Fault intersections control short period intraplate start-stop seismicity in the Korean Peninsula

Alireza Malehmir a, b, Tae-Kyung Hong b, c, Junhyung Lee b, Samuel Zappala a, Bojan Brodic a, Dongchan Chung b, Byeongwoo Kim b, Seongjin Park b, Jeongin Lee b, Dongwoo Kil b

a Dept. of Earth Sciences, Uppsala University, Villavägen, 16, Uppsala, Sweden
b Dept. of Earth System Sciences, Yonsei University, 50 Yonsei-ro Seodaemun-gu, Seoul, South Korea

1. Introduction

The Korean Peninsula’s bedrock is predominantly Paleoproterozoic (Cough et al., 2000) and seismically relatively stable. Quaternary faults are present and run through the country, including through metropol-itan Seoul (Choi et al., 2012; Bae and Lee, 2016). Although past major earthquakes are known from historical recordings (Lee and Yang, 2006; Park et al., 2020), the Peninsula has until recent days been in a stable intraplate seismic state sandwiched between Eurasian, and Pacific-Philippine plates (Fig. 1). The 2011 Tohoku-Oki mega-thrust Mw 9.0 earthquake in Japan appears to have changed the situation resulting in more than 5 Mw 5.0 earthquakes being recorded in the Peninsula since 2011, compared to only 5 events since the 70s up to 2011 (Hong et al., 2018). It resulted in coseismic displacements of ~2-4 cm around the east and west coasts of the Korean Peninsula and weakened the Korean crust, likely and partly increasing the seismic activity (Hong et al., 2017; Hong et al., 2018). This includes the 2016 Mw 5.4 (ML 5.8) Gyeongju earthquake, the largest event recorded in the history of recent seismic monitoring in South Korea.

South Korea is a densely populated country including metropolitan Seoul area that hosts over 20 million inhabitants. Any major earthquake in the region can be a significant threat to the people as well as can give damages to historical buildings. It is therefore essential that active faults and the relationship(s) between triggering mechanisms and fault geometry are identified for better earthquake magnitude estimations (Leonard, 2010; Malehmir et al., 2016), preparedness, and city planning. However, due to the high population density, mapping of these fault systems is challenging in this noisy and logistically difficult mega-city environment. There is a great need for improved understating of subsurface geology in major cities, especially since many mega-cities are in regions of high geohazard risks (Zoback et al., 2010). Geophysical methods such as seisms can be useful for this purpose (Malehmir et al., 2000).
Fig. 1. (a) Recent seismicity, showing mainly strike-slip focal mechanism, recorded in South Korea and the location of the two reflection profiles. (b) Profile 1 crosses the Chugaryeong fault, and a dense set of seismic events clustered between 4.5 and 5 km and 8–9 km depth intervals. (c) Profile 2 also crosses the Chugaryeong fault and on its most eastern part reaches the Pocheon fault. The locations of the fault systems are approximate and based on extrapolation from rivers and valleys. Note larger magnitude earthquakes in South Korea are not in the study area.

Fig. 2. (a-c) Photos from profile 1 showing how wireless recorders were positioned with respect to the sources and the landstreamer. Vib2 was used as the observer location for data recording and time stamping. Photos taken by Alireza Malehmir.
2011). Ambient vibrational noise is however a major challenge for urban seismic data acquisition, as well as ground-receiver coupling (Brodic et al., 2015; Malehmir et al., 2015). Encouraging results obtained in city environment using new acquisition setups and systems such as digital sensors (Malehmir et al., 2016; Malehmir et al., 2017; Kammann et al., 2019) can be used in mega-cities to define the deep geometry of faults and its relationship with seismicity clusters. For this reason, two reflection seismic profiles (Fig. 1) were planned and acquired during November 2020, which are the focus of this study.

