The Quaternary slip rate of the Yangsan Fault offshore the SE Korean Peninsula and implications for seismic hazard assessment

Seonghoon Moon¹,², Han-Joon Kim¹,², Chunho Kim¹, Hyunggu Jun¹, Sang-Hoon Lee¹, Hyeong-Tae Joo¹ and Kwang-Hee Kim³

¹Marine Active Fault Research Center, Korea Institute of Ocean Science and Technology, Busan, Republic of Korea; ²Department of Ocean Sciences, University of Science and Technology, Daejeon, Republic of Korea; ³Department of Geological Sciences, Pusan National University, Busan, Republic of Korea

ABSTRACT
The Yangsan Fault, a NNE-trending strike-slip fault, is a prominent active structure in the Korean Peninsula which recently generated an earthquake with moment magnitude $M_W$ 5.5 ($M_L$ 5.8) that was the largest instrumentally recorded event in Korea. High-resolution seismic profiles obtained on a dense grid reveal deformation of Quaternary sequences that indicates the offshore extension of the Yangsan Fault to the SE continental shelf of the Korean Peninsula. The offshore fault system comprises a main strand and subsidiary Riedel shears formed by dextral slip. We estimated the Quaternary lateral slip rate of the Riedel shear zone using seismic profiles. The Quaternary slip rate of $0.73 \pm 0.07$ mm/yr was estimated from the dextral displacement of the base boundary of the Quaternary sequences along the main strand. Modelling of fault activities based on empirical relations incorporating the slip rate indicates that (1) the offshore Riedel shear zone is capable of generating earthquakes with magnitude up to $M_W$ 6.07–6.25 with recurrence intervals of 550–1500 years and (2) the individual Riedel shears can generate earthquakes with magnitude less than $M_W$ 5.87.

1. Introduction
The Korean Peninsula, lying in the interior part of NE Asia, has experienced relatively less frequent lower magnitude seismicity, compared to the neighbouring Japan Arc at a convergent plate boundary (Figure 1). The earthquakes recorded in and around the Korean Peninsula since the beginning of instrumental monitoring in 1978 have rarely exceeded $M_L$ 5.0 in magnitude. An exceptionally large earthquake of magnitude $M_W$ 5.5 ($M_L$ 5.8) occurred in the SE part of the peninsula on September 12,
2016 that was the largest instrumentally recorded event in Korea (Kim et al. 2018b; Park et al. 2018), herein referred to as the 2016 MW 5.5 earthquake. This earthquake occurred in the zone of the Yangsan Fault, a dominant structure in the Korean Peninsula that is a NNE-trending strike-slip fault (Figure 1).

The 2016 MW 5.5 earthquake invoked a need to better understand the activity of the Yangsan Fault in the Quaternary in order to assess the seismic hazard potential of the fault. Crustal deformation at a specific site is dependent on the slip rate of a potentially active fault (Bungum 2007). Anderson et al. (1975) suggested that the slip rate of a fault improves the estimates of magnitude of shallow continental earthquakes. Therefore, the slip rate of a fault is an important component in estimating the potential magnitude and the recurrence interval of earthquakes on the fault. However, a structural resolution to determine the lateral slip rate of the Yangsan Fault on land in the Quaternary is not available because Quaternary sediments are scarcely deposited, making it difficult to perform seismic profiling and other detailed studies of the fault’s Quaternary activity (Kim et al. 2016). In addition, a significant

Figure 1. (a) Map showing the Korean Peninsula (KP) and the Japan Arc. The red rectangle indicates the study area in Figure 1b. A-A’ is a transect of P-wave velocity tomography in Figure 8. PA, PP, and OP = Pacific, Philippine Sea, and Okhotsk Sea Plates, respectively. (b) Geologic map of the SE Korean Peninsula. Inset shows the satellite image of the study area (from Google Earth). The 2016 MW 5.5 earthquake is shown with its focal mechanism from Kim et al. (2018a). The dashed-line rectangle indicates the study area in Figure 2. Epicenters of offshore earthquakes (1980.12-2020.7) are from the Korea Meteorological Administration. (1) Miocene sedimentary rocks, (2) Miocene volcanic rocks, (3) Cretaceous granite, (4) Cretaceous sedimentary rocks, (5) Cretaceous volcanic rocks, (6) Early Tertiary granite. (Modified from Kim et al. 2016)
portion of the Yangsan Fault runs through either highly populated and industrialized areas or inaccessible terrains, precluding those studies.

