Detailed paleoseismic history of the Hinagu fault zone revealed by the high-density radiocarbon dating and trenching survey across a surface rupture of the 2016 Kumamoto earthquake, Kyushu, Japan

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Funding Information
JSPS, Grant/Award Number: 20H00193; Atmosphere and Ocean Research Institute, The University of Tokyo

Abstract
The NE-trending Hinagu fault zone, length 81 km, is one of the major active faults in Kyushu, Japan. From north to south, it is divided into three segments based on geomorphic features and paleoseismic behavior: the Takano-Shirahata, Hinagu, and Yatsushiro Sea segments. The 2016 Kumamoto earthquake produced a 6-km-long surface rupture with a dextral strike-slip displacement on the northern part of the Takano-Shirahata segment. Surface rupture, a faint east-side-up flexure with a vertical offset of less than 8 cm, was observed near the middle of the Takano-Shirahata segment. To examine past surface-rupturing earthquakes on the Takano-Shirahata segment, including rupture frequency and timing, we conducted a paleoseismic study with boring and trenching at Yamaide. A trench across the surface rupture exposed multiple fault strands associated with multiple surface-rupturing events that deformed several strata of fine-grained sediments. By structural and stratigraphic interpretation, high-density radiocarbon dating and tephra analysis, and Bayesian modeling, we constrained the timing of seven events, Events 1–7, to 0.84–1.25, 1.31–7.06, 9.99–11.0, 10.8–12.1, 12.0–13.0, 14.2–15.1, and before 14.8 kcal BP. Slip during Events 1–6 was obviously larger than the 2016 slip. The estimated average recurrence interval was about 2596–2860 years, but the interval between Events 2 and 3 was much longer than other intervals. Moreover, the vertical throw associated with Event 2 was larger than that of other events. This implies that the Takano-Shirahata segment has a period with rare larger earthquakes and a period with frequent smaller earthquakes. Some events might have produced ruptures on both the Takano-Shirahata and the northern part of the Hinagu segments simultaneously or in a short time. The variety of recurrence intervals suggests that the seismic activity has been affected by one or both activities of the Futagawa fault zone and the Hinagu segment.

KEYWORDS
high-density radiocarbon dating, Hinagu fault zone, Paleoseismic history, the 2016 Kumamoto earthquake, trenching survey
1 | INTRODUCTION

The NE-striking Hinagu fault zone is a major right-lateral strike-slip fault in central Kyushu, Japan. It extends about 81 km from the Kumamoto Plain in the northeast to the southern Yatsushiro Sea on the southwest (Figure 1) and at its northern end it connects with the ENE-trending right-lateral strike-slip Futagawa fault zone. These fault zones are divided into segments based mainly on paleoseismic behavior and geomorphic features. According to Earthquake Research Committee, the Headquarters for Earthquake Research Promotion (ERC, HERP) (2002, 2013), the Hinagu fault zone consists from north to south of the Takano-Shirahata, Hinagu, and Yatsushiro Sea segments (Figure 1b). The nearby Futagawa fault zone is presumed to consist of the geomorphically distinctive Futagawa segment and the Uto and off-Uto Peninsula segments, but the existence of the latter two has been inferred from subsurface structural data because they mostly lack topographical expression (Figure 1b).

The 16 April 2016 Kumamoto earthquake (Mj7.3) produced a 6-km-long surface rupture along the northern part of the Takano-Shirahata segment of the Hinagu fault zone, as well as extensive surface ruptures along the entire length of the Futagawa segment of the Futagawa fault zone (Goto et al., 2018; Kumahara et al., 2017; Shirahama et al., 2016). The surface rupture on the Takaho-Shirahata segment is characterized by a dominantly dextral component with a smaller vertical component, and the displacement decreased southward from 70 cm at Takaki to less than 10 cm at Yamaide (Shirahama et al., 2016) (Figure 1c). Some cm-scale surface ruptures and broad deformations, probably due to tectonic faulting, were detected on the southern part of the Takano-Shirahata segment by InSAR image analysis (Fujiwara et al., 2016) and confirmed by field observations (Ministry of Education, Culture, Sports, Science and
Technology [MEXT] & Kyushu University, 2019). No surface ruptures were detected on the Hinagu or Yatsushiro Sea segments. Because the surface rupture produced by the 2016 event was limited to the northern Takano-Shirahata segment and the displacement were not enough to produce tectonic landforms along the segment, the 2016 event is not considered representative of rupturing earthquake on the segment: larger events that ruptured the entire segment (or more) likely occurred in the past. To better understand rupture behavior in the region where the Hinagu and Futagawa fault zones connect, it is vital to investigate paleoseismic activity in the area.

In this study, we performed a paleoseismic investigation at Yamaide, in the central part of the Takano-Shirahata segment, and documented multiple faulting events that were accompanied by over 0.3 m vertical throw predating the 2016 earthquake. By paleoseismic trenching and supplementary coring, high-density radiocarbon (¹⁴C) dating of faulted and unfaulted sediments, tephra analysis, and Bayesian modeling using OxCal 4.3.2 (Bronk-Ramsey, 2009), we constrained the timing of seven paleoearthquakes on the Takano-Shirahata segment. We then examined the past rupture behavior of the Hinagu fault zone by comparing the results of this study with previously documented paleoearthquakes in the fault zone.

2 | GEOLOGICAL SETTINGS

The Takano-Shirahata segment, the northernmost segment of the Hinagu fault zone, extends 16 km from the junction with the Futagawa fault zone (Figure 1b). Surface traces of this segment have been identified and mapped before the 2016 Kumamoto earthquake by interpreting aerial photographs (Ikeda et al., 2001; Nakata et al., 2001; Nakata & Imaizumi, 2002). Surface ruptures on this segment that appeared in 2016 were identified mainly along previously mapped fault traces. After the 2016 earthquake, refined fault maps were produced by reexamining the faulted landforms and surface ruptures (Goto et al., 2018; Kumahara et al., 2017). In these maps, the Takano-Shirahata segment is a mainly continuous, nearly straight fault trace. On the basis of these features and the regional stress field, movement on this segment has been interpreted to have a predominantly right-lateral strike-slip component and a subsidiary vertical component on a steeply dipping fault plane. This interpretation has been validated by the focal mechanism and aftershock distribution of the 2016 earthquake (Uchide et al., 2016).

The first paleoseismic investigation of the Takano-Shirahata segment was performed before the Kumamoto earthquake. Shimokawa and Kinugasa (1999) dug a series of trenches at Takaki to determine the right-lateral offset of the latest faulting event on the segment, which was dated to 1.2–1.6 ka. Yoshioka, Shintani, Iemura, and Miyawaki (2007) excavated a series of trenches and a pit at Wanize that exposed faulted Aso-4 pyroclastic flow deposits, which were deposited in this area at about 90 ka (Machida & Arai, 2003), but they found little evidence to constrain the paleoseismic history of the segment. These paleoseismic studies were conducted only in the Takaki area, along the northern part of the Takano-Shirahata segment (Figure 1a,b); data from the central and southern parts are lacking.

