Geochronology of faults

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博　士　論　文　要　旨

Geochronology of faults

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Abstract

This study attempted to elucidate the influence of fault activity on the luminescence signal using quartz samples collected from the Nojima active fault. Two basement samples showed concordant ages of 40 ka at 270°C and 340°C emissions and more than 80 ka at a 400°C emission. These ages may be representative of the uplifting process of the basement granite. Two samples collected near the fault showed young ages compared with those of the other samples, but they were not consistent with the time of the last fault activity (about 30 years ago) partly because thermoluminescence (TL) is not capable of dating modern events. The other trench samples showed various ages at 270°C and 340°C emissions different from that of the basement granite, indicating that the fault activity had some effects on the signal.

The frictional experiments revealed that the power density required for partial and complete optically stimulated luminescence (OSL) signal resetting is ~0.17 and 0.6 MW m^{-2}, respectively. Assuming a coseismic fault slip rate of 0.6 m s^{-1}, that is calculated based on the displacement found during the earthquake event caused by Nojima fault, the depths required for partial and complete resetting are expected to be ≥11 and ≥42 m.

The faults found at depths in drilled core samples were also analysed to see age resetting actually occureed.

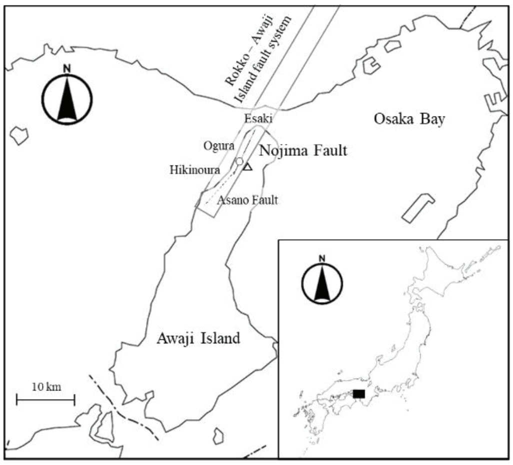

Fig. 1 Sample localities. The Nojima Fault is an active fault extending approximately 7 km from Esaki to Hikinoura. The southern part of the Nojima Fault (solid line) is connected to the Asano Fault (dotted line). These faults belong to the southern part of the Rokko–Awaji Island fault system (square frame). The open circle is the location of the trench, and the open triangle is the location from where the Tsushigawa granite (TS) was collected. The base rock (BR) was sampled about 200 m east of the trench.

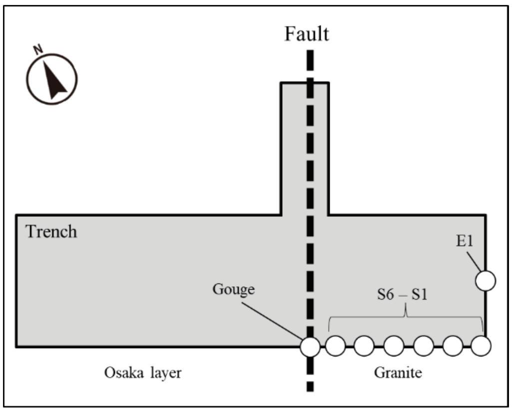

Fig. 2 Schematic image of the trench where the samples were collected.

Introduction

Japan is one of the most earthquake-prone regions in the world. Numerous attempts have been made to determine the age of fault activity recorded in fault rocks using dating methods such as K-Ar, fission track, electron spin resonance and luminescence dating methods. Compared to other methods, the signal reset occurs in very short time even at low temperatures in luminescence dating, and it has a potential to identify the time of final activity of faulting, for the faulting should cause the frictional heating and result in erasing accumulated luminescence signals. Therefore, this study attempted to elucidate the influence of fault

