Stratigraphic Constraints of Rupture Kinematics and Scenarios of Paleoearthquakes on the Southern Yangsan Fault, SE Korea

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Abstract

After the 2016 Gyeongju Earthquake (M$_W$ 5.5) in SE Korea, the NNE-SSW-striking Yangsan Fault (YF) seismicity has emerged as a significant scientific issue and hazard. Despite previous studies of the seismicity of the YF, the paleoseismic information of the fault remain uncertain. We carried out paleoseismic investigations to characterize surface rupturing and the paleoseismic history of the northern section of the southern YF. Deflected streams and displaced river terraces indicate a dextral sense of slip, and fault splays cutting unconsolidated sedimentary strata in trench walls show an east-side-up geometry. The dextral strike-slip faulting with a minor reverse component is characterized by several noticeable stratigraphic features, including fissure-filling deposits, sag ponds, and cut-and-fill streams along the fault splay. Based on fault-sediment cross-cutting relationships and optically stimulated luminescence ages of unconsolidated sediments, we propose two possible rupture scenarios for the most recent earthquake event along the studied fault section during the Late Pleistocene: (1) a single rupture along the entire section (WS-MH-IBN-IB) at ca. 30 ka and (2) individual partial ruptures along two segments of the section (WS-MH and IBN-IB) during 33-30 and 29-17 ka, respectively. It is also noted that the timings of earlier ruptures (penultimate earthquake events) of the two segments are 37-35 and 70-52 ka, respectively. Furthermore, the timing(s) of the most recent earthquake for our studied section is much older than that of the southern section of the northern YF.
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Key Points:
- Earthquake surface ruptures are newly detected by multiple trench surveys on the northern part of the Southern Yangsan Fault
- Horizontal slip was confirmed by stratigraphic observation and this is useful in intraplate regions with no geomorphic expression
- Two possible rupture scenarios along fault trace are presented considering uncertainties on OSL ages: a single event and partial events

Abstract
After the 2016 Gyeongju Earthquake (M$_W$ 5.5) in SE Korea, the NNE–SSW-striking Yangsan Fault (YF) seismicity has emerged as a significant scientific issue and hazard. Despite previous studies of the seismicity of the YF, the paleoseismic information of the fault remain uncertain. We carried out paleoseismic investigations to characterize surface rupturing and the paleoseismic history of the northern section of the southern YF. Deflected streams and displaced river terraces indicate a dextral sense of slip, and fault splays cutting unconsolidated sedimentary strata in trench walls show an east-side-up geometry. The dextral strike-slip faulting with a minor reverse component is characterized by several noticeable stratigraphic features, including fissure-filling deposits, sag ponds, and cut-and-fill streams along the fault splay. Based on fault–sediment cross-cutting relationships and optically stimulated luminescence ages of unconsolidated sediments, we propose two possible rupture scenarios for the most recent earthquake event along the studied fault section during the Late Pleistocene: (1) a single rupture along the entire section
(WS–MH–IBN–IB) at ca. 30 ka and (2) individual partial ruptures along two segments of the
section (WS–MH and IBN–IB) during 33–30 and 29–17 ka, respectively. It is also noted that the
timings of earlier ruptures (penultimate earthquake events) of the two segments are 37–35 and
70–52 ka, respectively. Furthermore, the timing(s) of the most recent earthquake for our studied
section is much older than that of the southern section of the northern YF.

Plain Language Summary:

Prehistoric earthquake research within an intraplate area is challenging because seismogenic
faults have a high degree of complexity and result in spatiotemporally irregular earthquakes. The
Yangsan Fault in the Korean peninsula is a long-lived intraplate fault in the Korean peninsula.
The fault zone shows a narrowly incised (< 2 km) valley without well-expressed geomorphic
features associated with prehistoric earthquakes due to a long period of seismic recurrence (a few
thousand years) and a high erosion rate. Here we deal with records of significant prehistoric
earthquakes through the excavation surveys along a part of the Yangsan Fault. We observed
several noticeable sedimentary strata deposited by surface processes due to lateral-slip rupturing.
We propose two possible earthquake scenarios for the most recent earthquake along the studied
fault section during the Late Quaternary. (1) a single rupture along the entire section at ca. 30 ka
and (2) individual partial ruptures along two segments of the section during 33–30 and 29–
17 ka, respectively. Furthermore, we compared the most recent earthquake timing with the other
part of the Yangsan Fault. We confirmed that several parts of the fault slipped individually
during the recent period.

1 Introduction

One of the critical issues in the field of earthquake hazards, which encompasses aspects
such as paleoseismology, earthquake forecasting, and anti-shaking building designs, is to define
a proper model of the recurrence cycle of large earthquakes that cause surface ruptures (e.g.,
Thatcher & Rundle, 1979; Schwartz & Coppersmith, 1984; Olaf et al., 2015). Geomorphic and
paleoseismic investigations are the main tools that are used to establish models of long-term
earthquake recurrence cycles, as evidence for surface-rupturing earthquakes is recorded both on
the surface and within strata (Keller & Pinter, 2002; Burbank & Anderson, 2013). Spatial
parameters of paleoseismicity, such as rupture length, cumulative displacement, and amount of
slip per event, are calculated mainly on the basis of offset geomorphic markers (e.g., Choi et al.,
2018; Gutiérrez et al., 2020). Paleoseismic investigation based on trench excavations can give
further temporal information on large paleoearthquakes, such as recurrence intervals, slip-rate
and so on (e.g., Grant & Sieh, 1994; Rockwell et al., 2009; Scharer et al., 2014; Elliot et al.,
2018).

