Evaluating variability in coseismic slips of paleo-earthquakes using a flight of displaced terraces across the Kamishiro fault, Itoigawa-Shizuoka Tectonic Line, central Japan

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Abstract
Examining the regularity between events during an earthquake slip leads to an understanding of earthquake recurrence and provides the basis for probabilistic seismic hazard assessment. Generally, scientists use systematic analysis of three-dimensional paleoseismic trenches and numerous offset markers along fault zones to study slip history. Flights of displaced terraces have also been used, under the assumption that the number of earthquakes contributing to the observed cumulative slip is known. This study presents a Monte Carlo-based approach to estimating slip variability from a series of displaced terraces when such an assumption cannot be satisfied. First, we mapped fluvial terraces across the Kamishiro Fault, which is an intra-plate reverse fault in central Japan, and systematically measured the cumulative net slip in the mapped terraces. By combining these measurements with the age of the paleoearthquakes, we estimated the amount of net slip for the penultimate event (PE) and antepenultimate event (APE) to be $1.5 \pm 0.2$ and $2.7 \pm 0.4$ m, respectively. The APE slip was twice that of the PE slip and 2.5 times larger than the most recent event, the Nagano-ken-hokubu earthquake, and measured $1.2 \pm 0.1$ m. This suggests that the APE ruptured along the entire length of the 26 km-long Kamishiro Fault or that there were multiple faults involving adjacent segments. As we are unsure how many earthquakes had occurred since the oldest terrace was formed, we assumed three cases based on available paleoseismic records. In each case, we calculated the slip that could reproduce the cumulative slips within a reasonable range of observed terrace offsets and then estimated the coefficient of variation for coseismic slips (COVs) of paleoearthquakes. The resulting COVs typically fell into the range of 0.3 to 0.5, indicating that, over the last few thousand years, the Kamishiro Fault did not regularly behave as it had done before the 2014 event. Instead, there were large variations in the fault’s coseismic slip, as suggested by the global dataset. Although we acknowledge that our approach may be oversimplified, the Monte Carlo-based approach should help assess the regularity of earthquakes from displaced terraces where limited data are available.

Introduction
Understanding the spatiotemporal patterns of past earthquakes provides a guide to estimating the size and timing of future earthquakes. As historical records cover only a short period of time
compared with the recurrence interval of large earthquakes (e.g., McCalpin, 2009), geological and geomorphic records contribute greatly when examining whether there is a certain regularity of inter-event times and magnitudes during large earthquakes that are caused by a single fault or fault system (e.g., Shimazaki and Nakata, 1980; Schwartz and Coppersmith, 1984; Grant, 1996; Weldon et al., 2004; Zielke et al., 2015). Although many studies have presented evidence that faults appear to behave regularly (e.g., Klinger et al., 2011; Berryman et al., 2012), others have reported fluctuations in the size and recurrence intervals of large earthquakes (e.g., Chen et al., 2007; Schlagenhauf et al., 2011; Rockwell et al., 2015; Komori et al., 2017; Scharer et al., 2017; Mechernich et al., 2018; Wechsler et al., 2018). This raises the question of how the recurrence of variable earthquakes changes in terms of size and recurrence interval.

The coefficient of variation (COV; a ratio of standard deviation to mean) is a statistical index of variability that is useful when discussing the recurrent behavior of large earthquakes. The COV of the recurrence interval (COVt) is equivalent to the aperiodicity widely used in seismic hazard assessment (e.g., Nishenko and Buland, 1987; Kumamoto and Hamada, 2005). When COVt is 0, it means that the recurrence is completely periodic. As COVt increases, this indicates reducing regularity, and COVt > 1 indicates temporal clustering (See Fig. 14 in Zielke et al., 2015 for a graphical representation). The COV for coseismic slips (COVs) is also used when discussing slip variability over seismic cycles. Repeated slips of a similar size are characterized by lower COVs and vice versa. One of the advantages of calculating COVs is that it facilitates the discussion about which earthquake magnitude–frequency distribution best describes the observation (e.g., Hecker et al., 2013; Zielke 2018).

There are several issues regarding the interpretation of COVs. The first is that the method used to obtain the timing or slip of earthquakes to calculate the COVs needs to be validated. This is because each approach has its own distinct error or uncertainty that would affect the values used to calculate the COVs. For example, when measuring the offset of many geomorphic and geological markers that are distributed along a section of a fault to estimate the average offset of past earthquakes (e.g., Sieh and Jahns, 1984; Zielke et al., 2010, 2012), the result largely depends on how to measure the offset
and assign probability density to each measurement (Zielke et al., 2015). The second issue is that COVs that is derived from points on a fault or a segment might not represent the same thing. When calculating COVs using slips observed at a site on a fault, the results should reflect the characteristics of the fault segment to which the site belongs. In contrast, if COVs is derived from slips averaged over multiple segments, the study area may contain fault segments that have different rupture histories (e.g., Haddon et al., 2016; Kurtz et al., 2018). Therefore, great care must be taken when comparing COVs derived from points and segments. The ability to detect small displacements from stratigraphy or geomorphology also complicates the interpretation of COVs. Here, “small displacements” are those that are hardly preserved because of surface processes after a major earthquake and cannot be detectable as discrete events in the geological record. Hecker et al. (2013) developed a probabilistic detection-of-threshold model based on global paleoseismic datasets and expert opinion. The model showed that ignoring earthquakes with small displacement could introduce additional errors to the observed COVs. Their results suggested that the observed variability may not capture the actual recurrent behavior of large earthquakes unless a long historical record of earthquakes (e.g., Wechsler et al., 2018) or high-resolution stratigraphy is available (e.g., Le Béon et al., 2018).

