Absolute Dating of Past Seismic Events Using the OSL Technique on Fault Gouge Material—A Case Study of the Nojima Fault Zone, SW Japan

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Abstract This study is the first part of a comprehensive paleoseismic study in the Nojima Fault Zone (NFZ), the seismogenic fault of the 1995 Mw 6.9 Kobe (Japan) earthquake, which explores the use of the luminescence dating method for understanding past faulting time and assessing the activity of faults developed in basement rocks. Our approach is focused on methodological aspects of the optically stimulated luminescence (OSL) technique and reports on a series of ages of fault gouge samples. Our analysis revealed that (1) quartz OSL signals have been reset (at least partially) during past seismic faulting events, (2) fault gouge layers bounded by sharp fault planes are younger than gouge layers far from the main fault planes, and (3) the most recent seismic faulting, affecting the different gouge layers on the Nojima fault took place from 62.8 ± 4.3 ka to 18.5 ± 1.3 ka, while on the Asano fault from 139.3 ± 8.9 ka to 45.8 ± 3 ka, with these ages representing maximum possible ages. In this regard, this is the first successful absolute dating attempt on the NFZ using quartz grains and the only luminescence study, as yet known, producing a series of ages representing neotectonic activity of the Nojima and Asano faults during the late Pleistocene and middle to late Pleistocene, respectively. The present work has indicated that OSL is potentially a promising technique for dating fault gouges and assessing the activity of faults, although more work is needed for further refinement.

Plain Language Summary Historical information of past earthquakes is generally inadequate for evaluating the activity of faults in the long past. Paleoseismology approaches this problem by using a number of techniques and methods for identifying and dating earthquake-disturbed materials for which recorded information is not available. To this end, the luminescence dating techniques may provide this information on time scales ranging from some years to even 2 million years. However, there is no systematic effort on their use for such purposes. This study explores the use of a geochronological technique, namely, the optically stimulated luminescence (OSL) technique, and reports on a series of ages of fault rock material, which are directly associated with past fault ruptures, collected from the Nojima and Asano faults (SW Japan). A number of tests performed to validate the reliability of the selected dating technique proved that it could produce accurate results. The derived ages provided evidence for faulting activity (fault ruptures) in the Nojima and Asano faults during the late Pleistocene and middle to late Pleistocene, respectively, with each individual age representing the maximum possible age of a past fault rupture event. Thus, it may be suggested that the selected geochronological technique is potentially reliable for dating past seismic events.

1. Introduction

During a faulting event, the pressure and friction developed within the fault core zone commonly lead to the deformation of the minerals found in the rock formations that make the two sides of the fault plane. In such cases, the luminescence signal of minerals that has been developed during geological time may be affected and reduced, making their use suitable for assessing the activity of a fault (e.g., Tsakalos et al., 2018). With recent advancements of the protocols used (e.g., the Single Aliquot Regenerative and Additive dose protocol by Buylaert et al., 2006) in the employment of the different luminescence techniques, it may now be possible to date sedimentary formations containing suitable minerals in the time-range from some hundred years to 2
million years (Rhodes et al., 2006; Sawakuchi et al., 2016). This could be possibly applicable for fault rock material. However, little has been done so far in this direction with thermoluminescence (TL) studies mainly focused on dating paleoearthquakes indirectly, using sediments that were developed on colluvial debris (e.g., Forman et al., 1991). Luminescence dating makes use of the ability of specific minerals (such as quartz and feldspar) to become dosimeters by trapping unbound electrons within their crystalline defects when minerals are exposed to radiation (e.g., Preusser et al., 2008; Rhodes, 2011). Eviction of electrons from electron traps may take place when the mineral grains are heated, are exposed to sunlight, and experience friction, mechanical stress, and high pressure. In the process of recombining with a lattice ion, electrons lose energy and emit photons, measurable in the laboratory as luminescence (e.g., Preusser et al., 2011; Takeuchi et al., 2004, 2006).

This method essentially dates the time elapsed since minerals were last exposed to light or high heat or pressure. Luminescence dating of past seismic events is built on the idea that during fault rupture, the electrons trapped in crystal defects of the minerals contained in the fault material are evicted (traps are fully reset) as a result of the effect of frictional heating and/or cataclastic deformation (Singhvi et al., 1994). Resetting is followed by electron reaccumulation (buildup of luminescence signal) due to exposure of the minerals to natural irradiation. The age of the faulting event is subsequently given by the expression Luminescence age = radiation dose received by a sample since its last faulting event/rate of radiation received.

To date, a few luminescence studies exist, which attempt to directly determine the age of past seismic events in active faults by studying the seismic deformed features of fault rocks, mainly using TL dating (e.g., Mukul et al., 2007; Singhvi et al., 1994) or using optically stimulated luminescence (OSL) on fault-scarp colluvium (e.g., Fattahi et al., 2007; Porat et al., 1997, 2008). Although there are instances where consistency of luminescence and radiocarbon ages exists (Singhvi et al., 1994), the full resetting (zeroing) of the luminescence signal of deformed materials found in faults has been doubted (e.g., Toyoda et al., 2000). This issue also exists when the electron spin resonance (ESR) method is used for dating previous fault activations, which has been employed to several seismogenic faults since the initial dating work of Ikeya et al. (1982). In this regard, a number of ideas have been developed and tested during the past decades (e.g., Fukuchi, 1988) to assess the ESR signals resetting potential of quartz grains. For instance, in the multiple center method, the ESR signals of the different resonance centers are assessed individually and then compared altogether to examine if each center could provide a similar age (Fukuchi, 1988).

As for luminescence, earlier experiments examined the resetting potential of the TL signal of quartz grains in the laboratory by simulating the friction that was developed along the fault surface (e.g., Toyoda et al., 2000). It was found that the intensity of the TL signal was reduced in the first external 500 nm layer of the quartz grains (Toyoda et al., 2000). This is an encouraging finding as this thin layer of reduced TL coincides with the disturbed zone, which suffered intense mechanical deformations during the frictional stage (Zöller et al., 2009).

However, our understanding is limited regarding the behavior of luminescence (optically or thermally stimulated) in cases where natural materials have experienced intense friction causing the formation of “high-strain tectonites” (e.g., fault gouge and breccias). It is well known that the sensitivity of the luminescence signal of quartz increases with frictional heat (Spencer et al., 2012). Furthermore, more recently, Yang et al. (2019) tested the effect of friction on the OSL, TL, and ESR signals of quartz and found that the OSL, TL, and ESR signals of Al center signals can be reset to zero when high friction is generated. Some studies have also indicated that quartz sensitivity of OSL is similar to the ESR signal sensitivity when a plateau in ESR ages is produced (Lee & Schwarcz, 1994; Rink et al., 1999). In contrast to these studies, however, a recent geochronological study reported an ESR age of ~1.1 Ma and an OSL age of ~2.2 ka on ground surface gouge material from the Nojima fault, southwest Japan (Kyoto University, 2018), indicating that the age resetting depth of OSL is shallower, most probably due to the high thermo-sensitivity of OSL as compared to that of ESR. This thermal and/or frictional activation of quartz OSL and TL signals could be used as “geochronometer,” allowing us to check if quartz grains on a fault zone have previously zeroed due to a past faulting event.

Our hypothesis is that during a single fault slipping event, brittle fracturing of rocks causes the formation of an individual gouge layer, with repeated fault slipping events making a thick fault gouge zone, composed of several individual gouge layers. The luminescence intensity of quartz in gouge layers, at the time of their
formation, is reduced (or even zeroed) due to frictional heating and/or mechanical deformation. Subsequently, a luminescence signal will build up again due to exposure of quartz to natural irradiation. Luminescence dating of the individual gouge layers will then provide the age of their development and thus the individual faulting event which formed them. However, this would be the case if the luminescence signal of minerals in an individual gouge layer has been affected only by a single fault slipping event (that took place at the time of its formation) and no subsequent fault rupture has caused luminescence resetting (partial or full). In either case, however, dating of individual gouge layers will provide the upper age limit of the last resetting (partial or full) event which affected the particular gouge layer, with the lower age limit being even a very recent fault rupture event.

