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The offshore Yangsan fault activity in the Quaternary, SE Korea: Analysis of high-resolution seismic profiles

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ABSTRACT

The NNE-trending dextral Yangsan fault is a > 190-km-long structure in the Korean Peninsula traced to the southeastern coast. The scarcity of Quaternary deposits onland precludes any detailed investigation of the Quaternary activity and structure of the Yangsan fault using seismic reflection profiling. We acquired offshore high-resolution seismic profiles to investigate the extension of the Yangsan fault and constrain its Quaternary activity using stratigraphic markers. The seismic profiles reveal a NNE-trending fault system consisting of a main fault and an array of subsidiary faults that displaced Quaternary sequences. Stratigraphic analysis of seismic profiles indicates that the offshore faults were activated repeatedly in the Quaternary. The up-to-the-east sense of throw on the main fault and plan-view pattern of the fault system are explained by dextral strike-slip faulting. The main fault, when projected toward the Korean Peninsula along its strike, aligns well with the Yangsan fault. We suggest that the offshore fault system is a continuation of the Yangsan fault and has spatial correlation with weak but ongoing seismicity.

1. Introduction

The historical and modern instrumental records of earthquakes in Korea highlight frequent seismic activities in its southeastern part (Choi et al., 2014), although instrumentally recorded earthquakes rarely exceed 5.0 in magnitude. The southeastern part of the Korean Peninsula is dominated by the Yangsan Fault System (YFS) comprised of the Miryang, Moryang, Yangsan, Dongrae, and Ilgwang faults all with a NNE-SSW strike (Fig. 1). Recent dating of fault gouges and trench surveys showed evidence for late Quaternary activity of the YFS (Lee and Schwarcz, 2001; Kyung, 2003). Consequently, the weak but relatively high seismicity in this region of the peninsula is inferred to be related to the activity of the YFS (e.g., Lee, 1985; Ree et al., 2003).

It is important to identify the nature and structure of the faults that deformed Quaternary sediments in addressing their activity in the zone of the YFS because Quaternary faults have potential to be the sources of earthquakes (e.g., Bianca et al., 1999). Understanding how those faults propagate, grow, and interact in a fault system is also important because they are primarily responsible for distributing strain in the upper crust (Lamarche et al., 2000). However, the study of YFS activity on land by means of seismic reflection profiling is difficult because (1) Quaternary deposits occur scarcely in the Korean Peninsula, largely restricted to small streams and valleys (Kyung, 2003), (2) a significant portion of the YFS is traced in either highly populated and industrialized areas or the rugged terrain, (3) near-surface erosion and weathering make it difficult to image Quaternary shallow structure immediately below the surface, and (4) land seismic sources for shallow structure such as a hammer, weight drop, and a shotgun do not generate high-frequency seismic pulses that enable high-resolution profiling.

In contrast, marine seismic reflection profiling is well suited for imaging fault structure in shallow sedimentary layers because (1) surficial sediments deposited in the sea are normally fully saturated with water; thus they do not generate a near-surface weathered zone as on land and (2) high-resolution seismic profiles can be obtained using seismic sources such as a boomer and a sparker that can generate seismic pulses with frequencies much higher than 100 Hz. Therefore, high-resolution marine seismic profiling of Quaternary sequences has been widely used to map in detail fault structure (e.g., Barnes and Audru, 1999), evaluate fault displacement rates (e.g., Lamarche et al., 2006), identify the offshore continuity of onshore faults (e.g., d'Arcemont et al., 2014), and derive direct paleoearthquake records (e.g., Pondard and Barnes, 2010).

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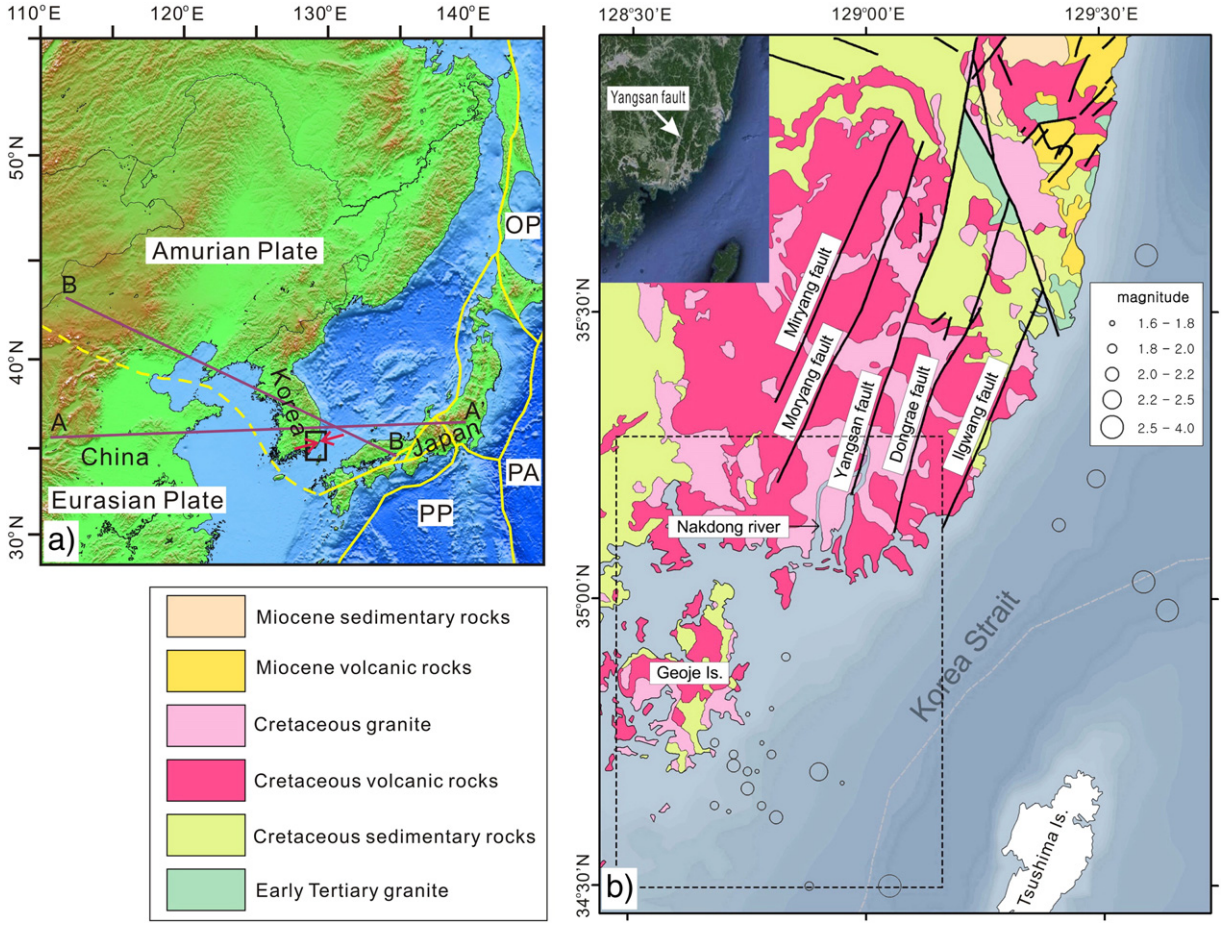

