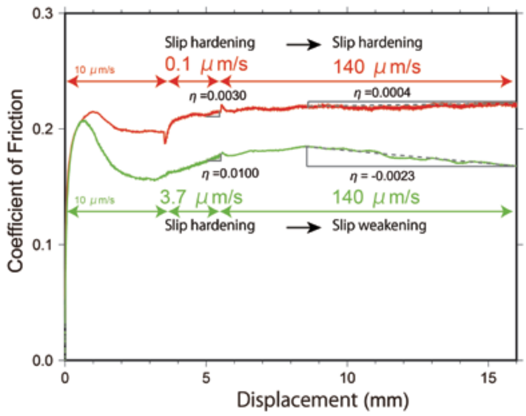


Figure 1.
Examples of friction data. The measurements for *Vo* = 0.1 μm/s and *V* = 3.7 μm/s are denoted by the red curved line, whereas the measurements for *Vo* = 3.7 μm/s and *V* = 140 μm/s are denoted by the green curved line. Both were measured with the slip dependence of friction η, where there was an increase in the coefficient of friction relative to the displacement.

The methods employed for the shear friction experiment are described below. The samples were disaggregated, placed in a cylindrical container, and saturated with sea water. A normal load of 16 MPa was applied to the cylindrical samples, and the samples were sheared at 10 μm/s for 3.5 mm. The shear experiment consisted of a stepped velocity profile, in which the samples were first deformed by an initial velocity *Vo* (2.7 nm/s or 0.1, 1.0, 3.7, or 10 μm/s) and then increased to the final value *V* (0.1, 3.7, or 140 μm/s) (Figure 1). Here we compare the slip dependence of friction with various velocity combinations. In this study, the slip dependence of friction, $\eta = d\mu/dx$, was measured, where μ is the coefficient of friction and x is the displacement.

The η values obtained in this study yielded positive values or velocity strengthening after the velocity step in most cases. Slip weakening was only observed in two cases : (1) at low velocities, where *Vo* = 2.7 nm/s and *V* = 0.1 μm/s; and (2) at *Vo* = 3.7 and 10 μm/s, and *V* = 140 μm/s. Although the mechanism that underlies this slip dependence after the velocity step changes with the initial slip velocity, even if the final velocity is constant, is still unclear, it might be related to the in situ development of specific microstructures, such as scaly fabric.

Two types of slow slip phenomena have been observed in the Japan Trench region within the zone of >30 m coseismic slip during the 2011 Tohoku-Oki main shock. One is an SSE that started one month prior to the main shock and lasted until at least the occurrence of the M7.3 largest foreshock of the 2011 Tohoku-Oki earthquake. The other is an afterslip of the largest foreshock that occurred 51 h before the main shock and continued up to the main shock. The slip rate of the SSE at the shallow subduction interface possibly increased due to the occurrence of the afterslip of the largest foreshock. The slip rates of these events are estimated from the total slip amount, and the event durations are ~0.1 μm/s for the SSE and ~2 μm/s for the afterslip. The slip rate for the SSE might have increased to ~2 μm/s right before the main shock due to the influence of the afterslip in the surrounding area.

Our analysis of the natural Tohoku megathrust gouge yields two key results: (1) slip weakening is observed for the velocity steps from the range of plate convergence rates to that of SSEs, and (2) slip strengthening is observed for velocity steps from the range of SSEs (0.1 μm/s) to higher velocities, while slip weakening is observed for the velocity steps from the 3.7–10.0 μm/s range to the velocities.

The friction instability due to slip weakening in (1) may result in the occurrence of SSEs, whereas the slip weakening in (2) can be interpreted as the initial occurrence of slow slip that accelerated at the time of earthquakes as the afterslip of the largest foreshock. This acceleration to high-speed slip in the slow-slip area might have been enabled by slip weakening generated by the transmission of high-speed slip to the area, where the slip velocity is slightly higher than the normal slow slip.

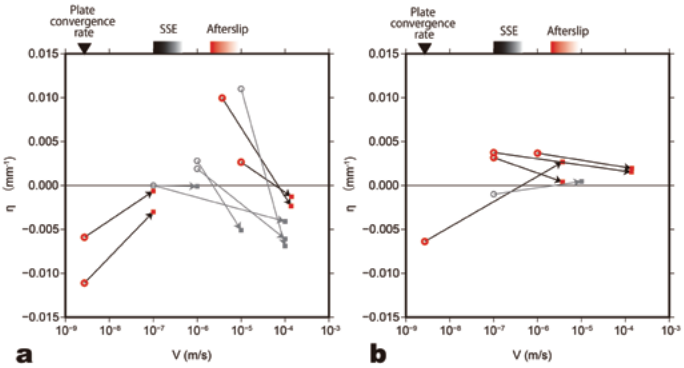


Figure 2.
Change in the slip dependence of friction η before and after the velocity step. η before and after the velocity step is indicated by red circles and squares, respectively, which are connected by arrows. (a) Weakened slip after the velocity step. (b) Strengthened slip after the velocity step. The gray symbols indicate the results of measurements from commercially obtained clay-rich sediment.