A scientific project entitled “Drilling into Active Fault Damage Zone (DAFD)” coordinated by Kyoto University was initiated in 2015 to assess the seismicity of faults that developed in basement rocks (Lin, 2016). For the purpose of the DAFD project, a series of trenching and drilling investigations have been conducted for collecting unique fault rock samples at different depths (Kyoto University, 2018; Lin, 2016, 2018; Lin & Nishiwaki, 2019). During the past 3 years, nine boreholes have been drilled throughout the Nojima Fault Zone (NFZ), from ~260 to ~900 m in depth, and full cores that penetrated the main fault damage zone have been collected (Kyoto University, 2018; Lin & Nishiwaki, 2019). Assessment of the structural characteristics of the borehole cores collected allowed the identification of the main and secondary faults, as well as material associated with faulting activity, namely, cataclasite, breccia, and fault gouge. As such, this was a unique opportunity for absolute dating studies on the fault gouge samples which are directly associated with the past seismic events that occurred within the NFZ. In addition to the Nojima fault borehole samples, this paleoseismic study also gave the opportunity to collect fault rock samples from an exposed outcrop of the Asano fault (a branch fault of the NFZ). The collected samples from the Asano fault outcrop comprised a series of cataclastic material made of granitic cataclasite, breccia, as well as fault gouge.

This work is the first comprehensive paleoseismic study in the Nojima and Asano faults, which explores the use of the luminescence method to date past seismic faulting events, focusing on methodological aspects of the OSL technique and reports on a series of luminescence ages. In this regard, this study also examines whether luminescence signals from highly deformed fault materials from the Nojima and Asano faults can be utilized to define the age of distinct microstructures, the development of which is associated with past earthquake ruptures. Our methodology in this introductory study was to date fine (4–11 μm) quartz grains using OSL.

2. Materials and Methods

Our study area is located in the northwest Awaji Island, SW Japan (Figure 1), where seven major active faults are found: the Nojima, Asano, Kusumoto, Higashiura, and Senzan faults, striking NE-SW, as well as the Shizuki and Yamada faults, striking NW-SE (Figure 1), all having principally strike-slip motions and creating one of the most active seismogenic systems in Japan (Research Group for Active Faults of Japan, 1991). All faults cross-cut the Cretaceous (66–88 Ma) Nojima granodiorite at depth (Takahashi, 1992). The granodiorite is superimposed by the Kobe Group, a middle–late Eocene formation (Mizuno et al., 1990), and by the Plio-Pleistocene Osaka Group (Murata et al., 2001). The vertical displacement of the Kobe Group has indicated an apparent vertical offset of ~490 to 540 m (Murata et al., 2001), a mean downdip slip rate of 0.04–0.05 mm/a, and a right-lateral rate of 0.09–0.10 mm/a (Mizuno et al., 1990). For the late Pleistocene and Holocene, Lin (2018) has calculated a strike-slip right-lateral rate of ~2.0–3.0 mm/a for the NFZ. The Kobe earthquake that took place in 1995 is linked to the formation of the coseismic surface rupture zone, developed along the NFZ (Lin et al., 1995; Lin & Uda, 1996), which has been studied extensively by several geological and geophysical disciplines (e.g., Lin et al., 1995; Lin & Nishiwaki, 2019; Nishiwaki et al., 2018).

Previous studies on the deformation and alteration textures suggested that the NFZ damage zone (a damage zone, as defined in Kim et al., 2004, is the volume of deformed wall rocks around a fault surface that result from the initiation, propagation, interaction, and buildup of slip along faults) has a width of ~50–60 m and an ~10–30 cm wide fault core (e.g., Lin et al., 2001; Lin & Nishiwaki, 2019; Nishiwaki et al., 2018).

This study examines highly deformed fault materials from the Nojima and Asano faults. Asano fault is a branch of the Nojima fault, striking northeast and dipping to the southeast (Mizuno et al., 1990; Murata et al., 2001), with the presence of granitic rocks on its southeast side and the Kobe and Osaka Groups...
(dipping 15–30°W) developing on its northwest side. The coseismic surface ruptures associated with the Kobe earthquake also exist along the Asano fault with a right-lateral offset of <0.5 m (Lin & Uda, 1996). Regarding the NFZ, a number of boreholes have been drilled in the Ogura site, which have clearly penetrated the Nojima fault at different depths (Figure 1), allowing the examination of the structural characteristics of the fault core zone and the surrounding host rocks (Kyoto University, 2018; Lin & Nishiwaki, 2019; Nishiwaki et al., 2018) and revealing the presence of a distinct zonation, including cataclasite, breccia, and gouge materials (Figure 2).

For this initial study, one borehole (NFD-1-S1-②) was chosen for collecting a fresh gouge core sample at ~506 m and the intercalated cataclasite and fault breccia for luminescence dating (Figure 2). All fault gouge core samples from NFD-1-S1 were stored at dark-room facilities located next to the sampling site. One half of each core was brought into light for macroscopic observations including CT scanning, while the other half was packed with the light-shielding material under dark-room conditions to be used for luminescence dating. A fresh thin fault gouge zone was identified from 506.2 to 506.6 m in depth, while three distinct fault planes (F1 to F3) were observed, with one of them probably representing the most recent slip plane of the fault that took place during the 1995 Kobe earthquake (Figure 2; Lin & Nishiwaki, 2019). Based on borehole CT image analysis and core visual observations, an ~60 m wide damage zone was revealed which includes a narrower fault gouge zone that contains 13 thin distinct layers. These layers vary in color and have a distinct foliation which is parallel or subparallel to the boundaries of the layers (Lin & Nishiwaki, 2019). Their width ranges from 1 mm to ~10 cm and in places contain breccia fragments that have a different color. Thus, for dating purposes, we tried to carefully separate each gouge and intercalated breccia and cataclasite layer (subsamples) by hand cutting, according to distinct changes in texture and color based on macroscopic observations (Figure 2).

In addition to the borehole, sampling was also performed on an exposed outcrop of the Asano fault which is located ~500 m SE of the Nojima drilling site (Figure 1). The exposed fault rocks comprise granitic cataclasite, fault breccia, and fault gouge (Figure 3). Five cylinder samples were taken, four at narrowly spaced vertical intervals and one standing alone. Sampling included hammering the five metal cylinders in freshly cleaned
exposures and covering the ends of the cylinders with black tape to secure the material from light leakage. Out of the five cylinder tubes, two were opened at a dark-room facility located at Kyoto University, and macroscopic observations were made in order to collect subsamples for luminescence dating. Although no light exposure was ensured during sampling and subsequent opening of both the Nojima and Asano fault rock samples, prior to subsampling, we nevertheless performed cleaning of at least 20 mm of the material face to remove the surface that may be exposed to the light (equivalent dose \([D_E]\) values may not be affected by light beneath ~7 mm; e.g., Ollerhead et al., 2001) and also eliminate potential contamination.

![Figure 2](image1.png)

**Figure 2.** Fault gouge zone core sample (NFD-1-S1-③) with International GeoSample Number (IGSN) IENOJ0001 from the Nojima fault retrieved from 506 to 507 m showing a fresh gouge formation and the intercalated breccia and cataclasite fault material (modified from Lin & Nishiwaki, 2019). Codes (G-XX, GB-XX, BR-XX, and CAT-XX) represent subsamples collected for luminescence dating, corresponding to the layering structures. G, gouge; BG, breccia and gouge; BR, breccia; CAT, cataclasite.

![Figure 3](image2.png)

**Figure 3.** Exposed outcrop (Loc. 1 in Figure 1) of the Asano fault and OSL sampling spots. Four cylinder tubes were collected. For this study, only tubes AF-01 and AF-04 were used for OSL dating. Codes represent subsamples collected for luminescence dating.
(e.g., mixing on the surface of the different gouge layers during cutting and opening the core) of the collected material during recovery of the cores. For the Asano fault rock samples, we also discarded ~1 cm of material from the two ends of the cylinder tubes. Subsequently, samples were placed into lightproof bags and delivered to the Luminescence Dating Laboratory of the National Centre for Scientific Research (N.C.S.R.), “Demokritos,” Greece, where they were chemically treated and prepared for luminescence measurements.

3. Luminescence Dating

3.1. Preparation and Measurement Facilities

Previous studies have indicated that quartz ESR signals from grains smaller than a certain size may be reset completely (Buhay et al., 1988; Lee & Schwarcz, 1994). Larger grains may retain some relic ESR signal which results in erroneous ages. Further, Takeuchi et al. (2006) have shown that full resetting of the TL signal is not possible in medium and coarse grains. Based on the above-mentioned findings and presupposing a similar OSL performance, fine-grained gouges may be considered as the best type of sample for OSL dating, and thus we initially (in this study) performed OSL measurements on fine (4–11 μm) quartz grains.

