

Paleoseismology of the Yangsan Fault, southeastern part of the Korean Peninsula

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Abstract

The NNE-trending Yangsan Fault (YSF) is the most prominent fault in the southeastern part of the Korean Peninsula and has a continuous trace about 200 km long. Activity on this fault was recently investigated using aerial photographs, topographic analysis, and trenching. The geomorphologic evidence of Late Quaternary faulting is clearly recognized on both the northern (Yugyeri and Tosung-ri areas) and southern parts (Eonyang to Tongdosa area) of the fault. The main YSF is marked by a zone of shattered rock that is tens of meters wide and zone of fault gouge. During the Late Quaternary, right-lateral movement occurred mainly on the southern part, as shown by low-angle striations on the fault plane, elongation of deformation features in the fault gouge. The estimated vertical slip rate is about 0.02-0.07 mm/yr, and the lateral slip rate may be several times larger than the vertical rate. The most recent event occurred prior to deposition of Holocene alluvium. In the northern part, the fault locally changes trend to almost N-S, dips to the east and has reverse movement. The average vertical slip rate is estimated less than 0.1 mm/yr. The most recent event probably occurred after 1314 cal. years BP (A.D. 536).

Key words *Yangsan Fault (YSF) – Korean Peninsula – average slip rate – most recent event*

1. Introduction

The level of seismicity in the Korean Peninsula is lower than that in neighboring parts of Northeastern China and Japan, but major damaging earthquakes have occurred in the peninsula during past 2000 years. Many of these earthquakes occurred in the Kyongju-Ulsan areas in the southeastern part of the Korean Peninsula (fig. 1). Historical records describe approximately ten damaging earthquakes in Kyongju-Ulsan area, some of which have caused fatalities and produced liquefaction.

Some of the earthquakes destroyed houses, created ground fissures, surface depressions, and

landslides, and caused liquefaction and sand blows. Eight of these large historical earthquakes occurred in and around the Kyongju area (A.D. 34, 100, 123, 304, 471, 510, 630, 779) (Lee, 1998). In particular, the Kyongju earthquake in A.D. 779 caused great damage, killed approximately 100 people, and is described in the historical literature 'Samguksaki'. The greatest earthquake (MMI X) in the Korean Peninsula occurred in the Ulsan area in 1643 (Lee, 1998), had a large felt area, triggered a tsunami, caused liquefaction along the coast, and destroyed some beacon lighthouses and castel.

Faults that could have caused these earthquakes include the NNE-SSW-trending Yangsan Fault and NNW-SSE trending Ulsan Fault (fig. 2). Of these two structures, the YSF has a strong linear expression and is continuously traceable for about 200 km (Yoon and Kim, 1990). The surface expression of the YSF is marked by a fault-controlled valley containing wide, NNE-SSW shatter zones, and sub-horizontal striations (Reedman and Um, 1975). The fault plane is

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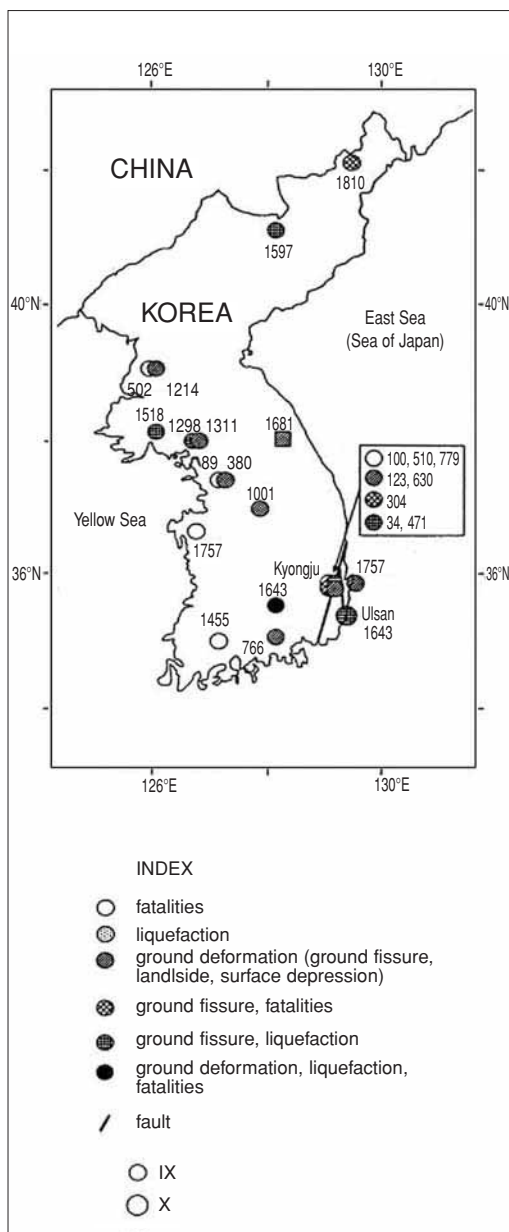


Fig. 1. Epicenters of large historical earthquakes (MMI equal to or greater than IX) which caused destructive damage in the Korean Peninsula from A.D. 27 to 2002. The number in the figure represents the occurrence time (in years) of earthquake.

almost vertical based on exposures in outcrops and geophysical data (e.g., Kim and Lee, 1988).

This study clarifies the history of the Late Quaternary movement on the YSF based on geomorphological studies, topographic mapping, and trenching. The study concentrated on two sites, one on the northern part of the fault at Yugye-ri area, and one on the southern part in the Eonyang to Tongdo-sa areas (Tn and Ts in fig. 2).

