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INDEX

Towards understanding of the scale effect in high-velocity rock friction : Evolution of normal stress heterogeneity and instability due to thermoelastic effect

Hiroyuki Noda (Disaster Prevention Research Institute, Kyoto University)

Friction laboratory experiments constitute an important approach to understanding the mechanical properties of faults. However, there is a large difference in the length scale between laboratory samples and faults that host large earthquakes or slow earthquakes. Therefore, it is crucial to investigate the applicability of experimental results to natural faults and the upscale methodology of friction experiments. Marone and Kilgore (1993) experimentally showed that the characteristic slip displacement of the friction law increases for thick fault gouge, and Aochi and Matsu'ura (2002) proposed a friction law accounting for the evolution of fault roughness over a wide range of length scales. Rice (2006) suggested that the scaling between seismological fracture energy and earthquake size can be explained by frictional heating and associated thermal pressurization of pore fluid without consideration of fault roughness. The scale effect of high-velocity friction was experimentally investigated by Yamashita et al. (2015), who reported that larger samples showed dynamic weakening at lower slip rates. Those authors explained the result in terms of normal stress heterogeneity and associated concentration of frictional heating, which causes local activation of dynamic weakening.

Normal stress heterogeneity may be due to insufficient precision in the preparation of frictional surfaces. If this were the case, then the observed size effect might be suppressed by very careful surface preparation. In the field of tribology, growth of normal stress heterogeneity due to thermoelastic instability (TEI, e.g., Burton, 1980) at high slip rates has been studied. TEI yields a lower critical slip rate for heterogeneity of a longer wavelength. In this study, an efficient numerical algorithm was proposed for numerical simulation of TEI in a quasistatic two-dimensional problem (Figure a) based on a spectral boundary integral equation method. In simulations for heterogeneity of a single wavelength component, it approaches a steady state at low slip rates (V<Vcr; Figure b) and grows indefinitely at high slip rates (V>Vcr; Figure c). Under a high-velocity regime, regardless of the amplitude of initial heterogeneity in normal stress, the heterogeneity increases and ultimately causes local dynamic weakening in a region of stress concentration. Physical properties of gabbro yield Vcr~1 mm/s for a 0.1-m-wide fault and Vcr~10 mm/s for a 10-mm-wide fault, suggesting the existence of a size effect in commonly adopted conditions for laboratory experiments. Evaluation of thermoelastic effects in laboratory experiments (e.g., by monitoring the temperature distribution) deserves future study.

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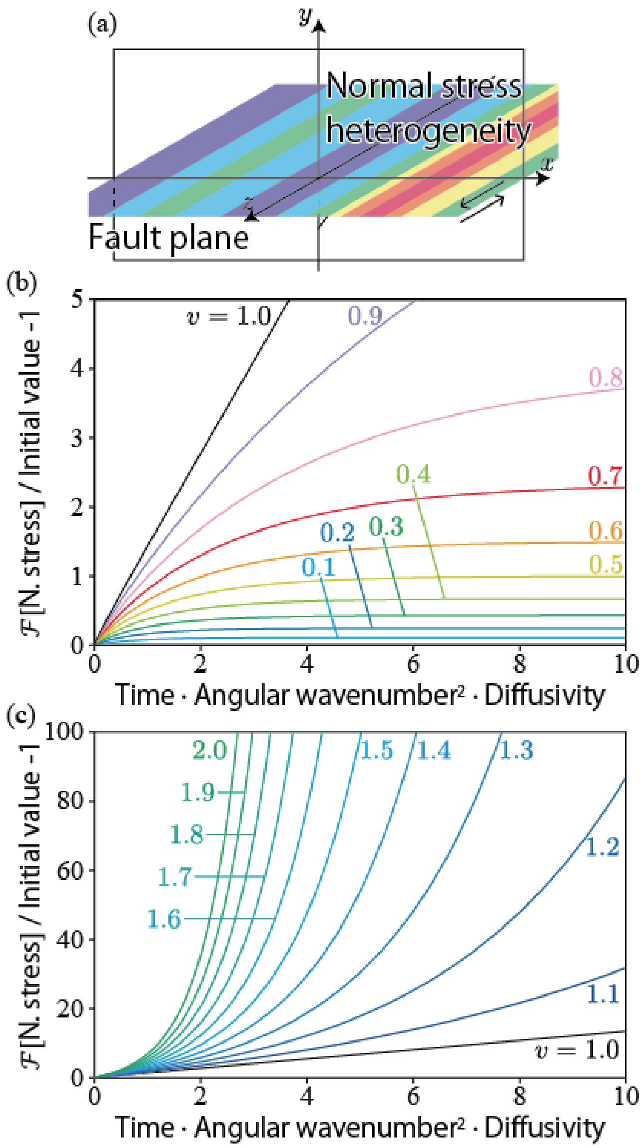

Figure: (a)A schematic diagram of the 2-dimenstional problem for a planar fault with heterogeneous normal stress. (b, c) Evolution of normal stress heterogeneity in the (b) low and (c) high slip rate regimes. V is the nondimensional slip rate V<Vcr.

Deformation patterns of an accretionary prism revealed by sandbox experiments

Satoshi Tonai, Motoharu Tsuboi and Takami Tachibana (Kochi University)

Some shallow slow earthquakes observed at plate boundaries are thought to occur inside subduction wedges (e.g., Ito and Obara, 2006). Therefore, it is important to understand the deformation process that occurs inside the tip of the wedge in order to illuminate the mechanism of shallow slow earthquakes. In this study, we constructed a Coulomb wedge in a sandbox experiment, and analyzed images of the development wedge using digital image correlation (DIC). In particular, we traced the transitions of the backthrust and frontal thrust (FT), measuring load to investigate the contribution of the backthrust to the deformation of the wedge. The experimental method is as follows; An adhesive sheet is placed inside an acrylic box with a load cell and an actuator. A 16 mm thick layer of Toyoura sand covers the bottom of the box, and a camera is placed next to the sand layer. The actuator was pulled 250 mm at a velocity of 0.4mm/s to create a wedge. Based on the scaling law of the strength properties of the sample, the scale of the experiments to the natural subduction wedge is about 1/50000. A total of 500 images were taken at intervals of 1 image for every 0.4 mm of sheet movement in the 50-250 mm displacement. This snapshot interval of 0.4 mm is corresponding to 500 years of real subduction, considering the natural plate convergence rate of 40mm/year. The taken images are imported into a PC and analyzed by the DIC. The linear region where the principal strain exceeded 1.0 % and is located most toward the fixed wall was identified as the backthrust, and the distance from the intersection of the backthrust and FT to the fixed wall is measured. The results are compared with the load data to investigate the correlation between the location of the backthrust and the load.

Experiments conducted on a layer of Toyoura sand densely packed by the air-drop method (porosity of about 35%) revealed that the backthrust is repeatedly displaced in two major positions during the displacement of one FT. Just before a new FT is formed and the load showed one peak, the backthrust developed in front of the wedge, and the wedge is uplifted only in the front part between the FT and the backthrust. The backthrust then slowly recedes and abruptly moves to the rear of the wedge. The amount of strain in the back thrust during this period is small and may not be found in the above-mentioned certification criteria. The position of the backthrust also moves with a certain width, forming a strain zone that can be called the back strain zone (BSZ). Furthermore, the rate of increase in load tends to decrease just before the backthrust moves forward, although this is not always clear. These results indicate that the displacement of the backthrust contributes significantly to the deformation inside the wedge and that the deformation is not localized, but occurs over a wide area.

In the future, we plan to further develop the DIC analysis and conduct experiments on sand layers with different initial conditions, and to compare the results to the natural deformation events such as shallow slow slip.

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Ito, Y. and K. Obara (2006) Geophys. Res. Lett., 33, L02311, Doi: 10.1029/2005GL025270.

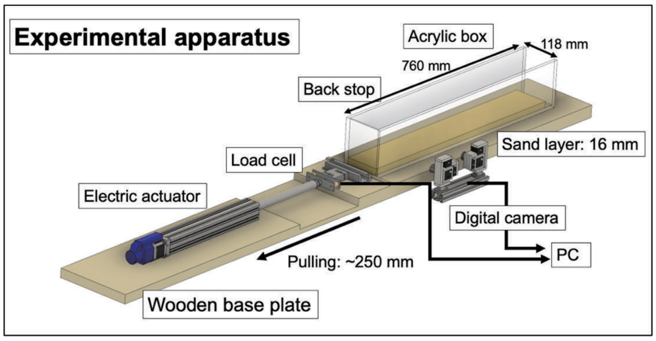

Figure1: Schematic image of the sandbox apparatus.

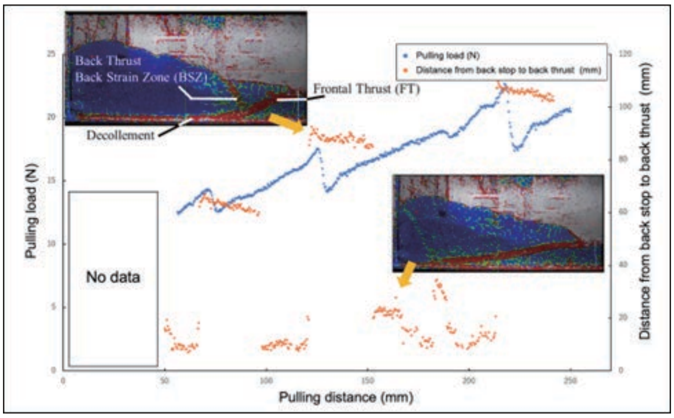

Figure2 : Change in backthrust location from fixed wall analyzed using digital image correlation (orange) and index load measured using load cell (blue).

Relationship between intraslab earthquakes, slow slip, and the anticipated Nankai megathrust event

Saeko Kita (Building Research Institute, National Research and Development Agency)

The timing of occurrence of intra-slab earthquakes is related to that of slow slip, but the detailed mechanism that underlies this relationship has not been revealed. To understand the relationship between intra-slab earthquakes and slow slip, we examined temporal variations in stress field and seismicity using focal mechanism data and hypocenters for intra-slab earthquakes beneath Kii Peninsula. We found that microearthquakes of intra-slab earthquakes became active ~1 month before the occurrence of short-duration slow-slip events with tremors (i.e., episodic tremor and slip, ETS) (Fig. 1a). The b-value reached a peak of ~1.5 before the occurrence of ETSs (Fig. 1b). These characteristics of microseismicity appear to be highly similar to those observed in water injection experiments in Switzerland (Bachmann et al. 2012) and those reported for inland earthquakes in Kitakata (western Fukushima) after the M9 Tohoku event in 2011 (Yoshida et al. 2017). We therefore infer that our observations of intra-slab earthquakes beneath Kii Peninsula represent fluid migration from the oceanic crust into the upper plate boundary of the oceanic plate. The maximum principal stress axis ($\sigma 1$) in the subducting slab shows a change in orientation (dip) during slow slip events in the oceanic crust beneath Kii Peninsula. The amount of temporal change in $\sigma 1$ is larger in the region closer to the trench axis (updip zone) than in the ETS zone (Fig. 2). We identified another small slow slip event from observations of repeating earthquakes that occurred in the updip zone after ETS events.

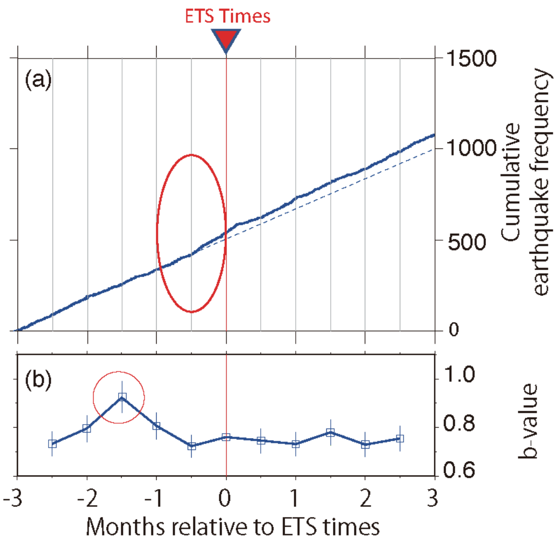

Figure 1: (a) Cumulative number of seismic events in the subducting slab deeper than 25 km (Mc = 1.0). (b) Temporal variation in the b-value of within-slab events for the study areas using a 1 month moving window.

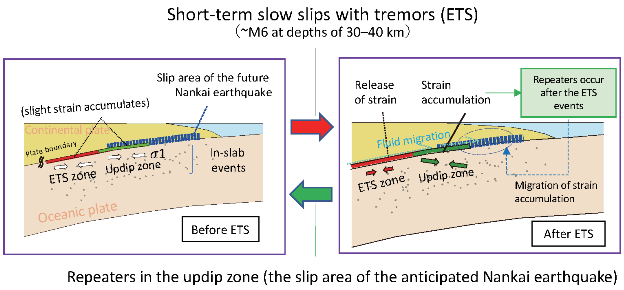

Figure 2 : Schematic cross-sections of Kii Peninsula before and after the occurrence of short-term slow slip events with tremors (i.e., ETS).

We interpret these various observations beneath Kii Peninsula as follows. When an ETS slow slip event occurs, strain on the plate boundary in the ETS zone is released first, whereas strain accumulates in the updip zone (Fig. 2). Subsequently, a small slow slip event occurs in the updip zone, and further accumulation of strain occurs near the trench axis. In summary, the strain accumulation process before the occurrence of the anticipated Nankai earthquake should be detectable via the monitoring of intraslab earthquakes. The contents of this study were published in December 2021 (Kita et al. 2021).

