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Identification of a suspected Quaternary fault in eastern Korea: Proposal for a paleoseismic research procedure for the mapping of active faults in Korea

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ABSTRACT

In terms of seismic hazard in the Korean Peninsula, the occurrence of destructive earthquakes has long been overlooked because of no serious modern instrumental seismicity and lack of historical earthquake records of large earthquakes. In recent years, although the importance and uses of paleoseismological studies has significantly increased in seismic hazard assessments of critical facilities, there is still a huge lack of paleoseismological data to improve our knowledge for Korean active tectonics and relevant seismic hazards. In this study, we identified and characterized a suspected Quaternary fault in the eastern part of the Korea Peninsula based on lineament analyses, field observations, and trench surveys. We focus on a prominent lineament around the northern part of the previously reported, but not sufficiently studied, Maeup Fault. Firstly, a potential fault lineament is recognized by geomorphic expressions in a mountainous area from satellite and digital elevation model (DEM)-generated images. Then, fault-related geomorphic and hydrologic features, such as disconnected drainages, sag ponds, and asymmetric water leaking out on an artificial ditch, were observed along the lineament in the field studies. Finally, the existence of the fault is confirmed by an exposure of a 2.5 m wide fault core in trench surveys. The internal structures of the fault core (i.e., slip surfaces, slickenlines, and S-C fabrics) indicate that the fault evolved via a series of slip events under a variety of tectonic settings, probably leading up to the current stress regime sustained during Quaternary. Thus our results suggest that the newly identified fault could be a Quaternary fault, and hence it is necessary to perform more paleoseismic investigations around the study region. This case study emphasizes the importance of the careful interpretation of tectonic landforms and fault zone structures in the study of active faults, and proposes a suitable research procedure for the identification of active faults in Korea.

1. Introduction

One of the primary goals of earthquake science is to predict future destructive earthquakes, and to facilitate seismic hazard assessment and loss mitigation. As almost all large earthquakes occur by reactivation of pre-existing active faults, it has been a very important work to identify Quaternary and/or neotectonic faults and to understand their past earthquake history. Over the last few decades, many studies have focused on identifying evidence for recent large paleoearthquakes in the geomorphic and stratigraphic records, because sufficiently large earthquakes (usually with magnitudes > 5.5, although few examples from smaller events are known) can form a range of coseismic features at the surface (Bonilla, 1988; Wells and Coppersmith, 1994; Michetti et al., 2005). These paleoseismic records contain evidence for large prehistoric earthquakes, so that they complement historical earthquake records and instrumentally measured seismicity, and therefore can play a key role even in tectonically quiet regions where large earthquakes do not frequently occur.

In some regions, however, conducting high quality paleoearthquake studies remains a challenge due to insufficient topographical expressions associated with active faults. This lack of data may be due to a low slip rate of the active faults and/or high erosion or deposition rates in the local climatic and geomorphic environment. In addition, rugged mountain areas and/or densely vegetated terrain may make it difficult to investigate the details

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of the tectonic landforms. Note that, in most stable continental regions, it is difficult to identify active faults and only inferred active faults or relevant lineaments are recognized because of the scarcity of data (Skobelev et al., 2004).

These conditions make the identification of active faults in the Korean Peninsula challenging. Most Korean paleoseismological studies have focused on the southeastern part of Korean Peninsula (Kyung, 2003; Ree et al., 2003; Kim et al., 2011; Choi et al., 2014). This spatial bias is the result of: (1) the location of a number of nuclear power plants along the eastern coastline; (2) relatively well-developed Quaternary marine terraces in this region; and (3) records of many large historic earthquakes around the old capital city of Gyeongju in southeast Korea. Although these studies have led to the discovery of over 50 Quaternary fault sites (Kee et al., 2009 and references therein), the results from local-scale investigations are barely mappable, and no valid active fault map has been drafted. In other regions, only a few active faults have been clearly identified based on trenching and seismic surveys. In particular, some mountainous areas have not been fully investigated in terms of active tectonics because of the heavy vegetation and highly rugged topography.

In the present study, a potential Quaternary fault is newly identified around Samcheok city in eastern Korea through a trench survey, which is performed on a prominent lineament characterized by fault-related hydrologic and geomorphic features. Here we first present a short review of regional-scale active tectonics around the study area. Then lineament analysis using a digital elevation model (DEM)-derived from topographic maps is presented, followed by field observations focusing on topographical features along the inferred fault lineament. Finally, the internal structures of the fault zone exposed on trench walls are described, and fault history including its potential Quaternary slip is interpreted based on the detailed geometric and kinematic analyses. Although the density and quality of datasets are limited, this case study provides a view of the suitable research procedure for paleoseismic investigations in regions where it is difficult to work in.