2. Background geology and seismicity

Korean peninsula sits in the Eurasian plate at the contact with the west Pacific-Philippine plate (Fig. 1). The basement rocks are cut by various rifts forming in the Palaeozoic period, linear basement features, and in Mesozoic and Cenozoic, troughs filled with thick continental clastic sediments (Kim, 1997). Tectonic evolution of the peninsula can be divided into three phases (Kim, 1997) namely (1) ancient geosyncline stage that occurred during Archean (2.6 Ga) to Proterozoic (1.8 Ga), (2) stable platform stage that occurred during Middle Proterozoic (1.7 Ga) to Late Palaeozoic (260 Ma) and (3) an intense stage influenced by the movement of the west Pacific plate during Mesozoic (230 Ma) to Holocene (present). The latter stage is more significant when studying the fault systems, magmatism, and deformation evolution of basement rocks. It is generally believed that quaternary tectonics are related to volcanic activities and that basement faults formed during the Mesozoic are responsible for much of the seismicity observed in the region.

The South Korean government has supported several initiatives to study the current state of seismicity and map active faults in the country. Based on these studies (Hong et al., 2018; Hong et al., 2021), two sites were chosen for the reflection seismic surveys (Fig. 1a). Seismic activity was a primary consideration in choosing the sites (Fig. 1a). Profile 1 was positioned on the northern side of the metropolitan Seoul and profile 2 in the central part of the city. Both profiles cross the Chugaryeong crustal-scale fault where seismicity appears to show a spatial relationship with the fault. The Pocheon and Wangsukcheon faults, mapped east of the Chugaryeong fault (Fig. 1b), appear to form splay faults as they reach in the city south of profile 2. The Pocheon fault is mapped approximately 17 km east of profile 1 and immediately east of profile 2 (Fig. 1c). Other fault systems are likely also present between the Chugaryeong and Pocheon faults but covered or have no surface expressions. Recent focal mechanism data (Fig. 1c) along the Chugaryeong fault show a near-vertical (or steep) strike-slip sense of movement (Hong et al., 2018; Hong et al., 2021).

3. Reflection seismic data

Two 9 t vibrators (Figs. 2 and 3 and supplementary Fig. S1) in a phase-locked time-synchronized manner were used to acquire the data. Along profile 1, four repeated sweeps at every shot location were used while for profile 2 five sweeps were used. The data quality is relatively good along profile 1 with occasionally strong reflections even observed in the raw shot gathers (Fig. 4) while along profile 2 data are much noisier. For profile 2, first arrivals were only occasionally observed beyond 3 km and, in most cases, limited to 500–1000 m offsets.

The processing steps and parameters were chosen and tailored to enhance the reflectivity in the data as much as possible. The landstreamer data processing focused on the bedrock reflection while the wireless data aimed at deeper reflections. The top 200 ms of the merged data is from the landstreamer. The wireless data cannot image the bedrock as the overburden effect is removed during the refraction static corrections and the receiver spacing between the wireless recorders is...
rather large (i.e., 20 m) for this purpose. Along profile 1, data processing of the wireless data focused on two-time windows: (1) top 2 s and (2) 2–4 s data. This strategy was needed as the uppermost 2 s contain significant surface-wave energy that required median and FK (frequency-wavenumber) filtering. After separate processing, the two datasets were merged amplitude levelled and migrated together.

3.1. Seismic data acquisition

Data triggering was done via a GPS (global system positioning) time disciplined data acquisition system connected to the streamer and towed by the so-called observer/recording source (second mini-vib behind, Fig. 3). The source points were positioned between the two mini-vibs at the receiver stations. The min-vibs are approximately 8 m long. The data acquisition equipped with a GPS-antenna provided microsecond

---

Fig. 4. (a) Example of a raw shot gather from profile 1 showing prominent reflections (S1) observed at around 1200–1500 ms. (b-d) The same as (a), but after various processing steps as illustrated by the zoomed-in part. The reflective set is in connection with the first cluster of seismicity observed at 4.5–5 km depth.
accuracy time sampling and stamping of the active source data on the landstreamer sensors. This time stamping of the active sources in the streamer data were later used to extract their corresponding data from the wireless recorders that were operating in an autonomous mode (passive) during the survey (Fig. S1). Prior to the data acquisition, we spent one full day to optimize sweep parameters and made sure that data quality was sufficient and the two mini-vibs operated simultaneously in a phase-locked manner. The sweep tests included change in the frequency ranges and lengths. We used our earlier experience from crystalline-setting surveys to optimize the testing and limit the number of sweep variables. The sweep tests ranged from 10 to 120 Hz (12–22 s), 10–140 Hz (16–18 s), 5–120 Hz (16 s) and 5–140 Hz (18 s). 10–140 Hz (18 s) was judged best for the data acquisition. The starting 5 Hz frequency produced enormous surface-waves and was judged sub-optimum for the ground condition along the profile. Amplitude spectrum of 10–140 Hz (18 s) appears also to be flatter than other cases.

