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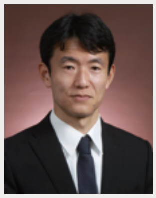
INDEX

Granular friction experiments for understanding slow earthquakes and slow landslides



Tetsuo Yamaguchi and Chengrui Chang (The University of Tokyo)

In our group, we have been working on elucidating the mechanisms of geophysical phenomena, particularly slow earthquakes and slow landslides, using laboratory experiments and theoretical descriptions. Here, we introduce granular friction experiments using halite particles.

For the study of shallow slow earthquakes and slow landslides, it is assumed that a slip event occurs while the host rocks remain unconsolidated. In addition, comminution (fracturing) is considered to occur during sliding. To simulate these features in laboratory experiments, we utilized halite particles as an analog material. In laboratory experiments, it is difficult to reproduce the large normal stress that acts on natural faults, while halite particles have a small yield stress of about 10 MPa and can easily generate comminution. In the past, Shimamoto (Shimamoto 1986) reported frictional properties of halite, that led to the derivation of the constitutive law for slowearthquakes (Shibazaki et al. 2007).

We conducted friction experiments for halite particles with a ring shear geometry [see Figure 1(a); Chang et al., under review]. The geometry is like the "pepper mill" that has attracted general attention. As presented in Figure 1(b), the friction coefficient shows a nearly constant value (μ_0) for some time after shearing starts, but slip weakening with exponential decay is observed after a certain sliding displacement (L_0). We also conducted experiments by changing the normal stress σ. We found that the larger the value of σ, the shorter both L_0 and the displacement required for slip weakening Lw become. Furthermore, we found that both L_0 and L_w are inversely proportional to the square of σ, as shown in Figure 2.

We have developed a theory to describe and explain our experimental findings. The theory assumes that angular halite particles fracture with slip displacement and produce small rounded particles. During the initial stage of sliding, small particles are generated but escape into voids between halite particles. Therefore, the contact state between halite particles remains unchanged during the initial stage, and the friction coefficient shows a constant value. When the small particles only fill the voids between the halite particles, the effective normal stress acting on the halite particles begins to decrease. As a result, we propose a mechanism whereby the friction coefficient is constant during the early process and decreases during the late process. This theory also reproduces the experimental observation that both slip displacements are inversely proportional to the square of the normal stress and can explain the exponential decrease in the friction coefficient during slip weakening.

By combining friction experiments using analog materials with theoretical descriptions of the observations, we have gained a deeper understanding of the processes and physical mechanisms involved. In the future, we will apply techniques such as visualization of internal states using X-ray CT, visualization and quantification of particle comminution processes, and particle simulations (using the discrete element method) to understand the processes and physical mechanisms in more detail.

Although we take a materials science perspective in this work, we are conducting studies on slow earthquakes and slow landslides by using analog modeling, rather than directly using real materials. By successfully identifying and modeling the problems that are difficult to understand through observation and impossible to analyze through numerical calculations, we aim to discover and elucidate new phenomena and understand universal phenomena.

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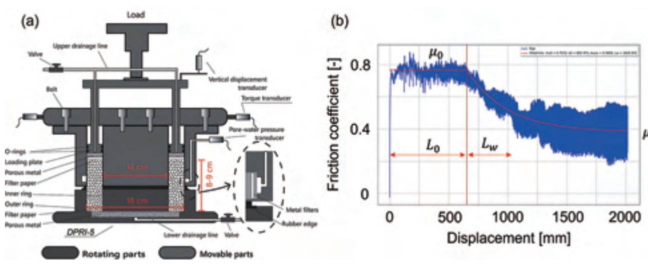

Figure1: (a) Schematic diagram of the ring shear friction testing machine. (b) Characteristic frictional behavior and definition of parameters.

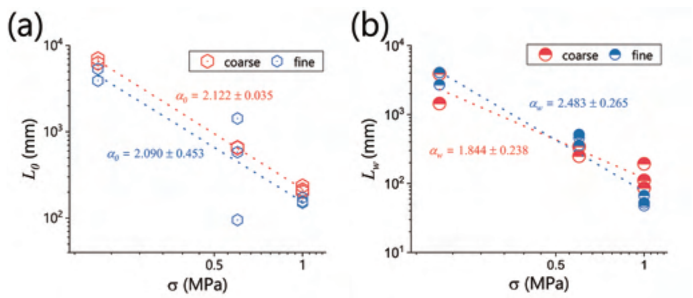

Figure2: Normal stress dependence of characteristic slip displacements during the early (a) and late (b) stages. The two lines in each figure correspond to the results from two different initial particle sizes (coarse and fine).

Change in the pore pressure of a fault in a shallow portion of an accretionary prism during fault deformation

Akito Tsutsumi and Keigo Tashiro (Graduate School of Science, Kyoto University)

Recent observations of slow earthquakes in the vicinity of high-pore-fluid pressure regions suggest an important role of pore fluids as the underlying mechanism of slow earthquakes. However, few relevant experimental studies have been performed to understand the mechanical properties of subduction-zone materials in the presence of pore fluids. This study aims to understand the faulting process in the shallow part of the subduction zone by conducting experiments using shallow-subduction-zone material.

The Miura-Boso accretionary complex, which consists of Lower–Middle Miocene to Lower Pliocene formations, has been buried to only ~1 km depth, meaning that the initial deformation of the accretionary body has been preserved. Thrust faults in the Miura-Boso accretionary complex are associated with the development of fault gouge. The gouge zone is commonly observed to be injected into the hanging wall side of the fault, suggesting the presence of high pore-fluid pressure at the time of fault formation (Yamamoto et al., 2005). We investigated the effect of pore-fluid-pressure increase accompanying shear deformation on the shear strength of the fault using a hemipelagic siltstone sample collected from the hanging wall side of the frontal thrust fault developed in the Miura accretionary complex.

An example of experimental results using the large ring shear testing machine at the Disaster Prevention Research Institute of Kyoto University (Sassa et al., 2004) is shown in Figure 1. For the experiments, we gradually increased the shear stress (0.1 kPa/s) from an initial stress condition of 500 kPa and investigated the fault behavior when deformation reached the failure line and macroscopic fault slip was initiated. In the experiment conducted under the undrained condition, macroscopic slip began as the shear stress gradually increased and reached the failure condition, and the effective normal stress gradually decreased with the increase in pore-fluid pressure, with the shear stress decreasing to a steady state value of ~40 kPa (Fig.1a). In addition, the pore-fluid pressure increased with increasing shear stress even before the initiation of macroscopic slip (Fig.1b). the experiment conducted under the drained condition, no increase in pore-fluid pressure was observed. A comparison of the decrease in shear stress with respect to the amount of fault slip between the undrained and drained conditions shows that whereas the drained condition required a slip of ~450 mm for the shear stress to decrease to a steady state, the corresponding slip for the undrained condition was ~100 mm.

The experimental results indicate that the increase in pore-fluid pressure due to fault deformation before the initiation of fault slip is of the same magnitude as the increase in pore-fluid pressure during slip. In the future, we plan to conduct detailed observations of the internal structure of experimental faults that have undergone an increase in pore-fluid pressure and compare this structure with that observed in natural faults.

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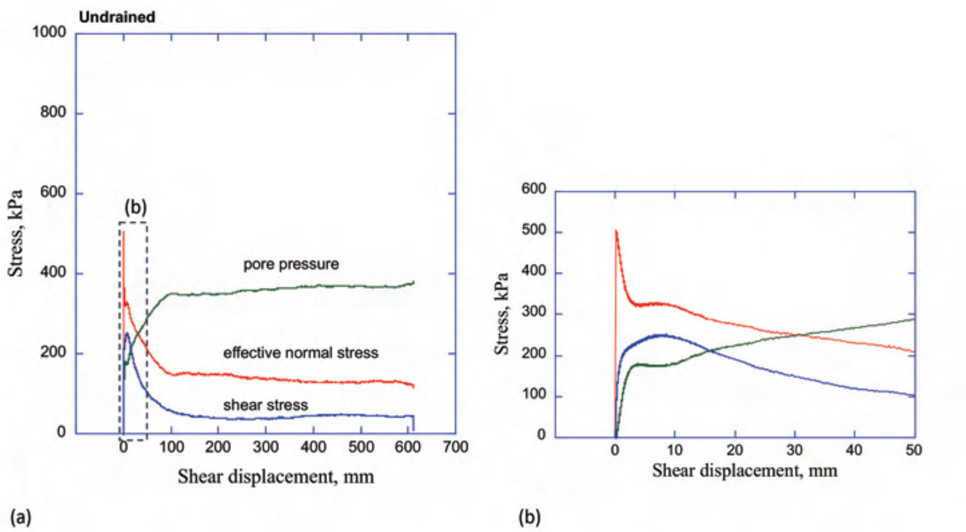

Figure: (a) Displacement weakening behavior of the analyzed Miura Group hemipelagic siltstone observed during large ring-shear experiments under the undrained condition. (b) Enlarged plot of the initial part of (a).

Discovery of upper-plate conduits linked to the plate boundary fault hosting slow earthquakes in the Hyuga-nada area

Ryuta Arai (Japan Agency for Marine-Earth Science and Technology)

The Hyuga-nada subduction zone in southwestern Japan provides an ideal setting for studying the relationship between subduction earthquakes and forearc hydrology. This zone is situated adjacent to the Nankai Trough, where frequent megathrust earthquakes with magnitudes exceeding 8 are known to have occurred. The Hyuga-nada area has historically hosted several interplate earthquakes with magnitudes of ~7. Recent seafloor observations have documented slow earthquakes on the up-dip side of the source areas. A notable fluid-related feature of the Hyuga-nada area is the abundance of mud volcanoes on the seafloor, which are considered to have been supplied by the dehydration of clay minerals at shallow crustal depths. However, the origin of the fluid and the hydrological system responsible for the transfer of deep fluids remain poorly understood.

To gain a better understanding of the geodynamic system in the Hyuga-nada subduction zone, we performed a dense seismic refraction experiment using ocean-bottom seismographs and a multichannel seismic reflection survey. The surveyed seismic line was aligned parallel to the regional trend of the Nankai Trough in the SW–NE direction and crossed the source area of the low-frequency tremor distributed between the shallow and deep seamounts (Arai et al., 2023; Fig.1). We applied the advanced full waveform inversion technique to seismic refraction data obtained from 50 ocean bottom seismographs deployed at a 2 km interval. The resulting P-wave velocity model reveals distinct kilometer-wide low-velocity columns in the upper plate that extend vertically from the seafloor to 10–13 km depth (Fig.2). We interpret these low-velocity columns as zones damaged by subduction of the Kyushu-Palau Ridge. The seismic-reflection image for the same line reveals that the sedimentary layers are highly disturbed and display an upwardly domed geometry on top of the low-velocity columns, suggesting the presence of active upwelling flows within these columns. In addition, the seafloor bathymetry reveals several circular mounds close to the areas of the upper-plate low-velocity columns. These observations suggest that the upper plate contains well-developed fluid conduits that facilitate efficient fluid flow to the seafloor and supply the mud volcanoes.

Our results also reveal velocity reversals at various depths within the upper plate, suggesting that fluids from the plate boundary may be trapped and accumulate at multiple depths. We also found a strong relationship between seismic reflectivity along the plate boundary and the distribution of tremors and very low-frequency earthquakes in the Hyuga-nada region. These findings support the notion that fluid behavior influences a range of geodynamic processes capable of regulating megathrust slip behaviors and forming mud volcanoes on the seafloor.

Reference
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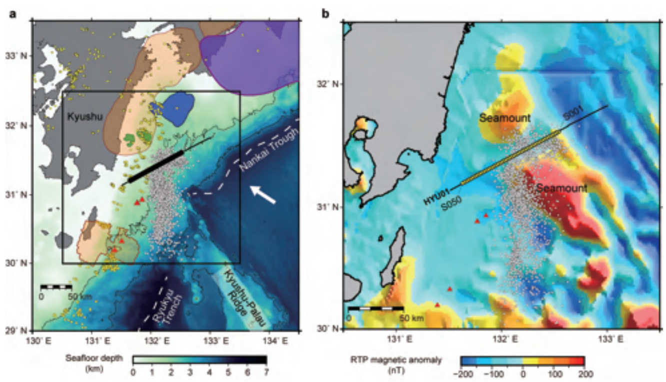

Figure1: Regional bathymetric map (a) and magnetic anomaly map (b) showing the tectonic setting of the Hyuga-nada area.

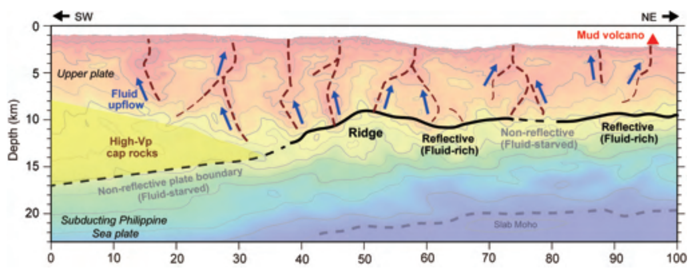

Figure2: Interpretation of upper-plate conduits and plate-boundary structure based on the P-wave velocity structure obtained from full-waveform inversion analysis.