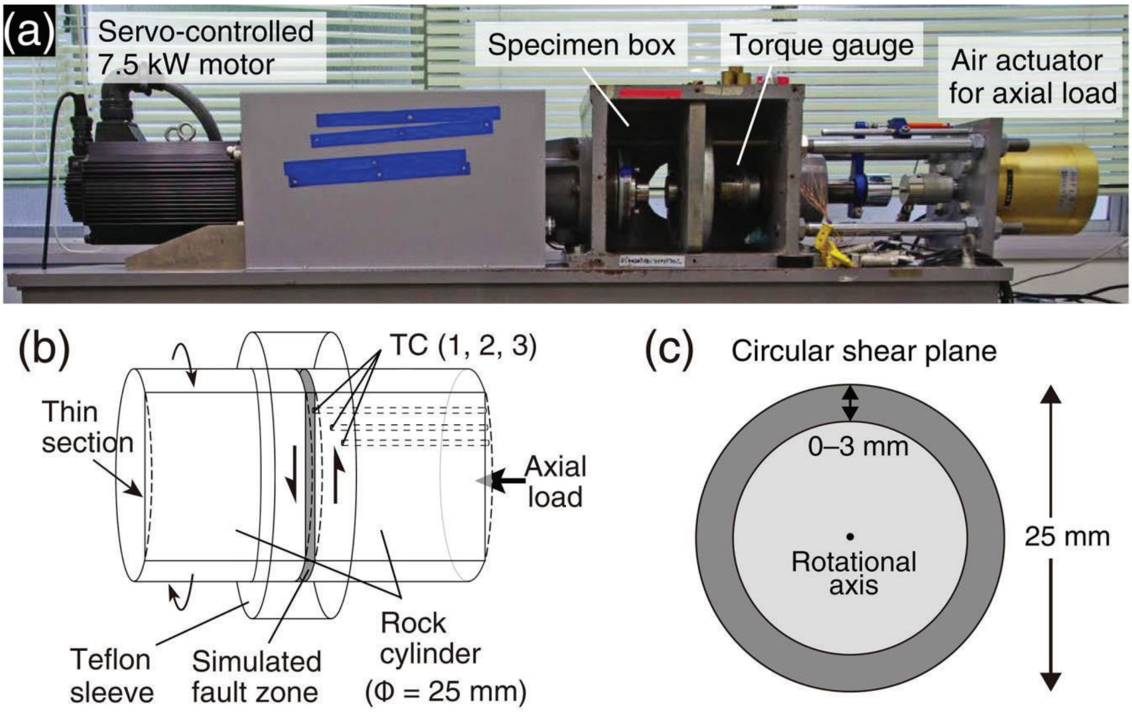

Fig.3(a) Rotary-shear, high-velocity friction apparatus at Yamaguchi University. (b) Specimen configuration used in this study. Simulated fault gouge was placed between two cylinders of gabbro. Temperature was measured using three K-type thermocouples (TC1, 2, and 3; buried at different depths) placed 2.5 mm inward from the circumference of the cylinder. (c) Schematic illustration showing the circular shear plane of the simulated fault gouge. The sample recovered from the annulus region (0–3 mm) was used for OSL measurement.

activity on the luminescence signal using quartz samples collected from the Nojima active fault. First we analysed the thermoluminescence (TL) signals and estimated signal decrease according to the distance from the fault. Second, we investigated how the optically stimulated luminescence (OSL)

Table 1 Results of the radioelement measurements and estimates of the annual doses

	K_20 (%)	Rb (ppm)	SE (ppm)	Th (ppm)	SE (ppm)	U (ppm)	SE (ppm)	AD (Gy/kyr)	Error (%)	cosmic ray (Gy/kyr)
TS	4.2	391.5	9.2	45.1	20.6	8.9	0.2	9.9	45.8	0.3
E1	4.3	297.4	22.1	11.9	1.6	2.9	0.6	5.8	24.5	
S5	5.0	226.9	22.8	88.7	11.3	15.4	3.9	15.0	30.2	
S7	4.4	189.2	15.8	27.6	3.2	3.3	0.6	6.7	22.3	
Weighted mean and error	4.5	363.4	7.7	42.8	3.0	8.8	0.2	9.4	7.7	

signal in quartz decrease by the faulting through friction experiments to determine the seismological and geological conditions necessary for the resetting of the OSL signal in natural fault zones. Third, the faults plane samples found at various depths in drilled core are analysed by TL and OSL to test the latest fault activity could be detected or not.