Fig. 5. Sweep parameter tests were conducted along profile 1 using the landstreamer sensors where this was possible without logistical complexities. Tests were done using linear sweeps ranging from 10 to 120 Hz (12–22 s), 10–140 Hz (16–18 s), 5–120 Hz (16 s) and 5–140 (18 s). 10–140 Hz (18 s) was judged best for the data acquisition. For the sweep length, 18 s produced higher quality data than others tested thus chosen for the data acquisition guaranteeing that low frequencies would have sufficient energy for deeper penetrations.

Analysis of the data along profile 2 suggests that occasionally receiver gathers have much higher data quality than the shot gathers. This implies while the ambient noise is high in the city, ground coupling is the main reason for the relatively poor data quality; i.e., where the ground coupling of geophones is good, reasonable quality data with even reflections are observed (c.f., a shot gather against receiver gather in Fig. 7).
3.2. Seismic data processing

Bandpass and spectral equalization were effective to partly handle strong surface-waves in the data. Spectral balancing was also applied poststack as well as coherency improvement filters such as FX-deconvolution. Various migration algorithms were applied; however, phase shift migration produced the least migration artefacts and was selected. Different velocities were used for the migration; for profile 1, a 1D velocity between 4000 and 6300 m/s was used. For the time-to-depth conversion we used a constant velocity of 6000 m/s. Slight changes in the dip (5–10 degrees) and positioning (100–300 m) of the reflections can consequently be expected but this is not so significant for the scale of this study.

The important processing steps were refraction static corrections, prestack data enhancement and velocity analysis (Table 2). Velocity analysis was important because of the steep and sometimes conflicting dips. The streamer and wireless data were processed separately and then merged later (supplementary Figs. S2 and S3). Along profile 1, data processing of the wireless data focused on two different time windows: (1) top 2 s and (2) 2–4 s data. Once the two parts were processed and imaged, they were then merged and using a levelling amplitude algorithm (Place and Malehmir, 2016), the data amplitudes between the two parts were adjusted (Fig. 8).

Along profile 2, apart from the conventional processing workflow like that applied along profile 1, a major time and effort was put into removing noisy traces and analysing which receiver gathers had good quality data (Fig. 7) to allow partial stacking of their reflections. This strategy helped to image the steepest reflections observed on the city profile (R4 in supplementary Fig. S4). Given the extreme crooked nature of the profile, we also performed cross-dip analysis (Malehmir et al., 2011) to benefit from the midpoint cloud distributions and make sure reflections not favouring the orientation of the profile could still be imaged and their out-of-the-plane nature identified. This resulted, for example, in a better imaging of a reflection (R5 in supplementary Fig. S4) observed at the most curved location of the profile.

Complex reflectivity is observed along profile 2 however profile 1 shows better correlation between reflectivity and the clusters of seismicity. A temporal and spatial correction is evident (Fig. 9). To complement the bedrock reflection imaging of the landstreamer data, first-break traveltime tomography was also implemented on wireless data.

