

[E] Oral | S (Solid Earth Sciences) | S-CG Complex & General

[S-CG45] Science of slow-to-fast earthquakes

convener:Aitaro Kato(Earthquake Research Institute, the University of Tokyo), Asuka Yamaguchi(Atomosphere and Ocean Research Institute, The University of Tokyo), Ryoko Nakata(Graduate School of Science, The University of Tokyo), Kurama Okubo(National Research Institute for Earth Science and Disaster Resilience), Chairperson:Yohei Hamada(Japan Agency for Marine-Earth Science and Technology), Kurama Okubo(National Research Institute for Earth Science and Disaster Resilience)

Wed. May 28, 2025 1:45 PM - 3:15 PM International Conference Room (IC) (International Conference Hall, Makuhari Messe)

Growing evidence of geophysical observations has demonstrated that earthquake faults host a broad spectrum of slip modes from slow to unstable fast slip, which may lead to complexity in the nucleation process, rupture behavior, and slip &energy distribution. This discovery has boosted up vigorous discussions about the connection between slow and fast earthquakes including large earthquakes. How and when does a slow earthquake become a fast earthquake? To answer this fundamental question, it is particularly important to proceed further interdisciplinary research through the integration of geophysics, seismology, geodesy, geology, and physics. Developments of measurement technology, application of information science and statistical methods to seismic big-data and utilization of high-performance computing are required as key ingredients in accelerating the integration. This session encourages presentations shedding light on geophysical observations, data analysis, field studies, laboratory experiments, numerical modeling, and theoretical studies. We also welcome contributions from cutting-edge science and technology fields that explore development of novel measurements, data-driven analysis, and large-scale computation etc., those are relevant to slow and fast earthquakes.

[SCG45-49] Geological evidence for fast earthquakes on the Milun Fault, Taiwan

*Li-Wei Kuo^{1,2,3}, Yung-Ya Ling¹, Kuo-Fong Ma^{1,2,3} (1.Department of Earth Sciences, National Central University, Taoyuan, Taiwan, 2.Institute of Earth Sciences, Academia Sinica, Taipei, Taiwan, 3.Earthquake-Disaster &Risk Evaluation and Management Center, National Central University, Taoyuan, Taiwan)

1:45 PM - 2:00 PM

[SCG45-50] Development of gouge triaxial shear experiments in Taiwan

*Ting-Yen Tai¹, Zhan-You Kuo¹, Szu-Ting Kuo¹, Li-Wei Kuo^{1,2,3}, Maciej Trzeciak⁴, Hiroki Sone⁴ (1.Department of Earth Sciences, National Central University, Taoyuan320, Taiwan, 2.Earthquake-Disaster &Risk Evaluation and Management Center, National Central University, Taoyuan 320, Taiwan, 3.Institute of Earth Sciences, Academia Sinica, Taipei 115, Taiwan, 4.Department of Civil and Environmental Engineering, University of Wisconsin-Madison, Madison, Wisconsin, USA)

2:00 PM - 2:15 PM

[SCG45-51] Earthquake Rupture Speed Dependence on Normal Stress in Laboratory Experiments

*Chun-Yu Ke¹, Gauss T. Chang¹, Gregory McLaskey², Chris Marone^{3,4} (1.National Taiwan University, 2.Cornell University, 3.La Sapienza Università di Roma, 4.Pennsylvania State University)

2:15 PM - 2:30 PM

[SCG45-52] Dynamic Strength and Fracture Energy of Rocks at Extreme Strain Rates: Insights into Seismic Energy Dissipation in Fault Zones

*Jun Muto¹, Takuma Sekiguchi¹, Kosei Ogita¹, Hiroyuki Nagahama¹ (1.Department of Earth Sciences, Tohoku University)

2:30 PM - 2:45 PM

[SCG45-53] Pressure oscillations caused by silica precipitation during fluid flow in a granite fracture

*Atsushi Okamoto¹, Edward L. Vinis¹, Hataka Nishimura¹ (1.Graduate School of Environmental Studies)

