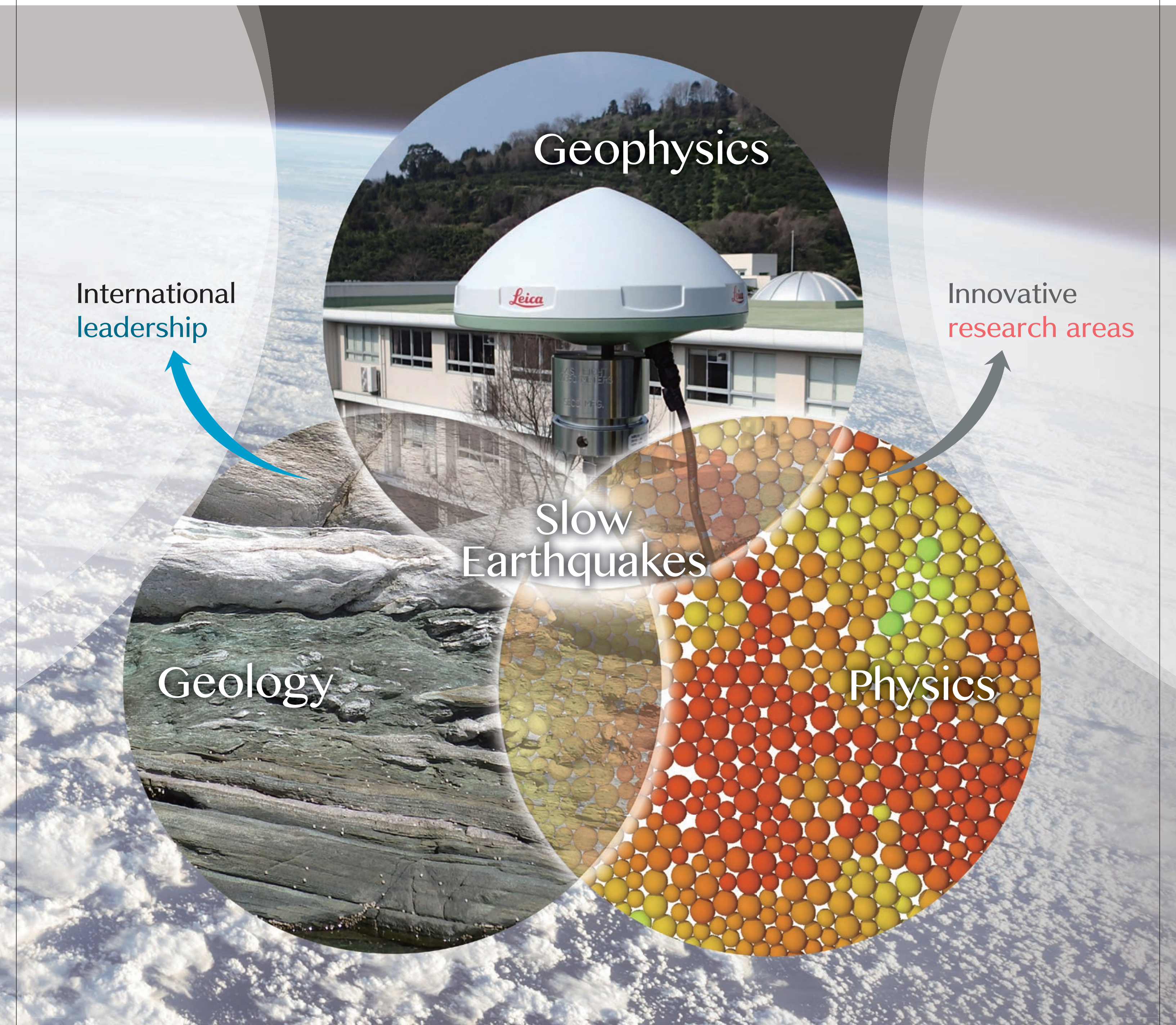
SLOW EARTHQUAKES

Newsletter03



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INDEX

Science of Slow Earthquakes **Activity report**

Introduction to Research in Group A01

Migrations of slow slip and slow earthquakes in SW Japan

Naoki UCHIDA, Graduate School of Science, Tohoku University

In the offshore areas of the Bungo Channel and Kyushu, Japan, simultaneous shallow very low-frequency earthquakes (VLFEs) and deep long-term slow slip events (SSEs) were observed in 2003 and 2010 (Hirose *et al.*, 2010). This suggests a relationship between the shallow and deep phenomena. The search for long-term SSEs (Introduction to Research in **Group A02**, this newsletter) also suggests along-trench migration of slow slip below the seismogenic depth (**Figure 1**). In this study, we identified small repeating earthquakes in southwestern Japan and estimated the spatio-temporal changes in the slow slip. We then investigated the relationship between slow slip and other slow earthquakes in the study area.

Repeating earthquakes occur small seismic patch on a fault whose slip is predominantly aseismic. The cumulative slip of these repeaters represents the aseismic slip history of the fault. In this study, we selected repeaters using waveform similarity at each Hi-net station in Kyushu and Shikoku. As a result, we find that repeaters are distributed at depths of 15–30 km offshore from Kyushu (**Figure 1a**). Their source regions are complementary with the source regions of deep non-volcanic tremor (Obara *et al.*, 2010), shallow VLFEs (Asano *et al.*, 2015), and areas of large interseismic slip deficit (Yokota *et al.*, 2016).

Temporal changes in slow slip are estimated for several locations from repeater data (**Figure 1c**). We find that slip rate increased before the 2003 and 2010 long-term SSEs at the Bungo Channel. Slip rate increases are clear for deep repeaters (**Figure 1c, regions d and e**) and are consistent with the timing of long-term SSEs (**Figure 1b and c, inverted triangles**; *see also* Takagi *et al.*, 2019, Introduction to Research in **Group A02**, this newsletter).

The cumulative slip of repeaters also suggests a short-term increase in slip at the time of long-term SSEs in Bungo Channel in 2003 and 2010 (**blue ellipsoids, Figure 1c**). The 0.2-year result at the time of the 2010 events show the short-term activity including other slow earthquakes seem to migrate for ~1 month along ~300 km of the plate boundary (**Figure 2**). This

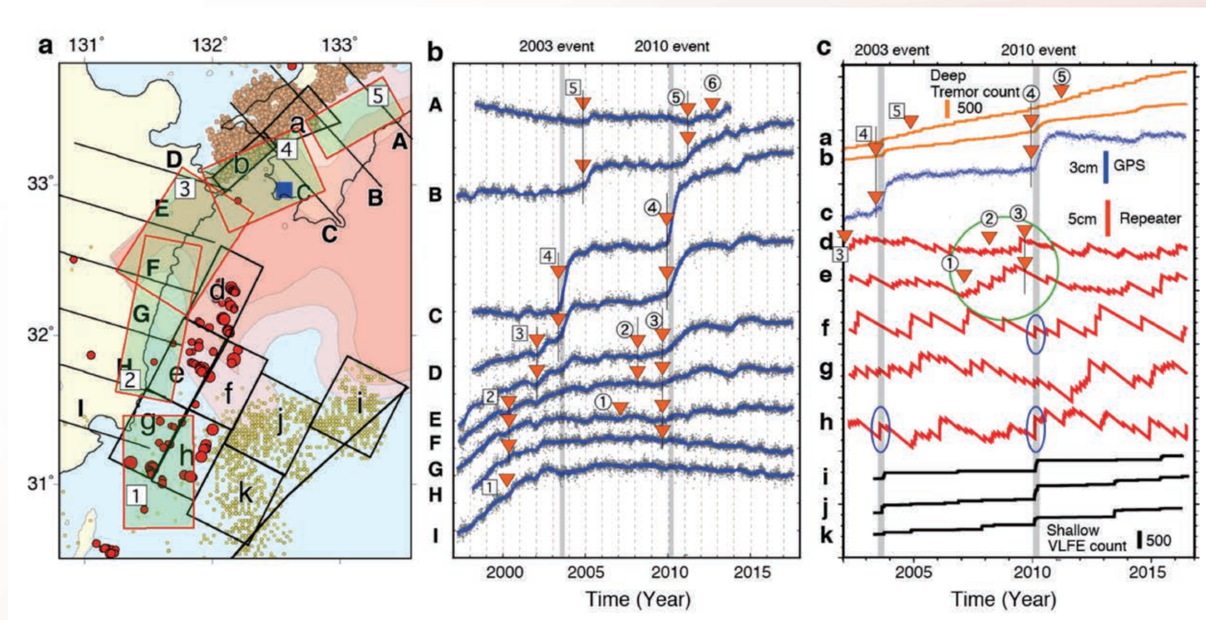

Figure 1. (a) Distribution of repeating earthquakes (red circles), 2000–2004 long-term SSEs (green squares), deep non-volcanic tremors (orange circles), shallow VLFEs (yellow circles), and interpolated slip deficit (pink). (b) Averaged GPS displacement along lines A–H. (c) Cumulative number of non-volcanic tremors, displacement of a GPS station, detrended cumulative slip of repeaters, and cumulative number of shallow VLFEs shown.

suggests the migration of slow earthquakes and interaction between slow earthquakes across a large area along the plate boundary.