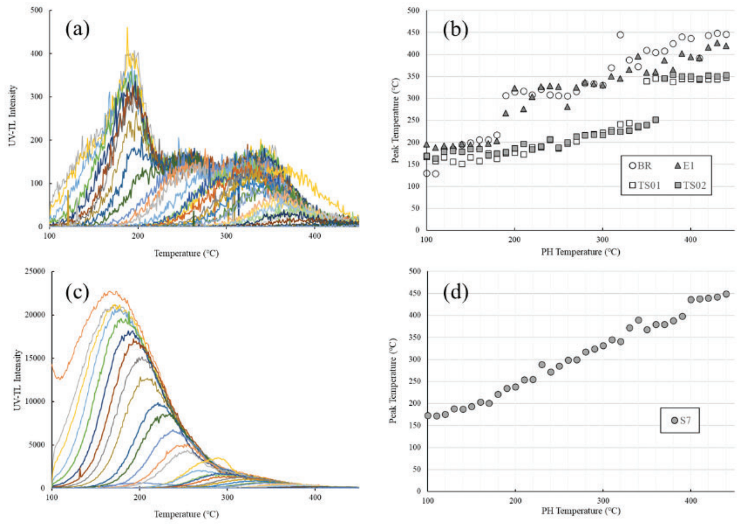

Fig. 4 Results of the T–Tmax measurements. (a) Example of glow curves (E1). The preheat temperature was increased every 10° from 100°, and the TL was measured. (b) The lowest peak temperature in the glow curves is plotted against the PH temperatures for three samples (BR E1, and TS). Two aliquots were measured for TS. (c) T–Tmax emission curves from S7. (d) The lowest peak temperature of the S7 glow curves plotte against PH temperatures. The results show no clear luminescence sites.

Geological background and samples

The Nojima Fault is extending from north-east to south-west of Awaji Island in south-west Japan (Fig. 1) and caused the 1995 Hyogo-ken Nanbu Earthquake (M = 7.3) at 5:46 a.m. on January 17, 1995. A clear surface displacement was discovered along the Nojima Fault. The trench survey was conducted at a locality 720 m east-southeast of the Hokudan Earthquake Memorial Park in Ogura, Awaji City, with a dimension of 15 m long in a northwest–southeast direction, 2.5–5 m wide (Fig. 2), and 1.5–3 m deep.

Samples were collected from the south wall of the trench. One sample was collected from the gouge and seven samples were collected from the granite breccia zone at 1 m intervals east to the gouge; S7 was taken from only a few millimeters away from the gouge sample. In addition, one sample was collected from the east wall, which is the furthest from the fault in the trench (E1). This E1 sample was applied to the frictional experiment. All of these samples were affected to some extent by fault activity. Two granite samples were also collected from the subsurface, which were less affected by fault activity. One was taken from a point approximately 200 m east of the trench (base rock [BR]) and the other from a point approximately 3 km from the fault in the Tsushigawa Granite (TS).

Experiments

The luminescence measurement system used in this study is a modified version of the one used in Ganzawa et al. (2013) and installed in Kanazawa University. It is equipped with photomultiplier tubes (Hamamatsu Photonics: R585s) with excellent reception in the ultraviolet (UV) to blue luminescence emission. RR0340 (Asahi Spectroscopy) was used as the filter. This filter has a lower transmittance in the infrared region than that of U340 used in conventional optically stimulated luminescence (OSL)

Table 2 The trap depth and frequency factor calculated using the peak shift method