Kita, S. et al., 2021, Effects of episodic slow slip on seismicity and stress near a subduction-zone megathrust. Nature Communications, 12, 7253.

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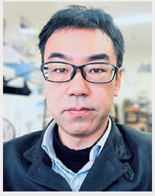
Introduction to the study "Geological constraints on dynamic changes of fluid pressure in seismic cycles" (Hosokawa and Hashimoto, 2022, Scientific Reports)

Yoshitaka Hashimoto and Takahiro Hosokawa (Kochi University)



Fluid pressure has a strong effect on fault slip behavior. Two models have been proposed to explain changes in fluid pressure during a slip: the thermal pressurization model, in which fluid pressure increases owing to frictional heating; and the fault-valve model, in which fluid pressure decreases owing to the development of new cracks. The two models describe opposite processes for fluid pressure change. Fluid pressure increase and decrease are competitive phenomena during a slip. We constrained dynamic changes in fluid pressure in seismic cycles using geological evidence.

The study area is the Mugi mélange in the Cretaceous Shimanto Belt (Figure 1a and 1b). A cataclastic zone is developed at the boundary of this mélange unit and is considered to represent an underplating fault. Immediately adjacent to the boundary, tensile cracks filled with calcite veins are observed as network veins in the mélange. These tensile cracks are inferred to be related to the underplating fault because of their location adjacent to the cataclastic zone. Crosscutting relationships between cracks of differing orientation indiacte that the tensile cracks developed in multiple stages under different stress states.

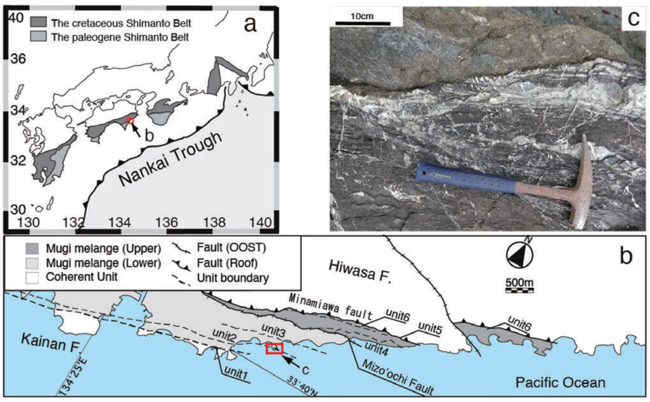


Figure1 : (a) Distribution of the Shimanto Belt. (b) Distribution of the Mugi mélange. (c) Network of tensile cracks. OOST: Out of sequence thrust

Paleo-stress analysis was conducted, using the orientations of the tensile cracks. The analysis yielded the orientations of the principal stresses, the stress ratio, and the over-pressure ratio P* (i.e., the difference between fluid pressure and the minimum principal stress normalized by differential stress). The results indicate two stress states: normal and reverse fault stress regimes, with the orientations of the principal stresses being switched in each state. The two stress states are interpreted to be related to seismic cycles. As the orientations of the principal stresses are vertical or horizontal to the foliation, the vertical stress derived from depth, density and gravity acceleration can be regarded as the vertical principal stress. The condition of formation of the tensile cracks, including P*, can be identified in the space defined by the fluid pressure ratio λ (fluid pressure divided by vertical stress) and differential stress. The minimum and maximum fluid pressures correspond to the conditions at which the differential stress is equal to four times the tensile strength (T) and with P* = 0 in the normal fault stress regime and with P* in the reverse fault stress regime (Figure.2). The maximum and minimum fluid pressures obtained from fluid-inclusion micro-thermometry can be regarded as representing the two conditions. Furthermore, if we assume that the normal and reverse fault stress regimes are achieved at the same depth, depth and T can be constrained.

The values of λ for the reverse and normal fault stress regimes are ~1.1 and ~0.83, respectively. Depth and T are ~5 km and 7–9 MPa. The λ value of >1 for the reverse fault stress regime represents an unstable state, which suggests that thermal pressurization occurred during faulting events. In contrast, for the normal stress regime, fluid pressure decreased owing to the development of new fractures, which may promote the recovery of shear stress along the fault.

Reference citations have been omitted owing to the limit on the word count. We would like readers to refer the paper for the citations.

Hosokawa, T. and Hashimoto, Y.(2022) Geological constraints on dynamic changes of fluid pressure in seismic cycles. Scientific Reports, 12, 14789.

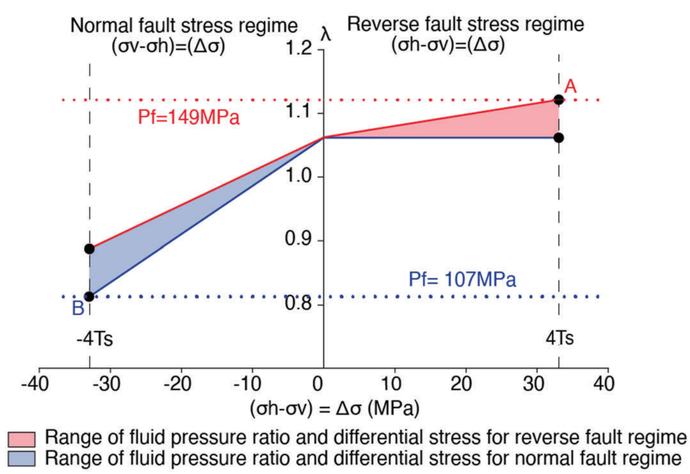


Figure 2 : Conditions for the formation of tensile cracks in a space defined by the fluid pressure ratio λ and differential stress. Points A (top right) and B (bottom left) indicate the maximum and minimum fluid pressure, respectively. Pf represents fluid pressure estimated from fluid-inclusion micro-thermometry. 4Ts: Tensile strength times 4, σv: the vertical principal stress, σh: the horizontal principal stress. Horizontal dotted lines indicate the maximum (red) and minimum (blue) fluid pressure estimated from fluid inclusion analysis.

Seafloor depth controls seismograph orientation uncertainty

Yasunori Sawaki (Graduate School of Science, Kyoto University (D3))

An accurate sensor orientation is crucial for data processing based on seismic wavefields. As ocean-bottom seismographs (OBSs) are deployed mainly as “free-fall” installations, there is a lack of information regarding the directions in which horizontal sensors face at the seafloor. In the Hyuga-nada region, long-term ocean-bottom seismological observations were started in 2014 and consist of broadband (360, 120, and 20 s) and short-period (1 s) observations by OBSs. With the aim of performing seismological analyses, we estimated the horizontal orientations of these OBSs using the teleseismic Rayleigh-wave polarization method (Stachnik et al., 2012; Doran & Laske, 2017).

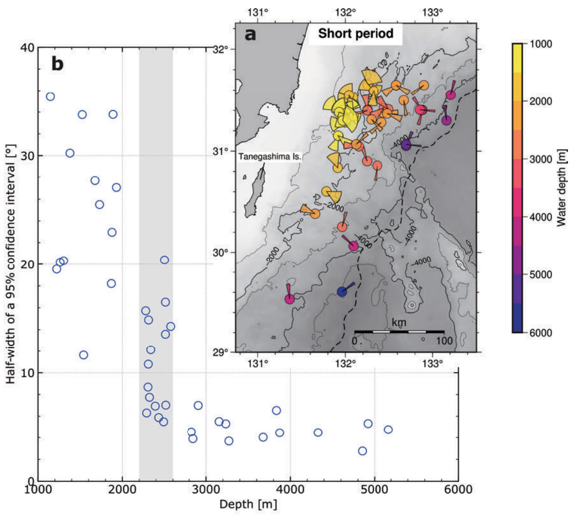


Figure 1 : (a) Estimated horizontal sensor orientations of the short-period OBSs. The color of each plot shows the water depth of the deployment. The wedge shows the estimated sensor orientation, whose extent indicates a range of twice the uncertainty. (b) Relationship between water depth and the estimated orientation uncertainties for the short-period OBSs. The grey-shaded area indicates the transition depth (2200–2600 m) of the orientation uncertainties for the short-period OBSs.

Fig.1a shows the estimated orientation and doubled uncertainty for short-period OBSs. Although most of the broadband OBSs had uncertainties of <6°, a number of short-period OBSs had larger orientation uncertainties of <20° and had been deployed on shallow seafloor of <2,000 m depth (Fig.1b). We found a clear depth dependence of orientation uncertainty, whereby the uncertainty increased with decreasing water depth, and we observed a transition depth for the increasing size of the uncertainty at 2,200–2,600 m. Furthermore, the measurement quality, as indicated by the cross-correlation coefficient between the radial and Hilbert-transformed vertical components, was lower at depths shallower than 2,000 m compared with greater depths. Moreover, noise power spectral densities (PSDs) showed that ambient noise levels during long periods (>10 s) also increased with decreasing depth. The dispersion curve of ocean infragravity waves accounted for the decreasing trend of long-period vertical noise levels with increasing water depth (Fig.2a), which demonstrates that compliance noise controlled vertical long-period noise levels. In this analysis, compliance noise is presumed to affect vertical Rayleigh waveforms at periods of 15–50 s (Fig.2b). While we could not find a similar dispersion relationship in the horizontal PSDs (Fig.2c), seafloor currents likely dominate horizontal long-period noise, and depth-dependent horizontal noise at depths of <2,000 m may reflect the varying magnitude of seafloor currents with water depth.

We conclude that compliance noise distorts Rayleigh waveforms and reduces Rayleigh-wave signals as a function of environmental noise as well as seafloor currents, which contributed to the sudden increase in orientation uncertainty and low measurement quality at shallow sites. We confirm that the variation in orientation uncertainty with water depth can be used as an index for the ambient noise environment on the seafloor. A newly developing network “N-net” (Nankai Trough Seafloor Observation Network for Earthquakes and Tsunamis) should provide further insights into oceanological and seismological observations of seafloor ambient noise in Nankai Trough including Hyuga-nada. See Sawaki et al. (2022, GJI) for details.

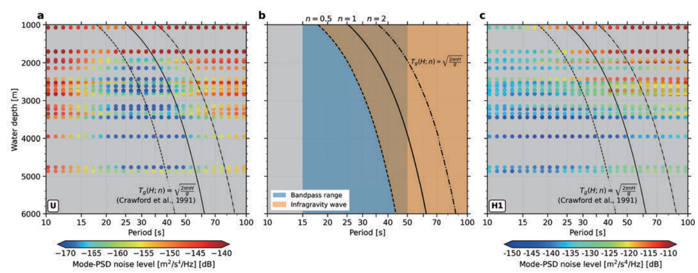


Figure 2 : Noise mode PSD at a period of 10–100 s for the broad-band OBSs colored by noise level for (a) vertical and (c) horizontal components. Black lines indicate the dispersion relationship representing the shortest periods of the ocean infragravity waves for a given ocean depth, H, and wavelength, nH, where g is the gravitational acceleration (Crawford et al., 1991), showing n = 0.5, 1 and 2 with dashed, solid and dashed–dotted lines, respectively. (b) Relationship with dominant periods of infragravity wave and the bandpass periods used in this analysis.

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Research topics

Kohtaro Ujiie (University of Tsukuba)

My field of expertise is structural geology. My laboratory studies the processes and mechanisms of megathrust and slow earthquakes in subduction zones using fieldwork, laboratory experiments, and deep ocean drilling. The following topics will be examined through the "Science of Slow-to-Fast Earthquakes" project.

Geological fingerprints of low-frequency earthquakes and tremor

Quartz veins are commonly concentrated in metamorphic rocks exhumed from the source depths of deep slow earthquakes. We examine whether a combination of shear and extension veins can explain the generation of low-frequency earthquakes and tremor using various approaches. We also examine the fluid source responsible for the development of quartz veins under high fluid pressure on the basis of trace-element and isotope analyses.

Role of metasomatic reactions in megathrust slip and rheology

We are investigating how metasomatic reactions affect megathrust slip and rheology using fieldwork and microstructural and geochemical analyses of mélange shear zones deformed near the thermally controlled base of the seismogenic zone and the mantle-wedge corner. In particular, we focus on whether metasomatic products control/modulate decreased megathrust strength around the down-dip limit of earthquake ruptures and how reaction-enhanced viscous shear affects the generation of slow slip events.

Link between shallow slow slip and silica diagenesis

We plan to examine how silica diagenesis affects shallow slow slip under elevated fluid pressure through fieldwork and laboratory experiments. The study area is a Jurassic accretionary complex in central Japan, which is thought to record megathrust shear deformation under the cold-slab environment such as the Japan Trench subduction zone. This project will start in FY2023.

Revisit of the 2011 Tohoku-Oki earthquake rupture zone

We will examine coseismic deformation mechanisms during shallow megathrust rupture and the degree of frictional healing after the 2011 Tohoku-Oki earthquake by drilling into the rupture zone and incoming sediments in the Japan Trench subduction zone off Miyagi. Data for this project will be collected by the deep-sea drilling vessel Chikyu in FY2024.

In addition, we have expanded our research area to include the continental collision zone in Corsica, France (Photo), the arc–continental collision zone in Taiwan, and the exhumed accretionary complex in North Island of New Zealand.

Photo：Geological survey in Corsica, France.