In summary, the present study identifies two types of slow earthquake migration: deep long-term SSE migration over several years, and shallow-to-deep SSE migration over ~1 month. Since these migrations occurred at the periphery and south of large, seismically locked areas offshore from Shikoku, they probably resulted in a non-steady stress increase in the locked areas.

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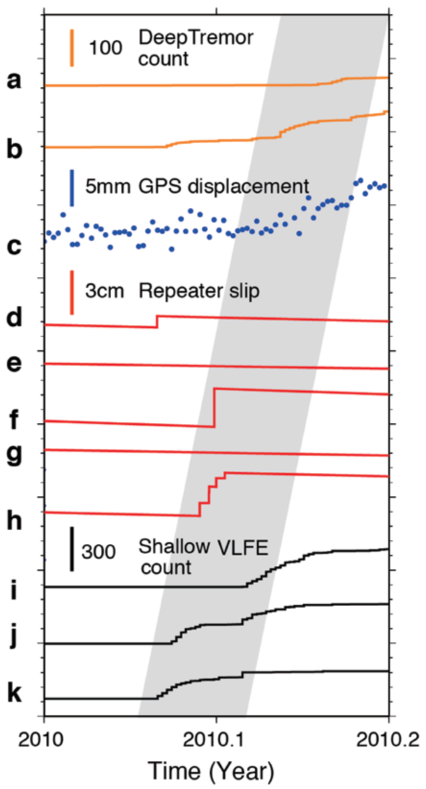


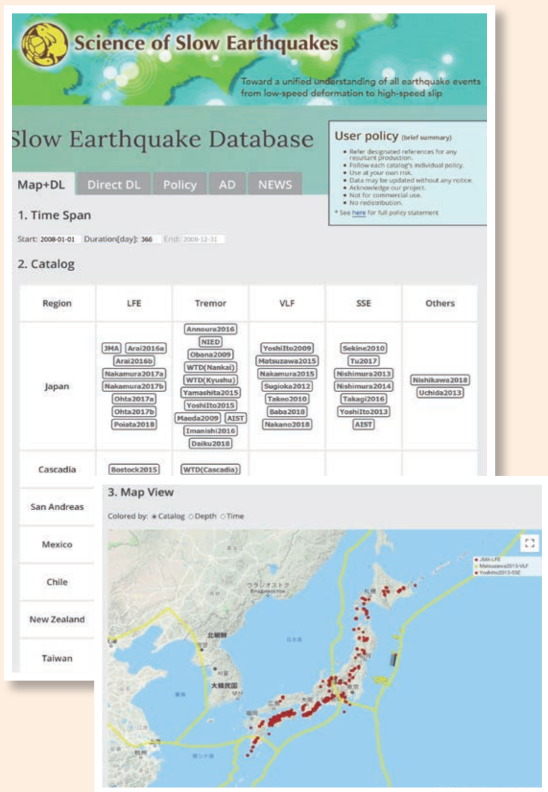
Figure 2. As in **Figure 1**, but for 2010.0–2010.2. Shaded area indicates a possible migration.

Science of Slow Earthquakes Activity report

Slow Earthquake Database

Takanori MATSUZAWA, NIED

The Catalog Working Group has compiled catalogs of slow earthquakes from many published studies and has operated the "Slow Earthquake Database" website since December 2017 (Kano, Aso, *et al., SRL*, 2018). The "Map+DL" page on this site (*see also* Figures) enables us to display the locations of various slow earthquakes in selected catalogs, and window and download catalogs in a standardized data format (Figure: An example of use of the catalogs in 2011 by Ito *et al., Tectonophys*., 2013, Katsumata and Kamaya, *GRL*, 2002, and Matsuzawa *et al., GRL*, 2015). The downloaded data should be useful to generate custom figures with other data, while following our general and individual catalog policies for data use. Twenty-nine catalogs were available when the website launched; as of November 2018, 46 are now available from the "Map+DL" page. If you have newly published slow earthquake catalogs, we welcome your contribution to the Slow Earthquake Database.



http://www-solid.eps.s.u-tokyo.ac.jp/~sloweq/

Introduction to Research in Group A02

Spatial relationship between slow slip events and interplate locking on megathrusts

Ryota TAKAGI, Graduate School of Science, Tohoku University

Slow slip events (SSEs) are located in the neighboring regions of megathrust earthquakes on subducting plate interfaces. The spatial proximity implies a stress interaction between megathrust earthquakes and SSEs. Some observed SSEs preceding and/or hastened by major earthquakes may be examples of the stress interaction. Since SSEs repeat after relatively short time intervals, spatiotemporal variations in SSE characteristics can be studied to improve our understanding of the relationship and interactions between SSEs and megathrust earthquakes. Here, we report a spatial relationship between SSE activity and interplate locking based on a newly developed catalog of SSEs in the western part of the Nankai subduction zone (Takagi *et al*., 2019, in revision).

A catalog of SSEs is generated by a newly developed method called GriD-SSE (Grid-based Determination of Slow Slip Events), which systematically detects SSEs and determines their fault parameters by fitting modeled displacement time series to observed GNSS time series. Here we focus on so-called long-term SSEs, which have the longest durations and largest magnitudes of slow earthquakes. GriD-SSE enables us to systematically detect long-term SSEs, which have been previously studied by visual detection and individual slip inversions.

Applying GriD-SSE to 20-year displacement data from GEONET, we detected 24 Mw 6.0–7.0 long-term SSEs, 11 of which have not been previously documented (**Figure 1**). The long-term SSEs are segmented along strike into four regions: southern Hyuga-nada, northern Hyuga-nada, Bungo Channel, and western Shikoku. The along-strike variations in SSEs appear related to the distribution of updip interplate locking. Less-frequent SSEs with small total slip amounts in western Shikoku and northern Hyuga-nada are located downdip of two strongly locked asperities, which correspond to the 1946 Mw 8.3 Nankai megathrust and 1968 Mw 7.5 Hyuga-nada earthquakes, respectively. Frequent SSEs with large total slip amounts in Bungo Channel and southern Hyuga-nada are located downdip of the gap between the two locked

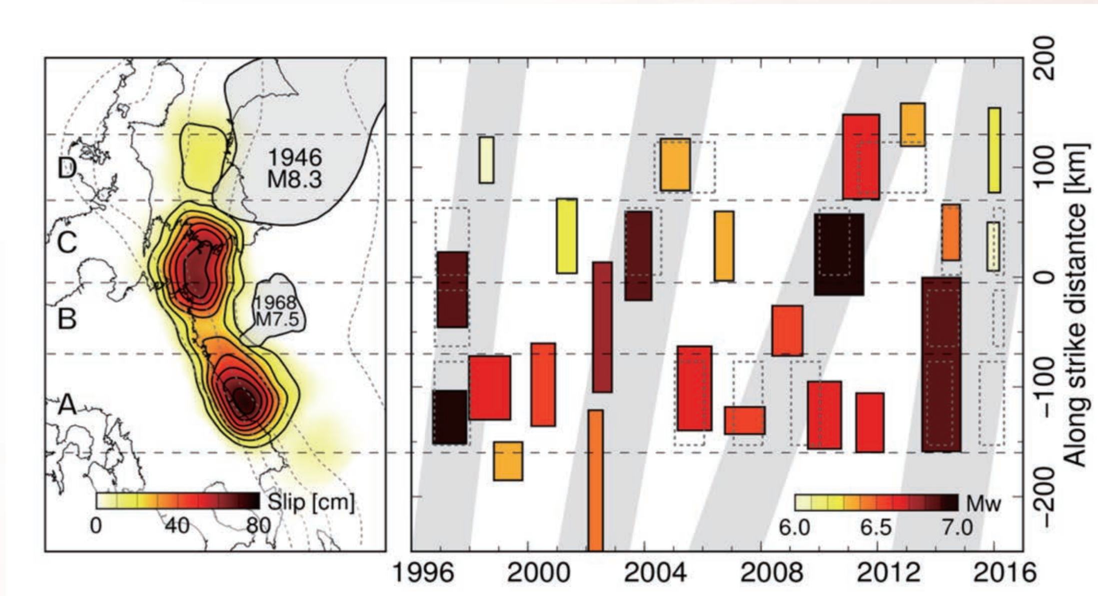


Figure 1.
(a) Cumulative slip of long-term SSEs, 1996–2017. A: southern Hyuga-nada, B: northern Hyuga-nada, C: Bungo Channel, and D: western Shikoku. Gray areas indicate coseismic slips of the 1946 Nankai and 1968 Hyuga-nada earthquakes. Dashed lines indicate isodepth contours of the subducting plate interface. (b) Space–time plot of long-term SSE activity. Colored rectangles are SSEs from our new catalog and gray dashed rectangles are SSEs from previous works. The gray shaded regions highlight the potential along-strike migration from southern Hyuga-nada (region A) to western Shikoku (region D); see also Introduction to Research in Group A01 (this newsletter).

asperities and a stable sliding region, where interplate coupling is relatively weak.