	Luminescence site	E (eV)	s (1/sec)
BR	site1 (200°C)	1.18 ± 0.01	$1.24 \times 10^{11} \pm (\times 10^{0})$
	site2 (270°C)	1.62 ± 0.23	$8.23 \times 10^{13} \pm (\times 10^{2})$
	site3 (320°C)	1.57 ± 0.13	$6.60 \times 10^{11} \pm (\times 10^{1})$
	site4 (400°C)	1.75 ± 0.25	$5.99 \times 10^{11} \pm (\times 10^{2})$
E1	site1 (200°C)	1.13 ± 0.17	$3.73 \times 10^{10} \pm (\times 10^{2})$
	site2 (270°C)	1.61 ± 0.14	$5.77 \times 10^{13} \pm (\times 10^{2})$
	site3 (320°C)	1.51 ± 0.11	$7.20 \times 10^{10} \pm (\times 10^{1})$
	site4 (400°C)	1.75 ± 0.25	$5.99 \times 10^{11} \pm (\times 10^{2})$
Spooner et al., (2000)	220 °C (5K/s)	1.63	3.40×10^{16}
	280°C (5K/s)	1.50	1.50×10^{13}
	325°C (5K/s)	1.65	3.90×10^{13}

measurements. Therefore, we detected TL in the UV region (UV-TL). An X-ray source (Varian: VF-50) was used to give an artificial dose (Hashimoto et al., 2002).

To estimate annual dose (Table 1), the K_2O concentration was measured using X-ray fluorescence (ZSX primus II, Rigaku Corporation) analysis (Kusano et al., 2014) and calculated by converting the concentration to 100% considering the ignition loss. Radioelement (U, Th, and Rb) concentrations were measured using laser ablation–inductively coupled plasma–mass spectrometry (LA-ICP-MS: MicroLas GeoLas Q-plus 193 nm ArF excimer laser system and Agilent 7500s), and the annual doses were calculated using the obtained values (Morishita et al., 2005, Ito et al., 2009; Tamura et al., 2015).

Friction experiments were conducted in Yamaguchi University with a rotary-shear, high-velocity friction apparatus (Fig. 3).

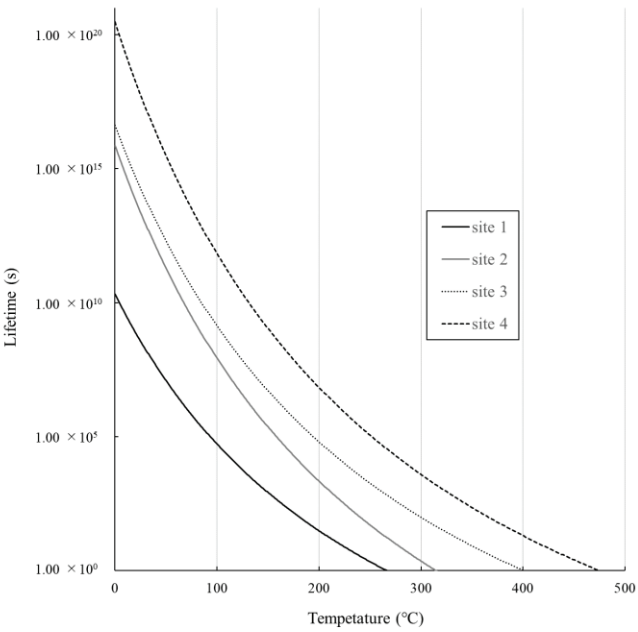

Fig. 5. Lifetime (τ: s) of the luminescence site calculated for sample E1 under particular ambient temperatures.

Results 1 :TL

The examination of luminescence-emitting temperatures revealed that quartz separated from granite has four luminescence sites (roughly the peak