Estimation of the temporal variation in pore-fluid pressure based on the geometry of mineral veins

Makoto Otsubo (Geological Survey of Japan/AIST)

Fracturing, fluid migration, and mineral precipitation in slow earthquake zones, along with changes in fluid pressure, are considered key processes for understanding the conditions and time scales of slow earthquake occurrence. Pore fluid pressure (P_f) is defined as the pressure of fluid that fills rock voids near the fault plane. It has been reported that the orientations and aspect ratios of mineral veins change according to pore fluid pressure. Mineral veins serve as records of fluid flow within rock fractures. Here, we introduce an approach (Otsubo et al., 2023) for estimating pore fluid pressure using mineral veins.

Accretionary complexes and metamorphic rocks can be formed in environments in and near plate boundaries at depths of 10 to 30 km, where slow earthquakes occur. These complexes and rocks contain mineral veins, including multiple mineral veins arranged in parallel geometry in outcrops. These parallel mineral vein groups may occur at a variety of spacings (Figure 1).

In the elastic model presented in this study, the distance between parallel mineral vein groups depends on the magnitude of the excess pore fluid pressure in fractures, Young's modulus, and fracture aperture width (Otsubo et al., 2023). The conceptual basis of the model is analogous to inserting another book into a bookshelf already full of books. If the jammed book is soft, a thicker book can be inserted easily. If the jammed book is hard, the book will not fit easily into the bookshelf without forcing it in. Analogously, when mineral veins form, the host rock must shorten elastically by an amount equal to the thickness of the mineral vein precipitated in the fracture (Price and Cosgrove, 1990). Therefore, in our elastic model, the relationship between the spacing D between groups of parallel mineral veins, the excess pore fluid pressure ΔP_f in fractures, Young"s modulus E of the host rock, and the aperture width W of the mineral veins is

$\Delta P_f = E(W/D)$, (Equation 1)

and Equation 1 can be rewritten for D as

$D = EW/\Delta P_f$. (Equation 2)

For example, let's consider the stress drop associated with a slow earthquake (approximately 0.01 to 1.0 MPa). We will calculate the parameter D under two conditions: when the excess pore-fluid pressure at the time of the formation of parallel mineral veins is 1 MPa and 50 kPa. These conditions correspond to the stress drop observed during a slow earthquake. In other words, these are two cases in which the pore fluid pressure is 1 MPa and 50 kPa greater than the minimum principal stress $\sigma 3$. We also assume that the Young's modulus of the host rock is 7.5 GPa and that the width of the mineral vein is 50 μm. Equation 2 yields D = 0.38 m for an excess pore fluid pressure of 1 MPa and D = 7.5 m for an excess pore fluid pressure of 50 kPa. This result implies that as the excess pore fluid pressure changes, the mineral vein spacing changes; i.e., the spacing of fractures through which fluid passes (the width of the fracture zone) changes. This in turn implies that if mineral veins are related to the occurrence of slow earthquakes, then the temporal variation in the excess pore fluid pressure within a slow earthquake cycle may be inferred from the mineral vein spacing. In this case, the excess pore fluid pressure (i.e., the amount of fluid pressure greater than $\sigma 3$) may provide insights into the size of slow earthquakes (e.g., shear zone width; Figure 2).

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Price, N. J. & Cosgrove, J. W. (1990) Cambridge University Press, Cambridge, 502 pp.
Ujiie, K. et al. (2018) Geophysical Research Letters, 45, doi:10.1029/2018GL078374.

Figure1: Example of a mineral-vein concentration zone at an outcrop in the coastal area east of Naomi, Nobeoka City, Miyazaki Prefecture, Japan. Ujiie et al. (2018) reported the quartz-vein concentration zone at this outcrop as a possible record of a slow earthquake. Variation in the spatial distribution of quartz veins is observed at this outcrop.

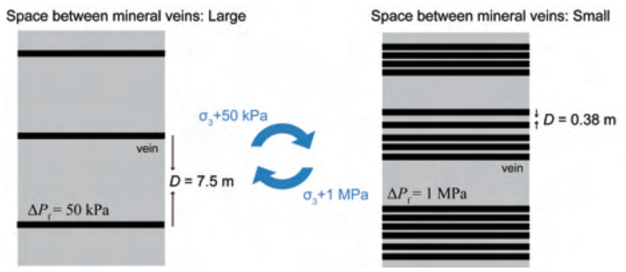


Figure2: Example of variation in pore-fluid pressure estimated from mineral vein spacing.

A systematic survey for slow-to-fast changes in tilt before volcanic eruptions

Yuta Maeda (Graduate School of Environmental Studies, Nagoya University)

Although the main topic of the Slow-to-Fast project is earthquakes, the A03 (international comparison) group accepts studies on other types of natural slow-to-fast phenomena, including those occurring at volcanoes. My volcanological and seismological interests have drawn me to study volcanological phenomena that may not be directly related to slow earthquakes but may be addressed from the viewpoint of slow-to-fast phenomena.

Volcanic eruptions are sometimes preceded by changes in tilt that typically start slowly and then accelerate, followed by an eruption, which is an even faster and catastrophic phenomenon (Figure). Therefore, pre-eruptive changes in tilt are considered to be a type of slow-to-fast phenomenon. The majority of documented pre-eruptive changes in tilt show polarities consistent with the inflation of volcanoes. Most of these changes in tilt are attributed to the migration of volcanic fluids, such as magma, volcanic gas, or underground water, toward shallower regions, or to volume change caused by the exsolution or vaporization of volatile components. The presence (or absence), magnitude, time scale, and temporal sequence of changes in tilt exhibit substantial variation among different volcanoes and eruptions. Although numerous studies have examined individual instances of changes in tilt, these phenomena have not yet been systematically cataloged and quantitatively compared.

In my systematic survey of the changes in tilt preceding eruptions of all active volcanoes in Japan (Maeda, 2023), I required publicly continuous waveform records from tiltmeters or broadband seismometers installed near a volcano and exact dates and times of eruptions. These criteria were met by 7890 eruptions at 12 volcanoes. I developed an algorithm to automatically detect changes in tilt before each eruption from continuous records and applied it to all 7890 eruptions.

Results revealed that approximately half of the eruptions were preceded by changes in tilt, irrespective of the eruption frequency. The detected changes in tilt showed large variations in the polarity, lead time, duration, amplitude, and temporal pattern of acceleration (slow-to-fast) or deceleration (fast-to-slow). The acceleration type was most frequent, although the deceleration type was not infrequent. The ratio of eruptions preceded by changes in tilt was slightly but statistically significantly higher for explosive eruptions than for non-explosive eruptions. Therefore, it appears that the eruption type might be one of many parameters that influence the occurrence or absence of pre-eruptive changes in tilt.

The next step in this research will be a systematic survey of pre-eruptive changes in tilt at volcanoes outside of Japan. The main advantages of this international study include an increased number of eruption examples and unrestricted access to continuous waveform records in some countries. This unrestricted access would enable a study to be performed on changes in tilt that are not followed by eruptions. A challenge in advancing this work is that the exact times of eruptions are not cataloged in a standardized format in most countries. Therefore, a strategy needs to be devised to efficiently obtain the eruption times.

Reference:
Maeda, Y. (2023) J. Volcanol. Geotherm. Res., 439, 107831.

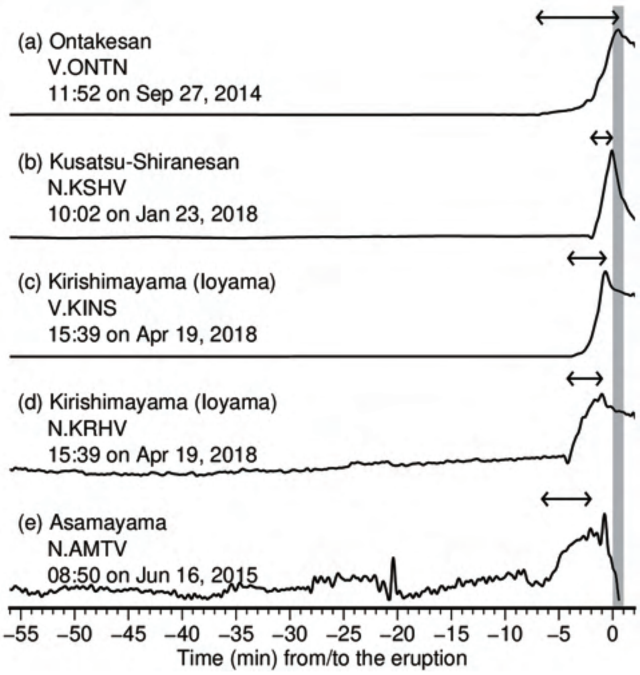
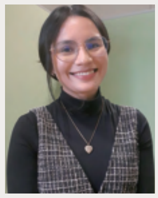


Figure: Examples of changes in tilt (arrows) that preceded eruptions (gray bar); after fig. 2 of Maeda (2023).

2D Visco-elasto-plastic subduction models applied to the subduction history of the Philippine Sea plate along the Nankai Trough



Erika Jessenia Moreno (Kobe University), Nobuaki Suenaga (Kyoto University) and Shoichi Yoshioka (Kobe University)

The Philippine Sea (PHS) plate subducting along the Nankai Trough is characterized by a young plate with ages between ~26 and 15 Ma, with subduction having initiated at 15 Ma (Tatsumi et al., 2020). The subduction history of the PHS plate along the Nankai Trough is not yet fully resolved. One of the proposed models of tectonic evolution involves the onset of a low subduction angle and a high convergence rate (Tatsumi et al., 2020). The low subduction angle can be explained by the onset of subduction of an extremely young, warm, and buoyant oceanic plate represented by the nascent Shikoku Basin (Tatsumi et al., 2020) (Figure 1). The high temperatures of the young PHS slab have generated rapid slab melting, resulting in the formation of the Setouchi volcanic arc and intense plutonism in Southwest (SW) Japan between 14 and 12 Ma (Tatsumi et al., 2020). Volcanism ceased in SW Japan after 12 Ma and was reactivated during the Quaternary.

In contrast, Kimura et al. (2014) proposed that the proto-Izu arc and the Izu–Bonin–Mariana Trench migrated during and after the Middle Miocene. This migration of the Izu–Bonin–Mariana arc in conjunction with the onset of subduction of the PHS plate along the Nankai Trough at 15 Ma resulted in large volumes of magmatism, which may have been related to the formation of plutonism in the vicinity of the Nankai Trough, as observed in the Kii Peninsula. This tectonic scenario explains the cessation of volcanism in SW Japan by an interruption in the subduction of the PHS plate between 12 and 6 Ma (Kimura et al., 2014).

Until now, no study has evaluated the different hypotheses of the tectonic evolution of SW Japan using a numerical methodology. In our recent study, we applied for the first time 2D subduction models using visco-elasto-plastic rheology to the Nankai Trough subduction zone in collaboration with Dr. Vlad Constantin Manea and Dr. Marina Manea, who are specialists in the numerical modeling of subduction processes at the Universidad Nacional Autónoma de Mexico. In this model, the visco-elasto-plastic conditions allow the slab to evolve freely in response to the rheology of the rocks, plate-motion velocity, and plate-age conditions. In this study, we conducted numerical simulations with the aim of reproducing the low subduction angle of the PHS slab along a profile passing through the Shikoku and Chugoku regions (Figure 1; Hirose et al., 2008).

Our numerical models show that it is possible to reproduce the low subduction angle currently observed beneath the Shikoku and Chugoku regions with a high convergence rate between 15 and 3 Ma, as proposed by Tatsumi et al. (2020) (Figure 2). As observed beneath Kyushu, the high-angle subduction causes the formation of volcanic arcs near the subduction zone. However, the volcanism in the Shikoku and Chugoku regions is located far from the Nankai Trough (Figure 1a). As observed in the Mexican subduction zone associated with the Trans-Mexican Volcanic Belt (Manea et al., 2013), we propose that the low subduction angle caused an interruption of volcanism near the Nankai Trough and its migration inland in SW Japan (Figure 2a). Our novel numerical study allows us to explain the tectonic evolution of SW Japan by understanding the sensitivity of a young oceanic plate to convergence rate and plate age. The paper summarizing the results of this research was accepted by Scientific Reports on 18 October 2023.

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Matsubara, M. et al. (2022) Earth, Planets and Space, 74(1), 1-27.
Manea, V. C., Manea, M. & Ferrari, L. (2013) Tectonophys., 609, 56-81.

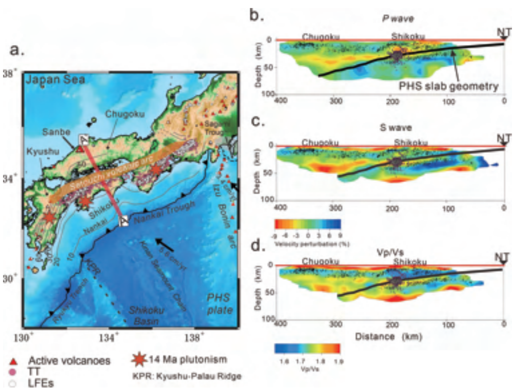

Figure1: (a) Study area with profile A–A' passing through the Shikoku and Chugoku regions. (b) P- and (c) S-wave velocity perturbations, and (d) Vp/Vs ratios (Matsubara et al., 2022), with the geometry of the upper surface of the PHS slab depicted by the solid black line (Hirose et al., 2008). Black dots in (a), (b), (c), and (d) represent the hypocenters of regular earthquakes, and white dots represent low-frequency earthquakes (LFEs). Data were obtained from the unified JMA hypocenter catalog for the period 2003–2019. Pink dots represent tectonic tremors (TTs) between 2011 and 2015, which were obtained from the database at http://www-solid.eps.s.u-tokyo.ac.jp/~sloweq/?page=map.