A similar spatial relationship can be observed between downdip SSEs and updip interplate locking in other megathrusts (**Figure 2**). Long-term SSEs are located downdip of weakly coupled segments and at the downdip edges of strongly coupled segments. This relationship can be explained by the stress shadowing effect due to locked segments. Strongly locked patches reduce the stress loading rate just downdip of the locked patches, resulting in longer SSE intervals and small amounts of total slip. In contrast, frequent SSEs with large total slip amounts could originate downdip of low-coupling segments with relatively high stress loading rates. Although segmented SSEs have only been attributed to environmental causes that change fault strength, a mechanical origin, such as a heterogeneous distribution of locked asperities, could also be partly responsible for SSE segmentation.

The spatial relationship between updip locking and downdip SSE activity implies that the temporal variations in long-term SSE activity are due to temporal changes in the locking state of the megathrust. Numerical simulations predict shortening of SSE recurrence intervals as the locked region shrinks, based on a rate-and-state friction law. Therefore, SSE activity can be an indicator of interplate locking and potentially a key to estimating the impendence of megathrust earthquakes.

References

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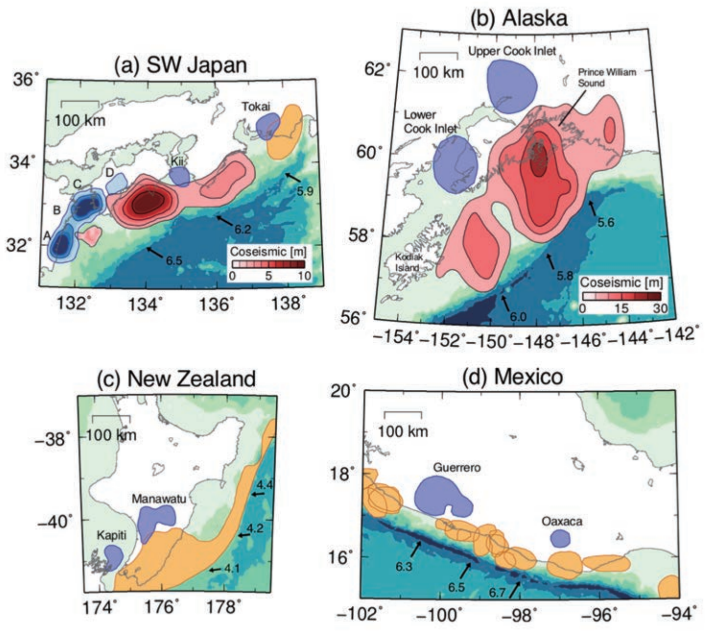

Figure 2.
Distribution of long-term SSEs (blue) and locked patches (red or orange) in (a) SW Japan, (b) Alaska, (c) New Zealand, and (d) Mexico.

Science of Slow Earthquakes
Activity report

Seismological Society of Japan (SSJ) Summer School 2018

Yuta MITSUI, Shizuoka Univ.

Sep. 5-6, 2018
SSJ summer school

An event titled "Seismology Summer School 2018: Slow Deformation", organized by the Seismological Society of Japan (SSJ) and co-organized by the Science of Slow Earthquakes project, was held at Hamamatsu City, Shizuoka, Japan from 5–6 September 2018. The workshop hosted five lecturers, including four participants in the Science of Slow Earthquakes project (Dr. Obara, the principal investigator; Dr. Tanaka of **A02 group**; Dr. Fukuyama of **C01 group**; and Dr. Morishige of **C01 group**), and nearly 30 attendees. Lecturers discussed state-of-the-art topics including current seismic and geodetic observations, frictional rock experiments, and deformation and flow of Earth materials. Many participants were students who received travel expense grants from the Science of Slow Earthquakes project. The event provided strong intellectual stimulation for master's and undergraduate students from many universities, some of whom have few opportunities to listen to expert lectures. The event was conducted in a "camp" style, including poster presentations. Attendees continued their exchanges after a barbecue reception party in the evening.

Introduction to Research in Group B01

The source region of deep LFEs

Katsuhiko SHIOMI

National Research Institute for Earth Science and Disaster Resilience

In southwest Japan, deep low-frequency earthquakes (LFEs) occur often along the subducting Philippine Sea Plate (PHS). Recently, the Cabinet Office introduced the anticipated megathrust source region along the Nankai Trough (Cabinet Office Japan, 2011). Its down-dip limit was determined based on the epicenter distribution of LFEs. LFE activity is among the most important phenomena related to megathrust earthquakes. To investigate the spatial relationship between LFE activity and subsurface structure in western Shikoku, the National Research Institute for Earth Science and Disaster Resilience (NIED) installed 30 seismographs for one year beginning in February 2014 (**star symbols in the map in Figure 1**). These observations were supported by MEXT's "Research Project for Compound Disaster Mitigation on the Great Earthquake and Tsunamis Around the Nankai Trough Region". In this report, we present the results of a receiver function (RF) study along the seismic survey line in western Shikoku (**Figure 1**).

When a seismic velocity interface, such as the Moho, exists beneath a seismograph, part of the direct *P* phase is converted to an *S* phase at the interface. Based on the arrival time difference between this converted *Ps* phase and the direct *P* phase, we can estimate the distance from the seismograph to the interface. The azimuthal dependence of *Ps* amplitudes is strongly related to the dip direction of the interface and/or anisotropy beneath the station. RF analysis emphasizes *Ps* phases within a teleseismic record by deconvolving the vertical waveforms from the radial and transverse components.

The right panel in Figure 1 shows a vertical cross-section of the radial-component RF amplitude. When a direct *P* comes from the up-dip direction of a dipping interface, the *Ps* amplitudes converted at the interface are smaller than those from other directions. Fifty percent of teleseismic events used in this study were in the southeast of the study region, which corresponds to the up-dip direction of the subducting plate. To enhance the *Ps* amplitudes converted at the plate-related velocity boundary, data from the southeast direction were excluded from the cross-section in **Figure 1**. Positive RF amplitudes, shown in red, indicate the existence of a velocity interface at depth, where the deeper part has a higher velocity than the shallower part; negative amplitudes, shown in blue, indicate the opposite. In the figure, the red inclined line from *A* to *B* is very clear. As normal earthquake activity (black dots) is distributed along this line, we conclude that this line denotes the oceanic Moho. A blue line that is 10 km shallower than the red line runs subparallel to it and can be detected to a horizontal distance of 60 km; this corresponds to the upper surface of the subducting plate. Precisely determined LFE hypocenters by Ohta and Ide (2011), plotted as

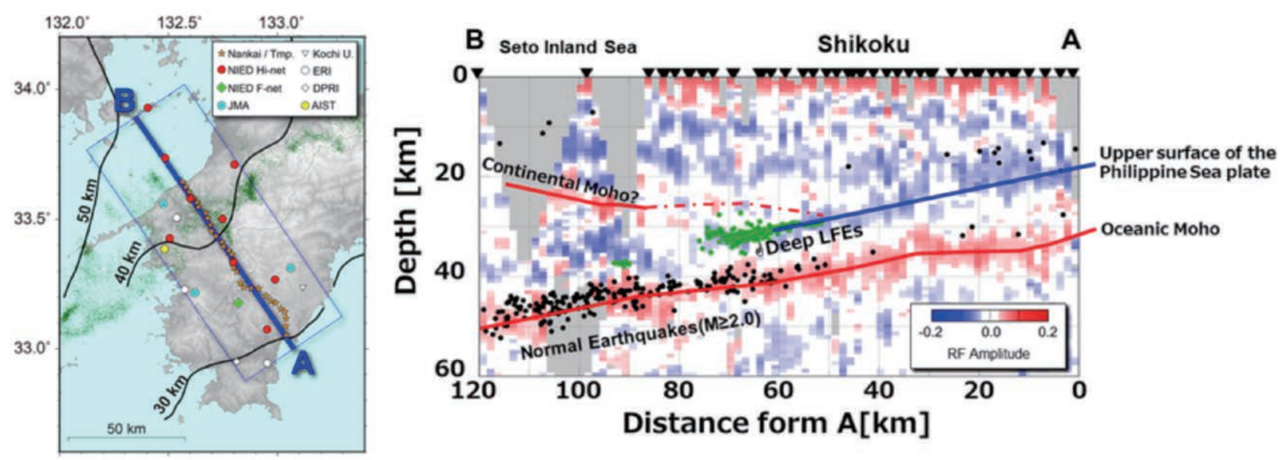

Figure 1. Left) Study region and stations used in this study. Green dots and black lines indicate the epicenters of deep low-frequency tremors (Maeda and Obara, 2009) and iso-depth contours of the oceanic Moho within the Philippine Sea Plate (Shiomi *et al.*, 2008), respectively. Right) Vertical cross-section of receiver function amplitudes along survey line A–B. Green and black dots denote the hypocenters of low-frequency earthquakes determined by Ohta and Ide (2011) and normal earthquake hypocenters determined by the JMA, respectively.

green dots, are distributed at the deeper extension of the blue line. Based on these observations, we conclude that the deep LFEs beneath western Shikoku occur along the upper surface of the subducting Philippine Sea Plate.