The Yamaide paleoseismic site is near the middle of the Takano-Shirahata segment (Figure 1b), on an alluvial plain of the Midori River (Figure 1c). The paleocurrents of the Midori River, as interpreted by identifying micro-landforms on aerial photographs (Book of History of Kosa Town Editing Committee, 2013), show that the plain is part of an alluvial fan with its apex at Koga (Figure 1c). Several surface rupture substrands extend parallel to the main fault strand associated with the 2016 Kumamoto earthquake on the alluvial fan (Figure 1c). For the trenching study, we selected the Yamaide site on the main strand, because there is a small fault scarp near the site (Figure 2a). In addition, the site is situated at the northeastern corner of the fan, far from the fan’s apex, where we expected fine sediment would have accumulated thickly and continuously. Faint surface ruptures at the site, which were precisely mapped shortly after the earthquake (Shirahama et al., 2016), show that the 2016 Kumamoto earthquake caused a few centimeters of right-lateral slip and a west-side-down vertical offset of 8 cm along the main strand (Figure 2b,c). Thus, it was possible to excavate the trench directly over the fault, even though the existing scarp was some distance away because of natural erosion or artificial modification of the landscape.

3 | METHOD

3.1 | Trench and boring survey

At the Yamaide paleoseismic site, we detected a faint northwest-side-down 2016 surface rupture 5–15 m northwest of the existing northwest-facing scarp (Figure 2). We therefore inferred that the fault scarp has retreated from the original fault scarp as a result of natural erosion or modifications to the landscape for cultivation. To identify an appropriate site for the paleoseismic trench, one with fine sediments and abundant materials for ¹⁴C dating, we conducted a boring survey at two sites (Figure 2a). At site 1, two cores (cores YMD-1 and YMD-2) were collected, one from ~20 m northwest and the other from ~8 m southeast of the surface rupture (Figure 2b). Cores YMD-3 and YMD-4 were collected at site 2, which is about 300 m south of site 1. Detailed descriptions of all four cores are given by Shirahama et al. (2018). The sedimentary sequences of cores YMD-1 and YMD-2 were similar; both were composed mainly of fine sediments and contained ¹⁴C dating materials (Figure 3). By correlating the sediments between the two cores, we inferred the existence of west-side-down deformation, probably due to repeated faulting, along section A–A’ (Figures 2b and 3). In contrast, the sediments exposed in cores YMD-3 and YMD-4 consisted chiefly of coarse gravel, and it was difficult to detect vertical deformation between the cores. We therefore decided to excavate the trench across the 2016 surface rupture at site 1. The trench, about 14 m long, 10 m wide, and 4 m in depth, was excavated with the long axis orthogonal to the strike of the surface rupture (Figure 2b). The trench walls were designed to slope at 45° to avoid collapse, because the exposed sediments are composed mainly of fragile unconsolidated fine materials. Figures 4a and 5a show photomosaics of trench walls on a corrected vertical
We imposed a 1 m × 1 m grid on the trench walls with sections numbered from 1 to 14 from east to west. On both the north and south walls of the trench (walls N and S, respectively), predominantly fine-grained sediments were exposed showing deformation by several faults beneath the 2016 surface rupture (Figures 4 and 5). As described later, this deformation was produced by multiple faulting.
events. We also divided the sediments vertically on the basis of the inferred sedimentary environments into four main units (A–D) and further subdivided them into subunits based on sedimentary facies, grain size, and organic content (Figure 4b and Table S1).

### 3.2 Dating method

We constrained the depositional ages of the sedimentary units and subunits and the timing of paleoseismic events on the basis of high-density \(^{14}C\) dating and tephrochronology. For \(^{14}C\) dating, we systematically collected multiple samples along one vertical section of each wall (sections N11.2 and S10.1) (Figures 4b and 5b). Most of the analyzed samples were bulk sediment, but some pieces of wood and charcoal were also analyzed (Table 1). Chemical pretreatment and accelerator mass spectrometry measurements for \(^{14}C\) dating were conducted at the Atmosphere and Ocean Research Institute, the University of Tokyo, Japan (referred to hereafter as AORI; Yokoyama et al., 2019), and Beta Analytic Testing Laboratory, USA (Beta). The samples measured by AORI and Beta were given the codes ‘YAUT’ and ‘Beta’, respectively. Measured conventional \(^{14}C\) ages were calibrated by using the OxCal 4.3.2 program (Bronk-Ramsey, 2009) with the INTCAL 13 calibration curve (Reimer et al., 2013). All \(^{14}C\) measurements are summarized in Table 1. Charred wood samples (YMD-T-C26, yw1-1, yw1-2, YMD-T-C25, yw2-1, and yw2-2) collected from units C-5 and C-6, which were measured at both laboratories, showed almost the same ages, within error; thus, the dating results did not differ between the two laboratories. The relationship between \(^{14}C\) ages and carbon content was determined by using carbon content measurements conducted at AORI.
In trench walls N and S, a lenticular body of yellowish-white, glassy volcanic ash was found in unit C-4. The volcanic ash, which was characterized on the basis of its mineral assemblage, volcanic glass refractive indices, and heavy minerals, was correlated to the Kikai-Akahoya tephra (K-Ah), a widespread volcanic ash on Kyushu Island that was erupted from Kikai caldera about 7.3 ka (Machida & Arai, 2003). Furthermore, sediment samples were collected at 10 cm intervals along five sections, N2.0, N6.5, N11.0, S2.0, and S10.0 (Figures 4b and 5b), for systematic tephra analyses by Furusawa Geological Survey Co. Ltd., Japan. In addition, to check whether the K-Ah tephra was contaminated with any other widespread tephras, some tephra samples were also analyzed to determine their major-element composition. The detailed results of tephra analysis were summarized in Shirahama et al. (2018).

4 | RESULT

4.1 | Stratigraphy and fault structures

The sediments exposed in the Yamaide trench consist mainly of alternating layers of silt, sand, and pebbles and humic silt (Figures 4 and 5). The four main sediment units A to D were subdivided into 25 subunits, generally ranging from 0.1 to 0.5 m in thickness, to facilitate the identification of individual paleoseismic event horizons. Here, we describe each unit briefly and then give the deformational features in detail. Detailed descriptions of the subunits are given in Table S1, and close-up photographs can be found in Shirahama et al. (2018).

Unit A is the present plowed soil of the rice paddy field at the trench site. Unit B is composed of unsorted, weakly organic silty and sandy gravel. The lower boundary of unit B is markedly different between the downthrown (west) side and the upthrown (east) side of the fault. On the downthrown side, unit B substrata are subparallel to those in the underlying unit C, whereas on the upthrown side, unit C has been eroded (Figures 4 and 5). This feature suggests that the part of unit C raised by past faulting was leveled by natural or artificial erosion before unit B formed. In addition, unit B includes some pottery fragments and stone tools. Therefore, we interpret unit B as an old cultivated soil. Unit C is composed primarily of organic silt containing poorly sorted or unsorted sand or pebbles. It is thus interpreted as flood deposits in a floodplain environment. Unit D is composed of alternating beds of normally graded laminated humic silt, sand, and pebbles. These depositional
TABLE 1
Radiocarbon ages (part 1)