Flights of displaced terraces, as well as paleoseismic trenching and systematic analysis of offset features, have been used to reconstruct the timing and displacement of paleoearthquakes (e.g., McCaipin et al., 2009; Bollinger et al., 2014; Berryman et al., 2018). The basic assumption is that the difference in cumulative displacement between successive terraces resulted from a single earthquake (McCalpin et al., 2009). Only when this assumption holds does the displaced terrace sequence reveal an accurate slip history. This approach is useful in that it can be applied even when the vertical deformation is so great that it requires an unrealistically large trench or an outcrop to identify multiple events (e.g., Bollinger et al., 2014). It can also be applied to areas where excavation of deep trenches is hindered by local conditions, such as high groundwater levels (McCalpin, 2009). However, it is often difficult to ascertain the number of paleoearthquakes that contributed to the cumulative displacement observed on each terrace, which inhibits us from reconstructing the history of large earthquakes from a succession of displaced terraces.
This study presents a method for exploring inter-event variability in coseismic slips at a site using a displaced terrace sequence across the Kamishiro Fault. A 9 km-long section to the north of the Kamishiro Fault was ruptured by the Nagano-ken-hokubu earthquake (Mw = 6.2) on November 22, 2014, which caused a vertical displacement of up to 1 m (e.g., Okada et al., 2015; Ishimura et al., 2019). We first mapped the fluvial terraces and measured the cumulative dip slip following a semi-automated method developed by Wolfe et al. (2020). We then estimated the coseismic slip of the penultimate event (PE) and the antepenultimate event (APE) of the Kamishiro Fault based on the ages of the paleoearthquakes from paleoseismic trenches and historical accounts. To reveal the plausible slip variability and the recurrent behavior of the fault, we performed a simple Monte Carlo simulation, taking into account the uncertainty of cumulative slip and age constraints. This approach allowed us to identify the slip regularity of the fault from observable terrace flights whose age constraints were limited and not accurate enough to determine the number of earthquakes since terrace formation.

**Study area**

The Kamishiro Fault is a 26 km-long, north-northeast trending reverse fault located at the northernmost part of the Itoigawa-Shizuoka Tectonic Line active fault system (ISTL, Shimokawa et al., 1995; Okumura, 2001, Fig. 1). The ISTL comprises three major segments: the northern ISTL, composed of east dipping reverse faults; the central ISTL, dominated by left-lateral strike-slip faults; and the southern ISTL, primarily structured by west dipping thrust faults. Because of the relocated aftershocks of the 2014 Nagano-ken-hokubu earthquake with a three-dimensional velocity structure, the subsurface portion of the Kamishiro Fault dips 30°–45° SE at a depth of 0–4 km and 50°–65° SE at a depth of greater than 4 km (Panayotopoulos et al., 2016). The Kamishiro Fault is approximately 4 km deep and merges with the Otari-Nakayama Fault (black lines in Fig. 1b), which initially developed as a normal fault that occurred with the opening of the Sea of Japan during the Miocene age and reactivated as a reverse fault (e.g., Okada & Ikeda, 2012; Panayotopoulos et al., 2016). The regional stress regime changed from an east-west extension to an east-west compression in the late Pliocene age (Sato, 1994; Sato et al., 2004; Ikeda et al., 2004), and continuous GPS observation indicates that the contraction strain axis is N110° E (Sagiya et al., 2004). As the steeply dipping Otari-
Nakayama Fault is unfavorably oriented to the current east-west compression, it has been inactive since the early Pleistocene age (Kato et al., 1989; Ueki, 2008), and instead the Kamishiro Fault formed as a footwall shortcut thrust (Panayotopoulos et al., 2016).