In **Figure 1**, the LFE source region appears whitish compared with the surrounding area. This means that the *Ps* phases are not excited; i.e., there are no large velocity discontinuities in this region. The shallower part of the LFE source region also appears white, though another red line can be seen at 25 km depth beginning at a horizontal distance of >90 km. Considering that this red line corresponds to the continental (land-side) Moho, our observations imply that the continental Moho does not exist in the LFE source region. Based on the azimuthal dependence of *Ps* amplitudes, we find that the anisotropic axes in the oceanic crust clearly differ from the area beneath the LFE source region in the southern part of the study area: their directions are almost orthogonal.

Below the region where the phase transition related to dehydration reactions occurs in subducting oceanic crust, seismic velocity increases. Water released by the dehydration reaction might cause deep LFE activity at the top of the subducting plate. If the water contributes to the serpentinization of mantle materials, then the seismic velocity in the mantle will be reduced. Thus, the velocity contrasts in the lower crust, mantle wedge, and oceanic crust become smaller. This explains why low *Ps* amplitudes were observed in this area. The change in anisotropy within the oceanic crust might be evidence of the phase transition.

The results shown in this report are based on one survey line in western Shikoku. Slow earthquakes occurring along the Nankai Trough show regional differences in their activity patterns. Future research should investigate the spatial relationships between subsurface structure and deep LFE activity in other areas, to clarify the controls on the characteristics of slow earthquake activity.

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Science of Slow Earthquakes
Activity report

Sep. 21–23, 2018
Joint WS

International Joint Workshop on Slow Earthquakes 2018

Aitaro KATO, ERI, UTokyo

The International Joint Workshop on Slow Earthquakes 2018 was held on 21–23 September 2018 in Fukuoka city, Fukuoka prefecture. This workshop was supported by the Coordinating Committee of Earthquake and Volcanic Eruption Prediction Researches (CCEVPR), the cooperative research programs of ERI at the University of Tokyo, and the Disaster Prevention Research Institute (DPRI) of Kyoto University. Post-workshop activities included a field excursion in Nagasaki prefecture, to a field site featuring exposed formations of Nishisonogi metamorphic rock, which are thought to have deformed at depths where slow earthquakes occur. A total of 129 researchers and students, including 31 foreigners (14 of which were invited speakers) participated in the workshop. Vigorous discussions among participants from a wide variety of fields (seismology, geodetics, geology, nonlinear physics, mathematical statistics, etc.) were conducted through oral and poster presentations.

Introduction to Research in Group B02

Geological perspective of episodic tremor and slip

Kohtaro UJIIE, Graduate School of Life and Environmental Sciences, University of Tsukuba

Episodic tremor and slip (ETS) has been detected from seismological and geodetic observations in subduction zones. The mechanism of ETS has been debated, mainly because of the limited spatial resolution of geophysical data from ETS sources. We examined how rocks record ETS events based on detailed geological study of subduction mélange (Makimine mélange) exposed in the Late Cretaceous Shimanto accretionary complex of eastern Kyushu, southwest Japan (Ujiie *et al*., 2018). The Makimine mélange records progressive plate boundary deformation during subduction of young, warm oceanic crust to a shallow (10–15 km) frictional-viscous transition where temperatures reached 300–350 °C. Whereas geological evidence for high-speed slip (e.g., pseudotachylyte solidified from frictional melt produced by seismic slip) has been reported from subduction zones (Ujiie and Kimura, 2014 and references therein), the low-speed deformation responsible for slow earthquakes such as ETS events remains poorly understood. Here, we attempted to find geological evidence that explains four key geophysical observations of slow earthquakes in active subduction zones (see Beroza and Ide, 2011, and references therein): (1) slow earthquakes typically occur in regions of high fluid pressure and low effective stress; (2) very low-frequency earthquakes and triggered swarms of low-frequency earthquakes associated with slow slip events have very low stress drops, implying that the effective fault strength is very weak; (3) slow earthquakes commonly exhibit shear slip on low-angle thrust faults subparallel to the plate boundary interface; and (4) ETS events repeat every several months to every few years. Zones of 10–60 m thickness containing concentrations of quartz veins are recognized in the lower part of the mélange, within which crack-seal shear and extension veins coexist with viscous shear zones that were accommodated by pressure solution creep (**Figure 1**). The geometry, kinematics, and microstructural features of crack-seal veins and viscous shear zones represent low-angle thrust faulting at very low shear strength under near-lithostatic fluid overpressures (**Figure 2**), which is consistent with key geophysical observations (1)–(3). Furthermore, the minimum time interval between low-angle brittle thrusting events, determined from a kinetic model of quartz precipitation in shear veins, was less than one or two years (**Figure 3**), which is comparable to key geophysical observation (4).

In total, crack-seal shear and extension veins, and viscous shear zones in the subduction mélange record

Figure 1. 'Tremor Island' in the lower part of the Makimine mélange. This island is marked by the coexistence of crack-seal shear and extension veins, and viscous shear zones, which are thought to record repeated ETS events. Geological evidence suggests the ETS source region is thin, on the order of tens of meters.

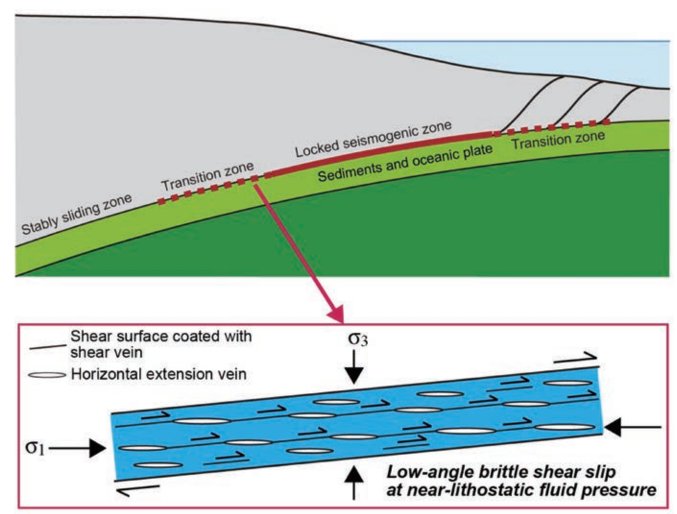

Figure 2. Schematic diagram showing the geological model of tectonic tremors in a subduction zone.

that low-angle brittle thrusting occurred repeatedly at very low shear strengths under near-lithostatic fluid overpressures at the timescales of ETS. The number of repeated brittle thrusting events, determined from the number of inclusion bands in shear veins, is ~100–150, suggesting the frequent release of accumulated strain in the transition zone between the locked seismogenic zone and deeper, stably sliding zones. Since crack-seal veins are also observed in other subduction mélanges and metamorphic rocks exhumed from the source depths of ETS, our results may be widely applicable to subduction zones.

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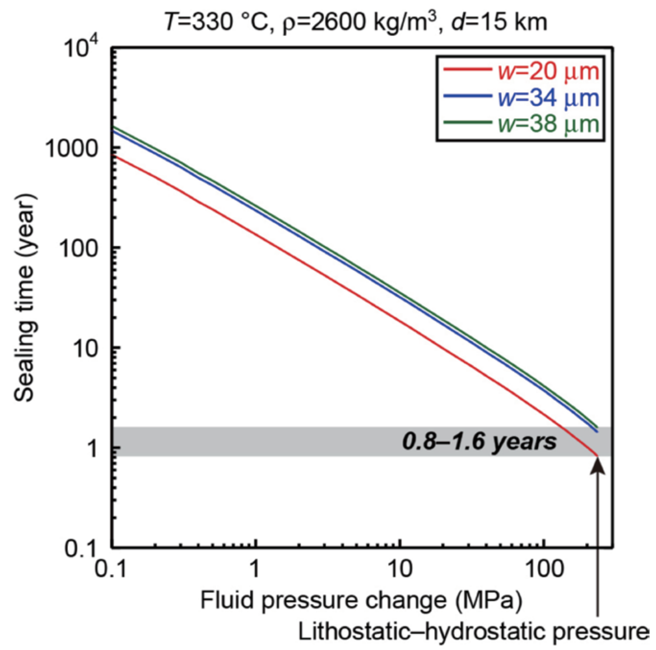


Figure 3. Sealing time for the widths (w) of inclusion bands in quartz-filled shear veins.