| Sample ID | Material | Code ref | Unit | δ^13C (‰) | Material Code | Carbon content (%) | Conventional 14C age (VBP) | Calibrated age (cal BP, ±1σ) | Calibrated age (cal BP, ±2σ) |
|-----------|----------|----------|------|------------|---------------|-------------------|----------------------|--------------------------|--------------------------|
| #922      | Sediment | YAUT-033216 | B-1  | -22.9      | 796-272      | 922-220           | 562-25               | 596-230                  | 554-644                  |
| #923      | Sediment | YAUT-028602 | B-2  | -12.3      | 1282-12       | 1978-211          | 1341-136             | 1315-140                 | 1301-149                 |
| #924      | Sediment | YAUT-033217 | B-3  | -10.4      | 2004-128     | 1478-211          | 1397-198             | 1396-203                 | 1395-199                 |
| #925      | Sediment | YAUT-028603 | C-2  | -8.1       | 2282-112     | 2884-184          | 2174-178             | 2174-178                 | 2174-178                 |
| #926      | Sediment | YAUT-028604 | C-3  | -3.4       | 2002-150     | 2499-273          | 2356-272             | 2356-272                 | 2356-272                 |
| #927      | Sediment | YAUT-028605 | C-4  | -6.2       | 2002-150     | 2499-273          | 2356-272             | 2356-272                 | 2356-272                 |
| #928      | Sediment | YAUT-028606 | C-5  | -1.1       | 2002-150     | 2499-273          | 2356-272             | 2356-272                 | 2356-272                 |
| #929      | Sediment | YAUT-028607 | C-6  | -3.1       | 2002-150     | 2499-273          | 2356-272             | 2356-272                 | 2356-272                 |
| #930      | Sediment | YAUT-028608 | C-7  | -1.9       | 2002-150     | 2499-273          | 2356-272             | 2356-272                 | 2356-272                 |
| #931      | Sediment | YAUT-028609 | C-8  | -2.5       | 2002-150     | 2499-273          | 2356-272             | 2356-272                 | 2356-272                 |
| #932      | Sediment | YAUT-028610 | C-9  | -5.1       | 2002-150     | 2499-273          | 2356-272             | 2356-272                 | 2356-272                 |
| #933      | Sediment | YAUT-028611 | C-10 | -8.6       | 2002-150     | 2499-273          | 2356-272             | 2356-272                 | 2356-272                 |
| #934      | Sediment | YAUT-028612 | C-11 | -1.9       | 2002-150     | 2499-273          | 2356-272             | 2356-272                 | 2356-272                 |
| #935      | Sediment | YAUT-028613 | C-12 | -4.2       | 2002-150     | 2499-273          | 2356-272             | 2356-272                 | 2356-272                 |
| #936      | Sediment | YAUT-028614 | C-13 | -7.7       | 2002-150     | 2499-273          | 2356-272             | 2356-272                 | 2356-272                 |
| #937      | Sediment | YAUT-028615 | C-14 | -1.9       | 2002-150     | 2499-273          | 2356-272             | 2356-272                 | 2356-272                 |
| #938      | Sediment | YAUT-028616 | C-15 | -3.1       | 2002-150     | 2499-273          | 2356-272             | 2356-272                 | 2356-272                 |
| #939      | Sediment | YAUT-028617 | C-16 | -1.9       | 2002-150     | 2499-273          | 2356-272             | 2356-272                 | 2356-272                 |
| #940      | Sediment | YAUT-028618 | C-17 | -3.1       | 2002-150     | 2499-273          | 2356-272             | 2356-272                 | 2356-272                 |
| #941      | Sediment | YAUT-028619 | C-18 | -1.9       | 2002-150     | 2499-273          | 2356-272             | 2356-272                 | 2356-272                 |

(Continues)
| Sample ID | Unit | Material | Code no. | δ¹³C (%) | Conventional ¹⁴C age (yBP) | Calibrated age\(^a\) (cal BP; ±1σ) | Calibrated age\(^a\) (cal BP; ±2σ) | Carbon content (%) |
|-----------|------|----------|----------|----------|--------------------------|--------------------------------|--------------------------------|------------------|
| YMD-T-C25 | C-6  | Wood     | Beta-456389 | −29      | 2242 ±19                | 2183–2320                        | 2158–2334                      | −                |
| #119      | C-6  | Sediment | YAUT-033511 | −28      | 7905 ±30                | 8635–8763                        | 8600–8972                      | 0.22             |
| #122      | C-6  | Sediment | YAUT-033512 | −33.4    | 9516 ±33                | 10 710–11 063                     | 10 692–11 072                   | 0.17             |
| YMD-T-C2 | C-6  | Wood     | YAUT-028904 | −29.7    | 2304 ±246               | 2067–2710                        | 1734–2923                      | −                |
| YMD-T-C3 | C-6  | Wood     | YAUT-028905 | −25.4    | 2328 ±43                | 2214–2423                        | 2160–2489                      | −                |
| #125      | C-7  | Sediment | YAUT-033513 | −57.7    | 9819 ±33                | 11 210–11 244                     | 11 195–11 265                   | 0.1              |
| #169      | D-1  | Sediment | YAUT-033518 | −26.5    | 9196 ±34                | 10 272–10 398                     | 10 249–10 486                   | 0.21             |
| #28       | D-3  | Sediment | YAUT-033212 | −11.4    | 10 231 ±44              | 11 827–12 056                     | 11 770–12 119                   | 0.25             |
| #127      | D-3  | Sediment | YAUT-033515 | 31.9     | 3598 ±718               | 3008–4874                        | 2341–5913                      | −                |
| YMD-T-C18 | D-4  | Sediment | Beta-456383 | −19.3    | 10 194 ±32              | 11 815–11 980                     | 11 760–12 046                   | −                |
| YMD-T-C20 | D-4  | Sediment | Beta-456385 | −19.6    | 10 076 ±31              | 11 418–11 758                     | 11 402–11 802                   | −                |
| #30       | D-4  | Sediment | YAUT-033213 | −20      | 10 210 ±45              | 11 820–12 012                     | 11 755–12 105                   | 0.53             |
| #128      | D-4  | Sediment | YAUT-033516 | −28.6    | 10 281 ±36              | 11 980–12 125                     | 11 829–12 372                   | 0.45             |
| YMD-T-C15 | D-8  | Sediment | Beta-456382 | −19.2    | 11 276 ±42              | 13 080–13 161                     | 13 058–13 225                   | −                |
| YMD-T-C19 | D-8  | Sediment | Beta-456384 | −19      | 11 107 ±33              | 12 945–13 061                     | 12 846–13 078                   | −                |
| YMD-T-C21 | D-8  | Sediment | Beta-456386 | −21.6    | 12 302 ±34              | 13 859–14 054                     | 13 810–14 108                   | −                |
| YMD-T-C021701 | D-8 | Sediment | Beta-45876 | −21.9 | 12 319 ±37 | 14 129–14 351 | 14 084–14 576 | − |
| #160      | D-9  | Sediment | YAUT-033517 | −39.1    | 10 653 ±37              | 12 590–12 675                     | 12 562–12 701                   | 0.13             |
| #46       | D-12 | Sediment | YAUT-033215 | −12      | 12 659 ±52              | 14 968–15 187                     | 14 787–15 249                   | 0.5              |
| YMD-T-C22 | D-12 | Sediment | Beta-456387 | −18.9    | 12 766 ±43              | 15 139–15 276                     | 15 058–15 368                   | −                |
| #47       | D-13 | Sediment | YAUT-033502 | −47.4    | 12 413 ±45              | 14 305–14 665                     | 14 179–14 833                   | 0.09             |
| YMD-1-D0.6 | YMD-1 | Sediment | YAUT-033519 | −35.3    | 7228 ±32                | 7980–8150                        | 7970–8159                      | 0.19             |
| YMD-1-D1.5 | YMD-1 | Sediment | YAUT-033523 | −30.2    | 9764 ±33                | 11 185–11 225                     | 11 165–11 241                   | 0.37             |
| YMD-1-D2.1 | YMD-1 | Sediment | YAUT-033524 | −24.5    | 5023 ±29                | 5715–5885                        | 5661–5892                      | 0.51             |
| YMD-1-D3.0 | YMD-1 | Sediment | YAUT-033525 | −38.1    | 13 051 ±40              | 15 550–15 762                     | 15 384–15 834                   | 0.12             |
| YMD-2-C021701D4.6 | YMD-2 | Sediment | Beta-458879 | −20.1    | 13 870 ±40              | 16 689–16 930                     | 16 573–17 009                   | −                |
| YMD-2-D3.0 | YMD-2 | Sediment | YAUT-033526 | −21.6    | 11 307 ±36              | 13 103–13 193                     | 13 075–13 249                   | 0.35             |
| YMD-2-D3.4 | YMD-2 | Sediment | YAUT-033528 | −20.6    | 12 516 ±39              | 14 666–14 992                     | 14 422–15 085                   | 0.39             |
| YMD-2-D3.8 | YMD-2 | Sediment | YAUT-033529 | −16.5    | 12 803 ±40              | 15 170–15 315                     | 15 104–15 433                   | 0.37             |