Recently, Kim et al. (2016, 2018a), based on the interpretation of high-resolution seismic profiles, identified an offshore extension of the Yangsan Fault and reported its Quaternary activity beneath the SE continental shelf off the Korean Peninsula where Quaternary sequences are well preserved (Figure 2); in the offshore, the Yangsan Fault was recognized as a fault system consisting of a main strand and
subsidiary Riedel shears created by dextral slip that were activated repeatedly in the Quaternary. The high-precision locations and source parameters of the 2016 $M_W$ 5.5 earthquake sequence (Kim et al. 2018b; Woo et al. 2019) suggest that (1) the aftershock area includes a complex multifault system and (2) the source structure of the 2016 $M_W$ 5.5 earthquake is a subsidiary fault bifurcated obliquely from the Yangsan Fault. Thus it is important to characterize the offshore Riedel shear zone of the Yangsan Fault imaged on seismic profiles and assess the zone’s potential seismic hazards.

The principal objectives of this study are (1) to resolve the rate of lateral slip in the offshore Riedel shear zone in the Quaternary by measuring the lateral displacement of the base of the Quaternary sequences along the strike of the Yangsan Fault and (2) to estimate the potential earthquake magnitude using empirical relations and associated recurrence intervals. For this purpose, we obtained high-resolution seismic profiles that, together with the profiles in Kim et al. (2016), created a dense grid of profiles for accurate fault mapping. For estimation, the utility computer program (‘moment_slip’) by Bungum (2007) and the regression by Anderson et al. (1975) were used that connect seismic activity of a fault with its slip rate.

2. Yangsan Fault and its offshore extension south of the Korean Peninsula

Because the geologic setting of the SE Korean Peninsula is well documented in the literature (e.g. Ree et al. 2003), descriptions are focused on the Yangsan Fault and its offshore extension. The SE part of the Korean Peninsula is a region of relatively higher seismicity historically and instrumentally, compared to other parts in the peninsula. The Yangsan Fault is recognized as the most prominent structural lineament trending NNE-SSW in the SE Korean Peninsula, traced on land for at least 190 km (Figure 1). Chang and Choo (1999) suggested that the Yangsan Fault has a recognizable dextral displacement amounting to 35 km in the northern part and 25 km in the southern part. They dated the fault gouges from the Yangsan Fault zone in the central part of the SE Korean Peninsula as far back as 59 Ma, which possibly indicates the time of the initial movement on the fault. Paleoseismic studies in the Yangsan fault zone including trenching showed activity in the Miocene and Quaternary (Kyung et al. 1999). The Yangsan Fault zone consists of several closely spaced, subparallel faults that constitute a fault zone of 5–6 km width (Kyung 2003). The 2016 $M_W$ 5.5 earthquake sequence occurred in a zone of ~2 km width perpendicular to the strike of the Yangsan Fault (Kim et al. 2018b), which may imply that the Yangsan Fault zone in the epicentral area is comprised of smaller segments.

The Yangsan Fault extends for more than 50 km in length beneath the SE continental shelf of the Korean Peninsula east of Geoje Island (Figure 2) (Kim et al. 2016, 2018a). A portion of the offshore extension developed into a fault system that consists of a main strand (‘F1’) and several subparallel Riedel shears (‘F2 to F4’) occurring in the western block of the main strand (Figure 2). Geometric analysis of these Riedel shears indicates ENE-WSW compression as the regional stress field in and around the SE Korean Peninsula (Kim et al. 2016). The ENE-WSW compression is in
agreement with the stress field computed from earthquake data (Rhie and Kim 2010). The reconstruction of Neogene-to-Quaternary sedimentary layers on the SE continental shelf off the Korean Peninsula indicates that this ENE-WSW stress field initiated after 5.5 Ma and has persisted to the present (Lee et al. 2011).