Science of Slow Earthquakes
Activity report

Sep. 24-25, 2018
Nagasaki field trip

Field trip to the Nagasaki metamorphic rocks

Yasushi MORI, Kitakyushu Museum of Natural History and Human History
Kohtaro UJIIE, Univ. of Tsukuba

A field trip to the Nagasaki metamorphic rocks was held after the International Joint Workshop on Slow Earthquakes 2018 in Fukuoka. On day 1, we observed serpentinite mélange that deformed at depths of ~30km and temperatures of ~460˚C, and recognized localized shear zones composed mainly of chlorite and actinolite. On day 2, we observed metasomatic reaction zones and associated shear zones in the mélange. A total of 24 people participated in the field trip, including researchers and students from Japan and overseas. Active and intellectually stimulating discussions were held at the field sites. In particular, the factors controlling shear localization in the mélange and the role of fluid in the generation of slow earthquakes were major topics of debate.

Introduction to Research in Group C01

Stochastic source physics and slow earthquakes

Naofumi ASO, School of Science, Tokyo Institute of Technology

Earthquakes are the physical manifestations of localized shear slip on faults, as they release part of the stress accumulated by plate motion into the ground. Many studies of earthquake source physics focus on rupture simulation on the fault and slip inversion using observed seismic waveforms. Earthquakes have been previously recognized as deterministic phenomena in earthquake source physics. For example, slip evolution on a fault can be computed deterministically if initial and boundary conditions are known, and seismic waveforms can be computed deterministically based on the slip distribution and Earth structure. These concepts are based on the simple logic that deterministic conditions and deterministic physics result in a deterministic solution. On the other hand, stochastic aspects of earthquakes, including Omori's law, have long been accepted in statistical seismology, which focuses on the patterns of seismicity to characterize earthquakes. In the field of seismic wave propagation, the stochastic concept has been considered to reproduce scattering effects. We believe that earthquake source physics can also be modeled based on stochastic concepts, for the following reasons. During the period of earthquake rupture evolution, there occur many non-linear processes, such as the evolution of fault gouge, and the resultant slip is expected to be deterministic chaos. Moreover, the physical conditions in the ground are difficult to capture completely. Hence, slip on the fault can be simulated stochastically; i.e., based on stochastic conditions and stochastic physics. To further our understanding of earthquake source physics, we need new approaches based on the concept of earthquake rupture as a stochastic process. In this study, we investigate the characteristics of rupture processes under stochastic stress perturbations as an innovative challenge in stochastic earthquake source physics. The perturbations represent various effects other than elasticity, including fault roughness and non-linear processes, but are equivalent to considering a time-dependent spatial heterogeneity (**Figure 1**). We model the along-strike rupture propagation of thrust-type earthquakes as an anti-plane crack problem in a two-dimensional homogeneous medium. We assume a rigidity of 30 GPa and an S-wave velocity of 3 km/s. We solve the problem using the BIEM (boundary integral equation method) scheme, assuming a slip-weakening friction law and Gaussian-type stochastic stress perturbations of 1 MPa. The perturbations are correlated at 2 km in space and 2/3 s in time. Stress drops by 8 MPa over the critical distance of 2 m. An initial stress that is 6 MPa smaller than the yield stress is set homogeneously

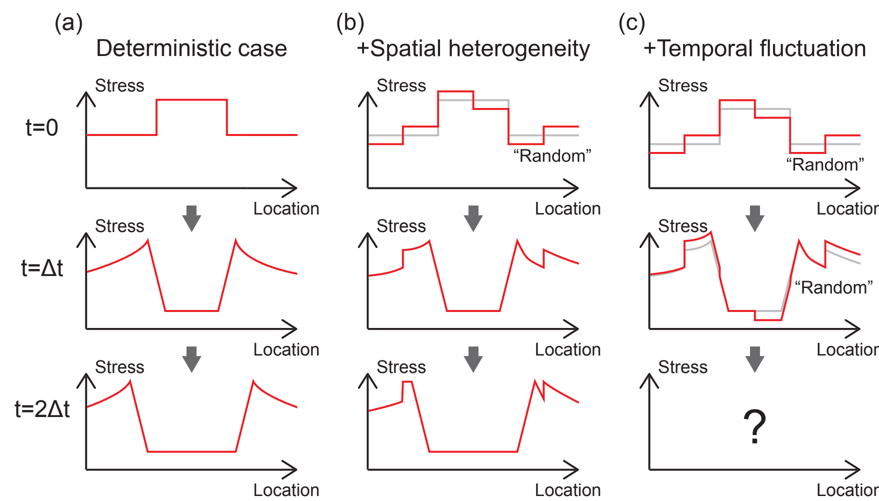


Figure 1. Conceptual diagram of stochastic rupture simulations. (a) Deterministic case. (b) Initial stress with spatial heterogeneity. (c) Time-dependent spatial heterogeneity.

except in the nucleus, where stress is set to be critical to modulate rupture nucleation. As a result of our simulations, a rupture propagates slowly over 15–20 km in a time of 2×10^5 s (~2.3 days), as shown in **Figure 2**. We also reproduce burst-like activity in the initial stage, followed by diffusional migration (~10^4 m^2/s) of pulse-like slip along the rupture front. Simulation at longer time-scales reproduces accelerated migration toward regular earthquakes a few days after nucleation. We interpret this transition from slow to fast earthquakes to be consistent with observations of slow earthquakes preceding large earthquakes. Regular earthquakes can be reproduced by changing only the initial stress and strength levels, including crack-like and pulse-like ruptures, depending on the conditions. Here, we successfully reproduced various characteristics of slow and regular earthquakes by introducing stochastic concepts in earthquake rupture simulations. Such a simple model can reproduce the variability and complexity of earthquakes, which hints at the potential of stochastic earthquake source physics. It is especially remarkable that the essential physical origin of slow earthquakes can be represented by stress perturbations in our model. Multiple approaches, including further numerical studies and comparison with observational data, will further the development of stochastic earthquake source physics.

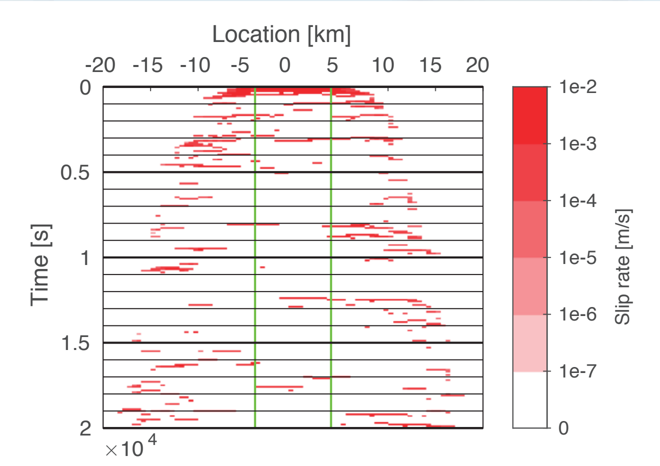


Figure 2. Simulation results. The spatio-temporal distribution of slip velocities is shown as a color intensity plot. Initial burst-like activity and resultant diffusional migration along the rupture front are reproduced.

Science of Slow Earthquakes Activity report

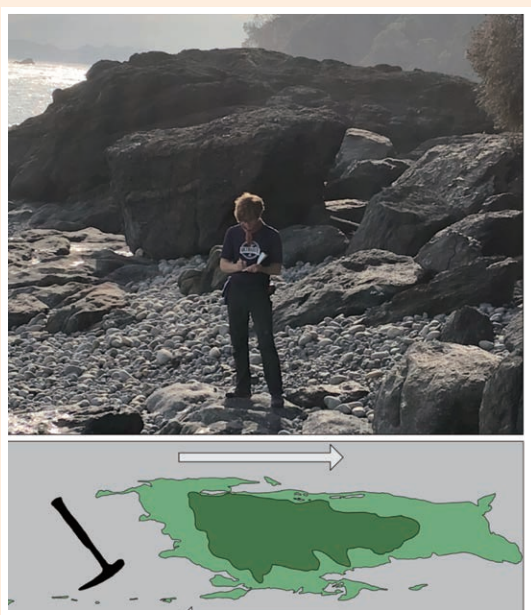
Sep.20–Nov.3, 2018 Long-term visiting program 1

Long-Term Visiting Program 1

Mapping the geology of shallow slow slip

Noah PHILLIPS, McGill Univ.

I conducted collaborative research with the University of Tsukuba on the geology of shallow slow slip. This year, we used drone photography to help create detailed maps of rock types and deformation structures from the Mugi Mélange, an on-land analog for shallow slow slip and very low frequency events (VLFEs) at the Nankai Trough. We have found localized slip surfaces along the margins of basaltic blocks. The basaltic blocks are individually ~1–5 m in size, are surrounded by a scaly shale matrix, and form several layers within a thin, ~20 m thick zone. We performed deformation experiments on samples from Mugi at Rice University, which showed that the margins of the basaltic blocks are velocity-weakening, while the shale matrix shows velocity-strengthening behavior. This mixture of rock types might explain geophysical models that require mixed zones of velocity-weakening and velocity-strengthening materials for the generation of VLFEs.