References:
Ito and Ikari (2015), *Geophys. Res. Lett.*, **42**, 9247–9254, doi:10.1002/2015GL065829.
Ito *et al.* (2017), *Geophys. Res. Lett.*, **44**, 8749–8756, doi:10.1002/2017GL074307.

Science of Slow Earthquakes
Activity report

Field trip in Okinawa Island

Jul. 7-9, 2017
Okinawa field trip

The field trip to the Shimanto accretionary complex, Okinawa Island took place on July 8th and 9th, 2017 guided by Dr. Kohtaro Ujiie of University of Tsukuba. Participants observed the fold and thrust formed during off-scraping accretion and fault rocks showing velocity-weakening and velocity-strengthening frictional behavior in the Kayo Formation and the deformation structures formed by shearing along the plate-boundary fault and high pore pressure in the Nago Mélange.

Field trip to Sambagawa metamorphic rocks

Sep. 22-23, 2017
Sambagawa field trip

After the joint workshop in Matsuyama city, Ehime prefecture, some participants took part in the field trip to the Sanbagawa metamorphic rocks guided by Professor Simon Wallis of Nagoya University. We observed metamorphic rocks along the Asemigawa river in Kochi prefecture on Day 1 and along the Kokuryogawa river in Ehime prefecture on Day 2. Total of 20 participants included researchers and students both from Japan and overseas with a wide variety of research fields such as geology, non-linear physics, seismology and mathematical statistics. It was exciting to see the hydration and dehydration process in the subduction zone, particularly for those who are not geologists. Active discussions took place on the reaction speed and fluid migration velocity. The findings from the field trip would accelerate multidisciplinary discussions on fluid-rock interaction in source areas of slow earthquakes.

Introduction to Research in Group C01

Precursory slow slip observed during meter-scale rock friction experiments

Futoshi YAMASHITA, National Research Institute for Earth Science and Disaster Resilience

Many of the slow earthquakes discovered in the plate-boundary subduction zones in Japan and around the world are observed in areas that are different from those where ordinary earthquakes occur due to fast slip over asperities and radiate strong seismic waves. Therefore, it was considered that slow and ordinary earthquakes did not occur in the same areas due to the differences in frictional properties associated with different pressure and temperature conditions. However, recent studies based on field observation have reported that some slow earthquakes occurred in areas that later ruptured during large ordinary earthquakes. This suggests that the same fault area can display a wide spectrum of behavior, ranging from slow deformation to fast slip. Furthermore, earthquake nucleation processes has been proposed by laboratory experiments and numerical simulations. During the process, precursory slow slip initiates at a certain part of the fault prior to the earthquake, and expands its slip area at an accelerated rate, and then leads to unstable slip, which suggests a potentially universal characteristic of faults possessing the ability to host both slow and fast slips. Therefore, clarifying the physics of the earthquake nucleation process may lead to a better understanding of the generation mechanisms of both ordinary and slow earthquakes. Here we conducted friction experiments using meter-scale rock specimens to monitor precursory slow slip on fault surfaces at a more realistic scale than in previous laboratory experiments by means of dense measurement arrays.

Figure 1 shows a schematic diagram of the experimental apparatus used in this study. The most significant feature is that a large-scale shaking table is used as a driving force. Since such tables were originally used to investigate the seismic bearing capacity and vibration characteristics of large-scale buildings/structures, they have a high loading capacity and are able to provide fast and long slip loadings. The shaking table used in this study belongs to the National Research Institute for Earth Science and Disaster Resilience in Tsukuba, Japan, and is able to achieve a maximum loading velocity of 1 m/s and a maximum loading displacement of 0.4 m. Such loading conditions enable us to slide meter-scale rock specimens faster and longer, which was hardly feasible in previous friction experiments. As shown in Figure 1 , a pair of meter-scale rock specimens (upper: L1.5 m × W0.5 m × H0.5 m; lower: L2.0 m × W0.1–0.5 m × H0.5 m) is stacked vertically, and the lower specimen is fixed to the shaking table with the frame of the apparatus. The side surface of the upper specimen is supported by a reaction force bar that is fixed to the external base, which is separate from the shaking table. Normal stress is applied by the jacks attached above the upper specimen via a roller. Frictional slip is generated on the simulated fault surface between the upper and lower specimens when the shaking table moves. The shear stress generated on the fault surface is measured by a load cell attached between the reaction force bar and the upper specimen. During the experiments, we record local stress data with a