3. Data acquisition

The study area covers the continental shelf up to 60 km southward from the coast of the SE Korean Peninsula. High-resolution single- and 16-channel seismic profiles from A-01 to A-28 and B-01 to B-13, respectively, were obtained in 2014 and 2015, using a sparker source that generated seismic pulses with 2000 joule power every 2 sec (Figure 2). The single- and 16-channel data were recorded to 1 and 2 s, respectively, with a 0.1 ms sample rate. Single-channel data were, then, band-pass filtered with low-cut and high-cut frequencies of 30–250 Hz and 1500–1600 Hz, respectively. Processing of 16-channel data included the constant velocity stack (CVS), post-stack deconvolution to suppress seafloor multiple reflections. These profiles provided the first high-resolution imagery of the offshore extension of the Yangsan Fault (Kim et al. 2016).

In 2017, we obtained an additional set of single-channel profiles (D-01 to D-07) using the same sparker source. These profiles were obtained along the seismic lines set midway between lines from A-07 to A-14 (Figure 2) that showed a well-defined fault system including a main strand and Riedel shears (Kim et al. 2016). As a result, a dense grid of profiles was created with a line spacing reduced to as small as 250–300 m.

4. Offshore extension of the Yangsan Fault

4.1. Quaternary slip rate in the Riedel shear zone

The stratigraphic succession on the seismic profiles in the study area is a stack of four distinguished units designated as U-1 (Pliocene and earlier), U-2a (Early Pleistocene), U-2b (Late Pleistocene), and U-3 (Holocene) in ascending order (Kim et al. 2016) (Figures 3–5). Reflectors R2, Rp, and R3 on seismic profiles represent the bases of U-2a, U-2b, and U-3 (Figures 3 and 4). The Pliocene and Pleistocene units (U-1, U-2a, and U-2b) deepen gradually and thicken seawards to the south in a wedge form. These units are dominantly lowstand systems tracts resulting from upbuilding and outbuilding in response to sea level change. The Holocene unit (U-3) occurs as a thin transgressive deposit on the mid-shelf as a result of shoreface erosion during the post glacier transgression; in contrast, it occurs in a relatively thick lens form close to the coast.

The Riedel shear zone in the offshore extension of the Yangsan Fault is 8.3 km long along the strike of the main fault (‘F1’) and up to 2 km wide (Figure 2). The subparallel Riedel shears, less than 5 km long, occur at an acute angle (>15°) clockwise to fault F1, consistent with the dextral sense of the NNE-trending main strand. The vertical displacement of reflectors R2 and Rp along the faults increases with depth, suggesting faulting took place concurrently and repeatedly with the deposition
Main fault F1 is characterized by a persistent up-to-the-east sense of throw of the Quaternary sequences, emplacing the eastern block higher than the western block. This persistent up-to-the-east sense of throw is explained by the southward (i.e. dextral) translation of the eastern block, considering that the Pliocene and Quaternary sequences generally deepen seaward to the south (Figure 6). Therefore, the distance moved dextrally by the eastern block in the Quaternary with respect to the western block can be estimated by measuring how much reflector R2 in the eastern block separated from the western block along the strike of fault F1 because reflector R2 marks the base of the Quaternary sequences. In other words, reflector R2 on the eastern and western blocks of fault F1 can be used as offset-piercing points with which to estimate the lateral (i.e. dextral) slip rate of the fault in the Quaternary.

The seismic profiles used to measure the depths to R2 include A-04 to A-26 and D-01 to D-07 that were obtained where fault F1 is fairly straight in plan view and
Riedel shears are well recognized (Figure 2). Figure 7 shows the depths to R2 in the eastern block along the strike of fault F1 and those in the western block on seismic profiles. The depth to reflector R2 on the western block was determined immediately outside the Riedel shear zone deformed by faulting (Figures 3–5). The horizontal distance between the points of the same elevation in the two blocks does not vary significantly along strike (Figure 7). In addition, the base of Quaternary sequences deepens monotonously seaward, which enables measuring the horizontal distance of dextral translation of the eastern block.