Top: Noah Phillips working in the field.
Bottom: Cartoon of a basaltic block (green) affected by alteration and cataclasis (light green) along its margin.

Introduction to Research in Group C02

Are slow earthquakes more predictable than regular events?

On the nature of slow earthquakes from the perspective of bifurcation analysis.

Yutaka SUMINO, Department of Applied Physics, Faculty of Science, Tokyo University of Science

At plate boundaries, slow earthquakes are observed at the transition between stable sliding and the seismogenic zone, which strongly suggests that analysis of bifurcations from steady sliding behavior could explain many characteristic features of slow earthquakes. One interesting characteristic of a slow earthquake is its repeatability and predictability compared with regular earthquakes. In addition, slow earthquakes are potentially coupled to regular earthquakes. Therefore, prediction of regular earthquakes that follow slow earthquakes might be possible. Here, we consider the degree to which slow earthquakes are repeatable and predictable.

We assume that the characteristics of slow earthquakes arise from weak oscillations due to instability near the bifurcation from steadily sliding behavior. Under these conditions, such a weak instability as a slow earthquake should be readily affected even by small perturbations. However, this suggests that a slow earthquake might be less repeatable (and less predictable) than a regular earthquake. In fact, slow earthquake generation appears sensitive to the surrounding environment, such as tidal forces [1]. The estimation of the response of slow earthquake to surrounding fluctuations and periodic perturbations is another relevant problem. The answers to these questions are necessary to explore the possibility that slow earthquakes can be used to predict regular earthquakes.

To answer the above question, we are currently trying to extract the essential features of a slow earthquake using a simplified equation derived near the bifurcation between stable and unstable sliding. Here, we adopt a rate-and-state friction law, which is often used for modeling regular earthquakes. Our spatial configuration is a one-dimensional thin elastic layer of thickness h, the top of which is loaded with constant velocity v_l (**Figure 2**). In this configuration, starting from Navie's equation, we obtain:

$$\frac{\partial^2 u(x,t)}{\partial t^2} = \frac{\mu}{\rho}\frac{\partial^2 u(x,t)}{\partial x^2} + \frac{2\mu}{\rho h^2}[v_l t - u(x,t)] - \frac{1}{\rho h}\sigma(v,\theta)$$

In this study, we use a slip law [2] for a rate-and-state friction model. With appropriate non-dimensionalization, we obtain:

$$\frac{\partial \chi}{\partial t} = \psi, \quad \frac{\partial \psi}{\partial t} = Y\frac{\partial^2 \chi}{\partial x^2} + \eta\frac{\partial^2 \psi}{\partial x^2} - G\chi - \left[\sigma_* + \theta + \ln\left(\frac{\psi + v_l}{v_*}\right)\right]$$

$$\frac{\partial \theta}{\partial t} = -(\psi + v_l)\left\{\theta + (\beta+1)\ln\left(\frac{\psi + v_l}{v_*}\right)\right\}$$

With such a mathematical model, we investigated the sliding behavior numerically near the bifurcation point (**Figure 2**). As shown in the phase diagram of **Figure 2a**, when G is small and the oscillation is spatially desynchronized, irregular oscillatory sliding appears. A small value of G corresponds to a large h and small μ in the original equation. A similar model for a regular earthquake is normally used with a semi-infinite space, which corresponds to an infinite h. Therefore, a small G is a commonly considered situation, and our analysis indicates that irregular oscillatory sliding inevitably occurs close to the bifurcation from stable sliding behavior. Irregular oscillations seem to be temporally regular with a constant period, in contrast to their irregular spatial behavior. However, it can be seen from the auto-correlation function of the sliding speed that the oscillation is irregular at longer timescales due to the spatial effect.

To investigate the mechanism of such irregular oscillatory sliding, we simplified the equation near the bifurcation point. This leads to a simplified expression of our model:

$$\frac{\partial W}{\partial \tau} = \lambda_1 W - g|W|^2 W + d\frac{\partial^2 W}{\partial x^2}$$

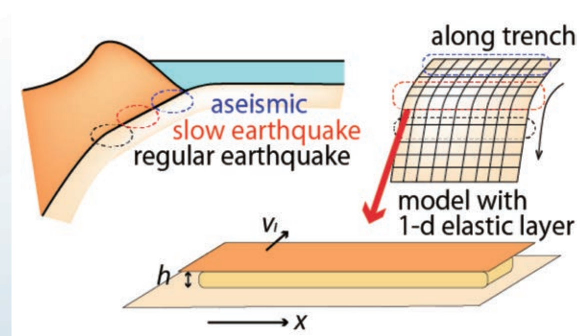


Figure 1. Schematic representation of our model. The transition between stable sliding and the seismogenic zone is modeled using a thin, one-dimensional elastic layer.

In this equation, spatio-temporal chaos appears due to Benjamin–Feir instability when

$$1+\frac{\mathrm{Im}\,d}{\mathrm{Re}\,d}\frac{\mathrm{Im}\,g}{\mathrm{Re}\,g}<0$$

This instability region is confirmed to coincide with the irregular oscillatory sliding region.

Our results show that irregular oscillatory sliding must occur when a thick plate with large h is assumed. We found that the oscillations are spatially irregular and temporally unpredictable on long timescales. However, we have also shown that short-term repeatability and predictability can be reproduced by our model. Future work will include attempts to compare our results with observations of slow earthquakes.

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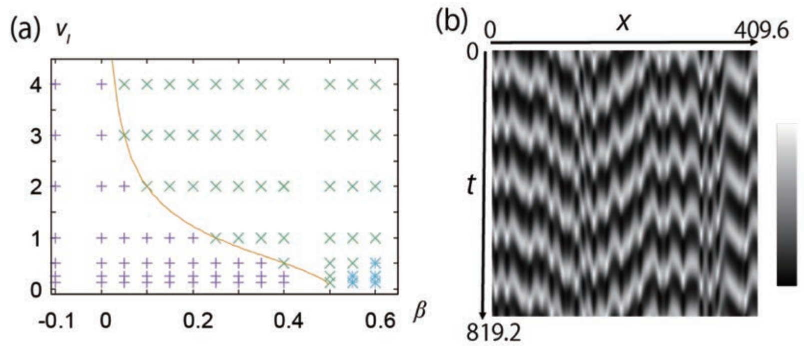


Figure 2. (a) Phase diagram of sliding behavior. The vertical axis corresponds to loading velocity v_l and horizontal axis corresponds to β which corresponds nondimensionalized notation of B-A in slip law. In this diagram, G = 0.5. The yellow curve corresponds to the theoretically predicted instability threshold for stable sliding; when v_l exceeds these values, oscillations occur. The green "x" symbols denote irregular oscillatory sliding. (b) Spatio-temporal plot of sliding velocity. Increasing brightness corresponds to higher sliding velocity.

Science of Slow Earthquakes

Activity report

Sep.12-Oct.13, 2018

Long-term visiting program 2

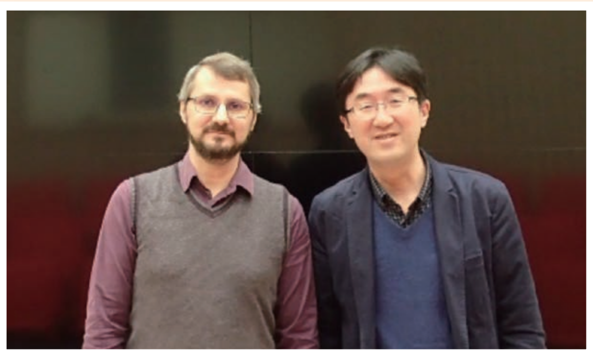
Long-Term Visiting Program 2

Collaborative research on numerical modeling of the role of seamount subduction in the generation of megathrust earthquakes and SSEs

Shoichi YOSHIOKA, Kobe Univ.

Dr. Vlad Constantin Manea (UNAM) was invited to Japan to give an invited talk at the International Joint Workshop on Slow Earthquakes 2018 in Fukuoka, and conducted collaborative research at Kobe University from 12 September 2018 to 13 October 2018. In this collaboration, we investigated the effects of seamount subduction on temperature variations along the subduction interface and its relationship with megathrust earthquakes and SSEs. Here we report some results of high-resolution three-dimensional coupled petrological–thermomechanical numerical simulations of seamount subduction.

