Fluid flow, detachment kinematics, and core complex formation in the extensional Basin and Range Province

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Metamorphic core complexes (MCCs) are crustal-scale structural features in the North American Cordillera that result from exhumation of middle crust through large extensional detachment systems. They contribute to thermal and mechanical re-equilibrium of the orogenic crust after and during the Cenozoic extensional collapse of the Cordilleran orogen and thus, record the kinematic boundary conditions during the late stage(s) of orogenic evolution of western North America. The interplay among various parameters such as strain localization, fluid-rock interaction, and surface processes dominates the evolution of these detachment systems. In particular, localized synextensional interaction of fault zone rocks with surface-derived fluids appears to be a common feature that directly impacts the conditions of crustal flow, mineral recrystallization, elemental and isotopic exchange, and temperature gradients of actively extending crust.

To resolve the temporal and kinematical relationship between core complex formation and fluid flow from the Earth`s surface to the actively extending middle crust, we used a multi-disciplinary approach, including (1) observation of microstructures, (2) $^{40}Ar/^{39}Ar$ thermochronology, and (3) oxygen isotope thermometry ($D\delta^{18}O$), and (4) hydrogen isotope analyses (δD) of syntectonic hydrous minerals. The hydrogen isotopic composition of recrystallized hydrous minerals allows us to track the infiltration of meteoric water into brittle fault zones (e.g. clay gouges) and strongly localized fluid flow down to the brittle-ductile transition (e.g. mica-bearing mylonites) at mid-crustal levels.

One key example to resolve the structural evolution and multiphase synkinematic fluid-rock interaction of a detachment system is the Raft River MCC (Utah, USA). Combined microstructural, $^{40}Ar/^{39}Ar$ geochronological, and stable isotopic evidence from exhumed mylonitic footwall rocks of the Raft River MCC suggest that very low-δD surface-derived fluids penetrated through brittle faults in the upper crust down to the brittle-ductile transition as early as the mid-Eocene during a first phase of exhumation. Thus, Eocene extension within the Cordilleran hinterland not only occurred at more northerly latitudes, but most likely also characterized regions of the northeastern Basin and Range Province. In the eastern part of the core complex, prominent top-to-the-east ductile shearing, mid-Miocene $^{40}Ar/^{39}Ar$ ages, and higher δD values of recrystallized white mica, indicate Miocene structural and isotopic overprinting of Eocene fabrics. Miocene shearing in the western Raft River MCC seems to be a reactivation and/or continuation of an Eocene top-to-the-east shear zone with accompanied localized rather than pervasive fluid flow. Moreover, a significant component of cooling of the core complex might be due to fluid-induced refrigeration rather than exclusively to rock uplift and circulating fluids appear to have actively influenced the kinematic of the detachment and as a consequence the exhumation history of the core complex.

Collectively, combined geochronological and stable isotope geochemical studies in MCCs along strike of the North American Cordillera document that meteoric fluid flow was an integral component of crustal extension and surface-derived water was able to penetrate extending upper crust down to the

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brittle-ductile transition. We therefore argue that meteoric fluid flow in extensional fault and detachment systems may be more common than previously assumed which permits to export this approach to extensional settings in other orogens.

Keywords: meteoric fluid infiltration, hydrogen isotopes, metamorphic core complex formation

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A new method to estimate fault activity based on the fraction of saturation of quartz luminescence and ESR signals in fault rocks