On November 22, 2014, a part of the Kamishiro Fault ruptured to generate the Mw = 6.2 earthquake (Japan Meteorological Agency, 2014). Continuous GNSS observation, InSAR analysis, and differential LiDAR analysis revealed widespread coseismic deformation, evidence of surface rupture, and subsurface slip on the source faults (e.g., Okada et al., 2015; Panayotopoulos et al., 2016; Kobayashi et al., 2018; Ishimura et al., 2019). The subsurface rupture length was approximately 20 km, of which 9 km was accompanied by a surface rupture with up to ~1 m of vertical displacement (e.g., Kobayashi et al., 2018; Ishimura et al., 2019). According to historical accounts (Usami et al., 2013), the PE on the Kamishiro Fault may correspond with the 1714 Otari earthquake of Mj ~ 6 1/4, and the APE is thought to have occurred either in the year 841 or 762. The estimated seismic intensity distribution in the 1714 Otari earthquake (Tsuji et al., 2003) is similar to the instrumental intensity of the 2014 event (National Research Institute for Earth Science and Disaster Resilience, 2014), which suggests that the magnitude of the Otari earthquake was comparable with the one in 2014 (Katsube et al., 2017). Multiple paleoseismic trenches also adequately constrained the PE and APE ages.

Katsube et al. (2017) discovered that the PE postdated 1645 and estimated that its vertical displacement was 0.5 m, which is equivalent to that of the 2014 event at the trench site. Toda et al. (2016) excavated two trenches across the 2014 rupture zone and argued that the PE occurred after 1659. For the APE, previous studies reached the same conclusion: the APE was likely to have occurred either in the year 841 or 762 (Okumura, 2001; Toda et al., 2016; Katsube et al., 2017). However, even though a compilation of all paleoseismic data across the ISTL suggests that at least the entire northern ISTL and a part of the central ISTL ruptured at the APE, the amount of slip on the Kamishiro Fault is still unknown (Okumura et al., 2001; Maruyama et al., 2010).

In this study, we focused on the Oide site, located in the northern part of the 2014 rupture zone, 2 km west of the epicenter (Figs. 1b and 2). There are two major rivers in this area: the Matsukawa River and the Himekawa River (Fig. 2a). The Matsukawa River flows eastward, forming a massive fan and
terraced flights that open the original fan surface. The Kamishiro Fault runs through the middle of the fan, creating an uphill facing scarp, which dams the Matsukawa River to form a swamp along the foot of the scarp (Fig. 2c). During the 2014 earthquake, surface ruptures appeared mainly along the pre-existing fault scarp and were accompanied by minor secondary faulting, such as flexure deformation and rupture on branch faults (Okada et al., 2015; Ishimura et al., 2019). The total amount of dip slip at Oide was $1.2 \pm 0.1$ m, which corresponds with the maximum value over the entire rupture area (Ishimura et al., 2019). Therefore, the paleoseismic record of the Oide site should be representative of the Kamishiro Fault.

Methods
We mapped fluvial terraces at Oide using a 1 m meshed digital elevation model (DEM) and aerial photographs taken in the 1940s by the United States Army. As the topography has been significantly altered from its original form by human activity, several terrace risers are barely visible, even with a high-resolution DEM. It was only the historical photographs that allowed us to map the original topography. Therefore, we mapped the terraces based on aerial photography interpretation and georeferenced the resulting images using ArcGIS. This process enabled us to accurately digitize the mapping results and measure the cumulative displacement of each terrace. We used a radiocarbon-dating technique to determine the age of the terraces. Immediately after the 2014 earthquake, the upslope-facing fault scarp stopped the river flow (Fig. 2), which locally submerged and formed a swamp on the footwall side (Figs. 2 and 3). The radiocarbon ages obtained from the upper part of the terrace deposits predate the terrace formation age, and the ages from the bottom of the swamp deposits overlying the terrace deposits on the downthrown side postdate the terrace formation age. We collected several radiocarbon samples from the swamp deposits, and together with the radiocarbon ages reported in previous studies (Sugito et al., 2015; Toda et al., 2016), we were able to calculate the age of the terraces using Oxcal v.4.3.2 (Bronk Ramsey, 2008, 2009) and IntCal13 (Reimer et al., 2013). Slip measurements often include errors due to the observer’s lack of experience or knowledge. To minimize the effects of human error, we systematically measured the cumulative dip slip of a terrace
using a semi-automated tool called the Monte Carlo Slip Statistics Toolkit (MCSST; Wolfe et al., 2020). Measuring fault offset requires the management of various uncertainties that can affect the measurement and even lead to misinterpretation (e.g., McGill & Sieh, 1991; Klinger et al., 2011; Zielke et al., 2012, 2015; Zielke, 2018). The MCSST helps us find a plausible dip slip by iteratively calculating the slip using several key fault parameters (e.g., extent and average slope of hanging/footwall and fault dip) and their uncertainties (Thompson et al., 2002). According to Thompson et al. (2002), the dip slip ($S$) is given by

$$S = \frac{x_p(m_h-m_s)+b_h-b_s}{\sin \delta + m_h \cos \delta} + \frac{x_p(m_s-m_f)+b_s-b_f}{\sin \delta + m_f \cos \delta}, \quad (1)$$