Gravity Observation and Technical Development

Yoshiyuki Tanaka (Graduate School of Science, The University of Tokyo)

Introduction

Group B01 is developing instruments with three major themes: gravity measurement, strain measurement using optical fiber, and seafloor measurement. In this article, we would like to focus mainly on gravity measurement and explain why we measure gravity and why technological development is required.

Slow earthquakes and fluids

It is known that fluids supplied by the subducting oceanic plate accumulates in the source region of slow earthquakes. Since the mode of fault slip differs depending on the degree of fluid accumulation, it is important to clarify the state and behavior of fluids to understand the diversity of slow earthquakes. Fluids (or water) is one of the common themes in the slow-to-fast earthquake project and is being investigated using a variety of approaches.

Why do we measure gravity?

When you think of gravity, you may imagine a spatial variation of gravity like the Bouguer anomaly. However, what we are trying to measure is the time variation of gravity, which is 3-4 orders of magnitude smaller than that (the order of magnitude of 1/1 billion G = 1 μGal). Gravity observations have long been used in volcanic regions because as magma moves underground, the gravitational force at the surface changes. Since it has been confirmed by laboratory experiments and numerical simulations that fluids move with the occurrence of slow earthquakes, we aim to verify whether fluid movement can occur by field observations.

Observed gravity changes

Previous studies are still limited because there are only a few research groups in the world that perform precision gravity measurements in slow slip areas. Figure 1 shows the observation results. In the Tokai region, gravity decreases synchronized with long-term slow slip (LSSE1, 2) are observed at three sites. In Cascadia, the observed result can be well explained by assuming that gravity increases at a constant rate during non-slow-slip events and decreases during slow-slip events (ETS).

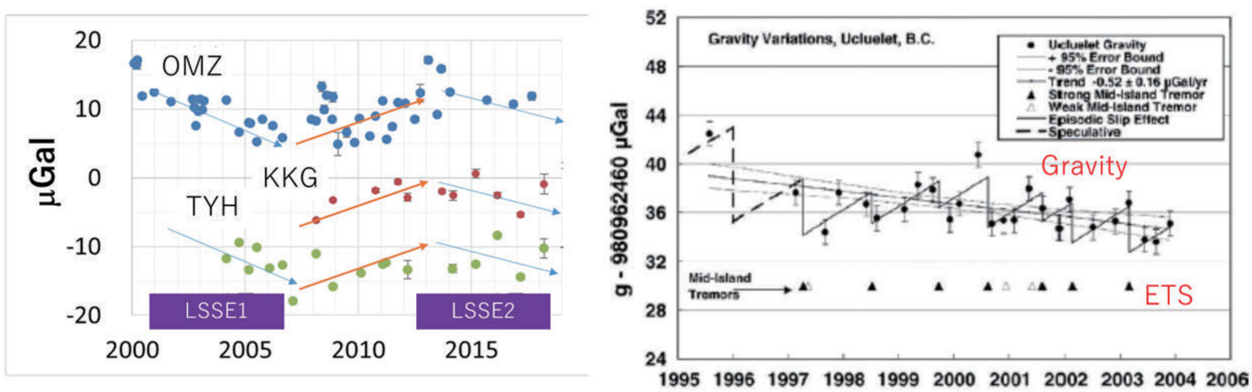

Figure 1: Gravity changes observed in Tokai region (left) and Cascadia (right) (Tanaka et al., 2018; Lambert et al., 2006)

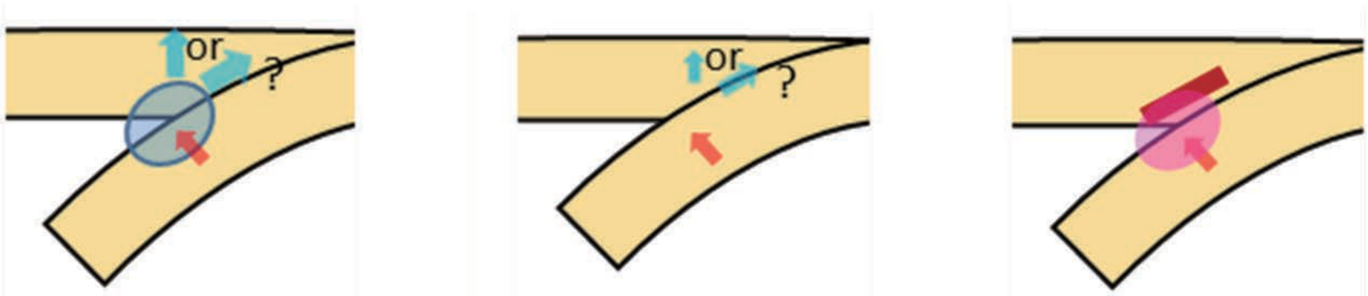

Figure 2: (left) The amount of fluids flowing out of the source region is larger than the amount flowing in, and gravity decreases. (center) Fluids flow in and out equally and gravity remains the same. (right) Fluids are trapped and accumulates, and gravity increases.

Potential causes of gravity change

Figure 2 shows one model that could explain the gravity change. It is assumed that slow slip causes a temporary increase in permeability near the source region and fluids runoff (Sibson, 1992). The observed change of a few μGal can be explained if a volume of water with a width of the epicenter fault and a thickness of about 30 cm flows out of the source region. However, whether the fluid movement is limited to the fault fracture zone or occurs over a wider area cannot be determined from the space-time resolutions of the gravity observations described above. If the movement occurs over the thickness of the plate, calculations can show that a stress drop of a few hundred kPa due to slow slip could move this amount of fluids.

Development of gravimeter

If we can continuously measure gravity at multiple sites, we will be able to learn more about the distribution of fluids and how it changes over time, and we may be able to elucidate the detailed processes of slow earthquakes. However, the laser interferometer used in the above observation is not suitable for continuous observation and is expensive to maintain, so it can barely be used for occasional observations at a few observation sites. Therefore, we are trying to develop a technique to measure gravity at multiple sites simultaneously at high frequency by receiving laser beams emitted from a single light source through optical fibers by interferometers installed at multiple distant sites.

Conclusion

Group B01 is developing optical fiber sensing instruments in addition to gravimeters. In another project, the application of gravity potential observation using optical lattice clocks to seismic research is also underway. The dense seismic and crustal deformation observation network developed in the late 1990s facilitated the world's pioneering discovery of slow earthquakes. If fiber-based optical monitoring networks are added to this network, we may be able to open a new era in the study of slow earthquakes. The basis for these measurements is to maintain a high degree of stability of light frequency over long distances and for long periods of time. The development of Group B01 reflects the desire to apply the excellent technology in the field of optics to disaster prevention.

Exploring the meaning of the location of “large and gentle” slow earthquakes

Yuta Mitsui (Faculty of Science, Shizuoka University)

The scaling relation proposed about 15 years ago for slow earthquakes (Ide et al., 2007) implied that large slow earthquakes tend to be gentle. In other words, larger slow earthquakes deviate from fast earthquakes of the same size. Whereas small slow earthquakes are the branching point of the slow-to-fast transition, large slow earthquakes are the end member of the slow-to-fast transition.

Large and gentle slow earthquakes that have been well investigated are (long-term) SSEs at the Nankai Trough, Japan. In particular, major SSEs with Mw > 6.5 have occurred in the Tokai region, the Kii channel, and the Bungo channel, respectively, on the deeper extension parts of the source areas of past Mw 8-class interplate earthquakes (e.g., Ozawa et al., 2002; Kobayashi, 2014; Hirose et al. et al., 1999).

In terms of along-strike heterogeneity, our study (Mitsui et al., 2022) focused on the fact that the three regions with the major SSEs, high background seismicity (near the plate boundary), and low gravity anomalies correspond to each other, and that these regions do not correspond to regions with active small slow earthquakes such as tectonic tremors or low-frequency earthquakes (Figure 1). It is interesting that the large slow earthquakes and fast earthquakes (the end members of the slow-to-fast transition) correspond to each other, while the small slow earthquakes do not. The above correspondence/non-correspondence relationship can be attributed to heterogeneity of stress or pore fluid pressure underground related to density differences near the surface.

Because large slow earthquakes are gentle, signal detection is performed from geodetic data such as GNSS, not from seismographs. In general, the signal-to-noise ratio of the geodetic data is low. Hence appropriate noise reduction is required.

We combine machine learning such as neural networks (Figure 2) and statistical methods such as independent component analysis to properly perform this noise reduction, and search for new signals.

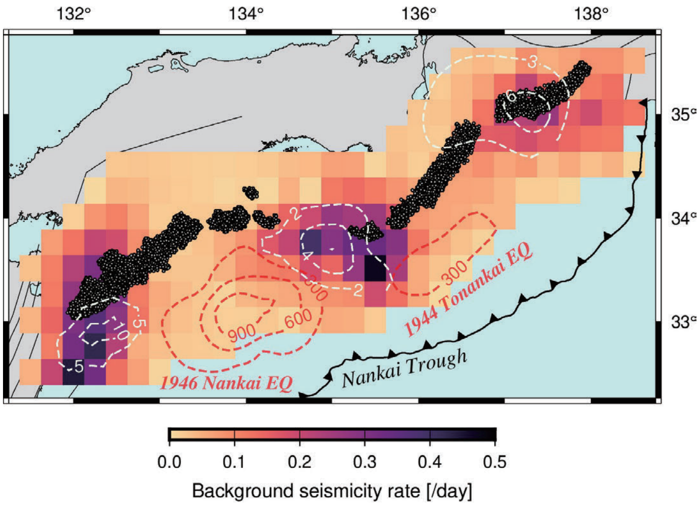

Figure1 : Spatial distribution of background seismicity rates near the plate boundary and deep slow earthquakes. White dotted lines represent the slip distribution of the major SSEs above Mw 6.5 (Ochi and Kato, 2013; Kobayashi, 2017; Yoshioka et al., 2015), and gray dots represent the epicenters of tectonic tremors, a type of small slow earthquake (Annoura et al., 2016). The red dotted lines indicate the slip distribution of past Mw 8-class earthquakes (Sagiya and Thatcher, 1999). Units are in cm.

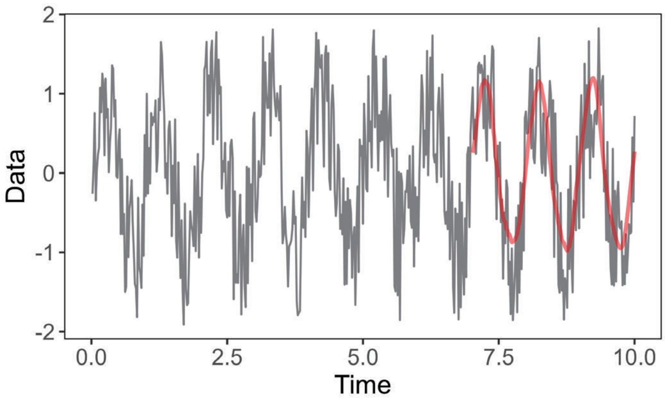

Figure 2 : A test of signal detection using a recurrent neural network (e.g., Yamaga and Mitsui, 2019). The gray line shows artificial data with random noise, and the red line shows a forecast result by the neural network.

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Source characteristics and spatiotemporal variation of shallow very low frequency earthquakes along

Shunsuke Takemura (ERI, The University of Tokyo)

To understand the source characteristics of slow earthquakes at the shallow plate boundary in the Nankai Trough, we investigated shallow very low frequency earthquake(VLFE) activity. First, we detected shallow VLFEs from continuous F-net broadband records using the template matching method. Then, we conducted re-location analysis and source time function estimation for the detected shallow VLFEs. Figure 1 shows the spatiotemporal variation of shallow VLFE activity in Nankai from April 2004 to March 2021. We identified three regions according to the obtained activity patterns(Regions A–C). Several shallow VLFE swarms are identified in each region(Figure 1a and b). Figure 1c shows the spatial variation of cumulative moments from shallow VLFEs. Shallow VLFEs occurred around the western edge of the subducted paleo-Zenisu ridge(shaded area in Region A). In contrast, in Region C, shallow VLFEs tended to be concentrated around the up-dip part of the subducted seamount. The relationships between slow earthquakes and subducted seamounts also vary within other subduction zones. In future studies, more detailed structural surveys(e.g., Nakamura et al., 2022) and precise hypocenter estimation should be conducted to understand the relationships between slow earthquakes and subducted seamounts.

We investigated the characteristics of shallow VLFE swarms (Figure 1b) because swarms of seismic slow earthquakes can be considered a proxy for geodetic slow slip on the plate boundary. The relationship between cumulative moment and activity areas (Figure 2a) roughly follows a scaling law of Mo ∝ A3/2 irrespective of region. In contrast, the relationships between cumulative moment and swarm duration (Figure 2b) and between cumulative moment and along-strike spreading speed (Figure 2c) differ between regions. Along-strike variation in pore fluid pressure or shear strength on slow earthquake faults may cause the observed differences between regions.