\(^a\)OxCal 4.3.2 (Bronk-Ramsey, 2017), INTCAL13 (Reimer et al., 2013).
characteristics are typical of sediments deposited in fan and channel-fill environments.

A distinct west-side-down flexure associated with multiple faults is exposed in the middle parts of walls N and S (Figures 4b and 5b). On each wall, the faults are numbered in order from the east: for example, F-N2a indicates a substrand of the second fault from the east on wall N. All faults dip steeply (70–80°) to the east with the west side downthrown, indicative of an apparent reverse slip component. On both walls, the faults occur within a relatively narrow (4 m wide) band or fault zone (Figures 4 and 5). The upper terminations of the faults are often located in different stratigraphic units, and a few faults show larger slip in the lower units, structural features that suggest multiple faulting events. The small surface rupture that appeared during the 2016 Kumamoto earthquake is at the top of the fault zone, but we observed no evidence of the 2016 slip in the trench walls.

Some faults fade out within a sediment unit (shown by dashed red lines at their terminations in Figures 4b and 5b). The slips on these faults are too small to determine their upper termination point. In some cases, slips on these faults might have occurred during a younger event. Unless an obvious deformation structure was observed along the fault or the fault termination was clear, fault terminations were not used as evidence for timing of a rupturing earthquake.

The deformation observed on the trench walls includes both discrete slip on faults and flexural folding. Units D and C are convex upward on the upthrown side, whereas on the downthrown side the strata are convex downward with their lowest points around grids N10 and S10. These features are consistent with a hanging wall anticline and a footwall syncline associated with faulting with a reverse slip component.

Many stratigraphic units were distributed across the fault zone (Figures 4b and 5b), so we were able to measure the vertical throw of each of those units across the fault zone. If the ratio of lateral to vertical slip produced by an earthquake was always the same, a difference in vertical throw of successive stratigraphic units across the fault zone could be used for the identification of a paleoseismic event.

### 4.2 Ages of sediment units

Tephra analysis identified the K-Ah tephra in and around unit C-4 (or at the lower boundary of unit C-3 where unit C-4 was missing) on each continuously sampled section (N2.0, N6.5, and N11.0 in Figure 4b, and S2.0 and S10.0 in Figure 5b). The K-Ah tephra was not detected in units below unit C-4 except in section N11.0 (Shirahama et al., 2018), where its presence can be explained by possible bioturbation, as described below. Therefore, the tephra fall occurred during the deposition of unit C-4, and unit C-4 was deposited at about 7.3 ka. In walls N and S, unit C-4 was identified only on the downthrown side of the fault zone (grids N10–N14 and S9–S14); on the upthrown side, unit C-4 could not be detected (possibly because of erosion), but the K-Ah tephra was detected in the basal part of unit C-3. This tephra distribution supports our identification of unit C sub-units on the upthrown side.

Samples for high-density 

\[ ^{14}C \] dating were collected systematically at closely spaced intervals along sections N11.2 and S10.1 for determination of the depositional ages of the floodplain deposits (unit C) and the upper part of the channel and fan deposits (unit D), as well as for inferring the formation age of the old cultivated soil (unit B) (Figures 4b and 5b). Most subunits of units C and D had a low carbon content and few organic materials such as wood and charcoal. The 

\[ ^{14}C \] dating results, including deposition curves calculated by Bayesian modeling using OxCal 4.3.2 (Bronk-Ramsey, 2009), are summarized in Figure 6.

The 

\[ ^{14}C \] ages of samples from units D–B range from about 15 000 to 1500 cal BP and most, but not all, are consistent with sampling depth (Figure 6a,b). In particular, the ages of the charred wood samples collected from unit C-5 (samples YMD-T-C26, yw1-1, and yw1-2) and unit C-6 (samples YMD-T-C25, yw2-1, and yw2-2) in wall N (2183–2343 cal BP) are much younger than the ages of other samples from the same stratigraphic units, and they are also younger than the depositional age of unit C-4 (7.3 ka) dated by the K-Ah tephra. The ages of these two wood samples measured at the laboratories, AORI and Beta, are identical each other, which implies that their anomalously younger ages are not due to analytical error. Moreover, the preserved epidermis of these wood samples, their gently curving shape, and lack of growth rings (Figure 7) suggest that they are fragments of tree roots that penetrated units C-5 and C-6 long after their deposition. Thus, we disregarded the ages of these two wood samples in our estimation of the ages of units C-5 and C-6.

The 

\[ ^{14}C \] ages of the samples collected from unit B are consistent with their stratigraphic position (Table 1). In addition, among these samples, sample C030601 (1185–1266 cal BP) was collected from near the bottom of unit B-2. Thus, we inferred from these 

\[ ^{14}C \] ages that the depositional ages of units B-1, B-2, and B-3 were 560–1200, 1200–1300, and 1300–1400 cal BP, respectively.

The 

\[ ^{14}C \] ages of samples collected from unit C-3 cover a wide range (Figure 6a,b). In particular, the 

\[ ^{14}C \] ages of samples #4 and #5, collected from section N11.2, are younger than those of samples from higher stratigraphic positions. The inconsistency between these 

\[ ^{14}C \] ages and their sampling depths can be explained by taking into account their carbon contents (Figure 6d), which are very high, similar to or higher than the carbon contents of the humus-rich old cultivated soil of unit B. Therefore, samples #4 and #5 may be contaminated with carbon from the overlying cultivated soil, and we regard them as outliers. Similarly, the age of sample #127 from unit D-3, collected from section S10.1, is markedly younger and has a larger error than ages from both the underlying and overlying units. We also regard the 

\[ ^{14}C \] age of sample #127 as an outlier, because the sample contained almost no carbon (Figure 6d).