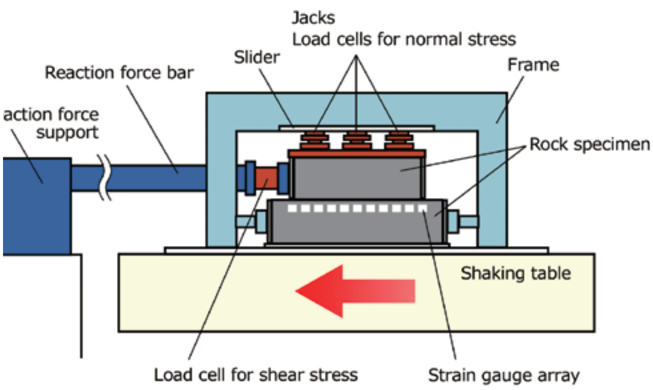


Figure 1. Schematic diagram of the apparatus for the rock friction experiment using a large-scale shaking table

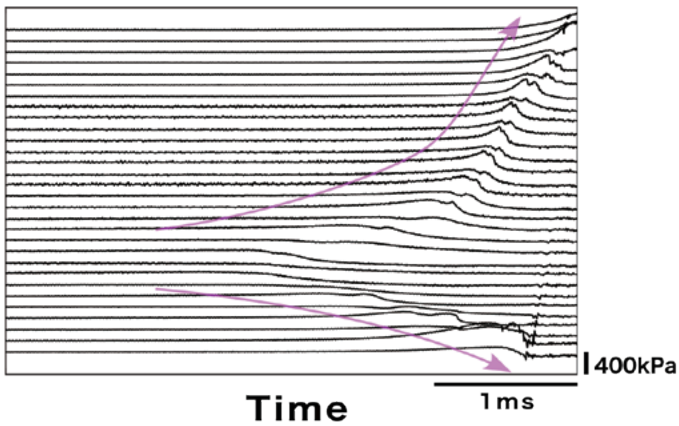


Figure 2. Precursory slow slip observed by a strain gauge array around a stick slip event

strain gauge array installed along the fault, as well as macroscopic mechanical data measured by the load cells.

Figure 2 shows time series of shear stress waveforms for one stick-slip event along the fault that were measured by the strain gauge array. Similar to the conventional nucleation model, the following aspects of precursory slow slip are observed: the slip initiates at a certain part of the fault, and the slip area slowly propagates and then expands at an accelerated rate. For a relatively smooth fault surface, we verified that such slow slip initiated at almost the same area of the fault interface every time. However, real faults are expected to be rougher and more heterogeneous. Therefore, we produced a rough fault surface by repeating the friction experiments using the same pair of specimens and investigated the influence of the fault surface conditions on precursory slow slip. The results show that the locations where slow slip initiates becomes increasingly scattered as the fault becomes rougher, and that the stress drop distribution across the fault is strongly influenced by the location of slow slip initiation, even if the total amount of the stress drop on the fault is similar.

These observations were obtained using specimens whose fault surface was relatively narrow (0.1m), with the local stress measured by a one-dimensional array along the fault strike, similar to that in conventional laboratory experiments. To mimic more realistic propagation processes relating to precursory slow slip, we monitored the stress evolution on the fault surface in two dimensions using a pair of specimens with a wide fault surface (0.5 m) and strain gauges installed into three boreholes beneath the fault surface of the lower specimen. Such an observation using a two-dimensional strain gauge array in the rock specimen is possibly the first attempt in the world. We observed a wide variety of occurrence and propagation modes for precursory slow slip, which also verified that observations made at the fault edge alone might not capture the entire process correctly.

We are planning to further investigate the physics of rupture propagation by employing denser arrays of strain gauges and then comparing the strain data with the observed elastic waves and numerical simulations.

Science of Slow Earthquakes
Activity report

Sep. 19-21, 2017
Joint WS

Joint workshop on slow earthquakes 2017

“Joint workshop on slow earthquakes 2017” was held on September 19th–21nd at Matsuyama city, Ehime prefecture supported by cooperative research programs of ERI, The University of Tokyo and DPRI, Kyoto University. Matsuyama is known for deep low frequency tremors occurring right beneath the city. 130 researchers and students participated in the workshop and presentations from a wide variety of fields (seismology, geodetics, geophysics, geology, nonlinear physics, mathematical statistics, etc.) were conducted.