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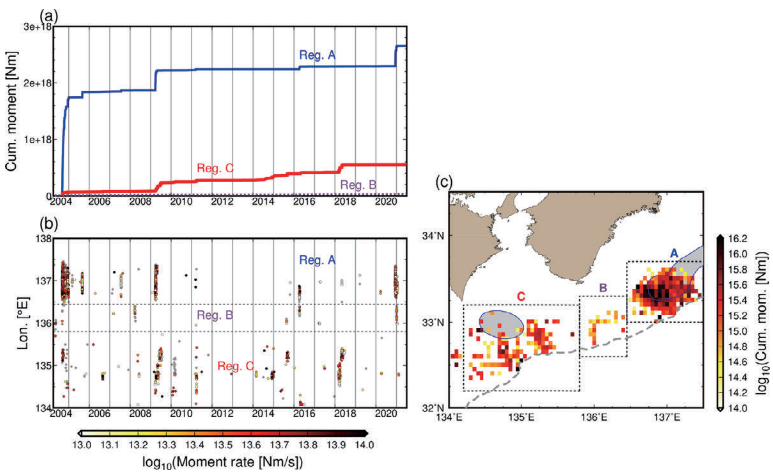


Figure 1 : Spatiotemporal distribution of shallow VLFE activity along the Nankai Trough. (a) Temporal changes in cumulative moments of shallow VLFEs in each region, (b) spatiotemporal distribution of shallow VLFE moment rates, and (c) map view of cumulative moments of shallow VLFEs. Shaded areas in (c) represent subducted seamounts (Kodaira et al., 2000; Park et al., 2004)

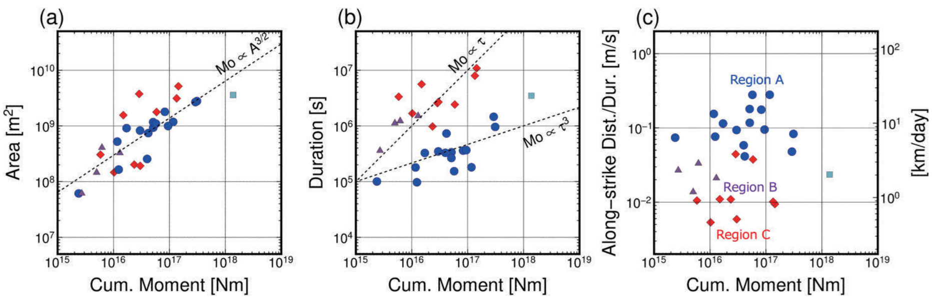
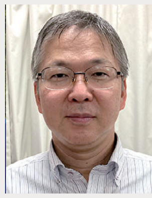


Figure 2 : Source characteristics of shallow VLFE swarms in each region. The light blue square represents the shallow VLFE swarm that started on 6 September 2004, which can be considered as a triggered VLFE swarm due to the Mw 7.4 intraslab earthquake.

Utilization of Large-Scale Simulations in Modeling and Forecasting Studies in Slow to Fast Seismology

Takane Hori (JAMSTEC)



There are two main approaches to using numerical simulation as a research tool. One approach is to construct a mathematical model that is as simple as possible and which is representative of the phenomenon of interest, and then investigate the behavior of the model by numerical simulation. In earthquake physics, as targeted by the Modeling and Forecast Group, examples of such numerical simulations are spring–slider models with friction (e.g., Ruina, 1983; Im et al., 2017) and numerical simulations of slow earthquakes with probabilistic models such as 1D Brownian walk models and 2D probabilistic cell automatons (e.g., Ide, 2008; Ide & Yabe, 2018). The other approach is to construct a model of the target phenomenon that can be directly compared with observed data, given realistic initial and boundary conditions, and then investigate the behavior of the model. In the case of earthquake physics, examples of this approach include numerical simulations of dynamic rupture processes that model fault geometry and the stress field applied to the fault as realistically as possible (e.g., Ando & Okuyama, 2010; Ando & Kaneko, 2018) and numerical simulations of crustal deformation and seismic motions that model heterogeneous structures as realistically as possible (e.g., Ichimura et al., 2013; Ichimura et al., 2022).

Both approaches are useful for understanding and predicting phenomena, but it is important to use them for different purposes. In the former approach, the goal is to evaluate the validity of the model based on the consistency between qualitative or semi-quantitative features extracted from observational data and the results of numerical simulations, or to predict new phenomena or characteristic behaviors not known previously from the behaviors obtained from simulation results. In the latter approach, the goal is to understand and predict the phenomenon more quantitatively, with the aim of comparing and reconciling observed data and numerical simulation results as directly as possible (so-called data assimilation). Ultimately, we are seeking to develop a "digital twin"," as used in the mechanical engineering and weather/climate fields.

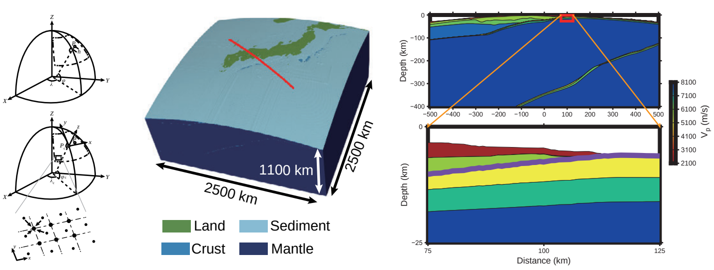


Figure : (Left) Coordinate system used to calculate the Green's functions. (Center) Overview of the finite element model. (Right) Cross-section of the P-wave velocity structure along the red line shown in the center panel. The right bottom figure shows the red rectangle box in the right above figure. Modified from Hori, Agata et al. (2021).

As an example of the latter approach, we used "Japan integrated velocity structure model version 1" (a 3D layered-structure model for long-period seismic motion calculations) to calculate the response function of crustal deformation due to slip at a plate boundary (Figure 1 ; Hori, Agata, et al., 2021). A key point here is that the 3D structure model used for seismic wave propagation calculations is introduced into the crustal deformation calculations. To generate a finite element mesh that discretizes the geometry of each layer of the 1 km grid as faithfully as possible, the simulation becomes huge with billions of degrees of freedom. The generation of such huge-scale finite element meshes and the resulting crustal deformation calculations are not simply the result of improved computer performance but also the result of technological developments in computational and computer science (e.g., Fujita et al., 2016; Ichimura et al., 2016). In terms of achieving a geometry closer to reality, another feature is the use of a reference ellipsoid, as employed in GNSS analysis (Figure).This is a first step toward building the ultimate "digital twin" in the sense of matching the coordinate system and geometry used to make observations in the real world with those in the virtual world of the simulation. In contrast, in the former approach, just because the mathematical model is as simple as possible does not necessarily mean that it should be a small-scale simulation. To understand and predict the multi-hierarchical physics of faults, which is considered to be important by the Modeling and Forecast Group, the modeling of hierarchical geometric heterogeneity is inevitable, no matter how much the physics is simplified. Therefore, numerical simulations must be large scale.

I hope to advance our understanding and forecasting of the behavior of slow to ordinary earthquakes, and to find new perspectives for understanding these phenomena and the directions for forecasting methods, by helping the members in the Modeling and Forecast Group to perform numerical simulations at a previously unattainable scale through the use of advanced computational and computer science techniques developed in projects related to high-performance computing.

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Rupture scenarios for megathrust earthquakes based on mechanical coupling

Akemi Noda (Meteorological Research Institute, Japan Meteorological Agency)

Earthquakes (fault slip events) are mechanical phenomena governed by the interaction between shear stress and frictional stress on a fault plane. In plate subduction zones, shear stress on the plate interface accumulates owing to interplate coupling, and when it exceeds the frictional strength of the interface, an interplate earthquake occurs. Therefore, the stress state at the plate boundary is important information in reliably predicting future earthquakes.

Crustal deformation data from the GNSS continuous observation system on land (Geospatial Information Authority of Japan) and GNSS-A seafloor position measurements (Japan Coast Guard) have made it possible to estimate the spatiotemporal distribution of interplate coupling along the Nankai Trough (e.g., Noda et al., 2018). In general, slip-deficit rates are directly estimated from geodetic data. Slip deficits are recognized as a “kinematic coupling” that represents the movement and deformation of the involved plates. To understand earthquakes as mechanical phenomena, however, slip deficits need to be converted to shear stress (mechanical coupling).

We have developed a method to generate possible future earthquake scenarios based on the stress accumulation rate calculated from the slip-deficit rate (Noda et al., 2021). However, the estimation errors of the slip-deficit rates can be amplified during calculation of the stress accumulation rate. Therefore, we developed a method to estimate the stress accumulation rate directly from geodetic data based on the idea that mechanical coupling, which is the essential mechanism or cause of earthquake generation, is the parameter to be estimated (Saito & Noda, 2022). We applied this method to geodetic data observed in southwestern Japan (Fig. 1a) to estimate the distribution of stress accumulation rates at the plate interface along the Nankai Trough (Fig. 1b). Of the regions with high stress accumulation, Muroto, Kii, Kumano, and Enshu correspond to the source regions of past great earthquakes, and Bungo may be associated with the Bungo Channel slow slip events.

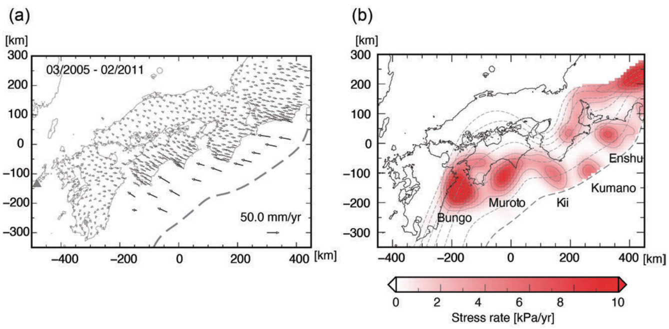

Figure 1: Estimation of mechanical coupling from geodetic data (Saito & Noda, 2022). (a) Surface displacement rates obtained from geodetic observations. (b) Distribution of shear stress accumulation rate at plate intarce.

Furthermore, we constructed a stress accumulation model assuming that stress accumulated for 100 years at the rate shown in Fig. 1b. As an example of the earthquake scenarios constructed from this model, an earthquake scenario consisting of a foreshock, an afterslip of the foreshock, and a mainshock is shown in Fig. 2. First, the foreshock occurs at Kii (Fig. 2a), followed by afterslip in the deep part of the plate boundary (Fig. 2b). Then, the afterslip that invades the high-stress region of Muroto triggers a mainshock (Fig. 2c). The stress accumulation model presented here was constructed with some simplifications, and there is room for further improvement, such as considering the spatiotemporal changes in mechanical coupling caused by slow earthquakes. The framework of the earthquake scenario generation proposed here will enable us to incorporate additional results on stress state and frictional characteristics to update and improve earthquake scenarios.

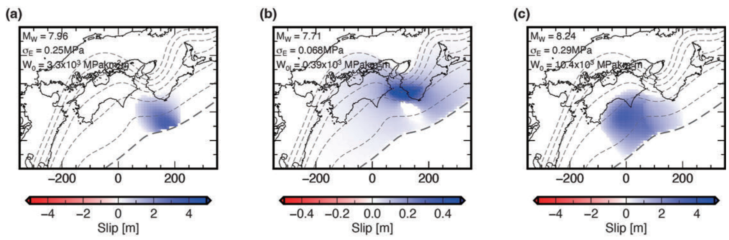

Figure 2: Slip distributions of (a) a foreshock, (b) an afterslip of the foreshock, and (c) the related mainshock (Saito & Noda, 2022).

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Publicly Offered Research in Group A01

Fault transitions and slow slip induced earthquakes by bilateral shear experiments

Wataru Tanikawa (JAMSTEC)

In recent years, observations that link between slow earthquakes and giant earthquakes have been reported. Since slow earthquakes may trigger large earthquakes, this phenomenon has attracted considerable attention from the perspective of improving the prediction of the occurrence of large earthquakes.

In this study, we focused on "fault transition" (a phenomenon in which only one fault starts to move when two weak fault plains are sheared simultaneously, but the first fault stops moving and another fault starts to slide), which was observed by chance in a friction experiment on a simulated fault with a complex plane structure, since we found similarities between "fault transition" and "slow earthquake". This research aims to clarify the similarity between fault transitions and the slow earthquake triggering that slow earthquakes can cause large earthquakes.

This research was inspired by "the Non-slippery Sand Koshien" (an event to determine the most slippery sand from sand in various regions of Japan through bilateral shear experiments), which was held in FY2021 as part of JAMSTEC's 50th anniversary celebration event. (https://www.jamstec.go.jp/50th/suberanai/).

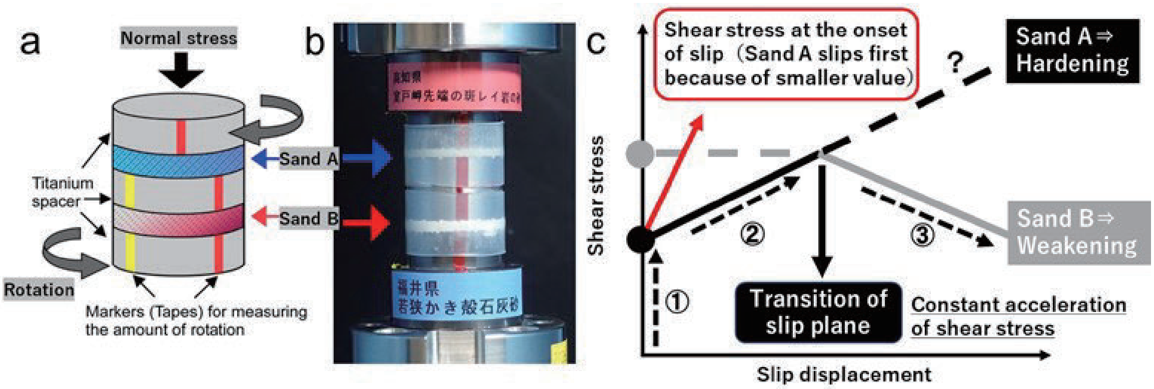


Figure : a) Overview of the two-surface shear experiment used in this study. b) "The Non-slippery Sand Koshien" that inspired this study. c) Conceptual diagram of the fault transition observed during bilateral frictional experiments.