2. General tectonic setting

The Korean Peninsula is part of the Amuria plate and is an important link between the continental blocks of North and South China and the island arcs of Japan. Major orogenic events in the Korean Peninsula occurred mainly in Late Paleozoic and Mesozoic time (e.g., Reedman and Um, 1975; Lee, 1987; Kim, 1996; Ree *et al.*, 1996). In Late Permian to Early Triassic time, the Songrim orogeny produced strong deformation and metamorphism, and compressional deformation occurred again in the Early to Late Jurassic (Daebo event). Dextral ductile shearing associated with thrusting and folding continued in the mid-southern Korean Peninsula due to northwestward subduction of the Izanagi plate under the Asian continent (Maruyama *et al.*, 1997; Chough *et al.*, 2000). In Cretaceous time, the northward subduction of Izanagi plate formed strike-slip basins and the emplacement of volcanic and granitic rocks (Chough *et al.*, 2000). Non-marine sedimentary rocks in these basins and volcanic rocks are mainly present in the southeastern part of the peninsula (Kyongsang Basin) (Chun and Chough, 1992). Figure 2 shows the general geology of the eastern part of the Kyongsang Basin. In Tertiary time, the southeastern margin of the Korean Peninsula experienced back-arc opening, resulting in deposition of Tertiary rocks in and around Pohang (Pohang Basin) in association with back-arc opening in the East Sea (Sea of Japan) (Chough *et al.*, 1990; Yoon and Chough, 1995).

No prominent tectonic movements occurred during the Quaternary except for some isolated volcanic events. However, evidence of uniform uplift exists for much of the southern half of the

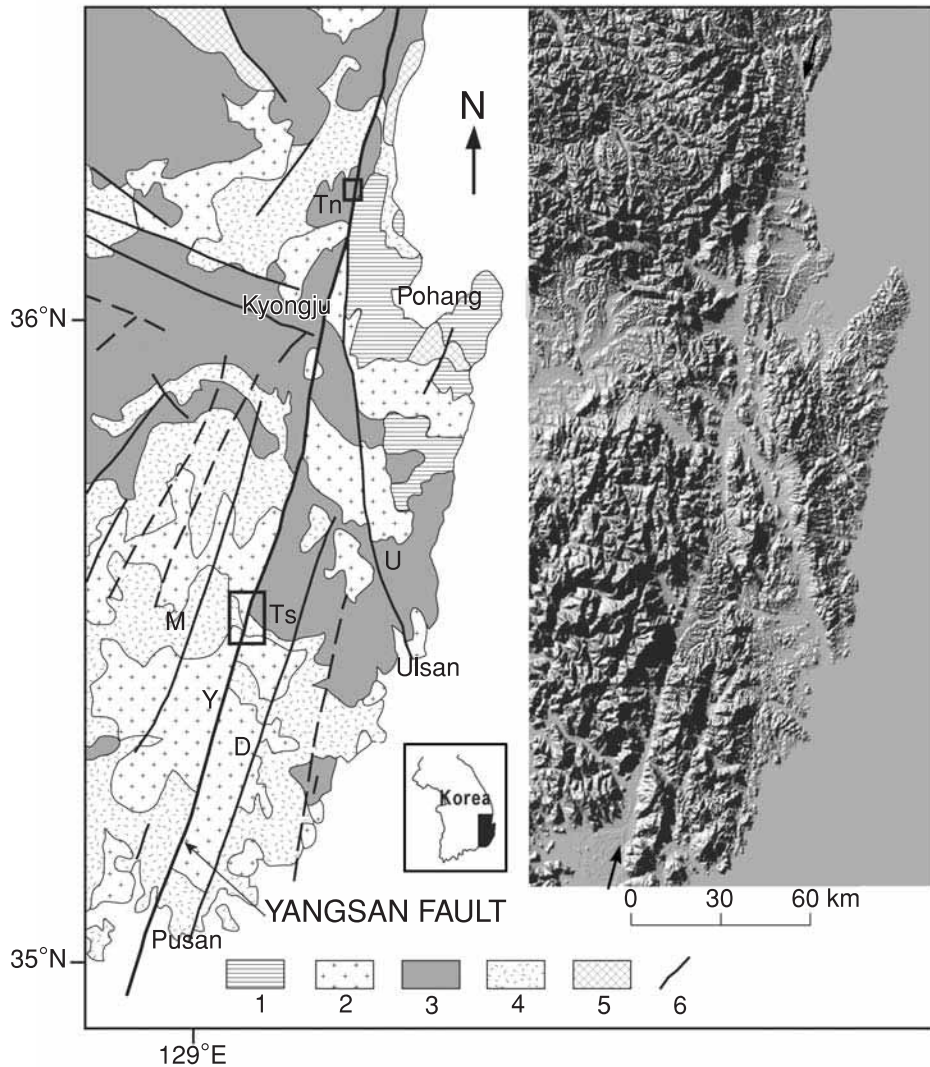


Fig. 2. Geological map (after Korea Institute of Energy and Resources, 1981) and the Yangsan Fault System in the shaded relief map of southeastern part of the Korean Peninsula. 1 - Tertiary basin deposits; 2 - Late Cretaceous to Early Tertiary igneous rocks; 3 - Late Mesozoic Kyongsang Basin deposits; 4 - Late Mesozoic Yucheon volcanics; 5 - Tertiary volcanics; 6 - Fault; M - Moryang Fault; Y - Yangsan Fault; D - Dongrae Fault; I - Ilgwang Fault; U - Ulsan Fault. Tn and Ts indicates the sites in the northern (Yugye-ri) and southern sectors (Eonyang to Tongdo-sa), respectively.

Korean Peninsula (Oh and Choi, 2001). Uplifted marine terraces are developed along the eastern coast (e.g., Oh, 1981; Choi, 1997, 2001; Oh and Choi, 2001). The average uplift rate

of the eastern coast is estimated to be about 0.1 m/ka since the last glacial culmination (oxygen isotope stage 5e) (Choi, 2001). Some faults, such as the Yangsan and Ulsan faults (fig. 2)

were active in the Late Quaternary, even though their slip rates are estimated to be less than 0.1 m/ka (Okada *et al.*, 1994; Kyung *et al.*, 1999a,b; Kyung and Im, 2001; Okada, 2001).

3. Yangsan Fault System

The Yangsan Fault System consists of several faults, including the Moryang Fault, the Tongrae Fault, the Ilkwang Fault and the Ulsan Fault (fig. 2). The YSF is one of the faults in the fault system and is a prominent dextral, strike-slip fault that has a clear, linear topographic expression for about 200 km. It consists of two or three closely spaced, sub-parallel faults. The width of the fault zone varies in a regular, cyclical patterns every 25-35 km along strike (Chang, 2001). Along the northern part of the fault zone, its maximum width is about 5 km and along the southern part, the maximum width is about 6 km. The significance of these regular changes in fault zone width are not known.