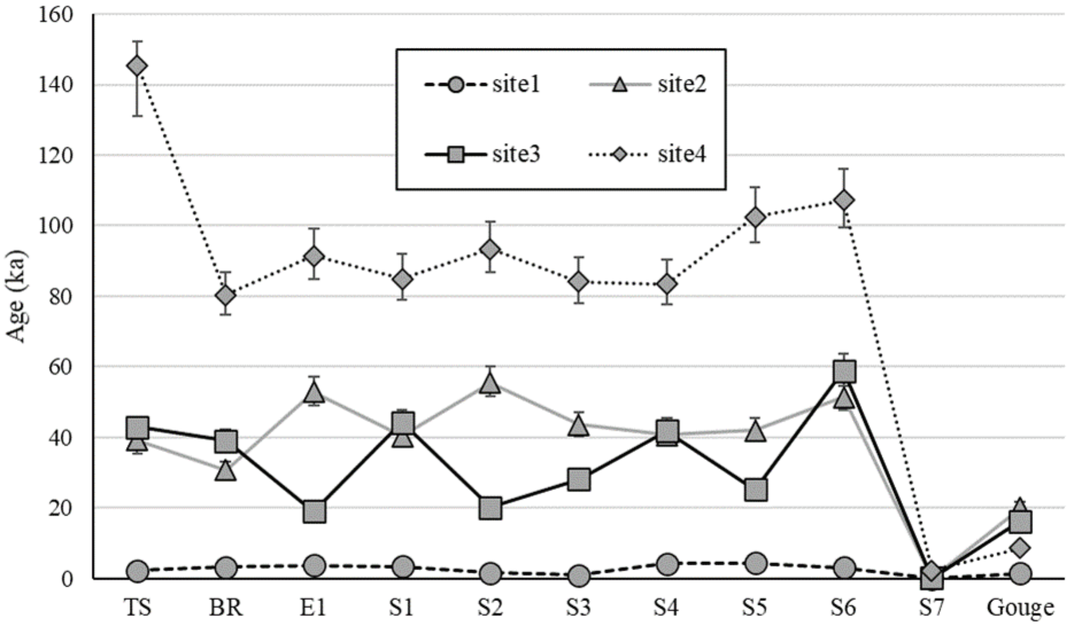

Fig. 6 Age estimate results.

temperatures of 200°C, 270°C, 340°C, and 400°C under a heating rate of 1°C/s) (Fig. 4). The lifetime of each luminescence site was then estimated (Table 2, Fig. 5).

Two basement samples showed concordant ages of 40 ka at 270°C and 340°C emissions and more than 80 ka at a 400°C emission. These ages may be representative of the uplifting process of the basement granite. Two samples collected near the fault showed young ages compared with those of the other samples, but they were not perfectly consistent with the time of the last fault activity (about 30 years ago) partly because TL is not capable of dating modern events (Fig. 6). The age of S7 is the youngest and closest to the age of the last activity. The other trench samples showed various ages at 270°C and 340°C emissions different from that of the basement granite, indicating that the fault activity had some effects on the signal. Further examinations on why the signal was lost for S7 but not for the gouge samples and how the samples were thermally damaged during faulting are necessary. In any case, more detailed studies on how deformation during faulting affects luminescence sites and accumulated signals are necessary.

The different ages of the trench samples from those of the basement samples suggest that signals were lost or even created in the past. Although we were not able to identify the cause of the age difference in this study, we can explore such further in future studies.

Results 2 :OSL during friction experiment

In the frictional experiments, we used quartz sand with a particle size of <150 μm and equivalent dose of 31.5 ± 16.6 Gy given artificially by gamma ray irradiation. Friction experiments were performed at slip rates (V) of 200 μm s^{-1} to 1.3 m s^{-1}, normal stress of 1.0 MPa, and displacement of