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The activity of faults is usually estimated from the fault-displaced Quaternary sediments, containing both measurable displacement markers as well as dateable materials (Research Group for Active Faults of Japan, 1991). However, geologically- or geomorphologically-recognized faults especially in erosion area are not always cutting, or covered by, dateable Quaternary units. For such faults, there is currently no available method to evaluate their activity. The same problem also arises for the detection and dating of seismic slip events from borehole cores. In this presentation, we introduce a new concept to evaluate fault activity using the fraction of saturation of trapped charge in quartz –specifically, of the optically stimulated luminescence (OSL), thermoluminescence (TL) and electron spin resonance (ESR) signals. These signals, alone or in combination, have the potential to quantify the activity of faults with presently unknown slip rates, in Japan and elsewhere.
Active faults in Japan are categorised according to their slip rates into three classes (A, B, and C-classes) (Matsuda, 1975). An A-class fault experiences more frequent and larger-energy earthquakes than B- and C-class faults, contributing to a greater removal of trapped charge in quartz by frictional heating. Therefore, our working hypothesis is that the fraction of trapped charge saturation of A-class faults should be significantly lower than that of B-class faults, which themselves are lower than those of C-class; i.e. the fraction of trapped charge saturation is a function of the fault activity. By inverting the fractions of saturation using their corresponding trap kinetic parameters, one can estimate one of the following: the frequency, the temperature, or the duration of the resetting events (earthquakes), if the other two parameters are independently constrained.
In this presentation, we share our preliminary results from the Atotsugawa Fault, central Japan (including experimental data, modelling and inversion), and discuss the method’ s potential contribution to understanding fault mechanics (flash heating, in particular) and to estimate fault activity.

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Keywords: luminescence, electron spin resonance, thermochronology, fault activity

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Geochronology and thermochronology of fault zones: an overview

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Thermal signatures as well as timing of fault motions can be constrained by thermochronological analyses of fault-zone rocks (e.g., Tagami, 2012). Fault-zone materials suitable for such analyses are produced by tectocic and geochemical processes, such as (1) mechanical fragmentation of host rocks, grain-size reduction of fragments and recrystallization of grains to form mica and clay minerals, (2) secondary heating/melting of host rocks by frictional fault motions, and (3) mineral vein formation as a consequence of fluid advection associated with fault motions. The geothermal structure of fault zones are primarily controlled by the following three factors: (a) regional geothermal structure around the fault zone that reflect background thermo-tectonic history of studied province, (b) frictional heating of wall rocks by fault motions and resultant heat transfer into surrounding rocks, and (c) thermal influences by hot fluid advection in and around the fault zone. Thermochronological methods widely applied in fault zones are K-Ar ($^{40}Ar/^{39}Ar$), fission-track (FT), and U-Th methods. In addition, OSL, TL, ESR and (U-Th)/He methods are applied in some fault zones, in order to extract temporal imformation related to low temperature and/or very recent fault activities. Here I briefly review the thermal sensitivity of individual thermochronological systems, which basically controls the response of each method against faulting processes. Then, the thermal sensitivity of FTs is highlighted, with a particular focus on the thermal processes characteristic to fault zones, i.e., flash and hydrothermal heating. On these basis, representative examples as well as key issues, including sampling strategy, are presented to make thermochronologic analysis of fault-zone materials, such as fault gouges, pseudotachylytes and mylonites, along with geological, geomorphological and seismological implications. Finally, the thermochronologic analyses of the Nojima fault are overviewed, as an example of multidisciplinary investigations of an active seismogenic fault system.

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Keywords: thermochronology, dating, fault zone, shear heating, hot fluid

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An investigation of coseismic OSL / TL time zeroing of quartz gouge based on high-velocity friction experiments