Table 1
Main reflection seismic acquisition parameters of profiles 1 and 2 in South Korea, November 2020.

| Spread parameters                  | Profile 1       | Profile 2       |
|------------------------------------|-----------------|-----------------|
| Recording system                   | Sercel Lite     | Sercel Lite     |
| Survey geometry                    | Fixed           | Move-along asymmetric split-spread |
| No. of receivers                   | Wireless: 282 (1001–1282) | Wireless: 393 (2491–2890) |
| No. of shots                        | 246 (4 sweep records/point) | 314 (5 sweep records/point) |
| No. of shots                        | 20 m wireless, 2 m | 20 m wireless, 2 m |
| Maximum offset                     | ~ 5640 m        | ~ 5660 m        |
| Source type                        | Two min-vibs, 10–140 Hz | Two min-vibs, 10–140 Hz |
| Geophone                           | Wireless: 10 Hz, spike | Wireless: 10 Hz, spike |
| Sampling interval                  | 1 ms            | 1 ms            |
| Record length                      | 23 s (5 s used for processing) | 23 s (5 s used for processing) |
| Wireless data harvesting           | GPS time        | GPS time        |
| Total no. of traces                | 69,370          | 79,442          |
| Maximum CDP fold                   | 141             | 151             |
| Geodetic surveying                 | corrected using 50 national grid | corrected using 50 national grid |
Fig. 7. (a) Example of a raw (after vertical stacking of the repeated four shot records) and (b) shot processed gather, and respective amplitude spectrum from profile 2. (c) Example of a raw and (d) processed receiver gather showing a reflection between 500 and 750 ms. Note that the shot gather at the same position does not show any clear evidence of the reflection. This implies that the position of the receiver has much more weight on the data quality than the shot energy.

Table 2
Key reflection data processing steps along profiles 1 and 2, South Korea.

| Steps     | Northern profile       | City profile              |
|-----------|------------------------|---------------------------|
| 1         | Read SEG data          | Read SEG data             |
| 2         | Zero-time correction and cross-correlation with the theoretical sweep | Zero-time correction and cross-correlation with the theoretical sweep |
| 3         | Vertical shot stacking (4 shot records) | Vertical shot stacking (5 shot records) |
| 4         | Geometry setup (CDP spacing 10 m for both streamer and wireless data) | Geometry setup (CDP spacing 10 m for both streamer and wireless data) |
| 5         | First break picking    | First break picking       |
| 6         | Refraction static corrections | Refraction static corrections |
| 7         | Elevation static corrections (310 m, 5000 m/s) | Elevation static corrections (110 m, 4000 m/s) |
| 8         | Notch filter: not applied | Notch filter: 60 Hz       |
| 9         | Band pass filter: 10–30-120-140 Hz | Band pass filter: 10–30-120-140 Hz |
| 10        | Spectral balancing: 20–45-90-130 Hz | Spectral balancing: 20–45-90-130 Hz |
| 11        | FK and median filters (steepest events) | FK and median filters (steepest events) |
| 12        | AGC (300 ms)           | AGC (300 ms)              |
| 13        | Residual static correction (2 runs) | Residual static correction (2 runs) |
| 14        | NMO corrections (50% stretch mute) | NMO corrections (50% stretch mute) |
| 15        | Stack (normal)         | Stack (normal)            |
| 16        | FX-deconvolution       | FX-deconvolution          |
| 17        | Balance amplitude (full window) | Balance amplitude (full window) |
| 18        | Padding (500 traces)   | Padding: not applied      |
| 19        | Migration (phase shift, 4000–6300 m/s) | Migration (phase shift, 4000–5500 m/s) |
| 20        | Time-to-depth conversion (6000 m/s) | Time-to-depth conversion (6000 m/s) |
| 21        | Export for plotting and 3D visualization | Export for plotting and 3D visualization |
since they have much higher offsets than the landstreamer (40–240 m depending on which profile).

4. Results

Profile 1 is rich in reflectivity from bedrock down to 4 s (approximately 12 km depth). An increase in bedrock depth on the landstreamer section has a corresponding velocity decrease and coincides with a gap in the shallow reflectivity where two sets of reflections (R1 and R2) are interrupted by a vertical zone of non-reflectivity (Fig. 10). A set of moderately westerly-dipping reflections are also imaged at approximately 4–4.5 km depth and at 8–9 km depth, a series of steep reflections. These two sets of reflectivity bands terminate at two clusters of seismicity. From the source mechanism and the reflectivity pattern, we position the location of the Chugaryeong fault between R1 and R2 as a subvertical fault (Fig. 10a) where an increase in bedrock depth is also observed suggesting a zone of crushed and disturbed rocks. The near-vertical zone of decreased amplitudes between the two sets of reflectivity (R1 and R2) would then be due to no coherent structures to generate reflections.