Publicly Offered Research in Group A01

Shear slip experiments under natural pore-pressure conditions using fluid injection of large rock specimens

Yusuke Mukuhira (Tohoku University)

Recent studies have discovered a connection between fluids and the occurrence of slow earthquakes. In the field of resource engineering related to fluid injection, phenomena similar to slow earthquakes have been observed. Currently, we are studying injection-induced seismicity by conducting laboratory-based rock experiments involving a large cubic specimen of rock (side length 60 cm) and an injection device (Figure). We are able to maintain a high injected pore pressure within a fault hosted in such large specimens. Our experiments can reproduce the actual pore pressure distribution in natural faults.

In this project, we are developing a device that can measure elastic waves continuously in an attempt to acquire the acoustic emissions related to elastic waves and slow earthquakes. With this measurement device, we will investigate the full-spectrum transition from slow to fast earthquakes in a laboratory space with spatial distributions of shear and normal strain and pore pressure in analyzed specimens that reproduce natural conditions.

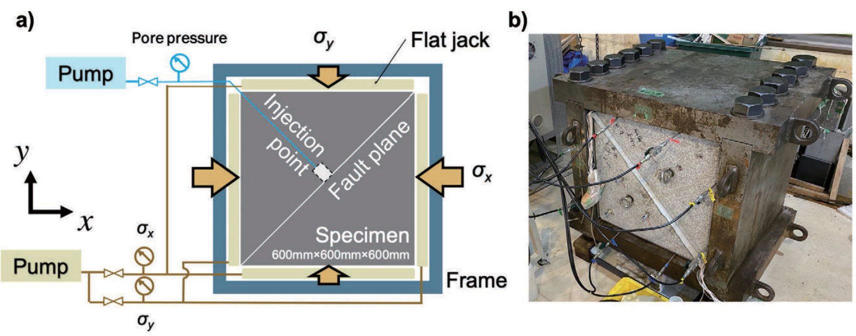


Figure : a) Conceptual view of the experiment system used in this study. Large rock specimen of one side 60 cm having fault are loaded biaxially by flat jacks. b) Picture of experiment system and rock specimen.

Publicly Offered Research in Group A01

Reproduction of slow-to-fast fault-slip motion using a rotary-shear apparatus

Takehiro Hirose (Kochi Institute for Core Sample Research, JAMSTEC)

Slow earthquakes are closely linked to the presence of water in subduction zones. However, how water affects the physico-chemical processes in faults responsible for the generation of slow earthquakes is not well understood. In this study, we test the hypothesis that a change in water pressure in a fault zone can lead to the generation of slow earthquakes that are in some cases followed by fast earthquakes, by reproducing slow-to-fast fault-slip motion using a rotary-shear friction apparatus housed at Kochi/JAMSTEC (Figure). In particular, we develop a torque- and water-pressure-controlled experimental method that enables us to initiate spontaneous fault-slip by changing water pressure in a critically stressed fault. The experiment should lead to a better understanding of the physico-chemical processes underlying the generation of slow earthquakes and the evolution of fault slip from slow to fast motion.

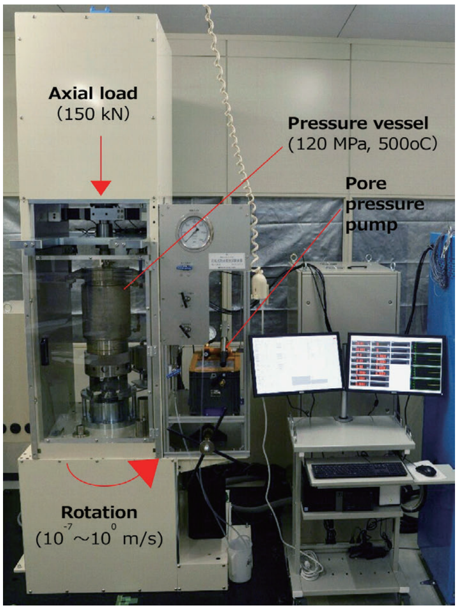


Figure : A hydrothermal rotary-shear apparatus in Kochi/JAMSTEC. The apparatus is capable of controlling a wide range of velocity (100 nm/s ~ 2 m/s) under hydrothermal conditions.

Publicly Offered Research in Group A02

Effect of seamount subduction on deep slow earthquakes

Ayumu Miyakawa (Geological Survey of Japan, AIST)

Although numerous studies have examined the effects of oceanic plate topographic features, such as seamounts, on the occurrence of shallow slow earthquakes and large earthquakes in subduction zones, the effects of seamounts on deep slow earthquakes are still unresolved. Therefore, we are working on modeling the effect of seamounts on the deep part of the subduction zone using numerical simulations. Simulation results suggest that in the shallow part of the subduction zone, the seamount, which is stronger than the sediments of the accretionary wedge, may deform the accretionary wedge, whereas in the deep part, the seamount itself may deform ductilely under the high-temperature conditions (Figure). We aim to investigate how deep slow earthquakes are related to such changes in deformation mode in and around seamounts.

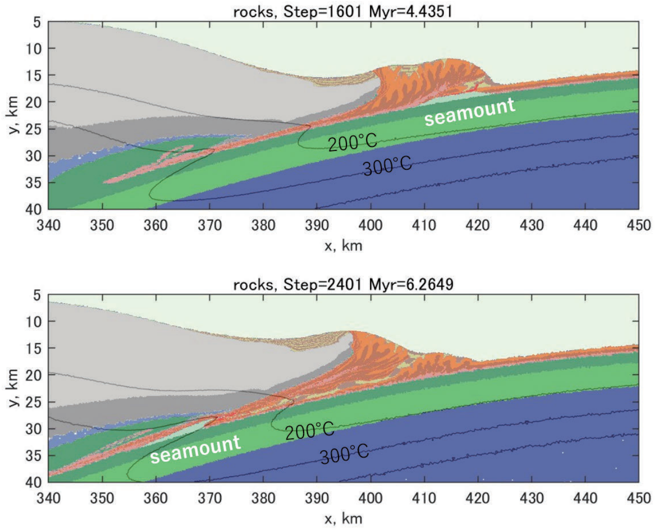


Figure : Simulation of seamount subduction. The seamount maintains its shape at shallow depths (top), whereas at greater depths it is strongly deformed (bottom).

Publicly Offered Research in Group A02

Fracturing and dissolution–precipitation processes recorded in the tip of the serpentinized mantle wedge and their possible link to deep slow earthquakes

Ken-ichi Hirauchi (Shizuoka University)

Episodic tremor and slip (ETS) in southwestern Japan occur in the tip of the serpentinized mantle wedge, suggesting a possible link between serpentinite deformation and ETS generation. I analyzed field (Hirauchi et al., 2021, Earth Planet. Sci. Lett.) and experimental observations to show that cyclic events of fracturing and mineral dissolution–precipitation may correspond to the generation and recurrence interval of ETS events, respectively. Mantle wedge serpentinite records a series of deformation and metamorphic events possibly related to tremor or slow slip, including (1) extensional (mode I) and extensional–shear (mode I–II) fractures that formed under high pore-fluid pressures (Pf), (2) precipitation of new serpentine along fractures and the formation of viscous shear zones, and (3) the re-attainment of the failure criterion owing to an increase in Pf. These findings suggest that the dissolution–precipitation rate of serpentine controls the recurrence interval of ETS events.

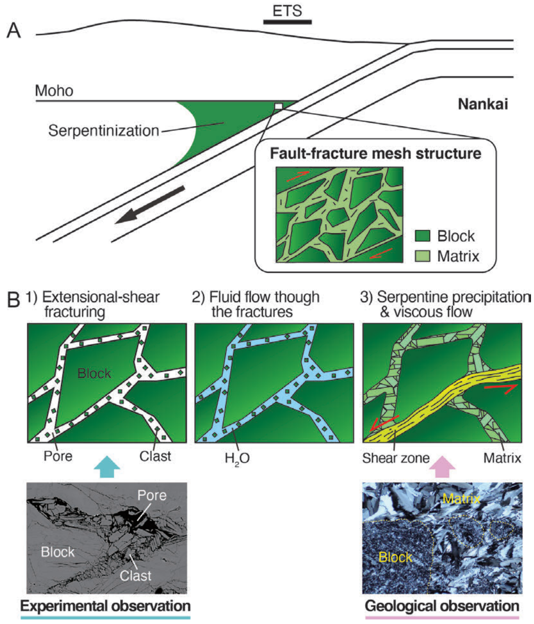


Figure : (A) Schematic cross section of the Nankai subduction zone. (B) Schematic model illustrating fracturing, viscous flow, and serpentine dissolution/precipitation.

Publicly Offered Research in Group A02

Origin and behavior of fluid at seismogenic zone investigated by direct chemical analysis of fluid inclusion in quartz vein

Akira Ijiri (Kobe University)

This study aims to clarify the origin and migration of fluid that is closely related to megathrust earthquakes. In order to reveal the origin and migration process of fluid, direct chemical analysis of fluid at seismogenic zone is most reliable way. However, since megathrust earthquakes occur at depths that cannot be reached by current scientific drilling, it is not possible to directly take the fluid samples. Therefore, I focused on fluid inclusions in quartz veins that fill fractures around fault zones exposed on land, which are relic of past seismic activity. Quartz is precipitated from water migrated through the fractures, and water and gases are trapped as fluid inclusions in the micrometer-scale voids created in the quartz veins. Recent advances in analytical techniques have allowed the analyses of the oxygen and hydrogen stable isotope ratios of water, and carbon isotopes of carbon dioxide and methane in fluid inclusions. I plan to conduct chemical and isotopic analyses of fluids (fluid inclusions) in quartz veins in fault zones found in onshore outcrops in the Southwest Japan, which is the onshore analog of the Nankai Trough subduction zone, and clarify the origin and migration path of fluids in the past seismogenic zone.

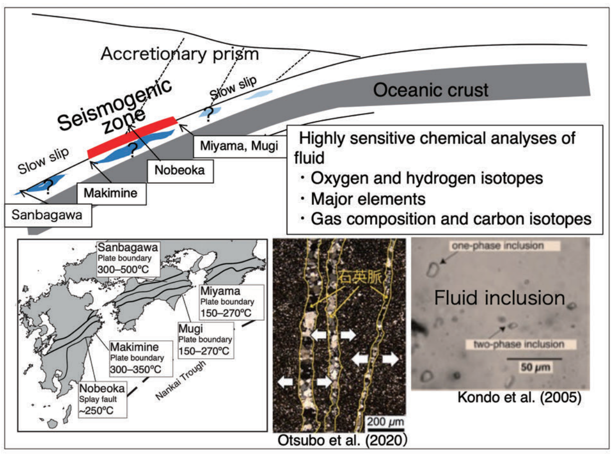


Figure : Graphical summary of research into the origin and migration of seismogenic-zone fluids.

Publicly Offered Research in Group A03

Development of a method for estimating the eruption rate of Sakurajima volcano

Haruhisa Nakamichi (Sakurajima Volcano Research Center, Disaster Prevention Research Institute, Kyoto University)

Haruhisa Nakamichi (Sakurajima Volcano Research Center, Disaster Prevention Research Institute, Kyoto University) and Ryohei Takahashi (Graduate School of Science, Kyoto University) have been conducting a project entitled "Development of an eruption rate estimation method for understanding the slow-to-fast phenomena of eruptions" fron June 2022 to March 2024. In this research, we are working on the development of a method for estimating the rate of production of pyroclastic products that determines the speed of a Vulcanian eruption from observations. The research will contribute to our understanding of the slow-to-fast nature of various eruption types. This research is complementary to the planned investigation of tilt changes that precede eruptions in a project entitled "Slow-to-fast earthquakes through comparisons across global subduction zones". Both research projects cover the period from the precursory stage to the end of eruptions. An example of the research is the investigation of Sakurajima volcano, where there are three underground observation tunnels with a length of 250 m, each of which houses three extension meters. By extracting the records associated with eruptions from the three-component instruments, the principal strain is estimated to obtain the reduced strain corrected for the distance from the crater to the extension meter. Results show a linear relationship between the monthly sum of the principal strain and the amount (weight) of volcanic ash falling around Sakurajima (Figure). In the future, we will construct a relational expression formula and estimate the weight of pyroclastic products generated by each eruption.

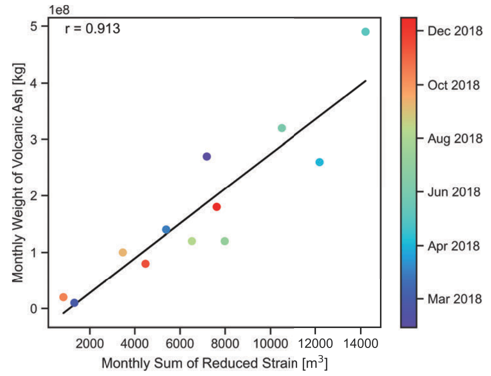


Figure : Monthly cumulative values of reduced strain (horizontal axis) and volcanic ash fall weight (vertical axis) in 2018. The correation coeeficient "r" between the cumulative values is 0.913.