where $x_p$ is the position at which the fault intersects the scarp, $\delta$ is the fault dip, and $m_{h,f,s}$ and $b_{h,f,s}$ are the slope and intercept, respectively, of the linear regression lines for the hanging wall, footwall, and scarp surface. The calculation process is summarized in Fig. 4. First, we defined the extent of the footwall, hanging wall, and fault scarp, based on topography and the 2014 surface displacement (Ishimura et al., 2019) (Fig. 4a). As an example, a significant 85 cm vertical separation of terrace T1 appeared at $x = 320$ m, and a minor 25 cm vertical separation occurred at $x = 450$ m (Fig. 5b). Therefore, we considered an area of $x > 450$ m to be the hanging wall. Then, we calculated the slope and interception of linear regression lines for the profile of each component. The probability density function of a slope and an intercept follows a normal distribution with a standard deviation equal to the standard error of linear regression. We then assumed the fault dip based on the ratio of the vertical and horizontal components of the 2014 displacement (Ishimura et al., 2019) (Fig. 4a). The PDF of the fault dip is given by a uniform distribution. In addition, we created 30 transects on each terrace and calculated the cumulative dip slip on each transect (Fig. S1). There were two reasons for doing this. The first reason was that the measurement depends on the relative orientation between the topographic transect and the fault strike. This caveat primarily relates to the measurements for terraces T2 and T5 (Fig. 5a). The second reason was to average the along-strike variation of the
surface displacements, as T1 extended 240 m along the fault (Fig. 5a), to consider the effect of along-strike fluctuation.

Results And Discussion

Previous studies have revealed that the PE resembled the most recent event in terms of slip volume (Katsube et al., 2017) and seismic intensity distribution (Tsuji, 2003); however, the APE slip is still unknown. In this section, we first estimate the amount of PE and APE slip based on the results of dip-slip measurements and paleoseismic history. Then, we perform the Monte Carlo simulation to estimate unknown pre-historic events and assess the slip regularity of the Kamishiro Fault from several past surface-rupturing earthquakes.

Terrace mapping and age determination

We labeled the mapped terraces T0 to T5, from the oldest to the most recent (Fig. 5a). We also mapped terraces Th1 and Th2 along the Himekawa River, which flowed down to the northeast. However, because these terraces were subparallel to the fault traces and did not cross the fault zone, they were not used. The relative heights of all the mapped terraces from the current Matsukawa River bed were lower than 10 m, and the vertical separations between successive terraces were from 1 to 5 meters, which may indicate that these terraces were formed over a short period of time. Although the terrace risers are clearly marked by the paddy field boundaries and change in land use indicated in aerial photographs taken in the 1940s, they are now largely unpreserved because of artificial alterations. On the hanging wall, terrace deposits consisting of clast-supported gravel were exposed, whereas, on the footwall, the terrace gravel was covered by alternating units of sand and mud layers that were deposited after the abandonment of the terraces (Sugito et al., 2015; Toda et al., 2016). This stratigraphic sequence of footwalls suggests that no erosion occurred after terrace abandonment. Instead, a small deposit was locally submerged, trapping fine sediment in close proximity to the descending fault zone. Therefore, we assume that the vertical separation that was observed across the fault zone primarily reflects single or multiple coseismic slips in past surface-rupturing earthquakes. During the 2014 event, a few subsidiary minor surface ruptures appeared to the east of the prominent fault zone. However, aerial photograph interpretation found no discernible
scarp along these secondary faults.

We determined the terrace ages of T1, T2, and T5 using Oxcal (Bronk Ramsey, 2009). We chose these three terraces because the other surfaces were not as well preserved on either or both the hanging walls and the footwalls. Radiocarbon samples were used directly from the top of the terrace deposits and the bottom of the swamp deposits, as shown in Fig. 3, to establish the age of the T2 surface. The modeled emergent age of the T2 terrace was in the range of 1,290–1,460 cal BP (1σ). For the age constraints on the T1 and T5 surfaces, the following approach was taken because of the lack of radiocarbon material. There are several fluvial terraces on the left bank of the Matsukawa River, one of which is approximately 5 m above the T1 surface. The radiocarbon age of a sample obtained from a post-emerged terrace deposit should predate the formation of the T1 surface. We estimated the age of the T1 surface to be 2,710–4,960 yBP (1σ) using samples taken at Loc. 1 (Fig. 1b) and Loc. 6 (Fig. 2). Similarly, we determined the age of T5 as 380–1,080 yBP (1σ) based on the samples taken at Loc. 2 (Fig. 2a) and Loc. 3 (Fig. 3a).