The sediments from the bottom of unit C-5 to the bottom of unit C-3 in section N11.2 were deposited continuously from about 10 000 to 4000 cal BP (Figure 6a). Although samples datable by 

\[ ^{14}C \] could not be collected from unit C-4, which contains the K-Ah tephra (7.3 ka), samples from both above and below unit C-4 (samples #7–#12) have 

\[ ^{14}C \] ages 2000–3000 years younger than the K-Ah tephra. Within unit C-5, the 

\[ ^{14}C \] ages of samples #14–#16 are also younger than those of
samples collected above and below them. The inconsistency of these \(^{14}\)C ages with the tephra age of unit C-4 and the stratigraphic inconsistency of ages for unit C-5 imply that samples #7–#12 and #14–#16 were affected by rejuvenation, for example, through bioturbation due to root penetration or contamination with younger organic matter transported by groundwater. Therefore, in constructing the deposition...
4.3 | Identification of paleoearthquake events and ages

We used structural features such as substantial differences in the vertical separation of stratigraphic units, the burial of structural relief by a stratigraphic unit, and in some cases the deformed structure of the upper fault termination to identify seven paleoseismic events preceding the 2016 Kumamoto earthquake. Here, we describe the evidence used to estimate the age range of each paleoseismic event in order from the most recent event (Event 0, the 2016 Kumamoto earthquake) to the oldest (Event 7) event. The age of each event was estimated by using the oldest $14^C$ age above and the youngest $14^C$ age below the event horizon and applying Bayesian modeling with OxCal 4.3.2 (Table 2). The probable age range of each event is based on the $2\sigma$ confidence level of each probability density distribution (Table 2 and Figure 8a).

Event 0: The most recent event recorded at this site is the 2016 Kumamoto earthquake. Although this event caused a west-side subsidence of 8 cm, no distinct stratigraphic evidence for this event such as disruptions of near-surface units could be detected in the trench walls.

Event 1: In wall N, unit B-2 shows west-side-down flexure with a height difference of ~0.5 m at the upper extension of fault F-N2a (Figure 9). In wall S, units B-2 and B-4 flex gently to the west, and unit B-1 overlies the subsided part of the flexure. We infer from this evidence that Event 1 occurred after the deposition of unit B-2 and before the deposition of unit B-1. Therefore, Event 1 occurred at 838–1246 cal BP based on the $14^C$ ages of sample YMD-T-C030602 from unit B-1 and sample YMD-T-C300601 from unit B-2 (Table 2). Since units from B-4 to B-1 are old cultivated soil (Table S1), inclined distribution of unit B-2 has possibility of man-made. Therefore, we consider that the reliability of this event is low.

Event 2: Unit C-3, which is distributed across the fault zone, exhibits west-side downthrown flexural deformation accompanied by distinct slip on fault F-N2a. We infer that Event 2 occurred after or during the deposition of unit C-3 and before that of unit C-2, because unit C-2 directly overlies unit C-3 only on the downthrown side. There is some ambiguity regarding the timing of this event, however, because although fault F-N2a can be easily traced up to the basal part of unit C-3, it is difficult to trace further upward in the coarse sediments of unit C-3 and the overlying units. Furthermore, unit C-3 decreases in thickness to the east on the east (upthrown) side of the fault, probably because of erosion associated with natural process or cultivation (Figure 4b). The faded out of the fault F-N2a might have been caused by a long time exposure after Event 2, or plastic deformation of the upper part of the unit C-3. Therefore, we cannot rule out the possibility that unit C-2 (or unit C-1) once covered unit C-3 conformably on the east side of the fault and, similar to unit C-3, was deformed by Event 2 before being eroded away. In addition, the lack of the upper boundary and unclear sedimentary structure of unit C-3 made difficult to constrain the timing of Event 2 after or during the sedimentation of unit C-3. In that case, Event 2 occurred during the deposition of unit C-3 and before that of unit B-4. Thus, we used the
oldest $^{14}$C ages of samples YMD-T-C030604 and YMD-T-C24, collected from units B-3 and unit C-3, respectively, to constrain the age of Event 2 to 1311–7062 cal BP (Table 2).

Event 3: In both walls, unit C-6 forms a west-facing flexure scarp around the fault zone, and faults F-N2a and F-N4a cut unit C-6 on the wall N and fault F-S4a also displaced the unit on the wall S (Figures 4b and 5b). Unit C-5 overlies unit C-6 only on the downthrown side of the scarp. Therefore, Event 3 occurred after the deposition of unit C-6 and before the deposition of unit C-5 that buries the flexure scarp. This interpretation is supported by fault F-S4a, across which unit C-6 is clearly displaced but which is covered by unit C-5, though its termination is not clear. Event 3 is estimated to have occurred at 9991–11 032 cal BP based on the $^{14}$C ages of samples #118 and #122, collected from units C-5 and C-6, respectively (Table 2).

Event 4: In both walls, units D-1 and D-2 have been eroded so that unit C-7 directly overlies unit D-3 above the subsided part of the flexure scarp. In wall S, faults F-S1a, F-S2a, and F-S7 cuts unit D-3, but not deformed some gravel lenses in unit C-7 (Figure 5b). Therefore, Event 4 occurred during the deposition of unit C-7. Event 4 would have occurred at 10 788–12 060 cal BP based on the $^{14}$C ages of samples #118 and #122, collected from units C-5 and C-6, respectively (Table 2).

Event 5: Apparent vertical throw of the top of unit D-4 across the entire fault zone is smaller than that of the top of unit D-8 in both walls N and S (Figure 9). Vertical throw of unit D-4 along faults F-N2a and F-N4a in wall N, and faults F-S2a and F-S4a in wall S, are also smaller than those of unit D-8. In wall S, the slope of unit D-8 is steeper than unit D-4. The thickness of unit D-7 decreases to the east across the fault zone. This pattern of decrease suggests that unit D-7 was deposited as fill the downthrown side of the fault after deposition of unit D-8. We therefore inferred that Event 5 occurred at some time between the deposition of unit D-8 and that of unit D-4, maybe before the deposition of unit D-7. The ages of samples YMD-T-C19 and #128, collected from units D-8 and D-4, respectively, constrain the age of Event 5 to 11 985–12 957 cal BP (Table 2).

Event 6: The dip separation of the basal part of unit D-8 is smaller than that of unit D-12 along fault F-S1 on wall S (Figure 5b). In wall N, units D-12 and D-11 and at least the lower part of unit D-10 are displaced by slip on faults F-N2a and F-N2b, but this deformation is not observed in wall N6. These structural features indicate that Event 6 occurred during the sedimentation of units D-10. The estimated age of Event 6 is 14 224–15 138 cal BP, based on the $^{14}$C ages of samples #46 and YMD-T-C021701, collected from units D-12 and D-8, respectively (Table 2).

Event 7: The oldest event detected at the Yamaide trench site is inferred to have occurred after the deposition of unit D-13 and before the deposition of unit D-12 because fault F-N1 cuts unit D-13 but is covered by unit D-12 in wall N (Figure 4b). Unit D-12 is apparently thicker between N6 and N7 on the west (downthrown) side of fault F-N1 than on the east (upthrown) side. This difference in thickness across the fault suggests that unit D-12 was deposited as fill to the west of the west-facing fault scarp produced by Event 7. The age of Event 7 is estimated to be older than 14 800 cal BP based on the $^{14}$C age of sample C22 collected from the unfaulted unit D-12 (Table 2).
5 | DISCUSSION

5.1 | Paleoseismic history of the Yamaide paleoseismic site

We identified seven surface-rupturing events prior to the 2016 Kumamoto earthquake by a combination of boreholes and paleoseismic trenches on the Takano-Shirahata segment together with high-density radiocarbon dating (Figure 8a). It is noteworthy that the charcoal dates do not necessarily provide reliable ages of the past events if the geological sequences are interpreted from sporadic dating results. Thus, a detailed description of geological trench walls in tandem with sequential radiocarbon dating is a powerful tool for obtaining high confidence paleoseismic history.