2:45 PM - 3:00 PM

[SCG45-54] Moment-duration scaling of experimental tremors at in-situ pressure and temperature conditions

Petr Zverev^{4,2}, Julien Gasc², Loic Labrousse⁴, Timm John⁵, Joern Kummerow⁵, Oliver Plümper⁶, *Alexandre SCHUBNEL^{1,2,3}, Satoshi Ide³ (1.CNRS , 2.ENS Paris - PSL University, 3.University of Tokyo, 4.ISTEP Sorbonne University, 5.Freie Universität Berlin, 6.Utrecht University)

3:00 PM - 3:15 PM

Geological evidence for fast earthquakes on the Milun Fault, Taiwan

*Li-Wei Kuo^{1,2,3}, Yung-Ya Ling¹, Kuo-Fong Ma^{1,2,3}

1. Department of Earth Sciences, National Central University, Taoyuan, Taiwan, 2. Institute of Earth Sciences, Academia Sinica, Taipei, Taiwan, 3. Earthquake-Disaster & Risk Evaluation and Management Center, National Central University, Taoyuan, Taiwan

Earthquakes are common natural phenomena in Taiwan, especially in the city of Hualien. The Milun fault in Hualien City ruptured in 1951 and was triggered by the 2018 Mw 6.4 Hualien earthquake, presumably as an active fault with a short recurrence interval. However, the fault zone characteristics of the Milun fault remain largely unknown due to the lack of an exposed fault zone. The Milun fault Drilling and All-inclusive Sensing (MiDAS) project was designed to penetrate the active fault zone of the Milun fault and deploy multiple monitoring systems. Here, we characterize the Milun fault zone sampled by MiDAS using microanalytical methods, including optical microscopy, scanning and transmission electron microscopy (SEM and FIB-TEM), in-situ synchrotron X-ray diffraction, and Raman spectroscopy.

Results show that the Milun fault zone is surrounded by the Milun conglomerate in the hanging wall and footwall. The Milun fault zone consists of variable widths of anastomosing clay-rich zones within spotted schists and dark gray gouges characterized by multiple black gouge layers. Both the dark gray gouges and the black gouge layers contain quartz, feldspar, carbonates, chlorite, kaolinite, and illite. In particular, the black gouge contains glassy materials. Fibrous minerals, as thermal decomposition products of carbonate (lime; CaO), are observed in small localized patches (~ a few hundred microns in size) within the black gouge. The presence of both glassy materials and lime suggests the coexistence of strain localization and frictional heating. In addition, since lime is an unstable mineral, the presence of lime suggests that the black gouge layers were recently sheared and preserved under dry conditions. We propose that the black gouge layers are the result of a fast earthquake, including the 2018 Mw6.4 Hualien earthquake.

Keywords: MiDAS, frictional heating, strain localization, lime, fast earthquake

Development of gouge triaxial shear experiments in Taiwan

*Ting-Yen Tai¹, Zhan-You Kuo¹, Szu-Ting Kuo¹, Li-Wei Kuo^{1,2,3}, Maciej Trzeciak⁴, Hiroki Sone⁴

1. Department of Earth Sciences, National Central University, Taoyuan320, Taiwan, 2. Earthquake-Disaster & Risk Evaluation and Management Center, National Central University, Taoyuan 320, Taiwan, 3. Institute of Earth Sciences, Academia Sinica, Taipei 115, Taiwan, 4. Department of Civil and Environmental Engineering, University of Wisconsin-Madison, Madison, Wisconsin, USA