Publicly Offered Research in Group A03

Analysis of slow earthquakes using strain and rotational observations: Exploration of non-double-couple components and the underlying physical mechanisms

Kazutoshi Imanishi (Geological Survey of Japan, AIST)

Nearly 20 years have passed since the discovery of slow earthquakes, which have different characteristics from ordinary tectonic earthquakes. The mechanism of slow earthquakes is an essential problem in seismology and has long been understood in terms of shear rupture at a plate boundary, primarily on the basis of seismic waveform analysis. However, slow earthquakes, which exhibit complex behavior, are unlikely to be explained by such a simple process. Now that numerous new findings have been accumulated, it is worth reconsidering the interpretation of "slow earthquakes = shear rupture".

In this study, we are developing a method for estimating the moment tensor of earthquakes using strain and rotational components as new observables, and aim to estimate the non-double-couple component of slow earthquakes with high accuracy. For the strain components, we will utilize data from borehole strainmeters deployed by the Geological Survey of Japan, AIST, in southwestern Japan. For the observation of rotational components, we are planning to conduct temporary array observations using broadband seismometers. Through this research, we will explore the characteristics of the non-double-couple components of slow earthquakes and the underlying physical mechanisms.

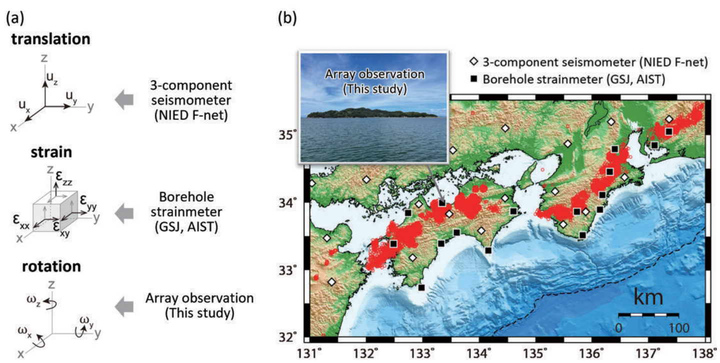


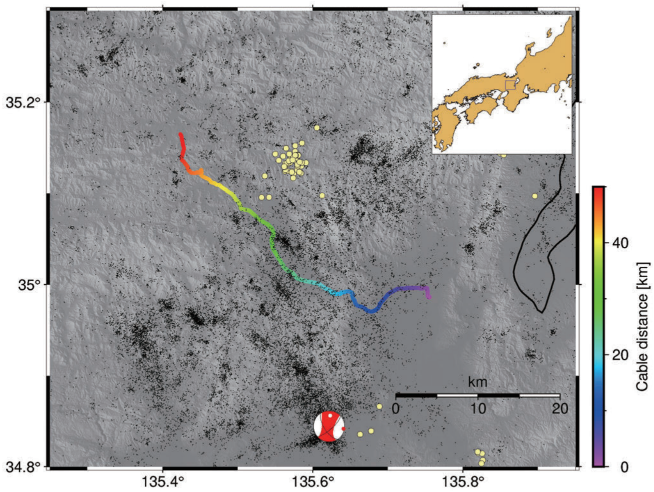
Figure : (a) Translation, strain, and rotational motion. (b) Map of the studied area and station distribution. The inset photograph shows Nii-Oshima in Niihama City, Ehime Prefecture, where the array observation is planned. Red circles represent deep low-frequency earthquakes reported by the Japan Meteorological Agency.

Publicly Offered Research in Group B02

Towards understanding slow earthquakes in the crust by big data analytics: observation of triggering phenomena using DAS

Masatoshi Miyazawa (Kyoto University)

Although various types of slow earthquake have been discovered, low-frequency earthquakes occurring in the crust away from volcanoes have not been frequently observed compared with those in subduction zones. Therefore, the mechanism that causes these slow events in the crust is not well understood. I am investigating low-frequency earthquakes that occur in southern Kyoto using high-sensitivity, high-density observations. The distributed acoustic sensing (DAS) technique is applied to measure changes in strain using a 50-km-long optic fiber cable along Route 9 in Kyoto. As the background seismicity of slow earthquakes in the crust is usually low, I utilize the fact that slow earthquakes are often dynamically triggered by passing seismic waves from large remote earthquakes. Although the triggered signal is extremely small, an investigation into these triggering phenomena using big data observed at about 10,000 seismic stations along the cable, acquired by DAS measurement, should help to explain how slow earthquakes occur in the crust.



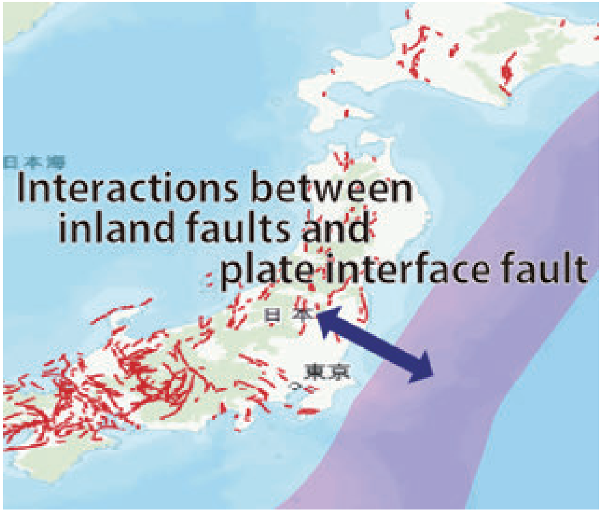
Figure：The 50 km-long optic fiber cable for DAS measurement, and seismicity in southern Kyoto from the JMA catalog. Yellow circles depict slow earthquakes.

Publicly Offered Research in Group B03

Simulation of the multi-scale "island arc–trench coupled system"

Ryosuke Ando (University of Tokyo)

The Japanese islands are an island arc generated by plate subduction and contain many inland active faults (Figure). M 9 huge earthquakes generated on the plate interface and M 7 large earthquakes generated on inland faults are activated at mean recurrence intervals of about 100 and 1000 years, respectively. These earthquakes have been modeled using different frameworks with an emphasis on differences in spatiotemporal scale. Recent observations have captured spatial and temporal variations in the geodetic deformation and seismicity associated with the pre-, post-, and inter-seismic periods of megathrust earthquakes. Hence, it is essential to understand the island-arc–trench system as a coupled mechanical system. However, multi-scale simulation for this coupled system has not yet been achieved because of the limitations of computational resources. In this study, we implement highly efficient boundary element algorithms for quasi-dynamic (Ozawa et al., 2023) and fully dynamic (Sato and Ando, 2021) simulations by applying hierarchy matrices. We will fully utilize the computational capabilities of these algorithms to enable direct comparisons between physics-based models and observational data. Furthermore, we expect to enhance our ability to forecast earthquake processes through a more profound understanding of the underlying physics.



Figure：Schematic diagram showing the island-arc–trench coupled system considering the inland faults (red lines) and the plate interface (purple area).

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A01 - RC

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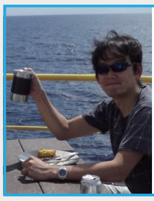
Specialty: Computational materials science
Keyword: Multiscale simulation, Atomic simulation, Micromechanics

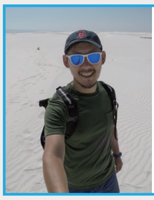


Yuzuru Yamamoto

A01 - RC

Professor, Graduate School of Science, Kobe University

Specialty: Structural logy
Keyword: Subduction zone, Liquefaction, MTDs



Yusuke Mukuhira

A01 - RC

Assistant Professor, Institute of Fluid Science, Tohoku University

Speciality: Observational seismology, Geomechanics, Resource engineering
Keywords: Injection induced seismicity, Fluid, Lab experiment

Shunya Kaneki

A01 - RC

Postdoc, Disaster Prevention Research Institute, Kyoto University

Specialty: Physico-chemistry of fault
Keyword: Rock experiments, Model calculation, Chemical reaction

Yasuhiro Yamada

A02 - RC

Professor, Faculty of Engineering, Kyushu University

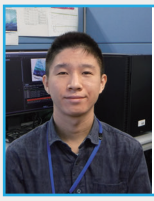
Specialty: Subsurface exploration
Keyword: Energy resources, Deformation process and geometry

Mari Hamahashi

A02 - RC

Lecturer, Faculty of Global and Science Studies, Yamaguchi University

Specialty: Structural geology
Keyword: Accretionary prism, Fold-and-thrust belt, Rock physical properties



Shuhei Tsuji

A02 - RC

Researcher, Research and Development Group for Seafloor Observatory, FEAT, IMG, JAMSTEC

Specialty: Active seismic monitoring, Seafloor geodesy
Keyword: Active seismic source, Seafloor crustal deformation, Long-term monitoring

Hiroaki Koge

A02 - RC

Researcher, GSJ, AIST

Specialty: Structural geology, Active tectonics
Keyword: Analogue modeling, Geomechanics, Marine geophysics

Ken-ichi Hirauchi

A02 - RC

Associate Professor, Faculty of Science, Shizuoka University

Specialty: Structural geology
Keyword: Field geological survey, High-pressure deformation experiment, Forearc mantle wedge, Serpentinite

Chengrui Chang

A01 - RC

Postdoc, Department of Biomaterial Sciences, The University of Tokyo

Specialty: Engineering geology, Experimental Rock mechanics
Keyword: Friction, Fault, Landslide dynamics, Failure-time forecast

Keishi Okazaki

A01 - RC

Associate Professor, Hiroshima University, Graduate School of Advanced Science and Engineering

Specialty: Experimental rock deformation, Rheology
Keyword: Rock deformation experiment, High pressure and temperature, Brittle deformation, Friction, Plastic deformation

Takehiro Hirose

A01 - RC

Principal Researcher, Kochi, JAMSTEC

Specialty: Rock mechanics, Structural geology
Keyword: Fault, Friction, Rheology

Katsuhiko Shiomi

A02 - RC

Principal Chief Researcher, NIED

Specialty: Observational seismology
Keywords: Crustal structure, Plate geometry, Seismicity

Rina Fukuchi

A02 - RC

Lecturer, Naruto University of Education

Specialty: Marine geology
Keyword: Accretionary prism, Southwest Japan, Paleotemperature

Hanae Saishu

A02 - RC

Researcher, Geological Survey of Japan, AIST

Specialty: Geochemistry
Keyword: Quartz vein, Hydrothermal flow-through experiment, Kinetics of quartz precipitation

Yusuke Shimura

A02 - RC

Researcher, Research Institute of Geology and Geoinformation, AIST

Specialty: Field geology, Tectonics
Keyword: Geological map, Accretionary complex, High-P/low-T metamorphic rocks

Tatsuhiko Kawamoto

A02 - RC

Professor, Department of Geosciences, Faculty of Science, Shizuoka University

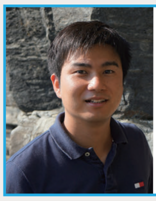
Specialty: Theory of mantle fluids, Theory of subduction-zone fluids
Keyword: Fluid inclusions, High-temperature and high-pressure experiments, Carbonation of mantle peridotite

Takayoshi Nagaya

A02 - RC

Assistant Professor, Graduate School of Science, The University of Tokyo

Specialty: Structural geology, Mineral physics, Structural seismology
Keyword: Structural Petrology, Mineral deformation mechanism, Rock rheology, Seismic property

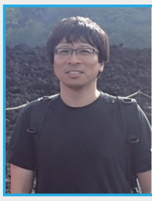


A02 - RC

Kazuki Sawayama

Assistant Professor, Institute for Geothermal Sciences, Kyoto University

Specialty: Rock physics
Keyword: Digital rock physics, Experimental rock deformation, Fracture



A03 - RC

Kazutoshi Imanishi

Deputy Director, Geological Survey of Japan, AIST

Specialty: Seismology
Keywords: Seismic observation, Crustal stress, Microearthquake

A03 - RC

Ryosuke Doke

Senior Researcher, Hot Springs Research Institute of Kanagawa Prefecture

Specialty: Space geodesy, Earthquake geology, Tectonic geomorphology
Keywords: Crustal deformation, Active fault, Active volcano

B01 - RC

Keisuke Ariyoshi

Leader of Earthquake and Tsunami Monitoring Group, JAMSTEC

Specialty: Geophysics of Crustal Deformation
Keywords: Seafloor Observation, Triggered Earthquake, Constitutive Friction Law

B01 - RC

Kinzo Kishida

Neubrex Co. Ltd.