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The OSL (optically stimulated luminescence) and TL (thermoluminescence) dating methods are mainly used to characterize an age of sedimentary rocks based on trapping of electron by natural radiation exposure. Recently, Ganzawa et al. (2013) suggest its applicability on direct age measurement of fault using fault zone material. The idea behind to the OSL/TL dating for a determination of paleo-earthquake event is the accumulated natural radiation damage becomes to zero (time zeroing) by the frictional heating and/or grinding. However, the relationship between fault motion and annihilation of the luminescence signals has not been fully understood. Understanding this relationship leads to expand measurable age range of active fault. In this study, we conduct low- to high-velocity friction experiments using quartz gouge under various experimental conditions (e.g., normal stress, displacement, moisture content) to establish an empirical relationship and physical and geological conditions of coseismic OSL time zeroing.
In the friction experiments, we used quartz grains of <150 μm separated from Tsushigawa granite (taken from the east wall of the Nojima fault Ogura trench site) as an analogue gouge. We conducted two series of experiments; (1) various slip rate experiments to see dependence of OSL/TL signal resetting on slip rate, (2) various displacement experiments to see dependence of OSL/TL signal resetting on displacement. In order to consider the effect of crushing, we separated the recovered sample into two grain sizes of <75 μm and 75-150 μm.
Our results of the OSL measurements are (1) <75 μm fraction of sheared gouge have high fast component ratio than the pre-sheared grains, (2) the fast component ratio of <75 μm fraction increases with increasing slip rate from 200 μm/s to 0.13 m, (3) OSL signal becomes to zero (time zeroing) in the experiment sheared under 0.65 m/s. The increase of the fast component ratio found in relatively low slip-rate experiments may be caused by the addition of the ionized electrons, that emitted from newly formed fracture surface during comminution, in electron center. The time zeroing observed in high-velocity friction experiment is attributable to rapid frictional heating up to 600 ℃ by temperature measurement. Based on the calculation of frictional energy we added to the experiment sheared under 0.65 m/s, we estimated the zeroing depth in natural conditions of earthquake (1.6 m in displacement) to 117 m.

Keywords: Asano fault, luminescence, high-velocity friction experiment, time-zeroing

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ESR technique for the assessment of fault activity; an approach from frictional tests using the Asano fault gouge collected by a trenching survey

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The ESR (electron spin resonance) dating method is a technique for the assessment of fault activity on the basis of the formation age of fault rocks (Fukuchi, 2004). In ESR dating, the age of the latest fault movement is determined by presupposing that ESR signals in fault rocks have been completely reset by frictional heating. When the ESR signals have been incompletely reset, the ESR ages obtained give older ones than the actual age of the latest fault movement. This problem on the incomplete resetting may be settled by collecting fault rocks from the depths under the ground where frictional heat temperature easily increases, however the deeper the drilling depth of borehole is, the higher the cost is. Therefore, it is important to reveal the depth where the complete resetting of ESR signals really happens. In this study, we carry out frictional tests using the Asano fault gouge collected by a trenching survey, and consider the necessary condition for the complete resetting of ESR signals on the basis of ESR analysis of the gouge samples after frictional tests. Moreover, we compare ESR spectra obtained from the gouge samples after frictional tests with those from the fault gouges collected from the Asano fault trenching and boring sites, and consider the resetting phenomenon of ESR signals by natural frictional heating.
The fault gouge sample used for frictional tests is grayish white gouge with a width of ~10mm distributed along the fault plane between granite and Osaka group on the north wall of the Asano fault trench. The grayish white gouge was dried under natural circumstances, ground with an agate mortar and set between a pair of columnar gabbro samples with a diameter of 24.98mm. In shearing, one columnar gabbro was fixed and another was rotated. Frictional tests were carried out at a normal stress of 2 MPa and a slip rate of 1.3 m/s under dry and wet conditions (Tsutsumi et al., 2016). When the total displacement was 30m, the maximum frictional heat temperature attained was estimated as 380 degree C under dry condition and 340 degree C under wet condition. The gouge samples after frictional tests under dry and wet conditions were divided into three parts of 0-9mm (central part), 9-16mm (intermediate part) and 16-25mm (circumference part), and ESR measurements of the three parts were carried out. As a result, a strong FMR (ferrimagnetic resonance) signal formed by frictional heat is detected from all the three parts under dry condition (Fukuchi, 2012), and the FMR signal intensity increases from the central part to the circumference part. Besides, E’ center in quartz and quartet signals in montmorillonite available for ESR dating have been completely reset. On the other hand, a weak FMR signal is detected from the circumference part under wet condition, however the E’ center and quartet signals have been hardly reset. These results mean that the FMR signal intensity is available for the judgement of resetting state of ESR signals. Moreover, as a result of ESR analysis of the fault gouge along a fault (fa-5) located at a depth of about 200m in the Asano fault 300m boring core sample, a similar FMR signal to that obtained from the circumference part under wet condition is detected. This suggests that frictional heat along the Asano fault may have been generated under wet condition.