The timing of the six youngest events was constrained by the high-density $^{14}$C ages of the sediments and the date of the tephra...
marker horizon as follows: Event 1, 838-1246 cal BP; Event 2, 1311–7062 cal BP; Event 3, 9991–11 032 cal BP; Event 4, 10 788–12 060 cal BP; Event 5, 11 985–12 957 cal BP; and Event 6, 14 224–15 138 cal BP (Table 2). The timing of Event 7, which occurred before 14 800 cal BP, could not completely constrained because age information on the pre-faulting units is lacking.

The average recurrence interval for Events 1 through 6 is 2596–2860 years. If we exclude Event 1 identified with low reliability, the average recurrence interval between Event 2 and Event 6, is 1791–3457 years. It is clear that the recurrence interval between all Events has varied (Table 2 and Figure 8b). Median values of intervals between events occurring from 10 to 15 ka (Event 3 to 6) were simulated by MCMC modeling to be relatively short at 819–2336 years (Table 2). In contrast, the interval between Events 2 and 3 is much longer than other intervals (Figure 8b).

Our detailed paleoseismic history provides Coefficient of Variations (COV), which is defined as a ratio of the mean and standard deviation of recurrence intervals (Berrymann et al., 2012; Kagan & Jackson, 1991). Kagan and Jackson (1991) defined faulting behavior based on COV; random earthquake recurrences (COV ~ 1); quasi-periodic (COV < 1), and clustering (COV > 1). Recurrence intervals at the Yamaide site provide a COV value of 1.0 with all events, or a value of 1.1 without Event 1, indicating random behavior (Table 2). These COV values indicate that the earthquake randomly occurred at the Yamaide site. Earthquake activity at this site might have been influenced by the activities of the adjacent segment as explained later on section 5.3. ERC, HERP mainly applies the Brownian Passage Time (BPT) probability to forecast earthquake probability of active fault in Japan (ERC, HERP, 2001). But in our case with a high COV value, BPT probability is not appropriate, the probability is based on the time-dependent model, which should show less than one as COV value (Matthews, Ellsworth, & Reasenberg, 2002; Parsons, 2008). Instead of the model, the Poisson probability in the next 30 years can be estimated to be in the range of 0.86 to 1.66 % (Table 2). These probabilities are defined as slightly high among the active fault in Japan (ERC, HERP, 2001).

### 5.2 Vertical throws of each paleoseismic event

We observed the west-side-subsidence of the lower (older) units are larger than those of the higher (younger) units (Figures 4b and 5b) showing a cumulative displacement of slip. The Hinagu fault zone is, however, a major right-lateral strike-slip fault. In the following discussion, we thus assumed the ratio of horizontal to vertical slip produced by an earthquake was constant.

To investigate the relationship between the relative displacement and the time interval between events, we measured the vertical throw of the ground surface and of the unit boundaries in the geological cross section (Figure 3). The height difference between the highest point on the upthrown side and the lowest point on the downthrown side of each marker horizon, such as a unit boundary, was considered to be the vertical throw. The measured cumulative vertical throws of the ground surface and of the top of unit B-2, the bottom of unit C-3, and the top of units C-6, D-4, and D-8 are 0.08, 0.5, 1.4, 2.0, 2.3, and > 2.6 m, respectively (Figure 9). Because the lowest point of the upper boundary of unit D-8 is not exposed on the trench walls (Figures 4b and 5b), the observed vertical throw for D-8 of 2.6 m is a minimum value. We estimated those vertical throws of marker horizons to correspond to the cumulative throw since Events 0–5, respectively. Thus, the calculated vertical throws of the individual events are 0.4 m (Event 1), 0.9 m (Event 2), 0.6 m (Event 3), 0.3 m (Event 4), and > 0.3 m (Event 5) (Figure 9). However, the reliability of the identification of Event 1 is low. If Event 1 is excluded, then the vertical throw of Event 2 is 1.3 m.

The vertical throw of detected events was clearly larger than that of the 2016 Kumamoto earthquake. So, Event 1–5 should have been clear surface-rupturing earthquakes larger than the 2016 Kumamoto earthquake at the trench site. The vertical throw of Event 2 is larger than that of the other events. This variety is similar to the variety of the recurrence interval. The Takano-Shirahata segment might have an active period when relatively smaller earthquakes occur frequently, and a calm period when relatively larger earthquakes occur rarely.

The average uplift rate is 0.20–0.57 mm/yr, utilizing the total vertical displacements and the ages of the unit boundary. To calculate the horizontal slip rate, we applied lines of indirect evidence: striation rake angle on a fault plane, and the amount of the horizontal displacement inferred by Matsuda's equation (Matsuda, 1975). The rake angle indicates the strike-slip rate is 0.6–1.6 mm/yr. At the trench, a F-N1 fault plane showed unclear striations with a rough rake angle of about 20 degrees to the north. However, the rake angle was taken from the only one fault plane among many faults in the trench. At the Takano-Shirahata segment,
the amount of the displacement per earthquake was about 2 m based on Matsuda's equation. The recurrence interval of 2596–2860 years at the Yamaide site indicates 0.7 mm/yr as the horizontal slip rate. Though they are a rough estimation, the strike-slip rate can be determined to be 0.6–1.6 mm/yr.

5.3 Seismic behavior of the Takano-Shirahata segment

Our survey first revealed a recurrence interval since 15 ka of the Takano-Shirahata segment. ERC, HERP (2013) reported recurrence intervals of 3600–11,000 years on the Hinagusu segment and of 1100–6400 years on the Yatsushiro Sea segment. The shorter recurrence interval of the Takano-Shirahata segment from the Yamaide site indicates that surface-rupturing earthquakes occurred more frequently than other segments. MEXT and Kyushu University (2019) reported the maximum recurrence intervals of 5700 years on the Hinagusu segment and 2800 years on the Yatsushiro Sea segment based on the paleoseismic survey in 2016–2018. Their and our results suggest that the recurrence interval of the Hinagu fault zone is shorter than previous estimation.

Comparison of the timing of individual events determined at other paleoseismic sites with our results from the seven events detected at the Yamaide paleoseismic site (YM in Figure 8c) shows that some events overlap in time. The age ranges of Events 1–5 and 7 overlap with the reported age ranges of events at site MB1 and MB2. Thus, the Takano-Shirahata segment and the northern part of the Hinagu segment might have ruptured simultaneously and produced surface ruptures ~25 km long. The age ranges of Events 2, 5, and 7 fall within those of some events at KK2. If the Takano-Shirahata segment and the entire Hinagu segment might have ruptured simultaneously, they would produce an M7.8 earthquake with surface ruptures more than 60 km long (Matsuda, 1975). The seismic behavior of the Takano-Shirahata-segment seems to be affected by the Hinagu segment.

The paleoseismic history of the Yamaide site is slightly inconsistent with that of the Futagawa fault zone. A paleoseismic trench surveys at the Terasako site and the Kurokawa site (see locations in Figure 1b) suggested the absence of events that could be associated with the Futagawa fault zone. This implies events similar to the Kumamoto earthquake have occurred which did not result in clear deformation at the Yamaide site. On the other hand, there is the possibility that the recurrence interval before 10 ka at the Takano-Shirahata segment would be affected by seismic activity of the Futagawa fault zone.