The initial chemical treatment of the samples included the use of hydrochloric acid and hydrogen peroxide. Sieving was performed to obtain samples with grain size ≥40 μm, while Stokes’ law was used for separating a fraction in the range of 4–11 μm. To obtain pure fine quartz, the 4–11 μm samples were submerged in 40% fluorosilicic acid, followed by 10% hydrochloric acid to dissolve any fluorides. Purity of quartz was checked by a scanning electron microscope (SEM) coupled with energy-dispersive X-ray spectrometer (EDX). Samples were mounted on stubs using double-sided carbon tape and coated with gold to prevent surface charging by the electron beam; thus, in elemental concentrations, we omitted the gold and carbon elemental peaks (oxygen present on the carbon tape also contributes to the oxygen elemental concentrations). SEM-EDX results for two samples are shown in Figure 4 below. All EDX data are available at https://doi.org/10.6084/m9.figshare.12607787.v1 (Tsakalos et al., 2020).

In total, 28 samples were obtained for dating, 20 from the Nojima and eight from the Asano fault. However, during chemical treatment to separate the fine 4–11 μm fraction of quartz, two samples from the Nojima fault did not provide enough quartz quantity and thus no OSL measurements were performed.

All luminescence measurements in this study were conducted in a Risø TL-DA 15 luminescence reader and using aliquots with only their central 2 mm diameter covered with fine (4–11 μm) quartz grains. Laboratory irradiations were from a calibrated 90Sr/90Y β source. Source calibration was performed on 2 mm aliquots, using fine grain calibration quartz (batch No. 108) provided by Risø DTU National Laboratory. LEDs in the blue light spectrum (470 nm) were employed for stimulating the fine-grained quartz, along with a 7.5 mm Hoya U-340 filter for detecting the luminescence signal generated. The single-aliquot regenerative (SAR) sequence (Murray & Wintle, 2000) was used for all D_E measurements (Table 1).

3.2. Dose Rate Determination

The determination of the natural radiation dose rate for each sample was based on the concentrations of uranium (U), thorium (Th), potassium (K), and rubidium (Rb) with an error of ±10%, derived by inductively coupled plasma mass spectrometry (ICP-MS) and employing the “The Dose Rate calculator (DRc)”
To acquire a DE value (equivalent dose) using the SAR protocol (Table 1), the bulk initial, 0.6 s of the OSL signal could be considered reliable. By fitting the CW-OSL curve to the three components of the decay curve (McKeever & Chen, 1997, pp. 653), such problematic cases can be identified and examined. The decay and dose-response curves from one aliquot of the Nojima (NFD-01) and one aliquot of the Asano (AF-01-02) fault gouge samples, along with signal deconvolution, are shown in Figure 5 (representative for all gouge samples). The signal decay curve for all gouge samples follows the typical behavior for quartz which is characterized by a strong signal which decays very fast during the first seconds of stimulation. Furthermore, signal deconvolution revealed that the fast component dominates the natural OSL signal (Figure 5) in both Nojima and Asano gouge samples, suggesting that the derived DE values calculated from the bulk initial signal could be considered reliable.

In contrast to gouge samples, during measurement, the OSL signal decay curves (Figure 6; representative also for Asano breccia and cataclasite samples) of all breccia and cataclasite quartz samples from both Nojima and Asano faults appeared unusual, not following the typical signal decay behavior for quartz. Signal deconvolution revealed that the medium and slow components contribute significantly to the initial bulk signal, and thus all breccia and cataclasite samples were excluded for further analysis.

### 3.3.2. Preheat Plateau Test

For the gouge samples, before the employment of the SAR protocol, a preheat plateau test (Murray & Wintle, 2000) and a dose recovery test (Murray & Wintle, 2003) were executed (Figures 7, 8, and 9). As it is shown in Table 1, high temperature is applied before blue LED stimulation (Step 2 in Table 1). This thermal treatment is necessary to facilitate eviction of the electrons which are gathered in unstable traps, thus avoiding their undesirable effect on the stable OSL signal. If an undesirable luminescence signal is present in the OSL signal, that would lead to an enlarged DE and consequently in an incorrect overestimated age. During a "preheat test," DE values are obtained at different preheat temperatures (e.g., Murray & Wintle, 2000; Wintle & Murray, 2006), and the temperature which provided DE values in a plateau area is chosen for measurement. However, scattered DE values may be expected for our samples, as they might have suffered from heterogeneous bleaching as well as mixing of the different gouge layers during subsampling, thus obtaining the right preheat plateau may be difficult. To this end, a preheat test and a dose recovery test were performed together, as this combination could allow the effect of heating upon DE to be considered...
Table 2

Samples Code, Radioelement Concentrations, Water Content, Elevation, Depths, Cosmic Rays Radiation, and Calculated Dose Rates

| Sample ID | Material | U (ppm) | Th (ppm) | K (wt%) | Rb (wt%) | Water (wt%) | Elevation (m) | Depth (m) | Cosmic rays | α (±) | β (±) | γ (±) | Total dose rate (Gy/ka) |
|-----------|----------|---------|----------|--------|--------|------------|-------------|----------|------------|-------|-------|-------|------------------------|
| NFD-1-S1-G01-Gouge | 6.1 | 9.5 | 2.75 | 96.4 | 10 | 22 | 506 | 0 | 0.72 ± 0.28 | 3 ± 0.21 | 1.63 ± 0.09 | 5.35 ± 0.36 |
| NFD-1-S1-G02-Gouge | 4 | 10.8 | 2.7 | 110.5 | 12 | 22 | 506 | 0 | 0.56 ± 0.21 | 2.67 ± 0.2 | 1.43 ± 0.08 | 4.66 ± 0.3 |
| NFD-1-S1-G03-Gouge | 4 | 10.1 | 2.4 | 98.6 | 14 | 22 | 506 | 0 | 0.53 ± 0.2 | 2.4 ± 0.17 | 1.31 ± 0.08 | 4.2 ± 0.27 |
| NFD-1-S1-G04-Gouge | 4.1 | 10.9 | 2.9 | 118.6 | 13 | 22 | 506 | 0 | 0.56 ± 0.21 | 2.8 ± 0.21 | 1.47 ± 0.09 | 4.84 ± 0.31 |
| NFD-1-S1-G05-Gouge | 4.2 | 11 | 2.8 | 128.1 | 10 | 22 | 506 | 0 | 0.6 ± 0.22 | 2.84 ± 0.21 | 1.51 ± 0.09 | 4.95 ± 0.32 |
| NFD-1-S1-G06-Gouge | 4.3 | 11 | 2.7 | 122.2 | 7.3 | 22 | 506 | 0 | 0.63 ± 0.23 | 2.86 ± 0.21 | 1.55 ± 0.09 | 5.03 ± 0.32 |
| NFD-1-S1-G07-Gouge | 4 | 10.7 | 3 | 125.4 | 11 | 22 | 506 | 0 | 0.57 ± 0.21 | 2.91 ± 0.22 | 1.51 ± 0.09 | 4.99 ± 0.32 |
| NFD-1-S1-G08-Gouge | 3.2 | 10.1 | 2.9 | 122.1 | 13 | 22 | 506 | 0 | 0.47 ± 0.17 | 2.67 ± 0.21 | 1.35 ± 0.08 | 4.5 ± 0.28 |
| NFD-1-S1-G09-Gouge | 3.7 | 9.9 | 3.1 | 134.6 | 12 | 22 | 506 | 0 | 0.52 ± 0.19 | 2.9 ± 0.22 | 1.45 ± 0.09 | 4.86 ± 0.31 |
| NFD-1-S1-G10-Gouge | 3.7 | 11.7 | 3.1 | 142.9 | 14 | 22 | 506 | 0 | 0.54 ± 0.2 | 2.88 ± 0.22 | 1.5 ± 0.09 | 4.92 ± 0.31 |
| NFD-1-S1-G11-Gouge | 3.7 | 11.4 | 2.9 | 132.2 | 16 | 22 | 506 | 0 | 0.52 ± 0.19 | 2.68 ± 0.2 | 1.41 ± 0.08 | 4.62 ± 0.29 |
| NFD-1-S1-G12-Gouge | 3.4 | 10.9 | 3 | 134.2 | 10 | 22 | 506 | 0 | 0.53 ± 0.19 | 2.88 ± 0.22 | 1.47 ± 0.09 | 4.88 ± 0.31 |
| NFD-1-S1-G13-Gouge | 3.6 | 11.6 | 2.7 | 116.5 | 12 | 22 | 506 | 0 | 0.55 ± 0.2 | 2.64 ± 0.2 | 1.43 ± 0.09 | 4.62 ± 0.29 |
| NFD-1-S1-G14-Gouge | 3.3 | 11.9 | 2.6 | 118.9 | 10 | 22 | 506 | 0 | 0.54 ± 0.2 | 2.6 ± 0.19 | 1.42 ± 0.08 | 4.56 ± 0.29 |
| NFD-1-S1-G18-Breccia | 2.4 | 11.5 | 2.9 | 118.8 | 12 | 22 | 506 | 0 | 0.45 ± 0.16 | 2.63 ± 0.21 | 1.55 ± 0.08 | 4.42 ± 0.28 |

Note: The grain size is 4–11 μm for all samples.
independently of variations in the natural $D_E$ which are commonly observed due to partial/heterogeneous bleaching (e.g., Thrasher et al., 2009).