Our preliminary results indicate that seamounts remain strong and preserve their shape and size during subduction. Furthermore, our modeling suggests that inactive seamounts with a cold thermal structure have a strong influence on the slab surface temperature by forcing slab isotherms to greater depths. Since the up- and down-dip limits of megathrust earthquakes and SSEs are believed to be thermally controlled, the thermal perturbations induced by seamount subduction could play a key role in determining the along-strike limits of rupture areas, as well as the areas of SSEs. The outcome of this project will advance our understanding of the short- and long-term influences of oceanic topographic irregularities on the generation of seismicity, the existence of seismic gaps, and the occurrence of SSEs.



Dr. Vlad Constantin Manea (left) and Shoichi Yoshioka (right)

Introduction to Multidisciplinary Research

Collaboration between non-equilibrium physics and geosciences: where do we stand and where do we go?

Takahiro HATANO, Earthquake Research Institute, The University of Tokyo

I'd like to begin this summary by re-emphasizing that the success of our project relies entirely on the collaboration between the physics group and other groups. We expect this joint venture to continue because one of the main aims of KAKENHI is to open up a new scientific field via "collective research efforts through collaboration". Fortunately, thanks to the efforts of everyone involved, we have begun several joint research projects involving various groups. Below are some examples that I hope will stimulate the readers and lead to new ideas for collaborative research. If you have any ideas for new collaborations, please do not hesitate to contact me.

1. Modeling water diffusion and fracture formation using cellular automaton (CA)

In VLFEs and earthquake swarms, the distribution function of the interoccurrence time can be approximated by a gamma distribution. It is believed that pore fluid plays a vital role in controlling the parameters of these power laws, but the physical mechanism that leads to the power-law distribution is unknown. We construct a physical model that combines pore fluid dynamics and stress variations in a general subduction zone to elucidate the physical process behind the distribution function. We have constructed a CA model that considers the influences on water movement and shear fracture, and which succeeds in reproducing the power-law distribution. This study is being conducted by Dr. Takeo, T. Hatano, and Mr. Tanaka.

2. Understanding the oscillating plate-convergence rate in the Tohoku area

We developed a simple mathematical model to reproduce the oscillations in plate subduction velocity reported by Prof. Uchida (**A01**). Along with an investigation based on bifurcation theory, our goal is to quantitatively explain the spatiotemporal distribution of the oscillation periods. For details, please refer to Dr. Sumino's article in this issue. This study is being conducted by Dr. Sumino, Prof. Uchida, Prof. Yamaguchi, and me.

3. Reproducing the spectrum of tremors in the laboratory

Considering the similarity between the spectra of tremors and acoustic waves emitted from sheared granular matter, as observed in experiments being conducted by Prof. Sumita's group (**C02**), we attempt to devise a new physical model for the dynamics of tremors. The experimental data are similar to the predictions of the CA model reported by Prof. Ide (e.g., Dr. Aso's article in this issue). We will therefore investigate the physical mechanism behind the similar spectra of these very different phenomena.

4. Tidal response of tremors: comparison of theory with observations

We have devised a theory of earthquake occurrence rate that depends on the stress history, including oscillatory stresses. We compare model predictions with observed data. This research is being conducted by Prof. Y. Tanaka and me, and hopefully by Dr. S. Tanaka.

5. Influence of humidity on the dynamic weakening of crystal quartz

Moisture strongly affects the frictional properties of fault gouge because the interparticle bridging effect strengthens as particle size decreases. We simulate the influence of moisture in a submicron particulate system and compare the results with laboratory experiments. This study is being conducted by Dr. Tsutsumi and me.

6. Can turbulence affect the migration properties of pore fluids?

We study the hydraulic properties of pore fluid under the influence of turbulence and incorporate the results into physical models of slow earthquakes. If possible, we would like to compare the theory with the experiments conducted by **B02 group**. This study is being conducted by Prof. Y. Tanaka and Dr. Suzuki.

7. Analog experiments on slip at subducted seamounts

We constructed an experimental system simulating slip on a subducted seamount to reproduce shallow tremors and slow slip events and to investigate the spatiotemporal dynamics of these systems. This research is to be conducted by Prof. Yamaguchi and Prof. Mochizuki.

Introduction to Joint Research

Global search for SSEs using GNSS data

Takuya NISHIMURA, Disaster Prevention Research Institute, Kyoto University

Slow slip events (SSEs) are the largest events observed by geodetic techniques with the longest durations of the family of events that are collectively termed “slow earthquakes”. Since the development of the GNSS network in the 1990s, SSEs have been discovered around the world and have been extensively studied. However, we still have only limited understanding of the fundamental characteristics of SSEs because it is difficult to detect small SSEs, whose signal amplitudes can be as small as the background noise of GNSS data. We developed an objective detection method for short-term SSEs along the Nankai trough and applied it to GNSS data along the Ryukyu trench, where SSEs had been identified only in the southernmost region. We succeeded in detecting ≥200 previously unidentified SSEs (Nishimura, 2014), which clearly demonstrates that many SSEs in the subduction zone have not yet been identified. This study applies the same method to GNSS data in other subduction zones to improve our understanding of the mechanisms of SSEs, by detecting as many SSEs as possible and improving the detection methods themselves.

This article presents the results of an analysis of the Hikurangi subduction zone, northern New Zealand, where the Pacific Plate subducts beneath the Australian Plate to form the Hikurangi trench. Previous studies (e.g., Wallace *et al.*, 2012) reported many SSEs with a wide variety of magnitudes, durations, and depths. Our study uses daily coordinates published by the Nevada Geodetic Laboratory, University of Nevada, Reno (http://geodesy.unr.edu/) to detect short-term SSEs that occur on the plate interface. We successfully detected ≥120 SSEs from April 2004 to March 2018. The cumulative slip distribution of detected SSEs (**Figure 1**) shows that SSEs occurred at depths between 0 and 50 km below the trench axis, and did not occur in a locked zone along the southern part of the Hikurangi trench. SSE slip is greatest in the shallow northern part of the subduction zone, where it accommodates more than half of the interplate motion. Slip is also large at depths of 30–50 km, which is manifested by a band of large slip in **Figure 1**. Our study is the first to identify this deep SSE band, although large, long-term SSEs have been found in the same depth range in the southern Hikurangi margin.

We estimated the durations of SSEs with high signal-to-noise ratios: shallow SSEs typically last less than 40 days, while deep SSEs last 30–80 days. Slip rates of deep SSEs are less than 1 mm/day, slower than those of shallow SSEs. Slip regions for shallow and deep SSEs are separated in the southern Hikurangi margin, but their separation becomes unclear in the northern region. These findings provide meaningful constraints on the conditions required to generate slow earthquakes along a fault. We plan to expand our analysis into other subduction zones.

References

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Wallace, L., *et al.* (2012), *J. Geophys. Res.* 117, B11402, doi:10.1029/2012JB009489.

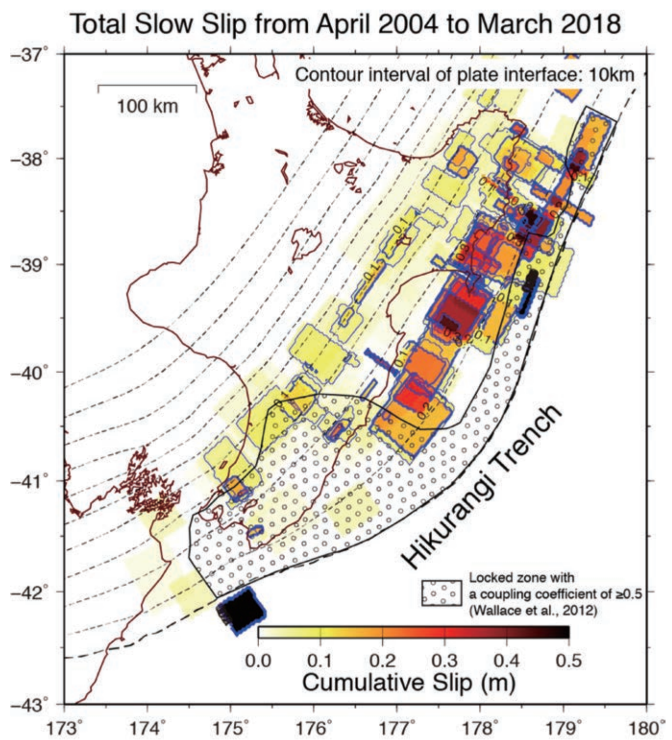


Figure. 1. Cumulative slip distribution of slow slip events (SSEs) detected using GNSS along the Hikurangi Trench, New Zealand.

Science of Slow Earthquakes Activity report

“Self-invited” workshop in NZ

Feb.26–29, 2018 “Self-invited” workshop in NZ

Kimihiro MOCHIZUKI, ERI, UTokyo

To better understand slow earthquakes through discussion with other researchers, and to strengthen Japan’s leadership in this research field, we organize small research meetings, or “self-invited workshops”, in cities worldwide in regions of slow earthquakes. The first such workshop, titled “New Zealand – Japan Joint Workshop on Slow Slip”, was held at Victoria University of Wellington (New Zealand) on 26–27 February 2018 (Photo 1). The workshop included 27 participants from Japan, including 5 graduate students, and more than 30 NZ participants, including 13 from Victoria University, 15 from GNS Science, and others from Otago University and NIWA [The National Institute of Water and Atmospheric Research]. Other participants included researchers from Cambridge University (UK) and Columbia University (USA). The workshop was successful in that it was truly an international workshop, with 65 researchers in total.