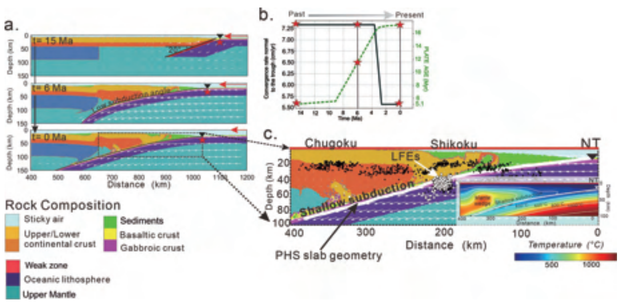

Figure2: 2D numerical subduction models using visco-elasto-plastic rheology for profile A–A' in Fig. 1(a). (a) Results of numerical simulations with rock composition at 15, 6, and 0 Ma. (b) Temporal change in plate motion velocity (solid black line) and plate age (dashed green line) for profile A–A' in Fig. 1(a) using the tectonic model of Tatsumi et al. (2020). (c) Rock composition and temperature fields (bottom right) at the final time step (0 Ma). The geometry of the upper surface of the PHS slab is represented by the white and black curves in the former and latter diagrams, respectively (Hirose et al., 2008). White and black dots represent LFEs and the hypocenters of regular earthquakes, respectively.

Observations of the Nankai Trough Seafloor by Optical Fiber Sensing

Eiichiro Araki (Institute for Marine Geodynamics, Japan Agency for Marine-Earth Science and Technology (JAMSTEC))

In the Nankai Trough, slow slip events (SSEs) occur at the plate interface around the epicenter region of large earthquakes, which occur with a 100–200 year cycle. Most of the epicenter region is under the seafloor, and occurrences of SSEs on the shallower side of the epicenter region are recognized only via seafloor observations, such as GNSS-A observations1) and observations in seafloor boreholes 2). Very low-frequency earthquakes (VLFEs) and low-frequency tremors (LFTs), which are thought to be closely related to shallow SSEs, are now being observed and analyzed by the DONET seafloor cabled broadband seismic observation network 3).

The aim of my work is to understand how slip on a plate boundary fault, such as SSEs, VLFEs, and LFTs, initiates and spreads, and how these events relate to the coupling of the plate interface and cause large earthquakes. These slip events are difficult to analyze because the density of our observations is still quite coarse compared with the scale of the events. I considered that the key is to obtain high-density, high-sensitivity observations of crustal deformation in the vicinity of fault slip at plate boundaries. Measurement of the strain distribution of submarine optical cables laid in the vicinity of the fault using a new observation technique termed “optical fiber sensing” should be useful for this purpose.

JAMSTEC has laid submarine optical fiber cables 120 km offshore of Muroto in the Nankai Trough. I and my colleagues developed a new optical fiber sensing instrument called “TW-COTDR” and made continuous observations of fiber strain with the off-Muroto submarine fiber optic cable for approximately one year. As a result, we were able to observe the strain and temperature fluctuations of the submarine optical fiber cable every 1 m, approximately every 20 min, up to about 80 km offshore, demonstrating that the submarine fiber optic cable can be used for high-density observations in the epicenter offshore region.

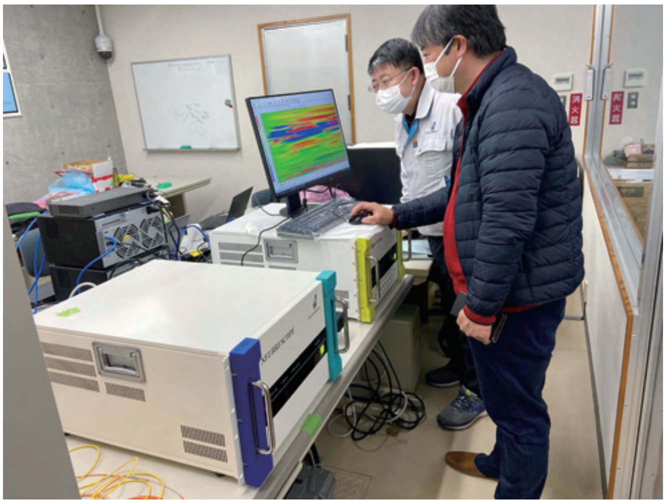

Figure1: Left) Off-Muroto submarine fiber optic cable shore station; Right) TW-COTDR fiber optic sensing observations performed at the shore station.

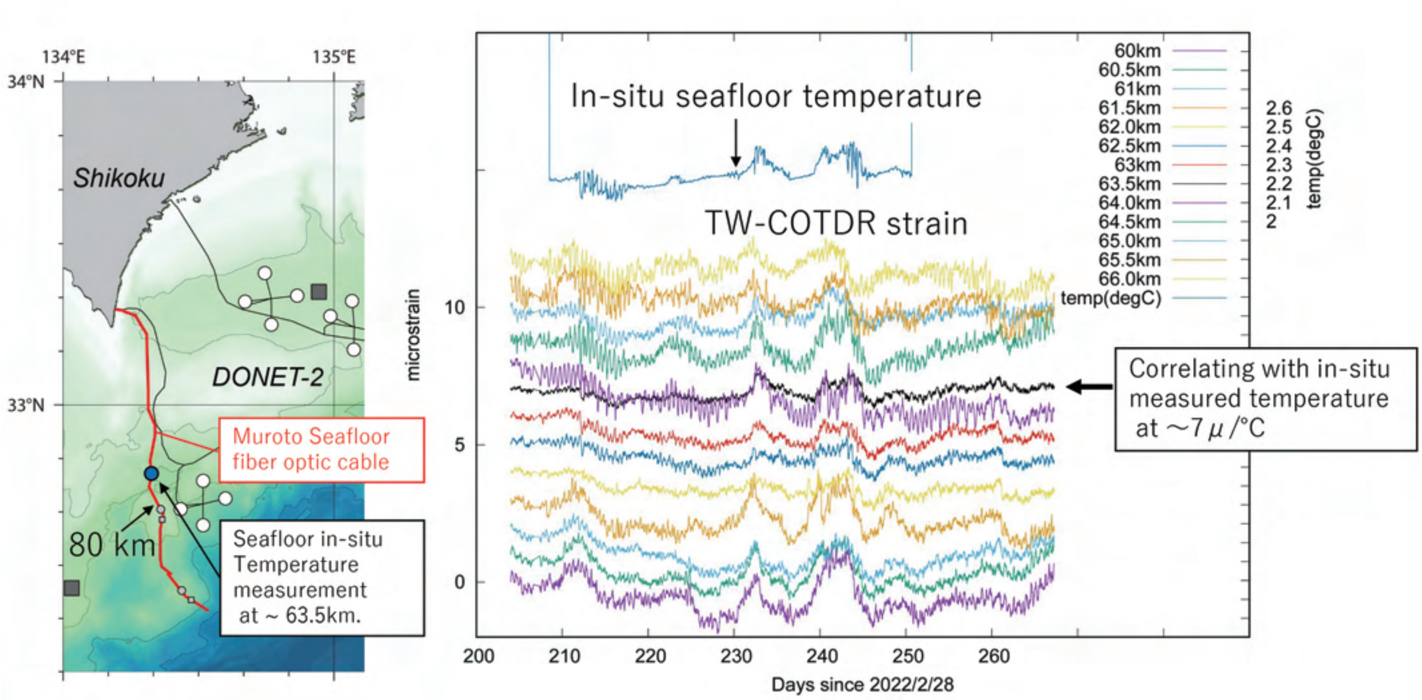

Figure2: Results of TW-COTDR fiber optic sensing observations using the off-Muroto submarine cable compared with in situ temperature at 63.5 km along the cable.

The observed seafloor optical fiber strain showed daily and long-term variations. The daily fluctuations observed were about 1 μ strain, even in the region of small fluctuations. The observed strain fluctuations are well correlated with seafloor in situ temperature, indicating that fluctuations in seafloor water temperature exert an influence on strain. Removal of the influence of seafloor water temperature fluctuations from the observed data, which would allow detection of slow fault slip, is challenging. For this reason, we have started development of a new fiber optic cable to separate temperature and strain in observations and are working on observations made in boreholes, where temperature fluctuations are minimal.

In addition, because a 20 min interval for observations is too coarse a time interval for observing crustal deformation associated with earthquakes and VLFEs, we are currently conducting observations in combination with Distibuted Acoustic Sensing (DAS) using an optical fiber sensing technology for earthquake observations. We are hoping to conduct observations covering all phenomena from slow slip to earthquakes with a single instrument, so we have also started to develop optical fiber sensing technology that can observe TW-COTDR at higher frequencies.

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2)Araki, E. et al. (2017) Science, 356, 1157–1160.
3)Yamamoto, Y. et al. (2022) Earth Planets Space 74:14.

Discrimination of seismic events using 1D and 2D CNNs

Masaru Nakano (Institute for Marine Geodynamics (IMG), JAMSTEC)

Event identification and phase picking are the most fundamental tasks in seismic event monitoring but are also quite laborious. The ever-increasing volume of seismic observational data from dense arrays covering entire nations means that these tasks now require automated systems. Various machine learning (ML) methods have been developed to resolve this issue, of which convolutional neural networks (CNNs) have frequently been used for seismic signal discrimination and phase picking. Although ML methods achieve higher performances in these tasks, ML methods are often referred to as "black boxes", and it is difficult to determine what characteristics are used in their processes, potentially limiting our understanding of seismic phenomena.

As the spectral characteristics of seismic signals depend on their source locations and source mechanisms, time–frequency-domain representation is expected to improve ML performance. Slow earthquakes that occur along subduction zones dominate low-frequency components compared with ordinary earthquakes. Similarly, volcanic earthquakes can also be classified by their dominant frequencies. Accordingly, we have developed a method to use time–frequency-domain representations (running spectra) to classify signals (Nakano et al. 2019). However, it is straightforward to use waveform traces as the input for ML applications to seismic data. Despite the importance of efficiently classifying these signals using automated ML systems for monitoring seismic and volcanic activity, detailed comparisons of the performances of ML methods using time–frequency-domain data with those using time-domain data are lacking.

In this study, we compared the performances of 1D (time-domain) and 2D (time–frequency-domain) CNNs by using the same time-window width, number of data points, and frequency components in the running spectral images (2D) as those of the 1D waveform traces. We used two datasets from different tectonic settings, one from the Nankai trough and one from Sakurajima volcano, to gauge whether CNN performance depends on the input dataset (Figure 1).

Our results show that the 1D and 2D CNNs performed comparably. Interestingly, about half of the samples of misclassified earthquakes or tremor events were misclassified to the same class by both CNNs (e.g., some tremor events classified as noise by both 1D and 2D CNNs). This result implies that both CNNs detect similar attributes in the seismic signal, namely, the difference in the frequency content. To further explore this, we investigated the classification process of the 1D CNN.

The convolutional layer of a 1D CNN is essentially equivalent to a set of finite-impulse-response (FIR) filters. In the first convolutional layer, the input seismic waveforms are filtered by the FIR filters then passed into the following layer after application of an activation function. Therefore, signals in the passband of the FIR filters in the first convolutional layer are used for classification in the first step. Figure 2 shows the responses of the FIR filters in the two channels of the first convolutional layer, namely, band-rejection filters with a stopband at 4–6 Hz and different amplitude responses for the higher-frequency components. The results presented in Figure 2 imply that the differences in the frequency components above and below 4–6 Hz are important for signal discrimination in our dataset.

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Nakano, M. et al. (2019) Seism. Res. Lett., 90, 530–538.
Nakano, M. & Sugiyama, D. (2022) Earth Planet. Space, 74:134.

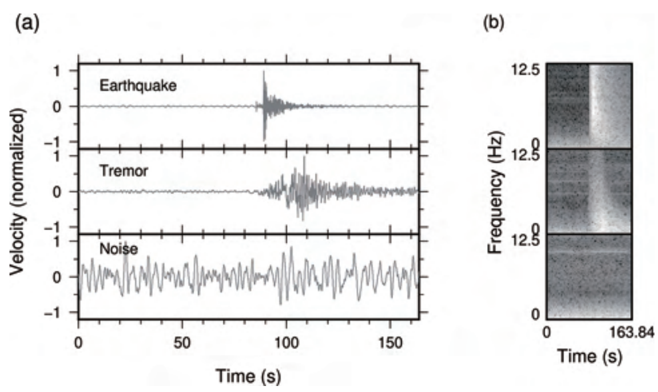

Figure1: Representative waveforms (a) and running spectral images (b) used as input data for the utilized CNNs (Nakano and Sugiyama, 2022).

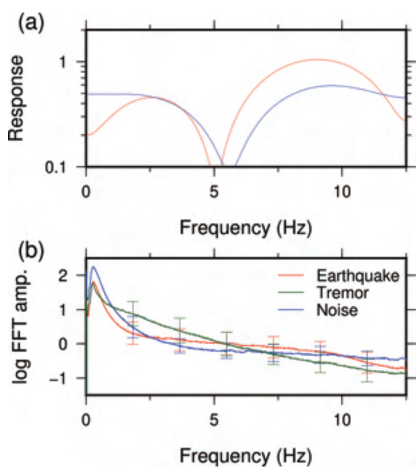

Figure2: (a) FIR filter responses in the first convolutional layer. (b) Average spectra of each signal class (Nakano and Sugiyama, 2022).