The natural quartz OSL signal from two samples (NFD-1-S1-②-G-01 and NFD-1-S1-x02461; G-06) was zeroed using the OSL reader, and then a fixed $\beta$ dose of 200 Gy was given. The aliquots were subsequently measured using preheat temperatures ranging from 200°C to 300°C (in 20°C step) with a cut-heat at 200°C. The ratio given/measured dose in the range 220°C to 260°C was found to be close to unity (the recovered dose is almost equal to the given) (Figure 7), and a preheat at 240°C was chosen for the following standard measurements. Sensitivity changes were checked through the recycling ratio values which were consistently in the range of 0.9 to 1.08, while recuperation did not exceed 5%. The preheat plateau test signified thermal stability of the OSL signal and confirmed no thermal transfer effect.

3.3.3. Pulse Annealing
Pulse annealing measurements (e.g., Timar-Gabor et al., 2012) performed on samples AF-01-02 and NFD-1-S1-x02461; G-04 (Figure 8) further confirmed the thermal stability of the OSL signal, since both samples only suffer negligible signal loss between 200°C and 280°C, with significant signal reduction only above 280°C.

3.3.4. Cut-Heat Test
Since several geochronological studies (e.g., Madsen et al., 2005; Wintle & Murray, 2006) have indicated that quartz may suffer thermal transfer, an extra test was employed, but in this case no dose was administered. The natural quartz OSL signal from two samples (NFD-1-S1-②-G-01 and NFD-1-S1-x02461; G-06) was zeroed using the OSL reader, and then it was remeasured using cut-heat temperatures between 140°C and 240°C (with a preheat at 240°C) to examine if a thermal transfer is present. The results indicated that the $D_E$ values obtained are insensitive to the different cut-heat temperatures (Figure 9). A cut-heat temperature at 200°C was selected for further OSL measurements.

3.3.5. Dose Recovery Test
The performance of the SAR protocol was finally checked using a dose recovery test (Figure 10). The natural signals of six aliquots from sample NFD-1-S1-x02461; G-01 and six from NFD-1-S1-x02461; G-06 were reset using blue LEDs, and a 200 Gy dose was subsequently given. Using the SAR protocol, the six
 aliquots were measured to check if the 200 Gy given dose could be obtained. The test produced reliable results with given/measured dose ratios close to unity, indicating that the SAR protocol can generate reliable results (Murray & Wintle, 2003). The mean ratio \( N = 6 \) of the given/measured DE was 0.99 ± 0.07 (for sample NFD-1-S1-S1-G-01) and 1.03 ± 0.06 (for sample NFD-1-S1-S1-G-06), suggesting that the use of the SAR protocol would provide accurate and precise DE values. Furthermore, almost all (10 out of 12 aliquots) “recycling ratio” values were within 5% of unity (mean ratio 0.95 ± 0.03).

Consequently, the SAR protocol as shown in Table 1 was employed in this study.

4. Results and Discussion

4.1. OSL Dating Results

The OSL age (with the 1σ uncertainty) for each sample was derived from the ratio of the \( D_E \) value to natural dose rate (Table 3). The Central Age Model (CAM) by Galbraith et al. (1999) was used for calculating the Central \( D_E \) values and overdispersion. Nevertheless, the significant number of available statistical approaches for calculating and selecting the most representative \( D_E \) value should be noted here (e.g., Galbraith et al., 1999; Lepper & McKeever, 2002; Olley et al., 1998), which are particularly useful for partially bleached or inhomogeneous samples. Several studies (e.g., Hanebuth et al., 2013; Kunz et al., 2013; Moska et al., 2019; Zhang et al., 2020) have applied many of the different statistical approaches for calculating \( D_E \) values of fine quartz grains. For gouge material, partial bleaching may be expected and depicted on \( D_E \) values distribution. However, the different available statistical approaches may be only useful in case of partial resetting, whereas their applicability may not be suitable when \( D_E \) scattering is due mainly to factors other than partial

Figure 6. Representative fine-grained quartz OSL signal decay curve for (a) one aliquot of a breccia sample (NFD-1-S1-BR-01) and (b) one aliquot of a cataclasite sample (NFD-1-S1-CAT-01). Both aliquots have an unusual signal behavior with very slow decay and low intensity for both the natural and regenerated/artificial dose. Associated natural bulk signal deconvolution of (c) NFD-1-S1-BR-01 and (d) NFD-1-S1-CAT-01 is also shown.

Figure 7. Preheat-dose recovery test on fine-grained quartz for samples NFD-1-S1-G-01 and NFD-1-S1-G-06. Three aliquots were measured at each temperature from 200 to 300°C. Squares and triangles show the mean given/measured ratio. The black line is the unity value, while the dotted lines show the commonly used acceptability limits (0.9 and 1.1).
signal was then measured at 125°C. Increasing temperatures from 180°C to 340°C (in steps of 10°C). The OSL dose of 180 Gy was administered. Aliquots were then preheated at 125°C, and then a signal was initially reset using blue LEDs for 100 s at 125°C, and then a β dose of 180 Gy was administered. Aliquots were then preheated at increasing temperatures from 180°C to 340°C (in steps of 10°C). The OSL signal was then measured at 125°C.

Regarding the present study, some scattering is apparent, with a number of samples provided low but notable overdispersion values ranging from 0% to 12.6% (Table 3), something that may indicate partially bleached grains and/or mixing of the different gouge layers during sampling. A reason for the observed overdispersion values could be the small (2 mm) aliquots used, which may reduce to some extent the averaging effect noted in other studies which used large aliquots. 

$D_E$ values from two samples are also shown in Abanico plots (Dietze et al., 2016) on Figure 11. These plots combine a radial plot (Galbraith, 1990), along with a histogram or other univariate plot type, in this case a kernel density estimate (KDE). On the radial plot, an individual $D_E$ value is presented together with relative precision and its relative standard error.

In an ideal case, it may be assumed that all grains within a gouge layer have experienced the same deformation history, causing reset (full or partial) of their OSL signal. In other words, if all quartz grains in a gouge layer were affected homogeneously during a single rupture, their signal should have depleted together at the same rate, but this alone did not ensure full resetting of the OSL signal, in which case the resulting age would represent the maximum age of this particular sample. However, this assumption may not be the case, and more complex processes may have taken place, where, for instance, the OSL signal of a gouge layer has been accumulated over multiple earthquakes (perhaps of different magnitudes), the balance between trapping and detrapping of electrons in quartz defects is variable (e.g., due to interaction of a gouge layer with fluids or movement along a geothermal), or changes in the dose rate due to grain size reduction during ruptures which in turn changes beta attenuation. Even in such complicated processes, our gouge ages represent the maximum possible age of the last resetting (fault rupture) event which affected the particular gouge sample.

The OSL dating results suggest that neotectonic activity at the particular gouge zones of the Nojima and Asano faults took place during the late Pleistocene and middle to late Pleistocene, respectively. The fault gouge samples from the Nojima fault yielded ages ranging from 18.5 ± 1.3 ka to 62.8 ± 4.3 ka, while the Asano fault gouge ages range from 45.8 ± 3 ka to 139.3 ± 8.9 ka. Both the Nojima and Asano fault gouge ages are remarkably younger than the geological age of their parent rocks, while the cataclasite and breccia samples yielded unusual decay signals and thus no age could be produced. Since the gouge material is a product derived by much older (million years) parent rocks, gouge ages may signify luminescence signal resetting (at least partial). We could hypothesize that partial resetting could be the result of intense deformation during

**Figure 8.** Pulse annealing data from the fine-grained quartz OSL signals of samples AF-01-02 and NFD-1-S1-②-G-04 and calibration quartz. Quartz signal was initially reset using blue LEDs for 100 s at 125°C, and then a β dose of 180 Gy was administered. Aliquots were then preheated at increasing temperatures from 180°C to 340°C (in steps of 10°C). The OSL signal was then measured at 125°C.