The two clusters of seismicity and reflectivity intersect each other at 4–4.5 km and 8–9 km depth. The seismicity is dominantly locked at the intersections of these three features in the reflection seismic section (Fig. 10b). While there are other smaller features in the seismic section (e.g., the western margin of the section), only the key reflections are focused here. S2 sets of reflectivity appear to be a thicker package, implying an extensive fault or shear zone. However, the most continuous reflective zone intersects the deeper cluster of seismicity.

Along profile 2, the images are rather complex showing a strong westerly-dipping reflective band (S3 in Fig. 11) on the easternmost side of the profile, extending from the surface down to approximately 1200 m depth, like S1 reflectivity along profile 1 but at much shallower depths.

Fig. 8. Unmigrated stacked section of profile 1 shown for (a) the merged top 2 s of the landstreamer data and wireless data and tailored processed 2–4 s data of the wireleses. This section now provides a complete image of the top 4 s along profile 1 with a number of reflections of different characters. (b) A zoom in the deeper reflectivity package. Coloured circles show the seismicity data from the area projected with the focal mechanism solutions (mainly thrust to strike-slip) and when they were recorded during 2010–2021. Note that not all the seismicity data have focal mechanism solution (shown with blue and red colours). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
bands of seismic reflectivity are interpreted to intersect these events along the Chugaryeong fault. These observations are also reported elsewhere from intracontinental, and splay thrust faults (Jackson, 1992; Jackson, 2002) where counter-clockwise rotation around the vertical axis triggers strike-slip displacement. This observation is important for both public safety consideration and for understanding how future earthquakes may be triggered and at what depth. The Pocheon fault may be also more moderately dipping than earlier thought.

The interconnection between seismicity and subsidiary faults has earlier been suggested elsewhere by several authors, however, mainly based on seismological observations (Walters et al., 2018) or where reflection data available in different geological settings (Ahmadi et al., 2015), and large uncertainty in locating the events and without any direct evidence from the subsurface. Fluid diffusion, channelled along fault intersections, is argued for the re-initiation of earthquakes. Interestingly, Gangopadhyay and Talwani (2005), through numerical modelling, also argued that fault intersections, at the presence of a weak crust, are ideal locations for stress build-ups and seismicity (Talwani, 1988). However, they had no subsurface images to support their claim. Furthermore, fault intersections and subsequent stress build-ups are observed to trigger strike slip motions on major faults because of kinematic adjustment and followed by vertical or horizontal movement on the splay faults (Talwani, 1988). These are consistent with the seismicity records along the two profiles and our interpretation of the fault intersections as the controlling factor of seismicity in the region. Notably, the well-known 2017 Pohang earthquake (Mw 5.4) in South Korea is thought to be associated with multiple fault intersections and geometries (Son et al., 2020). This further emphasizes why it is critical to image fault systems in the subsurface and integrate seismological studies with active-source reflection seismic data.

The seismicity not only spatially correlates with the fault intersections but also correlates in time (temporally), implying a start-stop mechanism for triggering and re-initiation of seismic events along the Chugaryeong fault. These observations are unique and open up for possibilities to predict where and possibly within what period earthquakes may occur. For the same magnitude seismic event, if geomechanically possible, shallower seismic events can be much more worrying than deeper ones when seismic risks are considered. Our data and the switching between depth and time provide for the first time a window of opportunity for studying risks and predicting potential hazards due to seismicity in the region. Long-term monitoring of seismicity is highly recommended to shed light into the interpretations provided in this study.