| Loc. (Fig. 1, 2) | Lab No. | Material | δ¹³C [%‰] | Conventional ¹⁴C age ± 1σ, yr BP | Calibrated age (1σ) [cal BP] | Reference |
|-----------------|---------|----------|------------|---------------------------------|-------------------------------|-----------|
| 2               | UNK_13516 1 | Plant fragment | -28.0 | 120 ± 50 | 280 – 90 | This study |
| 2               | UNK_13517 1 | Plant fragment | -27.5 | 140 ± 90 | 290 – 80 | This study |
| 1               | IAAA-62268 1 | Plant fragment | -18.0 | 4440 ± 30 | 5260 – 4970 | Sugito et al., (2015) |
| 3               | IAAA-62832 1 | Plant fragment | -27.7 | 1200 ± 30 | 1140 – 1060 | Sugito et al., (2015) |
| 6               | IAAA-123139 | Plant | -20.7 | 2470 ± 30 | 2710 – 2490 | Sugito et al., (2015) |
| 5               | IAAA-151839 | Bulk sediment | -24.7 | 1570 ± 20 | 1520 – 1410 | Toda et al., (2016) |
| 4               | IAAA-153022 | Bulk sediment | -23.5 | 1230 ± 20 | 1240 – 1130 | Toda et al., (2016) |

OxCal v4.3.2 (Bronk Ramsey, 2009), IntCal13 (Reimer et al., 2013)

Cumulative dip slip of mapped terraces

We modeled the cumulative dip slip of the T1, T2, and T5 surfaces iteratively using the MCSST (Wolfe et al., 2020). We estimated the dip angle on each profile based on the ratio of vertical to fault-normal (horizontal) component of the surface displacement in the 2014 earthquake (Ishimura et al., 2019).

The estimated dip angles were 54°–62° for T1, 48°–56° for T2, and 44°–52° for T5. For convenience, we used the LiDAR DEM taken before the 2014 event to calculate the cumulative dip slip. Using the measured slips from 30 profiles for each offset terrace (Fig. S1), we produced composite histograms
and determined the mean and standard deviation of the cumulative dip slip (Fig. 6). The calculated cumulative dip slip was 7.9 ± 0.5 m for T1, 4.6 ± 0.4 m for T2, and 1.7 ± 0.3 m for T5 (1σ). The dip slip for each terrace with a 1σ range of ages is plotted in Fig. 7. Note that dip slip shown in Fig. 7 includes the amount of coseismic slip at the 2014 earthquake derived from differential LiDAR (Ishimura et al., 2019).

On the basis of these dip-slip measurements and terrace ages, we were able to estimate the dip-slip rate in the last 3-5 ky at the Oide site to be 1.5-3.1 mm/yr. Assuming that the fault dip is 54°–62°, the equivalent vertical slip rate is 1.2–2.7 mm/yr, which is consistent with the rates obtained at limori (>2.1 mm/yr; Fig. 1b) (Katsube et al., 2017) and at Kamishiro (1.4–2.0 mm/yr; Fig. 1b) (Niwa et al., 2018).

**Dip slip of the PE and the APE**

Identifying slips per event from a terrace sequence requires a complete catalog of paleoearthquakes to ensure that the cumulative slip difference between successive terraces was produced by a single earthquake. A combination of historical accounts (Usami et al., 2013) and paleoseismic trenches (Okumura 2001; Toda et al., 2016; Katsube et al., 2017) has already allowed us to conclude that the date of the PE was 1714 and that the date of the APE was either in the year 841 or 762. However, we cannot rule out any missing events occurred after the APE where the displacement was too small to be identified in the paleoseismic trenches. Considering the magnitude–displacement scaling (Wells & Coppersmith, 1994; Wesnousky, 2008), even if there were such earthquakes after the APE, their displacement would be so small that it would be within or close to the measurement error and would, therefore, not change our interpretation of the PE and APE slips. Even if the possibility of a non-negligible amount of after-slip could be argued, the post-2014 InSAR analysis did not detect any significant slip on the surface rupture (Omata et al., 2017). Therefore, it is assumed that the paleoseismic records after the APE were complete and the slip amounts of the PE and APE can be reliably used for discussion of slip variability in seismic cycles.

On the basis of the dip-slip and age constraint for each terrace and the dates of the paleoearthquakes, we were able to calculate the dip slip at the PE and the APE. Before the 2014
earthquake, the T5 terrace only experienced the PE, whereas the T2 surface was deformed by the PE and the APE (Fig. 7). Simple subtraction allows us to estimate the dip slip of the PE to be $1.7 \pm 0.3$ m and that of the APE to be $2.9 \pm 0.5$ m. Since the dip slip of the most recent event at Oide was $1.2 \pm 0.1$ m (Ishimura et al., 2019), the slip of the PE was a little larger than that of the 2014 event. Similar conclusions are given by Katsube et al. (2017), that is, the PE showed a slightly smaller displacement than the 2014 slip on the paleoseismic trench walls in the center of the 2014 surface rupture zone (limori site in Fig. 1b). Two independent results showing the similarity of coseismic slips at both the PE and the 2014 earthquake, supported by the PE’s similar iso-seismicity (Tsuji, 2003), support the assumption that the events are similar. In contrast, based on his compilation of the paleoseismic trenches along the northern and central ISTL, Okumura (2001) argued that the event in the year 841 or 762 ruptured the entire northern segments of the ISTL and a part of the central ISTL. Our results show that the APE produced a much larger surface displacement than the two recent events, which is in agreement with Okumura (2001).