**Figure 9.** Cut-heat test on fine-grained quartz for samples NFD-1-S1-②-G-01 and NFD-1-S1-②-G-06 (NFD-1-S1-②-G-06 data have been slightly shifted horizontally to avoid overlap).
fault ruptures. In this regard, it could be deduced that both the Nojima and Asano fault gouges attained, at least to some degree, luminescence signals resetting, which may be due the actions of stress and/or heating developed on the fault plane during fault slipping events.

Regarding breccia and cataclasite samples from both the Nojima and Asano faults, quartz OSL signals appeared unusual, not following the typical signal decay behavior of quartz. This finding is unexpected, since quartz found in our samples derives from a common source and thus, a common behavior should be expected. It could be suggested that this inconsistency may be due to stress and/or heat during the development of the gouge material, which affected the nature of quartz grains sourced from the parent rock. Bøtter-Jensen et al. (1995) has demonstrated that high temperature signal resetting of both natural and synthetic quartz leads to an enhanced OSL and phototransferred TL (PTTL) signal sensitivity. A similar effect may be assumed for our samples. It seems that the degree of cataclastic deformation has an effect on the quartz signals of our gouge samples. It appears that quartz signals in highly deformed material (gouge which has experienced maximum shear stress and shear strain within the fault shear zone during a single slip event) have better luminescence behavior than that of quartz from cataclasite and breccia, which have experienced deformation to a lesser extent. Stress simulation experiments (e.g., Zöller et al., 2009) on our cataclasite and breccia samples will allow checking the effect of stress and/or heat on quartz signal behavior.

### 4.2. Implications for Tectonism

Over the past 20 years, many studies have indicated that the coseismic slip caused by large earthquakes is mainly restricted into a thin (usually 1–10 mm wide) gouge zone (e.g., Lin, 2008; Sibson, 2003), but generally

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**Table 3**

| Sample ID | Material     | No. of aliquots | D_E (Gy) | D_E overdispersion (%) | Dose rate (Gy/ka) | Age (ka) |
|-----------|--------------|-----------------|----------|------------------------|-------------------|----------|
| NFD-1-S1-G-01 | Gouge        | 20              | 98.9 ± 1.9 | 5.1                    | 5.35 ± 0.36       | 18.5 ± 1.3 |
| NFD-1-S1-G-02 | Gouge        | 20              | 150.4 ± 3.2 | 5.1                    | 4.66 ± 0.3        | 32.3 ± 2.2 |
| NFD-1-S1-G-03 | Gouge        | 20              | 117.5 ± 2.4 | 5.8                    | 4.2 ± 0.27        | 28 ± 1.2   |
| NFD-1-S1-G-04 | Gouge        | 20              | 169.1 ± 3.5 | 3.6                    | 4.84 ± 0.31       | 34.9 ± 2.4 |
| NFD-1-S1-G-05 | Gouge        | 20              | 146.1 ± 2.5 | 0                      | 4.95 ± 0.32       | 29.5 ± 2   |
| NFD-1-S1-G-06 | Gouge        | 19              | 305.6 ± 10.9 | 14                    | 5.03 ± 0.32       | 60.8 ± 4.4 |
| NFD-1-S1-G-07 | Gouge        | 20              | 313.2 ± 7.5 | 7.6                    | 4.99 ± 0.32       | 62.8 ± 4.3 |
| NFD-1-S1-G-08 | Gouge        | 20              | 90.6 ± 3.3  | 12.6                   | 4.5 ± 0.28        | 20.1 ± 1.5 |
| NFD-1-S1-G-09 | Gouge        | 20              | 121.3 ± 2.6 | 3.4                    | 4.86 ± 0.31       | 25 ± 1.7   |
| NFD-1-S1-G-10 | Gouge        | —               | —         | —                      | —                 | —         |
| NFD-1-S1-G-11 | Gouge        | —               | —         | —                      | —                 | —         |
| NFD-1-S1-G-12 | Gouge        | 20              | 103.8 ± 2.1 | 2.2                    | 4.88 ± 0.31       | 21.3 ± 1.4 |
| NFD-1-S1-G-13 | Gouge        | 20              | 220.1 ± 5.3 | 0                      | 4.62 ± 0.29       | 47.6 ± 3.2 |
| NFD-1-S1-G-14 | Gouge        | 20              | 214.2 ± 4.6 | 1                      | 4.56 ± 0.29       | 47 ± 3.2   |
| NFD-1-S1-CAT-01 | Breccia    | 20              | 108.4 ± 2.5 | 5.9                    | 4.42 ± 0.28       | 24.5 ± 1.7 |
| NFD-1-S1-BR-01 | Breccia    | —               | —         | —                      | —                 | —         |
| NFD-1-S1-BR-02 | Breccia    | —               | —         | —                      | —                 | —         |
| NFD-1-S1-BR-03 | Breccia    | —               | —         | —                      | —                 | —         |
| NFD-1-S1-BR-04 | Breccia    | —               | —         | —                      | —                 | —         |
| AF-01-01 | Gouge        | 20              | 136 ± 4.9 | 12                    | 2.97 ± 0.16       | 45.8 ± 3   |
| AF-01-02 | Gouge        | 14              | 401.2 ± 10.4 | 0                    | 3.03 ± 0.19       | 132.4 ± 9 |
| AF-01-03 | Breccia      | —               | —         | —                      | —                 | —         |
| AF-01-04 | Cataclasite  | —               | —         | —                      | —                 | —         |
| AF-04-01 | Gouge        | 17              | 413.7 ± 8.4 | 0                      | 2.97 ± 0.18       | 139.3 ± 8.9 |
| AF-04-02 | Gouge        | 20              | 321.9 ± 6.5 | 5.1                    | 2.95 ± 0.18       | 109.1 ± 7  |
| AF-04-03 | Gouge        | 18              | 358.5 ± 7.9 | 2.8                    | 2.89 ± 0.17       | 124.1 ± 7  |
| AF-04-04 | Breccia      | —               | —         | —                      | —                 | —         |

*Not enough quartz grains for dating. b Dominated by a medium signal component.*
<2–3 mm wide (Lin & Nishiwaki, 2019). The fault gouge zone of >10 mm would be produced by repeated faulting events, which result in increasing the thickness of a fault gouge zone (Scholz, 1987). A recent study has shown that each of the individual gouge layers observed in the Nojima fault was developed by a single rupture event, thus signifying that the 13 gouge layers in the ~30-cm-thick fault gouge zone could be considered to record at least 13 rupture events (Lin & Nishiwaki, 2019). This is further supported by the displacement (of up to ~60 m), accumulated on terraces and alluvial deposits, formed in the past ~20 ka (Lin, 2018).

Although there exist several paleoseismological studies across the Nojima fault which try to estimate the recurrence interval of fault ruptures (e.g., Awata & Suzuki, 1996; Lin, 2018; Nakata et al., 1996; Suzuki et al., 1996), uncertainty still remains, due to the complicated fault zone structure as well as the absence of past faulting records on stratigraphy. Nevertheless, research has provided evidence of an ~2,000-year recurrence interval during the Holocene. A more recent study, however, has suggested an irregular recurrence interval during the past ~4 ka ranging from ~900 to ~1,700 years, while for the late Holocene, it was estimated to be ~900 years (Lin, 2018). Based on the estimated ~900 years recurrence interval (Lin, 2018) and the characteristic offset of ~2 m, as that produced by the 1995 Kobe earthquake (Lin et al., 1995), we interpret the displacement of ~40–60 m accumulated in the past ~20 ka as the result of more than 20 individual fault slipping events which have been recorded in the ~30-cm-thick fault gouge zone (Lin & Nishiwaki, 2019).

Our OSL dating results did not provide the age of the most recent rupture of the Nojima fault, which took place in 1995 during the Kobe earthquake or other large rupture events during the Holocene in the NFZ. This may be due to many different reasons. First, the gouge materials which were collected and dated in this study might not be developed at the time of the most recent (Holocene) faulting events. This could be either because the more recent ruptures occurred at a different place within the fault gouge core zone (and thus we could not collect and date the material that might be formed during the most recent event) or due to environmental conditions (e.g., low frictional heating) which did not allow for the development of new gouge material (or full resetting of older gouge material) at our sampling spot. This assumption has been examined by Zöller et al. (2009), where high-pressure experiments provided no evidence for TL signal zeroing at room temperatures; while high pressure at 150°C was able to partially reset the TL signal. Zöller et al. (2009) suggested that partial resetting of the geological TL (and infrared stimulated luminescence [IRSL]) could be achieved by thermally assisted hydrostatic pressure, a mechanism similar to the phonon-assisted bleaching of IRSL of feldspars (Aitken, 1998; Hütter et al., 1988).

