Middle to lower crustal earthquakes in the western East Sea (Sea of Japan) and their implications for neotectonic evolution

Tae-Kyung Hong *, Seongjun Park, Junhyung Lee, Jeongin Lee, Byeongwoo Kim

Yonsei University, Department of Earth System Sciences, 50 Yonsei-ro, Seodaemun-gu Seoul 03722, South Korea.

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ABSTRACT

The western East Sea (Sea of Japan) is a seismically active region. A major earthquake in the western East Sea may cause damage in the eastern Korean Peninsula. The nature of seismicity in the western East Sea is important information for mitigation of seismic hazards. The seismicity in the western East Sea occur around the paleo-rifting structures where seismic and geophysical properties apparently change. Both reverse faulting and strike slip earthquakes occur in the region. Earthquake locations and focal depths are refined. The maximum focal depth generally increases from ~10 km in the coast to ~32 km in the continental slope of the western East Sea that is located in distance of ~60 km from the coast. Mid to lower crust earthquakes continue around the paleo-rifting structures that may extend to the lower crust and Moho. Offshore earthquakes rarely occur in oceanic basins of bathymetry with >2 km. Clustered episodic earthquakes occur in four local offshore areas including the stress-induced areas by the 12 September 2016 M6.8 (Mw5.4) Gyeongju and 15 November 2017 M5.4 (Mw5.5) Pohang earthquakes. The spatiotemporal clustering of earthquakes suggests stress accumulation at localized paleo-rifting structures and episodic stress release. The mid to lower crustal earthquakes are confirmed from phase arrival time analyses with collocated vertically-separated sensors. The laterally progressive focal depth changes suggest neotectonic evolution of thrust across the crust in the paleo-rifting structure.

1. Introduction

The Korean Peninsula experienced drastic seismicity change after the 2011 M9.0 Tohoku-Oki earthquake (Hong et al., 2015, 2017, 2018, 2023). Mid to lower crustal earthquakes increased since the megathrust earthquake. The midcrustal and lower crustal events occurred in regions where the seismicity was low before the event (Hong et al., 2017, 2020b). On the other hand, the earthquake occurrence is relatively low in the usual high seismicity regions. The feature may happen due to stress rebalancing in the crust after the megathrust earthquake (Hong et al., 2018, 2022, 2023).

The East Sea (Sea of Japan) is a major region of seismicity around the Korean Peninsula. Most earthquakes in the East Sea occur in distances of ≤60 km from the coast (Choi et al., 2012; Hong et al., 2020b). The East Sea (Sea of Japan) experienced complex tectonic evolution including continental rifting and sea opening, leaving traces in the crust. Tectonic evolution may incorporate long-term seismic activity change. Active seismogenic faults are associated with paleo continental rifting structures that are reactivated to produce earthquakes (Hong et al., 2020b; Kim et al., 2022). Also, paleo structures may present a room for neotectonics.

Seismic damage may occur by strong ground motions. Major earthquakes with shallow focal depths are potential sources of seismic damage in local distances. The earthquakes in the East Sea occur around paleotectonic structures that are opt to respond to the ambient stress. The identification of potential earthquake locations is important for seismic hazard mitigation. The earthquake-hosting faults are often associated with tectonic structures. However, geological features such as geological provinces and paleo-faults observed on the surface provide limited information on active tectonics. The seismicity properties in the East Sea may provide essential information on the tectonic evolution, which is also important for seismic hazard mitigation in South Korea.

In particular, clustered events provide information on rupture process and stress balancing process for lithospheric deformation and stress change. This feature may provide key information on internal physical process in the Earth. We understand the solid earth response to lithospheric deformation and stress induction with megathrust earthquake. We finally infer the seismogenic structures in the East Sea and their
implications from seismological observations.

2. Data and geology

The East Sea was formed by paleo-rifting in the Oligocene to the mid-Miocene (Otofuji et al., 1985; Jolivet et al., 1994). Oceanic crust underlies beneath deep-sea basins (Japan, Yamato, and Ulleung basins) that were formed by the continental rifting and seafloor spreading (Hirata et al., 1992; Kim et al., 1998). During the continental rifting, the Korea Plateau was fragmented from the northern margin of the Korean Peninsula (Kim et al., 2015). The Korea Plateau is composed of the North Korea Plateau and the South Korea Plateau along the coast of the peninsula (Fig. 1). The South Korea Plateau is further divided into the western South Korea Plateau and eastern South Korea Plateau (Kim et al., 2022). The South Korea Plateau experienced crustal extension by depth-dependent stretching during continental rifting (Kim et al., 2015, 2022).

The Ulleung basin is located in the south of the South Korea Plateau. Normal-faulting structures developed during the continental rifting. The crustal structure in continental shelf presents an extended continental crust with paleo normal-faults. The paleo-rifting developed complex crustal structures in the East Sea (Fig. 1(c)). The crustal structures in the East Sea change abruptly with distance from the east coast (Fig. 2). The crustal thickness becomes shallower with distance from the coast. The crustal thickness reaches ~8.5–14 km in the oceanic basins (Hirata et al., 1992; Kim et al., 1998).

Crust-guided shear waves (Lg) develop weakly in the East Sea, while they develop strongly in the Korean Peninsula (Hong, 2010; Furumura et al., 2014; Hong et al., 2016). The mantle-lid P (Pn) velocities in the western East Sea range are between 7.65 and 8.25 km/s (Hong and Kang, 2009). The Pn velocities are high along the continental shelf around the paleo-rifting structures (Fig. 2). The high Pn velocities may be due to upper mantle upwelling during continental rifting and/or lower-crustal magma underplating during uplift before continental breakup (White and McKenzie, 1989; Esedo et al., 2012).