In response to the 2050 net-zero emission in Taiwan, identifying potential sites for exploration of Enhanced Geothermal System (EGS) and Carbon Capture Utilization and Storage (CCUS) has become critical. Both technologies involve fluid injections into the subsurface, which can affect pore fluid pressure and fault stability, potentially leading to unstable slip and consequently increasing the risk of inducing seismicity. Recent studies have highlighted the linkage between induced seismicity and the rate-and-state friction law (RSF) to evaluate fault-slip instability during the operations of EGS and CCUS. Our team aims to establish the ability to run laboratory triaxial rock friction experiments in Taiwan. In this study, we used the direct-shear sample assembly for triaxial friction experiments on the GCTS servo-controlled Triaxial Rock Testing System (GCTS RTX-1000) at National Central University, Taiwan. We used kaolinite powder as synthetic gouge samples that were sandwiched between two 1-inch L-shaped stainless-steel platens. Normal stress was imposed through confining pressure (Pc) and maintained at 20 MPa, while the pore fluid pressure (Pp) was set at 10 MPa, resulting in an effective normal pressure of 10 MPa. After 8–12 hours of compaction to achieve equilibrium in Pp within the fault gouge, we applied a load-point displacement rate controlled by the load frame displacement transducer (DCDT). The initial velocity applied in all tests was set to 1 $\mu\text{m/s}$. Once the deviator stress (Sd) reached a steady state of 4 MPa, which represented the start of fault gouge shearing, we decreased velocity to 0.1 $\mu\text{m/s}$ until the load-point displacement reached 1.5 mm. The velocity was then adjusted in a 10-fold step sequence (e.g., 0.2, 0.02, 0.2 $\mu\text{m/s}$), with each test featuring different velocity values, applied at displacement intervals of 0.3 mm per step. All experiments showed a coefficient of friction from 0.16 to 0.22 after achieving a steady state and exhibited a velocity-strengthening behavior. The RSF constitutive parameters, direct effect coefficient (a), evolution effect coefficient (b), and critical slip distance (Dc) were obtained using RSFit3000 (Skarbek & Savage, 2019), with the assumed elastic stiffness $k = 0.15 \text{ mm}^{-1}$. Our results reveal that a-b, ranging from 0.001 to 0.002, is slightly lower than those documented by the previous studies (0.002–0.006 for saturated sample). The Dc was ranging from 10–100 μm . The results of fitting show an R-square of 0.6, indicating data dispersion that may be attributed to oscillations of DCDT and Sd. To improve the fitting quality of the a-b values, we can reduce noise by appropriately adjusting the sampling frequency or averaging data points during processing. We will conduct a stiffness test with dry gouge samples using a slide-hold-slide (SHS) stepping to obtain the elastic stiffness (k , units of mm^{-1}) for our confined direct shear assembly.

Keywords: rate-and-state friction law (RSF), triaxial friction experiments, confined direct shear assembly, fault-slip behaviors

Earthquake Rupture Speed Dependence on Normal Stress in Laboratory Experiments

*Chun-Yu Ke¹, Gauss T. Chang¹, Gregory McLaskey², Chris Marone^{3,4}

1. National Taiwan University, 2. Cornell University, 3. La Sapienza Università di Roma, 4. Pennsylvania State University

Rupture speed plays a critical role in earthquake dynamics, seismic energy release, and ground shaking characteristics. While variations in rupture speed of earthquake fault slip from fast to slow are well-documented in nature and in the lab, the responsible mechanisms are not fully understood. Here we address the physical mechanisms for variations in rupture speed using an array of strain gage rosettes in direct shear experiments to estimate the rupture speed of stick-slip instabilities. The experiments were conducted with applied normal stresses spanning one order of magnitude, ranging from 2 to 20 MPa. High-speed records of shear strains at 13 equidistant locations along 15-cm-long granite faults were analyzed to understand the effects of normal stress on rupture dynamics. Our data follow the expectation that higher normal stress generally promotes faster rupture speeds, consistent with observations from natural fault systems.

Our analysis reveals the interplay between stress conditions, stored elastic energy, and fault behavior. The experiments provide insights into how changes in normal stress affect the propagation of frictional rupture along a simulated fault surface with a thin layer of moisturized quartz gouge (Min-U-Sil, 40). A concise relation between normal stress and rupture speed based on linear elastic fracture mechanics is derived to explain our observations.

Fracture energy scales linearly with normal stress, which tends to reduce rupture speed as normal stress increases. However, the greater difference between peak and residual strength at higher normal stresses allows for more energy to be released during fault slip. Thus, as normal stress increases, the energy release rate, which scales quadratically with normal stress, outpaces the linear increase in fracture energy, leading to higher rupture speeds.