Although demonstrating the simultaneity of paleoseismic events is difficult because there is little information on the fault zone paleoseismic history before 10 ka, these relatively smaller events may be associated with paleoearthquakes that occurred at the adjacent fault zone. The Takano-Shirahata segment, showing a variety of slips and high COV as revealed by our trench survey, has some features of the ‘variable slip’ model proposed by Schwartz and Coppersmith (1984). The ‘variable slip’ behavior can appear near a segment boundary, due to the different faulting behaviors of the adjacent segment (DuRoss et al., 2016; Berryman et al., 2012; Schwartz, 1989). In the case of the Takano-Shirahata segment, seismic behavior might have been affected by the one or both activities of the Hinagu segment and the Futagawa fault zone.

6 SUMMARY

We performed a paleoseismic investigation at Yamaide, along the central part of the Takano-Shirahata segment of the Hinagu fault zone, and documented multiple faulting events accompanied by large surface deformation that occurred before the 2016 earthquake. On the basis of paleoseismic trenching, supplementary coring, numerous high-density ^14C dates of faulted and unfaulted sediments, Bayesian modeling, and tephrochronology, we successfully constrained the timing of paleoearthquakes on the Takano-Shirahata segment.

Seven surface-rupturing events preceding the 2016 Kumamoto earthquake were identified by our paleoseismic survey. Our survey revealed the detailed description of trench walls in tandem with sequential radiocarbon dating was a powerful tool to obtaining high confidence paleoseismic history. The timing of the youngest six events was constrained as follows: Event 1, 838–1246 cal BP; Event 2, 1311–7062 cal BP; Event 3, 9991–11 032 cal BP; Event 4, 10 788–12 060 cal BP; Event 5, 11 985–12 957 cal BP; and Event 6, 14 224–15 138 cal BP. Event 7 occurred before 14 800 cal BP, but its timing could not be further constrained. Assuming Events 1 to 6 represent six separate events, then the average earthquake recurrence interval at this site is 2596–2860 years. If low-reliability Event 1 is excluded, then the average recurrence interval is 1791–3457 years. Those recurrence intervals provide 1.0 of COV with all events or 1.1 without Event 1, indicating random behavior. Our survey also revealed that the recurrence interval is variable. During 10–15 ka, the recurrence intervals are relatively short (1000–2000 years). In contrast, the interval between Events 2 and 3 is much longer. Our results suggest that the recurrence interval of the Hinagu fault zone is shorter than previous estimation.

We examined the behavioral features of the Hinagu fault zone by comparing the results of this study with previously documented records of paleoearthquakes in the fault zone. Paleoeartquake estimates at site MB2 are generally consistent with the events revealed by our trench survey. If the Takano-Shirahata segment and the Hinagu segment ruptured simultaneously, they would produce an M7.8 earthquake with a 60-km-long rupture.

We measured vertical throws of events, assuming the ratio of horizontal to vertical slip is constant, and revealed the vertical throw of Event 2 showed larger than those of other events. The Takano-Shirahata segment may have a period when earthquakes with small displacements are frequent and a period when earthquakes with large displacements are rare. This seismic behavior might have been affected by the one or both activity of the Futagawa and Hinagu fault zones.

ACKNOWLEDGEMENTS

We thank staff members at the Kumamoto Prefectural Hall, Kousa Town Hall, and Mifune Town Hall for their cooperation with our
investigation. We also thank the landowners of the boring and trenching sites in Yamaide district for their collaboration and efforts to aid our survey. We appreciate Tadashi Maruyama for helpful advice in improving this paper. This manuscript was significantly improved by comments and suggestions from two reviewers; Prof. Shinji Toda and Jin-Hyuck Choi. Our survey was conducted as a part of the ‘Comprehensive Active Fault Survey Based on the Kumamoto Earthquake in 2016’ commissioned by MEXT and Kyushu University. This research was supported by Cooperative Programs (No. 144, 2017, and No. 148, 2018) of the Atmosphere and Ocean Research Institute, The University of Tokyo. Part of the radiocarbon work was supported by JSPS 20H00193.

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REFERENCES
Berrymann, K. R., Cochrane, U. A., Clark, K. J., Blasi, G. P., Langridge, R. M., & Villamor, P. (2012). Major earthquakes occur regularly on an isolated plate boundary fault. Science, 338(6089), 1690–1693.

Book of History of Kosa Town Editing Committee. (2013). The book of history of Kosa Town (p. 1200). Kosa town: Kosa town (in Japanese).

Brork-Ramsey, C. (2009). Bayesian analysis of radiocarbon dates. Radiocarbon, 51, 337–360.

Chida, N., Okamura, M., & Ogawa, M. (1991). A preliminary report on submarine active faults beneath Yatsushiro Bay, Southwest Japan. Active Fault Research, 9, 93–97 (in Japanese).

DuRoss, C. B., Personius, S. F., Crone, A. J., Olig, S. S., Hylland, M. D., Lund, W. R., & Schwartz, D. P. (2016). Fault segmentation: New concepts from the Wasatch Fault Zone, Utah, USA. Journal of Geophysical Research - Solid Earth, 121(2), 1131–1157.

Earthquake Research Committee, the Headquarters for Earthquake Research Promotion (ERC, HERP). (2002). Regarding methods for evaluating long-term probability of earthquake occurrence, 46p (in Japanese). Retrieved from http://www.jishin.go.jp/main/choukiyoka/01b/chouki020326.pdf

ERC, HERP. (2002). Long-term evaluation of the Futagawa and Hinagu fault zones, 35p (in Japanese). Retrieved from https://www.jishin.go.jp/main/chousa/katsudousou_pdf/93_futagawa_hinagu.pdf

ERC, HERP. (2013). Long-term evaluation of the Futagawa and Hinagu fault zones (2013 revision), 66p (in Japanese). Retrieved from http://www.jishin.go.jp/main/chousa/13feb_chy_kyushu/k_11.pdf

Fujiiwara, S., Yarai, H., Kobayashi, T., Morishita, Y., Nakano, T., Miyahara, B., … Une, H. (2016). Small-displacement linear surface ruptures of the 2016 Kumamoto earthquake sequence detected by ALOS-2 SAR interferometry. Earth, Planets and Space, 68, 160. https://doi.org/10.1186/s40623-016-0534-x

Goto, H., Kagohara, K., Kumahara Y., Inoue, N., & Nakata T. (2018). Active Fault Map in Urban Area [Yatsushiro: revised edition]. GSI Tech. Rep., D.1-No.868.

Ikeda, Y., Nakata T., Kaneda H., Tajikara M., Takazawa S., & Chida N. (2001). Active Fault Map in Urban Area [Kumamoto]. GSI Tech. Rep., D.1-No.368.

Inoue, N., Kitada, N., Echigo, T., Kubo, T., Kazui, N., Hayashida, A., … Kagohara, K. (2011). Piston coring survey of the Futagawa-Hinagu Fault Zone, Yatsushiro Sea, southwest Japan Naoto. In Annual report on active fault and paleoearthquake researches, no.11 (pp. 295–308) (in Japanese with English abstract).

Kagan, Y. Y., & Jackson, D. D. (1991). Long-term earthquake clustering. Geophysical Journal International, 104(1), 117–133.

Kagohara, K., Aiko, T., Adachi, I., Sakamoto, I., Takino, Y., Inoue, N., & Kitada, N. (2011). High-resolution multi-channel seismic reflection imaging of the Futagawa-Hinagu Fault Zone, Yatsushiro Sea, southwest Japan. In Annual report on active fault and paleoearthquake researches, no.11 (pp. 273–294) (in Japanese with English abstract).