The plate convergence at active plate boundaries (i.e., Okhotsk-Pacific plates, Eurasia-Philippine Sea plates, and India-Eurasia plates) produces compressional stress field in the East Sea. The ambient stress orientation changes with location. The maximum principle stress component is ENE-WSW compression, and the minimum principle stress component is WNW-SEE tension (Lee et al., 2017). The maximum principle stress (compression) range between N78.7° E and N92.4° E with a strength of 65 bar (Choi et al., 2012). The paleo-rifting structures respond to the current ambient stress field, producing earthquakes.

The stress field produces spatially heterogeneous earthquakes with various focal depths and locally clustered events. The seismicity in the East Sea presents both clustered events and scattered events. The clustered events are confined in local areas. Most seismicity is distributed in coastal regions with distances <~ 60 km from the coast (Hong et al., 2020b). Both reverse and strike-slip faulting earthquakes occur in the

Fig. 1. (a) Tectonic setting around the Korean Peninsula. (b) Major geological provinces and stations in the Korean Peninsula. The major geological provinces include the Namgim massif (NM), Gyeonggi massif (GM), Yeongnam massif (YM), Imjingang belt (IB), Okcheon belt (OB), Pyeongnam basin (PB), Gyeongsang basin (GB), and Yeonil basin (YB). Major faults (solid lines) and seismic stations (triangles) are marked. The lateral stress field (compression, tension) orientations along the east coast are presented (arrows). The study area (East Sea) is marked (box). (c) Major geological structures around the East Sea. Earthquakes (circles) and major faults (solid lines) are marked. The western East Sea area is divided by three subregions (Z1, Z2, and Z3). The paleo-rifting zone is indicated (shaded region).
western East Sea. Strike-slip events occur dominantly in the inland peninsula. The seismicity is low in the northwestern East Sea. Most earthquakes occur in the continental shelf near the southeast coast of the Korean Peninsula. Reverse activation of normal faulting structures produces thrust earthquakes (Choi et al., 2012; Hong et al., 2020b).

Recently, mid to low crust earthquakes have increased in the Korean Peninsula after the 2011 Mw 9.0 Tohoku-Oki megathrust earthquake (Hong et al., 2017, 2018, 2020a, 2022, 2023). Episodic earthquakes occur in the East Sea. The earthquake sequence occurs in the Korea Plateau that is located in the north from the Ulleung fault in the western margin of the Ulleung basin (Chough et al., 2018). A series of rifting structures may be present between the western margin of the Ulleung basin and east coast of the peninsula. There are the Wonsan Trough and the Gangneung Trough in the east and north of the Korea Plateau, respectively (Chough et al., 2018). The seismicity in the East Sea is clustered around the continental crust region near the coast. Few earthquakes occur in the northwestern East Sea at latitudes over 39° (Fig. 1).

National seismic monitoring of South Korea began in 1978. We collect the earthquake information from Korea Meteorological Administration (KMA), Korea Institute of Geoscience and Mineral Resources (KIGAM) and Japan Meteorological Agency (JMA). Available focal mechanism solutions of earthquakes are collected from various resources (Choi et al., 2012; Hong and Choi, 2012; Hong et al., 2015; Houngh et al., 2016; Hong et al., 2018).

We collect seismic records from 561 seismic stations in the Korean Peninsula. For depth constraints of moderate-size offshore events, we use vertically separated seismic sensors. We collect seismic data from borehole seismometers at depths of 300 m and 600 m in Yonsei University. The seismic records allow us to examine the relative difference in the arrival times for the same phase form earthquake.

### 3. Methods

We refine the locations of reported events using a joint hypocentral-parameter inversion method (VELHYPO), which is useful for regions of poorly constrained velocity structures (Kim et al., 2014, 2016). The method determines the hypocentral parameters and optimum velocity.
models. We calculate the event locations using seismic records along the coast where the raypaths are less affected by the heterogeneous crustal structures than those in inland regions. The stations on the coast are minimally influenced by the crustal structures. The inverted focal depths and event locations are dependent on the velocity models. The joint inversion method is useful for hypocentral parameter inversion for events that occur in poorly-known velocity structures (Kim et al., 2014, 2016).

We search small and micro earthquakes adjacent to reference events using a matched filter analysis for continuous waveforms bandpass-filtered between 5 and 20 Hz (Gibbons and Ringdal, 2006; Shelly et al., 2007; Peng and Zhao, 2009; Hong et al., 2020a). We choose well-determined earthquakes as reference events for the matched filter analysis. We select template waveforms of high signal-to-noise ratios. The template $P$ and $S$ waveforms are 2.5 s long, which is adjusted mildly depending on the distance and signal to noise ratio (Hong et al., 2020a).

The matched filter analysis searches signals of high correlation with template waveforms. The signal correlation coefficients are stacked over stations. We determine event detection when the stacked correlation coefficients are $>20$ times the median correlation coefficient for background noise. The locations of adjacent events detected by the matched filter analysis are refined using a double-diffERENCE method (hyPODD) based on relative phase travel times (WaldaUaMer and Ellsworth, 2000). We also determine the event magnitudes using relative amplitudes (Gibbons and Ringdal, 2006; Hong et al., 2020a).

Focal mechanism solution presents the geometry of the fault planes and rupture sense. We determine the focal mechanism solutions using long-period waveform inversion and polarity analysis. A long period waveform inversion is applied to determine the focal mechanism solutions of moderate-size earthquakes (Dregger and Helmerger, 1990; Hong et al., 2015). A one-dimensional velocity model (ak135) is used for the inversion (Kennett et al., 1995). The seismic waveforms are band-pass filtered between 0.05 and 0.1 Hz. The focal mechanism solutions of local moderate-size earthquakes are determined stably with an 1-D global average velocity model (Hong et al., 2017, 2018). We, additionally, apply a phase polarity analysis (FOCMEC) based on phase amplitudes and polarities to determine the focal mechanism solutions of small events where a long-period waveform inversion is not applicable (Snoke, 2003). The polarity analysis is applied for earthquake with reasonable azimuthal coverage.