In the shallow-waters, tides are enhanced and thereby increase short-term and diurnal fluctuations in sea level, which can result in variations in the depths to the
Figure 5. (a) Seismic profile D-05 showing faults F1 and F4, and (b) its interpretive line drawings. Green dots are used as offset piercing points. See Figure 2 for location.

Figure 6. Schematic model of the Yangsan Fault (‘YF’) (a) before and (b) after dextral translation in the Quaternary that caused an up-to-the-east sense of displacement on seismic profiles oriented E-W. Green dots are an offset piercing point pair as on seismic profiles in Figures 3 and 4. R2 = base of Quaternary sequences.
same stratigraphic reflectors on seismic profiles if they are obtained at different times. We corrected the depths to R2 for variations in tidal height with time, using the tidal height data recorded during the period of seismic data acquisition at the nearest tide observation post installed in Geoje Island by the Korea Hydrographic and Oceanographic Agency. The tidal height fluctuates about twice a day with a maximum range of ±0.8 m, which corresponds to ±1.1 ms in two-way traveltime, assuming 1500 m/s for sound wave velocity in water.

In this study, the depth to R2 was determined as the average of 100 consecutive depths to R2 that are located immediately outside the fault zone. The 23 horizontal distances between the two depth curves measure from 1.13 km to 2.79 km, averaging to 1.9 km. Division of the distances by 2.6 Ma representing the time since the onset of the Quaternary period yields 0.73 ± 0.07 mm/yr as the dextral slip rate of fault F1 in the Quaternary.

4.2. Uncertainties in the slip rate

4.2.1. Offset piercing point pair at the same depth

In estimating the slip rate, we assume that each pair of offset piercing points on either block of fault F1 formed at the same depth. The SE continental shelf of the Korean Peninsula is a narrow seaway called the Korea Strait between the SE Korean Peninsula and the SW Japan Arc (Figure 1). The continental shelf was created by back-arc rifting since the Late Oligocene (Kim et al. 2016) and ensuing marine
transgression since the Early Miocene (Kojima et al. 2001), accompanied by thick accumulation of sediments. Reflector R2 in the study area deepens very gradually seaward with an average slope $< 0.2$° (Figure 6). Global sea level around the onset of the Quaternary was as high as the present (e.g. Miller et al. 2005), which indicates that reflector R2, the base of the Quaternary sequences, was emplaced under water. The study area is characterized by dynamic dispersion of sediments discharged from large and small river systems. The Nakdong River is a major river system in the SE Korean Peninsula; the Yangsan Fault on land is traced exactly along the lower estuarine part of the river to the coast (Figure 1(b)). The Nakdong River alone discharges about $1.0 \times 10^7$ tons of sediments annually (Yoo et al. 2014). Therefore, we think that (1) sediments filled quickly the small depressed areas that might have been created by episodic dextral events because sediments accumulate preferentially in the tectonically depressed areas (Pondard and Barnes 2010) and (2) dextral movement of the eastern block of fault F1 did not cause a significant difference in the elevation of reflector R2 between the eastern and western blocks over a relatively short period of time in the beginning of the Quaternary. Taken together, we think that offset-piercing point pairs on reflector R2 were placed at the same or continuous depth levels when R2 was created, as no fault scarp is observed on the present seafloor on seismic profiles.

4.2.2. Erosion of the base of the quaternary sequences and oblique slip
Erosion of unconformity R2 was not considered in estimating the strike-slip rate. If the more elevated eastern block was subjected to a higher degree of erosion during and after translation, the slip rate would be higher than the above. Seismic profiles show that the package of reflections representing unconformity R2 and underlying strata outside of the fault zone in either block does not change noticeably in overall thickness and seismic character even though it is offset vertically by faulting. Internally, individual stratigraphic reflections are fairly flat and have good continuity. It thus appears that significant erosion of unconformity R2 did not occur differentially between the eastern and western blocks. Considering the above characteristics of stratigraphic reflections, it is also unlikely that subsidence or uplift took place, resulting in a recognizable across-strike difference in elevation between the eastern and western blocks. The subvertical fault plane and the absence of noticeable drag folding along fault F1 further suggest that the contribution of oblique-slip was not significant. Kyung et al. (1999), based on paleoseismic studies in southern part of Yangsan Fault onland, also suggested that dominant movement on the Yangsan Fault in the Late Quaternary (250–500 ka) was strike-slip. They estimated the upward vertical slip rate of the eastern block of the Yangsan Fault as 0.02–0.04 mm/yr from the height difference of the terraces displaced by faulting. The average vertical slip rate of 0.03 mm/yr is less than 1/20 of the estimated lateral slip rate; therefore, oblique-slip was not considered in this study. We, however, note that the lateral slip rate would decrease if the vertical slip component is significant.