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Keywords: ESR dating, Electron spin resonance, Asano fault, Fault gouge, Assessment of fault activity, Frictional test

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Repeated coseismic injection of pulverized fault rocks and infiltration of fluids including meteoric and sea-waters within fault damage zones

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In the past decades, increasing geological evidence has emerged that faults and shear zones within the middle to upper crust play a crucial role in controlling the architecture of crustal fluid migration and seismic faulting process. It is also well known that fluid can be released by dehydration reaction caused by seismic frictional heating during large earthquakes within both intracontinental faults and subduction zones that contain abundant hydrous minerals (Lin et al., 2003, 2013). Such rapid dehydration reaction would induce a sudden increase in fluid pressure that would simultaneously act to reduce the effective normal stress and markedly weaken the dynamic strength of seismogenic faults during seismic faulting, thereby facilitating seismic slip during large earthquakes. For an integrated multidisciplinary study on the assessment of activity of active faults involving active tectonics, rock-fluid interactions, geochemistry and geochronology of active fault and seismogenic fault zones, recently, a new project of "Drilling into Fault Damage Zone" has being conducted by Kyoto University on the Nojima Fault again after 20 years of the 1995 Kobe earthquake.

In this presentation, I will review the previous studies and report the recent progresses on the fluid infiltration concerning with coseismic faulting and recent activity on two seismogenic faults that recently triggered the large earthquakes, one from the active faults of the Longmen Shan Thrust Belt that triggered the 2008 M_w 7.9 Wenchaun earthquake in the Sichuan basin, China, the other is the Nojima Fault that triggered the 1995 M_w7.2 Kobe earthquake. Circulating fluids deposit fine-grained sediments including clay and carbonate material and pulverized rock materials into cracks within the fault zones. Such crack-fill fine-grained materials, calcite veins, and oxidized/weathered open cracks have well been observed in the drill cores, from both the Nojima Fault and the active faults of the Longme Shan Thrust Best. 3D micro-X-ray scanning data and powder X-ray diffraction analyses show that the fault core zone contains a numerous of veinlets which are composed of fine-grained materials, carbonate material and clay minerals. Isotopic analyses of carbonate material within the fine-grained materials and calcite veins reveal that the calcite veins are sourced from typical meteoric and seawater. ^{14}C dating ages of 10 calcite vein samples range from 35.0 to 58.4 kyr B.P. Geological, petrological, stable isotopic, and ^{14}C data suggest that these crack-fill fine-grained materials and calcite veins and brown open cracks were developed by the repeated infiltration of O_2- and CO_2-bearing meteoric and seawater downward into the deep fault zone during the last 35–60 kyr. We propose a seismic fault suction-pumping model to interpret the infiltration of subsurface waters being carried down into the deep fault zone by rapid potential change during episodes of seismic faulting.