Earthquakes may induce stress changes in adjacent regions. We calculate the induced stress from major earthquakes in the medium (Hong et al., 2017, 2018; Lee and Hong, 2021). We determine the source parameters of earthquakes such as fault dimensions and slip amounts using scaling laws (Wells and Coppersmith, 1994; Mai and Beroza, 2000; Blaser et al., 2010; Strasser et al., 2010). We calculate the corresponding induced Coulomb stress change at receiver faults in certain depth and geometry for earthquakes with given fault geometry, fault dimensions, and slip amounts. The cumulative stress changes induced by a set of earthquakes can be calculated by stacking the Coulomb stress changes by single events.

The Coulomb stress change, $\Delta$CFS, induced by an earthquake is given by (e.g., Harris, 1998):

$$\Delta\text{CFS} = \Delta \tau - \mu (\Delta \sigma_n - \Delta p),$$  \hspace{1cm} (1)

where $\Delta \tau$ is the shear stress change, $\mu$ is the frictional coefficient, $\Delta \sigma_n$ is the normal stress changes, and $\Delta p$ is the pore fluid pressure change. This expression can be simplified to be (King et al., 1994; Toda et al., 2005)

$$\Delta\text{CFS} = \Delta \tau - \mu' \Delta \sigma_n,$$  \hspace{1cm} (2)

where $\mu'$ is the effective frictional coefficient. We set the effective frictional coefficient $\mu'$ to be 0.4 (Toda et al., 2005; Hong et al., 2015, 2017). The magnitude of the principle compression is 65 bar (Hong et al., 2015, 2017). We set the lithospheric Young’s modulus to be 80 GPa, and the Poisson’s ratio to be 0.25 (King et al., 1994; Toda et al., 2005; Hong et al., 2015).

We calculate the synthetic waveforms for a point source using a reflectivity method (Kennett, 1983). Synthetic seismograms are calculated for 1D crustal velocity models (Kennett et al., 1995).

4. Strong ground motions and seismic hazard potentials

The western East Sea (Sea of Japan) is currently in an E-W directional compressional stress regime. The paleo rift structures near the east coast are oriented in N-S. The paleo rift structures are naturally weak, being subject to respond to the E-W directional compression stress field that is currently active around the region (Choi et al., 2012; Lee et al., 2017). Reverse faulting earthquakes occur in the paleo rift where normal-fault structures developed. The paleo-ripping structures with mechanical weak seed are seismogenic for the ambient stress field. The paleo-ripping structures are naturally located near the coast. Thus, earthquakes in the East Sea occur around the paleo-ripping structures (Fig. 3). There were 15 earthquakes with magnitudes $\geq M_L 4.0$ in the East Sea since 1978 (Fig. 1). Additionally, there were two earthquakes with magnitudes $\geq M_L 5.0$ in the region. A major earthquake in the East Sea may cause seismic damage around the coast where social infrastructures are clustered. The strong motions by the events enable us to infer seismic hazard potentials for offshore events.

We measure the strong ground motions by five representative moderate-size events in the East Sea that include two events from the northwestern East Sea, two events from the midwestern East Sea, and one event from the southwestern East Sea (see Table 1). The event magnitudes are $M_L 4.1$–$5.2$ (Fig. 4). The events include the 14 May 2023 $M_L 4.5$ ($M_W 3.9$) Donghae offshore reverse-faulting earthquake with focal depth of 28.0 km (E1), the 19 April 2019 $M_L 4.3$ ($M_W 4.0$) Donghae offshore reverse-faulting event with focal depth of 24.1 km (E2), the 29 May 2004 $M_L 5.2$ ($M_W 5.0$) Ulin offshore reverse-faulting earthquake with focal depth of 20.8 km (E3), the 10 February 2019 $M_L 4.1$ ($M_W 3.8$) Pohang offshore strike-slip event with focal depth of 18.2 km (E4), and the 5 July 2016 $M_L 5.0$ ($M_W 4.8$) Ulsan offshore strike-slip event with focal depth of 12.7 km (E5).

We first consider the 14 May 2023 $M_L 4.5$ ($M_W 3.9$) earthquake (event E1). The event occurred at an epicentral distance of 49 km from the east coast (Fig. 3). A long-period waveform inversion presents a reverse faulting earthquake with a moment magnitude of $M_W 3.9$ (Fig. 3). The observed waveforms match well with the theoretical waveforms (Fig. 3). The focal mechanism solutions present two nodal planes with a strike of 166$\degree$, dip of 45$\degree$, rake of 97$\degree$, and a strike of 353$\degree$, dip of 45$\degree$, and rake of 83$\degree$. The earthquake produced strong ground motions (Fig. 4). The earthquake was well observed in distances $>300$ km. The peak ground velocity (PGV) reaches 0.0011 m/s in distance of 56.0 km at bluestation TOHA, and the peak ground acceleration (PGA) reaches 0.071 m/s$^2$ in distance of 88.8 km at station YAYA (Fig. 4).

For comparison with the 14 May 2023 $M_L 4.5$ ($M_W 3.9$) Donghae offshore earthquake, a nearby moderate-size event (the 19 April 2019 $M_L 4.3$ ($M_W 4.0$) Donghae offshore event, E2) is considered. The event (E2) presents a similar focal mechanism solution (reverse faulting event with two nodal planes with a strike of 165$\degree$, dip of 47$\degree$, rake of 94$\degree$, and a strike of 340$\degree$, dip of 43$\degree$, and rake of 86$\degree$) with a larger moment magnitude ($M_W 4.0$). The peak ground velocity (PGV) reaches 0.0033 m/s, and peak ground acceleration (PGA) reach 0.150 m/s$^2$ in distance of 57.4 km at station TOHA near the coast (Fig. 4). The strong ground motions present a similar spatial attenuation distribution (Fig. 4).