Inter-event variability in coseismic slip at Oide
To explore the variability of each slip per event at Oide, we performed a simple Monte Carlo simulation to determine additional events and their possible slip amounts during the time period between the APE and the emergence of terrace T1. According to Okumura (2001), one to three surface-rupturing earthquakes occurred during this time period. Therefore, we can assume that one, two, or three earthquakes occurred during that time. Figure 8 shows the Monte Carlo simulation procedure. First, we modeled the dip slips of the 2014 event and the terraces by sampling them from a normal distribution. The mean and standard deviation of probability distributions used in this step are based on the results produced by the MCSST (Fig. 6). Next, we calculated the dip slip of the recent three events (in Fig. 8: represents the dip slip of the ith most recent event). We then calculated the dip slip of the simulated events ($S_4$, $S_5$, $S_6$), which occurred between the APE and the emergence of terrace T1, such that
We will discuss the minimum ($S^1$) and maximum ($S^3$) threshold in the next paragraph. We repeated the calculations until we obtained 10,000 sets of realizations, which satisfied the necessary conditions for the slip, and then calculated the COVs to assess the plausible variability of each slip per event on the Kamishiro Fault.

To eliminate unrealistic estimates, we introduced the minimum and maximum slip limits based on available paleoseismic records. The 2014 event slip was defined as the minimum, and the APE slip was defined as the maximum. The dip slip of the 2014 event was chosen as the minimum value because the paleoearthquakes in the modeled time window (Okumura, 2001) should have been larger than the dip slip in the 2014 event. This is because Okumura identified events based on angular unconformity, which is probably insensitive to small displacements near the surface. The fact that Okumura’s trench sites experienced a broad uplift (~20–30 cm) without any apparent surface break (Ishimura et al., 2019) also justifies our choice of the minimum value. The maximum simulated slip limit is based on a compilation of paleoearthquake records at 42 sites over the entire ISTL (Maruyama et al., 2010). The results show that an earthquake that took place either in the year 841 or 762 was the greatest earthquake on the Kamishiro Fault in the last 12 ky, which supports our choice of maximum threshold. We also performed the same Monte Carlo simulation without an upper limit on the dip-slip amount. It was confirmed that the variability in the results was almost consistent with the
results of the upper limit (Table 2).

|                  | Case 1     | Case 2     | Case 3     |
|------------------|------------|------------|------------|
| With upper limit | 0.45 ± 0.08| 0.38 ± 0.10| 0.36 ± 0.10|
| Without upper limit | 0.46 ± 0.08| 0.38 ± 0.09| 0.36 ± 0.09|

There are slight differences between the three cases; however, each case shows a similar slip variation (Fig. 9). Our results show that the COVs generally falls between 0.3 and 0.5 (1 σ range; Fig. 9d), which is comparable with the values calculated from a large global dataset (Hecker et al., 2013) and from a relatively small dataset, mostly made up of strike-slip faults (e.g., Zielke et al., 2015). We also calculated the COVt, on the assumption that the probability distribution of event ages reported in Okumura (2001) was uniform. The COVt ranged between 0.36 and 0.7 (Fig. 10) and was larger than that for the slip per event (63%, 89%, and 82% of all realizations in Cases 1, 2, and 3 exhibited a larger COVt than COVs). This indicates less slip variability than in the time between successive earthquakes. These results are also consistent with the variability reported in previous studies (e.g., Zielke, 2018 and references therein).

Our results, showing that COVt is generally greater than COVs, agree with those that have been reported in recent studies (e.g., Nicol et al., 2016; Zielke, 2018). This discrepancy may reflect the natural characteristics of earthquake recurrence but can be, in part, attributed to the varying abilities of geological and geomorphic markers to record an earthquake with small displacements or short recurrence intervals. Immediately after an earthquake, surface processes begin to degrade the surface ruptures. This degradation makes it difficult for the earthquake displacement to be preserved at the surface. Errors in topographical data, such as those recorded by a DEM or optical satellite images, may be too large to resolve small displacements from the terrain (e.g., Zielke et al., 2015).

These difficulties often prevent an observer from identifying small displacements, resulting in an apparent decrease in COVs. In addition, written records, archaeological evidence, and dating strategies (e.g., Lienkaemper and Bronk Ramsey, 2009) can distinguish temporally clustered earthquakes (e.g., Scharer et al., 2017; Wechsler et al., 2018), which tends to increase COVt. These
characteristics contribute to the apparent discrepancy between slip regularity and recurrence interval.