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Keywords: coseismic injection of pulverized fault rocks, coseismic infiltration of fluid, seismic fault suction-pumping model

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Influence of fault activity to hydration thickness of quartz: Application of SIMS analysis

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Occurrence of recent activity of faults is often evaluated based on displacements of young subsurface sediments covering the faults. However, this evaluation is not applicable for faults that occur where young subsurface sediments are not found. Faulting in brittle regimes often results in the development of fault gouge along a slip plane. In addition, the formation of hydrous silica gel has been proposed as one of indicators of paleo-earthquakes within the rock record (Faber et al., 2014). Analysis for silica hydration along faults as well as structural, mineralogical and geochemical analyses of a fault gouge may assist in reconstructing the history of fault activity, and also contribute to identification of recent faulting.
Hydration thickness measurement of silica glass has been applied for dating for archeological artifacts such as a stone figure and axe made from obsidian (Katsui and Kondo, 1967; Stevenson et al., 1989). Hydration thickness of volcanic glass estimated from refractive index analysis using optical microscopy has positive correlation with its sedimatation age (Yamashita and Danhara, 1995; Ikuta et al., 2016). Hydration rate of volcanic glass is about 1 μm/1,000 yr, depending on sedimentary environment. In contrast, hydration rate of quartz is too slow; diffusion coefficient values of quartz and glass at ambient temperatures are about 10^{-21} and 10^{-17} cm^2/s, respectively (Ericson et al., 2004). However, examinations of natural fault mirror surfaces and experimental studies for siliceous rocks have suggested that silica gel lubrication could cause coseismic weakening (Hayashi and Tsutsumi, 2010; Kirkpatrick et al., 2013). Near-surface faulting possibly facilitates a growth of quartz hydration.
In this study, we examined the relationship between development of quartz hydration and fault activity. The hydration thickness was estimated by secondary ion mass spectrometry (SIMS), Physical electronics PHI 6650 or PHI ADEPT 1010 housed at Foundation for Promotion of Material Science and Technology of Japan. Cesium ion was used as primary ion, and depth profile of secondary ion intensities of hydrogen, silicon, oxygen and aluminum ion was obtained for a 10 μm depth from a sample surface. Hydrogen ion concentration was calculated from normalization using a quartz standard sample. Primary accelerated voltage was 5.0 kV, and analyzed area was approximately 20 μm ×20 μm.
We analyzed chert samples from the Franciscan Complex in California and Mino Belt in central Japan. We compared depth profiles of hydrogen ion concentration between (1) mirror surfaces along fault plane, (2) natural, flat surfaces without fault slip, and (3) inside of the samples exposed by cutting and polishing. The analysis suggests that hydrogen ion concentration from the mirror surfaces to >1 μm depth increases severalfold compared to inside of the samples, while the natural surfaces without fault slip have no clear concentration change for depth. This study shows that the SIMS analysis could be applicable for the estimation of hydration thickness of quartz along faults as well as the measurement of obsidian hydration thickness (Liritzis and Laskaris, 2009). The tests for still more samples should be further studies to examine geochronological application for fault activity.

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Keywords: Fault, Quartz, Hydration, SIMS

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Luminescence measurement of quartz from Nojima Fault Trench

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1. Introduction
The Southern Hyogo prefecture earthquake occurred by the activity of the Nojima fault in 1995. The southeastern side of this fault was uplifted by 1.4 m with horizontal displacement of 2.1 m along the fault to southwestward. In this study, we investigated the effect of fault activity on luminescence signal and estimated dose in quartz from samples from trench of Nojima fault.
2. Luminescence measurement
In this study, the blue thermoluminescence (BTL) often observed for dating of granite-derived quartz sample and the ultraviolet region thermal luminescence (UV-TL) which is the same emission wavelength as the OSL method were measured. Luminescence signals are reset by heating or bleaching (Obata et al., 2015). When considering the temperature and time conditions necessary for resetting the signal, the τ value (the average lifetime) is calculated as an index of the time required for attenuation of the signal under a certain temperature. This temperature and time condition is very low and short compared with ESR and K-Ar methods. Therefore, this method has a potential to specify the latest activity of fault (Ganzawa et al., 2013).
3. Peak temperature of TL signal
The luminescence sites and their emission temperatures were determined by T-Tmax method perfomed by 10 ˚C interval. The host rock collected from Rokko granite (Host rock) and the granite sample (E1) collected about 5 m away from the gouge in trench were measured. As a result, the peak emission temperatures were 200 ˚C, 270 ˚C and 320 ˚C. These values were concordant for BTL and UV-TL.
4. Luminescence signal for granite
Quartz was extracted from Host rock, and several samples from the trench with different distance from the fault. Then, each TL emission curve was obtained. The shape and intensity of these signals are different among samples.
Furthermore, the signal growth rate against amount of dose were also not constant for each peak in all samples.
5. Dose of samples from trench
The dose (Gy) of each sample was calculated for each luminescence site after peak separation of the emission curve. Different peaks showed different dose values in all the samples. The dose estimated by peak at 200 ˚C showed the minimum value.