The 29 May 2004 $M_L 5.2$ ($M_W 5.0$) Ulin offshore earthquake (E3) produces a peak ground acceleration of 0.16 m/s$^2$, and a peak ground velocity of 0.0069 m/s in distance of 100.2 km at station POH. The 10 February 2019 $M_L 4.1$ ($M_W 3.8$) Pohang offshore earthquake (E4) produces a peak ground acceleration of 0.052 m/s$^2$, and a peak ground velocity of 0.0008 m/s in distance of 89.4 km at station ADO2. The 5 July 2016 $M_L 5.0$ ($M_W 4.8$) Ulsan offshore event (E5) produces a peak...
ground acceleration of 0.15 m/s\(^2\) in distance of 84.1 km at station YSB, and a peak ground velocity of 0.0047 m/s in distance of 60.9 km at station HDB.

The strong motion levels are large in near distances, decaying with distance (Fig. 4). However, ray path effects cause discriminative seismic amplification and attenuation. Stronger ground motions are observed at longer distances due to localized seismic amplification and attenuation. Sedimentary layers on the surface may enhance the ground motions (Park and Hong, 2017). Strong motions by a southwestern moderate event are observed in the Gyeongsang basin. The strong motion distribution illuminates the sedimentary layers on the surface. Thus, the site effect and distance control the strong ground motion distribution.

Synthetic modeling suggests that a \(M_w 6.0\) offshore event with focal depths of 5–15 km in epicentral distances of \(\sim 30–40\) km may produce a peak ground acceleration of 1.96 m/s\(^2\) (0.2 g) (Hong et al., 2020b). The strong motion may be controlled by the focal depth and distance as well as magnitude. However, it is intriguing to note that the focal depth effect on the strong ground motion becomes minor with increasing distance (Hong et al., 2020b). The focal depth heavily causes apparent differences in strong ground motions in epicentral distances > 50 km (Hong et al., 2020b). Mid- to low-crustal events may induce high seismic damage in inland regions, particularly strong around the coastal regions.

5. Spatiotemporal earthquake clustering

The seismicity in the Korean Peninsula increased after the 2011 Tohoku-Oki megathrust earthquake (Hong et al., 2018) (Fig. 5(a)). Apparent increase of spatially-clustered earthquakes is observed since 2019 in the northwestern East Sea (Fig. 5(b)). The spatiotemporal distribution of seismicity may provide information on the earthquake induction mechanism and neotectonic evolution. The focal depths indicate the seismogenic depths. The spatiotemporally clustered events suggests the temporal evolution of the seismogenic zone and its spatial dimension (Fig. 5). There are clustered events in some local regions (clusters R1–R4 in Figs. 6, 7, 8). Episodic earthquakes occurred in and around the Korean Peninsula since the 2011 \(M_w 9.0\) Tohoku-Oki megathrust earthquake.

The Coulomb stress changes induced by the the 12 September 2016 \(M_5.8\) (\(M_w 5.4\)) Gyeongju earthquake and the 15 November 2017 \(M_5.4\) (\(M_w 5.5\)) Pohang earthquake are compared with seismicity in the region (Fig. 7). The clustered events in R2, R3, and R4 are located in elevated stress regions. We examine four seismic clusters in a period of 2018–2022 after the 2017 \(M_5.4\) Pohang earthquake in the midwestern and southwestern East Sea (Figs. 6 and 8).

There are episodic earthquake occurrences in the midwestern East Sea (Fig. 5). One earthquake sequence has been observed since 2018 (cluster R1). The 19 April 2019 \(M_4.3\) earthquake occurred in this period. Another sequence was observed in April 22, 2023 to May 2023 (Fig. 6). The 14 May 2023 \(M_4.5\) earthquake occurred in this sequence. A part of the clustered events occurred before and after the \(M_4.5\) earthquake. Earthquakes in the region were first reported in 1996 since 1978. There were no reported events in the region before 2019.

Earthquakes were reported more often since 2019, presenting irregular earthquake occurrence rates. The focal depths of episodic earthquakes are \(\sim 28\) km. The \(M_4.5\) earthquake occurred in a series of episodic events (Fig. 3). We apply a matched filter analysis to find micro and small events in 2018–2023 that are located near reference events. We apply the 7 August 2018 \(M_1.9\) earthquake and the 23 April 2023 \(M_2.3\) earthquake for reference events. The number of detected events is 740. The event magnitudes are \(M_0 0.4–4.5\). The earthquakes occurred episodically, decreasing with time (Fig. 5).

The detected events are relocated using a double difference method (supplementary materials). The earthquakes occurred on the main fault, being few in stress increased regions away from the mainshock (Fig. 6). The focal mechanism solutions of clustered events are consistent with that of the \(M_4.5\) earthquake. Events occurred in a small region of 1.0 km by 0.7 km at focal depths of \(\sim 28.0\). The focal depth distribution