4.2.3. Age of the base of the quaternary sequences
Reflector R2 representing the boundary between the Pliocene and the Quaternary is not necessarily the horizon formed exactly at the very beginning of the Quaternary;
rather, it would be realistic that R2 formed sometime later, considering the periods of sea-level fall and lowstand in the Early Quaternary that might have caused erosion and progradation of sediments. If R2 formed later than the very beginning of the Quaternary, the Quaternary slip rate estimated as 0.73 mm/yr is likely to increase slightly.

5. Discussion

5.1. Implications of the slip rate

Scholz et al. (1986) categorized tectonic earthquakes into three types on the basis of slip rates of the source faults: interplate, intraplate (plate boundary-related), and intraplate (mid-plate) with a slip rate $>10$, $0.1-10$, and $<0.1$ mm/yr, respectively. The offshore portion of the Yangsan Fault with a slip rate of 0.73 mm/yr is regarded as a fault on which plate boundary-related earthquakes occur, although its slip rate is much lower than the average level. The Korean Peninsula and its surrounding continental shelf are in a back-arc region above the subducted Pacific Plate (Figure 8). The upper mantle in this back-arc region is characterized by low P-wave velocities. This low velocity anomaly suggests a high content of water that is known to promote thermal convection (Kim et al. 2015). It thus appears that the Yangsan Fault activity is weakly, or indirectly, associated with tectonic processes occurring in a subduction zone behind the plate boundary.

Figure 8. P-wave velocity (Vp) cross-section of the mantle along transect A-A’ (see Figure 1(a) for location) from the GAP-P4 model (Obayashi et al. 2013) available at http://csmap.jamstec.go.jp/csmap/.
The oldest age of the fault gouges from the Yangsan Fault zone dates as far back as 59 Ma (Chang and Choo 1999), which possibly indicates the time of the initial movement on the fault. Although displacement of the Yangsan Fault is explained essentially by dextral activity, temporary and local left-lateral displacement in the Middle Miocene was reported (e.g. Chang and Chang 1998). In addition, age constraints to resolve the full spectrum of chronological fault activity are not available. It thus is difficult to estimate the long-term slip rate of the Yangsan Fault.

In the Late Oligocene, the Japan Arc commenced separation away from the continental margin of the Korean Peninsula through back-arc rifting and spreading (e.g. Kim et al. 2015). This event placed the SE Korean Peninsula under regional extension principally to the SE direction. Ingle (1992), based on the subsidence analysis using deep-drilled well data obtained on the SE coast of the Korean Peninsula, suggested that tectonic subsidence associated with back-arc extension began around 30–25 Ma and continued to 12–10 Ma. The dextral motion of the Yangsan Fault is incompatible with the SE direction of extension during back-arc rifting and spreading. That is, it is likely that the dextral activity of the Yangsan Fault did not occur during back-arc extension. Kinematic and paleostress analysis suggested that the dextral displacement along the Yangsan Fault continued to 25 Ma (Cheon et al. 2017), which is in reasonable agreement with the above interpretation.