2. Neotectonic and geologic settings

The Korean Peninsula is located on the margin of the Eurasian intracontinental region, and is tectonically controlled by subduction of the adjacent Pacific and Philippine Sea Plates, and/or extrusion of the Indian Plate collision (Jin and Park, 2007; Jun and Jeon, 2010) (Fig. 1a). Although it has been considered a seismically stable region (compared to neighboring countries such as China, Japan, and Taiwan), there have been many indications of the potential for large earthquakes. Historical records have documented 240 earthquake events with seismic intensities greater than or equal to MMI VI between AD 2–1904 (Lee and Yang, 2006) (Fig. 1b). The most damaging earthquake (over 100 casualties) occurred in AD 779 (estimated magnitude of 6.7) around Gyeongju in southeast Korea during the Silla Dynasty (Lee, 1998). In addition, six earthquake events with a magnitude greater than or equal to M_W 5.0 have been recorded over the last 40 years (Houng and Hong, 2013) (Fig. 1b).

Recent studies of active tectonics in southeastern Korea have indicated that: (1) Cenozoic tectonic deformation is primarily associated with the NNE–SSW- and/or NNW–SSE trending faults that have slipped during the opening and closing of the East Sea (Yoon and Chough, 1995; Kim and Park, 2006; Choi et al., 2015); and (2) since the Pliocene, the stress field has changed to E–W or ENE–WSW trending compression, with the prevailing fault type being oblique-slip with dominant strike-slip and minor reverse-slip components (Choi et al., 2001; Ree et al., 2003; Jin and Park, 2007; Park et al., 2007). In some cases, faults show a dominant reverse-slip pattern depending on their orientation (e.g., Kim et al., 2011). Note that the bars in Fig. 1a show the present day tectonic stress field: the orientation of the maximum horizontal compressional stress axis with fault types, estimated by focal mechanisms from 40 earthquakes (greater than or equal to M_W 3 from 1996 to 2014) at a depth of approximately 9.5 km in and around the Korean Peninsula (data from the Saint Louis University Earthquake Center). Fig. 2 shows a dot distribution map of the sites of Quaternary faults in southeast Korea, and it is characterized by locational clusters around the Yangsan-Ulsan Fault System. Quaternary slips on these faults are commonly characterized by reactivation of pre-existing faults, which have generally experienced multiple slips including early normal and strike-slip events (e.g. Kim et al., 2004).

The study area, southern Samcheok city, is a mountainous region along the eastern coast in the northeastern part of the Yeongnam Massif (Fig. 2), which is mainly composed of Precambrian metamorphic and igneous rocks. The primary structural features in this area are the E–W trending folds and thrust faults, and the NNW–SSE trending faults. In the latter case, Osipcheon and Maeup Faults expressed along river canyons are representative (Fig. 3a). Kim et al. (2000) suggested a structural evolution of the study area based on the geologic and structural analyses for the Osipcheon Fault as follows: (1) NNE–SSW trending normal faults related to the formation of a Cretaceous sedimentary basin, (2) reactivation of pre-existing faults as tear faults associated with the E–W trending folds and thrust faults in age between 66.9 and 49.4 Ma, and (3) further reactivation as strike-slip with dextral movements. Lee et al. (2011) suggested that right-lateral slips on the Osipcheon Fault have occurred during the Quaternary based on geomorphic analyses and cosmogenic dating of fluvial terraces along the Osipcheon River.

Maeup Fault is parallel to the Osipcheon Fault, and is characterized by a straight-line geometry (Fig. 3a). Although the fault is expressed as an approximately 20 km long lineament, its related fault mechanisms and evolutional characteristics are still poorly understood.

3. Lineament analysis

In general, lineaments are expressions of underlying geological structures in a landscape, and fault-related lineaments are commonly formed by either erosion of the physically weak fault zone or by a series of geomorphic offsets associated with recent fault movements. Thus, a lineament analysis is regarded as an essential work in identifying and characterizing faults in a given region. Here we analyzed lineaments using a shaded relief image derived from DEM to infer regional-scale fault systems or tectonic faults (Fig. 3). The DEM is extracted from digital topographic maps, and the images have approximately 10 m of DEM cell resolution. Potential fault lineaments have been mapped by our judgements based on fault-related geomorphic markers, such as fault-aligned valleys, which are relatively obvious in a rugged mountainous region (Fig. 3a).

Numerous lineaments were identified with various orientations and lengths, and these can be roughly classified into two sets: (1) NNE–SSW trending lineaments including those associated with Osipcheon and Maeup Faults, (2) NW–SE or E–W trending lineaments, which are less dominant in terms of both frequency and length. We argue that the latter ones may be associated with the above-mentioned older faults, NW–SE trending normal faults and E–W trending thrust faults in the study region (Kim et al., 2000). Here we focus more on the NNE–SSW trending lineaments for further research, because our attention is more weighted toward large faults. We also focused on a subset of lineaments that showed straight and sharp patterns, because these geometric features may reflect young tectonic deformation. One such example is a dis-