The traditional approach in fault paleoseismology is to compare paleoearthquake histories
from different trench sites to determine whether or not different parts of the fault of interest have
ruptured simultaneously. However, this approach has limited application in intraplate regions,
such as South Korea, where seismogenic faults mostly have longer recurrence intervals for large
earthquakes compared with interplate regions (Talwani, 1988), meaning that geomorphic
evidence may have been destroyed or substantially degraded by surface processes over the
intervening time period, as well as by human activity (including urbanization). In such cases, it is
difficult to trace surface ruptures and to acquire sufficient paleoseismic information from
trenching surveys for placing accurate constraints on earthquake history.

Large earthquakes in intraplate regions can potentially produce more significant damage
than those in interplate regions because communities in the former regions are not well prepared
owing to sparse information about paleoseismicity and a lack of experience of seismic hazards
(Liu et al., 2011; England & Jackson, 2011). The Monte Cristo Range, USA (2020, Mw 6.5),
Iwate-Miyagi, Japan (2008, Mw 6.9), and Ungava, Canada (1989, Mw 6.3) earthquakes are
representative intraplate earthquakes with surface ruptures (e.g., Adams et al., 1991; Aydan,
2016; Bormann et al., 2020; Hammond et al., 2020; Koehler et al., 2020). In addition, some
intraplate seismogenic faults occasionally show multiple rupture events of small-to-medium
magnitudes with intervals of weeks to months, such as the 2016–2017 Amatrice seismic
sequences at the Central Italy (e.g., Chiaraluce et al., 2017; Pucci et al., 2017; Civico et al., 2018;
Improta et al., 2019; Porreca et al., 2020).

The Korean Peninsula has long been regarded as a seismically stable intraplate region
(Figure 1a) because there have been no destructive surface-rupturing earthquakes in modern
history. However, recent medium-sized earthquakes (the 2016 Gyeongju and 2017 Pohang
earthquakes; Figure 1b) in SE Korea have raised scientific and social interest in earthquake
hazards. Of the various faults on the peninsula, the NNE–SSW-striking Yangsan Fault (YF)
located in SE Korea is regarded as one of the largest seismogenic faults on the basis of
paleoseismic observations and historical and instrumental earthquake records (e.g., Lee & Jin,
1991; Kyung, 2003; Lee et al., 2015; Cheon et al., 2020; Song et al., 2020).

Figure 1. (a) Present-day tectonic map of East Asia showing plates and their velocities (modified
from Schellart & Rawlinson, 2010). Plate velocities are based on the Indo-Atlantic hotspot
reference frame (O’Neill et al., 2005) and the relative plate motion model of DeMets et al.
(1994). (b) Epicenter distributions of instrumental seismic records (modified from KMA, 2021;
Here we present new paleoseismic observations on surface rupturing along the northern section of the southern YF (SYF) (Figure 2a & b). Although the studied section is located close to the epicenter of the 2016 Gyeongju Earthquake (Mw5.5), few paleoseismic studies have been conducted in this fault section. Recently, Cheon et al. (2020) reported Late Quaternary earthquakes from the Inbo (IB) trench (Figure 2b). The purpose of the present study is to measure and interpret evidence for paleoearthquakes along the northern part of the IB trench (a 10-km-long section). To achieve this purpose, we describe detailed geomorphic, stratigraphic, and structural features of paleoearthquake surface ruptures at three trench sites [the Wolsan (WS), Miho (MH), and Inbo north(IBN)]. We further discuss (1) stratigraphic features related to strike-slip faulting and (2) possible rupture scenarios concerning the most recent event recorded in the studied section.
Figure 2. (a) Simplified geological map of the Cretaceous Gyeongsang basin and Miocene basins, SE Korea, with distributions of the major faults (modified after Chough & Sohn, 2010; Son et al., 2013 and 2015)(YG: Yugye site (Kyung, 2003); BG: Byeokgye site (Song et al., 2020); IB: Inbo site (Cheon et al., 2020); NYF: northern Yangsan Fault; SYF: southern Yangsan Fault). (b) Hill-shaded imagery of the northern section of the SYF derived from LiDAR imaging (from 2017), showing the trace of the Yangsan Fault and trench survey locations as well as areas of detailed geomorphic analysis (darkened rectangles).

2 Study area

2.1 Seismotectonic setting

The Korean Peninsula is located on the eastern part of the Eurasian plate, >500 km from the Eurasia–Pacific plate boundary (Figure 1a). The stress state of the peninsula is dependent on the interaction between the subducting Pacific and Philippine Sea plate, as well as collision of the northward-moving Indian plate with the Eurasian plate (Yin, 2010). Various investigations of the present tectonic stress, including those involving hydrofracturing/overcoring (e.g., Haimson et al., 2003; Bae et al., 2008; Chang et al., 2010), focal mechanisms (e.g., Park et al., 2007; Hoe & Kyung, 2008; Back et al., 2011; Choi, H. et al., 2012), and fault slip (e.g., Kim et al., 2016) analyses, indicate an ENE–WSW-trending maximum horizontal stress axis.