Fig. 1. (a) Map showing the tectonic plates around the Korean Peninsula (modified from Lee et al., 2011). The rectangle indicates the area in panel b. The arrows indicate the direction of the maximum compressive stress in the southeastern Korean Peninsula inferred from the slip analysis of Quaternary faults (from Park et al., 2006). A-A′ and B-B′ are two transects of P-wave tomography in Fig. 11. PA, PP, and OP = Pacific, Philippine Sea, and Okhotsk plates, respectively. (b) Geological map of the southeastern Korean Peninsula (modified from Ree et al., 2003). The dashed-line rectangle indicates the study area in Fig. 3. Inset shows the satellite image of the study area (from Google Earth). Epicenters of the earthquakes are from the catalogue of the Korea Meteorological Administration and are not relocated.

Of the faults belonging to the YFS, the Yangsan fault is most prominently defined in satellite images (Fig. 1); it extends linearly with a recognized length of >190 km to the southeastern coast of the Korean Peninsula, suggesting its projection onto the continental shelf. The Yangsan fault is also characterized by large dextral displacement as much as 35 km since its formation in the Eocene (Chang et al., 1990), whereas other faults in the YFS exhibit only a few or unknown km of displacement (Hwang et al., 2008). Earthquakes occur frequently offshore where the Yangsan fault is projected (Fig. 1). The earthquakes appear to form a seismic zone distinguished from the surrounding nonseismic or very weak seismic zones, although their magnitude is smaller than 5. However, geologic structure in this area has not been studied to address Quaternary fault activity. In this study, we acquired high-resolution seismic profiles on a closely spaced grid covering the offshore epicentral area. The principal objectives of this study are: (1) to track the offshore extension of the YFS and (2) to address its Quaternary activity by correlating the sedimentary structure with the pertinent stratigraphic framework established offshore.

2. Geologic setting

2.1. Tectonic setting of the southwestern continental shelf of Korea and the Yangsan fault

The southeastern continental shelf of the Korean Peninsula including the study area is interpreted to have formed coevally with continental rifting in the early stage of the separation of the Japan Arc through back-arc rifting in late Oligocene to early Miocene times (e.g., Kim et al., 2015). Afterwards, this region has been under compression in two directions: NW-SE from 15 Ma to the late Miocene and ENE-WSW or E-W since the Pliocene to the present (Lee et al., 2011). The 15-Ma compression is coincident with the acceleration in convergence of the Philippine Sea plate along the southwestern Japan Arc (Sdrolias et al., 2004). The compression since the Pliocene is attributed to the eastward movement of the Amurian plate (Lee et al., 2011), a small plate fragmented from the Eurasian plate as a result of the collision with the Indian plate (Park et al., 2006).

The K-Ar ages of the fault gouges from the Yangsan fault zone range from 58.7 to 37.3 Ma (Chang and Choo, 1999), which may indicate the timing of its main dextral displacement; whereas paleostress analysis suggested that the main phase of displacement on the Yangsan fault continued to the early Miocene (Chang and Chang, 1998). Although the sense of slip along the Yangsan fault has been dominantly dextral since its formation, a sinistral displacement occurred temporarily toward the end of the Miocene (Kyung, 2003). Geological surveys including trenching identified reactivation of the Yangsan fault in the Pleistocene in some places (Lee et al., 1999), suggesting that its activity has persisted into the Quaternary. Analysis of earthquakes recorded on the broadband seismic network in Korea since 1998 indicates that (1) the direction of maximum horizontal stress is fairly uniform in the entire southern Korean Peninsula and (2) the pseudo P-axis direction is predominantly ENE-WSW (Rhie and Kim, 2010). Analysis of Quaternary fault slip also suggests that the southeastern Korean Peninsula is under ENE-WSW compression (Park et al., 2006).