<table>
<thead>
<tr>
<th>Event</th>
<th>Date</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Depth (km)</th>
<th>(M_w)</th>
<th>(M_L)</th>
<th>Strike1</th>
<th>Dip1</th>
<th>Rake1</th>
<th>Strike2</th>
<th>Dip2</th>
<th>Rake2</th>
</tr>
</thead>
<tbody>
<tr>
<td>ID</td>
<td>(yy/mm/dd)</td>
<td>(N)</td>
<td>(E)</td>
<td>(km)</td>
<td>(°)</td>
<td>(°)</td>
<td>(°)</td>
<td>(°)</td>
<td>(°)</td>
<td>(°)</td>
<td>(°)</td>
<td>(°)</td>
</tr>
<tr>
<td>E1</td>
<td>2023/05/14</td>
<td>37.8759</td>
<td>129.5575</td>
<td>28.0</td>
<td>4.5</td>
<td>3.9</td>
<td>166</td>
<td>45</td>
<td>97</td>
<td>335</td>
<td>45</td>
<td>83</td>
</tr>
<tr>
<td>E2</td>
<td>2019/04/19</td>
<td>37.8891</td>
<td>129.5628</td>
<td>24.1</td>
<td>4.3</td>
<td>4.0</td>
<td>165</td>
<td>47</td>
<td>94</td>
<td>340</td>
<td>43</td>
<td>86</td>
</tr>
<tr>
<td>E3</td>
<td>2004/05/29</td>
<td>36.6877</td>
<td>130.1341</td>
<td>20.8</td>
<td>5.2</td>
<td>5.0</td>
<td>354</td>
<td>46</td>
<td>89</td>
<td>175</td>
<td>44</td>
<td>91</td>
</tr>
<tr>
<td>E4</td>
<td>2019/02/10</td>
<td>36.1671</td>
<td>129.8993</td>
<td>18.2</td>
<td>4.1</td>
<td>3.8</td>
<td>33</td>
<td>84</td>
<td>171</td>
<td>124</td>
<td>81</td>
<td>6</td>
</tr>
<tr>
<td>E5</td>
<td>2016/07/05</td>
<td>35.4982</td>
<td>130.0075</td>
<td>12.7</td>
<td>5.0</td>
<td>4.8</td>
<td>199</td>
<td>89</td>
<td>176</td>
<td>289</td>
<td>86</td>
<td>1</td>
</tr>
</tbody>
</table>
The clustered events are confined on the fault plane of the 14 May 2023 M4.5 earthquake, suggesting a small rupture plane (Fig. 6). The observation of induced earthquakes confined on the mainshock rupture plane suggests that the stress off the mainshock rupture plane may not be in near critical stress level at stress induction by the mainshock (Fig. 6). Local stress loading or high yield strength may be responsible for such event clustering in a small area.

There are apparent earthquake clusters in Pohang offshore regions of the southwestern East Sea (Fig. 8). Clusters R2, R3, and R4 are located along a line from Pohang. Cluster R2 is developed in the end of line between R3 and R4. Cluster R3 is located far from Pohang, while cluster R4 is located near Pohang. The reference events are the 17 December 2018 M4.4 Donghae offshore earthquake (E1), the 19 April 2019 M4.3 (Mw4.0) Donghae offshore earthquake (E2), the 29 May 2005 M5.2 (Mw5.0) Uljin offshore earthquake (E3), the 10 February 2019 M4.1 (Mw3.8) Pohang offshore earthquake (E4), and the 5 July 2016 M5.0 (Mw4.8) Uljin offshore earthquake (E5). The seismic stations are marked on the maps (triangles). The moment magnitudes (Mw), focal mechanism solutions, and focal depths are indicated. Moderate-size offshore earthquakes may produce strong ground motions in inland region.

The earthquakes in clusters R2, R3, and R4 present strike-slip motions. The nodal planes of the focal mechanism solutions agree with the event distribution in clusters R2, R3, and R4. The fault-inducing cluster R2 may have developed from the paleo-rifting structures as a consequence of the response to the ambient stress field. This strike-slip fault is oriented in WNW-ESE. In the cluster R2 migrate in ESE, deepening from ~23 to ~24 km. The cluster R3 is composed of two subclusters of events that occur at different times with time gaps. The NE subcluster in larger depths (~19–20 km) occurred before the SW subcluster in shallower depths (~18–19 km). There are apparent spatiotemporal gaps between the subclusters. The NE subcluster may present the NW-trending seismicity distribution, suggesting NW-orienting fault developing from the paleo-rifting structures. On the other hand, the SW subcluster may illuminate a NE-trending fault. The linear dimension of the SW subcluster is ~0.5 km. On the other hand, the NE subcluster occurred in an area of 0.6 km by 1.5 km. The NE subcluster fault may be suborthogonal to the SW subcluster fault.

Cluster R4 occurred linearly on a fault orientating in NE-SW, directing to Pohang. The strike-slip focal mechanism solutions of the events are consistent with the seismicity distribution. Cluster R4 presents linear distribution with a length of 0.4 km. The events in cluster R4 occurred at depths of ~9.5 km for a short time period (two weeks). The SW subcluster of cluster R3 is located in NE from cluster R4. The seismicity in clusters R3 and R4 presents eastward deepening. The focal depths of clusters R2, R3, and R4 are generally deeper than those of inland events. Clusters R2, R3, and R4 are located in a stress-loaded region by the 12 September 2016 M5.8 (Mw5.4) Gyeongju earthquake and the 15 November 2017 M5.4 (Mw5.5) Pohang earthquake. Stress
may be loaded in the seismic gaps between the clusters.

6. Vertical extent of the faulting structure

The stress (pressure), temperature, and mineralogy may control the earthquake nucleation depth (Beroza and Kanamori, 2007). Favorably-oriented preexisting structures such as paleo rift and geological interface may respond to the ambient stress field. Preexisting structures may offer room to nucleate earthquakes. The focal depth may suggest information on the vertical extent of seismogenic structures and active tectonic evolution. The focal depths of earthquakes in the East Sea can be poorly resolved due to limited azimuthal coverage of seismic stations and laterally heterogeneous crustal structures. In order to constrain the focal depths of offshore events, we propose to use seismic records at vertically-spaced seismometers. The seismic phases in seismic records from vertically-spaced seismometers experience the same source-side and path effects. The relative phase arrival times of major phases (Moho-refracted and Moho-reflected phases) enable us to identify the focal depths.