Back-arc extension behind the Japan Arc terminated when the Philippine Sea Plate moving from the south made a full contact with the arc around 15 Ma and began subduction (Lee et al. 2011). As a result, compression in the N-S (or NNW-SSE) direction was induced at the continental margin of the SE Korean Peninsula from ~12 Ma in the Middle Miocene to sometime after 5.5 Ma in the Early Pliocene (Lee and Kim 2002; Lee et al. 2011). The temporary and local left-lateral displacement on the NNE-trending Yangsan Fault in the Middle Miocene may be associated with this N-S (or NNW-SSW) compression, considering the stress direction and the strike of the fault. Subsequently, the SE continental margin of the Korean Peninsula became subjected to the ENE-WSW compression (Lee et al. 2011) that has persisted to the Quaternary. Analysis of Quaternary fault slip (Park et al. 2006; Kim et al. 2016) and focal mechanism (Rhie and Kim 2010) indicates that the Korean Peninsula and its offshore are under ENE-WSW compression, being compatible with the dextral activity of the NNE-trending Yangsan Fault in the Quaternary; i.e. the dextral activity of the Yangsan Fault resumed sometime after 5.5 Ma.

Taken together, we interpret roughly that the total dextral displacement of 25–35 km along the Yangsan Fault was achieved from 59 to 30–25 Ma and from after 5.5 Ma to the present, which sum up to 34.5–39.5 Ma. The long-term slip rate of the Yangsan Fault, accordingly, is 0.89–1.01 mm/yr and 0.63–0.72 mm/yr for 35 and 25 km displacement, respectively. Although the slip rate was estimated by assumptions on the age of dextral movement on the Yangsan Fault, the long-term slip rate, like the Quaternary slip rate, seems to be less than 1 mm/yr.

5.2. Potential earthquake magnitude and return period

The utility computer program, moment_slip, by Bungum (2007) computes the average of the models of Anderson and Luco (1983) and Youngs and Coppersmith
The maximum expected magnitude of earthquakes ($M_{\text{max}}$) is highly dependent on the fault length and width among the parameters (e.g. Bungum 2007) as they relate to the maximum extent of a seismic rupture (Klinger 2010). Important input parameters other than the slip rate were selected as follows:

1. **Fault length**: Strike-slip faults are normally divided into segments bounded by fault bends and step overs. It is, however, difficult to identify segments and their boundaries directly on seismic profiles in the study area where large earthquakes with aftershocks have not occurred since the beginning of instrumental recording in Korea. In this study, we consider the length of the Riedel shear zone measuring 8.3 km along the strike of fault F1 as the length of a fault segment because Riedel shears mark localized deformation within fault zones (e.g. Ben-Zion and Sammis 2003).

2. **Fault width**: The focal depths of the earthquakes in the Korean Peninsula and in the offshore within the realm of continental crust average to $\sim$10 km, mostly not exceeding 15 km (Sheen 2015). We thus estimate focal depths to range from 10 to 15 km. The ranges of the fault length and the fault width were used to determine the fault length-to-width ratio as an input parameter. The SE Korean Peninsula, as determined from a wide-angle seismic sounding experiment, is underlain by $\sim$30 km-thick crust consisting of equally $\sim$15 km-thick upper and lower crustal layers (Cho et al. 2006). The focal depth of 15 km, therefore, appears to indicate the depth limit of the brittle upper crust.

3. **b-value**: 0.98 was selected from Kim et al. (2017), which was determined for the SE Korean Peninsula and offshore using K-means cluster analysis of recorded earthquake data.

4. **Slip-to-length ratio**: The commonly reported range is $1.0 \times 10^{-5} - 1.0 \times 10^{-3}$ (Bungum 2007). We selected $1.0 \times 10^{-4}$ for this ratio.

Other parameters were the same as those in Bungum (2007) that are representative of crustal averages. Modelling shows that $M_{\text{max}}$ ranges from $M_W$ 6.07 to $M_W$ 6.25, increasing as the fault width increases from 10 to 15 km (Figure 9).

Anderson et al. (1975) suggested a regression in a simple form to estimate the largest magnitudes of earthquakes as:

$$M_{\text{max}} = (5.12 \pm 0.12) + (1.16 \pm 0.07) \cdot \log L - (0.20 \pm 0.04) \cdot \log \text{SR}, \tag{1}$$

where $L$ is the fault length (km) and SR is the slip rate (mm/yr). This regression yielded $M_{\text{max}}$ as 6.21, being in reasonable agreement with the previous estimate.