In particular, the two fault gouge layers B4 (sample NFD-1-S1-x02461; G-01) and B6 (sample NFD-1-S1-x02461; G-08), which yielded the youngest ages (18.5 ± 1.3 ka and 20.1 ± 1.5 ka respectively) and are close to the sharp fault planes F3 and F2 (Figure 12), were probably not (or partially) reset during the most recent fault slipping events, due to low friction coefficient of the gouge layers, as a result of the high water content in the gouge zone, which did not allow high temperature/stress to be developed. Additionally, if new gouge layers were developed during the most recent seismic faulting events at our sampling spot, these might not be thick enough to allow their separation from adjacent (older) gouge layers during subsampling, thus derived gouge ages may represent a mixture of fault ruptures. However, even if we consider partial resetting or some mixing of the different gouge layers during sampling, fault gouge ages should represent the upper age limit of the last resetting event (fault rupture), affecting a particular layer, with the lower age limit being even a very recent fault rupture event. Similar conclusions can be drawn regarding the time of rupture events in the Asano fault.

Figure 11. Abanico plots of the $D_E$ values from aliquots of samples (a) AF-01-01 and (b) NFD-1-S1-3-G-01 (representative for all Nojima and Asano fault gouge samples). $D_E$ values are shown on a log-scale. The dotted lines touching the $z$ axis, show the Central $D_E$ value calculated using the Central Age Model. Individual $D_E$ values along with their relative standard error ($\sigma$) depicted on the $x$ axis, decreasing from left to right, therefore $D_E$ values plotted toward the right side of the plot are more precise. $D_E$ values crossed by the radial line, drawn from the origin, have an equal value but different precision and relative standard error. Abanico plots, Central $D_E$ values, and overdispersion values were produced using R Luminescence package version 0.9.7 (Kreutzer et al., 2020).
Nevertheless, the OSL ages obtained in this study from the Nojima fault gouge zone show that several faulting events occurred in the past, between 18.5 ± 1.3 ka and 62.8 ± 4.3 ka (with individual ages representing the possible maximum age of the last rupture event affecting a particular gouge layer). The fault gouge samples NFD-1-S1_1-x02461;G-06 and 07, which are far (4.1 and 4 cm, respectively) from their adjacent distinct fault planes (F3 and F2), provided the oldest ages (60.8 ± 4.4 ka and 62.8 ± 4.3 ka, respectively), whereas gouge layers closer to a fault plane show younger ages (Figure 12). However, it should be noted here that the irregular shape and varied thickness of the fault planes and gouge layers only allow an approximate position to be used and displayed in Figure 12. Nevertheless, it may be suggested that the most recent faulting events occurred along these fault planes. One exception is sample NFD-1-S1_1-x02461;G-14, which is very close (0.3 cm) to F1 fault plane but has an age of 47 ± 3.2 ka. It is not possible to provide a concrete explanation on this observation. One suggestion might be that the very thin nature of this gouge layer did not allow its separation from the adjacent (older) gouge layer (NFD-1-S1_1-G-13), thus its old age may signify a mixture of fault ruptures.

It should be, however, kept in mind here that our dating results are representative only for the specific gouge zones, and thus, associated conclusions regarding faulting events and neotectonic activity only apply to the very particular sampling spots of the core zone. In other words, if a faulting event took place at a different spot (from the one we sampled) or in subsidiary faults in the damage zone of the Nojima fault, we would not be able to date it using the material collected.

As for the Asano fault, similar conclusions can be drawn; however, the faulting events that produced (or reset) its fault gouge zone may have started earlier than in the Nojima fault, during the middle to late Pleistocene transition. The gouge material from the particular exposed gouge zone from the Asano fault may be developed or reset during more than four faulting events during the last 139.3 ± 8.9 ka. It should, however, be mentioned here that during subsampling of the Asano fault gouge material, it was difficult to macroscopically distinguish between the different gouge layers; thus, each gouge age most probably represents a bulk age of different faulting events. In any case, as for the Nojima fault, the Asano fault gouge ages give the upper time limit of faulting events affecting its particular gouge zone.

The NFZ has been widely studied after the 1995 Mw 6.9 Kobe earthquake. However, previous attempts to date fault gouge materials collected from the NFZ have been either unsuccessful or producing dating results that are greatly dispersed (e.g., Fukuchi, 2001, 2016; Fukuchi & Imai, 1998; Kyoto University, 2018). Earlier dating studies on the Nojima fault (e.g., Fukuchi & Imai, 1998) suggested that evaluation of full resetting of the ESR signals is not possible. Further, two recent dating studies documented ESR ages on gouge from the Nojima fault of about 1.1 Ma at the ground surface (Kyoto University, 2018) and 0.15 to 0.28 Ma at 388 m depth (Fukuchi, 2001), indicating that samples from deeper depths preserve a younger age. The study conducted by Kyoto University (2018) also used OSL and reported ages of about 2.2 ka at the ground surface. However, it does not mention the grain size or other measurement parameters used. Our OSL ages are in fair agreement with these OSL dating results, indicating that the age resetting depth of OSL is indeed shallower, most probably due to the high thermo-sensitivity of the OSL signals compared to that of ESR. Regarding the Asano fault, an ESR dating study (Fukuchi, 2016) on fault gouge produced an age of 1.08 ± 0.26 Ma. Our OSL dating results from the Asano fault gouge do not agree with this study, producing much younger ages. We believe that this discrepancy may be due to the low potential of ESR signal resetting at shallow depths.

**5. Conclusions**

There is a limited number of luminescence dating studies of neotectonic events, with previous attempts to date seismic faulting events mainly focusing on TL and being limited by the use of grain size plateau for $D_E$ values. Absolute dating of fault gouges and intercalated breccia and cataclasite samples using the OSL technique on fine quartz grains from the Nojima and Asano faults has been attempted for the first time.
This study demonstrates the potential of fine-grained fault gouge to be dated using the OSL technique. Qualitative observations of the OSL signals of the natural and subsequent regenerated beta doses from both the Nojima and Asano fault gouge samples revealed that their OSL signals follow a typical decay, indicating that fine quartz grains respond well to radiation they receive. However, quartz OSL signals of breccia and cataclasite samples from both the Nojima and Asano faults appear unusual, not following the typical signal decay behavior, and thus, we considered them unsuitable for dating. The observation that the fault breccia and cataclasite samples have unusual luminescence signals in comparison to typical quartz signals of the fault gouge material suggests that intense deformation may lead to changes in quartz luminescence behavior and thus the successful use of the luminescence technique (e.g., Bøtter-Jensen et al., 1995). Further, all validation tests on quartz from gouge samples were successful, suggesting that the luminescence protocol employed produced reliable $D_E$ values.

The OSL dating results obtained from the fault gouge samples in this study represent the maximum age of the last faulting event affecting an individual fault gouge layer. Analyses of the luminescence ages suggest the occurrence of neotectonic activity with repeated faulting events at the Nojima fault during the late Pleistocene while at the Asano fault during the middle to late Pleistocene, coinciding with the geological, tectonic, and topographic evidence that shows the seismic faulting events repeatedly occurred during the late Pleistocene–Holocene in the study area (Lin, 2018). This OSL dating study did not provide the age of the most recent rupture of the Nojima fault which took place in 1995 during the Kobe earthquake. This may be due to any of the following main reasons: (1) mixing of an individual gouge layer with gouge material from adjacent older (or younger) gouge layers during sampling; (2) environmental conditions, which did not allow for the development of new gouge material or resetting of older gouge layers at our sampling spot; or (3) the 1995 seismic slip might have occurred at a different place within the fault gouge core zone and thus we could not collect and date the material which might be formed during this event. However, even if we consider some mixing of the different gouge layers during sampling or partial resetting of our samples, fault gouge ages represent the maximum age of the last resetting event (fault rupture), with the lower age limit being even a very recent fault rupture event. Similar conclusions can be drawn regarding the time of rupture events in the Asano fault.

The present work has indicated that OSL is potentially a promising technique for dating gouge material developed in the basement rocks. However, more work and case studies are needed for further refinement, first by an extensive analysis of luminescence in respect of parameters such as OSL signal behavior of fault breccias and cataclasites, OSL signal sensitivity, but also signal resetting potential based on stress simulation experiments. Additionally, future research should be pointed toward a comparative study of our fine-grained OSL results using coarse-grained quartz as well as the employment of IRSL of feldspar and TL and ESR dating to provide a specific and reliable luminescence method applicable to paleoseismology. We aim to perform such research in the near future.