Specialty: DFOS, Mechanics

B01 - RC

Ge Jin

Assistant Professor, Geophysics at Colorado School of Mines

Specialty: Distributed fiber-optic sensing, Seismic imaging
Keyword: Distributed fiber-optic sensing, Distributed acoustic sensing, Distributed strain sensing, Surface-wave imaging

B01 - RC

Yuya Machida

Resercher, IMG, FEAT, Research and Development Group for Seafloor Observatory, JAMSTEC

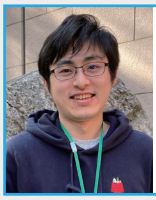
Specialty: Submarine geodesy, Downhole measurements, Ocean bottom seimsology
Keyword: Seafloor pressure gauge calibration, Fiber optical strainmeter

B02 - RC

Naoki Suda

Professor, Graduate School of Advanced Science and Engineering, Hiroshima University

Specialty: Seismology
Keyword: Low-frequency tremor, Very low-frequency earthquake



B02 - RC

Kodai Sagae

Postdoctoral Researcher, Geological Survey of Japan, AIST

Specialty: Seismology
Keyword: Tectonic tremor, Tremor migration, Seismic array analysis

B02 - RC

Ryo Kurihara

Researcher, Hot Springs Research Institute of Kanagawa Prefecture

Specialty: Observational seismology, Volcanology
Keyword: Tremor, Deep low-frequency earthquake, Matched filter technique

B02 - RC

Rouet-Leduc Bertrand

Assistant Professor, DPRI, Kyoto University

Specialty: Data science and geophysics
Keywords: Data science, Slow earthquakes, Earthquake nucleation

B03 - RC

Akihiro Ida

Researcher, VAiG, JAMSTEC

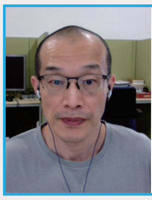
Specialty: Numerical linear algebra
Keyword: Low-rank structured matrices, High-performance computing, Discretization methods for integro-differential equations

B03 - RC

Ryoko Nakata

Project Researcher, Graduate School of Science, The University of Tokyo

Specialty: Seismology
Keywords: Earthquake cycle simulations

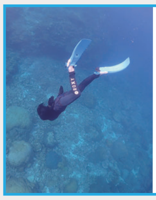


B03 - RC

Takao Kumazawa

Project Associate Professor, The Institute of Statistical Mathematics

Specialty: Statistical seismology
Keyword: Point process, Seismicity anomalies, ETAS model



Office

Michiko Watanabe

Earthquake Research Institute, The University of Tokyo

Office

Nami Tonegawa

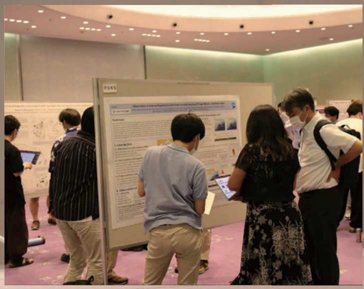
Graduate School of Science, The University of Tokyo

International Joint Workshop on Slow-to-Fast Earthquakes 2022

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

We held the International Joint Workshop on Slow-to-Fast Earthquakes 2022 at Nara Kasugano International Forum I-RA-KA from 14 to 16 September. The workshop was an outstanding success, with 134 participants on-site and 142 participants online. Despite the difficulties in traveling to Japan, there were 20 participants from overseas, including the U.S., Mexico, France, and Switzerland. We had 6 keynote speeches, 24 oral presentations, and 112 poster presentations (19 of which were online). The breakout sessions, which were held for the first time this year, were also very successful and represented a new activity of the workshop. Prior to the workshop, a meeting for young researchers was held on 13 September. After the workshop, a field trip to Matsuzaka and Ise in Mie Prefecture was held on 17–18 September. The field trip attracted 46 participants, including some from overseas.

Nohgaku Hall as the main hall



Poster Presentation Site

Visiting researcher program for foreign researchers

International Joint Workshop Slow-to-Fast Earthquakes 2022

Caroline Mouchon, Massachusetts Institute of Technology

My name is Caroline Mouchon, and I am a second-year graduate student at the Massachusetts Institute of Technology in the Department of Earth, Atmospheric and Planetary Sciences. I study slow slip event and their small time-scale dynamics using both geodetic and seismic datasets. I had the pleasure to attend the International Joint Workshop of Slow-to-Fast Earthquakes this year in Nara. I was able to receive the travel grant to fly to Nara from Boston, USA. I attended the full meeting and did an oral presentation of 15mins on the 1st Day of the meeting (09/14). I did not participate in the field trip organized at the end of the workshop. I really enjoyed this workshop for the incredible environment and venue, the interesting and broad scientific content, and the opportunities to meet and discuss with expert researchers on fast and slow earthquake rupture processes.

Summary of the workshop

The 1st Day was the most interesting for me as it was focused on slow earthquakes, and how we can explain the full spectrum of dynamics between fast and slow earthquakes. My presentation was the last of the morning session.

The 2nd Day was more focused on new methods and technology to study slow and fast earthquakes, like DAS or machine learning approach to study seismic and aseismic slip behavior.

Visiting researcher program for foreign researchers

The 3rd Day was mostly about geological evidence of changes in structures linked to slow or fast earthquakes. Some presentations also shared work on fluid dynamics and their link with slow rupture processes.

Overall, the Poster breaks were nicely organized but could have been longer or more divided.That way, we would have had more time to visit all the posters and still have meaningful and interesting conversations with the scientists.

I really enjoyed the breakout session, particularly the one focused on Slow Earthquakes Terminology (even if I wasn't in this group for the discussion). It was a great topic to discuss as slow earthquake terminology is still a very ongoing debate, with different communities using different names to probably talk about the same processes observed with different methods or approaches, in different regions.

Organization and venue

The location of this workshop was really beautiful, and I used the small break or lunch break to go visit the park and temples around the venue. Speakers were presenting their work on a stunning traditional Japanese stage. The hybrid format was very well organized; in-person people were not affected at all by the online part of the conference.

I thank you very much for this great meeting, the amazing opportunity to be in Japan, and meet very interesting researchers.

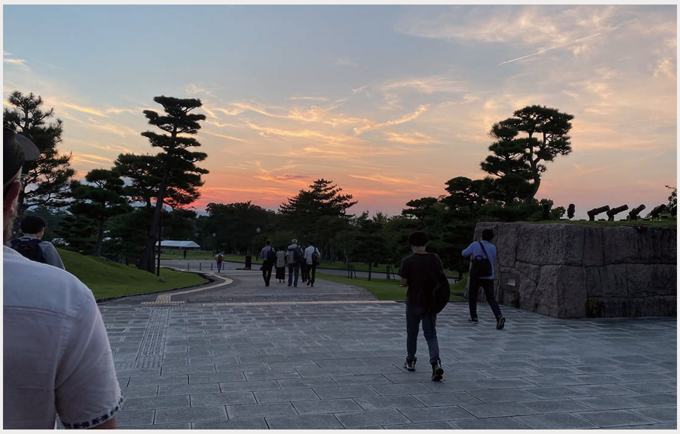
Report on International Joint Workshop on Slow-to-Fast Earthquakes 2022

Elizabeth Sherrill, Indiana University

Thanks to support from the Science of Slow-to-Fast Earthquakes project and my research advisor, I was granted the opportunity to attend the International Joint Workshop on Slow-to-Fast Earthquakes 2022 in Nara, Japan from September 14-16. There were many thought-provoking oral and poster presentations on all three days of the workshop. The first presentation by Ide-san on scaling slow and fast earthquakes was excellent and helped set the stage as we began the workshop. I also found the presentations by the geologists on the third day to be really enlightening. My work is centered on geophysical observations and inferences of slow-to-fast slip events so it was helpful to gain more understanding of the geologic processes and observations connected to the spectrum of slip events. The workshop allowed me to connect with scientists from Japan, Europe, and other parts of the

Elizabeth Sherrill presenting her research on stage at the International Forum in Nara.

United States and learn more about what they are doing for their research. It helped foster existing connections and build new ones that may lead to collaboration in the future. The International Forum in Nara was a magnificent facility for a workshop and it was an honor to get to present my work on the main stage. It was also nice to have the Japanese garden and Nara Park to walk around in during breaks. This was my first time in Japan and all of the people with the Science of Slow-to-Fast Earthquakes project and in Nara were very helpful and kind. This was definitely the best workshop I have ever attended in my short time as an early career researcher, and I expect it to be hard to beat with future workshops.



A beautiful sunset as workshop attendees leave at the end of the day.

September 2022, Slow-to-Fast Earthquakes Workshop Post-Meeting Report

John Weber, Grand Valley State University

1. Workshop: I was really impressed with the quality of technical presentations and posters at the meeting. I particularly enjoyed learning about the geological record of slow-slip earthquakes. Whitney Behr's keynote talk was excellent and helped me solidify and mesh together many of the related concepts. The workshop venue and Nara itself was idyllic and beautiful. It was a real pleasure to be there and such a great place to interact with many new colleagues and some old friends. The meeting was well-organized. The organizers were on top of all the details and available when even small items needed attention. This was a 100% professional operation. Thanks to Nami Tonegawa and her crew!

Photo2: Day 2. Interpretation of mesoscopic structures (possibly related to slow-slip?) as seen in well-exposed coastal outcrops of exhumed Sambagawa metamorphic (subduction zone) rocks under a sunny sky!

Photo1 : Day 1 weather conditions were not great, but the geology and leadership were!

2. Field Trips: Like the workshop itself, the field trips were 100% professionally organized and run. Kudos to Asuka Yamaguchi for his hard work, organization, and great communication. The rain on Day 1 came as a deluge and was relentless. (see photo1 on the right) Nonetheless, participants were treated to some great geology. It was a pleasure to be able to see and learn about the MTL. We all made it to our hotels, got dry and warm, and had an excellent group dinner that revived our dampened spirits. On Day 2 we were treated to sunny skies and again some excellent geology. We examined and discussed beautiful coastal outcrops of the Sambagawa rocks. It was a pleasure to see these two classic Japanese geological localities with such an august group of geoscientists. This was a great learning experience that I truly treasure.

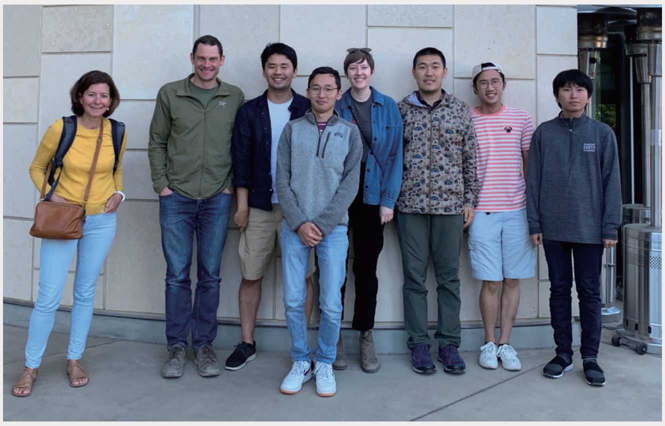
Visiting researcher program for young researchers

Report on the visiting researcher program for young researchers (Stanford University)

Osamu Sandanbata, NIED/ JSPS research fellow (PD)

In the spring of 2022, I visited Stanford University and conducted collaborative research with Prof. Eric Dunham to develop a numerical method to reproduce volcanic earthquakes that are unique to caldera volcanoes. This type of volcanic earthquake is generated by stresses created by magma pressure accumulating gradually for a long time ("slow") beneath a caldera and the subsequent rapid rupture of a fault structure within the caldera ("fast"). To understand this slow-to-fast process, broad knowledge in both seismology and volcanology is necessary. I had been preparing for this collaboration with Prof. Dunham, who has extensive knowledge of various geophysical phenomena, since the spring of 2019. Through weekly meetings, we discussed strategies and detailed methods for code development. We finally succeeded in reproducing an earthquake in a caldera for the first time, at which point Prof. Dunham said, "Welcome to earthquake cycle simulation!". I was impressed by his words. The two-month visit gave me a meaningful start-up opportunity, and this collaboration is ongoing.

Although I was excited about this visit before traveling, I felt anxious about the COVID-19 pandemic. Despite the difficult circumstances, I was able to complete this travel safely thanks to the support of many people. I am grateful to Dr. Tatsuhiko Saito and other members of the National Research Institute for Earth Science and Disaster Resilience for encouraging me to carry out this travel. I also thank researchers and staff of the Science of Slow-to-Fast Earthquakes for supporting my safe travel. I hope to contribute back to this research field, seismology, through these experiences and research outcomes.



Group photograph of Prof. Dunham (second from left) and his laboratory members. The author is third from left.

mini invited-ourselves workshop

Report on the "Mini invited-ourselves workshop on SF Earthquake Science" in New Zealand

Yoshihiro Ito, DPRI, Kyoto University

On 17 August 2022, we, Kimihiro Mochizuki, Martha Savage, and others held a "Mini invited-ourselves workshop on SF Earthquake Science". The invited-ourselves workshop is one of the most important events of our "Science of Slow to Fast Earthquakes" project. The workshop aimed not only to achieve a deep understanding of the physics of slow-to-fast earthquakes but also to establish a network for future collaborative research in some of our target regions around the world. In August 2022, Kimihiro Mochizuki, and Yoshihiro Ito visited New Zealand, following Kohtaro Ujiie, to perform fieldwork in Hawkes Bay, North Island. We acknowledge the generous support of Martha Savage, Victoria University of Wellington, in arranging the workshop. Despite the short notice, many researchers and students from the University of Victoria and GNS Science (about 30 people; 17 oral presentations and 1 keynote lecture) attended the conference and were able to learn about the latest research on slow-to-fast earthquakes in New Zealand. We also had the opportunity to present our research from Japan, including an introduction to our current project as the keynote lecture. We are pleased to report that we were able to achieve significant results for the promotion of future joint work. I thank all the collaborators from New Zealand for their participation in the workshop.

Promoting study activity of early career scholars and diversity

Task force of promoting study activity of early career scholars and diversity
Saeko Kita, Building Research Institute
Yohei Hamada, JAMSTEC
Shunsuke Takemura, Akiko Takeo, ERI, University of Tokyo

Random group event

A random group event was held to promote interaction among researchers from various study fields in our project group. We received applications from a wide variety of careers, including students, and then divided them into 10 groups of 3~4 members each. One of the groups developed into a face-to-face exchange event, which was a good start to our project.