The YSF contains evidence of multiple deformation events through geologic time. Initial movement on the YSF probably occurred after 45 Ma (Eocene) based on radiometric dating of volcanic rocks along the northern part of the fault (Chang *et al.*, 1990). Paleo-stress analysis (Chae and Chang, 1994; Chang and Chang, 1998; Chang, 2001) indicates that movement on the YSF has been right-lateral strike-slip caused by NE-SW compression since Eocene time, including during its most active period in the Late Miocene. Later, the sense of movement changed to left-lateral under a NW-SE compressional stress regime at the end of the Miocene. In the Pliocene, N-S compression affected the fault, and in the Quaternary, the fault was reactivated by a right-lateral strike-slip movement in an E-W to ENE-WSW compressional stress regime. This is the present stress regime in the Korean Peninsula (Jun, 1991).

The total amount of dextral displacement on the fault is estimated to be about 35 km in the north (Chang *et al.*, 1990) and about 25 km in the south, most of which occurred between 14 and 42 Ma (Reedman and Um, 1975; Choi and Park, 1985).

To document the fault's Quaternary history, it is necessary to quantify the deformation of Quaternary deposits, but Quaternary deposits are not abundant or widespread on the Korean Peninsula. Locally, Quaternary deposits are present along the YSF, although these are largely restricted to small streams and valleys. We have studied these deposits at several sites to clarify the Late Quaternary faulting history of the Yangsan Fault (Okada *et al.*, 1994; Kyung *et al.*, 1999a,b; Kyung and Chang, 2001).

3.1. Northern part of the YSF (Tn in fig. 2)

In the Yugye-ri area on the northern part of the YSF (fig. 2), fluvial terraces along the Seojeong stream can be divided into four levels: Qt1, Qt2, Qt3 and Qt4 (fig. 3.). Here, Qa indicates the deposits of undifferentiated alluvium of the latest Pleistocene to Holocene. The fault was exposed in two excavations during construction of a dam. In this area, terrace Qt2 is cut by several fault splays, which are buried with alluvial deposits (unsorted pebble to boulder gravel). A fault scarp on the Qt2 terrace has a down-to-the-west vertical displacement of about 1.5 m (fig. 3; profile d-d' and e-e'). The fault plane forms the boundary between alluvial deposits on the west and Cretaceous sedimentary rocks on the east. It strikes almost N-S, dips to the east about 45°, and reverse-slip striations plunging about 40°E with hanging wall up-to-the west, resulting in right-lateral reverse movement. The fault has a gouge zone that is as wide as 1 m and a cataclastic zone several meters wide.

A trench at site A (fig. 3) exposed, alluvium consisting of unweathered pebble to boulder gravel with silty lenses (fig. 4). This alluvium was strongly deformed and overturned near the fault zone. The long axis of the slender gravel clasts near the gouge zone has been rotated and dips to the east, sub-parallel to the fault plane. Charcoal in silty sediments in the gravel yielded calibrated radiocarbon ages of 7182 (SNU 99-136) years BP, 11 230 (SNU 99-135) years BP, and 25900 ± 730 (SNU 99-118) years BP (table I) from the upper to the lower parts of the gravel. A humic layer in the lower of the terrace

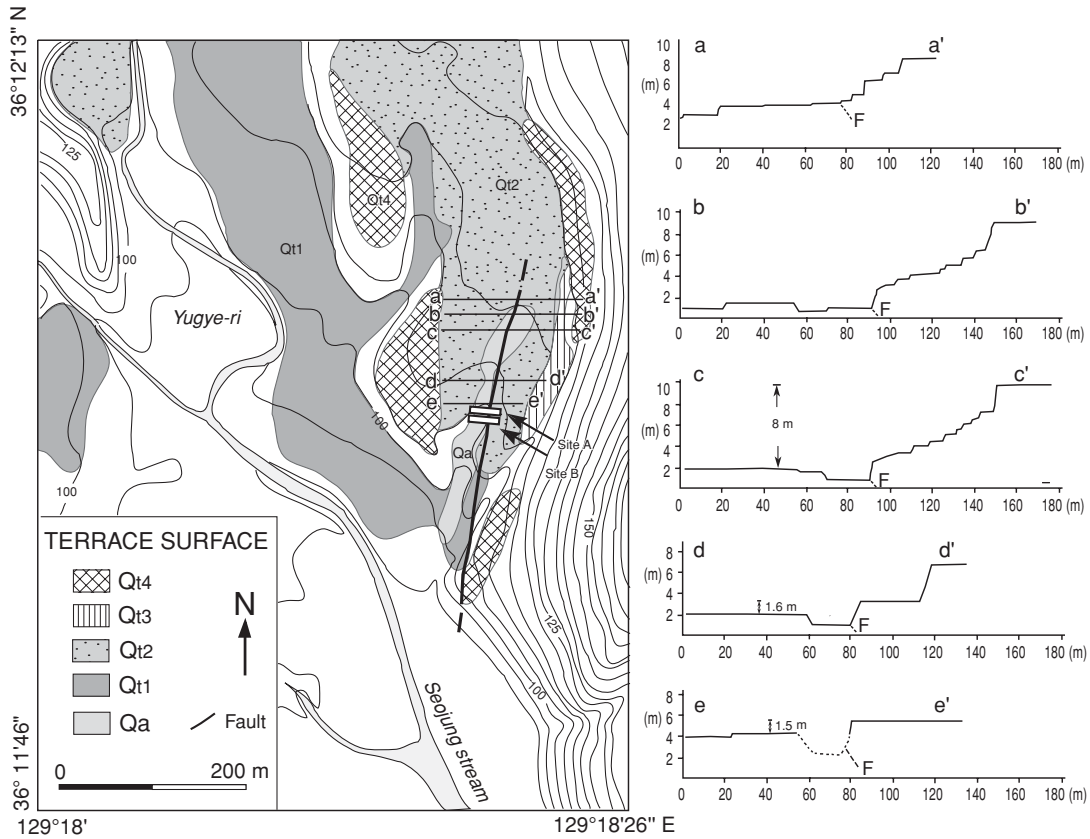


Fig. 3. Geomorphic map around the Yungye-ri area and topographic profiles across the YSF. A and B are the locations of excavations across fault. The lines from a-a' to e-e' indicate topographic profiles.