Data analysis techniques that contribute to the detection and analysis of slow-to-fast earthquakes

Keisuke Yano (The Institute of Statistical Mathematics)

In the slow-to-fast earthquake project, I have developed data analysis techniques aimed at identifying and understanding slow-to-fast seismic events. The connection between seismology and statistics has a rich history, as evidenced by the continued widespread application of statistical methods such as the spatio-temporal Epidemic-Type Aftershock Sequence (ETAS) model, Bayesian approaches, and the Akaike information criterion. However, as measurement technologies have advanced, the volume of seismic and geodetic data has expanded, increasing in both detail and complexity. To identify slow-to-fast phenomena within this vast volume of data, cutting-edge information science techniques are required in addition to traditional analysis methods. My contributions include an advanced earthquake detection method from multiple stations via graph-partitioned convolutional neural networks (Yano et al., 2021) and improved tomography with structural regularization (Yamanaka et al., 2022).

In the following, I introduce some of the new information science techniques in which I have been involved. First, we developed an automatic slow-slip detection method (Yano and Kano, 2022). Slow slip can be observed using global navigation satellite systems and tiltmeters; however, highly accurate automatic detection techniques are required, as it is not usually accompanied by visible crustal deformation. We have applied sparse modeling and p-value integration to develop a method for automatically detecting slow slip from global navigation satellite system data. Our approach uses sparse modeling to detect abrupt change points in time series data and focuses on observation of the slow-slip feature of interest at multiple stations. We applied this new method to western Shikoku and successfully identified 12 cases of slow slip that had not been detected previously (Figure 1).

Second, we developed a method for detecting tremors in the Japan Trench using deep learning (Takahashi et al., 2021). The conventional tremor detection method, referred to as the "envelope correlation method", detects tremors on the basis of the similarity of waveform envelopes between multiple stations, but this method incorrectly detects not only tremors but also regular earthquakes. We assessed the deep learning discriminator for tremor, regular earthquake, and noise proposed by Nakano et al. (2019) and constructed a deep learning model for discriminating tremors, regular earthquakes, and noise in the Japan Trench.

Third, as our latest research achievement, we developed a statistical tool for analyzing dependencies among variables that contributes to the analysis of earthquake catalog data (Sei and Yano, 2023). Earthquake catalogs contain complex data, including continuous values such as latitude, longitude, and depth, categorical values such as seismic intensity, and two mutually orthogonal axes of the mechanism solution. We formulated a minimum information dependence model to analyze the dependence between multivariate data in a mixed domain. Figure 2 shows the results of applying our model to the mechanism solution and the analysis of epicenter depth. The minimum information dependence model allows quantitative evaluation of the axial direction in which the dependence on the depth of the epicenter is strong, as well as the uncertainty involved in estimation of the depth of the epicenter.

I am continuing to develop various data analysis methods in seismology. Please contact me if you need help with data analysis.

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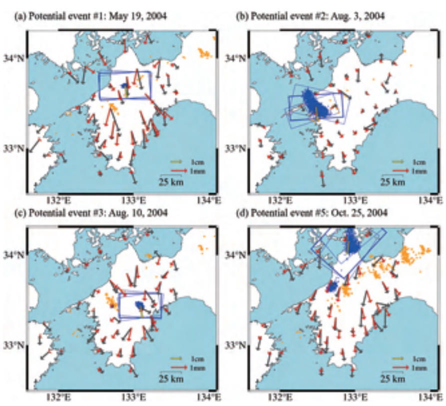
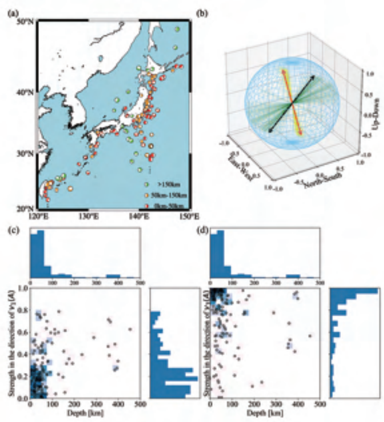
Yano, K. & Kano, M. (2022) J. Geophys. Res. Solid Earth, 127, 5, e2021JB023258.
Sei, T. & Yano, K. (2023) accepted at Bernoulli.



◀Figure1: Inversion results of the proposed method. Gray and red arrows represent observation and calculation using a rectangular fault model, respectively. The yellow arrow represents the slip vector calculated using the mean of the MCMC samples. After Yano and Kano (2022).



◀Figure2: Relationship between the mechanism solution and depth. (a) Observations; (b) direction of the P-axis that is most related to depth; (c–d) Joint histograms. After Sei and Yano (2023).

A scaling law for slow earthquakes, 2023 version

Satoshi Ide (Department of Earth and Planetary Science, The University of Tokyo)

Slow earthquakes are distinct from regular earthquakes in that they do not emit strong seismic waves, but the cause of this difference remains enigmatic. "A scaling law for slow earthquakes" proposed in 2007 has been effective for distinguishing the physical processes of slow and fast (regular) earthquakes. According to this law, slow earthquakes are phenomena in which the seismic moment increases over a duration ranging from less than one second to more than one year, in direct proportion to the duration. This is in stark contrast to fast earthquakes, where the seismic moment is proportional to the cube of the duration.

Since its discovery, this law has been debated by scientists worldwide. Fundamental questions include whether we are missing phenomena that bridge slow and fast earthquakes, and whether the proportionality breaks down at a certain event size. In some regions, slow earthquakes may follow the same relationship as that of fast earthquakes. Moreover, numerical models considering these possibilities have been proposed, leading to a somewhat chaotic situation, a few years ago. Given the numerous developments that have occurred in the field of slow earthquakes since 2007, our study (Ide and Beroza, 2023) reevaluates the scaling law.

In our recent study, we confirmed that although not all phenomena of slow and fast earthquakes can be observed, fast earthquakes can be clearly distinguished from slow earthquakes within seismological observational limits. We showed that the proposed possible breakdown in proportionality is due to the misinterpretation of distributed data points or, in some cases, to fundamental issues in data processing methodologies.

The accumulation of research results worldwide has supported the law suggested by discrete data points in 2007 with nearly continuous data points from earthquake magnitudes M1 to M7 (Figure 1). This includes recent hypotheses that consider the successive occurrence of tectonic tremors as one event and that slow earthquakes emit signals across a wide frequency band of 0.1–100 s.

Understanding the essential difference in scaling laws between slow and fast earthquakes is also crucial. Fast earthquakes occur almost entirely within seismological observational limits, but slow earthquakes are at the very edge of these limits, implying a high probability that unobservable phenomena are occurring. Therefore, we must understand the scaling law for slow earthquakes as one that constrains the maximum scale (highest speed) of the phenomenon.

Various deformation phenomena occur at different speeds within Earth. The phenomena that just exceed observational limits and are recognized as slow earthquakes are defined by the proposed scaling law. Conversely, fast earthquakes, which proceed at vastly different speeds and do not follow this scaling law, may be considered “irregular” as deformation phenomena within Earth. Scientists have traditionally viewed earthquakes as regular phenomena and slow earthquakes as irregular, but it might be time to reexamine this perception.

Reference:
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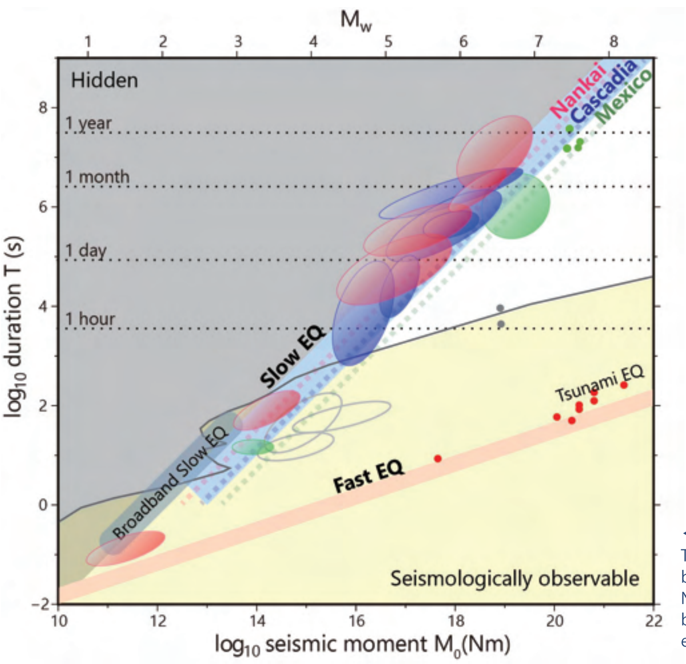
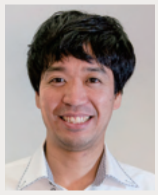


◀Figure:
The 2023 revised version of the scaling law for slow earthquakes, which delineates the relationship between seismic moment and duration. For slow earthquakes, data points from catalogs for the Nankai, Cascadia, and Mexico regions have been approximated by ellipses to represent their distribution. The scaling law for slow earthquakes is compared with the relationship for fast (regular) earthquakes.

Physical mechanism for a temporal decrease of the Gutenberg–Richter *b*-value prior to a large earthquake

Yoshihiro Kaneko (Graduate School of Science, Kyoto University)



Foreshocks are earthquakes that occur before a large earthquake (i.e., a mainshock) and are related to the mainshock in both time and space. Observations of seismicity prior to large earthquakes show that the slope of a Gutenberg–Richter magnitude–frequency relation, referred to as a *b*-value, decreases with time prior to the mainshock (e.g., Nanjo et al., 2012). Similar phenomena have been reported in rock-friction laboratory experiments (e.g., Yamashita et al., 2021). However, the underlying physical processes associated with the temporal change in *b*-values remain unclear. In this study, we utilize continuum models of fully dynamic earthquake cycles (Kaneko et al., 2016; Lapusta et al., 2000) with a relatively simple distribution of fault frictional heterogeneities to simulate the temporal variation in *b*-values. First, we identify a parameter regime in which the model generates an active and accelerating foreshock behavior prior to the mainshock. Then, we focus on the spatio-temporal pattern of the simulated foreshocks and analyze their statistics.

We find that the *b*-value of simulated foreshocks decreases with time prior to the mainshock (Fig. 1). A marked decrease in the resulting *b*-value occurs over a duration of less than a few percent of the mainshock recurrence interval, which differs from the widely adopted notion (Scholz, 1968) that the decrease in *b*-value is caused by a gradual increase in shear stress that promotes micro-crack growth. In our model, increased shear stresses on creeping (or velocity-strengthening) fault patches resulting from numerous foreshocks make these creeping patches more susceptible to future coseismic slip, thereby increasing the likelihood of large ruptures and leading to smaller *b*-values with time (Fig. 2). In other words, the temporal decrease in *b*-value is caused by the reduction of rupture barrier effectiveness resulting from the increasing shear stress within creeping regions (Fig. 2). The average shear stress over the entire fault remains nearly constant with time during the accelerating foreshock activity, as expected from the slow tectonic loading.

Our proposed mechanism is broadly consistent with foreshock behavior and changes in b-values observed in nature (e.g., Nanjo et al., 2012) and in rock-friction laboratory experiments (e.g., Yamashita et al., 2021). This mechanism may also explain why mainshock rupture becomes large, instead of resulting in another foreshock (i.e., a smaller event). Furthermore, a higher rate of *b*-value change occurs during the time closer to the mainshock, indicating that it may be possible to use detailed monitoring of earthquake *b*-values to accurately forecast the timing of a future mainshock.

This work has been published as Ito & Kaneko (2023).

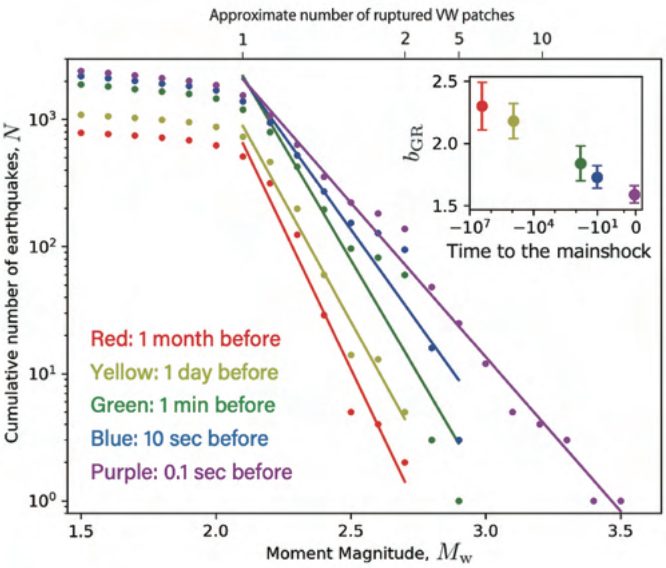


Figure1: Temporal change in the Gutenberg–Richter *b*-value (*b*GR) in a representative model. Colored dots correspond to magnitude–frequency relations for different time windows. The inset figure shows the evolution of *b*-values with time. *b*-values were obtained by maximum likelihood estimation. The lines of best fit were obtained using the least squares method. The *b*-value decreases with time prior to the mainshock.