Our results provide important information for seismic hazard assessment and the development of more accurate rupture models for earthquake forecasting. By clarifying the role of normal stress in modulating rupture speed, our work illuminates the complex interactions between stress conditions and earthquake rupture dynamics. Overall, our data underscore the significance of considering normal stress variations in seismological methods to improve earthquake estimations and hazard assessments.

Keywords: Laboratory Earthquake, Rupture Speed, Fracture Energy

Dynamic Strength and Fracture Energy of Rocks at Extreme Strain Rates: Insights into Seismic Energy Dissipation in Fault Zones

*Jun Muto¹, Takuma Sekiguchi¹, Kosei Ogita¹, Hiroyuki Nagahama¹

1. Department of Earth Sciences, Tohoku University

This study examines how seismic energy dissipates within the damage zone surrounding a fault core, a process increasingly recognized as critical based on numerical simulations (e.g., Okubo et al., 2018JGR) and field studies of pulverized rocks (e.g., Muto et al., 2015GRL). It highlights the essential role of rock fracturing in the damage zone in modulating rupture propagation along the main fault, which in turn influences seismic damages. However, precise quantification of this dissipation process has remained challenging due to the limited availability of data on the dynamic strength of damaged rocks and the rarity of pulverized rocks in certain strike-slip faults (see recent review by Johnson et al., 2018).

To overcome these limitations, we conducted high-strain-rate rock deformation experiments to assess the mechanical properties of fault zone rocks under extreme conditions (Jayawickrama et al., 2023). Our findings suggest that the dynamic strength of these rocks is substantially greater than previously assumed and follows a predictable relationship with strain rate, which can be mathematically expressed through a unified equation. Additionally, we propose a novel analytical approach—the "seismic energy meter"—which links the fractal dimension of fault rocks to their fracture energy at high strain rates. By analyzing the particle size distribution of fault materials, this method provides a robust framework for estimating the energy dissipated during rock fragmentation in fault zones.

Ultimately, this research advances our understanding of seismic energy dissipation mechanisms, offering new perspectives for evaluating earthquake hazards and the mechanical behavior of fault systems.

References

- Jayawickrama, E. G., Sekiguchi, T., Muto, J., Sawa, S., Nagahama, H., Kono, Y., Bae, K-O., Shin, H-S., 2023, A split Hopkinson pressure bar for experimental investigation of dynamic pulverization under very high strain rates, Rev. Sci. Instrum., 94, 085110. <https://doi.org/10.1063/5.0151448>.
- Johnson, S. E., Song, W. J., Vel, S. S., Song, B. R., & Gerbi, C. C. 2021, Energy partitioning, dynamic fragmentation, and off-fault damage in the earthquake source volume. Journal of Geophysical Research: Solid Earth, 126, e2021JB022616. <https://doi.org/10.1029/2021JB022616>.
- Muto, J., Nakatani, T., Nishikawa, O., Nagahama, H., 2015, Fractal particle size distribution of pulverized fault rocks as a function of distance from the fault core. Geophys. Res. Lett., 42, 3811–3819. <https://doi.org/10.1002/2015GL064026>.
- Okubo, K., Bhat, H. S., Rougier, E., Marty, S., Schubnel, A., Lei, Z., et al. 2019, Dynamics, radiation, and overall energy budget of earthquake rupture with coseismic off-fault damage. Journal of Geophysical Research: Solid Earth, 124. <https://doi.org/10.1029/2019JB017304>

Keywords: Pulverized rocks, Impact experiment, Earthquake energy budget, Off-fault damage

Pressure oscillations caused by silica precipitation during fluid flow in a granite fracture