Introduction to Research in Group C02

Towards an understanding of scaling relations for earthquakes

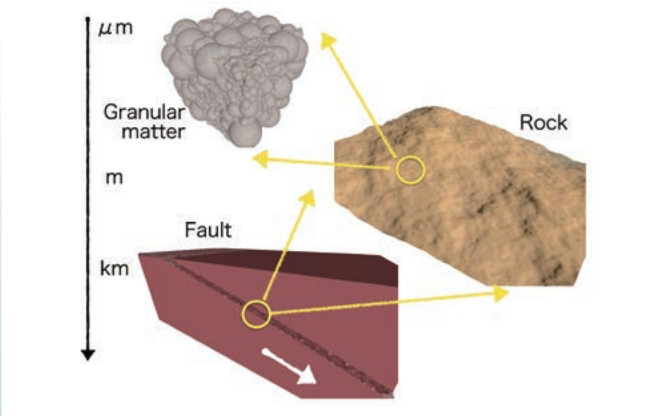
Takahiro HATANO, Earthquake Research Institute, The University of Tokyo

What is the key to comprehending earthquake source processes, including those for slow earthquakes, from a physical point of view? In a classical physics approach, we usually decompose a complicated issue into more simplified sub-issues. Namely, we divide the process into smaller elements and comprehend them on a step-by-step basis. In the case of earthquakes, comprehension of seismological, geological, and electromagnetic structures and physical properties (friction, permeability, etc.) would be such sub-issues. Groups B01 and B02 are working primarily on these sub-issues to identify the physical and electromagnetic structures that influence slow earthquakes. Then, how do we understand the physics of real earthquakes after these sub-issues have been addressed? This question is a research focus of Groups C01 and C02. Here we consider this second question.

Structures and physical properties are closely linked. We first look at physical properties, such as friction and permeability. These characteristics can be examined by laboratory experiments of rocks and core samples. While the size of the sample is generally at the centimeter-scale in laboratory experiments, the fault slip of actual earthquakes can occur over areas of up to several hundreds of square kilometers. Therefore, the spatial scale of actual earthquakes is many orders of magnitude larger than the experimental samples. Given that the plate interface is two-dimensional, the area where earthquakes occur would be a surface composed of 10^{12}–10^{14} experimental samples. This number is less than the Avogadro number, but similar to the number of molecules in a cube of material with sides of 10μm. The phenomena at the molecular-scale and at the 10-micron cube are qualitatively different. Does this also mean that the physical properties obtained in laboratory experiments and those observed and/or inferred in M_w8-scale earthquakes are also distinct? If so, then how can we comprehend earthquakes based on their elementary processes?

Laboratory experiments show that the physical properties of rocks, such as friction, are sensitive to temperature, pressure, and rock type. All of them should be highly heterogeneous across the whole plate interface. Earthquakes at the plate interface are thus fully characterized using the simulation of rupture in such a heterogeneous structure at 10-cm resolution, which is approximately the same size as most experimental samples. The complex slip behavior should arise from these heterogeneous conditions at such a super-fine scale, but there are two problems: 1) For a M_w8-scale earthquake, 10^{12}–10^{14} meshes would needed for such simulations. However, this is impossible due to current computational limitations. 2) The size of the actual plate interface is so large that it is impossible to fully understand the physical properties along the actual plate interface. These two problems may be resolved in the future, but we currently need to find a different approach.

The following road map immediately comes to mind. It is impossible to cut the plate interface into a laboratory-scale mesh, but it is possible to cut it into an observation-scale mesh. The size of the observational mesh is several kilometers. Though the laboratory-scale friction law is being applied to these meshes in most simulations, there is no guarantee that the friction law would hold true for geological materials that are thousands of times larger than the laboratory samples. The characteristics of the system, which are essentially defined by centimeter-scale samples, must be different from those of actual geological material. Our mission is to find a friction law that is theoretically applicable to the plate interface at the scale of several kilometers. A naive approach in this regard is to investigate the system that is heterogeneous at a wavelength of 10-cm. The question here is how to generate 10-cm-scale heterogeneity, as this cannot be derived from observations.



Another difficulty expected in this simple approach is the dynamic instability (chaos) of the system. Here the word 'chaos' means that the behavior of a given system is deterministic and uniquely determined according to the initial and boundary conditions provided, whereas a system with slightly different initial and boundary conditions exhibits a totally different behavior over time. To my knowledge, no previous study has characterized the dynamic fracture of earthquakes as chaos. If this is the case, there would be a serious problem in the prediction of large earthquakes from simulations because this would mean that the simulated earthquakes could show marked variations within a parameter range that is allowed within observation errors. For example, simulations with almost the same parameter set may reproduce M_w6, M_w9, or slow slip earthquakes. The unpredictability of the system is determined quantitatively by the balance between the degree of dynamic instability and the uncertainties in the initial and boundary conditions. It will therefore be necessary to conduct tangible studies on the dynamic instability and unpredictability in earthquake rupture dynamics.