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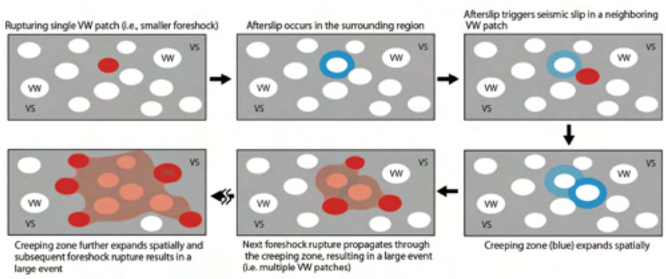

Figure2: Schematic diagram illustrating how *b*-values decrease with time prior to the mainshock. Background gray and white areas represent velocity-strengthening (VS) and velocity-weakening (VW) fault patches, respectively. Red represents coseismic slip regions, and blue indicates afterslip regions. Orange represents coseismic slip regions that include both VS patches that were slipping at a faster slip rate and VW patches that had already been ruptured during previous foreshocks. The larger the size of the combined red and orange regions, the larger the foreshock.

Publicly Offered Research in Group A01

Influence of fluid chemistry on fluid–rock reactions and hydraulic properties in subduction zones

Atsushi Okamoto (Graduate School of Environmental Studies, Tohoku University)

At plate subduction boundaries, the decomposition of hydrous minerals generates a large amount of fluid, which changes pore pressure and frictional behavior. In addition, the fluid contains various elements as ions and complexes (Figure), which react with rocks and cause the dissolution–precipitation of minerals. Recently, mineral–fluid equilibrium analysis has become applicable, even under deep conditions. However, the effects of rock–fluid reactions on the hydraulic and mechanical properties of faults and on the process of earthquake generation remain poorly understood. In this study, we investigate alteration and quartz-vein formation, which are characteristic rock–fluid reactions in high-pressure metamorphic rocks that are possibly related to slow earthquakes. We use hydrothermal flow-through experiments (Figure) to clarify the elementary processes of reaction progression, including element transfer and solid volume change, microstructural evolution, and changes in hydraulic properties (porosity and permeability) due to these processes. We then link the natural microstructure of high-pressure metamorphic rocks with hydrothermal experiments under low-pressure conditions, incorporating mineral–solution equilibrium calculations along subduction zones, to investigate the influence of fluid chemistry on seismic phenomena in subduction zones.

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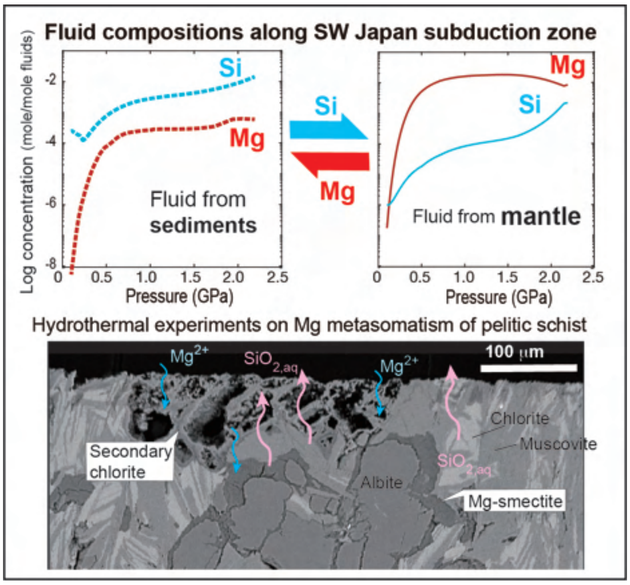


Figure : (top) Fluid compositions in equilibrium with sediment and mantle rock calculated for the SW Japan subduction zone and (bottom) an example of Mg-metasomatism of pelitic schist formed in a hydrothermal experiment.

Publicly Offered Research in Group A01

The transition between slow and fast earthquakes as a first-order phase transition

Takehito Suzuki (Department of Physical Sciences, Aoyama Gakuin University)

To establish whether repeating slow earthquakes can lead to fast earthquakes is important from both seismological and societal viewpoints. This behavior could be described as a transition from a slow to fast earthquake. Moreover, as both types of earthquake can be considered to belong to different phases, the difference between these phases is also a transition. We report the analysis of this transition using a simple spring-block model and the interactions among heat, fluid pressure, and porosity. First, we found a function $F(u_f)$ of the slip u_f for a single earthquake that has a double-well form and passes the origin. In addition, as all of the maxima are in the region of $u_f>0$, there are three (one) positive solutions when the maxima are positive (negative). In brief, the three-solution case corresponds to a slow earthquake, whereas the one-solution case corresponds to a fast earthquake. We conclude that the difference between the two types of earthquake is a first-order phase transition. In particular, the fluid pressure p_0 and porosity ϕ_0 on the fault plane at the onset of slip determines which phase emerges. We were also able to draw the boundary of the phase transition in p_0-ϕ_0 space to a certain approximation. We consider that the approximation should be applicable for many natural fault zones.

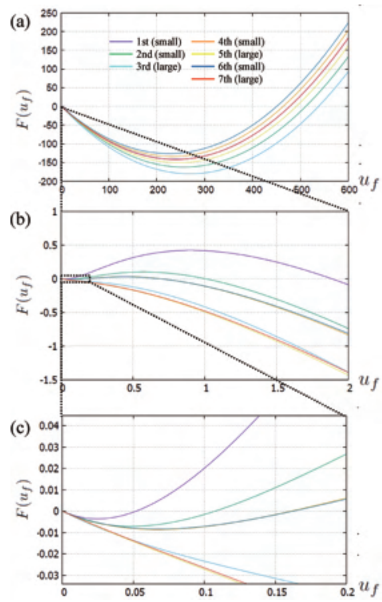


Figure : Functional form of $F(u_f)$. Curves were drawn using the values of p_0 and ϕ_0 for seven slips under a certain initial condition, where the 1st, 2nd, 4th, and 6th slips were slow earthquakes and the 3rd, 5th, and 7th were fast earthquakes. As seen in (a) and its enlarged diagrams (b) and (c), the maxima are positive for the slow earthquakes and negative for the fast earthquakes. The curves for the 4th and 6th earthquakes almost overlap unexpectedly.

Publicly Offered Research in Group A01

Estimations of silica transport in slow-to-fast seismogenic zones using geochemical machine-learning

Masaoki Uno (Tohoku University)

The precipitation of silica (SiO_2) in rock fractures is one of the main controls on the recurrence of slow and fast earthquakes. However, the distribution of the amounts of silica transport in slow-to-fast seismogenic zones has not been clarified systematically.

By combining a global geochemical database of sediments with machine-learning and chemical analyses of metasediments, this study quantifies the amounts of silica transport across slow-to-fast seismogenic zones. Quantification of the amount of silica transport requires comparison of the compositions of the present rock with its protolith (i.e., the rock before alteration). However, as the exact protolith of a rock sample no longer exists, it is difficult to quantify silica transport. In this study, we developed a protolith reconstruction model (PRM) that predicts protolith compositions from those of metamorphosed sediments, utilizing the contents of low-solubility elements whose contents remain stable during metamorphism, such as Ti, Th, Zr, and Nb.

We have applied our PRM to metasediments of the Shimanto accretionary rocks and Sanbagawa metamorphic rocks. Our results suggest that the amount of silica transport differs between these two geological units. We are further analyzing global trends in silica transport from a geochemical compilation and the modes of silica transport from field surveys.

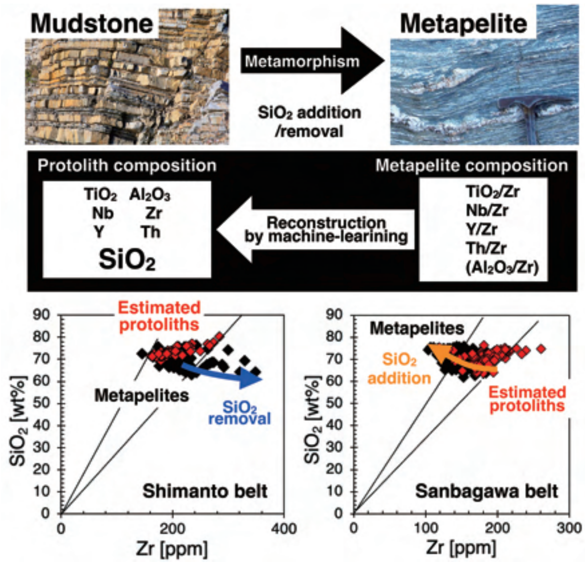


Figure : Quantification of the amount of silica transport using geochemical machine-learning. (Upper) Conceptual depiction of the protolith reconstruction model. SiO_2 content in the protolith is estimated from the elemental ratios of TiO_2, Zr, Nb, Y, and Th, which are essentially immobile during metamorphism. (Middle) Application of the model to metasediments in the Shimanto belt. The metasediments are depleted in SiO_2 compared with the estimated protoliths, showing silica depletion during metamorphism. (Lower) Application of the model to metasediments in the Sanbagawa belt, showing silica enrichment during metamorphism.

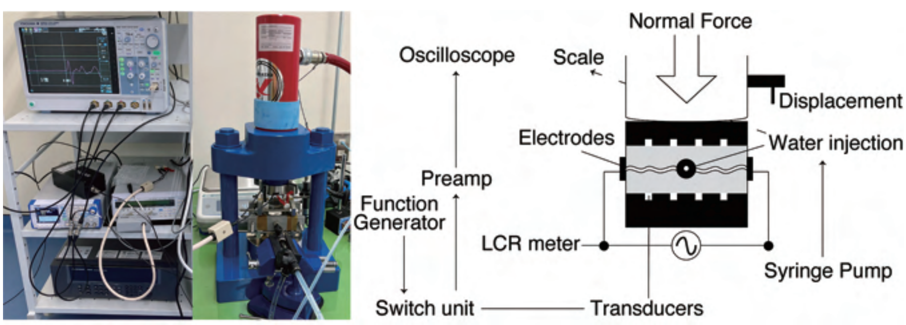
Publicly Offered Research in Group A02

Measuring rock physical properties that control permeability

Kazuki Sawayama (Graduate School of Science, Kyoto University)

Although crustal fluids may be associated with the occurrence of slow earthquakes, we have been unable to visualize the actual subsurface flow. Fluid flow is closely controlled by subsurface structure, meaning that indirect estimation using geophysical observations such as seismic velocity and electrical resistivity is appropriate. However, in complex subsurface structures such as faults, the relationship between rock physical properties (seismic velocity and electrical resistivity) and permeability is not well understood. In this study, an experimental system was developed to simultaneously measure permeability, seismic velocity, and electrical resistivity at elevated normal stresses against a fault plane through which water flows (Figure).

In the experimental system, the flow fields are channeled, and the resistivity changes accordingly with increasing stress. The 32-transducer miniature seismic survey showed that seismic velocity correlates closely with local asperities on fault surfaces. The characteristic structures derived from these properties (local flow and asperities) have the potential to increase pore pressure, which could be related to the occurrence of tremor. This hypothesis will be further evaluated by the computer modeling of a large-scale (1 km × 1 km) fault.



◀Figure : Simultaneous measurement system for rock physical properties of faults. The locations of the instruments of the system outline (right) correspond to those in the photograph (left).

Publicly Offered Research in Group A02

Subduction zone fluids and deep tremor

Tatsuhiko Kawamoto (Faculty of Science, Shizuoka University)

The nature and role of aqueous fluids in subduction zones remain enigmatic. Since the discovery of saline fluid inclusions in the Pinatubo mantle xenoliths, I have proposed seawater-like NaCl- and CO2-bearing fluids as subduction-zone fluids. The salinity results in high concentrations of dissolved CO2 and Pb in these fluids. A cross-section showing the salinity variation in fluids of a composite subduction zone based on data collected from several arcs (Figure) reveals that these fluids are more saline than seawater. When fluids enter the mantle wedge at 1000°C, magmas are produced; below 600°C, fluids produce the Arima-Takarazuka hot springs in the forearc. At cooler temperatures, hydration and carbonation occur at the base of the mantle wedge. Talc and magnesite can be formed in a certain pressure and temperature range, between 400°C at 30 km deep and 600°C at 90 km deep. coinciding with the regions of deep tremor in the Nankai and North Cascadia arcs. Deformation experiments involving talc and magnesite are anticipated to be conducted soon. Subduction zone fluids are associated with magmatism, hot springs, and deep tremor, suggesting the importance of fluid salinity in generating these phenomena.

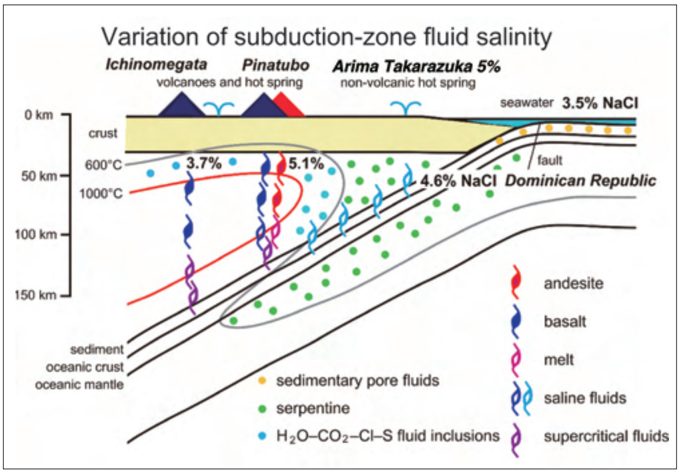


Figure : Variation in fluid salinity along a cross-section of a composite subduction zone.