Table I. C¹⁴ dating result in the northern part of the YSF.

Sample n.	Lab. n.	Radiometric age	Calibrated age (calendar year): years BP (yr)	2 σ
NYSF-1	SNU 99-137	1550 ± 90	1314 (A.D. 536)	A.D. 261-660
NYSF-2	SNU 99-138	1930 ± 90	1875 (A.D. 75)	B.C. 163-A.D. 321
NYSF-3	SNU 99-116	2410 ± 90	2359 (B.C. 409)	B.C. 796-B.C. 233
NYSF-4	SNU 99-115	3060 ± 80	3298 (B.C. 1348)	B.C. 1504-B.C. 1050
NYSF-5	SNU 99-136	6250 ± 150	7182 (B.C. 5232)	B.C. 5482-B.C. 4801
NYSF-6	SNU 99-135	9870 ± 340	11230 (B.C. 9280)	B.C. 10845-B.C. 8323
NYSF-7	SNU 99-118	25900 ± 730	NA	—
NYSF-8	SNU 99-133	36600 ± 780	NA	—
NYSF-9	SNU 99-134	39400 ± 570	NA	—

* NA: not applicable, calibrated data set only extends back to 24900 years BP (Stuiver *et al.*, 1998).

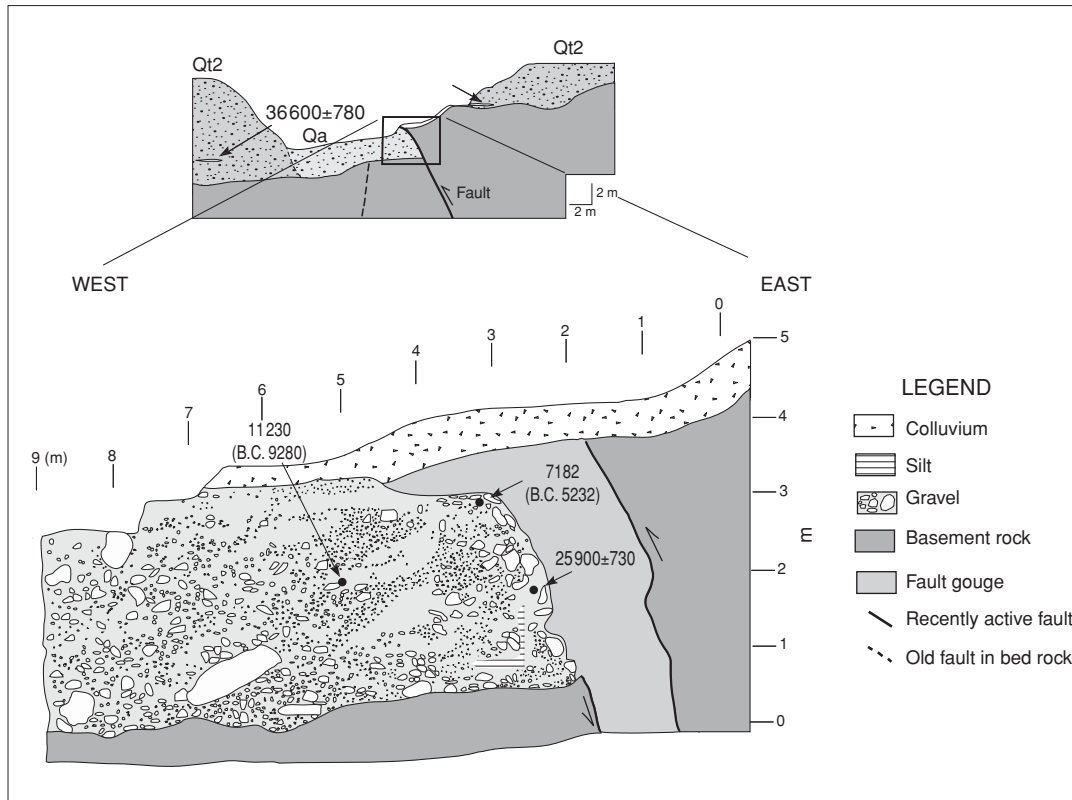


Fig. 4. Log of the northern wall across the YSF at site A in fig. 3.

deposits on both sides of the fault has AMS radiocarbon dates of 36600 ± 780 (SNU 99-133) years BP and 39400 ± 570 (SNU 99-134) years BP, but these data cannot be calibrated because the calibration of the data extend only back to 24900 years BP (Stuiver *et al.*, 1998).

A trench at site B, which was about 10 m south from site A, exposed gravelly alluvium covered by humic, silty sediments (fig. 5). The gravel deposits and humic silt were displaced by reverse faulting. The fault plane is steep in bedrock and becomes less steep upward to the west. Calibrated radiocarbon dating on organic material in the humic layer was dated at 1314 (A.D. 536) (SNU 99-137) years BP, 1875 (A.D. 75) (SNU 99-138) years BP, 2359 (B.C. 409) (SNU 99-116) years BP and 3298 (B.C. 1348)

(SNU 99-115) years BP from the upper to the lower layer, as shown in table I. The humic silt and gravel are vertically displaced about 50 cm down to the west. The four radiocarbon ages from the humic silt suggest that deposition of this unit began before about 2400 years BP and ended after 1314 years BP. However, the humic material in this silt was from samples that were buried only about 0.75-1.25 m below the surface. At such shallow depths in a humid climate such as Southeastern Korea, it is possible that some of the carbon in these samples could be from younger sources such as soluble humic acids. If these samples are contaminated by younger carbon, then the apparent age of this deposit could be too young. If the samples are not contaminated, then the radio-