Keywords: luminescence dating, quartz, active fault

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Development of direct dating methods of fault gouges focused on the latest fault slip event

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We started a research project to develop methods to determine the age of the latest fault slip event using fault gouges. The methods would be used for evaluation of activities of faults without overlying sediments. In order to estimate the latest fault slip event, it is necessary to use fault gouges which have been experienced age resetting (AR) by frictional heating. Near-ground surface fault gouges have been sometimes dated to be older than the true age because the gouges have not been completely reset at the AR temperature. Therefore, we investigate fault gouges at deep depth (300-1,500m) to compare thelatest fault slip event with known recent historical earthquakes.

This study includes the following 1)-3): 1) AR condition check: We conduct a deep borehole observation throughthe target fault damage zone to measure physical temperature, pressure and geological conditions in which the sample expecting a reliable dating can be acquired. We are now drilling a deep borehole with multiple depths through the Nojima Fault ruptured during the 1995 Hyogo-ken Nanbu earthquake to understand conditions of AR. 2) Luminescence and electron spin resonance (ESR)dating: We apply the luminescence and ESR dating techniques to estimate precisely determination of the age of the latest fault event. 3) Friction test: Rotary-shear high-velocity friction tests using natural fault gouge under water-pressure conditions are expected to clarify frictional behavior of faulting and AR conditions. Combining results from 1)-3), integrated analysis on fault activity will be performed. Our goal of this study is to establish the dating methods of fault gouges for precise determination of the age of the latest fault slip event.

Keywords: fault gouge, fault activity, dating, deep borehole drilling, high-velocity friction test, fault damaze zone

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New authigenic illite age and hydrogen isotope data to constrain the geochronological and geochemical framework of brittle faulting within the Nojima fault zone, Japan.

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Numerous recent case studies have successfully constrained the timeframe of brittle faulting through dating of clay-size fault gouge fractions. However, the involved fluids sources are not well constrained. K-Ar dating of fault rocks coupled with hydrogen isotope analysis allows to both constraining the timing of brittle faulting and to constrain the influx of variable fluids sources into such fault systems. We present a novel application of hydrogen isotope-based analyses that explores the hydrogen isotope values of fluid sources in Paleocene to Miocene clay gouge-bearing faults from outcrops and drill core samples from the Nojima fault (Awaji island, Japan; [1]). K–Ar ages provide have an age range from 63.4 ±1.3 Ma (Early Palaeocene) to 42.2±1.0 (Palaeogene–Middle Eocene). Several <0.1 and <0.4 μm fractions in proximity to a pseudotachylyte zone are thermally influenced with loss of radiogenic Ar. The illite age data support a model that the Nojima fault zone was initiated ~ 55 Ma ago by ZFTA data [2]. Hydrogen isotope (δD) values of −119 to −97 for fault gouges and cataclasite zones and document meteoric fluids infiltrating the upper crustal brittle fault zones. The data document elevated temperatures and a heterogeneous thermal history within the study area and influence of a secondary thermal heating event probably caused by circulation of hot fluids within the fault zone about 31–38 Ma ago and even a potential influence of Quaternary faulting.

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Keywords: brittle fault, authigenic illite, K-Ar dating, Hydrogen isotopes, Nojima fault, Japan

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