Publicly Offered Research in Group A02

Elucidation of the internal structures and formation mechanisms of the seismogenic zone of Japan, based on a field survey

Yusuke Shimura (Geological Survey of Japan, AIST)

Recent studies have clarified that various types of slip occur in seismogenic zones, and it is important to understand slip phenomena at various depths in slow-to-fast slip regions (Figure). However, ocean drilling is limited to depths of a few kilometers, preventing the investigation of slip materials in the full depth range of seismogenic zones. Accretionary complexes and high-pressure metamorphic rocks are widely exposed in the Cretaceous seismogenic zone of the Japanese Islands, and these complexes and rocks are important analogs of slips that occur in the present seismogenic zone of Japan. We conducted a field survey of the Cretaceous shallow and deep accretionary complexes (estimated depths of formation of 5–15 and 15–20 km, respectively) and high-pressure metamorphic rocks (estimated depth of formation of 20–35 km) on the Kii Peninsula (Figure). The aim of this study is to clarify the following points: (1) How does the slip mechanism change in response to changing depth? (2) What are the materials that cause slip? (3) What are the characteristics of the internal structures in the seismogenic zone? One outcome of the study is the generation of a geological map at a scale of several tens of kilometers, which gives insights into slip materials and mechanisms in the seismogenic zone and provides a basis for future research into slow-to-fast earthquakes on the Kii Peninsula and other areas.

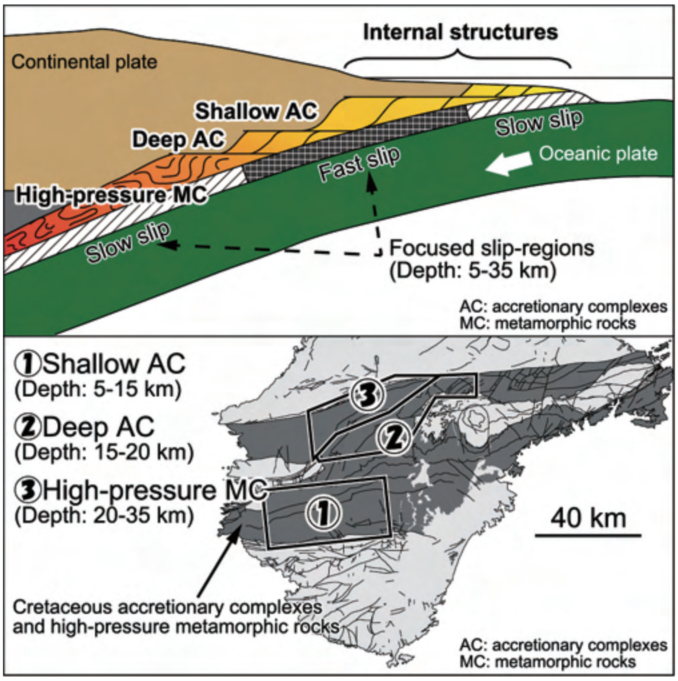


Figure : (Upper) Internal structures of the seismogenic zone of Japan and (lower) distribution of Cretaceous accretionary complexes and high-pressure metamorphic rocks on the Kii Peninsula.

Publicly Offered Research in Group A03

Detection of crustal deformation around plate collision zones by high-resolved strain rate mapping

Ryosuke Doke (Graduate School of Science and Technology, Hirosaki University)

Plate-collision zones are locations where large earthquakes occur; therefore, it is important to understand the tectonic processes of these zones and clarify the characteristics of these large earthquakes. This understanding requires investigation of crustal deformation that occurs both steadily and transiently in plate-collision zones. However, the spacing of existing GNSS stations is inadequate for understanding the highly complex deformation processes of plate-collision zones. This study examines the Izu collision zone, which is located at the front of the collision of the Izu Peninsula on the Philippine Sea Plate with the Honshu arc and is a region in which complex phenomena have been observed. We note that transient crustal deformation sometimes occurs in this region. In this study, we attempt to estimate high-resolution crustal strain rate fields in the Izu collision zone by integrating GNSS data, including our original sites and newly developed networks constructed by private companies, as well as interferometric SAR time series analysis results.

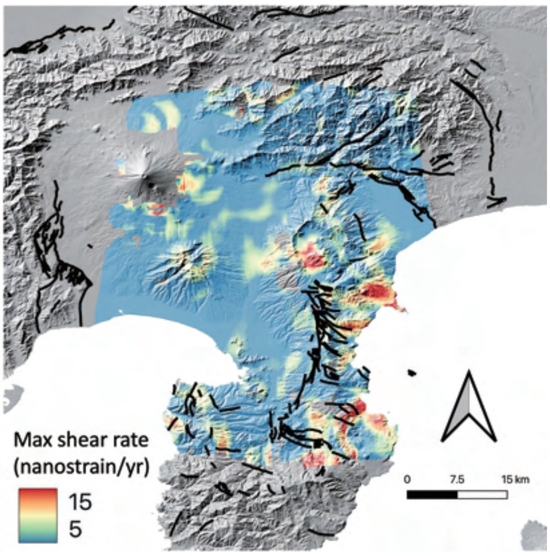


Figure : Maximum shear strain rate field estimated from GNSS and interferometric SAR time series analysis results. The field represents a preliminary result.

Publicly Offered Research in Group B01

Improvement of measurement accuracy of the conditions of slow-slip spatiotemporal transitions

Yuya Machida (Research Institute for Marine Geodynamics, JAMSTEC)

Slow-slip events in the Nankai Trough have been studied using land-based borehole strain gauges, which have successfully detected both deep and shallow slow-slip events. However, the accuracy of borehole measurements can be jeopardized by the expansion and cracking of cement in bedrock and the presence of water in surrounding aquifers. Developing an understanding of the environmental changes around borehole observatories may enable more accurate measurements to be made. In this study, we propose to install distributed optical fiber strainmeters at borehole observatories in order to understand environmental changes and to improve measurement accuracy within the observational bandwidth for slow slip. The distributed fiber optic strainmeter can measure strain changes at arbitrary points along the entire length of a borehole and is expected to enable the monitoring of local environmental changes, such as minute changes in temperature and groundwater flow due to rainfall and changes in atmospheric pressure. Furthermore, we will advance the measurement of strain by developing and using distributed optical fiber strainmeters and comparing observations between these optical fiber strainmeters and borehole strainmeters.

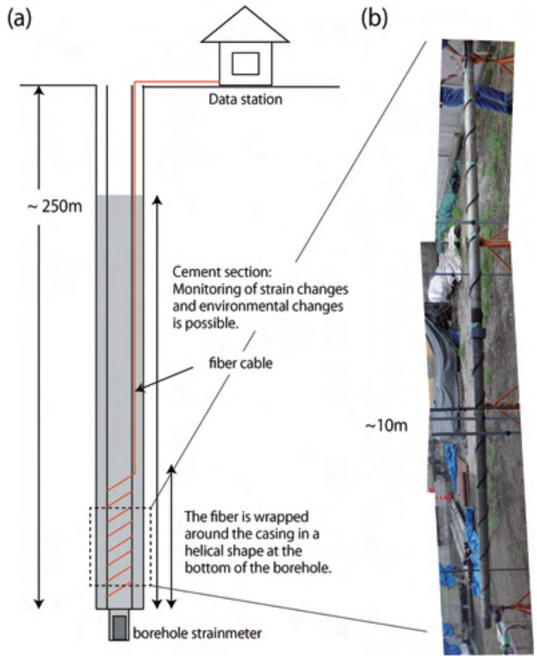


Figure : (a) Schematic diagram of the installation of a distributed optical fiber strainmeter. (b) Confirmation test of the fiber optic cable wrapped section at the bottom of a borehole.

Publicly Offered Research in Group B02

Forecasting slow earthquake activity

Tomoaki Nishikawa (Disaster Prevention Research Institute, Kyoto University)

Slow earthquakes are closely related to the occurrence of fast (ordinary) earthquakes. For example, slow earthquakes are known to sometimes trigger megathrust earthquakes and swarms of fast earthquakes. Furthermore, earthquake cycle simulation studies have identified the possibility of changes in slow earthquake activity prior to the occurrence of large earthquakes. Therefore, understanding and forecasting slow earthquake activity is essential for improving the accuracy of fast earthquake forecasts. However, there is currently no standard model that successfully describes slow earthquake activity. As such, it is currently challenging to forecast future slow earthquake activity.

This study involves the development of a new model that can successfully describe and forecast slow earthquake activity. Specifically, I am developing a statistical model that successfully describes low-frequency earthquake activity in the Nankai subduction zone. In this research, I have formulated an empirical equation that successfully describes the temporal variation in the frequency of aftershocks (subsequent low-frequency earthquakes) of a low-frequency earthquake. This empirical formula corresponds to Omori–Utsu's law for aftershocks of fast earthquakes. I will further improve my slow-earthquake forecasting model using this new empirical equation.

Empirical formula for aftershock frequency of low-frequency earthquakes $h(t)$:

$$h(t) = \frac{f(t)}{1 - F(t)}$$

$$f(t) = \frac{\phi_1}{\sqrt{2\pi}\sigma_1 t} \exp\left\{-\frac{(\log(t)-\log(\mu_1))^2}{2\sigma_1^2}\right\} + \frac{\phi_2}{\sqrt{2\pi}\sigma_2 t} \exp\left\{-\frac{(\log(t)-\log(\mu_2))^2}{2\sigma_2^2}\right\}$$

$$F(t) = \int_0^t f(t')\,dt'$$

$\mu_1, \mu_2, \sigma_1, \sigma_2, \phi_1$, and ϕ_2 are parameters.

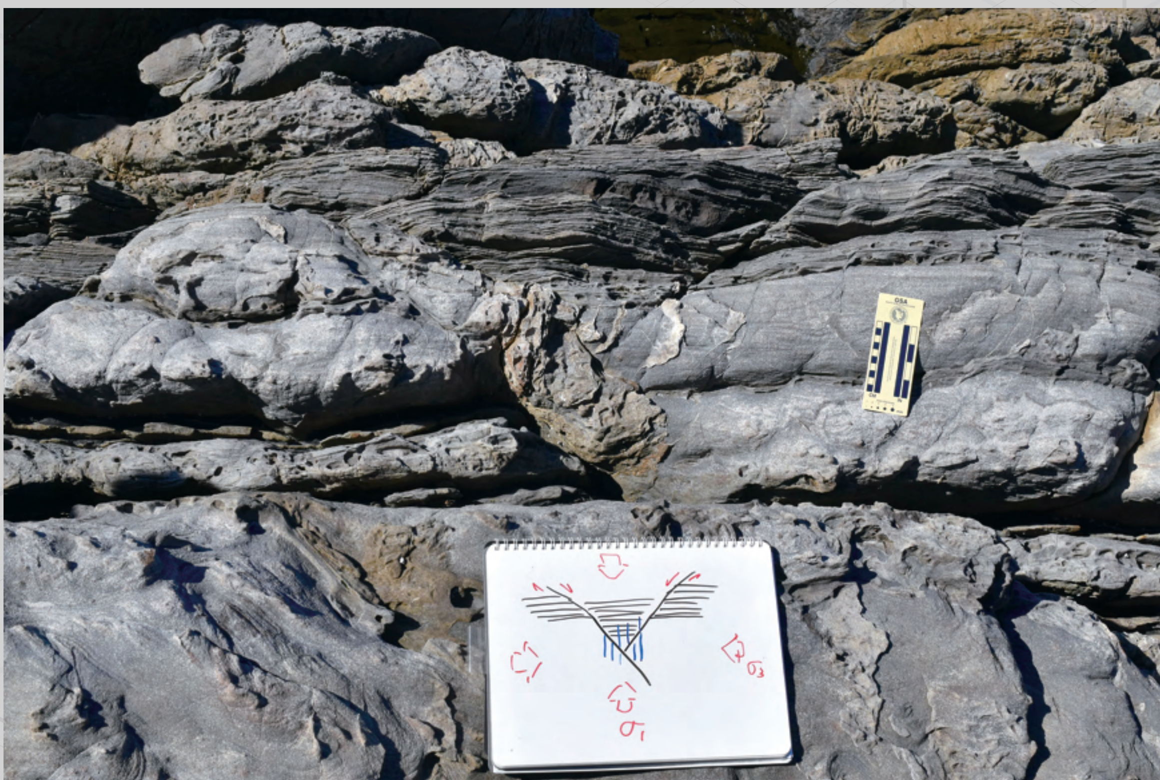
Empirical formula for aftershock frequency of fast earthquakes $h(t)$:

Omori-Utsu's law

$$h(t) \propto \frac{1}{(t + c)^p}$$

c and p are parameters.

Figure : Empirical formulae for the temporal variation in aftershock frequency of low-frequency and fast earthquakes (top and bottom, respectively).