Kumahara Y., Okada S., Kagohara K., Kaneda H., Goto H., & Tsutsumi H. (2017). Active Fault Map in Urban Area [Kumamoto: revised edition]. GSI Tech. Rep., D.1-No.868.

Kumamoto Prefecture. (1998). Research grant for earthquake research in Heisei 9, report of results on investigations of Hinagu Fault Zone, 180p (in Japanese). Retrieved from https://www.hp1039.jishin.go.jp/danso/kumamoto2frnm.htm

Machida, H., & Arai, F. (2003). Atlas of tephra in and around Japan: Revised edition (p. 336). Tokyo: University of Tokyo Press (in Japanese).

Matsuda, T. (1975). Magnitude and recurrence interval of earthquake from a fault. Zisin, 28, 269–283 (in Japanese with English abstract).

Matthews, M. V., Ellsworth, W. L., & Reasenberg, P. A. (2002). A Brownian model for recurrent earthquakes. Bulletin of the Seismological Society of America, 92(6), 2233–2250.

Ministry of Education, Culture, Sports, Science and Technology (MEXT), & Kyushu University. (2019). Comprehensive active fault survey related to the Kumamoto earthquake in 2016, 883p (in Japanese). Retrieved from http://www.jishin.go.jp/main/chousa/13feb_chy_kyushu/k_11.pdf

Nakata T., Chida N., Kaneda H., Tajikara M., Takazawa S., & Okada A. (2001). Active fault map in urban area [Yatsushiro]. GSI Tech. Rep. D.1-No.388.

Nakata, T., & Imaizumi, T. (2002). Digital active fault map of Japan. Tokyo: Univ Tokyo Press.

National Institute of Advanced Industrial Science and Technology (2007). Investigations on the activity and tectonic history of the Futagawa-Hinagu fault zone. In Report of results on “basic investigations of additional fault zone”, Vol. H18-7, p. 37 (in Japanese). Retrieved from https://www.jishin.go.jp/main/chousakenkyuu/tsuka_hokan/h18_futagawa_hinagu.pdf

NIAIST, Geo-Research Institute, & Tokai University (2011). Central and Southwestern part (Sea area) of Futagawa-Hinagu fault zone. In Report of results on “investigations of active fault at coastal area”, 105p (in Japanese). Retrieved from https://jishin.go.jp/main/chousakenkyuu/engankaihii/h22/h22_futagawa-hinagu.pdf

Parsons, T. (2008). Monte Carlo method for determining earthquake recurrence parameters from short paleoseismic catalogs: Example calculations for California. Journal of Geophysical Research, 113(B3), 1–14. http://dx.doi.org/10.1029/2007JB004998

Reimer, P. J., Bard, E., Bayliss, A., Beck, J. W., Blackwell, P. G., Bronk-Ramsey, C., … Plicht, J. (2013). IntCal13 and Marine13 radiocarbon age calibration curves 0-50,000 years cal BP. Radiocarbon, 55(4), 1869–1887.

Schwartz, D. P. (1989).Paleoseismicity, persistence of segments, and temporal clustering of large earthquakes—examples from the San Andreas, Wasatch, and lost River Fault Zones. Proceedings of Conference XLV ‘Fault Segmentation and Controls of Rupture Initiation and Termination’ US Geol. Surv. Open File Rep., 89–315, 361–375.

Schwartz, D. P., & Coppersmith, K. J. (1984). Fault behavior and characteristic earthquakes: Examples from the Wasatch and San Andreas Fault Zones. Journal of Geophysical Research - Solid Earth, 89(B7), 5681–5698.

Shimokawa, K., & Kinugasa, Y. (1999). Seismic history and activity survey of Hinagu Fault System. In Annual report on active fault and paleoearthquake researches, no. EQ/99/3 (pp. 253–262). Japan: Geological Survey of Japan/AIST. (in Japanese)

Shirahama, Y., Miyashita, Y., Kametaka, M., Suzuki, Y., Miyairi, Y., & Yokoyama, Y. (2018). Sedimentary environment changes at Yamaide district, Kosa town, Kumamoto prefecture revealed by the trench investigation and densely spaced radiocarbon dating. In Annual report
on active fault and paleoearthquake researches, 18 (pp. 125–160) (in Japanese with English abstract).

Shirahama, Y., Yoshimi, M., Awata, Y., Maruyama, T., Azuma, T., Miyashita, Y., ... Miyakawa, A. (2016). Characteristics of the surface ruptures associated with the 2016 Kumamoto earthquake sequence, central Kyushu, Japan. *Earth, Planets and Space*, 68, 191. https://doi.org/10.1186/s40623-016-0559-1

Toda, S., Torii, M., Okuno, M., Konno, A., Ono, H., & Takahashi, N. (2019). Evidence for Holocene paleoseismic events on the 2016 Kumamoto earthquake rupture zone within the Aso caldera: A trench excavation survey at Kurokawa, the town of Minami-Aso, southwest Japan. *Active Fault Research*, 51, 13–25 (in Japanese with English abstract).

Uchide, T., Horikawa, H., Nakai, M., Matsushita, R., Shigematsu, N., Ando, R., & Imanishi, K. (2016). The 2016 Kumamoto-Oita earthquake sequence: Aftershock seismicity gap and dynamic triggering in volcanic area. *Earth, Planets and Space*, 68, 180. https://doi.org/10.1186/s40623-016-0556-4

Ueta, K., Miyawaki, R., Iemura, K., Yokoyama, T., & Miyawaki, A. (2018). Paleoseismological study on surface fault ruptures produced by the 2016 Kumamoto earthquake. *JPGU 2018, Abstract* (in Japanese). Retrieved from https://confit.atlas.jp/guide/event-img/jpgu2018/SSS08-P23/public/pdf?type=in&lang=ja

Yagi, M., Sakamoto, I., Tanaka, H., Yokoyama, Y., Inoue, T., Mitsunari, K., ... Nemoto, K. (2016). Identification of faulting history of active faults in coastal area using high-resolution seismic survey and piston coring - A case study on the offshore extension of the Hinagu Fault Zone in the Yatsushiro Sea. *Active Fault Research*, 45, 1–19 (in Japanese with English abstract). https://doi.org/10.11462/afr.2016.45_1

Yokoyama, Y., Miyairi, Y., Aze, T., Yamane, M., Sawada, C., Ando, Y., ... Fukuyo, N. (2019). A single stage Accelerator Mass Spectrometry at the Atmosphere and Ocean Research Institute, The University of Tokyo. *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms*, 455, 311–316.

Yoshioka, T., Shintani, K., Iemura, K., & Miyawaki, R. (2007). Paleoseismicity of the Futagawa-Hinagu fault zone, central Kyushu, Japan. In *Annual report on active fault and paleoearthquake Researches*, 7 (pp. 241–258) (in Japanese with English abstract).

**SUPPORTING INFORMATION**
Additional supporting information may be found online in the Supporting Information section at the end of this article.

**How to cite this article:** Shirahama Y, Miyashita Y, Kametaka M, Suzuki Y, Miyairi Y, Yokoyama Y. Detailed paleoseismic history of the Hinagu fault zone revealed by the high-density radiocarbon dating and trenching survey across a surface rupture of the 2016 Kumamoto earthquake, Kyushu, Japan. *Island Arc*. 2021;30:e12376. https://doi.org/10.1111/iar.12376