Online lunch meeting

Since our project started in October 2021, the online lunch meetings have been held almost every month (11 times in total). Among these lunch meetings, participants enjoy chatting about various topics, such as recent seismic activities, overseas research activities, and issue of promoting diversity within our project.

Session "Study abroad during the COVID-19 pandemic" at the JpGU meeting

We collaboratively held a union session at the JpGU Meeting to share knowledge and experiences of overseas research activities in the COVID-19 pandemic situation. There were 5 oral presentations and 3 poster presentations, and 3 people from our slow-to-fast project, including Yoshihiro Ito, Kyoto University (A03 group), reporting and sharing information on study abroad and overseas research experiences. Most of in-person participants were students and young researchers. At the end of the session, there was a discussion among the speakers; how international exchange should be in the future and how to promote joint research. Despite the convenience of online tools, all the speakers felt that face-to-face activities have a great advantage to build friendship with overseas researchers, that plays an important role in promoting international joint research. In addition, the session also introduced the results of a questionnaire on the situation of each institution's response to the COVID-19 issue, targeting universities and research institutes participating in Slow-to-Fast project. Summary of answer sheets reports that universities have relatively few travel restrictions, but several national research

institutes still had difficulty in business trips overseas at the timing of April 2022. Questionnaire results are posted on the research website.

Pre-event for Early Career Researchers at Nara

On the day before the International Joint workshop on Slow-to-Fast Earthquakes 2022, we held an icebreaker event for early career researchers at Nara Prefectural Culture Hall to promote friendship between young participants. Twenty-first young researchers attended this event. We hope to hold more events for early career researchers in 4 years to promote interdisciplinary collaborative research among young researchers.

Equipments

A large-scale analog experimental device for studying plate-boundary deformation

Atsushi Noda, Geological Survey of Japan, AIST

AIST has installed a new large-scale analog experimental device funded by the Science of Slow-to-Fast Earthquakes. This apparatus reproduces deformation and failure mechanisms in the laboratory using particles such as dry sand and is used to investigate the formation of deformation zones along plate boundaries and accretionary wedges (e.g., Koge et al., 2018; Noda et al., 2020; Okuma et al., 2022). Important features of this equipment include the following: (1) the basal plate corresponding to the oceanic plate and the wall corresponding to the backstop can be moved vertically, and (2) multiple load cells installed on the basal plate and the wall can measure loads in real time during experiments. Regarding point (1), by moving the base up and down (i.e., changing its height), changes in deformation patterns and fault activity in the accretionary wedge can be observed as the dip angle of the oceanic plate changes over time. In addition, by adjusting the amount of sediment outflux (flow rate of the subduction channel), subduction erosion and basal accretion (underplating) can also be reproduced. Regarding point (2), because dry sand exhibits similar behavior to that of brittle rocks that respond to elastic–frictional plastic deformation with pre-failure strain hardening and post-failure strain softening until a dynamically constant shear load is reached, by measuring the stress change in real time during the experiment, the states of strain hardening and weakening of the accretionary wedge can be observed during its long-term growth. In addition, dynamic equilibrium conditions can be artificially created by instantaneously raising or lowering the base plate according to the measured loads. We have been preparing the hardware and software in 2022 and will start experiments in 2023. We are planning to perform experiments on stress changes, deformation structures, and fault activity over long-term (10^5–10^6 years) time scales in the shallow part of the subduction zone. These long-term stress changes are thought to affect short-term (10^0–10^2 years) seismicity and stress conditions that have been observed in modern subduction zones. We are now looking for researchers to participate in the experiments. Please contact us if you are interested in performing experiments using this apparatus or if you are interested in investigating the long-term processes of subduction zones using experimental approaches.

Figure1 : Photo of the experimental apparatus. The height of the basal plate is changeable in response to rising and lowering of the electronic cylinders.

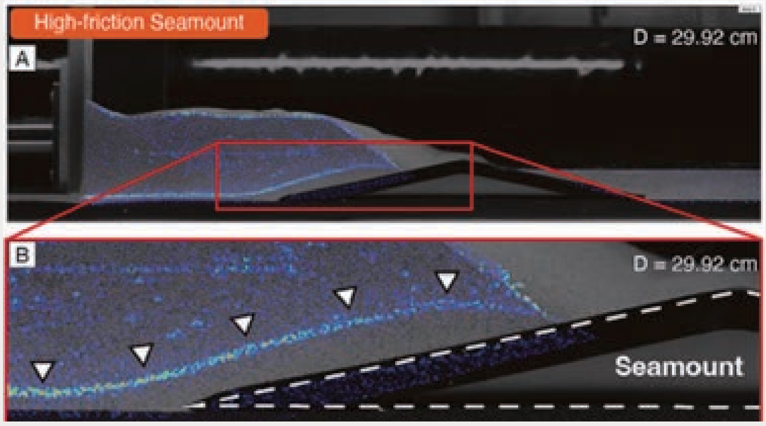


Figure2 : An example of the image analysis of experiments related with seamount subduction (Okuma et al., 2022).

Koge, H. et al. (2018) Prog. Earth Planet. Sci., 5(1), 69. Doi: 10.1186/s40645-018-0230-5.

Noda, A. et al. (2020) Tectonics, 39, e2019TC006033. Doi:10.1029/2019TC006033.

Okuma, Y. et al. (2022) Tectonophysics, 845, 229644, Doi:10.1016/j.tecto.2022.229644.

Rotary-shear friction apparatuses

Akito Tsutsumi, Kyoto University

By using two different velocity-range rotary-shear friction apparatuses with the same sample holder, it is possible to perform friction experiments such as constant-velocity and velocity-step experiments over a wide range of slip velocities from slow to fast. These apparatuses cover slip velocities in the range of about 3 × 10 −9 mm/s to 1.3 m/s for a cylindrical specimen with a diameter of 25 mm.

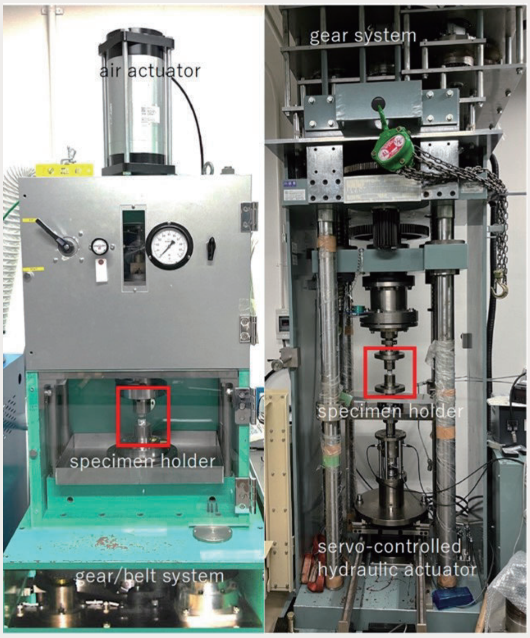


Figure : Left: Medium to High-velocity rotary-shear friction apparatus.
Right: Very low to Low-velocity rotary-shear friction apparatus.

Nine-component seismic observations

Suguru Yabe, Geological Survey of Japan, AIST

We conducted test field observations of a rotational seismometer (blueSeis-3A by iXblue) at Iitaka observatory of the Geological Survey of Japan, AIST, from November 2021 to January 2022. Although there are still technical difficulties in observing rotational ground motion, this rotational seismometer is a cutting-edge instrument that uses fiber optic gyroscopes to measure rotational ground motion. It is reasonably portable (20 kg weight). Iitaka observatory has three boreholes, and a Gladwin tensor strainmeter is installed in the 200-m-deep borehole, allowing measurement of the horizontal strain tensor. We have also installed a broadband seismometer (Trillium-compact) next to the blueSeis-3A. As a result, we have created a rare opportunity to measure three types (translation, strain, and rotation) and nine components of ground motion at a single place and time. During our observation period, a moderate-size earthquake (Mw 5.1) occurred at 17 km depth beneath the Kii Channel, whose signal was observed by all sensors. We confirmed that the rotational seismometer can capture seismic signals of natural earthquakes above the 1 Hz frequency band. A new analysis strategy based on multi-type and multi-component observations is expected to be developed.

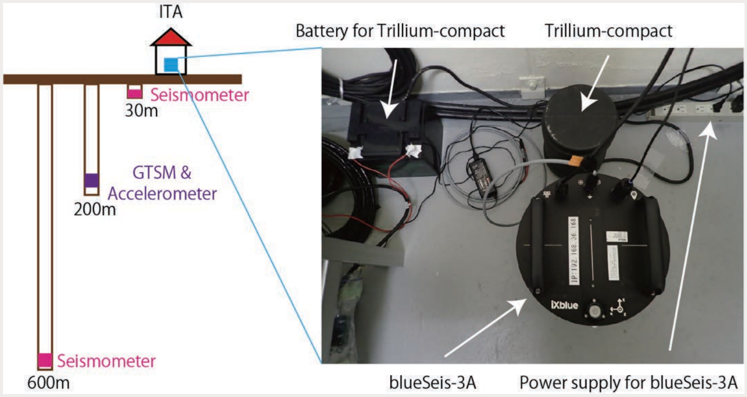


Figure : Seismic sensors in the three boreholes of Iitaka observatory. A Gladwin tensor strainmeter (GTSM) and an accelerometer are installed at the bottom of the 200-m-deep borehole. Seismometers are installed at the bottom of other boreholes. We installed a rotational seismometer (blueSeis-3A) and broadband seismometer (Trillium-compact) on the ground surface. The instrumental array provides three-type, nine-component seismic observations.

Award

Young Scientist Award of Seismological Society of Japan
Hisahiko Kubo (B02:Collaborator / NIED)
Akiko Takeo (Administrative Group･B02:Co-Investigator / ERI, University of Tokyo)
Suguru Yabe (A03:Co-Investigator / AIST)

Student Presentation Award of JpGU
Shogo Soejima (A02:Student / University of Tokyo)

Seto Prize of the Geodetic Society of Japan
Issei Kosugi (B02:Student/Shizuoka University)

The Geological Society of Japan H. E. Naumann Award
Ikuo Katayama (A01:Co-Investigator/Department of Earth and Planetary Systems Science, Hiroshima University)

The Geological Society of Japan Sakuyama Masanori Award
Keishi Okazaki (A01:Collaborator/Graduate School of Advanced Science and Engineering, Hiroshima University)
Masaoki Uno (A02:Collaborator/Graduate School of Environmental Studies, Tohoku University)

FY2020 Prime Minister's Award for Disaster Management Contributions
Aitaro Kato (Administrative Group･B02:Co-Investigator /ERI, University of Tokyo)

Medal with Purple Ribbon
Kazushige Obara (Principal Investigator, Japan Society for the Promotion of Science/Administrative: GroupCollaborator/Earthquake Research Institute, University of Tokyo)

The 30th Tsuboi Prize of the Geodetic Society of Japan
Masayuki Kano (B03:Collaborator / Graduate School of Science, Tohoku University)

Student Presentation Award of Seismological Society of Japan
Yasunori Sawaki (A03:Student / Kyoto University)
Koki Nakamura (A03:Student / University of Tokyo)

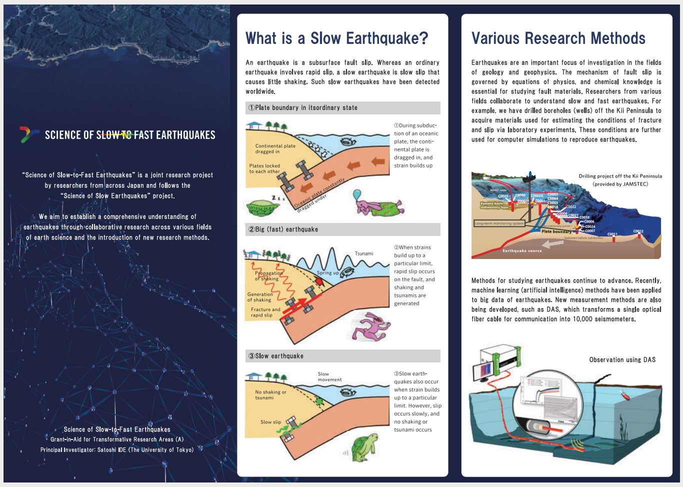
Introduction of the Slow-to-Fast Earthquakes Official Social Networking Service (SNS)

We are posting announcements and reports of Slow-to-Fast Earthquakes events and seminars on Twitter 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　Twitter

Publication of Slow-to-Fast Earthquakes Leaflet ver.1

A leaflet (Japanese and English versions) has been prepared to introduce the research areas in Slow-to-Fast Earthquakes and to provide comparisons of slow and fast earthquakes. The leaflet was distributed at the International Research Meeting in Nara, Japan, in September 2022. Printed copies of the leaflet are available at the Secretariat (sfeq-post-group [at] g.ecc.u-tokyo.ac.jp). Please let us know if you need one. A pdf version of the leaflet is also available on the Slow-to-Fast Earthquakes website.



Upcoming Events

Japan Geoscience Union Meeting 2023
Hybrid (in-person & online): May 21 (Sun.) - 26 (Fri.), 2023
On-site: MAKUHARI MESSE, Chiba

International Joint Workshop on Slow-to-Fast Earthquakes 2023
Date: September 13 (Wed.) - 15 (Fri.), 2023
Venue: Ito International Research Center, Univ. of Tokyo

Grant-in-Aid for Transformative Research Areas (A)

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