Mineral veins and conjugate faults showing mutually crosscutting relationshops, interpreted to have been formed under the same stress field. Cape Muroto, Kochi Prefecture. (Photo taken by Asuka Yamaguchi)

A01・A02 - RC

Hanaya Okuda

Researcher, Kochi Institute for Core Sample Research, JAMSTEC

Specialty: Experimental rock deformation
Keyword: Friction, Accretionary complex, Fault

A02 - RC

Diana Mindaleva

Assistant Professor, Graduate school of Environmental Studies, Tohoku University

Specialty: Geology, Petrology
Keyword: Short fluid infiltration timescales, Geochemical modelling

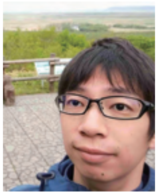
A02 - RC

Hinako Hosono

Researcher, Geological Survey of Japan, AIST

Specialty: Geomechanics
Keyword: Crack, Experimental study, Field survey

A03 - RC

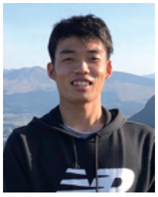


Yasunori Sawaki

Postdoc, Geological Survey of Japan, AIST

Specialty: Seismology
Keyword: Earthquake fault geometry, Clustering, Crustal structure, Receiver function, Eafloor observation

A03・B01 - RC



Tomohiro Inoue

Postdoc, Institute of Industrial Science, The University of Tokyo

Specialty: Geodesy
Keyword: Seafloor crustal deformation, Slow slip

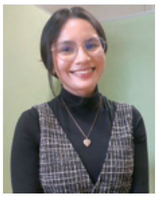
A03 - RC

Nobuaki Suenaga

Postdoc, Research Center for Earthquake Hazards, Disaster Prevention Research Institute, Kyoto University

Specialty: Solid earth physics
Keyword: Subduction zone, Thermomechanical modeling, Interplate earthquake

A03 - RC



Erika Jessenia Moreno

Research Associate, Research Center for Urban Safety and Security, Kobe University

Specialty: Geodynamics
Keyword: Subduction, Computational modeling, Philippine sea plate, Subduction history

B02 - RC

Lina Yamaya

Affiliation: Special Researcher, NIED

Specialty: Marine seismology
Keyword: Seismic waveform analysis, Focal mechanism, Seismic velocity structure

B02 - RC

Taku Ueda

Postdoc, Disaster Prevention Research Institute, Kyoto University

Specialty: Statistical Seismology
Keyword: Seismicity, Crustal deformation, ETAS model

B03 - RC

Daisuke Sato

Researcher, Research Institute for Marine Geodynamics, JAMSTEC

Specialty:Fault mechanics, Seismology
Keyword: Rupture simulations, Fault friction, Bayesian inference

B03 - RC

Tetsushi Watanabe

Deputy General Manager, Earthquake & Soil Dynamics Research Department, Kobori Research Complex Inc.

Specialty: Earthquake Engineering
Keyword: Earthquake ground motion estimation, Seismic wave propagation analysis

International Joint Workshop on Slow-to-Fast Earthquakes 2023

Oral presentation at Ito Hal

International Workshop at The University of Tokyo

Satoshi Ide, Graduate School of Science, The University of Tokyo

The International Joint Workshop on Slow-to-Fast Earthquakes 2023 was held at Ito Hall, Ito International Research Center, Hongo Campus, The University of Tokyo, Japan, from 13 to 15 September as a conference with hybrid oral sessions and on-site poster sessions. There were 158 attendees on-site, with participants from many countries, including Taiwan, the US, France, and Italy, and an additional 71 participants online. This year's workshop focused on three topics: "Slow-to-Fast Earthquakes around Metropolitan Areas," "Connecting Geophysical and Geological Timescales of Slow and Fast Earthquakes," and "Comparative Convergentology on Slow-to-Fast Earthquake Science." There were 36 oral presentations (including six keynote presentations related to the special topics) and 79 poster presentations, sparking various discussions. On the second day, breakout sessions facilitated lively debate on various issues, such as research directions, young researcher development, and international collaboration in small groups. The graduate-student-led campus tour on the third day was also successful. On the day before the workshop, approximately 50 young researchers gathered for a special discussion event, and a field trip to the Boso Peninsula was conducted on 16 September, during which participants explored marine terraces in the southern part of the peninsula.

Post-meeting field trip: Geomorphic record of the Great Kanto Earthquakes in the southern part of Boso Peninsula

Asuka Yamaguchi, Atmosphere and Ocean Research Institute, the University of Tokyo

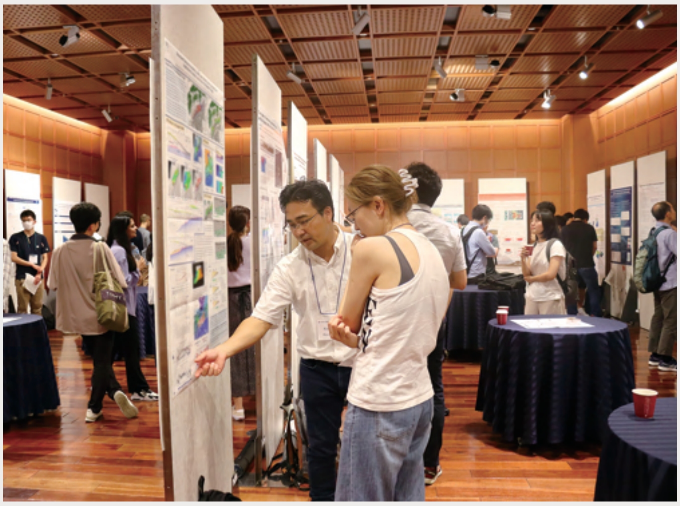
On 16 September, the day after the International Joint Workshop, a field trip to the southern part of the Boso Peninsula was conducted under the guidance of Dr. Junki Komori (Nanyang Technological University, Singapore) and Dr. Ryosuke Ando (The University of Tokyo). Thirty-seven participants traveled in one large bus. On the coast of Kenbutsu, Tateyama City, uplift caused by the two Kanto earthquakes of Genroku and Taisho was observed as represented in the topography of the area. After lunch at Nojimazaki, we visited Shirahama, Minami-Boso City, where it was explained that the amount of uplift varied from east to west across Boso Peninsula. In Chikura, Minami-Boso City, which was the final field-trip stop, we walked along three terraces that have recorded uplift caused by more ancient earthquakes. During the trip, submarine landslide deposits and turbidite layers found in the strata exposed on the terrace faces were also discussed from a sedimentological point of view. Although it was the first day of a consecutive holiday weekend, there were no traffic jams, despite the prior concern. The day was very warm, and the interdisciplinary discussions on geodesy, topography, and geology were lively in a relaxed atmosphere.

Group photograph at Kenbutsu Beach; the second and third rows of participants are standing on the marine terraces uplifted by the 1923 and 1703 Kanto earthquakes, respectively.

Embracing a Familial Vibe at the Academic Meeting

Novia Anggraini, Institute of Seismology and Volcanology, Hokkaido University

This was my first time participating in a Slow-to-Fast Earthquake meeting. It is always thrilling to attend an academic meeting for the first time; however, this meeting had a family feel, which made me comfortable being a part of it. I had a presentation on the first day. I could see that the committees had prepared everything well, meaning that I could present my topic smoothly. I learned new information from other presentations, heard new terms, gained knowledge about new approaches, and became aware of recent developments in the study of slow earthquakes. One of my favorite sessions in this workshop was the group discussion. I joined a group discussing a topic that I considered relevant to me: “International Joint Research with Developing Countries”. In this group, we discussed the problems that we thought had become obstacles in conducting joint research with developing countries and proposed some solutions. As a young researcher, this session was beneficial in broadening my point of view on the research world in general, and on slow earthquake research specifically. On the second day, I visited the Earthquakes Research Institute (ERI) and heard an explanation of the construction of that earthquake-resilient building and also visited the seismograph museum. This meeting provided valuable and practical knowledge. I hope the science of slow-to-fast earthquakes and this meeting continue to generate innovative thinking and approaches for the scientific and other communities.



Discussions in front of poster presentations

Reports of the International Joint Workshop in Tokyo

Matt Ikari, Marum, University of Bremen

The International Joint Workshop on Slow-to-Fast Earthquakes took place Sept. 13-15 in Ito Hall on the University of Tokyo. Ito Hall was a perfect venue, an impressively designed high-ceilinged building fit for an award ceremony. Among the roughly 150 participants was a good mix of scientists, mostly several students and early career researchers, along with some very prominent and well-respected leading scientists. The meeting itself was quite well structured, with longer keynote talks for invited speakers and shorter more “standard” length talks. There was ample time reserved for poster viewing, and the poster hall was well populated and the science was high quality. Thematically, there was a good mix of observational geophysics, numerical simulations and laboratory studies, but the tremendous amount of seismologic and geodetic observations was impressive and clearly the current driving force of slow-to-fast earthquake science. An organized set of breakout sessions to discuss other topics, such as machine learning, social aspects of slow-to-fast earthquakes, the state of earthquake prediction, and current knowledge gaps in slow-to-fast earthquake science was a welcome part of the program, and I believe that this aspect of the workshop should be built on for workshops in the future. The meeting was a fantastic blend of cutting edge science from leaders in the field and new developments driven by young researchers, and all conversations were enjoyable.

Discussions in the breakout sessions

Self-invited workshop on SF Earthquakes Science in Taiwan

Slow-to-Fast Earthquake Workshop in Taiwan

Yoshihiro Ito, Disaster Prevention Research Institute, Kyoto University

The self-invited workshop entitled "Slow-to-Fast Earthquake Workshop in Taiwan" was held during 13–14 March 2023 at National Cheng Kung University in Tainan City, southern Taiwan. After oral/ poster presentations and breakout sessions for collaborative research, the workshop was followed by a field trip from 15 to 17 March. The trip included a visit to a mud volcano in Kaohsiung, a creep fault in Taitung, and the observation facilities of the Milun fault Drilling and All-inclusive Sensing project (MiDAS) in Hualien. A total of 127 participants attended the workshop, including 39 from Japan. In late February, before this workshop, three researchers from Group B01 also gave lectures at Cheng Kung University, Yang-Ming Jiao Tong University, and Academia Sinica Institute of Earth Sciences, taking advantage of the framework of bilateral exchange between Japan and Taiwan regarding new technologies. Through these exchanges, researchers and students from both Japan and Taiwan deepened exchanges while introducing the latest research and technological developments being conducted in their respective fields.

The workshop was broadcast on TV in Taiwan.Please check it on YouTube. (https://www.youtube.com/watch?v=byIcAu_XcN 8)
The website for the workshop:
https://youb1707.wixsite.com/2023-sf-eq-tw

Group photograph at the front of the building of the International Conference Room, National Cheng Kung University

Report on the self-invited workshop entitled "Slow-to-Fast Earthquake Workshop in Taiwan"

Yusuke Shimura, Geological Survey of Japan, AIST

The "Slow-to-Fast Earthquake Workshop in Taiwan" was held on 13 and 14 March at the National Cheng Kung University, Tainan. After recovering from the COVID-19 pandemic, many Japanese participants were on their first visit abroad on business for several years. This workshop centered on three main topics, namely, "the Ryukyu subduction zone", "Creeping faults", and "Emerging technology". Researchers and students with various scientific backgrounds engaged in numerous discussions during the oral and poster presentations. The most inspiring aspect was the discussion on Japan–Taiwan international joint research collaboration. Japan and Taiwan have different seismogenic systems (Japan: subduction type; Taiwan: collision type), and workshop participants discussed the differences in the processes of earthquake generation and geological records in these two systems.

Active structures associated with earthquakes (field trip)

A field trip was conducted from 15 to 17 March and included observations of geology and active structures in Taiwan and a visit to the Milun fault Drilling and All-inclusive Sensing project. This was a valuable introduction to the geology and formation processes of mountains and their relationship to earthquakes. Several geological phenomena remain unanswered, which allowed me to consider my own further research.

Report on Cargèse 2023 School on Subduction Zone Processes

Why am I in Corsica?

Nishizawa Takashi, Graduate School of Faculty of Science, Kyoto University

Nishikawa-sensei (DPRI) introduced us to this event by saying "go and see the highest in this field”. Apparently, when he was a Ph.D. student, he had attended this summer school and was very impressed by the international researchers. Hearing that, I decided to go abroad for the first time in my life.

The weather in Corsica was perfect, and we were able to spend two days touring the rock exposures and shear zones formed by subduction (see photograph). In particular, the mechanism involved in the uplift of the duplex structure to the surface was very interesting, as it was related to my research theme (landform formation of island arcs).

During the summer school, nearly 100 researchers gave presentations on subduction zones. On the second day, I also gave an oral presentation, and I was able to join discussions with foreign Ph.D. students and professors from overseas. Okuda-san (Kochi JAMSTEC) and other Japanese researchers who are working abroad have a huge passion for scientific research. I will never forget this experience.

I am extremely grateful for being supported through my travel expenses for the summer school. It was of great benefit to me to learn more about subduction-zone formation and the scientific approaches used by researchers involving both fieldwork and experimental work. I will continue to do my best in my research.

Greenschist shear zone in the Tenda massif, Corsica

Mini self-invited workshop on SF Earthquake Science in Italy

Report on the “Mini self-invited workshop on SF Earthquake Science” at the University of Pisa, Italy

Kohtaro Ujiie, Graduate School of Science and Technology, University of Tsukuba

The mini self-invited workshop on SF Earthquake Science was held at the University of Pisa, Italy, on 18 October 2023. From the Japanese side, Yoshihiro Ito, the principal investigator of Group A03, myself (Ujiie), a research associate of Group A03, and Tatsuhiko Kawamoto, a research collaborator of Group A02, and his student (Yosuke Osawa) participated in the workshop, and from the Italian side, a total of six faculty, undergraduate, and graduate students specializing in structural geology and seismology attended. The Japanese participants presented the results of geological, seismological, and geochemical studies on slow earthquakes in subduction zones, and the Italian participants presented the results of studies of tectonics and fluid migration in continental collision zones, induced earthquakes, and seismic observations in Italy. Generous times allotted for each presentation allowed lively discussions to take place. The workshop led to the launch of two collaborative research projects based on geology and seismology between Japan and Italy, which will confirm the close link between the two sides into the future. We thank Dr. Francesca Meneghini and all the participants for their kind cooperation in organizing the workshop.