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**Data Availability Statement**

The data sets are publicly accessible via https://doi.org/10.6084/m9.figshare.12607787.v1.

**References**

Aitken, M. J. (1985). *Thermoluminescence dating*. London: Academic Press. https://doi.org/10.1016/0033-5894(86)90112-2

Aitken, M. J. (1998). *An introduction to optical dating*. Oxford: Oxford University Press.

Arnold, L. J., & Roberts, R. G. (2009). Stochastic modelling of multi-grain equivalent dose (De) distributions: Implications for OSL dating of sediment mixtures. *Quaternary Geochronology*, 4, 204–230. https://doi.org/10.1016/j.quageo.2008.12.001

Awata, Y., & Suzuki, Y. (1996). Paleoseismological study of the Nojima and Ogura faults in the northern part of Awaji Island by trenching experiments. Additionally, future research should be pointed toward a comparative study of our fine-grained OSL results using coarse-grained quartz as well as the employment of IRSL of feldspar and TL and ESR dating to provide a specific and reliable luminescence method applicable to paleoseismology. We aim to perform such research in the near future.

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Aitken, M. J. (1985). *Thermoluminescence dating*. London: Academic Press. https://doi.org/10.1016/0033-5894/86/90112-2

Aitken, M. J. (1998). *An introduction to optical dating*. Oxford: Oxford University Press.

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Forman, L., Nelson, R., & McCalpine, P. (1991). Thermoluminescence dating of fault-scarp derived colluvium: Deciphering the timing of paleoearthquakes on the Weber Segment of the Wasatch Fault Zone, north-central Utah. Journal of Geophysical Research, 96(B1), 595–605. https://doi.org/10.1029/90JB02081

Fuchs, M., & Lang, A. (2001). OSL dating of coarse-grain fluvial quartz using single-aliquot protocols on sediments from NE Peloponnese, Greece. Quaternary Science Reviews, 20, 783–787. https://doi.org/10.1016/S0277-3791(00)00040-8

Fukuchi, T. (1988). Applicability of ESR dating using multiple centres to fault movement—The case of the Itoigawa-Shizuoka Tectonic Line, a major fault in Japan. Quaternary Science Reviews, 7(3–4), 509–514. https://doi.org/10.1016/0277-3791(88)90054-6

Fukuchi, T. (2001). Assessment of fault activity by ESR dating of fault gouge; an example of the 500m core samples drilled into the Nojima earthquake fault in Japan. Quaternary Science Reviews, 20(5), 1005–1008. https://doi.org/10.1016/S0277-3791(00)00644-0

Fukuchi, T. (2016). Assessment of fault activity by ESR dating of fault gouge; the case of the Asano fault in Awaji City, Japan. Proceedings of the 123rd Annual Meeting Annual Meeting of the Geological Society of Japan, Tokyo, Japan. https://doi.org/10.14863/geoscabst.2015.0.027

Fukuchi, T., & Imai, N. (1998). ESR Isochron dating of the Nojima fault gouge, Southwest Japan, using ICP-MS: An approach to fluid flow events in the fault zone. Geological Society London Special Publications, 144, 261–277. https://doi.org/10.1144/GSL.SP.1998.144.01.19

Galbraith, R. F., Roberts, R. G., Laslett, G. M., Yoshida, H., & Olley, J. M. (1999). Optical dating of single and multiple grains of quartz from Jinnium rock shelter, Northern Australia: Part I, Experimental design and statistical models. Archaeometry, 41(2), 339–364. https://doi.org/10.1111/1475-4754.1999.tb00987.x

Guérin, G., & Mercier, N. (2012). Preliminary insight into dose deposition processes in sedimentary media on a scale of single grains: Monte Carlo modelling of the effect of water on the gamma dose rate. Radiation Measurements, 47(7), 541–547. https://doi.org/10.1016/j.radmeas.2012.05.004

Guérin, G., Mercier, N., & Adamiec, G. (2011). Dose-rate conversion factors: Update. Ancient TL, 29(1), 5–8.

Hanebuth, T., Kudrass, H., Linstädter, J., Islam, B., & Zander, A. (2013). Rapid coastal subsidence in the central Ganges (Bangladesh) since the 17th century deduced from submerged salt-producing kilns. Geology, 41, 987–990. https://doi.org/10.1130/G34646.1

Hätt, G., Jaek, I., & Tchonka, J. (1988). Optical dating: Feldspars optical response stimulation spectra. Quaternary Science Reviews, 7, 381–385. https://doi.org/10.1016/0277-3791(88)90033-9

Ikeya, M., Miki, T., & Tanaka, K. (1982). Dating of a fault by electron spin resonance on intrafault materials. Science, 215(4538), 1392–1393. https://doi.org/10.1126/science.215.4538.1392

Jain, M., Murray, A. S., & Better-Jensen, L. (2003). Characterisation of blue-light stimulated luminescence components in different quartz samples: Implications for dose measurement. Radiation Measurements, 37A(4–5), 441–449. https://doi.org/10.1016/S1350-4487(03)00520-2

Kim, Y. S., Peacock, D. C. P., & Sanderson, D. J. (2004). Fault damage zones. Journal of Structural Geology, 26(3), 503–517. https://doi.org/10.1016/j.jsg.2003.08.002

Kreutzer, S., Burow, C., Dietze, M., Fuchs, M., Schmidt, C., Fischer, M., & Friedrich, J. (2020). Luminescence: Comprehensive luminescence dating data analysis. R package version 0.9.7. https://CRAN.R-project.org/package=Luminescence

Kunz, A., Pflanz, D., Weniger, T., Urban, B., Krüger, F., & Chen, Y. G. (2013). Optically stimulated luminescence dating of young fluvial deposits of the Middle Elbe River Flood Plains using different age models. Geochronometria, 41(1), 36–56. https://doi.org/10.2478/s13386-013-0140-7

Kyoto University. (2018). Comprehensive analyses on the cataclastic materials acquired from the added drill core samples. (Technical Report on the 2017 Commissioned Project Results of the Secretariat of the Nuclear Regulation Authority of Japan (1/3), pp.132). Kyoto, Japan: Kyoto University. (in Japanese).

Lai, Z. P., Zöller, L., Fuchs, M., & Brückner, H. (2008). Alpha efficiency determination for OSL of quartz extracted from Chinese loess. Radiation Measurements, 43, 767–770. https://doi.org/10.1016/j.radmeas.2008.01.022

Lee, H. K., & Schwarz, H. P. (1994). Criteria for complete zeroing of OSL signals and of screening of ESR signals. Earth Science, 94(1), 95–101. https://doi.org/10.1002/9781118839853.ch3

Lepp, K., & McKeeve, S. W. S. (2002). An objective methodology for dose distribution analysis. Radiation Protection Dosimetry, 101(1–4), 349–352. https://doi.org/10.1093/oxfordjournals.rpd.a005999

Lin, A. (2008). Fossil earthquakes: The formation and preservation of pseudotachylytes. Berlin, Heidelberg: Springer-Verlag.

Lin, A. (2016). Comprehensive assessment on recent activity of active fault damage zone: examples from the active faults in central Japan. Paper presented at 2016 AGU Fall Meeting, San Francisco, CA.

Lin, A. (2018). Late Pleistocene-Holocene activity and paleoseismicity of the Nojima Fault in the northern Awaji Island, southwest Japan. Tectonophysics, 747-748(13), 402–415. https://doi.org/10.1016/j.tecto.2018.10.009

Lin, A., Imiya, H., Uda, S., Iinuma, K., Mizawa, T., Yoshita, T., et al. (1995). Investigation of the Nojima earthquake fault that occurred on Awaji Island in the Southern Hyogo Prefecture earthquake. Journal of Geography, 104(1), 113–126. (in Japanese with English abstract).