We consider the 14 May 2023 $M_L 4.5$ Donghae offshore earthquake in cluster R1 of which the focal depth was reported to be 32 km by the Korea Meteorological Administration (KMA). Other events in cluster R1 were determined similarly by the KMA. The focal depths of the events are refined to be \( \sim 28 \) km by VELHYPO. The detected events have magnitudes less than $M_L 1.5$. The observation suggests deep focal depths near the Moho, corresponding to ductile lower crust in the continental crust or mantle lid. Such deep earthquakes may suggest brittle failure with seismogenic activation of paleo-rifting structures around the Moho.
7. Correlation between earthquakes, faults, and bathymetry

The earthquakes in the East Sea present characteristic spatial distribution, clustering near the coast. The focal depths change across the coast from inland to offshore regions. The focal depths of events in the East Sea are relatively deeper (>15 km) than those in the inland.
Also, the maximum focal depths generally increase with distance from the coast (Figs. 11, 12 and 13).

Most seismicity in the East Sea is distributed in a narrow region in distances ≤ 80 km from the coast where paleo-rifting structures are present (Hong et al., 2020b). Earthquakes rarely occur inside the Ulleung basin. Localized seismicity areas including the Pohang offshore region where the 12 September 2016 $M_{L} 5.8$ ($M_{W} 5.4$) Gyeongju earthquake and the 15 November 2017 $M_{L} 5.4$ ($M_{W} 5.5$) Pohang earthquake induced stress in the offshore regions, incurring successive aftershocks in the NE from the event.

We study the seismicity in local regions in the East Sea. The earthquakes occur in regions of bathymetry less than ∼ 2 km, including continental slope (western Ulleung basin). The continental slope is located around at bathymetry of ∼ 1 km. The bathymetry naturally il-

Fig. 8. (a) Map of event cluster R2. (b) Focal depths and (c) earthquake occurrence sequence in event cluster R2 in 2018–2023. Events are distributed in WNW-ESE. The focal depths are ∼23–24 km, deepening in SE. The earthquakes occurred sequentially from WNW to ESE. (d) Map of event cluster R3. (e) Focal depths and (f) earthquake occurrence sequence in event cluster R3. Events are clustered in two regions. The focal depths are ∼18–20 km, deepening in SW. The earthquakes occurred in the SW region before the NE region. (g) Map of event cluster R4. (h) Focal depths and (i) earthquake occurrence sequence in event cluster R4. Events are distributed in NE-SW. The focal depths are ∼9.5 km. The earthquakes occurred episodically for two weeks.
luminates the seafloor topography. The bathymetry is naturally controlled by the tectonic activity and structures in the region. Gravitational collapse occurs at the continental slope (Lee et al., 2003), suggesting possible stress concentration around the continental slope. Thrust events indicate possible links with preexisting structures. The tectonic history is responsible for the current seismic activity.

7.1. Zone Z1: northwestern East Sea

The offshore events in the northwestern margin of the Ulleung basin (zone Z1) are distributed in NE-SW (Fig. 11). High seismicity was observed in the offshore region at latitudes < 39°, while few earthquakes occurred at latitudes > 39°. The offshore events present reverse-faulting or strike-slip motions. The fault plane orientations of reverse-faulting events are subparallel to each other, suggesting successive development of subparallel structures around the coast. The subparallel

![Fig. 9](image_url)
structures may develop effectively near the coast.

The ambient stress field is composed of the maximum principal stress oriented in N79.9° E to N82.6° E, and the minimum principal stress oriented in N7.4° W to N10.1° W (Fig. 11(b)). The fault plane solutions suggest that the ambient stress field is responsible for the offshore events. The North Korean Plateau and South Korea Plateau are placed in latitudes > 37.5° N, which may not respond to ambient stress effectively in the region above 39° N. The orientation of the preexisting structures may hardly respond to the ambient stress field, presenting few earthquakes in the region. The observation suggests that the structure posture is important in earthquake occurrence (Fig. 14).

There is clustered seismic activity in the region (cluster R1) where the 14 May 2023 M4.5 earthquake is the mainshock in the earthquake sequence from April to June 2023 (Fig. 5). The M4.5 event. The earthquake sequence includes 287 events with magnitudes ≥ M0.7 (Fig. 5(c)). The earthquake sequence presents episodic earthquake occurrence (Fig. 11). The events are distributed linearly in NE-SW.

The events occur sequentially, expanding the fault zone in NW-SE from the center. The events in SW are slightly deeper than the NE events, suggesting NE to SW directional dimpling of the fault plane. The event occurrence moves from SE to NW. Successive subparallel strike-slip faulting occur. The events are clustered in small areas with lateral dimensions of 0.5 km. The mainshock, the 14 May 2023 M4.5 earthquake, occurred in the northwestern margin of the fault zone. After-shocks followed the mainshock on the fault plane. Small events increased one day before the mainshock. The focal mechanism solutions of events including the M4.5 earthquake present reverse faulting sense. The seismicity distribution agrees with the focal mechanism solutions. The linear distribution of events may suggest fault-slip associated events.

7.2. Zone Z2: midwestern East Sea

Most offshore earthquakes in the region are distributed in a region between the east coast and the western margin of the Ulleung basin. The seismicity is concentrated in the offshore region of bathymetry ≤ 2 km, mostly < 1 km, that corresponds to continental slope and continental margin (western margin of the Ulleung basin). The structure geometry is generally consistent with the bathymetry. The structure was formed by tectonic activity. Paleo-rifting structures may be present in the crust. The deep bathymetry region (oceanic basin) was formed during the continental rifting. High Pn (mantle-lid P wave) velocity anomalies along the western margin of the Ulleung basin may suggest the embedding of mantle materials (Hong and Kang, 2009). The observation suggests highly perturbed media by paleo-rifting fractured regions in the region between the coast and continental slope beside the western margin of the Ulleung basin.