Global positioning system (GPS) data derived from the recently installed permanent Korean GPS network show that the Korean Peninsula is moving towards the southwest at a rate of 1 to 5 mm y\(^{-1}\) relative to the Eurasian plate (Figure 1a; e.g., Kato, 2003; Jin & Park, 2006; Schellart & Rawlinson, 2010). The deformation rates and directions of movement observed at all of the Korean GPS stations are highly similar, implying that the Korean Peninsula is located on a relatively rigid plate and is a tectonically stable region (Jin & Park, 2006).

More than 3,000 instrumentally recorded earthquakes have occurred since 1978 on the Korean Peninsula (Figure 1c; KMA, 2021). The largest instrumental event (M\(_{w}\)5.5) occurred in 2016 at Gyeongju city, through which the YF extends (Figures 1b and 2a), although no earthquake-related surface rupture was reported. Kim et al. (2017) interpreted the causative fault to be an N28°E-striking subsidiary linking fault, oblique to the main trace of the YF, on the basis of the distribution of aftershocks and lineament patterns.

Historical seismic phenomena on the Korean Peninsula, including surface rupture, tsunamis, mass movements, ground shaking, and liquefaction, as well as the resultant damage to buildings, have been documented in records from AD 2 to AD 1904 (Figure 1c; Kyung, 2011). A compilation of the epicenters and intensities for the historical seismicity by Kyung (2011) shows that there have been ten significant earthquakes (intensity IX), of which four were located in/around Gyeongju city. However, there is no clear information on the locations of causative faults for these historical earthquakes.

2.2 The Yangsan Fault

The YF is one of the largest faults on the SE Korean Peninsula, striking NNE–SSW with a length of ~200 km on land (Figure 2a; e.g., Chang & Chang, 1998; Cheon et al., 2019, 2020). The finite horizontal displacement of the fault is 25–35 km with dextral kinematics inferred on
the basis of displaced basement rocks (Chang et al., 1990; Hwang et al., 2007a, 2007b; Figure 2a). The fault has evolved as a crustal-scale mature fault that has undergone multiple episodes of movement/deformation owing to long-term variation in the regional tectonic stress field since the Late Cretaceous (Cheon et al., 2019). Thus, the internal fault deformation zone (core and damage zones) measured up to hundreds of meters wide, although there is variation along the fault strike. Several models have been proposed regarding the segmentation of the YF based not only on fault geometry but also seismic activity and fault kinematics (e.g., Lee & Jin, 1991; Chang & Chang, 2009; Choi et al., 2017). Nevertheless, these segmentation models have not been examined with respect to paleoseismic parameters. In this study, we divided the fault into two major parts; i.e., NYF and SYF, with reference to the junction of the YF with the Ulsan Fault (Figure 2a).

Several paleoseismic studies along the YF have been conducted since the 1990s (e.g., Okada et al. 1994; Choi, S.-J. et al., 2012; Lee et al., 2015; Kim et al., 2016; Cheon et al., 2020; Song et al., 2020). However, it is difficult to identify field evidence for paleoseismicity owing to intense modification of the geomorphic expression of ruptures by surface processes (mostly erosion and deposition) and urbanization. Recently, Kim et al. (2020) calculated the horizontal geomorphic offset (about 20–195 m) along the central SYF using river terraces through high-resolution digital elevation models (DEMs) built from light detection and ranging (LiDAR) and aerial photography. However, slip-rate data for the entire fault during the Quaternary remain uncertain and contentious.

Various stratigraphic investigations have been made by means of trench excavations (e.g., Okada et al., 1994; Kyung et al., 1999a, 1999b; Kyung, 2003; Cheon et al., 2020). Optically stimulated luminescence (OSL) ages of deformed unconsolidated strata in surveyed trenches indicate that some sections of the YF have undergone surface rupturing during the Late Quaternary (Lee et al., 2015; Song et al., 2020; Cheon et al., 2020).

2.3 Inbo trench

Cheon et al. (2020) reported surface-rupturing paleoearthquakes from around Inbo village located in the northern SYF through a large-scale trench survey. The IB trench was excavated to a depth of ~8 m and a length of ~20 m, with the following results: (1) the fault splay cut unconsolidated sediments with ~7.5 m of vertical offset; (2) at least two events of surface rupturing can be interpreted from stratigraphic evidence; and (3) the penultimate earthquake (PE) is constrained to between ca. 70 and 29 ka, and the most recent earthquake (MRE) is constrained to after 29 ka on the basis of the OSL ages of the sediments.

3 Methods

3.1 Fault tracing and trench locations

The northern SYF is characterized by a relatively narrow (a few kilometers wide) incised fault valley formed by selective erosion along the weak fault zone (Figure 2b). Much of the fault valley is urbanized and covered by recent sediments. To find evidence of surface rupture along the northern SYF, we extracted geomorphic markers using aerial photographs from the 1960s and high-resolution DEM data (with a resolution of 0.5 m/pixel) derived from 2017 airborne LiDAR images. Three trench locations were selected on the basis of geomorphic markers and
detailed field data: WS, MH, and IBN. At the MH site, we drilled three boreholes to identify the exact fault trace and to design the depth, length, and width of the trench.