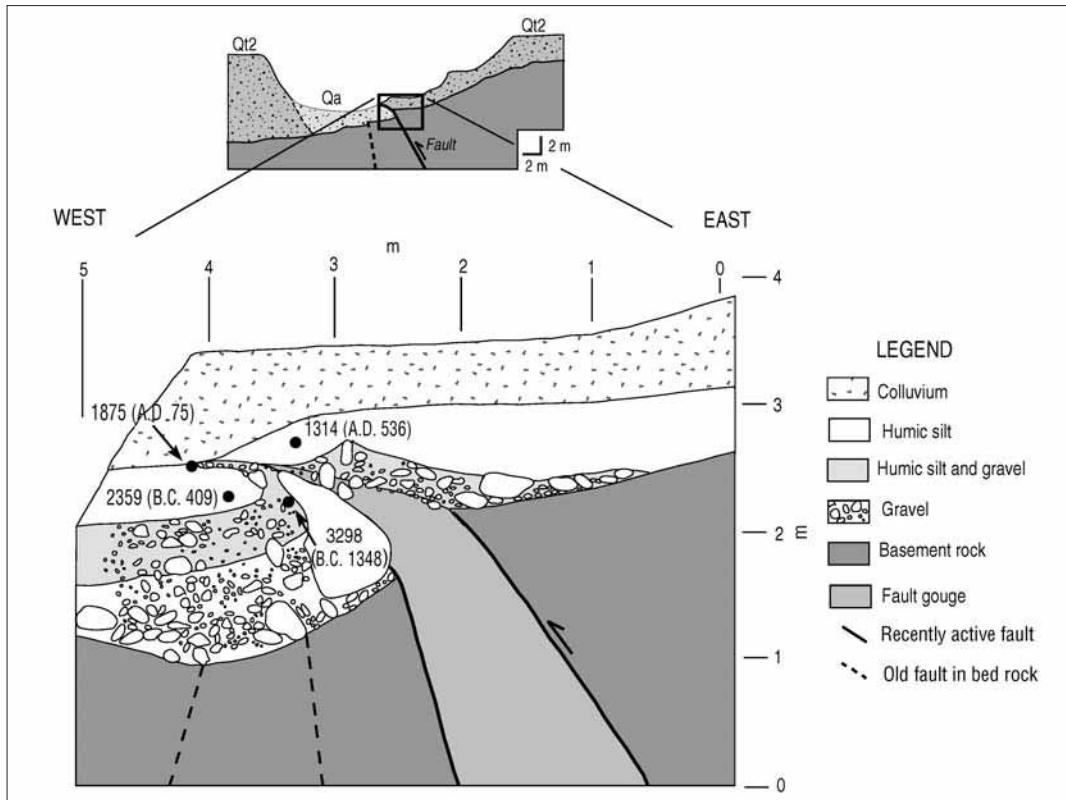


Fig. 5. Log of the northern wall across the YSF at site B in fig. 3.

carbon ages indicate that the silt was faulted less than 1314 (A.D. 536) years BP, which is the maximum age of the most recent event at this site.

3.2. Southern part of the YSF (Ts in fig. 2)

In the Eonyang to Tongdo-sa area on the southern part of the YSF, fluvial terraces formed by eastward-flowing streams are well developed in a relatively wide (a few km) fault valley (fig. 6). The terraces can be divided into four levels (Qt1, Qt2, Qt3, Qt4), as shown in fig. 6. Following geomorphologic and geological studies in the area, we excavated several trenches across the YSF in a 10 km long section

between Eonyang to Tongdo-sa area. The trenches exposed clear fault traces and steeply dipping fault contacts between old terrace gravels and the basement rocks.

3.2.1. Trench T_{IE} and T_{IW}

Studies of the topography and aerial photographs show evidence of three sub-parallel fault strand between Kyodong-ri and Shinhwa-ri (fig. 6). The eastern strand has a clear scarp about 0.6 km long and 12 m high. The trench across this scarp exposed a sharp fault contact between alluvial gravel and Cretaceous rocks of Taegu Formation (fig. 7a) (Kyung *et al.*, 1997). The fault strikes N40°E and dips northwest-