Mini self-invited workshop on SF Earthquake Science at the University of Pisa, Italy

Visiting researcher program for young researchers

Report on the visiting researcher program for young researchers (Earth Observatory of Singapore)

Mari Hamahashi, Faculty of Global and Science Studies, Yamaguchi University

I had the opportunity to visit the Earth Observatory of Singapore, Nanyang Technological University, during 10–24 February 2023. The purposes of this visit were 1) to conduct an integrated analysis of the distribution of incoming sediments along the Sunda megathrust offshore Northern Sumatra drilled during International Ocean Discovery Program Expedition 362 in relation to the geology of the forearc accretionary prism, and 2) to create a 3D visualization platform for teaching materials on subduction zones. During my stay, I collaborated with Drs. Shengji Wei, Aron Meltzner, Lujia Feng, Lauriane Chardot, and Research Assistant Victoria Khoo to discuss the characteristics of seismic events and geological structures in the Sunda Trench based on knowledge of the Sumatran GPS Array network, the seismic observation network in northern Sumatra, geological maps of the forearc islands, and paleoseismological data, and compared the Sunda features with those of the Nankai Trough and the Japan Trench. I also worked on the effective visualization of geological data, including exploring 3D tools for teaching materials in educational settings. During my visit, I was able to lay the groundwork for a new joint research project and proposal writing. I express my gratitude to the "Science of Slow-to-Fast Earthquakes" project for supporting my overseas trip.

Seminar with Dr. Shengji Wei's research group (Author: front left)

Visit to Caltech Seismological Laboratory

Ritsuya Shibata, Department of Earth and Planetary Sciences, School of Science, Tokyo Institute of Technology

From October 2022 to February 2023, I visited the Seismological Laboratory, California Institute of Technology (Caltech), to collaborate with Dr. Weiqiang Zhu and Dr. Zachary E. Ross. We launched a new research project on the validation of models of fault-rupture initiation. To achieve this, we applied the machine learning method "PhaseNet", which was developed by Dr. Zhu, to foreshock detection and investigated foreshock activity using a stochastic method. Dr. Zhu was of great help in the application of the machine learning method, and Dr. Ross provided advice on how to evaluate the detected foreshock sequences. This research project is ongoing.

This stay allowed me to deepen my knowledge of the latest techniques and research in seismology through discussions with researchers at Caltech and at other universities in California. This valuable experience has benefited me as a scientist and will shape the type of research that I wish to do in the future. I express my deep gratitude to all the people involved in Slow-to-Fast Earthquakes who supported me before and during this stay, especially the secretariats.

Dr. Zachary E. Ross (left) and me

Promoting study activity of early career scholars and diversity

Early-career event prior to the international workshop

Hanaya Okuda, Kochi Institute for Core Sample Research, JAMSTEC

Prior to the International Joint Workshop on Slow-to-Fast Earthquakes 2023 held at the University of Tokyo, we organized an event for students and early-career researchers on 12 September 2023 at the Earthquake Research Institute. Forty on-site participants and ten online participants from various scientific backgrounds joined the event. We had two lectures entitled "Comparative studies on subduction zones: structures of seismogenic zones and seismic activity from seismic observations" by Dr. Arai (JAMSTEC) and "Geologic records of fluid activities and rock fracturing in deep plate boundaries" by Assoc. Prof. Uno (Tohoku University) regarding the characteristics of seismic wave velocity structures in various subduction zones and fluid behavior in deep regions and its relationship to slow earthquakes. As the lectures encompassed fundamentals and up-to-date results, we were able to deepen our understanding of subduction zone processes, which was beneficial for the following workshop. After the lectures, we had a poster session in which 11 posters were presented in the lounge of the Earthquake Research Institute, including discussion of seismic phenomena among the participants.

Poster session

Annual report from the Young Researchers and Diversity Promotion Task Force

Saeko Kita
Building Research Institute

As a member of the Young Researchers and Diversity Promotion Task Force, here I provide an annual report. As reported in the previous section, young researchers in this science project successfully held an in-person discussion event for young researchers and students in September, just before the international workshop at the University of Tokyo. During the in-person event, there were various requests and conversations about the Task Force. An event in response to one of the requests will be held in late fall. The upcoming event will provide the opportunity for 30-minute research discussions between overseas researchers and young researchers involved in the project. Professor Anne Socquet (Université Grenoble Alpes, France) and Professor Alex Schubnel (Ecole Normale Superieure) will attend individual discussions for each young researcher who has requested to have a 1-on-1 discussion via Zoom. All events run by this Task Force are held to encourage activities in this project with respect to diversity among participants.

Extended group meeting

Extended Group Meetings

Asuka Yamaguchi, Atmosphere and Ocean Research Institute, the University of Tokyo

Group A02 has been holding online seminars (regular group meetings) in the morning of the first Tuesday of each month. In August and September 2023, we held extended regular meetings for all project members to discuss two topics: "The thickness of plate-boundary fault zones and their depth variation" and "The a–b values of slow earthquakes". We believe that the discussions during the extended regular meetings were useful in organizing our knowledge for the International Joint Workshop in Tokyo in September.

On 27 and 28 November, a joint meeting of Groups A01 and A02 was held at the Kochi Core Center. There were 14 presentations on theoretical, experimental, observational, and field studies over the two days, which stimulated engaging discussion. The afternoon of the first day of the meeting involved a tour of the marine core repository of the International Ocean Discovery Program (IODP), a demonstration of a sandbox experiment and structural analysis of the sandbox using X-ray CT (by Dr. Satoshi Tonai and his students), and a demonstration of a high-velocity friction experiment and an introduction to rock-deformation machines by Drs. Hanaya Okuda and Takehiro Hirose.

We hope to continue to hold events that transcend the boundaries of groups in efforts to further stimulate and encourage collaboration and joint research between groups.

Tour of the marine core repository at Kochi Core Center (27 November)

Hot spring camp

Hot-Spring Camps in 2023 – Beppu and Hakone

Yoshihiro Ito, Disaster Prevention Research Institute, Kyoto University

Group A03 organized two camp-style meetings in 2023. The first meeting was held at Kamenoi Hotel in Beppu City on 9–11 February and was attended by 28 participants, including attendees from Groups A02, B01, and B03. The speakers were asked to report on their research progress and provide introductory lectures on each topic for students. Consequently, the students who attended the meeting commented that they found the presentations easy to understand and comprehensible.

Seminar room in Kamenoi Hotel, Beppu

The second meeting was held on 26–27 August at the Kanagawa Institute of Hot Spring Geosciences. Before the session, a short-term observation campaign was held by deploying five seismometers in northern Itoh City on 24–25 August. High strain rates have been reported from this area, as analyzed by Ryosuke Doke at the camp in Beppu. We set up five seismometers directly over the area and conducted temporary seismic observations for about five days. Fourteen people participated in the meeting and the observation campaign, including participants from Groups A02 and B02.

Extended group meeting

Geological field excursions organized by the A02 Group

Asuka Yamaguchi, Atmosphere and Ocean Research Institute, the University of Tokyo

The A02 Group organized three field trips in 2023 to gain a common understanding of the reality of slow-to-fast seismogenic zones in subduction zones. During the 12–16 May Kii Peninsula field trip (guided by Yusuke Shimura, 20 participants), we traversed the peninsula and observed various rocks and deformation structures in the Cretaceous plate boundary from deep to shallow regions. Outcrops of the Nanki-Kumano Geopark were also visited. During the 14–16 July Nobeoka field trip (guided by Makoto Otsubo and Asuka Yamaguchi, 18 participants), we discussed crack initiation and fluid movement in an ancient subduction zone from various perspectives in front of the outcrop of the Nobeoka Thrust, which is a fossilized megasplay fault. During the 24–26 November Mugi/Muroto field trip (guided by Yoshitaka Hashimoto, Satoshi Tonai, and Asuka Yamaguchi, 20 participants), we observed sedimentary and igneous rocks of the Shimanto Belt and discussed a range of topics from slow and fast deformation to the regional tectonics of the Cretaceous to Miocene plate boundary. The field trips were attended by mid-career and young researchers, as well as senior researchers, students, and several principal investigators of publicly offered research programs. We enjoyed lively discussions from diverse perspectives, including field, experimental, observational, and theoretical perspectives, and deepened friendships among participants.

Group photo of participants in front of the Nobeoka Thrust (July 15)

Lecture

A lecture event at the Nanki Kumano Geopark Center in Kushimoto Town, southwestern Japan

Building Research Institute
Saeko Kita

On 16 January 2023, I presented the 6th Nanki Kumano Geopark Center Lecture at the Nanki Kumano Geopark Center in Kushimoto Town, located at the southernmost tip of the Kii Peninsula, southwestern Japan. I presented a one-hour lecture entitled "Slow earthquakes, intraslab earthquakes, and the anticipated Nankai Megathrust earthquake." A total of 40 people attended this lecture. The lecture was aimed at general citizens, but several local government officials and staff of the Geopark also attended. The lecture was supported by sign language interpretation and written summaries (Photograph). I express my deep gratitude to everyone who was involved in the arrangements and made efforts to attend this event.

Photograph of the lecture by Saeko Kita at the Nanki Kumano Geopark Center in Kushimoto Town (16 January 2023)

Award

The Asahiko Taira International Scientific Ocean Drilling Research Prize
Takeshi Tsuji (A02: Co-investigator/University of Tokyo)

Best Paper Award of Seismological Society of Japan
Ayumu Miyakawa, Atsushi Noda and Hiroaki Koge
(A02: Collaborators/AIST)

The Geological Society of Japan Best Paper Award
Atsushi Noda (A02: Collaborator/AIST)

Ogawa prize of Japan Statistical Society
Takeru Matsuda (B02: Co-investigator/The University of Tokyo)

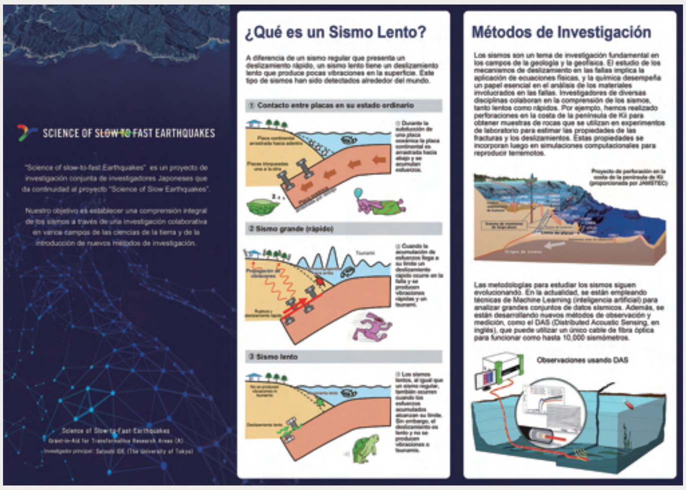
JpGU 2023 Outstanding Student Presentation Award
Koki Masuda (B03: Student/The University of Tokyo)
Takashi Nishizawa (B02: Student/Kyoto University)
Ritsuya Shibata (B03: Student/Tokyo Institute of Technology)
Mizuki Ueda (A03: Student/Tsukuba University)

The Geological Society of Japan Outstanding Student Presentation Award
Takahiro Hosokawa (A02: Student/Kochi University)
Taizo Uchida (A02: Student/Kochi University)
Manamu Miyazoe (A02: Student/Kyoto University)

The Seismological Society of Japan Outstanding Student Presentation Award
Rikuto Fukushima (Collaborator/Kyoto University)

Publication of Slow-to-Fast Earthquake Leaflet in Spanish

In 2022, we created a leaflet in both Japanese and English to introduce slow and fast earthquakes. In 2023, we additionally prepared the Spanish version for the upcoming self-invited workshop in Mexico, 2024. The pdf version is available on the Slow-to- Fast Earthquakes website. For the printed copies, please contact us from the Contact Form on the website.



Introduction of the Slow-to-Fast Earthquakes Official Social Networking Service (SNS)

We are posting announcements and reports of Slow-to-Fast Earthquakes events and seminars on X and Facebook, not only for those involved in Slow-to-Fast Earthquakes research but also for the general public. If you are involved in Slow-to-Fast Earthquakes research and have information that you would like to share, please contact the Slow-to-Fast Earthquakes Office at sfeq-post-group [at] g.ecc.u-tokyo.ac.jp. Photographs are also welcome!

Website Facebook X

Upcoming Events

Japan Geoscience Union Meeting 2024
Date: May 26 (Sun.)-31 (Fri.), 2024
Hybrid (in-person & online)
Venue: MAKUHARI MESSE, Chiba

International Joint Workshop on Slow-to-Fast Earthquakes 2024
Date: Sep. 17(Tue.)-19 (Thu.), 2024
Venue: B-CON PLAZA, Beppu, Oita

【Cover photos】
(Left) International Joint Workshop on Slow-to-Fast Earthquakes 2023
(Upper right) Field trip in the Nanki Kumano Geopark
(Lower right) Self-invited workshop on SF Earthquakes Science in Taiwan

Grant-in-Aid for Transformative Research Areas (A)
SCIENCE OF SLOW-TO-FAST EARTHQUAKES
Newsletter Vol.3
Date of issue 2024 March
https://en.slow-to-fast-eq.org