Before the workshop began, opening addresses were presented by Prof. Grant Guilford, Vice-Chancellor of Victoria University of Wellington, and Mr. Toshihisa Takata, Japanese Ambassador to New Zealand, in which they expressed their anticipation of further developments of Japan–NZ collaborative research. The two-day workshop featured 30 oral presentations on four major themes: “Shallow slow slip” and “Areas with deeper slow slip and/or locking” on the first day, and “Kaikoura earthquake and relation between slow slip and earthquakes” and “Geology and physics / modeling” on the second day. Lively discussion followed each presentation. In addition to the 30 oral presentations, the workshop featured 15 posters, and the conference room, which might have been slightly large for a small research meeting, was full. Before concluding, a constructive discussion was held on how to proceed with collaboration, and we agreed that we would promote the exchange of personnel.

After the workshop, two excursions were organized: a one-day excursion around the Wellington area, visiting NIWA, GNS, and the Wellington Fault, and a two-day course observing the fault area of the 2016 Kaikoura earthquake.

Kimihiro Mochizuki (ERI, Univ. of Tokyo) and Yoshihiro Ito (DPRI, Kyoto Univ.) gave public presentations at Victoria University of Wellington on 28 February, and at the National Aquarium in Napier on 1 March, organized by East Coast LAB, a local NPO. We were interviewed by the New Zealand Herald about the presentations, and the resulting article was published in the morning newspaper on 7 March 2018. All participants expressed their satisfaction with the fruitful workshop and the excursions. The public presentations were also successful, with a large audience.

Photo 1: Self-invited workshop at Victoria University of Wellington, with 65 participants from Japan, NZ, and U.S.A.

Photo 2: Presentation for the public at the National Aquarium in Napier.

Science of Slow Earthquakes
Activity report

NHK TV programs and the Seismological Society of Japan (SSJ) award

Kazushige OBARA, ERI, UTokyo

I appeared in two NHK programs related to slow earthquakes. One was an NHK special entitled “Megaquake, Nankai trough huge earthquake, Prepare for impending X day” (broadcast on 1 September 2018). Dr. Ryota Takagi initially presented his research results on slow slip migration and the possibility of connections to huge earthquakes, after which I offered commentary from the broadcast studio. The second program was Tanken Bakumon, titled “ERI, search the frontiers of disaster prevention and prediction” (broadcast on 3 October 2018). I guided Bakushou-mondai, Sahel Rosa, and Rei Kikukawa through the OBS laboratory and other locations at the Earthquake Research Institute. I also explained the discovery of deep low frequency tremor. I realized that program production requires ‘much time detailed planning, and careful arrangements.

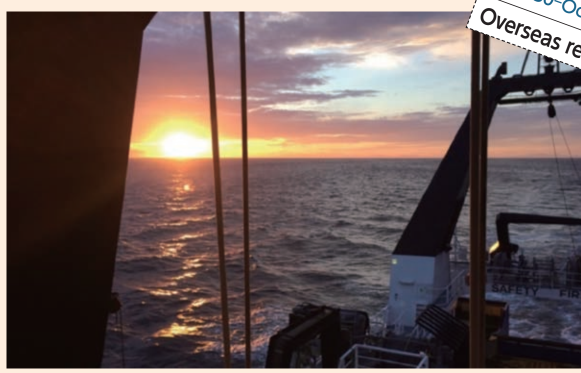
In addition, I received the 2017 SSJ award on 9 October 2018. The target performance was titled “Creation of the science of slow earthquakes”. This award recognizes that the study of slow earthquakes is well established as an important research field, as exemplified by selection for a JSPS Grant-in-Aid for Scientific Research on Innovative Areas. I thank everybody who supported this research and expect that young researchers will greatly contribute to the future development of slow earthquake studies.

Overseas research program

Tomohiro INOUE, M1, Kyoto Univ.

Sep.30-Oct.23, 2018
Overseas researches

I was sent abroad as a researcher in the first half of FY2018. My name is Tomohiro Inoue. I’m a student at the graduate school of Kyoto and I went to New Zealand from 30 September to 23 October. I was on board a research vessel for two weeks within this period. On land, I prepared to deploy observation gauges on the seafloor: my duties included attaching circuit boards and batteries to ocean bottom pressure sensors (OBP) and ocean bottom seismometers (OBS). On the ship, I deployed and recovered these gauges. I mainly studied the occurrence of slow slip events (SSEs) using OBP and OBS, and analyzed OBP data recovered from this cruise. It was a rewarding experience for me, preparing OBP data for use in my own research and talking with scientists from abroad. Though the deployment and recovery of OBPs was tiring, I saw the work through to completion thanks to the inspiration provided by a beautiful sunset observed from the bridge of the vessel.



Top: Sunset from the bridge.
Bottom: On the deck of RV Tangaroa (Inoue is the second one from the right in the third row.)

Slow Earthquakes Café

A total of 10 Slow Earthquakes Cafés took place in 2018, including researchers from a variety of fields. Below we list a brief summary of the speakers.

Jan. 12
Ryoko NAKATA (JAMSTEC)
Geodetic data inversion for spatial distribution of long-term slow slip events beneath the Bungo Channel using sparse modeling

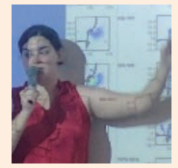
Mar. 13
Natalia POIATA (IPGP, National Institute for Earth Physics, Romania)
An automated multi-scale network-based scheme for detection and location of seismic sources

Mar. 14
Takane HORI (JAMSTEC)
Application of HPC for understanding and forecasting of generation processes of megathrust events and slow earthquakes in subduction zones: Present and future perspectives

May 31
Christopher JOHNSON (SCRIPPS, University of California San Diego)
Climate modulated water storage, the deformation, and California earthquakes

Jul. 30
Junichi NAKAJIMA (Tokyo Institute of Technology)
Where slow earthquakes occur and what happens during slow earthquakes

Sep. 18
Ken CREAGER (University of Washington)
Imaging Northern Cascadia slow slip on scales from seconds to weeks and 100 m to 300 km



Sep. 25
Noel BARTLOW (University of California, Berkeley)
Mechanics of slow slip events in Cascadia and New Zealand

Sep. 26
David SHELLY (U.S. Geological Survey)
Earthquake swarms in high definition: migrating seismicity and fluid-faulting interactions beneath Long Valley Caldera, California

Oct. 1
Heidi HOUSTON (University of Southern California)
Evolution of stress and strength through slow slip and tremor cycles

Oct. 29
Noah PHILLIPS (McGill University)
The Life and Death of Frictional Melts (Earthquakes) in the Rock Record: Implications for the Short- and Long-Term Strength of Faults

Slow Earthquakes Special Seminars

Special seminars took place at ERI and in Yokohama, Kobe, Fukuoka, Hiroshima, and Tsukuba, with invited speakers from JpGU2018 and the International Joint Workshop on Slow Earthquakes 2018.

Feb. 21
Natalia POIATA (IPGP, National Institute for Earth Physics, Romania)
An automated multi-scale network-based scheme for detection and location of seismic sources

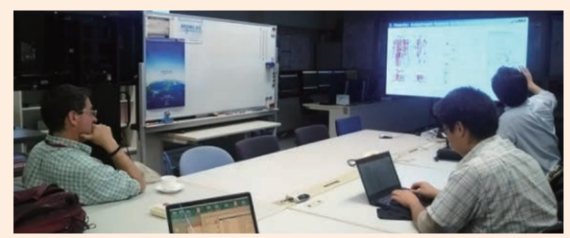
Jun. 1
Stephen KIRBY (Scientist Emeritus and Senior Scientist, U.S. Geological Survey)
Fluid Fluxes from Dehydrating Serpentinized Forearc Mantle: Possible Roles in Non-Volcanic Tremor and Related Phenomena

Sep. 18
Vlad C. MANEA (Computational Geodynamics Laboratory, Geosciences Centre, National Autonomous University of Mexico)
Slow-slips and tectonic tremors diversity in subduction zones

Sep. 20 Jean-Francois MOLINARI (EPFL, Switzerland)
Evolution of roughness during dry sliding: insights from atomistic and mesocale models

Sep. 24 Hiroko KITAJIMA (Texas A and M University)
Experimental constrains on in-situ stress and strength in the Nankai accretionary prism

Sep. 26 Geoffrey ABERS (Cornell University)
Recent Cascadia work, related to a volcano project



Brainstorming with Prof. Geoffrey Abers at NIED, Tsukuba.

Science of Slow Earthquakes

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