*Atsushi Okamoto¹, Edward L. Vinis¹, Hataka Nishimura¹

1. Graduate School of Environmental Studies

A well-known model that links the fluid pressure change and earthquake cycle is called as fault-valve model, in which increasing fluid pressure causes a reduction in the effective normal stress, rupture occurs when the imposed shear stress becomes equal to the shear strength. The rupture leads to a sudden increase in permeability and a drop in fluid pressure. As fault healing or sealing proceeds, the fault strength gradually increases and permeability increases again. Ubiquitous occurrences of quartz veins within the seismogenic zones indicate that the contribution of silica precipitation to fault sealing and fluid pressure change during earthquake cycle; however, there are no studies that show the temporal evolution of fluid pressure by silica precipitation. In this study, we conducted a hydrothermal flow through experiments on silica precipitation in fluid flow with a constant flow rate. We showed that characteristic fluid pressure oscillation occurred during sealing of the fracture. We also showed that a preliminary results on the silica precipitation experiments with artificially-imposed fluid pressure oscillation to test whether fluid pressure change can be recorded in cathodoluminescence (CL) zoning of quartz.

The flow-through experiments were conducted at fluid pressure at 25 MPa, and to induce silica precipitation within the slit of granite (6 mm × 0.5 mm × 100 mm), we established a temperature gradient between the inlet (370 °C) and outlet (425–430 °C) of the granite core to exploit the decrease in quartz solubility with increasing temperature to ~450 °C. Flow-rate were 0.5 mL per min and 0.2 mL per min, respectively. We used the granite-dissolved high Si solution as input solution. Following an induction period, the difference in pressure between the inlet and outlet (ΔP) exhibited an increase and oscillations with a sigmoidal pattern to a peak before an abrupt decrease. As sealing progressed, the background ΔP increased until reaching a stable state. The observed oscillations in fluid pressure resulted from the repeated blockage of flow pathways by silica precipitation and the subsequent rupture of locally sealed layers, which produced characteristic quartz textures such as blocky textures and banded fluid inclusions as observed in natural veins. Our results suggest that the generation and transport of silica particles in fluid, driven by rupture events, may induce transient and local variations in fluid pressure, thereby contributing to earthquake nucleation and rupture. Therefore, although the failure events are not shear failure, but are likely mode I extension failure. However, our experimental results on silica precipitation and pressure change represent a demonstration of fault-valve model.

In the second flow-through experiments with silica precipitation, we artificially imposed fluid pressure oscillation as square waves between 20 MPa and 25 MPa every 4 hours. Based on the SEM-CL observation, we found the repeated bands composed of CL-bright and CL-dark in quartz, corresponding to the fluid pressure change. The CL-bright bands show high Al and K concentration in quartz. Similar zonings are often reported in the quartz veins within the seismogenic zones, suggesting that these repeated CL zonings represents the fluid pressure changes in the earthquake cycle.

Sibson, R.H., Robert, F., Poulsen, K.H., (1988) Geology, 16, 551-555.

Raimbourg, H., Famin, V., Canizares, A., Le Trong E., (2022) Geochem Geophys Geosys, 23 e2022GC010346.

Okamoto, A., Vinis E., (accepted) Nature Communications.

Keywords: quartz vein, hydrothermal experiment, fluid pressure oscillation, silica precipitation

Moment-duration scaling of experimental tremors at in-situ pressure and temperature conditions

Petr Zverev^{4,2}, Julien Gasc², Loic Labrousse⁴, Timm John⁵, Joern Kummerow⁵, Oliver Plümper⁶,
*Alexandre SCHUBNEL^{1,2,3}, Satoshi Ide³

1. CNRS , 2. ENS Paris - PSL University, 3. University of Tokyo, 4. ISTEP Sorbonne University, 5. Freie Universität Berlin, 6. Utrecht University

The source mechanics of tectonic tremors, low amplitude-long duration seismic signals, either invokes the migration of fluids or the frictional breakdown of small ‘seismogenic’ asperities. Here, mantle rock powders containing up to 15 vol.% hydrous phyllosilicates, thought as analogues for dry and water-rich subducting lithologies, were compressed hydrostatically along a P-T path typical of hot subduction zones. Both in dry and wet lithologies, tremor-like acoustic emission (AE) signals were recorded at the same P-T conditions where natural tremors occur. Like the natural ones, experimental tremors followed a linear scaling between moment release and duration. Our experiments demonstrate that tremor signals originate from ductile or viscous deformation rather than from fluid circulations, but yet may be triggered by stress transfer at the onset of mineral dehydration.