6. Conclusions

Two high-resolution high-fold reflection seismic profiles were acquired in the metropolitan Seoul, South Korea, for studying fault systems with the aim of helping to explain the current seismicity in the Peninsula after the devastating 2011 Tohoku-Oki earthquake. The northern profile presents a reflectivity-seismicity relationship. The city and northern profiles have one important feature in common and that is the reflective character from the same fault zone, which we have interpreted to be a splay fault from the sub-vertical Chugaryeong fault. It is an important observation for the citizens in a megacity like Seoul and it is worth verifying. This interpretation along with the observation of clustered

Fig. 9. Eleven years (2010–2021) of seismic activity records along profile 1 showing time clustered seismicity at two depth intervals where two distinct bands of seismic reflectivity are interpreted to intersect these events along the Chugaryeong fault. (Fig. 10c), and although about 70 km to the north, so highly speculative. From surface geological mappings and seismicity data (Fig. 1), a fault can be interpreted where S1 reflectivity is interrupted, extending down to where the seismicity is observed. The bedrock is not well imaged since a limited number of landstreamer sensors were used due to the logistical challenges in the city. The seismicity occurs at 7–9 km depth on the westernmost portion of profile 2 and mainly in this cluster. It occurs at a region of distinct discontinuous reflectivity (e.g., between R3 and R4 in Fig. 11). From the surface expression of topography and subsurface reflectivity patterns, a series of interrupted curved-shaped geological features can be interpreted. These features are likely due to a series of fault systems rather than lithology. The noise level is rather high in the city, and it is not possible to image deeper than 1500 m. Surface geological mapping suggests that most faults in the region are steep to vertical, although the lack of sufficient exposure and road cuts hinder definite identification of the fault geometries.

5. Discussion

Reflection sections from the two profiles indicate a direct relationship between the clustered seismicity and reflectivity. The Chugaryeong fault is sub-vertical as it cuts through reflections R1 and R2 and the two sets of reflectivity (S1 and S2) represent splay faults or zones of deformation associated with it. The S1 and S2 deeper bands of reflectivity are either smaller faults between the Pocheon and Wangsukcheon fault systems or being parts of the faults themselves, especially since the Pocheon fault may show itself on the city profile. The Chugaryeong fault is seismically active, and mainly locked at the intersections of these splay faults. The oblique shortening (Fig. 1a) is responsible for the strike-slip faulting at these fault intersections. Similar observations are also reported elsewhere from intracontinental, and splay thrust faults (Jackson, 1992; Jackson, 2002) where counter-clockwise rotation around the vertical axis triggers strike-slip displacement. This observation is important for both public safety consideration and for understanding how future earthquakes may be triggered and at what depth. The Pocheon fault may be also more moderately dipping than earlier thought.
Fig. 10. (a) Seismic section of profile 1 showing strong temporal and spatial correlation between zones of reflectivity and the two clusters of seismicity. (b) The sudden increase in bedrock depth along with the interruption in the reflectivity at shallow depth (R1 and R2) is interpreted as due to the presence of the Chugaryeong sub-vertical fault. (c) The two other sets of reflectivity at 4–4.5 and 8–9 km depths are interpreted to represent splay faults or zones of deformation and likely are related to the Pocheon fault or nearby fault systems. The intersections of these fault systems are where the seismicity is dominant and provide evidence for a release and locking, or start-stop, mechanisms, both spatially and temporally.

Fig. 11. Seismic section of profile 2 with seismicity (at depth of 7–9 km) projected onto the surface (yellow spheres). S3 reflections have similar character as the S1 observed along profile 1 and projects onto the surface at the location of the mapped Pocheon fault. The Chugaryeong fault should be presence at where the S3 reflections terminates and a major river runs. If this interpretation is correct (preferred interpretation), then the Chugaryeong fault will not be vertical in this part of the region and would have a steep dip towards the west reaching seismic events recorded at 8–9 km depth intervals. It is also possible that the Chugaryeong fault is present between the R3 and R4 sets of reflections where a sudden change in the reflectivity character is observed. R5 reflection that is better imaged in the cross-dip corrected section (see supplementary Fig. S4) could also project to the location of the seismicity however there is not support for this. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
seismicity associated with the reflectivity implies that much of the current seismicity in the Korean Peninsula is controlled both temporally and spatially at the intersection of fault systems forming a major flower structure showing a start-stop faulting mechanism that is both temporally and spatially controlled at the fault intersections.