3.2 Trench excavation

We designed trenches of 10‒20 m length and 3‒5 m width that were perpendicular or subperpendicular to the NNE–SSW-striking fault trace. For detailed mapping of trench walls, we installed grids measuring 1 m × 1 m using nylon string. Trench walls were photographed using a digital camera and an unmanned aerial vehicle (DJI Phantom 4 Pro and Mavic 2 Pro). Commercial software (Agisoft Metashape) was used to produce orthogonal images of trench walls using the structure-from-motion method (Bemis et al., 2014; Johnson et al., 2014). We logged trench walls to classify the young unconsolidated strata on the basis of their sedimentological features, such as grain size, matrix-to-grain ratio, compactness, roundness, sorting, and color. Unconsolidated deposits were classified into several units and subunits, and their relative ages and inferred paleo-environments of formation were also considered. We also described structural features (distribution, geometry, and kinematics) of fault splays cutting the young sediments.

3.3 Age dating

To constrain the timings of the PE and MRE of the studied fault section, we collected seven OSL samples from three trenches (WS, MH, and IBN). We also analyzed one OSL sample from unit 1.3 of the IB trench (figure 5b of Cheon et al., 2020) to accurately identify the PE event in the Inbo area. For all samples, coarse-grained (25‒90 μm) particles were separated by wet sieving, and then treated with 10% HCl (for 3 h), 33% H₂O₂ (for 1 h), and 48% HF (for 40 min) to remove carbonates, organic materials, and feldspar grains, respectively. After acid treatment, infrared stimulated luminescence (IRSL) measurements were conducted to examine any feldspar contamination (Duller, 2003).

The OSL intensities and dose rates of all samples were analyzed using a Risø TL/OSL automatic reader (TL/OSL-DA-20) and gamma-ray spectrometer system (Broad Energy Germanium Detector, BE 6530) installed at the Korea Institute of Geoscience and Mineral Resources (KIGAM). Equivalent doses (Dₑ) values were measured using the single aliquot regeneration (SAR) protocol (Murray & Wintle, 2000, 2003) with a preheat of 220 °C for 10 s and a cut-heat of 160 °C for 0 s by the preheat plateau test. Before De analysis, dose recovery tests were performed to examine the adequacy of the SAR protocol. All samples show dose-recovery ratios within ±10%. The results of OSL age dating are expressed as central age ± 1σ standard error (Table 1).

4 Results

Here we describe stratigraphic and structural characteristics and then present a comprehensive surface rupture history for each site based on the OSL ages of unconsolidated sediments. Newly traced surface ruptures in this study are situated only within the mature fault zone.
4.1 WS trench

The WS trench is located along a narrow fault valley that follows a presumed main strand of the YF, near the Wolsan area. Dextrally deflected and beheaded channels, as well as offset terraces, are identified along the fault trace (Figure 3a–c). These geomorphic offset markers have been cumulatively displaced up to a maximum of 130–160 m with a dextral sense of slip (Kim & Seong, 2021). We excavated an E–W-oriented trench (15 m long × 2 m wide × 2.5 m deep) across the lineament (Figure 3d).

Figure 4 shows detailed sketches of the WS trench. The lithology observed in the trench wall comprises five unconsolidated sedimentary units overlying basement rocks (Cretaceous sedimentary rock and mature fault rock). The block to the east (‘eastern block’) of the fault consists mainly of Cretaceous fine sandstone with ENE-dipping minor faults and shear fractures, whereas the block to the west (‘western block’) of the fault comprises mainly fault breccia. The unconsolidated strata below artificial fill can be divided into Unit 1 to 5 from top to bottom. Units 1, 2, and 3 are found only in the western block of the fault, whereas Units 4 and 5 are observed only in the eastern block. Unit 1, which shows a subvertical wedge-shaped, downward-tapering narrow geometry along the fault splays, comprises poorly sorted, angular to subangular pebbles and cobbles. The gravels are randomly oriented and show no stratification. Unit 2 consists mainly of granules with subangular pebbles. Unit 3 is composed of dark-grey clayey silt with lenticular pebble layers. The clayey silt part of Unit 3 exhibits soft-sediment deformation structures (SSDSs), such as convolute structures and ball-and-pillow structures. Unit 4 can be subdivided into Unit 4.1 (granules with pebble gravel) and Unit 4.2 (matrix-supported boulder gravel). Unit 5 comprises subrounded to subangular cobbles and boulders.
Figure 3. (a) DEM overlain on hill-shaded imagery from LiDAR data (from 2017), and (b) vintage aerial photograph (from the 1960s) showing geomorphic features in the Wolsan area. (c) Topographic map (5 m contour interval) showing the lineament and complex drainage patterns in the vicinity of the WS trench (yellow square; contour interval 5 m). Small channels are deflected and beheaded across the NNE–SSW-striking, narrow, incised fault valley with a dextral sense of slip. A terrace riser is also dextrally offset by the valley. (d) Photograph of the WS trench.

Several east-dipping branched fault splays with dips of >70° are developed along the eastern margin of the mature fault core and cut the entire column of unconsolidated sediments except the uppermost artificial layer. The depth to the unconformity between basement rock and overlying unconsolidated sediments is ~1.5 m higher to the east of each fault relative to the west. Other kinematic indicators were unable to be obtained from the fault splay.