The return period ($T_{\text{red}}$) of earthquakes was computed using the relation:

$$T_{\text{red}} = \frac{S}{\text{SR}}, \tag{2}$$

where $S$ is the slip per event computed using the equation (Hanks and Kanamori 1979):

$$\log_{10}\{M_0(= \mu \cdot A \cdot S)\} = 16.1 + 1.5 M_W, \tag{3}$$
where $M_0$, $\mu$, and $A$ are seismic moment, rigidity modulus, and area, respectively. $T_{\text{red}}$ increases log-linearly with increasing magnitude (Figure 10), as expected in the above equations. If the fault length is 8.3 km, $T_{\text{red}}$ ranges widely from about 550 to 1500 years as $M_{\text{max}}$ increases from 6.07 to 6.25, averaging to about 1000 years. Consequently, the seismic hazard on the SE continental shelf of the Korean Peninsula appears not-high in terms of $T_{\text{red}}$ in association with the activity of the Yangsan Fault. As mentioned previously, the lateral slip rate in this study was estimated assuming that the base of the Quaternary sequences formed at 2.6 Ma; if it formed a little later, the slip rate would be slightly larger, which would result in a small reduction in $T_{\text{red}}$.

The individual Riedel shears F2, F3, and F4 measure 4.3, 4.4, and 2.6 km in length, respectively. The source structure of the 2016 $M_W$ 5.5 earthquake in the SE Korean Peninsula is a ~5 km-long splay fault of the Yangsan Fault (Kim et al. 2018b), similar to the offshore Riedel shears. The empirical relationship between the potential magnitude of earthquakes and the fault length proposed by Anderson et al. (1975) provides $M_W$ 5.60–5.87 for the offshore individual Riedel shears.

Riedel shears are common fault patterns related to the embryonic stage of fault formation (e.g. Katz et al. 2004). No other type of subsidiary faults such as p-shears resulting from progressive development of Riedel shears (e.g. Davis et al. 2000) is recognized clearly in the Quaternary sequences within the limit of resolution of the seismic profiles in the study area; nor is a through-going linking network that may represent a later (or final) stage. It thus is likely that fault activity will continue to take place offshore the SE Korean Peninsula under the present stress field.

We have constrained the dextral slip rate of the offshore extension of the Yangsan Fault in the SE Korean Peninsula and estimated its seismic activity. Our study
demonstrates the potential of high-resolution seismic profiling in the characterization of the activity of major faults in the Korean Peninsula that extend offshore and further assessment of their seismic hazard.

6. Conclusions

We assessed potential seismic hazards of the offshore extension of the Yangsan Fault that recently generated the largest earthquake on land ever recorded instrumentally in the Republic of Korea, based on the fault structure recognized on seismic profiles. The results of our study are as follows:

1. The dextral slip rate of the offshore portion of the Yangsan Fault in the Quaternary was estimated from the dextral displacement of the base of the Quaternary sequences resolved on high-resolution seismic profiles. The slip rate was computed as $0.73 \pm 0.07$ mm/yr, which is consistent with the estimated long-term dextral slip rate of the fault on land over its history.

2. The Riedel shear zone in the offshore extension of the Yangsan Fault is capable of generating earthquakes with the maximum magnitude ($M_{\text{max}}$) from $M_W$ 6.07 to 6.25 as the fault width increases from 10 to 15 km.

3. The return period of earthquakes with $M_{\text{max}}$ approximated from empirical equations ranges from 550 to 1500 years, suggesting a relatively long time interval of occurrence.
4. The developing Riedel shears suggest further continuing seismicity on the SE continental shelf of the Korean Peninsula.

Acknowledgements

We thank the reviewers for their careful and constructive review. H.J. Kim thanks H. Bungum for providing the computer program for modelling fault activities.

Funding

This work was supported by the Korea Institute of Ocean Science and Technology (KIOST) under Grant PE99841 and the Korea Meteorological Administration (KMA) Research Development Program under Grant KMI2018-02810.

Data availability statement

The seismic data that support the findings of this study are available on request from the corresponding author, H.J. Kim.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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