The paleo-rifting structures are oriented in N-S along the coast. The seismicity distribution suggests the presence of a series of structures subparallel to the coast. Strike-slip events are dominant in the region. Also, reverse faulting events occur in the subparallel structures. The stress field effective for earthquake occurrence is composed of ambient stress and induced stress from precedent local events. The increased seismicity is located in a region of increased Coulomb stress changes by the 12 September 2016 M5.5 (Mw5.5) Gyeongju earthquake and the 15 November 2017 M5.4 (Mw5.5) Pohang earthquake (Fig. 7). The strike-slip earthquakes occur in the stress increased region by the 12 September 2016 M5.5 (Mw5.5) Gyeongju earthquake and the 15 November 2017 M5.4 (Mw5.5) Pohang earthquake. The mid and lower crustal events may suggest the persistent development of paleo structures in the region.

The lateral stress field is composed of compression oriented in N82.8° E to N86.0° E and tension oriented in N4.0° W to N7.2° W (Fig. 12).
The stress field causes the reverse faulting in the paleo structures (Fig. 12). The reverse faulting events present the fault plan orientations that are subparallel to the paleo-rifting structures. Strike-slip events display nodal planes in the NE-SW and NW-SE, which are consistent with those of strike-slip events in the coastal inland region. The maximum focal depths of the events are 12–15 km around the coast, 15–22 km in 30 km from the coast, and 18–32 km in 60 km from the coast (Fig. 12(c)). The maximum focal depth generally increases with the distance from the coast. The observation suggests effective seismogenic activity in the paleo-rifting structures (Fig. 14).

Fig. 12. (a) Map of the midwestern East Sea (zone Z2). (b) Spatial distribution of earthquakes with focal depths and focal mechanisms. Most earthquakes occur in distances <80 km. The bathymetry is parented (contour). The ambient stress field is indicated. (c) Maximum focal depths. The maximum focal depth increases with bathymetry.

(b)). The stress field causes the reverse faulting in the paleo structures (Fig. 12). The reverse faulting events present the fault plan orientations that are subparallel to the paleo-rifting structures. Strike-slip events display nodal planes in the NE-SW and NW-SE, which are consistent with those of strike-slip events in the coastal inland region. The maximum focal depths of the events are 12–15 km around the coast, 15–22 km in 30 km from the coast, and 18–32 km in 60 km from the coast (Fig. 12(c)). The maximum focal depth generally increases with the distance from the coast. The observation suggests effective seismogenic activity in the paleo-rifting structures (Fig. 14).

Fig. 13. (a) Map of the southwestern East Sea (zone Z3). (b) Spatial distribution of earthquakes with focal depths and focal mechanisms. The bathymetry is parented (contour). The ambient stress field is indicated. (c) Maximum focal depths. The maximum focal depth is large around the continental slope.
However, the nodal plane directions of the strike-slip events are not subparallel to the existing paleo structure orientations that are generally in N-S along the coast. The observation suggests that the strike-slip faults might develop across the preexisting backbone structures in accordance with the current stress field (Choi et al., 2012; Hong et al., 2020b; Park et al., 2023). The preexisting structures develop faults spawning earthquakes (Park et al., 2023). There are clustered events in the region where stress is induced from the 12 September 2016 $M_{L}5.8$ ($M_{W}5.4$) Gyeongju earthquake and the 15 November 2017 $M_{L}5.4$ ($M_{W}5.5$) Pohang earthquake (clusters R2, R3, and R4 in Figs. 7 and 8). The seismicity increased in the Pohang offshore region after the 12 September 2016 $M_{L}5.8$ ($M_{W}5.4$) Gyeongju earthquake and the 15 November 2017 $M_{L}5.4$ ($M_{W}5.5$) Pohang earthquake. The observation suggests that the current seismicity is remarkably affected by precedent seismicity.

7.3. Zone Z3: southwestern East Sea

The southwestern region presents complex seismicity distribution (Fig. 13). The region is located in the southwestern corner of the Ulleung basin. Geological structures develop in a fan shape around the basin. It is argued that the southwestern corner of the Ulleung basin is located near the pivot location to open the East Sea (Otofuji et al., 1985). The fault plane orientations are subparallel with the geological structures in a fan shape. The fan-shaped structures are present around the southwestern margin of the Ulleung basin, which may have developed during the opening of the East Sea. Strike-slip events are dominant in the region. On the other hand, reverse-faulting events are rare in the region.

The bathymetry of 1 km is a confining boundary for the seismicity in the region similar to zone Z2. The bathymetry of $<1$ km may be a constraint to find the seismicity region in zone Z3. The bathymetry generally follows the fan-shaped structures in which the medium was perturbed due to tectonic evolution. We observe relatively low seismicity in regions of deep oceanic basins (bathymetry $>1$ km). Most focal depths of offshore events are $>10$ km. The focal depths of inland events near the coast present the focal depths of $<10$ km. The focal depth increases with the distance from the coast.

The lateral stress field is composed of compression oriented in N$78.8^{\circ}$E to N$87.0^{\circ}$E and tension oriented in N$3.0^{\circ}$W to N$11.2^{\circ}$W (Fig. 13 (b)). The successive ambient stress field change in zone Z3 incurs earthquakes around the fan-shaped preexisting structures (Fig. 13). Fault plane solutions are consistent with the fault structures around the Dolgorae thrust belt. The observation suggests that the preexisting structures behave as backbone structures to induce seismicity and new faults (Fig. 14). Also, the correlation between the bathymetry and seismicity suggests a possible fault structure development mechanism and event distribution.