As discussed above, it may be difficult to predict the size of an earthquake occurring at a certain place deterministically, due to the uncertainties in the initial and boundary conditions and dynamic instability (if it exists). Neither the timing ("when") nor the size of earthquakes are predictable. Then, is there a suitable approach to comprehending earthquakes and their processes?

One guiding principle is the statistical inference: to make an unbiased presumption on what is unknowable. Any results must be stated on a statistical manner. This is similar to assuming the principle of equal a priori weights (no bias presumption) and finding the probability distribution of the physical quantities to determine its statistical likelihood. When we study earthquakes, we apply a statistical distribution to what is unknowable about earthquake occurrence (short-wavelength heterogeneity, stress field, etc.) and statistically discuss the distribution of the factor of interest (earthquake behavior and occurrence). This, for example, is how we discuss the "probability of a M_w8 or greater earthquake at the moment." It is therefore necessary to deepen our understanding of the degree of dynamic instability of dynamic fracture along faults as well as to develop a large-scale (coarse-grained) friction law.

Science of Slow Earthquakes
Activity report

Feb. 21-22, 2017
C01/C02 joint WS

Workshops/seminars by physics groups

Many workshops and seminars are actively organized for further interactions and better understandings between **Group C02** and the other research groups.

C01/**C02** joint workshop was held at Kyushu University, Fukuoka city, on February 21st–22nd, 2017. Dr. Ahmed Elbanna of the University of Illinois, who studies laws of friction in granular materials, gave a keynote lecture there. Dr. Elbanna spent one month in Japan for our project. In the workshop, total of 14 lectures were given introducing leading-edge and interdisciplinary studies on slow earthquakes: tremor observation, mathematical modeling, and large-scaled rock experiments.

In 2017 "**Group C02** seminar" took place every few months welcoming various speakers: Dr. Ryohei Seto (OIST), Dr. Osvanny Ramos (University of Lyon), Dr. Takehito Suzuki (Aoyama Gakuin University) and Dr. Naofumi Aso (University of Tokyo).

C01/C02 joint workshop [Feb. 21, 2017]

Newly open! Slow Earthquakes Café

"Slow Earthquakes Café" opened in March, 2017. It is a seminar by speakers from various fields within or outside of the project for better understandings on slow earthquakes. Another important purpose of this "Café" is to enhance the inter-disciplinary collaborations. Participants enjoy talks in a relaxed atmosphere over soft drinks and snacks. In 2017, we had 6 times of such "Café" as below.

March 30th

"Ask not what seismology can do for physics, ask what physics can do for seismology" by Dr. Takahiro HATANO, the Earthquake Research Institute, The University of Tokyo

June 15th

"Spatio-temporal relationship among various phenomena of slow earthquakes: Examples in Tohoku and Hyuganada subduction zones" by Dr. Naoki UCHIDA, Tohoku University

July 20th

"Dynamic triggering of tectonic tremor: What are the similarities and differences between triggered and ambient tremor?" by Dr. Kevin CHAO, Northwestern University

July 29th

"The spectrum of fault slip behaviors and the mechanics of slow earthquakes: A View From The Laboratory" by Dr. Chris MARONE, Pennsylvania State University

September 8th

"Fast and scalable implicit finite element solver for solid earth science-towards application to slow earthquakes-" by Dr. Tsuyoshi ICHIMURA, the Earthquake Research Institute, The University of Tokyo

November 9th

"Towards construction of simple experimental model system for slow and regular earthquake–Introduction from reduction of spring-block model" by Dr. Yutaka SUMINO, Tokyo University of Science

On July 29th, 2017 we invited Dr. Chris Marone of Pennsylvania State University to Kobe University to give a talk in our café. This was the first café in the Kansai region. As the discussions were very active, the entire seminar took almost 3 hours with an unplanned coffee break.

Science of Slow Earthquakes

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Publisher/Contact

Office for Scientific Research on Innovative Areas:
Science of Slow Earthquakes
1-1-1 Yayoi, Bunkyo-ku, Tokyo, JAPAN 113-0032
(within the Earthquake Research Institute)
TEL: +81-3-5841-2956
E-mail: sloweq-office@eri.u-tokyo.ac.jp

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http://www.eri.u-tokyo.ac.jp/project/sloweq/en/