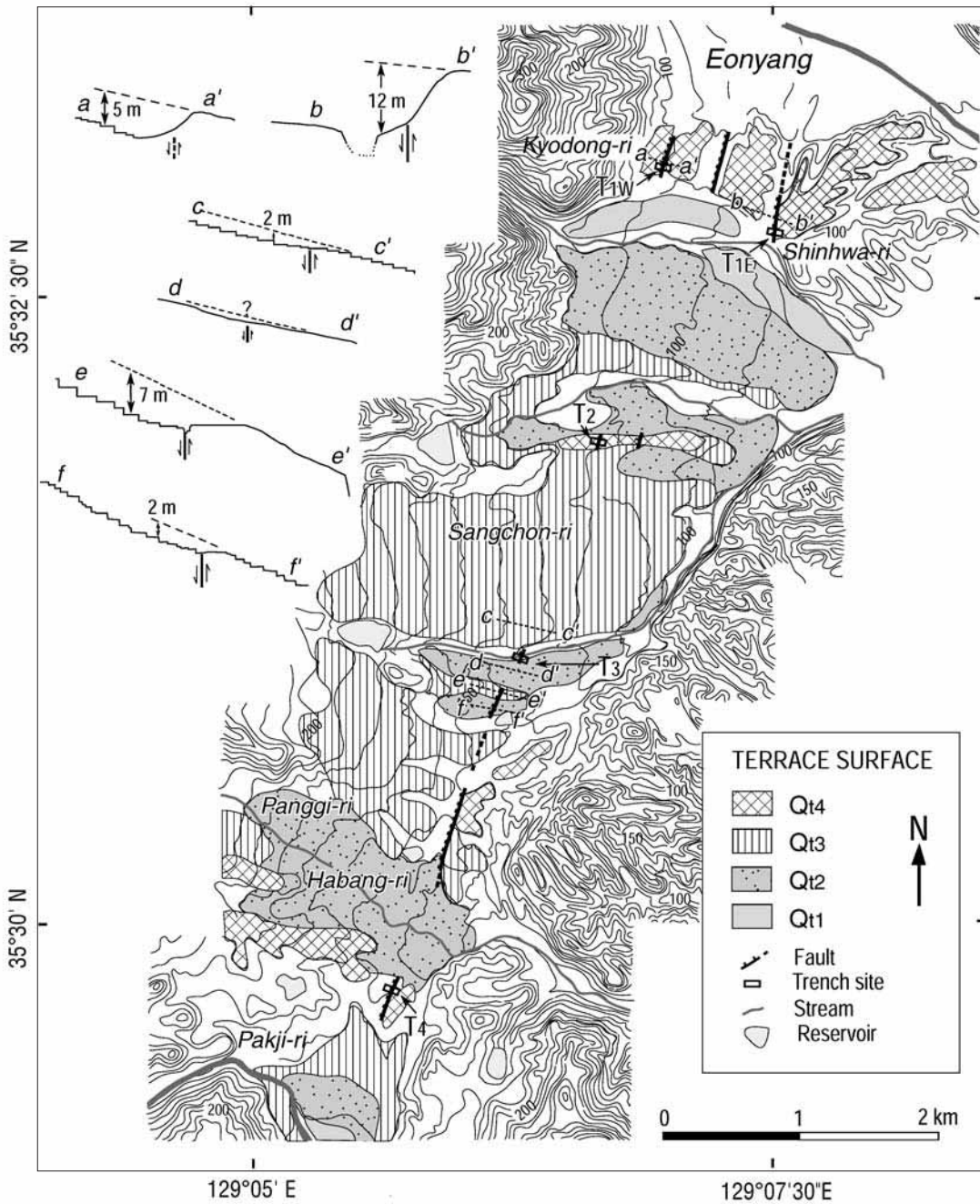


Fig. 6. Geomorphic map and topographic profiles in the southern part of Eonyang area, showing active faults and trench sites. The lines from a-a' to f-f' indicate topographic profiles.

ward about 80°N. The fault was covered with highly weathered reddish soil.

The total vertical displacement on the fault is about 12 m from the topographic profile. Although the fault has been active since deposition of Qt4 terrace gravel, its activity was probably not so high, judging from narrow cataclas-

tic and gouge zone. A road sub-parallel to the central strand of the fault made it impossible to make a trench. However, the fault scarp is as high as about 8 m with up-to-the-east displacement (Okada *et al.*, 1994). Several trenches were dug across the western strand of the fault, which has a 5 m high scarp. These trenches did

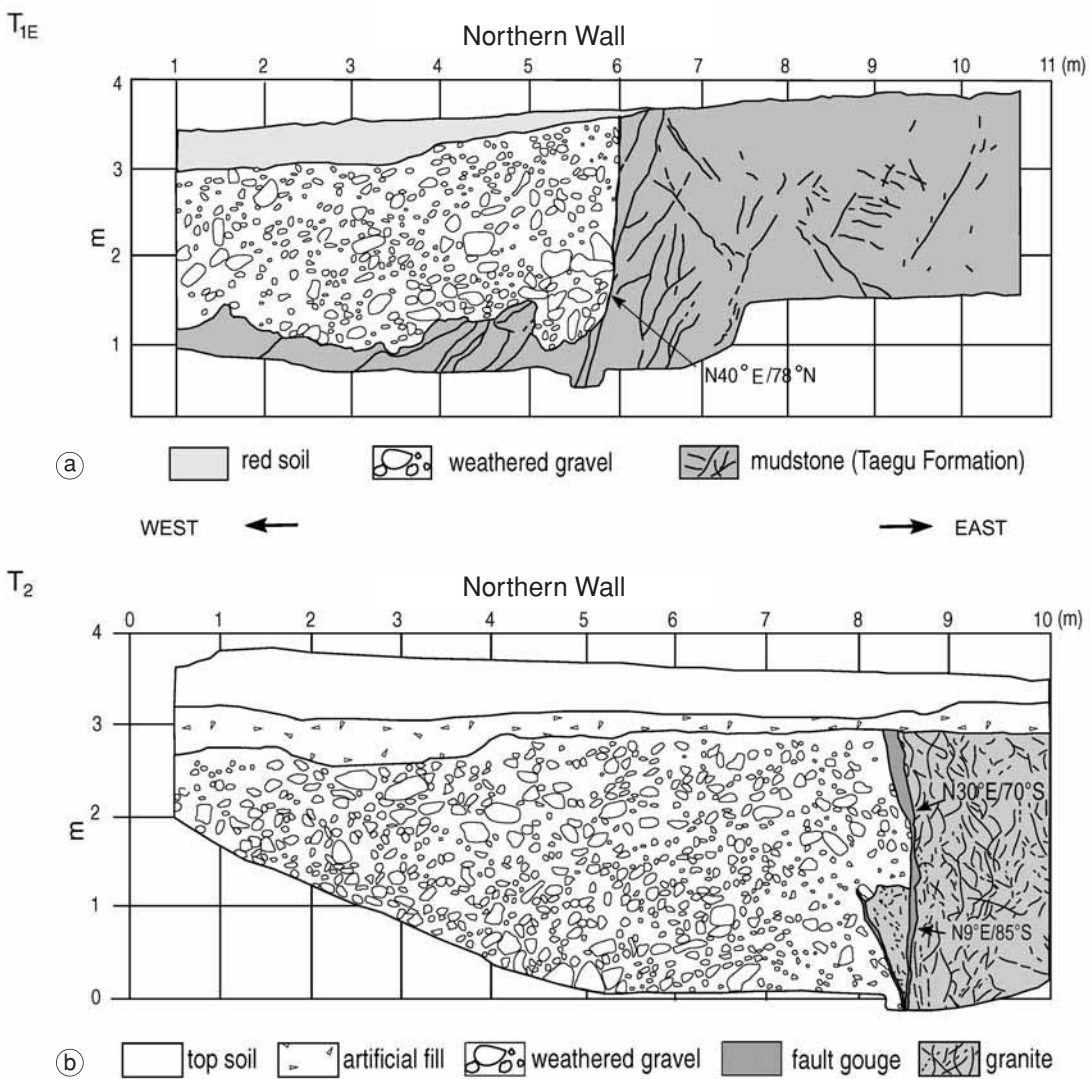


Fig. 7a,b. Sketches of the northern wall across the YSF at site T_{1E} (a) and T₂ (b) in fig. 6.

not expose a clear fault contact, but rather surficial reddish soil and highly weathered gravels were gently warped in to a westward-dipping monocline that formed after deposition of the Qt4 terrace gravels (Kyung *et al.*, 1999b).

The total vertical displacement on all three strands of the fault in this area is about 25 m.

3.2.2. Trench T₂

South of trench T₁, we identified two Quaternary fault splays in Qt4 terrace deposits that form a subtle monoclinical scarp (fig. 6). The eastern strand seems to be the main YSF and has a clear scarp and a zone of shattered rock that is tens of meters wide with a prominent fault gouge. Although the ground surface is modified, it shows vertical displacement of about 10 m on the fault. A highway close to the eastern strand made it impossible to trench here. So we excavated trench T₂ across the western strand. On this strand, the surface still has an east-side-up scarp that has a few meters of relief even though the surface has been modified artificially.