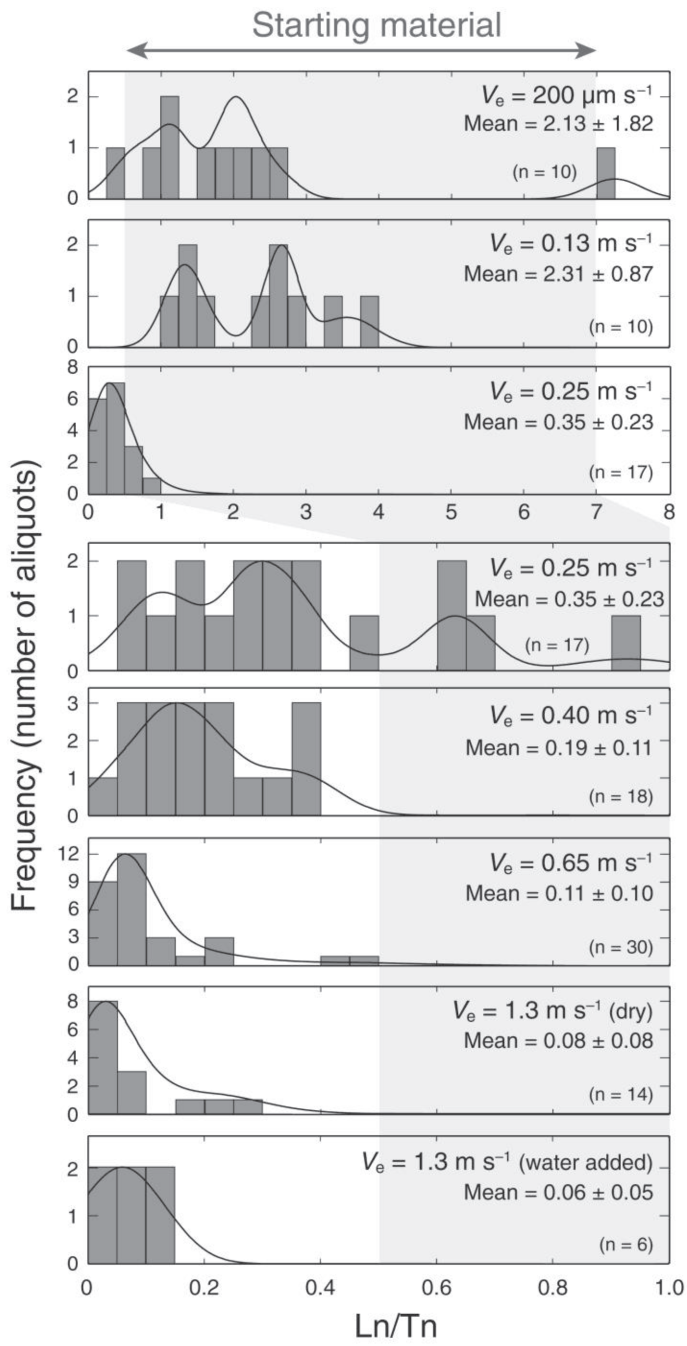

Fig.7 Histograms with kernel density estimates (KDE) of Ln/Tn for samples recovered after the friction experiment. Note that horizontal axes for the upper three diagrams range from 0 to 8, whereas those for the lower five diagrams range from 0 to 1. Double arrow and shaded area indicate the range of Ln/Tn observed in the starting material. Error is derived from the standard deviation (1σ) of measurements. KDE plots were generated using Density Plotter 8.5 from Vermeersch (2012).

10 m.

In the experiments conducted under dry conditions, the OSL signal starts to decrease from V = 0.25 m s^{-1} and becomes near zero at V ≥ 0.65 m s^{-1}. OSL signal resetting is also observed in the experiment sheared at 1.3 m s^{-1} under water-added conditions. At V = 0.25 and 0.40 m s^{-1}, partial resetting occurs, which is characterized by coexistence of particles with and without an OSL signal (Fig. 7).

OSL signal intensity shows a strong correlation with applied power density and frictional heat during high - velocity friction (Fig. 8), and the signal exponentially decreases with increasing power density and temperature. The power density required for partial and complete OSL signal resetting is ~0.17 and 0.6 MW m^{-2}, respectively (Fig. 9).

Results 3: TL and OSL of faults at depths

The luminescence analyses applied to the fault gouge at depths was not successful to calculate the exact timing of the last activity (Table 3). One possible reason is that if the gouge had already developed, the energy to reset the luminescence signal to zero would escape as the gouge deformed when the fault became active without the