Discrepancy between observed COVs and true COVs

We consider that the recent three paleoseismic records, MRE, PE, and APE are complete. However, we may have overlooked minor events before the APE that relied entirely on paleoseismic evidence at one of Okumura’s sites. If this is the case, the modeled COVs may not represent the true variability in slips from event to event (e.g., Hecker et al., 2013). Here, we attempt to quantify the effect of such missing events on the discrepancy between observed COVs and true COVs by introducing additional small events to the simulation. The dip slips associated with those small events () are modeled as follows:

\[ S_{\text{min}} \leq S_j \leq S_1, \quad (5) \]

\[ \sum_{i=4}^{n} S_i + \sum_{j=1}^{m} S_j = S_{T1} - S_{T2}, \quad \text{and} \quad (6) \]

\[ 1 \leq m, \quad (7) \]

where \( S_{\text{min}} \) denotes the minimum amount of dip slip. Technically, to estimate the true variability in slips at the Oide site, \( S_{\text{min}} \) must be the minimum surface displacement that can occur at the site, which is difficult to determine. Instead, we set \( S_{\text{min}} \) to be 0.25 and 0.50 m based on a threshold of detection developed by Hecker et al. (2013). The threshold of detection is based on expert comments and represents the threshold displacement with a 50% chance of being detected as a discrete event in a geological record. The threshold values of 0.25 and 0.50 m are generally applied to paleoseismic trenches, with lower thresholds considered to be better stratified (see Figure B1 in Hecker et al., 2013 for the details). Except for these conditions, the calculation process was almost identical to the
process of ignoring small events in the previous section. We repeated this calculation until we generated 10,000 realizations. For example, when n = 4 and m=1 in Eq. 6 (Fig. 11), we first calculated true COVs from all events (three recent events and two simulated events). As for the observed COVs, we added the slip of Eq. 4* to that of Eq. 4 and then calculated the COVs. This is because, even when a small event is not identified as a discrete event, its slip is conserved and interpreted in conjunction with other events (Fig. 11).

The results show that COVs increases as more small events are added to the dataset (Fig. 12 and Table 3). It should be noted that, although unlikely, COVs can also decrease (negative value in Fig. 12), which is the opposite of what would be expected (e.g., Zielke et al., 2015). This happens when the average slip of an observed event is close to the slip of a missing event. Given that the recurrence intervals of the recent three events are approximately 300 and 900 years (Fig. 7), true COVs is expected to be around 0.5–0.7 (Fig. S2). These results demonstrate the significant impact of ignoring small earthquakes when estimating COVs and reaffirm that the Kamishiro Fault exhibits a more irregular recurrent behavior than expected before the 2014 event (e.g., Okada et al., 2015).

| Number of missing earthquakes | Case1 | Case2 | Case3 |
|-------------------------------|-------|-------|-------|
| 1                             | 0.12  | 0.17  | 0.15  |
| 2                             | 0.29  | 0.30  | 0.26  |
| 3                             | 0.40  | 0.37  | 0.34  |
| 1                             | 0.13  | 0.12  | 0.11  |
| 2                             | 0.23  | 0.21  | 0.19  |
| 3                             | 0.31  | 0.25  | 0.21  |

*Numbers in this table are the mode values of each 10,000 realizations.

Conclusions

Accurate cumulative slip measurements and detailed chronologies are indispensable components when revealing slip history from a flight of displaced terraces. We measured the cumulative dip slip based on key fault parameters and their uncertainties to obtain plausible estimates. We used these estimates, together with paleoseismic records, to reconstruct the amount of dip slip in the PE and APE. The results showed that the slip of the APE was twice as large as that of the 2014 event and the PE, emphasizing the need to assess the earthquake regularity of the Kamishiro Fault. We also estimated the possible range of COVs at the Oide site based on the available paleoseismic records.
and the Monte Carlo approach. The resulting COVs is most likely to be between 0.31 and 0.49, which is comparable with the ranges previously reported (e.g., Hecker et al., 2013; Zielke, 2018).

We demonstrated that it is possible to estimate a possible range of COVs, even when it is uncertain how many earthquakes contributed to the observed cumulative displacement of a terrace sequence. Identifying multiple paleo-slips requires an ideal environment for past surface displacements to be preserved and detected as discrete events. Finding a site that fully satisfies such conditions is not always easy, which limits the number of detectable events at one site. We recognize that our modeling approach may be too simplistic to explain some fundamental issues in interpreting earthquake regularity. However, we believe that the concept itself should facilitate research into earthquake variability when using paleoseismic records that are missing some events or those that are conflicting.

Abbreviations
APE: Antepenultimate event; COV: Coefficient of variation; DEM: Digital Elevation Model; ISTL: Itoigawa-Shizuoka Tectonic Line; JMA: Japan Meteorological Agency; MCSST: Monte Carlo Slip Statistics Toolkit; PD: Probability Density; PDF: Probability Density Function; PE: Penultimate event

Availability of data and material
1-m DEM was provided by Nagano prefecture and the Ministry of Land, Infrastructure, Transport and Tourism.