Data availability

The seismicity data analysed in this study were collected from the website of the Korea Meteorological Administration (KMA, http://www.kma.go.kr). The reflection seismic data are being archived in the Swedish National Data Service (https://www.snd.gu.se) and additional hard copies are presented in the Supporting Information in the form of shot records and final seismic sections.

Author contributions

T.-K.H initiated the project. A.M planned the survey and together with the team from Uppsala University and Yonsei University performed the data acquisition. A.M. processed the data, prepared the figures and wrote the first draft of the article in discussion with T.-K.H, J.L, S.Z, B-B, Junhyung-L, D-C, B-K, S-P, Jeongin-L, and D-K, finalized the manuscript. S.Z performed the traveltime tomography and cross-dip analysis. All authors, particularly, A.M, T.-K.H, Junhyung-L, S.Z, B-B, were involved in the discussions of the results and their interpretations.

Declaration of competing interest

The authors declare no competing financial and non-financial interests.

Acknowledgements

We thank the contributions of many students and post-docs from Yonsei University and Uppsala University, Geopartner and C&H Company. This work was supported by the Korean Meteorological Administration (KMA) Research and Development Program under grant KMI2022-00710, and partly by the Basic Science Research Program of National Research Foundation of Korea (NRF-2017R1A6A1A07015374). We thank Saeid Cheraghi and an anonymous reviewer along with the editor for their constructive comments on an early version of this manuscript.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.tecto.2022.229387.