This subsidiary strand is parallel to and about 300 m west of the eastern fault. In the trench, the fault dipped 70-85°E and had a strike of N20-30°E. It defines the contacts between gravel of Qt4 deposits and granitic basement rock (fig. 7b) (Kyung *et al.*, 1999a). The fault is marked by a zone of clay fault gouge that is as wide as 20 cm and a cataclastic zone of about 1 m wide.

Striations on the fault plunge 20-30°N. Elongate gravel clasts near the fault are rotated parallel to the fault plane, and fault breccia in the gouge zone is elongated in the strike direction of fault. The *en échelon* arrangement of fault clay in the gouge zone indicates that recent fault movement has been predominantly right-lateral. The total amount of vertical displacement at this site is estimated to be about 10 m based on the offset of a gravel layer found in a drill hole. Thermoluminescence dating of the fault gouge suggests that the most recent movement on the fault is younger than about 100 ka (Kyung *et al.*, 1999a). But we could not find datable material in the terrace gravel to farther constrain the age of the faulting. The total ver-

tical displacement on these two strands of the fault in this area is more than 20 m.

3.2.3. Trench T₃

South of trench 2, we excavated a trench across the fault where it crosses Qt1 terrace deposits (Qt1), which are present only adjacent to the Sangcheon stream. The fault in this trench strikes N25°E and dips 80°SE. It separates highly weathered gravels (probably Qt4 alluvium) from Cretaceous granitic rock (fig. 8a). In the trench, the faulted Qt4 gravel is buried by about 1 m of unweathered gravel, which extends across the fault zone and is not displaced. Based on its unweathered character, this gravel is thought to be Holocene in age, but we could not find datable materials in this deposit. The topographic profile does not indicate a meaningful deformation across the fault strike. The stratigraphic relations in this trench show that the weathered gravel of probable Late Quaternary age is faulted, but younger Holocene (?) gravel is not faulted.

The zone of fault gouge in this trench is as wide as 20 cm and the zone of cataclastic rock is several meters wide. Stereographic projection of the long axes of elongate gravel clasts adjacent to the fault are oriented subhorizontally (angle of 0-30°), which is subparallel to striations in the fault gouge. These observations indicate that the predominant sense of motion on the fault has been right-lateral with a minor component of up-to-the-east reverse slip.

3.2.4. Trench T₄

At site T₄, Qt4 gravel across the estimated fault was excavated by Okada *et al.* (1994). Here, the up-to-the-east vertical displacement is estimated about 12 m based on a topographic profile. In this trench, the fault plane separates terrace gravels and basement rocks, strikes N25°E, and is nearly vertical (fig. 8b). The trench exposed a shattered zone several meters wide and typical fault gouge. The attitude of clasts in the gravel and elongation of clay fabric and breccia in the gouge zone suggest mainly strike-slip movement on the fault.

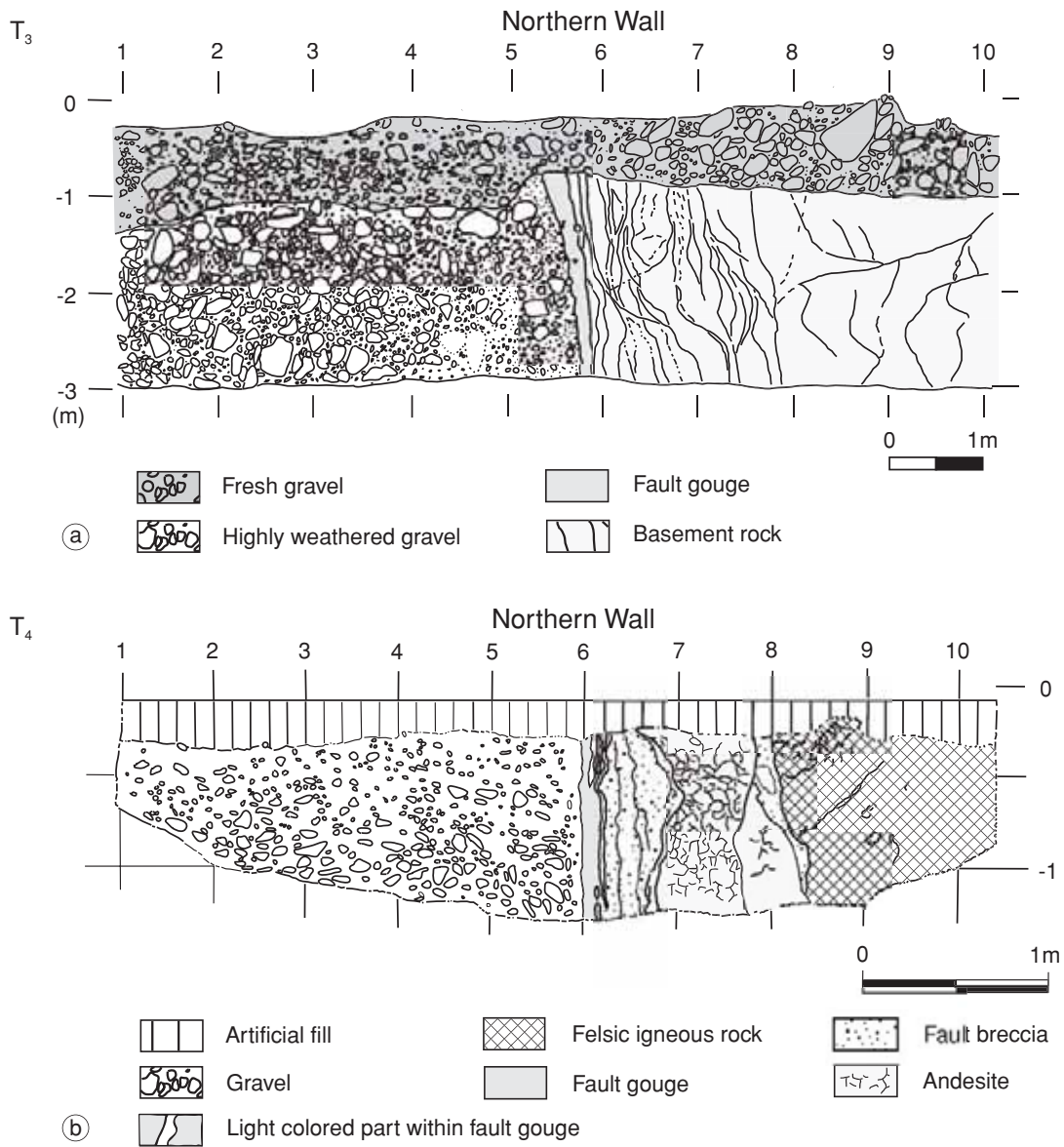


Fig. 8a,b. Sketches of the northern wall across the YSF at site T₃ (a) and at site T₄ (b) (after Okada, 1994) in fig. 6.