8. Neotectonics

Reverse faulting earthquakes occur in the East Sea. The earthquake distribution may illuminate the seismogenic structures in the East Sea. The brittle-ductile transition zone may be placed at a depth of $>20$ km in the continental crust (Hong and Menke, 2006; Beroza and Kanamori, 2007). Additionally, the brittle deformation may occur up to a depth of 35 km in the mantle. The extended (transitional) continental crust...
presents similar brittle deformation in the mantle lid. The stress may accumulate at depths of $\geq 20$ in the extended crust.

The maximum principle stress ($\sigma_1$) and minimum principle stress ($\sigma_3$) are lateral stress components that are mainly controlled by lithospheric deformation (compression or extension). In the seismogenic zones in the western East Sea, the lateral compression stress field is oriented in N78.8$^\circ$E to N87.0$^\circ$E, and lateral tension stress field is in N3.0$^\circ$W to N11.2$^\circ$W (Figs. 6, 11(b), 12(b), 13(b)). The stress field changes gradually with location. The intermediate principle stress is the vertical stress component that corresponds to the gravity effect. The principle stress is effective in the lithosphere. The yield strength depends on the lithology and temperature, presenting depth-dependent variation. Brittle failure is difficult to happen at low crust and mantle-lid in the intraplate regime (Scholz, 1989; Beroza and Kanamori, 2007).

Earthquakes around the continental slopes in the western Ulleung basin suggest lower crustal or mantle-lid events. The events occur linearly in NE-SW. The events migrate linearly in NW. The events rupture over the fault plane. The continental-slope region presents a transitional structure between the continental crust and oceanic crust. The continental slopes are both in the shallow east coast, and 2' in the north-western East Sea.

Mantle-lid $P$ ($P_n$) velocity distribution suggests low density materials in oceanic basins (Fig. 2(o)) (Hong and Kang, 2009). On the other hand, high $P_n$ velocity anomalies around the paleo continental rifting structures along the east coast suggest mantle uplifting during the continental rifting. The current seismicity is clustered in the paleo rifting structures. Reverse-faulting earthquakes occur in the lower crust and mantle lid including the Korean plateau of the north-eastern East Sea. Earthquakes in the mantle are unusual in the continental crust. The episodic earthquake occurrences may suggest effective stress release. The features may occur in existing paleotectonic structures.

The observation suggests that the reverse slip may continue from the upper crust to the Moho (Fig. 14). The paleo-rifting structures behave as reverse faulting systems, initiating a primitive subduction. The primitive subduction is supported by independent geological and geophysical observations (Choi et al., 2012; Kim et al., 2018). A west-dipping major thrust and coincident thrust buckling of the Ulleung Basin, gravity anomaly suggests an east-west structural asymmetry, and ongoing crustal uplift and high-angle faults suggest the initiation of primitive subduction in the paleo-rifting structures (Choi et al., 2012; Kim et al., 2018). Further, we observe a series of reverse faulting system extending to the lower crust, suggesting a development a fault system across the crust.

The 2011 $M_w$9.0 Tohoku-Oki megathrust earthquake might enhance the stress instability in the lithosphere (Hong et al., 2018, 2020a). The primitive subduction may be effective along the paleo-rifting structures. However, the seismicity poorly envisions the subduction geometry. Primitive subduction may be initiated piecewise along the western margin of the Ulleung basin.

9. Discussion and conclusions

The East Sea is a unique place to have a paleo continental rifting zone under the lateral maximum principle compression (Fig. 1) (Choi et al., 2012; Kim et al., 2018). The paleo-rifting structures respond to the ambient stress, incurring seismic activity. A major earthquake in the region may cause high damage around the coastal and inland regions. The seismic and geophysical properties change across the paleo-rifting structures, and the medium property changes in the paleo-rifting structures. Both reverse faulting earthquakes and strike slip earthquakes occur in the region. The reverse faulting events occur on the paleo normal faults of paleo-continental rifting. The weak media around the paleo-rifting system respond to the ambient stress, causing strike slip earthquakes.

The maximum focal depth generally increases with distance from the coast (Figs. 11(c), 12(c), 13(c)). The maximum focal depths are large around the continental slope of the western East Sea. The maximum focal depths suggest the vertical extent of seismogenic structures. The lower-crustal focal depths can develop at effective stress loading and weak-structure presence in the lower crust. The increasing maximum focal depths with distance from the coast suggest effective development of structures in offshore regions.

The observation suggests that the preexisting paleo-rifting structures may be responsible for the lateral variation in maximum focal depths. Mid to lower crustal earthquakes occur around the paleo-rifting structures. Deep crustal earthquakes were refined from phase arrival time analyses. Episodic clustered earthquakes occur in local areas where stress was induced from the 12 September 2016 $M_w$ 5.8 ($M_{W}$5.4) Gyeongju earthquake and the 15 November 2017 $M_w$5.4 ($M_{W}$5.5) Pohang earthquake. The spatiotemporal clustering of earthquakes suggests episodic stress release at local structures that extend to the lower crust and Moho. This seismogenic activity suggests active stress loading and releasing around the Moho, satisfying that the loaded stress should be greater than the yield strength to have seismic events.

The reverse faulting earthquakes may occur in preexisting structures in intraplate regions. The paleo-rifting structures extending in the crust provide weak media to respond to the ambient stress seismically. The ambient stress is a composite effect of tectonic loading from active plate boundaries and vertical gravity instability on the continental slope, incurring earthquakes in the paleo-rifting structures across the crust effectively. The seafloor topography and faulting type suggest the discriminative response of paleo-rifting structures on the ambient stress. The lateral variation in maximum focal depths suggests thrust evolution across the crust in the paleo-rifting structure. Also, the reverse-faulting earthquakes around the Moho may suggest a neotectonic evolution of primitive subduction to cause successive crustal and mantle deformation along the paleo rifting structures.

CRediT authorship contribution statement


Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests.

Tae-Kyung Hong reports financial support was provided by National Research Foundation of Korea. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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