Lin, A., Matsuo, N., & Nishiwaki, T. (2019). Repeated seismic slipping events recorded in a fault gouge zone: Evidence from the Nojima Fault drill holes, SW Japan. Geophysical Research Letters, 46, 1276–1283. https://doi.org/10.1029/2019GL081927

Lin, A., Shimamoto, T., Maruyama, T., Shigemori, M., Takao, M., Takemura, K., et al. (2001). Comparative study of the cataclastic rocks from a core and outcrops of the Nojima fault on Awaji Island, Japan. The Island Arc, 10(3–4), 368–380. https://doi.org/10.1002/1440-1738.2001.00335.x

Lin, A., & Uda, S. (1996). Morphological characteristics of the earthquake surface ruptures on Awaji Island, associated with the 1995 Southern Hyogo Prefecture earthquake. Island Arc, 5(1), 1–15. https://doi.org/10.1111/j.1440-1738.1996.tb00008.x

Madsen, A. T., Murray, A. S., Andersen, T. J., Pejuan, M., & Breuning-Madsen, H. (2005). Optically stimulated luminescence dating of young estuarine sediments: A comparison with 210Pb and 137Cs dating. Marine Geology, 224(1), 251–268. https://doi.org/10.1016/j.margeo.2004.10.034

McKeever, S. W. S., & Chen, R. (1997). Luminescence models. Radiation Measurements, 27, 625–661. https://doi.org/10.1016/S1350-4487(97)00203-5
Mizuno, K., Hattori, H., Sangawa, A., & Takahashi, Y. (1990). Geology of the Akashi district, quadrangle series (scale 1:50,000). Japan: Geological Survey of Japan. (in Japanese with English abstract).

Moska, P., Jary, Z., Adamiec, G., & Bluszcz, A. (2019). Chronostratigraphy of a loess-palaeosol sequence in Bialy Kościół, Poland using OSL and radiocarbon dating. *Quaternary International*, 502, 4–17. https://doi.org/10.1016/j.quaint.2018.05.024

Mukul, M., Jaiswal, M., & Singhvi, K. (2007). Timing of recent out-of-sequence active deformation in the frontal Himalayan wedge: Insights from the Darjiling sub-Himalaya, India. *Geology*, 35(11), 999–1002. https://doi.org/10.1130/G23860A.1

Murata, A., Takemura, K., Miyata, T., & Lin, A. (2001). Quaternary vertical offset and average slip rate of the Nojima Fault on Awaji Island, Japan. *Island Arc*, 10, 360–367. https://doi.org/10.1111/j.1440-1738.2001.tb00345.x

Murray, A. S., & Wintle, A. G. (2000). Luminescence dating of quartz using an improved single- aliquot regenerative-dose protocol. *Radiation Measurements*, 32(1), 57–73. https://doi.org/10.1016/S1350-4487(99)00253-X

Murray, A. S., & Wintle, A. G. (2003). The single aliquot regenerative dose protocol: Potential for improvements in reliability. *Radiation Measurements*, 37(4–5), 377–381. https://doi.org/10.1016/S1350-4487(03)00053-2

Nakata, T. J., Odaka, H., Goto, K., Asahi, N., Chida, Y., Suzuki, M., et al. (1996). A trench study on the surface fault rupture in Awaji Island associated with the 1995 Hyogoken-Nambu earthquake. *Active Fault*, 14, 23–27. https://doi.org/10.1016/AF1985-1996.14_23

Singhvi, K., Banerjee, D., Pande, K., Gogte, V., & Valdiya, S. (1994). Luminescence studies on neotectonic events in south central Kumaon Himalaya—A feasibility study. *Quaternary Researches*, 18(5–7), 595–600. https://doi.org/10.1016/0277-3791(94)90083-3

Spencer, J., Hadizadeh, J., Gratier, J. P., & Doan, M. L. (2012). Dating depth? Luminescence studies of fault gouge from the San Andreas Fault zone 2.6 km beneath Earth’s surface. *Quaternary Geochronology*, 10, 280–284. https://doi.org/10.1016/j.quageo.2012.04.023

Stokes, S., Ingram, S., Aitken, M. J., Sirocko, F., Anderson, R., & Leuschner, D. (2003). Alternative chronologies for Late Quaternary (last interglacial–Holocene) deep sea sediments via optical dating of silt-sized quartz. *Quaternary Science Reviews*, 22, 925–941. https://doi.org/10.1016/S0277-3791(02)00041-5

Szabo, B. J., & Rosholt, J. N. (1989). Uranium-series nuclides in the Golden fault, Colorado, U.S.A.: Dating latest fault displacement and measuring recent uptake of radionuclides by fault zone materials. *Applied Geochemistry*, 4(2), 177–182. https://doi.org/10.1016/0883-2957(89)90048-6
Takahashi, Y. (1992). K-Ar ages of the granitic rocks in Awaji Island—With an emphasis on timing of mylonitization. *Journal of Mineralogy Petrology and Economic Geology, 87*(7), 291–299. (in Japanese with English abstract). https://doi.org/10.2465/ganko.87.291

Takahashi, Y., Sangawa, A., Mizuno, K., & Hattori, H. (1992). *Geology of the Sumoto district. quadrangle series* (scale 1:50,000). Japan: Geological Survey of Japan.

Takeuchi, A., Nagahama, H., & Hashimoto, T. (2004). Surface electrification and charge trapping centers. *Physics and Chemistry of the Earth, 29*(4–9), 359–366. https://doi.org/10.1016/j.pce.2003.09.016

Takeuchi, A., Nagahama, H., & Hashimoto, T. (2006). Surface resetting of thermoluminescence in milled quartz grains. *Radiation Measurements, 41*(7–8), 826–830. https://doi.org/10.1016/j.radmeas.2006.05.009

Thrasher, I. M., Mauz, B., Chiverrell, R. C., Lang, A., & Thomas, G. S. P. (2009). Testing an approach to OSL dating of Late Devensian glaciofluvial sediments of the British Isles. *Journal of Quaternary Science, 24*, 785–801. https://doi.org/10.1002/jqs.1253

Timar-Gabor, A., Vasiliniuc, S., Vandenberge, D. A. G., Cosma, C., & Wintle, A. G. (2012). Investigations on the reliability of SAR–OSL equivalent doses obtained for quartz samples displaying dose response curves with more than one component. *Radiation Measurements, 47*(9), 740–745. https://doi.org/10.1016/j.radmeas.2011.12.001

Toyoda, S., Rink, J., Schwarz, F., & Rees Jones, J. (2000). Crushing effects on TL and OSL on quartz: Relevance to fault dating. *Radiation Measurements, 32*(5–6), 667–672. https://doi.org/10.1016/S1350-4487(00)00088-3

Tsakalos, E., Christodoulakis, J., & Charalampos, L. (2016). The dose rate calculator (DRC)—A Java application for dose rate and age determination based on luminescence and ESR dating. *Archaeometry, 58*(2), 347–352. https://doi.org/10.1111/arcme.12162

Tsakalos, E., Kazantzaki, M., Lin, A., Bassiakos, Y., Filippaki, E., & Takaful, N. (2018). Seismic moment and recurrence: Microstructural and mineralogical characterization of rocks in carbonate fault zones and their potential for luminescence and ESR dating. *Journal of Structural Geology, 117*, 186–202. https://doi.org/10.1016/j.jsg.2018.09.018

Tsakalos, E., Lin, A., Kazantzaki, M., Bassiakos, Y., Nishiwaki, T., & Filippaki, E. (2020). Absolute dating of past seismic events using the optically stimulated luminescence (OSL) technique on fault gouge material—A case study of the Nojima Fault Zone, SW Japan. Supplementary data. Figshare, https://doi.org/10.6084/m9.figshare.12607787.v1

Urban, B., Kunz, A., & Gehrt, E. (2011). Genesis and dating of Late Pleistocene–Holocene soil sediment sequences from the Lüneburg Heath, Northern Germany. *E & G Quaternary Science Journal, 60*, 164–184. https://doi.org/10.3285/eg.60.1.01

Wintle, A. G., & Murray, A. S. (2006). A review of quartz optically stimulated luminescence characteristics and their relevance in single aliquot regeneration dating protocols. *Radiation Measurements, 41*(4), 369–391. https://doi.org/10.1016/j.radmeas.2005.11.001

Yang, H. L., Chen, J., Yao, L., Liu, C. R., Shimamoto, T., & Thompson, J. A. (2019). Resetting of OSL/TL/ESR signals by frictional heating in experimentally sheared quartz gouge at seismic slip rates. *Quaternary Geochronology, 49*, 52–56. https://doi.org/10.1016/j.quageo.2018.05.005

Zhang, J. F., Qiu, W. L., Hu, G., & Zhou, L. P. (2020). Determining the age of terrace formation using luminescence dating—A case of the Yellow River terraces in the Baode Area, China. *Methods and Protocols, 3*, 17. https://doi.org/10.3390/mps3010017

Zöller, L., Blanchard, H., & McCammon, C. (2009). Can temperature assisted hydrostatic pressure reset the ambient TL of rocks?—A note on the TL of partially heated country rock from volcanic eruptions. *Ancient TL, 27*(1), 15–22.