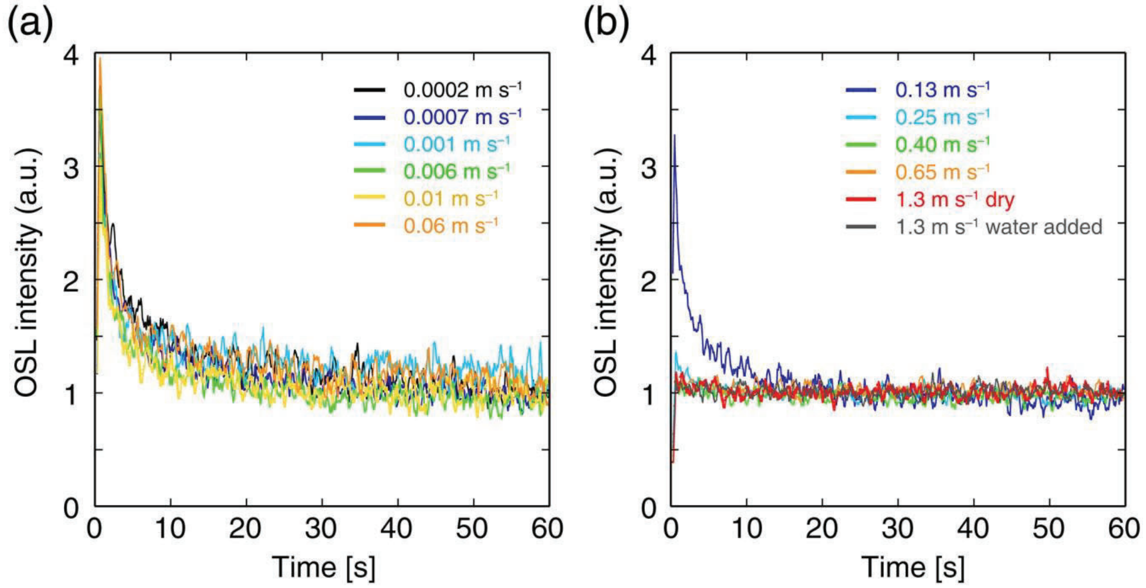

Fig.8 OSL decay curves of recovered samples sheared at (a) $V = 0.0002–0.06$ m s^{-1} and (b) $V = 0.13–1.3$ m s^{-1}.

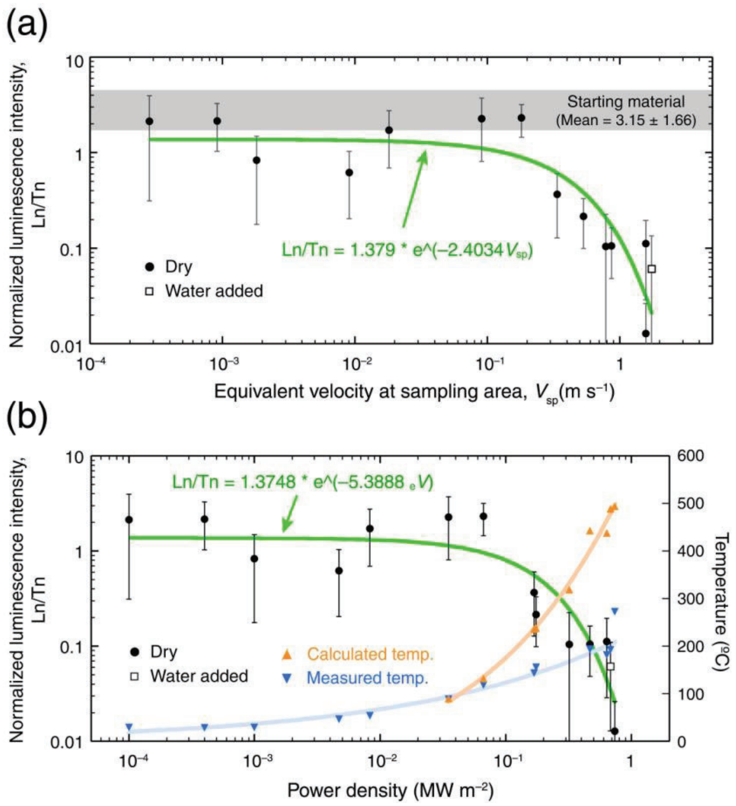

Fig.9 (a) Ln/Tn plotted versus equivalent velocity at sampling area (V_{sp}). The green curve is a least squares fit with an exponential function. (b) Measured (TC1) and calculated (FEM) temperatures plotted together with Ln/Tn against power density ($\tau_e V$). Blue and orange curves are a least squares fit to the temperatures with a power law. Error is derived from the standard deviation (1σ) of measurements.

production of any frictional heat. However, it was found that luminescence measurements of samples in the vicinity of the gouge can be used to calculate an age close to zero-reset. It was also found that the influence of geothermal energy needs to be taken into account, and that it is important to compare the accumulated dose against the underlying rocks, which are quite far away from the fault.