4. Discussion and conclusions

The YSF is a major structure in the southeastern Korea, and the data presented here provides new insight into Late Quaternary move-

ment on the fault. The fault's linear trace, its orientation with respect to the current compressive stress field, and slip indicators in several of the trenches described here all show that recent motion on the fault is dominantly right-lateral

strike-slip. However, the presence of prominent scarps locally along the fault and the evidence of reverse slip documented in several trenches indicates a significant component of compression on the fault. This combination of lateral and reverse faulting is common in many major strike-slip fault systems (*e.g.*, Van Dissen and Yeats, 1991).

4.1. Northern Yansang Fault

The northern part of the YSF (Yugye-ri area) is characterized by several fault strands, zones of shattered bedrock tens of meters wide, and a prominent zone of fault gouge as wide as 1 m. Eastward-plunging striations and stretching of gravel beds parallel to the fault plane indicate that recent movements have been mainly reverse slip. On terrace Qt2, reverse slip has formed a 1.5 m high scarp (fig. 3), and Holocene alluvial gravels are vertically offset about 0.5 m (fig. 5).

Based on the analysis of aerial photographs and field mapping, we recognize four terraces along this part of the YSF. The ages of individual terraces are only generally known, but estimating the age of these deposits permits us to generally estimate slip rates on the fault. The formation of major alluvial terraces is probably related to significant climate events in the Quaternary. The formation of marine terraces along the adjacent parts of the Korean coastline have been correlated with climatically related high stands of sea level, and the climatic conditions that produced these high stands may have also produced conditions favorable for the formation of alluvial terraces inland.

According to the general classification of river terrace in south Korea (Park and Kong, 2001), the high terrace surface formed during the Mindel glacial, the middle terrace surface during Riss glacial, and the lower terrace surface during the last glacial. Based on the relative height from the level of stream, the degree of weathering the gravel, and the characteristics of soil development, we can generally correlate the terraces as follows: Qt1 - last glacial (30-10 ka), Qt2 - early last glacial (30-70 ka), Qt3 - late Riss glacial (?), Qt4 - late Mindel glacial (about 450 ka?).

On the basis of the estimated ages of the terraces, the amount of vertical displacement on those terraces, the vertical slip rate on the northern section of the fault is in the range of about 0.03-0.05 mm/yr. We do not have data that permit us to estimate the amount of Quaternary lateral slip or a lateral slip rate. In the trench at site B (fig. 5), a humic silt that has an age of about 1314 cal years BP, has been offset by recent faulting. Thus the most recent event on this part of the fault occurred about A.D. 536 (table I; 2σ of A.D. 221-A.D. 667).

Historical accounts describe several strong, damaging earthquakes that have occurred in this part of the Korean Peninsula. These accounts indicate that strong earthquakes occurred in A.D. 304, A.D. 471, A.D. 510, and A.D. 630 (fig. 1). Although the two-sigma range of ages for this sample spans the time range for many of these events, the preferred calibrated age for this event (A.D. 536) may correspond to the historical accounts of a damaging earthquake in A.D. 510 that caused fatalities.

4.2. Southern Yangsan Fault

Locally, the southern part (Eonyand to Tongdo-sa) of the YSF consists of at least three strands. Fault scarps of different heights on Quaternary deposits of different ages are evidence of repeated Late Quaternary movements. The trace of the fault in this area is very linear, and the fault plane exposed in trenches is high angle to vertical. Fault motion in this area is mainly right-lateral strike-slip as shown by rotated clasts adjacent to the fault zone and striations on the fault plane. A component of reverse slip has elevated the eastern side of the fault and resulted in scarps that are more than 10 m high on terrace Qt4.

Based on the analysis of aerial photographs and field mapping, we recognize several sets of prominent terraces along parts of the YSF. The ages of individual terraces are only generally known, but estimating the age of these deposits permits us to establish general estimates of the slip rate. Jo (1997) approximately correlated the higher terrace (Qt4) to the Mindel period or Mindel/Riss interglacial period. Okada *et al.* (1994) estimated an age of 250-500 ka for terrace

Qt4, about 100 ka for terrace Qt3, and 30-60 ka for terrace Qt2. Based on the relative height of terraces above stream level, weathering of the gravel and characteristics of soil development, we can approximately correlate the terraces to the classification of river terraces (Park and Kong, 2001) as follows: Qt1 - last glacial (30-10 ka), Qt2 - early last glacial (30-70 ka), Qt3 - late Riss glacial (?), Qt4 - late Mindel glacial (about 450 ka?).

The cumulative amount of vertical offset on Qt4 deposits is about 25 m on all strands, and scarps as high as 2-7 m are present on Qt3 deposits. Scarps as high as about 2 m are present on Qt2 deposits. Using the height of scarps on terraces of different ages, the vertical slip rate is in the general range of 0.02-0.07 mm/yr. The lateral slip rate may be several times larger than the vertical rate, based on the observation of near the horizontal striation for the part of the fault between Eonyang and Tongdo-sa. The most recent event on this part of the fault is thought to be pre-Holocene in age based on the evidence of unfaulted deposits of probable Holocene age (fig. 8a) and the absence of any scarps in Holocene deposits.

Acknowledgements

I thank Anthony Crone for critical advices and reviews that led to substantial improvement of this paper. I am also grateful to two anonymous referees for their constructive comments on the original manuscript. The work was supported in part by KOSEF (Korea Science and Engineering Foundation) and by KIGAM (Korea Institute of Geoscience and Mineral Resources).

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