At the trench site, we regard Unit 1 as a key unit for characterizing earthquake history. Its geometry and sedimentological characteristics strongly suggest that it could have been rapidly deposited along a narrow zone. We thus interpret this unit as a fissure-filling deposit that formed during or immediately after surface rupturing. In addition, the eastern margin of the unit is bounded by a sharp fault splay. The OSL ages of Units 1 and 2 are 33 ± 2 and 37 ± 2 ka, respectively (Table 1). Therefore, the age of the PE event that formed Unit 1 can be constrained to between 37 ± 2 and 33 ± 2 ka. The MRE event that cut Unit 1 occurred after 33 ± 2 ka.
Figure 4. Photographs and detailed sketches of the (a) northern and (b) southern walls of the WS trench. Yellow circles indicate OSL sampling points with ages. The grid interval is 1 m × 1 m.

4.2 MH trench

The Miho area is located ~5 km south of the WS trench site. A straight linear fault zone valley and abnormally developed step-like geomorphology are observed in the DEM image and the 1960s aerial photo (Figure 5a–c). Before excavation, we drilled three boreholes to design trench size and to constrain the exact location of a recent fault splay within a wide mature fault core (tens of meters). Basement rock of the western borehole (MHC-01) and the central borehole (MHC-02) is Cretaceous dactitic welded tuff, which is detected up to 4 m below the unconformity. In contrast, basement rock of the eastern borehole (MHC-03) is composed mainly
of fault rocks up to 2 m below the unconformity (Figure 5a). On the basis of these observations, we excavated a trench between the locations of boreholes MHC-02 and MHC-03. The trench was designed with dimensions of 16 m × 6 m × 4 m and an orientation of N70°W (Figure 5d).

Figure 5. (a) DEM overlain on hill-shaded imagery from LiDAR data (from 2017) and (b) vintage aerial photograph (from the 1960s) showing geomorphic features in the Miho area. (c) Topographic map (5 m contour interval) showing the lineament and complex drainage patterns in the vicinity of the MH trench (yellow square; 5 m contour interval). Some minor channels from the western mountains flow northward along the incised fault valley. (d) Photograph of the MH trench showing borehole locations (MHC-01–03). Cyan and green circles represent Cretaceous dacitic welded tuff and fault gouge derived from Cretaceous sedimentary rock, respectively. Numbers in parentheses near boreholes indicate depths to the unconformity between basement rocks and overlying sediments.

Figure 6 shows detailed sketches of trench MH. The lithology in the trench wall consists of four unconsolidated units and underlying basement rocks (Cretaceous volcanic rock and mature fault rock derived from Cretaceous sedimentary rock). Basement of the eastern block comprises mature fault core consisting of fault gouge, breccia, and enclosed host-rock lenses, which are derived mainly from Cretaceous sedimentary rock. In contrast, the basement of the western block is Cretaceous dacitic welded tuff. Overlying unconsolidated sediments can be
divided into Units 1 to 4 from top to bottom. Unit 1 comprises angular granule- to pebble-bearing clayey-sand layers. Unit 2 is composed of angular cobble to fine sand (partly clay) layers. Unit 2 can be subdivided into three subunits based on their sedimentological characteristics: Unit 2.1 (brownish pebble gravel), Unit 2.2 (greyish clay to medium sand), and Unit 2.3 (orange to light-brownish pebble to cobble gravel). Unit 2 exhibits a variety of SSDSs, such as flame structures and load casts. The boundaries of each subunit of Unit 2 exhibit wavy or irregular geometry and show mixing with adjacent sedimentary units. Unit 3N of the northern wall is cut by a main fault splay and consists mostly of poorly sorted, subangular gravel beds in the lower part and fine greyish sand to clay with some pebbles in the upper part. The unit shows a wedge-shaped geometry that widens towards fault splay, and the grain-size coarsens towards the fault splay in the trench wall. Unit 3S of the southern wall displays a U-shaped cut-and-fill geometry and comprises mostly subangular to subrounded pebbles to cobbles, although it has similar clast compositions to those of Unit 3N in the northern wall. Unit 4, the lowest unconsolidated unit, is composed largely of angular cobbles in a yellowish sandy matrix.
Figure 6. Photographs and detailed sketches of the (a) northern and (b) southern walls of the MH trench. Yellow circles indicate OSL sampling points with ages. The grid interval is 1 m × 1 m.

In the MH trench wall, a fault splay, developed along the western margin of the mature fault core, transects Units 3 and 4 and is covered by Unit 2.3. The fault splay strikes NNE–SSW and dips toward the ESE at angles of >70°. The vertical offset between units across the fault is ~1.5 m, based on the differing position of the unconformity between unconsolidated strata and basement rocks.

The above-mentioned observations show that the MRE event occurred after the deposition of Unit 3 and before the deposition of Unit 2.3. Unit 3N has a wedged-shape geometry and shows upward fining and faultward coarsening sediments, with poorly sorted
coarse sediments in the lower part and very fine-grained sediments in the upper part. The OSL ages of Units 2.3 and 3 are $30 \pm 1$ ka and $35 \pm 2$ ka, respectively (Table 1). We therefore propose that the PE event involving surface-rupturing and forming Unit 3N occurred immediately before $35 \pm 2$ ka, following which the fault splay underwent reactivation. The MRE occurred between the depositions of Units 3 and 2.3 and can therefore be constrained to between $35 \pm 2$ and $30 \pm 1$ ka.