References

Ahmadi, O., Juhlin, C., Ask, M., Lund, B., 2015. Revealing the deeper structure of the end-glacial Parvie fault system in northern Sweden by seismic reflection profiling. Solid Earth 6, 621–632.
Bae, H.K., Lee, H.K., 2016. Quaternary activity patterns of the Wangsukcheon Fault in the Pocheon-Namyangju area, Korea. J. Geol. Soc. Korea 52, 129–147 (in Korean with English abstract).
Brodic, B., Malehmir, A., Juhlin, C., Dynesius, L., Bastani, M., Palm, H., 2015. Multicomponent broadband digital based seismic landstreamer for near surface applications. J. Appl. Geophys. 125, 227–241.
Choi, S.-J., Chwae, U., Lee, H.-K., Song, Y., Kang, I.-M., 2012. Review on the Chugaryeong Fault. Journal of Korean Society of Economic and Environmental Geology 45, 441–446 (in Korean with English abstract).
Chough, S.K., Kwon, S.-T., Ree, J.-H., Choi, D.K., 2000. Tectonic and sedimentary evolution of the Korean peninsula: a review and new view. Earth Sci. Rev. 52, 175–235.
Gangopadhyay, A., Talwani, P., 2005. Fault intersections and intraplate seismicity in Charleston, South Carolina: Insights from a 2-D numerical model. Curr. Sci. 88, 1609–1616.
Hong, T.-K., Lee, J., Chi, D., Park, D., 2017. Seismic velocity changes in the backarc continental crust after the 2011 M w9.0 Tohoku-Oki megathrust earthquake. Geophys. Res. Lett. 44, 10997–11003. https://doi.org/10.1002/2017GL075447.
Hong, T.-K., Lee, J., Park, S., Kim, W., 2018. Time-advanced occurrence of moderate-size earthquakes in a stable intraplate region after a megathrust earthquake and their seismic properties. Sci. Rep. 8, 13331.
Hong, T.-K., Chung, D., Lee, J., Park, S., Kim, B., Kim, W., 2021. Earthquake-spawning faults in the Seoul metropolitan area and their seismic implications. Earth and Space Science 8. https://doi.org/10.1029/2021EA001662 e2021EA001662.
Jackson, J.A., 1992. Partitioning of strike-slip and convergent motion between Eurasia and Arabia and Eastern Turkey and the Caucasus. J. Geophys. Res. 97, 12471–12479.
Jackson, J.A., 2002. Using earthquakes for continental tectonic geology. In: Lee, W.H.K., Kanamori, H., Jennings, P.C., Kisslinger, C. (Eds.), International Handbook of Earthquakes and Engineering Seismology. Academic Press, pp. 491–503 (Part A).
Kammann, J., Malehmir, A., Brodic, B., Tagliavento, M., Stemmerik, L., Normark, E., Lykke-Andersen, H., Nielsen, L., 2019. Deep onshore reflection seismic imaging of the chalk Group strata using a 45 kg accelerated weight-drop and combined recording systems with dense receiver spacing. Geophysics 84, B259–B268.
Kim, C.S., 1997. Overview of the Tectonic Environment in Korea with Reference to HLW Disposal. KAERI, Korea. Report accessible at. https://inis.iaea.org/collection/NCLCollectionStore/_Public/29/009/29009933.pdf (last access: 2022-04-26).
Lee, K., Yang, W.-S., 2006. Historical seismicity of Korea. Bull. Seismol. Soc. Am. 96, 846–855.
Leonard, M., 2010. Earthquake fault scaling: self-consistent relating of rupture length, width, average displacement, and moment release. B. Seismol. Soc. Am. 100, 1971–1985.
Malehmir, A., Dahiin, P., Lundberg, E., Juhlin, C., Sjostrom, H., Hogdahl, K., 2011. Reflection seismic investigations in the Dannemora area, Central Sweden: insights into the geometry of poly-phase deformation zones and magnetite-skarn deposits. J. Geophys. Res. 116, B11307.
Malehmir, A., Zhang, F., Debghahannejad, M., Lundberg, E., Dose, C., Friberg, O., Brodic, B., Place, J., Svensson, M., Moller, H., 2015. Planning of urban underground infrastructure using a broadband seismic landstreamer—Tomography results and uncertainty quantifications from a case study in southwest of Sweden. Geophysics 80, B177–B192.
Malehmir, A., Andersson, M., Mehta, S., Brodic, B., Munier, R., Place, J., Maries, G., Smith, C., Kamm, J., Bastani, M., Milko, H., Lund, B., 2016. Post-glacial reactivation of the Bollnäs fault, Central Sweden – a multidisciplinary geophysical investigation. Solid Earth 7, 509–527.
Maries, A., Maries, G., Backstrom, E., Schön, M., Marsden, P., 2017. Developing cost-effective seismic mineral exploration methods using a landstreamer and a drophammer. Sci. Rep. 7, 10325.
Park, S., Baek, I., Hong, T.-K., 2020. Six major historical earthquakes in the Seoul metropolitan area during the Joseon dynasty (1392-1910). Bull. Seismol. Soc. Am. 110, 3037–3049. https://doi.org/10.1785/0120200004.
Place, J.A.P., Malehmir, A., 2016. Using supervirtual first arrivals in controlled-source hardrock seismic imaging—well worth the effort. Geophys. J. Int. 204, 717–730.
Son, M., Cho, C.S., Lee, I.H.K., Han, M., Shin, J.S., Kim, K., Kim, S., 2020. Partitioned fault movement and aforeshock triggering: evidence for fault interactions during the 2017 Mw 5.4 Pohang earthquake, South Korea. Journal of Geophysical Research: Solid Earth 125. https://doi.org/10.1029/2020JB020005 e2020JB020005.
Talwani, P., 1988. The Intersection Model for Intraplate Earthquakes. Seismol. Res. Lett. 59, 305–310. https://doi.org/10.1785/igrf.59.4.305.
Walters, R.J., Gregory, L.C., Wedmore, L.N.J., Craig, T.J., McCaffrey, K., Wilkinson, M., Chen, J., Li, Z., Elliott, J.R., Goodall, H., Jezzi, F., Livio, F., Michetti, A.M., Roberts, G., Vittori, E., 2018. Dual control on fault intersections on stop-start rupture in the 2016 Central Italy seismic sequence. Earth Planet. Sci. Lett. 500, 1–14. https://doi.org/10.1016/j.epsl.2018.07.045.
Zoback, M.D., Hickman, S., Ellsworth, W.L., 2010. Scientific drilling into the San Andreas Fault. Eos Trans. AGU 91, 197–204. https://doi.org/10.1029/2010EO220001.