Competing interests
The authors declare that they have no competing interest.

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Authors' contributions
NT conducted all analysis and drafted the manuscript. NT and ST interpreted the results and revised the manuscript. All authors read and approved the final manuscript.

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Figures
Active fault map around the ISTL active fault system. (a) Active faults in central Japan and the ISTL composing of three major segments, each separated by change in slip direction and surface geometry of the fault trace. (b) The 2014 surface rupture, denoted as blue lines, occurred on approximately one-third of the previously known Kamishiro Fault. The trench site corresponds with those in Fig. 7. The Otari-Nakayama Fault is from Kato et al. (1989) and Nakano et al. (2002). ISTL: Itoigawa-Shizuoka Tectonic Line, JMA: Japan Meteorological Agency.
Figure 2

Topography around Oide in the northern section of the 2014 rupture zone. (a) Color-coded altitudes and 14C sampling site. The black arrows in rivers indicate flow direction. (b) Fault scarp running between an uplifted terrace and swamp on the footwall side. (c) A shallow pond developed on the footwall. The locations of (b) and (c) are shown in (a).
Figure 3

Schematic illustration to explain our strategy for determining terrace age. The emergent age for each terrace is bracketed by post-event 14C age from the swamp deposit and the pre-event terrace-forming deposit.
General steps to calculate dip slip using the MCSST. (a) Step 1: For each of the 30 profiles on each terrace (Fig. S1), define extents of footwall, hanging wall, and fault scarp on each topographic profile. The fault dip is determined from a ratio of the vertical and horizontal displacement of the 2014 earthquake. The PDF of the fault dip is assumed to be uniform. Slope and interception of topographic profiles (footwall, hanging wall, and fault scarp) are determined from linear regression, and their probability densities are assumed to be normally distributed with mean and standard deviation being the best fit and standard error of the regression. The fault is assumed to intersect with the scarp within the lower 5% of the scarp, and its PDF is uniform. (b) Step 2: Calculate the dip slip using the PDF defined in Step 1. We performed 10,000 realizations for each of the 30 profiles and calculated the mean (denoted as $\bar{S}$ in the figure). (c) Step 3: Calculate the mean and standard deviation of $\bar{S}$ in Step 2 as a plausible dip slip and its uncertainty. Results are shown in Fig. 6.
Figure 5

(a) The interpreted distribution of terraces. (b)–(d) Pre-2014 event topography and vertical and horizontal displacements associated with the 2014 earthquake. (b) Profile A-A’. (c)
Profile B-B'. (d) Profile C-C'. The profile locations are shown in (a). Horizontal displacement is a component normal to the general strike of the Kamishiro Fault (N18° E); a positive value represents eastward movement (Ishimura et al., 2019).

![Histograms](image)

**Figure 6**

Histograms of the cumulative dip slip of terraces T1, T2, and T3 calculated by the MCSST.

The amount of slip shown in this figure does not include that of the 2014 event.
The slip at the recent three surface-rupturing events at Oide. (a) Terrace ages and their cumulative dip slip; both are shown in the 1σ range. Note that the amount of slip in this figure includes that of the 2014 event. (b) Earthquake timings estimated from paleoseismic trenches. The trench sites are shown in Fig. 1b: Oide and lida (Toda et al., 2016), limori (Katsube et al., 2017), and Kamishiro (Okumura, 2001).
Flowchart illustrating the procedure to calculate the COV of the slip. $S_{2014}$ is the dip slip of...
the 2014 event. $S_{(T1,T2,T5)}$ is the dip slip of terraces T1, T2, and T5; they do not include that of the 2014 event. $S_i$ is the dip slip of the ith most recent event.

![Figure 9](image)

Probability distributions of COVs in simulated cases: (a) Case 1, which assumes that the cumulative slip increased once during the period between T1 formation and the APE; (b)
Case 2, which assumes that the cumulative slip increased twice in the period between T1 formation and the APE; (c) Case 3, which assumes that the cumulative slip increased three times in the period between T1 formation and the APE; and (d) a composite of all cases.

Figure 10

Probability distribution of COVt for each modeled case. (a) Case 1, (b) Case 2, and (c) Case 3.
An example of the observed and true paleoseismic record. Eq4* is an event that cannot be identified as a discrete event. Therefore, the slip of Eq4* is interpreted together with the slip of Eq4.

Figure 11

| Slip | Eq1 | Eq2 | Eq3 | Eq4* | Eq4 | COVs |
|------|-----|-----|-----|------|-----|------|
| Observed | 1.2 | 1.5 | 3.3 | 2.5  | 0.45|      |
| True    | 1.2 | 1.5 | 3.3 | 0.4  | 2.1 | 0.64 |

Event missing in available records

Figure 12

Difference between true COVs and observed COVs. A positive value represents true COVs > observed COVs. The threshold of detection ($S_{\text{min}}$ in equation 5) is (a) 0.25 and (b) 0.50.
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