### 4.3 IBN trench

The IBN trench was excavated ~500 m north of the IB trench (Cheon et al., 2020) and is located along an eastern branch of the main YF (Figure 2b). Dextrally deflected channels and river terraces are developed along the prominent lineament (Figure 7a–c). The depth of the unconformity shows an abrupt gap between the eastern and western blocks across the fault splay, as revealed by borehole investigation (Cheon et al., 2020). The trench was oriented at N70°W, subperpendicular to the lineament, with dimensions of $18 \text{ m} \times 3 \text{ m} \times 3 \text{ m}$ (Figure 7d).

**Figure 7.** (a) DEM overlain on hill-shaded imagery from LiDAR data (from 2017) and (b) vintage aerial photograph (from the 1960s) showing geomorphic features in the Inbo area. (c) Topographic map (5 m contour interval) showing the lineament and complex drainage patterns in the vicinities of the IBN (yellow square) and IB (white square) trenches (Cheon et al., 2020). Along the northern part of the lineament, small gullies draining the eastern block appear to be
deflected dextrally. Along the southern part of the lineament, an abandoned and deflected stream flows southwards along the fault scarp. (d) Photograph of the IBN trench.

Figure 8. Photographs and detailed sketches of the (a) northern and (b) southern walls of the IBN trench. Yellow circles indicate OSL sampling points with ages. The grid interval is 1 m × 1 m.
Figure 8 shows detailed sketches of the IBN trench. The lithology of the trench is composed primarily of three unconsolidated sedimentary units overlying basement rock. The eastern basement comprises severely damaged Cretaceous sedimentary rock with fault gouge and breccia. Unfortunately, we did not reach the basement of the western block in the trench wall. The overlying unconsolidated deposits are grouped into Units 1 to 3 from top to bottom. Unit 1 is subdivided into Unit 1.1 (greyish mud) and Unit 1.2 (clast-supported sub-rounded pebble gravel). Unit 1.2 covers the fault splay. Unit 2 is composed mainly of angular-pebble-bearing sand and is cut by the fault splay. Some parts of Unit 2 are mixed with Unit 1.2 as load casts. Unit 3 is subdivided into Unit 3.1 (greyish mud to fine sand) and Unit 3.2 (pebble-bearing medium sand), but the boundaries are wavy and deformed irregularly, suggesting that the materials might have acted in as fluid-like manner during deformation.

The fault splay transects Unit 3 and is covered by Units 1 and 2. In the trench wall, Unit 3 underlies the older basement rock. In addition, Unit 3.2 shows a dragging pattern close to the fault splay, indicating a reverse sense of movement. Gouge foliations along the fault splay and striations on slip surfaces also indicate a dextral sense of slip.

At the trench site, we recognized only one earthquake event in the trench wall. Unit 1.2 is cap layer that is not deformed by the MRE. Unit 2 is the uppermost layer cut by the fault splay. OSL ages of Units 1.2 and 2 are 17 ± 1 and 37 ± 2 ka, respectively (Table 1). On the basis of the earthquake horizon between Units 1.2 and 2 and their OSL ages, we constrain the age of the MRE at 37 ± 2 to 17 ± 1 ka. At the IB trench, 500 m south of the IBN trench, the MRE event occurred after 29 ka (Cheon et al., 2020). Combined with previous findings and our new results, the age of the MRE of the IBN and IB trenches can be constrained to between 29 and 17 ka. We also obtained an additional OSL age of 52 ± 3 ka from unit 1.3 in the IB trench (Cheon et al., 2020; IBT1-05 in Table 1), and this unit overlies the PE rupture. Our new OSL age constrains the timing of the PE in the IB trench as 70 to 52 ka.

5 Discussion

5.1 Stratigraphic features related to fault splay kinematics

Recent morphotectonic studies, after acquisition of air-borne LiDAR data, have shown that the YF has undergone dominantly dextral slip with a minor reverse slip (e.g., Cheon et al., 2020; Kim et al., 2020; Song et al., 2020). A series of river terrace risers across the SYF are typical dextral slip markers (Kim et al., 2020), and the reverse slip corresponds closely to streamflow change in the Inbo area, including damming-up streams by the eastern block (Cheon et al., 2020). We argue that, however, earlier excavation surveys had tended to focus only the minor reverse component due to a limited 2D observations at trench walls. For some cases, indeed, vertical offset was estimated by height or vertical separation of displaced layers by horizontal slip.

Our observations of stratigraphic features in trench walls indicate that fault scarps are closely associated with horizontal slip. In the WS trench, Unit 1 shows a downward-tapering geometry along the subvertical fault splay and consists of poorly sorted, angular to subangular gravels. Although fissures are observed in a variety of structural settings (McCalpin et al., 2009), we propose that the near-vertical void space could have been formed by a surface rupture event with strike-slip-related faulting on the basis of the general kinematics of the fault splay and the distribution, geometry, and sedimentological features of the fissure (Figure 9a; Wright et al.,
In the northern wall of the MH trench, we identified a westward-tapering colluvial wedge deposit showing coarsening of sub-angular clasts with decreasing distance from the fault (Unit 3N). The unit probably evolved as a local sag pond owing to minor damming-up of streamflow (Figure 9b). It is noted that colluvial wedge and damming-up streamflow could be indicators of reverse slip. In the southern wall of the MH trench, however, the corresponding layer, Unit 3S, show a cut-and-fill geometry implying channel deposits. It means that a small gully developed along the rupture traces with the sag-pond formation. Variation in topographic features in a short distance (trench width of several meters) is one of the typical markers of horizontally displaced undulating relief (Figure 9c).