These findings suggest that it may be possible to identify the most recent active part of an active fault.

Concluding remarks

In many previous faulting

Table 3. Accumulated dose and age values by OSL method for NFD1 S2.

		De (Gy)	Average De (Gy)	Age (a)*	Age (a)**
NFD1 S2 1	1	0.29	0.22	26	41
	2	0.15			
NFD1 S2 2	1	1.01	1.41	166	261
	2	1.81			
NFD1 S2 3	1	0.35	0.49	57	90
	2	0.63			

* The average annual dose is used to calculate the age value.

** NFD1 S4 annual doses are used to calculate age values.

studies, the energy released by faults has been discussed (e.g., Kaneko et al., 1997, Shimamoto et al., 2003, Mori et al., 2009). However, these studies calculated the total energy in the active fault zone and the frictional heat at depth, but not the energy at a specific location near the ground surface, such as the sites of the samples used in this study. Luminescence measurements can estimate the amount of heat generated locally and may contribute to the understanding of physical processes occurring in fault zones.

Based on current results, it is currently difficult to identify the timing of the last activity using a sample collected from the surface fault gouge. The difficulties in estimating the annual dose, especially for the granite samples analyzed here, also pose a challenge in the luminescence dating of fault activities.

However, assuming a coseismic fault slip rate of 0.6 m s^{-1}, which is the estimated value from the displacement during Hyogo-ken Nanbu earthquake in 1995, the depths required for partial and complete resetting are expected to be ≥11 and ≥42 m. With future improvements in sampling methods and measurement precision and accuracy, with the use of a larger number of samples, and with the possibility of collecting fault samples from deeper seismic intensities, it may be possible to identify the timing of the final activity period.

General conclusions

The following should be considered for the dating of active faults.

1. Instead of measuring only gouge samples, comparisons of data among healthy basement rocks and damaged rocks is necessary. Furthermore, the most important aspect is to measure the sample adjacent to the gouge sample.
2. Samples collected between the depth where luminescence signal reset calculated from the displacement of the fault and the depths at which the luminescence signal can accumulate even at

the ambient geothermal condition.

3. Luminescence signals from the outer part of the core are affected due to the heat generated during drilling. It is therefore essential to collect samples from the centre of the core.
4. In TL and OSL measurements, the signal components must always be separated and accumulated doses should be estimated for each component.

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令和５年　１月３０日

学位論文審査報告書（乙）

１．学位論文題目（外国語の場合は和訳を付けること。）

Geochronology of Faults (断層の年代学)

２．論文提出者　氏名　三浦（みうら）　知督（かずまさ）

３．審査結果の要旨（600～650 字）

2023 年 1 月 30 日に審査会を開催し以下の結論を得た。本学位論文では 1995 年 1 月 17 日に発生した阪神淡路大震災の原因となった兵庫県南部地震の際に活動した野島断層を対象に，断層活動の年代決定を実施するための基礎的な知見を得たものである。これまで利用されてきた年代測定が中新世より古い時代に適しているのに比して，より若い第四紀の活動史に利用できるルミネッセンス法の活用可能性を吟味した。野島断層のトレンチ調査で得たガウジや周辺試料，また同じく野島断層の掘削試料で観察された深部の断層試料の分析を行った。分析に際してはルミネッセンスサイトの同定や熱的な安定性の調査も行った。また断層運動を模した人工的な摩擦によってどのようにルミネッセンスシグナルが減少するかの実験も行なった。得られた知見より，観測時代における地震発生がない断層等で断層ガウジなどの地質試料を利用して断層活動の周期性や，最後に活動してからどれくらい経過したかを調査するのに必要な試料の条件などを提示し，ひいては地震による災害に対する対策を講じることにも貢献するものである。内容の一部は学会誌・学術雑誌にて公表済みであり，不適切な引用や剽窃もない。以上より博士（理学）を授与するのに値すると判断した。

４．審査結果　(1) 判定（いずれかに○印）　合　格　・　不合格

(2) 授与学位　博　士（　理学　）