The studied section of the SYF has acted as a dextral slip fault with only a small reverse component during the imposed neotectonic regime. However, in naturally exposed outcrops or trench walls, the reverse component appears to be highlighted because of exposure/trench geometry. To understand the kinematics of a fault splay, both topographic analysis and trench surveys should be conducted. Our study has shown that even for a strike-slip-dominant fault such as the YF, detailed sedimentological analysis can provide useful information regarding rupture kinematics.

Figure 9. Schematic diagrams showing landforms and stratigraphic features associated with strike-slip ruptures. Fissure-filling deposit observed at the WS site (a-a’ profile). Sag pond deposit developed by fault scarp damming observed in the northern wall of the MH site (b-b’ profile). U-shaped cut-and-fill deposit along the fault splay observed in the southern wall of the MH site (c-c’ profile).
5.2 Rupture scenarios for the northern section of the southern Yangsan Fault

Information on spatiotemporal variations in slip behavior is important for the assessment of seismic hazards, including estimation of the possible magnitude of future earthquakes and their recurrence interval (Baker, 2008; McCalpin, 2009; Scharer & Yule, 2020). In this study, we complied paleoseismic data from three new trenches (the WS, MH, and IBN trenches) and one previously excavated trench (the IB trench) along an 11-km-long section. Rupture scenarios for the MRE and PE events based on paleoseismic trench interpretation are presented in Figure 10. In the WS trench, we recognized at least two surface rupture events. The PE event forming a narrow fissure along the splay fault occurred during 37–33 ka, following which the fissure-filling deposit was offset by reactivation of the fault splay during the MRE event (after 33 ka). In the MH trench, we identified two surface rupture events. The PE event that eventually formed the sag-pond (Unit 3N) and stream (Unit 3S) deposits along the fault splay occurred before 35 ka, following which these deposits were cut by the MRE event of 35–30 ka. Combining the IBN and IB trenches results, we infer at least two paleoearthquake events with surface rupture. Ages of the PE and MRE events derived from the IBN and IB trenches are constrained as 37–52 and 29–17 ka, respectively. Considering the paleoseismic data at each trench site, we determine that the PE events of the WS–MH and IBN–IB segments are constrained as 37–35 and 70–52 ka, respectively (Figure 10) (We here use the term ‘segment’ to avoid confusion with the term 'section').

5.2.1 Possible rupture scenarios for the most recent earthquake

The determination of rupture scenarios for an intraplate fault with a long recurrence interval using paleoseismic observations has several limitations, including locally distributed study sites along the fault, different depositional ages of strata at each site, and uncertainties on ages measured using OSL, $^{14}$C, and $^{10}$Be methods. Because of these limitations, paleoseismologists have tended to present alternative scenarios consistent with the available paleoseismic data. For example, DuRoss et al. (2016) proposed two different rupture models (partial-segment and multi-segment ruptures) along the Weber segment of the Wasatch Fault zone, consistent with the wide range of uncertainties on the $^{14}$C ages. In the present study, we propose two possible MRE rupture scenarios based on the chronology of each surface rupture at four trench sites. The MRE ages of the WS, MH, and IBN–IB trenches are well constrained as <33, <35–30, and <29–17 ka, respectively, on the basis of OSL dating of offset and non-offset strata (Figure 10). However, considering the limitations of OSL dating accuracy (e.g., inaccurate measurement of the paleo-water content and random analytical errors), the ages of the non-offset layer of the MH trench (30 ± 1 ka) and the offset layer of the IB trench (29 ± 1 ka; Cheon et al., 2020) may coincide within the error ranges. Thus, we present two possible rupture scenarios of the MRE along the studied section, taking into account the error ranges of OSL ages. As the first scenario, we propose that the MRE event at all trench sites occurred simultaneously at ca. 30 ka, taking into account the overlapping periods of the MRE at each site with respect to the 1σ error ranges of the OSL ages (Figure 10). This scenario suggests that a section measuring ≥11 km in length was fully ruptured during the MRE and that there was no subsequent rupture along the section. The estimated magnitude of the MRE in this scenario using the empirical surface rupture length–magnitude relationship proposed by Wells and Coppersmith (1994) can be calculated as 6.3. The second scenario involves individual MRE events along the WS–MH and IBN–IB segments. The MRE ages of the WS and MH sites are very similar (33–33 ka), but the MRE ages of the IBN and IB sites are younger (29–17 ka). According to this dual-slip model, the WS–MH segment is
hypothesized to have ruptured first, following which the IBN–IB segment underwent the MRE event. We note that although there were two individual events they could be an indicator of a sequence of temporal clusters of large earthquakes.

Geomorphic and geological differences can be identified between the WS–MH and IBN–IB segments: (1) The WS–MH segment is situated along a narrow fault valley, whereas the IBN–IB segment is located along the eastern part of a relatively wide fault valley (Figure 2b); and (2) recent fault splays observed at the WS and MH sites are located along the boundary of the main fault core zone, whereas those at the IBN and IB sites are situated along the eastern branch fault of the YF, with the branching point being situated between the MH and IBN sites (Figure 2b; Lee et al., 2020). Therefore, we infer that the recent rupture behaviors are associated with the distinct structural patterns of the mature fault.
Figure 10. (a) Late Quaternary earthquake history along the SYF and NYF. (b and c) Two possible rupture scenarios based on the MRE timing along the northern section of the SYF: (b) The first rupture scenario and (c) the second rupture scenario, showing three and four individual earthquake events, respectively. See the text (chapter 5.2.1) for a detailed explanation.
5.2.2 Comparison of the northern part of the southern Yangsan Fault with other parts of the fault

Although the YF zone, which is expressed topographically as a continuous and narrow incised valley, can be traced for ~200 km on land, many parts of the fault have not been investigated with respect to paleoseismic behavior because the fault passes through rice paddies and urbanized areas. For this reason, the distribution and interpretation of most recent surface rupture traces are still uncertain. The Yugye (YG) and Byeockgye (BG) sites located along the southern NYF are the most-studied sites of the entire YF with respect to paleoseismology (Figure 2a; Kyung, 2003; Lee et al., 2015; Kim et al., 2020; Song et al., 2020). Ages of the MRE events of the YG and BG sites have been estimated as ≤2.7–1.3 ka (Kyung, 2003) and ≤3.2 ka (Song et al., 2020), respectively. It is clear that the ages of MREs along the YG–BG section are much younger than those of our studied section. These results suggest that the two sections have undergone different seismic histories during the imposed neotectonic regime. Unfortunately, there are no reliable reports of the timing of MREs along other sections of the YF, but we expect that further studies along these other sections will give valuable information for deciphering the paleoseismic behavior of the entire fault during the current neotectonic regime.

Fault behavior is influenced by geometrical variations in fault structure, such as bending, steps, configuration (e.g., branch and fault splays), and interconnections with other faults (Vallage et al., 2016; Choi et al., 2018). In particular, adjacent large structures can strongly influence fault slip behavior and seismicity (Eberhart-Phillips et al., 2003; Nanjo et al., 2019). Nanjo et al. (2019) documented a decrease in stress around the junction of the Futagawa and Hinagu fault zones during the 2016 Kumamoto earthquake event. Eberhart-Phillips et al. (2003) also showed that the slip distribution, slip rate, and geodetic GPS velocity along the Denali and Totschunda faults changed markedly at their junction. In the present study, the junction between the YF and the NNW–SSE-striking Ulsan Fault is located to the north of our studied section (Gyeongju city), between the BG and WS sites (Figure 2a). Furthermore, the strike of the YF changes slightly in this area. Our comprehensive investigation reveals that the NYF and SYF show distinct paleoseismic histories, and we infer that the interconnection of the YF with the Ulsan Fault has acted as one of important structural breaking points (or barriers) controlling seismic behaviors.

We observed SSDSs within the young sedimentary strata at all studied trench sites. Some strata with SSDSs at the MH and IBN trenches are not cut by fault splay (Figures 6 and 8), suggesting that the SSDS were developed by strong shaking during rupture on other sections or strands of the YF. This interpretation is consistent with the overall structure of the YF, which is characterized by many anastomosing and linked mappable strands (Cheon et al., 2019). Mapping of the distribution of SSDSs associated with younger seismic events along the YF is one of our emerging research projects.

6 Conclusions

We conducted detailed geomorphic analyses and paleoseismic trench surveys at three sites (WS, MH, and IBN) and OSL dating of unconsolidated sediments along the northern section of the SYF in SE Korea to characterize the temporal and spatial distribution of Late Pleistocene surface ruptures. Combining our results with previous findings for the IB trench allows the following conclusions to be drawn.

1. The kinematics of fault splays causing surface ruptures in the studied fault section show dextral slip with a small reverse component, expressed in the field as east-side-
up geometry along eastward-dipping fault splays and dextrally offset streams and terraces. Stratigraphic features related to the fault splay kinematics include fissure-filling deposits, sag ponds, and U-shaped cut-and-fill stream deposits along fault splays in two-dimensional trench walls. Generally, these types of stratigraphic features should provide helpful information regarding rupture kinematics in intraplate regions, where geomorphic expression of surface ruptures can be limited.

2. We suggest two possible rupture scenarios of the timing of the MRE along the studied section considering the uncertainties on OSL ages: (1) a single rupture along the entire studied section at ca. 30 ka, and (2) individual partial ruptures along the WS–MH segment during 33–30 ka and the IBN–IB segment during 29–17 ka. The PE ruptures of the WS–MH and IBN–IB segments are constrained at 37–35 and 70–52 ka, respectively. We emphasize distinct rupture distributions between two segments: the ruptures of the WS–MH segment were constrained along the boundary of the main fault core zone, whereas the ruptures of the IBN–IB segment propagated along the eastern branch fault of the YF.

3. The timing of the MRE on the studied section of the SYF differs markedly from that of the YG–BG section of the NYF. The timing of MRE of the YG–BG section is presumed as the Late Holocene, whereas that of our studied section is presented as the Late Pleistocene. Our findings suggest that these distinct rupture histories along each segment but also each section could be due to the mappable branching geometry of the mature fault; in particular, a branching point situated between the WS–MH and IBN–IB segments, and the junction of the YF and NNW–SSE-striking Ulsan Fault located between the SYF and NYF.
Acknowledgments, Samples, and Data

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References


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<th>Gamma dose^b (Gy/Ka)</th>
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^aCoarse (90 – 250 μm) grained quartz was used for OSL dating from all samples.
bBeta, gamma, cosmic dose and total dose rates are rounded to two decimal places.

Central age ± 1σ standard error.